Lifetimes for Levels above the "Rotational Phase Change" in ^{158}Er

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Recoil-distance decay curves for ground-band transitions in ^{158}Er were measured using a γ-γ coincidence technique and the reaction ^{130}Te(^{32}S, $4n$)^{158}Er. We find that the mean lifetimes for the 14^+, 16^+, and 18^+ levels are, respectively, 3.0 ± 0.7, 2.5 ± 0.9, and < 2.2 psec. These results are consistent with the rotational model in spite of the severe "backbending" of the level spacings.

Experiments have shown that rotational-energy-level spacings in some rare-earth nuclei exhibit anomalous behavior above spins of $\sim 14^+$.[1-5] One interpretation of the effect attributes it to the sudden change in the moment of inertia which accompanies a phase transition between the superconducting and normal states.[6] Other explanations have been given in terms of the apparent crossing of the ground band with an excited band having a larger moment of inertia.[7,8] In the case of a phase transition one would expect that reduced $E2$ transition probabilities between states in different phases should be severely hindered.[6] However, in the case of band crossing, calculations by Stephens and Simon[8] indicate that $B(E2)$ values in the region of the crossing will be changed only slightly from the rotational values. To test these predictions we have used the Doppler-shift recoil-distance method to measure lifetimes of the 8^+, 10^+, 12^+, 14^+, and 16^+ levels in ^{158}Er, a nucleus in which the effects of the phase transition on the ground-band spacing is particularly marked.[3] Lifetimes to spin 8^+ have been measured by Diamond *et al.*[9]

The recoil distance apparatus used is described by Rud *et al.*[10] The target-stopper distance was monitored on an event-by-event basis during the measurements, and the zero of distance was determined by extrapolation of the 1/capacity versus distance curve to 1/capacity = 0. Data were taken at five target-stopper separations in the range 14–45 μm. The high-spin levels in ^{158}Er were populated in the reaction ^{130}Te(^{32}S, $4n$)^{158}Er using 135-MeV ^{32}S ions from the upgraded Chalk River tandem accelerator. The ^{130}Te targets were prepared by evaporating ~ 1 mg/cm^2 of enriched ^{130}Te onto a ~ 150-μg/cm^2 stretched Al backing. The beam was incident on the Te-coated side of the target foil so as to utilize the maximum available ^{32}S energy and to avoid any possibility of bulk transfer of target material to the lead stopper. De-excitation γ rays were detected in 70-cm^3 Ge(Li) detectors positioned at $+0°$ and $-54°$ to the incident beam. γ-γ coincidences were recorded as four-parameter related address events on magnetic tape (two pulse heights, time, and target-stopper capacity). Examples of the coincidence γ-ray spectra are shown in Fig. 1.

The relative intensities of the ground-band transitions as seen in singles are given in Table I and show that the lower spin states are populated by side feeds as well as by cascades from higher members of the band. Side feeding makes no contribution to the γ peaks in coincidence spectra gated by band members higher than themselves. The decay curves derived from these coincidence data are interpretable in terms of the "singles" decay curve for the gating transition and the mean lives of the intervening levels between the gate transition and the analyzed peak. The greatest simplification results when the gating transition is chosen to be the one immediately preceding the level of interest. Unfortunately, the small number of counts in the $16^+ \to 14^+$, $14^+ \to 12^+$, and $12^+ \to 10^+$ γ peaks in the coincidence spectra led to very noisy decay curves. For each of these cases we have therefore summed the data for all five distances (for example, the third spectrum in Fig. 1) and determined the "stopped" peak intensity γ_s and the total peak intensity $\gamma_s + \gamma_m$ from these summed spectra. The corresponding predicted ratio $\gamma_s/(\gamma_s+\gamma_m)$, for a given level mean life τ, is a weighted mean of the predictions for the five distances involved. We have

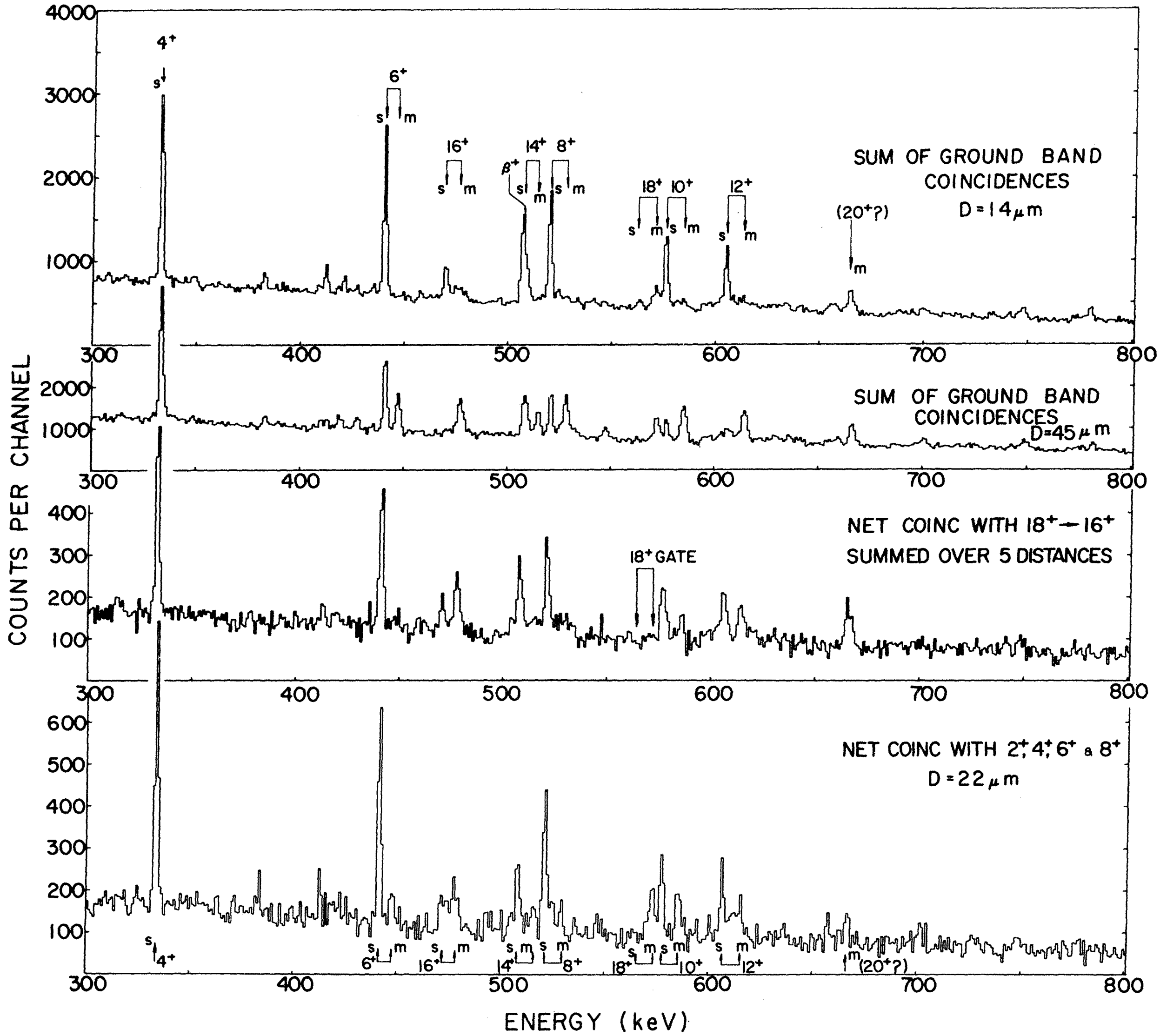

FIG. 1. Sample coincidence spectra at 0° recorded for various plunger-target separations. γ-rays emitted when the recoiling ^{158}Er nuclei were at rest appear in their unshifted position (labeled *s*) while those emitted in flight were shifted by the Doppler effect ($v/c = 1.5\%$) and are labeled *m*. The recoil velocity corresponded to ~4.5 μm/psec.

used the intensity of the $4^+ \rightarrow 2^+$ γ ray as observed at each distance as the weighting factor in deducing the composite ratio. The overlap of the stopped peak of the 510-keV $14^+ \rightarrow 12^+$ transition with annihilation radiation called for special treatment of this case. The intensity of the "stopped" peak was not deduced from the 510-keV peak of the spectrum but was inferred from the fact that the total intensity of the $14^+ \rightarrow 12^+$ transition equals that of each of the lower rotational transitions in the relevant coincidence spectra. The lifetimes obtained for the 16^+, 14^+, 12^+, and 10^+ levels are given in Table I.

Given this knowledge of the 16^+-, 14^+-, 12^+-, and 10^+-level lifetimes, it is possible to deduce qualitative information concerning the side-feed times from decay curves deduced from the singles spectra or from the total coincidence projections. Decay curves from these data are shown in Fig. 2. The lifetimes for side feeding were analyzed with a computer program which calculates decay curves for a cascade with arbitrary side feedings at each step. The solid line through the $16^+ \rightarrow 14^+$ data in Fig. 2 is calculated from the

TABLE I. Summary of lifetimes in ^{158}Er.

Transition	Energy (keV)	Relative Intensity (This expt)	Lifetime τ (ps)	B(E2) $e^2\ 10^{-48}\ cm^{-4}$	B(E2)/Rot
2 → 0	192.7	100 ± 5	433 ± 22[a]	0.55 ± 0.03	1
4 → 2	335.7	100 ± 4	20.8 ± 1.0[a]	0.87 ± 0.04	1.10 ± 0.05
6 → 4	443.8	100	4.0 ± 0.7[a]	1.14 ± 0.19	1.31 ± 0.27
8 → 6	523.8	89 ± 5	1.74 ± 0.70[a]	1.08 ± 0.34	1.17 ± 0.40
			1.60 ± 0.5[c]		
10 → 8	578.9	65 ± 5	1.1 ± 0.5[c]	1.12 ± 0.50	1.20 ± 0.56
12 → 10	608.1	63 ± 4	$\lesssim$ 1[c]	$\gtrsim$ 0.9	$\gtrsim$ 1
14 → 12	510	40 ± 4	3.0 ± 0.7[c]	0.77 ± 0.18	0.80 ± 0.19
16 → 14	473.2	37 ± 4	2.5 ± 0.9[c]	1.35 ± 0.48	1.4 ± 0.35
18 → 16	567	27 ± 3	< 2.2[b,c]	> 0.6	> 0.6

[a]Ref. 9.
[b]The decay curve for the $18^+ \to 16^+$ transition corresponds to this lifetime; this is an upper limit since there will also be a contribution from the "feed time."
[c]This work; see text.

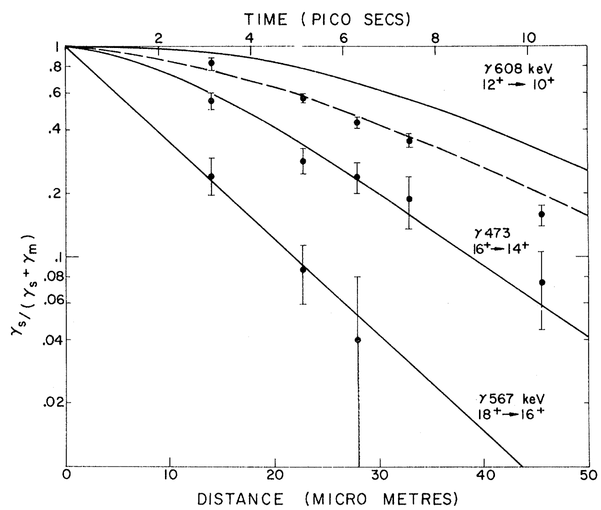

FIG. 2. Recoil-distance decay curves for high-spin states in ^{158}Er. The data shown for the $18^+ \to 16^+$ and $16^+ \to 14^+$ curves were derived from the total coincidence projection, whereas the $12^+ \to 10^+$ data were derived from a singles spectrum. The solid line through the $18^+ \to 16^+$ is a simple exponential decay curve corresponding to $\tau = 2.2$ psec. The $16^+ \to 14^+$ curve is a two-parameter fit assuming a 2.2 psec feed through the 18^+ level and $\tau(16^+) = 2.5$ psec. The solid curve which falls above the $12^+ \to 10^+$ data is obtained when side feeding is ignored. Using side feeds inferred from a smoothed plot of γ intensity versus spin and side-feed lifetimes of 1.5 psec (to 14^+) and 1.6 psec (to 12^+), we obtain the dashed curve which fits the data well.

lifetime values of Table I, $\tau(18^+$ plus feed$) = 2.2$ psec and $\tau(16^+) = 2.5$ psec and neglects side feeding. The agreement obtained may indicate that the time distribution for side feeding into the 16^+ state is very similar to the distribution arising from the 18^+ state or, alternatively, that the amount of this side feeding is very small. Lower in the band, side feeding results in a faster decay curve than that predicted from the lifetimes in Table I for a simple cascade down the band. This is illustrated in Fig. 2 by the solid line for the $12^+ \to 10^+$ transition. We find that the $12^+ \to 10^+$ and $10^+ \to 8^+$ results can be reproduced simultaneously by assuming side-feed intensities (as inferred from a smooth curve through the intensities of Table I plotted against spin I) and lifetimes of 1.5 psec into the 14^+, 1.6 psec into the 12^+, and 2.4 psec into the 10^+ levels. It is difficult to assess the uncertainties in these quantities. Because of the overlap of the "stopped" peak of the $14^+ \to 12^+$ transition and annihilation radiation in the spectra we have not attempted an analysis of the $14^+ \to 12^+$ decay curve.

In summary, the mean lifetime for side feeding to the 12^+ and 10^+ levels is ~1–3 psec, which is appreciably faster than feeding down the rotational band from spin 18^+. However, this is much slower than would be expected for ~12-MeV direct dipole transitions to the rotational level from the region of the continuum populated following the last neutron evaporation. The absence of fast side feeding to the 10^+ and 12^+ states suggests that at the peak of the $4n$ reaction the probability for entering ^{158}Er with initial angular momentum in the range $(9-13)\hbar$ is small, presumably because of the preferential evaporation of a fifth neutron in low-angular-momentum collision.[11]

If one interprets the "backbending" of the curve of the nuclear moment of inertia versus the square of the rotational frequency for the ^{158}Er ground band (Ref. 3) as indicative of the nucleus undergoing a phase change, then the 18^+ and 16^+ levels should belong to the "normal phase," whereas the 12^+ level (and down) should belong to the "superconducting phase." One would expect that the $B(E2;16^+\to 14^+)$ and $B(E2;14^+\to 12^+)$ would be inhibited relative to the rotational value, but this is not the case according to the present measurements. We hope that these results will stimulate detailed calculations of $B(E2)$ values in the neighborhood of the "phase change" in ^{158}Er.

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Mixing of Two-Particle, Two-Hole States in ^{208}Po†

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States of ^{208}Po up to an excitation energy of 2 MeV have been investigated via the two-neutron pickup reaction ^{210}Po$(p,t)^{208}$Po. We have extracted angular distributions for the five observed states of ^{208}Po and have made J^π assignments. These states are discussed in terms of the excitation of simple modes observed in ^{206}Pb and ^{210}Po. Matrix elements have been extracted for the interaction between the two-neutron-hole 2^+ excitations and the two-proton-particle 2^+ excitations and compared with simple theoretical estimates.

A well-known feature of the excitation spectra of spherical even-even nuclei is the low-energy collective 2^+ state. It is usually the first excited state and is strongly excited in both inelastic scattering and two-nucleon transfer reactions. Its properties have been discussed extensively in the literature[1,2] both in terms of microscopic wave functions resulting from some residual interactions and also as an elementary excitation mode or "building block" of the nuclear excitation scheme. Both these approaches have been applied successfully in the lead region. In the present paper we address ourselves to the question of what role the neutron-proton force plays in the generation of these states. In the vicinity of a doubly magic nucleus, as ^{208}Pb, some of the elementary excitations may be characterized as specifically particle or hole type as well as neutron or proton type, and the question becomes, to what extent are neutron- and proton-type build-