Feeding of High-Spin Particle Yrast States by Collective Structures in the Continuum

P. Chowdhury, J. Borggreen,[a] T. L. Khoo, I. Ahmad, and R. K. Smither
Argonne National Laboratory, Argonne, Illinois 60439

and

S. R. Faber, P. J. Daly, C. L. Dors, and J. Wilson
Purdue University, West Lafayette, Indiana 47907
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The population of yrast states in ^{152}Dy and properties of continuum γ rays have been measured as a function of input angular momentum, l, via the ^{122}Sn(^{34}S, $4n$) reaction. With increasing l an eventual saturation of the high-spin population with a narrow region of yrast feeding is observed, together with an enhanced yield in the continuum spectra. This implies that the decay of very-high–spin states is diverted from the yrast line by continuum cascades and suggests collective modes which might be built on high-J particle states.

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Yrast isomers and states up to very high spin have been identified in several nuclei with $A \sim 150$ (Refs. 1–5). In ^{152}Dy, for instance, yrast states up to spin 38 have been observed.[1-4] The yrast configurations have been established to be predominantly of a few-particle nature,[1,2] with the spins of individual nucleons aligned about a symmetry axis.[6,7] The high degree of alignment of particle orbits and the concomitant core polarization are believed to lead to an oblate deformation along the yrast line with $\beta \sim 0.1$–0.2 (Refs. 6 and 7).

The character of yrast states at higher spin and of states above the yrast line still remain to be explored. Of particular interest are the collective modes which might be built upon few-particle states with very high J. The nature of the states above the yrast line will affect the γ deexcitation pattern following (heavy ion, xn) reactions and the population intensities of the yrast states.

We have measured both the intensities of the yrast transitions in ^{152}Dy and the properties of the continuum γ rays for different initial angular momentum, l, using the reaction ^{122}Sn(^{34}S, $4n$)^{152}Dy, induced by ^{34}S beams from the Argonne superconducting linear accelerator. The target was placed at the center of a 33×30 cm NaI sum spectrometer which was divided into eight segments. A coincidence among at least four segments and a window on the sum energy enhanced high multiplicity events and suppressed unwanted reaction channels. As in previous experiments,[8,9] the γ multiplicity was found to increase with the sum energy, and hence with l.

Excitation functions for the yrast transitions were measured with Ge detectors at beam energies from 144 to 184 MeV. Figure 1 shows the population intensities as a function of spin. The intensity of the $2^+ \rightarrow 0^+$ transition defines 100% population in the ^{152}Dy channel. At the lowest bombarding energy (144 MeV), the population stays close to 100% up to spin 12 and then falls off gradually. The population at higher spin in-

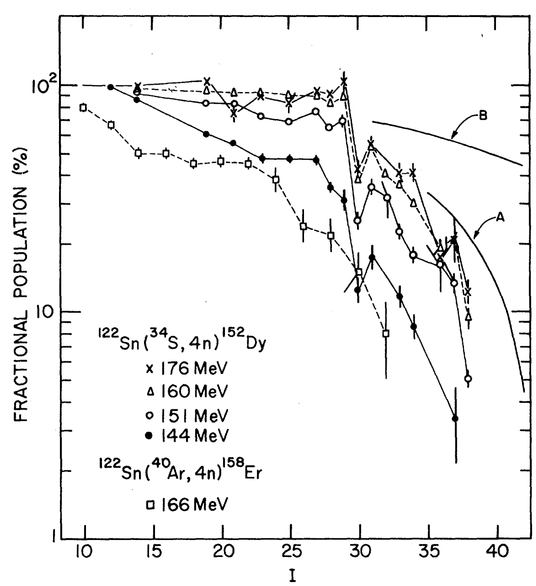

FIG. 1. Yrast population intensities in ^{152}Dy as a function of spin for various ^{34}S bombarding energies. The results for 168- and 184-MeV ^{34}S energies (not shown) essentially fall on the 160- and 176-MeV data. For comparison, yrast population intensities (Ref. 10) of a prolate deformed nucleus, ^{158}Er, are shown. Lines A and B [which are the ratios $\Sigma_{l=I}^{l_{max}} \sigma(l) \Sigma_{l=0}^{l_{max}} \sigma(l)$, calculated with $\sigma(l) = \pi \lambda\!\!\!^{-2} (2l+1)$ and l_{max} given by the Bass model (Ref. 11)] indicate the expected yrast intensities for direct population from the entry line for ^{34}S energies of 144 and 160 MeV (l_{max} = 42 and 55), respectively.

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creases with bombarding energy, reaching ~90% for spin 29 at 160 MeV. However, when the beam energy is further increased to 168, 176, and 184 MeV, the population no longer grows, even though the measured γ-ray multiplicity and the sum energy indicate that the maximum l in the ^{152}Dy reaction channel continues to increase. *The population of the highest-spin yrast states saturates near 160 MeV.* The sharp dropoff in the population intensity for $I > 29$ implies that the population of the yrast line is largely funneled through states in the spin interval between 29 and 38.

The observed feeding of ^{152}Dy contrasts with that for prolate deformed nuclei, where the yrast population in a similar reaction decreases gradually above spin 10 (see Fig. 1). The markedly larger population at high spins in ^{152}Dy is nevertheless still smaller than that expected (cf. lines A and B in Fig. 1) if the yrast line were fed directly by statistical γ rays. This fact and the saturation of the high spin population for bombarding energies exceeding 160 MeV indicate that the γ deexcitation of the highest spin states does not feed the yrast line directly via statistical transitions, but is diverted by continuum cascades—not observed as discrete γ rays—and only reaches the yrast line in the spin interval between 29 and 38. This deduction is also supported by the observation that the intensities of transitions from the high spin yrast states do not increase with sum energy.

To investigate the γ rays feeding the yrast line, we have measured the continuum γ spectra at 160 MeV bombarding energy. The detector was a 25 × 30 cm NaI crystal, with a Pb shield restricting target γ rays to a 10 cm diameter central region to improve the response function. Measurements were made at 0° and 90°, with the detector located 75 cm from the target to allow neutron discrimination by time of flight. Spectra corresponding to coincident sum energy slices ~6 MeV wide were obtained and normalized to the measured multiplicity for each sum slice. To obtain the actual spectrum of continuum γ rays feeding the yrast states, the contribution of the discrete lines —identified with a Ge(Li) detector—were subtracted with use of the measured response of the NaI crystal. The net spectra were then corrected for the detector response (unfolded). The relatively small contribution of statistical γ rays, estimated in the manner described in Ref. 12, was also subtracted. With the reasonable assumption of mainly stretched dipole and quadrupole γ rays, it was possible to decompose the continuum transitions into stretched quadrupole and dipole components using the 0° and 90° spectra [see Fig. 2(a)]. The quadrupole transitions are undoubtedly $E2$ because of the observed short feeding times[2] and γ polarization.[13]

The dipole component is located around 0.5 MeV, while the $E2$ part shows two discernible components, centered around 0.6 and 1.3 MeV. With increasing sum energy, and corresponding increase in l, the following features are observed: (i) All components increase in multiplicity; (ii) the higher energy $E2$ component grows with respect to the lower energy one; and (iii) the centroid of the higher energy $E2$ component inincreases rapidly initially and then only gradually at the highest sum energies. The third feature is clearly observed by taking differences between successive slices [see Fig. 2(b)] to reveal the transitions occurring within successive l windows. The continuum transitions belong mainly to ^{151,152}Dy, with some contribution from ^{150}Dy and ^{153}Dy at low and high sum energies, respectively. The continuum γ rays of these nuclei have properties distinctly different from those of a prolate rotor, where the centroid energies of

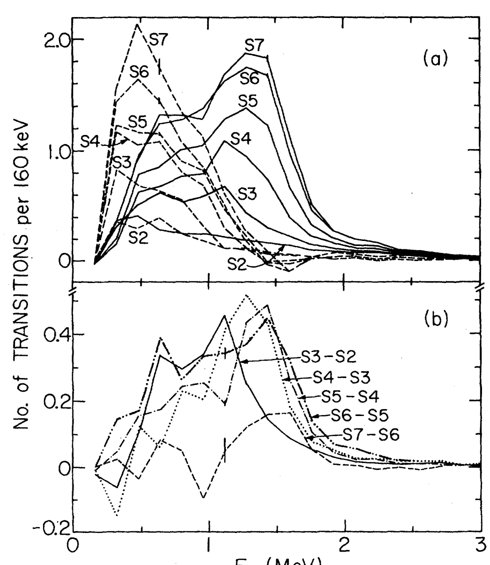

FIG. 2. (a) Stretched-quadrupole (solid lines) and stretched-dipole (dashed lines) components of the unfolded spectrum of continuum γ rays coincident with sum energy slices 2 to 7, where each slice is ~6 MeV wide. Contributions from discrete and statistical γ rays have been subtracted. (b) Differences between spectra associated with successive slices of Fig. 2(a) for the stretched-quadrupole component. Typical error bars are shown for each spectrum.

successive difference spectra increase steadily with sum energy at a much faster rate.[9,12]

The mean entry spin corresponding to each sum slice has been determined by using the relation, $\overline{I}_{\text{entry}} = M_1 + 2M_2 + \overline{I}_{\text{yrast}}$. M_1 and M_2 are the multiplicities of the stretched dipole and quadrupole continuum transitions obtained by summing corresponding spectra of Fig. 2(a). These multiplicities do not include the contributions of the discrete and statistical γ rays, which have been subtracted. $\overline{I}_{\text{yrast}}$ is the mean entry spin into the yrast line, averaged over the different residual Dy isotopes. For the slices 2 to 7 shown in Fig. 2(a), $\overline{I}_{\text{entry}} = 23$, 34, 44, 50, 55, and 59, with an estimated uncertainty of 3. Whereas the energies of the dipole and lower $E2$ components show no apparent correlation with entry spin, the energy of the higher $E2$ component evidently increases with spin. We have attempted to characterize this increase by fitting a Gaussian to the upper $E2$ component in the difference spectra [Fig. 2(b)]. For increasing slice differences centroids, C, of 1.08, 1.28, 1.39, 1.42, and 1.47 MeV (all ± 0.04 MeV) were obtained. Effective moments of inertia, $\mathscr{I}$, were then deduced by use of the relation $C = (\hbar^2/2\mathscr{I})(4\overline{I} - 2)$, where $\overline{I}$ is the average entry spin of the two successive slices. Unlike the case for a prolate rotor where $\mathscr{I}$ appears to remain constant,[12] $\mathscr{I}$ for the Dy isotopes with $A \sim 152$ increases with spin approximately as $2\mathscr{I}(I)/\hbar^2 = (51 + 1.81I)\ \text{MeV}^{-1}$. This expression for $\mathscr{I}(I)$ can then be used to describe the energies of the transitions in the higher $E2$ component as a function of spin. The resulting trajectories of continuum transitions feeding high-J yrast states at $5\hbar$ intervals are shown in Fig. 3. Similar trajectories built on single-particle states above the yrast line are also expected.

Both the yrast population pattern and the properties of the continuum γ rays can be understood if we associate these trajectories with transitions within collective bands. Following neutron emission, the γ deexcitation takes place with the emission of statistical γ rays until a region of high density of bands is encountered. The fast collective $E2$ transitions within bands compete with the statistical decay, diverting the γ flow away from the yrast line and channeling it along the bands into a narrow region of the yrast line. Interband transitions could also occur, which may be responsible for the observed stretched dipole and quadrupole γ-ray components around 0.5 MeV. The dominance of stretched $E2$ transitions and the fast feeding times—<1.2 ps for the

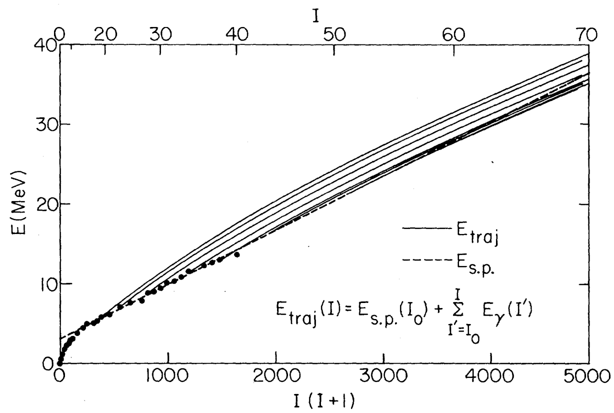

FIG. 3. Trajectories of $E2$ transitions feeding high-J yrast states at $5\hbar$ intervals in ^{152}Dy, calculated from the measured energy vs entry-spin relation for the higher-energy $E2$ continuum component (see text). The full circles denote the known yrast states in ^{152}Dy and the dashed line is a linear fit through these mainly single-particle states.

$I = 37$ state (Ref. 2)—argue for the occurrence of collective excitations above the yrast lines in $^{150-152}$Dy. A similar phenomenon occurs in ^{147}Gd (Ref. 14). Other explanations for our data may be possible. For example, the yrast population intensities may be interpreted[4,7,15] in terms of a large increase in the density of few-particle excitations for spins larger than the maximum value possible with use of only valence nucleons outside an $N = 82$, $Z = 64$ core ($I_{\max} = 30$ in ^{152}Dy). However, the fast feeding times and the dominance of stretched $E2$ transitions may not be readily explained in these terms, unless collective modes are also included. Another possibility, suggested[16] on the basis of the continuum spectra in neighboring ^{154,155}Er, is a transition from spherical or weakly oblate to prolate rotational structures at spin 40. Our data for ^{151,152}Dy, however, indicate that even below this spin collective components may occur *above* the yrast line.

An interesting speculation regarding the bands of Fig. 3 may be made. Bohr and Mottleson[17] have recently pointed out that the collective mode likely to be built on high spin aligned oblate structures is a γ vibration, with its spin aligned along the large particle spin. Presumably, higher spin collective states may be constructed from coupling multiple γ phonons. Building many such γ phonons upon an initially oblate structure should result in a rotating triaxial shape, which tends towards prolate with increasing spin. An excited state of this type efficiently utilizes both particle and collective angular momenta by aligning them. At the largest spins the nucleus fissions, so one should expect prolatelike shapes to become yrast. We note that around $I = 55$ the bands of Fig. 3 begin to have lower energy than the line extrapolated from the known few-particle states. This suggests that these collective modes may be associated with the expected pathways towards eventual fission.

This interpretation raises the exciting possibility that, whereas the yrast lines of nuclei like ^{152}Dy are dominated by oblate aligned few-particle structures, there is a transition to collective (possible triaxial) structures above the yrast line, and even at the yrast line at larger spin. Detailed calculations and further experiments are clearly called for. In any event, the *combination* of the two sets of data presented here, the yrast population intensities and the properties of the continuum transitions, serves as a constraint on theoretical models which address the interesting topic of collective excitations built on high-spin aligned-particle states.

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[a]Present address: Niels Bohr Institute, Riso 4000, Roskilde, Denmark.

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