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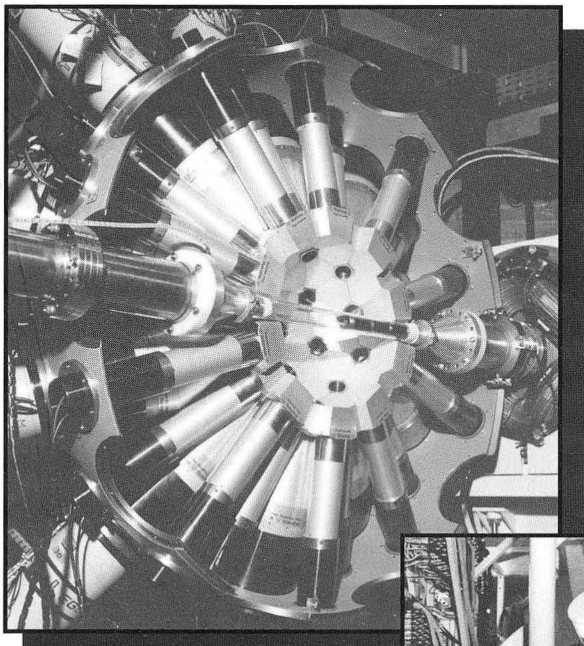
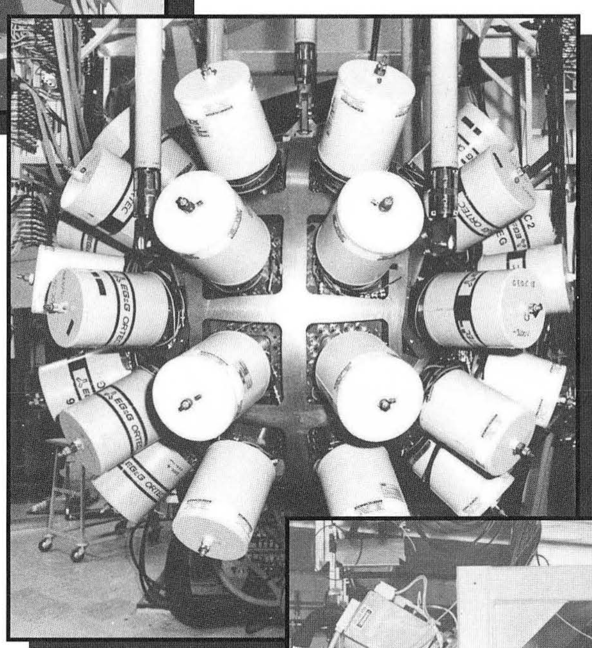
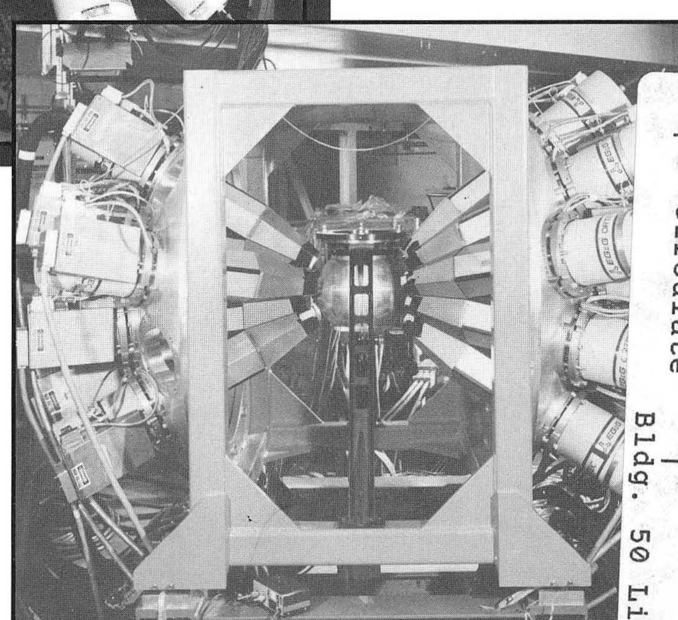
CONFERENCE ON PHYSICS FROM LARGE γ-RAY DETECTOR ARRAYS



Clark Kerr Campus
August 2–6 1994
Volume 1
Contributions





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CONFERENCE ON PHYSICS FROM LARGE γ-RAY DETECTOR ARRAYS

Clark Kerr Campus
Berkeley, California

August 2-6, 1994

Volume I
Abstracts

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Foreword

The Conference on "Physics from Large γ-ray Detector Arrays" is a continuation of the series of conferences that have been organized every two years by the North American Heavy-ion Laboratories. The aim of the conference this year is to encourage discussion of the physics that can be studied with such large arrays. These have been in operation for some time now and their success can be measured by the impressive number and quality of abstracts received. Volume I contains abstracts submitted by the participants. There are six experimental sections and within each section, where possible, we have tried to order the abstracts by increasing mass of the nuclei studied. Section VII covers theory, and for this section we have tried to group the abstracts by related topics in an order similar to that of the meeting sessions. Volume II will contain expanded versions of the topics presented by the speakers. We wish you an exciting and fruitful meeting!

The Organizing Committee

I. SUPERDEFORMED NUCLEI

II. NUCLEI AT "NORMAL" DEFORMATIONS

A New Island of Superdeformation in the A=80 Region

C. Baktash,[a] D.M. Cullen,[a] J.D. Garrett,[a] C.J. Gross,[a] N.R. Johnson,[a] W. Nazarewicz,[a] D.G. Sarantites,[b] J. Simpson,[c] T. Werner[a]

[a]*Oak Ridge National Laboratory*, Oak Ridge TN 37831-6371*
[b]*Washington University, St. Louis, MO 63130*
[c]*Daresbury Laboratory, Daresbury, Warrington, WA4 4AD, United Kingdom*

Medium-mass nuclei in the A=80 region manifest a remarkable diversity of shapes and rapid changes of collectivity with particle number and angular momentum. As such, they provide a strong challenge to the microscopic models. For example, although both cranked Nilsson-Strutinsky and Hartree-Fock calculations predict coexistence of non-collective spherical shapes with collective prolate, triaxial, oblate and superdeformed shapes in the light Sr isotopes, they differ significantly in details. Therefore, experimental studies of these novel shapes may provide information about the nuclear force (e.g., the spin-orbit potential), or the delicate balance between the microscopic and macroscopic forces which governs the emergence of superdeformation in certain mass regions.

In an experiment using the EUROGAM spectrometer at the Daresbury Laboratory, we have succeeded in establishing an extensive set of band structures in ^{82}Sr that includes a discrete superdeformed band. The observed superdeformed band consists of about ten discrete transitions, with energies in the range of ~1300-2650 keV. The top transition in this cascade corresponds to the largest collective rotational frequency yet observed. The separation energies of the gamma rays are nearly constant and about 150 keV, which corresponds to a deformation parameter of β~0.5 and an axis ratio of 2:1. Using the early implementation of the GAMMASPHERE, a ridge-valley structure with a similar gamma ray separation energy was recently observed in an experiment which populated mostly ^{83}Y and ^{80}Sr nuclei. It, thus, appears that there exists a new island of superdeformation which is centered around nuclei with particle numbers Z~38 and N~44. The experimental dynamical moments of inertia of these bands are in excellent agreement with the predictions of the microscopic-macroscopic cranking calculations, but are much smaller than the values obtained using the relativistic mean field approach.

*Managed by Martin Marietta Energy Systems, Inc. under contract DE-AC05-840R21400 with the U.S. Department of Energy.

ABSTRACT SUBMITTED TO THE CONFERENCE ON

PHYSICS FROM LARGE γ-RAY DETECTOR ARRAYS

Berkeley, California, August 2-6, 1994

An enhanced-deformation strongly-coupled band in ^{131}Pr*.

A. GALINDO-URIBARRI, D. WARD, V.P. JANZEN, D.C. RADFORD, *AECL, Chalk River*; T.E. DRAKE, *U of Toronto*; G. HACKMAN, S.M. MULLINS, N. SCHMEING, J. C. WADDINGTON, *McMaster U*; S. PILOTTE, *U of Ottawa*; I. RAGNARSSON, *Lund*.–

In the mass-130 region 'superdeformed bands' or 'enhanced deformation' (ED) bands seem to be concentrated mainly in even-Z nuclei (Ce-Nd-Sm-Gd). These bands exhibit regular sequences of E2 transitions with dynamical moments of inertia, $\mathcal{J}^{(2)}$, values ranging from 45 to 60 $\hbar^2$MeV^{-1}, and measured lifetimes indicating quadrupole moments in the range 4.0 to 7.5 eb. An enhanced-deformation (ED) rotational band with unusual characteristics has been discovered in the odd-Z nucleus ^{131}Pr. The $\mathcal{J}^{(2)}$ = 50-to-60 $\hbar^2$MeV^{-1} and the extracted quadrupole moment $Q_0 = (5.5 \pm 0.8)$ eb (β_2=0.32±.05) are comparable with other ED bands in the mass-130 region. The two signature partners of the ED band are connected by dipole transitions which can be followed down to a $K = 9/2$ band-head, which decays by a few strong transitions to the normal-deformed states. An unusual feature of the ED band in ^{131}Pr is the decay of a normal-deformed structure *into* the ED states. Results of a cranked Nilsson-Strutinski calculation with the modified oscillator potential will be presented.
To date, it has been widely accepted that the occupation of the highly alignable $i_{13/2}[660]_{1/2}$ neutron intruder orbital plays the crucial role in stabilising states with enhanced deformation by polarizing the core. Indeed, all such ED bands in this mass region are thought to have at least one $i_{13/2}$ neutron involved in their valence configuration. This band is unlike all other ED bands in the A~130 region in that the $i_{13/2}$ intruder neutron orbital is unoccupied. The experiment was performed at the Chalk River TASCC facility with the 8π γ-ray spectrometer. High-spin states in ^{131}Pr were populated via the reaction ^{98}Mo(^{37}Cl,4n) at 155 MeV.

* Work supported by AECL Research and NSERC (Canada).

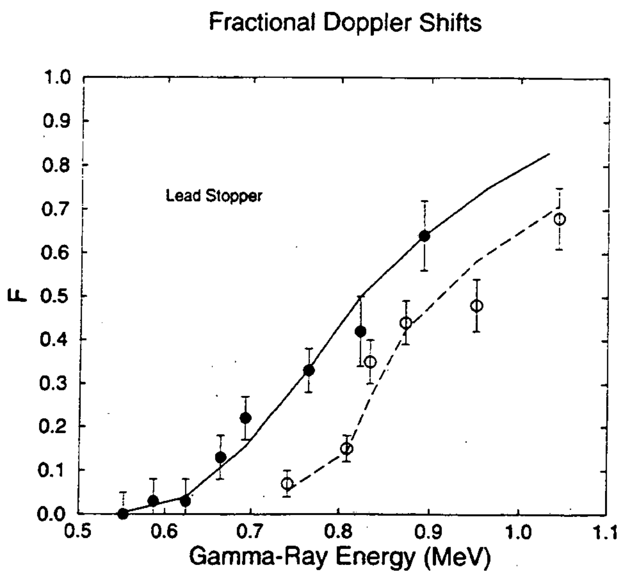


Figure 1: Fractional Doppler shifts of γ rays in the ED band (filled circles) and in the yrast band (open circles). The calculated curves were obtained assuming constant quadrupole moments Q_0 = 5.5 eb (solid line) and Q_0 = 3.9 eb (dashed line).

Three identical degenerate bands in the second minimum in ^{131}Ce

P. J. Nolan, C. W. Beausang, S. A. Forbes, E. S. Paul, A. T. Semple and J. N. Wilson
Oliver Lodge Laboratory, University of Liverpool, Liverpool, L69 3BX, U.K.

R. M. Clark, K. Hauschild and R. Wadsworth
Department of Physics, University of York, York, Y01 5DD, U.K.

J. Gizon, D. Santos, A. Gizon, C. Foin, J. Genevey and J. A. Pinston
Institut des Sciences Nucleaires, Grenoble, France.

B. M. Nyakó and L. Zolnai
Institute of Nuclear Research, Debrecen, Hungary.

High deformation bands in the second minimum in the potential well have been studied in ^{131}Ce. A band had been found previously with a measured deformation of $\beta = 0.35$ [1, 2]. This band has been assigned the configuration $\pi 5^4\ \nu 6^1$. The new bands have been found in an experiment using the EUROGAM I spectrometer at Daresbury. The reaction used to populate the states was ^{100}Mo (^{36}S, 5n) ^{131}Ce at a beam energy of 155 MeV using one thin ^{100}Mo target. A high statistics data set was obtained containing in excess of 2×10^9 for each of γ-γ, γ-γ-γ and γ-γ-γ-γ suppressed coincidence events.

Analysis of the data reveal a new band in ^{131}Ce with gamma-ray energy spacings and hence $\Im^{(2)}$ moment of inertia identical to the known band in ^{132}Ce. The ^{132}Ce band has a measured deformation of $\beta = 0.43$ [3] and has been assigned the configuration $\pi 5^4$ $\nu 6^2$. Further analysis of the data showed that all the gamma-ray peaks in the new band had widths (FWHM) of about 3 keV greater than other bands populated in the same reaction. The peaks have now been decomposed into three components each with the expected lineshape resulting in three identical degenerate bands. The structure of these bands is unclear. The similarity in $\Im^{(2)}$ to ^{132}Ce and the feed-out point of $\hbar\omega \sim 0.4$ MeV ($I \sim 20\hbar$) suggests they have a $\nu 6^2$ configuration. The orbitals available at the Fermi surface for the hole are the $\nu[411]\frac{1}{2}^+$ and the $\nu[523]\frac{7}{2}^-$. The various possibilities will be discussed.

[1] Y X Luo et al Z Phys A329 (1988) 125.

[2] Y He et al J Phys G16 (1990) 657.

[3] A Kirwan et al Phys Rev Lett 58 (1987) 467.

COMPARISON OF THE INTRINSIC QUADRUPOLE MOMENTS OF THE YRAST SUPERDEFORMED BANDS IN ^{131}Ce and ^{132}Ce

D. Ward, H.R. Andrews, A. Galindo-Uribarri, V.P. Janzen and D.C. Radford
AECL Research, Chalk River Laboratories, Chalk River, ON K0J 1J0, Canada

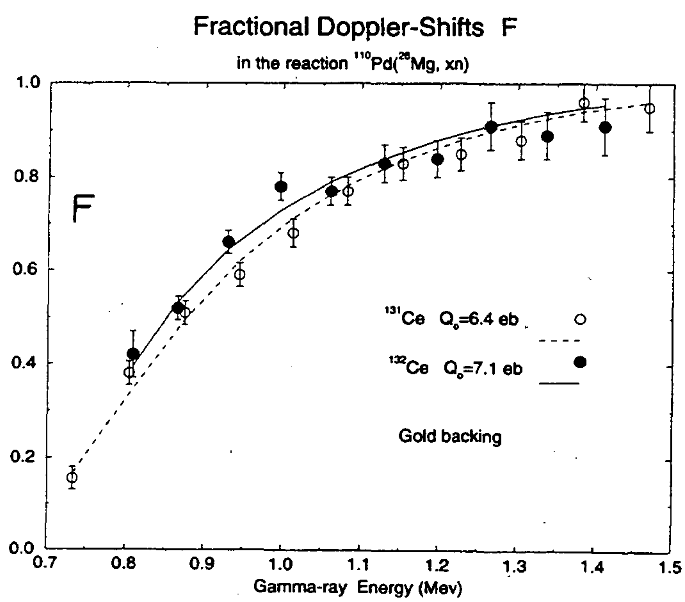
S.M. Mullins, S. Flibotte, G. Hackman and J.C. Waddington
Dept. of Physics and Astronomy, McMaster University, Hamilton, ON L8S 4M1, Canada

T.E. Drake, M. Cromaz and J. deGraaf
Physics Dept., University of Toronto, Toronto, ON M5S 1A7, Canada

An interesting question concerning the nature of deformation in nuclei is the relative importance of shell-gaps in the system of normal-parity states, versus the occupation of special unique-parity deformation-driving orbitals in determining the nuclear shape. Although these deep waters, e.g. [1,2], are unlikely to be fathomed by a single definitive experiment, it could be instructive to measure as precisely as possible any shifts of deformation that might be attributed to the occupation of special orbitals. To this end, we have remeasured the deformations (derived from intrinsic quadrupole moments) of the yrast superdeformed bands in ^{131}Ce and ^{132}Ce in a single experiment. The band in ^{132}Ce differs from that in ^{131}Ce only by the occupation of an N=6 neutron intruder orbital, which is strongly down-sloping with respect to deformation in a Nilsson diagram.

The reaction was ^{110}Pd + ^{26}Mg at 130 MeV incident, by which ^{131}Ce and ^{132}Ce were populated in 5n and 4n evaporations. The beam was provided by the TASCC facility at Chalk River Laboratories. Excited residues recoiled in a gold backing, and γ-ray lineshapes and centroid shifts (F values) to extract lifetimes were determined with the 8π spectrometer. In this experiment, systematic uncertainties, such as the treatment of the slowing down process, were expected to largely cancel.

Previous experiments performed by different groups gave $\beta_2 = 0.34 \pm 0.06$ [3] and 0.44 ± 0.04 [4], for ^{131}Ce and ^{132}Ce, respectively and suggest a large change in deformation. Our results based on the F values (c.f. Fig. 1) give deformations $\beta_2 = 0.36 \pm 0.02$ and 0.39 ± 0.02 where we include only statistical uncertainties. We conclude that the occupation of an extra N=6 orbital in ^{132}Ce has only a small effect on the deformation.



[1] M. Guidry and C.-L. Wu, Int. Journal of Modern Physics **2** (1993) 17.
[2] W. Nazarewicz, Int. Journal of Modern Physics **2** (1993) 51.
[3] Y. He *et al.*, J. Phys. **G16** (1990) 657.
[4] R.M. Diamond *et al.*, Phys. Rev. **C41** (1990) R1327.

Configurations of excited SD bands in ^{132}Ce and identical bands in the mass 130 region

J.Gizon[1], D.Santos[1], C.W.Beausang[2], R.M.Clark[3], J.Dudek[4], N.El-Aouad[4], C.Foin[1], S.A.Forbes[2], J.Genevey[1], A.Gizon[1], K.Hauschild[3], M.Józsa[1], W.Klamra[5], P.J.Nolan[2], B.M.Nyakó[6], E.S.Paul[2], J.A.Pinston[1], A.T.Semple[2], J.Simpson[7], R.Wadsworth[3], J.N.Wilson[2], L.Zolnai[6]

1 Institut des Sciences Nucléaires, Grenoble, France
2 Oliver Lodge Laboratory, University of Liverpool, Liverpool, U.K.
3 Departement of Physics, University of York, Heslington, U.K.
4 Centre de Recherches Nucléaires, Strasbourg, France
5 Manne Siegbahn Institute, Stockholm, Sweden
6 Institute of Nuclear Research, Debrecen, Hungary
7 SERC Daresbury Laboratory, Warrington, U.K.

Two excited superdeformed (SD) bands have been observed in ^{132}Ce. These bands were populated in the reaction ^{100}Mo(^{36}S,4n) at 155 MeV [1]. The experiment was performed at the NSF, Daresbury using the EurogamI gamma-ray spectrometer equipped with 42 escape suppressed HPGe detectors.

Configurations are proposed for these excited SD bands in terms of particle-hole excitation from a theoretical analysis based on the cranking approximation with the Woods-Saxon deformed potential: the most probable configurations correspond to the excitation of neutrons from the [523]7/2($\alpha = \pm 1/2$) orbitals to the [530]1/2($\alpha = -1/2$) orbital.

The yrast and excited SD bands known in ^{132}Ce[1,2] and ^{131}Ce[3,4] have been compared. As shown previously [5], various bands have the same $J^{(2)}$ dynamical moments of inertia and related gamma-ray energies. They are also characterized by incremental alignments [6] multiples of $\hbar/2$.

The present results will be discussed.

[1] D. Santos et al., to be published
[2] P.J. Nolan et al., J.Phys. G11(1985)L17
[3] Y.X. Luo et al., Zeit.Phys. A329(1988)125
[4] P.J. Nolan et al., this Conference
[5] J. Gizon, XIth Int. School on Nucl. Phys., Varna, Bulgaria (Oct.1993)
[6] F.S. Stephens et al., Phys.Rev.Lett. 65(1990)301

Polarisation effects within the second minimum

P. J. Nolan, C. W. Beausang, S. A. Forbes, E. S. Paul, A. T. Semple and J. N. Wilson
Oliver Lodge Laboratory, University of Liverpool, Liverpool, L69 3BX, U.K.

R. M. Clark, K. Hauschild and R. Wadsworth
Department of Physics, University of York, York, Y01 5DD, U.K.

A. Gizon, J. Gizon and D. Santos
Institut des Sciences Nucleaires, Grenoble, France.

A search has been carried out for bands in the second minimum in ^{133}Pr. The motivation was to study the proton orbitals in a neighbouring nucleus to ^{132}Ce where a superdeformed band has been known for some time.

The experiment was carried out using the EUROGAM I spectrometer and the ^{100}Mo (^{37}Cl, 4n) ^{133}Pr reaction at a beam energy of 155 MeV. A single thin ^{100}Mo target was used. The resulting data set contains greater than 2 x 10^9 for each of the γ-γ, γ-γ-γ and γ-γ-γ-γ suppressed coincidence events. Analysis of the data yielded four bands with $\mathfrak{J}^{(2)}$ values similar to those in the known superdeformed band in ^{132}Ce. One pair of bands is assigned to the $\pi[404]^9/_2^+$ orbital. These bands have dipole linking transitions, the branching ratios being consistent with the value expected for a $g_{9/2}$ proton. The other pair of bands arose from the $[532]^5/_2^-$ orbital. These are the only orbitals expected near the Fermi surface, so no other bands are expected at the same population intensity.

One interesting aspect of the data is the population distribution of the bands as a function of spin. The $g_{9/2}$ bands are equally populated and are more than double the intensity of the $h_{11/2}$ bands at low spins. At the highest spins the situation has reversed with the $h_{11/2}$ bands being more strongly populated. In addition the $h_{11/2}$ bands show signature splitting, both in energy and population intensity. One signature is populated at twice the level of the other. This behaviour can only be explained if the bands have differing deformations.

In order to confirm this an experiment is planned using the EUROGAM II array. The DSAM method will be used to determine the mean lifetimes and hence the quadrupole moments and deformations.

[1] A Kirwan et al Phys Rev Lett <u>58</u> (1987) 467.

Shape Co-Existance in ^{133}Ce at High Rotational Frequency

K. Hauschild, R. Wadsworth, R. M. Clark† and I. M. Hibbert
Department of Physics, University of York, Heslington, York Y01 5DD, UK

P. Fallon and A. O. Macchiavelli
Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, California 94720

D. B. Fossan, H. Schnare and I. Thorslund
Department of Physics, State University of New York, Stony Brook, New York 11794

P. J. Nolan, A. T. Semple and L. Walker
Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 3BX, UK

The recent work on the EUROGAM Phase I array has lead to a increase in our knowledge in the spectroscopy of the second minimum in the A∼130 mass region. In particular both neutron and proton excitations play an important role in the structure of many of the newly discovered superdeformed bands in ^{131,132}Ce [1] and ^{133}Pr [2]. These are the first excited superdeformed bands to be observed in this mass region. In order to obtain a more complete picture of the role played by the neutrons the high–spin states in ^{133}Ce have been studied in an experiment performed at the Lawrence Berkeley Laboratory using the early implementation of the **GAMMASPHERE** array. The reaction used to populate these states was ^{116}Cd(^{22}Ne,5n)^{133}Ce at a beam energy of 120 MeV.
Analysis of these data has revealed three new superdeformed bands in ^{133}Ce. Two of these bands have values of the dynamic moment of inertia, $\mathcal{J}^{(2)}$, similar to those in the known superdeformed band in ^{132}Ce [3]. Another interesting feature is that one of these new bands in ^{133}Ce has energies which are indentical to the yrast band in ^{132}Ce over a large frequency range. These similarities suggest that the two bands have a $\nu 6^2$ configuration with the odd neutron occupying either the favoured or unfavoured signature of the [530]1/2$^-$ orbital. The structure of the third band is still unclear at the present time.
In addition to these superdeformed bands three new structures, which extend to high rotational frequency ($\hbar\omega\simeq$0.85 MeV), have also been observed. These bands have energy spacings $E_\gamma\sim$100 keV. A comparison of the moments of inertia with the known oblate band in ^{133}Ce [4] suggest an oblate structure for these bands.

[1] J. Gizon and A. T. Semple et al., private communiction
[2] J. N. Wilson et al., private communiction
[3] P. J. Nolan et al., J. Phys. G11 (1985)L17
[4] R. Ma et al., Phys. Rev. C36 (1987)2322

† Present address;
Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, California 94720

Multiple highly deformed bands in the nucleus ^{134}Nd

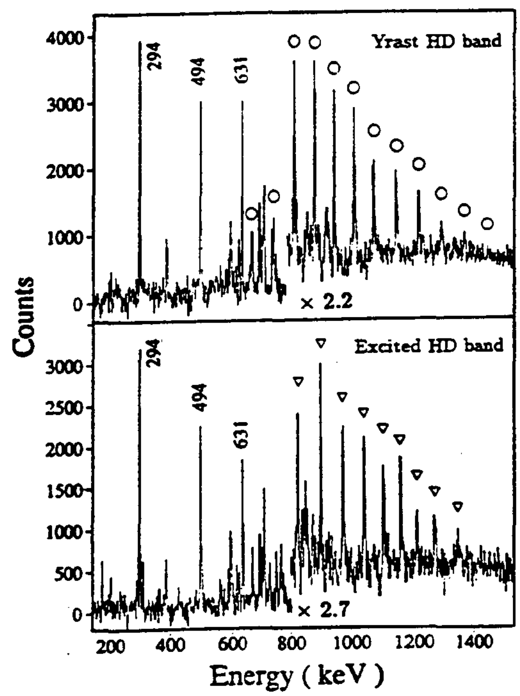
C. M. Petrache[1,3], G. de Angelis[1], D. Bazzacco[2], S. Lunardi[2], C. Rossi-Alvarez[2], D. Bucurescu[3], C. Ur[3], R. Wyss[4]

[1] INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy
[2] Dipartimento di Fisica and INFN, Sezione di Padova, Padova, Italy
[3] Institute of Physics and Nuclear Engineering, Bucharest, Romania
[4] Royal Institute of Technology, Physics Dept. Frescati, Stockolm, Sweden

Excited highly deformed (HD) bands are expected in the A=130 mass region for β= 0.35 as a prediction of cranked shell model calculations using a Woods-Saxon potential. We report here evidence of multiple bands in a nucleus of the A=130 mass region, namely ^{134}Nd, where no HD bands were previously known since the band which was assigned to this nucleus some time ago, turned out to be instead in the ^{131}Ce nucleus.

The states in ^{134}Nd were populated by the reaction ^{110}Pd(^{28}Si,4n)^{134}Nd at a beam energy of 130 MeV. The beam was provided by the Tandem XTU accelerator of Legnaro and gamma-rays have been detected using the GASP spectrometer. From the analysis of the data two rotational cascades of 12 and 11 transitions respectively have been found which have an energy spacing of about 70 keV, very similar to that of other HD bands of the A=130 mass region. The figure shows the two bands as obtained from a (2k)^3 symmetrized cube gating two times on the HD band members. The two bands are assigned to ^{134}Nd, since the only γ-lines present in the spectra, apart from the band members, are transitions deexciting known yrast states of ^{134}Nd.

The analysis of the spectra with gates on low lying yrast transitions in ^{134}Nd gives intensities of 1.5 % of the total population of ^{134}Nd for the band which we call yrast and 0.5% for the excited one. The HD band previously assigned to ^{134}Nd is also present in our data, however we can prove that it belong to the ^{131}Ce nucleus which is also populated in the reaction. The dynamical moment of inertia of the yrast HD band exhibits a broad "hump" at a rotational frequency $\hbar\omega \approx$0.45 MeV, which is a common feature of highly deformed (or superdeformed) bands in the neighbouring isotopes ^{133}Nd, ^{135}Nd and which can be attributed to the rotational alignment of a pair of $h_{11/2}$ protons. The dynamical moment of inertia of the excited band has a completely different behaviour since it presents a quite large and narrow hump at higher frequency, $\hbar\omega \approx$0.55 MeV, which requires a different explanation.



Superdeformation in $^{135-137}$Nd: New Results from GAMMASPHERE.

R.M.Clark[1], M.A.Deleplanque[1], J.A.Becker[2], M.Brinkman[2], B.Cederwall[1], R.M.Diamond[1], J.E.Draper[3], C.Duyar[3], P.Fallon[1], L.Farris[2], E.Henry[2], H.Hübel[4], J.R.Hughes[2], W.Korten[4], I.Y.Lee[1], A.O.Macchiavelli[1], E.Rubel[3], F.S.Stephens[1]

[1] Lawrence Berkeley Laboratory, Berkeley, California, 94720
[2] Lawrence Livermore National Laboratory, Livermore, California, 94550
[3] University of California, Davis, California, 95611
[4] Institut für Strahlen- und Kernphysik, Universtät Bonn, Nussallee 14–16, D-5300 Bonn, Germany

Superdeformation in the A$\sim$130 region is now well established. An energetically favourable shell structure and a strong polarizing effect on the core by the occupation $i_{13/2}$ neutron orbitals pull these nuclei to strongly deformed prolate shapes (β_2 $\sim$0.35).

A recent experiment on GAMMASPHERE, aimed at investigating superdeformation in $^{135-137}$Nd, has resulted in the observation of an excited SD band in ^{136}Nd. In addition all of the known yrast SD bands have been significantly extended. The new band lies at the half points of the ^{136}Nd yrast SD sequence, implying that there is an integer difference in alignment between the two structures. This unusual feature, along with the behaviour of all the other bands in $^{135-137}$Nd, will be discussed in terms of cranking model calculations.

A further exciting result, that will also be described, is the confirmation of the linking transitions from the ^{135}Nd SD band to the normal deformed states [1]. Over 65% of the in–band intensity has been accounted for. Angular correlation measurements have established the multipolarities of the linking γ–rays, confirming the previous spin assignments.

(1) E.M.Beck et al, Phys. Rev. Lett 58 (1987) 2182

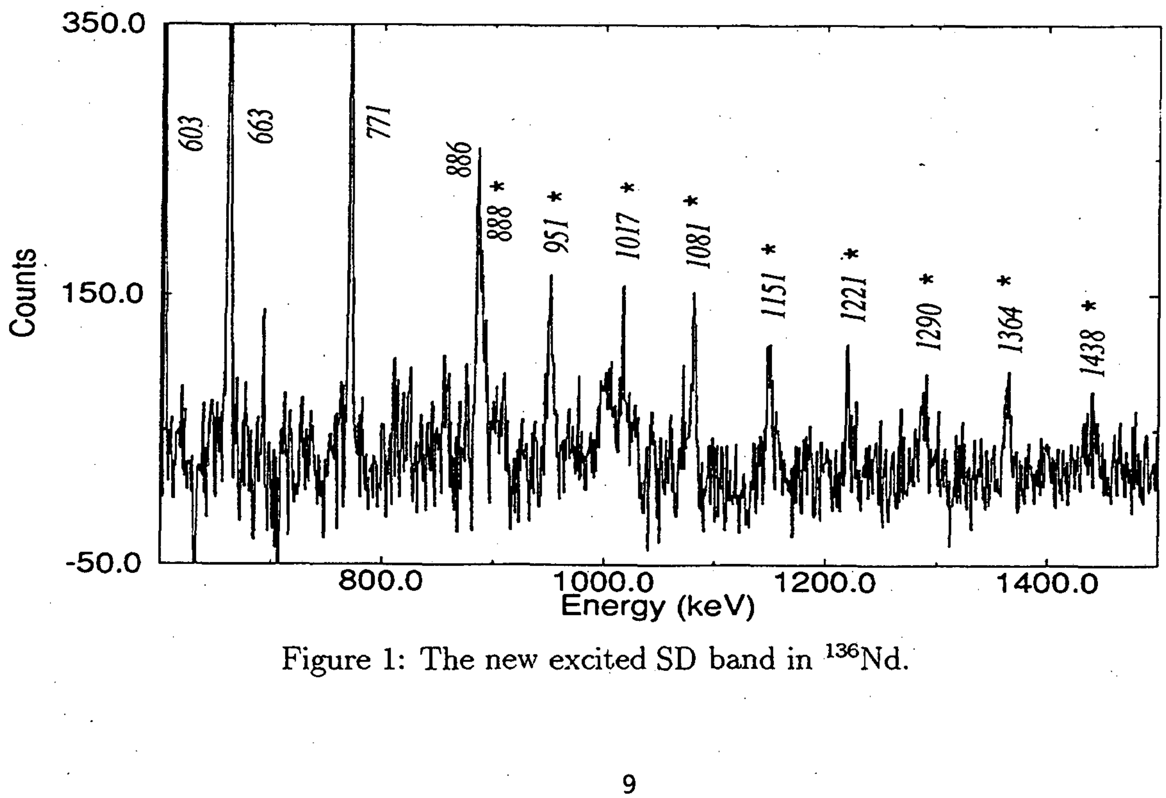


Figure 1: The new excited SD band in ^{136}Nd.

Decay of the highly deformed band of ^{137}Nd

S. Lunardi[1)], C.M. Petrache[2)], R. Venturelli[1)], D. Bazzacco[1)], D. Bucurescu[2)], G. de Angelis[3)], C. Rossi-Alvarez[1)], C. Ur[2)]

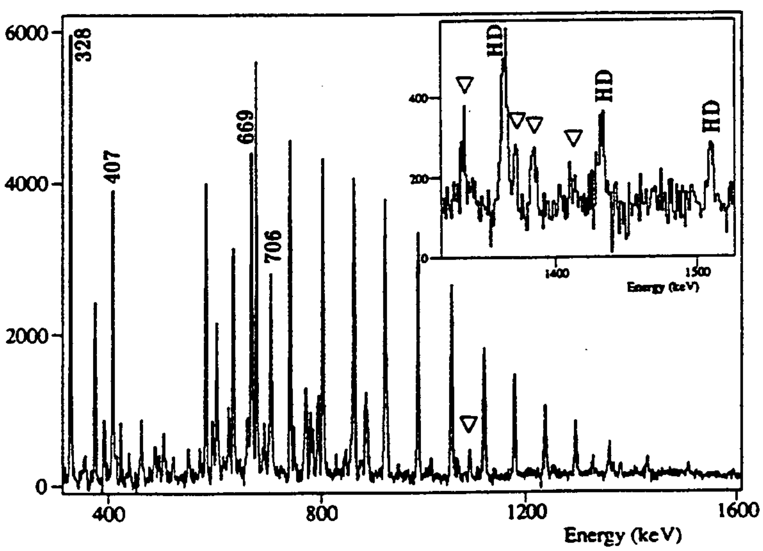
[1)] Dipartimento di Fisica and INFN, Sezione di Padova, Padova, Italy

[2)] Institute of Physics and Nuclear Engineering, Bucharest, Romania

[3)] INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy

In the nucleus ^{137}Nd an highly deformed band was found as in many other nuclei of the A=130-140 region. These bands originate from the collective rotation of highly deformed shapes predicted by potential energy surface calculations. The deformation associated with the second minimum has been extracted in many cases from lifetime measurements. For ^{137}Nd a deformation of β_2= 0.22 has been measured[1)] which is the smallest among the highly deformed bands in this region. In this nuclear region it is the occupation of the $i_{13/2}$ intruder orbital by the valence neutrons which drives the nucleus to a larger deformation. Calculations which consider the occupation of such orbital give for ^{137}Nd a deformation β_2 of 0.27-0.29. Since the measured value is much lower the possibility of the occupation of the $h_{9/2}$ has been discussed.

In order to understand the configuration of the band it is necessary to know excitation energy, spin and possibly parity of the levels of the band. We have studied the ^{137}Nd nucleus trough the ^{110}Pd(^{30}Si,3n) reaction at 125 Mev beam energy. Actually this beam energy has been chosen for the study of highly deformed bands in the nuclei ^{136}Nd and ^{136}Pr but the ^{137}Nd nucleus is also populated with appreciable cross-section. The GASP array with all 40 Compton suppressed Ge detectors has been used for a standard coincidence experiments where only triple or higher fold events have been collected. The highly deformed band of ^{137}Nd is populated in the reaction at the same level as that of the ^{136}Nd nucleus which is anyway the dominant reaction channel. This fact confirm earlier results on the odd-even dependence of the population of the HD bands in Nd nuclei. By proper selection of the BGO ball parameters and using the triples data we could obtain very clean spectra for both bands. High energy transitions (with a ΔI=1 character extracted from the DCO ratios analysis) have been found to connect the HD band of ^{137}Nd to the normal deformed states (see figure).



Four of them (1330, 1369, 1383 and 1412 keV) have been placed in the level scheme, thus fixing the excitation energies and the spins of the states of the HD band in ^{137}Nd. The lowest state of the band is at 4885 keV above ground state and has I = 29/2. The four linking transitions account for about 30% of the band intensity.

1) S. M. Mullins et al., Phys. Rev. **C45** (1992) 2683

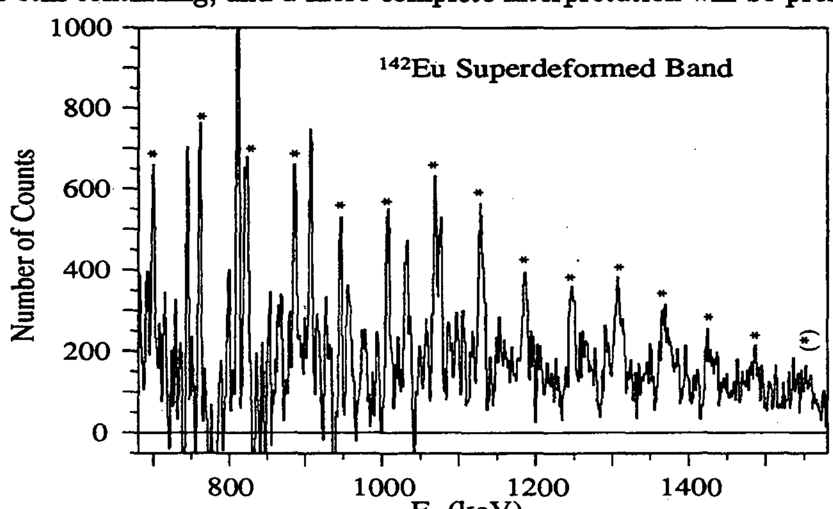
Studies of Superdeformation near N = 80

S.M.Mullins† and the 8π Consortium

†*Dept. of Physics and Astronomy, McMaster University, Hamilton, ON L8S 4M1, Canada*

Since the initial case of ^{143}Eu [1], superdeformed bands have been reported in two other N = 80 nuclei, namely ^{142}Sm [2] and ^{144}Gd [3]. We have recently found a superdeformed (SD) band in the next N = 80 isotone, ^{145}Tb, and a systematic picture of the proton configurations for the N = 80 SD bands has emerged. The behaviour of the $\mathcal{J}^{(2)}$ dynamic moments of inertia suggests that a proton band-crossing occurs in ^{144}Gd which is blocked in ^{143}Eu, ^{142}Sm and ^{145}Tb. Cranked Woods-Saxon-Strutinsky calculations [4] predict that the band-crossing in ^{144}Gd arises when a pair of N = 6 quasiprotons align, giving the band a $\pi 6^2$ intruder configuration. Since the first N = 6 orbital is occupied in both ^{143}Eu and ^{142}Sm, the crossing is blocked. The absence of the crossing in ^{145}Tb suggests that the intruder configuration is either $\pi 6^1$ or $\pi 6^3$. Comparison with Total Routhian Surface and Cranked Wood-Saxon calculations strongly suggest that the band only has the first proton-intruder occupied, and that the sixty-fourth and sixty-fifth protons reside in the $g_{9/2}[404]9/2^+$ orbital. New 8π-data on the next N = 80 isotone, ^{146}Dy, will be presented. We will also report on the search (in collaboration with the University of York, U.K.) for excited superdeformed-bands in ^{142}Sm with GAMMASPHERE.

Whether superdeformed bands occur when we move away from N = 80 has also been investigated. There is evidence for superdeformation in ^{144}Eu [5] from 8π-data, and new data taken with GAMMASPHERE should allow the determination of the effective-alignment of the $\nu 7_1$ intruder orbital. Recently we have found a ~1% superdeformed band in ^{142}Eu with the 8π-spectrometer (see below). The lack of a signature-partner suggests that the hole in the N = 80 closed-shell probably occurs in the the 6_4 neutron orbital. The analysis of the band is still continuing, and a more complete interpretation will be presented.



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Bandcrossings in the Superdeformed Nucleus ^{144}Gd

S. Lunardi[1)], D. Bazzacco[1)], C. Rossi-Alvarez[1)], P. Pavan[1)], G. de Angelis[2)], D. De Acuna[2)], M. De Poli[2)], G. Maron[2)], J. Rico[2)], S. Utzelmann[3)], P. Hoernes[3)], W. Gast[3)], R. M. Lieder[3)], O. Stuch[4)], D. Weil[4)], W. Satuła[5)], R. Wyss[5)]

[1)] Dipartimento di Fisica and INFN, Sezione di Padova, Padova, Italy

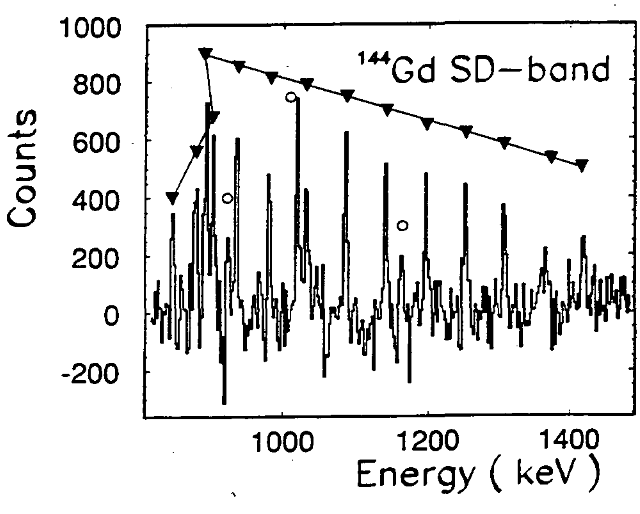
[2)] INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy

[3)] Institut für Kernphysik, KFA Jülich, Jülich, Germany

[4)] Institut für Kernphysik der Universität Köln, Köln, Germany

[5)] Royal Institute of Technology, Physics Dept. Frescati, Stockolm, Sweden

In an experiment performed recently with the GASP array we have been able to observe for the first time a superdeformed (SD) band in the nucleus ^{144}Gd using the reaction ^{100}Mo + ^{48}Ti at 221 MeV beam energy [1]. As expected the intensity of the band is very small being only $\approx$ 0.2 % of the total population of the ^{144}Gd nucleus. The figure shows the SD band as it emerges by gating twice on the transitions assigned to the band into a cube obtained from triples and higher fold data. From the figure it is evident that the band undergoes a backbending at $\hbar\omega$=0.45 MeV, where the band intensity is still at its maximum. The decay-out of the band is occurring over three transitions and starts just at the backbending. Utilizing the method first used by Atac et al. [2], we have searched for two step transitions connecting the SD band to the normal deformed states. Seven of these possible two-step transitions could be placed into the level scheme of ^{144}Gd. Assuming an E1 character for all the decay transitions, a spin value of 21 $\hbar$ is the most probable for the lowest SD band level. The observed backbending at $\hbar\omega$ = 0.45 MeV is interpreted as a band crossing phenomenon related to the alignment of a proton pair in the N=6 $i_{13/2}$ orbital. This band crossing is well reproduced by calculations with a Wood-Saxon potential treating both pairing and deformation selfconsistently. A second band crossing is predicted by calculations at $\hbar\omega$ = 0.75 MeV which is related to the occupation of the aligned N=7 neutrons. Experimentally we see a small rise at the highest frequency, which could be taken as an indication of the onset of the next crossing. This crossing will drive the nucleus to an even larger deformation. Further experiments are planned in order improve the statistics at the backbending and to possibly observe also the second crossing at $\hbar\omega$ = 0.75 MeV.



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Study of Superdeformation in ^{146}Gd

C. Schumacher[1], O. Stuch[1], T. Rzaca–Urban[2], P. von Brentano[1], A. Dewald[1], A. Georgiev[3], R.M. Lieder[3], F. Linden[4], J. Lisle[4], J. Theuerkauf[1], W. Urban[4], S. Utzelmann[3], D. Weißhaar[1]
[1]Univ. zu Köln, [2]Warsaw University, [3]KFA Jülich, [4]University of Manchester

We carried out an experiment at the tandem accelerator of the NFS at Daresbury (UK) to study superdeformation in ^{146}Gd using the reaction ^{102}Ru(^{48}Ca, 4n)^{146}Gd at 203 MeV. In two days, about 700 million high fold events were recorded with the EUROGAM spectrometer consisting of 45 Compton-suppressed Ge detectors. Both known superdeformed bands [1], [2] in ^{146}Gd could be expanded to 15 transitions. All transitions within each band were clearly observed in coincidence with each other and accurate γ-ray energies were determined. A further band with energies corresponding to the first known SD band in ^{147}Gd was also observed in the data. Several methods to search for new bands were tested. The results clearly show the advantages of three- and four-dimensional spectra analysis for the study of superdeformation.

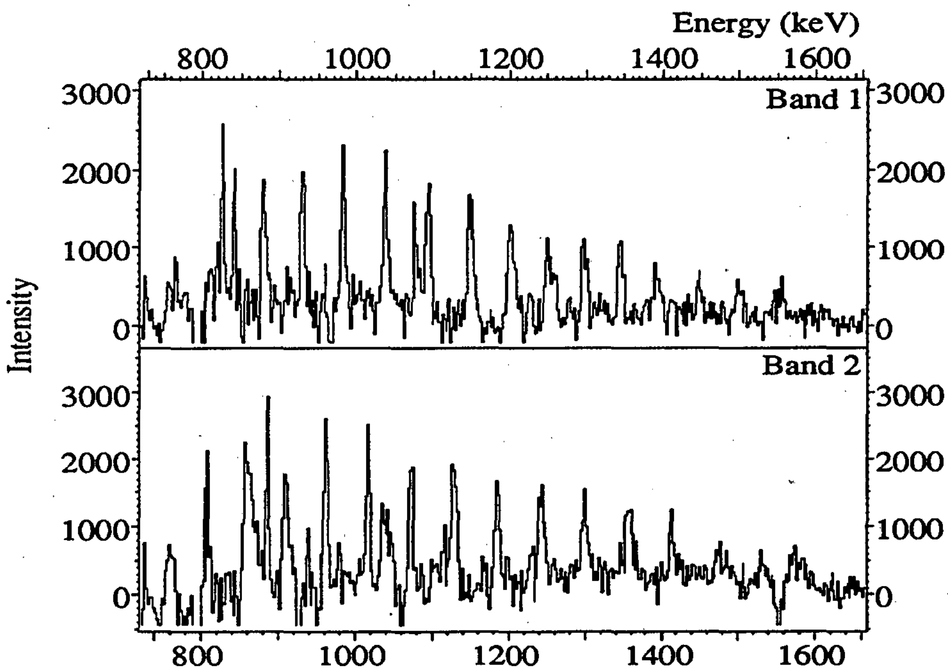

Figure 1: Sum spectra of the two superdeformed bands in ^{146}Gd obtained from triple data. In both cases the 8 cleanest gates have been added.

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Intrinsic Quadrupole Moments for the two Superdeformed Bands in ^{146}Gd

J. Altmann[1)], D. Weil[1)], P. Sala[1)], M. Luig[1)], M. Eschenauer[1)], S. Albers[1)], A. Dewald[1)], K.O. Zell[1)], P. von Brentano[1)], W. Gast[2)], R.M. Lieder[2)], D. Bazzacco[3)], C. Rossi Alvarez[3)], M. De Poli[4)], G. Maron[4)], J. Rico[4)], G. Vedovato[4)], N. Blasi[5)], G. Lo Bianco[5)]

1) IKP University of Cologne, Germany, 2) IKP Jülich, Germany
3) INFN Sezione di Padova, Italy
4) INFN Laboratori Nazionali di Legnaro, Italy
5) Dipartimento di Fisica and INFN Sezione di Milano, Italy

In ^{146}Gd up to now two superdeformed bands were found first by Hebbinghaus *et al.* (1) and later by the Chalk–River/Strasbourg–Collaboration (2). For the first time a bandcrossing in a SD–band was discoverd by Hebbinghaus *et al.* (1) in the first SD–band. Up to now in the A=150 mass region 19 SD bands have been found which could be described in a consistent way by Ragnarsson (4) in the framework of standard Nilsson–Strutinsky cranking model calculations neglecting pairing. In his interpretation the bandcrossing in the first SD–band of ^{146}Gd is due to the crossing of the s.p. orbitals $[642, \alpha = -1/2]$ and $[651, \alpha = -1/2]$ which is in contradiction to the configuration proposed by Hebbinghaus *et al.* (1). In his calculations Ragnarsson obtained values for the intrinsic quadrupole moments Q_0 which agree quite well with the experimentally deduced ones except that of the second SD–band in ^{146}Gd. In order to investigate further this problem, we performed a thick target experiment at the GASP spectrometer with the aim of measuring the E2 strength of the two SD–bands, for which only results with quite large experimental errors have been obtained so far (1,3).

The experiment was performed at an early stage of the GASP spectrometer with 32 Compton suppressed Ge detectors and with the 80 BGO detectors of the inner ball. The $^{122}Sn(^{29}Si, 5n)$ reaction was used at beam–energies of 155 MeV and 158 MeV.

It was possible to determine the quadrupole moments for both SD–bands, by comparing the measured with the calculated F–factors (fractional Doppler-shift) for several Q_0's. For the first SD–band our value of Q_0 agrees within the errors given with that determined in (3) but we could reduce the experimental error by a factor of two. The value of $Q_0 = (8 \pm 2)$ eb for the second SD–band given by (3) is in contradiction with the result of this work.

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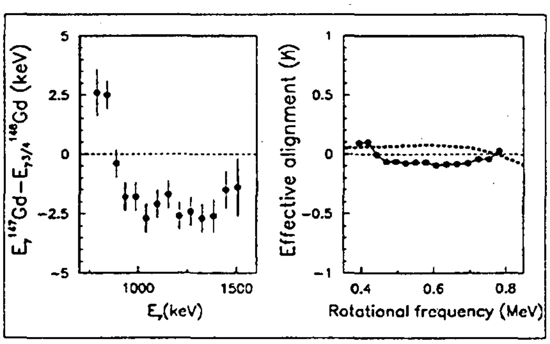
Neutron excitations in ^{147}Gd superdeformed nucleus.

J.P. Vivien[1], I.Ragnarsson[3], C.W.Beausang[2], F.A.Beck[1], G.Bélier[1], Th.Byrski[1], D.Curien[1], P.J.Dagnall[2], D.Disdier[1], G.Duchêne[1], G.de France[1], S.Flibotte[4], B.Haas[1], B.Herskind[5], N.Khadiri[1], B.Kharraja[1], S.Leoni[6], J.C.Merdinger[1], A.Nourredine[7], B.Nyako[8], C.M.Petrache[1], D.Prévost[1], V.Rauch[1], H.Savajols[1], Ch.Theisen[1], P.J.Twin[2], L.Wei[1] and K.Zuber[9].

[1] *Centre de Recherches Nucléaires, F-67037, Strasbourg CEDEX-2, France.*
[2] *Oliver Lodge Lab., Univ. of Liverpool, L69 3BX, United Kingdom.*
[3] *Dept. of Mathematical Physics, Lund Institute of Technology, S-22100 Lund, Sweden.*
[4] *Dept. of Physics and Astronomy, McMaster Univ., Hamilton, Ontario, Canada M5S 1A7.*
[5] *Niels Bohr Institute, Tandem Accelerator Lab., DK-4000 Roskilde, Denmark.*
[6] *Dept. of Physics, Univ. of Milano, Milano, Italy*
[7] *Dept. of Physics, Chouaib Doukkali Univ., BP20 El-Jadida, Morocco.*
[8] *Institute of Nuclear Research, Berm tér 18/c, H-4001 Debrecen PF51, Hungary.*
[9] *Institute of Nuclear Physics, Pl-342 Kracow, Poland.*

The ^{147}Gd nucleus has been studied using the EUROGAM array installed at the Daresbury Nuclear Structure Facility. High spin states were populated by the ^{30}Si+^{122}Sn reaction at a silicon beam energy of 158 MeV with two stacked self-supporting targets of 400μg/cm^2 each. SD bands have been investigated using the quadruple coincidence data set . Configurations $\pi(6)^2$,$\nu(7)^1 + \nu(6)^2$, with two neutrons either in the [642]5/2 α=$\pm\frac{1}{2}$ for the yrast band or in the [642]5/2 α =-$\frac{1}{2}$ and [651]1/2 α=-$\frac{1}{2}$ for the first excited band where the crossing of these two levels is blocked, reproduce quite well the experimental data (J^2 moment of inertia and effective alignments of band (1) and (2)) * A new SD band with 14 transitions has been observed. Their energies are identical with the triquarter-point energies of the ^{148}Gd yrast SD band to within 2 keV.



Left:
Transition energy differences between the new ^{147}Gd band and the triquarter-point of ^{148}Gd (1).

Right:
Experimental effective aligment compared to that calculated for ^{148}Gd (1) with the [411]1/2 α=+1/2 orbital empty (heavy dashed line).

The absence in the data of a band identical with the quarter-point energies of ^{148}Gd (1) suggests a signature splitting of the orbital concerned. Calculations of the Nilsson-Strutinsky type with cranking using a modified oscillator potential have been performed. With increasing deformation, the [411]1/2 orbital comes closer to the Fermi surface. Effective alignment and J^2 moment of inertia, promoting a neutron from the [411]1/2 α=+1/2 to the [651]1/2 α=-1/2 orbital, fit the experimental values observed for this new band.

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Excited superdeformed bands in ^{148}Gd

G. de Angelis◇, M. Sferrazza•, D.Bazzacco•, D.De Acuna•, M. De Poli◇, S.Lunardi•, G. Maron◇, D.Napoli◇, P.Pavan•, J.Rico◇, C.Rossi-Alvarez•, G.Vedovato◇, B. Rubio▷, R. Wyss◁

◇*INFN, Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy*
•*Sezione INFN and Dipartimento di Fisica dell'Università, Padova, Italy*
▷*Instituto de Fisica Corpuscular, Valencia, Spain*
◁*Royal Institute of Technology, Dept. of Physics Frescati, Stockolm, Sweden*

In a recent experiment at GASP, we obtained results on the decay out of the yrast superdeformed band into the normal deformed states of the ^{148}Gd nucleus [1]. Detailed spectroscopic studies have also been performed in order to characterize excited SD bands in ^{148}Gd. The nucleus was populated in the reaction ^{124}Sn(^{29}Si,5n)^{148}Gd at beam energies of 147 and 158 MeV. About 0.7×10^9 triples and higher fold events were collected for each run. After unfolding, a total of 2×10^9 triples and 0.5×10^9 quadruples events were obtained. Six SD rotational bands have been observed in the ^{148}Gd nucleus. Four of them are reported here for the first time while two, the yrast (band 1) and the first excited (band 2), have been extended to higher angular momenta by 4 and 2 transitions respectively. A very interesting feature is observed: one of the new bands (band 3) is seen clearly in coincidence with the five lowest transitions of the first excited band. In the Gd nuclei the properties of the SD bands have been interpreted by successive occupation of the [642]5/2, [651]1/2, Nilsson orbitals and of one N=7 intruder orbital. In the case of ^{148}Gd, the lowest SD bands are formed via a particle hole excitation from the [651]1/2 Nilsson orbital into the 7^1 orbital[2]. The small hump of the moment of inertia J^2 vs $\hbar\omega$ at ~0.6 MeV in band 2 has been explained by a crossing of the $\alpha = -1/2$ branch of the [642]5/2 and [651]1/2 orbitals. The new band (band 3) that we observe in coincidence with the first excited band (band 2) might be the continuation of the [651]1/2 branch, which decays at the crossing point, where the two bands get mixed. Analogously, we suggest that band 4 is the signature partner of band 3 (i. e. a hole in the [651]1/2 α=+1/2 orbital). Band 5 shows a dynamic moment of inertia similar to that of the yrast SD band in ^{152}Dy and of one excited band of ^{149}Gd [3] which are interpreted as $\nu 7^2$ (+,0). However, these assignments are only tentative, and a detailed study of the decay properties might shed new light on the systematics of the SD bands in the Gd-region. Further experiments are planned in the near future in order to get improved data both at high spin as well as at the decay out.

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C_4 Symmetry and Bifurcation in a Superdeformed Band of ^{149}Gd

I. M. Pavlichenkov
Russian National Center "Kurchatov Institute", Moscow, 123 182, Russia
and
S. Flibotte
Department of Physics and Astronomy, McMaster University, Hamilton, ON L8S 4M1, Canada
AECL Research, Chalk River Laboratories, Chalk River, ON K0J 1J0, Canada

An unexpected ΔI=4 staggering was recently reported in the yrast superdeformed band of ^{149}Gd [1]. This feature suggests the presence of a small perturbation which is invariant under a rotation of 90° around the rotation axis (C_4 symmetry). The observed quantum effect is analogous to a C_4 bifurcation in classical mechanics [2].

The local character of the considered critical phenomenon allows one to obtain a universal Hamiltonian [2] describing the lowest quantum states near the critical angular momentum I_c.

$$H_{C_4} = E_0(I) + \alpha(I - I_c)\frac{I_3^2 - I^2}{I^2} + a\left(\frac{I_3^2 - I^2}{I^2}\right)^2 + c\frac{I_+^4 - I_-^4}{I^4} \tag{1}$$

The first term $E_0(I)$ represents the regular part of the nuclear Hamiltonian and $I_\pm = I_1 \pm iI_2$ are the ladder operators. The quantification axis is the 3-axis which is perpendicular to the long deformation axis of the prolate nucleus. The remaining C_4 Hamiltonian has been diagonalized and the lowest energy levels have been compared with the experimental data in order to deduce the parameters α, I_c, a and c. The results of a χ^2 minimization are shown in figure 1 together with the experimental staggering data. All the important features of the experimental data are reproduced: 1) there is a spin region where the staggering effect is small followed by 2) large ΔI=4 oscillations and 3) an inversion of the oscillating pattern at high spin. This inversion is produced by the crossing of the two lowest sub-bands described by the Hamiltonian (1). This is characteristic of a local bifurcation of the C_4 type. The calculations predict that the magnitude of the oscillations should continuously increase after the phase inversion.

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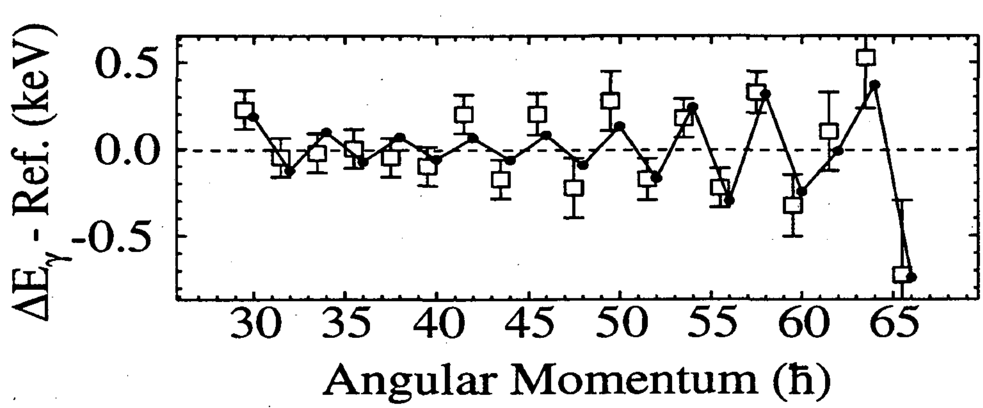

Figure 1: Energy differences ΔE_γ between two consecutive γ-ray transitions of the superdeformed band in ^{149}Gd as a function of angular momentum after subtraction of a smooth reference given by $\Delta E_\gamma^{ref}(I) = [\Delta E_\gamma(I+2) + 2\Delta E_\gamma(I) + \Delta E_\gamma(I-2)]/4$. Empty squares refer to the experimental data assuming the theoretical spin assignments of Ragnarsson [3]. Filled circles correspond to a calculation performed with the phenomenological theory of the local C_4 bifurcation [2] with the parameters $\alpha = -0.6$, $I_c = 45$, $a = 725$ and $c = 354$.

Pair Excitations and a Proton Band-Crossing in Superdeformed ^{150}Gd.

P. Fallon[1], C.W. Beausang[2], S. Clarke[2], P.J. Twin[2], F.A. Beck[3], Th. Byrski[3], D. Curien[3], P.J. Dagnall[2], G. deFrance[3], G. Duchêne[3], P.D. Forsyth[2], B. Haas[3], M.J. Joyce[2], A.O. Macchiavelli[1], E.S. Paul[2], J.F. Sharpey-Schafer[2], J. Simpson[4] and J.P. Vivien[3].
and
S. Åberg[5] and W. Nazarewicz[6,7]

[1] *Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley CA 94720, U.S.A.* [2] *Oliver Lodge Laboratory, University of Liverpool, L69 3BX, United Kingdom.* [3] *Centre de Recherches Nucléaires, F-67037 Strasbourg CEDEX, France.* [4] *SERC Daresbury Laboratory, Warrington, WA4 4AD, United Kingdom.* [5] *Department of Mathematical Physics, Lund Institute of Technology, S-22100 Lund, Sweden* [6] *Joint Institute for Heavy Ion Research and Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, U.S.A* [7] *Department of Physics, University of Tennessee, Knoxville, TN 37996, U.S.A.*

High spin states in ^{150}Gd were populated by the reaction ^{26}Mg $+^{130}$Te at a beam energy of 149 MeV. The Eurogam spectrometer was used to record the coincident γ-ray energies. An unsuppressed Ge fold $\geq$7 was required before accepting an event and the resulting event rate was $\sim 5\times 10^3$ events per second. A total of $\sim 1\times 10^9$ suppressed coincidence events with Ge fold $\geq$3 were obtained.

Five SD bands, assigned to ^{150}Gd, have been observed in this data set. Four of the SD bands have been reported previously, the fifth is the subject of this abstract. The new band in ^{150}Gd (band 5) has an intensity of $\sim$40% relative to the yrast SD band (band 1). Above E_γ=1 MeV the transition energy spacing for band 5 is regular ($\Delta E_\gamma \approx$ 49 keV) and thus its dynamical moment of inertia, $\Im^{(2)} \equiv 4\hbar^2/\Delta E_\gamma$, is constant as a function of rotational frequency ($\hbar\omega \equiv E_\gamma/2$) and similar to that of the yrast SD band (band 1) in ^{152}Dy. Since the $\Im^{(2)}$ moment of inertia is sensitive to the occupation of specific high-N intruder states, band 5 in ^{150}Gd is assigned the same intruder configuration ($\pi 6^4 \nu 7^2$) as ^{152}Dy band 1. In addition, at high spins, the transition energies in band 5 are similar to those in ^{152}Dy band 1. The most likely excitation, involving two N=6 protons, can be associated with the two-particle two-hole (2p-2h) proton excitation from the $[301]\frac{1}{2}$ level to the $[651]\frac{3}{2}$ intruder level and thus, at least at high spins, the configuration of band 5 is considered to be two proton holes in the ^{152}Dy yrast SD core.

However it is the differences, rather than the similarities between ^{150}Gd band 5 and ^{152}Dy band 1 which are most interesting. At $E_\gamma \sim 1$ MeV the transition energy spacing becomes irregular, in addition the peaks at $\sim$997 and $\sim$996 keV are broader than the neighboring SD transition peaks. The extra intensity carried by these transitions is consistent with them being SD doublets. Based on this information we suggest that ^{150}Gd band 5 is undergoing a backbend in this region. Band 5 is seen to decay through the proposed backbending region.

It is interesting to note that the spectrum gated by band 5 contains peaks which have the same energy as the low spin transitions observed in ^{150}Gd band 1. These band 1 transitions show an increase in intensity (as a function of decreasing spin) which is consistent with the decay of band 5. Thus these data may also include evidence for the decay of the excited SD band 5 into the yrast SD band.

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Excited Superdeformed Bands in ^{150}Tb.

P.Fallon[1], C.W.Beausang[2], D.Nisius[3], R.V.F.Janssens[3], S.Asztalos[1], M.Bergstrom[2], M.Carpenter[3], B.Cederwall[1], S.Clarke,[2] B.Crowell[3], M.A.Deleplanque[1], R.M.Diamond[1], R.G.Henry[3], T.L.Khoo[3], T.Lauritsen,[3] I.Y.Lee[1], A.O.Macchiavelli[1], F.S.Stephens[1], P.J.Twin[2].

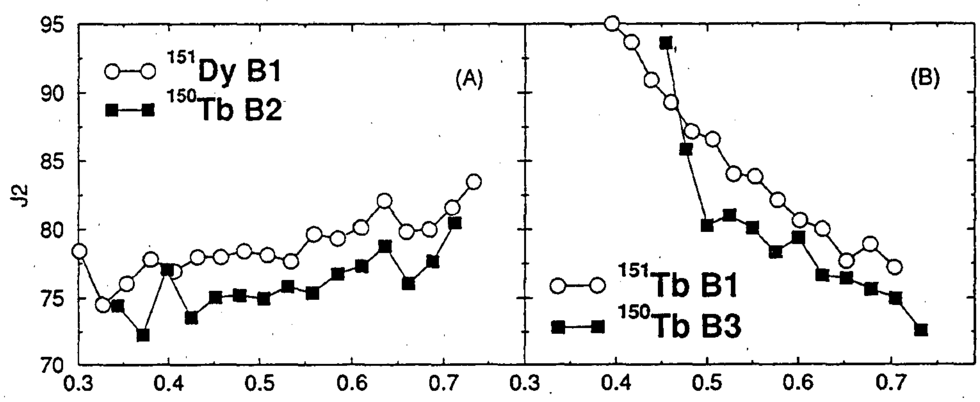
[1]*Lawrence Berkeley Laboratory, Berkeley CA 94720, USA.* [2] *Liverpool University, Liverpool L69 3BX, UK.* [3]*Argonne National Laboratory, Argonne IL 60499, USA.*

An experiment to study SD states in ^{150}Tb was performed at the Lawrence Berkeley Laboratory 88 cyclotron using the reaction ^{31}P+^{124}Sn at a beam energy of 167 MeV using the early implementation of the GAMMASPHERE detector array. Approximately 1×10^9 fold$\geq$3 suppressed Ge events were collected.

In total, three SD bands have been observed in this data set, one of which (band 1) has been reported previously [1] and has been assigned a $\pi 6^3 \nu 7^1$ high-N intruder configuration. Bands 2 and 3 are interpreted as excited SD bands and were observed for the first time in this data set.

The $\Im^{(2)}$ curve (fig. A) for ^{150}Tb band 2 is reduced, by a constant amount, relative to that in ^{151}Dy band 1 [2]. Since the 3rd N=6 intruder is calculated [3] to contribute a constant amount to the total $\Im^{(2)}$ over the frequency range of interest, the properties of band 2 are consistent with a particle-hole excitation from the favoured signature of the [651]3/2 ($\alpha = +\frac{1}{2}$) proton intruder (3rd N=6) orbital into the unfavoured signature [651]3/2 ($\alpha = -\frac{1}{2}$) (4th N=6), i.e., band 2 is a proton intruder hole in the ^{151}Dy band 1 SD configuration.

The $\Im^{(2)}$ (fig. B) of ^{150}Tb band 3 exhibits a similar slope to that seen in ^{151}Tb band 1 [4], except at the lowest frequencies. In this case, the intruder configuration ($\pi 6^3 \nu 7^2$) is the same as in ^{151}Tb band 1 and the hole is in the [651]3/2 orbital. The rise in $\Im^{(2)}$ at low frequencies can be interpreted as a quasineutron (N=7) band-crossing. Similar observations, concerning both the rise and the relative comparisons in the $\Im^{(2)}$ moments of inertia, have also been reported for the pair of SD bands in ^{149}Gd band 2 [5] and ^{150}Gd band 1 [4].



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Neutron Excitations Accross the N=86 Shell Gap and Unfavoured Proton Signature Partners Excited Superdeformed Bands in ^{151}Tb

F. A. Beck[(1)], T. Byrski[(1)], D. Curien[(1)], G. Duchêne[(1)], G. de France[(1)], B. Haas[(1)], B. Kharraja[(1)], J. C. Merdinger[(1)], C. M. Petrache[(1)], D. Prévost[(1)], C. Theisen[(1)], J. P. Vivien[(1)], C. W .Beausang[(2)], S. Clarke[(2)], P. J. Dagnall[(2)], S. Forbes [(2)], P. D. Forsyth[(2)], J. F. Sharpey-Schafer[(2)], P. J. Twin[(2)], P. Fallon[(3)], S. Flibotte[(4)], Z. Fulop[(5)], A. Kiss[(5)], J. C. Lisle[(6)], I. Ragnarsson[(7)], J. Simpson[(8)], and K. Zuber[(9)]

[(1)] *Centre de Recherches Nucléaires, IN2P3-CNRS/Université Louis Pasteur F-67037 Strasbourg Cedex, France*

[(2)] *Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 3BX, United Kingdom*

[(3)]*Nuclear Science Division, Lawrence Berkeley Laboratory, 1 Cyclotron Road, Berkeley, California 94720*

[(4)] *Department of Physics and Astronomy, McMaster University, Hamilton, Ontario L8S 4M1, Canada*

[(5)] *Institute of Nuclear Research, Bem tér 18/c, H-4001 Debrecen PF51, Hungary*

[(6)]*Schuster Laboratory, University of Manchester Manchester M139PL, United Kingdom*

[(7)] *Department of Mathematical Physics, Lund Institute of Technology, P. O. Box 118, S-221 00 Lund, Sweden*

[(8)]*Science and Engineering Research Council, Daresbury Laboratory, Daresbury, Warrington WA4 4AD, United Kingdom*

[(9)]*Institute of Nuclear Physics, PL-31-42, Krakow, Poland*

Abstract

Using the Eurogam array, seven excited superdeformed (SD) bands have been observed in the nucleus ^{151}Tb. Three of these have been interpreted as a single proton excitation whereas the four remaining ones suggest the promotion of the last neutron from a high-N into low-N orbitals. Data for the proton excited SD bands have been compared with recent fully self-consistent relativistic calculations and this shows large disagreement. Furthermore, if the signature partner of the yrast configuration has been most probably identified, a doubt remains about the possible observation of the signature partner of the first excited SD band which originated, a few years ago, the field of identical bands. The other four bands have been extensively studied in the frame of a systematic investigation of neutron excitation across the N=86 shell gap also observed in several neighbouring nuclei. It turns out that most of these bands exhibit the characteristic features of degenerate signature partners. Furthermore the present investigation shows that pairing correlations may still play a role even at high spin.

"Identical" SD Band in ^{151}Dy and the Pseudospin Coupling Scheme

D. Nisius[1,3], R.V.F. Janssens[1], P. Fallon[2], B. Crowell[1], I. Ahmad[1], M.P. Carpenter[1], B. Cederwall[2], P.J. Daly[3], M.A. Deleplanque[2], R.M. Diamond[2], Z.W. Grabowski[3], R.G. Henry[1], T.L. Khoo[1], T. Lauritsen[1], I.Y. Lee[2], A.O. Machiavelli[2], R.M. Mayer[3], F.S. Stephens[2], P.J. Twin[4]

1: Argonne National Laboratory, Argonne, IL 60439 2: Lawrence Berkeley Laboratory, Berkeley, CA 94720 3: Purdue University, West Lafayette, IN 47907 4: Oliver Lodge Laboratory, U. of Liverpool, Liverpool L693BX, United Kingdom

Using the early implementation phase of GAMMASPHERE, superdeformed (SD) bands have been studied in ^{151}Dy with the ^{122}Sn(^{34}S,5n) reaction at a beam energy of 175 MeV. These are the reaction conditions under which the yrast SD band of ^{151}Dy was first discovered by Rathke et al[1]. In the present measurement, all triple and higher order coincidence events between compton suppressed Ge detectors were recorded. The total number of events recorded was 1.3×10^9.

Five SD bands have been observed in ^{151}Dy. In addition to the yrast SD band (band 1) reported in ref. 1, four new bands with dynamic moments of inertia J(2) similar in magnitude to that seen in band 1 were found. These four SD bands have respective intensities of 39(7), 30(5), 20(7) and 13(4)% relative to the intensity of band 1. The yrast SD band carries about 1% of the total γ-ray flux reaching the^{151}Dy ground state.

The J(2) moments of inertia of the new SD bands can be compared with those of neighboring nuclei. In particular, two of them (bands 2 and 4) exhibit a clear relation to the ^{152}Dy yrast SD band [2]: the transition energies in band 2 lie at the 3/4 point energies of those seen in ^{152}Dy over a wide frequency range, while the transition energies in band 4 lie at the mid-way points over the entire frequency range. No obvious relation appears to exist for bands 3 and 5. It should be noted that the average J(2) values measured in band 5 are somewhat smaller than those of the four other bands.

Following the first report of SD bands with identical transition energies in the pairs (^{151}Tb*,^{152}Dy), (^{150}Gd*,^{151}Tb) and (^{153}Dy*,^{152}Dy)[3,4] (where * denotes an excited SD band), it was proposed by Nazarewicz et al [5] that the observations could be understood in a strong-coupling approach if the pseudo SU(3) symmetry was invoked. The two first pairs mentioned above are interpreted as proton excitations involving the $[\tilde{2}\tilde{0}\tilde{0}]1/2$ orbital coupled to the ^{152}Dy core which result in an a=+1 decoupling parameter. The (^{153}Dy*,^{152}Dy) pair involves a [514]9/2 neutron excitation in ^{153}Dy with a decoupling parameter a=0. Band 4 reported here can be associated with the $[\tilde{3}\tilde{1}\tilde{0}]1/2$ neutron hole excitation relative to a ^{152}Dy core predicted in ref. [5], and corresponds to a decoupling parameter a=-1. This long-sought SD band provides further support for the applicability of the pseudospin coupling scheme in the description of identical SD bands near ^{152}Dy.

This work is supported by the U.S. Department of Energy under contracts W-31-109-ENG-38, DE-AC03-76F00098 AND DE-FG02-87ER40346.

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[2] P.J. Twin et al., Phys. Rev. Lett. 57 (1986) 811.
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[4] J.K. Johansson et al., Phys. Rev. Lett. 63 (1989) 2200.
[5] W. Nazarewicz et al., Phys. Rev. Lett. 64 (1990) 1654.

Excited Bands in the Doubly-Magic Superdeformed ^{152}Dy Nucleus: Band Talk, Band Interaction and Evidence for the First N=7 Proton Hyper-Intruder Orbital

C.W. Beausang[1], P.J. Dagnall[1], P.J. Twin[1], M.A. Bentley[2], F.A. Beck[3], Th. Byrski[3], S. Clarke[1], D. Curien[3], G. Duchene[3], G. deFrance[3], P.D. Forsyth[1], B. Haas[3], E.S. Paul[1], J. Simpson[4], J. Styczen[5] , J.P. Vivien[3], and K. Zuber[5]

[1] Oliver Lodge Laboratory, University of Liverpool, L69 3BX, United Kingdom.

[2] School of Sciences, Staffordshire University, Stoke-on-trent, United Kingdom.

[3] Centre de Recherches Nucleaires, IN2P3-CNRS/Universite Louis Pasteur, F-67037 Strasbourg, Cedex, France.

[4] SERC Daresbury Laboratory, Daresbury, warrington, WA4 4AD, Cheshire, United Kingdom.

[7] Institute of Nuclear Physics, PL-31-42, Krakow, Poland.

Following a recent Eurogam Phase 1 experiment five excited superdeformed bands have been observed in the doubly closed-shell superdeformed nucleus ^{152}Dy.

Three of the new bands are interpreted in terms of single neutron excitations across the N = 86 shell gap. The other two excited SD bands are believed to involve single proton excitations across the Z = 66 shell gap. In particular a proton excitation into the N = 7 [770]1/2 intruder orbital has been identified. This is the first evidence of the influence of this deformation driving 'hyper-intruder' orbital in the superdeformed minimum. At $\hbar\omega \sim 0.5$ MeV the dynamic moment of inertia for this band shows a large deviation. This behaviour is characteristic of a band crossing and can qualitatively be explained by a crossing between the [770]1/2 and [530]1/2 proton orbitals. This crossing is reminiscent of the low frequency pseudo-crossing previously observed in two SD bands in ^{193}Hg [1] where the presence of octupole correlations in SD shapes was invoked to understand the alignment gain, interaction frequency, interaction strength, etc.

One of the neutron excited bands, assigned the $\pi 6^4 \nu 7^3$ high-N intruder configuration, appears to partly decay into the yrast superdeformed band (configuration $\pi 6^4 \nu 7^2$) as well as to states in the normal deformed minimum. A forthcoming Eurogam Phase 2 experiment is planned in which we hope to identify the discrete transitions linking these two SD bands and hence measure the relative excitation energy of the bands, In addition, using the linear polarisation sensitivity of the new array, we hope to measure the electric or magnetic nature of the SD $\rightarrow$ SD linking transitions and hence establish the parity of the excited band.

The analysis of the data is in progress and the latest results will be presented.

1 D.M. Cullen *et al*, Phys. Rev. Lett.**65**, 1547, (1990).

Search for Linking Transitions Between the Superdeformed and Normal Deformed States in ^{152}Dy using Eurogam

M.A.Bentley[a], P.J.Dagnall[b], C.W.Beausang[b], P.J.Twin[b], A.Atac[c], F.Beck[d], T.Byrski[d], S.Clarke[b], D.Curien[d], G.Duchene[d], G.DeFrance[d], P.D.Forsyth[b], B.Haas[d], B.Herskind[e], J.A.Hodgkinson[a], J.C.Lisle[f], B.M.Nyako[g], J.Nyberg[c], E.S.Paul[b], J.Simpson[h], J.Styczen[i], J.P.Vivien[d] and K.Zuber[i].

(a) School of Sciences, Staffordshire University, Stoke-on-Trent, U.K.
(b) Department of Physics, University of Liverpool, L69 3BX, U.K.
(c) Svedberg Laboratory, Uppsala University, Box 533, S-75121, Uppsala, Sweden.
(d) CRN Strasbourg, 67037 Strasbourg Cedex, France.
(e) Neils Bohr Institute, Riso, DK-4000, Denmark.
(f) Schuster Laboratory, University of Manchester, M13 9PL, U.K.
(g) INR Hungarian Academy of Sciences, H-4001 Debrecen, Pf51 Hungary.
(h) SERC Daresbury Laboratory, Daresbury, Warrington, WA4 4AD, Cheshire, U.K.
(i) Institute of Nuclear Physics, Krakow, Poland.

Abstract

One of the outstanding questions in high spin nuclear structure is that of the mechanisms by which superdeformed states decay into the normal-deformed yrast structures. Indeed, this problem has been one of the driving forces towards the construction of the modern generation of γ-ray spectrometers. An experiment was performed on Eurogam I to search for these transitions in ^{152}Dy.

^{152}Dy is an ideal case for the study of these decays as the states into which the yrast superdeformed band decays are well known and non-yrast. Additionally the existence of the $I^{\pi} = 17^{+}$ isomer in ^{152}Dy allows clean selection of the reaction channel. The data set contained 4.5 billion triple γ-ray coincidences and very clean spectra of the yrast superdeformed band were obtained. In this data no definite candidates for discrete linking transitions have been identified. An approach involving the study of sums of two γ-rays observed in coincidence with the superdeformed band was employed (see for example reference 1). Summed γ-ray transitions have been identified which are believed to correspond to pathways between the superdeformed and normal deformed minima. It has to date proved difficult to place these transitions in the decay scheme and hence determine the spins and excitation energies of the superdeformed states. The analysis of the data is progressing and the latest results will be presented.

[1] *A.Atac et al.* Phys. Rev. Lett. **70**(1993)1069

HYPERDEFORMATION IN ^{152}Dy

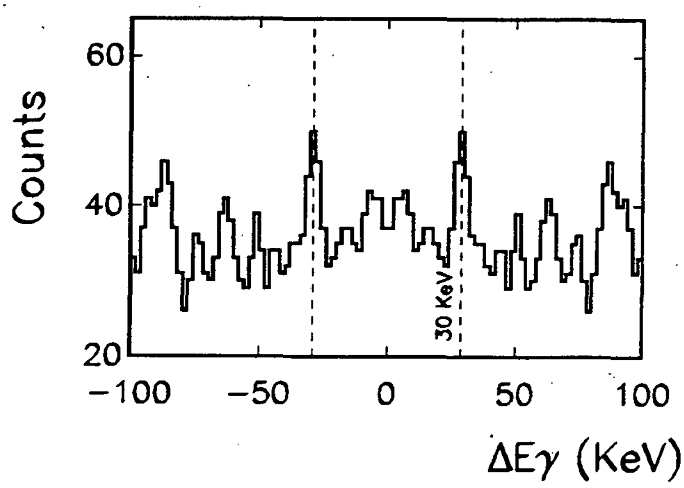
FROM PROTON-GAMMA COICIDENCE EXPERIMENTS

M. Lunardon[1)], D. Bazzacco[1)], R. Burch[1)], G. de Angelis[2)], M. De Poli[2)], D. Fabris[1)], E. Fioretto[2)], S. Lunardi[1)] , N. Medina[1], G. Nebbia[1)], G. Prete[2)], J. Rico[2)],C. Rossi-Alvarez[1)], G. Vedovato[2], G. Viesti[1)]

[1)] Dipartimento di Fisica and INFN, Sezione di Padova, Padova, Italy
[2)] INFN Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy

The first evidence for hyperdeformed (HD) nuclear shape was recently reported in the reaction 187 MeV ^{37}Cl + ^{120}Sn [1]. A ridge structure at $\Delta E_\gamma = E_{\gamma 1}$ - $E_{\gamma 2} = \pm 30 \pm 3$ keV was evidenced in a proton gated $E_{\gamma 1}$-$E_{\gamma 2}$ matrix. Furthermore, a cascade of 10 discrete lines with the same spacing was suggested. We have performed a new measurement using the same reaction at the GASP spectrometer. 800 millions of γ-γ-γ Ge coincidences were collected in a 8 days long run. From those events only 25 millions were in coincidence with protons detected in a large solid angle ($\sim$20% of 4π) light particle hodoscope. We have observed the ridge at 30 keV in the same energy range and using the same cuts in fold and sum energy of the BGO ball as in ref. 1 . The $E_\gamma \geq 1250$ keV region was also explored by summing a grid of 6 cuts each 5 keV wide. A well defined maximum in the ridge intensity is observed when the grid includes transitions having energies $\sim 1263 + (n \times \Delta)$ keV with $\Delta = 30$ keV. Such energies are compatible with those listed in ref.1 for the proposed members of the HD band. Furthermore, γ-γ matrices were produced setting gates on the prominent discrete lines of different Dy isotopes. We found that the bulk of the 30 keV ridge events generated by the above grid is present in the matrix gated with the ^{152}Dy transitions as shown in the figure. Very few events appear in the ^{153}Dy matrix. This indicates that the proposed HD band is in ^{152}Dy.

[1] A. Galindo-Uribarri et al., Phys. Rev. Lett. 71 (1993) 231.



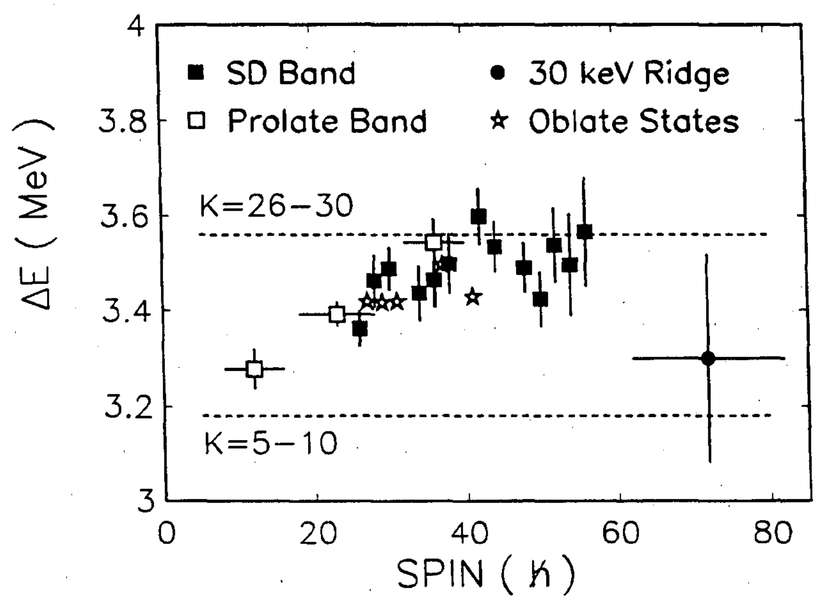
PROTON SPECTRA IN COINCIDENCE WITH SUPER- AND HYPER-DEFORMED STRUCTURES IN ^{152}Dy

M. Lunardon[1)], G. Viesti[1)], D. Bazzacco[1)], A. Brondi[3)], R. Burch[1)], G. de Angelis[2)], M. De Poli[2)], D. Fabris[1)], E. Fioretto[2)], G. LaRana [3)], S. Lunardi[1)], N. Medina[1], R. Moro[3)], G. Nebbia[1)], G. Prete[2)], J. Rico[2)], C. Rossi-Alvarez[1)], G. Vedovato[2], E. Vardaci[3)]

[1)] Dipartimento di Fisica and INFN, Sezione di Padova, Padova, Italy
[2)] INFN Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy
[3)] Dipartimento di Fisica and INFN, Sezione di Napoli, Napoli, Italy

We have analyzed the proton spectra emitted in the reactions of 187 MeV ^{37}Cl on ^{120}Sn studied at the GASP spectrometer. A large area hodoscope (190 cm^2) made by 300 μm thick silicon detectors was employed. Four fold coincidence events γ-γ-γ-protons were used in the analysis. The average proton energy loss ΔE was found to be strongly dependent on the phase space open to the decay for the different *pxn* channels or to different cuts in fold K for a given nucleus, as expected from statistical models. In the figure ΔE values are shown as a function of the spin of the gating transition for the different structures in ^{152}Dy. The differences between prolate, oblate and S.D. bands at a given spin are very small. The measured ΔE increases (i.e. the average proton energy decreases) with spin, as expected. For spin higher than 40 $\hbar$ the energy of the protons feeding the S.D. band exhibits an unexpected saturation. Furthermore, the protons associated with the suggested hyperdeformed ridge [1] are characterized by a lower ΔE, i.e. they are more energetic. The emission of protons with energy higher than expected from statistical models seems to be correlated to a larger survival probability against fission of the compound nucleus at extreme angular momenta.

[1] A. Galindo-Uribarri et al., Phys. Rev. Lett. 71 (1993) 231 and M. Lunardon et al. contribution to this conference.



High Spin Pairing Effects in Superdeformed ^{153}Dy and ^{194}Hg

B. Cederwall,(1) I. Ahmad,(2) J. A. Becker,(3) M. J. Brinkman,(3) M. P. Carpenter,(2) B. Crowell,(2) M. A. Deleplanque,(1) R. M. Diamond,(1) J. E. Draper,(4) C. Duyar,(4) P. Fallon,(1) L. P. Farris,(3) A. Galindo-Uribarri,(5) G. Hackman,(6) E. A. Henry,(3) R. G. Henry,(2) J. R. Hughes,(3) R. V. F. Janssens,(2) T. L. Khoo,(2) T. Lauritsen,(2) I. Y. Lee,(1) A. O. Macchiavelli,(1) S. M. Mullins,(5) D. C. Radford,(5) E. Rubel,(4) F. S. Stephens,(1) M. A. Stoyer,(3) W. Satuła,(7) J. C. Waddington,(6) I. Wiedenhoever,(8) and R. Wyss(9)

(1) *Lawrence Berkeley Laboratory, Berkeley, California 94720, USA*
(2) *Argonne National Laboratory, Argonne, Illinois 60439, USA*
(3) *Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
(4) *Physics Dept., University of California, Davis, California 95616, USA*
(5) *Chalk River Nuclear Laboratories, Canada*
(6) *Tandem Accelerator Laboratory, McMaster University, Canada*
(7) *Institute of Theoretical Physics, University of Warsaw, PL-00681 Warsaw, Poland*
(8) *Universität zu Köln, IKP, D-5000 Köln, Germany*
(9) *Royal Inst. of Technology, Physics Dept., S-100 44 Stockholm, Sweden*

The role of nucleonic pair correlations at large deformation and angular momentum is a topic of great current interest in nuclear structure physics. For experimental investigations into this problem, superdeformed (SD) states serve as an important laboratory. Not only do the SD bands reach very high spin states at very elongated nuclear shapes, the generally strong rigidity of the SD well against deformation changes also make these bands excellent objects for studies of single-particle properties and pairing. A striking difference between the SD nuclei near A = 190 and those in other regions of the nuclear chart is the behavior of the dynamic moment of inertia, $\Im^{(2)}$. While the $\Im^{(2)}$ patterns of the SD bands near A = 130 and A = 150 show pronounced variations, the majority of the SD bands near A = 190 display a large, smooth increase of $\Im^{(2)}$ with $\hbar\omega$. Current understanding of this effect within mean field theories (see e.g. [1]) involves gradual alignments of quasiparticles occupying high-N intruder orbits in the presence of pair correlations. In direct consequence of this picture, $\Im^{(2)}$ will decrease toward the rigid-body value after the quasiparticle alignments have taken place. The absence of experimental evidence for such a turnover in $\Im^{(2)}$ has raised some doubt as to our understanding of pairing at these large spins and deformations. For SD bands in the A$\sim$150 region the role of pair correlations is even more uncertain. There now exists several cases (^{144}Gd[2], ^{149}Gd[3] and ^{150}Gd[4]) where sharp irregularities in the dynamical moments of inertia are observed and ascribed to either proton or neutron paired bandcrossings.

High spin states in ^{153}Dy and ^{194}Hg were produced at the LBL 88-Inch Cyclotron and the GAMMASPHERE Ge detector array was used to detect γ rays emitted in the reactions. A decrease of the dynamic moment of inertia is observed in the SD bands of ^{194}Hg for rotational frequencies $\hbar\omega \geq 0.4$ MeV, confirming the predictions based on mean field calculations with pairing. In the ^{153}Dy experiment, five SD bands could be assigned to this nucleus, two of which are new observations. Here we will focus on the detailed behavior of the yrast SD band at the very highest spin states. At the top of the band, a sharp increase in the dynamical moment of inertia is observed. Interestingly, in paired Woods-Saxon calculations,[5] a paired bandcrossing is predicted to occur at $\hbar\omega \approx 0.8$ MeV due to alignment of a pair of $j_{15/2}$ protons in the pairing field still remaining at this very high rotational frequency.

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2. S. Lunardi *et al.*, P.R.L. **72**, 1427 (1994)
3. S. Flibotte *et al.*, P.R.L. **71**, 688 (1993)
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5. W. Nazarewicz *et al.*, N.P. **A503**, 285 (1989)

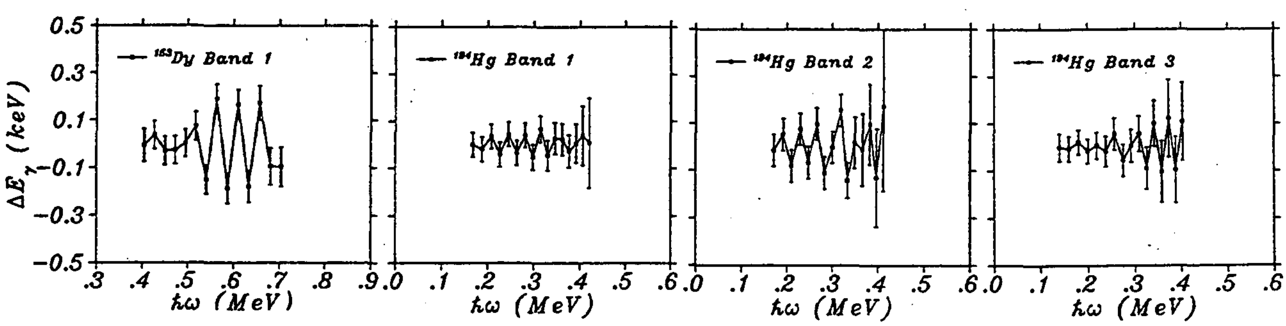
Evidence for $\Delta I = 2$ Staggering in Superdeformed ^{153}Dy and ^{194}Hg

B. Cederwall,(1) I. Ahmad,(2) J. A. Becker,(3) M. J. Brinkman,(3) M. P. Carpenter,(2) B. Crowell,(2) M. A. Deleplanque,(1) R. M. Diamond,(1) J. E. Draper,(4) C. Duyar,(4) P. Fallon,(1) L. P. Farris,(3) A. Galindo-Uribarri,(5) G. Hackman,(6) E. A. Henry,(3) R. G. Henry,(2) J. R. Hughes,(3) R. V. F. Janssens,(2) T. L. Khoo,(2) T. Lauritsen,(2) I. Y. Lee,(1) A. O. Macchiavelli,(1) S. M. Mullins,(5) D. C. Radford,(5) E. Rubel,(4) F. S. Stephens,(1) M. A. Stoyer,(3) W. Satuła,(7) J. C. Waddington,(6) I. Wiedenhoever,(8) and R. Wyss(9)

(1)Lawrence Berkeley Laboratory, Berkeley, California 94720, USA; (2)Argonne National Laboratory, Argonne, Illinois 60439, USA; (3)Lawrence Livermore National Laboratory, Livermore, California 94550, USA; (4) Physics Dept., University of California, Davis, California 95616, USA; (5) Chalk River Nuclear Laboratories, Canada; (6) Tandem Accelerator Laboratory, McMaster University, Canada; (7)Institute of Theoretical Physics, University of Warsaw, PL-00681 Warsaw, Poland; (8)Universität zu Köln, IKP, D-5000 Köln, Germany; (9)Royal Inst. of Technology, Physics Dept., S-100 44 Stockholm, Sweden

The new generation of detector arrays for γ-ray spectroscopy has enhanced our possibilities to study nuclei as quantum rotors into a new realm of excited band multiplets and possible new symmetries. Specifically, spectroscopy of superdeformed (SD) bands has and continues to reveal new aspects of the physics of atomic nuclei under extreme conditions. Maybe the most challenging features of superdeformation found to date are the appearance of so called "identical" bands and the very recent discovery of SD bands exhibiting a $\Delta I = 2$ staggering. The possibilities of new symmetries revealed by these features are intriguing and may have important implications for the general understanding of finite many-body systems. The $\Delta I = 2$ staggering phenomenon was first observed in a SD band in the nucleus ^{149}Gd[1] and the possibility of a four-fold rotational symmetry term in the Hamiltonian was thereby inferred.

High-spin states in the SD nuclei ^{153}Dy and ^{194}Hg have been studied with the GAMMASPHERE Ge detector array located at the LBL 88-Inch Cyclotron facility. The counting statistics in the two experiments was of the order of 1×10^9 and 5×10^8 triple- and higher-fold events, respectively. The high quality of the data yielded extended spectroscopic information on the known SD bands in both nuclei and in addition we observed two new SD bands which could be assigned to ^{153}Dy. Furthermore, the accuracy in the determination of the transition energies is higher than that obtained in the previous work due to the greater resolving power achieved with high-statistics high-fold data. Similarly to the ^{149}Gd case, when analyzing the transition energies carefully we observe evidence for a $\Delta I = 2$ staggering in the yrast SD band of ^{153}Dy as well as in all three SD bands in ^{194}Hg. This is shown in the figure below where the γ-ray transition energies are plotted vs rotational frequency, with a quadratically interpolated smooth reference subtracted. As in ^{149}Gd, the effect is very small, of the order of 10^{-4} of the γ-ray transition energies, which is just barely within the limits of the present detector systems. The results of this analysis will be presented.



1. S. Flibotte *et al.*, Phys. Rev. Lett. 71, 4299 (1993)

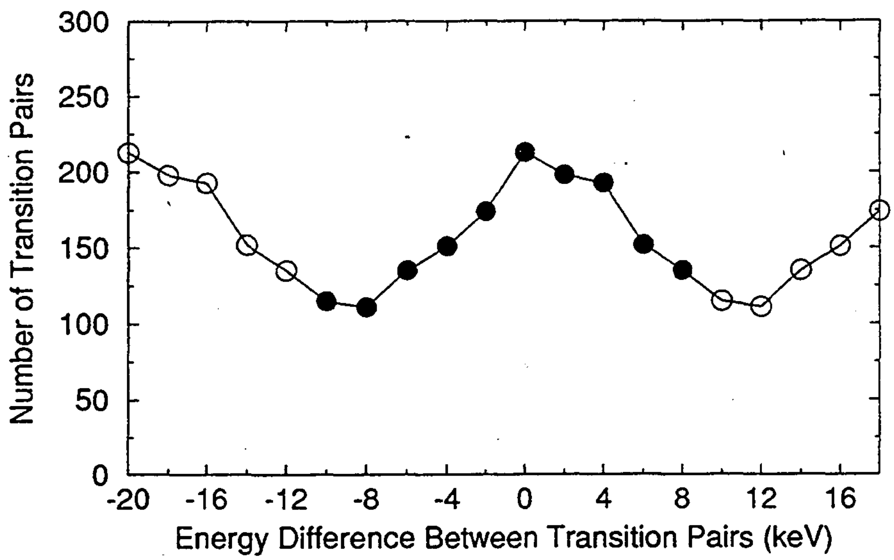
How Identical is *"Identical"* ?

P.Fallon, F.S.Stephens, S.Asztalos, B.Cederwall, R.M.Clark, M.A.Deleplanque, R.M.Diamond, I.Y.Lee, A.O.Macchiavelli.
Lawrence Berkeley Laboratory, Berkeley, Ca 94720.

The observation of identical superdeformed (SD) bands in both the mass 150 and 190 regions, has been one of the most unexpected (and at times controversial) discoveries in high-spin nuclear structure physics. Since the initial observations of this remarkable phenomenon many more SD bands have been reported, eg. approximately 40 SD bands in each of the above mass regions. Thus we are now able to address questions relating to the extent and statistical significance of the occurrence of identical bands (i.e., is this a real phenomenon ?). With this in mind we have developed a method to compare band-pairs, the result of which is a spectrum of the transition energy differences between band-pairs.

The band comparison utilises all band-pair combinations of a given type within a given region. Since the spins of the SD states are not known, we use the closest transitions energies in the particular band-pair. Consequently the comparison is only valid over a spin interval of $1\hbar$ ($\sim$20 keV). When determining the transition energy difference we also take account of the half integer difference in spin when comparing odd- and even-mass nuclei. We note that for a purely statistical (random) effect one may expect to observe a flat spectrum (all E_γ differences are equally probable), whereas any excess of identical bands would result in a peak centered around zero.

The results of a band comparison, for the A=190 region, are shown in the figure (the spectrum repeats in $1\hbar$ cycles and we have indicated the appropriate $1\hbar$ interval by filled symbols). For the search indicated in the figure all SD bands ranging from ^{189}Hg to ^{195}Pb were included, however we only compared SD bands which had different neutron numbers but the same proton numbers. A clear peak is observed in the distribution of the transition energy differences and hence, in our opinion, this indicates a *non-random* effect. However it is also clear that the distribution is not sharply peaked, indeed the width is of the order of $\pm$3 keV. It remains unclear as to whether an E_γ difference of zero results from an accidental cancellation involving particular nucleon orbitals or from some systematic effect, probably involving an underlying symmetry. Results from band comparisons, carried out in other mass regions will be discussed.



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IDENTICAL BANDS AND DYNAMICAL SYMMETRIES IN A≈190 SUPERDEFORMED NUCLEI

J.A. Cizewski
Rutgers University, New Brunswick, New Jersey 08903 USA

Considerable excitement has been generated by the observation of superdeformed bands in which the γ-ray energies in one nucleus are identical or simply related to those in another nucleus. The A≈190 region of superdeformed excitations is especially rich in this phenomena with many identical SD bands which also have alignment quantized with respect to a reference.

The microscopic structure of the identical bands is valence particles in non-unique parity orbitals, or orbitals which can also be interpreted in terms of a pseudo-harmonic oscillator with little pseudo-spin-orbit splitting. This suggests that all of the excitations could be understood in terms of rotors, with angular momentum L, to which the spins of the particles, S, are coupled, with little spin-orbit splitting. The spectrum would then be dominated by the angular momentum L of the core, rather than **J=L+S**. In this case the eigenvalues and γ-ray energies would be given by

$$E = E_0 + A\,S(S+1) + B\,L(L+1) + C\,J(J+1)$$

$$\begin{array}{lll} N_F=0 & S=0 & E_\gamma = (B+C)\,(4J+2) \\ N_F=1 & S=1/2 & E_\gamma = B\,(4J) + C\,(4J+2) \\ N_F=2 & S=1 & E_\gamma = B\,(4J-2) + C(4J+2) \end{array}$$

for the even-even core with $N_F=0, S=0$; odd-A with $N_F=1$, $S=1/2$; and two-nucleon with $N_F=2$, $S=0,1$. With the condition $B=-2C$ quantized alignment $i=1\hbar$ relative to the $N_F=0$ core can be obtained for $N_F=1$ and $i=2\hbar$ for $N_F=2$. This coupling scheme can explain the data for many of the odd-A nuclei in which identical γ-ray energies have been observed and some of the data for odd-odd ^{194}Tl. However, $i=1\hbar$ cannot be obtained in both one and two neutron nuclei with this coupling scheme.

Since the total wave function has to be antisymmetric, for two neutrons with S=1, the orbital angular momenta of the particles must be different. Therefore, an alternative coupling scheme is needed, for example, one in which the spin of the first nucleon is coupled to the L of the core, with $J_1=L+1/2$, and the total J for $N_F=2$ is given by $J=J_1+1/2$. This is an entirely new type of coupling scheme[1] and the eigenvalues are:

$$E = E_0 + B_1\,L(L+1) + C_1\,J_1(J_1+1) + D_1\,J(J+1)$$

With the condition $B_1 = -C_1 = 2D_1$, $i=1\hbar$ can be obtained for both $N_F=1$ and $N_F=2$ systems, reproducing the data for one <u>and</u> two neutron SD bands.

The present talk would present the details of these proposed coupling schemes and would compare the predictions with the plethora of data on identical superdeformed bands in A≈190 nuclei.

Work supported by National Science Foundation. The theoretical work was stimulated by discussions with F.Iachello and R.Bijker. The author also thanks her colleagues at Lawrence Livermore and Lawrence Berkeley Laboratories for their work on the identification of the SD bands and the critical role that alignment plays in these systems.

1. J.A.Cizewski, et al., preprint RU-93-59, and proceedings of "Perspectives for the Interacting Boson Model," Padua, Italy, June 1994.

Evidence for Octupole Vibration in the Superdeformed Well of ^{190}Hg

B. Crowell,(1) R.V.F. Janssens,(1) M.P. Carpenter,(1) I. Ahmad,(1) S. Harfenist,(1) R.G. Henry,(1) T.L. Khoo,(1) T. Lauritsen,(1) D. Nisius,(1) A.N. Wilson,(2) J.F. Sharpey-Schafer,(2) and J. Skalski(3)
(1) Argonne National Laboratory, Argonne, Illinois 60439; (2) Oliver Lodge Laboratory, University of Liverpool, P O Box 147, Liverpool L69 3BX; (3) Soltan Institute for Nuclear Studies, Hoza 69, 00-681 Warsaw, Poland

Using the early implementation phase of GAMMASPHERE, an excited superdeformed (SD) band with an unusual pattern of decay has been observed in ^{190}Hg. The coincidence spectra gated on the yrast SD band contain transitions belonging to a second band, which is populated five times more weakly. This excited band begins an accelerating pattern of de-excitation to the yrast SD band (fig. 1) at a rotational frequency of $\hbar\omega$=0.30 MeV, and no measurable intensity remains in the band below $\hbar\omega$=0.25 MeV. The transitions are apparently of E1 character, since M1 transitions, except those between signature partners, are unlikely to compete with in-band SD E2 transitions [1].

The strengths of the interband transitions are all $(8\pm2)\times10^{-3}$ W.u. This very large value is in good agreement with calculations [2] of the decay of the (unobserved) octupole-vibrational band in the neighboring nucleus ^{192}Hg, which predict B(E1)=11×10^{-3} W.u. No clear evidence for strong E1 transitions between SD bands has been reported prior to this work. The large and constant moment of inertia of the band (fig. 2) is also consistent with the calculations. This is the first experimental information to become available regarding the susceptibility to octupole deformation of nuclei in the A~150 and A~190 regions of superdeformation. This work was supported by U.S. DOE contract no. W-31-109-ENG-38.

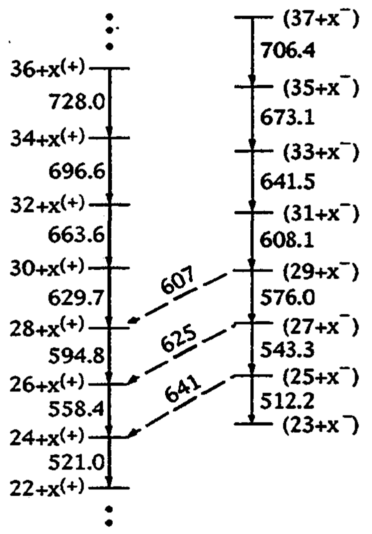

Fig. 1: Partial level-scheme of states in the SD well of ^{190}Hg.

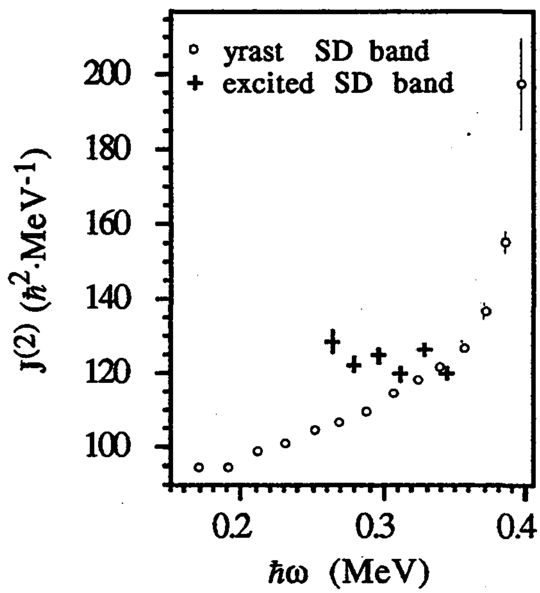

Fig. 2: Moments of inertia of the two SD bands in ^{190}Hg.

[1] D.M. Cullen et al., Phys. Rev. Lett. **65**, 1547 (1990); P. Fallon et al., Phys. Rev. Lett. **70** (1993) 2690; M.J. Joyce et al., Phys. Rev. Lett. **71** (1993) 2176.

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New Superdeformed Bands in ^{191}Hg

M.P. Carpenter(1), R.V.F. Janssens(1), B. Cederwall(2), B. Crowell(1), I. Ahmad(1), J.A. Becker(3), M.J. Brinkman(3), M.A. Deleplanque(2), R.M. Diamond(2), P. Fallon(2), L.P. Farris(3), U. Garg(3), D. Gassmann(1), E.A. Henry(3), R. Henry(1), J.R. Hughes(3), T.L. Khoo(1), T. Lauritsen(1), I.Y. Lee(2), A.O. Machiavelli(2), E.F. Moore(5), D. Nisius(1,6), F.S. Stephens(2)

(1)*Argonne National Laboratory, Argonne, IL 60439;* (2)*Lawrence Berkeley Laboratory, Berkeley, CA 94720;* (3)*Lawrence Livermore National Laboratory, Livermore CA 94550;* (4)*University of Notre Dame, Notre Dame, IN 46556;* (5)*North Carolina State University, Raleigh, NC 27695;* (6)*Purdue University, West Lafayette, IN 47907*

A study of superdeformed (SD) structures in ^{191}Hg has been carried out at GAMMASPHERE with the ^{160}Gd(^{36}S,5n) and ^{174}Yb(^{22}Ne,5n) reactions at 172 and 120 MeV, respectively. The three previously identified SD bands have been extended, and their feeding into the yrast states has been delineated. Two new SD bands have been observed and preliminary evidence for a third new band was obtained as well.

Superdeformation in the A $\sim$ 190 region was first reported by Moore *et al.* [1] who observed one SD band in ^{191}Hg. Two other SD bands were found subsequently [2]. The evolution of the dynamic moment of inertia ($\mathcal{J}^{(2)}$) with rotational frequency for all three bands can be understood in CSM calculations which suggest that the yrast SD band (band 1) is built on the $\nu j_{15/2}$ intruder orbital and that bands 2 and 3 are signature partner bands built on the [642]3/2 orbital.

The average entry spin into the yrast states has been obtained for bands 1–3. Even though bands 1 and 3 have nearly identical transition energies at the point of decay towards the yrast line, the average entry spin into the yrast states for band 1 is significantly higher than that for band 3. The implication of this observation is that band 1 has a relative alignment with respect to band 3 of $\sim 2\hbar$, in agreement with the single-particle assignments.

The most intense new SD band has $\mathcal{J}^{(2)}$–values on average 10% lower than those of bands 1–3. The behavior of this band is similar to that of a SD band reported in ^{193}Hg [3]. Interestingly, these two bands share nearly identical transition energies at the lowest and highest frequencies but differ by as much as 8 keV near the middle of the bands. It has been suggested [3] that the new band in ^{193}Hg is associated with either the unfavored signature of the [761]3/2 orbital or with the favored signature of the [752]5/2 orbital, both of which are $\nu j_{15/2}$ excitations. However, due to the large gap at N=112 for the superdeformed shape, the [752]5/2 orbital is pushed up in energy relative to the Fermi level in ^{191}Hg. Thus, the observation of similar bands in ^{191,193}Hg implies that the [732]3/2 assignment is likely the correct one.

This work is supported by the DOE under contracts W-31-109-ENG-38, DE-AC03-76F00098, W-7405-ENG-48 and the NSF.

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[2] M.P. Carpenter *et al.*, Phys. Lett. **B**240 (1990) 44.

[3] M. Joyce *et al.*, to be published.

Excited Superdeformed Bands in ^{192}Hg.

P. Fallon[1], T.L.Khoo[2], F.Hannachi[3] I.Ahmad[2], M.P.Carpenter[2], B.Cederwall[1], B.Crowell[2], M.A.Deleplanque[1], R.M.Diamond[1], B.Gall[4], R.G.Henry[2], R.V.F.Janssens[2], T.Lauritsen[2], I.Y.Lee[1], A.O.Macchiavelli[1], C.Schuck[4] and F.S.Stephens[1].

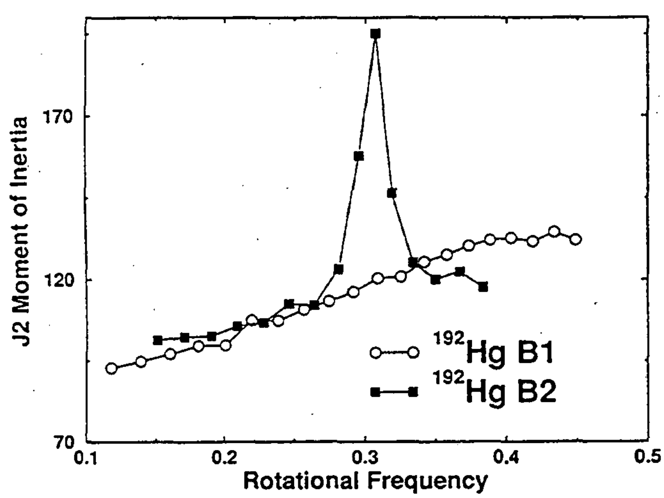
[1] *Lawrence Berkeley Laboratory, Berkeley CA 94720, USA.* [2] *Argonne National Laboratory, Argonne IL 60499, USA.* [3] *Centre de Spectrometrie Nucleaire et de Masse, F-91405, Orsay, France.* [4] *Institute de Physique Nucleaire de Lyon, F-69622, Villeurbanne, France.*

The nucleus ^{192}Hg was studied at the Lawrence Berkeley Laboratory 88″ Cyclotron using the high resolution γ ray spectrometer GAMMASPHERE. High angular momentum states were populated using the reaction ^{160}Gd(^{36}S,4n)^{192}Hg at a beam energy of 159 MeV. This work resulted in the first observation of excited superdeformed (SD) bands assigned to ^{192}Hg.

One of the new SD bands (band 2) has properties that are very different from those of the ^{192}Hg yrast SD band (band 1). Band 2 (most likely to be a 2 quasiparticle band) has a pronounced increase or 'hump' in the dynamical moment of inertia, $\Im^{(2)}$ (see figure). A likely cause for the increase in $\Im^{(2)}$ would be a crossing between neutron quasiparticles based on an N=7 intruder and the [512]5/2 high-K state, analogous to the interpretation proposed for ^{193}Hg band 1 [1].

The second excited SD band (band 3) has properties that are very similar to those of the ^{192}Hg yrast SD band (band 1). Indeed the transition energies for band 3 follow the 1/4 points relative to band 1 and, in addition, the band 3 energies are within 1-2 keV of the transition energies reported for one of the excited SD bands in ^{191}Hg [2] (band 2). However it is clear, from coincidence data, that band 3 belongs to ^{192}Hg. It is therefore puzzling to observe an excited (2-qp band) in ^{192}Hg which has transition energies equal to those observed in a neighboring odd system, since this implies an alignment of $1/2\hbar$.

There is no evidence for a signature partner to either of the excited SD bands in this data set. However band 2 appears at the 1/2 way points relative to the much stronger yrast SD band (band 1) and any signature partner to band 2 may well be obscured by band 1. The intensities for these excited bands, relative to band 1, are ~10% and ~5% for bands 2 and 3 respectively.



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First observation of a superdeformed nucleus in an αxn channel

J. Duprat[a], M.G. Porquet[b], F. Hannachi[b], F. Azaïez[a], B. Gall[b], M. Aïche[b], G. Bastin[b], R.Beraud[c], C.W.Beausang[f], C. Bourgeois[a], R.M. Clark[d], I. Deloncle[b], R. Duffait[c], K. Hauschild[d], H.Hübel[e], M.J. Joyce[f], M. Kaci[b], A. Korichi[a], Y. Le Coz[c], M. Meyer[c], E. Paul[f], N. Perrin[a], N. Poffé[a,g], N. Redon[c], C. Schuck[b], H. Sergolle[a], J.F. Sharpey-Schafer[f] J. Simpson[h], A.G. Smith[i], R. Wadsworth[d]

a) Institut de Physique Nucléaire, 91406 Orsay Cedex, France

b) C.S.N.S.M., IN2P3-CNRS, Bat 104-108, 91405 Orsay, France

c) I.P.N., Université C. Bernard Lyon-1, 69622 Villeurbanne, France

d) University of York, Dept. of Physics , Helsington, York, YO1 5DD, UK

e) ISKP, University of Bonn, D-53115 Bonn, Germany

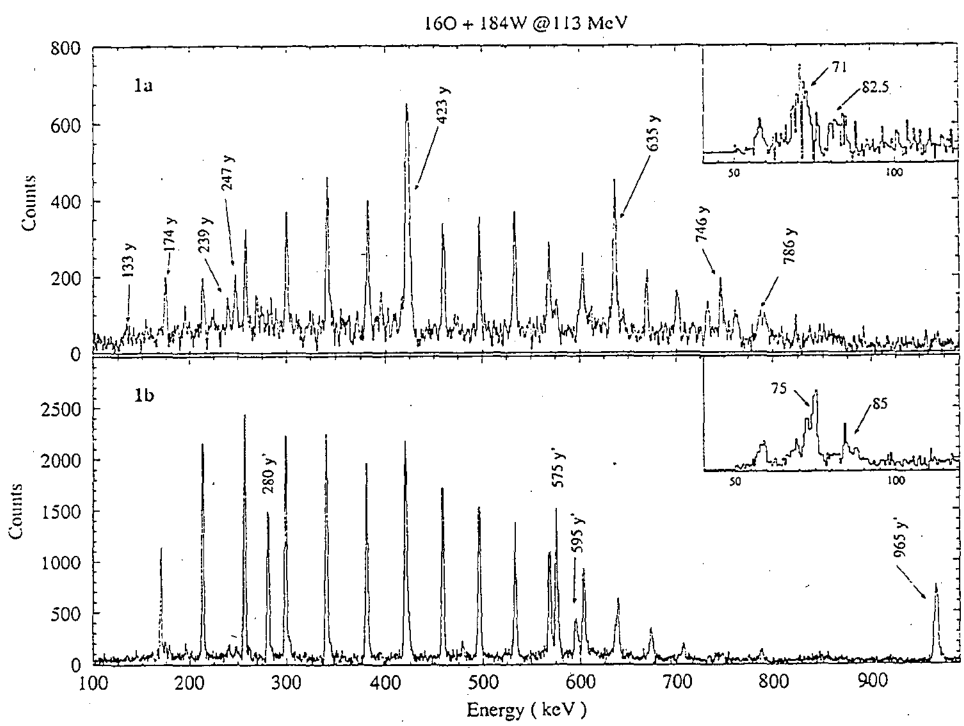
f) Oliver Lodge Laboratory, University of Liverpool, PO Box 147, Liverpool L69 3BX, UK

g) University of Oxford, Department of Physics, Keble Road, Oxford OX1 3RH, UK

h) SERC, Daresbury Laboratory, Warrington, WA4 4AD, UK

i) Schuster Laboratory, University of Manchester, Manchester M13 9PL,UK

An experiment aiming for the study of the superdeformed (SD) band in ^{194}Pb has been performed recently[1]. The ^{16}O + ^{184}W reaction has been used at 113 MeV incident beam energy. The beam was delivered by the tandem Van de Graaf accelerator at the Nuclear Structure Facility, Daresbury Laboratory. The target consisted of two 325μg/cm^2 enriched ^{184}W deposited on 10μg/cm^2 carbon backing. Approximately 1.3 10^9 of four-fold Compton-suppressed events have been collected. Within the experimental condition (at least five unsuppressed γ-rays are detected in coincidence), mainly three reaction products, ^{194}Pb, ^{193}Pb and ^{192}Hg have been produced with respectively 60%, 13% and 27% relative intensity. The relative importance of the α4n channel offered the opportunity to check whether the SD band in ^{192}Hg is populated in an αxn channel. For that purpose the transition energies of the yrast SD band in ^{192}Hg have been used to construct triple gated spectra from the data. In order to avoid any contamination brought by the few identical transition energies (within one keV) in the two SD bands of ^{194}Pb and ^{192}Hg nuclei[1,2], only a selected number of combinations of triple gates has been used to produce the spectrum of figure 1a. This spectrum exhibits a band with the same transition energies as the yrast SD band of ^{192}Hg.



Only the low-lying γ-transitions between normal deformed states in ^{192}Hg (denoted y in the spectrum of figure 1a) are observed in coincidence with the band. In addition, the Hg X-rays are in coincidence with the band as shown in the insert of figure 1a. Figure 1b exhibits a spectrum carefully gated on the transition energies of the SD band of ^{194}Pb, where only the γ-transitions between low-lying normally deformed states in ^{194}Pb (denoted y') and the Pb X-rays (insert of figure 1b) are observed. From these observations we conclude that for the first time the SD band in ^{192}Hg is populated in an αxn channel. Comparison between the population and decay-out of the band in xn and αxn channels will be discussed.

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Study of Superdeformation in ^{192}Hg and ^{194}Pb with EUROGAM

B. Gall[1],F. Hannachi[1],C. Schück[1], I. Deloncle[1], M. Kaci[1], M.G. Porquet[1], A. Korichi[2], F. Azaiez[2], C. Bourgeois[2], J. Duprat[2], N. Perrin[2], N. Poffé[2], H. Sergolle[2], R. Henry[3], I. Ahmad[3], M.P. Carpenter[3], B. Crowell[3], R.V.F. Janssens[3], T. Lauritsen[3], T.L. Khoo[3], Y. Le Coz[4], R. Béraud[4], R. Duffait[4], M. Meyer[4], N. Redon[4], P. Willsau[5], H. Hübel[5], W. Korten[5], C.W. Beausang[6], M.J. Joyce[6], E. Paul[6], J.F. Sharpey-Schafer[6], J. Simpson[7], A.G. Smith[8], R.M. Clark[9] and R. Wadsworth[9]

1 C.S.N.S.M. CNRS-IN2P3, F-91405 Orsay, France
2 I.P.N. CNRS-IN2P3, F-91406 Orsay, France
3 Argonne National Laboratory, Argonne, IL 60439, U.S.A.
4 I.P.N. Lyon CNRS-IN2P3, F-69622 Villeurbanne Cedex, France
5 I.S.K.P. University of Bonn, Nussalle 14-16, D-53115 Bonn, Germany
6 OLiver Lodge Laboratory, University of Liverpool L69 3BX. U.K.
7 S.E.R.C., Daresbury Laboratory, Warrington WA4 4AD, U.K.
8 Schuster Laboratory, Univ. of Manchester, Manchester M13 9PL, U.K.
9 Univ. of York, Dept of Physics,Helsington, York, Y01 5DD, U.K.

Detailed investigations of superdeformed (SD) states of $^{192}_{112}$Hg$_{80}$ and $^{194}_{112}$Pb$_{82}$ have recently been performed[(1-4)] with the EUROGAM spectrometer array (phase I) on line with the NSF Tandem accelerator in Daresbury. Lifetimes of individual states for band1 and band2 in ^{192}Hg[(5,6)] have been measured. The deduced average quadrupole moments are equal and constant, which confirms the stability and rigidity of the SD well. Accurate $\Im^{(2)}$ determination was performed for ^{192}Hg and ^{194}Pb[(2,3)] and there is evidence that the yrast SD bands of these nuclei are no longer identical at the highest frequencies ($\hbar\omega \geq 0.28$ MeV)[(3)]. The experimental dynamic moments of inertia $\Im^{(2)}$ are compared with recent theoretical calculations[(7)], which confirms the importance of pairing correlations in these SD nuclei. Intensities of the states in the first well fed in the depopulation of the SD bands and average entry spin into the yrast lines of both nuclei were determined. The SD yrast bands of both nuclei decay to all available states independent of specific configurations, contrary to the decay of the high-lying normal deformed (ND) states which proceeds mainly through yrast states. Therefore the SD $\rightarrow$ ND decay seems to be essentially statistical in this region. However, in both nuclei a number of transitions up to $\sim$ 4 MeV have been found to be coincident both with the SD band and with the ND states and thus to be part of the SD $\rightarrow$ ND link. Some of the low energy transitions could be placed in the level schemes and new levels close to the yrast line were identified.

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6 A. Korichi et al., to be published
7 B. Gall et al. Z. Phys. in press

Lifetimes of low lying superdeformed states in ^{192}Hg and ^{194}Pb

R. Krücken[1)], A. Dewald[1)], P. Sala[1)], C. Meier[1)], H. Tiesler[1)], J. Altmann[1)], K. O. Zell[1)], P. von Brentano[1)], D. Bazzacco[2)], C. Rossi-Alvarez[2)], G. Maron[2)], R. Burch[2)], R Menegazzo[2)], G. de Angelis[3)], M. de Poli[3)]

[1)] *Institut für Kernphysik, Universität Köln, Köln, Germany*
[2)] *Dipartimento di Fisica, Universita and INFN Sezione Padova, Italy*
[3)] *INFN, Laboratori Nationali di Legnaro, Italy*

The decay of superdeformed (SD) bands has been subject of intensive work during recent years. The SD bands in the A=190 mass region has found special interest because of their decay at very low spin of about 10 $\hbar$. Several theoretical approaches have been developed to explain the sudden drop of intensity in SD bands. Other theories predict the existence of a shape isomeric state in the second well of the deformation potential. The lifetimes of the lowest observed states in SD bands can help considerably to understand the mechanism of the sudden decay out of the band. Due to the relatively low transition energies inside the SD bands in the A=190 mass region the lifetimes of the lower levels are in the picosecond range and can be measured with the Recoil Distance Doppler-shift (RDDS) method. The weak population and the required statistics make RDDS experiments on SD bands rather difficult even if large detector arrays are used.

We want to report on two RDDS experiments for ^{192}Hg[1)] and ^{194}Pb employing the GASP spectrometer[2)] at the LNL Legnaro. For both experiments the Cologne plunger apparatus was used which was especially adapted for γ-γ-coincidence measurements.

It was possible to measure the RDDS lifetimes of two SD states in ^{192}Hg and three lower SD levels in ^{194}Pb. The results obtained were used to discuss the decay out of the SD band in terms of the mixing of normal deformed (ND) states to the SD states. The lifetime of the second observed SD state in ^{194}Pb is reduced as compared to the rotational value which was calculated using the average Q_0 value found for the higher lying SD-states. The intra band transition at this point is only about 78 % of the maximum intensity observed in the band. The decay out could be described by a very small admixture of normal deformed states to the I = (10) SD-state. The γ-decay in the ND well is assumed to be dominated by statistical E1 transitions for which the electromagnetic transition probabilities were calculated with the statistical Fermi-gas model. It was possible to determine the tunneling probability through the potential barrier between the first and second well. using the semi-classical tunneling model. The action of the tunneling process and the barrier height were calculated with the usual assumptions made for the barrier and the second well.

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DECAY FROM SUPERDEFORMED TO NORMAL STATES IN 192Hg: SPECTRUM OF CONNECTING γ RAYS

T. Lauritsen[a], R.G. Henry[a], T.L. Khoo[a], I. Ahmad[a], M.P. Carpenter[a], B. Crowell[a], T. Dossing[a,i], R.V.F. Janssens[a], F. Hannachi[b], A. Korichi[c], C. Schuck[b], F. Azaiez[c], C.W. Beausang[d], R. Beraud[e], C. Bourgeois[c], R.M. Clark[f], I. Deloncle[b], J. Duprat[c], B. Gall[b], H. Hubel[g], M.J. Joyce[d], M. Kaci[b], Y. Lecoz[e], M. Meyer[e], E.S. Paul[d], N. Perrin[c], N. Poffe[c,i], M.G. Porquet[b], N. Redon[e], H. Sergolle[c], J.F. Sharpey-Schafer[d], J. Simpson[h], A.G. Smith[b], R. Wadsworth[f], P. Willsau[g]

We have used a new approach to study the decay out of SD states: instead of trying to decipher the highly fragmented individual decay pathways, we extract the spectrum of all γ rays following the decay. SD states in ^{192}Hg were populated in the ^{160}Gd(^{36}S,4n) reaction with a 159 MeV beam from the SERC Daresbury Tandem Accelerator and γ rays were detected with the EUROGAM array. The γ spectrum coincident with pairwise gates on SD lines was measured. A distinction between γ rays which precede and follow the SD band is made on the basis of the Doppler shift, where possible. (γ rays from the decay out of the SD band are emitted after the evaporation residues are stopped in a backing.) However, the spectrum of statistical γ rays feeding the SD band has to be calculated, using a model which is able to reproduce all observables connected with feeding of SD states.

The spectrum (see Fig.) of γ rays connecting SD and normal states has a statistical-like distribution, with a superposed prominent bump between 1.3 and 2.2 MeV, as well as sharp normal yrast transitions (not shown in Fig.). The average number of steps from the SD band to the normal yrast line is 3.2 $\pm$ 0.6; the SD state from which the decay predominantly occurs has excitation energy above the yrast line of 4.3 $\pm$ 0.9 MeV and its spin is 10.1 $\pm$ 0.7 $\hbar$. The statistical-like decay spectrum shows that a SD state decays by coupling with the dense sea of normal states in which it is embedded. The γ spectra corresponding to the different stages of the γ cascade through a SD band directly reveal an unusual sequence of chaos, order, chaos and order. In particular, the sudden transition from equally-spaced sharp SD lines to a thermal decay spectrum shows a transition from a cold ordered SD system (isolated within a secondary well) to a hot chaotic one (in the primary well).

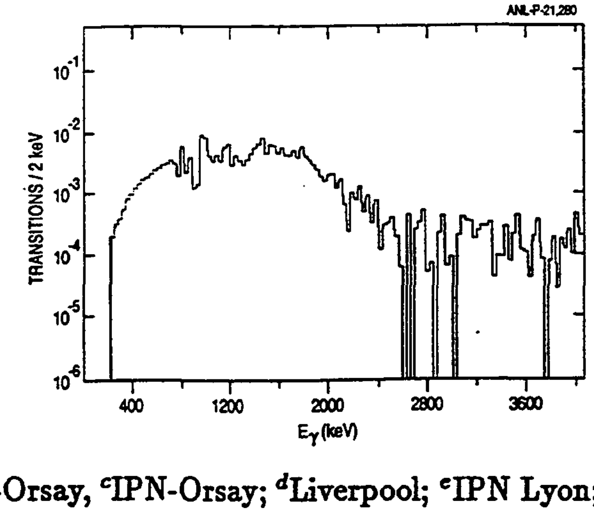

Fig. 1: Spectrum of γ rays connecting the SD and normal states in ^{192}Hg.

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[a]Argonne National Laboratory; [b]CSNSM-Orsay, [c]IPN-Orsay; [d]Liverpool; [e]IPN Lyon; [f]York; [g]Bonn; [h]SERC, Daresbury; [i]Oxford;

Spectra from Decay out of Superdeformed Bands in ^{194}Hg and ^{191}Hg*

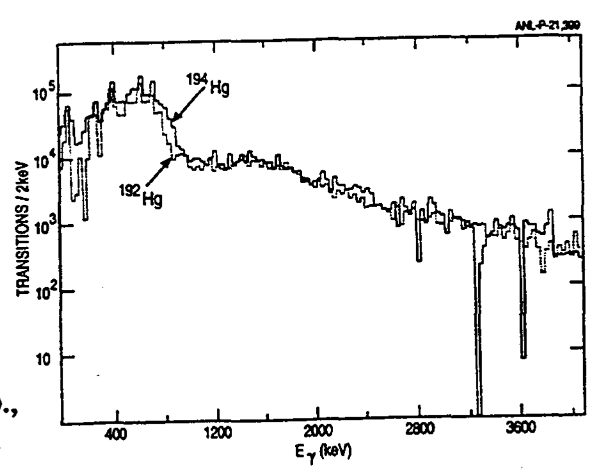
R. G. Henry,[a] T. L. Khoo,[a] T. Lauritsen,[a] T. Døssing,[a] D. Gassmann,[a] I. Ahmad,[a] D. Blumenthal,[a] M. P. Carpenter,[a] B. Crowell,[a] S. Harfenist,[a] R. V. F. Janssens,[a] D. Nisius[a,b] J. A. Becker,[c] M. J. Brinkman,[c] B. Cederwall,[d] M. A. Deleplanque,[d] R. M. Diamond,[d] J. E. Draper,[e] C. Duyar,[e] P. Fallon,[d] E. A. Henry,[c] R. W. Hoff,[c] J. R. Hughes,[c] I. Y. Lee,[d] E. Rubel,[e] F. S. Stephens,[d] and M. A. Stoyer[c]

The spectrum connecting superdeformed (SD) and normal states in ^{192}Hg (Ref. 1) contains a quasicontinuous component on which is superimposed a broad bump. It is proposed (Ref. 2) that this clustering of transition strength is due to pairing, which leads to a region ('gap') of depleted level density up to ~1.2 MeV above the yrast line. A prediction of this model is that the bump should be pronounced in an even-even nucleus, where there is a significant reduction of levels in the 'gap' and significantly weaker in an odd-even nucleus, where levels fill the 'gap'.

To test this prediction, we have extracted the spectrum of γ rays coincident with pairwise gates on SD lines in ^{194}Hg and ^{191}Hg, with the expectation that the bump should be significant in only the former case. In each case, measurements were performed with GAMMASPHERE. Reactions used were ^{150}Nd(^{48}Ca,4n)^{194}Hg, ^{174}Yb(^{22}Ne,5n)^{191}Hg, and ^{150}Gd(^{36}S,5n)^{191}Hg, with beams from the LBL 88" Cyclotron. The data analysis on ^{194}Hg is almost complete, while that on ^{191}Hg is still in progress. The spectra coincident with the yrast SD bands in ^{192,194}Hg are nearly identical above 1 MeV, with prominent bumps between 1.4 and 2.2 MeV--see Fig., where the spectra are normalized to be correct for an A_2 of -0.12, appropriate for only statistical decay. In contrast, preliminary analysis on ^{191}Hg shows that this bump is significantly attenuated. Hence, the tentative indication is that pairing may indeed lead to observable effects in the spectra following decay out of SD bands. This raises the hope that the decay out of SD bands may now provide a tool for studying the reduction of pairing in excited nuclear states.

The remarkable similarity between the spectra of ^{192}Hg and ^{194}Hg for $E_\gamma > 1$ MeV supports the suggestion (Ref. 1) that the decay between SD and normal states is a statistical process, which leads to some interesting ramifications, e.g. for inferring the spins of SD band members.

Another observation from the ^{194}Hg spectrum is that the high-energy edge of a strong broad E2 peak around 700 keV shows approximately full Doppler shift. This means that this structure is from excited SD bands which feed the yrast SD band.



1. T. Lauritsen et al, abstract to this Conf.
2. T. Døssing et al, abstract to this Conf.

*Work supported by U.S. Dept. of Energy, under Contract Nos. W-31-109-ENG-38, DE-FG02-87ER40346, W-7405-ENG-48, DE-AC03-76SF00098 and by the National Science Foundation. [a]Argonne National Lab., [b]Purdue University; [c]Lawrence Livermore Lab., [d]Lawrence Berkeley Lab., [e]Univ. of California

Discrete Decay from the Superdeformed Band in $^{194}Pb^{*}$

M.J. Brinkman, J.A. Becker, E.A. Henry, L.P. Farris, J.R. Hughes, M.A. Stoyer–Lawrence Livermore National Laboratory B. Cederwall, M.A. Deleplanque, R.M. Diamond, P. Fallon, I.Y. Lee, A.O. Macchiavelli, F.S. Stephens–Lawrence Berkeley Laboratory L.A. Bernstein, J.A. Cizewski, H.Q. Jin, W. Younes–Rutgers University J.E. Draper, C. Duyar, E. Rubel–U.C. Davis W.H. Kelly, D.T. Vo–Iowa State University

Within the past five years the neutron–deficient Au, Hg, Tl, and Pb nuclei near A ~ 190 have been shown to support a broad region of superdeformation. Despite worldwide experimental activity, a number of the most fundamental quantities remain unknown—in particular, the excitation energy, well depth, and barrier width of the second minimum and the spins and parities of the superdeformed bands are not directly measured. The observation of discrete decay from the superdeformed band to the states at more moderate deformation may provide direct experimental data on these open questions. Recently a series of experiments on ^{194}Pb were conducted on the Early Implementation of GAMMASPHERE, in an attempt to observe discrete transitions connecting the superdeformed levels to the low–lying yrast states. The ^{174}Yb(^{25}Mg,5n)^{194}Pb* reaction was used to populate the known superdeformed band in this nucleus. Over three experiments a total of 1.9 billion unfolded three–fold events were collected. Early analysis of these data has uncovered a discrete transition at ~2.75 MeV that is in coincidence with both the superdeformed band and a select number of low–lying yrast transitions in this nucleus (see the figure below). This transition populates the 6_1^+ state. The simplest interpretation of this decay implies that for the SD band, $E_x(6/8) \geq 4.89$ MeV. Our analysis and interpretation of this result will be presented.

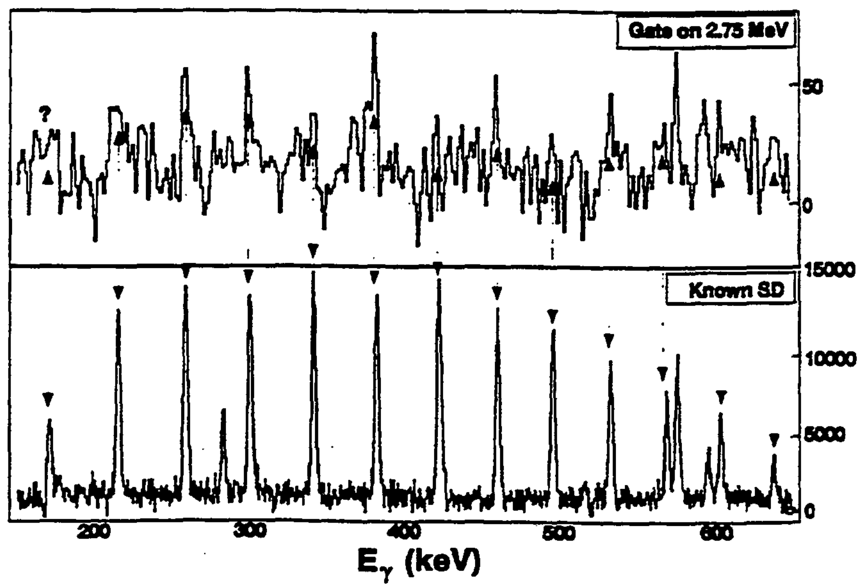


Figure: Top–A gate set at ~2.75 MeV with a resolution of 2 keV/channel. Bottom–The known superdeformed band from double–gated triples with a resolution of 0.5 keV/channel. The arrows denote the energies of the known superdeformed transitions with energies ≤ 650 keV.

* This work was supported in part by the U.S. Department of Energy under contracts W–7405–ENG–48 (LLNL) and DE–AC03–76SF00098 (LBL), and in part by the National Science Foundation (Rutgers).

Absence of Statistical Decay from the Superdeformed Band in ^{194}Pb

M.J. Brinkman,[1] J.A. Becker,[1] E.A. Henry,[1] L.A. Bernstein, [5] B. Cederwall,[2] J.A. Cizewski,[5] M.A. Deleplanque,[2] R.M. Diamond,[2] J.E. Draper,[3] C. Duyar,[3] P. Fallon,[2] L.P. Farris,[1] J.R. Hughes,[1] H.Q. Jin,[5] W.H. Kelly,[4] I.Y. Lee,[2] A.O. Machiavelli,[2] E.C. Rubel,[3] F.S. Stephens,[2] M.A. Stoyer,[1*] D.T. Vo,[4] W. Younes[5]

[1] *Lawrence Livermore National Laboratory, Livermore, CA 94551*
[2] *Lawrence Berkeley Laboratory, Berkeley, CA 94720*
[3] *University of California, Davis, CA 95616*
[4] *Iowa State University, Ames, IA 50010*
[5] *Rutgers University, New Brunswick, NJ 08901*
[*] *present address: Lawrence Berkeley Laboratory*

We have studied the decay out of the superdeformed band in ^{194}Pb using GAMMASPHERE Early Implementation. The experiments were done using the ^{174}Yb(^{25}Mg,5n)^{194}Pb reaction at 130 MeV. The LBL 88-Inch Cyclotron provided the ^{25}Mg beam. The target consisted of three stacked $500\mu g/cm^2$ foils of ^{174}Yb. A total of 1.9 billion unfolded triples were collected during the experiments.

The superdeformed band may depopulate through two distinct mechanisms: discrete transitions or statistical decay. The signal for the statistical decay channel is a broad continuum structure in the gamma-ray spectrum in coincidence with the SD band. Statistical decay dominates the depopulation in ^{192}Hg. [1]. In contrast to this, Figure 1 illustrates the apparent lack of statistical transition strength in ^{194}Pb.

The spectrum in Figure 1 is generated as follows: Three double gated spectra were taken—both gates on peak regions (PP), one gate on a peak region and one on a background region (PB), and both gates on background regions (BB). These three spectra were then normalized in the region of $E_\gamma \approx$ 3–4 MeV. The background-subtracted gate spectrum was generated by taking $PP - 2PB + BB$. The resulting spectrum was then compressed by a factor of 16, in order to smooth out statistical fluctuations.

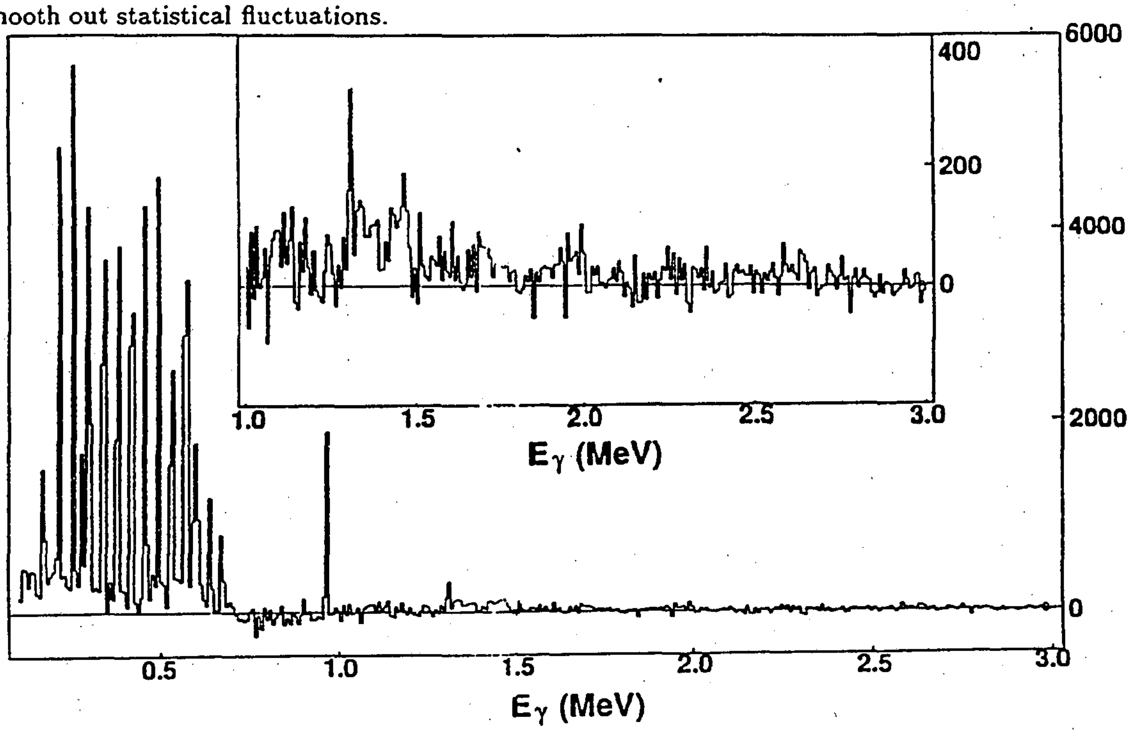


FIG. 1. Background-subtracted double-gated coincidence spectrum for the ^{194}Pb SD band. This spectrum was extracted from a data set of 1.3 billion unfolded triples.

[1] T.L. Khoo et al., Nucl.Phys. A557 83c (1993).

Observation of an excited superdeformed band in ^{194}Pb*

J. R. Hughes, J. A. Becker, M. J. Brinkman, L. P. Farris, E. A. Henry, R. W. Hoff, M. A. Stoyer
Lawrence Livermore National Laboratory, Livermore, California 94550
B. Cederwall, M. A. Deleplanque, R. M. Diamond, P. Fallon, I. Y. Lee, A. O. Machiavelli, F. S. Stephens
Lawrence Berkeley Laboratory, Berkeley, California 94720
J. A. Cizewski, L. A. Bernstein
Rutgers University, New Brunswick, New Jersey 08903
J. E. Draper, C. Duyar, E. Rubel
Physics Department, University of California, Davis, California 95616
W. H. Kelly, D. T. Vo
Iowa State University, Ames, Iowa 50010

Observation of excited superdeformed (SD) bands is of particular importance for understanding the structure in the second well. Questions regarding the single-particle spectrum near the SD Fermi surface, the effects of pairing (blocking), deformation changes, and the phenomenon of identical bands (IB) can all be addressed by the characterization of excited SD bands. In the $A \sim 194$ region, numerous excited SD bands have been observed in Hg, Tl and recently Pb nuclei. The behaviour of the moments of inertia of such bands has in some Hg nuclei allowed configuration assignments to be suggested, and in the odd-odd Tl nuclei, led to insights into the effects of pairing and blocking on the moments of inertia.
Calculations suggest that nuclei with N=112, and Z=80, 82 should be particularly stable at large deformations due to the existence of SD gaps in the single-particle spectrum. Excited SD bands in ^{192}Hg and ^{194}Pb therefore have somewhat higher excitation energies, and consequently populated with lower intensity.
The strongest SD band within a nucleus typically has an intensity $\sim 1-2\%$ of the respective channel, while the excited SD bands observed to date are usually much lower in intensity, and hence relatively difficult to observe. The new generation γ-ray arrays provide the increased sensitivity and resolving power to observe weaker bands than previously possible. The increased dimensionality of the data, while providing increased resolution, presents a huge space in which to search for SD bands. For this purpose, an algorithm designed to find the most promising candidates for SD band members has been implemented. The algorithm has been applied to a number of recent GAMMASPHERE data sets aimed at studying superdeformation in the neutron-deficient ^{193,194,195}Pb isotopes.
We shall briefly describe the search algorithm, and present the results obtained. Our results include the observation of a new excited SD band in ^{194}Pb, which is a factor $\sim$ 20 weaker than the strong band. The new band will be compared with neighboring nuclei, and related to current calculations.

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Superdeformation in ^{195}Pb

L.P. Farris,[1] E.A. Henry,[1] J.A. Becker,[1] M.J. Brinkman,[1] B.Cederwall,[2] J.A. Cizewski,[5] M.A. Deleplanque,[2] R.M.Diamond,[2] J.E. Draper,[3] C. Duyar,[3] P. Fallon,[2] J.R. Hughes,[1] W.H. Kelly,[4] I.Y. Lee,[2] E.C. Rubel,[3] F.S. Stephens,[2] M.A. Stoyer,[1*] D.T. Vo[4]
[1] *Lawrence Livermore National Laboratory, Livermore, CA 94551*
[2] *Lawrence Berkeley Laboratory, Berkeley, CA 94720*
[3] *Univ. of California, Davis, CA 95616*
[4] *Iowa State University, Ames, IA 50010*
[5] *Rutgers University, New Brunswick, NJ 08901*
* *present address: Lawrence Berkeley Laboratory*

Superdeformed bands have been identified in ^{195}Pb, the first odd-A Pb nucleus where such states have been found. ^{195}Pb was populated in the ^{174}Yb(^{26}Mg,5n) reaction with a beam energy of 133 MeV provided by the LBL 88-inch Cyclotron. The target consisted of three stacked 500μg foils of ^{174}Yb. Data were obtained with the Early Implementation of Gammasphere with 29 detectors. More than 4×10^8 events were collected with a coincidence requirement of three or more Compton-suppressed gamma rays. Two pairs of signature partner superdeformed bands, four bands in all, were discovered. These have been labeled bands 1, 2, 3a and 3b.

The properties of the ^{195}Pb bands are expected to be similar to those of the superdeformed bands in its isotones, ^{194}Tl and ^{193}Hg, because of the superdeformed shell gaps at Z=80 and 82. However, bands 1 and 2 of ^{195}Pb have an approximately constant dynamic moment of inertia (Figure 1). The only other nucleus in this mass region with superdeformed bands displaying this property is ^{192}Tl [1] in which blocking of high-j intruder orbitals by odd proton and neutron quasiparticles was invoked as an explanation. In the case of ^{195}Pb, this mechanism would require proton excitations across the Z=82 superdeformed shell gap, whereas, based on relative intensities and other properties, the bands with flat $\mathcal{J}^2$s are most likely the yrast band and its signature partner, a quasineutron excitation.

Properties of all the SD bands in ^{195}Pb will be discussed, and compared to theoretical expectations and the properties of bands in neighboring nuclei.

This work was supported in part by U.S. Department of Energy, under Contract No. W-7405-ENG-48 (LLNL), and No. DE-AC03-76SF00098 (LBL), and in part by the U.S. Department of Energy, Nuclear Physics Division under Contract No. W-31-109-ENG-38 (ANL), and in part by the National Science Foundation (Rutgers,Davis).

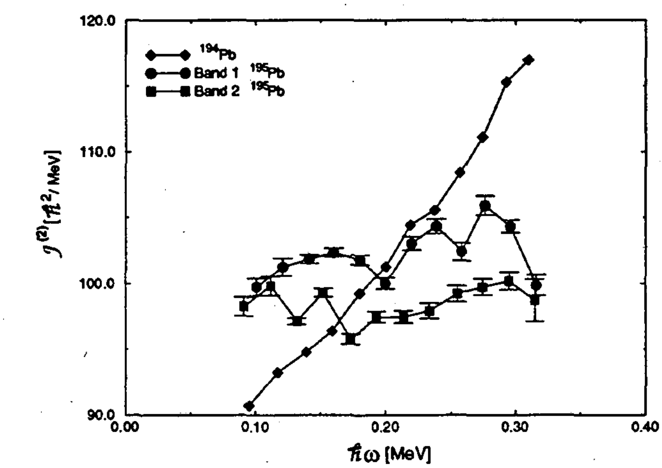

FIG. 1. Dynamic moments of inertia for SD bands 1 and 2 of ^{195}Pb, with the SD band for ^{194}Pb[2] for comparison.

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[2] M.J. Brinkman, et al., Z. Phys. A336, 115 (1990).

M1 transitions between superdeformed states in ^{193,194,195}Tl: the fingerprint of the proton $i_{13/2}$ intruder orbital

J. Duprat[a), F. Azaïez[a), M. Aïche[b), A. Astier[c), G. Bastin[b), C.W. Beausang[h), C. Bourgeois[a), R.M. Clark[g), I. Deloncle[b), R. Duffait[c), B. Gall[b), F. Hannachi[b), I. Hibbert[g), M.J. Joyce[h), M. Kaci[b), W.H. Kelly[e), A. Korichi[a), Y. Le Coz[c), M. Meyer[c), N. Perrin[a), N. Poffé[a,f), M.G. Porquet[b), N. Redon[c), C. Schuck[b), H. Sergolle[a), J.F. Sharpey-Schafer[h), J. Simpson[d), R. Wadsworth[g),

a) Institut de Physique Nucléaire, 91406 Orsay Cedex, France

b) C.S.N.S.M., IN2P3, CNRS, 91405 Orsay, France

c) I.P.N., Université de Lyon I, 69622 Villeurbanne Cedex, France

d) SERC, Daresbury Laboratory, Warrington, WA4 4AD, UK

e) Iowa State University, Ames, IA 50011

f) University of Oxford, Department of Physics, Keble Road, Oxford, UK

g) University of York, Dept. of Physics , Helsington, York, YO1 500, UK

h) Oliver Lodge Laboratory, University of Liverpool, PO Box 147 L69 3BX, UK

Detailed properties of the superdeformed (SD) bands in ^{193}Tl, ^{194}Tl and ^{195}Tl have been measured using the EUROGAM spectrometer. Dipole transitions linking signature partner SD bands have been observed for the three different nuclei. In the case of ^{195}Tl, measurements of the photon decay branching ratios, together with the average SD quadrupole moment measured in neighbouring nuclei , enable the M1 strength to be determined[1)]. Using the experimental B(M1) values, it has been shown that the pair of SD bands in ^{195}Tl correspond to a configuration where the single proton is occupying the intruder $i_{13/2}$ (Ω=5/2) orbital[2)] (see figure). The three pairs of SD bands in ^{194}Tl (odd-odd nucleus) were found to exhibit a smaller M1 strengths[3)], in agreement with the configurations where the single proton is occupying the same proton orbital and the single neutron is occupying one of the [512]5/2,[624]9/2 or the $j_{15/2}$ orbitals, and where the neutron-proton interaction is favoring the triplet spin state (Gallagher-Moskowski rule). Theoretical calculations based on the mean field approximation (Woods-Saxon or self-consistent Hartree-Fock) give the mentionned neutron and proton orbitals as being the first available configuration above the N=112 and Z=80 shell gaps[4,5)].

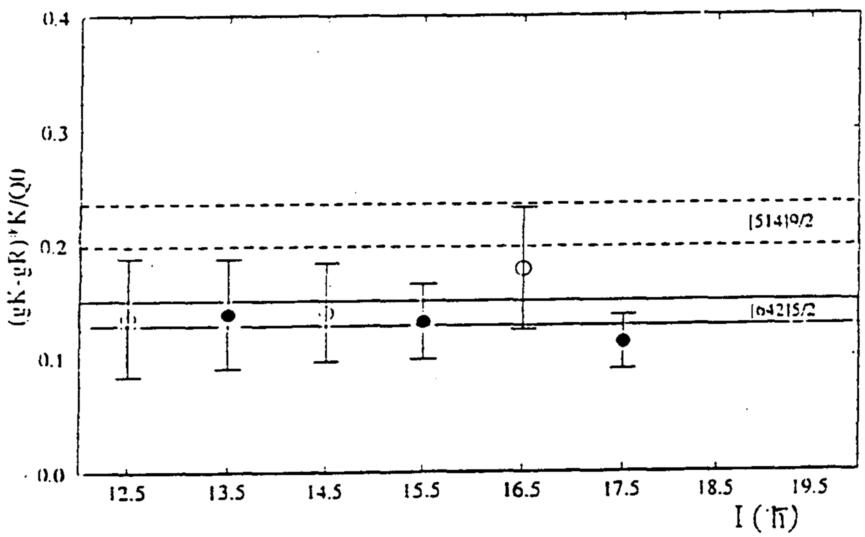

Figure: The extracted $(g_K-g_R)K/Q_0$ values for SD states in band 1 (full circles) and band 2 (empty circles) of ^{195}Tl (the unit is μ_N/eb) as a function of their evaluated spins. Assuming $Q_0 = 19 \pm 2$ eb, the theoretical values[1)] are indicated for [514]9/2$^-$, g_K=1.31 (dashed lines) and the [642]5/2$^+$, g_K=1.45 (full lines) proton configurations. The theoretical limits come from the uncertainty on the experimental quadrupole moment (g_R is taken equal to Z/A).

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High Spin Structure of the Doubly Odd Nuclei ^{76,78}Br.

J.X.Saladin, F.Cristancho, D.Winchell*, E.Landulfo, L.Wehner University of Pittsburgh, S.Tabor, M.Riley and J.Doering Florida State University.

The study of the high spin structure of nuclei in the A=70 to 90 region has attracted a great deal of attention since, in this region, protons and neutrons occupy the same shell. Of particular interest is the study of odd-odd systems since they provide interesting information about the interaction between the two odd particles with one another and with the even-even core. Both ^{76}Br and ^{78}Br have previously been investigated by a number of authors [1 - 5]. In this work we present the results of two experiments on ^{76}Br based on the reactions ^{63}Cu(^{16}O,n2p)^{76}Br and ^{63}Cu(^{19}F,3p3n)^{76}Br and of an experiment on ^{78}Br which utilized the reaction ^{70}Zn(^{11}B,3n)^{78}Br. The experiments were carried out using the Pitt multi-detector array at the University of Pittsburgh and at the University of Notre Dame, and the Pitt-FSU array at Florida State University. In ^{76}Br a new negative parity band has been established which is likely to be the signature partner of the previously known negative parity band built on a 4^- isomeric state.

In ^{78}Br the signature partners of the positive parity band have been extended to the 16^+ and 17^+ states, respectively and in the negative parity band to the 14^- and 15^- states, respectively. A particularly interesting feature of odd-odd systems in this region is the systematic occurrence of signature inversion. Kreiner and Mariscotti [2] predicted the occurrence of signature inversion on the basis of two quasiparticle plus rotor calculations. The effect was subsequently observed in ^{74,76}Br [5]. The present work establishes for the first time the occurrence of signature inversion in ^{78}Br. Signature inversion was also found for the negative parity band of ^{78}Br. There exits now an extensive set of data on signature inversion in odd-odd nuclei in the A=70 to 90 region which we will discuss. We will also present a cranked shell model analysis for the data on ^{76,78}Br. The results will be compared with cranked Wood-Saxon Bogoliubov calculations.

* Present address: Physics Department, University of Pennsylvania

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Band Termination in ^{82}Sr.

D.M. Cullen[1], C. Baktash, J.D. Garrett, C.J. Gross, N.R.Johnson, *Oak Ridge National Lab.*[2], *TN 37831-6371.* J. Simpson *Daresbury Laboratory, Warrington, WA4 4AD, U.K.* D.G. Sarantites *Washington University, St. Louis, Missouri 63130.* I. Ragnarsson, *Lund Institute of Tech., S-221 00, Lund, Sweden.*

High-spin states were populated in ^{82}Sr with the ^{56}Fe(^{30}Si,2p2n) reaction at a beam energy of 128 MeV. The 5pnA-^{30}Si beam was provided by the N.S.F. tandem accelerator at Daresbury Laboratory. A total of 4x10^9 (raw fold $\geq$5) $\gamma - \gamma$ events were recorded in 9 shifts with the Eurogam array of 45 Ge detectors. Within 1 shift of beam time it was possible to observe the highest known transitions in ^{82}Sr. However, after a further 8 shifts and using triples matrices gated on each of the rotational bands it was only possible to add 1–2 *higher* spin transitions to the known level scheme. The collective rotational bands were observed to fragment to other levels around the same spin.

These data reveal the **first** observation of band termination in the A$\approx$80 region. Indeed none of the rotational bands based on collective states survive beyond I$\approx$25$\hbar$ where the population of the low-lying single-particle states compete strongly. Band termination in this region can be understood from the Cranked-Nilsson-Strutinsky calculations. The $g_{9/2}$ orbitals reach maximum occupation for both protons and neutrons with a maximum angular momentum of 25$\hbar$. In order to generate higher angular momentum states excitations to the $f_{5/2}$ orbits are required. These states lie above the deformed shell gap and therefore, considerably higher in excitation energy.

[1]Present address; N.S.R.L., University of Rochester, Rochester, N.Y. 14620.

[2]Oak Ridge National Laboratory is managed by Martin Marietta Energy Systems, Inc., for the U.S. Department of Energy under Contract No. DE-AC05-84OR21400.

High Spin Behaviour of Nuclei Near & At The Neutron Magic Numbers, N = 50 & 82.

S. B. Patel[(1)], S. S. Ghugre[(1)] & R. K. Bhowmik[(2)].
(1) Physics Dept., University of Bombay, Bombay 400 098, India.
(2) Nuclear Science Centre, P. Box 10502, New Delhi 110 067, India.

We are systematically investigating the behaviour of the shell model nuclei near and at the neutron magic numbers N = 50 and 82, to understand their structure at high angular momentum. These nuclei are particulary interesting because : (i) Enlarged configuration space and breaking of the neutron core is required to interprete the observed spectra and (ii) the role of the $h_{11/2}$ and $g_{9/2}$ intruder orbitals could be dramatic. For example deformed rotational-like intruder bands were observed in nuclei near Z = 50.

We have used the following reactions : $^{66}Zn(^{31}P$, xpyn) at 115 MeV, $^{64}Zn(^{35}Cl$, xpyn) at 140 MeVand $^{122}Sn(^{32}S$, xpyn) at 163 MeV. The heavy ion beams were delivered by the 15 UD Pelletron Accelerator at the Nuclear Science Centre, New Delhi. γ-γ coincidences were measured by using an array of 6 Compton suppressed Ge detectors and a 14 element BGO multiplicity filter.

The nuclei studied so far are :$^{92,93,94}Tc$, $^{94,95,96}Ru$, ^{95}Rh and ^{149}Dy. We have found 21 new γ rays in ^{92}Tc, 22 new transitions in ^{93}Tc, about 40 new γ rays in ^{95}Ru, 4 new transitions in ^{95}Rh and 7 new transitions in ^{94}Tc. The analysis of Dy data is in progress. the new γ rays have been placed in the level schemes. Extensive shell model calculations have been performed for $^{92,93,94}Tc$ and $^{94,95,96}Ru$ within a model space consisting of ^{66}Ni as the closed core and the π ($0f_{5/2}$, $1p_{3/2}$, $1p_{1/2}$, $0g_{9/2}$) and the ν ($1p_{1/2}$, $0g_{9/2}$, $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$) orbitals. The observed high spin states could be well understood on the basis of the single neutron excitation across the N = 50 closed core.

High Spin Structures and Rotational Alignments in Cadmium Nuclei.

P.H. Regan, A.E. Stuchbery, G.D. Dracoulis, A.P. Byrne, G.J. Lane, T. Kibédi
Dept. Nucl. Phys., Australian National Uni. ACT 0200, Canberra, Australia

S.M. Mullins, G. Hackman,
Dept. Physics and Astronomy, McMaster University, Ontario, L8S 4M1, Canada

D.C. Radford, A. Galindo-Uribarri, V.P. Janzen, D. Ward,
AECL Research, Chalk River Labs. Chalk River, Ontario, K0J 1J0, Canada

J. DeGraaf, M. Cromaz,
Dept. Physics, University of Toronto, Toronto, Ontario, Canada.

S. Pilotte
Dept. of Physics, University of Ottawa, Ottawa, Ontario, K1N-6N5, Canada

Due to their close proximity to the Z=50 closed shell, at low spins the cadmium isotopes (Z=48) are almost spherical in shape and are well described in terms of quadrupole vibrators. However, the prolate deformation-driving nature of the neutron $h_{\frac{11}{2}}[550]\frac{1}{2}^-$ orbital can give rise to deformed band structures at medium to high spins. The combination of large rotational frequencies ($\hbar\omega$ ~0.7 MeV) and small prolate deformations (β_2 ~0.15) make these structures an excellent test of the limits of the cranked shell model.

We have studied the high spin states in ^{105,106}Cd using (a) the ^{94}Zr(^{16}O,xn) reaction at a beam energy of 92 MeV at the Australian National University and (b) the ^{76}Ge(^{34}S,xn) reaction at 140 MeV at the Chalk River Tandem and Super Conducting Cyclotron (TASCC). In ^{105}Cd we have observed states above the first band crossing in the yrast $\nu h_{\frac{11}{2}}$ band [1]. In contrast to the $h_{\frac{11}{2}}$ bands in the heavier odd-N isotopes, where an increase in i_x of ~9 $\hbar$ is observed [2] only ~4 $\hbar$ is observed in ^{105}Cd. We interpret the ^{105}Cd effect as the alignment of a pair of $g_{\frac{7}{2}}$ neutrons, as opposed to the crossing with the $(\nu h_{\frac{11}{2}})^3$ configuration, proposed for ^{109,111}Cd.

In ^{106}Cd, a rotational band built upon a 10^+ bandhead extending to spin 28^+ has been observed. This structure undergoes a band crossing at $\hbar\omega$ ~0.45 MeV, close to the frequency where the $(\nu g_{\frac{7}{2}})^2$ alignment is observed in ^{105}Cd. We interpret this band as a two-quasi-neutron, $(h_{\frac{11}{2}})^2$ configuration, starting from a fully aligned 10^+ bandhead. Similar bands have been recently reported in ^{108,110}Cd [3,4]. We have also observed a collective, strongly coupled structure, with an excitation energy and branching ratios consistent with a six-quasi-particle, two-proton-four-neutron configuration. A full investigation of the alignment processes in this region as function of both proton and neutron number is necessary to provide information on the applicability of the CSM in weakly deformed, transitional nuclei.

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(2) P.H. Regan *et al.* *Phys. Rev.* **C49** (1994) 1885
(3) I. Thorslund *et al.* *Nucl. Phys.* **A564** (1994) 285
(4) S. Juutinen *et al.* *Z. Phys.* **A336** (1990) 475

High Spin Multi-Quasi-Particle Bands in Silver Nuclei*.

P.H. Regan[1] , J. DeGraaf[2], S.M. Mullins[3], A.P. Byrne[1], M. Cromaz[2], G. Dracoulis[1], A. Galindo-Uribarri[4], G. Hackman[3], V.P. Janzen[4], T. Kibédi[1], G.J. Lane[1], S. Pilotte[5], D.C. Radford[4], N. Schmeing[3,4], A.E. Stuchbery[1] and D. Ward[4]

[1] *Dept. Nucl. Phys., Australian National Uni. ACT 0200, Canberra, Australia*

[2] *Dept. Physics, University of Toronto, Toronto, Ontario, M5S 1A7, Canada.*

[3] *Dept. Physics and Astronomy, McMaster University, Ontario, L8S 4M1, Canada*

[4] *AECL Research, Chalk River Labs. Chalk River, Ontario, K0J 1J0, Canada*

[5] *Dept. of Physics, University of Ottawa, Ottawa, Ontario, K1N-6N5, Canada*

High spin states in the Z=47 nuclei ^{106,107}Ag, have been studied using the heavy-ion induced reactions ^{94}Zr(^{16}O,pxn) and ^{76}Ge(^{36}S,pxn) at beam energies of 92 and 155 MeV respectively with the aim of investigating collective multi-quasi-particle structures in these nominally 'transitional' nuclei. For prolate shapes, the proton fermi surface for Z=47 lies in the upper-mid $g_{\frac{9}{2}}$ shell. The coupling of these high-K proton orbitals to the deformation driving low-K neutron $h_{\frac{11}{2}}$ orbital can give rise to collective structures with large average K values and B(M1)/B(E2) strengths.

The ^{16}O induced reaction was performed at the Australian National University 14UD tandem accelerator with the emitted γ-rays detected using the six detector array, CAESAR. The latter experiment was performed at the Chalk River Tandem and Super Conducting Cyclotron (TASCC) facilty using the 8^{π} array. The ALF light-charged particle detector was used to software gate off-line on events associated with the emission of a proton from the compound nucleus. This enabled clean identification of γ-rays from residual silver isotopes. Proton-gated $\gamma - \gamma$ coincident matrices with sum-energy cuts to enhance various particle out channels were used to create clean data sets. The data revealed cascades of strongly coupled structures with large relative intensities for the dipole cascade transitions in ^{106,107}Ag.

In ^{106}Ag, we observe the previously reported bands built on the 8^- and 10^- bandheads [1]. We also observe a third strongly coupled structure, built on an apparent 12^+ bandhead. The excitation energy of this structure implies a four-quasi-particle nature. Lifetime information using the Doppler Shift Attenuation Method has also been obtained for this band. In the stable isotope, ^{107}Ag, we have extended the previously observed band built upon the proposed spin $\frac{21}{2}^+$ bandhead [2] to a tentative spin $\frac{45}{2}^+$ and have observed another strongly coupled band which we associate with a possible three quasi-particle structure. The experimental data have been compared with Total Routhian Surface calculations which predict the existence of weakly deformed prolate (β_2 ~0.17) structures in these nuclei.

* This work is partially supported by the DITAC (Australia) Access to Overseas Facilities Program.

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Intruder bands to very high frequencies in ^{109}Sb and ^{114}Te: smooth termination

D B Fossan[1], D R LaFosse[1], H Schnare[1], C W Beausang[2], K Hauschild[3], I M Hibbert[3], J R Hughes[1], V P Janzen[4], S M Mullins[5], E S Paul[2], D C Radford[4], I Ragnarsson[6], I Thorslund[1], P Vaska[1], R Wadsworth[3], M P Waring[1]

[1] *Department of Physics, State University of New York at Stony Brook, NY*
[2] *Oliver Lodge Laboratory, University of Liverpool, United Kingdom*
[3] *Department of Physics, University of York, Heslington, York, United Kingdom*
[4] *Chalk River Laboratories, AECL Research, Chalk River, Ontario, Canada*
[5] *Department of Physics, McMaster University, Hamilton, Ontario, Canada*
[6] *Department of Mathematical Physics, Lund Institute of Technology, Lund, Sweden*

The early implementation (EI) of GAMMASPHERE has been employed to investigate the properties of intruder bands near the Z=50 closed shell. Earlier results in Z=51 ^{109}Sb [1] have been extended to higher frequencies ($\hbar\omega \geq 1.4$ MeV) and to a total of five intruder bands using the ^{54}Fe(^{58}Ni,3p) reaction at 243 MeV. Four of the five bands show smoothly decreasing dynamic moments of inertia with increasing spin to values as low as 1/3 the rigid-body value. The improved resolving power of the array (FWHM$\sim$0.5% despite a recoil v/c=4.7% with the forward/backward geometry) is believed to have identified the terminating γ-ray transitions, which are near 2.8 MeV, reaching tentative termination spin values ranging from $(83/2)\hbar$ to $(89/2)\hbar$. Although the band decay patterns are observed, definite links to the low-lying levels have not been identified. Calculations, [2] showing a gradual alignment of the configuration valence particles outside Z=N=50 with the nuclear shape moving across the γ plane from a collective prolate shape ($\gamma = 0°$) to a noncollective oblate shape ($\gamma = +60°$) over many transitions, are remarkably consistent with these experimental results for all five intruder bands. Band termination occurs when the valence particle spin of the specific band configuration has been exhausted.

A second EI GAMMASPHERE experiment searched for intruder bands in Z=52 ^{114}Te with the ^{54}Fe(^{63}Cu,3p) reaction at 245 MeV. Three intruder bands were found and observed to high frequencies with the linking transitions to the low-lying levels established for two of the bands and with less certainty for the third. The bands reached spins ranging from $(34)\hbar$ to $(42)\hbar$ and transition energies above 2.2 MeV; the dynamic moments of inertia decreased slowly with spin but not to the low values as in ^{109}Sb. With the larger number of valence particles, the calculations [2] suggest that termination may not yet have been reached for these ^{114}Te intruder bands.

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High Spin Spectroscopy of ^{109}In

J.H. DeGraaf[1] and the 8π Collaboration[1,2,3,4]

[1] *Dept. Physics, University of Toronto, Toronto, Ontario, M5S 1A7, Canada.*
[2] *Dept. Physics and Astronomy, McMaster University, Ontario, L8S 4M1, Canada*
[3] *AECL Research, Chalk River Labs. Chalk River, Ontario, K0J 1J0, Canada*
[4] *Dept. of Physics, University of Ottawa, Ottawa, Ontario, K1N 6N5, Canada*

Rotational bands near the $Z = 50$ shell closure have been observed in several Sb ($Z = 51$) isotopes. These bands are primarily based on a $\pi h_{11/2}$ intruder orbital configuration coupled to an excited 2p-2h core. Rotational bands have also been found below the shell gap in ^{111}In ($Z = 49$) [1]. The similarity between the bands in ^{111}In and ^{113}Sb [2] suggests that

it is also based on the $\pi h_{11/2}$ intruder configuration coupled to a 2h core. We have investigated the systematics of these structures in lighter In isotopes.

High spin states in ^{109}In were populated with the reaction ^{76}Ge(^{37}Cl,4n)^{109}In at 138MeV at the Tandem Accelerator Super-Conducting Cyclotron (TASCC) facility in Chalk River, Canada. Gamma-ray spectroscopy was performed with the 8π spectrometer. Both thin-target and gold-backed-target experiments were performed, the latter for the purpose of obtaining lifetime information with a Doppler Shift Attenuation Measurement (DSAM).

A rotational band extending to $\frac{55}{2}\hbar$ was found and has been placed in a level scheme connecting it with the previously known low-spin states [3]. The $\mathcal{I}^{(2)}$ dynamic moment of inertia is strikingly different than that of ^{111}In, and the alignment gain versus rotational frequency is similiar to that of the core nucleus ^{108}Cd [4]. Since there is no perturbation of the first $\nu h_{11/2}$ alignment the band is not based on the $\pi h_{11/2}$ intruder orbital. Indeed, the absence of a second crossing observed in ^{111}In which was attributed to a $\pi g_{7/2}$ alignment suggests that the band in ^{109}In is based on a $\pi g_{7/2}$ configuration. This is consistent with cranked shell model calculations at the small deformation indicated by the DSAM information.

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High Spin Spectroscopy of ^{112}Sn

J.H. DeGraaf[1] and the 8π Collaboration[1,2,3,4]

[1] *Dept. Physics, University of Toronto, Toronto, Ontario, M5S 1A7, Canada.*
[2] *Dept. Physics and Astronomy, McMaster University, Ontario, L8S 4M1, Canada*
[3] *AECL Research, Chalk River Labs. Chalk River, Ontario, K0J 1J0, Canada*
[4] *Dept. of Physics, University of Ottawa, Ottawa, Ontario, K1N 6N5, Canada*

The rotational behaviour of nuclei near the $Z = 50$ closed shell has been studied extensively. The high-spin yrast states observed in this region, particularly in the Sb ($Z = 51$) isotopes, are based on a $\pi h_{11/2}$ intruder orbital configuration. It is therefore of interest to understand the role of this orbital, in particular its effect on quasiparticle alignments. In addition, the contribution to the deformation arising from this orbital can be deduced by measuring the quadrupole moment of the rotational bands observed in Sb isotopes and their corresponding isotones in the Sn ($Z = 50$) nuclei.

High-spin states in ^{112}Sn were populated with the reaction ^{94}Zr(^{23}Na,p4n)^{112}Sn at 120 MeV at the Tandem Accelerator Super-Conducting Cyclotron (TASCC) facility at Chalk River, Canada. Gamma-ray spectroscopy was performed with the 8π spectrometer. Both thin-target and gold-backed-target experiments were performed, the latter for the purposes of a DSAM lifetime measurement.

The yrast band has been extended up to spin $26\hbar$ and two previously reported bands [1] have been extended up to spins of approximately $22\hbar$. The $\mathcal{I}^{(2)}$ moment of inertia plot shows two alignments, at $\hbar\omega \approx 0.3$ and ≈ 0.6 MeV. The first alignment has been previously observed and attributed to a pair of $h_{11/2}$ neutrons. The onset of a second alignment is also observed, and may be due to a pair of $g_{7/2}$ protons, as suggested for ^{113}Sb [2]. Results from the DSAM measurement suggest that the deformation of the yrast band in ^{112}Sn is only slightly smaller than that in ^{113}Sb implying that the occupation of the intruder orbital does not have a large effect on the shape of the nucleus.

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Identification and spectroscopy of $^{108,109,110}Te$ nuclei

B. M. Nyakó[1], Zs. Dombrádi[1], M. Józsa[1], G. E. Perez[1], C. Fahlander[2], D. Seweryniak[2], J. Nyberg[2], A. Atac[2], B. Cederwall[3], A. Johnson[3], A. Kerek[3], J. Kownacki[4], L-O. Norlin[3], R. Wyss[3], E. Adamides[5], E. Ideguchi[6], R. Julin[7], S. Juutinen[7], W., Karczmarczyk[4], S. Mitarai[6], M. Piiparinen[7], R. Schubart[8], G. Sletten[9], S. Törmänen[7] and A. Virtanen[7]

[1] Institute of Nuclear Research, Debrecen, Hungary, [2] The Svedberg Laboratory, Uppsala, Sweden, [3] The Royal Institute of Technology, Stockholm, Sweden, [4] Institute of Experimental Physics, Warsaw, Poland, [5] National Centre for Scientific Research, Attiki, Grece, [6] Kyushu University, Fukuoka, Japan, [7] University of Jyäskylä, Jyväskylä, Finland, [8] Hahn-Meitner Institute, Berlin, Germany, [9] The Niels Bohr Institute, Copenhagen, Denmark

It is of great interest to identify and study the structure of nuclei close to the proton drip line, especially of those close to the doubly magic nucleus ^{100}Sn. In this line we have investigated, for the first time by in-beam γ-spectroscopic methods, the neutron deficient $^{108,109,110}Te$ isotopes with two valence protons outside the closed shell.

The experiment, the $^{54}Fe(^{58}Ni,2pxn\gamma)$ reaction at 270 MeV, was performed at the Tandem Accelerator Laboratory of the Niels Bohr Institute, Risø, Denmark. $\gamma\gamma$-charged particle-neutron coincidence events were collected using the NORDBALL detector system [1], which was configured with 15 BGO-shielded Ge detectors, 11 liquid scintillator neutron detectors of 1π solid angle in the forward direction [2], an inner 4π charged-particle ball of 21 ΔE type Si detectors [3] and a 30-element BaF_2 γ-ray calorimeter in the backward 2π hemisphere. In the data analysis, carried out in Debrecen and Uppsala, $E_\gamma - E_\gamma$ matrices were generated from the coincidence events by setting different conditions on the number of detected protons, α particles and neutrons to enhance γ rays belonging to a given final nucleus. A successive matrix subtraction technique was applied to reduce the contamination by γ rays of other nuclei in the channels of interest.

The level schemes of the three Te nuclei were constructed from $\gamma\gamma$ coincidence relations in the cleaned matrices. The spin and parity assignments were deduced from the measured DCO ratios. In ^{108}Te the first few members of the ground state vibrational band have only been firmly identified, while in ^{110}Te, in addition to this band, we found a quasi-rotational band based on the $\nu(h_{11/2}g_{7/2})$ 9^- configuration, as well as several side bands. In ^{109}Te two quasi-rotational bands built on the $\nu g_{7/2}$ and $\nu h_{11/2}$ neutron quasiparticle states were identified. The experimental results are discussed on the basis of the cranked shell model (^{110}Te) and in the framework of the particle-vibration coupling model using the IBFM formalism (^{109}Te).

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Evidence for Octupole Correlations at High Spins in Neutron-Deficient ^{110}Te

V.P. Janzen[1], E.S. Paul[2], H.R. Andrews[1], T.E. Drake[3],
S. Pilotte[4], D.C. Radford[1] and D. Ward[1]

[1] *Chalk River Laboratories, AECL Research, Chalk River, ON, K0J 1J0 Canada*
[2] *Oliver Lodge Laboratory, University of Liverpool, P.O. Box 147, Liverpool L69 3BX, UK*
[3] *Department of Physics, University of Toronto, Toronto, ON, M5S 1A7, Canada*
[4] *Department of Physics, University of Ottawa, Ottawa, ON, K1N 6N5, Canada*

The neutron-deficient ($N \sim 60$) tellurium ($Z = 52$) and xenon ($Z = 54$) isotopes are interesting because they lie in one of a very few regions of the nuclear chart where $\Delta j = \Delta l = 3$ orbitals approach the Fermi surface for both protons and neutrons. The interaction of these orbitals is expected to lead to octupole correlations, and the onset of octupole shapes has been predicted for $N \leq 58$ [1].

High-spin states in neutron-deficient ^{110}Te were populated with the ^{58}Ni(^{58}Ni,α2p)^{110}Te reaction at 250 MeV. The ^{58}Ni beam, provided by the Tandem Accelerator Superconducting Cyclotron (TASCC) facility at AECL Laboratories, Chalk River, was incident upon a 1 mg/cm^2 ^{58}Ni target with a thick ^{197}Au backing. Coincident γ-γ data were acquired with the 8π spectrometer which consists of 20 Compton-suppressed HPGe detectors plus a 71-element bismuth germanate (BGO) inner-ball calorimeter which provides γ-ray sum-energy, H, and fold, K, information. Approximately 3.5×10^7 events with $K \geq 10$ were recorded on tape. We find a sequence of interleaved states of negative and positive parity at high spins ($I \geq 18$) which are connected by very strong $E1$ transitions; this is good evidence for octupole correlations. Values of $B(E1)/B(E2) \sim 10^6$fm^{-2} were found, as detailed in Table 1. We extracted the dipole moment D_0 assuming a quadrupole moment of $Q_0 = 200$e.fm^2 based on the predicted quadrupole deformation of $\beta_2 \sim 0.15$. The values obtained for the intrinsic diple moment in ^{110}Te are similar to those found in the neutron-rich barium ($Z = 56$) nuclei and are slightly smaller than values typical of the Ra-Th region; they are, however, larger than those found in ^{114}Xe [2]. The nuclei ^{110}Te and ^{114}Xe both have isopsin $T_Z = 3$, whereas the other known regions of octupole correlations occur in nuclei with $T_Z \sim 16$ (neutron-rich Ba region) and $T_Z \sim 20$ (Ra-Th region). Results will also be presented from a recent 8π-spectrometer experiment with the same ^{58}Ni-on-^{58}Ni reaction at a lower beam energy.

Table 1: Observed dipole strengths in ^{110}Te, assuming $Q_0 = 200$e.fm^2.

I initial	B(E1)/B(E2) (fm^{-2})	B(E1) (e^{2}fm^2)	B(E1) (W.u.)	$\|D_0\|$ (e.fm)
18	6.3×10^{-7}	0.89×10^{-3}	0.60×10^{-3}	0.087
20	9.4×10^{-7}	1.33×10^{-3}	0.91×10^{-3}	0.107
22	13.7×10^{-7}	1.95×10^{-3}	1.33×10^{-3}	0.130

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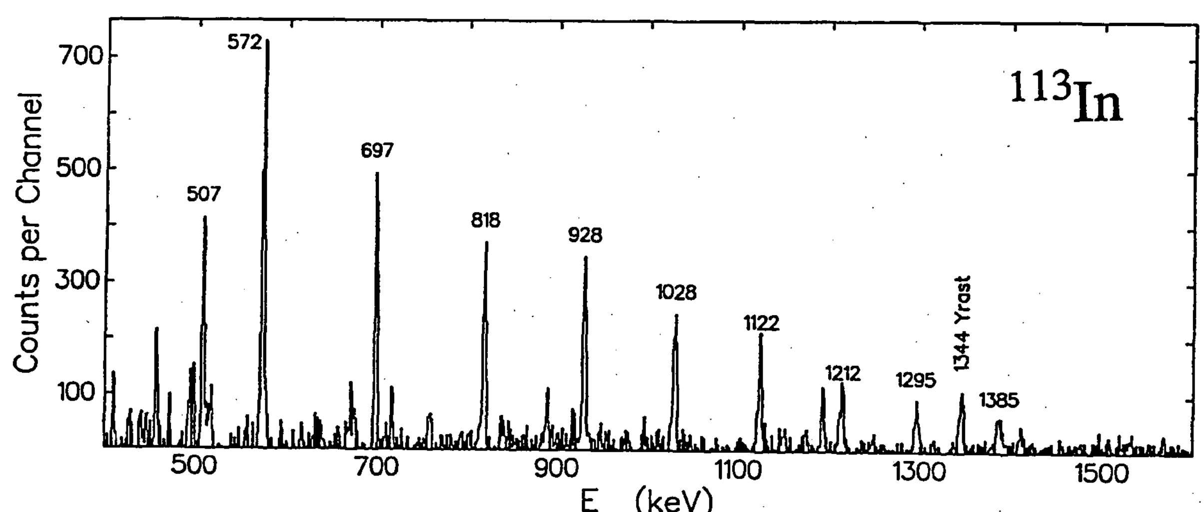
A Proton Intruder Band in ^{113}In*

S. Naguleswaran, U. Garg, K. Lamkin, G. Smith, J.C. Walpe
Physics Department, University of Notre Dame; Notre Dame, IN 46556.
A. Galindo-Uribarri, V.P. Janzen, D.C. Radford
Chalk River Laboratories, AECL Research, Chalk River, ONT K0J 1J0, Canada.
S. Pilotte
Department of Physics, University of Ottawa, Ottawa, ONT K1N 6N5, Canada.
C. Doste, D.B. Fossan, D.R. LaFosse, T. Morek, P. Vaska
Department of Physics, State University of New York, Stony Brook, NY 11794.
J. DeGraaf, T. Drake
Department of Physics, University of Toronto, Toronto, ONT M5S 1A7, Canada.
R. Kaczarowski
Soltan Institute of Nuclear Studies, 05-400 Swierk, Poland.

As a part of our ongoing studies of nuclei near the Z=50 closed shell, the nucleus ^{113}In has been investigated by means of γ-ray spectroscopic measurements following the ^{100}Mo(^{18}O, p4n)^{113}In reaction, using a 95 MeV ^{18}O beam provided by the TASCC facility at Chalk River. Particle γ–γ coincidence measurements were made with the 24 CsI detectors of the charged-particle array, ALF, in conjunction with the 8π γ–ray spectrometer. The previously-known level scheme of this nucleus [1] has been significantly extended, with spins and parities assigned on the basis of DCO ratios. The low-lying structure of the nucleus is well reproduced by particle + vibrational core model calculations. In addition, a very regular sequence of nine transitions, with energies reminiscent of a rotational band and DCO ratios compatible with E2 multipolarity, was observed (see figure below). The dynamic moments of inertia were extracted and compared to a similar band recently observed in ^{111}In [2]; the evolution of $\mathfrak{J}^{(2)}$ with the rotational frequency in ^{113}In is different from that in ^{111}In, especially in the band-crossing region. Further analysis and TRS calculations are in progress to understand the nature of this band.



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Multiple intruder bands and unfavoured band termination in $^{113,115}I$

E S Paul[1], H R Andrews[2], C W Beausang[1], R M Clark[3], T Davinson[4], J DeGraaf[5], T E Drake[5], S A Forbes[1], D B Fossan[6], S J Gale[1], A Gizon[7], J Gizon[7], K Hauschild[3], I M Hibbert[3], A N James[1], V P Janzen[2], P M Jones[1], M J Joyce[1], D R LaFosse[6], R D Page[4], S Pilotte[8], D C Radford[2], I Ragnarsson[9], P J Sellin[4] H Schnare[6], J Simpson[10], R Wadsworth[3], D Ward[2], M P Waring[6], P J Woods[4]

[1] *Oliver Lodge Laboratory, University of Liverpool, L69 3BX, UK*
[2] *Chalk River Laboratories, AECL Research, Chalk River, Canada*
[3] *Department of Physics, University of York, Heslington, York YO1 5DD, UK*
[4] *Department of Physics, University of Edinburgh, Edinburgh EH9 3JZ, UK*
[5] *Department of Physics, University of Toronto, Ontario M5S 1A7, Canada*
[6] *Department of Physics, State University of New York at Stony Brook, NY 11794, USA*
[7] *Institut des Sciences Nucléaires, Université Joseph Fourier, Grenoble, France*
[8] *Department of Physics, University of Ottawa, Ottawa K1N 6N5, Canada*
[9] *Department of Mathematical Physics, Lund Institute of Technology, Lund, Sweden*
[10] *SERC Daresbury Laboratory, Daresbury, Warrington WA4 4AD, UK*

Several rotational bands have been established in ^{113}I at high spin using the symmetric $^{58}Ni(^{58}Ni,3p\gamma)$ reaction at 240 MeV. The data were collected with the Eurogam spectrometer at Daresbury, which was used in conjunction with the recoil separator. Six similar rotational bands have also been established in ^{115}I using the $^{60}Ni(^{58}Ni,3p\gamma)$ reaction at 250 MeV. These data were acquired with the 8π γ-ray spectrometer at Chalk River Laboratories, Canada.

Several of the new bands are observed to extremely high rotational frequencies beyond $\hbar\omega$=1.0 MeV (spin approaching $50\hbar$). All the bands show a characteristic stretching out of the γ-ray energy spacings with increasing spin. This effect leads to a fall off in their dynamic moments of inertia with increasing rotational frequency such that unusually low values are observed at high spin, much lower than the rigid-body estimate. These novel features are suggested to arise from a "soft" band termination in which the nucleus traces a gradual path through the γ plane from a collective prolate shape ($\gamma = 0°$) to the noncollective oblate shape ($\gamma = +60°$) over many transitions. During this slow shape transition, the single-particle angular momenta of the valence particles (outside the N=Z=50 core) are gradually aligned with the "rotation" axis. The final energetically "unfavoured" terminating states reside well above yrast. This behaviour is to be contrasted with the abrupt "favoured" termination seen in several neighbouring nuclei in this mass region, e.g. ^{121}I shows yrast noncollective states at $39/2^-$ and $55/2^-$ [1]. Theoretical results, based on a modified oscillator potential without pairing [2], will be presented in order to assign specific configurations to the new bands in $^{113,115}I$.

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OBSERVATION OF THE $\pi h_{11/2}$ BAND IN ^{117}Cs

X.Sun, Z. Liu, X. Zhou, X. Lei, H. Jin, Q. Pan, Y. Zhang, Y. Guo and Y. Luo
(Institute of Modern Physics, Academia Sinica, Lanzhou 730000, China)
S. Wen, G.Yuan, G.Li and C. Yang
(China Institute of Atomic Energy, Beijing 102413, China)
Z. Xing and X.Q. Chen
(Lanzhou University, Lanzhou 730000, China)

This report presents the experimental observation of the $\pi h_{11/2}$ band in ^{117}Cs for which no excited states were previously known.

The experiment was performed at the HI−13MV tandem accelerator, Beijing via the reaction $^{92}Mo(^{28}Si,p2n)$ at 100−120MeV. An array of 7 BGO(AC) HPGe detectors and a 14 element BGO crystal ball were used. A clean rotational band consisted of 307, 494, 626, 712 and 796 keV transitions was found from the gated spectra. The band has been considered as the $\pi h_{11/2}$ band of ^{117}Cs based on the measured excitation functions and γ−ray intensity of the new band. The new band manifests itself as the $\pi h_{11/2}$ band of ^{117}Cs by the systematics of the $\pi h_{11/2}$ bands in odd Cs nuclei and the same trend has been observed in the $\pi h_{11/2}$ bands of ^{A-2}I and ^{A-1}Xe isotopes (Fig.1). Particle-plus-triaxial-rotor model calculations have been performed in which the moments of inertia are taken as a function of the total angular momentum[1] $J \propto J_{oo}(1+(1+bI(I+1))^{1/2})$. The parameters J_{oo} and b are obtained by fitting the γ− transition energies, and the deformation parameter β (and thereby the potential parameter κ) is taken from TRS calculations[2] to be 0.249, 0.251, 0.251, 0.248, 0.232 and 0.210 for $^{117,119,121,123,125}Cs$ and ^{127}Cs, respectively. Other parameters used are $\gamma = 5^o$, $\lambda = 0.79\kappa$ and $\Delta = 0.52\kappa$ for all these odd Cs isotopes. The calculated results reproduce the systematics rather well. Therefore the β-deformation is strongly dependent on the number of neutrons and γ−deformation stays constant for the odd-A Cs nuclei.

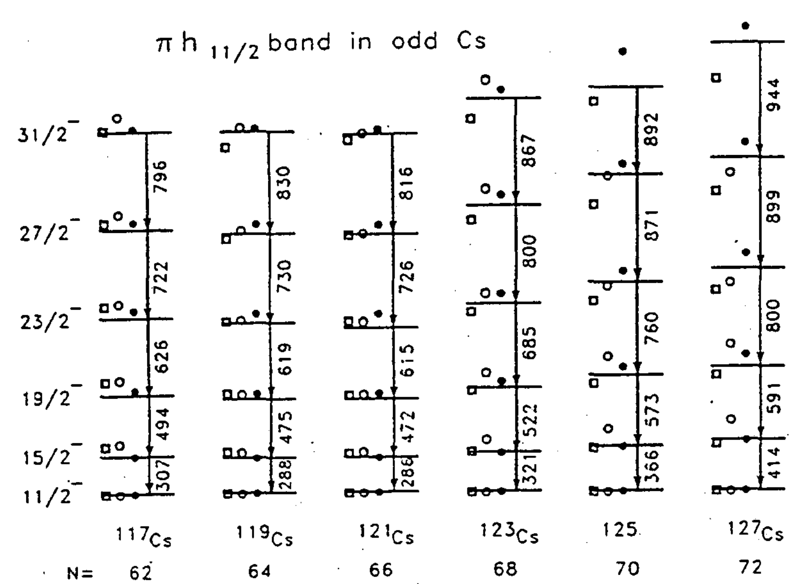

Fig.1 Systematic comparison of the $\pi h_{11/2}$ bands in odd Cs, ^{A-2}I (o) and ^{A-1}Xe (□) and the calculated results (•).

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High Spin States in ^{117}Xe

Z.Liu, X.Sun, X.Zhou, X.Lei, Y.Zhang, H.Jin, Q.Pan, Y.Guo, X.Chen and Y.Luo
(Institute of Modern Physics, Academia Sinica, Lanzhou 730000)
S.Wen, G.Yuan, C.Yang, W.Luo and Y.S.Chen
(China Institute of Atomic Energy, Beijing 102413)

High spin states of ^{117}Xe, populated via the reaction $^{92}Mo(^{28}Si, 2pn)$ from 100-120 MeV at the HI-13MV Tandem Accelerator Beijing, were studied with an array of 7 HPGe(AC) detectors and a BGO crystal ball of 14 elements. The obtained partial level scheme is shown in Fig.1. Three new cascades 1, 2, 4 have been definitely assigned to ^{117}Xe based on the low lying transitions identified in the ^{117}Cs decay study[1]. Band 5 and 6 are signature members of the [532]5/2 $\nu h_{11/2}$ band[2]. Band 3, the $\nu g_{7/2}$ $\alpha=-1/2$ band of ^{117}Xe[3], was extended up to $47/2^+$. Two backbends resulting from the alignment of a pair of $h_{11/2}$ neutrons and a pair of $h_{11/2}$ protons respectively, were observed at 0.33 and 0.43 MeV, well consistent with CSM calculations. The shape of this band is expected to evolve to $\gamma=60°$ at $45/2^+$, and a weakly observed 541 keV transition coincident with every intraband transition of band 3 may be the evidence of the non-collective rotation of this oblate shape. The 271keV transition is confirmed to be of M1, 507keV and 546keV manifest the property of E2 transition in DCO ratio analysis. Therefore band 2 and 4 are positive parity bands, and band 2 is possibly based on the [411]3/2 $\nu g_{7/2}$ configuration. Five distinct transitions from band 4 to 5 have been observed and band 4 seems like the signature partner of band 3 on account of the similarities between their alignments. Band 1 is the first example with irregular level spacings in this mass region. The present TRS calculations for the 5/2[413] $\nu g_{7/2}$ configuration suggest a shape coexistence of a collective prolate shape with $\gamma\sim-10°$, on which band 3 is based, and a prolate shape rotating around its symmetric axis ($\gamma=-120°$), on which band 1 is likely based.

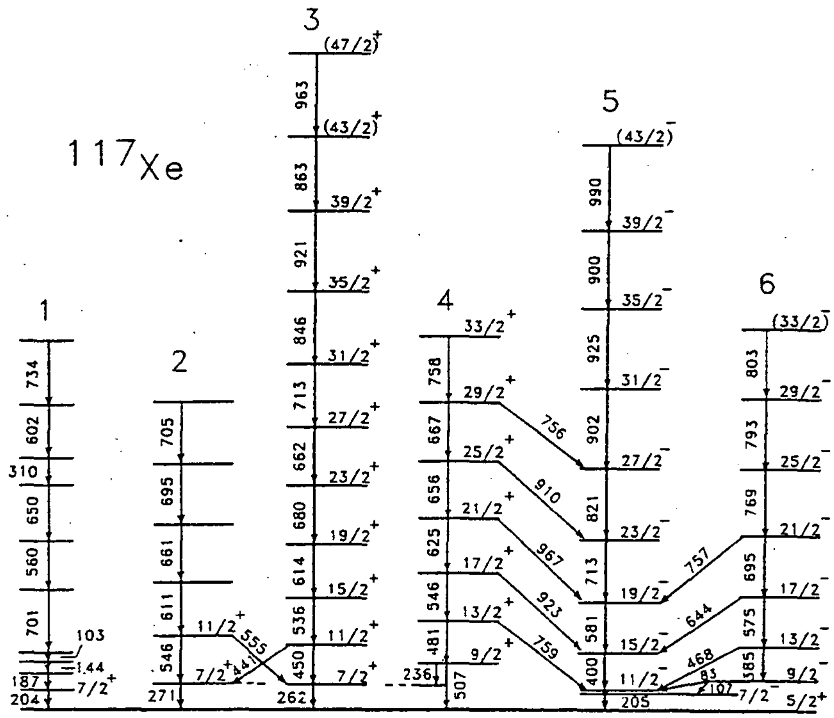

Fig.1 Partial level scheme of ^{117}Xe proposed from this work

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A New High Spin Band in ^{118}I Nucleus

*H.Kaur, J.Singh, A.Sharma, J.Goswamy, B.Chand, #D.Mehta, N.Singh, *R.K.Bhowmik and P.N.Trehan.*
Physics Department, Panjab University, Chandigarh-160014, India.
#Physics Department, Delhi University, New Delhi, India.
**Nuclear Science Centre, New Delhi, India.*

The high spin states in ^{118}I were populated by means of ^{106}Pd(^{16}O,p3n) reaction at 89 MeV. This experiment was performed using the GDA set-up and 16UD pelletron accelerator at NSC, New Delhi. A total of 56 million $\gamma\gamma$-coincidences were collected with atleast one-fold hardware trigger of BGO filter.

Two bands have been identified of which one was reported earlier [1] to be based on $\nu h_{11/2} \otimes \pi g_{9/2}$ configuration. The other band has been observed for the first time and has weak links with the earlier known band. This band is possibly based on the $J^{\pi} = 2^{-}$ isomer populated in the β^{+} decay of ^{118}Xe. This band exhibits signature splitting with very weak unfavoured branch. This band shows a loss in collectivity at $I=19^{-}$ similar to that observed in odd-A Iodine nuclei.

This band has recently been assigned to ^{118}Cs [2]. The present work rules out this assignment and convincingly proves this band to belong to ^{118}I. These arguments will be presented therein.

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Band termination and new rotational bands in ^{118}Te

C. Duyar[1], J.E. Draper[1], E.C. Rubel[1], M.A. Deleplanque[2], R.M. Diamond[2], F.S. Stephens[2]
E.M. Beck[3], M.A. Stoyer[2]

[1] Physics Department, University of California, Davis, CA 95616 USA

[2] Lawrence Berkeley Laboratory, Berkeley, CA 94720 USA

[3] Alexander-von-Humbolt Stiffung, Jean Paul, Str. 12, D-5300, Bonn 2 (Bad Godesberg), Germany

High spin states of ^{118}Te have been studied using ^{82}Se (^{40}Ar at 185MeV, 4n) ^{118}Te and ^{76}Ge (^{48}Ca at 190 MeV, 6n) ^{118}Te reactions. The coincidence intensities of all assigned transitions were measured, and the multipolarity and spin assignments of the most intense transitions were made using a new method combining the angular distribution and correlations techniques.

Two new rotational bands were found in ^{118}Te, and they were assigned to be signature partners due to the similarities between their static and dynamic moments of inertia. Spin assignments for one of these bands could be done. This band (called band 2) extends from spin 9 to 25. No transitions connecting the other band (called band 1) to the ground state band or any other bands have been observed. Therefore, the spin assignments for band 1 are tentative. Band 1 extends from spin 10 to 30. The parity assignments for these bands could not be done.

Strong E2 transitions up to a 16^+ are observed. Above this level, there exist strong high energy transitions (above 1 MeV), and it appears that the collectivity disappears above the 16^+ level. Six more strong transitions (stretched dipoles) with irregular energies were observed. This structure extends up to a spin of $22\hbar$. Above this level (I=22), no transitions were observed.

The Total Routhian Surface (TRS) calculations were done for different configurations to interpret the data. Also, cranked shell model calculations were done to find out which orbitals are contributing the structures mentioned above.

The rotational bands could be interpreted as $\pi(h_{11/2}g_{7/2}g_{9/2}^2)_{K=1^-}$ if their parities were negative. If positive parity, the TRS calculations strongly suggest that these bands may be due to the π-vacuum and ν-vacuum configuration and the πAC and ν-vaccum configuration. Then the assignment for these bands would be $(\pi(g_{7/2})^2 \otimes {}^{116}\mathrm{Sn}0_2^+)_{K=0^+}$.

Because of the TRS calculations for the π-vacuum and ν-vacuum configuration, the 16^+ and (22) levels are proposed to be due to the full alignment of $(\pi(g_{7/2})^2_{6^+}\nu(h_{11/2})^2_{10^+})_{16^+}$ and $(\pi(g_{7/2})^2_{6^+}\otimes \nu(h_{11/2})^4_{16^+})_{22^+}$, respectively, both having oblate non-collective shapes.

The π-vacuum and ν-vacuum configuration also shows rotational collectivity with deformation parameters $\beta_2 \sim 0.145$ and $\gamma \sim -1.5°$. At ω=0.366, the calculated spin is nearly equal to 14. The experiment shows that at I=14, there is a 774.1 keV transition depopulating this level. Also there is a 400.5 keV transition is feeding it. The 14^+ level is probably the last level after which the deformation parameter γ moves from the collective prolate axis to the non-collective oblate axis in β_2-γ plane (indicating band termination).

High Spin Structures in ^{118,119}Te Nuclei

*A.Sharma, J.Singh, H.Kaur, J.Goswamy, B.Chand, #D.Mehta, N.Singh, *R.K.Bhowmik and P.N.Trehan.*
Physics Department, Panjab University, Chandigarh-160014, India.
#Physics Department, Delhi University, New Delhi, India.
**Nuclear Science Centre, New Delhi, India.*

The high spin states in ^{118,119}Te nuclei were populated through the ^{110}Pd(^{13}C,5n;4n) reaction at 66 MeV. This experiment was performed using GDA set-up comprising of 6 Ge/ACS and 14 BGO element multiplicity filter and 16UD pelletron accelerator at NSC, New Delhi. A total of 35 million γ-γ coincidences were collected with atleast one fold trigger from BGO filter. The level schemes of ^{118,119}Te nuclei have been established using measurements of γ-ray intensities and $\gamma\gamma$-coincidence relations and DCO ratios.

In ^{118}Te five new bands have been identified with the addition of more than 35 new transitions. The positive parity yrast band was established upto I=25. This band is found to be fed by a sequence of alternate quadrupole and dipole transitions at I=16 state. A near rigid rotational band feeding 10^+ yrast state has been established. This feature is similar to that observed in ^{116}Te[1].

In ^{119}Te four new bands have been established with the addition of 40 new transitions. The yrast band has been established upto I=55/2$^-$. This band is found to split into three branches at I=39/2$^-$.

Reference :

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DECOUPLED PARTICLES, ACCIDENTAL DEGENERACIES, AND IDENTICAL BANDS. Wm. C. McHarris, National Superconducting Cyclotron Laboratory and Departments of Chemistry and Physics/Astronomy, Michigan State University, East Lansing, MI 48824.

Among the many explanations proffered for identical or nearly-identical rotational bands seen in superdeformed (and other) nuclei, some of the more intriguing, such as quasi-spin, have been group-theoretically based. Here we attempt to combine group-theoretical and semi-geometrical arguments: It is well known that many high-spin states involve multiple particle decouplings, and it can be argued that such decouplings lead to large deformations—if enough particles were to decouple, perhaps even superdeformation. Now, states comprised of multiple decoupled and recoupled particles, be they atomic or nuclear, contain many so-called accidental degeneracies; this fact encouraged the development of seniority coupling schemes and coefficients of fractional parentage, and many such accidental zeroes and degeneracies occur naturally when viewed in the context of higher Lie groups. Our experimental group, a combination of MSU and ORNL personnel, has characterized many nearly-identical bands in the neutron-deficient Ce-Pr region, including four almost identical bands in odd-odd ^{132}Pr. We use the decoupling-recoupling approach to yield a good qualitative fit for some of these bands.

A K^π=8$^-$ Band for N=74: High-K States in ^{136}Sm.

P.H. Regan, G.D. Dracoulis, A.P. Byrne, G.J. Lane, T. Kibédi
Dept. Nucl. Phys., Australian National Uni. ACT 0200, Canberra, Australia

P.M. Walker
Dept. of Physics, University of Surrey, Guildford, GU2 5XH, UK

A.M. Bruce
Dept. of Mathematical Sciences, University of Brighton, Brighton, BN2 4GJ, UK

For more than twenty years, low lying isomeric states for nuclei with neutron number 74 have been known to exist in the light rare earth region around mass 130. These isomers are thought to be due to a high-K structure built from the coupling of the 7/2$^+$[404] and 9/2$^-$[514] orbitals to a K^π=8$^-$ state which is hindered in its decay to the K=0$^+$ ground band. However, in order to independently test this assignment, it is important to measure the characteristics of the bands built upon these states. Since their lifetimes are in the millisecond region, measurement of the transitions above the N=74 isomers are difficult, indeed, no information exists on bands built upon the previously observed isomers in $^{130}_{56}$Ba [1], $^{132}_{58}$Ce [2] and ^{134}Nd [3].

To extend the systematics, we have studied the N=74 nucleus, ^{136}Sm, using the reaction ^{107}Ag(^{32}S,p2n) with a pulsed, 140 MeV beam provided by the ANU 14UD accelerator. Emitted γ-rays were detected using the CAESAR Compton suppressed detector array. The $\frac{7}{2}^+$ and $\frac{9}{2}^-$ ground states of ^{135}Sm and ^{137}Sm can be associated with the 7/2$^+$[404] and 9/2$^-$[514] Nilsson orbitals respectively, so a K^π=8$^-$ two-quasi-neutron state is expected to exist with an excitation energy close to twice the neutron pair gap. An isomer with a half life of 15$\pm$1 μs was observed [4].

In an attempt to detect states above this isomer, a second experiment was performed with the particle detector ball (PDB) in conjunction with the CAESAR array. The PDB consists of fast/slow plastic phoswhich detectors packed in close geomtery and enabled clean selection of 1-proton events, substantially reducing the background due to Coulomb excitation of the ^{107}Ag target. The experiment was successful in observing discrete transitions populating the isomer in ^{136}Sm.

The level scheme constructed includes a band based on the isomeric 8$^-$ bandhead extending to spin/parity 15$^-$. The measured dipole/quadrupole branching ratios for this structure yield a deduced g_K value which is consistent with the 7/2$^+$[404] $\otimes$ 9/2$^-$[514] two-quasi-neutron configuration. Angular distribution measurements for the lowest dipole cascade transition in the new K^π=8$^-$ band (414 keV) imply a negative mixing ratio, again consistent with the proposed configuration. A new, high-K structure is also observed to feed into the K^π=8$^-$ band.

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(4) A.M. Bruce *et al.* *submitted to Phys. Rev.* **C**

High spin states of ^{140}Sm in the interacting boson model with broken pairs

D. Vretenar[1)], Y. Li[2)], R. Menegazzo[3)], G. de Angelis[2)], D.Bazzacco[3)], G. Bonsignori[4)], M.De Poli[2)], S.Lunardi[3)], C. Rossi Alvarez[3)], M. Savoia[4)]

[1)] Physics Department, University of Zagreb, Zagreb, Croatia

[1)] INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy

[2)] Dipartimento di Fisica and INFN Sezione di Padova, Padova, Italy

[4)] Dipartimento di Fisica and INFN, Sezione di Bologna, Bologna, Italy

The interacting boson model can be extended to describe the structure of high spin states in even-even nuclei by including non-collective two and four fermion excitations in the model space. This approach applies especially well in regions of transitional nuclei. The structure of high spin states in light Zr nuclei[1)] as well as those of Hg isotopes[2)] are nicely reproduced by the model. Using the GASP spectrometer, we have studied the transitional nucleus ^{140}Sm by means of the ^{110}Pd(^{34}S,4n) reaction at 150 MeV. The level scheme has been extended up to 10 MeV excitation energy and spin I≈26. The two bands built on the two 10^+ states of $h_{11/2}^2$ neutron and proton configuration respectively could not been extended to higher spin with respect to previous experiments [3]. Instead new collective structures which start at $E_x \approx 6$ MeV and continue to the highest spins have been observed. We have analysed the experimental results in the framework of the IBM with broken pairs. The main features of the excitation spectrum of ^{140}Sm up to $E_x \approx 7$ MeV are well reproduced by the calculations within a model space wich contain only one neutron or one proton broken pair. The excitation energies of the ground state band, of the proton and neutron 2qp bands built on the two isomeric 10^+ states and of the lowest negative parity band are in very nice agreement with results of model calculation. Furthermore by extending the model space to include one- and two-broken pairs we have been able to interprete one of the high spin collective structure as a proton 4qp band, in agreement with the decay pattern experimentally observed.

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Collectivity in "Spherical" ^{143,144}Eu Nuclei

M. Piiparinen[1,2], A. Ataç[3], S.J. Freeman[2], T. Lönnroth[2,4], D. Müller[1], J. Nyberg[3], G. Sletten[2], S. Törmänen[1], A. Virtanen[1], C.T. Zhang[5]

[1] *Department of Physics, University of Jyväskylä, Jyväskylä, Finland*
[2] *Niels Bohr Institute, Tandem Accelerator Laboratory, Roskilde, Denmark*
[3] *The Svedberg Laboratory, Uppsala, Sweden*
[4] *Department of Physics, Åbo Academy University, Turku, Finland*
[5] *Institut für Kernphysik, Forschungszentrum Jülich, Jülich, Germany*

The level schemes of ^{143,144}Eu have been established [1] in NORDBALL experiments up to spin 75/2 and ~36, respectively. These nuclei have one proton hole and one or two neutron holes in respect to the doubly magic ^{146}Gd core nucleus and the level schemes exhibit very complex and irregular structures, typical to spherical or slightly oblate nuclei where multiparticle excitations dominate.

In both nuclei, we have observed a long straight cascade of about 10 stretched $E2$ transitions. Although the transition energies in the cascade form an irregular sequence, not resembling any rotational band, already the existence of such a cascade in a "spherical" nucleus indicates some kind of increasing collectivity in the nucleus.

For further probing this possible collectivity we have now performed a plunger experiment at NORDBALL. The array consisted of 20 Compton-suppressed Ge spectrometers in four conical rings at 37°, 79°, 101° and 143° in respect to the beam direction. The 60 element BaF_2 inner ball served as a calorimeter for total γ-ray energy and multiplicity. A new plunger device especially designed for the NORDBALL array was used.

In the experiment the ^{110}Pd(^{37}Cl,xn) reactions at 160 MeV bombarding energy were used which gave v/c=2.1% for the recoil velocity. A 1.05 mg/cm^2 97% enriched ^{110}Pd foil served as a target and an 8 mg/cm^2 thick Au foil as a stopper. We measured 20 target-to-stopper distances between 5 and 4000 μm, in average about 50 million coincidence events for each distance.

The results of the plunger experiment show $B(E2)$ values close to the single particle estimate for the $E2$ transitions in the "normal" spherical part of the level scheme. In a sharp contrast, we have observed very fast $E2$ transitions in the above mentioned $E2$ cascade in both nuclei. The 548, 615 and 867 keV transitions [1] in ^{143}Eu give mean life values for the initial (7392 keV)$43/2^-$, (8008 keV)$47/2^-$ and (8875 keV)$51/2^-$ levels as τ = 9.2(4), 3.1(3) and 0.6(2) ps corresponding to reduced transition rates of $B(E2)$ = 41(2), 68(7) and 63(21) *W.u.*, respectively. In ^{144}Eu the $E2$-cascade is not connected to the other part of the level scheme and therefore the accurate level spin and excitations energy values are not known. The 480 and 659 keV transitions give level lifetime values of 12.3(4) and <2 ps and transition rates of 58(2) and >74 *W.u.*

In the upper part of the $E2$ cascades the transitions are emitted during the slowing down process of the recoiling nuclei in the gold backing of the target in the backed target experiment [1]. A DSAM analysis of the data is in progress but already a rather qualitative comparison to the stopping time of the recoiling nuclei gives lifetime estimates which, in many cases, correspond to equally high (or higher) $B(E2)$ values as those mentioned above for the $E2$ cascades.

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Oblate Dipole Cascades in ^{144}Gd

R.M. Lieder[1], T. Rzaca-Urban[1,2], S. Utzelmann[1], K. Strähle[1], W. Gast[1], A. Georgiev[1], D. Kutchin[1], G. Marti[1], K. Spohr[1,3], P. von Brentano[4], J. Eberth[4], A. Dewald[4], J. Theuerkauf[4], I. Wiedenhöfer[4], K.O. Zell[4], K.H. Maier[3], H. Grawe[3], J. Heese[3], H. Kluge[3], W. Urban[5] and R. Wyss[6]

[1]KFA Jülich, 52425 Jülich, Germany [2]University of Warsaw, Poland [3]HMI Berlin, 14091 Berlin, Germany [4]Universität zu Köln, 50937 Köln, Germany [5]University of Manchester, Manchester M13 9PL, UK [6]Royal Institute of Technology, 104 05 Stockholm, Sweden

High–spin states in ^{144}Gd were studied with the γ-spectrometer OSIRIS. The final nucleus has been produced in the ^{108}Pd(^{40}Ar,4n) reaction with a beam energy of 182 MeV at the VICKSI accelerator of the HMI Berlin. A portion of the ^{144}Gd level scheme is shown in fig.1. An interesting feature is the existence of an intense $\Delta I = 1$ sequence above the 14^+ state. The DCO ratios of the transitions forming this sequence have values consistent with quadrupole/dipole mixing ratio changing from $\delta \approx -1.0$ to $\delta \approx -0.2$ with increasing spin. The large negative mixing ratios indicate M1/E2 character for the $\Delta I = 1$ transitions and that a dipole sequence related to an oblate nuclear shape has been observed in ^{144}Gd, similarly to the dipole bands in the $^{198-201}$Pb nuclei (see, e.g., [2, 3]). For an oblate shape of ^{144}Gd, the $\Omega = 1/2$ orbital of the neutron $h_{11/2}$ subshell lies in the vicinity of the Fermi surface. For the proton $h_{11/2}$ subshell the Fermi surface lies close to the $\Omega = 11/2$ state. Hence, the $h_{11/2}$ neutron holes easily align their angular momenta along the rotation axis, whereas the $h_{11/2}$ protons remain deformation aligned. The situation is thus similar to Pb and we propose a $\nu h_{11/2}^{-2} \otimes (\pi h_{11/2}^2)_{K=10^+}$ configuration for the dipole sequence. It is expected that the lowest band member has a spin of $\approx 14\hbar$ in agreement with experimental observation. The observed sequence is not regular, i.e., the transition energies do not follow the $I(I+1)$ law. This behaviour reflects the fact that the oblate minimum is rather shallow, as found in TRS calculations.

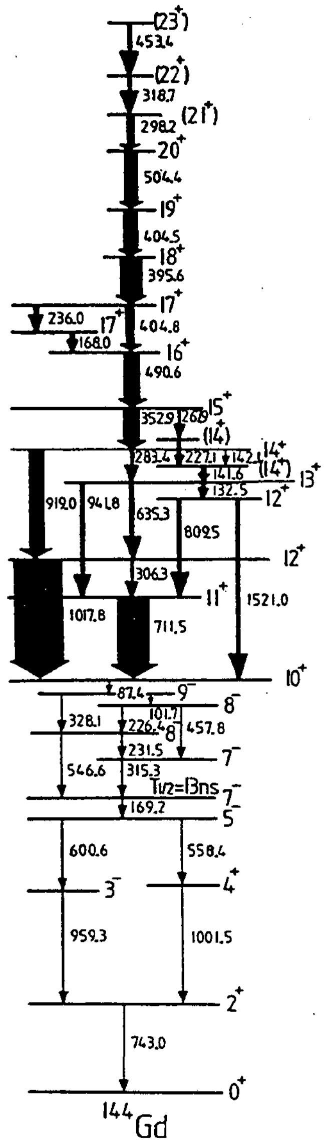

Figure 1: Partial level scheme of ^{144}Gd

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OCTUPOLE EXCITATIONS IN ^{144}Nd AND ^{146}Sm

P.G. Bizzeti[(a)], A.M. Bizzeti–Sona[(a)], L. Bargioni[(a)], D. Bazzacco[(b)], S. Lunardi[(b)], P. Pavan[(b)], C. Rossi–Alvarez[(b)], G. de Angelis[(c)], G. Maron[(c)], J. Rico[(c)].

[(a)] I.N.F.N. and University of Florence, Italy; [(b)] I.N.F.N. and University of Padova, Italy; [(c)] I.N.F.N., Laboratori Nazionali di Legnaro, Italy.

Nuclei around ^{146}Gd are known to present, together with normal shell model states, low lying octupole excitations whose collective nature is proved by the rather large E3 strenghts. In fact, the 3^- octupole state is the lowest-lying excitation in the core nucleus ^{146}Gd and examples of two-octupole-phonon states have been identified only in this nuclear region after many attempts around the doubly magic nucleus ^{208}Pb. Actually, in ^{147,148}Gd [1, 2] two such states ($I = 19/2^-$ and $I = 12^+$, respectively) have been found, which result from the stretched coupling of two octupole phonons to states of pure single-particle character. Lifetime measurements [3] of the two states gave further support for such attribution.

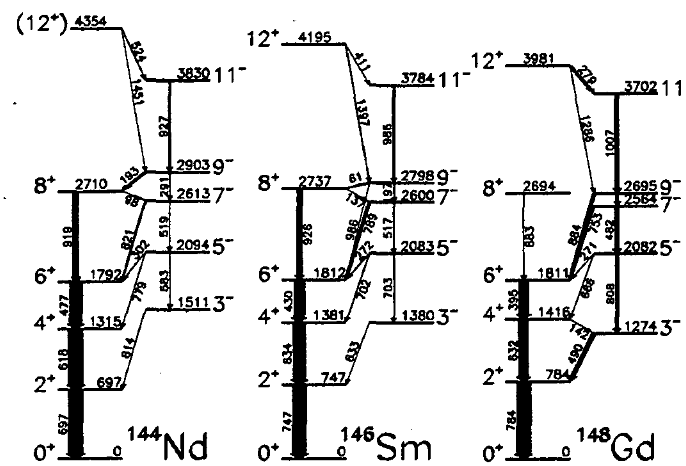

Figure 1. Partial level schemes of ^{148}Gd (from ref.[1]), ^{144}Nd and ^{146}Sm (present work). Only levels including a large component of collective octupole excitation or belonging to the lowest shell model configuration $(\nu f_{7/2}, h_{9/2})^2$, are shown.

We have investigated the two lighter isotones of ^{148}Gd, produced *via* the ^{139}La(^{11}B,4n)^{146}Sm and ^{139}La(^{11}B,α 2n)^{144}Nd reactions at $E(^{11}\mathrm{B})$ = 45 MeV, with the GASP array of L.N.L.. The level sequence, interpreted in ^{148}Gd as due to the stretched coupling of one or two octupole phonons to the positive-parity states of the ground-state band, is apparent also in ^{146}Sm and ^{144}Nd (Fig. 1). In particular, by means of triple γ coincidences it has been possible to identify, also in ^{146}Sm, the $12^+ \rightarrow 9^-$ and $9^- \rightarrow 6^+$ E3 transitions corresponding to those already known in ^{148}Gd. The E3 branch from the 9^- states reaches almost $3 \cdot 10^{-2}$ of the total. If, according to ref.[4], one assumes a mean life $\tau = 0.84$ns for the 9^- level of ^{146}Sm, the B(E3) decay strength comes out to be about 30 W.u., somewhat smaller than in ^{148}Gd. The E3 transition probability from the 12^+ state is rather weak (about $2 \cdot 10^{-2}$); at the moment, the mean life of this level is unknown, and it is not possible to decide whether the E3 decay is weaker or the E1 decay is stronger than in ^{148}Gd.

A good candidate for the 12^+ collective state has also been found in ^{144}Nd. The E3 decay from this state to the collective 9^- state is a relatively large branch (12%) compared to the E1 decay (55%); in addition, a further branch to a 4045 keV level (not shown in the figure) has been observed. The E3 decay from the 9^- to the 6^+ state in ^{144}Nd is, instead, strongly suppressed in comparison with the two heavier isotones, due to the larger available energy of the competing E1 and E2 transitions.

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Identical Bands in the Even-Even Rare-Earth Nuclei

C. Baktash

Oak Ridge National Laboratory, Oak Ridge, TN 37831-6371*

In a survey of the low spin identical bands in the even-even rare-earth nuclei, Casten et al. have reported the existence of several nuclei that form an alpha chain and have nearly identical moments of inertia.[1] At first glance, this may be simply due to the cancellation of the positive contributions of neutrons (that fill the lower half shell) and negative contributions of the protons (that fill the upper half shell) to the moments of inertia. However, since neutrons and protons occupy different shells, this cancellation is not expected to occur frequently. To study where, or how well this cancellation applies, we have analyzed the fractional changes in the moments of inertia, $FC(A)=[J(A)-J(A-2)]/J(A)$, for the neighboring even-even isotopes and isotones of Dy-Os nuclei with N>90, following the procedure described in Ref. 2. To avoid the perturbations in the moments of inertia caused by the first band crossing, the analysis was restricted to states with a maximum spin of $8\hbar$. The following observations may be made:

(1) Along an isotopic chain, the FC values are, with few exceptions, positive and large for N=90-98, small for N=100-104, and negative for N>104. The cross over from positive to negative FC occurs at N~106, marking N=105 as the midshell point.

(2) Along an isotonic chain, the FC values are all negative for Dy-Os nuclei which progressively fill the upper half shell.

(3) Surprisingly, the proton-neutron cancellation works well for Z=66-74, and N=90-98, thus producing *many identical bands* along several alpha chains. These identical bands continue, first, along *isotopic* chains for N=100-106, and proceed along *isobaric* chains for N>106. In short, they conform to the naive expectation that the contours of the identical bands would follow a trapezoidal path over the nuclear chart for collective nuclei with N>90 and Z>64.

It remains to be theoretically investigated if there exists a simple mechanism that explains the cancellation of the contributions of protons and neutrons to FC, despite the fact that protons and neutrons occupy different shells. Another interesting finding is that FC values are nearly zero at N=100 for all Z>64. This indicates that moments of inertia are quite sensitive to such microscopic shell structures as the presence of a gap at N=98.

* Managed by Martin Marietta Energy Systems, Inc. under contract DE-AC05-84OR21400 with the U.S. Department of Energy.

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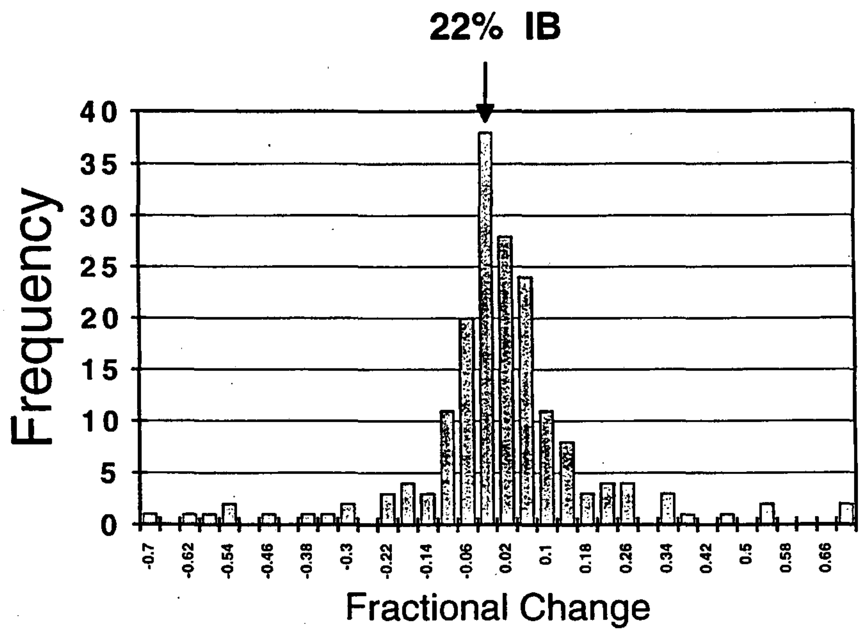
Anomalies in the Odd-Even Differences in the Moments of Inertia of the Odd-Z Rotational Bands in Rare Earth Nuclei

C. Baktash, D.F. Winchell, J.D. Garrett, A. Smith
Oak Ridge National Laboratory, Oak Ridge, TN 37831-6371*

An earlier search for nearly identical bands (IB) at low spin and normal deformations led to the discovery of an unexpectedly large number of these bands among the odd-Z rotational bands in rare-earth nuclei.[1] This finding runs against the naive expectation that, according to the BCS pairing theory, the moments of inertia (MoI) of the one-quasiparticle bands are typically 10-15% larger than those of the zero-quasiparticle bands in their adjacent even-even nuclei. The question raised by the above study is whether this apparent "failure" of the BCS blocking happens in only a limited set of bands, namely the IB, or occurs more frequently. Answering this question would narrow down the range of possible mechanisms that have been invoked to explain the identical bands.

To address this question, we have evaluated the experimental fractional changes in the MoI of the adjacent odd- and even-Z bands in the rare-earth region, as described in Ref. 2. Figure 1 shows the frequency distribution of the experimental fractional changes, which is approximately a Gaussian distribution centered around 2%. In nearly 22% of the 180 bands studied, the MoI of the odd-Z bands differ by less than 2% from those in their adjacent even-even nuclei with one less proton. While pairing- and shape-selfconsistent cranking calculations[3] occasionally give rise to IB, they generally predict fractional changes that (i) vary greatly with spin ; and (ii) differ significantly from the experimental values, especially for the non-identical bands based on high-j orbitals. These studies, as well as a similar investigation of the odd-neutron bands in this region, point to a serious deficiency in our understanding of nuclear moments of inertia.



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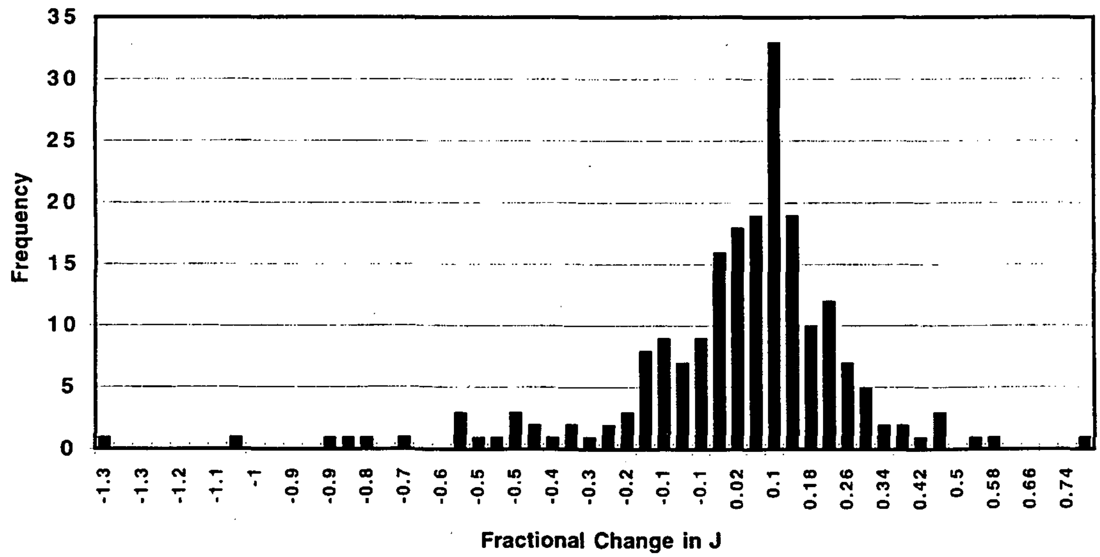
Identical Bands in Normally-Deformed Odd-Neutron Bands

C. Baktash, A.M. Snauffer, D.F. Winchell

Oak Ridge National Laboratory, Oak Ridge, TN 37831-6371*

Following the procedure described in Ref. 1, a systematic search for nearly identical bands (IB) among approximately 200 odd-N rotational bands in the rare-earth region has been conducted. Figure 1 shows the frequency distribution of the fractional changes, FC= $(J_0 - J_E)/J_0$, in the moments of inertia of these bands relative to their adjacent even-even nucleus with one less neutron. The distribution of FC is nearly Gaussian and is centered at a value of about 3.4%. We have identified 18 bands (8.8%) with a fractional change of less than 2% . These bands are based on the [521]1/2, [512]5/2, [505]11/2 and $i_{13/2}$ high-j neutron orbitals. Although the relative alignments of many of these bands are quantized (i.e., they are close to multiples of $0.5\hbar$), the absolute values of the relative alignments are anomalous. No significant correlation was found between the occurrence of IB and the K-values, or the band head energies of the orbitals involved. The only noticeable correlation found was that between the magnitude of the FC and the relative alignments. Thus, it may be concluded that the odd-even differences in the moments of inertia are significantly affected by the susceptibility of the orbital to rotational alignment.

Perhaps the most interesting aspect of this study is the opportunity that it affords to explore any link between IB and the failure of the putative BCS "blocking" effect. According to the BCS pairing theory, the critical frequency of the first band crossing in an odd nucleus is expected to decrease relative to that in its adjacent even-even nucleus because of the reduced pairing strength in the odd system. Surprisingly, this expected reduction was not observed in those identical bands where such a comparison was possible. This constitutes the first evidence that links identical bands to a possible failure of the blocking effect.



* Managed by Martin Marietta Energy Systems, Inc. under contract DE-AC05-84OR21400 with the U.S. Department of Energy.

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Statistical Distribution of Differences in Moment of Inertia for Normally Deformed Bands: Odd-A and Even-even Nuclei

Jing-ye Zhang[1,2], I. Ragnarsson[3] and L.L. Riedinger[1]

[1] Department of Physics, Univ. Tennessee, Knoxville, TN, 37996-1200
[2] Institute of Modern Physics, Lanzhou, 730000, P.R. China
[3] Dept. of Math. Physics, Lund Inst. of Techn., P.O. Box 118, S-221 00 Lund, Sweden

Through a statistics [1] and decomposition procedure, the distribution of the average relative difference of moment of inertia, R($J^{(1,2)}$) [2] between bands of odd-Z and adjacent even-even nuclei has been analyzed as a function of configuration. The sample includes 161 pairs of bands in nuclei with $A = 66 - -77$ in the region $A = 150 - -190$. In pairs of bands that have R($J^{(1)}$) $\leq 5\%$ (up to 5 times the difference in $A^{5/3}$), it is found that most are upsloping configurations in odd-Z partners (odd proton occupies upsloping orbitals [402]5/2, [404]7/2, [514]9/2 and [505]11/2). Flat ([411]3/2, [411]1/2 and [523]7/2) and downsloping ([541]1/2) configurations seldom if ever yield such a $J^{(1)}$ difference. The distribution as a function of different types of configurations (upsloping: solid; flat: long dash; downsloping: dash) is presented in the figure. Secondly, as one can see from the insert, 42% of all upsloping configurations leads to R($J^{(1)}$) ≤ 5, compared to 5% and 0 for flat and downsloping configurations. Perhaps most interesting is the finding that 95% and 100% of flat and downsloping configurations lead to R($J^{(1)}$) greater than 5, that is $J^{(1)}$ differs by more than 5 times the $A^{5/3}$ difference. The R($J^{(2)}$) distribution is similar and will be discussed as well.

One of us (JYZ) thanks Drs. R. Casten and V. Zamfir for valuable discussions.

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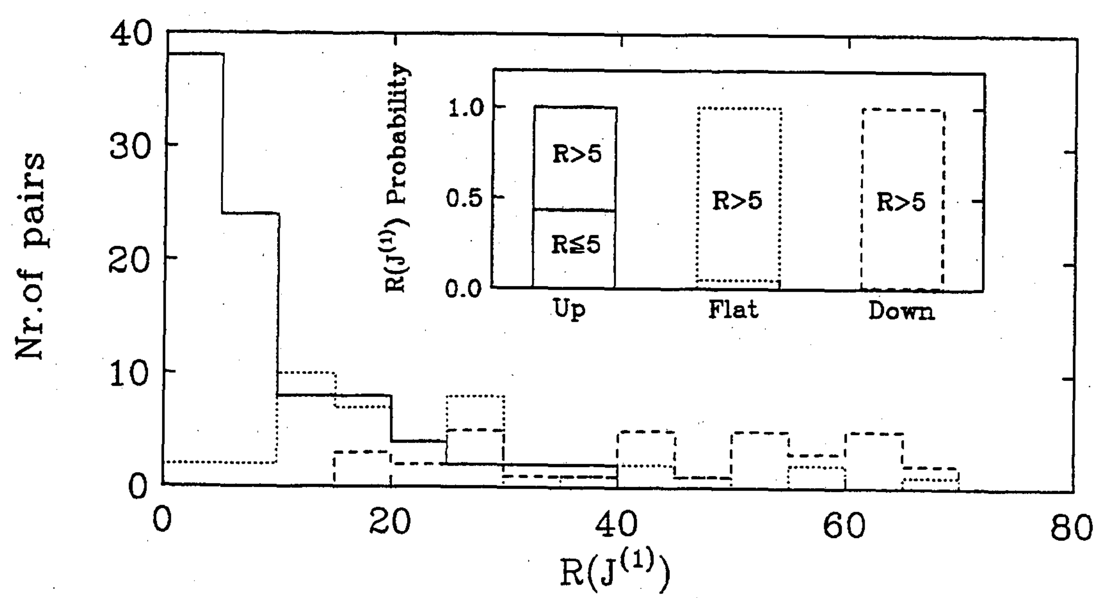

Statistical Distribution of Differences in Moment of Inertia for Normally Deformed Bands: Even-even Nuclei

Jing-ye Zhang[1,2,3], R.F. Casten[1], N.V. Zamfir[1,4]

[1] Physics Department, Brookhaven National Laboratory, Upton, NY, 11973
[2] Department of Physics, Univ. Tennessee, Knoxville, TN, 37996-1200
[3] Institute of Modern Physics, Lanzhou, 730000, P.R. China
[4] Clark University, Worcester, MA, 01610

The distribution of the variation in $J^{(1)}$ and $J^{(2)}$ values [1] for 2145 pairs of positive parity yrast bands in the even-even nuclei with Z=60–78 and A=152–188 has been analyzed in terms of several variables relating to the mass and valence proton and neutron numbers. It is found that the P-factor [NpNn/(Np+Nn)] [2] gives a good correlation to the data. The figure below illustrates two of the results. The left side gives the probability that a pair of nuclei whose $J^{(1)}$ values differ by $\leq$ 5% (or 15–20 %; dashed line) has P values that differ by the percentages given along the abscissa. Clearly, low $\delta J^{(1)}$ values have a large probability of having low δP values. The plot on the right side gives the analogous probability distribution of $\delta J^{(1)}$ values for pairs of bands whose P values differ by $\leq$ 5% (or 15–20 %; dashed line). Again a good $J^{(1)}$ – P correlation is found. Similar comparisons have been done for $J^{(2)}$ and for negative parity bands as well. These results will be discussed.

One(JYZ) of us thanks Dr. I. Ragnarsson for a valuable discussion. This work was supported by DOE contracts DE-AC02-76CH00016, DE-FG02-88ER40417 and DE-FG05-87ER40361 and NSF contract INT-9001476.

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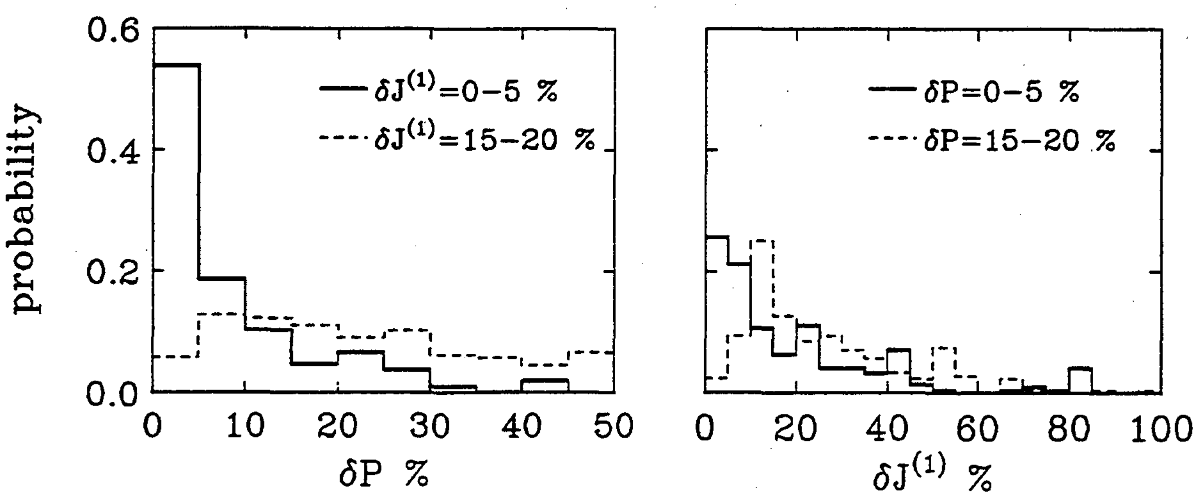

THE NEW "UNPAIRED" SPECTROSCOPY AROUND AND BEYOND SPIN 50 $\hbar$ IN ^{156}Dy.

M.A.Riley[1], T.B.Brown[1], J.Simpson[2], J.F.Sharpey-Shafer[3]
D.E.Archer[1], J.Doring[1], P.Fallon[4], C.Kalfas[5] and S.L.Tabor[1]

[1] FSU, [2] Daresbury, [3] Liverpool, [4] LBL and [5] Democritos.

The search for definitive experimental evidence for the transition from the paired to unpaired nuclear phase has been one of the major goals of γ-ray spectroscopy. A suggested test for the existence of static pairing correlations at large angular momentum has been through the study of band crossings. Where pairing is significant band crossings are expected to occur at similar rotational frequency in all rotational bands where the alignment is not blocked. Well over 700 alignments are observed in normally deformed rotating nuclei which fit into this systematic pattern. Thus one characteristic of the decline of static pairing correlations would be the observation at high angular momentum of band crossings not correlated in rotational frequency.

The first observations of this latter type of "unpaired band crossing" in heavy nuclei were recently reported at very high spin in ^{159,160,161,162}Er and ^{156}Dy. These N$\sim$92 nuclei appear the best candidates for pushing forward the limit of maximum angular momentum observed in collective normal deformed nuclei. However, measurements in the unpaired regime are still very much in their infancy and in order to advance this subject an experiment has been performed using the GAMMASPHERE spectrometer on the nucleus ^{156}Dy.

Previous measurements of ^{156}Dy had observed several rotational sequences above spin 40$\hbar$ including one weak branch tentatively established up to a spin of 53^-, the world record spin for a normally deformed nucleus. Also the observation of strong discontinuities in the lowest (+,0) and (−,1) bands near spins 40^+ and 45^- were in reasonable agreement with the theoretical predictions of collective unpaired band crossings. Such collective band crossings near spin 40$\hbar$ in ^{156}Dy are in quite sharp contrast to those in the neighboring N = 90 nuclei ^{157}Ho and ^{158}Er where classic examples of prolate/oblate shape coexistence and band terminations are observed. One intention of this experiment was to test if this difference between the Z = 66 and Z = 67,68 N = 90 isotones is really so dramatic or that in fact the high spin near yrast line of ^{156}Dy also constitutes a competition between prolate collective and oblate - non collective structures.

The high spin structure of ^{156}Dy was investigated using the reaction ^{124}Sn(^{36}S,4n) at a beam energy of 160 MeV. Data with stacked thin targets was collected for 8 shifts and a thick (1.5 mg/cm^2 of ^{124}Sn + 10 mg/cm^2 of Au) backed target was used for two shifts. Initial analysis has pushed all the known bands to higher spins and a complicated set of discontinuities and intensity fragmentation is observed in all these structures between 40−50$\hbar$. A new 53^- state has been observed, possibly representing band termination and candidate transitions pushing to higher spins are observed. The new results on both ^{156}Dy and ^{155}Dy will be presented along with comparisons with cranked Nilsson and Woods-Saxon calculations.

Multiple Band Termination Spectroscopy in ^{157,158}Er with EUROGAM.

J.Simpson[1], M.A.Riley[2], S.J.Gale[3], J.F.Sharpey-Schafer[3], E.S.Paul[3], M.A.Bentley[4], A.M.Bruce[5], R.Chapman[6], R.M.Clark[7], S.Clarke[3], J.Copnell[8], D.M.Cullen[9], P.Fallon[10], A.Fitzpatrick[8], P.D.Forsyth[3], S.J.Freeman[11,14], P.M.Jones[3], M.J.Joyce[3], F.Liden[8], J.C.Lisle[8], A.O. Macchiavelli[10], A.G.Smith[8], J.F.Smith[3], J.Sweeney[8], D.M.Thompson[8], S.Warburton[8], J.N.Wilson[3] T.Bengtsson[12] and I.Ragnarsson[13].

[1] *Daresbury Laboratory, UK.*
[2] *Department of Physics, Florida State University, USA.*
[3] *Oliver Lodge Laboratory, University of Liverpool, UK.*
[4] *School of Sciences, Staffordshire University, UK.*
[5] *Department of Mathematical Sciences, University of Brighton, UK.*
[6] *Department of Physics, University of Paisley, UK.*
[7] *Department of Physics, University of York, UK.*
[8] *Schuster Laboratory, University of Manchester, UK.*
[9] *Oak Ridge National Laboratory, USA.*
[10] *Nuclear Science Division, Lawrence Berkeley Laboratory, USA.*
[11] *Niels Bohr Institute, Tandem Accelerator Laboratory, Denmark.*
[12] *ABB Corporate Research, S-721 78, Västerås, Sweden.*
[13] *Department of Mathematical Physics, Lund Institute of Technology, Sweden.*

Abstract

The classic example of where band termination occurs in heavy nuclei is in the N = 88−91 rare earth region. In these nuclei the collective rotation of a prolate nucleus which dominates the yrast structure at low spin $I \leq 40\ \hbar$ is replaced by yrast oblate non collective or weakly collective structures at high spin. Band termination states, where all the available valence particles are fully aligned, are observed in some nuclei. Spectroscopy near band termination enables the balance and interplay between the two basic mechanisms by which nuclei can generate angular momentum, collective rotation or alignment of the spins of individual nucleons, to be investigated. The high quality data from the Eurogam spectrometer has enabled the phenomena of high spin band termination to be studied in great detail. In ^{157,158}Er multiple band terminating and aligned states have been established between $40\hbar \leq I \leq 50\hbar$. These special states are found to be related by rather simple single-particle excitations. These data indicate that an oblate mean field ($\epsilon \sim -0.14$) is established for a nuclear core plus ~12 aligned valence nucleons which is stable a Eurogam data on ^{159}Er and ^{160}Er will be presented along with a discussion of how the behaviour of these systems near spin $50\hbar$ compares with the lighter Er isotopes.

Mass Dependence of the Loss of Collectivity Phenomenon – New Measurement of High Spin Lifetimes in ^{162}Yb

C.-H. Yu, M.J. Fitch, D.M. Cullen, R. Gray, X.H. Wang (*Univ. of Rochester*), M.P. Carpenter, R.V.F Janssens, R.G. Henry, T.L. Khoo, T. Lauritsen, D. Nisius (*ANL*)

Previous lifetime measurements have shown[1,2,3,4] a "loss of collectivity" (*i.e.* decrease of the transition quadrupole moments, Q_t, with increasing spin) occurring in a number of light rare earth nuclei, especially Yb isotopes, see fig. 1. One of the explanations of this phenomenon attributes[5] the decrease of Q_t to the rotationally-induced deoccupation of high-j configurations, and thus predicts a mass dependence of the phenomenon. For light rare earth nuclei, where the $i_{13/2}$ neutrons are the principal source of the effect, the "shrinking effect" should be less pronounced with decreasing neutron number. In fig. 1, the Q_t's for ^{164,166,168}Yb typically drop by 30%, whereas the Q_t's for ^{160}Yb (ref. 6) do not show a clear decrease at high spin. The behavior of ^{160}Yb may be a hint of the mass dependence of the "shrinking" effect. However, the lack of high spin data for ^{162}Yb (ref.7) makes it impossible to draw any definite conclusions.

To test this mass dependence and to complete the systematics, we measured high spin lifetimes of ^{162}Yb with the DSAM technique at Argonne National Lab using the ^{126}Te(^{40}Ar, 4n)^{162}Yb reaction at a beam energy of 170 MeV. About 120 million double or higher coincidence events were collected from the Au-backed target experiment. An example of the Doppler shifted line shape spectra (for the 838-keV transition in the backward and forward detectors) along with a tentative fitting is shown in fig. 2. Our preliminary analysis has shown no obvious decrease of Q_t for ^{162}Yb at high spin. More accurate results will be available soon for the completion of this systematic analysis.

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Figure 1:

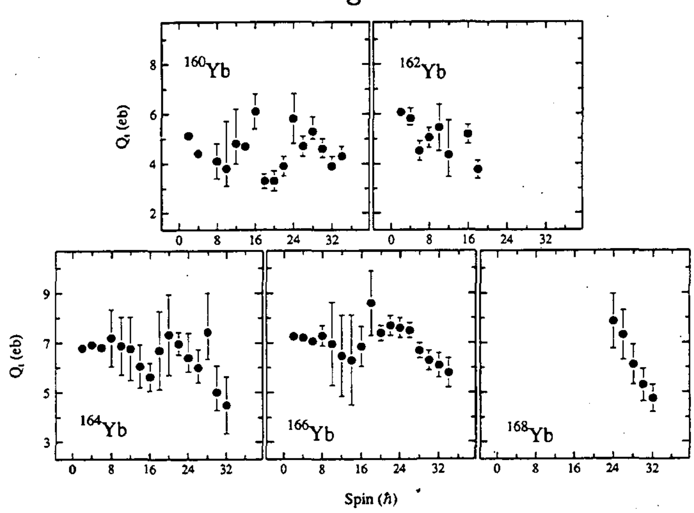
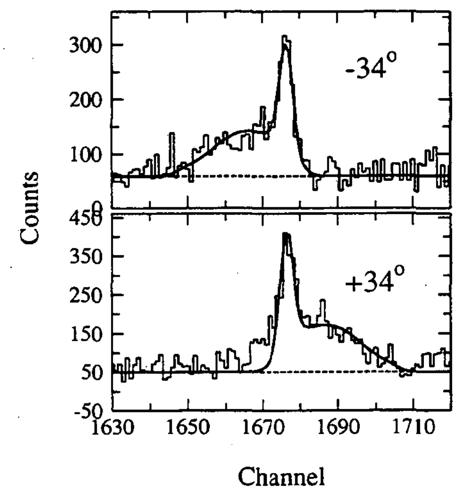


Figure 2:



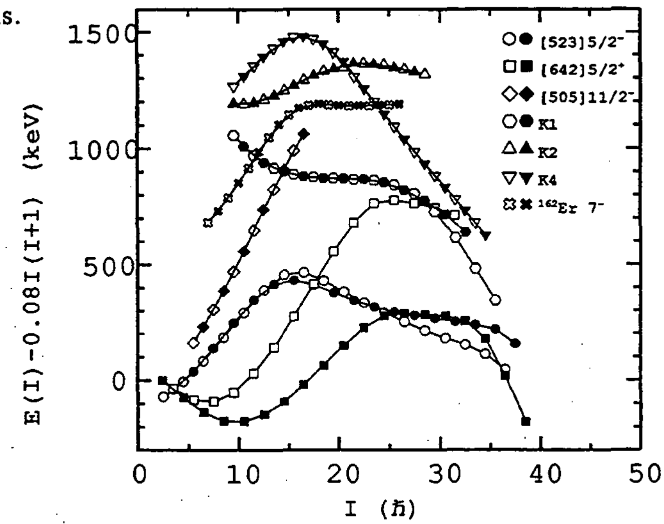
A Multitude of High-K Rotational Bands in ^{163}Er.

A. Brockstedt[c], P. Bosetti[a], G. B. Hagemann[b], H. Ryde[c], H. Carlsson[c], L.P. Ekströ m[c], A. Nordlund[c], S.X. Wen[c], R. A. Bark[b], J. Borg[b], O.Friedrichsen[b], B. Herskind[b], L. Kjærgård[b], S. Leoni[a,b], A. Bracco[a], F. Camera[d], S. Frattini[a], M. Mattiuzzi[a], B. Million[d], C. Rossi Alvarez[e], G. de Angelis[f], D. Bazzacco[e], S. Lunardi[e] and M. de Poli[f].

a) Dipartimento di Fisica, Università di Milano, Milano, Italy,
b) Niels Bohr Institute, Roskilde, Denmark,
c) Department of Physics, Lund University, Lund, Sweden,
d) INFN sezione di Milano, Milano, Italy,
e) Dipartimento di Fisica, Università di Padova, Padova, Italy,
f) Laboratori Nazionali di Legnaro, Legnaro, Italy.

The band structure of the well deformed nucleus ^{163}Er has been studied by several authors [1] and also recently interpreted within the tilted rotation scheme [2] Special interest is thereby focused on the high-K rotational bands. To understand the structure of these bands it is important to know their performance above the expected crossing frequences.

An experiment with high statistical accuracy was performed at the tandem accelerator and the GA.SP multidetector array at L.N. di Legnaro using the reaction ^{150}Nd(^{18}O,5n)^{163}Er at a beam energy of 87 MeV. The data are sorted into 2D matrices as well as into a cube of 0.5 Giga events with conditions in sum energy and foldness to improve the observation of the weakly populated high-K rotational bands.



The figure shows the energy of the rotational bands, with a subtracted reference frame, as a function of spin. The [642]5/2$^+$ bands, A and B, show a signature splitting as do the [523]5/2$^-$ bands, E and F for the high spin parts. However, neither the [505]11/2 nor the high-K bands up to I=28 show any signature splitting. The new K4 band shows an AB crossing, which suggests a 7$^-$ $\otimes$ [523]5/2$^-$ configuration, which was assigned to the K2 band in ref. [2] while the K1 band without any AB crossing contains the blocking [642]5/2$^+$ neutron.

The observed signature splitting in the K1 band above spin 28 may be interpreted as due to the presence of three $i_{13/2}$ neutron after the BC crossing. The K2 band most probably contains the [642]5/2$^+$ orbital, as there is no AB crossing, and the close-lying [505]11/2$^-$ and [521]3/2$^-$ orbitals. The 7$^-$ band observed in ^{162}Er from the present data is also shown in the figure, shifted by 900 keV to correct for the pairing energy. One notes the AB crossing at the expected spin values.

Yet another high-K rotational band (not shown in the figure) feeding into the K1 band at a spin value of 43/2 with several members has been observed. The configuration of this 5th high-K band is still unknown.

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Search for Shape Variations among Bands in odd-odd ^{164}Tm

W. Reviol, X.Z. Wang, J.M. Lewis, L.L. Riedinger, J.-Y. Zhang
University of Tennessee, Knoxville, TN 37996, USA
H.J. Jensen, G.B. Hagemann, P.O. Tjøm, R.A. Bark, S. Leoni, T. Lönnroth,
H. Schnack-Petersen, T. Shizuma, J. Wrzesinski
Niels Bohr Institute, DK-4000 Roskilde, Denmark

While even-even and odd-A deformed rare-earth nuclei have been studied extensively, there is also increasing interest in the high-spin states of the odd-odd neighbors. Because of the complexity of their decay schemes, these nuclei are difficult to study, but the new generation of γ-ray detector arrays has made it possible to measure decay properties in great detail.

One major reason for our experiment on ^{164}Tm was to establish the $\pi h_{9/2} \otimes \nu i_{13/2}$ band and study the deformation (β_2) driving effect of the proton intruder orbital through reduction of the $\nu i_{13/2}$ signature splitting, $\Delta e'$. For some doubly-odd Ta and Re nuclei, $\Delta e'$ for the $\pi h_{9/2} \otimes \nu i_{13/2}$ band is substantially smaller (50% or less) than that in the $\nu i_{13/2}$ band of the adjacent even-odd isotone. This effect should rather continue for systems with smaller proton numbers.

High spin states in ^{164}Tm were populated with the ^{150}Nd(^{19}F,5n) reaction at 85 MeV, using the NBI Tandem Accelerator and the Nordball detector system. The previous known three rotational bands [1] have been extended significantly and four new band structures have been established. Our preliminary assignments are: $\pi h_{11/2} \otimes \nu i_{13/2}$ ($K = 6^-$ and 1^-), $\pi g_{7/2} \otimes \nu i_{13/2}$ (6^+ and 1^+), $\pi h_{9/2} \otimes \nu i_{13/2}$ (2^-), $\pi d_{3/2} \otimes \nu i_{13/2}$ (2^+), and $\pi h_{11/2} \otimes \nu h_{9/2}$ (6^+). These assignments are based on the presence of band crossings ("normal" or blocked $(\nu i_{13/2})^2$ alignment), the $B(M1)/B(E2)$ ratios (only the $\pi h_{11/2}$ orbital has a large g-factor), the degree of signature splitting, and the relative sizes of the dynamic moments of inertia.

The small $\Delta e'$ values observed in five of these bands reflect the signature splittings of the strongly coupled $\pi h_{11/2}$ and $\pi g_{7/2}$ orbitals. One band ($\pi d_{3/2} \otimes \nu i_{13/2}$) has a relatively large value $\Delta e' \sim 160$ keV (at $\hbar\omega = 0.2$ MeV), which agrees with that for the $\nu i_{13/2}$ orbital in the neighboring nuclei. The band we assign to $\pi h_{9/2} \otimes \nu i_{13/2}$, however, has a value $\Delta e' \sim 100$ keV, much reduced for the $\nu i_{13/2}$ orbital. We interpret this reduction as a product of the β_2 driving of the $\pi h_{9/2}$ orbital. TRS calculations for ^{164}Tm indicate that the β_2 values should be 0.25, 0.24, 0.26, and 0.28 for the couplings of $\pi h_{11/2}$, $\pi g_{7/2}$, $\pi d_{3/2}$, and $\pi h_{9/2}$, respectively, to the $\nu i_{13/2}$. A 12% increase in β_2 for $\pi h_{9/2} \otimes \nu i_{13/2}$ compared to $\pi h_{11/2} \otimes \nu i_{13/2}$ is insufficient in causing such a drastic reduction in the $\nu i_{13/2}$ signature splitting. More detailed calculations, as described in our recent paper [2], are being performed in order to find in detail how much $\Delta e'$ is reduced by increasing β_2.

For the bands with presumably high K or/and large g-factor, the $B(M1)/B(E2)$ ratios will be compared with Tilted Axis Cranking calculations. As in neighboring Er and Yb nuclei [3], these configurations should lead to significant deviations from the principal axes.

Research supported by U.S. DOE.

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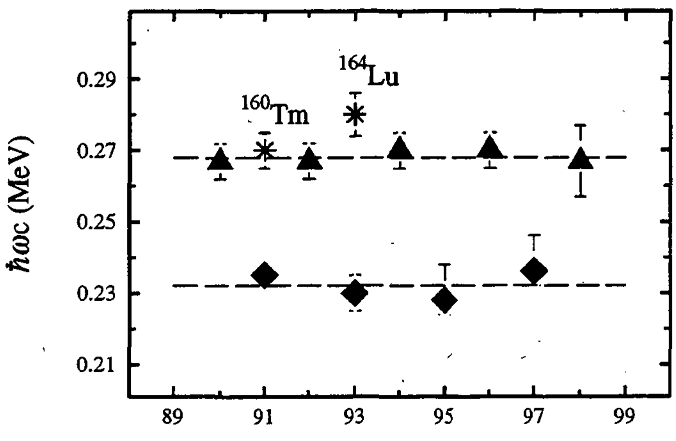
Study of Odd-Odd ^{164}Lu at High Angular Momentum

X.-H. Wang, C.-H. Yu, D.M. Cullen, M.J. Fitch. R.W. Gray, M. Devlin, R.W. Ibbotson, M.R. Satteson, M. Simon, C.Y. Wu, D.C. Brian, D.M. Herrick, and K. Kurtz (*Univ. of Rochester*), A. Galindo-Uribarri, V. Janzen, D.C. Radford, D. Ward *(Chalk River Laboratories)*, S. Mullions, L.H. Yao *(McMaster Univ.)*, S. Pilotte (*Univ. of Ottawa)*

High spin states of ^{164}Lu were populated using the ^{149}Sm(^{19}F, 4n)^{164}Lu reaction at a beam energy of 85 MeV (at the University of Rochester), and the ^{146}Nd(^{23}Na,5n)^{164}Lu reaction at a beam energy of 110 MeV (at Chalk River Laboratories). About 15 million and 500 million gamma-gamma coincidence events were accumulated from the two experiments respectively. Preliminary data analysis established 4 rotational bands in ^{164}Lu. Configuration assignments for these bands are based on comparison to the neighboring odd-A and odd-odd nuclei, as well as their characteristics of B(M1)/B(E2) ratios extracted from the data.

One of the interesting phenomena observed in ^{164}Lu is the disappearance of the "blocking" effect when comparing the AB neutron band crossing in the $\pi 9/2^-[514] \otimes \nu 3/2^-[521]$ band of ^{164}Lu to that in the yrast bands of the neighboring even-even and odd-A nuclei. The following figure summarizes the AB neutron crossing frequencies observed in the yrast bands of even-even Yb isotopes (triangles), those in the $\nu h_{9/2}$ bands of odd-A Yb isotopes (diamonds) and those in odd-odd ^{164}Lu and ^{160}Tm (stars). The $\hbar\omega_c'$s in the odd-A Yb isotopes are systematically reduced relative to those in the yrast bands of even-even isotopes due to the blocking effect of the odd neutron. However, this blocking effect is not observed in either ^{164}Lu or ^{160}Tm. The anomalously large $\hbar\omega_c$'s in odd-odd nuclei cannot be explained by shape differences, but may be an indication of n-p interactions that are more pronounced in odd-odd nuclei.



AB neutron band crossing frequencies observed in the yrast bands of even-even Yb isotopes (triangles), the negative-parity bands of odd-A Yb isotopes (diamonds), and the $\pi 9/2^-[514] \otimes \nu 3/2^-[521]$ band in odd-odd ^{164}Lu and ^{160}Tm (stars). Data for Yb isotopes are taken from J. Kownacki, *et al.*, Nucl. Phys. A394 (1983) 269, and for ^{160}Tm from S. Andre, *et al.*, Z. Phys. A 333 (1989) 247.

Magnetic moments of excited states in the pseudo-Nilsson model

Andrew E. Stuchbery

Department of Nuclear Physics, Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia

The pseudo-Nilsson model is attractive for studying a number of problems in heavy, deformed nuclei because the pseudo-spin-orbit splitting is so reduced compared with the normal spin-orbit splitting that it may be neglected [1,2]. As the magnetic moments of odd-A, deformed nuclei are sensitive to the wavefunction of the odd nucleon, they provide a useful test of the pseudo-Nilsson wavefunctions. Calculations for ground-state magnetic moments have been reported by Ratna Raju *et al.* [1] and Troltenier *et al.* [2].

Recently, we have measured magnetic moments of excited states in several odd-A nuclei using the transient field technique (e.g. refs. [3-5]). To begin to make comparisons between these data and the pseudo-Nilsson model, the g-factors of excited states have been calculated for pure pseudo-Nilsson bands. Results are shown for the odd-N nuclei ^{155}Gd, ^{171}Yb and ^{183}W in fig. 1. Experimental data are from [3-5]. The core g-factor has been set to Z/A and g_s quenched by 20%, as in ref. [2]. Given that there has been no adjustment of parameters and no inclusion of Coriolis mixing, agreement between theory and experiment is satisfactory. The magnetic decoupling has the correct sign for the bands with K = 1/2.

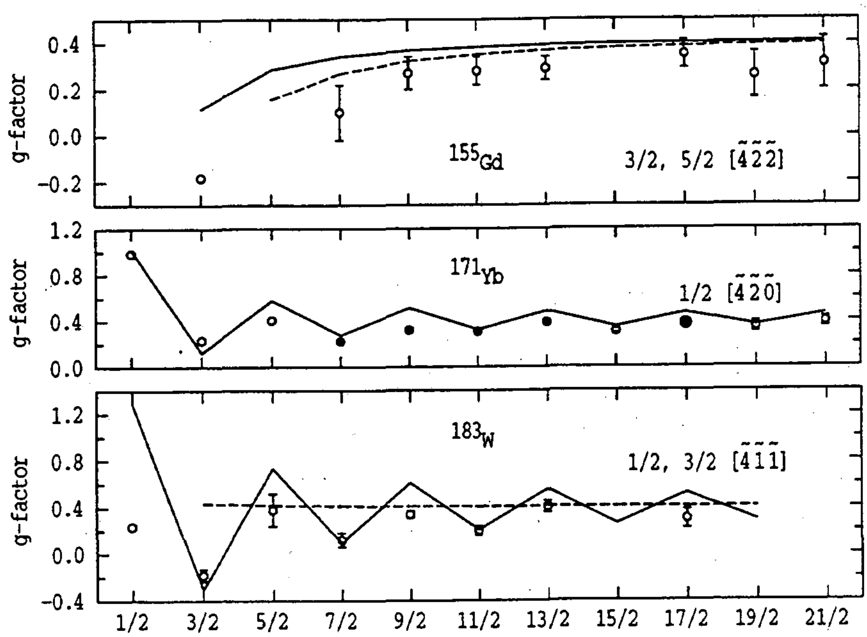


Fig. 1 Experimental and theoretical g.s.b. g-factors.

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The structure of $\pi i_{13/2}[660]1/2^+$ bands in Lu-isotopes

H. Schnack-Petersen[1], R.A. Bark[1], R. Bengtsson[2], P. Bosetti[3], A. Brockstedt[4], H. Carlsson[4], L.P. Ekström[4], G.B. Hagemann[1], B. Herskind[1], F. Ingebretsen[5], H.J. Jensen[1], S. Leoni[1,3], A. Nordlund[4], H. Ryde[4] and P.O. Tjøm[5]

Recently a strongly deformed rotational band has been discovered[1] in ^{163}Lu with $\beta_2 \sim 0.42$. Based on the large deformation this band was interpreted as corresponding to the $\pi i_{13/2}[660]1/2^+$ configuration which is expected to be deformation driving.[1] The nucleus ^{165}Lu has been studied using Nordball at the NBI Tandem accelerator laboratory, using the reactions, ^{138}Ba(^{31}P,4n)^{165}Lu and ^{150}Sm(^{19}F,4n)^{165}Lu at bombarding energies of 155 and 86 MeV respectively. A rotational band with transition energies identical (within 1-2 keV) to those in the strongly deformed band in ^{163}Lu was found. This band decays to the $[404]7/2^+$ as well as to the $[402]5/2^+$ structures but no connecting transitions have been found. Both bands show very small alignments, in contrast to the expectation for a $[660]1/2^+$ band.

Calculations of potential energy surfaces using the "Ultimate Cranker"[2] have been performed for ^{165}Lu and ^{163}Lu at several spin values. In ^{165}Lu, both at moderate and higher spin the yrast positive parity configuration with signature $\alpha = +1/2$ has minimum energy at $\varepsilon_2 = 0.23$ whereas the configuration corresponding to $[660]1/2^+$, followed diabatically through band crossings, reveals a minimum at $\varepsilon_2 = 0.26$ which is substantially smaller than the experimental value for ^{163}Lu. However, highly deformed ($\varepsilon = 0.39$) local minima at $\gamma \sim \pm 18°$ with excitation energies relative to the global minimum of ~ 0.2 and 0.8 MeV for positive and negative γ, respectively, are found. Similar highly deformed local minima exist also for the yrast $(\pi, \alpha) = (-, +1/2)$ configuration, as well as for the $(\pi, \alpha)=(+,+1/2)$ configuration, corresponding throughout the deformation plane to the $[404]7/2^+$ or $[411]1/2^+$ Nilsson orbital. For the latter (+,+1/2) configuration, the local minimum with $\gamma < 0$ is lower than that with $\gamma > 0$, with an excitation energy relative to the global minimum at $\varepsilon = 0.23$ of ~ 1.4 MeV.

For the $[660]1/2^+$ band in ^{163}Lu very similar deformed structures are, as could be expected, found in the calculated potential energy surfaces. Furthermore, the calculated relation between I and ω show for both of the two neighbouring even-N Lu isotopes a very similar gradual increase with ω, in qualitative agreement with the data.

These nonaxial, highly deformed local minima seem to appear as a general phenomenon. An investigation of the wave functions of these potential energy surfaces indicate a more complex structure of the highly deformed bands involving changes in occupation for both neutrons and protons. In the proton system particles are transferred from the less polarizing orbitals into the down-sloping intruder orbitals in a rearrangement of the core. These same orbitals are responsible for shape coexistence in the Pb-Hg-Pt region, and superdeformation in the A$\sim$ 150 region.

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1 The Niels Bohr Institute, University of Copenhagen, 4000 Roskilde, Denmark.
2 Dept. of Math. Physics, Lund Institute of Technology, P.O. Box 118, S-221 00 Lund, Sweden
3 Department of Physics, University of Milano, Italy
4 Department of Physics, University of Lund, Sweden
5 Department of Physics, University of Oslo, Norway

High-K bands in the ^{166}Yb region

J.R.B.Oliveira,[*] S.Frauendorf,[†] M.A.Deleplanque, B. Cederwall,
R.M.Diamond, A.O.Macchiavelli, F.S.Stephens, J.Burde [‡]
Nuclear Science Division, Lawrence Berkeley Laboratory,
1 Cyclotron Rd., Berkeley, CA 94720
J.E.Draper, C.Duyar, E.Rubel,
University of California, Davis, CA, 95616
J.A.Becker, E.A.Henry, M.J.Brinkman, A.Kuhnert, M.A.Stoyer, T.F.Wang
Lawrence Livermore National Laboratory, Livermore, CA 94550

Weakly populated high-K bands have been observed in the ^{166,167,168}Yb isotopes following the ^{124}Sn(^{48}Ca,$xn\gamma$) reaction. The very high $B(M1)/B(E2)$ ratios of the bands, observed for the first time in ^{166}Yb and ^{168}Yb, have led to rather uncommon tentative configuration assignments, i.e. the $\pi([404]7/2 \otimes [523]7/2)$ quasiproton configuration (known to couple to a $I^\pi = 7^-$ bandhead state in some Er and Yb isotopes) coupled to the $\nu[AB]$ quasineutron configuration (from the lowest two $i_{13/2}$ states) for ^{166}Yb, and the same quasiproton configuration coupled to the $\nu[AE]$ quasineutron configuration (from the lowest negative parity two quasineutron configuration) for ^{168}Yb. These two configurations are distinguished by the different behavior of their dynamic moment of inertia around the AB crossing frequency. The results have been interpreted within the tilted axis cranking model [1], in which the cranking axis is no longer considered to coincide with one of the principal axes of the nuclear quadrupole deformation. The tilted cranking model predicts lower excitation energies for such bands than would be expected from traditional models, and is able to reproduce the large $B(M1)/B(E2)$ ratios observed. Another possible configuration would be the $\nu[h_{11/2} \otimes i_{13/2}]$ for both bands in the even-even nuclei, which should present, however, lower $B(M1)/B(E2)$ ratios. The $\nu h_{11/2}$ band ($K = 11/2$) in ^{167}Yb has been extended up to $I = (37/2^-)\hbar$. A smooth increase in dynamic moment of inertia as a function of spin is observed up to $I = 33/2\hbar$. The presence or absence of the AB crossing is not clear from the experimental data, and the possibility of weaker pairing for this band is considered.

References

[*] Present address: Universidade de São Paulo, S. Paulo, SP, 01498, C.P. 20516, Brazil

[†] Present address: Institut für Kern und Hadronen Physik, FZ- Rossendorf, PF.19 0-8051 Dresden,Germany

[‡] Present address: The Racah Institute for Physics, The Hebrew University, Jerusalem, Israel

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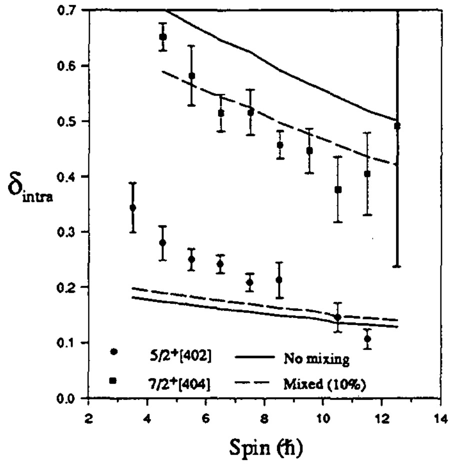
E2/M1-mixing ratios of the pseudo-spin doublet $[\widetilde{303}]$ in ^{173}Ta

H.Carlsson[1], *R.Bark*[2], *L.P.Ekström*[1], *G.B.Hagemann*[2], *S.J.Freeman*[3], *F.Ingebretsen*[4], *H.J.Jensen*[2], *T.Lönnroth*[5], *S.Mitarai*[6], *A.Nordlund*[1], *M.J.Piiparinen*[7], *H.Ryde*[1], *H.Schnack-Petersen*[2], *P.Tjøm*[4]

Several new bands have been found, earlier known bands [1] have been extended and detailed spectroscopic properties have been revealed from the new experimental data on the level structure of ^{173}Ta. However, here we will focus only on the properties of the [402]5/2 and [404]7/2 Nilsson configurations. These orbitals can in the pseudo SU(3) limit be classified as a pseudo-spin doublet with the new quantum numbers $[\widetilde{303}]$5/2,7/2.

The experiment was performed at the Tandem Accelerator Laboratory at the Niels Bohr Institute, using the detector system NORDBALL. The reaction used was ^{160}Gd(^{19}F,6n) at a beam energy of 105 MeV. Nine (ΔI=1) linking transitions from the [402]5/2 band to the [404]7/2 band have been observed. We have measured the angular correlations of the emitted γ-rays [2] from which very accurate E2/M1-mixing ratios for intraband transitions in the strongly coupled bands are determined. Linking transitions from the [404]7/2 to the [402]5/2 band have been observed in ^{175}Re [3,4] and ^{177}Re [5]. In these nuclei the excitation energy of the [404]7/2 band is about 100 keV higher than that of the [402]5/2 band. Jin et al. [3] have analysed the magnetic dipole transition rates of these bands in terms of the pseudo SU(3) coupling scheme, including Coriolis mixing to explain the interband transitions.



In ^{173}Ta the [402]5/2 band lies about 120 keV above the [404]7/2 band in excitation energy. The M1 interband transitions are weaker due to the competition from the strong intraband M1 transitions in the [402]5/2 band. This is in good agreement with the calculations made by Jin et al. [3] for ^{175}Re, which in the present case corresponds to a mixing of ~10% between the bands at I ~19/2. This mixing influences also the measured mixing ratios as can be seen in the figure. For the [404]7/2 band the agreement is very satisfactory, but for [402]5/2 the calculated values are under estimated. From the mixing ratio and the branching ratio the ratio Q_1/Q_2 defined as

$$\frac{Q_1}{Q_2} = \left[\frac{B(E2: I \rightarrow I-1)}{B(E2: I \rightarrow I-2)}\right]^{1/2} \cdot \left|\frac{< IK20|I-2K >}{< IK20|I-1K >}\right|$$

have been extracted. Data for the [402]5/2 band in ^{173}Ta indicate ratios which are significantly larger than one, wheras Q_1/Q_2 ~1 for the [404]7/2 band. In both cases the effect of the mixing (<5%), between the bands is included. At present, the mixing ratios for the [402]5/2 band seems not compatible with a simple mixing, likewise the extracted values of Q_1/Q_2 present a problem.

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[1] Department of Physics, University of Lund, Sweden
[2] The Niels Bohr Institute for Astronomy, Physics and Geophysics, University of Copenhagen, Risø, Denmark
[3] Schuster Laboratory, University of Manchester, Manchester, UK
[4] Department of Physics, University of Oslo, Norway
[5] Department of Physics, Åbo Akademi, Finland
[6] Department of Physics, Kyushu University, Fukuoka, Japan
[7] Department of Physics, University of Jyväskylä, Finland

Lifetimes and Deformation-Driving Effects at High Spins in ^{173}Re

N. R. Johnson,[a] J. C. Wells,[a,b] C. J. Gross,[a] C. Baktash,[a] D. M. Cullen,[a] Y. A. Akovali,[a]
F. K. McGowan,[a] C. H. Yu,[c] I. Y. Lee,[d] and A. O. Macchiavelli[d]

[a]*Oak Ridge National Laboratory,* Oak Ridge, TN 37831-6371, U.S.A.*
[b]*Tennessee Technological University, Cookeville, TN 38505, U.S.A.*
[c]*University of Rochester, Rochester, NY 14627, U.S.A.*
[d]*Lawrence Berkeley Laboratory, Berkeley, CA 94720, U.S.A.*

Recently we carried out both γ-ray coincidence spectroscopy experiments and Doppler-broadened line shape (DBLS) lifetime measurements on the nucleus ^{173}Re with the GAMMASPHERE array. These measurements were motivated by our continuing efforts to understand the properties and seemingly anomalous behavior of some of the light W-Re-Os-Ir-Pt nuclei. In one of the earlier experiments at the HHIRF we performed recoil-distance lifetime measurements on ^{173}Re and in partial reports[1,2] on this work we pointed out that the lifetimes in the $\pi d_{5/2}$ band ($5/2^+[402]$) indicate a coexistence picture with a deformation of $\beta_2 \approx 0.21$ at low $\hbar\omega$, accompanied by an abrupt change at $\hbar\omega \approx 170$ keV to $\beta_2 \approx 0.29$ as predicted by theory. In addition, we found evidence of rather large deformation for the $29/2^+ \rightarrow 25/2^+$ transition in the $i_{13/2}$ band ($1/2^+[660]$). Although there remained numerous compelling reasons to measure the very short lifetimes (<1 ps) of yet higher-spin states in the $\pi h_{11/2}$, $\pi d_{5/2}$, $\pi i_{13/2}$ and $\pi h_{9/2}$ bands strongly populated in the ^{150}Sm (^{27}Al,4n)^{173}Re reaction, we were especially intrigued with questions about the band assigned as $1/2^+[660]$. Serious questions have been raised on whether this band and those so assigned in neighboring nuclei do indeed belong to the $\pi i_{13/2}$ configuration. Bengtsson[3] has carried out TRS calculations for diabatic configurations in ^{173}Re and concludes that there are four positive-parity configurations that could possibly be identified with this assigned $\pi i_{13/2}$ band. However, only the band built on the intruder $1/2^+[660]$ configuration would have an appreciable deformation.

Preliminary analyses of our GAMMASPHERE data have enabled us to assign three new states in the $i_{13/2}$ band (up through $I = 73/2^+$) and to obtain lifetimes of most of the states up through $I = 69/2^+$. The preliminary Q_t values extracted in this band scatter about the value 7.2 eb which corresponds to a deformation of $\beta_2 \approx 0.26$. This is about a 25% enhancement over that at low frequencies in the $d_{5/2}$ band and is probably a sufficient basis to conclude that the band is built on the $1/2^+[660]$ intruder configuration. The results for all four bands of ^{173}Re will be presented and the new insights on the properties of nuclei in this region will be discussed.

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Very Long-Lived Yrast Isomers, Multi-Quasiparticle States and Blocking in ^{176}Ta and ^{177}Ta

M. Dasgupta, P.M. Walker[a)], G.D. Dracoulis, A.P. Byrne, P.H. Regan, T. Kibédi, G.J. Lane and K.C. Yeung[a)]
Department of Nuclear Physics, Research School of Physical Sciences and Engineering,
The Australian National University, Canberra ACT 0200, Australia
[a)] *permanent address; Department of Physics, University of Surrey, Guildford, UK*

High-K intrinsic states, with lifetimes ranging from nanoseconds to years occur at low excitation energies in the Z≈72, N≈106 region. Their character (configuration, excitation energies, decay strengths) depends on basic nuclear properties, such as the pairing strength, residual interactions and K-purity. Although, the decline in pairing as a function of rotational frequency has been extensively studied [1], its behaviour as a function of seniority has been largely neglected, partly due to paucity of experimental data. A spectroscopic study of $^{176}_{73}$Ta$_{103}$ and $^{177}_{73}$Ta$_{104}$ has been carried out, partly to complement the comprehensive results obtained recently for the odd-neutron nucleus $^{179}_{74}$W$_{105}$ [2].

States in ^{177}Ta and ^{176}Ta were populated using pulsed beams of ^{10}B and ^{11}B, incident on a ^{170}Er target. Extensive level schemes were established using the results of measurements of γ-ray singles, $\gamma - time$ and $\gamma - \gamma$ -time correlated coincidences using the CAESAR array. Conversion coefficients were determined from intensity balances and also from electron and γ-ray singles measured using the superconducting electron spectrometer. Previously known bands were extended to higher spins and many new bands and intrinsic states found.

Most notable of the new isomers found are the $K^\pi = 20^-$ and $49/2^-$ yrast states in ^{176}Ta and ^{177}Ta, with meanlives of 1.4 ms and 0.19 ms, respectively. The long meanlives arise from substantial K-hindrance in the ^{176}Ta case but from spin-trapping in the ^{177}Ta case. Quasiparticle calculations, which treat the Fermi and pairing energies self-consistently [2, 3] and includes particle-number conservation [4], reproduce the excitation energies of these isomers and the other multi-quasiparticle high-K states observed. Due to blocking, pairing is significantly reduced in the 3-quasiparticle states, the extent depending on the specific configurations. It is completely quenched for both protons and neutrons in the highest seniority states which involve up to seven quasi-particles. Yrast traps of even higher spins are predicted in these and in neighbouring nuclei.

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PSEUDO-SPIN FLIP IN DOUBLY DECOUPLED STRUCTURES AND IDENTICAL BANDS

A.J. Kreiner,[1,3] M.A.Cardona,[1] H.Somacal,[1] M.E.Debray,[1] D.Hojman,[1,3] J.Davidson,[2,3] M.Davidson,[2,3] D.De Acuña,[4] D.R.Napoli,[4] J.Rico,[4] D.Bazzacco,[5] R.Burch,[5] S.M.Lenzi,[5] C.Rossi Alvarez,[5] N.Blasi,[6] G.Lo Bianco,[6]

[1] *Departamento de Física, Comisión Nacional de Energía Atómica, 1429 Buenos Aires, Argentina*
[2] *Departamento de Física, Facultad de Ciencias Exactas y Naturales, UBA, Buenos Aires, Argentina*
[3] *CONICET, 1033 Buenos Aires, Argentina*
[4] *INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy*
[5] *Dipartimento di Fisica, Sezione di Padova, Padova, Italy*
[6] *Dipartimento di Fisica and INFN, Sezione di Milano, Milano, Italy*

Rotational structures in deformed doubly odd nuclei, called doubly decoupled, which involve aligned(and quantized) pseudospins were reexamined utilizing the last generation GASP[1] array at the Legnaro Tandem facility. In particular we report here a study on ^{176}Re, through the ^{165}Ho(^{16}O, $5n$) fusion reaction at 101 MeV bombarding energy. Only triple and higher fold Ge coincidences were stored on video tapes, recording $\approx 10^9$ events in a two-day run.

Doubly decoupled bands[2,3] in which an aligned neutron pseudospin is coupled to an aligned proton ($i_{np} = i_p + 1/2$) appear systematically in the upper rare-earth region. So far only the favored components (namely those where neutron pseudospin and proton alignment are parallel) were found, consisting in odd-spin ($I_f = 3, 5, 7, 9, ...$) sequences connected by stretched $E2$ transitions. The unfavored components ($I_u = 4, 6, 8, ...$), in which the neutron pseudospin is flipped from being aligned with the rotation axis to the opposite direction, were predicted[2,3] to be rather degenerate with the favored ones; the degenerate partners being characterized by $I_f = R + i_p + 1/2$, $I_u = R + i_p - 1/2$ $((I_u, I_f) = (4,5), (6,7), ...)$. These unfavored components are reported here for the first time. Furthermore, the differences in consecutive transition energies along the favored and unfavored sequences are strikingly similar among them up to $I^\pi = 15^+$ and 14^+ respectively. This feature arises from a cancellation of differences in alignments and moments of inertia showing that identical bands (other than twin bands) do not exist in a strict sense. A constant difference in transition energies is only possible if the inertia parameters of the two bands are slightly different[4]. This is due to the fact that the equality in consecutive transition energy differences (and hence of the dynamic moments of inertia) occurs in the two bands at slightly different values of rotational frequency.

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Dependence of Moments-of-Inertia of Multi-quasiparticle bands in ^{177}Ta and ^{179}W on Reduced Pairing

G.D. Dracoulis[1)], P.M. Walker[2)], Kiran Jain[2)] and M. Dasgupta[1)]
[1)] *Department of Nuclear Physics, Research School of Physical Sciences and Engineering, The Australian National University, Canberra ACT 0200, Australia*
[2)] *Department of Physics, University of Surrey, Guildford, UK*

Recent measurements [1 − 3] which exploit time-correlated $\gamma-\gamma$- coincidence studies are producing a comprehensive map of the excitation energies and properties of states formed by combining individual nucleon orbits close to the Fermi surface. Proton subshell gaps near Z = 66 and Z = 76, and neutron subshell gaps at N = 98 and N = 108 result in the effective isolation of the intervening groups of orbitals of both protons and neutrons. Properties of states in nuclei such as $^{179}_{74}$W$_{105}$ and $^{177}_{73}$Ta$_{104}$ can thus be profoundly affected both by how many (seniority), and which orbitals are populated.

Comparisons of the observed excitation energies of multi-quasiparticle states in these nuclei with the results of quasiparticle calculations, which treat the Fermi and pairing energies self-consistently [3, 4] and which include particle-number conservation [5], show that blocking has dramatic consequences for the pairing correlations, the extent depending on the specific configurations.

Configuration-dependent pairing reduction has also been shown previously to explain differences in band-crossing frequencies in certain 1-quasiparticle cases [6], essentially through the dependence of the energies of the excited bands on pairing.

As well, the rotational properties themselves, such as alignments, static and dynamic moments-of-inertia etc, should be affected by the proposed reductions in proton and neutron pairing . For many of the intrinsic states now known, (with 1-, 3- , 5-... quasiparticles) associated rotational bands have been identified and these can be examined quantitatively with respect to the proposed configuration - dependent pairing [1 − 4], with the hope of elucidating and uncoupling the role of neutrons and protons in the collective motion [7] .

Even at a semi-quantitative level, differences in rotational properties are a useful signature for the assignment of specific multi-particle configurations.

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High-K structures at the yrast line

P.M. Walker

Department of Physics, University of Surrey, Guildford GU2 5XH, UK

K isomers, with half-lives ranging from nanoseconds to years, are widespread in deformed nuclei, due to the approximate conservation of the K quantum number. However, the observation of $K > 10$ isomers, with four or more excited quasiparticles, is restricted exclusively to the $A \approx 180$ deformed region. The experimental investigation of even this region is severely constrained by the limited availability of suitable (stable) beams and targets. Of the approximately 41 candidate isotopes, which might be expected to have 6-(or more)-quasiparticle isomers, only twelve are accessible with stable beams and targets. Of these twelve, six contain 6- or 7-quasiparticle isomers with $T_{1/2} > 5$ ns, three have 6- or 7-quasiparticle states with $T_{1/2} < 5$ ns, and three remain to be adequately investigated.

The isomer excitation energies are now reasonably well understood [1-3], taking into account the position of the Fermi surface, the blocking of pairing correlations, and nucleon-nucleon residual interactions. Predictions may be made about the location of new isomers. However, different models, accounting for different degrees of freedom, have been proposed to explain the isomer half-lives and decay paths: K mixing, or orientation hopping [4]; and tunneling, or shape hopping [5].

Of the isomers so far investigated experimentally, there is the appearance of a decline in the integrity of the K quantum number with increasing angular momentum. However, this effect could arise from the limited portion of the favoured region that is currently accessible. Furthermore, the discovery of t-bands [1,4] in the $A \approx 180$ region provides a new mechanism by which high-K components can arise in the states to which an isomer decays. After taking these factors into account, there remains a strong correlation between a multi-quasiparticle isomer's decay rate (in Weisskopf units) and its excitation energy relative to the yrast line, which suggests a K-mixing mechanism that depends upon the density of states. Yrast-isomer decays remain strongly K hindered, and prospects appear to be good for the future discovery of very-high-spin, very-long-lived K isomers.

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Band Structure Studies in Odd-odd ^{178}Ir

H.-Q. Jin, J.A. Cizewski, L.A. Bernstein
Department of Physics, Rutgers University, New Brunswick, NJ 08903
W.F. Mueller, L.L. Riedinger, X.-Z. Wang, C.-H. Yu
Department of Physics, University of Tennessee, Knoxville, TN 37996
C. Baktash, J.D. Garrett, N.R. Johnson, I.Y. Lee, F.K. McGowan, D.F. Winchell
Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831

Odd-odd nuclei are very complicated systems because many coupling schemes are possible between the various quasiparticle configurations. By studying these nuclei one can test different coupling schemes and their effects on the nuclear structure. Fruitful information on the neighboring odd-A and even-even nuclei may be obtained by examining different quasiparticle aligning processes and the blocking effect from the odd particles.

The previously unknown odd-odd nucleus ^{178}Ir has been studied via the reactions ^{156}Gd(^{27}Al,5n) and ^{152}Sm(^{31}P,5n). The measurements were performed at the Holifield Heavy Ion Research Facility at Oak Ridge National Laboratory, using the Spin Spectrometer and the Compact Ge array. The excitation functions and the multiplicity K distributions of γ rays were used to identify transitions belonging to this nucleus.

Six rotational bands have been observed in ^{178}Ir. Although the ground state is unknown and no definite spins and parities can be assigned to the sequences, tentative configuration assignments to the rotational bands in ^{178}Ir have been established. These assignments are based on the signature splittings and electromagnetic properties ($B(M1)/B(E2)$ ratios) of each band. Results from neighboring odd-odd ^{180,182,184}Ir nuclei [1,2] have provided systematic information on possible band assignments in ^{178}Ir.

Of the observed six bands, two have signature partners with noticeable splitting. The energy staggering in the bands resembles the "semidecoupled" structure [2] observed in the heavier odd-odd Ir nuclei. They have been assigned as a decoupled $h_{9/2}$ or $i_{13/2}$ proton coupled to the two signatures of the $i_{13/2}$ neutron. Two strongly-coupled bands with strong $M1$ in-band transitions have been thought to be built on $\pi h_{11/2}, \pi d_{5/2} \otimes \nu i_{13/2}$. We have also observed a band that has only one rotational sequence and is believed to be doubly decoupled, based on the coupling of two $K = 1/2$ orbitals ($\pi h_{9/2} \otimes \nu 1/2^-[521]$).

The decay patterns and alignment processes in each band have been investigated within the framework of the Cranked Shell Model. The results will be discussed in comparison with the neighboring odd-A nuclei. The $B(M1)/B(E2)$ ratios will be compared with calculations from the extended Dönau and Frauendorf formalism [3] as well as the particle-rotor model.

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Lifetimes in ^{181}Ir and ^{187}Au: Enhanced Deformation of the Intruder $\pi i_{13/2}$ Orbital*

J.C. Walpe, U. Garg, S. Naguleswaran, Q.-W. Ren
Physics Department, University of Notre Dame; Notre Dame, IN 46556.
M.P. Carpenter, R.V.F. Janssens, I. Ahmad, I.G. Bearden, R.G. Henry, T.L. Khoo, T. Lauritsen
Physics Division, Argonne National Laboratory, Argonne, IL 60439.
W. Reviol, L.L. Riedinger, X.-Z. Wang
Department of Physics & Astronomy, University of Tennessee, Knoxville, TN 37996.

One of the striking features of the level structures in the transitional Re and Ir nuclei is the very different evolution of the aligned angular momentum as a function of rotational frequency for the $\pi i_{13/2}$ band compared to the other bands observed in these nuclei: the alignment of this band shows a steady increase for the entire frequency range for which data are available (typically $0.1<\hbar\omega<0.4$ MeV) whereas a clear $\nu i_{13/2}$ band crossing is observed near $\hbar\omega=0.3$ MeV in the other bands. A possible explanation of this anomalous alignment increase in the $\pi i_{13/2}$ band attributes it to a larger quadrupole deformation of the $\pi i_{13/2}$ band compared to that of the other bands. If so, since the deformation-driving effect of the individual orbits is strongly dependent on their location with respect to the Fermi level, it would also be expected that this effect would be more pronounced in the Ir isotopes than, for example, in the Au isotopes.

In order to test these conjectures, we have measured lifetimes of levels in ^{181}Ir and ^{187}Au using the Recoil-Distance technique. The experiments were performed at ATLAS using the ^{154}Sm(^{31}P, 4n)^{181}Ir and ^{154}Sm(^{37}Cl, 4n)^{187}Au reactions at beam energies of 140 and 160 MeV, respectively. The Notre Dame Plunger device was employed in conjunction with the Agonne-Notre Dame γ-ray facility and approximately 20 runs of 2-3 hours each were taken for each nucleus at recoil distances ranging from 7μm to 10000μm. From a standard analysis of the data, lifetimes were extracted for a number of levels in the $\pi h_{9/2}$ and $\pi i_{13/2}$ bands in both nuclei. The resulting average transition quadrupole moments are: for the ^{181}Ir ($\pi h_{9/2}$) band, Q_t(avg)=6.04±0.33 eb and for the ($\pi i_{13/2}$) band, Q_t(avg)=8.99±0.37 eb; for the ^{187}Au ($\pi h_{9/2}$) band, Q_t(avg)=6.18±0.35 eb and for the ($\pi i_{13/2}$) band, Q_t(avg)=8.25±0.50 eb. It is clear that the $\pi i_{13/2}$ orbital indeed significantly enhances the core deformation--the resulting increase in Q_t (avg) is as much as 50% in case of ^{181}Ir! These results provide clear experimental support for the explanation of the anomalous band-crossing behavior of this orbital in terms of significantly different deformations associated with the different bands. In addition, the fact that the deformation of the $\pi i_{13/2}$ band in ^{181}Ir is larger than that in ^{187}Au is consistent with the expectation from the position of the proton Fermi level (which lies closer to the $\pi i_{13/2}$ level in ^{187}Au than in ^{181}Ir).

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Systematics of $\nu i_{13/2}$ Signature Splitting for Even-Odd Rare Earth Nuclei*

W.F. Mueller, H.J. Jensen,† W. Reviol, L. L. Riedinger, C.-H. Yu,‡ J.-Y. Zhang
Department of Physics, University of Tennessee, Knoxville, TN 37996, USA
W. Nazarewicz
Joint Institute for Heavy Ion Research, Oak Ridge, TN 37831, USA
R. Wyss
Manne Siegbahn Institute, S-10405 Stockholm, Sweden

A systematic study of signature splitting ($\Delta e'$) has been done for all $\nu i_{13/2}$ yrast rotational bands in odd-N isotopes of even-Z Dy through Os nuclei. Cranked Shell Model calculations [1] were performed, with deformation parameters obtained from TRS calculations [2]. The results from these calculations are compared with extracted experimental $\Delta e'$ values. In an earlier account of this work, it was reported that current theoretical models are successful at predicting $\nu i_{13/2}$ signature splitting in Dy, Er, and Yb [3]. Now, we have extended the calculations to higher Z, also including the more γ-soft Os nuclei.

The results of these calculations, and their comparison to experimental data are shown in Fig. 1. The calculations reproduce the experimental signature splitting rather accurately. Notable exceptions are light Dy, where coupling to γ-vibrations may play a significant role [4], and ^{175}W and ^{175,177}Os, where a significant gap in the single-particle levels produces an inaccurate pair gap in the calculations, hence an improper signature splitting.

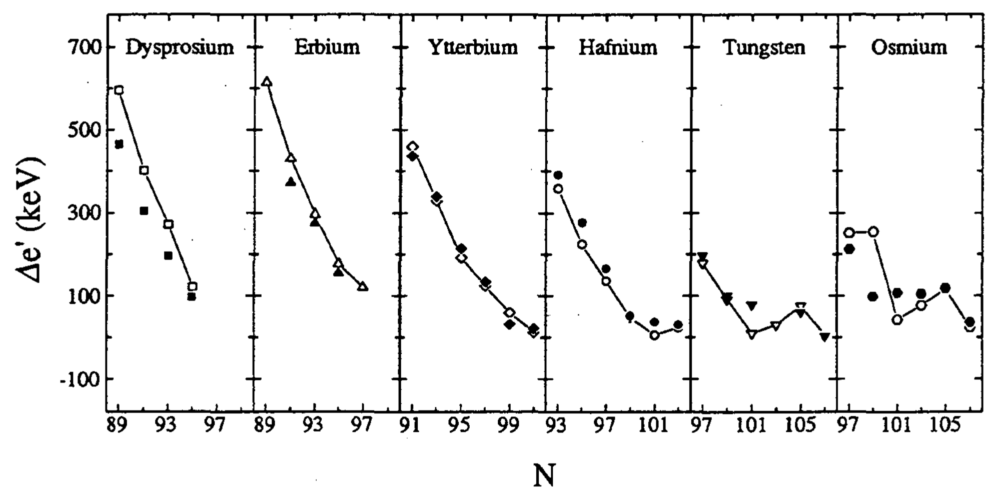

Fig. 1. Experimental (filled symbols) and calculated (open symbols) $\nu i_{13/2}$ signature splitting at $\hbar\omega = 0.2$ MeV for odd-N isotopes of even-Z Dy through Os.

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† Present Address: Niels Bohr Institute, DK-4000, Roskilde, Denmark
‡ Present Address: Univ. of Rochester, Rochester, NY 14627, USA

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INVERTED SIGNATURE SPLITTING OF HIGHLY-ALIGNED THREE-QUASIPARTICLE BANDS IN ^{171}Lu AND ^{173}Ta

R.A. Bark[a], H. Carlsson[b], S.J. Freeman[a], G.B. Hagemann[a], F.Ingebretsen[c], H.J. Jensen[a], T. Lönnroth[a], S. Miterai[d], M.J. Piiparinen[a] H.Schnack-Petersen[a] and P. Tjom[c]

We present results of recent spectroscopic measurements at Nordball on the nuclei ^{171}Lu and ^{173}Ta. These experiments were motivated by our measurements on ^{177}Re which gave the surprising result that the previous assignment[1] to a $\pi i_{13/2}$ band was probably incorrect. Instead the band is likely to be of a three-quasiparticle structure. We decided to study ^{171}Lu and ^{173}Ta to try find their $\pi i_{13/2}$ bands or similar 3-quasiparticle bands.

The reaction ^{160}Gd(^{19}F,α4n) at 105 MeV was chosen as it is one of the few ways available of populating ^{171}Lu, a nucleus close to the line of stability, at high spins. The α4n channel represents about 3% of the total cross section, ^{173}Ta being populated the strongest. Thus the reaction conveniently allowed the study of two nuclei at once. The charged particle channels were seperated by the use of the Si ball, and a total of about 2×10^9 raw events (spread over all channels) were collected on thin and backed targets.

Selected bands from the three nuclei ^{171}Lu,^{173}Ta, and ^{177}Re are plotted in the figure below. Surprisingly, bands labelled 3qp in the figure, have been found in both ^{171}Lu and ^{173}Ta with nearly identical moments-of-inertia. The bands probably have the same structure as that previously assigned to the $\pi i_{13/2}$ configuration in ^{177}Re. In ^{177}Re the band is mixed and crossed by several other bands and so the unperturbed band, the result of a three band mixing calculation, is plotted in the figure. Considering the excitation energy, aligned angular momentum and in-band B(M1)/B(E2) transition rates of these bands the most likely assignment is a three-quasiparticle structure of the form $\pi h_{9/2} \otimes \nu$AE,BE, where the neutron orbital A and E are 7/2$^+$[633] and 1/2$^-$[521]. However, this assignment would imply that the favoured signature should be α = -1/2. Instead, in all cases, it is α = 1/2. Attempts to understand this signature inversion in terms of deformation changes have not proved fruitful. Although calculations with the CSM code Ultimate Cranker do predict small or negligible splitting, an inversion is unlikely. The signature inversion and the CSM calculations therefore suggests that effects outside of the mean-field approximation, such as residual interactions, need to be considered.

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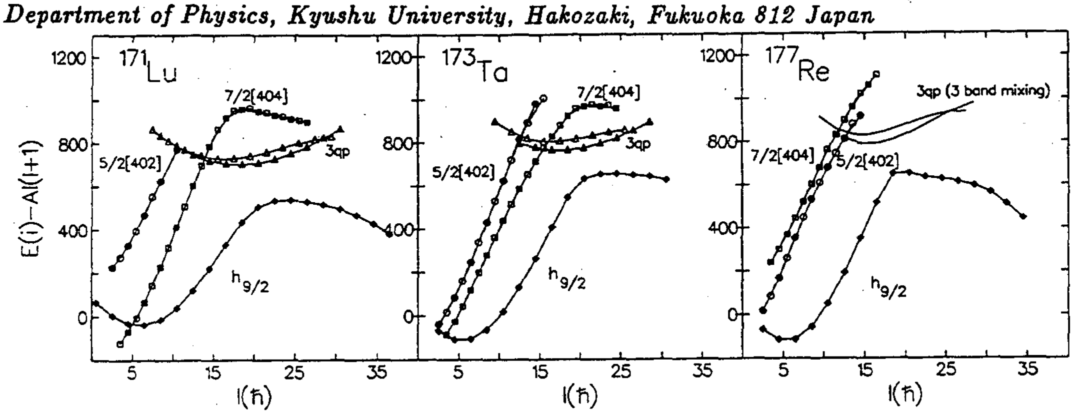
a The Niels Bohr Institute, University of Copenhagen, 4000 Roskilde, Denmark.
b Department of Physics, University of Lund, Sweden
c Department of Physics, University of Oslo, Norway
d Department of Physics, Kyushu University, Hakozaki, Fukuoka 812 Japan



CALCULATED SHAPES OF INTRUDER BANDS IN Re AND Ir NUCLEI

R.A.Bark[1], R.Bengtsson[2] and H.Carlsson[3]

1) The Niels Bohr Institute, Tandem Accelerator Laboratory, DK-4000 Roskilde, Denmark

2) Dept. of Mathematical Physics, Lund Institute of Technology, Lund Sweden

3) Department of Physics, University of Lund, Sweden

Rotational bands which have been assigned to the proton $i_{13/2}$ and $h_{9/2}$ configurations have been observed in several odd Re and Ir isotopes. The behaviour of the aligned angular momentum as a function of frequency of these two types of bands differ remarkably from each other in a systematic way. The $h_{9/2}$ bands usually show a clear backbending that is normally attributed to the alignment of $i_{13/2}$neutrons. On the other hand, the $\pi i_{13/2}$ bands usually do not show clear backbending, but rather a puzzling gradual gain in alignment, which has provoked several differing explanations.

TRS calculations[1] have predicted that the $i_{13/2}$ bands should have a larger deformation than the $h_{9/2}$ bands. In both cases the deformation is predicted to be very stable with increasing spin, giving support to one explanation[2]. Namely that the gradual increase in alignment may be just an artifact of the reference chosen to derive the alignment. Also on the basis of predicted *stable* deformations, a very large interaction was deduced[1] when trying to interpret the alignment curve of the $i_{13/2}$ band of ^{175}Ir in terms of a crossing of the one-quasiparticle bands with the s-band, comprised of aligned neutrons. The large interaction led to the suggestion[1] that a residual proton-neutron interaction should be added to the hamiltonian. However, later data[3] for ^{171}Re revealed a sharp backbend in the π $i_{13/2}$ band, suggesting instead a weak g-s interaction. By comparing with the alignment curves of the nearby Osmium yrast bands, where upbending has been attributed to a β stretching of the nucleus, it was suggested that in the π $i_{13/2}$ bands, a similar mechanism may be responsible for an *apparent* gain in $i(\omega)$.

Clearly, it is important to understand the shape evolution of the $i_{13/2}$ bands to test all of these notions. Therefore we have improved the cranking code Ultimate Cranker[4] to reliably remove interactions so that configurations can be followed diabatically across a surface, without confusion between one and three-quasiparticle structures. The results are calculated using the Nilsson parameters of both Zhang et al[5] and Bengtsson and Ragnarsson[6]. Near the bandhead our results predict comparable deformations to those of Nazarewicz et al[7] for both types of bands. For the $h_{9/2}$ bands, values of $\epsilon_2 = 0.23$ are typical in both one and three-quasiparticle bands. The deformation is also predicted to be stable as a function of spin. However for the $i_{13/2}$ bands, a totally new picture emerges. The one-quasiparticle $i_{13/2}$ bands are predicted to stretch with increasing spin, beginning near the bandhead with a typical deformation of $\epsilon_2 = 0.24$ and increasing to 0.28 near the crossing with the s-band. The alignment of $i_{13/2}$ neutrons is predicted to force the nucleus back to its original shape. The calculations for the $i_{13/2}$ bands are also in good agreement with the recent measurements of Q_t in ^{179}Ir of Müller et al[8].

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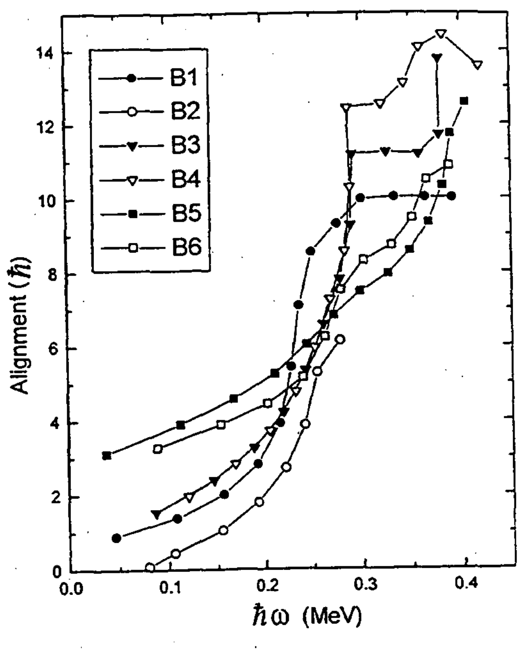
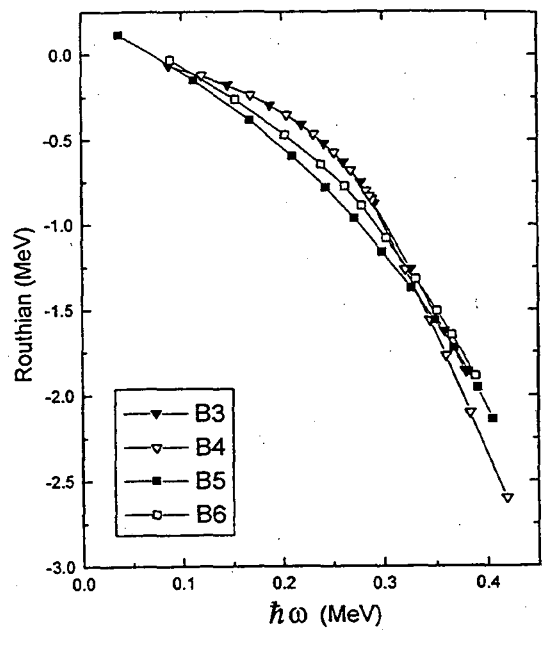
High Spin States in ^{183}Pt*

W.C. Ma[a], J.H. Hamilton[a], A.V. Ramayya[a], J.K. Deng[a], J. Kormicki[a], D.T. Shi[a], R.Wyss[b+], C. Baktash[c], J.D. Garrett[c], N.R. Johnson[c], I.Y. Lee[c#], F. McGowan[c]

[a] Vanderbilt University, Nashville, TN 37235
[b] Joint Institute for Heavy Ion Research, Oak Ridge, TN 37831
[c] Oak Ridge National Laboratory, Oak Ridge, TN 37831

High spin states of ^{183}Pt were populated by using the reaction of ^{154}Sm(^{34}S, 5n) at the Holifield Heavy Ion Research Facility. The coincidence γ-rays were measured with 20 Compton-suppressed Ge spectrometers mounted in a compact geometry. The energy levels of the five previously known [1] rotational bands were extended to 6 - 14 $\hbar$ higher for different bands. In addition, five new bands were found. Signature splitting is seen very strong in *Band 1* and *2* (ν[521]1/2$^-$ structure, the ground state band), intermediate in *Band 5* and *6* (ν[624]9/2$^+$ structure), and also develops in *Band 3* and *4* (ν[514]7/2$^-$ structure) at higher rotational frequencies. The first i13/2 neutron crossings occur at $\hbar\omega$ = 0.23~0.27 MeV. The second band crossings (probably πh9/2) are also observed at $\hbar\omega \geq$ 0.35 MeV.





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$^+$ present address: Manne Siegbahn Institute of Physics, Stockholm, Sweden

$^\#$ present address: Lawrence Berkeley Laboratory, Berkeley, CA 94720

Shape coexistence in ^{185}Tl and ^{187}Tl - investigation of the deformed minima

G.J. Lane[a], G.D. Dracoulis[a], A.P. Byrne[a], P.M. Walker[b], A.M. Baxter[a], J.A. Sheikh[c] and W. Nazarewicz[c]

[a] Department of Nuclear Physics, RSPhysSE, Australian National University, Canberra ACT 0200, Australia
[b] Department of Physics, University of Surrey, Guildford, UK
[c] Joint Institute for Heavy Ion Research, Oak Ridge National Laboratory.

The coexistence of bands built upon both prolate and oblate shape in the neutron-deficient even-even mercury isotopes is now well established[1]. With the recent discovery[2,3] of well-deformed prolate shapes in ^{186}Pb and ^{188}Pb, there has been further motivation for studying the intervening odd-mass thallium isotopes, as they provide a method of probing the microscopic structure of the even-even cores via the effects of the odd particle/hole. Thus a series of experiments have been performed to establish the spectroscopy of ^{185}Tl and ^{187}Tl.

Gamma-gamma coincidence measurements have been performed with the CAESAR array and level schemes for ^{185}Tl and ^{187}Tl constructed[4]. Strongly coupled rotational bands built upon the previously known oblate deformed $\frac{9}{2}^-$[505] states were observed, while the decay properties of newly observed $\frac{13}{2}^+$ isomers in ^{185}Tl and ^{187}Tl, with meanlives of 12 ± 2ns and 1.0 ± 0.2ns respectively, were evidence for the assignment of oblate deformed $\frac{13}{2}^+$[606] states. Decoupled bands with ΔI=2 character were also observed in both nuclei. Examination of the experimental alignments, and comparison with the mercury and lead isotones, leads to their assignment in ^{187}Tl as aligned $i_{13/2}$, $h_{9/2}$ and $f_{7/2}$ protons coupled to the prolate shape. Similar bands due to the $i_{13/2}$ proton, and possibly also the $h_{9/2}$ proton, are assigned in ^{185}Tl.

Equilibrium deformation calculations have been performed for the intrinsic states in a range of thallium isotopes, together with calculations of intruder orbital occupation probabilities for both the newly observed, prolate deformed intrinsic states in the thallium isotopes, and for the prolate deformed mercury cores. The general experimental trends of the excitation energies are reproduced, however the absolute energies, and the neutron number at which they minimise in energy, are not. The occupation probability calculations demonstrate that the prolate deformation is in both cases linked with significant population of low-Ω orbitals from the $h_{9/2}$, $f_{7/2}$ and $i_{13/2}$ proton shells.

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Competing Shapes in Light Tl Nuclei *

L.L. Riedinger, J.M. Lewis, W. Reviol, C.R. Bingham, W.F. Mueller, J.-Y. Zhang, B. E. Zimmerman

Department of Physics, University of Tennessee, Knoxville, TN 37996, USA

Near the $Z = 82$ closed shell, light mercury nuclei ($Z = 80$) exhibit a variety of shapes, ranging from a slightly oblate ground state ($\beta_2 \approx 0.15$) to a well deformed prolate intruder band ($\beta_2 \approx 0.23$), and even to a superdeformed prolate structure ($\beta_2 \approx 0.45$) [1]. Understanding this variety of shapes in nuclei with an almost closed proton shell has been a challenge for some years. Recently, co-existing prolate bands have even been found at $Z = 82$, in ^{186}Pb and ^{188}Pb [2]. We have concentrated on studying the variety of level structures and nuclear shapes in light Tl nuclei ($Z = 81$), to find the manner in which the low lying $h_{9/2}$ and $i_{13/2}$ proton orbitals couple to these shapes. Our recent experiments on ^{191}Tl (Oak Ridge and Argonne), ^{189}Tl (GAMMASPHERE), and ^{187}Tl (Argonne) lead us to new insights into nuclear structure near a closed shell.

The lowest lying rotational band throughout the light Tl nuclei is built on the $\pi h_{9/2}$ orbital (9/2[505]) coupled to the slightly oblate core. The long known $13/2^+$ state in various Tl isotopes (at 1001 keV above the $9/2^-$ state in ^{191}Tl) has been curious since there has not been seen a comparable rotational band (13/2[606]). Now, however, we propose two structures built on the $13/2^+$ state in ^{191}Tl, one beginning at $13/2^+$, extending to $(29/2^+)$, and appearing to have no rotational character; and another structure beginning at $21/2^+$, extending to $(45/2^+)$, and possessing a rotational signature expected for 13/2[606] [3]. The former appears to be a coupling to the spherical ground state of ^{192}Pb, the latter to an oblate ^{190}Hg core.

A "normal" deformed prolate band in ^{190}Hg apparently lies rather high in energy and so we see no evidence of a coupling to it in ^{191}Tl. In ^{187}Tl, however, we do observe in addition to the common oblate $\pi h_{9/2}$ band, two decoupled bands [4] that we attribute to the couplings of $\pi h_{9/2}$ and $\pi i_{13/2}$ to the prolate configuration seen in in ^{186}Hg [1] at $E(0_2^+) = 523$ keV and in ^{188}Pb [2] at $E(0_2^+) \approx 720$ keV.

Both the $h_{9/2}$ and $i_{13/2}$ proton orbitals are strongly downsloping in energy with increasing deformation. Thus, they are expected to play a major role in the formation of the excited prolate minimum in light Hg and Pb nuclei. The two new decoupled bands in ^{187}Tl are assigned to $\pi i_{13/2}$, $K = 1/2$ and $\pi h_{9/2}$, $K = 3/2$ configurations, both associated with prolate shapes of $\beta_2 \approx 0.25$. The presence of both disproves the suggestion [5] that the prolate Hg core is largely of $(\pi h_{9/2})^2$ character, and indicates that it is more collective. To further test this idea, we have performed a measurement on ^{189}Tl at GAMMASPHERE, to search for the expected $h_{9/2}$ band, in addition to the $i_{13/2}$ structure seen by Porquet *et al.* [5]. By the time of the conference, we will have determined if both prolate bands are present in the nucleus.

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Two proton high spin excitations and dipole bands in ^{192}Hg

Y.Le Coz[a], A.Astier[a], R.Béraud[a], R.Duffait[a], M. Meyer[a], N. Redon[a], G.Bastin[b], I. Deloncle[b], B. Gall[b], F. Hannachi[b], M. Kaci[b], M.G. Porquet[b], C. Schück[b], F. Azaiez[c], C. Bourgeois[c], J. Duprat[c], A. Korichi[c], N. Perrin[c], N. Poffé[c,d], H. Sergolle[c], C.W. Beausang[e], S.J. Gale[e], M.J. Joyce[e], E.S. Paul[e], J.F. Sharpey-Schafer[e], R.M. Clark[f], K. Hauschild[f], R. Wadsworth[f], J. Simpson[g], M.A. Bentley[h], G. Smith[i], H. Hübel[j], P. Willsau[j], G. De France[k], I. Ahmad[l], M. Carpenter[l], R. Henry[l], R.V.F. Janssens[l], T.L. Khoo[l] and T. Lauritsen[l]

[a] *IPN Lyon, IN2P3/CNRS and Univ. C. Bernard, France;* [b] *CSNSM Orsay, IN2P3/CNRS, France;* [c] *IPN Orsay, IN2P3/CNRS, France;* [d] *Univ. of Oxford, U.K.;* [e] *Univ. of Liverpool, U.K.;* [f] *Univ. of York, U.K.;* [g] *Daresbury Lab., U.K.;* [h] *Staffordshire Univ., U.K.;* [i] *Univ. of Manchester, U.K.;* [j] *Univ. of Bonn, Germany;* [k] *CRN Strasbourg, IN2P3/CNRS, France;* [l] *Argonne National Lab., USA.*

The ^{192}Hg nucleus has been populated via the ^{36}S (^{160}Gd , 4n) reaction at 159 MeV with the beam being provided by the MP Tamdem of the Daresbury Nuclear Structure Facility multidetector array EUROGAM phase 1. A total of 6.5×10^8 events have been written to tape with an unsuppressed fold ≥ 5. These data have been sorted into γ-γ correlation matrices, some of them gated on the $2^+\rightarrow 0^+$ or $4^+\rightarrow 2^+$ γ - ray transitions to select unambiguously the ^{192}Hg nucleus and angular distribution informations have been extracted from coincidence data.

The level scheme of ^{192}Hg, known previously [1], has been extended up to 10.4 MeV excitation energy and spin $34\,\hbar$ [2]. Two new structures, composed of competing $\Delta\,\mathrm{I}=1$ and $\Delta\,\mathrm{I}=2$ transitions, have been observed and, for the first time in Mercury isotopes, some links with the known low-lying levels have been established. The two bands are based on states located at 6.304 MeV ($\mathrm{I}=22^+$) and 6.879 MeV ($\mathrm{I}=23^-$) excitation energy. The second band is more regular than the first one and shows a regular behaviour for the transition probabilities B(M1)/B(E2) ratios with a mean value of $5.5\,(\mu_N/eb)^2$.

These experimental results have been discussed in terms of mean-field Hartree-Fock plus BCS calculations [3,4] and are consistent with two high-K quasi-proton excitations for an axial oblate shape of the nucleus, in a collective motion. The new bands are proposed to originate from deformation-aligned quasi-proton excitations, $\pi(i_{13/2}*h_{9/2})_{K^\pi=11^-}$ and $\pi(h_{9/2})^2_{K^\pi=8^+}$ coupled to rotation-aligned quasi-neutrons $\nu(i_{13/2})^n$ and quasi-proton $\pi(h_{11/2})^2$ excitations.

The comparison between the dipole bands observed in Hg isotopes and those observed in Pb isotopes shows that the transition probabilities B(M1)/B(E2) ratios are smaller in Hg isotopes. This can be interpretated as different configurations leading to smaller B(M1) values (rotation-aligned quasi-protons $\pi(h_{11/2})^2$) or to higher deformation in Hg isotopes. The last possibility should be discussed in terms of GCM calculations [5,6].

Another structure, in coincidence with the negative parity band labelled ABCE [1] and the new $\Delta\,\mathrm{I}=1$ band (a) [2] based on the state $\mathrm{I}=23^-$, appears at higher excitation energy with very weak intensity and is not yet clearly connected to the yrast levels. The analysis and, in particular, its assignment are still in progress.

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NEW DIPOLE BANDS IN ^{195}Pb

B. Fant[1], B. Cederwall[2], L.O. Norlin[2], C.W. Beausang[3], P.A. Butler[3], D.M. Cullen[3], P. Fallon[3], S.M. Mullins[3], J.W. Roberts[3], A.M. Bruce[4], R.J. Poynter[5], R. Wadsworth[5], M.A. Riley[6], A. Atac[7], J. Nyberg[7], H. Hübel[8], W. Korten[8], P. Willsau[8], R.A. Bark[9], B. Herskind[9], M.J. Piiparinen[9], T. Ramsøy[9], G. Sletten[9] and J. Gerl[10].

[1] *Department of Physics, University of Helsinki, SF-00014 Helsinki, Finland*
[2] *Manne Siegbahn Institute of Physics, S-104 05 Stockholm, Sweden*
[3] *Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 3BX, UK*
[4] *SERC, Daresbury Laboratory, Warrington WA4 4AD, UK*
[5] *Department of Physics, University of York, Heslington, York Y01 5DD, UK*
[6] *Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*
[7] *The Svedberg Laboratory, S-751 21 Uppsala, Sweden*
[8] *Institut für Strahlen- und Kernphysik, Universität Bonn, W-5300 Bonn, Germany*
[9] *Niels Bohr Institute, Tandem Accelerator Laboratory, DK-4000 Roskilde, Denmark*
[10] *Gesellschaft für Schwerionenforschung, W-6100 Darmstadt, Germany*

We have performed experiments on ^{195}Pb using the Tandem Accelerator and the TESSA spectrometer at Daresbury Laboratory and the Tandem Accelerator and the Nordball set up at the Niels Bohr Institute. The reaction $^{164}Dy(^{36}S, 5n)^{195}Pb$ at 170 MeV bombarding energy was used at the Daresbury Laboratory and the reaction $^{164}Dy(^{34}S, 3n)^{195}Pb$ at 160 MeV was used at NBI. Several runs were performed and in the longest runs $540 \cdot 10^6$ events of fold selected double and triple coincidences were recorded.

Nuclei close to ^{208}Pb are well understood by means of the nuclear shell model and consequently the excited states of light lead isotopes known down to ^{190}Pb, can reasonably well be described by few orbital configurations. Recently ^{188}Pb and ^{186}Pb have been studied [1)] and in these nuclei the influence of nuclear rotation is observed in the yrast cascade of the ground band. Three-quasiparticle configurations are dominating the yrast states of the odd lead nuclei known down to ^{193}Pb, ref. [2)]. Prior to this investigation high spin states in ^{195}Pb were observed [3)] up to spin $33/2^+$. In this investigation we report two dipole gamma cascades which feed into the yrast $25/2^+$ state and thus bypassing the isomeric $33/2^+$ state. New cascades feeding into the yrast $27/2^-$ state are also observed.

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Recoil Distance Lifetime Measurements of States in the Oblate Dipole Bands of ^{197,198}Pb

R.M.Clark[1,†], R.Wadsworth[1], H.R.Andrews[2], T.Drake[3], A.Galindo–Uribarri[2], G.Hackman[4], I.Hibbert[1], V.P.Janzen[2], R.W.MacLeod[2], S.M.Mullins[4], D.C.Radford[2], D.Ward[2], G.Zwartz[3]

[1] Department of Physics, University of York, Heslington, York, Y01 5DD, UK
[2] AECL Research, Chalk River Laboratories, Chalk River, ON KOJ 1J0, Canada
[3] Department of Physics, University of Toronto, Toronto, ON M5S 1A7, Canada
[4] Department of Physics and Astronomy, McMaster University, Hamilton, ON L8S 4M1, Canada
† Present Address: Lawrence Berkeley Laboratory, Berkeley, California, 94720

The recent observation of cascading sequences of magnetic dipole transitions in the neutron deficient Pb and Bi nuclei [1] has prompted a great deal of interest. These structures have generally been interpreted in terms of weakly oblate (β_2 ~–0.05 to –0.15) high–K proton configurations coupled to rotationally aligned neutrons. The assignment of the underlying configuration of each band has so far been based only on qualitative considerations, such as:

- Regularity of energy spacing, ΔE_γ, between successive transitions.
- Lower limits of the $B(M1)/B(E2)$ ratios.
- Behaviour of the dynamic moments of inertia, $\Im^{(2)}$, as functions of rotational frequency, ω.
- Identical transition energies (to within ~3 keV) of different bands in different nuclei.

Clearly, in order to provide firm evidence for the configuration assignments accurate lifetime measurements, for states within the bands, have to be made. These can then be related to the g–factor of each configuration, through the magnetic dipole (M1) transition rate. The first Doppler Shift Attenuation Method (DSAM) lifetime measurements have been reported for a band in ^{197}Pb [2] and for two of the bands in ^{198}Pb [3]. A Recoil Distance Method (RDM) experiment was performed using the 8π–spectrometer at the TASCC facility, Chalk River. This was specifically aimed at measuring lifetimes of states near the bandheads of the dipole structures in ^{197,198}Pb, complementing the DSAM measurements.

Using all the available data, B(M1) transition rates for 27 states in four different structures (two in ^{197}Pb and two in ^{198}Pb) have been deduced. The B(M1) values display clear systematic differences between the sequences, indicating that several different configurations must be involved. In addition, it has been possible to use measured branching ratios and lifetimes to estimate the quadrupole moments, Q_0, of levels in bands for which associated E2–crossover transitions can be seen. They indicate very weak deformations with Q_0=1–3eb (i.e., β_2 ~0.03–0.08). The configuration assignments suggested in [1] are qualitatively consistent with the results.

One very interesting aspect of this work is that it provides a stringent test for the Tilted Axis Cranking (TAC) model [4]. In principle, TAC provides a natural geometric picture of the manifest combination of high–spin protons and high–spin neutrons for these M1–bands. However, preliminary calculations seem to overestimate the B(M1) values by around a factor of two. Also, the B(M1) values are predicted to decrease as angular momentum grows. This tendency has not been observed. The origin of these discrepancies remains unclear.

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High Spin Quasi-Vibrations and the Search for Exotic Structures in ^{198}Po

L.A. Bernstein, J.A. Cizewski, H.Q. Jin, W. Younes, D.P. McNabb
Rutgers University, New Brunswick, New Jersey 08903
J.A. Becker, E.A. Henry, M.J. Brinkman, J.R. Hughes, M.A. Stoyer
Lawrence Livermore National Laboratory, Livermore, California 94550
M.A. Deleplanque, R.M. Diamond, F.S. Stephens, I.Y. Lee, P. Fallon, B. Cederwall
Lawrence Berkeley National Laboratory, Berkeley, California 94720
J. Draper, C. Duyar, E. Rubel
U.C. Davis, Davis, California 95616
D. Vo
Iowa State University, Ames, Iowa 50011

The polonium isotopes near the semi-magic ^{210}Po display a low-lying structure that is well-described by the shell model. As the number of valence neutrons increases, the transition from single-particle to collective behavior in the low lying states is expected. The evolution from single-particle to collective motion will also be a function of angular momentum. Three dimensional Hartree-Fock and Total Routhian Surface calculations[1,2] predict a minimum in the potential energy surface at large (ε=0.5) deformation for light (N=110-116) Po isotopes. Nilsson model calculations[3] also show a gap in the single-particle energies for a deformation of ε=0.5 for Z=84 and N=114.

To study the structure of ^{198}Po we have performed in-beam measurements at the 88" Cyclotron via the ^{174}Yb(^{29}Si,5n) reaction using the HERA array of 20 Compton-suppressed Ge counters with a 40-element BGO inner array. Data were taken with 141 and 146 MeV ^{29}Si beams. Over 350 million γ–γ events were recorded. We have established the level scheme to $\approx$ 5 MeV and $\approx$ 20$\hbar$. In addition, in May 1994 we will perform a search for superdeformed and oblate structures at high spin using the early implementation configuration of GAMMASPHERE.

The low-lying structure of ^{198}Po is suggestive of an anharmonic vibrator, with equally spaced yrast levels and non-yrast states with properties of members of vibrational multiplets. At moderate angular momentum the structure is that of two protons in high-j orbitals such as $(\pi h_{9/2})^2_{8^+}$ and $(\pi h_{9/2} i_{13/2})_{11^-}$.

Above $\approx$12$\hbar$ three stretched quadrupole cascades have been identified, which promptly feed the yrast states. The spacings in these cascades are nearly equal, and suggest vibrational motion built on two quasiparticle states, such as the J=9$^-$ $(\nu f_{5/2} i_{13/2})^{-2}$ state. We have also identified a quasi-vibrational structure built on the $(\nu i_{13/2})^{-2}$ 12$^+$ isomer. We will compare the predictions of the vibrational and rotational models with the data in order to characterize these excitations.

The systematical behavior of the Po isotopes will be discussed, as well as the preliminary results from our search for deformed oblate, and possibly superdeformed prolate, excitations.

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Lifetimes of Shears Bands in ^{199}Pb

H. Hübel, M. Neffgen, G. Baldsiefen, W. Korten, D. Mehta, N. Nenoff, U.J. van Severen (Institut für Strahlen- und Kernphysik, Universität Bonn), H. Grawe, H. Kluge, K.H. Maier (HMI Berlin), A. Korichi (IPN Orsay), M. Piiparinen (NBI Risø), Jie Meng and S. Frauendorf (Forschungszentrum Rossendorf)

In several isotopes in the Pb region regular sequences of enhanced magnetic dipole transitions have been found. They are built on weakly oblate deformed proton-neutron excitations and show very small quadrupole collectivity. Nevertheless, most of them form very regular bands up to high angular momentum. It has been suggested [1,2] that these bands represent a new nuclear structure effect to generate angular momentum: The total spin within the bands is increased by a continuous and simultaneous reorientation of proton (particle) and neutron (hole) angular momenta, which are approximately at right angles at low spin, into the direction of the total angular momentum (shears bands).

A straightforward prediction of the shears mechanism is that the magnetic transition probabilities should decrease with increasing spin along the bands. We have performed DSAM lifetime measurements in two of these bands in ^{199}Pb. They were populated in the reaction ^{186}W(^{18}O,5n)^{199}Pb. Two backings, Al and W, were used. Gamma-ray coincidences were measured with the OSIRIS and NORDBALL arrays at Berlin and Risø, respectively. Coincidence spectra with gates set on transitions below and above the states of interest were analysed. Lifetimes were obtained by fits of calculated line-shape curves to the Doppler-broadened lines in the high-spin regions of the two bands. In the overlap region, the results for the two different backings are in agreement.

The results show a decrease of the B(M1) values with increasing spin which is compatible with the tilted-axis cranking model [1] prediction for the shears bands. In addition, using the lifetimes and the $\Delta I = 1$ to $\Delta I = 2$ branching ratios, an estimate of the quadrupole collectivity can be obtained. The resulting small B(E2) values confirm the predicted [2] small oblate deformation of the shears bands in ^{199}Pb.

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Transition from Single-particle to Collective Motion in Polonium Isotopes

W. Younes, J.A. Cizewski, L.A. Bernstein, H.Q. Jin, D.P. McNabb
Rutgers University, New Brunswick, New Jersey 08903 USA

The polonium systematics provide a good framework for the study of transitional behavior in nuclear structure. The semi-magic ^{210}Po is very well described as two protons outside an inert core, interacting via a surface-delta potential. ^{196}Po, on the other hand, displays groupings of levels with regular energy spacings, as in a vibrational system. It is therefore tempting to describe the even polonium isotopes as undergoing a smooth transition from single-particle to collective vibrational behavior over the span of eight nuclei.

We have studied the low-lying Po systematics using the Particle-Core Model (PCM)[1] in which a vibrational core is adiabatically coupled to two valence protons. Each nucleus is then described by three parameters: the quadrupole phonon energy $\hbar\omega$, the proton-proton interaction strength $G\hbar\omega$, and the proton-phonon interaction strength $\xi\hbar\omega$. These parameters are fit to energy levels across the systematics as a function of neutron number. Transition strengths and branching ratios are used as an additional gauge of the success of the model.

The onset of vibrational collectivity in neutron-deficient polonium isotopes is thought to be caused by the quadrupole interaction between proton and neutron pairs. The details of this process, however, are not well understood. Although the PCM does not offer a description of the internal structure of the phonons, it does factor out the single-particle contribution of the valence protons.

The polonium energy systematics of low-lying states show sudden changes near $N = 114$. The observed drops in low-lying levels as N decreases betray significant changes in the underlying structure of neutron-deficient Po. Because ^{196}Po and ^{198}Po were the lightest isotopes for which spectroscopy was available, the picture was frustratingly incomplete. In February of this year, we obtained the first data on excitations in ^{194,195,197}Po at the Argonne ATLAS facility. We used a 142 MeV ^{28}Si beam on an enriched (70%) ^{170}Yb target. The setup consisted of 10 Compton-suppressed Ge detectors and the fragment-mass-analyzer (FMA) which provided mass/charge separation of the recoil products. We recorded FMA-γ, γ-γ and FMA-γ-γ events in a 5-day run.

The sudden changes in energy systematics near $N \leq 112$ can be attributed to the opening of the $\nu i_{13/2}$ orbital. However, the specific role of this orbital is not well understood. The available levels in ^{195,197}Po can now be used to shed some light on the contribution of the neutrons to the collective behavior of $N < 116$ Po isotopes.

We shall present the PCM analysis of the even polonium chain with $N = 126 - 112$ and use model parameters and wavefunctions to track the onset of vibrational collectivity in these nuclei. The nature of the collectivity in the lighter isotopes will be discussed in light of the new data on ^{194,195,197}Po.

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Multiplets and Collective Structures in ^{202}Po

T. Kibédi, G.D. Dracoulis, A.P. Byrne, M. Dasgupta, G.J. Lane, P.H. Regan
Dept. Nucl. Phys., RSPhysSE, Australian National Uni. ACT 0200, Canberra, Australia

P.M. Walker
Dept. of Physics, University of Surrey, Guildford, GU2 5XH, UK

The coexistence of different shapes in the same nucleus is a well established feature for many nuclei. The $Hg - Pb$ region is of particular interest in this respect because a variety of shapes – spherical oblate, prolate and superdeformed prolate – have been observed, in close proximity to the $Z = 82$ closed shell. In a recent study cascades of dipole transitions in ^{199,200}Pb [1] have been identified with rather regular energy spacings. They have been characterised as bands of weak collectivity, with angular momentum provided largely by alignment of the $h_{9/2}$ or $i_{13/2}$ proton orbitals and the $i^{-2}_{13/2}$ neutron-holes. In these cases, the proton orbitals above the $Z = 82$ gap must be populated by excitation of protons, leaving proton holes below. We have initiated a study of ^{202}Po, the isotone of ^{200}Pb, in which the two valence protons ($Z = 84$) can occupy the same orbitals without involving holes.

Excited states in ^{202}Po have been populated using the ^{194}Pt(^{12}C,4n) reaction and a variety of γ-ray and conversion electron techniques, using pulsed beams from the ANU 14UD Pelletron accelerator, giving sensitivity to isomeric states. The determination of transition multipolarities is based on the γ-ray anisotropies and the conversion coefficients obtained from single electron and γ-ray spectra with appropriate gates on time (see Fig. 1).

Many new transitions have been assigned depopulating states up to $\sim 25\,\hbar$. The recently published level scheme of the ^{202}Po [2] has been extended including the 10^-,12^- states of the $\pi h_{9/2}\,\nu f^{-1}_{5/2} i^{-1}_{13/2}$ configuration.

Three cascades of dipole transitions feeding 14^+, 15^- and 17^+ states have been observed. The most prominent one feeds the 15^- isomeric state, whose configuration has been identified as $\pi h_{9/2}\,\nu f^{-1}_{5/2} i^{-1}_{13/2}$. Large $B(M1)/B(E2)$ ratios are common to all cascades, however the sequences are not regularly spaced.

The results will be discussed within the alternative approaches involving either multi-particle states as quasi-collective bands or multiplets predicted by empirical shell model calculations.

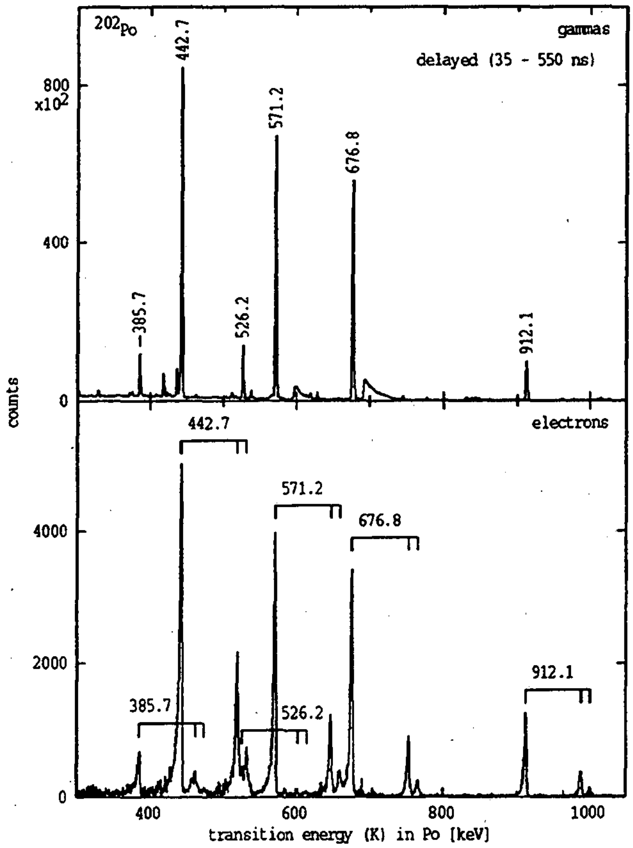

FIG. 1. Delayed electron and γ-ray spectra

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On the angular momentum dependence of the parity splitting in nuclei with octupole correlations

R.V.Jolos[a,b] and P.von Brentano[a]
[a] *Institut für Kernphysik, Universität zu Köln, FRG*
[b] *Bogoliubov Theoretical Laboratory, JINR, Dubna, Russia*

Experimental data [1,2] on the angular momentum dependence of parity splitting of yrast bands in different nuclei are analysed using a one-dimensional model of octupole motion with axial symmetry. A two parameter formula, based on a solution of the Schrödinger equation with a double-minimum potential,

$$\Delta\epsilon(I) \equiv \Delta E(I)/\Delta E(2) = exp[-\frac{I(I+1)/J_0(J_0+1)}{1+aI(I+1)} + \frac{6/J_0(J_0+1)}{1+6a}], \qquad (1)$$

where $\Delta E(I)$ is the parity splitting, predicts that the parity splitting exponentially decrease with $I(I+1)$ and gives a good fit to data.

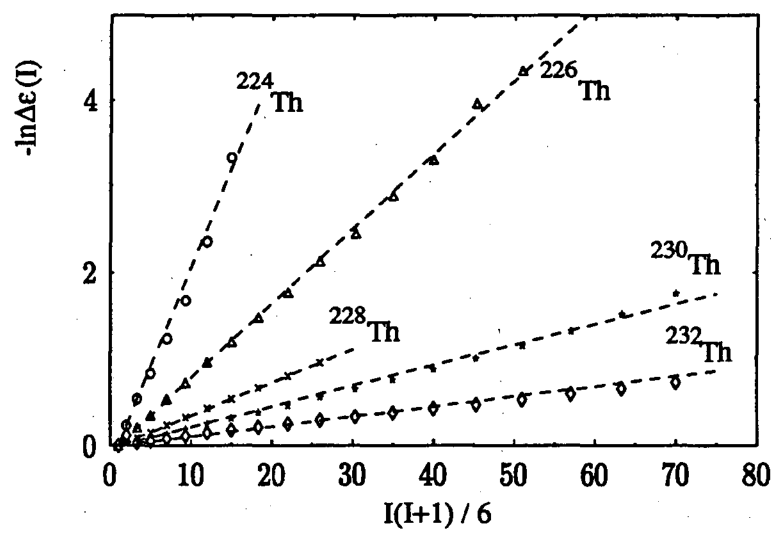

Figure 1: Experimental data for $-ln\Delta\epsilon(I)$ versus $I(I+1)/6$ for Th isotopes. The straight lines show the quality of the linear approximation.

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Experimental approach towards ^{100}Sn

(NORDBALL-GASP collaboration)
A. Ataç, D. Bazzacco, P. Bednarczyk, J. Cederkäll, G. de Angelis, M. de Poli, Zs. Dombrádi, C. Fahlander, D. Foltescu, H. Grawe, D. Jerrestam, A. Johnson, R. Julin, S. Juutinen, A. Kerek, W. Klamra, J. Kownacki, A. Likar, M. Lipoglavsek, E. Mäkelä, L-O. Norlin, J. Nyberg, M. Palacz, J. Persson, C. Rossi-Alvarez, H. Roth, R. Schubart, D. Seweryniak, T. Shizuma, O. Skeppstedt, G. Sletten, P. Spolaore, S. Törmänen, T. Vass, A. Virtanen and R. Wyss

Investigations of nuclei far from stability provide new information on nuclear structure specific to extreme N-Z combinations. A variety of new shapes and exotic matter distributions are expected to be revealed far off the line of beta stability. New combinations of proton and neutron numbers may lead to configurations where residual interactions can be quite different. In this respect nuclei with N=Z are the most interesting, since in this case the protons and the neutrons fill the same orbitals with largely overlapping wave functions giving rise to enhanced neutron-proton correlations.

In a previous experiment using the NORDBALL multi-detector array, and the reaction ^{58}Ni on ^{54}Fe at a beam energy of 270 MeV, γ-ray transitions belonging to 29 final nuclei were identified [1,2]. In one of them, ^{110}Te, only the energy of one excited state was previously known, and in seven of them, namely ^{102}In, ^{106,107,108}Sb, ^{108,109}Te and ^{111}I, excited states were observed for the first time [4-6]. To search for nuclei even closer to ^{100}Sn, two new experiments have been carried out. The first used the NORDBALL multi-detector system. The beam was 261 MeV ^{58}Ni bombarding a target of ^{50}Cr with a thickness of 3.5 mg/cm^2 on a thick Au backing. During the evaporation process several light particles, mainly protons, rarely α particles and very seldom neutrons were emitted followed by a cascade of γ rays. To select different reaction channels NORDBALL was equipped with a 4π charged particle detector system, a 1π neutron detector assembly, and a 2π γ-ray calorimeter of 30 BaF_2 crystals. The second experiment utilzed the GA.SP multi-detector array in coincidence with a particle detector set-up containing 40 Si ΔE detectors and the Recoil Mass Separator CAMEL. The reaction was again ^{58}Ni on ^{50}Cr with a beam energy of 210 MeV, and a target thickness of 0.5 mg/cm^2. The specific aim of the experiments was to find: ^{102}Sn which have only 2 neutrons outside the ^{100}Sn core and would be the first observed T=1 neighbour of ^{100}Sn; ^{105}Sb which is expected to lie outside the proton drip line; the T=3/2 nuclei ^{103}Sn, ^{101}In and ^{99}Cd. Data analysis is in progress.

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Towards ^{100}Sn with GASP + Si-ball + Recoil Mass Spectrometer

G.de Angelis[◦], D. Ackermann[◦], D. Bazzacco[•], P. Bednarczyk[◦], P. G. Bizzeti[△], A. M. Bizzeti Sona[△], F. Brandolini[•], R. Burch[•], A. Buscemi[•], D. De Acuna[•], M. De Poli[◦], C. Fahlander[◁], E. Farnea[•], Y. Li[◦], M. Lipoglavsek[◁], S. Lunardi[•], A. Makishima[‡], R. Menegazzo[•], L. Müller[•], D. Napoli[◦], M. Ogawa[†], P. Pavan[•], C. Rossi-Alvarez[•], F. Scarlassara[•], G. F. Segato[•], D. Seweryniak[◁], F. Soramel[▷], P. Spolaore[◦], R. Zanon[•] and Nordball Collaboration

[◦] *INFN, Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy*
[•] *Sezione INFN and Dipartimento di Fisica dell'Università, Padova, Italy*
[△] *Sezione INFN and Dipartimento di Fisica dell'Universitá, Firenze, Italy*
[◁] *The Svedberg Laboratory, University of Uppsala, Uppsala, Sweden*
[‡] *Center for Radioisotope Science, National Defense Medical College, Tokorozawa, Japan*
[†] *Department of Energy Sciences, Tokyo Institute of Technology, Yokohama, Japan*
[▷] *Sezione INFN and Dipartimento di Fisica dell'Università, Udine, Italy*

The new large γ-ray detector arrays have been especially designed to improve the study of nuclei at high spin produced in fusion-evaporation reactions. Their sensitivity and selectivity can also be of great help, when coupled with various kinds of particle detectors, for studying exotic nuclei far from stability. We have started at the GASP spectrometer a program to investigate proton rich nuclei in the vicinity of ^{100}Sn. For this goal we have built a Si-ball composed of 40 ΔE detectors of 130 μm thickness, covering 92% of the total solid angle, which fits into the BGO inner ball of GASP. In the first experiment we have used the ^{58}Ni+^{50}Cr reaction at 210 MeV to produce the nuclei of interest. The beam was provided by the Tandem XTU accelerator of the Legnaro National Laboratory (LNL) and γ-rays have been detected using all the 40 high efficiency Ge detectors of the GASP array. Together with the Si-ball, in order to get mass and charge identification, we made use also of the recoil mass spectrometer (RMS). About 0.5×10^9 triples and higher fold events were collected that, after unfolding, gave a total of 1×10^9 triple and 0.1×10^9 quadruple coincidence data. For the RMS we obtained an efficiency of 5%. After mass selection by using the high fold Ge data we could identify all the known evaporation residues. Several level schemes have been greatly improved. They show both the single particle level sequences typical of this region and well developed collective structures. Obviously the goal of the experiment is to extend our knowledge to new more exotic nuclei. We have established some level sequences which are candidates for such nuclei. The analysis is in progress in order to complete the identification of those γ-rays and their attribution to a definite nucleus. Further experiments are planned which will take advantage of the Si-ball completed also with 40 E - detectors.

New Level Structures in Neutron Rich Nuclei from Spontaneous Fission

Q. Lu[1], K. Butler-Moore[1], S. Zhu[1,2], J.H. Hamilton[1], B.R.S. Babu[1], A.V. Ramayya[1] W.C. Ma[1], V.E. Oberacker[1], J. Kormicki[1], D. Shi[1], J.K. Deng[1], D.B. Wang[2],
L.K. Peker[3] J.D. Cole[4], R. Aryaeinejad[4], Y.X. Dardenne[4], M. Drigert[4],
N.R. Johnson[5], I.Y. Lee[5,6], F.K. McGowan[5], G.M. Ter-Akopian[1,7],
Yu. Ts. Oganessian[7], J.O. Rasmussen[6], M.A. Stoyer[6], S.Y. Chu[6], K.E. Gregorich[6],
M. Mohar[6], J.M. Nitschke[6], K. Moody[8], R. Lougheed[8], S.G. Prussin[9], S. Asztalos[9]

[1]*Physics Department, Vanderbilt University, Nashville, TN 37235*
[2]*Physics Department, Tsinghua University, P.R. China*
[3]*Brookhaven National Laboratory, NNDC, Upton, LI 11973*
[4]*Idaho National Engineering Laboratory, Idaho Falls, ID 83415*
[5]*Oak Ridge National Laboratory, Oak Ridge, TN 37831*
[6]*Lawrence Berkeley Laboratory, Berkeley, CA 94707*
[7]*Joint Institute for Nuclear Research, Dubna, 141980 Russia*
[8]*Lawrence Livermore Laboratory, Livermore, CA 94550*
[9]*University of California-Berkeley, Berkeley, CA 94720*

The level structures of many neutron rich nuclei produced in the spontaneous fission of ^{252}Cf and ^{242}Pu have been investigated from γ-γ and γ-γ-γ coincidences in the 20 Compton suppressed Ge Close-Packed Ball at the Holifield Heavy Ion Research Facility and the early implementation of Gammasphere at Lawrence Berkeley Laboratory. The triples γ data are particularly important in helping unravel the complex prompt γ spectra from the over 100 isotopes produced in the spontaneous fission. In any gate set on one particular gamma ray energy, there is a good probability that there is a gamma ray of essentially the same energy in two or more isotopes. However, by double gating on two gamma rays in the same isotope or on one gamma ray in the light and one in the heavy partner (for example, the 2-0 transition in each partner), then one sees in the double gated spectra only the peaks associated with the two associated partners. We have exploited this technique to gain new insights into the structure of many neutron rich nuclei. For example, significant differences are observed from the reported shape coexistence in the Sr-Zr nuclei with A=96-100. New, higher spin states in ^{108}Ru and ^{110}Ru indicate the importance of significant ground state deformation in this region. The ground state bands in these two nuclei are among the most identical bands known with transition energies from the 2^+ to the 8^+ and possibly 10^+ levels differing by 0 to a maximum of only 0.5%. In addition, both nuclei have extended (to 7^+) gamma vibrational bands with nearly identical energies. This is the first observation of identical γ bands. The gamma band in ^{110}Ru has the second lowest 2^+ band head energy (612 keV) known across the periodic table. The regular spaced energies of the gamma band are characteristic of a well-deformed rotor with little triaxiality. New high spin bands are seen in ^{143,145,147}Ba, tentatively to $31/2^+$ in ^{143}Ba and $25/2^-$ in ^{145}Ba. When compared with ^{142,144,146}Ba where clear octupole band structure is seen in ^{144}Ba, one sees that ^{143}Ba has a band structure characteristic of the octupole structure seen in ^{144}Ba, but ^{145}Ba does not exhibit such a structure. These are only selected examples of the new structure insights being gained. Work at Vanderbilt, INEL, ORNL, and LBL is supported by the U.S. Dept. of Energy under grants and contracts DE-FG05-88ER40407, DE-AC07-76ID01570, DE-AC05-84OR21400, and DE-FG03-87ER40323, respectively.

Gammasphere Study of Spontaneous Fission Gamma Rays

The GANDS Collaboration*

We report on the Gammasphere results on ^{242}Pu and ^{252}Cf spontaneous fission gamma rays with emphasis on the dependence of spin distributions on numbers of neutrons emitted. Earlier studies of spontaneous and neutron-induced fission have called attention to a class of fission events with very low excitation energy of the fragments and high total kinetic energies. Some were identified by their high fission kinetic energies and others by gamma-gamma coincidences showing fission partners with no neutrons lost. This phenomenon has been called "cold fission."[1]

In late 1993, we measured for $\sim$ 590 hours a double-sealed source of ^{242}Pu oxide having about 10^4 fission/sec in Early Implemenation of Gammasphere with (on average) 32 Compton-suppressed Ge detectors. Approximately 2×10^9 doubles events and 200×10^6 triples events were recorded on magnetic data tapes. In April 1994, we measured a $\sim 6 \times 10^4$ fission/sec sealed source of ^{252}Cf with 36 Compton-suppressed Ge detectors, 1 Ge LEPS "x-ray" detector, and 4 scintillators for neutron detection.

Our analysis has concentrated first on extracting relative intensities of ground rotational transitions as a function of number of neutrons emitted. We clearly find the "cold fission". Some isotopic series show a clear trend of decreasing fragment average spin with increasing numbers of neutrons emitted. This is contrary to our first expectations by a simple quantal model based on neck thickness expected at scission. Some analysis has investigated nuclear structure information of odd-A neutron-rich nuclides.[2] Further analysis on this rich data set is continuing.

* *J.O. Rasmussen, M.A. Stoyer, S.Y. Chu, K.E. Gregorich, I.Y. Lee, M.F. Mohar, and J.M. Nitschke,* LBL, Berkeley, CA 94720, *K. Moody and R. Lougheed,* LLNL, Livermore, CA 94550, *S.G. Prussin and S. Asztalos,* UC Berkeley, Berkeley, CA 94720, *R. Aryaeinejad, J. Cole, Y.X. Dardenne, and M. Drigert,* INEL, Idaho Falls, ID 83415, *J. Hamilton, Q.H. Lu, W.C. Ma, and A.V. Ramayya,* Vanderbilt Univ., Nashville, TN 37235.

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Models for Spin Distributions of Deformed Fission Fragments

R. Donangelo and L.F. Canto
UFRJ, Rio de Janiero, Brazil

J.O. Rasmussen and M.A. Stoyer
LBL, Berkeley, CA 94720

Recent Gammasphere data of ^{242}Pu spontaneous fission gamma rays have been examined for rotational band population patterns. In some series of isotopes a clear trend is seen in going from fission with zero neutrons emitted ("cold fission"[1]) to several neutrons emitted. That is, the average spin of the light fragment decreases monotonically with number of neutrons emitted. This behavior is the reverse of that expected from simple angular wave packet considerations of the thickness of the neck at scission. It is also the reverse of expectation in a simple thermal picture where the temperature at scission goes as the number of neutrons emitted. Consequently, we examine several models based on normal-mode analysis of scission shapes. These include works of Nix, et al.[2] on classical vibrational modes of touching spheroids, a model of three touching spheres or spheroid touching sphere with purely Coulombic restoring force, and a triatomic molecular model in which the excess nucleons outside three doubly-magic clusters play the role of bonding particles in molecular orbitals.

Long ago there was an attempt[3] at modeling the spin distribution of a deformed fission fragment. They took the model of a spheroid touching a doubly-magic ^{132}Sn, assuming zero-point wave function in polar angle of the spheroid, with restoring force from the gradient of an optical-model potential. With these initial conditions the Coulomb excitation on the outward path of the fragments was evaluated to give a spin distribution in a similar fashion to the alpha decay theory for deformed even nuclei. They obtained an average spin value of 5.6 for ^{108}Ru from thermal neutron fission of ^{239}Pu, with there being the somewhat arbitrary parameter of the optical potential force at scission. In the present work we consider more general initial conditions and handle the Coulomb excitation in a better semiclassical non-sudden approximation.

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NEUTRON EMISSION IN FISSION

J L Durell, The University of Manchester, Manchester, UK

The advent of multi-detector arrays has permitted detailed studies of prompt γ rays emitted following fission. These studies have led [1–3]) to a considerable extension of our knowledge of the nuclear structure of neutron-rich nuclei in the A=90-160 region.

The data also contain information concerning the fission process itself. The observed γ rays allow the precise identification of fission fragments, overcoming the difficulties associated with the finite mass and charge resolutions of heavy-ion detectors. It is therefore possible to determine the yields of particular fragment pairs as a function of their A and Z. These yields depend upon the distribution of primary fragments and the probabilities of neutron emission from them. It is therefore possible, in principle, to deduce from observed yields of fission products details of primary fragment production and neutron decay.

Of particular interest are the cold fission channels in which fission products are formed without neutron emission. The process of cold fission is theoretically predicted to be associated with the existence of particular fission paths which have special scission configurations exhausting the Q-value and hence lead to post-scission fragments at low excitation energy. We have observed cold fragmentation in the fission of both ^{248}Cm and ^{236}U. A comparison of the two cases should shed light on the possible existence of the special fission paths predicted to exist.

The EUROGAM I array was used at Daresbury Laboratory to investigate the spontaneously fissioning nucleus ^{248}Cm. Triples (and higher) coincidence events have been used to produce a $\gamma - \gamma - \gamma$ cube of high statistics, the analysis of which provides clean spectra of good selectivity. In addition The POLYTESSA array was set up at Brookhaven National Laboratory in order to study prompt γ rays from the thermal neutron induced fission of ^{236}U. In this case only a $\gamma - \gamma$ matrix was constructed. The coincidence data have been used to construct decay schemes of many nuclei. Once the details of the levels are known the intensities of the observed γ rays can be used to establish fragment yields.

The results presented here are part of those from a fission studies collaboration between the University of Manchester and the Argonne National Laboratory, the Brookhaven National Laboratory, Daresbury Laboratory and the Centre de Recherches Nucleaires, Strasbourg.

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Yields and Neutron Multiplicities of Correlated Fragment Pairs in Spontaneous Fission of ^{252}Cf

G. M. Ter-Akopian[1,2], J. H. Hamilton[2], Yu. Ts. Oganessian[1], J. Kormicki[2], G. S. Popeko[1], A. V. Daniel[1], Q. Lu[2], A. V. Ramayya[2], K. Butler-Moore[2], W.-C. Ma[2], J. K. Deng[2], J. Kliman[3], V. Polhorsky[3], M. Morhac[3], J. D. Cole[4], R. Aryaeinejad[4], N. R. Johnson[5], I. Y. Lee[5], F. K. McGowan[5]

[1] *Joint Institute for Nuclear Research, Dubna, 141980 Russia*
[2]*Physics Department, Vanderbilt University, Nashville, TN 37235*
[3]*Institute of Physics SASc, Bratislava, Slovak Republic*
[4]*Idaho National Engineering Lab., Idaho Falls, ID 83415*
[5]*Oak Ridge National Laboratory, Oak Ridge, TN 37831*

Prompt γ-γ and γ-γ-γ coincidences in the spontaneous fission of ^{252}Cf were measured at the Holifield Heavy Ion Research Facility with the a ^{252}Cf source in the center of the 20 Compton suppressed Ge Close-Packed Ball. All events with multiplicity ≥2 were recorded. Approximately $2 \cdot 10^9$ γ-γ coincidences were collected. The γ-rays originating from the complementary fragment pairs of Zr-Ce and Mo-Ba were identified by double gating on one γ-ray in each. The yields for the Mo-Ba pairs normalized to the sum of the known independent yields of ^{142}Ba, ^{144}Ba and ^{146}Ba are given below (for each pair the frequency of appearance is given in relation to 100 fission events). Similar data were obtained for $^{146,148}Ce$ with $^{98\text{-}104}Zr$. Such detailed data characterizing nuclear fission are obtained directly for the first time in this work. The prompt fission neutron multiplicity distributions for various charge divisions between fission fragments and for the fission modes resulting in the observation of individual fission fragments are determined directly by gating on the 2-0 or ground state transitions (double gated as needed) and observing the coincidence intensities of the 2-0 transitions in the partners. Zero up to 10 neutron emission are observed. Previous measurements of neutron multiplicities involved measuring neutrons from all SF events except zero neutron emission and extracting multiplicities from a complex unfolding procedure. Our 0, 8 and 10 υ Mo-Ba yields are significantly higher than reported for all events. We are working to extract the parameters of the mass and excitation energy distributions for the fission fragment pairs formed just after scission. Work at Vanderbilt, INEL, and ORNL is supported by the U.S. Dept. of Energy under grants and contracts DE-FG05-88ER40407, DE-AC07-76ID01570, DE-AC05-84OR21400, respectively.

	^{138}Ba	^{140}Ba	^{142}Ba	^{143}Ba	^{144}Ba	^{146}Ba	^{148}Ba
^{102}Mo			<0.07	<0.07	0.07±0.05	0.18±0.05	0.04±0.02
^{103}Mo			<0.04	0.19±0.09	0.48±0.05	0.35±0.05	<0.05
^{104}Mo	0.11±0.03	0.17±0.05	0.26±0.04	0.63±0.11	1.05±0.04	0.41±0.05	0.04±0.02
^{105}Mo	<0.05	0.13±0.03	0.67±0.05	1.30±0.14	1.17±0.07	0.17±0.07	
^{106}Mo	<0.07	0.14±0.02	1.04±0.04	1.54±0.12	0.70±0.04	0.03±0.02	
^{107}Mo	<0.04	0.24±0.09	0.63±0.09	0.42±0.16	<0.06		
^{108}Mo	0.04±0.02	0.12±0.05	0.16±0.04	0.12±0.09	0.04±0.01		

The $N = 40$ neutron subshell closure in the ^{68}Ni nucleus

R.Broda[1], B.Fornal[1], W.Królas[1], T.Pawłat[1], D.Bazzacco[2], S.Lunardi[2], C.Rossi-Alvarez[2], R.Menegazzo[2], G.de Angelis[3], P.Bednarczyk[3], J.Rico[3], D.De Acuña[3], P.J.Daly[4], R.H.Mayer[4], M.Sferrazza[4], H.Grawe[5], K.H.Maier[5], R.Schubart[5]

[1] *H.Niewodniczański Institute of Nuclear Physics, Kraków, Poland*
[2] *Dipartimento di Fisica dell'Universitá and INFN, Padova, Italy*
[3] *INFN Laboratori Nazionali di Legnaro, Italy*
[4] *Purdue University, West Lafayette, Indiana, USA*
[5] *Hahn–Meitner–Institut Berlin, Germany*

The only known excitation in the ^{68}Ni nucleus is the 0^+ state assigned at 1.77 MeV in the ^{70}Zn(^{14}C,^{16}O) reaction [1]. In an effort to search for other excited states in this very neutron–rich $N = 40$ nickel isotope we used the deep–inelastic processes taking place in heavy–ion collisions. The thick target gamma–gamma coincidence experiments were performed for the ^{208}Pb + 350 MeV ^{64}Ni and the ^{130}Te + 275 MeV ^{64}Ni coliding systems at the HMI Berlin with the OSIRIS and at the INFN Legnaro with the GASP array correspondingly. The data analysis provided firm identification of three gamma rays which establish three new states in the ^{68}Ni nucleus. Fig. 1 shows the systematics of the lowest excited states in even Ni isotopes including the present result. In a separate pulsed beam experiment performed at the INFN Legnaro we measured the half–life of 0.86(5) msec for the 2847 keV long–lived isomeric state, which is naturally assigned as the expected $\nu g_{9/2}p_{1/2}$ 5^- excitation decaying via the 0.022 W.u. retarded 814 keV E3 transition to the 2033 keV 2^+ state. From the systematics the tentative 4^+ or 3^- assignment is proposed for the 3147 keV level. The observed level structure of the ^{68}Ni is remarkably similar to the ^{90}Zr doubly closed shell nucleus. In contrast to the neutron–defficient $N = Z = 40$ ^{80}Zr nucleus, which was found to be deformed [2], the ^{68}Ni appears to be spherical and displays substantial subshell closure at $N = 40$.

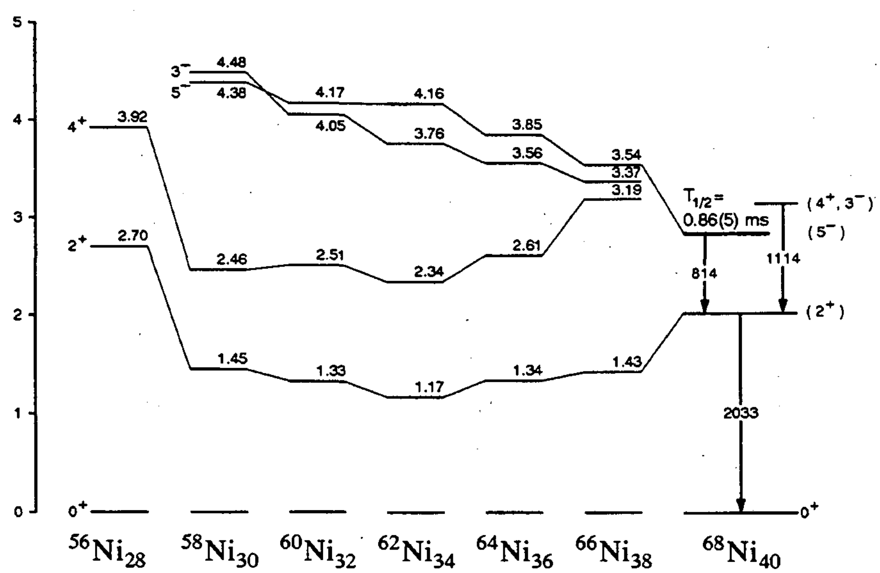

Fig. 1. Systematics of selected states in even Ni isotopes and ^{68}Ni results.

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Spectroscopy of neutron-rich A=93-97 Zr nuclei

B.Fornal[1], R.Broda[1], W.Królas[1], T.Pawłat[1], D.Bazzacco[2], S.Lunardi[2], C.Rossi-Alvarez[2], R.Menegazzo[2], G.de Angelis[3], P.Bednarczyk[3], J.Rico[3], D.De Acuña[3], P.J.Daly[4], R.H.Mayer[4], M.Sferrazza[4]

[1] *Institute of Nuclear Physics, Kraków, Poland*
[2] *Dipartimento di Fisica dell'Universitá and INFN, Padova, Italy*
[3] *INFN Laboratori Nazionali di Legnaro, Italy*
[4] *Purdue University, West Lafayette, Indiana, USA*

The in-beam and off-beam γ-γ coincidence data taken with the multidetector system GASP during the bombardment of ^{130}Te target (backed with Pb) with the 272 MeV ^{64}Ni beam from the XTU Tandem at LNL in Legnaro gave valuable spectroscopic information on many neutron-rich products with A$\sim$64 and A$\sim$130. In addition, the data include intense γ-rays from fusion-fission fragments, in particular from the very poorly known Zr isotopes (products of the symmetric fission) with A=92-98. In fact, there was practically no information on yrast excitations in ^{93}Zr, ^{95}Zr and the knowledge of ^{97}Zr was fairly incomplete. Also in the even isotopes ^{94}Zr and ^{96}Zr the highest identified spins were only 6 and 8, respectively. We performed a detailed spectroscopic analysis of these, hard-to-reach in any other processes, Zr isotopes. The quality of the data is demonstrated in fig.1, which shows the coincidence spectrum with the $2^+ \to 0^+$ transition in ^{96}Zr nucleus.

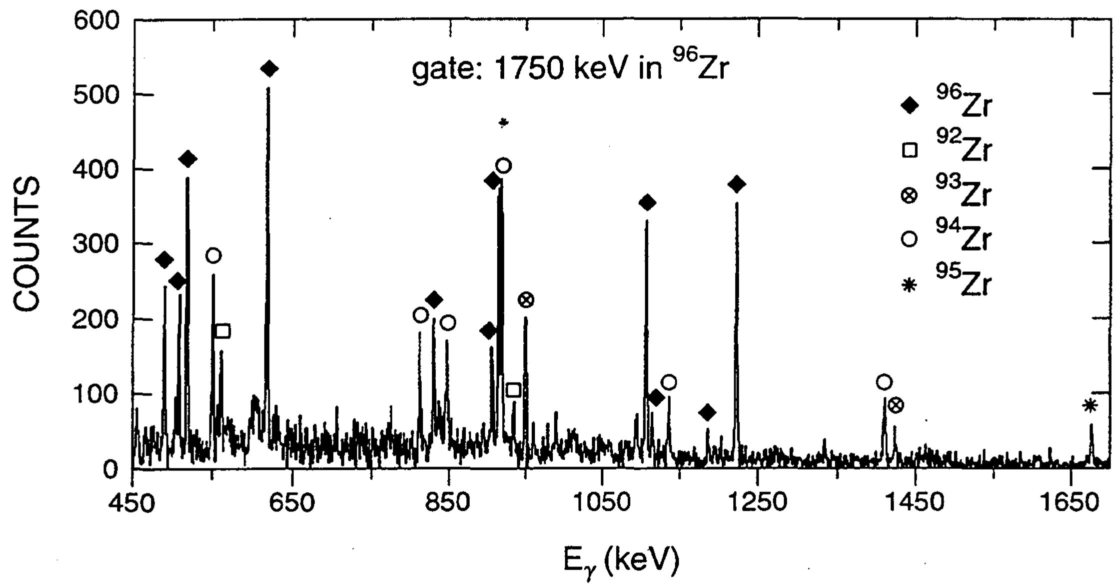

Fig. 1. Representative $\gamma-\gamma$ spectrum for ^{96}Zr product of the ^{130}Te + 272 MeV ^{64}Ni reaction.

Clearly visible are γ-rays from ^{96}Zr itself as well as from the other Zr nuclei with A=92, 93, 94 and 95; those are the exit channel reaction partners to the ^{96}Zr associated with different numbers of evaporated neutrons. The coincidences between γ-rays from the different reaction partners, so called "cross-coincidences", happen to be very intense in the Zr case and they can be exploited for assigning unknown transitions. Here, by setting gates on a γ-transition in a specific nucleus, the characteristic intensity pattern of the displayed cross-coincidence transitions from other nuclei provides unique isotopic assignment. Using this method we have identified for the first time yrast cascades in ^{93}Zr and ^{95}Zr nulei and located new yrast states in ^{94}Zr, ^{96}Zr and ^{97}Zr.

The $^{208}Pb+^{64}Ni$ Collisions above the Coulomb Barrier Studied with γ-γ Coincidences

W.Królas, R.Broda, B.Fornal, J.Grębosz, T.Pawłat,
H.Niewodniczański Institute of Nuclear Physics, Kraków, Poland
M.Schramm, H.Grawe, J.Heese, K.H.Maier, R.Schubart
Hahn–Meitner–Institut Berlin, Germany

The thick target γ-γ coincidence experiment was performed for the ^{208}Pb + 350 MeV ^{64}Ni system with the OSIRIS array at the HMI Berlin. At this energy, 11 % above the Coulomb barrier, but much below the "extra push" energy needed to form the compound nucleus deep–inelastic processes contribute predominantly to the reaction cross section. From the analysis of the in–beam and off–beam (pulsed beam) coincidence data as well as from the detailed radioactivity measurements, nearly complete distribution of production yields was obtained for all nuclei produced in the range from ^{52}Ti to ^{213}Fr. The results show some interesting features concerning mass and charge transfer between the colliding ions; examples are displayed in Figs 1 and 2. The result of Fig. 1 indicates that even for such integrated data obtained from the thick target γ experiments one can still control the kinetic energy loss parameter by selecting the number of transferred protons. The average N/Z ratio (Fig. 2) extracted for the primary fragments as a function of mass shows rather unexpected features similar to those reported recently [1] for a very different ^{106}Cd + ^{54}Fe colliding system.

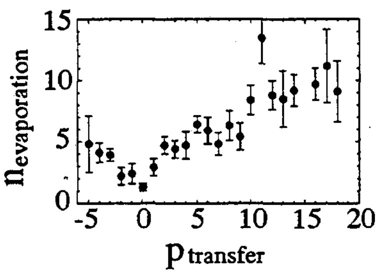

Fig. 1. Number of evaporated neutrons versus number of protons transferred to the projectile.

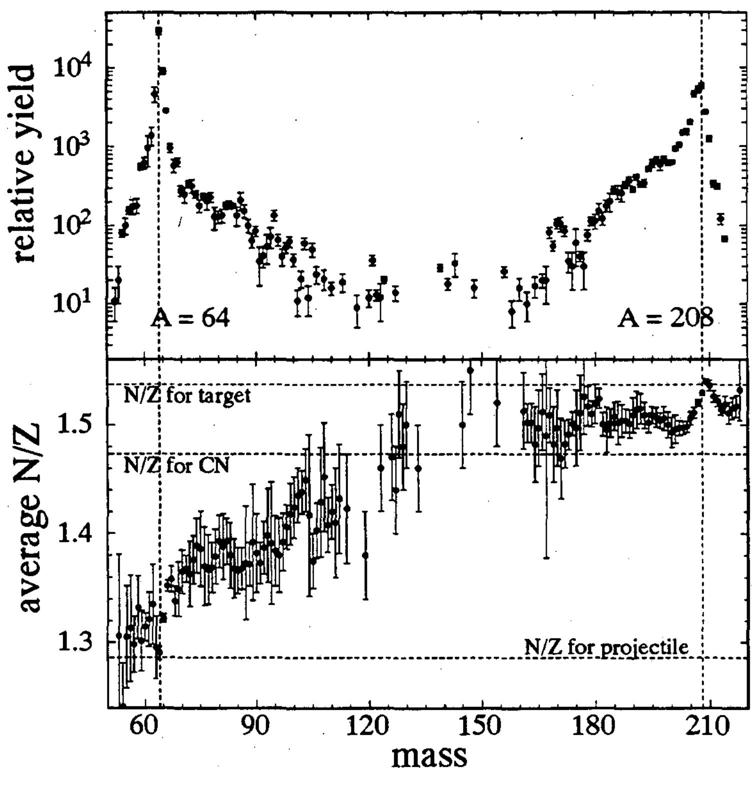

Fig. 2. Mass distribution of reaction products (up) and average N/Z for primary products as a function of mass (down).

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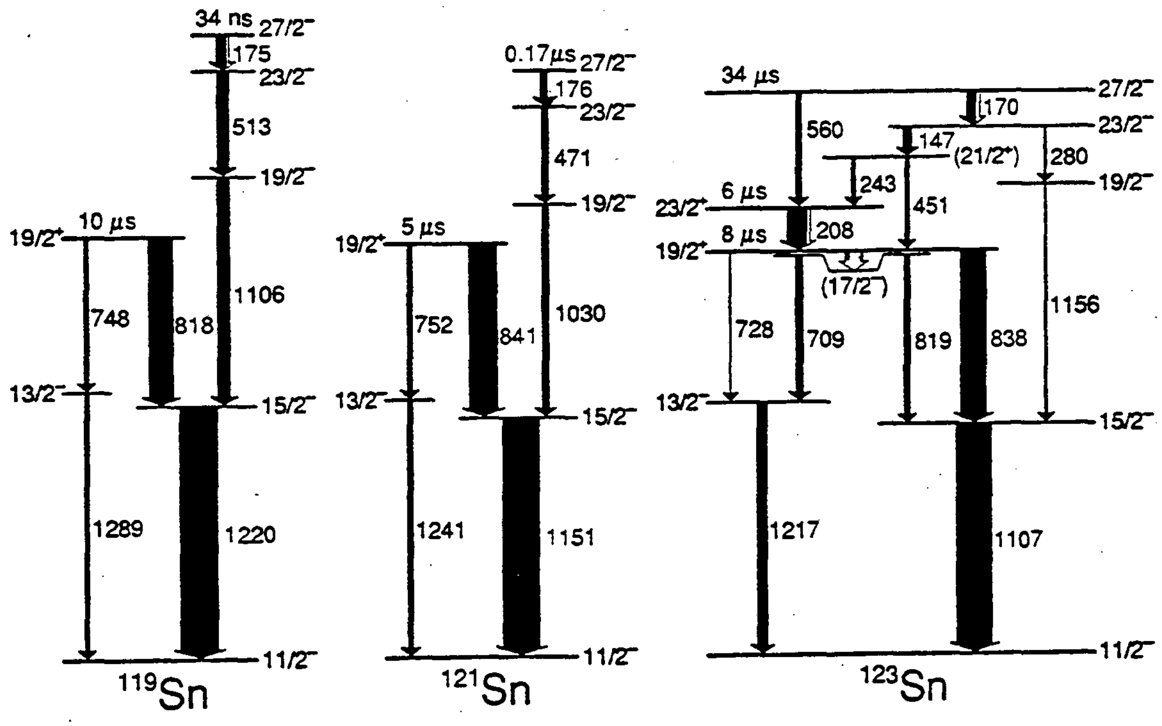
YRAST SPECTROSCOPY OF ODD-A TINS PRODUCED IN DEEP INELASTIC COLLISIONS

R. H. Mayer[1], D. Nisius[1], I. Bearden[1], L. Richter[1], M. Sferrazza[1], Z. W. Grabowski[1], P. J. Daly[1], R. Broda[2], B. Fornal[2], M. P. Carpenter[3], R. V. F. Janssens[3], T. L. Khoo[3], T. Lauritsen[3], J. Blomqvist[4]

[1]*Purdue University, W. Lafayette, IN 47906, USA*
[2]*Institute of Nuclear Physics, Cracow, Poland*
[3]*Argonne National Laboratory, Argonne, IL 60439, USA*
[4]*Manne Siegbahn Institute, Stockholm, Sweden*

Since tin isotopes with A>120 are inaccessible by fusion-evaporation, we looked for $(\nu h_{11/2})^n$ isomers expected in these nuclei in $\gamma\gamma$ coincidence experiments at ATLAS using pulsed beams of ^{76}Ge and ^{80}Se ions on lead-backed ^{124}Sn targets. Long-lived 10^+ isomers in ^{122,124}Sn were identified, but little ^{126}Sn was produced; the B(E2; $10^+ \rightarrow 8^+$) values across the even-A tins located half-filling of the neutron $h_{11/2}$ subshell close to N=73 (whereas the $\pi h_{11/2}$ half-filling occurs just below Z=71). Analysis of the data from the ^{124}Sn + ^{80}Se experiment brought to light delayed γ-rays families that were assigned to decays of previously unknown $(\nu h_{11/2}{}^2\ s_{1/2})$ 19/2$^+$ isomers in ^{119,121,123}Sn and of $(\nu h_{11/2})^n$ seniority 3, 27/2$^-$ isomers in ^{119}Sn and ^{121}Sn. In a follow-up experiment using a ^{136}Xe beam (with higher N/Z) on ^{124}Sn, the overall yield pattern showed a shift towards higher N; for example, the ^{126}Sn 10^+ isomer, with a 7 μs half-life, was finally observed. Another notable discovery was a 34 μs 27/2$^-$ ^{123}Sn isomer; the tiny B(E2; 27/2$^-$$\rightarrow$23/2$^-$) in ^{123}Sn - less than 0.002 W.u. – manifests anew the $\nu h_{11/2}$ subshell half-filling at N=73. Isomeric decay schemes for ^{119,121,123}Sn are shown below. Definite configurations can be confidently assigned because the observed level energies have been correctly predicted with high precision (within a few keV) by fractional parentage techniques making use of the known tin ground state masses.

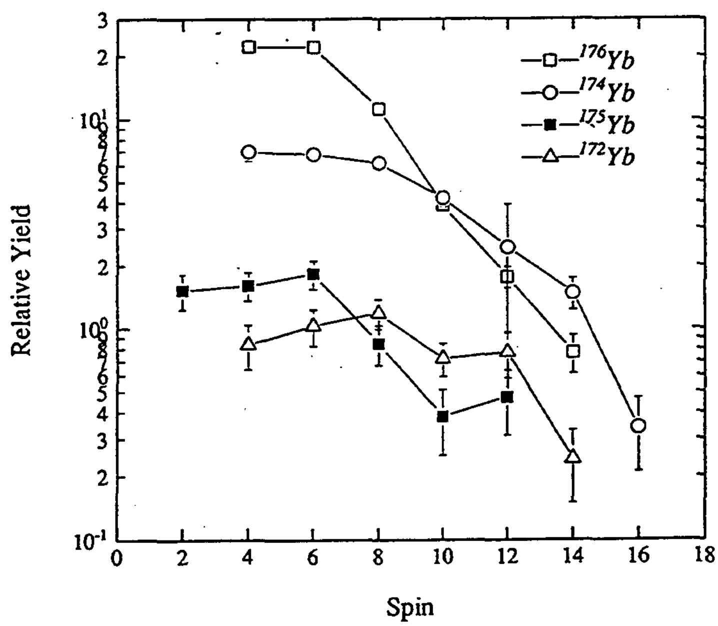


Gamma Ray Spectroscopy Using Deep-Inelastic Reactions

I.Y. Lee[1], J.A. Becker[3], B. Cederwall[1], M.-A. Deleplanque[1], R.M. Diamond[1], P. Fallon[1], P.F. Hua[2], A.O. Macchiavelli[1], J.X. Saladin[4], D.G. Sarantites[2], F.S. Stephens[1], G.J. Wozniak[1], C.H. Yu[5]; [1]LBL, Berkeley CA 94720; [2]Washington University St. Louis, MO 63130; [3]LLNL, Livermore, CA 94550; [4]University of Pittsburgh, Pittsburgh PA 15260; [5]University of Rochester, Rochester NY 14627

Currently, nuclear high spin states are produced almost exclusively by heavy-ion induced fusion reactions and in a few cases by Coulomb excitation. However, with a stable beam and target, only neutron-deficient nuclei can be produced in fusion reactions. So far, high spin states in neutron-rich nuclei and in most of the odd-even and odd-odd nuclei near the stability line have not been studied due to the lack of suitable nuclear reactions. However, deep inelastic reactions have been shown to produce a high multiplicity of gamma-rays [1] and attempts have been made to use them and quasi-elastic reactions to populate and study high spin states[2,3]. Since these reactions produce many final nuclei, a high efficiency gamma-ray detector array, such as Gammasphere, is needed to resolve and study the gamma rays from such reactions.

To test the feasibility of using deep-inelastic reactions to populate high spin states in neutron-rich products, we have carried out the reaction ^{48}Ca + ^{176}Yb at beam energies of 250 and 275 MeV. The Ca-like products were detected at 66° in a counter telescope consisting of a gas ΔE and a position-sensitive silicon-strip E-detector with a solid angle of 130 msr. The early implementation of Gammasphere with 32 detectors was used to detect the gamma-rays. Particle-gamma coincidence data were taken at a rate of 1 k/sec. The velocity vector of the target-like product was calculated from the measured energy and angle of the projectile-like product and the Doppler-shift correction of the gamma rays was based on this vector and the direction of the gamma ray. Gamma-rays of Er, Tm, Yb, and Hf nuclei were identified from particle-gamma-gamma coincidence data. We observed several new high spin states in ^{173}Tm, ^{175}Yb and ^{178}Yb. The nucleus ^{173}Tm which has one less proton and two less neutrons than the target is four neutrons richer than the stable ^{169}Tm, whereas ^{178}Yb has two more neutrons than the most neutron rich Yb. From this 10-hour run, we were able to observe gamma rays from nuclei produced with a cross section $d\sigma(66°)/d\Omega$ down to approximately 0.1 mb/sr. The population of the yrast states of the Yb nuclei are shown in the figure. States with spin up to 16 were populated, and the nuclei further away from the target are produced at higher spin. A follow up experiment is scheduled which will provide a 100-fold increase in data. These data will be discussed. We expect to observe new high spin states in many neutron-rich nuclei such as ^{178}Yb.



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Lifetimes of low-lying states in ^{165}Ho

M.W. Simon, D. Cline, M. Devlin, R. Ibbotson, and C.Y. Wu
Nuclear Structure Research Laboratory[1], University of Rochester, Rochester, New York 14627, USA

The recoil distance method has been used to measure directly the lifetimes of 15 low-lying states in ^{165}Ho. The goal of the present work, and a series of Coulomb excitation experiments,[2] performed using ^{16}O, ^{58}Ni and ^{208}Pb beams, is to determine a complete set of matrix elements connecting the low-lying states in ^{165}Ho to provide a stringent test of the collective model in odd-A nuclei. The present lifetime measurements provide an independent determination of E2 and M1 matrix elements as well as a test of the accuracy of the results derived from the more complicated analysis of the Coulomb-excitation data.

The experiment was performed using a beam of 230 MeV ^{58}Ni ions, accelerated by the Rochester MP Tandem Van de Graaff, to Coulomb excite a 280μg/cm^2 ^{165}Ho target. Backscattered ^{58}Ni ions were detected in an annular parallel-plate avalanche detector in coincidence with deexcitation γ-rays detected using a forward Ge detector. The target was prepared by sputtering ^{165}Ho onto a 480μg/cm^2 Ni foil. The recoiling nuclei were slowed by a movable 2.8mg/cm^2 stretched ^{58}Ni foil (shifter foil) mounted between the target and the Ge detector. The shifter foil reduces the velocity of the recoiling nuclei from $\beta = .0421 \pm .0007$ to β=.0228 $\pm$ .0005. The recoil velocities of the nuclei were measured by replacing the shifter foil with a foil (11.3mg/cm^2 Ni) sufficiently thick to stop the recoils. The tables below show the 15 lifetimes derived from measurements of 23 observed transitions.

A partial set of E2 and M1 matrix elements connecting the low-lying states were extracted from the lifetimes and measured γ-yields. The in-band and interband E2 and M1 matrix elements involving both the K=$\frac{7}{2}$ ground band and the K=$\frac{11}{2}$ band are in good agreement with the results of the earlier Coulomb excitation work. These matrix elements exhibit behavior characteristic of the rotational model. The intrinsic quadrupole moments of the K=$\frac{11}{2}$ band, derived from the measured ΔJ=2 in-band transitions, are significantly larger (>20%) than the intrinsic quadrupole moments for the in-band transitions in the ground band, confirming similar results from the Coulomb excitation work.

Ground Band Transitions	
level	measured τ (ps)
$\frac{27}{2}^-$	1.14 ± .12
$\frac{25}{2}^-$	1.29 ± .05
$\frac{23}{2}^-$	1.87 ± .07
$\frac{21}{2}^-$	2.52 ± .08
$\frac{19}{2}^-$	3.88 ± .08
$\frac{17}{2}^-$	5.60 ± .10
$\frac{15}{2}^-$	7.20 ± .11
$\frac{13}{2}^-$	12.27 ± .28
$\frac{11}{2}^-$	17.89 ± .46
$\frac{9}{2}^-$	34.44 ± 1.01

K=$\frac{11}{2}^-$ Band Transitions	
level	measured τ (ps)
$\frac{19}{2}^-$	2.51 ± .26
$\frac{17}{2}^-$	2.79 ± .69
$\frac{15}{2}^-$	5.74 ± 1.14
$\frac{13}{2}^-$	6.32 ± .60
$\frac{11}{2}^-$	9.22 ±.49

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[2]E.G. Vogt, et al., unpublished

Multi-phonon states in ^{232}Th*

W. Korten[1], P. Bröcking[1], Th. Kröll[2], D. Bazzacco[3], Ch. Ender[4], Th.W. Elze[2], J. Gerl[5], T. Haertlein[4], Th. Happ[5], H. Hübel[1], M. Kaspar[2], D. Napoli[3], I. Peter[2], W. Pohler[1], P. Reiter[4], C. Rossi Alvarez[3], H. Schaffner[5], R. Schubert[5], D. Schwalm[4], U.J. van Severen[1], K. Vetter[2], P. Willsau[1], H.J. Wollersheim[5]
[1]Univ. Bonn, [2]Univ. Frankfurt, [3]INFN Padova, [4]MPI Heidelberg, [5]GSI Darmstadt

The nucleus ^{232}Th is particularly well suited for an investigation of multi-phonon excitations since it shows well developed rotational bands built on low-lying one-phonon vibrational excitations and two-phonon states are predicted below the pairing gap energy (E_{pg} ≈1.6MeV). Coulomb excitation with heavy ions is used to populate these collective nuclear states.
In a first experiment we employed the Doppler-shift recoil-distance method (RDM) to measure the lifetime of the 4^+ state at 1414 keV. This state shows all the characteristics of a nearly-harmonic two-phonon γ-vibrational excitation [1]: (i) the excitation energy of the band-head is about twice the excitation energy of the 2^+ γ-vibrational state; (ii) the band decays exclusively into the γ-band and (iii) the excitation strength and decay branching ratios have the appropriate values for a two-phonon state.
The RDM experiment was performed at the Heidelberg-Darmstadt Crystal Ball spectrometer with 153 NaI(Tl) detectors and a Ge detector mounted at 0°. The ^{232}Th nuclei were Coulomb excited by a 410 MeV ^{90}Zr beam and the backscattered projectiles were detected in an annular Si detector mounted within the Bonn plunger device. ¿From the result for the lifetime of the $4^+_{\gamma\gamma}$ state, τ=3.2±0.9 ps, a reduced transition probability $B(E2; 4^+_{\gamma\gamma} \rightarrow 2^+_\gamma) = 0.12(3)\ e^2b^2$ was deduced, which is in agreement with an earlier estimate of the collectivity from Coulomb-excitation yields and supports the interpretation of the 1414 keV state as a two-phonon γ-vibrational excitation.
In a second experiment at the 4π Ge-array Ga.Sp. at LNL Legnaro with 40 HPGe detectors and an 80-element BGO inner ball, we searched for higher-lying multi-phonon excitations. Here, Coulomb excitation was performed with a 265 MeV ^{58}Ni beam and the PYRAMID array [2] of parallel plate counters covering the backward hemisphere ($80^0 \leq \vartheta_{lab} \leq 160^0$) was used for the detection of backscattered projectiles.
While the analysis is still in progress first results indicate that the two-phonon γ-vibrational band could be extended to higher spins. The search for other two-phonon excitations seems to be most promising for octupol vibrational states. Coincidences with decays of the K^π=0^- octupole band reveal transitions from three new states which are excellent candidates for the 0^+, 2^+ and 4^+-members of a K^π=0^+ two-phonon band. The band head lies at an excitation energy of 1352 keV – almost twice the energy of the K=0^- band head – and the band has nearly the same moment of inertia as the K^π=0^- one-phonon band.

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SEARCH FOR THE TWO-PHONON OCTUPOLE VIBRATIONAL STATE IN ^{208}Pb

E. F. Moore[1], W. Henning[2], R. V. F. Janssens[2], T. L. Khoo[2], I. Ahmad[2], D. Blumenthal[2], M. P. Carpenter[2], B. Crowell[2], D. Gassman[2], R. G. Henry[2], T. Lauritsen[2], C. J Lister[2], S. J. Sanders[3], M. W. Drigert[4], D. Nisius[2,5]

[1]*North Carolina State University and Triangle Universities Nuclear Laboratory*
[2]*Argonne National Laboratory*
[3]*University of Kansas*
[4]*Idaho National Engineering Laboratory*
[5]*Purdue University*

The first excited state of the doubly magic nucleus ^{208}Pb has $J^\pi = 3^-$ and is interpreted as a one-phonon vibration of octupole character. The vibrational nature of this state leads to the expectation of a multiplet of 2-phonon octupole states with $J^\pi = 0^+, 2^+, 4^+$, and 6^+ at roughly twice the energy of the 3^- state (i.e., around 5.2 MeV). Recently, an experiment to search for members of this multiplet was performed at GSI by bombarding a thin ^{208}Pb target with ^{208}Pb beams at an energy of about 10% above the Coulomb barrier. A 2485 keV γ ray was observed to be in coincidence with the $5^- \rightarrow 3^-$ and $3^- \rightarrow 0^+$ transitions in ^{208}Pb and was attributed to the depopulation of one of the members of the 2-phonon multiplet [1]. Subsequently, experiments were performed at HMI bombarding ^{208}Pb targets with ^{64}Ni and ^{82}Se beams. A γ ray at 2485 keV was observed in these experiments as well. However, these data indicated that the γ ray belongs most likely in ^{207}Pb [2].
In order to confirm the placement of this γ ray and search for other members of the 2-phonon multiplet, we have performed an experiment at ATLAS using 1305 MeV beams of ^{208}Pb to bombard thick targets of ^{208}Pb, ^{209}Bi, ^{58,64}Ni, and ^{160}Gd. Gamma rays were measured using the Argonne–Notre Dame BGO gamma ray facility, consisting of 12 Compton Suppressed Ge detectors surrounding an array of 50 BGO scintillators. From our preliminary analysis, we have identified some 30 known γ rays from ^{208}Pb in the spectra gated by the $5^- \rightarrow 3^-$ and $3^- \rightarrow 0^+$ transitions in ^{208}Pb. In addition, after unfolding these spectra for Compton response, we observe broad coincident structures in the energy region expected for the decay of 2-phonon states. Furthermore, we have confirmed the placement of the 2485 keV line in ^{207}Pb. We see no evidence for coincidences between the 2485 keV line and the $5^- \rightarrow 3^-$ and $3^- \rightarrow 0^+$ transitions of ^{208}Pb in excess of the strength of the transfer lines from other states in ^{207}Pb. We are currently in the process of: (i) investigating the origin of the broadened lines observed in our spectra; (ii) extracting the excitation probability of states in ^{208}Pb; (iii) determining the relative probability of mutual excitation and neutron transfer in this reaction.

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COULOMB EXCITATION WITH HEAVY IONS

S.R.Ofengenden

Institute for Nuclear Research, Kiev, Ukraine

In a number of recent papers (see [1] and references therein) the formalism based upon the path integral technique has been developed for the inelastic scattering problem. Later it has been applied to the investigation of the Coulomb excitation of deformed nuclei by heavy ions. A Hamiltonian may include both quasiclassical variables and quantum ones. Expanding the quantum propagator in orders of 1/n and K, where n is the Sommerfeld parameter and K is the parameter measuring the influence of excitation potential upon the relative motion of nucleus and heavy ion, we get the quasiclassical approximation as the limit of large n. Other possible quasiclassical schemes appear whenever we neglect or keep different terms in the expansion in 1/n or in K.

In the present paper the quasiclassical scheme is used which results in the known approximation by Alder and Winther and corrections to it. Within the framework of this approach the excitation probabilities and populations of magnetic substates of rotational states in the ground-state band of 238U under the Coulomb excitation by 208Pb ions (with the laboratory energy of 1102 MeV) have been calculated. The detailed comparison has been performed of magnetic substate populations calculated in Alder-Winther approach with and without the abovementioned corrections, and in the sudden approximation [2]. It should be noted that the sensitivity of magnetic substate populations for high spin levels of 238U to the corrections far exceeds the sensitivity of excitation probabilities for the same levels.

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STUDY OF NUCLEAR ISOMERISM BY HEAVY IONS TRANSFER REACTION

J. Blons, D. Goutte, A. Leprêtre, R. Lucas, V. Méot, D. Paya and X.H. Phan
DAPNIA / SPhN, CE Saclay, 91191 Gif-sur-Yvette, FRANCE

G. Barreau, T.P. Doan and G. Pedemay
CENBG, Domaine du Haut Vigneau, 33175 Gradignan, FRANCE

Ph. Dessagne and Ch. Miehé
CRN Strasbourg
23 rue du Loess, BP 20 CR, 67037 Strasbourg, FRANCE

We have undertaken in 1990, at SACLAY, an experimental program aiming to observe and study nuclear isomerism taking advantage of the high selectivity of the transfer reactions associated with high resolution gamma detection.
The experimental procedure consist in bombarding a target with a heavy ion beam delivered by the Saclay Superconducting Postaccelerated Tandem, detect and identify the ejectile in a QDDD spectrometer and observe the gamma decays in a Germanium array composed of six triple-telescopes BGO Compton suppressed surrounding the target.

The measure of the particle-gamma delay allows a very precise determination of the isomers half lives in a range of 10 to 500 ns.

This technique was used to characterize new isomeric states.
For instance, in ^{65}Ni formed by ^{64}Ni(^{18}O,^{17}O) at 72 MeV, a 1013 keV gamma ray was observed. The high energy resolution of the spectrometer allowed to attribute unambiguously this gamma ray to the $9/2^{+}$-->$5/2^{-}$ transition. The $9/2^{+}$ state was already known but its decay was seen here for the first time.
This state is an 26.5 +/- 0.5 ns half live isomer. An interesting feature about this state is that recent HFB calculations by M. Girod et al. or BCS calculations by P. Bonche show that this state is quite oblate as the $5/2^{-}$ ground state is more or less spherical. How does this property affect the life time of this state?

Search for so-called shape isomer was also addressed. Both, light nuclei (^{66}Ni) and heavier systems like ^{194}Hg or ^{210}Po were studied.

In Ni isotopes, no firm experimental evidence for shape isomerism was observed even if a good candidate was found in ^{68}Ni.
In our study of the ^{64}Ni(^{18}O,^{16}O)^{66}Ni reaction a delayed 1020 keV gamma ray was observed which could correspond to the transition from the O^{+} predicted shape isomer to the first excited 2^{+} state. The lack of statistics does not allow any firm conclusion about the existence of this isomer in this Ni isotope. Additional data taking is planned before summer.

Latest results will be presented.

Reaction mechanism of multinucleon transfer in the system $^{110}Pd + ^{52}Cr$

K.Vetter[1], D. Bazzacco[2], Th.W. Elze[1], J. Gerl[3], T. Happ[3], T. Härtlein[4], W. Korten[5], T. Kröll[1], D. Napoli[2], C. Rossi Alvarez[2], R. Schubert[3], H.J. Wollersheim[3], H. Xie[3]

[1]Univ. Frankfurt, [2]INFN, Padova,[3]GSI, Darmstadt, [4]Univ. Heidelberg, [5]Univ. Bonn

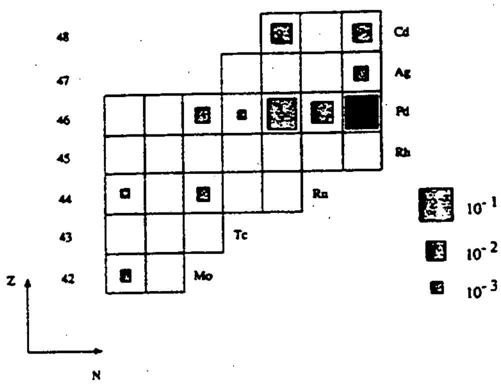

Fig.1 Relative intensities of transfer products (E_{lab}=200MeV).

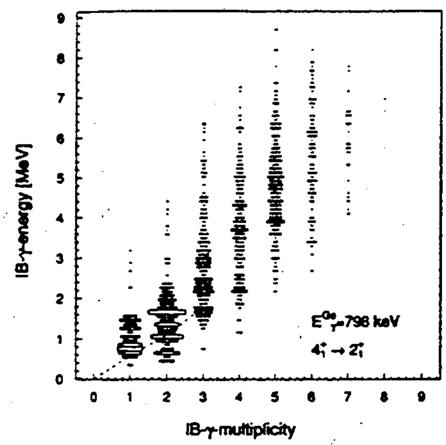

Fig. 2 Sum-energy versus multiplicity for the 2p-stripping channel.

The system $^{110}Pd + ^{52}Cr$ characterized by well adjusted Q-values for neutron and proton transfer and large nucleon pairing energies was chosen to study the mechanism of multinucleon transfer at beam energies in the vicinity of the Coulomb barrier. The set-up consisted of the 4π-γ spectrometer GASP in Legnaro and the PYRAMID array of position sensitive parallel plate avalanche counters covering the scattering angle region 80° ≤160°.

The high efficiency of Gasp enabled the identification of 10 different transfer channels (up to the 4p6n channel) by their characteristic γ-decay. The observed even-even nuclei have similar effective Q-values. Fig. 1 shows the relative intensities of the identified nuclei. Considering the underlying Q-values the observed population pattern for exotic channels seems to be in favour of correlated multinucleon transfer.

With the inner BGO ball of GASP it was possible to measure total excitation energies as a function of the γ-multiplicity. The correlation for the 2p-stripping ($\rightsquigarrow$ ^{112}Cd) channel is shown in fig. 2. The 2n-pick-up transfer is leading mainly to collective excitations near the yrast-line, which can be interpreted as an indication for correlated pair transfer. The 2p-stripping-channel has also a 'cold' component but is dominated by higher sum energies, interpreted as quasi-particle excitations.

The projection of the excitation energies above the yrast line enables a quantitative determination of the 'cold' part, being defined as lying at the yrast line within the resolution (FWHM) of the γ-spectrometer. For the 2n-pickup channel this component corresponds to 30±5% of all events. For the 2p-stripping channel the fraction is 17±10%.

Excitation-energy partition in quasielastic transfer reactions at near barrier energies

C.Y. Wu[1], D. Cline[1], M. Devlin[1], K.G. Helmer[1], R.W. Ibbotson[1], M.W. Simon[1], P.A. Butler[2], A.J. Cresswell[2], G.D. Jones[2], P.M. Jones[2], J.F. Smith[2], R.A. Cunningham[3], and J. Simpson[3]

1. Nuclear Structure Research Laboratory, University of Rochester, Rochester, NY 14627
2. Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 3BX, UK
3. SERC, Daresbury Laboratory, Warrington WA4 4AD, UK

The study of the partition of excitation-energy between reaction partners in heavy-ion collisions is important for characterizing the underlying reaction dynamics and provides a stringent test of models of the interaction between heavy nuclei.[1] For the quasielastic one-neutron transfer channel ^{161}Dy(^{58}Ni,^{59}Ni) at E_{lab} = 270 MeV, the reconstructed total γ-ray energy-multiplicity distribution showed that the average total excitation energy is about 1 - 2 MeV above the Dy yrast line.[2] A later study of the same system, with a more sensitive experimental arrangement, showed that the Dy nucleus gains about 1 MeV of intrinsic excitation energy while still no conclusive result was obtained for excitation energy shared by the Ni(receptor).[3] In this report, we show that the excitation-energy partition between receptor and donor in quasielastic transfer reactions can be measured using γ-ray spectroscopy and the results demonstrate that the receptor receives a substantial fraction of the excitation energy and that nuclear structure is important in the sharing process for one-neutron transfer reactions.

Experiments were carried out with self-supported ^{161}Dy targets, ranging from 400 to 580 μg/cm^2 thick, bombarded by ^{58,61}Ni at E_{lab} = 265 (Rochester) and 270 MeV (Daresbury) respectively. The target material was enriched to about 96% of ^{161}Dy, ~ 0.22% of ^{160}Dy and ~ 2.46% of ^{162}Dy. The deexcitation γ rays were detected in an array of Compton-suppressed Ge detectors in coincidence with the detection of backscattered Ni-like particles by an annular position-sensitive parallel-plate avalanche counter (PPAC). This position information, plus the assumption of 2-body kinematics, was used to correct the Doppler shift of γ rays from either projectile-like or target-like particles. The corrected γ-ray energy thus serves to identify the exit channels for these reactions. In the case of the EUROGAM array at Daresbury, approximately 4.6 M events, with at least 2-fold γ rays, were collected out of a total ~40 M particle-γ's coincident events.

For the one-neutron transfer channels ^{161}Dy(^{58,61}Ni,^{59,62}Ni), the average excitation energy for ^{59}Ni is about 0.8 MeV, in contrast to 2.5 MeV for ^{62}Ni. The average intrinsic excitation energy carried by the corresponding Dy is about 1 MeV for the ^{58}Ni case[3] and about 1 - 2 MeV for the ^{61}Ni case derived from our EUROGAM data. DWBA calculations of one-neutron transfer cross section involving $i_{13/2}$ and $h_{9/2,11/2}$ in Dy and $p_{1/2,3/2}$, $f_{5/2}$, and $g_{9/2}$ in Ni have been carried out. These calculations are compared with the experimental results and the implications will be discussed.

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GIANT DIPOLE RESONANCE STUDIED WITH GASP

D. Bazzacco[1]), P.F. Bortignon[5]), B. Burch[1]), M. Cinausero[4]), G. DeAngelis[2]), D. Fabris[1]), E.M. Fiore [3]), L. Fiore [3]), E. Fioretto[2]), B. Fornal [6]), N. Gelli[4]), M. Lops[1]), F. Lucarelli[4]), G. Maron[2]), G. Nebbia[1]), V. Paticchio[3]), G. Prete[2]), C. Rossi-Alvarez[1]), G. Viesti[1])

[1]) Dipartimento di Fisica and INFN, Sezione di Padova, Padova, Italy
[2]) INFN Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy
[3]) Dipartimento di Fisica and INFN, Sezione di Bari, Bari, Italy
[4]) Dipartimento di Fisica and INFN, Sezione di Firenze, Firenze, Italy
[5]) Dipartimento di Fisica and INFN, Sezione di Milano, Milano, Italy
[6]) Institute of Nuclear Physics, Krakow

The giant dipole resonance (GDR) from the decay of excited ^{156}Er nuclei populated in the reaction 241 MeV ^{64}Ni + ^{92}Zr has been studied with the GASP spectrometer. The aim of the experiment is to shed light on the anomalous shape of energetic gamma rays spectra detected in nickel induced reactions [1,2]. This effect has been interpreted as evidence of dynamical effects in the entrance channel of the fusion reactions [2]. Two Ge of the GASP spectrometer have been replaced by large BGO crystals (4" $\times$ 4") for detecting hard gamma rays (Hγ). We have studied the correlations between the emission of Hγ and the fold K and sum energy Σ distributions in the GASP inner ball. In this analysis the Ge detectors allows the monitoring of the residues as a function of K and Σ showing the presence of reactions different from the compound nucleus formation at low fold K. Direct correlations between Hγ and discrete lines Ge are also possible. As an example we show in fig.1 the spectra of energetic gamma rays detected in coincidence (a) with discrete lines of ^{154}Er and (b) requiring only the gate in K corresponding to the events in (a). The data analysis is in progress. The advantage of exclusive measurements of GDR by using GASP will be discussed.

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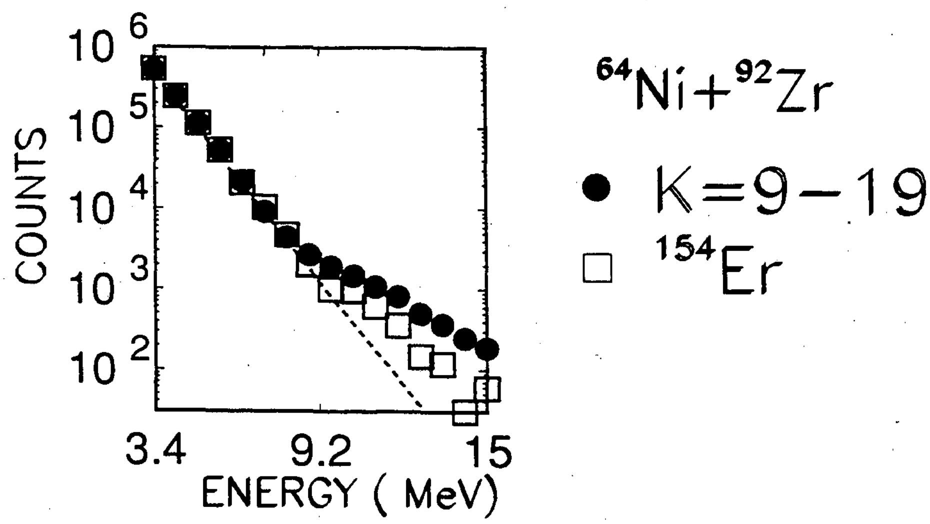

Exclusive measurements of the GDR photons from hot rotating compound nuclei

A. Bracco, F. Camera, M. Mattiuzzi, B. Million
Dipartimento di Fisica, Università di Milano, Milano, and INFN sez. Milano,Italy
and
J.J. Gaardhøje, A. Maj, Z. Zelazny, T. Tveter
Niels Bohr Institute, Roskilde, Denmark

Progress in the study of the Giant Dipole Resonanse (GDR) in hot rotating nuclei at T= 1-2 MeV have been made with the measurements of the spectral and angular distributions of high energy γ rays associated to selected angular momentum and excitation energy regions. This interval of temperature is of relevance to investigate the expected prolate-oblate transition in the A$\sim$ 160-170 mass region and spherical-oblate transition in the A$\sim$ 110 region.

Because of the coupling of the giant dipole resonance to the nuclear quadrupole deformation the mapping of nuclear shapes far away from the yrast line is possible. In that region nuclei are described by an ensemble of shapes and orientations and the GDR response reflects the shape and orientation distributions.

One of the central problem in the understanding of the GDR width at final temperature and rotational frequency is the role played by thermal fluctuations. While the GDR line shape is affected only by shape fluctuations, the angular distribution is affected also by orientation fluctuations.

Several exclusive experiments made for A=110 and A = 160- 170 at T=1-2 MeV with the HECTOR detector array allow a better understanding of the properties of hot rotating nuclei and of the damping mechanisms of the giant dipole resonance. In this connection some of the interesting results are:
1) At low rotational frequency the effect of orientation fluctuations is large.
2) Orientation fluctuations decrease strongly with increasing angular momentum suggesting that at high angular momentum it may be possible to study the temperature dependence of the GDR strength function.
3) At low rotational frequency the effective deformations extracted from the GDR strength function and angular distribution are very different due to the role of fluctuations.
4) The collisional damping width that , besides thermal fluctuations, is the other mechanism that together with the centrifugal stretching contributes to the total GDR width is found to be independent of temperature and spin.

In addition, to study the GDR associated to narrow intervals of excitation energy E^*, γ rays from compound nuclei differing in E^* by the energy removed by the emission of one neutron were measured. The data obtained offer the possibility to make a very detailed test of the statistical model and to investigate the compound nucleus formation mechanisms.

Fission and Internal Pair Studies of Hot Giant Resonances

P. Paul, State University of NY at Stony Brook.

The study of giant resonances in hot nuclei is providing new information about the properties of nuclear matter at moderate, but non-zero temperatures. This is based on the fact that the systematics of giant resonances are sufficiently well understood so that they can be used to test the environment of the hot compound nucleus. The most extensive such application has been the study of dissipation in nuclear matter flow by use of the GDR clock. I will present recent results on the explicit and apparently large temperature dependence of nuclear dissipation in the fission process. An important extension of such studies is the measurement of the properties of monopole and quadrupole giant resonances, both isoscalar and isovector, as a function of nuclear temperature. An highly relevant example is the energy of the IS E0 mode which is strongly affected by nuclear dissipation as the nuclear medium changes from a zero sound to a first-sound environment. Attempts of such studies use the additional parameters offered by internal pair decay from giant resonances to separate the other modes from the dominant GDR. I will present the recent progress that has been made along these lines throughout the periodic table with large-solid angle detector arrays developed at Stony Brook and at the KVI in Groningen. While pair decay from giant resonances is now routinely observed adequate discrimination against the GDR is still a problem.

Pre-Fission GDRγ-Decay in Superheavy Nuclei

T. S. Tveter, J. J. Gaardhøje, B. Herskind, W. Korten, T. Ramsøy, G. Sletten, and Z. Żelazny, J. Bacelar, A. Buda, A. Bracco, F. Camera, W. Krolas, A. Maj, A. Menthe, B. Million, H. Nifenecker, M. Pignanelli, J. A. Pinston, H. v. d. Ploeg, F. Schussler.
NBI-Grenoble-Krakow-KVI Collaboration.

Measurements of neutron multiplicities from hot fissile nuclei at various initial excitation energies reveal that the number of pre-fission neutrons emitted increases with E_x^i, while the number of post-fission neutrons stays approximately constant. This result suggests that fission is a slow process, taking place only when the nucleus has been cooled to some lower excitation energy, contrary to statistical expectations. Since neutron evaporation is obviously able to compete favourably with fission at high temperatures, this should also be the case for GDR γ-ray emission. Recent experiments measuring γ-rays from fissioning systems confirm this idea: Both a pre-fission and a post-fission component can be seen in the γ-spectra, at different γ-energies due to the different radii of the compound nucleus and the fragments. The pre-fission GDR radiation offers insight into nuclear behaviour at extreme conditions with respect to spin and nucleon number, a region which has previously been closed to direct scrutiny.

At the SARA Cyclotron Laboratory in Grenoble, we have synthetized the superheavy nucleus $^{272}_{108}$Hs employing the reaction ^{40}Ar + ^{232}Th $\rightarrow$ ^{272}Hs at bombarding energies 6.8,10.5 and 15.5 MeV/nucleon. The experimental setup included the 8 BaF_2 HECTOR detectors, mounted in the plane perpendicular to the beam axis. An array of small BaF_2 crystals defined the events in time and served as a common start for time-of-flight measurements. Four PPACs (Parallel Plate Avalanche Counters) were used for detection of fission fragments.

Due to the disappearance of shell effects at high temperature, hot thermalized fissile nuclei tend to decompose into two fragments of approximately the same mass. By gating on symmetric fission fragments from very heavy systems formed using heavy projectiles, we can select events connected with complete fusion reactions and full thermalization.

Assuming that the excitation energy at which fission takes place is essentially independent of E_x^i, information about the earliest decay steps can be obtained from the difference of gamma ray spectra from reactions at different bombarding energies. This procedure has been applied to the fission gated gamma ray spectra from the 15.0 and 10.5 MeV/A runs. The difference spectrum shows a narrow distribution, centered at the γ-energy at which we expect the GDR radiation from the heavy composite system. No significant intensity is present in the energy region associated with fission fragment GDR radiation. This indicates that fission only takes place after cooling of the system down to an excitation energy below the one initially introduced by the 10.5 MeV/A beam. On the other hand, the difference between the total coincident γ-spectra from the 10.5 and the 6.8 MeV/A runs reveals strong GDR contributions from both the superheavy compound nucleus and the fission fragments.

The yields of pre- and post-fission GDR γ-rays at the three beam energies contain valuable information about the time constant for the fission process, which is related to the viscosity of nuclear matter. We compare the γ-spectra extracted in coincidence with symmetric fission with theoretical calculations performed with a modified version of the program CASCADE. In this way we extract a lifetime for the hot fissile $^{272}_{108}$Hs nuclei.

Continuum Energy-Ordered Spectra and the Determination of the Level Density Parameter at High Excitation Energy and Spin

F. Cristancho[1], C. Baktash[2], J. X. Saladin[1], and I.-Y. Lee[3]

[1] *Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260.*
[2] *Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831.*
[3] *Lawrence Berkeley Laboratory, Berkeley, CA 94720.*

Modern spectroscopy techniques allow detection of nearly all the gamma rays emitted from the excited states of a compound nucleus. This can be achieved with such 4π detector arrays as the Spin Spectrometer at Oak Ridge National Laboratory which can record, in an event-by-event mode, nearly all gamma ray transitions emitted from a narrow region of the excitation energy-spin map [1]. In continuum gamma ray spectroscopy, it is ideally desirable to distinguish the temporal order of these primary gamma rays. However, this goal cannot be experimentally realized. To circumvent this difficulty, an alternative ordering scheme has been proposed [2]: we choose to forget about the temporal sequence of emission and order the gamma rays in a decay sequence (event) according to their energy. Let us say that a certain gamma cascade is composed of n gamma rays. The time-ordering of the cascade consists in placing the gamma energies in the same sequence as they are emitted. The energy-ordering of the cascade is done when an ordinal N is associated to each transition so that $E_{\gamma_{N=1}} \geq E_{\gamma_{N=2}} \geq ... \geq E_{\gamma_{N=n}}$. Using the Monte Carlo code GAMBLE [3], we have simulated Time-Ordered and Energy-Ordered Spectra (TOS and EOS, respectively) from a specific product of a fusion-evaporation reaction. Our study shows that the high energy side of N=1 EOS that originate in a narrow intrinsic energy slice can be fitted by a function obtained from the theoretical description of the N=1 TOS to obtain the temperature, T, of the entry state region. These simulations suggest that, from a knowledge of the intrinsic excitation energy U, fits to the N=1 energy-ordered spectra would yield accurate estimates of the level-density parameter (a) from the expression $U = aT^2$. Thus, this procedure may be used to obtain the level density parameter a as a function of intrinsic excitation energy and spin. Work in progress shows that it is possible to obtain an analytical EOS fitting function for the entire range of transition energies -not only for the high energy side-, making the determination of a more exact and opening the possibility of experimentally studying other continuum related quantities.

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Study of the rotational transition strength in the warm nuclei ^{163}Tm and ^{168}Yb.

S. Leoni[1,2], T. Døssing[1], B. Herskind[1], P. Rasmussen[1], P. Bosetti[2], A. Bracco[2], R. Broglia[2], S. Frattini[2], E. Vigezzi[2], M. Matsuo[3].

[1] *The Niels Bohr Institute, University of Copenhagen, Denmark.*
[2] *Department of Physics, University of Milano and INFN Milano, Italy.*
[3] *Yukawa Institute for Theoretical Physics, Kyoto University, Japan.*

The *Rotational Plane Mapping Method* (RPM) for the study of the damping of the rotational motion has been applied to two different nuclei of the rare earth region, ^{163}Tm and ^{168}Yb. The data sets have been obtained with the NORDBALL and EUROGAM I arrays, with a final statistics of 3.5×10^8 and 9×10^9 triple events respectively. The aim of the RPM technique is to extract the distribution of the rotational transition strength from the analysis of the "central" valley of 2- and 3-dimensional γ-ray spectra [1]. For both nuclei the rotational transition strength has been obtained as a function of the rotational frequency and its width is found to be rather constant and approximately equal to 80 keV for ^{163}Tm and 100 keV for ^{168}Yb, significantly smaller than the value predicted theoretically for the rotational damping width Γ_{rot} [2]. Also the ratio between the observed depth and width of both the 2-D and 3-D valleys does not agree with the simple model adopted by the RPM method, which assumes that the γ-ray transitions of the damped rotational cascades are *uncorrelated*, i.e. independently chosen at each spin from the $B(E2)$ distribution. The assumptions underlying the damping model are presently being investigated by realistic band-mixing calculations for rare-earth nuclei [3]. Studying in detail the shape of the calculated spectra of two consecutive γ-ray transitions, corresponding to the first ridge in a γ-γ matrix, one can clearly see even up to 1.1 MeV, well into the damped region, the presence of two different components: a narrow one with a width ≈ 50 keV, and a more wide one behaving as expected for damped transitions. The presence of a narrow component is important for the analysis of the experimental data, since it implies that rotational correlations are still present in the spectra also in the regime of damped motion. At present, attempts are made to study correlations over several units of angular momentum, and to understand the nature of the rotational correlations displayed by the narrow component.

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Configuration Dependent Fluctuation Analysis Tested on ^{163}Er

P. Bosetti[a], A. Bracco[a], R. A. Broglia[a], T. Døssing[b], B. Herskind[b], S. Leoni[a,b], E. Vigezzi[d], G. B. Hagemann[b], R. Bark[b], A. Brocksted[c], P. Ekström[c], H. Carlsson[c], A. Nordlund[c], H. Ryde[c], F. Camera[d], S. Frattini[a], M. Mattiuzzi[a], B. Million[d], C. Rossi Alvarez[e], G. de Angelis[f], D. Bazzacco[e], S. Lunardi[e] and M. de Poli[f].

a) Dipartimento di Fisica, Università di Milano, Milano, Italy,
b) Niels Bohr Institute, Roskilde, Denmark,
c) Department of Physics, Lund University, Lund, Sweden,
d) INFN sezione di Milano, Milano, Italy,
e) Dipartimento di Fisica, Università di Padova, Padova, Italy,
f) Laboratori Nazionali di Legnaro, Legnaro, Italy.

The decay of high spin rotational nuclei can be studied by a Fluctuation Analysis Method (F.A.M.) recently developed and applied so far to γ-γ coincidence spectra of normally deformed nuclei in the rare earth region. The method allows us to obtain information on the average properties of the nuclear rotational motion, related to the number of paths the nucleus effectively follows decaying through different decay modes to the ground state.

With the new generation of multi-detector arrays it is now possible to collect extremely high statistic triples and higher fold γ coincidences. This offers the possibility of selecting specific single particle configurations, like for example super-deformed states or discrete rotational bands built on high K orbitals. The measurement of the fluctuations associated to these configurations is expected to give information on the coupling of the single particle states to the quasi-continuum. This type of analysis has been applied to a rich data set on ^{163}Er displaying discrete rotational bands with high K values very weakly populated ($\approx$ 8% of yrast intensity) at an excitation energy of more than 1 MeV above yrast, i.e. in a region where the damping of the rotational motion is expected to play an important role, and where the nuclear residual interaction is strong enough to mix the nuclear single particle states.

The data have been collected with the multidetector array GA.SP (Legnaro, Italy) in the standard configuration. The reaction used was ^{18}O on ^{150}Nd with a 87 MeV beam energy and a 700 μg/cm^2 target. A total of more than 6×10^9 triple events was collected.

The Fluctuation Analysis Method was applied to the ^{162,163,164}Er γ-γ spectra both for the analysis of the ridges and of the central valley. A number of paths in the order of 30 has been extracted from the first ridge, in addition to those used for constructing the level scheme (subtracted out), suggesting that 30 unresolved two-step rotational bands have still to be found in the energy region below $U_0 \approx$ 800 KeV. Above 800 KeV the number of two step rotational bands, extracted from the valley, is much higher ($N^{(2)}_{path} \approx 10^5$) , in agreement with the rotational damping picture and with the results previously obtained applying the F.A.M. on nuclei in the same mass region and with comparable deformations (^{168}Yb ^{166}Hf and ^{163}Tm). The number of paths in the valley from γ-γ spectra gated on discrete transitions belonging to the high-K bands K1, K2 and on the newly found band K4

was also extracted and found to be an order of magnitude smaller. This shows for the first time that the intensity of the fluctuations is strongly dependent on the single particle configuration selected, and it will be demonstrated how it is possible to select weakly populated high K states out from a background of the strongly populated normally states, by means of the Fluctuation Analysis Method.

RECENT RESULTS FROM THE APEX EXPERIMENT.

C.J. Lister
Argonne National Laboratory, Argonne Ill 60439

On behalf of the APEX Collaboration:
Argonne Nat. Lab. and Florida State, Michigan State, Princeton, Queen's, Rochester, Yale, Washington Universities.

The emission of electrons and positrons during the collisions of very heavy ions has been a subject of great interest for the last decade. The intense, rapidly changing electromagnetic fields cause a variety of mechanisms which induce lepton emission. Early experiments found surprising results; in addition to the expected continuous distributions of positrons and electrons, sharp peaks were found both in positron singles spectra and later in positron-electron coincidence spectra. To date there is still no satisfactory explanation for these peaks, despite many experimental and theoretical studies.

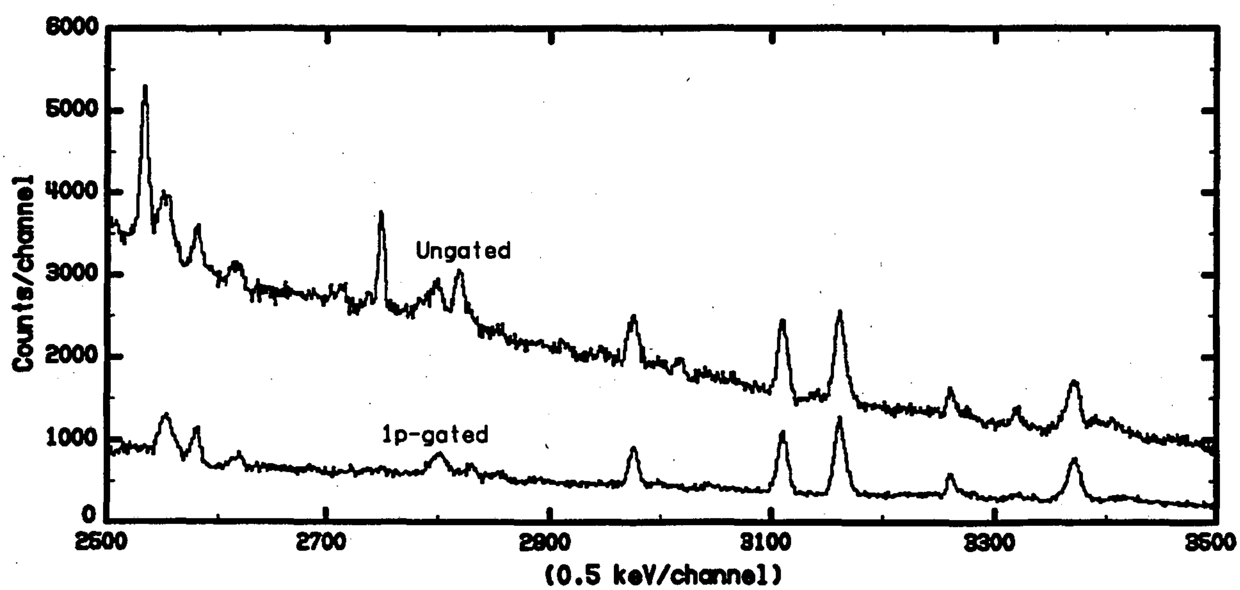
APEX, the Argonne Positron EXperiment, is a new spectrometer designed to allow more detailed studies of the peaks. In particular, the low field design allows the angle of emission of the leptons to be measured for the first time, which, when combined with the full characterization of the heavy-ion scattering allows full kinematic reconstruction of events. Clean identification of positrons is of pivotal importance, as they are emitted in a prolific background of delta and internal conversion electrons. Continuous monitoring of the beam and target condition permit the measurements to be made under reproducible conditions. Large data sets have been collected for the uranium plus tantalum reaction at 5.95, 6.10 and 6.30 MeV/A using 1 mg/cm**2 targets.

In this talk I will review the open questions arising from the electron-positron peaks and discuss how the APEX experiment should help resolve them. The operation of the spectrometer will be described and preliminary data from our first experiments will be presented. In the spirit of the conference, emphasis will be put on the gamma ray aspects of the data, including positron identification and on interesting spectroscopic features observed in the monitor germanium detectors.

FIRST RESULTS WITH THE MICROBALL AND GAMMASPHERE

D.G. Sarantites, P.-F. Hua, D. LaFosse, M. Korolija, J. Elson, J.T. Hood, Washington University, C. Baktash, C. Gross, Hao-Qiang Jin, D.W Stracener, Oak Ridge National Laboratory, I.Y. Lee, A. Machiavelli, B. Cederwall, P. Fallon, W. Rathbun, Lawrence Berkeley Laboratory, and A. Vandermolen, Michigan State University.

The MICROBALL, a 4π-charged particle detector array, was used recently in conjunction with GAMMASPHERE in three different experiments. The MICROBALL consists of 95 CsI(Tl) scintillators with individual photodiode readout, arranged in 9 rings. It provides a 98% solid angle coverage and can achieve single charged-particle detection and identification efficiencies between 90-95%, depending on counting rate and reaction system. For reactions leading to neutron deficient systems heavier than A$\sim$100, it can keep up with GAMMASPHERE with overall pile-up losses smaller than those of GAMMASPHERE. For moderate to low cross section charged particle channels, the peak to background improves by a factor of 3-5, without sacrificing a coincidence fold. Detailed comparisons of the enhancement of GAMMASPHERE for spectroscopic studies in different regions will be shown. Results taken from two recent experiments will be discussed. The first of these was aimed at a search for hyperdeformation in ^{146}Gd produced by the reaction ^{100}Mo(^{51}V, p4n) at 230 MeV. A total of $8 \cdot 10^8$ proton gated unfolded triple events were collected in 80 hours and analyzed. A previously observed SD ridge was seen in a preliminary examination of the data. In this reaction the proton gating gave an increase of the peak to background ratio by a factor of 4 (see figure below). All of the shown lines in the proton gated spectrum are from ^{146}Gd.



In the second experiment a search for superdeformation in ^{83}Y produced by the reaction ^{58}Ni(^{29}Si, 3pn) at 130 MeV was undertaken. The superdeformed bands in this nucleus are expected to occur at lower spins compared to the recently observed [1] SD band in ^{82}Sr. In this experiment excellent charged particle channel selection was achieved.

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Collective *versus* single-particle excitation in ^{86}Nb

S.L. Tabor, J. Döring, and G.D. Johns, Florida State University; C.J. Gross, UNISOR; C. Baktash, Y.A. Akovali, and D.W. Stracener, ORNL; F.E. Durham, Tulane University; D.G. Sarantites, M. Korolija, P.F. Hua, and D.R. LaFosse, Washington University; A. Macchiavelli, I.Y. Lee, and W. Rathbun, LBL; and A. Vandermolen, Michigan State University

Recent investigations [1-5] have revealed the prominent role played by the $\pi g_{9/2} \otimes \nu g_{9/2}$ structure in the yrast states of odd-odd $A \approx 80$ nuclei. Lifetime measurements [1-4] have demonstrated highly collective rotational bands, but an observed reversal of signature splitting has been interpreted [6] as arising from competition between quasiparticle recoupling and rotation. A careful study of the details of the reversal in signature splitting should provide valuable information on the neutron-proton residual interaction, especially if the effect can be tracked over a range of nuclei.

This investigation of ^{86}Nb was initiated to fill a gap in information on odd-odd $A \approx 80$ nuclei above mid-shell in proton number and to use the power of GAMMASPHERE plus the MICROBALL to provide a much more thorough investigation of one odd-odd nucleus. Two decay sequences of relatively low-spin states were previously observed [7] in ^{86}Nb. In the present experiment, high-spin states were populated in ^{86}Nb using the ^{58}Ni(^{32}S,$3pn$) reaction at 135 MeV. Cascades of three or more γ rays were detected with the early implementation of GAMMASPHERE (36 detectors) and the evaporated charged particles were detected in the 96-element MICROBALL for channel selection.

A preliminary analysis of part of the triples γ coincidence data has allowed one band to be extended to at least the (21^+) state. The behavior of this band is quite similar to that of bands in other odd-odd nuclei which have been identified as based on a predominantly $\pi g_{9/2} \otimes \nu g_{9/2}$ configuration. A reversal of the phase of the signature splitting is seen between the (10^+) and (11^+) states and the branching ratios suggest large alternations in the $B(M1)$ strengths. In contrast to these similarities with neighboring nuclei, another band, with tentatively positive parity, has been observed which has no obvious analogy in nearby nuclei. Depending on the exact spin assignments, which will be determined from the DCO ratios, the new band may become yrast at higher spins and remove decay strength from the previously described band.

A presumably negative-parity decay sequence has been observed up to the (25^-) level. Unlike the bands in neighboring odd-odd nuclei, the level spacings do not take on a rotation-like spacing until a spin of about $13\hbar$. This appears to be another example of the competition between collective and single-particle excitations. The signature splitting is also larger than in nearby nuclei. A complete analysis including the charged-particle data is in progress.

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Gamma Spectroscopy with the Recoil Filter Detector – Recent Results and Perspectives

K. Spohr[1], W. Meczynski[2], J. B. Fitzgerald[1], D. B. Fossan[5], M. Gorska[3], H. Grawe[1], J. Heese[1], M. Lach[2], K. H. Maier[1], A. Maj[2], J. C. Merdinger[4], M. Rejmund[3], R. Schubart[1], J. Styczen[2]

[1] HMI Berlin, [2] IFJ Krakow, [3] Warsaw University, [4] CRNS Strasbourg, [5] SUNY Stony Brook

A detector (RFD) has been developed that measures evaporation residues in coincidence with γ-detection in a Ge-array. The RFD brings two advantages to fusion-evaporation γ-ray experiments: (1) The recoil time of flight discriminates against other types of reactions, in particular inelastic scattering including Coulomb excitation, fission and reactions with light target impurities (C, O); (2) The velocity vector of the γ-decaying recoil nucleus is determined by the location of the firing RFD module, which allows for event-by-event Doppler-shift correction. The existing detector is used with OSIRIS at VICKSI, HMI Berlin. It covers an angular range from 2.7° to 12.1° with 18 individual elements placed 73cm from the target. The recoiling ions knock electrons ($\sim$100) out of a thin foil, which are accelerated with 20kV and focussed onto a thin scintillator. Phototube signals of reasonable pulse height are obtained for slow heavy ions (10MeV Pb), which are identified by their time of flight. The detector is also fast enough to recover within 50ns after a hit by scattered beam particles, i.e. before the evaporation residues reach the RFD. The performance of the RFD in recent experiments [1] will be discussed, along with new results for the most neutron-deficient odd-A Pb isotopes produced in (^{36}Ar,4n) reactions. Transitions in ^{199}At were identified for the first time in the reaction ^{175}Lu(^{32}S,4n). The cross-section of this reaction is 0.1mb, while Coulex and fission (100mb) dominate. A scheduled experiment for nuclei around ^{56}Ni will primarily exploit the Doppler-correction information. An RFD combined with the new γ-detector arrays of 100 times greater efficiency for γ-γ-coincidences would allow the study of correspondingly weaker reaction channels. Since the RFD occupies only a small solid angle, it does not obstruct other detectors. With the increased granularity of the γ-detectors in the large arrays, it will be even more important to eliminate the Doppler broadening due to the velocity distribution of the recoil nuclei. A second version of the detector for EUROGAM is almost completed.

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COLLECTIVE HIGH SPIN STATES IN ^{45}Sc

P.Bednarczyk[1,2] , J.Styczeń[1] , R.Broda[1] , M.Lach[1] , W.Męczyński[1],
G. de Angelis[2] , D. Bazzacco[3] , S. Lunardi[3] , R. Menegazzo[3], L. Müller[3] ,
C. Petrache[2], C. Rossi-Alvarez[3], G.F. Segato[3], F. Scarlassara[3] , F. Soramel[4]

[1] *Institute of Nuclear Physics, Kraków, Poland*
[2] *INFN, Laboratori Nazionali di Legnaro,Legnaro, Italy*
[3] *Dipartimento di Fisica dell'Universitá and INFN, Padova, Italy*
[4] *Dipartimento di Fisica dell'Universitá and INFN, Udine, Italy*

The nuclei in the $f_{7/2}$ shell exhibit properties which reflect an interplay between the dominant single-particle motion and collective degrees of freedom which become more and more important for the nuclei in the middle of the shell [1,2]. The experimental data for high spin states are still scarce due to the unsatisfactory efficiency and limited selectivity of the techniques used so far. The new generation of high efficiency γ-ray arrays combined with recoil mass spectrometer may therefore open new perspectives in the study of high spin phenomena in such light nuclei. We report here an investigation of high-spin excitations in light $f_{7/2}$ nuclei. The experiment was performed with the GASP multidetector array and the Recoil Mass Spectrometer at Legnaro. The level scheme of ^{45}Sc built on the base of triple γ coincidences is presented in fig.1. The analysis of DCO ratios has allowed to establish spin assignments for the most populated levels. A shell model calculation [3] reproduces well the sequence and excitation energies for the negative parity states. One striking feature is the smooth behavior of the moments of inertia for the positive parity **A** and **B** intruder bands, illustrated in fig.2, which points to their collective character. The lifetimes estimated for the transitions of band **A** suggest a quite high deformation $\beta \approx 0.3$.

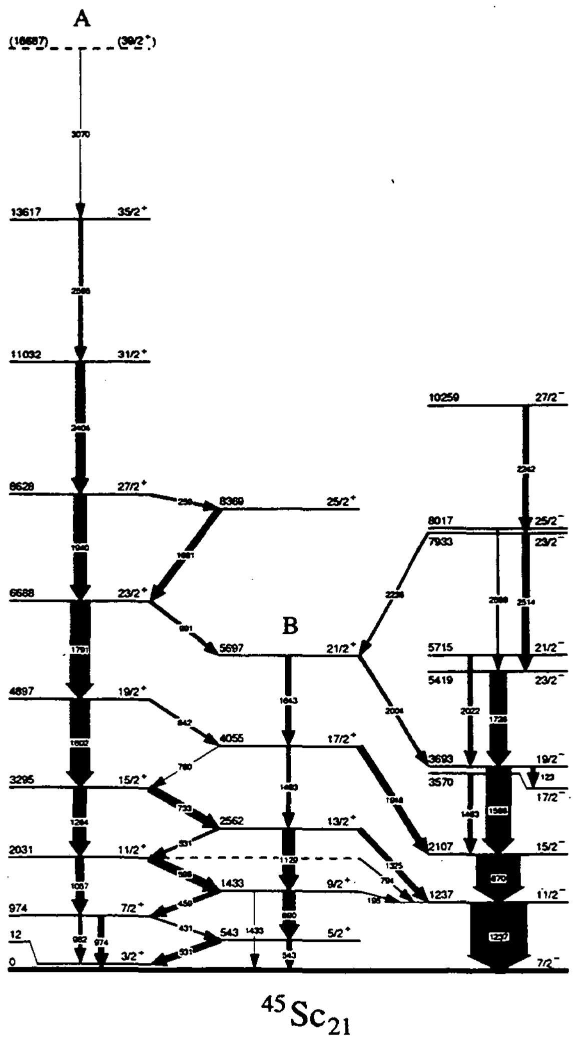

Fig.1.The level scheme of ^{45}Sc

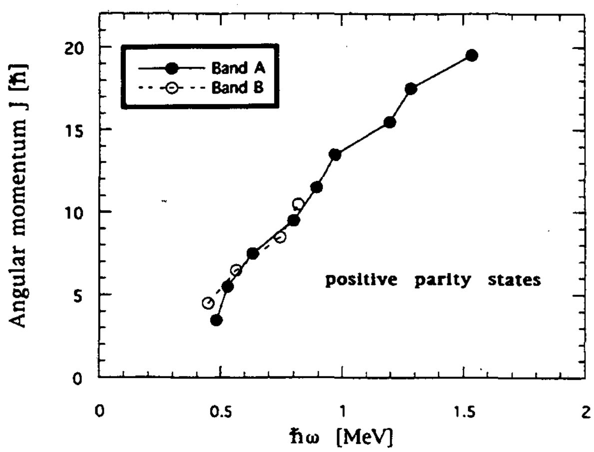

Fig.2. The angular momentum versus rotational frequency plot for bands observed in the ^{45}Sc nucleus

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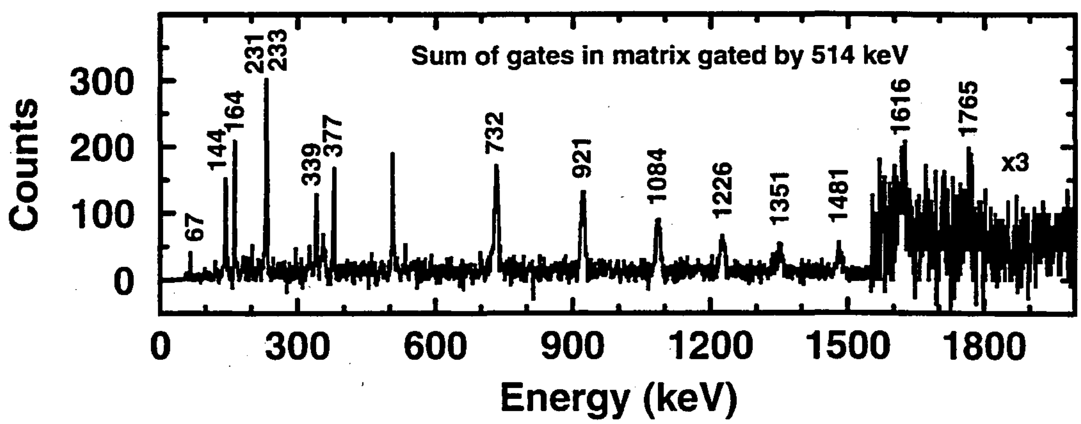
Identification of Excited States in the $T_z=\frac{1}{2}$ Nucleus ^{75}Rb*

C. J. Gross, ORNL, UNISOR; C. Baktash, D. M. Cullen, J. D. Garrett, ORNL; R. A. Cunningham, J. Simpson, D. D. Warner, DARESBURY LAB.; B. J. Varley, MANCHESTER U.; D. Rudolph, A. Harder, M. K. Kabadiyski, K. P. Lieb, U. of GÖTTINGEN; Ö. Skeppstedt, H. A. Roth, CHALMERS INST. of TECH.; W. Gelletly, U. of SURREY; D. G. Sarantites, WASHINGTON U.; C. J. Lister, YALE U.; J. A. Sheikh, JIHIR.

Excited states in the $T_z=\frac{1}{2}$ nucleus ^{75}Rb were observed for the first time using the 45 Compton-suppressed Ge Detectors of EUROGAM, the Daresbury recoil separator, and the reaction ^{40}Ca(^{40}Ca,αp) at 128 MeV. Recoiling nuclei were mass separated and passed through an ionization chamber which provided discrimination between ^{75}Rb and ^{75}Kr ions. The data was sorted into several γ gated two dimensional $\gamma\gamma$ matrices which were used to construct a level scheme. The data reveal a complicated level structure at low spin more similar to the light Br isotopes than to the other odd mass Rb nuclei. Only one rotational band is observed stretching up to $I^\pi=(\frac{41}{2}^+)$. The band's kinematical moment of inertia is larger (21-22 $\hbar^2$/MeV) than most of the neighboring nuclei which may be characteristic of a reduction in pairing. Weaker pairing correlations are expected due to the large deformed shell gap at N=Z=38 and the blocking of the unpaired proton. In the same experiment, a cascade relationship is observed between the three γ-rays previously assigned [1] to the self-conjugate nucleus ^{76}Sr. The kinematical moment of inertia of ^{76}Sr is slightly larger than ^{78}Sr which is suggestive of a slight change in deformation or pairing correlations in ^{76}Sr.



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Measurement of Magnetic Moments of High Spin States in $^{193,194}Hg^{\star}$.

L. Weissman, M.Hass, C. Broude, Weizmann Inst.
N. Benczer-Koller, G. Kumbartzki, N. Matt, Rutgers
J.Sharpley-Schafer, M.Joyce, Liverpool, R.Clark, York.

A transient field experiment has been carried out using the EUROGAM array at Daresbury. The goal of the experiment was to explore the feasibility of measuring magnetic moments of superdeformed bands. The reaction $^{150}Nd(^{48}Ca,xn)^{193,194}Hg$ at 205 Mev was used to populate high spin levels and provide the recoiling Hg nuclei sufficient velocity to traverse the Gd ferromagnetic layer. The target consisted of 1 mg/cm^2 ^{150} Nd deposited on 2.2 mg/cm^2 Gd and backed by a 25 mg/cm^2 layer of gold and was cooled to 80 K. The magnetization properties of Gd foil were checked off line. For the conditions of this preliminary run, the intensity of the superdeformed bands was too low for g-factor measurements. However, the yield of normal transitions was adequate for this purpose.
γ-γ matrices of individual detectors, close to the horizontal plane (perpendicular to the transient field) and at angles of large logarithmic slope of the angular distribution were generated with respect to all other detectors. The double ratios $\rho_{ij}=[N_i\uparrow/N_i\downarrow/N_j\uparrow/N_j\downarrow]^{1/2}$ ($N_i\downarrow$, for example, is the number of counts in detector i with the field in "down" direction) of the different bands were measured by setting gates on the lines within the respective bands and by summing statistically results for all lines of the band. The angular correlation for these lines was determined experimentally from the data to yield corresponding precession angles. The precession carries information about both the observed lines and higher unobservable transitions. A more quantitative analysis regarding the reaction's time-decay history will be carried out as the next stage of this work. In particular we will present results for the ABC, ABCDF and ABCDE bands of ^{193}Hg. The data of ^{194}Hg is being presently analysed. The significance of the results for understanding the single particle nature of these high-spin levels will be discussed. The feasibility of future magnetic moment measurements of superdeformed bands will also be addressed.

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Magnetic moment measurements using large detector arrays

A.E. Stuchbery and S.S. Anderssen

Department of Nuclear Physics, Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia

The measurement of magnetic moments for short-lived excited states in heavy, unstable nuclei presents many challenges. (i) A heavy ion reaction must be employed to excite the states and implant the nuclei of interest into a suitable ferromagnetic host. Care must be taken that the presence of the host material does not lead to an unacceptable level of background radiation. (ii) The perturbations of the γ radiation depopulating the states of interest must then be measured with sufficient precision. This requires both a sufficient counting rate for the lines of interest and a radiation pattern that has an adequate anisotropy. (iii) Appropriate corrections for feeding must be made – the precession observed for a given state may reflect the precession not only taking place in the state itself, but also the precessions of all states that feed it. (iv) Finally, extraction of the magnetic moments requires a knowledge of the hyperfine fields.

This paper discusses the utility of large detector arrays two kinds of g-factor measurement: (i) In-beam measurements employing transient hyperfine fields; (ii) Out-of-beam measurements employing static fields. In-beam measurements using static hyperfine fields are set aside because recent work [1] suggests that there may be pre-equilibrium effects associated with the implantation process which quench the static field for about 10 ps after implantation.

On one hand, a large array offers the advantages of coincidence experiments where gating leads to cleaner spectra, enhanced anisotropies and control of feeding paths to the states of interest. On the other hand, there may be associated disadvantages, such as: loss of counting statistics; many of the detectors may be at angles where they are not sensitive to the precession; and one may have to interpret a complicated perturbed directional correlation from oriented nuclei (PDCO), rather than a more familiar perturbed angular correlation/distribution (PAC/PAD).

A series of measurements of type (ii) have been completed [2] for the even, neutron-deficient Pt isotopes between ^{184}Pt and ^{192}Pt, using the ANU array CAESAR with 7 Ge detectors. Heavy ion reactions were used to create and implant the β-decay parents of the nuclei of interest into a polarized Fe foil which was subsequently carried to the centre of the array by a "rabbit". The problem of unwanted radiation from the Fe backing is thereby eliminated and interpretation of the data is straight forward. An experiment, employing a modification of this technique to study ^{180}Pt, has also been performed using the 40 detector array GaSp [3].

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THE PERFORMANCE OF CLUSTER DETECTORS

J. EBERTH, University of Köln, Germany

The sensitivity of 4π γ–arrays essentially depends on the total–absorption efficiency of the Ge–detectors, their peak–to–total ratio and the granularity of the Ge–detectors which determines the energy resolution for γ–rays emitted from fast recoiling nuclei.

To optimize these quantities, a Ge CLUSTER detector has been developed for EUROBALL by a collaboration of the University of Köln, the KFA Jülich and the company Eurisys. The CLUSTER detector is composed of seven individually encapsulated Ge detectors tapered to a hexagonal shape at the front end which are surrounded by a common BGO suppression shield. With a total Ge volume of 2000 ccm the CLUSTER detector is the largest composite detector built so far.
15 CLUSTER detectors with a solid angle of 1π will be implemented in phase III of the EUROBALL. The expected total–absorption efficiency of the segment is $\geq$4% which means that 4π–arrays with 16% efficiency can be realized using the CLUSTER detectors [1,2,3].

The prototype of the CLUSTER detector recently became operational. Series production of these detectors for the EUROBALL members institutions in Bonn, Göttingen, Köln and Rossendorf has been launched. 29 encapsulated Ge detectors have been delivered to date. Remarkable features of the detectors are:

- Easy handling by the experimentalist.
- Full access to the preamplifier.
- Easy annealing of neutron damage.
- Vacuum cryostat decoupled from the detector vacuum.
- Ge detectors can be rearranged for different applications.

The experience with the new technology of the encapsulated Ge detectors will be discussed.

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Performance of Gammasphere Split Detectors†

A.O.Macchiavelli, I.Y.Lee, B.Cederwall, R.M.Clark,
M.A.Deleplanque, R.M.Diamond, P.Fallon and F.S.Stephens
Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, CA 94720

An important property of large HPGe detector arrays is the energy resolution (δE) of the individual counters. The sensitivity or figure of merit of such an array for F-fold coincidence events depends on $1/\delta E^F$. While intrinsic resolutions are usually 2 keV at 1 MeV, in a typical (Heavy-Ion,xn) reaction the *effective* resolutions are affected by Doppler broadening. These are most severe for those detectors positioned around 90° with respect to the beam direction. For example, with a recoil velocity of $\approx$ 3% the resolution of a 90^0 detector in Gammasphere will be $\approx$ 5 keV. Using a detector split in two halves, it is possible to reduce the degradation in the resolution by correcting the energy in software using information on the energy deposited in each half of the detector.

Shown in fig.1 are two possible solutions that have been considered for Gammasphere:

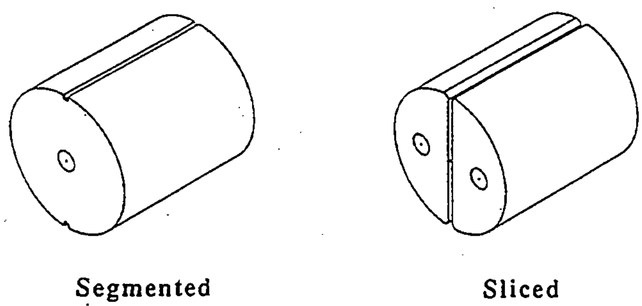

Fig. 1 Schematic drawing of the split detectors for Gammasphere.

1) A split detector consisting of two D-shaped HPGe crystals housed in a single cryostat, usually referred to as "*sliced*" and 2) A single crystal with a "*segmented*" outer electrode.

In the *sliced* configuration the two halves are treated as different detectors requiring two high-resolution electronic channels. In the *segmented* configuration there is only one high-resolution signal common to both sectors, obtained from the inner electrode; signals from the outer contact provide low resolution position information. Detectors of each design have been tested with radioactive sources and in beam. Results on peak-to-total, efficiency and resolution are shown in table 1. Their overall performance will be discussed.

Configuration	P/T	Efficiency(%)	FWHM (keV)
Sliced	0.50	65	3.0
Segmented	0.53	82	2.4

Table. 1 Performance of split detectors at Eγ=1.33 MeV (^{60}Co source) in the array.

† Work supported in part by U.S. DOE under contract number DE-AC03-76SF0098.

The SEGMENTED CLOVER detector for EUROBALL

J. Gerl[1], K. Vetter[2], Th. W. Elze[2], Th. Kröll[2] and H. Xie[1]

[1] GSI, Darmstadt, [2] Universität Frankfurt

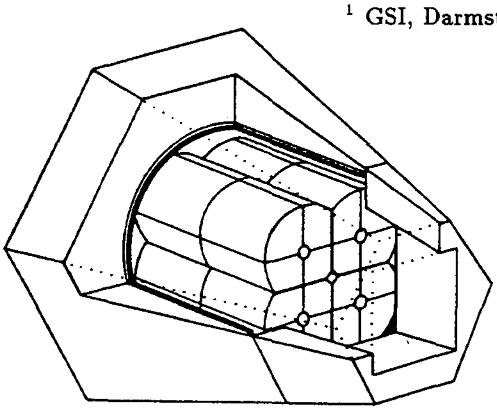

Fig.1 Sketch of the SEGMENTED CLOVER detector.

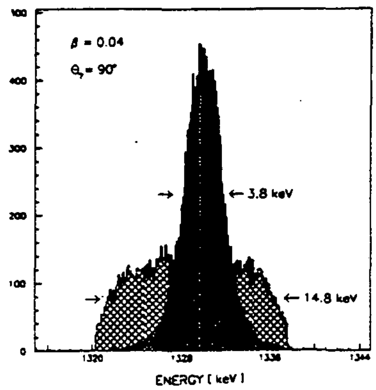

Fig.2 Simulated photopeak with and without correction of the Doppler broadening.

The aim of the EUROBALL project is the development of γ-ray detectors with substantially improved qualities, to be employable in different kinds of arrays ranging from one detector up to the 4π spectrometer EUROBALL III [1]. To achieve a total photopeak efficiency substantially larger than 10% for the 4π array and to preserve the necessary energy resolution deteriorated by Doppler effects it is necessary to build composite detectors consisting of several Ge crystals. The most advanced designs which have been realized so far are the CLOVER and the CLUSTER detector with four and seven crystals.

Even more ambitious is the SEGMENTED CLOVER detector (fig. 1), which is currently being developed. It will consist of 8 closely packed coaxial Ge detectors arranged in two layers. To further improve the Doppler correction capability the detector elements are segmented radially in quarters. This segmentation scheme is especially well suited for nuclear reactions, where the γ-ray emitting nucleus is scattered within a broad range of scattering angles, e.g. Coulomb excitation experiments. Fig. 2 shows the excellent recovery of the energy resolution, being degraded by Doppler broadening.

Using standard Ge-crystals (l=65mm, d=70mm) the peak efficiency of the collimated SEGMENTED CLOVER detector has been calculated at 1.33MeV (11.7MeV) to be ϵ_{ph}=0.36 (ϵ_{ph}=0.09) with a P/T ratio of P/T=0.82 (P/T=0.6).

The first prototype element of the SEGMENTED CLOVER detector with a segmented Ge crystal of 67mm diameter and 72mm length has been delivered in spring 1994 by the company Urisys Mesures. It has an efficiency at 1.33MeV of ϵ_{ph}=0.189±0.009 for the full detector and ϵ_{ph}=0.021 ... 0.030 for the segments. The Peak/Compton ratio is 50.3 for the sum and about 26 for the segments. All measured values agree within the experimental errors with corresponding Monte Carlo calculations, which shows the reliability of detector simulations. The energy resolution of the ac-coupled sum signal has been measured to be 2.35keV and ranges from 2.2keV to 2.6keV for the segments. The time resolution of all five signals is better than 6ns.

After solving the main technical obstacle, the segmentation of a n-type Ge detector, the completion of the SEGMENTED CLOVER detector is expected for 1995.

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New electronic developments for GAMMASPHERE

F. S. Goulding, D. A. Landis, N. W. Madden, M. R. Maier, B. Turko, and H. Yaver
Lawrence Berkeley Laboratory, Berkeley CA 94720

We have developed and built the signal processing electronics for GAMMASPHERE at the Lawrence Berkeley Laboratory. The large coaxial reverse electrode Germanium detectors of this device pose new challenges : since the charge collection times in these detectors are long and vary with the interaction site a new shaping technique was developed that minimizes the 'ballistic deficit', i.e. the dependence of the amplitude of the amplifier on the rise time of the preamplifier output pulse. The shape chosen approximates a trapezoid with a flat top [1]. To avoid ballistic deficit one uses long shaping times which lead to rate limitations. Since the detectors in GAMMASPHERE run at singles rates of 10 000 events/sec a pulse width of 10μsec was chosen. A standard pseudo-Gaussian shaper produces a resolution of 2.7 keV with this choice, the new shaper, however, gives 2.4 keV for a 'typical' GAMMASPHERE detector at 1333 keV (Co60). We have also designed a 'fast-slow' transistor reset preamplifier which produces a slow charge signal and a fast signal which reflects the current in the detector. With the fast signal we have obtained time-resolutions of <5 nsec at the Co60 gamma lines. This current signal also serves to correct for charge carrier trapping losses by deriving from it information about the radial distance of the charge production sites from the central electrode. This is an indication of the drift distance of the carriers and therefore provides a measure for losses which depend on this distance [2]. To get the best time resolution for the BGO anti Compton shields we decided to use first electron triggering [3]. Three discriminators are used in the timing : one biased at the 'one photoelectron level' to derive a time mark, another at 15 keV to validate the timing and the third to trigger at 100 keV for the total sum energy. The time resolution is also ~5 nsec for the Co60 lines. The actual Compton suppression is done in software after an event has been read. The detector electronics 'Boxes' are mounted at the 'Detectormodules' consisting of the Germanium detectors surrounded by the BGO anti Compton shield. A 'Box' has individually regulated high voltage supplies for the Germanium and BGO detectors. They are controlled via a bi-directional serial link connection which also reads the status of the 'Detectormodule'. The 'Box' is connected to the processing electronics in the 'counting house' via an 'umbilical' cable with 12 coaxes for the signals, the 6 serial communication lines and the low voltage power supply lines. Signal processing occurs in modules residing in VXI-crates. One D-size VXI module serves two detector 'Boxes'. The different processing functions are performed on small 'daughterboards' mounted on a big 'motherboard'. In addition to the shaper we have built a 14 bit 'high resolution ADC' with 5 μsec digitizing time and a differential nonlinearity of <1% [4]. Shaping and digitizing is done in the VXI module. The trigger for the device is derived from a combination of 'clean' Germanium detectors, BGO + Germanium detectors (for sum energy), and external triggers. One VXI crate houses 10 VXI processor modules, a local readout -, a local trigger -, and a resource manager - module. The information is combined in the 'master' VXI crate where the master readout module receives the data from the different 'slave' crates after the master trigger module has indicated an interesting event was detected. There is also room in the master crate to plug in modules to read data from external auxiliary detectors. At present ADCs with FERA readout can be accommodated.

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Kinematic reconstruction of HI-γ events using particle detectors

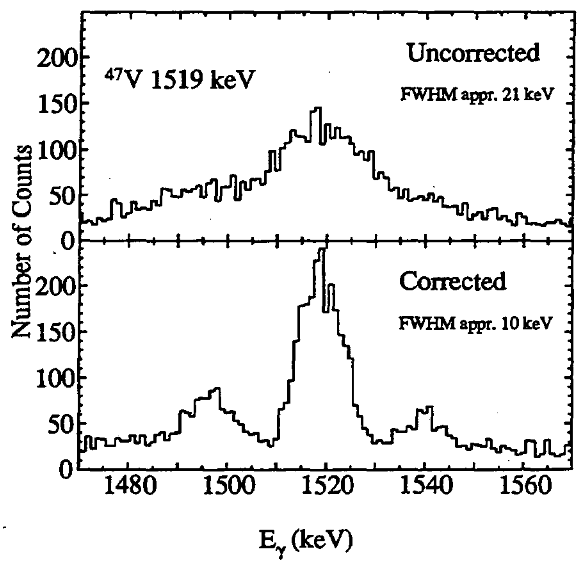
J. A. Cameron, J. Jonkman, J. Rodriguez *Department of Physics, McMaster University, Hamilton, Canada*

A. Galindo-Uribarri and the 8π group *Chalk River Laboratory, AECL, Chalk River, Canada*

One of the impediments to HI-γ spectroscopy, particularly of light nuclei, is the large recoil velocity and consequent Doppler broadening. In addition to the usual effects of target thickness and detector solid angle, a major contributor to line width is the variation in both magnitude and direction of recoil momentum resulting from ejectile momenta.

At the Chalk River 8π facility, a central charged particle detector array (ALF) has been used for some time to measure light fragment energy and angular distributions, and to tag reaction channels. Its usefulness in reducing Doppler broadening is here demonstrated. The 24 detectors are CsI scintillators bonded to photodiodes. Pulse height and risetime allow moderate energy resolution as well as discrimination of alphas from protons.

A playback program has been constructed in which kinematic reconstruction of each event is made using energy and angular information from each charged particle detected. Typical reductions in linewidth are about a factor of two for gamma energies above 1 MeV, provided al the ejectiles are detected.



The "Snowflake" Method: Analysis of Continuum Bands in Triple-Coincidence Data

G. Hackman, J. C. Waddington
Department of Physics and Astronomy, McMaster University, Hamilton, ON L8S 4M1, Canada

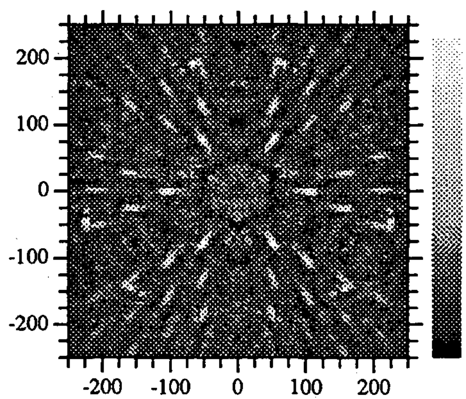
The first observations of superdeformation[1] and hyperdeformation[2] at high spin appeared in double-coincidence gamma-ray data as peaks in ridge projections which arise from several bands with the same moment of inertia. These data from good rotors revealed lines in the 2-D histograms which were parallel to the $x = y$ diagonal axis. Projecting and summing the coincidence histogram along this axis yields the peaks presented in [1,2]. With the arrival of third-generation spectrometers capable of collecting high statistics high-fold gamma-ray coincidences, it is necessary to extend previously well-established analysis methods to fully exploit the maximum sensitivity near the optimal fold.

A method for generating the triple-coincidence analogue of a ridge projection is presented. Each triple-coincidence event E_x, E_y, E_z is represented as a vector $\vec{e}$ in a 3-D energy space $\mathcal{E}$. This vector is then transformed by an orthogonal matrix,

$$\vec{e'} = \overleftrightarrow{R} \cdot \vec{e} \tag{1}$$

where $\overleftrightarrow{R}$ is chosen such that events with $E_x = E_y = E_z$ are rotated to a point on the z' axis in the new $\mathcal{E}'$ space. Integrating along z' yields a two-dimensional histogram analogous to the ridge projections of double-coincidence data. The 2-D histogram so described will have $C_{3\sigma}$ symmetry. As shown in [3], the gamma-ray cascade from any regular rotational band with a given moment of inertia will form a hexagonal lattice of peaks, excluding by coincidence relationships those sites on the symmetry axes, hence the "snowflake" name.

This method, in conjuction with a high-fold global background subtraction method[4], has been applied to high-spin studies of ^{149}Gd[5] and ^{153}Dy[6]. Early results such as the figure shown below will be reported.



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In-Memory Storage of Large γ–γ / γ–γ–γ Correlation Arrays

M. Cromaz

Department of Physics, University of Toronto

The in-memory storage and manipulation of γ–γ/γ–γ–γ correlation arrays would provide advantages to software ranging from tape sorting programs to super-def search programs. Unfortunately limitations in the physical memory size of today's computers do not allow us to store this data in simple fixed wordlength arrays. To address this problem we have developed and implemented a simple lossless compression scheme which takes advantage of the general characteristics of correlation arrays.

In essence, correlation arrays are composed of mostly small integers punctuated by many localized regions of large integers which correspond to peaks and Compton scattering tails. Hence, an array is divided into numerous equally sized subarrays to separate regions of high counts from low. Subarrays are represented in such a way that the effective wordlengths of each are just sufficient to store the largest element. This is accomplished by allocating a linked list of memory blocks called bitplanes (bitcubes). The first memory block in the list contains the least significant bit for each element of the subarray. Higher order bits are stored in the corresponding memory blocks of the list. Simple and efficient algorithms have been developed to manipulate arrays stored in this manner.

The method described lends itself easily to tape sorting software and has been implemented in the program 's5' which allows for the replay of up to six $4k \times 4k$ γ–γ matrices simultaneously using a Sun10/Model31 with 64Mb of memory. This method could also prove very useful for programs which search for regularly spaced bands in three dimensional correlation arrays. Currently, work is being completed on a set of programs which will allow one to store and manipulate a $1k \times 1k \times 1k$ fully symmetrized cube in memory.

Distributed Data Analysis for High-Fold Nuclear Structure Data*

D.F. Winchell, P.H. Kutt, and D.P. Balamuth

Department of Physics, University of Pennsylvania, Philadelphia, PA

The new generation of large γ-ray detector arrays are producing large data sets consisting of three-, four-, and five-fold high-resolution data. One of the critical issues in the analysis of such data is the speed at which it can be accessed. We are developing a software package which uses a network of workstations for storage and manipulation of high-fold data. Having the data distributed in this fashion allows the disk access and much of the numerical processing of the data to proceed in parallel for different parts of the data set, thus decreasing the overall access time.

The software is being developed on a network of five SGI Iris Indigo workstations, each with a 1 gigabyte disk. Programs run as a set of cooperating processes, with a "master" process on one node coordinating the execution of the "slave" processes which access and manipulate the data stored on each node. Internode communication is achieved using the "Parallel Virtual Machine" (PVM) software package developed at ORNL[1]. The software is being tested using data obtained by Baktash *et al.* in a EUROGAM experiment[2].

Data is stored as a "histogram of lists"; that is, the n-dimensional space is broken down into sectors, and data within a sector is stored in an event-list format. The division of the data space into sectors is done dynamically during the initial sort from tape, in order to distribute the data evenly among the workstations.

At the present time, a library of routines for the storage and retrieval of the data has been written, and two programs are in use: a tape scanning program which takes the data and creates a user-configured n-dimensional data set on the network, and a slicing program which creates one- or two-dimensional histograms from the higher fold data based on user-defined gates. The results of the analysis of EUROGAM data using these programs will be discussed.

Current and planned development efforts include interfaces to currently used analysis packages, an algorithm for n-dimensional peak finding, and a software library which will allow users to write personalized analysis programs in such a way that the distributed nature of the system is transparent.

* Research supported by a grant from the NSF.

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C_{4v} SYMMETRY IN ROTATIONAL SPECTRA OF SUPERDEFORMED BANDS

Ikuko HAMAMOTO* and Ben MOTTELSON**

* Department of Mathematical Physics
Lund Institute of Technology
University of Lund
Lund, Sweden.

** NORDITA
Blegdamsvej 17
Copenhagen, Denmark
and
ECT*
c/o Dipartimento di Fisica
I-38050 Povo (Trento), Italy.

The observation of $\Delta I = 4$ staggering in the rotational spectra of superdeformed nuclei suggests the occurrence of Y_{44} deformations in the nuclear shape with associated C_{4v} point-symmetry for the rotational Hamiltonian. We have investigated the general class of Hamiltonians with such symmetry. In addition, we require the axially symmetric terms to favour rotation about an axis that is perpendicular to the long axis of nuclear shape. The $\Delta I = 4$ staggering can indeed result from the tunneling between the four equivalent minima that occur in the plane perpendicular to the superdeformation symmetry axis, but the occurrence of this effect is a subtle matter depending sensitively on the axially symmetric terms in the Hamiltonian.

C4 Symmetry and Bifurcation in Rotational Bands

I. M. Pavlichenkov

Russian National Center "Kurchatov Institute", Moscow, 123182, Russia

Recently superdeformed bands have been found in ^{149}Gd [1], ^{194}Hg [2] and may be in ^{153}Dy [3] that have a small energy shift for levels separated by four units in spin I. The same phenomenon but not so pronounced has been observed before in normal bands [4]. There are reasons to consider this phenomenon as the manifestation of a statical or dynamical hexadecapole deformation of nuclei. We discuss the possible relationship of the $\Delta I = 4$ staggering with the local C_4 type bifurcation suggested in Ref. [5].

In quantum rotational spectra, there exist five different types of bifurcations, which classified according to the point symmetry group C_n. The majority of bifurcations has been found in past five years in molecular rotational spectra [5]. The simplest bifurcation of the C_2 type accompanies the well known phenomenon in nuclear rotational dynamics: the transition from a tilted band to aligned one in odd-A nuclei as I increases. The local character ot this as well as the C_4 bifurcation allows one to obtain a universal Hamiltonian describing the rotational states near the critical point I_c. This phenomenon may be named a "quantum catastrophe," and can be used for the phenomenological description of the $\Delta I = 4$ staggering. A bifurcation manifests itself both in the rearrangement of rotational levels and in the abrupt changes of E2 and M1 transitions in the critical point. The theoretical analysis of experimental data on molecular and nuclear rotational spectra shows that rotational excitations near the critical point are sensitive to the internal structure of a system. That is why the bifurcation allows us to identify a small non-axial or hexadecapole deformation.

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New Symmetry ("P-Symmetry") in High-Spin Nuclear Physics

Jerzy DUDEK
Strasbourg University and Nuclear Research Center
Strasbourg, France

Abstract

It is shown, first using the unitary-group symmetry-properties of the effective nuclear hamiltonians (such as realistic cranking or particle-rotor hamiltonians with pairing) that the corresponding solutions of the Schrödinger equation must obey a new symmetry called in what follows P-symmetry. Two-body hamiltonians of the pairing type obey this symmetry exactly. One body hamiltonians with the two-dimensional cranking terms obey this symmetry exactly as well under the condition that they commute with the signature (or simplex) operators - which is usually the case.

Implications of the new symmetry in the form of the corresponding good quantum number (called P-quantum-number) are discussed and illustrated using a single-shell "toy model". However, the exercice performed on the toy model is shown to indicate a way of the generalization to the realistic cases such as the large scale calculations with the Nilsson or Woods-Saxon average field potentials. The method of the diagonalisation of the related hamiltonians using the adequate many body basis, the problems of the basis cut off, and some technical aspects like e.g. bit manipulation techniques to tackle the multifermion bases are briefly discussed.

A practitioner's approach to the use of the new quantum number is presented and illustrated in some detail. It is suggested how the P-symmetry (which should not be confused with parity, signature, simplex, etc.) can be detected experimentally. A relation between P-quantum number, which e.g. for an even system of n-fermions (nucleons) takes the values P= -n, -n+2,.... n-2, n, - and the signature is presented. It is shown that various P-blocks of the hamiltonian correspond in such a case to the alternating signatures. Finally a relation to the "standard" ways of interpreting the high-spin phenomena in terms of quasiparticle (and/or) particle-hole excitations is illustrated.

APPLICATION OF QUANTUM ALGEBRA TO SUPERDEFORMATION

ASHWANI KUMAR PANDE

NUCLEAR SCIENCE CENTRE,
P O BOX 10502
NEW DELHI 110 067 (INDIA)

ABSTRACT:

The Quantum group algebra $SU_q(2)$ and $SU_q(3)$ may be the important tool to describe the spectra of Superdeformed bands in even - even nuclei and rotational bands with normal deformation.

The results from our calculation for the ^{152}Dy nucleus and ^{151}Tb nucleus shows good agreement with the experimental results . In this paper I would like to present some future aspects of $SU_q(3)$ algebra.

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AN APPROXIMATE DESCRIPTION OF LARGE AMPLITUDE COLLECTIVE MOTIONS: APPLICATION TO NUCLEAR ROTATIONS BEYOND THE ROUTHIAN APPROACH(+)

Ph. Quentin[1,2] and I.N. Mikhailov[2,3]

1) CENBG (IN2P3/CNRS and Univ. Bordeaux I), Gradignan, France
2) Bogolyubov Lab. of Theor. Phys., JINR, Dubna, Russia
3) CSNSM (IN2P3/CNRS), Orsay, France;

We generalize to a wide class of large-scale collective motions in atomic nuclei. the so-called routhian approach, upon incorporating into the quantal theory, classical concepts concerning matter and current distributions as well as using analogies between the formalisms of canonical transformations in classical mechanics and of unitary transformations in quantum mechanics. The stationary solutions so obtained satisfy cranking-like equations with a time-odd (cranking) constraint of the form $\alpha.\mathbf{p}$ where α is a vector field (function of the position **r**) unequivocally associated to the corresponding classical motion velocity field and **p** is the momentum operator.

The solutions of such generalized cranking equations are then searched within the Hartree-Fock approximation using a Skyrme effective nucleon-nucleon interaction. We will present here the corresponding results within a semiclassical approximation (specifically in the Extended Thomas-Fermi framework[1)] up to $\hbar^2$ terms) similar to the one used recently for the routhian case[2)]. Explicit expressions are obtained for the current density whose Thomas-Fermi approximation is exactly found to be the classical one whereas the semiclassical corrections are surface-peaked and similar to Landau diamagnetic corrections for a confined electron gas. Upon extracting the collective velocity-dependent part of the lab energy we have also obtained generalized inertia parameters and the corresponding coupling terms whenever more than a mode is present.

The domain of applications of the present formalism is naturally rather extended. Explicit results will be presented here for the coupling between a rigid body rotation and a specific vortical motion (namely the motion of an ellipsoid having a finite uniform vorticity in the body-fixed frame). The semiclassical results obtained as above discussed, will serve as a guideline to describe the quantal energy/angular momentum curve for the yrast line beyond the usual routhian description. In particular, a possible staggering in this curve will be demonstated.

(+)This work has been made possible by a grant received through a collaboration agreement between JINR (Russia) and IN2P3 (France).

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Microscopic Study of Wobbling Motions

Yoshifumi R. Shimizu and Masayuki Matsuzaki*)
Department of Physics, Kyushu University, Fukuoka 812, Japan
*) *Department of Physics, Fukuoka University of Education,*
Munakata, Fukuoka 811-41, Japan

The wobbling motions are spinning motions of the asymmetric (triaxially deformed) rotor. When quantized, the energy spectra in the (E, I)-plane are classified differently in two groups of bands. One is the "horizontal" sequences and the other is "vertical" sequences, which correspond asymptotically to the Regge trajectories associated with the largest and the smallest moment of inertia, respectively. In the high-spin limit[1], the physical meaning of these two sequences gets more transparent by introducing an elementary excitation of the "wobbling phonon" mode. The horizontal sequences parallel to the yrast line are rotational bands in which the number of wobbling phonons does not change, while the vertical sequences starting from each yrast state consist of the $\Delta I = 1$ multiple wobbling phonon bands.

It is very interesting to ask whether such an "exotic" rotational motion, where the nuclear body rotates *non-uniformly* around a *non-inertia* axis, is realized in atomic nuclei as a collective motion, since it certainly reflects the three-dimensional nature of the nuclear rotations. Notice that the so-called "tilted-axis" cranking scheme is similar in a sense that the cranking axis does not coincide with an inertia axis but the rotation is *uniform* (stationary), which never realizes in the macroscopic rotor model (the uniform rotation is only possible around an inertia axis).

If the non-uniformity is small, i.e. the number of wobbling phonon is small so that the band appears near the yrast line, a fully microscopic formulation is possible in terms of the random phase approximation (RPA)[2]. We have recently extended the results of ref.3) and would like to show and discuss the followings:

1. For (not all but) suitable solutions of the RPA equation, not only the energy spectra but also the interband ($\Delta I = \pm 1$ vertical) E2 transitions can be expressed in the same way as in the macroscopic rotor model.
2. Thus the moments of inertia around all three axes associated to each solution can, in principle, be extracted from the measured energy and B(E2)-values.
3. Theoretical simulations, where the static triaxial deformation of nuclear mean-field is artificially changed, show that the three moments of inertia as functions of the triaxiality, γ, are neither rigid-body like nor irrotational like.
4. Some examples of possible interpretations of existing data are presented.

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Angular-Momentum Cranking Applied to Multiphonon Collective Vibrations

E. R. Marshalek
Department of Physics, University of Notre Dame, Notre Dame, IN 46556

It is shown that the self-consistent angular-momentum cranking technique can be used to generate large-amplitude multiphonon collective vibrational solutions of time-dependent mean-field equations. The method is applicable to nuclei having axially symmetric (uncranked) mean field solutions. It is founded on a new theorem (Cranked Bifurcation Theorem), according to which cranking about an equilibrium axis of symmetry leads to new symmetry-breaking solutions that bifurcate from the axially symmetric solution at the critical cranking frequencies given by $\Omega = \omega_\mu / K_\mu$, where ω_μ is an RPA frequency for any mode carrying $K_\mu \neq 0$ units of angular momentum along the symmetry axis. The bifurcating solutions correspond to aligned multiphonon excitations including possible large-amplitude anharmonicities. A general heuristic proof of the method is provided, as well as a perturbative demonstration within the framework of the cranked Hartree-Fock approximation. In particular, a derivation of the RPA is given using the cranking method. The form of the RPA shows that the cranking method is applicable not only to vibrations built on the ground state, but also to those built on high-K isomers or rotational-band termination states, and to odd-A nuclei. It is also shown that the cranking approach may be extended to phenomenological mean-field models, such as the Nilsson model, to obtain anharmonic corrections to the Vibrating Potential Model. Finally, illustrative examples are given for simple soluble models.

Multiphonon structure of γ-unstable nulcei

T. Otsuka,
Department of Physics, University of Tokyo, Hongo, Tokyo, 113, Japan

P. von Brentano and N. Pietralla
Institut für Kernphysik, Universität zu Köln, Zülpicher Str. 77, W-50937, Köln, Germany

The γ-unstable nulcei are neither a simple vibrator nor rotor. It is, in fact, a quite unique object in many-body problems, and might be found only in nuclei, providing nuclear physics with various challenges. In the Interacting Boson Model (IBM), γ-unstable nulcei are treated as one of the limiting cases; O(6) dynamical symmetry [1]. The mathematically exact description of the O(6) limit is given by quantum numbers such as N (boson number), σ and τ in terms of three Casimir operatrors. But this description is too abstract to see the physical structure of the limit. Recently, we reported [2] that there is a multiphonon structure in the O(6) limit. The multiphonon state is attracting, in general, much interest recently in a wide range of nuclei. The present multiphonon structure has similarities and differnces to the usual phonon model. First of all, eigenstates can be constructed by successive actions of the quadrupole operator $Q=d^{\dagger}s+s^{\dagger}\tilde{d}$. For instance, $|2_1^+\rangle \propto Q|0_1^+\rangle$, $|2_2^+\rangle \propto [QQ]^{(2)}|0_1^+\rangle$, $|4_1^+\rangle \propto [QQ]^{(4)}|0_1^+\rangle$, $|4_2^+\rangle \propto [QQQ]^{(4)}|0_1^+\rangle$, *etc.*, where $|0_1^+\rangle$ is the ground state. This aspect is the strongest similarity. Note that $|0_1^+\rangle$ is neither the boson vacuum nor the s-boson condensate, but it is the real ground state. We mention that $B(E2; 4_1^+\rightarrow 2_1^+) = B(E2; 2_2^+\rightarrow 2_1^+)$ holds as in the usual phonon model. The major difference is that the ground state is deformed due to the quadrupole interaction $H=-\kappa(Q\bullet Q)$, and indeed contains various configurations with many s and d bosons. Because of this, the double action coupled to spin zero yields $[QQ]^{(0)}|0_1^+\rangle \propto |0_1^+\rangle$, i.e., the state is kept to be the ground state. Therefore, the two-phonon 0^+ state is forbidden, as confirmed recently for ^{130}Ba experimentally [2]. The eigenstates can be constructed exactly in the above way up to three-phonon states. Above four-phonon states, the scheme becomes slightly more complex due to the orthogonalization process for some states [2], while all states of σ=N, which are lowest in energy, can still be created.

Thus, the O(6) can be considered as a system of multiphonon states. It is now of much interest how widely this mulitiphonon structure prevails if the rigorous O(6) dynamical symmetry is broken more or less. Such theoretical and experimental studies are in progress. There should be a similar structure in the Wilet-Jean model.

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Tilted Axis Cranking Description of Four Quasi–Particle Bands in Xe– and Ba–Nuclides

F. Dönau[1], P. von Brentano[2], S. Frauendorf[1], A. Gelberg[2], and O. Vogel[2]

[1] *Forschungszentrum Rossendorf, Dresden, Germany*
[2] *Institut für Kernphysik, Universität zu Köln, Köln, Germany*

Excited bands characterized by strong $\Delta I = 1$ transitions and relatively weak crossover $\Delta I = 2$ transitions have been identified in several even-even Xe and Ba nuclei [1–4]. The similarity of the transition energies in different nuclides suggests a common intrinsic structure of these bands. The theoretical investigation is based on the Tilted Axis Cranking Model [5] which allows one to treat the case of a non-principal axis of rotation. The calculation for ^{128}Ba specifies so-called t-bands which carry substantial quasiparticle angular momentum along both the symmetry and the collective axis in an oblate shaped configuration. The intrinsic orientation of the calculated angular momentum $\vec{J}$ is shown in Fig.1. The experimental energy and spin sequence can be reasonably reproduced for a negative parity configuration $(\nu h^2_{11/2})(\pi h_{11/2} d_{5/2})$. Within the same approach the B(M1) and B(E2) values of intra band transitions are calculated. Strong M1 rates are found as a consequence of the tilted quasiparticle spins. The calculated branching ratios B(M1)/B(E2) for the t-band are consistent with the observation of relatively strong M1 and weak E2 transitions. An excitation energy of 5-6 MeV is estimated for the band head having an effective K-value of approximately 10 $\hbar$. Experimentally the decay out of the t-band was not seen which indicates that the available final states possess rather different intrinsic structure.

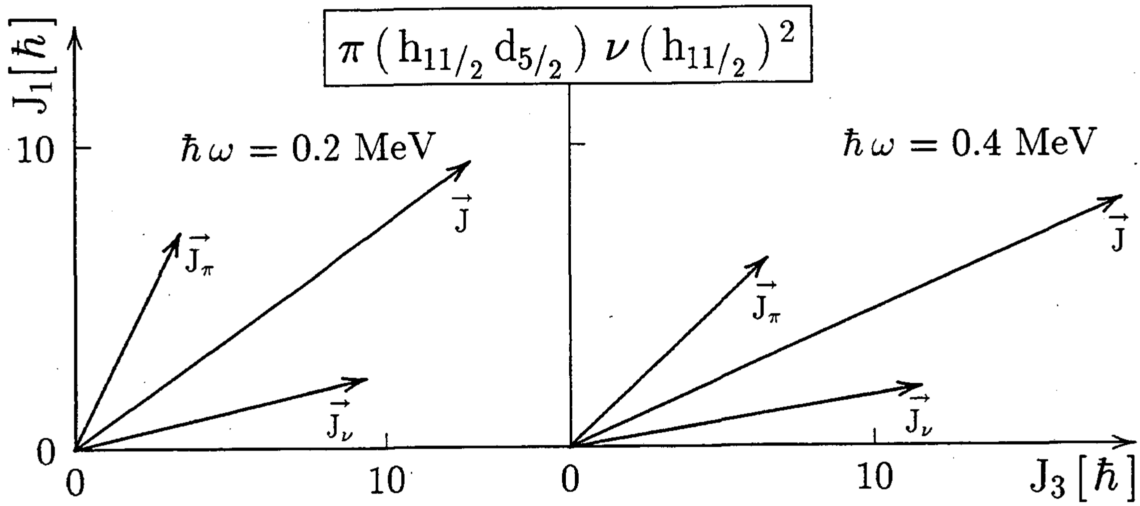

Fig.1 Angular momentum composition in the tilted 4qp configurations for two frequencies. In the considered case the intrinsic 1-axis is the symmetry axis.

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Tilted Cranking

S. Frauendorf
Institut für Kern- und Hadronenphysik,
Forschungszentrum Rossendorf e.V.,
PF 510119, 01314 Dresden, Germany

The recently developed Tilted Axis Cranking (TAC) theory [1] is applied to study two novel phenomena in nuclei:

1. Magnetic Rotation

2. Shapes with a fourfold symmetry axis

Magnetic rotation is characterized by regular $\Delta I = 1$ bands with strong M1 transitions and almost vanishing E2 transitions. It appears close to magic shells, in nuclei are almost spherical. The anisotropy of the single particle density matrix, leading to the regularity of the energy spacings is measured by the magnetic dipole vector. In contrast, ordinary rotational bands in open shell nuclei have a deformed charge distribution that measures the anisotropy of the density matrix. We call the latter electric rotation, since the deformed charge couples to the electromagnetic field, whereas for magnetic rotation the magnetic vector is responsible for this coupling. In many cases rotation is both electric and magnetic. Almost pure magnetic rotation has been observed in the light Pb isotopes (Shears Bands) [2]. It is predicted for other regions of shperical nuclei, when high j-protons combine with high j-neutron holes or vice versa. The nature of the symmetry breaking is studied by comparing the TAC with shell model calculations and the experiment.

The rotation of nonaxially deformed nuclei, whose long axis (3-) is a fourfold symmetry (C_4-) axis is studied by means of the TAC. Expanding the energy into powers of the angular momentum components $I^2_{1,2,3}$ a quartic term $B(I_1^2 - I_2^2)^2$ is obtained. A quantal hamiltonian with such a term may have low lying bands showing a $\Delta I = 4$ staggering of the transition energies. The relation of these theoretical estimates with the recently observed $\Delta I = 4$ staggering in some superdeformed and deformed nuclei [3] is discussed.

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Angular Momentum Orientation in $^{181,182}Os$

S. Frauendorf[1], Jie Meng[1,2], R.M. Lieder[3] and T. Kutsarova[4]

[1]Institut für Kern- und Hadronenphysik, Forschungszentrum Rossendorf, 01314 Dresden, Germany [2]Institute for Theoretical Physics, Academica Sinica, Bejing, China [3]Institut für Kernphysik, KFA Jülich, 52425 Jülich, Germany [4]Institute for Nuclear Physics and Nuclear Energy, 1784 Sofia, Bulgaria

It has been suggested [1, 2] that in the heavier rare earth nuclei the first crossing in the yrast band is not always due to the familiar s-band, where two $i_{13/2}$ neutrons couple to a configuration with a large angular momentum component along the collective axis 1 and none along the symmetry axis 3. As a competing configuration appears the t-band, for which the two $i_{13/2}$ neutrons couple to an angular momentum with large components along both axes, the total angular momentum pointing into a direction between the two axes. In $^{181,182}Os$ such band crossings have been observervered [3], as shown in fig. 1. In ^{182}Os three bands of $\nu i^2_{13/2}$ configuration have been found. One has the characteristics of an s-band and two have at low frequencies the features of t-bands, since they show no signature splitting. In ^{182}Os the individuality of the s- and t-bands disappears at the crossing with the ground band. Studying the structure by means of a particle rotor model a strong mixing of the t- and s-bands is found. This can be interpreted as strong fluctuations of the angular momentum orientation in ^{182}Os. In ^{181}Os the t-band results from a coupling of the $7/2^-[514]$ quasineutron to the $\nu i^2_{13/2}$ configuration. It is a $\Delta I=1$ sequence which shows no signature splitting and starts at a band head with $I=K=23/2$. It acquires quickly considerable alignment with respect to the $7/2^-[514]$ band. Hence it has all features of a t-band. Futhermore, the experimental B(M1)/B(E2) ratios agree well with the values predicted for a t-band [3]. The t-band in ^{181}Os lies considerably lower in excitation energy than that in the neighbouring nucleus ^{182}Os. In ^{181}Os, therefore, the crossing with both the s- and t-bands is seen. The t-band preserves its character to high rotational frequencies since the odd $7/2^-$ neutron fixes the direction.

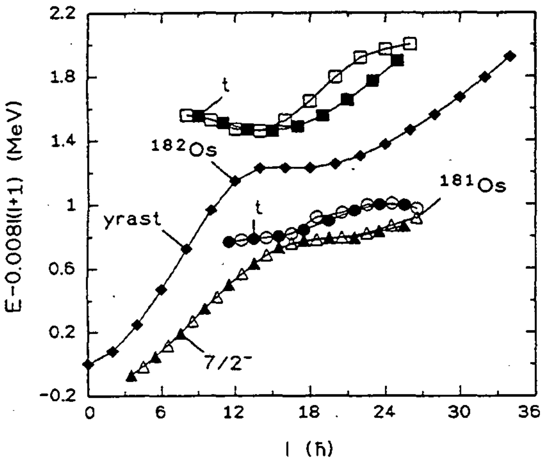

Figure 1: Plots of excitation energy vs. spin in $^{181,182}Os$

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Tilted Axis Rotation Studied by Self-consistent Cranking Model

Naoki Onishi

Institute of Physics, College of Arts and Sciences, University of Tokyo,
Komaba, Meguro-ku, Tokyo 152, Japan

and

Takatoshi Horibata

Department of Information System Engineering, Aomori University
Kouhata, Aomori-city, Aomori, 030, Japan

The dynamics of nuclear rotation including precession and wobbling is studied in order to make clear the mechanism dominating collective motions in nuclei, especially in the γ-unstable region, e.g., isotopes of tungsten or osmium. The wobbling motion is associated with triaxiality of nuclear deformation, and hence is likely to be strongly coupled with the fluctuation of γ-degrees of freedom. In fact, classical motions for a macroscopic model of the γ-soft rotor exhibit a remarkable dynamics interweaving the γ-vibration and the wobbling motion, and are shown to possess a typical feature of nonlinear mechanical systems[1]. It is interesting to see how these mechanisms manifest themselves in the collective state in the microscopic nuclear system.

A semi-calassical microscopic model, based on a kind of time-dependent variational method[2),3)], is employed for the analysis of the motion, in which intrinsic wave functions $|\Phi\rangle$ related with total wave function $|\Psi\rangle$ through $|\Psi\rangle = e^{-i\phi \hat{J}_z} e^{-i\theta \hat{J}_y} e^{-i\psi \hat{J}_z} |\Phi\rangle$, are labeled by tree components of the angular momentum vector $\boldsymbol{J} = \langle \Phi \mid \hat{\boldsymbol{J}} \mid \Phi \rangle$. The Euler angles $(\phi\theta\phi)$ and three components of the angular momentum $\boldsymbol{J}$ are considered as dynamical variables describing the nuclear rotation and wobbling motion. The intrinsic states are generated by the following variational equation for the constrained HFB,

$$\delta\langle\Phi \mid \left[\hat{H} - \sum_{k=1}^{3}\left(\mu_k \hat{J}_k + \xi_k \hat{B}_k\right) - \sum_{\tau=\pi}^{\nu} \lambda_\tau \hat{N}_\tau\right] \mid \Phi\rangle = 0 \,, \tag{1}$$

where $\hat{B}_k$'s stand for the off-diagonal element of mass-quadrupole operators. The chemical potentials λ_τ are determined to keep the expectation value of the nucleon number $\langle \Phi \mid \hat{N}_\tau \mid \Phi \rangle$ at a certain value. The variational equation having eight constraints is solved numerically with the method of steepest descent.

Intrinsic wave functions of three dimensional space are set up first by cranking up along the principal axis of the mass quadrupole moment (PAR). After constructing the PAR states, we launch off from the PAR-states to explore to three dimensional rotation. In the course of study, states of stationary rotation along an axis tilted from the principal axis of the mass-quadrupole moment are found in yrast states of ^{182}Os nucleus for a set of parameters employed in a model calculation[4]. Local minima of energy on the sphere of $|\, \boldsymbol{J} \,| = M$ are found. This suggests the existence of tilted axis rotating states (TAR), because the gradient of energy $\boldsymbol{\mu}$ is parallel to the angular momentum $\boldsymbol{J}$ and time derivative of the angular momentum refered to intrinsic frame is proportional to $\boldsymbol{J} \times \boldsymbol{\mu}$ [2].

In TAR states, the signature is not good quantum number, in other words, the states includes states possessing odd number angular momentum. Back and forth tunneling motion recovers the signature (even-odd of angular momentum). The existence of TAR solutions in yrast implyes a possible new interpretation for the backbending phenomena in nuclei of γ-unstable region, and serves an explanation of abnormal spectrum observed in the γ-vibrational band in ^{182}Os nucleus. We study intensively and present the microscopic feature of the wave functions of TAR in detail.

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Terminating bands

I. Ragnarsson
Department of Mathematical Physics, Lund Institute of Technology,
P.O. Box 118, S-221 00 Lund, Sweden

The yrast spectra of nuclei with a few particles outside closed shells are non-collective, i.e. there main features can be understood by rearranging the valence particles over spherical j-shells. If more valence particles are added, however, collective spectra are formed where the spin is built from small contributions of many particles resulting in smooth collective bands (rotational bands). For medium-heavy nuclei with mass numbers 100-150, a minimum number of $\sim$ 10-15 valence particles are needed before collective bands are really formed. With so few valence particles and with the core particles in filled j-shells, it is evident, however, that the spin in the configuration is limited. Assuming that each particle on the average can contribute with $3-4\hbar$, this limiting spin will correspond to $40-50\hbar$. Yrast states in this spin range can be studied experimentally today.

A special situation occurs if one can follow how one configuration in a continuous way evolves from high collectivity at low spin to a terminating state at high spin corresponding to the maximum spin within the configuration, a terminating *band*. The ground band of ^{20}Ne with the valence configuration $\pi(d_{5/2})^2\ \nu(d_{5/2})^2$ has a maximum spin of $I = 8\hbar$ and the ground band of this nucleus is since long known up to this terminating spin value. However, the whole concept of a rotational band is somewhat questionable in this light nucleus.

An interesting region is the nuclei around ^{158}Er, which at high spin can be described as a ^{146}Gd core + valence particles. For example, in the nucleus ^{158}Er, several terminating states with spins in the $40-50\hbar$ range are known and the relative energies of these states fit well with what one gets from shifting the last valence particle within the active j-shells[1]. However, from the terminating *band* point of view, the ^{158}Er configurations are not ideal because with decreasing spin they quickly go away from the yrast line and are thus difficult to follow over a large spin range. Even if they can be followed, they interact with other bands so the configuration does not remain pure.

Relative to the ^{158}Er region, the possibility to follow some terminating sequence over many transitions would be better if, close to the termination, the slope of the E vs. I curve was similar to (or larger than) the average E vs. I slope for the yrast states. Then, if the terminating state is yrast, one could expect the terminating sequence to stay yrast and thus relatively pure over a large spin range. Consequently, one could hope to observe a smooth terminating band. The case with a large E vs. I slope appears to be realized in collective bands in nuclei with a few particles outside the ^{100}Sn core, e.g. ^{109}Sb[2,3] and neighbouring nuclei[4]. The properties of the corresponding configurations and their relations to terminating bands in other regions will be discussed.

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Alignement properties of superdeformed fast rotating nuclei in a microscopic mean field description.

P.-H. Heenen [1], P. Bonche [2], H. Flocard [3]

[1] *Service de Physique Nucléaire Théorique U.L.B - C.P. 229 - B1050 Bruxelles - Belgium*

[2] *Service de Physique Théorique, CE Saclay - F91191, Gif sur Yvette Cedex, France*

[3] *Division de Physique Théorique, IPN - F91406, Orsay Cedex, France*

Abstract Mean field calculated from two body interactions are affected in several ways by the rotation of the nucleus. Shape changes can be phenomenologically incorporated in potential approximations of the mean field by minimising the total routhian with respect to the parameters describing the shape of the nuclear density. However, shape changes are not the only effect of rotation: the functional form itself of the mean field is affected. New terms appear when time reversal invariance is broken; their explicit form can be written in the case of a Skyrme like interaction.

In this communication, we analyse the effect of these terms on the dynamical moment of inertia of superdeformed nuclei. Although the contribution of these terms to the total energy is always small (1.0Mev in ^{194}Pb at $40\hbar$), they modify significantly the alignements of some single particle states. We will show on specific examples that the rotational frequency effectively felt by the nucleons is increased inside the nucleus but is significantly decreased and can even change sign on the nuclear surface.

High spin physics with density dependent forces

J. L. Egido and **L. M. Robledo**
Departamento de Fisica Teorica, Universidad Autonoma de Madrid, E-28049 Madrid, Spain

In the past, most of the studies on nuclear properties at high angular momentum have been performed within the Strutinski approximation or with separable forces, such as Pairing plus Quadrupole. Not much has been done, however, with realistic effective forces, mainly because of computational difficulties, but also due to the not very promising early results.

In recent publications [1] we have shown the feasibility of performing high angular momentum calculations with the density dependent Gogny force within the selfconsistent Hartree-Fock-Bogoliubov (HFB) approximation with cranking. The Gogny force has the advantage on other density dependent forces, as the Skyrme force, of dealing properly with the pairing correlations. Its' finite range makes it possible to take into account pairing correlations of all multipolarities.

In this work we review on extended calculations performed within this approximation for the A=100 region, the Rare Earth and the Actinide regions. We discuss, among others, energy levels, moments of inertia, pairing gaps and electromagnetic properties up to very high spin. Results on normal deformed, superdeformed and hyperdeformed nuclei are shown for several nuclei. The comparison with the experimental data is very good. Several predictions on hyperdeformed nuclei are also presented.

Preliminary results on particle number projected HFB calculations with the Gogny force are also discussed for superdeformed nuclei at high angular momentum.

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MICROSCOPIC MODEL OF DEGENERATE $K = 5/2$ BANDS IN ^{153}Eu

C.R. Praharaj[1] and A.K. Rath[2]

[1] Institute of Physics, Bhubaneswar - 751005. India

[2] Sambalpur University, Jyoti Vihar - 768019. India

The band structure in ^{153}Eu have been calculated by angular momentum projection from deformed intrinsic configurations. The intrinsic configurations were obtained by Hartree-Fock calculation involving thirteen protons in $g_{7/2}, d_{5/2}, s_{1/2}, h_{11/2}, d_{3/2}$ and $h_{9/2}$ orbits and eight neutrons in $f_{7/2}, p_{3/2}, f_{5/2}, h_{9/2}, p_{1/2}, i_{13/2}$ orbits (Z = 50, N = 82 core was assumed) using surface delta residual interaction. Axial symmetry was imposed in the Hartree-Fock calculation. Some details of the theoretical formalism are given in ref.1. The last odd proton occupies $5/2^+$ state with $5/2^-$ and $3/2^+$ orbits nearby in energy. The angular momentum projected spectra for $K = 5/2^+, K = 5/2^-$ and $K = 3/2^+$ bands are compared with experimental results [2]. The main features of the nearly degenerate $K = 5/2^-$ and $K = 5/2^+$ bands are well reproduced and we predict these bands upto $I = 51/2$. A lowlying $K = 3/2^+$ band is predicted in our calculation. The question of octupole deformation in A = 150 region is also under study. ^{152}Sm and ^{153}Eu have parity-mixed Hartree-Fock solutions which are lower in energy than the HF solutions with good parity.

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Nuclei Around $^{44}_{16}S_{28}$

T.R. Werner[1,2,5], J.A. Sheikh[3,6], W. Nazarewicz[1,2,3,5],
M.R. Strayer[1,2], A.S. Umar[4], and M. Misu[2]

[1] *Physics Division, Oak Ridge National Laboratory**
[2] *Department of Physics and Astronomy, University of Tennessee*
[3] *Joint Institute for Heavy-Ion Research, Oak Ridge, Tennessee*
[4] *Department of Physics, Vanderbilt University, Nashville, Tennessee*
[5] *Institute of Theoretical Physics, Warsaw University*
[6] *Tata Institute of Fundamental Research, Colaba, Bombay*

Exotic nuclei far from the β-stability line are now becoming a new challenge for nuclear structure theory. In this work we study the Si, S, and Ar isotopes, with special emphasis on neutron-rich ones. Of special interest among them are isotones with N$\sim$28. This choice was motivated by recent experimental and astrophysical interest in this mass region. We focus our attention on: (i) the onset of deformation around the N=28 magic gap, (ii) stability of the heaviest Si, S, and Ar nuclei, and (iii) the role of pairing correlations.

Our analysis is based on the Hartree-Fock (HF) model with Skyrme forces, and the relativistic mean-field approximation (RMF). HF calculations are performed by discretizing the energy functional on a three-dimensional Cartesian spline collocation lattice. No self-consistent symmetry has been imposed. In the RMF calculations, we employ the NL-SH set of parameters. The pairing Hamiltonian was approximated by monopole pairing with approximate particle number projection by means of the Lipkin-Nogami method. On the drip line nuclei, pairing leads to the scattering of pairs from bound states to continuum, yielding "particle gas" surrounding the nucleus. To analyze this phenomenon, we also perform calculations with strongly reduced pairing.

The quantities being calculated are separation energies, masses, mass radii, charge radii, and deformations (quadrupole moments.) The results are compared with predictions of the finite-range droplet model, extended Thomas-Fermi with Strutinsky integral model, and with experimental data, where available. Differences between all the models when approaching the drip lines are discussed.

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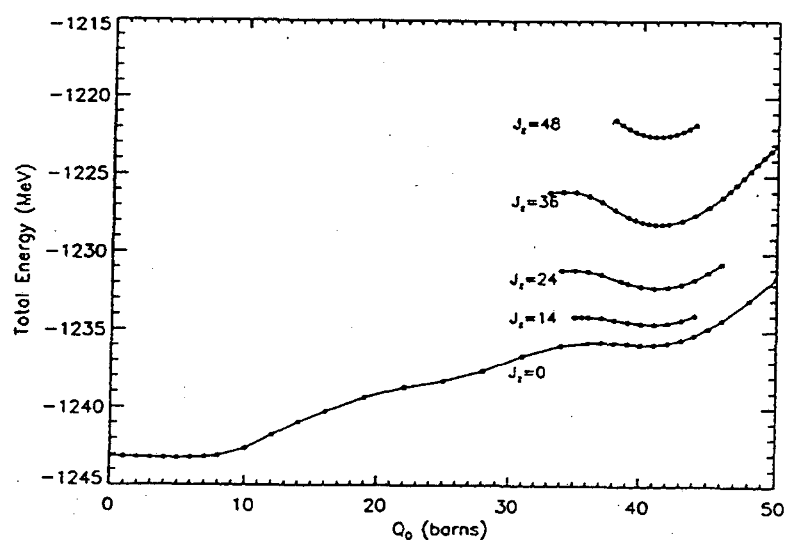
Explanation of the Disappearance of Rotational Bands at Low Angular Momentum

R. Mehrem, P. Bonche, H. Flocard, P.H. Heenen, S.J. Krieger and M.S. Weiss
Physics Department, LLNL, Livermore, California 94550, USA

Nuclear Structure has been significantly revived by the discovery of superdeformed (SD) bands at high spins. Following the initial finding of a band in ^{152}Dy, many nuclei of the Dy, Ce and Hg regions of the chart table have been shown to possess SD rotational bands within their excited spectrum. The question of a minimum angular momentum for the establishment of the band heads has been of significant interest to both experimenters and theorists. We present here for the first time the results of an ab initio, completely microscopic, calculation which explicilty displays the importance of angular momentum in stabilizing the superdeformed well. Our method uses an effective two-body density-dependent interaction of the Skyrme type to describe the mean-field and a seniority interaction for the pairing correlations, which are treated in the Lipkin Nogami approximation. Simultaneously constraining the quadrupole moment and j_z, we have effected Hartree-Fock-Bogoliubov calculations to calculate the deformation energy curve in the quadrupole degree of freedom for several values of j_z for the nucleus ^{152}Dy. As may be observed in the figure there is a superdeformed well at approximately 40 barns with a depth which increases from 1 MeV at $j_z = 24$ to 2 MeV at $j_z = 36$. The disappearance of the well as the angular momentum is decreased below $j_z = 24$ is strongly supportive of the experimental observation that no superdeformed states have been found at such values of the angular momentum .



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Study of Nuclear Energy Surfaces Using Massively Parallel Processors

R. R. Chasman, Physics Division, Argonne National Laboratory, Argonne, IL 60439

Using the Strutinsky method, I am studying nuclei in the mass region A = 140 to A = 200 to find nuclei with superdeformed and hyperdeformed shapes that are experimentally accessible. The time intensive step, in this approach, is the calculation of single particle energies and shell corrections at all grid points in a multi-dimensional shape space. Because of the limitations of conventional computer resources, searches on a grid in shape space are usually limited to two, and sometimes three, dimensions. Massively parallel processor systems, such as the SP1 at Argonne, are making it feasible to carry out extensive four dimensional studies of nuclear energy surfaces in shape space. Typically, the axes in shape space are the magnitudes of amplitudes in a Legendre expansion of the nuclear shape. However, we have found[1)] that the introduction of an explicit necking degree of freedom is quite advantageous for the study of very extended nuclear shapes. In this study, I extended the shape space to include octupole deformation in addition to explicit necking, quadrupole and hexadecapole deformations. The quadrupole, hexadecapole and necking degrees of freedom cover the same range as given in Ref. 1. The octupole deformation is varied from 0 to 0.20 in steps of 0.05. Cranking is used to study the nuclear energy surfaces up to angular momenta of 90 $\hbar$.

A preliminary analysis of our results shows quite distinct effects of the octupole degree of freedom for the three high spin minima that are roughly characterized by axis ratios of 1.5:1, 2.2:1 and 3:1 in the A = 180 mass region. The shape minima characterized by axis ratios of 2.2:1 are found to be accessible in more nuclides than was the case in our previous calculations. Octupole deformations play an important role in describing these shapes. The nuclides in which these minima are accessible will be discussed in detail. The energies of the minima characterized by 1.5:1 axis ratios go up fairly steeply as a function of octupole deformation. The minima characterized by a 3:1 axis ratio are somewhat softer with respect to octupole deformation. The inclusion of both the octupole and necking degrees of freedom also modifies the energy surface in the vicinity of the fission barrier. These degrees of freedom typically give reductions of 1 to 2 MeV in the nuclear energy surface in the barrier region. Results of a four dimensional study of the ^{152}Dy region, where a hyperdeformed minimum has been reported, will also be discussed.

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Shape coexistence and shape change path in Hg isotopes

K. Sugawara-Tanabe and K. Tanabe†

Otsuma Women's University, Tama, Tokyo 206 Japan
† Saitama University, Urawa, 338 Japan

The deformation parameters β and γ are self-consistently determined within a mean field theory accompaning three constraints on nucleon numbers and angular momentum. The interaction strength parameters are only 4 and chosen to reproduce the yrast energy level sequence of ^{190,192,194}Hg, a total of 40 levels reasonably well. However the mean field theory gives the absolute value of β and not its phase. So we solve RPA equations for the giant dipole resonance, where the behaviour of three strength functions S_x, S_y and S_z gives another decision of β including its sign. We found the shape change occurs according with the increasing angular momentum and mass number. For example the yrast band of ^{194}Hg has three different shapes; the 0^+ state has collective oblate shape, but the 10^+ state non-collective prolate shape and the 30^+ state non-collective oblate shape. These results agree with the experimental observation[1]. The absolute value of β does not change much keeping almost 0.13 over these nuclei and over the spin range from 0^+ to 34^+. In ^{192}Hg the 0^+ has collective oblate shape, 10^+ state spherical shape and 30^+ collective prolate shape. In ^{190}Hg, both of 0^+ and 10^+ has collective oblate shape, but 30^+ changes to collective prolate shape. Then we have extended our formalism to include the temperature effect quantum mechanically using the same 4 parameters. We found the shape change path is different between the yrast case ($kT = 0$ MeV) and $kT = 3$ MeV case ($\sim$ 95 Mev excitation from the yrast). In ^{194}Hg at $kT = 3$ MeV, both of the 0^+ and 10^+ states have collective oblate shapes, but 30^+ has spherical shape. Both in ^{192}Hg and ^{190}Hg all 0^+, 10^+ and 30^+ states have collective oblate shape at $kT = 3$ MeV. The resonance energy moves to the lower energy and the peak height of the absorption cross section decreases according with the increasing temperature or the increasing angular momentum. These characteristics are explained easily from the thermal energy weighted sum rule[2] and agrees with the experimental observation[3].

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Signature inversions of odd-odd $A \sim 130$ nuclei with the particle-rotor model

N. Tajima,
Institute of Physics, University of Tokyo, Komaba, Meguro, Tokyo 153, Japan.

In a region of mass number $A \sim 130$, signature inversions of rotational spectrum have been observed in odd-odd nuclei at low spins including the bandhead states. The inversions also have been found in another region of mass number $A \sim 160$, where they take place in odd-A nuclei at higher spins than the first backbending, *i.e.*, in 3qp bands.

It has been known for 11 years that signature inversions can be caused in the cranking model by violating the axial symmetry of the potential and choosing the shortest axis of deformation as the rotation axis. However, this explanation suffers from a serious problem that, assuming as usual that the moments of inertia depend on the deformation in the same manner as those of irrotational flow do, the nucleus prefers to rotate around its intermediate-length principal axis: Such rotation increases the signature splitting with the normal sign rather than reverse it. Therefore, as several authors have already tried, one should consider the effects of another important ingredient, *i.e.*, the residual interaction between quasiparticles.

In this paper, I adopt the framework of Semmes and Ragnarsson, who introduced a zero-range residual interaction, and intend to improve their results. The model is a particle-rotor model in which a proton and a neutron quasiparticles are coupled with a triaxial rotor. The quasiparticles interact with each other through a zero-range force.

Firstly, I take up a nucleus ^{124}Cs, for which the results of very reliable spin assignment experiment are available, and show that one can reproduce the signature dependence of energy and B(M1)/B(E2) ratio best when one takes into account γ-deformation with irrotational-flow moment of inertia in addition to the proton-neutron interaction proposed by Semmes and Ragnarsson.

Secondly, including both effects, I perform a systematic calculation of signature splittings for Cs, La isotopes and some N=75 isotones. The agreement with experiment is good for Cs isotopes except ^{128}Cs. For La isotopes and ^{128}Cs, the experimental splittings are of the opposite sign to those of $^{120-126}$Cs. My calculation does not produce such opposite-sign behaviors between ΔZ=2 or ΔN=2 nuclei. To clarify the origin of these discrepancies, I dare suggest that more reliable experimental spin-assignments for these nuclei seem necessary as well as refinements of theoretical models.

I thank Drs. I. Ragnarsson and P. Semmes for providing their particle-triaxial-rotor model code for odd-odd nucleus.

Ground state correlations and charge transition densities

D.Karadjov[a], V.V.Voronov[b] and F.Catara[c]

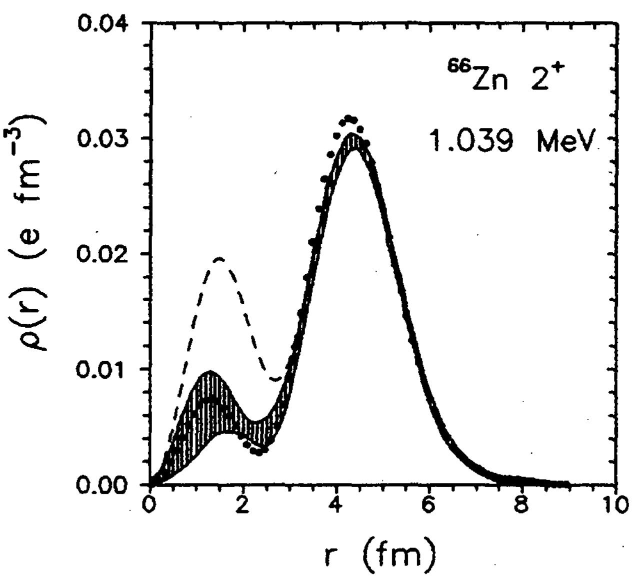
[a)]Institute for Nuclear Research and Nuclear Energy, boul. Tzarigradsko Chaussee 72, 1784 Sofia, Bulgaria

[b)]Bogolubov Laboratory of Theoretical Physics, JINR, 141980 Dubna, Moscow Region, Russian Federation

[c)] Dipartimento di Fisica dell' Universita' and INFN, Sezione di Catania, 57, Corso Italia – I 95129 Catania, Italy

It is well known that many basic features of the nuclear vibrational states can be described within the Random Phase Approximation (RPA), which enables one to treat some correlations in the ground state. Being the spatial overlap between the ground state wave function and the excited state wave function the charge transition density provides a good test for nuclear models. Recent experimental and theoretical (based on the RPA) studies [1] of the charge transition densities to investigate the interplay between single–particle and collective degrees of freedom in the excitation of the low-lying states in some spherical nuclei are in reasonable agreement, but the theory gives fluctuations of the transition densities in the interior region. In RPA, as in the Hartree-Fock approach, the theoretical fluctuations are too large in the nuclear interior, which indicates a systematic problem of a more fundamental nature.

The effect of ground state correlations on the charge transition densities of vibrational states in spherical nuclei is studied. The problem for the ground state correlations (GSC) beyond RPA leads to a non–linear system of equations [2], which is solved numerically. The influence of the correlations on the pairing is taken into account too. As one can see from a figure the inclusion of ground state correlations beyond RPA (dotted curve) results in an essential suppression of the charge transition density in the nuclear interior in comparison with the RPA calculations (dashed curve) and enables one to reproduce the experimental data (dashed area).



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SHAPE COEXISTENCE AND DEFORMATION-INCREASING DECAY IN ^{131}PR

N.C. Schmeing
McMaster University

Abstract. Two pairs of rotational bands with no signature splitting and strong inband M1 transitions have been observed in ^{131}Pr. One pair are the enhanced deformation (ED) bands reported separately at this meeting [Galindo-Uribarri et al]. The other pair of bands (high-K bands) have the same structure as the K=7$^-$ isomeric bands in the ^{130}Ce core [Todd et al, J. Phys. G. **10**(1984)1407]; plus an additional $h_{11/2}$ quasiproton as in the ^{131}Pr yrast band. Despite significant differences in structure, and the possibility in principle to decay into bands of similar deformation, the high-K bands are found to decay into the more deformed ED bands.

Although both pairs have positive parity, the ED bands have positive-parity neutrons and a positive-parity odd proton, while the neutrons in the high-K bands have a two-quasiparticle, negative-parity neutron configuration combined with a proton configuration bearing the negative parity of the odd proton. Thus the bands differ by at least 3 quasiparticles. The K value for the ED bands is 9/2, 4 units smaller than the prediction of 17/2 for the high-K bands. Furthermore, the deformation is not even close: Total Routhian Surface calculations show coexisting prolate minima at β_2 of 0.33 (ED) and 0.25 (high-K) for these bands.

Corresponding to the smaller deformation are also the $\pi h_{11/2}$ yrast band and a pair of [411]3/2 quasiproton bands.

Because the rotational frequency is very low at the bottom of the ED bands (<200 keV $\hbar^{-1}$), their dynamical moment of inertia provides opportunity to view the pairing quite sensitively. BCS monopole pairing calculations indicate that the moment of inertia should rise strongly from a small magnitude at the bottom of the band; this is not consistent with the data. Unpaired calculations reproduce well the magnitude of the moment of inertia, which is similar to that of other ED bands in the region, even at the lowest frequencies. Some effects of pairing are, however, observed, so that one can conclude that for the ED bands the pairing has a different form from the usual BCS.

Quadrupole Pairing Interaction Suitable for Deformed Rotating Nuclei

Yoshifumi R. Shimizu
Department of Physics, Kyushu University, Fukuoka 812, Japan

Recent high-spin data, both in normal and superdeformed nuclei, seem to require rather strong state-dependent pairing correlations which cannot be accounted for by the usual monopole-type pairing force. One might naturally think of the quadrupole-type pairing interaction as a next order term of the expansion of a short range interaction. It should, however, be noticed that the explicit form of the interaction may be modified for deformed nuclei, as it is demonstrated by Sakamoto and Kishimoto for the QQ interaction in the particle-hole channel.

In order to find what is the most suitable form of the quadrupole pairing interaction, systematic calculations in medium and heavy nuclei are performed. The criteria are similar to those of ref.1); (a) the even-odd mass differences and (b) the moments of inertia for the ground states in even-even nuclei should be well reproduced. Since the moment of inertia is sensitive not only to the pairing correlations but also the deformations, the deformation parameters, (ϵ_2, ϵ_4), in the Nilsson potential are fixed by the Nilsson-Strutinsky method. The pairing interaction used has the form

$$V_{pair} = -G_0 P_0^\dagger P_0 - G_2 \sum_K P_{2K}^\dagger P_{2K},$$

where $P_{2K}^\dagger$ is either the usual quadrupole or the doubly-stretched quadrupole pair operator. The strength G_0 is determined by the smooth-gap method through $\tilde{\Delta}_0 = g/\sqrt{A}$ (MeV), and then G_2 is parametrized as $G_2 = f\, G_0/R^4$ with $R = 1.2A^{1/3}$fm. Two parameters, g and f, are fixed so as to obtain good agreements for more than a hundred of nuclei. It is found that a reasonable fit can be obtained if using the doubly-stretched quadrupole pairing force but not when the non-stretched one is used.

Now the quadrupole interaction thus determined is applied to the high-spin states. I would like to discuss the followings:

1. Is the values of the strength G_2 obtained consistent with other previous works, for example, ref.1)-3) ?
2. How much the property of collective rotations is improved, especially the rotational frequency dependence of moment of inertia?
3. How about the effects on the first band-crossing, especially the difference of crossing frequencies in even and odd nuclei[4) ?
4. Does the quadrupole pairing help to make the moment of inertia of even and odd nuclei identical?

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Deformation, pairing and g(2^+) values in rare-earth nuclei

Andrew E. Stuchbery

Department of Nuclear Physics, Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia

The discovery of "identical bands" in nuclei at both superdeformation and normal deformation has renewed interest in the theory of moments of inertia. In rotational nuclei, the g-factors of the excited states reflect the ratio of the proton moment of inertia to the total moment of inertia and so provide a means of separating the behaviour of the proton and neutron fluids. Consequently, studies of magnetic moments could illuminate the identical bands problem.

Zhang *et al.* [1] performed an empirical survey of ground-state rotational bands in even-even rare-earth nuclei, finding that changes in the moments of inertia are correlated with changes in the ratio of deformation to pairing gap (ϵ/Δ). Halbert and Nazarewicz [2] have shown that the global features of this empirical study can be understood theoretically using the Migdal estimate of the moment of inertia [3].

The present work uses the same approach as Halbert and Nazarewicz [2] to calculate g(2^+) values in rare-earth nuclei, treating the average behaviour of the nucleon superfluid approximately and taking account of the underlying single-particle motion only through microscopic calculations of the deformations and pair gaps. Results are shown in fig. 1. With some clear exceptions, the agreement between the experimental and theoretical g(2^+) values for nuclei between ^{146}Nd and ^{192}Os is good.

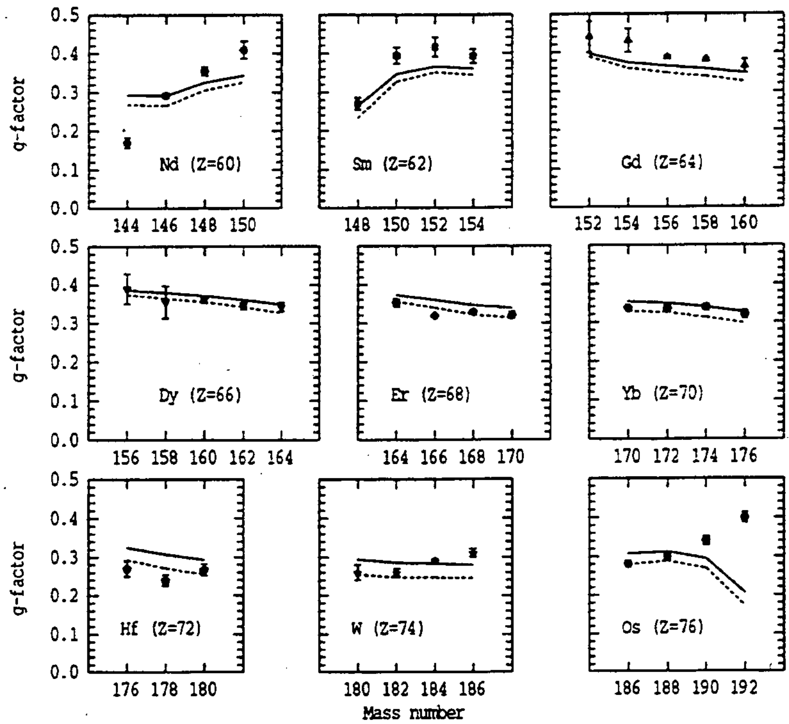

Fig. 1
Measured and calculated g-factors in rare-earth nuclei.

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g factors and high spin structure of ^{154}Dy

A. Ansari
Institute of Physics, Bhubaneswar- 751 005, India

Recently [1] g factors of ^{154}Dy have been measured up to very high spins ($I \approx 34$). The uncertainties are rather large. The experimental value of g_4 seems to be slightly larger than g_2, but for $I > 6$ it shows a decrease with a minimum at $I \approx 16$ and $g_{34} > g_2$. We [2] have performed a selfconsistent cranked Hartree - Fock - Bogoliubov (CHFB) calculation for ^{154}Dy with a standard pairing plus quadrupole model hamiltonian. The minimum in g-value at $I \approx 16$ and rise for the higher spins is very well reproduced. But in the low spin part the value of g factor starts decreasing right after $I = 2$. The experimentally observed ratio g_4/g_2 , slightly greater than unity, is not obtained though beyond $I = 4$ the decreasing trend is very well understood in terms of the rotation alignment of $i_{13/2}$ neutrons.

We have also investigated the effect of hexadecapole deformation degrees of freedom but there is no improvement on the variation of g factors with I. On the other hand the shape remains almost axial upto $I = 40$. Otherwise (without hexadecapole) the shape comes out to be triaxial for $I > 30$ with deformation parameter $\beta \approx 0.20$.

In a very recent paper [3] g factors of ^{150}Sm, an $N = 88$ isotone of ^{154}Dy, have been measured for $I = 2$, 4 and 6. It seems with the decrease of proton numbers (66 to 62) the value of the ratio g_4/g_2 ($= 1.60$) is getting much more enhanced. Preliminary results with standard pairing + quadrupole interaction yields a decreased value $g_4/g_2 = 0.65$ for ^{150}Sm. Thus, it should be interesting to investigate the effects of various kinds, like for example,basis single particle energies, interaction strengths and higher multipoles on the values of g factors in the low spin region for $N = 88$ isotones with $Z = 62 - 70$.

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Relativistic Theory for Identical Bands in Superdeformed Nuclei [1]

P.Ring
Physik Department, Technische Universität München,
D-85747 Garching, Germany

Using the framework of Relativistic Mean Field theory, which has turned out to provide a very realisitic description of properties of nuclear structure even at low energies, we present a fully selfconsistent description of rotating superdeformed nuclei. This theory is based on the exchange of σ-, ω- und ρ-mesons and photons. As in the non-relativistic case a Cranking approximation can be formulated to take into account the angular momentum on the average. One then ends up with a relativistic mean field theory in the rotating frame. Because of the violation of time reversal invariance baryonic currents have to be taken into account at finite angular velocities. They are the source of spatial components for the Lorentz vector fields ω^μ and ρ^μ, and are taken into account in a self-consistent way.

Using the parameter set NL1, which includes a non-linear self-coupling between the σ-mesons, and which has been adjusted in the literature to experimental data of nuclear matter and of a few finite spherical nuclei, we investigate superdeformed bands in the Dy-region. We find excellent agreement with the observed quadrupole deformations as well as the dynamical moments of inertia $\mathcal{J}^{(2)}$ in these bands. In particular we are able to reproduce the experimental moments of inertia of identical bands in even-even and odd-even nuclei in the Dy-region without any further parameters up to an accuracy of ± 2 keV in the transitional γ-energies. Three facts, taken into account in a fully selfconsistent way, lead to an astonishing cancelation: small spin-alignement, polarization induced by the extra particle or hole, and time-reversal breaking parts of the mean field, induced by the spatial components of the vector-fields.

We show that this theory can, in semiclassical approximation, formulated in a similar way as the density dependent Hartree-Fock theory based on Skyrme forces and discuss in particular discrepances betweeen these two selfconsistent descriptions of rotating nuclei, which have their origin in a consistent description of relativistic effects.

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Is spin-spin inteaction seen in superdeformed bands ?

K. Tanabe

Saitama University, Urawa, Saitama 338, Japan

Many identical superdeformed (SD) bands have been observed in recent experiments, and these seem to be well interpreted in terms of pseudo-spin picture. On the other hand, quantization of relative alignment has been found for many identical SD bands in $^{191-194}$Hg, ^{194}Tl(6 bands), ^{194}Pb relative to ^{192}Hg; and ^{151}Tb, ^{153}Dy relative to ^{152}Dy [1]. In this paper we propose a mechanism to bring about the quantization of spin alignment in unit of $1\hbar$. By the pseudo SU(3) transformation [2], $U = 2(\xi\cdot \mathbf{s})(\eta\cdot\xi - 2\mathbf{l}\cdot\mathbf{s})^{-1/2}$ with $\xi, \eta = (\mathbf{r}\pm i\mathbf{p})/\sqrt{2}$, cranked Nilsson Hamiltonian H_ω is brought to $UH_\omega U^\dagger$, in which the coefficient of the $\mathbf{l}\cdot\mathbf{s}$ term becomes small. Then four Nilsson wavefunctions are nearly degenerated at large deformation, and given by four pseudo-wavefunctions $\psi_{[\tilde{N}\tilde{n}_z\pm\tilde{\Lambda}]}\tilde{\chi}_{\pm 1/2}$ and $\psi_{[\tilde{N}\tilde{n}_z\pm\tilde{\Lambda}]}\tilde{\chi}_{\mp 1/2}$ with $\tilde{N} = N-1, \tilde{\Lambda} = \Lambda - 1$ and $\tilde{n}_z = n_z$. Application of the same transformation to the δ-functional spin-spin interaction gives $UJ_s\mathbf{s}_1\cdot\mathbf{s}_2\delta(\mathbf{r}_1-\mathbf{r}_2)U^\dagger = J_s\tilde{\mathbf{s}}_1\cdot\tilde{\mathbf{s}}_2\delta(\mathbf{r}_1-\mathbf{r}_2) +$ (derivatives of δ-function). We assume this pseudo-spin-pseudo-spin term as a part of residual two-body interaction between same nucleons, protons or neutrons. Then two-particle Routhian is given by

$$\tilde{h}_\omega = \varepsilon_1 + \varepsilon_2 + J_s\tilde{\mathbf{s}}_1\cdot\tilde{\mathbf{s}}_2\delta(\mathbf{r}_1-\mathbf{r}_2) - \omega(s_{1x}+s_{2x}). \quad (1)$$

As an example, let us consider the SD states in ^{192}Hg, the occupied neutron pseudo-orbital is $[\tilde{5}41]$ and the unoccupied one $[4\tilde{1}3]$. Thus an additional pair of neutrons enters $[4\tilde{1}3]$ orbital, and the wavefunction for these neutrons is for pseudo-spin singlet state (spatial part is symmetric) or for triplet state (spatial part is antisymmetric), i.e. $\frac{1}{2}[\psi_{[4\bar{1}3]}(\omega,\mathbf{r}_1)\psi_{[41\bar{-}3]}(\omega,\mathbf{r}_2) \pm \psi_{[4\bar{1}3]}(\omega,\mathbf{r}_2)\psi_{[41\bar{-}3]}(\omega,\mathbf{r}_1)] \times [\tilde{\chi}_{1/2}(1)\tilde{\chi}_{-1/2}(2) \mp \tilde{\chi}_{1/2}(2)\tilde{\chi}_{-1/2}(1)]$. Therefore, these two neutron energies for pseudo-spin singlet and triplet states are respectively given by

$$E_0 = \varepsilon_1 + \varepsilon_2 - \frac{3}{4}J_s\int_{-\infty}^{\infty}|\psi_{[4\bar{1}3]}(\omega,\mathbf{r})\psi_{[41\bar{-}3]}(\omega,\mathbf{r})|^2 d^3\mathbf{r}, \quad E_1 = \varepsilon_1 + \varepsilon_2 - \omega. \quad (2)$$

If $E_0 \geq E_1$ holds, alignment of pseudo-spin pair in unit of $1\hbar$ takes place, and the critical angular frequency ω_{c1} is determined from the integral equation

$$\omega_{c1} = \frac{3}{4}J_s\int_{-\infty}^{\infty}|\psi_{[4\bar{1}3]}(\omega_{c1},\mathbf{r})\psi_{[41\bar{-}3]}(\omega_{c1},\mathbf{r})|^2 d^3\mathbf{r}. \quad (3)$$

If the pseudo-spin pair can be aligned also in the SD state in ^{192}Hg, apparent reduction of the relative alignment for ^{194}Hg starts at the second critical ferequency given by

$$\omega_{c2} = \frac{3}{4}J_s\int_{-\infty}^{\infty}|\psi_{[5\bar{4}1]}(\omega_{c2},\mathbf{r})\psi_{[54\bar{-}1]}(\omega_{c2},\mathbf{r})|^2 d^3\mathbf{r}. \quad (4)$$

The copling strength $J_s(>0)$ can be determined from experimental critical frequencies, ω_{c1} and ω_{c2}.

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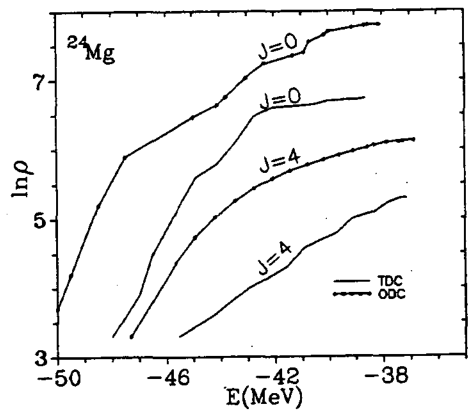
Level density of a hot nucleus in three dimensional cranking approach

B. K. Agrawal and A. Ansari
Institute of Physics, Bhubaneswar-751005, India

Recently, three dimensional cranking(TDC) approach has been applied to study the properties of rotating nuclei at zero-temperature(ground state)[1] as well as finite-temperature[2]. This approach allows any arbitrary orientation of the rotation vector $\vec{\omega}$ relative to the principal axes of the quadrupole shape of the nucleus. It is observed through mean field studies that in most of the cases the energy is minimum when the vector $\vec{\omega}$ conincides either with one of the principal axes or it lies in one of the principal planes. However, significant contribution due to thermal fluctuations can not simply be ignored. The static path approximation(SPA)[3] applied to three dimensional cranking Hamiltonian with quadrupole interaction enables one to incorporate appropriately the thermal fluctuations of shape as well as orientaion. Applying this approach, we have studied the level density of ^{24}Mg as a function of spin and temperature. The results are compared with the usual one-dimensional cranking(ODC) within SPA.



In the above figure we see that the level density $\rho_{TDC} < \rho_{ODC}$ for J = 0 and 4. For J = 6(not shown), we find $\rho_{TDC} \approx \rho_{ODC}$.

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PROLATE NON-COLLECTIVE ROTATION ABOVE THE CRITICAL TEMPERATURE

Alan L. Goodman

Physics Department, Tulane University
New Orleans, Louisiana 70118

If a nucleus is not rotating, then it has a critical temperature T_c, above which the deformation producing shell effects become ineffective, and the equilibrium shape is spherical. It has been expected that this hot nucleus would resemble a classical liquid drop. Consequently one expects a small rotation of this hot spherical nucleus to generate a slightly oblate spheroid rotating about its symmetry axis.

Finite-temperature HFB cranking calculations were performed for ^{188}Os. The critical temperature is 1.33MeV. For T= 1.5MeV, rotating the spherical shape produces a *prolate* spheroid rotating around its symmetry axis, for all positive spins up to I=60. This result contradicts the classical expectation.

A simple argument is given to explain this rotation induced prolate spheroid (RIPS) above the critical temperature. A small rotation of a hot spherical nucleus breaks the degeneracy in the quantum number m, thereby creating a residual quantum shell effect, which accounts for this RIPS phenomenon. It is predicted that many nuclei have prolate shapes rotating about the symmetry axis when $T > T_c$.

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LEVEL SPACING DISTRIBUTION AT HIGHER SPINS

M. Matsuo, Yukawa Inst. for Theor. Phys., Kyoto University, Kyoto 606-01, Japan
T. Døssing, Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA

Recent analysis of high spin levels sampled from the existing data set in rare-earth nuclei revealed that the level spacings obey a Poisson-like distribution[1]. We here suggest that slightly different level spacing distributions show up at higher spins where the static pairing does not dominate the spectra.

In order to calculate the spectra of excited levels at high spins, we use the extended cranked shell model which takes into account np-nh excitations of the cranked Nilsson orbits and the surface-delta residual interaction[2]. We sample level spacings associated with the lowest 10 levels near yrast in 30 nuclei around $A \sim 170$.

As shown in Fig 1, the Brody parameters fitted to the calculated level spacing distributions are mostly located at around $\omega = 0.3 - 0.4$, indicating an intermediate distribution between the Wigner ($\omega = 1$) and the Poisson ($\omega = 0$) limits with slight favour of the Poisson. In addition, a noticeable deviation from this overall behaviour is found for the spacings ($n = 1$) between the yrast level and the next yrare level with same I and π obeying a distribution with $\omega \sim 0.85$, which is close to the Wigner limit.

For unmixed cranked rotational bands, the first spacings between the lowest and the next levels correspond to the spacings between the single-particle orbits with same parity and signature, whereas the higher spacings often involve orbits with different parities and signatures. In this way, the distribution of the first spacings ($n = 1$) reflects in a rather direct way properties of the single-particle routhians while the second and third etc. show that the bands are not yet interacting strongly as these exhibit Poisson-like distributions.

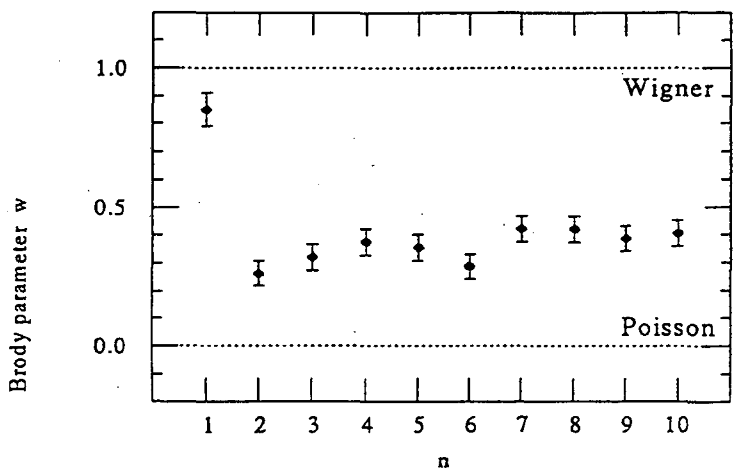

Figure 1: The Brody parameter fitted to the calculated level spacing distribution between the n-th level (counted from yrast) and the next one with same I and π.

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IBM Approach to the Rotational Damping

Takahiro Mizusaki and Takaharu Otsuka
Department of Physics, University of Tokyo, Hongo, Tokyo 113, Japan

P. von Brentano
Department of Physics, University of Cologne, Germany

Recently much attentions have been paid to the statistical feature of off-yrast nuclear structure of the rapidly rotating warm nuclei at high spin because of recent development of the experimental technique of the 4π detectors, *i.e.*, Nordball and Eurogam. The fluctuation analysis, which has recently been developed [1], plays a substantial role for clarifying the gross feature in the off-yrast region. For the theoretical counterpart, Lauritzen *et.al.* [2] advocated the concept of the damping of the rotational band. Matsuo *et.al.* [3] gave an extensive study by the crancked shell model, and concluded that the off-yrast states are very sensitive to mixing interaction, and that high multipole component of the two-body residual interaction serves as a trigger to the damping.

We apply the Interacting Boson Model (IBM) for describing the rotational damping. The first advantage of this approach is to carry out the calculation in the laboratory frame, *i.e.*, we can treat exactly the eigenstates with the definite angular momentum, in contrast to the cranked shell model. The second one is that IBM has the group theoretical rotational limit and we can utilize it for the discussion of the damping of the rotational bands. The third one is that recently the chaotic feature of IBM is clarified by several authors [4] and we have a possiblity of making a link between the chaotic feature of IBM and the rotational damping phenomena. We consider the branching number $n_i = (\sum_j w_{ij}^2)^{-1}$ where w_{ij} is a transition probability from i state to j state, which has a close connection to the experimental values [3]. In the chaotic limit, the smooth branching number has the relation : $\bar{n}(\varepsilon) \approx 0.5\Gamma_{rot}\rho(\varepsilon)$ where $\rho(\varepsilon)$ is the level density and Γ_{rot} is the damping width. We show its relation in the case of the chaotic limit of IBM in Fig.1.

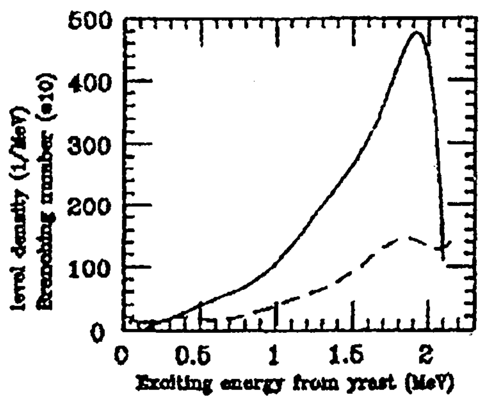

Fig.(1) Level density (solid line) and Branching number (dash line)

We conclude that IBM is also useful for the description of the rotational damping, and that the triaxiality is a possible candidate of the mixing among highly excited rotational bands. Some of details of the chaotic feature of the high spin states of IBM hamiltonian are also studied.

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THE RATE OF COOLING IN γ-CASCADES OF ROTATING NUCLEI

E. Vigezzi, INFN Sezione di Milano, Milano, Italy and
T. Døssing, Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA

A well deformed nucleus in an excited state at high angular momentum decays towards the yrast line mostly by statistical dipole and by rotational quadrupole emission. Knowledge of the properties of such γ−cascades is essential to studies of the structure of excited states in rotating nuclei. Analytic results for the γ−decay flow can be obtained by expressing the decay widths to leading order in temperature and angular momentum, and applying techniques from transport theory.

To leading order, the decay widths obey the following power laws:

$$\Gamma_{E1} = c_{E1}T^5 \qquad \Gamma_{E2} = c_{E2}I^5 \qquad < E_\gamma >_{E1} = 5T \qquad U = aT^2 \qquad (1)$$

where we have included also the expression for the average statistical γ−ray energy and the standard relation between heat energy U and temperature T. One now obtains the following equation and solution describing the average cooling of the nucleus during its decay cascade:

$$\text{equation}: \frac{dT}{T^5} = \frac{5c_{E1}}{4ac_{E2}}\frac{dI}{I^5} \qquad \text{solution}: T = \left(\frac{4ac_{E2}}{5c_{E1}}\right)^{1/4} \frac{I}{(1+CI^4)^{1/4}} \qquad (2)$$

where C is an integration constant. Figures 1 and 2 display solutions for various initial conditions, together with results from complete cascade simulations. As shown by the figures, the influence of the initial condition is lost within roughly the first quarter of the cascade. The γ−decay flow is converging rapidly towards a *generic behavior*, described by $U \propto I^2$, $\sigma_U^2 \propto I^3$.

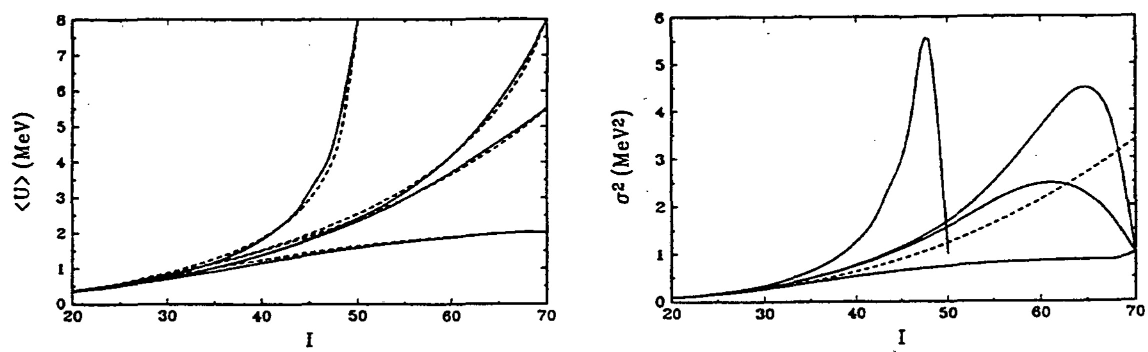

Figure 1 and 2: The mean heat energy U and its variance σ_U^2 as obtained by cascade simulations (full drawn lines) and analytic approximations (dashed lines) are shown as function of angular momentum for decay cascades initiated at the values of angular momentum and heat energy (I, U) = (50,8),(70,8),(70,5.5) and (70,2). The initial value of the dispersion in heat energy σ_U is 1 MeV for all cases. The parameters are chosen to represent the nucleus ^{168}Yb.

SIMULATION OF γ–DECAY CASCADES WITH INTERACTING ROTATIONAL BANDS

E. Vigezzi [a)], A. Bracco[a)], R.A. Broglia [a,b)], T. Døssing [b,c)], S. Frattini [a)], B. Herskind [b)], S. Leoni [a),d)] and M. Matsuo [e)]

a) Istituto di Fisica, Università di Milano, and INFN Sez. Milano, Italy
b) The Niels Bohr Institute, University of Copenhagen, Denmark
c) Physics Division, Argonne National Laboratory, Illinois, USA
d) Institute of Nuclear Physics, Orsay, France
e) Yukawa Institute for Theoretical Physics, Kyoto, Japan

The ridges and valleys [1] seen in two-dimensional energy spectra of unresolved γ–rays yield important information about the rotational motion at varying rotational frequencies and temperatures. Especially, the count fluctuations [1] show uniquely that only rather few discrete rotational bands exist above the yrast line in well deformed nuclei. Theoretical studies of interacting rotational bands covering the first 2 MeV of excitation energy above yrast [2] are in qualitative agreement with this experimental result. However, the comparison of theory and experiment has been based until now on a very schematic assumption, namely that there exist discrete bands with energies displaying Poisson statistics below a certain heat energy, abruptly changing above that energy to mixed bands with transitions strengths displaying Porter-Thomas fluctuations.

In order to make a more satisfactory connection between theory and experiment, a code simulating the decay cascades of a rotational nucleus has been set up. It makes use of the energies and transition strengths of energy eigenstates calculated from cranked mean field rotational bands, interacting via a surface-delta interaction. The competition between the rotational transitions, emerging from the diagonalization of the cranked bands, and the statistical dipole transitions, is treated according to a Montecarlo procedure. The code essentially only requires two input parameters, the strength of the residual interaction and the normalization of the statistical E1-strength, in addition to standard cranking single particle potential parameters.

It is then possible not only to compare the general appearance of the simulated and experimental $E_{\gamma_1} \times E_{\gamma_2}$ spectra, but also their fluctuations properties. In fact, in both spectra, fluctuations of size larger than those caused by ordinary counting statistics are caused by the finite number of decay possibilities available to the nucleus in each decay step. The preliminary results obtained until now are encouraging. In particular, the number of decay paths obtained in the experimental and simulated spectra are of the same order of magnitude, both in the valley and on the ridges. One can obtain useful information about the strength of the residual interaction, which has a significant influence on the $\gamma - \gamma$ spectra, especially on the number of paths on the ridges. It will also be possible to test the experimental procedures [1] employed until now to determine the rotational damping width.

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Rotational Damping in Superdeformed Nuclei

K. Yoshida and M. Matsuo*

Department of Physics, Kyoto University, Kyoto 606-01, Japan
* *Yukawa Inst. for Theor. Phys., Kyoto University, Kyoto 606-01, Japan*

The rotational damping is a crucial phenomenon which characterizes excited superdeformed (SD) levels and E2 transitions among them. It not only influences the SD quasi-continuum spectra but also puts the upper-boundary of excitation energy where excited SD rotational bands can exist and limits the number of SD bands.

In order to quantitatively describe the rotational damping in SD nuclei on a microscopic basis, we performed an extended cranked shell model calculation, in which are taken into account excited many-particle many-hole configurations in the Nilsson-Strutinsky potential as well as the surface-delta two-body residual interaction causing band mixing[1]. The branching number n_{branch} which represents number of branches of stretched E2 transitions is calculated in order to classify undamped transitions ($n_{\text{branch}} < 2$) and damped transitions ($n_{\text{branch}} > 2$). The result for ^{152}Dy is shown in Fig.1. An average excitation energy E_{onset} for the onset of rotational damping is extracted from an average n_{branch} as a function of the excitation energy above SD yrast (Fig.1(b)).

The calculated onset energy is about $E_{\text{onset}} = 1.5 - 2.5$(MeV), which is much larger than the value (~ 1.0 MeV) for normal deformed nuclei, but is consistent with a simulation analysis[2] of the quasi-continuum intensity of SD ridge. A distinctive feature in this calculation is that the sizable lowering of E_{onset} at high frequencies $\omega_{\text{rot}} \geq 0.7(\text{MeV}/\hbar)$. This originates from a single-particle level structure that a $N = 7$ proton orbit intrudes the shell gap and causes quasi-degeneracy at $Z = 66$ Fermi surface at the high frequencies. The rotational damping in SD nuclei is sensitive to the single-particle structure.

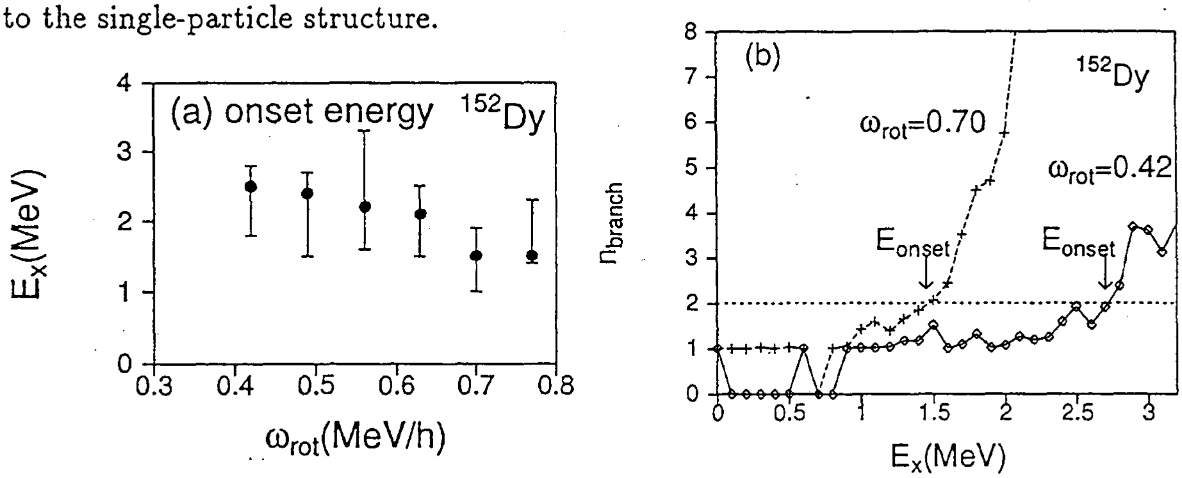

Figure 1: (a) Calculated excitation energy for the onset of rotational damping in ^{152}Dy as a function of the rotational frequency ω_{rot}. The dots represent the average onset energy E_{onset} and bars indicate the energy range where damped and undamped E2 transitions coexist. The rotational frequency ω_{rot} is scaled to 1.4 times of cranking frequency in order to cure the problem that the Nilsson model overestimates the moment of inertia. (b) Calculated average branching number n_{branch} as a function of the excitation energy above SD yrast for $\omega_{\text{rot}} = 0.42$ and 0.70 (MeV/$\hbar$). The arrow indicates the average onset energy E_{onset} of rotational damping.

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CALCULATION OF THE SPECTRUM OF STATISTICAL γ-RAYS EMITTED IN THE DECAY-OUT OF SUPERDEFORMED BANDS

T. Døssing, T. L. Khoo, T Lauritsen, I. Ahmad, D. Blumenthal, M. P. Carpenter, B. Crowell, R. G. Henry, R. V. F. Janssens, and D. Nisius
Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA

The energy spectra of γ rays depopulating superdeformed bands are calculated in two models, both based on the decay occuring through mixing with a near-lying normal state 4.3 MeV above the yrast line. In one model, we perform a Monte Carlo simulation of the γ cascade, with an additional single last-step transition from around 1.7 MeV above the normal yrast line. The second model is based on a theory which self-consistently treats the weakening of pairing correlations with increasing number of quasiparticle excitations. Many-quasiparticle excitations are generated using a single- particle spectrum with equidistant spacing. Pairing correlations are treated in various schemes: BCS, number projected BCS, and diagonalization of the states after number projection.

Fig. 1 shows the experimental spectrum [1] for ^{192}Hg, together with spectra calculated with the statistical Monte Carlo simulation and with the BCS approximation for even-even and for odd-odd systems. The strength of the pairing interaction is chosen to produce a BCS gap parameter $\Delta = 0.8$ MeV in the ground state of the even systems, and the spacings of the neutron and proton single particle spectra are 0.29 and 0.41 MeV, respectively. It is found that the bump around 1.3 MeV seen in the spectrum is more pronounced with increasing pairing strength. Furthermore, it is strong in an even-even nucleus, but becomes rapidly attenuated in the odd-even and odd-odd systems. The bump arises from a combination of piling up of the spectra from the sequential steps of the deexcitation cascade and from clustering in energy of transitions across the pair 'gap' in the even-even system. Preliminary calculations without pairing, but with a gap in the single particle spectrum at the Fermi energy, produce smooth spectra without a bump.

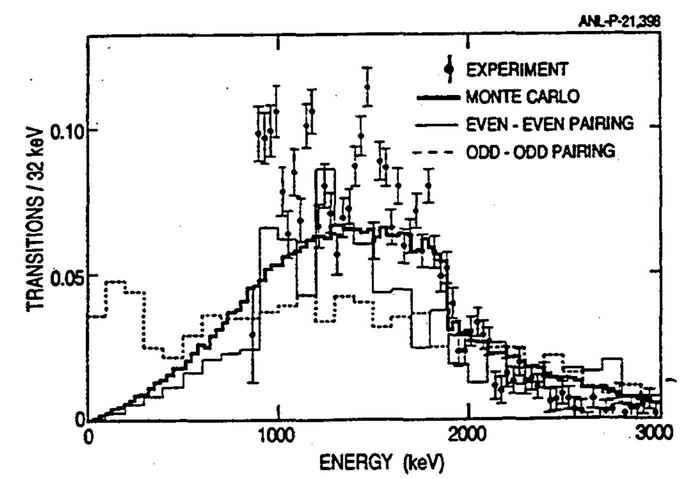

Fig. 1: Statistical spectra from decay-out the SD band in ^{192}Hg [1]; experimental spectrum [1] and calculated spectra from statistical Monte Carlo model (thick line) and from the pairing model for even-even (thin line) and odd-odd (dashed) systems.

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Microscopic basis of saturation and motional-narrowing of GR width

K. Tanabe and K. Sugawara-Tanabe†

Saitama University, Urawa, Saitama 338, Japan
† *Otsuma Women's University, Tama, Tokyo 206, Japan*

High-temperature behaviour of the damping width of collective modes built on a finite many-body system like a nucleus is a subject of broad interest. To take into account temperature effect on the giant resonances (GR), we have derived a microscopic expression for the GR spreading width based on the 2nd thermal RPA (TRPA) on top of the quasiparticle ensemble provided by the solution to the THFB equation[1]. In this scheme the 2nd TRPA explicitly describes temperature-dependence in terms of the TRPA metric matrix $\mathbf{M}$ and the quasiparticle distribution function f_μ. We expand the TRPA amplitude for a GR level $\mathbf{X}$ into the orthonormal set of the 2qp (or 1p-1h) excitations, $\{\mathbf{X}_{\rm n}^{(2)}, \hbar\omega_{\rm n}\}$, and 4qp (or 2p-2h) amplitude $\mathbf{X}^{(4)}$. Eliminating $\mathbf{X}^{(4)}$ from the 2nd TRPA equation and applying the picket fence approximation assuming equal spacing $d_{\rm n}$ for the 4qp energies around $\hbar\omega_{\rm n}$, we obtain an explicit expression for the spreading width of the n-th RPA level $\Gamma_{\rm n}^{\downarrow}$. Since the diagonal elements of $\mathbf{M}^{(44)}$ become $\sum_{\mu=1}^{4} E_\mu/16kT + O(1/kT)^3$ in the high-temperature limit, where E's are quasiparticle energies, we arrive at an expression with explicit temperature-dependence[1],

$$\Gamma_{\rm n}^{\downarrow} = \frac{2\pi\overline{|(\Omega\mathbf{M})^{(42)}\mathbf{X}_{\rm n}^{(2)}|^2}}{\hbar\, d_{\rm n}} \cdot \frac{\hbar\omega_{\rm n}}{16kT}\,, \tag{1}$$

where the numerator in the first factor stands for the average square of the 4qp-2qp couplings. The n-th individual GR mode is a superposition of p-h configurations, i.e. $\sum_\alpha f_\alpha^{\rm n}|\alpha>$, whose main contributions are composed of a coherent sum of N terms. Then, the size of spreadig interval is given by $2\gamma_{\rm n} \sim Nd_{\rm n}$. Following the argument adopting stochastic approximation [2], the spreading width is giben by $\Gamma_{\rm n}^{\downarrow} = 2\pi h^2/Nd_{\rm n} = \pi h^2/\gamma_{\rm n}$ in terms of the average square of the matrix element of residual interaction between the collective and doorway states, h^2. Since the spreading interval $2\gamma_{\rm n}$ corresponds to the cutoff for the relevant level sequence, it is not sensitive to the excitation energy and the temperature. Thus the coupling factor appearing in (1) can be further approximated by h^2/N. Due to the factor $\hbar\omega_{\rm n}/16kT$, (1) decreases slowly with increasing T, which is nothing but the motional-narrowing. In conclusion, the saturation or slow increase of observed GR widths can be interpreted in the framework of our microscopic formalism. The motional-narrowing is predicted, however, in kT much higher than the centroid energy, i.e. $\hbar\omega \sim 15$ MeV for the case of GDR, if it would still exist.

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LOOKING INSIDE GIANT RESONANCE FINE STRUCTURE

V.Yu. Ponomarev and V.V. Voronov

Bogolubov Laboratory of Theoretical Physics,
Joint Institute for Nuclear Research, 141 980 Dubna, Russia

Microscopic calculations of the fine structure of giant resonances for spherical nuclei will be presented. Excited states are treated by wave function which takes into account coupling of simple one-phonon configurations with more complex ones [1]. Nuclear structure calculations are applied to description of the γ-decay of resonances into low-lying states and the relativistic Coulomb excitation of the double resonances.

As an example, we consider γ-decay properties of the High Energy Octupole Resonance (HEOR) in ^{90}Zr [2]. In our calculation, the HEOR has the energy centroid $E_x = 22.4$ MeV and the total width $\Gamma = 4.4$ MeV. The total width $\Gamma_{HEOR \to 2^+_{1,4}, 4^+_{1,2}}$ is equal to 3 keV or about 10% of the GDR γ-decay width into the ground state. It opens a new possibility to investigate the HEOR.

For the first time the relativistic Coulomb excitation of the double giant resonance in ^{136}Xe is calculated based on the microscopic structure of the GDR [3]. Second order perturbation theory is used to describe the excitation process. It is found that the two-phonon cross section is essentially equal to that of the non-interacting phonon model and that the associated width is 1.5 times the width of the one-phonon resonance. Calculated and experimental [4] cross section (in mb) for the excitation of the single GDR, GQR_{is} and GQR_{iv} and the double $[GDR \otimes GDR]_{0^+,2^+}$ resonances are presented in table. The results of calculations are strongly dependent on the minimal value of the impact parameter $R_{min} = r_o(A_t^{1/3} + A_p^{1/3})$ used and the ones in table are obtained with $r_o = 1.5 fm$. While the predictions associated with the one-phonon states provide an overall account of the experimental findings, the calculated cross section for the two-phonon states is much smaller than that extracted by the involved analysis of the data.

GDR	GQR_{is}	GQR_{iv}	$GDR+GQR_{is}+GQR_{iv}$	$[GDR \otimes GDR]_{0^+ + 2^+}$
1480	110	60	1650	50
1024 ± 100	–	–	1485 ± 100	215 ± 50

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New Shell Structure Originated from A Combination of Quadrupole and Octupole Deformations

K. Arita and K. Matsuyanagi

Department of Physics, Kyoto University, Kyoto 606-01, JAPAN

We investigate new feature of single-particle spectra for the reflection-asymmetric deformed oscillator Hamiltonian

$$H = \frac{\mathbf{p}^2}{2M} + M\omega_0^2 \left[\frac{r^2}{2} - \lambda_{30} r^2 Y_{30}(\Omega)\right]'' ,$$

where the double primes denote that the variables in square bracket are defined in terms of the doubly-stretched coordinates $x_i'' \equiv (\omega_i/\omega_0)x_i$. The axis ratio $\omega_\perp/\omega_z$ is put to an irrational value $\sqrt{3}$, so that the spectrum shows no shell structure at $\lambda_{30} = 0$. However, we see that new significant shell structure appears at $\lambda_{30} \simeq 0.3$. For what reason such a change of the structure occur? To answer this question, we consider the classical-quantum correspondence using the Gutzwiller trace formula [1]. In the trace formula, the density of states is represented by the sum of contributions from classical periodic orbits. The above Hamiltonian has the scaling property $H(\alpha\mathbf{p}, \alpha\mathbf{q}) = \alpha^2 H(\mathbf{p}, \mathbf{q})$, which enables us to analyze the Fourier transform of the density of states: In such a case, the Fourier transform of semiclassical density of states has the functional form that has peaks at the periods of classical periodic orbits [2,3]. The left-hand side of the figures below shows the Fourier transforms of quantum mechanically calculated energy level density $g(E; \lambda_{30}) = \sum_n \delta(E - E_n)$,

$$F(t) \equiv \int dE\, E^{-1/2} g(E; \lambda_{30})\, e^{iEt/\hbar} = \sum_n E_n^{-1/2} e^{iE_n t/\hbar},$$

for $\lambda_{30} = 0$ and 0.3. Arrows in the figure indicate the periods of classical periodic orbits. We see very good classical and quantum correspondence. Furthermore, one may notice that the peak (denoted $*$), which corresponds to the orbits with period $T \sim 2\pi/\omega_z$, grows up as the octupole deformation parameter λ_{30} increases. Classical analysis shows that these periodic orbits (see the right-hand side of the figures) meet resonances at $\lambda_{30} \simeq 0.3$, indicating their importance for the above new shell structure to appear.

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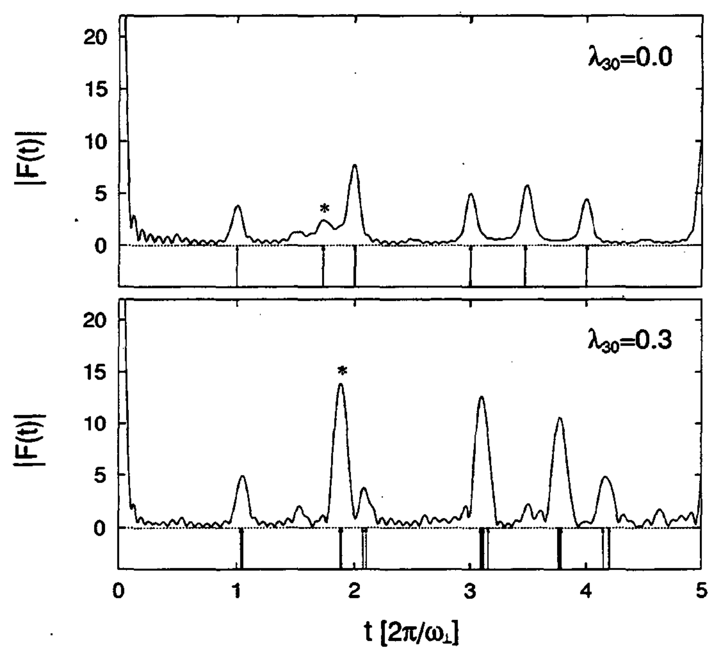

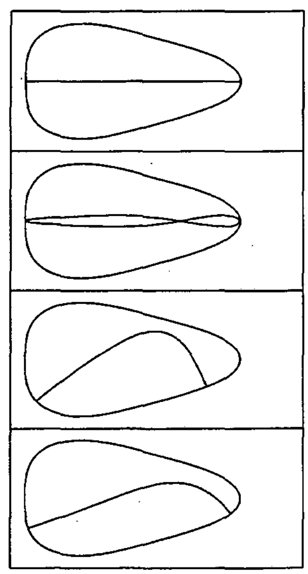

Shell Effect due to the Periodic Orbit Resonances in Reflection-Asymmetric Deformed Oscillator

K. Arita and K. Matsuyanagi

Department of Physics, Kyoto University, Kyoto 606-01, JAPAN

Nuclear deformation is intimately related with the shell structure of single particle spectrum. We apply the semiclassical theory for the density of states and discuss the correspondence between classical and quantum mechanical results for reflection-asymmetric deformed oscillator Hamiltonian [1]:

$$h = \frac{\mathbf{p}^2}{2M} + \frac{M\omega_\perp^2}{2}(x^2+y^2) + \frac{M\omega_z^2}{2}z^2 - \lambda_{30}M\omega_0^2\,[r^2Y_{30}(\Omega)]'',$$

where the double primes denote that the variables in square bracket are defined in terms of the doubly-stretched coordinates $x_i'' \equiv (\omega_i/\omega_0)x_i$. We calculate classical periodic orbits and quantum energy spectra for this Hamiltonian as functions of the deformation parameters $\delta_{\rm osc} = (\omega_\perp - \omega_z)/\bar{\omega}$ and λ_{30}. The Gutzwiller trace formula represents the density of states $g(E) = \sum_n \delta(E-E_n)$ in terms of classical periodic orbits as [2]

$$g(E) = \bar{g}(E) + \sum_\gamma A_\gamma(E)\cos\left[\frac{1}{\hbar}\left(S_\gamma(E) - \frac{\pi}{2}\mu_\gamma\right)\right],$$

where the sum is taken over periodic orbits and S denotes the action integral along the orbit. At deformations where the orbit γ meets resonance (bifurcation), the Gutzwiller amplitude A_γ in the trace formula suffers divergence, suggesting the importance of such orbit for the density of states [1,3]. As a measure of the intensity of shell effect, we define the following quantity $I_{\rm sh}$:

$$I_{\rm sh} \equiv \sum_N \frac{|E_{\rm sh}(N)|}{\sqrt[3]{N}},$$

where $E_{\rm sh}(N)$ is the shell structure energy for particle number N. In the figure below, $I_{\rm sh}$ is plotted by contours. The significant maxima on the horizontal axis at $\delta_{\rm osc} = 0$, 0.6 and $\simeq 0.85$ correspond to spherical, superdeformed and hyperdeformed shapes, respectively. The thick (solid, dashed and dotted) curves drawn in the same figure represent the points where some of the short classical periodic orbits meet various kind of resonances. We observe that some thick lines run along the ridges of the $I_{\rm sh}$-contour, which indicate the significance of their contributions to the shell effect.

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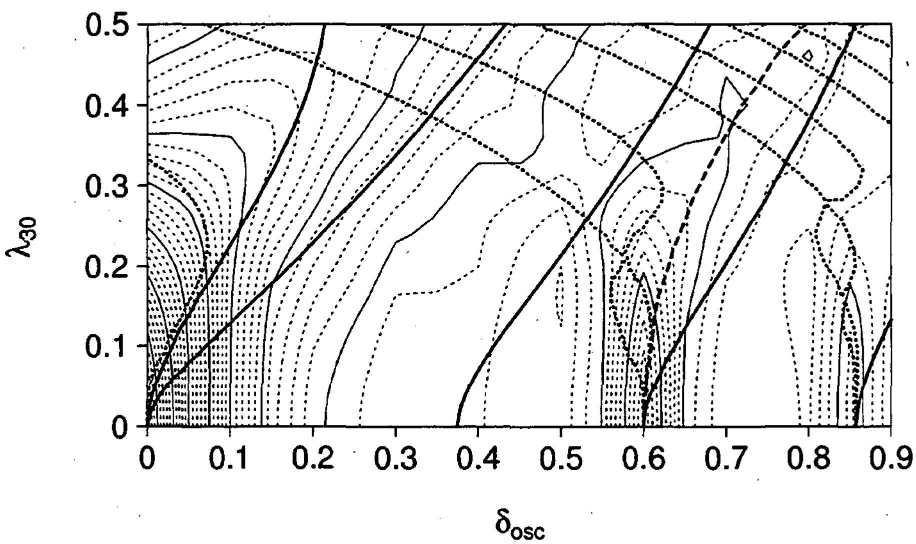

Microscopic Structure of Octupole Correlations in Superdeformed Open-Shell Nuclei

S. Mizutori, Y. R. Shimizu* and K. Matsuyanagi**
Department of Mathematical Physics, Lund Institute of Technology
*Department of Physics, Kyushu University
**Department of Physics, Kyoto University

Octupole softness is often discussed in the superdeformed region. However, there are some questions yet to be answered. 1) What is the quantity suitable to characterize the octupole vibrations instead of K, under the strong K-mixing effects expected in rapidly rotating systems? 2) What is the microscopic mechanism producing the octupole softness? Whether a single 2-qp configuration with strong octupole strength plays a dominant roll, or strong collective octupole vibrational states made up from many 2qp excitations emerge? To find the answers, we performed an RPA calculation based on the cranked shell model with the use of the doubly stretched octupole-octupole interactions.

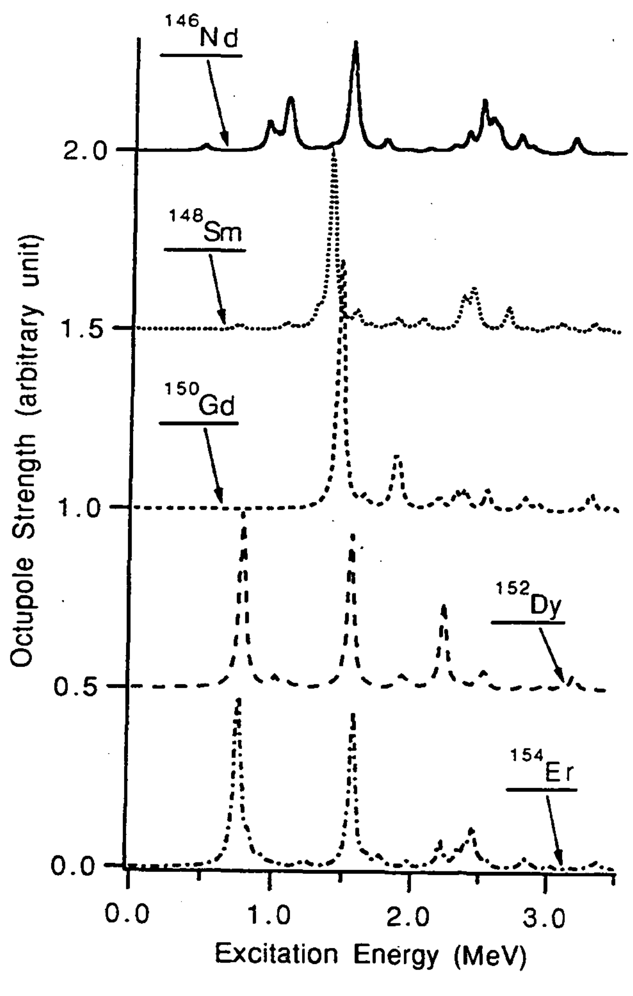

Figure: Smoothed $\mu = 3$ octupole strength functions for isotones of N=86 at rotational frequency 0.7MeV. The abscissa indicate excitation energy in MeV, while the ordinate represents the strength in arbitrary unit.

The result of calculation shows that the K-mixings are indeed significant for negative parity excitations. In many cases the angular momentum projection of the octupole strength to the cranking axis, μ, is useful to characterize the excitations. We find that the octupole strengths for positive μ tend to have peaks at lower energy than those for negative μ. Especially, the lowest negative-parity negative (positive) signature state has tendency to have largest strength for $\mu = 3$ ($\mu = 2$).

If we compare $\mu = 3$ octupole strengths on superdeformed bands of various nuclei in the A$\sim$150 region, we see that the $\mu = 3$ strength functions show prominent peaks at lower energy in open shell superdeformed nuclei compared to the peak in ^{150}Gd. Examples of some N=86 isotones are shown in the figure.

This tendency of "octupole softness" is especially remarkable in heavier isotones of N=86 nuclei. In the figure, both ^{152}Dy and ^{154}Er show prominent peaks around 0.7 MeV The dominant component of the RPA phonons corresponding to these peaks are proton 2qp excitations, whose excitation energies are about 1 MeV. (the proton $6^4 - 7^1$ in ^{152}Dy and various valence proton excitations in ^{154}Er.) Unperturbed strengths carried by these dominant configurations are not very strong. The major part of the strengths are rather carried by other numerous smaller components. In these nuclei, the octupole softness emerges as a result of interplay of valence 2qp excitations and collective effects.

E1 Strengths Carried by Octupole Vibrations built on Superdeformed Bands.

S. Mizutori, Y. R. Shimizu* and K. Matsuyanagi**
Department of Mathematical Physics, Lund Institute of Technology
*Department of Physics, Kyushu University
**Department of Physics, Kyoto University

Recently, some experimental data suggesting dipole transitions between negative-parity superdeformed bands and the yrast superdeformed bands have been reported in both the A~ 150 region and the A~ 180 region.

In superdeformed nuclei, there are some reasons to expect "strong" E1 transitions. 1) Semi-classical estimate of the dipole moments of octupole deformed states shows that they depend on the quadrupole deformation parameter squared. 2) In superdeformed nuclei, some components of giant dipole resonances have low excitation energies (8~9 MeV in the A~150 region).

We have performed an RPA calculation based on the cranked shell model with the use of the doubly stretched octupole-octupole interactions. Since the proper treatment of giant dipole resonances and translational motion is quite important, we add other effective interactions. We add isovector dipole-dipole interactions so that we can explicitly take into account the couplings between octupole modes and isovector dipole mode. We also add other separable interactions so that the RPA Hamiltonian conserves both the translational and the Galilean invariances.

Calculated intrinsic dipole transitions are of the order of 10^{-3} Weisskopf unit. This corresponds, for example, to $T(E1) \approx 10^{12}$ for the E1 transition energy of 1 MeV, which is one order of magnitude smaller than the intra-band E2 transition probability, when the intra-band transition energy is about 0.6 MeV.

In the figure, we compare the calculated intrinsic E1 strength with octupole strength for several isotopes of ^{150}Gd. We see that the particle-number dependence of the E1 strengths is strong and has no correlation with that of the octupole strengths. Examining the microscopic structure of the octupole vibrational states, we found that the dipole strengths are determined by mostly incoherent contributions of large number of 2qp configurations. Thus, values of the low-energy E1 strengths are quite sensitive to details of microscopic wave functions. Accordingly, vibrational states with strong octupole collectivity do not always have large E1 decay rate in contrast to the expectation from the macroscopic collective models.

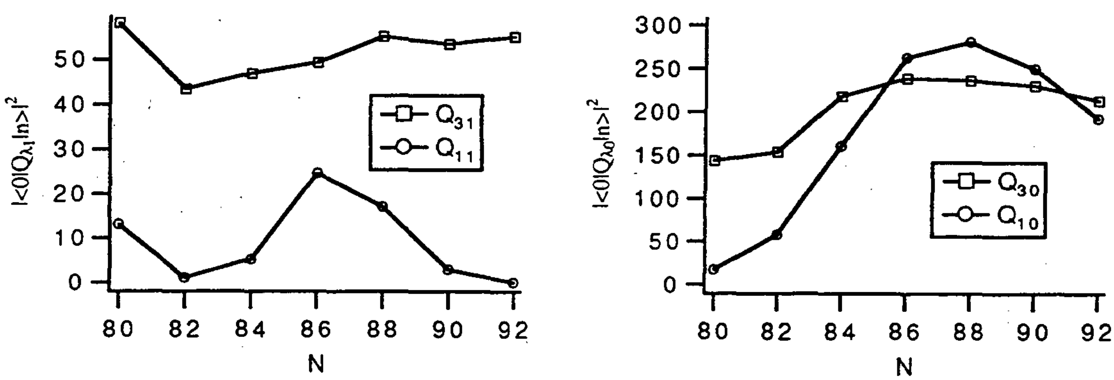

Figure: Intrinsic E1 and octupole strengths between RPA ground states and lowest octupole vibrational states calculated for isotopes of ^{150}Gd. Circles are for E1 and squares are for octupole strengths. The left (right) panel is for K=1(K=0). The abscissa indicates the neutron number, while the ordinate the strength in Weisskopf unit. The E1 strengths are multiplied by 10^5.

Octupole Correlations in Superdeformed ^{152}Dy

T. Nakatsukasa, S. Mizutori*, K. Matsuyanagi** and W. Nazarewicz***

Research Center for Nuclear Physics, Osaka University, Ibaraki 567, Japan
** Dept. of Math. Phys., Lund Institute of Technology, Box 118, S221-00 Lund, Sweden*
***Department of Physics, Kyoto University, Kyoto 606-01, Japan*
**** JIHIR, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831, U.S.A.*

Recently, five excited superdeformed (SD) bands (Bands 2–6) have been discovered in ^{152}Dy at EUROGAM (P.J. Dagnall et al., private communication). Theoretically, collective octupole excitation modes are expected to appear near the yrast SD band in ^{152}Dy, a doubly magic superdeformed system.

In order to investigate the effects of octupole correlations on the excitation spectrum of SD ^{152}Dy, we have carried out the RPA calculations based on the cranked Nilsson-Strutinsky model. The results are shown in the figure below. The calculated Routhians of the low-lying negative-parity modes built on the yrast SD band in ^{152}Dy are displayed in panel (a) as functions of rotational frequency $\omega_{\rm rot}$. The lowest excitation mode with signature $\alpha = 1$ (thick dotted line) can be associated with a strongly collective octupole vibrational band. On the other hand, the lowest $\alpha = 0$ band (solid line) is weakly collective, and at $\omega_{\rm rot} \sim 0.5$MeV/$\hbar$ it is crossed by an aligned proton configuration involving the first N=7 proton, $\pi(76^{-1})$.

Assuming that the RPA vacuum, the lowest and the second lowest excited $\alpha = 0$ states, [thick solid lines in Figure (a)], and the lowest $\alpha = 1$ state (thick dotted line) correspond to the SD yrast and bands 2, 3, and 6, respectively, we compare experimental and calculated dynamical moments of inertia $\mathcal{J}^{(2)}$ in Figure (b). The main characteristics of the experimental data, especially strong $\omega_{\rm rot}$-dependence of Bands 2 and 3, and weak $\omega_{\rm rot}$-dependence of Band 6, are well reproduced. We also expect that strong octupole collectivity of Band 6 is associated with the significant E1 decay probablility into SD yrast, which might be able to compete with intra-band E2 transitions.

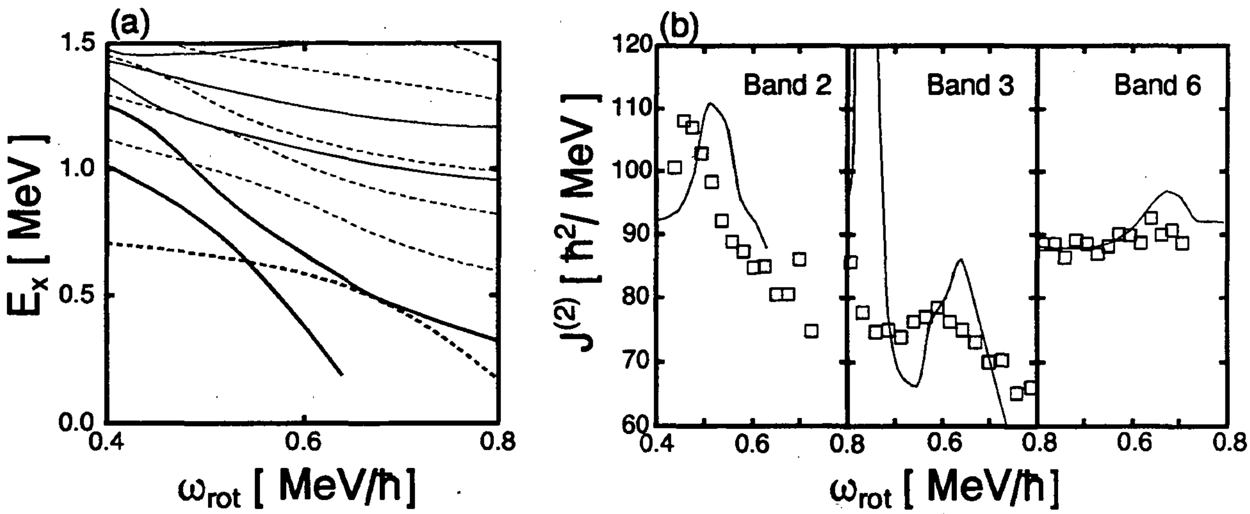

Figure a) Calculated Routhians of the low-lying RPA modes plotted as functions of $\omega_{\rm rot}$. Solid (dotted) lines indicate $\alpha = 0 (\alpha = 1)$ $\pi = -$ states. b) Calculated (lines) and experimental (symbols) dynamical moments of inertia for Bands 2, 3 and 6 in ^{152}Dy. For simplicity, the dynamical moment of inertia $\mathcal{J}_0^{(2)}$ for the yrast SD band is approximated as a linear function of $\omega_{\rm rot}$, $\mathcal{J}_0^{(2)} = 92 - 13\omega_{\rm rot}\hbar^2/$MeV ($\omega_{\rm rot}$ in units of MeV/$\hbar$).

Two-Octupole-Phonon States in ^{146,148}Gd

Kenjiro Takada and Yoshifumi R. Shimizu
Department of Physics, Kyushu University, Fukuoka 812, Japan

One of challenges in recent nuclear structure studies is the observation of multi-phonon states. Although two, or even three in some cases, -phonon states of quadupole vibrations are identified in many spherical nuclei, there are only a few cases where are observed the two-phonon states of the β, γ-vibrations in deformed nuclei or of other types of vibrational motions. As is well known, the octupole correlation is as important as quadrupole one in medium-heavy nuclei, so that it is natural to expect multi-phonon states of octupole vibrations, which is the main subject of this contribution.

We have studied two-octupole-phonon states in ^{208}Pb [1] with the result that the unharmonicities are rather small, but the experimental situation is not yet so definite. One of other nuclear regions to look for the octupole collectivity is the Gd region, where $^{146}Gd_{82}$ is supposed to be a double-closed shell nucleus ($Z = 64$ is a rather good subshell closure). In fact candidates of two-phonon octupole states are observed in adjacent nuclei; especially, in ^{148}Gd both the $BE3$'s from two to one and from one to zero -phonon states have been recently measured[2], see $12^+ \rightarrow 9^-$ and $9^- \rightarrow 6^+$ in Figure 1.

We analyze these very interesting data microscopically by means of the Dyson boson mapping method as in the previous work 1), using an isoscalar octupole-octupole interaction and modified SDI ν-ν and π-π interactions, with extensions suitable to treat non-closed shell nuclei, ^{148}Gd, such that correlated neutron-pair modes with $0^+, 2^+, 4^+, 6^+$ and $3^-, 9^-$ spin-parity are included as elementary modes of excitations. The former modes are necessary to describe "vacuums" from which the p-h octupole-phonon mode is multiply excited, and the latter negative parity modes are found to be crucial to get a good agreement of calculations to the data, which is shown in Figure 1. The importance of the mode-mode coupling effects was first suggested in ref. 3), and our result can be considered to be a microscopic realization of the relatively simple picture introduced in it.

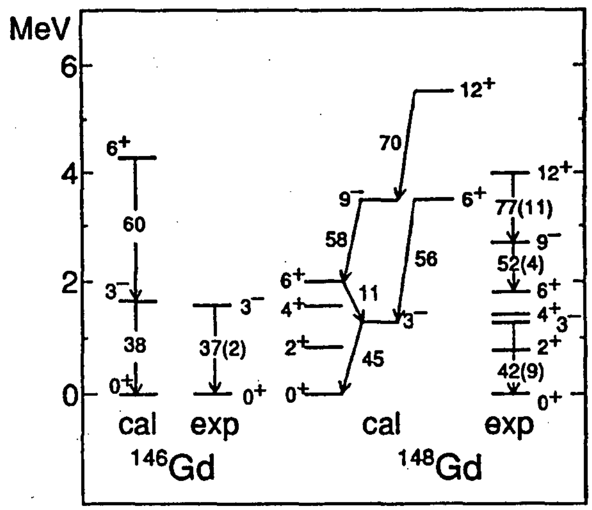

Figure 1: Calculated energy spectra of ^{146,148}Gd together with experimental data. The B(E3) values in units of $B_w = 1.31 \times 10^3 e^3 \mathrm{fm}^6$ are also included for some important transitions.

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Description of octupole-deformed nuclei within the Interacting Boson and Interacting Boson-Fermion Models

A Vitturi•, H.M. Sofia◇, S.M. Lenzi•, C.E. Alonso△ and J.M. Arias△

• *Dipartimento di Fisica dell'Università and INFN, Padova, Italy*
◇ *CNEA, Buenos Aires, Argentina*
△ *Departamento de Fisica Atomica, Molecular y Nuclear, Sevilla, Spain*

We develop a model for the description of odd-even and even-even octupole-deformed nuclear systems within the framework of the Interacting Boson Model and Interacting Boson-Fermion Model, originally introduced in connection with the quadrupole degree of freedom. The model is based on the introduction, besides the conventional monopole and quadrupole s and d bosons, of the negative-parity dipole and octupole p and f bosons, and on the use of a model hamiltonian which includes an octupole-octupole term in addition to the usual quadrupole-quadrupole one. By increasing the strength of the octupole term one obtains a transition from the standard quadrupole equilibrium deformation, characterized by a pure positive-parity boson intrinsic state, to a reflection-asymmetric quadrupole plus octupole deformation, where the intrinsic state is of mixed parity. This latter situation leads to a characteristic pattern of excited bands, which can be interpreted as associated with different combinations of vibrations of the quadrupole and octupole degrees of freedom. Correspondingly, characteristic behaviours of inter-band transitions are derived in the case of stable octupole deformation.

By cranking the hamiltonian one can study the evolution of the basic intrinsic boson with increasing rotational frequency and the hamiltonian can be modelled to produce a proper transition from a low-spin regime of positive-parity character (only quadrupole shape) to a high-spin regime of alternating-parity states (quadrupole plus octupole shape). The model is applied to the case of ^{226}Ra.

Finally in the case of odd systems, described in terms of the coupling of a single fermionic particle to the bosonic core, the boson-fermion hamiltonian leads, in the intrinsic frame, to a corresponding evolution of the single-particle states from a behaviour similar to the standard Nilsson levels to that characteristic of a quadrupole plus octupole mean-field.

Separation and identification of ^{100}Sn at the GSI projectile-fragment separator FRS

R. Schneider, J. Friese, J. Reinhold, K. Zeitelhack, T. Faestermann, R. Gernhäuser, H. Gilg, F. Heine, J. Homolka, P. Kienle, and H. J. Körner
Technische Universität München, D-85747 Garching, Germany,
H. Geissel, G. Münzenberg, and K. Sümmerer
Gesellschaft für Schwerionenforschung mbH, D-64220 Darmstadt, Germany

In an experiment performed between March 10 and April 11, 1994, at the GSI projectile-fragment separator FRS by a TU München - GSI collaboration, the doubly-magic N=Z nucleus ^{100}Sn could be identified for the first time[1]. This isotope was produced by high-energy projectile fragmentation using a 1 A·GeV ^{124}Xe beam made from isotopically enriched gas. Apart from the spatial separation by the FRS, the purity of the separation was improved by identifying each fragment event by event with respect to nuclear mass and charge by measuring its energy loss, time of flight, and magnetic rigidity. The relativistic energies provided by the SIS synchrotron facilitate an in-flight identification without ambiguities due to different ionic charge states that pose problems at lower incident energies. The separated fragments were implanted into a stack of position-sensitive silicon detectors to observe correlated decay events after implantation. The experiment was the third in a series of projectile-fragmentation studies of Xe isotopes at the FRS[2]. A total of seven events was observed within a period of 11 days, from which a preliminary cross section of about 5 pb can be deduced for ^{100}Sn.

Presently an off-line analysis of the data is performed to search for correlated decay events in the implantation detector for ^{100}Sn and neighbouring isotopes to measure half lives and decay modes. In principle, the GSI secondary-beam facility would also allow to envisage more detailed spectroscopic studies of this and other exotic nuclei in the future, e.g. direct mass measurements in the ESR storage ring coupled to the SIS synchrotron, or γ-decay measurements after Coulomb excitation. This requires, however, much higher production rates which can only be provided when SIS can be filled to the space charge limit. For this purpose, the construction of a new high-intensity injector for SIS is currently under consideration.

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720