Coexistence of Prolate and Oblate Structures up to Spin $40\hbar$ in ^{152}Dy

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A rotational band with a constant moment of inertia $\mathcal{J}^{(2)}=58\hbar^2$ MeV^{-1} has been observed in ^{152}Dy extending from spin 18^+ to 40^+. The band coexists with the known oblate yrast states although it is up to 1.5 MeV higher in excitation energy. It carries 4% of the decay strength and it is proposed to be a four-quasiparticle aligned structure. It is conjectured that the superdeformed states at the highest spins may decay via this band rather than via the yrast oblate states.

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The decay scheme of ^{152}Dy has been determined[1-3] up to $40\hbar$ and above spin $18\hbar$ it was found to exhibit no collective structure. The levels have an irregular energy spacing and they are formed by particles in equatorial orbitals with aligned spins giving the nucleus a weak oblate deformation.[4,5] At higher spins, structures have been observed in the gamma-ray continuum[6,7] which have been identified with the large prolate superdeformations predicted by many calculations.[8,9] The structure of the low-spin yrast levels has been a subject of some uncertainty as the separations between the even-spin members do not follow the simple $I(I+1)$ behavior expected of a rotational nucleus. Rather, they have gradually increasing separations more characteristic of a vibrational structure. Styczen *et al.*,[10] using the $(\alpha,4n)$ reaction to bring in only a moderate amount of angular momentum, have shown that the ground-state sequence can be extended up to 18^+. The sequence becomes nonyrast at 8^+ and the level separations are grouped irregularly around 600 keV. In this Letter we present data which show that the ground-state sequence continues up to $40\hbar$ and lies over 1 MeV above the oblate yrast states. Above 18^+ the level sequence forms a well-deformed rotational band with a constant moment of inertia just below $60\hbar^2$ MeV^{-1}. We propose that this band has a four-quasiparticle structure with pairs of both $i_{13/2}$ neutrons and $h_{11/2}$ protons aligned. The measured intensity of the decay strength in the band is not inconsistent with its being the major decay path of the superdeformed structures at the highest spins.

The experiment was carried out at the NSF tandem accelerator at the Daresbury Laboratory with use of the TESSA2 spectrometer.[11] The levels in ^{152}Dy were populated by the reaction ^{108}Pd(^{48}Ca, $4n$) at 205 MeV with a target of two 500-μg-cm^{-2} self-supporting foils isotopically enriched to 95% in ^{108}Pd. Gamma rays were detected in the six escape-suppressed germanium detectors and fifty-element bismuth germanate (BGO) crystal ball of TESSA2. Coincidence events were recorded between any two of the Ge detectors together with the total energy and number of hits (fold) measured in the BGO ball. A total of over 4×10^7 events was obtained. The major reaction channel is the $4n$ to ^{152}Dy but considerable intensity is observed in the $3n$ (^{153}Dy) and $5n$ (^{151}Dy) channels. There are 10- and 60-ns isomers in ^{152}Dy and a 13-ns isomer in ^{151}Dy. The probability of detection of gamma rays deexciting these isomers was greatly reduced by the tight collimation of the Ge detectors such that decays occurring more than 20 mm downstream of the target could not be detected. Thus in ^{152}Dy the three gamma rays below the 10-ns 21^- isomer had an intensity of 14% relative to the prompt transitions feeding the 27^- level, and those below the 60-ns 17^+ isomer less than 1%. A search has been made for the gamma rays observed by Styczen[10] that formed the continuation of the ground-state sequence. This search was hampered by the occurrence of a number of these gamma rays having similar energies to contaminants. The 2^+ and 6^+ decays are similar to the 613- and 685-keV transitions occurring at high spin in ^{152}Dy and the 4^+, 10^+, and 12^+ decays have counterparts in ^{153}Dy of 647, 693, and 636 keV. These difficulties make it hard to obtain uncontaminated spectra of the continuation of the ground-state band. Both fold and sum-energy conditions on the BGO ball data were necessary to accentuate the ^{152}Dy channel and produce the spectrum shown in Fig. 1, which was obtained with only the 758- (8^+), 633- (12^+), 622- (14^+), 547 (16^+), and 566-keV (18^+) gates.

The spectrum in Fig. 1 clearly shows the continuation of the ground-state band up to $40\hbar$ by a series of gamma rays with an almost constant separation of 70 keV. We interpret this sequence as a rotational band of stretched quadrupole transitions. The intensity of the total decay in ^{152}Dy deexciting via this band was measured from the spectrum of gamma rays in coincidence with the 613/614-keV transitions. The high-spin component of 613 keV (see Fig. 2) has been mea-

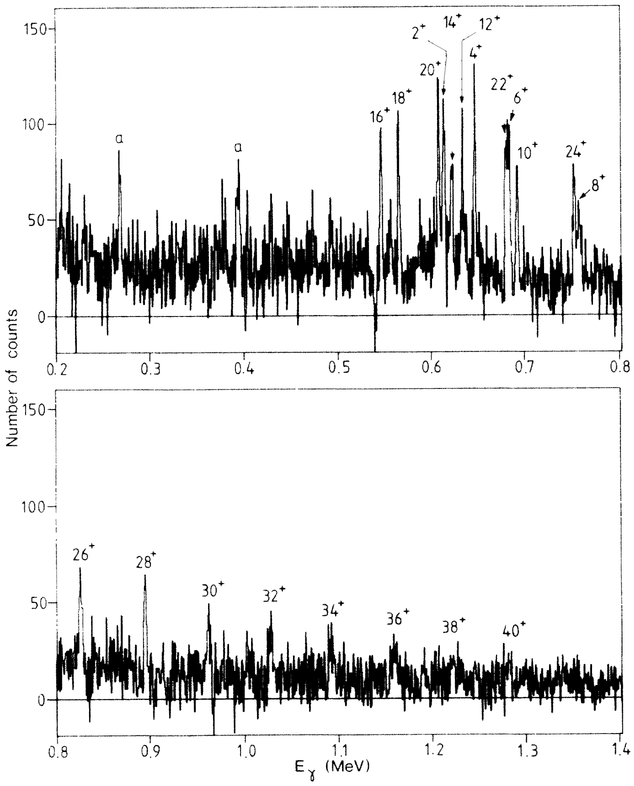

FIG. 1. The gamma-ray spectrum obtained in coincidence with the 758- (8^+), 634- (12^+), 622- (14^+), 547- (16^+), and 566-keV (18^+) decays in the ground-state band in ^{152}Dy. The peaks marked (a) are known weak contaminants from another nucleus.

sured to have an intensity of 9% relative to the feeding of the 21^- isomer. The intensity of the gamma rays in the collective band was then measured relative to the 402-keV transition in the oblate structure which is fully fed from the 613-keV gamma ray. This established that $(4 \pm 1)\%$ of the total decay was proceeding via the new collective band. The present data indicate that this band is almost entirely fed to the highest spins. The decay scheme for both collective and oblate states is shown in Fig. 2. No evidence was found of any transitions connecting the two structures even though the collective states are over 1 MeV above the yrast states. This means that the in-band transitions probably have $E2$ strengths greater than 25 Weisskopf units as, for example, at this strength the in-band 1093-keV $(34^+\text{-}32^+)$ gamma ray competes with a possible 1-Weisskopf unit 2064-keV $E2$ transition between the collective 34^+ and the particle-hole 32^+ states.

A plot of the total spin projection along the rotational axis, I_x, against rotational frequency $\hbar\omega$ is shown in Fig. 3. The collective band in ^{152}Dy shows a constant rotational behavior from spin 20^+ to 40^+ with the moment of inertia $\mathscr{J}^{(2)}$ increasing slowly from $56\hbar^2$ MeV^{-1} to $59\hbar^2$ MeV^{-1}. We also note that the projec-

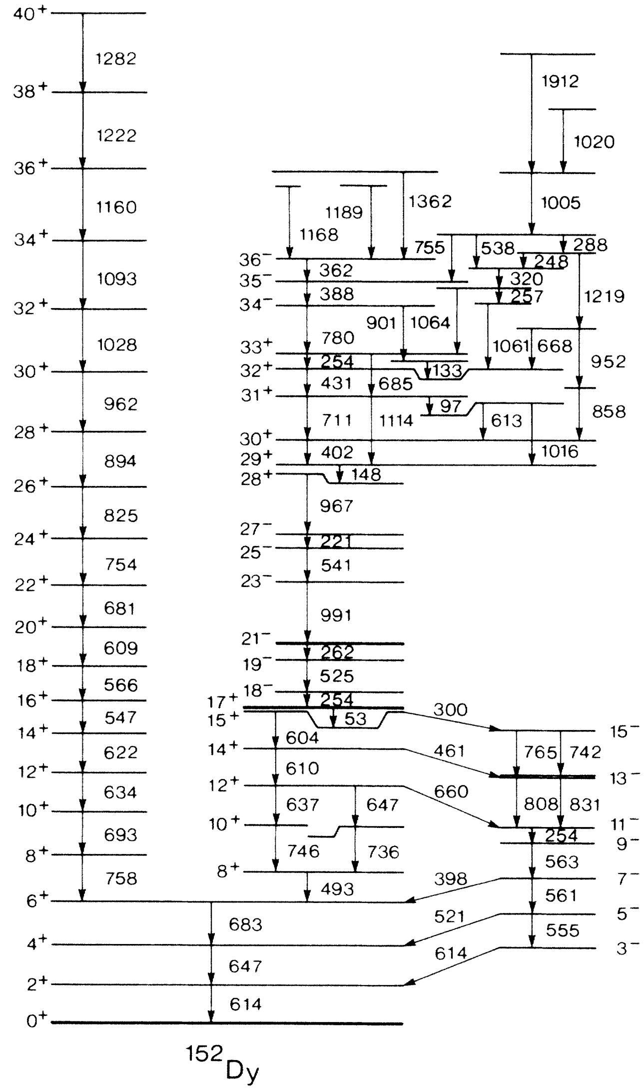

FIG. 2. The decay scheme for ^{152}Dy. It is derived from the present work and Styczen *et al.*[10] for the ground-state band, and from Khoo *et al.* (Ref. 1), Merdinger *et al.* (Ref. 2), and Twin *et al.* (Ref. 3) for the oblate particle-hole states.

tion of the linear part of this graph passes close to the origin which is similar to the behavior in other rare-earth nuclei.[12] The band shows no evidence of particle alignments between frequencies of 0.35 and 0.65 MeV. This can be understood in terms of the cranked shell model if both the first neutron $i_{13/2}$ alignment and the first proton $h_{11/2}$ alignment occur below 0.35 MeV. Such an explanation is consistent with the experimental and predicted trends of the $h_{11/2}$ proton crossing[13] which is lowered in frequency as the deformation decreases. The alignment increase at 0.35 MeV between the quasivibrational low-spin states and the rotational band is $16\hbar$ (see Fig. 3). Again this is consistent with the sum of alignments expected from $i_{13/2}$ neutrons $(\sim 10\hbar)$ and $h_{11/2}$ protons $(\sim 5\hbar)$. In Fig. 3 the data

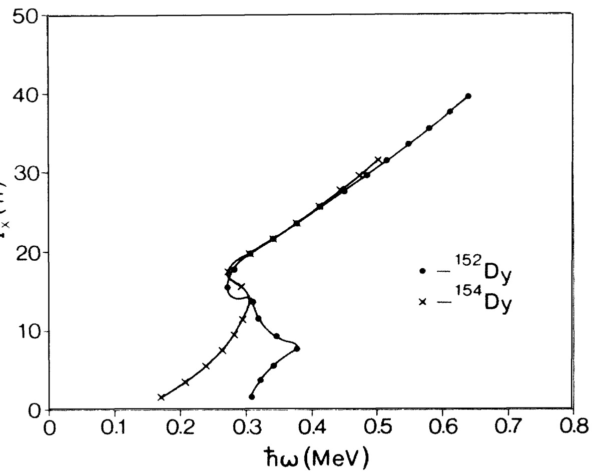

FIG. 3. Plots of spin I_x vs rotational frequency $\hbar\omega$ for the lowest-energy positive-parity bands in ^{152}Dy (circles) and ^{154}Dy (crosses).

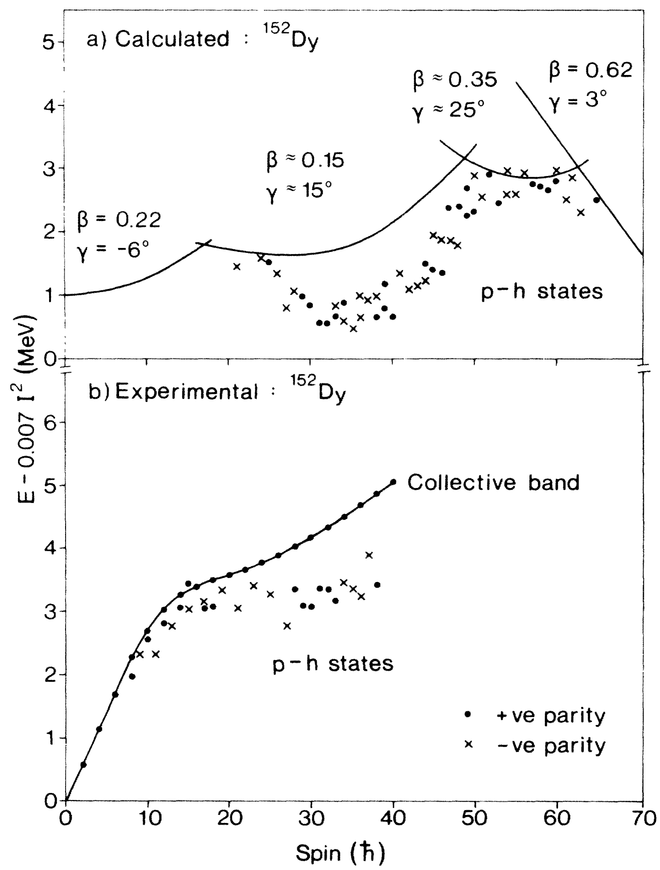

FIG. 4. The excitation energies of levels in ^{152}Dy relative to a smooth rotational-like reference of $0.007I^2$ MeV. The calculations are by Dudek and Nazarewicz (Ref. 9) using the Strutinsky cranking calculation with Woods-Saxon potentials and no pairing.

are also shown for the positive-parity yrast states in ^{154}Dy up to $I=30^+$ where they are crossed by a sequence of levels terminating in oblate states.[14] The curves for the two nuclei coincide between spins of 20^+ and 30^+ indicating they probably have the same structure and that the $h_{11/2}$ proton alignment in ^{154}Dy is also lowered to below 0.35 MeV.

Dudek and Nazarewicz[9] have calculated the relative energies of many low-lying structures in ^{152}Dy and other dysprosium nuclei. They used the Strutinsky cranking method with Woods-Saxon potentials and neglected pairing which should be a good approximation above spin $20\hbar$. Their calculations are shown for ^{152}Dy in Fig. 4(a) and compared with the experimental data in Fig. 4(a). In both cases the excitation energies of the levels are plotted relative to a smooth rotational-like reference of $0.007I^2$ MeV. In Fig. 4(a) we have only plotted the lowest bands in each of the four different shape regimes. Between spins of $20\hbar$ and $40\hbar$ a small prolate deformation of 0.15 with some triaxiality of around $\gamma=15°$ is predicted to be the lowest collective structure and this probably corresponds to the new experimental rotational band. At higher spins more deformed bands with $\beta\approx 0.35$ and $\gamma\approx 25°$ are predicted to become the lowest collective states with the superdeformed bands becoming yrast above $60\hbar$. Evidence for the population of the superdeformed bands has been observed[6,7] under the same experimental conditions as the present observation of the nonyrast rotational band up to spin $40\hbar$. This leads us to the conjecture that the two observations are linked as the intensities of the superdeformed (< 10%) and normal collective bands [(4 ± 1)%] are similar. The superdeformed bands could decay by slightly enhanced $E2$ transitions either directly to the new band around spin $40\hbar$ or via the more deformed triaxial shape. This infers that the decays out of the superdeformed bands would occur just above spin $40\hbar$. At this spin the in-band gamma-ray energy is 0.95 MeV if the spin of the superdeformed band follows the simple relationship $I=\omega\mathscr{I}^{(2)}_{\rm band}$ where $\mathscr{I}^{(2)}_{\rm band}=85\hbar^2$ MeV^{-1}. As the superdeformed ridge has been observed down to around 0.85 MeV it appears that a relationship $I-I_0=\omega\mathscr{I}^{(2)}_{\rm band}$ with $I_0>5$ would be more appropriate.

In summary, we have observed a well-defined band of rotational-like levels in ^{152}Dy which are a continuation of the ground-state sequence. The levels are interpreted as members of a prolate collective band which coexists with the oblate particle-hole states with no observable links between the two sets of states. This is the first observation of shape coexistence over a very wide spin range, in this case from 8^+ to 40^+. In terms of the cranked shell model the band is assigned a four-quasiparticle configuration with both $i_{13/2}$ neutrons and $h_{11/2}$ protons aligned, implying that the frequency of the proton crossing is less than 0.35 MeV. The band may also be identified as a member of the $\beta\approx 0.15$, $\gamma\approx 15°$ structures predicted by Dudek and Nazarewicz.[9] It is suggested that the band may be involved in the decay of the superdeformed bands which have been previously observed to exist at very high spin in ^{152}Dy.

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