Deformed Ground-Band States in the $N = 86$ Nucleus ^{152}Dy

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The ground-band levels of ^{152}Dy have been established up to 18^+ at 5.8 MeV by ^{152}Gd(α, 4n) in-beam experiments with 60-MeV α particles. The band members with $I \geq 8$ lie above the known ^{152}Dy yrast states which are formed by aligned multiparticle configurations typical for a spherical nucleus. An analysis of the ground-band energies in a gauge-backbending plot suggests that the ground-band levels with $I > 8$ are deformed.

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The yrast lines of the even Dy isotopes with 82 or more neutrons clearly reveal the transition from single-particle to collective nature (see Fig. 1). In the spherical nuclei, ^{148}Dy and ^{150}Dy, the yrast level sequence[1,2] is characterized by irregular energy spacings, frequent parity changes, and by an abundance of yrast isomers. In contrast, the $N \geq 88$ nuclei have highly regular collective $\Delta I = 2$ yrast level sequences, in general, with energy spacings, and to a large extent also $B(E2)$ values, characteristic for deformed rotors.[3-7] The yrast line of the $N = 86$ nucleus ^{152}Dy is of intermediate character. The levels below spin 8 have energy spacings as well as $B(E2)$ values typical for a collective vibrator,[8] whereas the yrast line above spin 8 up to spin 38 at 13 MeV (Ref. 9 and this work) is formed by aligned multiparticle configurations, as similarly observed in the spherical nuclei ^{150}Dy and ^{148}Dy.

Numerous theoretical calculations[10-13] predict that the nuclei around ^{152}Dy should become prolate superdeformed ($\epsilon \simeq +0.6$) at $I \gtrsim 45$, but experimental attempts to observe this superdeformation have not been quite[13,14] successful. In particular, so far it has not been possible to infer a drastic shape change from discrete line spectroscopy for ^{152}Dy or its neighbors. Up to now, however, little attention has been paid to lower-lying collective states in ^{152}Dy. Specifically, it was not known whether the collective excitations manifest from the lowest yrast transitions might continue towards higher spins above the yrast line. In the present (α,4n) study we have identified a $\Delta I = 2$ ground-band sequence up to $I^\pi = 18^+$ at 5.8 MeV. An analysis of the level energies suggests that the ground-band levels with $I > 8$ are deformed, contrary to the yrast states which exhibit the character of a spherical nucleus.

Previous high-spin studies of ^{152}Dy mainly utilized heavy-ion–induced compound reactions which strongly favor the γ decay along the yrast line. The (α,4n) reaction transfers significantly less angular momentum to the compound nucleus. Consequently, γ-ray side feeding occurs in a wide region at low excitation between 2 and 6 MeV. In the side-feeding region, levels above the yrast line can be observed if coincidence experiments with high counting statistics are performed.

In our experiments we have bombarded a ^{152}Gd

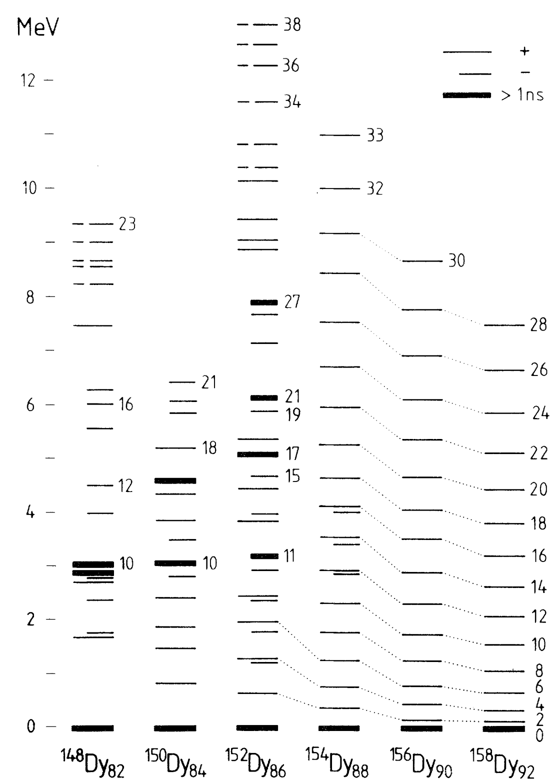

FIG. 1. Observed yrast states in the even Dy isotopes (Refs. 1–5, 9, and this work) with 82 to 92 neutrons, showing the change in character between spherical and deformed nuclei.

target enriched to > 99% with a pulsed beam of 60-MeV α particles and measured two-detector four-parameter $\gamma\gamma$ coincidences, γ-ray angular distributions, and conversion electrons. These data gave the ^{152}Dy level scheme of Fig. 2. The γ-ray intensities shown are as measured in the $(\alpha, 4n)$ experiment. It is apparent from Fig. 2 that more than 80% of the side feeding occurs in the region from $I=6$ to 16, i.e., below the 60-ns isomer at 5.1 MeV, and therefore excellent angular distributions could be measured for the ^{152}Dy γ rays of Fig. 2. Together with the results of Ref. 15, the present data provide for the 60-ns isomer and the level 253 keV above it firm spin-parity assignments of 17^+ and 18^+, which from the earlier studies[9] were not known unambiguously.

Of particular interest here is a cascade of five previously unobserved $\Delta I=2$ $E2$ transitions which extend the ground band from $I^\pi = 8^+$ up to 18^+. [We assign the 2703-keV 8^+ level as a ground-band member; β-decay data[16] suggest a dominant aligned $(\nu h_{9/2} f_{7/2})_8$ contribution for the 8^+ yrast state at 2437 keV.] In the spectra these new transitions are too weak to determine their α_K values, and the $E2$ assignments are based exclusively on angular distribution results. Although $B(E2)$ values are not known at present the highly regular energy spacings of this $\Delta I = 2$ level sequence suggest collective character for these states. This suggestion is also supported by the failure to detect any γ-ray branch from an yrast state to the $I > 8$ ground-band levels which lie only ~ 0.2 MeV above the yrast line. One may conclude that admixtures between the two types of states are small.

In the backbending plot of Fig. 3, showing the spin I minus a half versus half the $I \rightarrow I-2$ transition energy (alignment plot), the ^{152}Dy ground band is compared with the yrast bands of the neighboring heavier even Dy isotopes. In such a plot the heavier nuclei show highly similar characteristics above the first backbend at $I \simeq 18$ caused by the alignment of two $i_{13/2}$ neutrons. Furthermore, in this region the energy spacings agree unusually well[3,17] with those for an ideal rotor. Whereas for $I \lesssim 12$ the ^{152}Dy transition energies differ drastically from those of the heavier isotopes, we observe that for the higher spins all backbending curves become quite similar. The identification of more band members would be desirable to strengthen this similarity which could indicate a close relationship to the ground bands of the $N \geqslant 88$ nuclei. However, whether firm conclusions can be drawn from this observation about pertinent nuclear structure features is not quite clear.

It is more elucidating to examine our results

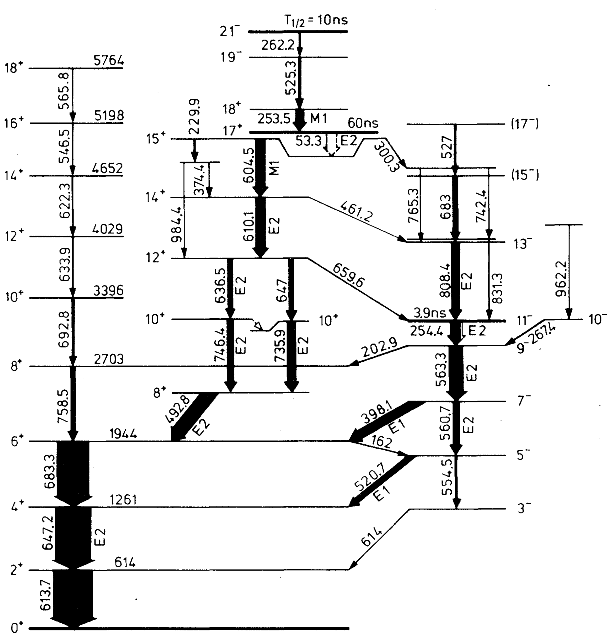

FIG. 2. The high-spin states of ^{152}Dy as observed in the $(\alpha, 4n)$ reaction at 60 MeV. Multipolarities are specified when supported by the conversion-electron measurements.

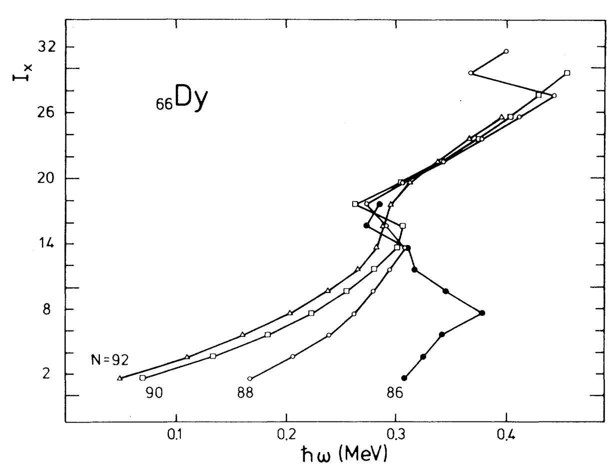

FIG. 3. Backbending plot showing the spin vs the rotational frequency for the even Dy nuclei with 86 to 92 neutrons. For $N=88$ to 92 the yrast states (Refs. 3, 4, and 6) are plotted. The points for $N=86$ represent the ground-band energies.

in a gauge-backbending plot as recently proposed[17] by Bengtsson, Zhang, and Åberg who pointed out the analogy between backbending in ordinary space and in gauge space. An ordinary backbending plot as in Fig. 3, based on the transition energies, reveals the angular momentum gain caused by the alignment of the spin vectors of a nucleon pair. Analogously, the gauge-space plot will show a backbending behavior when a change in deformation occurs. In such a plot one examines the difference in excitation energy $E_x(I)$ for the ground-band members with spin I in a pair of neighboring even-even nuclei. This energy difference, together with the two-nucleon separation energy S_{2n}, specifies the Fermi energy λ as a function of spin. According to the prescription given in Ref. 17 the Fermi energies are calculated from the relation

$$\lambda(N,I)=\tfrac{1}{2}[E_x(N+1,I)-E_x(N-1,I)-S_{2n}{}^{N+1}],$$

where N is the (odd) neutron number between the two even isotopes which are compared. Figure 4 gives the results for the Dy nuclei calculated from the experimental energies of the even isotopes with 82 to 96 neutrons. The figure clearly shows the backbend between the spherical nuclei with $N \lesssim 86$ and the deformed nuclei with higher neutron number.

It has earlier been pointed out[17] that at $N \simeq 88$ the $I=0$ line of this plot is well separated from the deformed branch, indicating a small ground-state deformation, and that the curves for the higher spins suggest that the deformation increases smoothly when going up the ground band. Equivalently, the deformed shape persists down to lower neutron number when the angular momentum becomes large. The gross trend of the ground-band $B(E2)$ values measured[3,7] for the $N=88$ nucleus ^{154}Dy is in accord with this conclusion. The transition moment for the $2\to 0$ transition is about 4 $e\cdot$b; towards higher spins the values increase and reach a maximum of $\simeq 7.5$ $e\cdot$b, which is equal to the values found (independent of I) in the well-deformed rotors with more than 90 neutrons.

Our new data in Fig. 4 for the ^{152}Dy ground band show a similar, but distinctly more pronounced spin dependence. The transition moments[7,8] of $\lesssim 2$ $e\cdot$b measured for the 2^+, 4^+, and 6^+ states independently evince the yet smaller deformation suggested by the figure for these states. For the ground-band levels with $I=10$ and above, the λ values lie closely spaced on the upper branch of the gauge-backbending plot, which can be taken to indicate that for these levels the deformed shape persists down to 86 neutrons. Confirmation of this finding via half-life measurements would be particularly valuable in this extreme case where for $I<8$ the transition moments as well as the level energy spacings suggest a spherical nuclear shape. Unfortunately, such experiments are difficult since the pertinent region of the ground band lies above the yrast line, thus excluding conventional Doppler-shift experiments with heavy-ion beams.

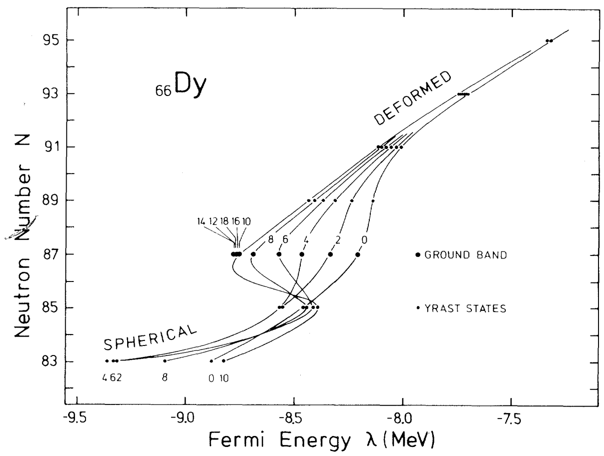

FIG. 4. Backbending plot in gauge space for the even Dy isotopes, showing the neutron number vs the Fermi energy λ for each spin. The points at $N=87$ are calculated with use of the ground-band energies of ^{152}Dy; the yrast levels are not shown at $N=87$, but they are considered in the λ values at $N=85$. The level energies used are those of Fig. 1; the two-neutron separation energies are from Refs. 18 and 19.

In conclusion, we have identified a collective $\Delta I = 2$ ground band in ^{152}Dy extending up to $I=18$ at 5.8 MeV. Examination of the ground-band energies in a gauge-backbending plot suggests that the band members with $I \geqslant 10$ are deformed in this $N=86$ nucleus where the aligned-particle-type yrast line from spin (38) at 13 MeV down to spin 8 at 2.4 MeV, as well as the vibrational yrast levels below 2.4 MeV, are typical for a spherical nucleus.

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