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[8] For comparison with our hadronic data the $\psi \to \mu\mu$ cross section is 1.8 ± 1.0 nb/nucleon with $a = 3$ GeV^{-2} in Eq. (1). Alternatively, with $a = 1$ GeV^{-2} our hadronic cross section upper limits increase by a factor of $\sim 2.1 \pm 0.2$.

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[10] For comparison two ~ 3 standard deviation peaks are observed: $\bar{p}p$ at 2.66 GeV and $K^-\pi^+$ at 2.42 GeV.

[11] Cherenkov momentum and geometrical cuts, as well as the thinner target used in the hadronic data, result in improved mass resolution with respect to the 2 μm data.

[12] This corresponds to a probability of occurrence of $6.34 \times 10^{-3}\%$ times ~ 500 data bins.

Coulomb Excitation into the Backbend Region of ^{164}Er†

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It has been demonstrated that multiple Coulomb excitation is an effective method for studying levels in the backbending region. Members of the ground band above the backbend in ^{164}Er have been excited. The ground-band $B(E2)$ values obey the rigid-rotor relation within ± 25%. A two-band mixing analysis shows that the intersecting bands have remarkably small interaction matrix elements at the backbend, i.e., < 40 keV. This weak band interaction is expected in the rotation-alignment model.

The discovery[1] of backbending (an anomalous behavior of the moment of inertia at high spin in nuclear rotational bands) has stimulated an intensive theoretical investigation of this phenomenon.[2-5] Present experimental evidence[3,4] suggests that backbending is caused by the intersection of the ground-state rotational band with a second rotational band possessing an appreciably larger moment of inertia. Two possibilities have emerged for the most likely nature of this second band. The Coriolis antipairing[6] model considers it to be a band for which the pairing has collapsed while the rotation-alignment[5] model attributes the band to two quasiparticles which are aligned with the rotating core by the Coriolis force. Observation of additional levels and a determination of the interaction matrix elements between the intersecting bands can shed considerable light on the structure of the bands.

Previously, backbending has been studied exclusively using (HI,xn) reactions to populate highly excited high-spin states which subsequently deexite by γ-ray cascades into the yrast sequence of states. In contrast, multiple Coulomb excitation specifically excites those collective bands which are strongly coupled to the ground state and thus is a complementary probe of the backbending phenomenon. In addition, Coulomb excitation can be used to study neutron-rich nuclei which cannot be reached by (HI,xn) reactions. The present paper describes the first case where states through a reasonably sharp backbend region have been Coulomb excited. The nucleus ^{164}Er has been studied because the high-spin

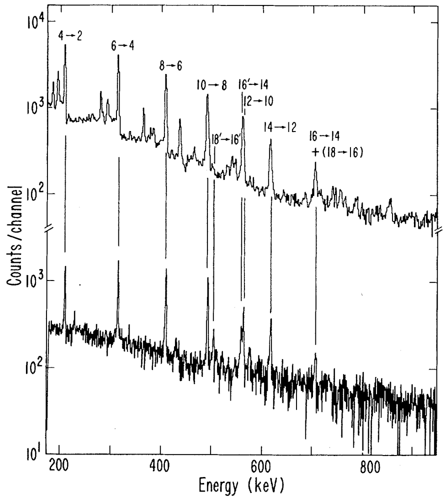

FIG. 1. Coincidence γ-ray spectra for ^{164}Er. The upper spectrum is for the excitation of ^{164}Er by ^{136}Xe ($E_{\mathrm{Xe}}=612$ MeV). The lower spectrum is for the sum of the coincidence spectra gated by the transitions from states with spin $\geqslant 12$ fed by the reaction ^{164}Dy(α, $4n$) ($E_\alpha=51$ MeV).

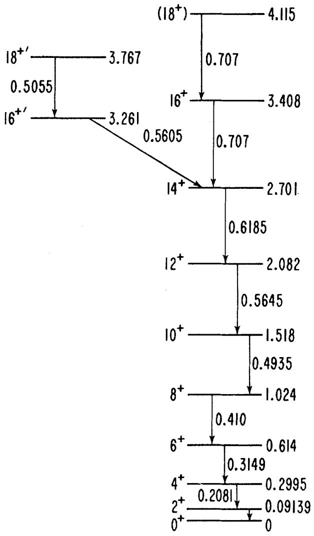

FIG. 2. Level scheme of ^{164}Er.

yrast states up to spin 18^+ have been seen previously[7,8] via the reaction ^{164}Dy(α, $4n$) and because ^{164}Er is one of the few stable isotopes known to backbend sharply.

Beams of 612- and 547-MeV ^{136}Xe ions from the Lawrence Berkeley Laboratory (LBL) Super-HILAC were used to bombard a 1.34-mg/cm^2 self-supporting metallic foil of ^{164}Er. The isotopic enrichment was 73.6%. Three silicon detectors were used to detect scattered Xe ions at angles of 65°, 77°, and 90° in coincidence with de-excitation γ rays observed in a Ge(Li) detector located at $-30°$ to the incident beam. The Ge(Li) detector was placed in the average recoil direction where the Doppler shift is a maximum, 8%, and the Doppler broadening is a minimum. A γ-ray energy resolution of $\leqslant 1\%$ full width at half-maximum (FWHM) was achieved. Four 7.6-cm by 7.6-cm NaI detectors, serving as a multiplicity filter, were placed around the target. The number of NaI detectors in coincidence was used to determine the multiplicity of each γ-ray transition observed in the Ge(Li) spectrum in coincidence with the scattered ions. The dependence of the γ-ray yields on the multiplicity distribution, on the bombarding energy, and on the projectile scattering angle provided three independent measures of the location of each de-excitation γ transition in the nuclear decay scheme. A γ-ray spectrum is shown in the upper section of Fig. 1. The unmarked γ-ray lines are due to Colomb excitation of the ^{166,168}Er contaminants and also to excited target nuclei which recoil into the silicon detectors and exhibit a small Doppler shift.

The reaction ^{164}Dy(α, $4n$)^{164}Er was studied, in addition to the Coulomb excitation, to search for weak branching at the backbend. A 10-mg/cm^2 self-supporting metallic foil, enriched to 93% in ^{164}Dy, was bombarded with a 51-MeV α-particle beam from the LBL 88-in. cyclotron. Two 50-cm^3 coaxial Ge(Li) detectors, with energy resolution of 2.3-keV FWHM at 1.1 MeV, were used and both singles and coincident γ-ray spectra were accumulated. The lower part of Fig. 1 shows the coincidence spectrum gated by transitions originating from states with $I \geqslant 12$.

The decay scheme derived from the present work is shown in Fig. 2. The yrast sequence up to spin $18^{+\prime}$ has been seen in earlier work where spin assignments were made on the basis of γ-ray angular-distribution data.[7,8] The present work supports these previous results. In addition, the reaction ^{164}Dy(α, $4n$) clearly shows that an incompletely resolved 707-keV self-coincident doublet feeds into the yrast 14^+ state. This unresolved doublet, which has not been seen previously, was strongly excited by Coulomb excitation suggesting $E2$ character. The observed yield of this doublet is 1.5 times the calculated yield for Coulomb excitation of the ground-band 16^+ state but is in agreement with the predicted sum of the yields of the $18^+ \to 16^+$ and $16^+ \to 14^+$ transitions if rigid-rotor $B(E2)$ values are assumed. Thus this doublet is presumed to de-excite the 18^+ and 16^+

members of the ground band. Neither the $14^{+\prime}$ nor the $20^{+\prime}$ members of the second band was located in the present work. However, the transitions involving these states could have been masked by transitions in ^{162}Er excited by ^{162}Dy(α, 4n) since the 506-keV ($10^+ \rightarrow 8^+$) transition in ^{162}Er and the ($18^{+\prime} \rightarrow 16^{+\prime}$) in ^{164}Er coincide.

Above the $14^+ \rightarrow 12^+$ transition, the discontinuity in the spacing between the ground-band transition energies is a striking feature of the Coulomb-excitation spectrum shown in Fig. 1. The measured yields of these ground-band transitions were compared with calculations using the Winther-deBoer[9] semiclassical Coulomb-excitation code. An axially symmetric rigid rotor was assumed with $\langle 0 \| M(E2) \| 2 \rangle = 2.315\ e \cdot \mathrm{b}$ taken from an α-particle Coulomb excitation measurement,[10] and with $\langle 0 \| M(E4) \| 4 \rangle = 0.2\ e \cdot \mathrm{b}^2$ taken from systematics.[11] The ratio of experimental yields for adjacent ground-band transitions agreed with the calculated ratio to better than ± 15%. The systematic uncertainties involved in using this code are expected to be less than ± 20% from comparison with experimental yields for high-spin ground-band states in other strongly deformed nuclei.[12,13] Thus the ground-band $B(E2)$ values obey the rigid-rotor relation to within $\leq 25\%$. Unfortunately the Coulomb excitation of the second band was difficult to observe because the $16^{+\prime} \rightarrow 14^+$ transition was unresolved from the strong $12^+ \rightarrow 10^+$ transition and the yrast $18^{+\prime} \rightarrow 16^{+\prime}$ transition is predicted to be weak. The Coulomb excitation data places an upper limit on the ratio $B(E2; 14 \rightarrow 16')/B(E2; 14 \rightarrow 16)$ of ≤ 0.4. On a two-band mixing picture this ratio should be the same as the ratio $B(E2; 16' \rightarrow 14)/B(E2; 16' \rightarrow 14')$ if both bands have the same intrinsic quadrupole moment. This second ratio is given by the branching ratio for de-excitation of the $16'$ state. Systematics would suggest that the $16' \rightarrow 14'$ transition energy falls between 380 and 480 keV. No such transition was observed and the upper limit for branching to a $14^{+\prime}$ state is ≤ 0.25 from the reaction ^{164}Dy(α, 4n) data. This sets a lower limit of $B(E2; 16' \rightarrow 14)/B(E2; 16' \rightarrow 14') \geq 0.5$.

A conventional backbending plot of these results is shown in Fig. 3. The $N = 96$ isotones ^{166}Yb, ^{168}Hf, and ^{170}W also exhibit very similar backbending and the upper band has about the same moment of inertia and excitation energy in all these nuclei.[14] Below the backbend the moment of inertia in the ground band increases slightly with increasing spin, presumably due to the influence of Coriolis antipairing.

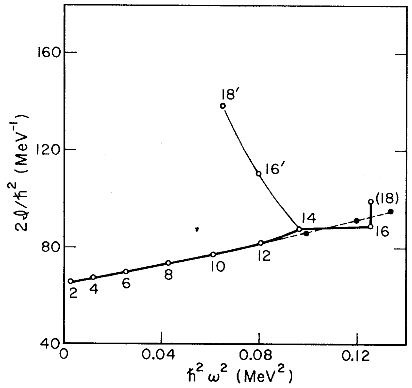

FIG. 3. Plot of the moment of inertia versus the square of the angular velocity for ^{164}Er. The dashed line indicates a smooth extrapolation of the line through the lower-spin states.

The ratio of the intraband to interband $B(E2)$ values at the band intersection directly determines the interaction strength when only two bands are interacting, provided that the level energies are known and the bands have the same intrinsic quadrupole moments. The Coulomb-excitation and branching-ratio data suggest that the ratio $B(E2; 16' \rightarrow 14)/B(E2; 16' \rightarrow 14') \approx 0.45$ which leads to an average interaction matrix element of 38 keV for these states if the splitting of the 14^+ states is 130 keV. In addition, the unperturbed ground-band 14^+ and 16^+ states fall on an extension of the line through the lower spin states on a backbending plot, as indicated by the dashed line in Fig. 3, provided that the interaction matrix elements are taken to be 38 keV. This interaction predicts a 24% reduction in the ratio $B(E2; 16 \rightarrow 14)/B(E2; 14 \rightarrow 12)$ for the ground band which is within the experimental limit given by the Coulomb-excitation yields. The γ-ray branching ratio at the backbend has been measured[15,16] in two other nuclei, the $N = 90$ isotones ^{154}Gd and ^{156}Dy. A similar analysis gives an average interaction matrix element for the 16^+ and 18^+ states of 23.5 ± 1.5 keV in ^{154}Gd and 8.5 ± 1.5 keV for the 16^+ state in ^{156}Dy which is consistent with the values previously reported.[15,16]

The energy for the 18^+ state given by the smooth extrapolation in Fig. 3 lies 27 keV above the experimental energy. The two-quasiparticle-plus-rotor model suggests additional bands occur in this energy region and the above shift could be due to the intersection of the ground band with one of these additional bands. Such behavior would result in a rapid loss of identity of the ground band at higher spin values.

Band-interaction matrix elements of less than 40 keV at the backbend are remarkably small, i.e., they are nearly two orders of magnitude smaller than might be expected for Coriolis matrix elements at these spins. However, this behavior can be understood in the rotation-alignment model. Calculations with the two-quasiparticle-plus-rotor model[5,17] show that the aligned two $i_{13/2}$ quasineutron eigenfunctions for the yrast states become localized around $J = 12$ and $R = I - 12$ with increasing spin I. On the other hand the zero-quasiparticle ground band has $I = R$ for a fully paired state. The Coriolis force does not couple states with differing core rotation R and thus the two bands interact only via the overlap of weak components in the wave functions. This overlap becomes progressively smaller with increasing spin due to the increased localization in R space of the aligned states. Two calculations within this model[5,17,18] suggest that the interaction is $\leqslant 140$ keV and is nearly constant for $10 < I < 22$. However, the assumptions made in these calculations may not be adequate for accurately reproducing the interband interaction strength. A more complete Hartree-Fock-Bogoliubov calculation by Mang[19] also predicts a small interaction strength.

This first example of Coulomb excitation through a known backbend illustrates the power of this technique to excite high-spin levels and provide the information needed to establish their relationship to the ground band. In addition, it can be used on many nuclei that cannot be excited by (HI,xn) reactions. The ground-band $B(E2)$ values have been measured in ^{164}Er and follow the rigid-rotor relation to within ± 25% throughout the backbend. The band intersecting the ground band in ^{164}Er is closely similar to the bands seen in ^{154}Gd and ^{156}Dy which shows that this type of behavior is not peculiar to the $N = 90$ region. The $B(E2)$ data and the level energies in all three nuclei are consistent with a two-band mixing model having a remarkably weak interaction strength at the backbend, i.e., < 40 keV. This behavior is reasonably well described by the rotation-alignment model.

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