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Measurement of In-Band Transition Probabilities at High Spin

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Quantitative measurements have been made of correlations in the γ-ray continuum emitted by rotational nuclei populated in heavy-ion compound-nucleus reactions. The experimentally deduced intensity of the "ridge" structure in the correlation spectrum implies an average probability for in-band stretched $E2$ decay of $< 20\%$ at spins above $30\hbar$ in contrast to traditional expectations.

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It is important to understand the mechanisms of γ-ray decay from the entry region following heavy-ion compound-nucleus evaporation reactions because they are sensitive to nuclear structure at high spin and excitation energy and also an aid to interpreting and planning high-spin γ-ray spectroscopy experiments. Conventional models[1] of the deexcitation of the residual nuclei from the entry region assume first the emission of several "statistical" γ rays, most likely dipole, of comparatively high energy. The resulting "cool" system decays further towards the ground state mainly by stretched $E2$ transitions in many rotational bands parallel, or nearly so, to the yrast line. Eventually all the intensity feeds the observable discrete-line transitions. It has been further assumed[2] that the unresolved transitions in these yrastlike cascades are mainly in band (as in the region in which discrete-line spectroscopy is possible). This Letter reports measurements of the in-band transition probability at high spin. Preliminary reports of the data have already been given.[3]

A suitable tool for studying the unresolved transitions is the elegant method of "γ-γ correlations."[4] γ-γ coincidence data are sorted into a matrix of $E_{\gamma 1}$ vs $E_{\gamma 2}$. Coincidences between transitions in rotational bands will form well-defined "ridges" parallel to a "valley" around $E_{\gamma 1} = E_{\gamma 2}$ in this matrix. Such patterns are expected even in cases where alignment effects are important.[5] Moments of inertia $\mathscr{I}^{(2)}_{\rm band}$ (Bohr and Mottelson[6]) may be deduced from the ridge separation. Until recently[7] correlation studies have been bedeviled by problems with the background and often by poor statistics or bad resolution. They have needed to use rather unsatisfactory background-subtraction methods[1] to see correlated structure at all; these methods destroy information on the intensity distribution. In the work of Hjorth *et al.*,[8] however, an approximate unfolding was performed of the correlation spectrum obtained with poor NaI resolution from a reaction including at least twenty exit channels, no channel selection, and rather low-input angular momentum. After a rather complicated analysis the authors concluded that "at least half of all $E2$ γ rays showed no rotational correlations."

The TESSA2 spectrometer[9] at the Daresbury Nuclear Structure Facility has enabled us to overcome many of the previous experimental problems. TESSA2 comprises six Compton-suppressed Ge detectors and a fifty-element calorimeter. It has low background, high resolution and efficiency, and the ability to select the entry region in reaction γ-ray total energy and multiplicity simultaneously. The response function of the Compton-suppressed Ge detectors is particularly easy to unfold from the data. Simultaneous discrete-line and correlation studies are possible, enabling a proper understanding of the spectrum in general and providing the necessary normalization between discrete and continuum intensities in this work. Using these features we have obtained for the first time an excellent approximation to the true intensity distribution in γ-γ spectra with high resolution and selection.

Here we present data comprising 40 million coincidence events from the ^{36}S + ^{98}Mo reaction at 155 MeV, making ^{130}Ce the main channel of interest. The nucleus ^{130}Ce shows the now-familiar high-spin behavior of a good rotor: The discrete lines observed in both yrast and sidebands fall smoothly in intensity until they comprise $\sim 5\%$ of the total intensity at the highest spins observed ($\sim 30\hbar$). This limit on the observation of discrete lines should be compared with the peak of the entry region at around spin $50\hbar$. Only the two lowest proton band crossings are observed and cranking calculations indicate only a couple of additional crossings below $50\hbar$. The intensity missing from the high-spin discrete lines was expected to contribute to strong correlated rotational features in the continuum part of the γ-γ matrix. In fact in the raw data ridges are clearly visible but on a very large background. The ridges in these data are as strong as any of which we are aware. (See Ref. 7 for spectra which exhibit these features from a similar reaction making ^{130}Ce in TESSA1.)

The large background seen in diagonal cuts across the raw correlation matrices from this and other reactions is obviously not all due to Compton scattering from the detectors and has been a puzzle. In Fig. 1, spectrum *a*, we show a cut across the raw matrix after application of a two-dimensional gate on the reaction sum energy (H) and fold[10] (k) to select the four-particle channels preferentially; Fig. 1, spectrum *b*, shows the same data with the effect of the measured detector response function "stripped" off, while Fig. 1, spectrum *c*, is the unfolded data corrected for the photopeak efficiency. The "stripping" method of unfolding the spectrum[11] utilizes the particularly simple response function (essentially a flat background plus a one-channel-wide photopeak) and high peak/total of the TESSA detectors. These features allow a particularly reliable unfolding to be achieved noniteratively, ensuring that Fig. 1, spectrum *c*, is a good approximation to the real γ-ray intensity distribution.

Crystal-ball data[12] indicate that only fusion-evaporation reaction events will contribute to the spectrum after application of the chosen H,k gate. The only additional contribution should be from evaporation-neutron–induced secondary reactions and these contribute $\sim 5\%$ of the intensity in the energy region of interest. Events due to reactions with any light-target impurities will not pass the H,k gate used.

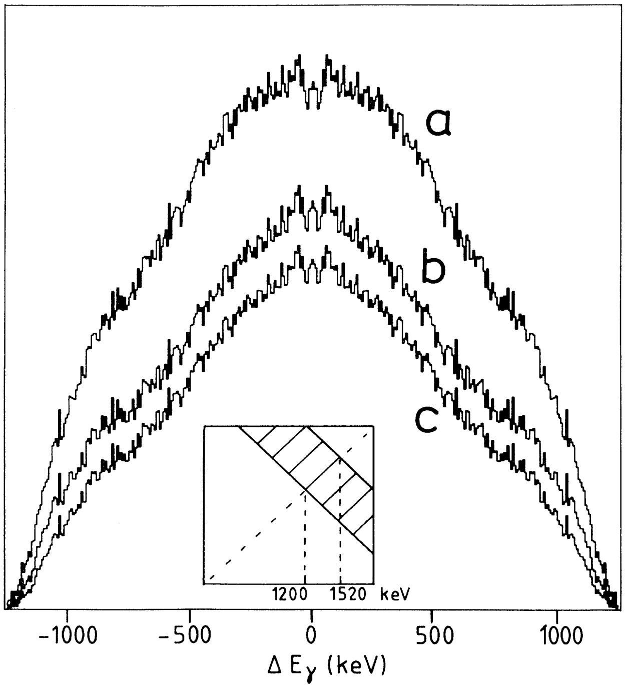

FIG. 1. Cuts perpendicular to the diagonal $E_{\gamma 1} = E_{\gamma 2}$ in the region indicated on matrices symmetrized about the diagonal and with an appropriate H,k gate. Spectrum *a*, raw data; spectrum *b*, with the effect of the detector response function stripped off; spectrum *c*, stripped and corrected for photopeak efficiency—arbitrary normalization.

It should be possible to fit spectrum *c* of Fig. 1 with a sufficiently detailed model of the complete deexcitation process after allowance for the neutron effects. Clearly the data are not consistent with a high probability for in-band transitions along rotational bands. They may be compared, for instance, with the calculated spectra of Sorensen[13] (Fig. 1). See also Ref. 5. We may estimate the in-band probability independently by considering the intensity of the rotational ridges.

First, however, note that it is not possible to select a particular nucleus very cleanly by applying an H,k gate. With the assumption of no strongly fed isomers, the most reliable way to measure the amount that an even-even nucleus contributes to the data is to compare the intensities of the total spectrum and one requiring a coincidence with the $2^+ \rightarrow 0^+$ ground-state transition. After normalization to the $4^+ \rightarrow 2^+$ transition the ratio of the two spectra yields the fraction of the total γ-ray intensity due to the even-even nucleus as a function of energy. For ^{130}Ce in our data the fractions measured thus varies from 33% at 1 MeV to 24% at 2 MeV *after* application of the H,k gate. This is probably as good a selection as is possible with current H,k filters for this type of reaction in which charged-particle evaporation is important.

The average intensity of coincidences making up the ridge structure relative to the total ^{130}Ce intensity may be estimated as follows. Since $> 95\%$ of the intensity passes through both the $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ transitions, the intensity of the coincidence between them (S_{420}) may be used as a measure of the total intensity. The intensity of the ridge in some diagonal cut of width ΔE_γ is S_{ridge}. Now for in-band stretched $E2$ transitions $\Delta I_x = \Delta\omega \mathscr{I}^{(2)}_{\text{band}}$ (Ref. 6), where I_x is the component of the total spin I along the rotation axis, $I_x \sim I$ and the rotational frequency $\omega \sim E_\gamma/2$. The number of transitions per band in the cut region is $N = \Delta I/2 \sim \mathscr{I}^{(2)}_{\text{band}} \Delta E_\gamma/4$. Hence the average relative intensity of coincidences forming the rotational ridges is $f \sim S_{\text{ridge}}/NS_{420}$ and this may be identified with the fraction of feeding of the ground state via transitions in the ridges at a spin I_{ridge}. To estimate I_{ridge} we assume that the moments of inertia[6] $\mathscr{I}^{(2)}_{\text{band}} \sim \mathscr{I}^{(1)}_{\text{band}} \equiv \mathscr{I}$ as is roughly true for the highest-spin, highest-seniority states observed in the ^{130}Ce discrete-line spectrum. Then $I_{\text{ridge}} \sim \mathscr{I} \langle E_\gamma \rangle /2$.

We have followed this prescription for our data, multiplying S_{ridge} by the fraction of the intensity in ^{130}Ce as a function of E_γ. The results are then quoted for ^{130}Ce under the assumption that the deexcitation mechanisms are similar for the other nuclei (^{129}Ce, ^{127}Ba, ^{130}La, and ^{131}Ce) present in the data. We have used values of $\mathscr{J}^{(2)}_{\rm band}$ derived as usual from the positions of the ridge centroids as in Ref. 7; these are roughly constant. The results are shown in Fig. 2 as a function of the average γ-ray energy and the implied spin $I_{\rm ridge}$. The relative ridge intensity can be seen to decrease form $\sim 22\%$ at γ-ray energies of 1100 keV to $\sim 6\%$ at 1550 keV. The extent of the frequency (energy) region accessible for these measurements is limited to that in which the ridge is clearly distinguishable. This corresponds to an approximate spin range of $30\hbar$ to $40\hbar$.

In the above we have assumed the usual model[4] in which the ridges are due to transitions in simple rotational bands and ascribed the ridge width to a spread in $\mathscr{J}^{(2)}_{\rm band}$. The inner and outer edges of the ridge correspond to $\mathscr{J}^{(2)}_{\rm band} = 59\hbar^2$ and $45\hbar^2$ MeV^{-1}, consistent with deformations of $\epsilon_2 \sim 0.4$ and zero, respectively, for an axial-rigid, ellipsoidal nucleus with a sharp surface—a reasonable spread in nuclear shapes subject to the assumptions. If the assumption that the feeding pattern is similar for all the neighboring nuclei is not correct then some of them must have an even lower probability for in-band transitions than deduced below.

The average behavior of the spectra for both the ^{130}Ce channel and the overall reaction is just that expected for a good rotor. We have derived unfolded spectra, both total coincidence and gated by the ^{130}Ce $2^+ \rightarrow 0^+$ transition, for different folds (k) and hence multiplicity. In both cases the height of the "$E2$ bump"[1] remains constant but the edge moves to higher γ-ray energy roughly proportional to multiplicity. Thus we do not expect our results to be influenced by departures from good rotational behavior. The edge of the $E2$ bump in the spectrum corresponding to the lowest fold selected occurs at 1300 keV.

A low relative intensity of the ridge could be due to either a low in-band transition probability or a low probability for feeding rotational bands, or both, in the relevant spin–excitation-energy region. However, the average behavior is rotational, and from the position of the edge of the $E2$ bump we conclude that the rotational bands are fully fed up to 1300-keV γ-ray energy. Thus the ridge relative intensity implies a low in-band probability, and this is supported by the absence of a clear second ridge. The decrease in f above 1300 keV may be influenced by incomplete feeding.

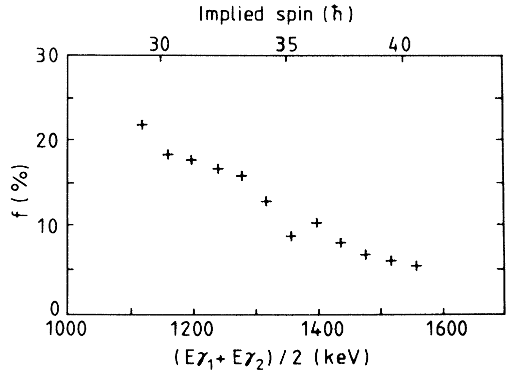

FIG. 2. The average intensity of coincidences forming the "ridge" relative to that of the $4^+/2^+$ coincidence, derived as explained in the text.

The observed lack of rotational correlations cannot be due to the few simple band crossings expected at high spins; the observed ridge structure is quite continuous[7] and there is no piling up of intensity within 200–300 keV of the diagonal as would be expected at band crossings.[4] Alignment effects could only account for the data if there were many crossings in most configurations in the spin range $(30–40)\hbar$, which would be highly unexpected and equivalent to the breakdown of rotational behavior.

Thus we conclude that the relative intensity of the ridge implies $< 20\%$ probability on average of in-band transitions in rotational sequences above $30\hbar$. Then the observed ridge/background intensity ratio is easily explicable. Such a low in-band probability is contrary to traditional expectations for such rotational nuclei populated at high spin. For instance, the available calculations of this quantity predict a value around 80% (Table IV of Ref. 5).

Away from the region where discrete lines contribute "stripes" there appears to be little correlation of a wider extent than that responsible for the ridges. The narrow ridges appear in cuts on a broad bell-shaped background whose shape is similar to that of the usually "uncorrelated" background,[4] as observed in previous studies.[1]

We have analyzed by this method data from similar reactions making rotational nuclei in the rare-earth region, for example ^{160}Er, which has been studied previously.[2] This analysis indicates that the above results are quite general. (For nuclei heavier than ^{130}Ce and nearer to stability as much as 60% of the H,k gated data may be in the nucleus of interest.) Thus nuclei which are good rotors at high spin appear to decay from the entry region to the region of observable discrete lines mainly by the stretched $E2$ transitions which constitute the $E2$ bump but with a small probability to stay in band, as defined by the requirement that consecutive transitions should have their energy differences correlated with ~ 15 keV. Therefore the energies of the unresolved transitions in the $E2$ bump have their rotational $B(E2)$ strength spread over a range much greater than 15 keV. Cranking[5] and γ-soft triaxial rotor calculations[14] so far do not reproduce this effect. These measurements thus pose a challenge to theoretical understanding of average nuclear behavior in the region in which discrete-line spectroscopy is currently not possible.

These results explain why γ-γ correlation studies have proved difficult, and may be of relevance to future experiments and plans for new spectrometers, as well as furnishing nuclear-structure information. The observation that the bulk of the data in unfolded correlation spectra is "background" justifies the assumption of the usual "projection" method of background subtraction[4] for anti-Compton data. A fuller account of this work and further systematic measurements is being prepared for publication.[15]

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