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Second Discontinuity in the Yrast Levels of ^{158}Er†

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Discrete yrast transitions from states with spins up to $30\hbar$ have been observed in ^{158}Er from ^{40}Ar-induced compound-nucleus reactions. A second discontinuity in the level sequence occurs around $I=28\hbar$. Possible causes and implications of this effect are discussed.

For low spin values in the deformed rare-earth nuclei, the lowest-energy state of a given spin (yrast state) is the member of the ground-state rotational band. In some light rare-earth nuclei, there is a discontinuity in this yrast level sequence around spin $I \simeq 14\hbar$ so that the regular increase in the γ-ray transition energies with increasing spin is temporarily reversed. This can be interpreted as a reduction of the rotational frequency and an increase of the moment of inertia. Since the discovery[1] of this "backbending" effect, a considerable amount of experimental data has been accumulated on the properties of collective states[2] with spins up to $I \simeq 20\hbar$ from studies of (HI,xn) reactions and Coulomb excitation. Recent results from continuum γ-ray experiments[3] show that states with $I \simeq 60\hbar$ are formed in Ar-induced compound-nuclear reactions. Although no discrete transitions were observed, the nuclear moment of inertia at these spins was determined to be consistent with the rigid-body value. In the present work we have combined several recently developed techniques to study the discrete transitions from states with $I > 20\hbar$.

We have studied the high-spin yrast levels of ^{158}Er using the reaction ^{122}Sn(^{40}Ar, $4n$). This nucleus was studied previously using ^{4}He, ^{18}O, and ^{32}S beams.[4-6] A backbend was observed at $I=14\hbar$ and levels with spin up to $24\hbar$ were identified. With use of ^{40}Ar as a projectile, the compound nucleus can be formed with higher angular momentum, so that there is a larger population for the higher-spin states. However, because of the larger linear-momentum input, the Doppler broadening of the γ-ray lines becomes more serious.[7] Simple estimates using rigid-rotor $B(E2)$ values indicates that the lifetime of a transition with energy about 700 keV is comparable to the stopping time of the compound nucleus in a thick target. Thus, with a thick target, this γ-ray line will have a width corresponding to the full Doppler shift (2%) of 14 keV. In addition, because of the large angular momentum of the compound nucleus, several reaction channels will be open. Thus it is essential to be able to enhance a particular channel in the experiment.

The experiments were performed with use of the ^{40}Ar beam from the 88-in. cyclotron of the Lawrence Berkeley Laboratory. A self-supporting enriched ^{122}Sn foil of 1 mg/cm^2 thickness was used as a target. The thin target allows the compound nuclei to recoil out of the target and decay in flight, thus avoiding the Doppler broadening from the slowing-down in the thick target. The broadening due to the finite size (acceptance angle) of the detector can be minimized by placing the γ detector at the average recoil direction (0°). However, because of space limitation, the two 40-cm^3 coaxial Ge(Li) detectors used in the γ-γ coincidence measurement were placed at ± 30°. Since there is a rather large difference in the angular momentum deposited in different xn channels, the value of the γ-ray multiplicity can be used to determine the reaction channel to which any transition belongs. A multiplicity filter consisting of six 7.5×7.5-cm^2 NaI detectors

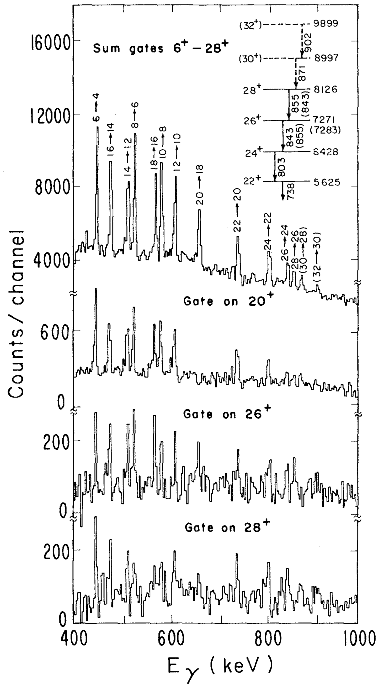

FIG. 1. Coincidence γ-ray spectra from reaction ^{122}Sn(^{40}Ar, 4n)^{158}Er.

TABLE I. Relative intensities and anisotropies for γ transitions of ^{158}Er.

Trans. $I_i \to I_f$	E_γ (keV)	Relative intensity[a]	$\frac{I(0°)}{I(90°)}$
6→4	443	1.00(3)	1.25(7)
8→6	523	1.02(3)	1.17(7)
10→8	579	0.79(3)	1.13(7)
12→10	608	0.67(3)	1.19(8)
14→12	510	0.50(3)	b
16→14	473	0.50(3)	1.12(8)
18→16	566	0.45(3)	1.31(9)
20→18	658	0.46(3)	1.41(9)
22→20	738	0.45(3)	1.54(10)
24→22	803	0.39(5)	c
26→24	843	0.24(4)	1.30(15)
28→26	855	0.22(4)	1.33(15)
30→28	871	0.15(3)	1.18(20)
32→30	902	0.08(3)	•••

[a] For transitions from states with $I \geqslant 14$, the summed coincidence spectra with gates on 6–12 (which have better peak-to-background ratios) are averaged with the singles spectra.

[b] The 90° detector contains a contribution from the 511-keV annihilation radiation.

[c] Since the singles spectra contain a contribution from a contaminating line, only the coincidence data are used.

was used, and the number of NaI detectors firing in coincidence with each event (singles or coincidence) observed in the Ge(Li) detectors was recorded. The 4n reaction was chosen for our study because it has a large cross section at beam energies somewhat above the Coulomb barrier. The use of a low beam energy can reduce the interference from other reaction channels (e.g., deep inelastic reaction); however, the energy must be high enough to bring a large angular momentum into the system. The 166-MeV beam energy was carefully chosen so that the 4n channel had the highest multiplicity among all the xn channels. Therefore by selecting the events with more NaI coincidences, the γ rays from the low-multiplicity channels (e.g., 5n) could be progressively filtered out, even though they were nearly as large as those from the 4n channel in total cross section.

Figure 1 shows some of the γ-γ coincidence spectra where one or more NaI detectors fired ($\geqslant$ onefold coincidence spectra). The yields of these γ rays were measured at 0° and 90° from $\geqslant$ onefold singles spectra. These intensity ratios between the yields at 0° and 90° were found to be consistent with stretched $E2$ decays and are given in Table I together with the intensities. From these (and other) data, the yrast level sequence can be established with reasonable certainty up to $I = 28\hbar$ and tentatively on to $I = 32\hbar$. The transitions are placed in an order which is based on their observed intensities, and since the 843- and 855-keV transitions differ in intensity by less than 10%, the order of these transitions is not completely certain. The coincidence data are not good enough to show that the 871- and 902-keV γ-rays are in coincidence with every lower transition in the yrast sequence, so that these assignments are considered tentative and are shown as dashed lines on the inset to Fig. 1 and on Fig. 2. A second discontinuity in the yrast-level sequence at $I = 28\hbar$ is evident from the close spacing of the $26^+ \to 24^+$, $28^+ \to 26^+$, and $30^+ \to 28^+$ transitions. Even without considering the tentatively assigned $30^+ \to 28^+$ transition, the existence of this discontinuity is clear. Figure 2 shows a plot of the moment of inertia versus the square of the rotational frequency for this level sequence, and in this plot the second discontinuity shows up as a rapid increase of the moment of inertia of the states with spin larger than 26^+. (If the 843- and 855-keV transitions were reversed in order, there

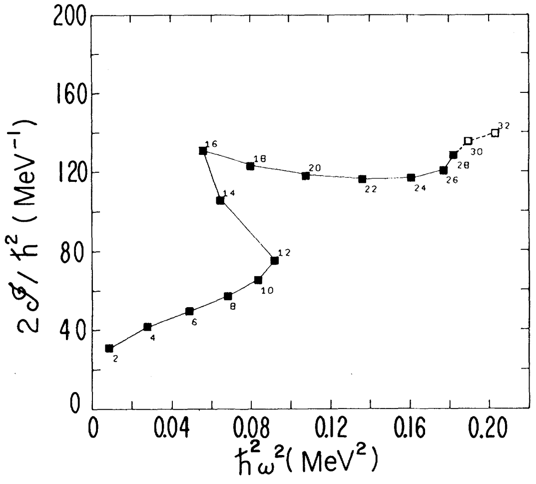

FIG. 2. Plot of the moment of inertia vs the square of the angular velocity for ^{158}Er.

would be a small backbend at this point rather than this increase in moment of inertia.) These two discontinuities may also be affecting the population of the yrast levels, since there appears to be almost no sidefeeding between them ($I = 14$ to $24\hbar$).

Backbending has been shown in several cases to be due to the crossing of a second band below the ground-state rotational band. Three possible explanations have been given for the nature of this second band. They are (1) a shape change of the nucleus,[8] (2) a collapse of the pairing correlation,[9] (3) an algnment of the angular momentum of two high-j nucleons with the rotational angular momentum.[10] Although shape changes have been observed in light Hg isotopes,[11-13] potential-energy calculations[14] suggest that this is not very likely, where the deformation is stabilized by a strong shell effect. It has been suggested[9] that a sudden collapse of the pairing correlation may occur at a critical rotational frequency resulting in the rigid-body moment of inertia. The present data show the rigid-body value (140 MeV^{-1}) is reached after the second discontinuity so that this possibility cannot be ruled out; however, calculations[15,16] suggest that pairing effects do not cause sudden changes in the moment of inertia. It has been shown[17] that the first backbending of the light rare-earth nuclei is probably due to the alignment of a pair of $i_{13/2}$ neutrons. At higher spins, additional pairs of high-j nucleons will tend to be aligned and this might well cause additional discontinuities in the level sequence. For ^{158}Er this second pair would probably be either additional $i_{13/2}$ neutrons or $h_{11/2}$ protons. Since the first backbending is due to alignment, it seems most likely to us that the second discontinuity is also due to this effect.

The alignment of particles breaks the axial symmetry of these prolate-shaped nuclei. It has been pointed out that the liquid-drop model of the nucleus predicts that the shape at higher spin values will be oblate,[18] with all the angular momentum carried by aligned particles. The first backbend seems to be a step directly toward this situation, and if the alignment explanation is correct, the second discontinuity observed here would indicate a second step in this direction. It would be interesting to find out whether this trend continues at still higher spins.

This work has demonstrated the feasibility of observing discrete yrast transitions of spin up to at least $30\hbar$ in (HI,xn) reactions. Three developments have made these high spins accessible. These are (1) ^{40}Ar projectiles to bring in high angular momentum; (2) the elimination of the Doppler broadening by using thin targets and observing in the forward direction; and (3) the enhancement of a particular reaction channel using γ-ray multiplicities. The observed second discontinuity in the yrast levels of ^{158}Er around $I = 28\hbar$ may be due to several possible effects, with alignment of a second pair of particles appearing most likely to us. It will be interesting to find out whether such discontinuities are a general phenomenon and also whether there is a connection between them and the population pattern in (HI,xn) reactions.

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Complexity of the Potential-Energy Surface for Fission of ^{238}U†

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Recent analyses of fission probabilities for ^{238}U in ^{236}U(t,pf) and ^{238}U(γ,f) suggest the possiblity of two distinct second saddle points which provide two independent paths to fission. These two saddle points consist of one which is mass asymmetric and axially symmetric and another which is axially asymmetric and lies ~ 300 keV higher. Potential-energy calculations based on single-particle corrections to the liquid-drop surface corroborate the existence of such a complex structure at the second barrier.

The nucleus ^{238}U provides a unique case for testing the microscopic statistical models which have been used recently[1-3] to fit fission-probability distributions, P_f, and obtain estimates of fission barrier heights. For this nucleus there exists three independent sets of experimental data: (1) ^{236}U(t,pf) measurements[2] which show subbarrier resonance structures, (2) ^{238}U(γ,f) data[4] show subbarrier resonances in the $K=0$, $J^\pi=1^-$ state, and (3) ^{238}U(γ,f) data[5] which give P_f in the 7-11-MeV excitation-energy region.

In a recent paper[3] we have shown that (1) P_f data can be fitted without arbitrary normalization factors if the enhancements[6,7] due to the addition of low-lying collective rotations are accounted for correctly, and (2) for the heavier nuclei, fission at the higher excitation energies is dominated by the second barrier, E_B, even though it may be lower than the first barrier, E_A, by a few hundred keV. For most of the cases studied via ^{3}He reactions[3] we could estimate values of E_A from the behavior of P_f near threshold and E_B from the high-energy results. However, for ^{238}U, E_A and E_B for the $K=0^+$ and 0^- bands can both be determined from fits to the observed resonance structures and, therefore, there are no additional free parameters to be used for an absolute fit to the new high-excitation-energy data.

In this Letter we show that simultaneous analysis of the three sets of data is *not* compatible with the usual assumption that fission of ^{238}U should be governed by passage over an axially deformed first barrier and a mass-asymmetric, axially symmetric second barrier. Instead, an enhance-