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Complex band interactions in ^{170}Er

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Inelastic excitation of ^{170}Er by a ^{238}U beam, studied at near-barrier energies, has led to the observation of unusual features in rotational bands built on low-lying vibrations. The population of the high-spin members of the $K^{\pi}=0^{+}$, β-vibrational band is enhanced due to mixing with the $K^{\pi}=2^{+}$, γ-vibrational band at spin 4^{+}. Strong mixing of the $K^{\pi}=0^{+}$ band with a rotationally aligned 2 qp band results in this band losing its β-vibrational character and in a rapid gain in spin alignment leading to a crossing with the ground-state band between spins 20^{+} and 22^{+}. The low-lying $K^{\pi}=3^{+}$ band also is populated. It subsequently decays to both the γ-vibrational and the ground-state bands. The occurrence of appreciable K-forbidden $E2$ transitions from the $K^{\pi}=3^{+}$ to the ground-state band is attributed to mixing with the $K^{\pi}=2^{+}$ band, caused by the interaction between the quadrupole γ-vibrational and the hexadecapole vibrational motions.

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Two low-lying quadrupole vibrational modes of motion, important in deformed nuclei, are ascribed to β and γ vibrations. There is considerable and compelling evidence for the presence of low-lying γ-vibrational collective excitations in deformed nuclei. In contrast, experimental evidence for the low-lying β-vibrational mode is sparse and often ambiguous. In ^{170}Er both the β and γ vibrations are located at nearly the same excitation energy [1], making this nucleus an ideal case to study the β-vibrational mode of motion. In addition, low-lying octupole and hexadecapole vibrational bands also have been identified in ^{170}Er. The closeness in the phonon excitation energies associated with all of these collective modes provides an opportunity to study possible second-order interactions among them. Measurements of these second-order interaction strengths can help elucidate the validity of collective model descriptions and the microscopic structure underlying these low-lying excitations.

The present paper describes a study of the inelastic excitation of ^{170}Er targets, with thickness 320 to 540 μg/cm^2, by a $E_{\mathrm{lab}}=1358$ MeV ^{238}U beam provided by the ATLAS facility at the Argonne National Laboratory. The bombarding energy was chosen to optimize inelastic excitation as well as to provide favorable Q-matching conditions for nucleon-transfer reactions in order to populate neutron-rich nuclei. The latter aspect is not the focus of this paper. The present experiment exploited the combination of the 4π heavy-ion detector array, CHICO [2,3], for the kinematics measurement, and Gammasphere [4], which provides nearly 4π coverage, for γ-ray detection. The potential of this technique was shown earlier in the case of ^{162}Dy populated by inelastic excitation using ^{118}Sn at near-barrier energies [5] where the high-spin structure of the excited bands was extended considerably. In the present experiment, scattering angles of both the projectilelike and targetlike nuclei, and their time-of-flight difference, were measured by the highly segmented parallel-plate avalanche detector array, CHICO. This detector covers scattering angles from 20° to 85° and 95° to 168° relative to the beam axis and an azimuthal angle totaling 280° out of 360°. Valid events required the coincident detection of both scattered nuclei plus at least two γ rays detected by the 100 Compton-suppressed Ge detectors of Gammasphere. A total of 2.4×10^{8} events were collected in about three days with an average beam intensity of about 0.5 particle nA; about 36% of these events had a coincident γ-ray fold of 3 or more.

Reconstruction of events from the measured two-body kinematics allows the determination of the masses of the reaction products, the velocity vectors, and the reaction Q value. CHICO achieved an angular resolution of $\approx1°$ in θ and 9° in ϕ and a time resolution of ≈500 ps, leading to a mass resolution, $\Delta m/m$, of about 5%, which is similar to the resolution obtained previously [2,6,7]. This mass resolution is sufficient to distinguish projectilelike from targetlike nuclei and appropriate Doppler-shift corrections for the detected γ rays were applied accordingly. The typical energy resolution for the total Doppler-corrected γ-ray spectrum is about 1.3% for a 1 MeV γ ray using the centroid angle of the individual Ge detectors. This resolution improved to 1.1% by utilizing the side-channel energy of individual Ge detectors to better locate the interaction region in the Ge crystals [8]. Shown in Fig. 1 are the γ-ray spectra, Doppler-shift corrected for either the targetlike or projectilelike nuclei detected near the grazing angle. The deexcitation γ rays from both reaction products are clearly resolved from each other.

Both one- and two-neutron transfer channels were observed in addition to the dominant inelastic channel dis-

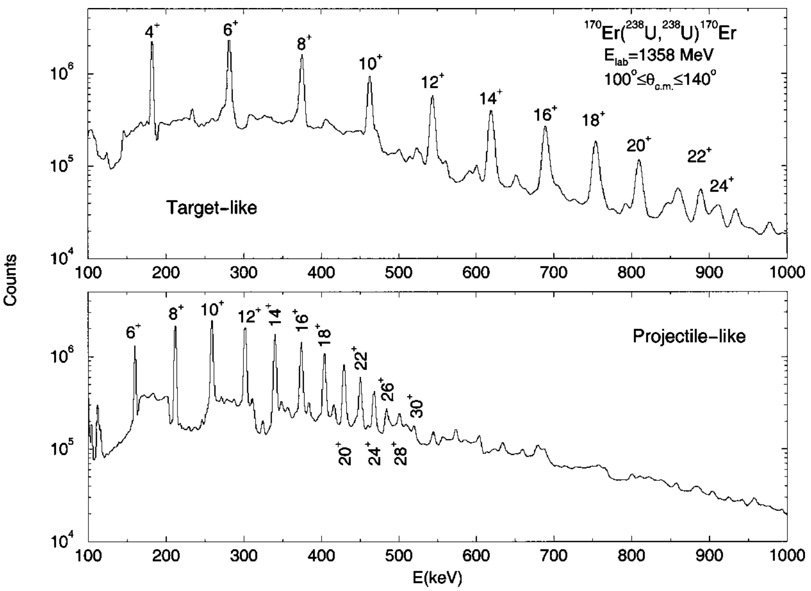

FIG. 1. Doppler-shift corrected γ-ray spectra for the projectilelike nuclei (lower panel) and the targetlike nuclei (upper panel). The labeled peaks are the $I\rightarrow(I-2)$ transitions for the inelastic channel.

cussed in this paper. For example, two unassigned rotational bands, observed previously in experiments with a ^{209}Bi beam on a thick ^{238}U target [9], were positively assigned here to ^{237}U through their correlation with transitions of ^{171}Er, the reaction partner in the one-neutron transfer channel. The two-neutron transfer channel leading to ^{172}Er was populated with a probability of about 1.4% with respect to the inelastic channel for $110° < \theta_{\rm c.m.} < 140°$. The advantage of using a ^{238}U beam is illustrated in this case by the fact that this two-neutron transfer cross section is about five times larger than that measured in the same scattering angular range for the reaction ^{118}Sn(^{164}Dy,^{166}Dy)^{116}Sn. This is due to a less favorable ground-state Q value in the latter case [6].

For the inelastic channel, the ground-state band in ^{170}Er was extended from spin 12^+ [10] up to 26^+ at 7531.8 keV, while states with spin up to 19^+ in the $K^\pi=2^+$, γ-vibrational band, and 22^+ in both the first excited $K^\pi=0^+$, presumed β-vibrational band, and the $K^\pi=3^+$ bands were populated. All the transitions and level placements were deduced from coincident events with at least three γ rays. The spins and parities were straightforward to assign because Coulomb excitation selectively populates collective states of natural parity via $E2$ transitions, multiple decay transitions were observed for many excited states, and interacting states must have identical spin and parity.

The deduced level scheme is shown in Fig. 2. The summed coincidence γ-ray spectrum double gated on the ground-state band transitions of ^{170}Er, shown in Fig. 3, has one notable feature: unusual gaps occur in the transition energies between states with spin 20^+, 22^+, and 24^+. Figure 4 shows the moments of inertia for the ground-state, β-vibrational, γ-vibrational, and $K^\pi=3^+$ bands.

The first excited $K^\pi=0^+$ band exhibits a rather unusual and intriguing behavior. This band has been interpreted to be the β-vibrational band, but the transition strength $B(E2;0_g^+\rightarrow2_\beta^+)=0.28$ W.u. [1] indicates that the β-vibrational strength is weak: it corresponds to only 8% of the γ-vibrational $B(E2;0_g^+\rightarrow2_\gamma^+)$ strength. The population of this band is complicated by strong mixing with the $K^\pi=2^+$, γ-vibrational band at spin 4^+. This mixing is inferred from (a) an irregularity in the moment of inertia for both the excited $K^\pi=0^+$ and 2^+ bands at spin 4^+ (see Fig. 4), as well as from (b) the strong population of the $K^\pi=0^+$ band. Three-band (ground-state, β-, and γ-vibrational) mixing calculations were performed using identical in-band intrinsic matrix elements of $\langle E2\rangle=2.44$ e b [1] and interband intrinsic matrix elements of 0.098 and 0.24 e b for the transitions between the β-vibrational and the ground-state bands, and between the γ-vibrational and the ground-state bands, respectively. The latter values were derived from the interband transition matrix elements assuming first-order band mixing. The intrinsic $E2$ matrix elements coupling the β and γ bands was taken to be zero since there should be no first-order coupling. Note that a value of $+1.7(8)$ [11] was adopted for the $E2/M1$ mixing ratio of the $2_\beta^+\rightarrow2_g^+$ transition in the present work because it is consistent with our data for the higher spin members. The major components of the wave function for the 4^+ state of the excited $K^\pi=0^+$ band were determined to be $-0.63|4_\gamma\rangle_{\rm unpert}+0.77|4_\beta\rangle_{\rm unpert}$ to reproduce the observed branching ratios. This large mixing is mainly due to an accidental degeneracy rather than to a strong interaction. Assignments, made previously [1], for states above spin 2^+ to both the excited $K^\pi=0^+$ and 2^+ bands have been modified in this work based on this mixing, the systematics of the moments of inertia, and their interband decay branchings to the ground-state band. The interaction matrix element was determined to be about $+10$ keV for the coupling between the β- and γ-vibrational motions at spin 4^+. This is comparable to the strength (≈-12 keV at spin 4^+) for the coupling between the β vibrational and the rotational motion. The strong mixing between these two 4^+ states is further supported by the fact that the $E1$ hindrance factors for the decay of the 4^- state at 1268.6 keV are nearly the same to both 4^+ states.

Another important feature of this excited $K^\pi=0^+$ band is that the moment of inertia increases rapidly above spin 12^+

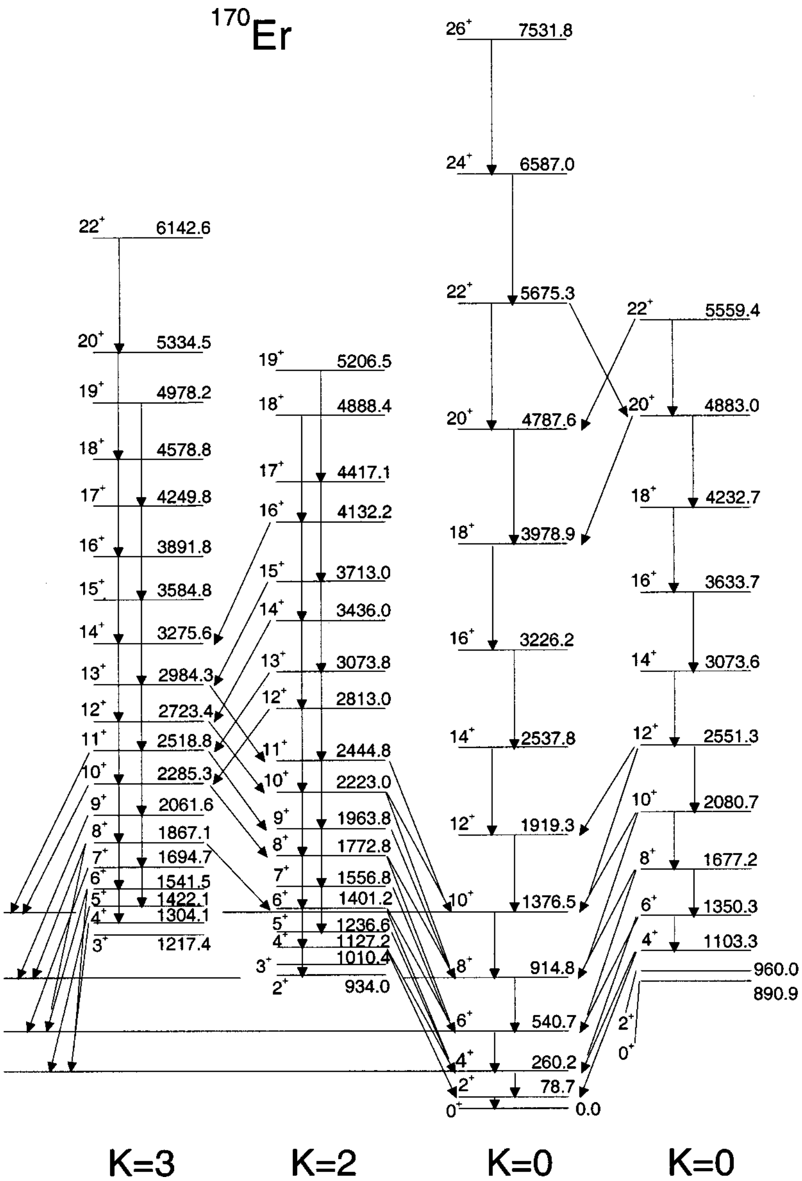

FIG. 2. Partial level scheme of (from left to right) the $K^{\pi}=3^{+}$, γ-vibrational, ground-state, and β-vibrational bands for ^{170}Er. The energies are labeled in keV.

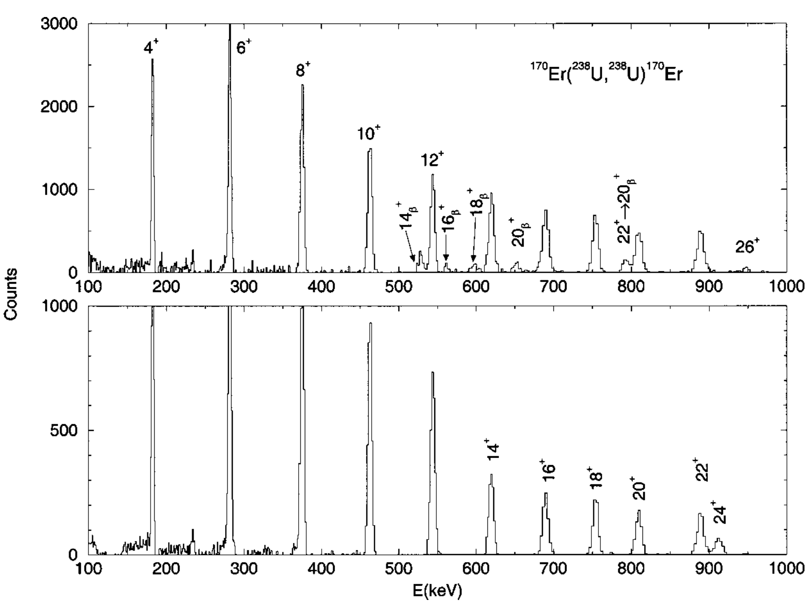

FIG. 3. Gated coincident γ-ray spectra for ^{170}Er. The lower spectrum is the summed double-gated γ-ray spectrum on the ground-state band transitions with spin 14^{+}, 16^{+}, 18^{+}, and 20^{+}. The upper spectrum shows the two decay branchings for the spin 22^{+} state at 5675.3 keV obtained by gating on the $24^{+}\rightarrow 22^{+}$ transition.

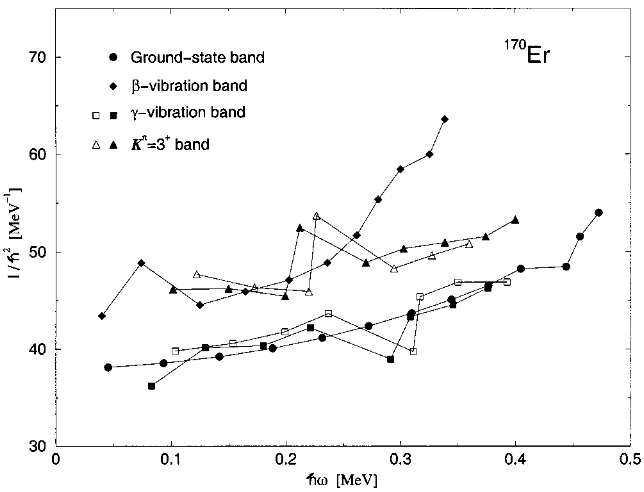

FIG. 4. The moments of inertia as a function of rotational frequency for the ground-state, β-vibrational, γ-vibrational, and $K^\pi=3^+$ bands. Level repulsion is visible at spin 4^+ for the β- and γ-vibrational bands and at spin 22^+ for the ground-state and the excited $K^\pi=0^+$ bands. The level repulsion between the $K^\pi=2^+$ and $K^\pi=3^+$ bands at spins 12^+ and 13^+ also is visible. The filled symbols correspond to the even-spin states and the open ones to the odd-spin members of a given band.

causing it to become yrast at spin 22^+. The wave function for the spin 20^+ level in the ground-state band was determined to be $-0.96|20_g\rangle_{\rm unpert}+0.29|20_{K=0'}\rangle_{\rm unpert}$ from two-band mixing calculations. Mixing components of the same order were found for the spin 22^+ states. The interaction matrix element between the ground and excited $K^\pi=0^+$ bands is ± 31 keV, as determined from the measured decay branching ratios for the spin 22^+ state at 5675.3 keV according to the prescription in Ref. [12]. This interaction matrix element is significantly weaker than the ≈ 200 keV obtained by extrapolation of the interband transitions between the lower spin members of the first-excited $K^\pi=0^+$ band and the ground-state band. The observed behavior of this band, from the band-head to the crossing with the ground band, provides evidence for a strong interaction between the β-vibrational and the rotationally aligned *S* bands. Weak interactions between the *S* band and both the β-vibrational and the ground-state bands have been observed in ^{154}Gd [13,14] and ^{156}Dy [15,16], in contrast to the strong interaction observed in ^{170}Er. Evidence for a similar type of band crossing in ^{174}Hf was presented in Refs. [17,18].

Another surprising observation of this work is the appreciable population of the $K^\pi=3^+$ band at 1217.5 keV [1] and its subsequent decay to both the γ-vibrational and the ground-state bands. Since the dominant excitation path in Coulomb excitation is via $E2$ transitions, it is difficult to explain the population of the $K^\pi=3^+$ band without invoking a *K* mixing scheme. Similar low-lying $K^\pi=3^+$ bands have been identified in the isotones ($N=102$) ^{172}Yb [19] and ^{174}Hf [20]. The strong $E4$ strength to the 4^+ state of the $K^\pi=3^+$ band in ^{172}Yb, measured by α inelastic scattering [21], points to the importance of collective hexadecapole vibrational motion. This hexadecapole collectivity is likely to be responsible for the existence of the low-lying $K^\pi=3^+$ band in ^{170}Er. The level energies, transition intensities, and gamma decay of the $K^\pi=3^+$ band provide compelling evidence for sizable mixing of the $K^\pi=2^+$ and 3^+ bands. The level repulsion between these bands is clearly visible in Fig. 4 for both spins 12 and 13. The assignment for states above 10^+ to both the $K^\pi=2^+$ and 3^+ bands is not dictated by the transition intensity, because of the strong mixing at spin 12^+, but rather by the systematics of the moments of inertia shown in Fig. 4. For instance, the cross-band transitions for both 12^+ states are stronger than the in-band transitions. The decay branching ratios between the in-band transition and the interband transition for the spin 10^+ level at 2285.3 keV and 12^+ state at 2813.0 keV were used in two-band mixing calculations to establish that the interaction matrix element between the $K^\pi=2^+$ and 3^+ bands is ± 31 keV, following the prescription of Ref. [12]. The components of the wavefunction for the 12^+ state in the $K^\pi=2^+$ band were determined to be $0.71|12_\gamma\rangle_{\rm unpert}+0.70|12_{K=3}\rangle_{\rm unpert}$, consistent with strong mixing. The interaction strength between the γ-vibrational and hexadecapole bands is relatively weak compared to the interaction between the γ-vibrational and the ground-state bands. The latter interaction matrix element is extrapolated to be ≈ 200 keV from the decay of the 2^+ state of the γ-vibrational band. The relative $B(E2)$ ratio between the interband transition with $\Delta I=0$, leading to the ground-state band, and the in-band transitions for the $K^\pi=3^+$ band, increases eighteenfold from 0.00026 for the 6^+ state to 0.0047 for the 10^+ level. The latter number is about 60% of the corresponding ratio for the 10^+ state at 2223.0 keV in the $K^\pi=2^+$ band. The occurrence of sizable *K*-forbidden $E2$ transitions between the $K^\pi=3^+$ and the ground-state bands also is attributed to *K* mixing. The observed behavior of the $K^\pi=2^+$ and 3^+ bands provides strong evidence for an interaction between the quadrupole γ-vibrational and the hexadecapole vibrational motions.

In summary, the reaction between the two well-deformed nuclei ^{170}Er and ^{238}U, has been studied at near-barrier energies by combining 4π coverage for both particle and γ-ray detection to unambiguously identify the deexcitation γ rays from either projectilelike or targetlike nuclei. In addition to the inelastic channel, both one- and two-neutron transfer channels were identified in this experiment. The inelastic excitation of ^{170}Er has resulted in the observation of new spectroscopic features and complex band interactions in ^{170}Er. Among those is the strong population of the first excited $K^\pi=0^+$, β-vibrational band, due to strong mixing with the γ-vibrational band. This first excited $K^\pi=0^+$ band gains spin alignment faster than the ground band because of strong mixing with the rotationally aligned two-quasiparticle band and it becomes yrast at spin 22^+. Another interesting feature is the appreciable population of the low-lying $K^\pi=3^+$ hexadecapole vibrational band due to its mixing with the quadrupole γ-vibrational band. The weakness of the interaction strength between the β- and γ-vibrational motions and between the quadrupole and hexadecapole vibrational motions ensures that their interactions are of second order in nature and that the collective band classification presented remains valid.

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