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Correlation Studies of Rotational Behavior at Very High Angular Momentum

M. A. Deleplanque,[(a)] F. S. Stephens,[(b)] O. Andersen, J. D. Garrett, and B. Herskind
The Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

and

R. M. Diamond, C. Ellegaard,[(c)] D. B. Fossan,[(d)] D. L. Hillis, H. Kluge,[(e)] M. Neiman,[(c)] C. P. Roulet,[(a)] and S. Shih[(f)]
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

and

R. S. Simon
Gesellschaft für Schwerionenforschung, Darmstadt, West Germany
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Transition-energy correlations are studied in rotational erbium nuclei up to 1250 keV. A collective moment of inertia $\mathcal{J}_c$ corresponding to in-band transitions is directly deduced from the data and compared to the effective moment of inertia, $\mathcal{J}_{\rm eff}$, deduced from multiplicity measurements. For $I\sim(30-45)\hbar$ it is found that $\mathcal{J}_c$ is 25–50% smaller than $\mathcal{J}_{\rm eff}$, which suggests an important contribution to the total spin from a few aligned particles. This description implies band crossings for which there is independent evidence.

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Nuclear structure studies based on the analysis of γ rays are limited at the present time to spins below ~$70\hbar$ in the mass region around $A=160$, since for higher spins the compound nucleus fissions[1] prior to γ-ray emission. For the deformed rare-earth region, detailed spectroscopic measurements[2,3] now extend up to spin $30\hbar$, above which the γ-ray spectrum can no longer be resolved. Many measurements have shown that this "continuum" γ-ray spectrum consists of a statistical part plus a bump formed by "yrastlike" γ rays which deexcite the nucleus through many pathways roughly parallel to the yrast line.[4,5] This yrastlike cascade contains nuclear structure information, and in deformed nuclei, it is dominated by stretched $E2$ rotational transitions, whose energies are correlated. The correlations can be studied in some detail, even in an unresolved spectrum, by a method[6] which isolates correlated events from an uncorrelated background. Although these events cannot isolate individual rotational bands, they are sensitive to certain features, in particular the single-particle angular-momentum alignment, shared by many bands.

The measurement was performed at the 88-in. cyclotron at Lawrence Berkeley Laboratory. It consisted essentially of γ-γ coincidences, but four Ge(Li) detectors were used simultaneously, which gave six times the coincidence rate of one pair. These detectors were all placed at 135° to the beam to equalize the Doppler shifts, and 10 cm from the target to reduce true pileup. In addition, a pulse in any one of three 7.5-cm×7.5-cm NaI detectors was required in order to reduce low-multiplicity events. The gains of the Ge(Li) detectors were carefully matched so that all the coincident pairs could be added in the event-by-event computer analysis, giving a single two-dimensional γ-γ matrix, N_{ij}. We have studied the deexcitation of the ^{164}Er compound system (using lead-backed targets) since it leads to relatively neutron-rich *rotational* erbium nuclei. The maximum angular momentum brought into the system by the 185-MeV ^{40}Ar nuclei is $80\hbar$, which ensures the highest possible spin in the evaporation residues.

A background of uncorrelated events, $\tilde{N}_{ij}$, has been subtracted from the γ-γ matrix[6] of 40 million events. Basically, this background is calculated for the point ij from the projections of the row $\sum_k N_{ik}$, and column $\sum_l N_{lj}$, on the assumption that every observed γ ray occurs in coincidence with any other observed one with equal probability. The correlated two-dimensional spectrum ΔN_{ij} is then

$$\Delta N_{ij} = N_{ij} - \tilde{N}_{ij} = N_{ij} - \sum_k N_{ik} \sum_l N_{lj} / \sum_{l'k'} N_{l'k'} . \qquad (1)$$

This subtracted background is too large since the projections already contain the correlated events, and the absolute number of correlated events is not obtained. Some improved subtraction methods are being tested; however, the qualitative features presented below are independent of the subtraction method used.

A contour plot of the correlated two-dimensional coincidence spectrum ΔN_{ij} is shown in Fig. 1. It is symmetric about the 45° diagonal because the two independent halves of the ΔN_{ij} matrix have been added to improve the statistics. In the low-energy region (up to $E \approx 1$ MeV), there is an absence of counts along the diagonal, which produces a valley. This valley reflects the absence of the γ-ray transitions having the same energy, which is a property of a rotational band with a constant moment of inertia. Such a band should appear as a series of ridges parallel to the diagonal, the ridge next to the diagonal corresponding to the coincidences of adjacent rotational transitions, and ridges further out corresponding to the coincidence of nonadjacent transitions. On Fig. 1 the first ridge is clearly observed up to at least 1 MeV though its separation from further ridges is not clear. This same general pattern exists at a bombarding energy of 170 MeV.

The left part of Fig. 2 shows a cut of the two-dimensional correlated spectrum parallel to the 45° diagonal, along the valley and along the first ridge [Fig. 2(a)]. The right part of this figure represents three slices perpendicular to the 45° diagonal so that $[E_{\gamma 1} + E_{\gamma 2}]/2$ are within the three energy regions 750–820 keV [Fig. 2(b)], 900–950 keV [Fig. 2(c)], and 1160–1240 keV [Fig. 2(d)]. The three cuts are made on the matrix compressed to only 4 keV per channel. The slice in Fig. 2(d) has then been compressed to 12 keV

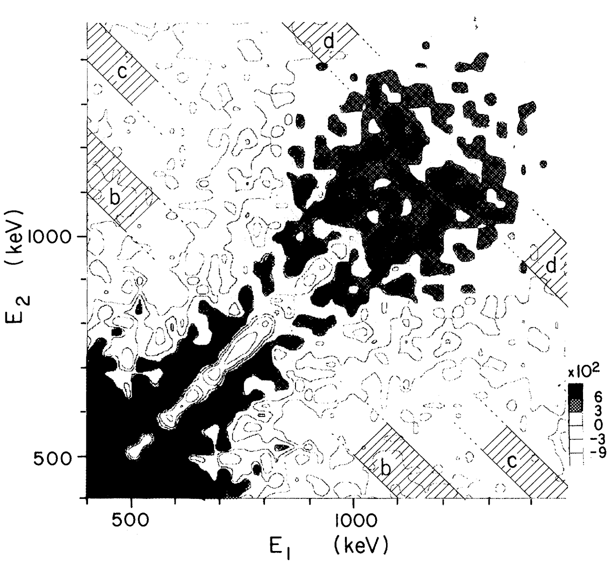

FIG. 1. Correlated γ-ray spectrum. The contour levels are statistically significant up to ~1.2 MeV along the diagonal.

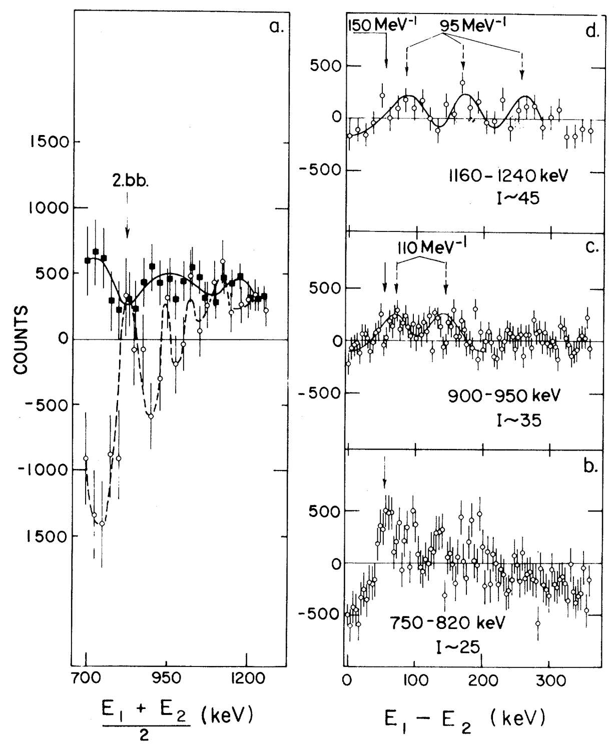

FIG. 2. Projected number of counts for selected slices of the data shown in Fig. 1. (a) Cuts along the diagonal (open circles) and the first ridge (closed symbols); (b)–(d) cuts across the diagonal such that $(E_{\gamma 1} + E_{\gamma 2})/2$ is within the energy interval 750–820, 900–950, and 1160–1240 keV for (b), (c), and (d), respectively.

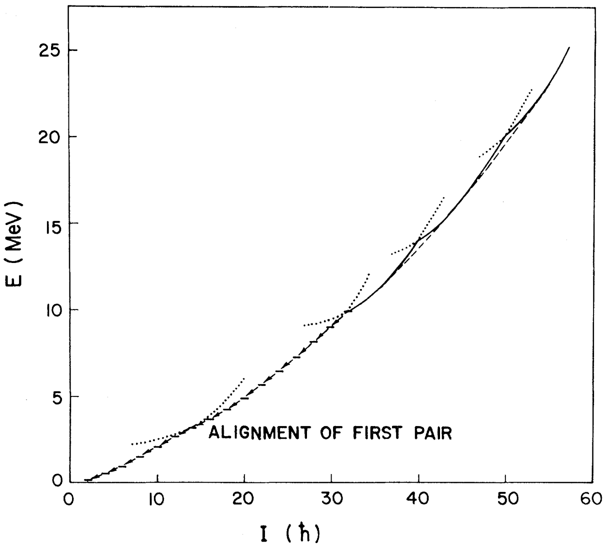

FIG. 3. Schematic of *one* typical γ-decay path.

per channel to obtain better statistics.

Although there is a wealth of detailed information in the lower-energy part of the spectrum, the present discussion will be confined to the transitions of energy around 900 keV up to as high an energy as allowed by the statistics. Figures 1 and 2 show that the valley can be seen up to 1250 keV, although it is largely filled beyond about 1 MeV and even completely in some locations. We consider first the width of this valley, which is related to a moment of inertia. To understand *what* moment of inertia, we refer to Fig. 3 which shows the kind of decay path we envision for the γ-ray deexcitation through *one* typical cascade. It consists of several intersecting rotational bands (solid curves) having collective moments of inertia, and their envelope (dashed curve). The bands have displaced origins corresponding to differing amounts of aligned single-particle angular momentum, j_a. The energy of such bands is expressed by

$$E(I)=(\hbar^2/2\mathfrak{g}_c)(I-j_a)^2+E_{j_a}, \tag{2}$$

where we neglect 1 compared to $I-j_a$, and E_{j_a} is the energy of the aligned particles. The γ-ray energy in such a band corresponds to the slope of the above energy expression, where j_a and $\mathfrak{g}_c$ are presumed to be constant within the band:

$$E_\gamma=2(dE/dI)_{j_a,\mathfrak{g}_c}=(\hbar^2/2\mathfrak{g}_c)4(I-j_a). \tag{3}$$

The effective moment of inertia, defined by $E_\gamma=(\hbar^2/2\mathfrak{g}_{\rm eff})4I$, relates to the envelope of the bands, and is connected to $\mathfrak{g}_c$ by $\mathfrak{g}_{\rm eff}=[I/(I-j_a)]\times\mathfrak{g}_c$. Since j_a very probably is large at high spins in nuclei around ^{160}Er (after the first backbend, j_a is around $10\hbar$ in the yrast sequence, for $I\approx 20\hbar$) the difference in these moments of inertia should become increasingly larger at higher spin on the average. The half-width of the valley in the correlation spectrum (Fig. 1) is just the energy *difference* between successive rotational transitions, and directly related to the curvature of the energy expression, again for constant j_a within a band:

$$\Delta E_\gamma=4\left.\frac{d^2E}{dI^2}\right|_{j_a,\mathfrak{g}_c}=8\frac{\hbar^2}{2\mathfrak{g}_c}. \tag{4}$$

This width of the valley measures the collective moment of inertia, and can be combined with $\mathfrak{J}_{\rm eff}$ to determine the aligned angular momentum, j_a. Previous measurements of moment of inertia at high spins have always measured $\mathfrak{g}_{\rm eff}$ and found it to be near the rigid-body value. It appears that $\mathfrak{g}_c$ must be significantly lower if j_a is large, which simply reflects the fact that single particles cannot contribute fully both to the aligned angular momentum and to the collective moment of inertia. Data of the present type are not easy to interpret along this line. In Figs. 2(c) and 2(d) we have indicated very tentative locations for the ridges. The width of the ridges is large, perhaps because of large spreads in j_a for the populated bands. The location of a ridge corresponding to a moment of inertia of 150 MeV^{-1} is indicated. The width of the valley is pretty clearly 25–50% larger than this, indicating an $\mathfrak{g}_c$ smaller than $\mathfrak{g}_{\rm eff}$ and an average j_a value around $(10-20)\hbar$, whereas I is around $45\hbar$. These values seem consistent with the ideas outlined above but are still rather tentative. A nonconstant moment of inertia within the bands ($\mathfrak{g}_c$) can affect these values considerably and one should not try to be too quantitative until these effects are better understood.

The observed filling of the valley in the high-energy region (>1 MeV) probably implies many band crossings, which is consistent with the above discussion. The behavior at such band crossings depends on the interaction strength between the bands and the gain in aligned angular momentum, but in general the regular rotational pattern is disturbed. It is clear from Figs. 1 and 2 that there are irregularities in the valley ("bridges") and also along the ridges ("gaps"). There are only a limited number of these, at least discernible within the present statistics. In the lower-spin region, the bridges correspond to known band crossings. This has been established from the detailed spectroscopic studies of many nuclei in this region. These band crossings occur at specific rotational frequencies ($\hbar\omega = E_\gamma/2$) which depend, in a given nucleus, only on which orbitals are crossing.[3] A given orbital crossing can occur in many bands differing in the rest of the configuration, and thus produce a feature in the correlation spectrum even though one cannot resolve individual bands. For example, the known first backbend in the ^{160}Er region (at $\hbar\omega \approx 0.3$ MeV) corresponds to the crossing of a two-quasiparticle $i_{13/2}$ neutron state with the vacuum (ground band), and the second backbend (at $\hbar\omega \approx 0.41$ MeV) involves a two-quasiparticle $h_{11/2}$ proton configuration crossing the vacuum. Both of these crossings can be involved in many bands and produce readily observable bridges in Fig. 1 at $E_\gamma = 0.6$ and 0.82 MeV, respectively.

In the high-energy region (where pairing correlations probably no longer exist) one expects crossings with the large angular momentum transfer due to only a *few* strongly aligned configurations based on the high-j orbitals. If these configurations are filled at high rotational frequencies, they will experience a band crossing and empty at a characteristic orbital-crossing frequency *irrespective* of the rest of the state configuration. We propose that these characteristic frequencies are related to those where the few bridges and gaps are observed. It seems too early to attempt detailed assignments of the bridges in Fig. 1; however, the large filling of the valley around $\hbar\omega = 0.55$ ($E_\gamma = 1.1$ MeV) may be connected with the $h_{9/2}$ proton orbital, and/or with $\Delta N = 2$ orbitals, $i_{13/2}$ protons or $j_{15/2}$ neutrons. Another possibility is that it is related to the loss of pairing correlations, which tends to suppress crossings in the lower-spin region.

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[a]Permanent address: Institut de Physique Nucléaire, B. P. No. 1, 91406 Orsay, France.

[b]Permanent address: Lawrence Berkeley Laboratory, Berkeley, Cal. 94720.

[c]Permanent address: Niels Bohr Institutet, Risø, DK-4000 Roskilde, Denmark.

[d]Permanent address: State University of New York at Stony Brook, Stony Brook, N.Y. 11794.

[e]Permanent address: Hahn-Meitner-Institut für Kernforschung Berlin, D-1000 Berlin 39, West Germany.

[f]Permanent address: Institute of Nuclear Research, Shanghai, People's Republic of China.

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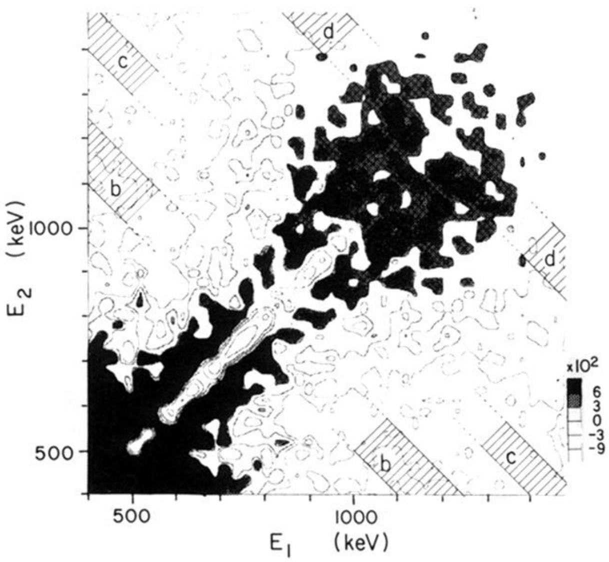

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