Lawrence Berkeley National Laboratory

Recent Work

Title

THREE-PHOTON CORRELATIONS IN ROTATIONAL NUCLEI

Permalink

<https://escholarship.org/uc/item/6r07h35w>

Author

Stephens, F.S.

Publication Date

1987

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

RECEIVED
LAWRENCE
BERKELEY LABORATORY

MAR 30 1987

Submitted to Physical Review Letters

LIBRARY AND
DOCUMENTS SECTION

THREE-PHOTON CORRELATIONS IN ROTATIONAL NUCLEI

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

January 1987

TWO-WEEK LOAN COPY

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

LBL-22881
c2

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.

Three-Photon Correlations in Rotational Nuclei

F.S. Stephens, J.C. Bacelar,¹ E.M. Beck,²
M.A. Deleplanque and R.M. Diamond

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

and

J.E. Draper

University of California
Davis, California 95616.

Abstract: We have studied the correlations among three γ -ray energies emitted by high-spin nuclear states. The correlation features (ridges and dip) in coincidence with two γ -rays of a given energy are found to be the same, within our statistics, as those in coincidence with a single γ ray of that energy. We believe this implies that the full γ -ray spectrum is a mixture of some essentially undamped rotational cascades and some rather strongly damped ones.

1. Permanent address: Kernfysisch Versneller Instituut, Rijksuniversiteit, 9747 AA Groningen, The Netherlands.
2. Present address: Institut f. Strahlen-u. Kernphysik, University of Bonn, D5300 Bonn, West Germany.

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.

Collective rotational motion is very well established in nuclei--bands exist that follow the $I(I+1)$ energy relationship within a few percent over ranges of spin as large as $\sim 40\hbar$, with intraband transition probabilities up to several hundred times that expected for non-collective motion. These are seen when the nuclei are cold with respect to other degrees of freedom. One of the questions that has very recently come under study has to do with what happens to the rotational motion when other degrees of freedom are present; i.e., in "hot" nuclei--or using nomenclature in better context with other types of current nuclear studies, slightly "warm" nuclei. Evidence has been presented¹⁻⁶ that the rotation persists but becomes mixed with the other degrees of freedom (especially single-particle ones); that is, it is damped. The damping of various types of nuclear motion plays an important role at high temperature in nuclei, but has been virtually impossible to study in detail because of the complexity and the difficulty in controlling conditions. It appears that rotational motion, with its very characteristic decay pattern, offers a unique opportunity to study this process in the region where it initially sets in. In addition, we can hope to learn something about the underlying rotational properties of such nuclei.

Warm nuclei ($0.2 < T < 0.7$ MeV) with high spins are produced following the evaporation of particles in heavy-ion fusion reactions. The subsequent γ -ray decay initially follows so many pathways that the spectrum cannot be resolved. However, the rotational behavior can still be studied through the average γ -ray properties. Thus, studies of the average lifetimes, directional correlations and correlations of γ -ray energy (E_γ) with spin, have shown rather convincingly that the behavior is rotational.

However, more detailed studies ^{1,2} found that the correlations between two γ -ray energies are much weaker than expected for good rotational behavior, leading to the suggestion of some damping ³. More recently ^{4,5} attempts have begun to characterize the damping in greater detail. The present note represents an important step in this direction, where we examine the correlations between three γ -ray energies at high resolution. The first result seems to be a rather clear indication that the main damping widths are larger than was first thought ^{1,2}, in better agreement with other types of recent studies ^{4,5}.

We have studied the reactions, $^{48}\text{Ti}(215 \text{ MeV}) + ^{124}\text{Sn} \rightarrow ^{168}\text{Hf} +$, $^{40}\text{Ar}(180 \text{ MeV}) + ^{124}\text{Sn} \rightarrow ^{160}\text{Er} +$, and $^{40}\text{Ar}(176 \text{ MeV}) + ^{100}\text{Mo} \rightarrow ^{136}\text{Nd} +$, using beams from the LBL 88-Inch Cyclotron. In each case the main (4n) product is given, but there are two or three others (indicated by the "+") made in sizeable yield. The data were taken on HERA, our array of 21 Compton-suppressed germanium detectors, each of which subtends 0.75% of 4π and has a peak to total ratio of about 0.5 for the ^{60}Co γ rays. Between 3 and 7×10^8 three- and higher-fold events were taken in each of the three cases. These were sorted into a symmetrized 250-channel three-dimensional matrix beginning at 200 keV with 8 keV per channel. This matrix was unfolded to correct for the response function of the germanium detectors and, in addition, statistical γ rays, which are essentially uncorrelated, were subtracted using a spectral shape, $E_Y^3 \cdot \exp(-E_Y/T)$, normalized to the high-energy part of each spectrum. The temperature, T , was obtained by fitting the high-energy part of the total projection of the matrix. Thus single- and double-gated spectra from this matrix should not be influenced by either detector response or statistical γ -rays.

Single-gated spectra were generated by taking the full projection of the two-dimensional matrix (plane) in coincidence with a single (8 keV) channel of the third dimension. A number of full projections of consecutive planes were sometimes added, but only after shifting their individual energy scales so that the gates were aligned. Thus, features correlated with the gate were preserved with no loss of resolution, whereas those not correlated with the gate were smeared out. To generate the double-gated spectra, a second gate was required at the same energy as the first gate. This second gate was 24 keV wide, and corresponded to a three-channel projection in a given plane, centered at the energy of the plane. These three-channel projections were also shifted (like the full projections) to align the gates and added over rather broad energy regions, the lower limit of which was determined by the size of the resolved-line effects, and the upper limit by the absence of any significant structure. The double-gated spectra had effectively one 8 keV gate and one 24 keV gate. The wider 24 keV gate gave a factor of three better statistics and essentially no additional smearing detectable with our statistics. The single- and double-gated spectra are normalized to the same number of counts and shown superposed in Fig. 1 for the three reaction systems.

A good rotational band has γ -ray energies proportional to spin, and thus decays by a sequence of equally spaced γ rays. The spectrum coincident with one of these will contain all the others, but have one missing at the position of the gating transition. A superposition of γ rays from many good (undamped) rotational bands (that have different moments of inertia, alignments, etc.) will still have this property, where the area missing at the gate position corresponds to one transition, the width of the missing area is

given by the average moment of inertia, and the coincident spectrum drops to zero in the gate region. Essentially all the experimental evidence for damping at present is that, whereas other data indicate that the higher-energy γ rays (from the higher-spin states) are rotational, there is not one full transition missing at the gate position. Instead, the coincident spectra have only a small "dip" at this position, whose area varies from 30-40% of one transition at γ -ray energies somewhat less than 1 MeV (for our reactions), down to zero above ~ 1.5 MeV. A large damping width will wash out this ($E_{\gamma_1} - E_{\gamma_2}$ correlation) dip, since each rotational state will be able to emit any one of a variety of γ -ray energies instead of the usual single energy that generates the dip.

To learn more about the processes occurring, we place a second narrow gate at the position of the first gate. In a superposition of γ rays from good rotational bands, there would be no counts in the coincident spectrum, since the dip, after just one gate, would go to zero, leaving nothing to provide a second gate. Experimentally, however, the dip is never large, so there are counts in this double-gated spectrum as shown in Fig. 1. To understand what the damping will do to such a spectrum, we have written a computer code to simulate the cascade.

Only the most general features of the simulation code will be discussed here; some additional information is available in ref. 5. The relevant results are not at all sensitive to the details of this code. An initial spin and excitation energy are chosen at random from reasonable distributions. Then a cascade of rotational- and statistical-type transitions deexcites the nucleus. At each step of this cascade, the transition type is chosen at

random from the two possibilities, weighted by the expected transition probabilities. The rotational properties are the most important and at low temperature, these are good rotational bands whose properties (moments of inertia and alignment) are chosen (initially, and following each statistical transition) at random from reasonable distributions. Above some critical temperature, where the damping is supposed to set in, this type of rotational behavior ends and every rotational transition energy is chosen at random from a gaussian distribution whose FWHM ("damping width" or Γ_{rot}) is a particular chosen value. It is essential to realize that at low temperatures band properties are chosen at random, but then the cascade typically stays in that band for several transitions (producing the $E_Y - E_Y$ correlations); whereas, at high temperatures every rotational transition energy is chosen at random within an energy range determined by Γ_{rot} .

Since the dips in Fig. 1 all have a FWHM around 100 keV, a first trial in the simulation is simply $\Gamma_{\text{rot}} = 100$ keV for all temperatures. The average moment of inertia is taken to be 60 MeV^{-1} , and the gates are always 8 keV wide and placed at 1.2 MeV. Fig. 2a shows the result of this calculation, which can be easily understood. Both dips have roughly the FWHM of Γ_{rot} , and areas of one and two transitions, respectively, for the single- and double-gated spectra. Also, the area of the calculated dips is too large. One can make the calculation somewhat more realistic by having good rotational behavior below an excitation energy of 2 MeV above the yrast line ($T=0.3$ MeV), and damped behavior above that, with Γ_{rot} still equal to 100 keV, as shown in Fig. 2b. Some features are better here (e.g., the ridge structures beside the dip--due to the low-temperature undamped bands--and the steeper side walls

of the dip due to the innermost ridges whose separation is determined by the moment of inertia), but the factor of two difference in area between the single- and double-gated spectra is unchanged, as is the dip area, in striking disagreement with the data. Since there must be one and two transitions missing in the single- and double-gated spectra, respectively, the only solution we have found is to make the main damping width very large, so that the associated dip becomes quite wide and therefore difficult to see. Changing Γ_{rot} from 100 to 300 keV gives the spectra in Fig. 2c, which now begin to look very much like the data, both in the absolute and relative areas of the dips. The broad dip corresponding to the 300 keV Γ_{rot} can hardly be seen in these spectra, and the apparent dips come from the undamped cascades below $T=0.3$ MeV. To understand this result, one should remember that one gate on an undamped γ ray excludes the second gate (at the same energy) catching an undamped γ ray (the dip in undamped cascades goes all the way to zero). Thus, the second gating γ ray must come from the broad damped distribution, which does not affect the dip very much. One could adjust a number of additional parameters in order to make detailed fits to the experimental data, but that will not be pursued here.

These data indicate the overall behavior rather clearly: an observed dip that is (nearly) undamped, together with a broad (~ 300 keV) damping width at higher temperatures. This type of behavior was previously suggested based on the temperature dependence of the dip area⁴ and on the detailed shape of the dip⁵. However, the present three-fold correlation data are by far the most direct indication of it. Nevertheless, this analysis represents only the first step in extracting information from three- (and higher-) fold data,

which we feel hold great promise for giving us a much more detailed understanding of the damping process.

While the general behavior of these warm rotational bands is becoming clearer, there remain many open questions. First, we would like to know the excitation energy or temperature at which the damping sets in, as this is the point where the average separation between levels of a given spin becomes comparable to the average matrix element connecting these levels. Whereas the dip area (in the simulation) is quite sensitive to this excitation energy, it is also strongly coupled to the cascade parameters, especially the rotational and statistical γ -ray transition probabilities. Thus, we need to be sure of the cascade parameters before this energy can be known reliably, but 2 MeV (as above) is in reasonable accord with theory. Secondly, we would like to know how suddenly the damping sets in. Since we see only essentially undamped and strongly damped behavior, a rather sudden onset of the damping is indicated (again as is expected by the theory), but more specific information would be interesting. Thirdly, we would very much like to know if the damping is complete: i.e., whether there are types of states (like superdeformed or strongly triaxial ones) that have much smaller matrix elements connecting them with the bulk of the states, and therefore remain largely undamped over our populated temperature regions. In this connection, Egido⁶ found that alignment variations may be damped before the normal shape variations. Finally, it would be nice to have more direct evidence that damping is indeed the process causing the observed effects. An onset of large irregularity in the rotational-band energies around 2 MeV (for example, due to more triaxial shapes) could explain the dip behavior, and is considered less likely than

damping only because: 1) lifetime measurements suggest the behavior is fully rotational, and 2) damping is expected to occur generally, whereas sources of irregular rotational energies (e.g., triaxiality) are not. We believe that understanding this (damping) behavior is one of the most open and interesting problems in high spin physics.

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. J.E. Draper et al., Phys. Rev. Lett. 56, 309 (1986); F.S. Stephens, in: Proc. of the Second International conference on Nucleus-Nucleus Collisions, Visby, Sweden (North-Holland, Amsterdam, 1985).
2. J.C. Bacelar et al., Phys. Rev. Lett. 55, 1858 (1985).
3. T. Døssing, in: Niels Bohr Centennial Conference on Nuclear Structure (Elsevier Science Publishers, 1985); B. Lauritzen, R.A. Broglia, and T. Døssing, Nucl. Phys. A457, 61 (1986).
4. F.S. Stephens et al., Phys. Rev. Lett. 57, 2912 (1986).
5. F.S. Stephens et al., submitted to Phys. Lett.
6. J.L. Egido, unpublished work; see also ref. 4.

Figure Captions

Fig. 1 Gamma-ray spectra in coincidence with a single gate (circles) and a double gate (solid line), for the: a) ^{168}Hf data; b) ^{160}Er data; and c) the ^{136}Nd data. The energy regions covered by the gates (see text) are: a) 0.68–1.00 MeV; b) 0.60–1.00 MeV; and c) 0.92–1.16 MeV, and they are shifted to centers: a) 0.72 MeV; b) 0.64 MeV; and c) 0.96 MeV.

Fig. 2 Same as Fig. 1 except for simulated data with gates at 1.2 MeV (see text): a) fully damped, width 100 keV; 2) undamped below $T=0.3$ MeV, damped above (width 100 keV); 3) undamped below $T=0.3$ MeV, damped above (width 300 keV). The resolved lines are suppressed in all these simulated spectra.

XBL 871-264

Fig. 1

XBL 871-265

Fig. 2

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*