LEVEL STRUCTURE OF ^{153}Dy AND THE COMPETITION BETWEEN COLLECTIVE AND FEW-PARTICLE EXCITATION MODES IN Dy NUCLEI ☆

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The ^{153}Dy level structure has been studied through the ^{124}Sn(^{34}S, 5n) reaction. The low-spin collective character of ^{153}Dy gives way to single particle yrast configurations at $I > 41/2$; an $I = 47/2$ isomer at 5591 keV shows the single particle character (and overall oblate shape) to be well established at that spin. Nuclear shape changes in Dy nuclei are discussed.

Nuclei with $N = 82$–86 are spherical in the ground state but become oblate at high spin along the yrast line as successive high-j nucleons align their spins along the symmetry axis. In contrast, the yrast states of nuclei with $N \geq 90$ are prolate even at high angular momenta. One consequence is the absence of nanosecond isomers of high multiplicity in nuclei with $N \geq 90$ [1]; the shell effects which drive nuclei prolate are apparently still dominant up to the highest observed spins. The level spectra of the transitional nuclei with $N = 87$ and 88 feature low-lying collective band structures indicative of small prolate deformation. It is in these soft nuclei, where prolate driving shell effects are barely established, that one might hope to observe the prolate to oblate shape change with increasing spin suggested by liquid drop considerations [2].

To explore these possibilities, we recently studied the high-spin level structure and lifetimes of the $N = 88$ nucleus ^{154}Dy by means of the (^{34}S, 4nγ) reaction. The results [3] indicated a transition above spin 32 in the character of the yrast states from collective to few-particle, and gave evidence for an evolution in the nuclear shape along the yrast line from prolate through triaxial to oblate. Since one could expect a similar transition to be manifested in the high-spin level spectrum of the neighboring $N = 87$ nucleus ^{153}Dy, we have now studied that nucleus in detail to learn more about how the nuclear shape changes in this region depend on neutron number N and spin I.

The levels of ^{153}Dy have previously been studied in (α, xnγ) reactions. Kleinheinz et al. [4] used the (α, 3n) reaction to locate levels up to $I \sim 33/2$, including $\Delta I = 2$ bands built on weakly deformed $i_{13/2}$, $h_{9/2}$, and $f_{7/2}$ neutron in-

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trinsic states and a $\Delta I = 1$ band built on a strongly deformed $\nu h_{11/2}$ state. Subsequent (α, 5n) and (α, 6n) measurements by Jansen et al. [5] generally confirmed the (α, 3n) results and extended them to slightly higher spins. However, there are some significant disagreements between the conclusions of the two groups. Particularly, a cascade including prominent 441, 481, and 552 keV transitions was observed with too much intensity in the (α, 5n) reaction to be compatible with its earlier placement [4], and it was relocated in the level scheme proposed in ref. [5].

We have performed an extensive set of in-beam γ-ray spectroscopy experiments using the ^{124}Sn (^{34}S, 5n) reaction induced by 145–165 MeV ^{34}S beams from the Argonne Tandem-Linac. They included excitation function, angular distribution, and electronic timing measurements, as well as comprehensive γ–γ coincidence measurements using three Ge detectors and a large NaI sum-spectrometer. In the (^{34}S, 5n) reaction we observed two strong parallel cascades of mainly stretched E2 transitions, one of which consisted of the known γ-rays in the $i_{13/2}$ band and some higher lying transitions. The other strong cascade included the 441, 481, and 552 keV γ-rays as well as many other transitions not observed in the (α, xn) studies; connections between the members of this new band and the lowest transitions in the $i_{13/2}$ band were clearly indicated by the coincidence data. A high-lying 2.3 ns isomer was found to de-excite predominantly through the new band with much weaker decay pathways feeding all known members of the $i_{13/2}$ band. In determining the relative positions of the two bands, we performed quantitative analyses of the coincidence intensities and also took account of the reported (α, xn) data. Crucial steps in the construction of the level scheme (fig. 1) were the introduction of the 1601 keV level, de-exciting by three branches, and the placement of the weak 441, 394, and 342 keV interband transitions. The 2.3 ns isomeric state is also firmly located, with the required connections to the $\nu i_{13/2}$ band identified. An analysis of the delayed γ-ray intensities also showed satisfactory intensity

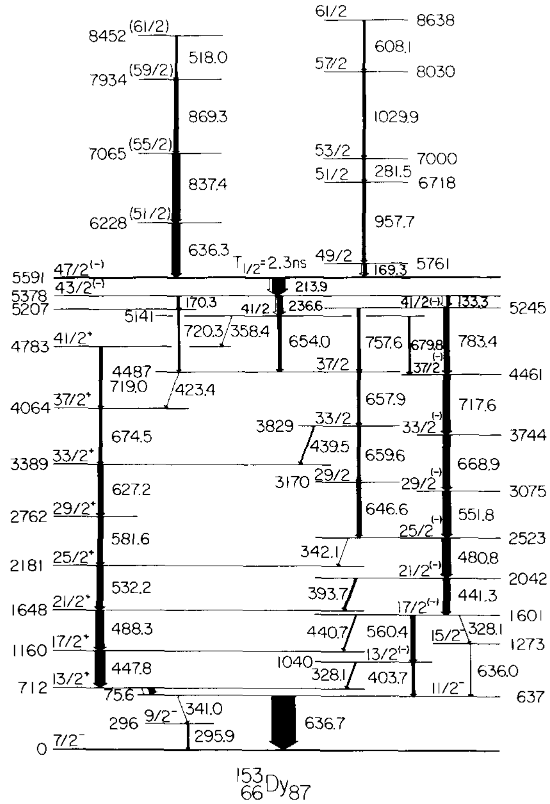

Fig. 1. The level scheme of ^{153}Dy. The widths of the transition arrows are proportional to the singles intensities at 165 MeV beam energy.

balance throughout the scheme. The transition ordering above the isomer is not certain, especially for the 636 keV transition, which forms part of an unresolved multiplet with complex coincidence relations.

The spin–parity assignments shown are based on the angular distribution results, which indicate stretched E2 character for most of the strong transitions. (The A_2 coefficients of transitions below the 2.3 ns isomer were observed to be attenuated by variable amounts depending on the ratio of prompt-to-delayed feeding.) For the 133 keV transition, M1 character was deduced from delayed intensity balance. Unfortunately, the parity of the right-hand band (fig. 1) could not be settled, since an uncertainty in the assignment of the 1040 keV level propagates all the way up to the isomeric level; the available evidence distinctly favors negative parity, and we shall refer to this as the negative parity band.

The lower portions of the ^{153}Dy and ^{154}Dy schemes broadly resemble one another, each with two main de-excitation pathways, one involving even parity, the other odd parity states. While the ^{153}Dy $\nu i_{13/2}$ band and the ^{154}Dy S-band are related, it is not clear whether the negative parity band in ^{153}Dy is a structural counterpart of the extensive band built on the 3^- octupole in ^{154}Dy. The $\nu i_{13/2}$ band exhibits collectivity in smoothly increasing transition energies, giving a straight line on a plot of the angular momentum I_x versus $\hbar\omega$ (fig. 2). We note that the data for the S-band in ^{154}Dy also lie along a straight line which passes close to the origin, in this way approximating the behavior of a perfect rotor, but the full implications of these observations are not yet understood. That the negative parity bands in ^{153}Dy and ^{154}Dy have much less regular structures is also clearly illustrated in fig. 2.

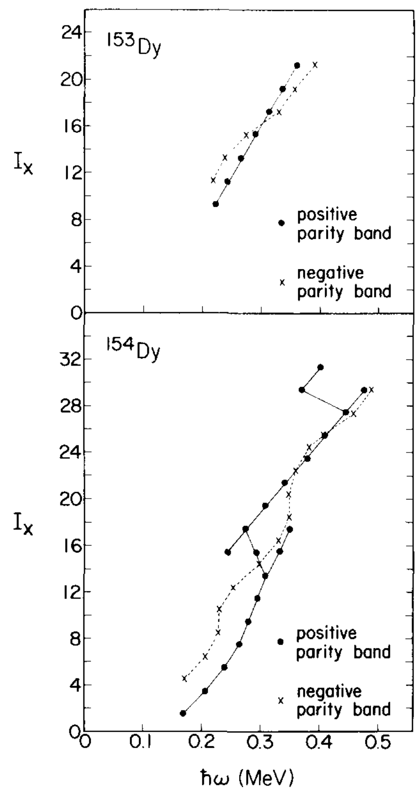

Fig. 2. Plots of I_x, the angular momentum along the rotation axis, versus rotational frequency for the positive and negative parity bands in ^{153}Dy and ^{154}Dy.

The population of the two main ^{153}Dy bands drops sharply at high angular momenta, and no band members with $I > 41/2$ could be identified. In the region around 5 MeV excitation, where the $I = 41/2$ band members occur, the level scheme is extremely complex with several competing de-excitation pathways consisting of cascades of dipole and quadrupole transitions with highly irregular energies. These observations show that the low-spin collective character of ^{153}Dy gives way to single-particle configurations at higher spins. The complexity of the level scheme around 5 MeV indicates that the collective and single particle modes of generating angular momentum here compete on a roughly equal basis, giving rise to many alternative de-excitation possibilities.

The existence of the 2.3 ns 5591 keV isomer with $I = 47/2$ shows that the single-particle character is already well established at that spin. The E2 transition speed is 10 WU, similar to the values observed [6,7] for aligned particle yrast isomers in ^{151}Dy and ^{152}Dy. With seven valence nucleons outside the ^{146}Gd core, there are many ways to generate $I = 47/2$ in ^{153}Dy; from the systematics of yrast isomers in lighter Dy nuclei, it seems most likely that the 2.3 ns isomeric state has a seniority-five configuration involving two aligned $h_{11/2}$ protons and three active neutrons. Whatever the configuration of the isomer, its main significance in the present context is that if manifests the occurrence in ^{153}Dy of aligned particle yrast structures (and overall oblate shapes) similar to those observed in ^{151,152}Dy, whereas no high-spin yrast isomers are known in heavier Dy nuclei.

In summary, this investigation has shown that ^{153}Dy has collective character at low-spin, marked by regular cascades of stretched E2 transitions, but a change to single particle yrast excitations and irregular cascades with both dipole and quadrupole transitions occurs around $I = 41/2$. These single particle excitations are almost certainly aligned particle configurations, leading to an oblate nuclear shape.

The present results and those of ref. [3] show

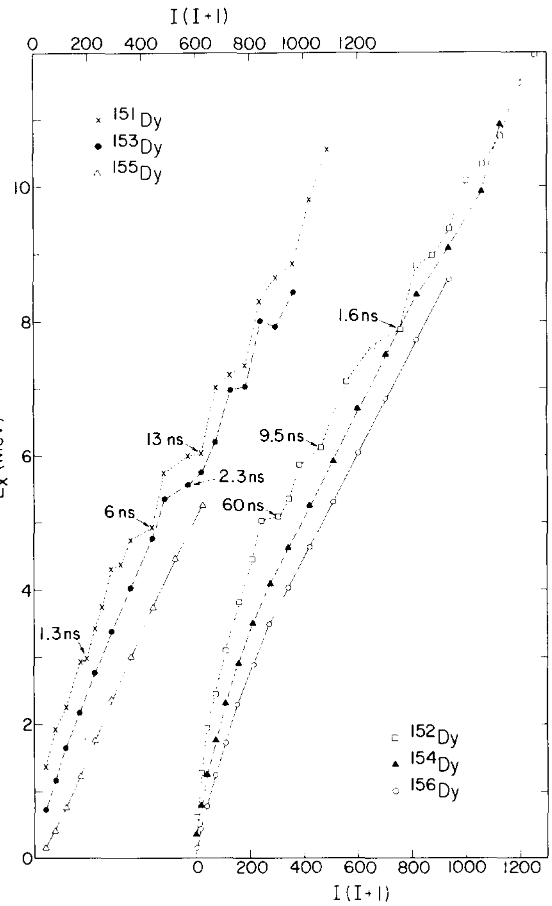

Fig. 3. Excitation energies E_x of yrast levels in $^{151-156}$Dy plotted as a function of $I(I + 1)$. The upper abscissa scale refers to the odd-A isotopes, the lower scale to the even-A isotopes. Half-lives of known yrast isomers are shown. The data are from refs. [3,7,10–12] and the present work.

the Dy isotopes with $N = 87$ and 88 to be transitional in two respects. Not only do they connect isotopes that have spherical or oblate shapes ($N \leqslant 86$) to those with prolate shapes characterized by pronounced collectivity ($N \geqslant 90$), they also exhibit features of both groups. The transition from collective to single-particle character occurs at a higher spin in ^{154}Dy ($I > 32$) than in ^{153}Dy ($I > 41/2$), consistent with the tendency towards greater collectivity for higher neutron number. This is illustrated in fig. 3, where the energies of the yrast states of $^{151-156}$Dy are plotted as a function of $I(I + 1)$. In ^{151}Dy, even the lowest spin yrast states are of aligned particle character, and many yrast isomers are observed. In ^{152}Dy, ^{153}Dy, and ^{154}Dy, the low-lying states are weakly collective, and the transition from collective to single-particle character, usually accompanied by the appearance of yrast isomers, happens at spin values of approximately 10, 41/2, and 32, respectively. In ^{155}Dy and ^{156}Dy, the yrast states are collective up to the highest observed spins and no yrast isomers occur. Angular momentum-induced shape transitions in the Dy nuclei have been predicted in theoretical calculations [8,9], in qualitative agreement with the experimental findings. The observed transitions, however, occur at lower spins than these calculations indicate. While the general features are now seen, important details still need to be understood, for example, how weakly collective (even vibrational) structures evolve into strongly collective ones represented by rotation of deformed shapes.

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