LBL-23068
Preprint c.2

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

RECEIVED
LAWRENCE
BERKELEY LABORATORY

MAY 12 1987

LIBRARY AND
DOCUMENTS SECTION

Submitted to Physical Review Letters

HIGH-SPIN SPECTROSCOPY OF ^{168}Hf

E.M. Beck, M.A. Deleplanque, R.M. Diamond,
R.J. McDonald, F.S. Stephens, J.C. Bacelar,
and J.E. Draper

March 1987

TWO-WEEK LOAN COPY

This is a Library Circulating Copy
which may be borrowed for two weeks.

NUCLEAR SCIENCE DIVISION

LBL-23068 c.2

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBL-23068

High-Spin Spectroscopy of ^{168}Hf

E.M. Beck, M.A. Deleplanque, R.M. Diamond, R.J. McDonald,
and F.S. Stephens
Nuclear Science Division, Lawrence Berkeley Laboratory, University of
California, Berkeley, California 94720, U.S.A.

J.C. Bacelar
Kernfysisch Versneller Instituut, Rijksuniversiteit, 9747 AA Groningen,
The Netherlands

J.E. Draper
University of California, Davis, California 95616, U.S.A.

Abstract: The nucleus ^{168}Hf was studied up to spin (38^+) in the yrast band and to spins (41^-) and (38^-) in the lowest two negative-parity bands. The onset of a proton alignment ($h_{9/2}$ or $i_{13/2}$ quasiparticles) is observed in these three bands for the highest transitions. A new band with even spins and negative parity was found. The interaction strength between the ground-state band and the AB band is measured.

PACS: 21.10.Re 23.20.Lv 27.70.+q

1. Introduction

Spectroscopy of high-spin states began in the well-deformed rare-earth nuclei [1-3]. These nuclei have the experimental "advantage" of exhibiting rotational band structures ($E_\gamma \propto I$) with transitions having large E2 strength connecting the states of spin I and I-2. More recently, the heavier rare earths have been well studied [e.g. 4-6] and understood in the framework of the cranked shell model. ^{168}Hf was one of the first nuclei studied up to spins above 30 [7]. With Z=72 and N=96, ^{168}Hf is a typical mid-shell nucleus with stable quadrupole deformation. In fact, it is surprising how good a rigid rotor this nucleus appears to be between spin 22 and 32, though individual orbitals may carry a quarter of the total angular momentum. In this paper we present new high-spin data on ^{168}Hf. For the highest spins observed in this study the regular behavior of the transition energies is disturbed due to an alignment. Additionally, a new band is found. From the branching ratio the interaction strength between the ground-state band and the AB band is measured. The experimental technique and results will be presented in section 2. A discussion of the new findings follows in section 3, and section 4 summarizes the paper.

2. Experimental technique and analysis

High-spin states in the nucleus ^{168}Hf were populated by the reaction ^{124}Sn(^{48}Ti,4n) at beam energies of 210 and 215 MeV. The beam was provided by the 88-inch cyclotron of the Lawrence Berkeley Laboratory. Three tin foils of ~0.45 mg/cm^2 were used as a target such that the evaporation residues recoiled into vacuum. The γ rays emitted by the highly excited nuclei were measured with the Berkeley High Energy-Resolution Array (HERA) [8] which consists of 21 Compton-suppressed Ge detectors. The detectors were gain matched on-line to compensate for the Doppler shifts of the γ rays. The different angles of the detectors provided angular correlation information, and spin and parity assignments were made using the method described in ref. [9]. A total of ~ 280 million three- and higher-fold events was recorded on tape, of which approximately 50% came from the 4n channel.

Previously [7] the nucleus ^{168}Hf was known up to spin (34^+) in the yrast band, 22^+ in the ground-state band, and (33^-) and (30^-) in the negative-parity bands. The level scheme which was extracted from the present data is shown in Fig. 1. Energies in parentheses indicate that a transition is tentative, and spins in parentheses indicate that the multipolarity of the line could not be determined (due to weakness of the line or contamination). First, standard techniques were used to generate and study an E_γ-E_γ correlation matrix. Special use of the triples data was then made in order to solve ambiguities in the scheme. For that purpose, two gates on specific γ-ray energies were required and a spectrum of the third γ ray in coincidence updated. Typically, several such double-gated spectra, e.g., using transitions in a band, were summed (for discussion of triples data analysis, c.f. ref. [6]).

We were able to extend the yrast band (tentatively) to spin 38. Figure 2 (top) is a sum of spectra gated on the yrast transitions from 26^+ through 34^+. The order of the 634 keV and 684 keV transitions in the ground band was found to be reversed from ref. [7], but in agreement with the placement of the 684 keV line of ref. [10]. Intensity studies suggested this order, and it became clear with the observation of the 320 keV cross-band transition from the 16^+ yrast state to the 14^+ of the ground-state band. Figure 3 (top) shows a spectrum where one gate required a 320 keV line and the second gate a 262 keV or 371 keV transition. The 453 keV, 551 keV and 634 keV transitions are missing as they should, whereas the other yrast transitions are all present (aside from the higher spin states which cannot be seen because of statistics). The 766 keV transition, previously [7] placed above the 727 keV ground-band transition, was assigned as a cross-band transition from the ground-band 16^+ to the 14^+ yrast state, because of its coincidence with the 551 keV transition and with the ground-band transitions apart from the 634 keV and 684 keV lines. The continuation of the ground-state band beyond the 727 keV transition is not very clear, and the 714 keV transition was tentatively assigned.

Figure 2 (middle) shows a spectrum of the lowest odd-spin negative-parity band up to spin 41^-. This spectrum is a sum of double-gated spectra, where almost any two of the in-band transitions served as double gates. The same technique was used to obtain the spectrum of Fig. 2 (bottom), which shows the lowest negative-parity band with even spins up to the (38^-) state. The de-excitation of that band seems to be more branched than previously reported. Transitions of spin change one (either pure dipoles or almost pure $(\Delta I=1)$ quadrupoles with little dipole admixture) of 181 keV and 145 keV were found to depopulate the 12^- and 10^- states. A 201 keV transition was placed below the 273 keV transition. From these intermediate states the decay path proceeds to the ground band via high-energy transitions (> 1 MeV). We confirm the coincidence relationships at the bottom of the band in that the 273 keV - 380 keV and 311 keV - 342 keV pairs form a circle. All these transitions were previously determined to be stretched quadrupoles by angular distribution and conversion electron measurements [7,10]. Since our data are consistent with the 273, 311, 342 and 380 keV transitions all being stretched quadrupoles, we assign the spins of the involved levels accordingly. (However, the angular correlation techniques used in the present analysis are not able to distinguish stretched quadrupoles $(\Delta I=2)$ from $\Delta I=1$ transitions with certain M1-E2 mixing ratios or from pure unstretched dipoles $(\Delta I=0)$.) With the observed branching ratio between the 273 and 311 keV transitions, the 273 keV transition is the in-band transition in contrast to the assignment of ref. [7]. Further evidence for this rearrangement is the observation of a band built on the 342 keV transition. Figure 3 (bottom) shows that new band. The spectrum is a sum of double-gated spectra, where one gate was the 262 or 371 keV transition and the other gate was the 398, 424 or 734 keV transition. Hence, this is the second negative-parity band with even spins. In spite of our effort, a few γ-ray lines that appear to belong to the nucleus ^{168}Hf could not be placed in the scheme. These are 600 and 649 keV lines, which most likely feed the 12^+ state, and a rotational-like sequence of 627, 703, 763 and 812 keV. Extra 522 keV intensity was noticed in the clean 407 keV gate, which suggests that there is a third line of that energy in the nucleus. Table 1 summarizes the experimental results on ^{168}Hf obtained from the present analysis.

2. Discussion of the bands in ^{168}Hf

The structure of the previously observed bands seems quite clear. The positive-parity band crossing the ground-state band is the AB band. The two strongest negative-parity bands are AE and AF respectively. This was also concluded by Chapman et al. [7]. In this notation [12] A, B, C, D are the lowest unique-parity single-particle orbitals ($i_{13/2}$ neutrons for this neutron number) in the cranking model; E and F are the lowest two natural-parity orbitals (derived from the $h_{9/2}$ and $f_{7/2}$ neutrons for this neutron number). Studies of nuclei in this region also show that typically the two lowest negative-parity bands (odd and even spins) are populated with comparable intensity by HI,xn reactions, e.g., refs. [4,5,6,7]. In Fig. 4, spin is plotted against rotational frequency (taken to be $E_\gamma/2$) for all bands in ^{168}Hf. In the negative-parity bands AE and AF, the BC alignment is seen at a rotational frequency ~0.3 MeV, and thereafter there is little signature splitting. The second negative-parity band with even spins follows the other two negative-parity bands at lower spins, but seems to deviate somewhat in the region of the BC alignment. This suggests that the same or very similar orbitals are involved in the new band as are in the other two bands and that either the B or C orbital is blocked. The assignment BE is consistent with the even spins and negative parity. The difference between the BC and AD alignments, which are expected to happen around the same frequencies, might explain the observed behavior. A proton structure for the new band is rather unlikely since no cascade transitions are observed (which should then be enhanced) and the AB neutron backbend appears to be blocked (see Fig. 4). Also, the neutron assignment is more plausible considering the decay of the AF band to the lowest states of BE. However, it is not clear why the BE 8^- state lies ~40 keV lower than the AF 8^- state. A band of about the same intensity with presumably negative parity and even spins was observed in the nucleus ^{166}Yb (which is only different from ^{168}Hf by two protons) over a similar frequency range [6], and was interpreted as BE, c.f. ref. [13]. As suggested for this band in ^{166}Yb [13], the lowest observed states of the BE band in ^{168}Hf might be mixed with an octupole band or even be interpreted as the continuation of an octupole band. As a consequence the 8^- state might fall below the AF 8^- state. The states to which the AF band branches weakly by a 181 and 145 keV transition may be BF. One might then expect decay to these states from its signature partner BE, but this was not found. However, if the branching ratio were comparable to that of AF to these states, this decay could not have been detected because of its weakness.

The bands which were seen up to frequencies above 0.5 MeV all exhibit an irregularity in their highest transition energies. Figure 4 shows the onset of that upbend. It is most likely due to the alignment of a pair of $h_{9/2}$ or $i_{13/2}$ protons, which is expected around these frequencies from cranked-shell model calculations [14]. The onset of an alignment is seen around the same frequencies in ^{166}Yb [6], where it was also suggested to be due to protons. This alignment ends the string of consecutive transitions with very regular energy spacings, a feature of the yrast band (and also to a somewhat lesser extent of the negative-parity bands) which was discussed by Chapman et al. It seems to us that a cancellation of effects increasing the moment of inertia (e.g., alignments, reduction of pairing, c.f. ref [15]) and effects decreasing the moment of inertia (as would a gradual shape change) probably produces the observed constant moment of inertia. This has been suggested for the yrast band in ^{166}Yb [16], where lifetime measurements indicate a drop in the collectivity of the states having the very constant moment of inertia. The overall similarity of the band structure and the alignments in the two nuclei suggests similar behavior for ^{168}Hf, but lifetime measurements are needed to test this hypothesis.

The continuation of the ground-state band shows a large "wiggle" at its crossing with the AB band, c.f. the full squares in Fig. 4. This is due to the perturbation of closely spaced levels having the same spin (ground-state band and AB band) which interact. The energy shift due to the interaction can be estimated from the energies of the known 14^+ and 16^+ states and the measured branching ratios, using a simple four-level model [6,17,18]. Assuming the same Q_0 for the two interacting bands, this model predicts immediately that the B(E2) ratio for the two 16^+ to 14^+ states should be the same. Experimentally one finds good agreement for the 634 keV/ 767 keV and 453 keV/ 320 keV branching ratios after correction for the E_γ^5 dependence of the transition probability on γ-ray energy (5.0 ± 1.5). This branching ratio determines the interaction strength to be 63 $(\pm\,^{2}_{3})$ keV, where an I-independent strength was assumed in the calculation. That means, the two 14^+ states were "repelled" ~45 keV from each other by the interaction, and the 16^+ states only ~13 keV, because the unperturbed 16^+ states are further apart in energy than the two 14^+ states. The large irregularity at the bandcrossing is thus removed in the unperturbed states, but nevertheless smooth upbending is observed in the ground-state band in that frequency region. In neighboring nuclei [5,6,13] this upbend is interpreted as the BC alignment, which is gradual for this neutron number (c.f. BC alignment in AE and AF). Whether there is still another upbending in addition to BC at higher frequencies in the ground-state band is not clear, because the total gain in alignment cannot yet be read from the data.

3. Conclusion

High-spin states in the nucleus ^{168}Hf were studied by means of γ-ray spectroscopy. The observed bands are typical of a well-deformed nucleus in the heavier rare earths. Their structure can be understood on the basis of the cranked shell model. The interaction strength between the ground-state and AB band is found to be ~63 keV, in agreement with theoretical expectations for that neutron number. An irregularity due to $i_{13/2}$ or $h_{9/2}$ proton alignment is seen for the highest frequencies in the yrast and lowest two negative-parity bands. This upbend ends the very regular behavior of the transition energies between spin 22 and 32. Lifetime measurements will still be needed to understand in more detail this regular behavior.

We would like to thank M.K. Lee and R.A. Belshe for help with the electronics and computer software, and C. Duyar for assistance during the experiment. Discussions with Dr. A.O. Macchiavelli are acknowledged. One of us (EMB) acknowledges a grant of the Hanns-Seidel Foundation. This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

References

[1] Morinaga, H., Gugelot, P.C.: Nucl. Phys. 46, 210 (1963)

[2] Hansen, G.B., Elbek, B., Hagemann, K.A., Hornyak, W.F.: Nucl. Phys. 47, 529 (1963)

[3] Stephens, F.S., Lark, N.L., Diamond, R.M.: Phys. Rev. Lett. 12, 225 (1964) and Nucl. Phys. 63, 82 (1965)

[4] Bacelar, J.C., Diebel, M., Ellegaard, C., Garrett, J.D., Hagemann, G.B., Herskind, B., Holm, A., Yang, C.-X., Zhang, J.-Y.: Nucl. Phys. A442, 509 (1985)

[5] Blume, K.P., Huebel, H., Murzel, M., Recht, J. Theine, K., Kluge, H., Kuhnert, A., Maier, K.H., Maj, A., Guttormsen, M., de Lima, A.P.: Nucl. Phys. (in press)

[6] Beck, E.M., Bacelar, J.C., Deleplanque, M.A., Diamond, R.M., Stephens, F.S., Draper, J.E., Anders, H., Herskind, B., Tjøm, P.O.: Nucl. Phys. (in press)

[7] Chapman, R., Lisle, J.C., Mo, J.N., Paul, E., Simcock, A., Willmott, J.C., Leslie, J.R., Price, H.G., Walker, P.M., Bacelar, J.C., Garrett, J.D., Hagemann, G.B., Herskind, B., Holm, A., Nolan, P.J.: Phys. Rev. Lett. 51, 2265 (1983)

[8] Diamond, R.M., Stephens, F.S.: The High Resolution Ball, September 1981, unpublished; and R.M. Diamond: The Berkeley High-Resolution Ball in Instrumentation for Heavy-Ion Nuclear Research, ed. Shapira, D. p.259. New York: Harwood Acad. Pub. 1985

[9] Stephens, F.S., Deleplanque, M.A., Diamond, R.M., Macchiavelli, A.O., Draper, J.E.: Phys. Rev. Lett. 54, 2584 (1985)

[10] Janssens, R.V.F., de Voigt, M.J.A., Sakai, H., Aarts, H.J.M., van der Poel, C.J., Arciszewski, H.F.R., Scherpenzeel, D.E.C., Vervier, J.: Phys. Lett. 106B, 475 (1981)

[11] Bacelar, J.C., Ph.D. thesis, University of Manchester, Manchester, U. K. 1982 (unpublished)

[12] Riedinger, L.L., Andersen, O., Frauendorf, S., Garrett, J.D., Gaardhøje, J.J., Hagemann, G.B., Herskind, B., Makovetzky, Y.V., Waddington, J.C., Guttormsen, M., Tjøm, P.O.: Phys. Rev. Lett. 44, 568 (1980)

[13] Jonsson, S., Roy, N, Ryde, H., Walus, W., Kownacki, J., Garrett, J.D.,

Hagemann, G.B., Herskind, B., Bengtsson, R., Åberg, S.: Nucl. Phys. A449, 537 (1986)

[14] Bengtsson, T., Ragnarsson, I.: Nucl. Phys. A436, 14 (1985)

[15] Mutz, U., Ring, P.: J.of Phys. G 10, L39 (1984)

[16] Bacelar, J.C., Holm, A., Diamond, R.M., Beck, E.M., Deleplanque, M.A., Draper, J.E., Herskind, B., Stephens, F.S.: Phys. Rev. Lett. 57, 3019 (1986)

[17] Bengtsson, R., Frauendorf, S.: Nucl. Phys. A314, 27 (1979)

[18] Davydov, A.S.: Quantum Mechanics 2nd Edn. p.191. Oxford: Pergamon Press 1976

Table 1: Summary of experimental results on ^{168}Hf

Energy (keV)[a]	Intensities[b]	Assignment[c]
123.7		2+ → 0+ gsb
144.6	1.5	10- → (9-)
181.4	1.	12- → (11-)
201.0	1.4	8- →
240.	<1.	(9-) →
261.5	100.	4+ → 2+ gsb
273.3	7.9	10- → 8- AF
311.1	2.	10- → 8-
320.	2.0	16+ → 14+
325.	<1.	(11-) → (9-)
331.	1.	(9- → 10+)
342.4	4.	8- → 6- (BE)
361.4	10.8	12- → 10- AF
371.4	100.	6+ → 4+ gsb
380.0	2.3	8- → 6-
397.6	3.6	10- → 8- (BE)
399.9	1.3	10- → 9-
407.0	5.0	11- → 9- AE
423.8	4.0	12- → 10- (BE)
441.0	13.9	14- → 12- AF
452.	1.	15- → 14+
452.8	44.	16+ → 14+ AB
456.6	96.	8+ → 6+ gsb
463.6	13.7	13- → 11- AE
475.8	4.0	14- → 12- (BE)
504.5	15.	15- → 13- AE

508.2	12.9	16- → 14- AF
522.0	80.	10+ → 8+ gsb
522.0	36.	18+ → 16+ AB
536.7	3.3	16- → 14- (BE)
547.7	14.5	17- → 15- AE
551.5	49.	14+ → 12+
558.6	12.5	18- → 16- AF
570.0	70.	12+ → 10+ gsb
588.4	13.8	19- → 17- AE
590.0	2.5	18- → 16- (BE)
598.0	11.4	20- → 18- AF
607.5	29.	20+ → 18+ AB
619.5	11.1	21- → 19- AE
632.1	15.	13- → 12+
633.9		16+ → 14+ gsb
635.3	1.6	20- → 18- (BE)
640.3	8.6	22- → 20- AF
656.0	8.9	23- → 21- AE
680.6	1.3	22- → 20- (BE)
684.0	12.	14+ → 12+ gsb
684.4	24.	22+ → 20+ AB
694.6	7.2	24- → 22- AF
698.5	6.2	18+ → 16+ gsb
712.7	7.0	25- → 23- AE
714.	2.2	(22+ → 20+ gsb)
726.6	5.1	20+ → 18+ gsb
734.1	1.	24- → 22- (BE)

738.1	9.	11- → 10+
751.1	18.	24+ → 22+ AB
760.5	6.4	26- → 24- AF
767.0	3.4	16+ → 14+
780.9	5.1	27- → 25- AE
795.5	<1.	(26- → 24- BE)
812.6	13.	26+ → 24+ AB
831.4	4.3	28- → 26- AF
851.0	11.5	29- → 27- AE
853.0		9- → 8+
875.4	7.3	28+ → 26+ AB
902.0	2.9	30- → 28- AF
916.9	2.4	31- → 29- AE
939.4	3.9	30+ → 28+ AB
942.	<1.	8- → 8+
967.9	1.8	32- → 30- AF
975.	<1.	(→ 26+)
976.9	1.7	33- → 31- AE
979.4	4.	8- → 8+
999.5	2.5	32+ → 30+ AB
1026.0	1.3	34- → 32- AF
1026.5	1.4	35- → 33- AE
1051.0	1.6	34+ → 32+ AB
1056.5	5.	6- → 6+
1062.5	0.8	37- → 35- AE
1071.9	0.7	36- → 34- AF
1076.	<0.5	(39- → 37- AE)

1087.0	1.	36+ → 34+ AB
1088.	<0.5	(41- → 39- AE)
1104.	<0.5	(38- → 36- AF)
1104.5	0.5	(38+ → 36+ AB)
1109.	2.	(9-) → 8+
1236.	1.	(→ 6+)
1325.	1.	→ 6+

[a] Energies are known to ~0.3 keV except for the weakest transitions where the uncertainties are larger.

b) Intensities are mostly obtained from gated spectra and normalized to the 261.5 keV $4^+ \rightarrow 2^+$ transition. Uncertainties are ~10% except for the weakest transitions where the uncertainties may be up to 50%.

[c] The bands are referred to by their configuration at low spins. The nomenclature from section 3. is used. Parentheses indicate that a transition or spin assignment is tentative.

Figure Captions

Fig. 1: Level scheme of ^{168}Hf as obtained from the present analysis. Transition energies are given in keV. Bands are identified by their configuration at low spins, see section 3. in the text.

Fig. 2: Sum of γ-ray coincidence spectra in ^{168}Hf: (top) yrast band, (middle) AE band, (bottom) AF band.

Fig. 3: Coincidence spectra in ^{168}Hf: (top) gated on the 320 keV line and the 262 or 371 keV lines, (bottom) gated on (BE) and ground-band transitions.

Fig. 4: Spin plotted versus rotational frequency. Full/ open squares represent the ground-state/ AB band, full/ open circles represent the AE/ AF band, and triangles the (BE) band.

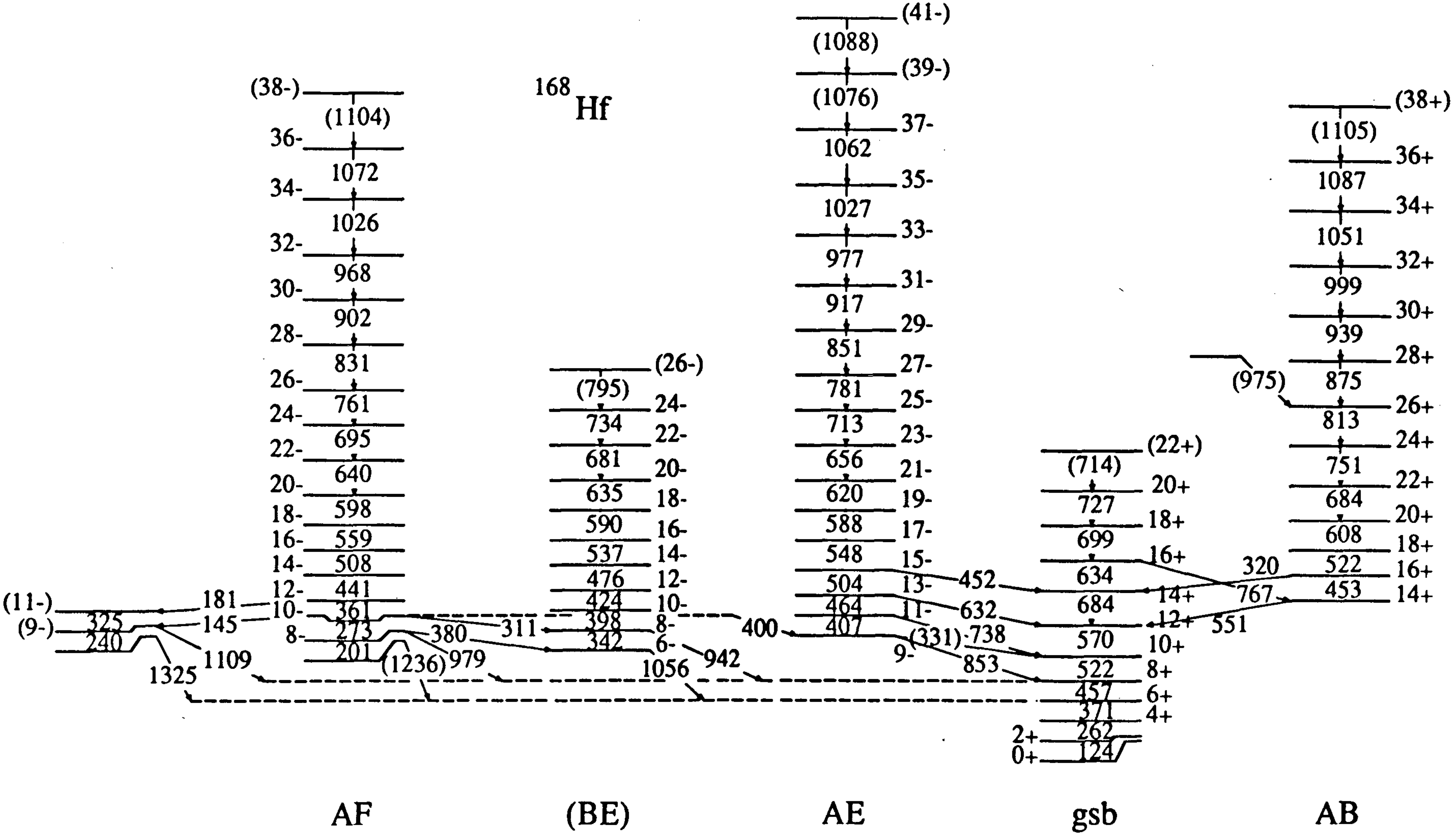
Addresses:

E.M. Beck
Institut f. Strahlen- u. Kernphysik
Nussallee 14-16
D-5300 Bonn 1
Fed. Rep. of Germany

M.A. Deleplanque, R.M. Diamond,
R.J. McDonald, F.S. Stephens
Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720
U.S.A.

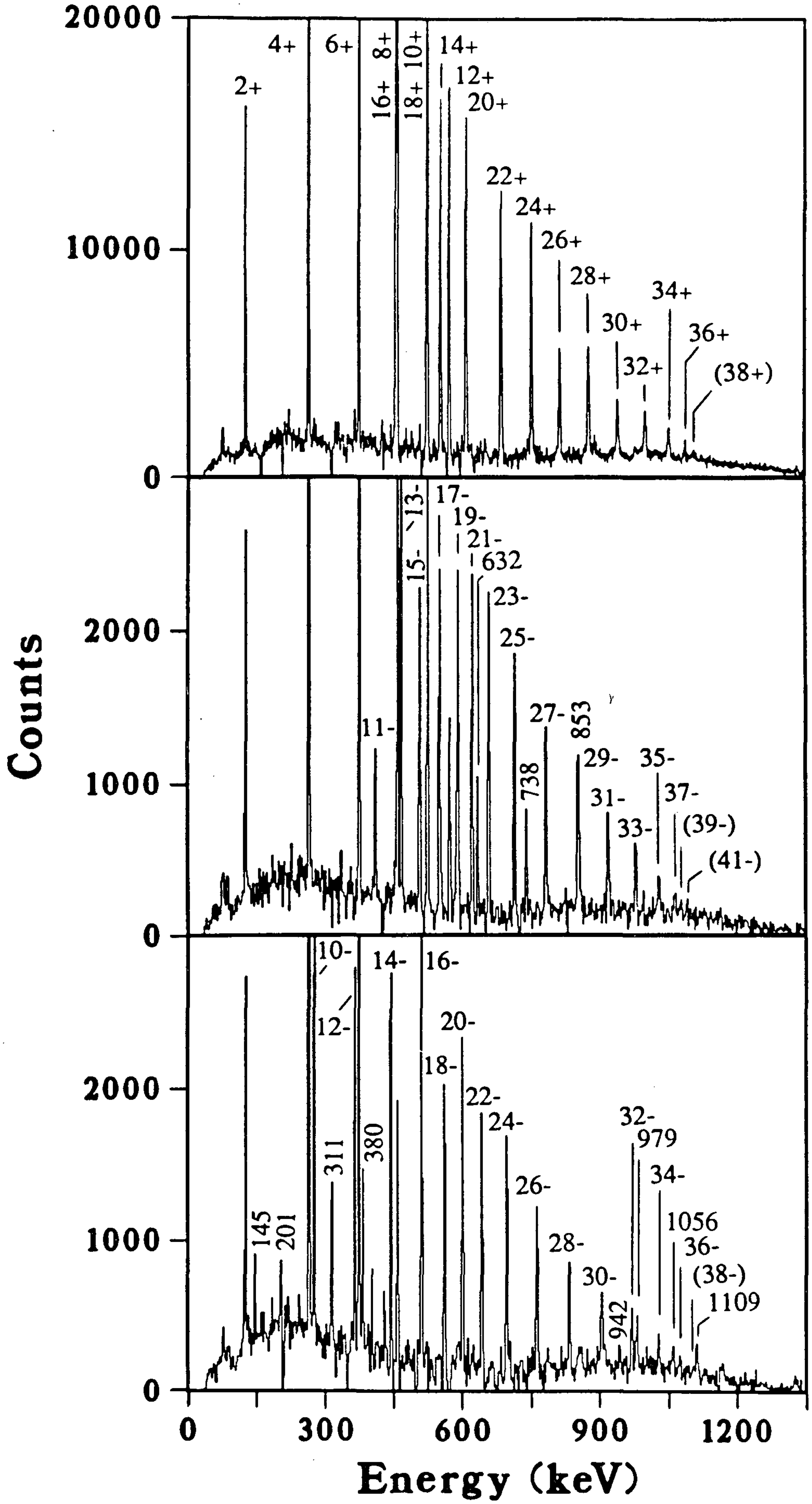
J.C. Bacelar
KVI
Rijksuniversiteit
9747 AA Groningen
The Netherlands

J.E. Draper
University of California
Davis, California 95616
U.S.A.



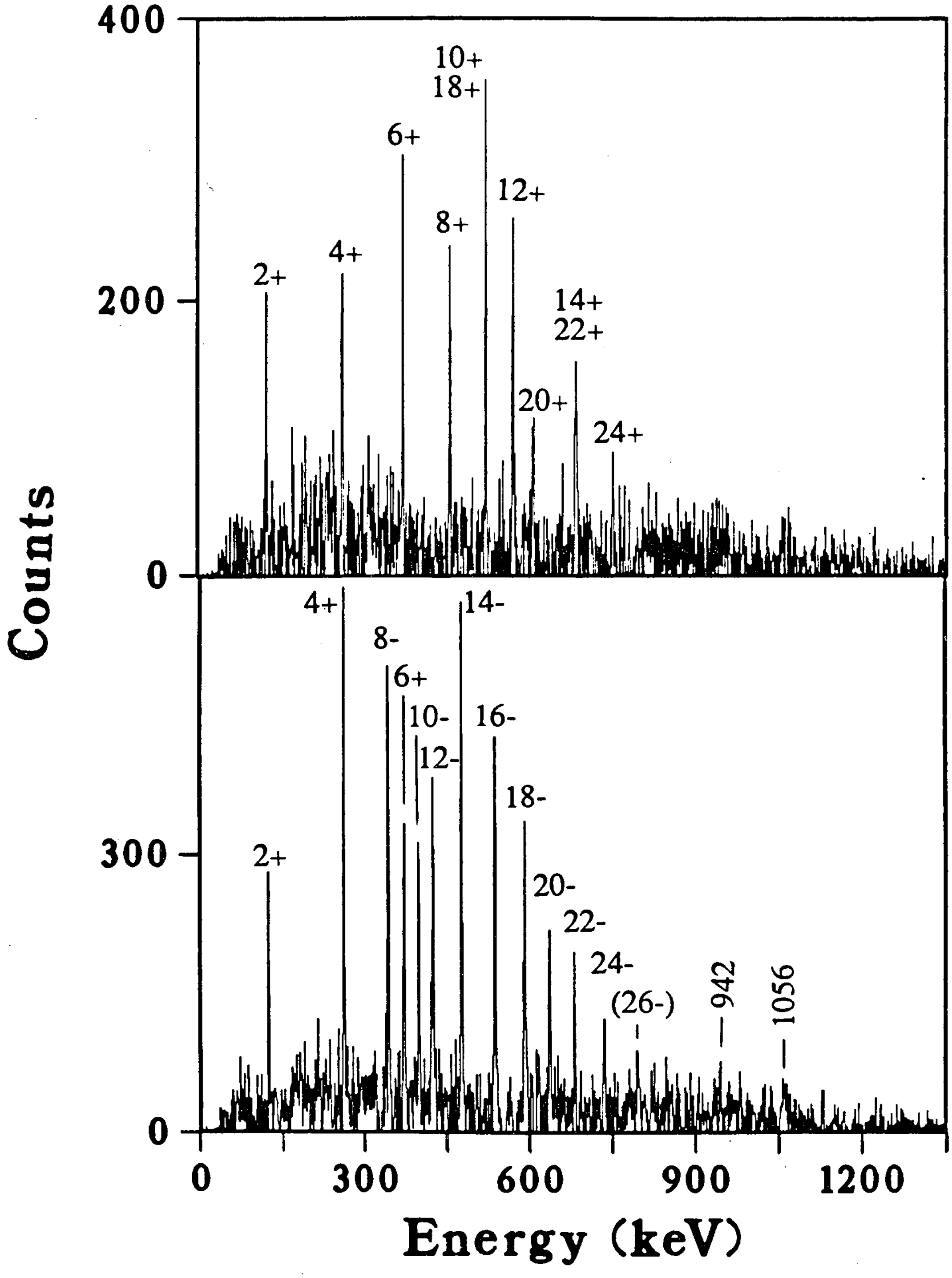
XBL 873-884

Fig. 1



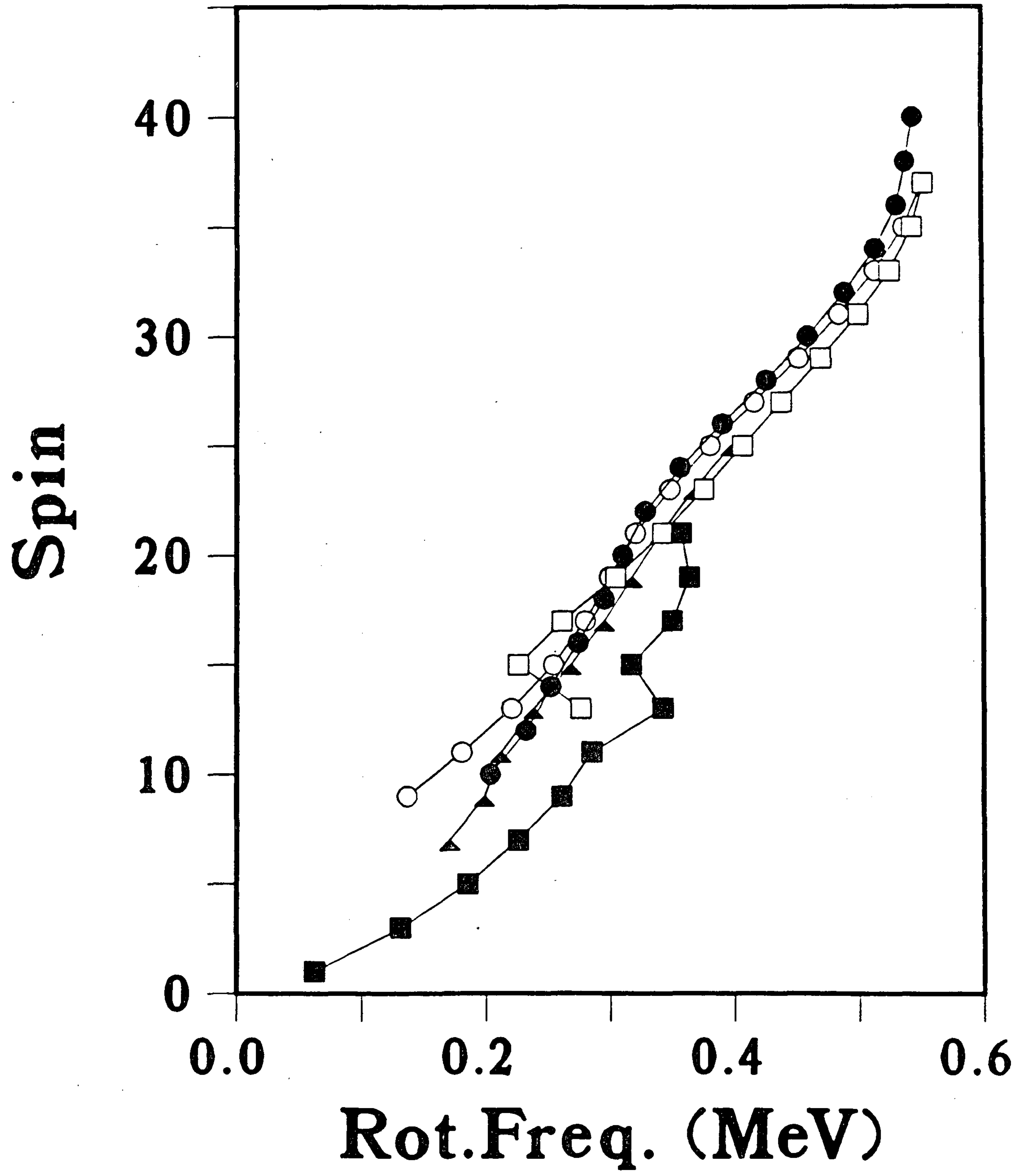
XBL 873-885

Fig. 2



XBL 873-886

Fig. 3



XBL 873-887

Fig. 4

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720