Yrast Traps and Very High-Spin Yrast States in ^{152}Dy

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We have identified yrast states of ^{152}Dy to spin ~37, with unusually strong population of high-spin states in the (^{32}S, $4n\gamma$) reaction. Yrast isomers with spins ~17, 21, 27, and 31 were detected. For $I \geq 14$ the yrast states scatter about a straight line on an E vs $I(I+1)$ plot, consistent with predictions for aligned-particle configurations. The slope of the line yields an effective moment of inertia 18% larger than the rigid-sphere value. This and other arguments suggest possible oblate deformation at high spin.

Investigations of high-spin nuclear states, $I > 30\hbar$, have so far been limited to studies of continuum γ radiation.[1,2] Such experiments by their nature provide information only on gross properties of nuclear states over a wide range of excitation energy above the yrast line. Data on the yrast line itself to very high spin will open up a domain of nuclear structure which has hitherto not been explored. In particular one might learn whether there is a general relation between the energies and spins of yrast states, as has been predicted for an independent-particle system,[3] and how shell effects modify this relation; whether dramatic shape changes are induced in nuclei by large angular moments; and how spin is generated with the least expenditure of energy.

A recent extensive survey[4] located an "island" of high-spin isomers with $N \sim 82$. Guided by this work we have initiated studies of isomers formed in ^{32}S bombardment of $^{120-124}$Sn and $^{122-124}$Te to form compound systems of Dy and Er, respectively. Isomers were observed in ^{148,149,151,152}Dy, ^{147}Gc, ^{148}Tb, and possibly some Ho and Er isotopes. The occurrence of such isomers is of considerable interest in its own right, since they may be related to the yrast traps first suggested by Bohr and Mottelson.[5] In addition it opens up experimental possibilities for the study of discrete high-spin states of the yrast line itself. We have taken advantage of this to observe states of spins as high as 36 or 37 in the nucleus ^{152}Dy. This Letter reports results of γ-ray spectroscopic studies of ^{152}Dy.

The reaction ^{124}Sn(^{32}S, $4n$) was employed with 129–160-MeV ^{32}S beams, provided by the Chalk River MP tandem accelerator, which were pulsed with repetition periods of 400 or 800 ns. An extensive range of γ-ray spectroscopic experiments was investigated, including measurements of prompt and delayed γ rays, prompt γ-γ and delayed γ-γ coincidences both in and out of beam, γ-γ angular correlations of delayed γ rays, γ-excitation functions, and γ angular distributions. By recording the time with respect to the beam of events in each of two detectors, and also the time between events, it was possible to select clean spectra of γ rays either feeding or de-exciting isomers. This fact was exploited in measuring the excitation functions and angular distributions. Preliminary measurements of very short lifetimes were made with a recoil-distance technique. Finally, complementary angular-distribution and excitation-function data were obtained from the reactions ^{142}Nd(^{12}C, $2n$) and ^{143}Nd(^{12}C, $3n$) at Argonne National Laboratory.

The level scheme of ^{152}Dy, shown in Fig. 1, has been determined up to an energy of ~13 MeV and spin of ~37. Four yrast isomers with half-lives of 60 ns, 10 ns, 1.4 ns, and ~70 ps have been found with spins of 17, 21, 27, and 31, respectively. There is an uncertainty of one unit in the spin of the 60-ns isomer (see below) which propagates to all higher spins. Below 6 MeV the level scheme is fairly similar to that of Jansen *et al.*[6] On the basis of prompt components in the time spectra for coincident γ-ray pairs, one of which was the 605-keV transition, we confirm the existence of the unobserved transtion "Δ" proposed in Ref. 6. (The coincident condition was necessary to remove prompt contribution from a strong 605-keV component in ^{151}Tb.) The unobserved transition has an energy of less than 54 keV.[6] The 60-ns half-life limits its multipolarity to either dipole or quadrupole, giving a problable spin of 16 or 17 for the isomer. All other multipolarity and spin assignments are made on the basis of angular distribution, excitation function, and also, for γ rays de-exciting the 60-ns isomer

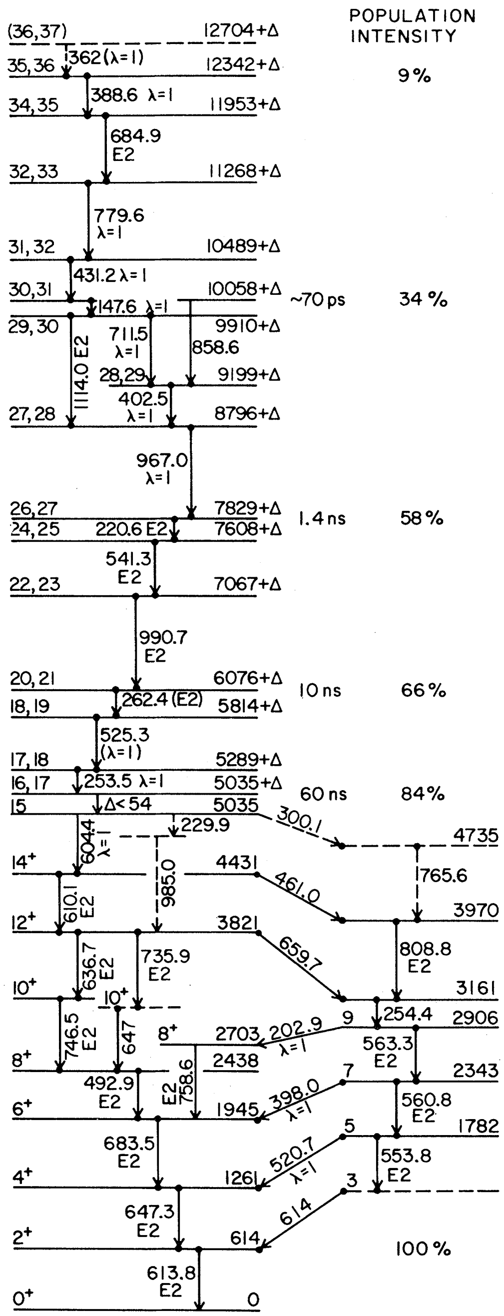

FIG. 1. Level scheme for ^{152}Dy. Assignments in parentheses are tentative. Filled circles indicate γ rays entering and leaving a level in prompt or delayed coincidence. The numbers to the right-hand side of some levels are population intensities in the (^{32}S, $4n$) reaction with 145-MeV ^{32}S.

in the (^{32}S, $4n$) reaction, γ-γ angular correlation measurements. The level ordering is based on γ intensities and is simplified by the occurrence of successive isomers.

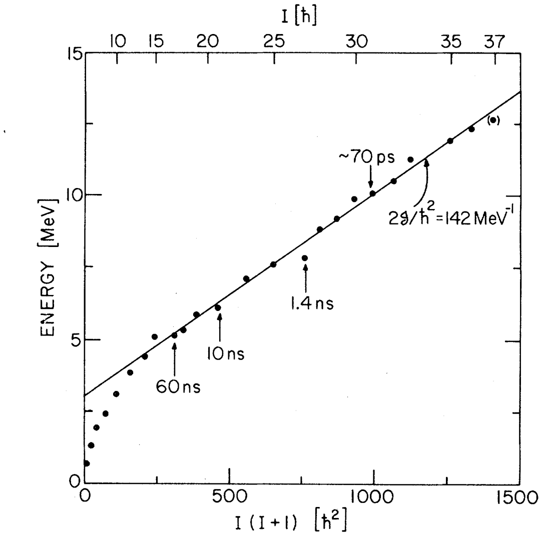

FIG. 2. Plot of energy vs $I(I+1)$ for yrast levels of ^{152}Dy assuming $I=17$ for the 60-ns isomer. For $I \geq 14$, the data lie close to a straight line with slope corresponding to $2\mathcal{J}/\hbar^2 = 142$ MeV^{-1}. For rigid-body rotation about the symmetry axis of a sphere and an oblate spheroid with $\beta = 0.3$, $2\mathcal{J}/\hbar^2 = 120$ and 142 MeV^{-1}, respectively.

The energies of the presumed yrast levels of ^{152}Dy are plotted as a function of $I(I+1)$ in Fig. 2, assuming $I=17$ for the 60-ns isomer and $\Delta = 20$ keV (see Fig. 1). (With $I=16$, the plot would be essentially unchanged except for an $\sim 4\%$ increase in the slope of the yrast line.) It is remarkable how little the yrast states deviate from a straight line for $I \geq 14$.

It should be noted that the yrast line is irregular. This is in contrast to the yrast structure expected from collective rotation of a prolate rotor (such as ^{156}Dy), for which the excitation energies would increase *smoothly* with spin. The irregularity of the yrast line and the existence of four isomers with decay rates typical of single-particle transitions imply that the yrast angular momentum originates mainly from the alignment of individual particle spins.

When angular momentum is generated by aligning that of individual nucleons along a symmetry axis, the yrast energies should increase linearly with $(\hbar^2/2\mathcal{J})I(I+1)$, on the average.[3] $\mathcal{J}$ is an effective moment of inertia characteristic of that for rigid-body rotation in the Fermi-gas model.[3] A test of this prediction requires an examination of states over a sufficiently large spin range. We observe this behavior for states with I between 14 and 37 (see Fig. 2), whose energies are fitted with an effective moment of inertia $2\mathscr{I}/\hbar^2 = 142$ MeV^{-1}. Our data thus provide the first experimental demonstration of this fundamental aspect of nuclear behavior. The departure from the straight line for spins less than 14 reflects the effects of pairing correlations.

The experimental value of $2\mathscr{I}/\hbar^2 = 142$ MeV^{-1} is substantially larger than the rigid-sphere value of 120 MeV^{-1} and exceeds those for *deformed* prolate nuclei at spin 30 [$2\mathscr{I}/\hbar^2 = 130$ MeV^{-1} in ^{156}Dy (Ward *et al.*[7]) and 135 MeV^{-1} in ^{158}Er (Lee *et al.*[8])]. As noted above, the effective moment of inertia associated with aligned configurations should be that of a rigid body with the same density distribution as the nucleus.[3] Thus, the very large observed value of $\mathscr{I}$ suggests the possibility of an oblate deformation at high spin in ^{152}Dy. (The irregular yrast line together with the large moment of inertia rules out a prolate shape.) The observed value of $2\mathscr{I}/\hbar^2$ is that for an oblate spheroid, of $\beta = 0.3$, rotating rigidly about its symmetry axis. However, the actual value of the oblate deformation derived from the observed yrast line should take into account the local microscopic shell structure. Shell effects, and in particular the availability of high-j orbitals near the Fermi surface, can also contribute toward increasing $\mathscr{I}$ beyond the spherical value. The large observed moment of inertia may well be due to a combination of both local shell structure and oblate deformation. However, it should be realized that probably no clear-cut separation of the two effects can be made since shell effects will have a profound influence on the shape. For instance, for a high-spin state with aligned high-j particles, there will be a tendency for the particles to polarize the core into an oblate shape. This is turn would lower the energy of the system by decreasing the single-particle energies, further enhancing the tendency towards oblateness. In other words, the effects of shell structure and core polarization may be incorporated into a deformed oblate potential. The basic question is whether the core itself is deformed. The problem may be resolved by performing, on the one hand, shell-model calculations with a fixed spherical core, and on the other, a model calculation where the shape is allowed to vary with spin to minimize the total energy. Indeed, calculations of the latter type[9-11] indicate that nuclei with $N \sim 82$ become oblate at high spin. This possibility was foreseen earlier[5,12] from liquid-drop considerations. Bohr and Mottelson[5] also predicted that for an oblate shape the yrast states would be formed from particle alignment along the symmetry axis. Under these circumstances the yrast transitions will be of single-particle character and isomers may occur—the so-called yrast traps. (Recent calculations[9,10] based on an oblate deformed oscillator potential have predicted such yrast traps in ^{152}Dy.) The irregular yrast line of ^{152}Dy, its large effective moment of inertia, and the occurrence of four yrast isomers are all compatible with this picture.

Another interesting observation in our studies is the unusually large population of the high-spin isomers. For instance, the 60-ns isomer with $I = 16$ or 17 receives ~ 84% of the total (^{32}S,$4n$) cross section at a bombarding energy of 145 MeV, while the $I \sim 31$ isomer receives ~ 34%. Such a high funneling of γ de-excitation into very high-spin yrast states has not previously been observed, although the tendency for a higher than usual population of high-spin states in (^{12}C,xn) reactions in the mass region $A \sim 150$ has been noticed recently.[13,14]

This very large high-spin cross section can be understood within the framework of the description given above for the high-spin structure of ^{152}Dy. With an oblate or spherical shape, one indeed expects a rapid funneling of the γ decay to the yrast line via statistical cascades following neutron emission. On the other hand, with a prolate or triaxial shape, enhanced stretched $E2$ transitions can compete with the statistical decays several MeV above the yrast line.[15] The γ decay is thus channeled along paths roughly parallel to the yrast line but several MeV above it, with the consequence that the yrast line itself is largely bypassed at high spin. This may provide an explanation for why so few states with spins higher than 22 have been observed in previous (H.I.,xn) studies, which have mainly centered on prolate cases.

In summary, we have observed yrast states in ^{152}Dy to higher spins than have ever been observed before. Over the range $14 \leq I \lesssim 37$ the yrast states originate from aligned-particle configurations and have energies which increase linearly with $I(I+1)$, on the average; this appears to verify for the first time fundamental predictions of Bohr and Mottelson regarding such aligned configurations. The nature of the yrast line suggests the possibility of oblate deformation at large angular momentum.

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Branching Ratio for Radiative Pion Capture with Respect to Absorption of Stopped Negative Pions

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A theory of the branching ratio for radiative pion capture with respect to absorption of stopped negative pions is developed by analogy to the Primakoff theory for the total capture rate of μ^-. It is shown that the systematics of pion absorption predict a linear dependence of the ratio of $(A-Z)/2A$. A comparison to experimental data tends to confirm this prediction.

Viewed as tools for the study of nuclear structure, the processes of muon capture,

$$\mu^- + (N, Z) \to \nu_\mu + (N+1, Z-1)^*,$$

and radiative pion capture,

$$\pi^- + (N, Z) \to \gamma + (N+1, Z-1)^*,$$

are capable of yielding similar information about transitions between ground and excited states. One of the early successes in the field of muon capture was the derivation by Primakoff[1] of the A and Z dependence of the total capture rate. His formula (now generally referred to as a non-energy-weighted sum rule, NEWSR) was derived by invoking closure and has provided an adequate basis for making semiempirical fits to the total capture rates throughout the periodic table. The main assumption of the Primakoff theory is that the transition rate, considered as a function of the final neutrino energy, is strongly peaked around some average neutrino energy. Since the neutrino spectrum is unobservable, this key assumption has no direct experimental support, and, as a result, considerable effort has gone into developing theories where this requirement is relaxed. Thus, in the more recent energy-

