

Complex band interactions in ^{170}Er

C. Y. Wu, D. Cline, M. W. Simon, and R. Teng

Nuclear Structure Research Laboratory, University of Rochester, Rochester, New York 14627

K. Vetter

Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720

M. P. Carpenter, R. V. F. Janssens, and I. Wiedenhover

Argonne National Laboratory, Argonne, Illinois 60439

(Received 27 September 1999; published 21 January 2000)

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.

PACS number(s): 21.10.Ky, 21.10.Re, 23.20.Lv, 27.70.+q

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 $\mu\text{g}/\text{cm}^2$, by a $E_{\text{lab}}=1358$ 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 $\approx 1^\circ$ 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-

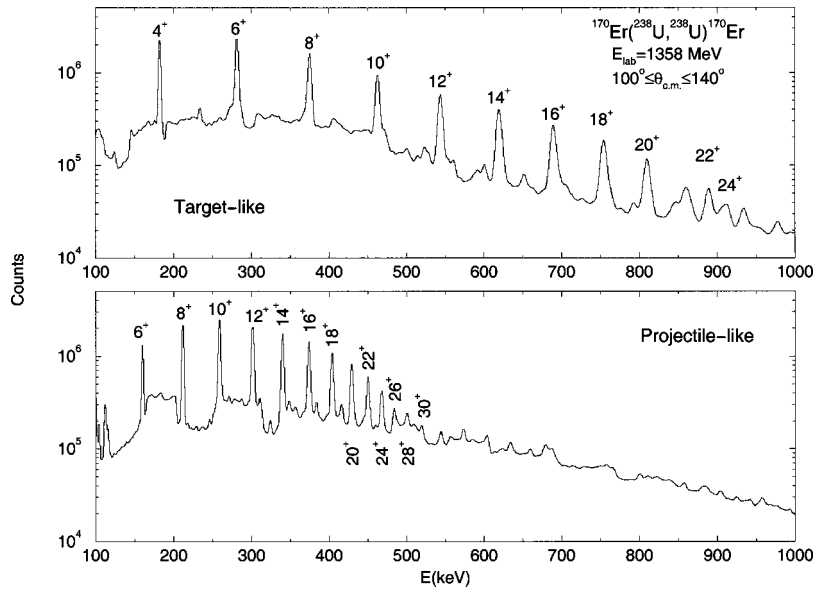


FIG. 1. Doppler-shift corrected γ -ray spectra for the projectilelike nuclei (lower panel) and the targetlike nuclei (upper panel). The labeled peaks are the $I \rightarrow (I-2)$ transitions for the inelastic channel.

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 $110^\circ < \theta_{\text{c.m.}} < 140^\circ$. 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 $^{118}\text{Sn}(^{164}\text{Dy}, ^{166}\text{Dy})^{116}\text{Sn}$. 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 $B(E2; 0_g^+ \rightarrow 2_\beta^+) = 0.28$ W.u. [1] indicates that the β -vibrational strength is weak: it corresponds to only 8% of the γ -vibrational $B(E2; 0_g^+ \rightarrow 2_\gamma^+)$ 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 $2_\beta^+ \rightarrow 2_g^+$ 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 $-0.63|4_\gamma\rangle_{\text{unpert}} + 0.77|4_\beta\rangle_{\text{unpert}}$ 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^+

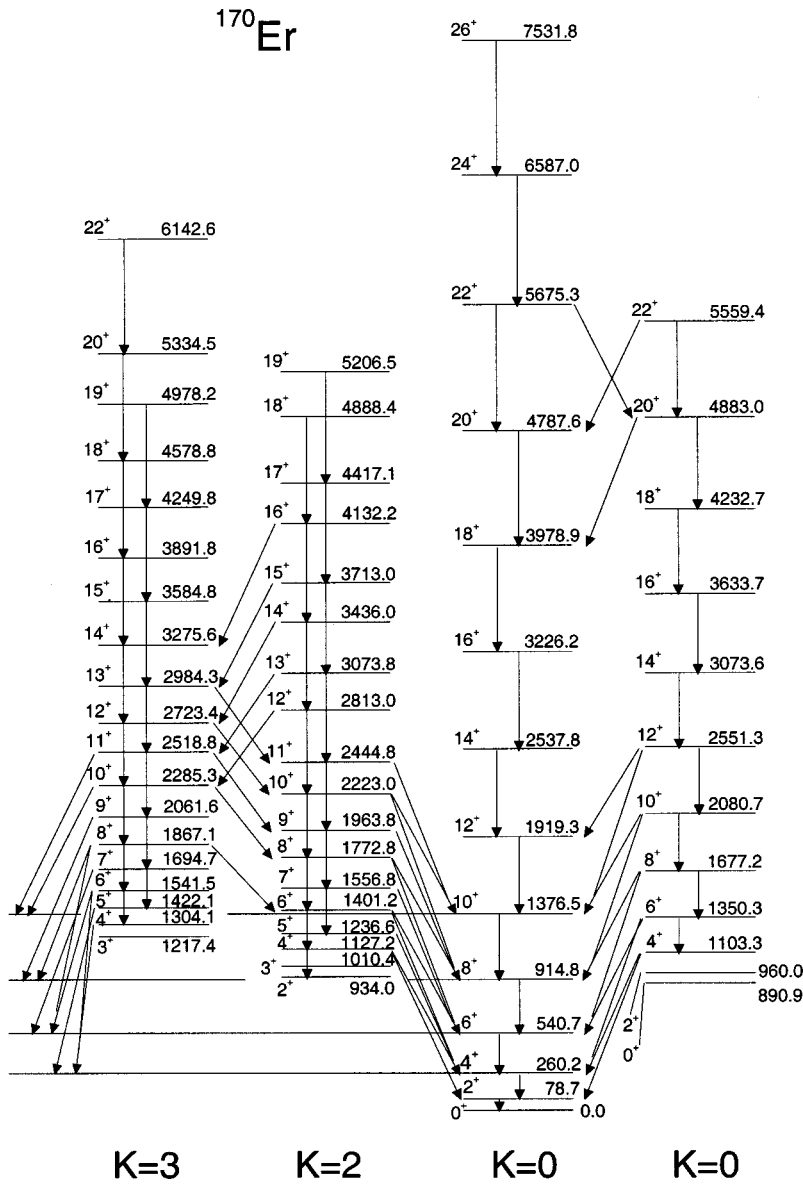


FIG. 2. Partial level scheme of (from left to right) the $K^\pi=3^+$, γ -vibrational, ground-state, and β -vibrational bands for ^{170}Er . The energies are labeled in keV.

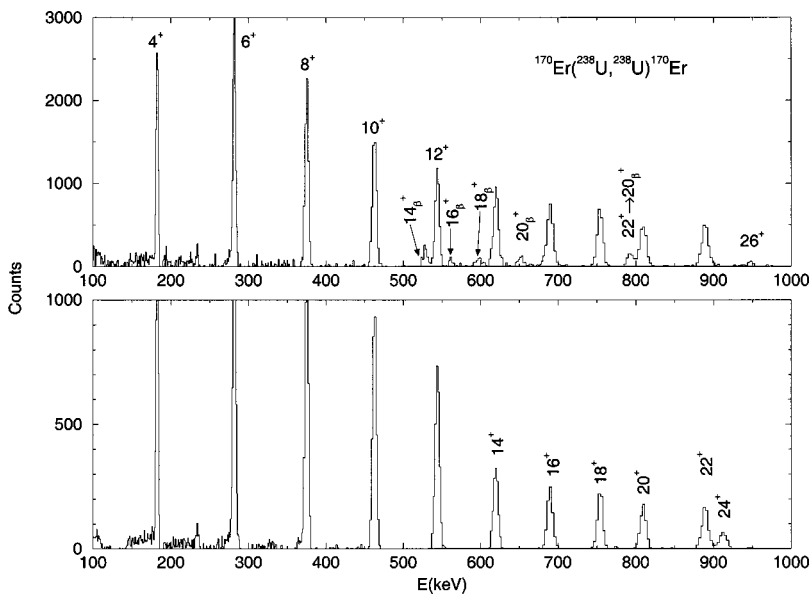


FIG. 3. Gated coincident γ -ray spectra for ^{170}Er . The lower spectrum is the summed double-gated γ -ray spectrum on the ground-state band transitions with spin 14^+ , 16^+ , 18^+ , and 20^+ . The upper spectrum shows the two decay branchings for the spin 22^+ state at 5675.3 keV obtained by gating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

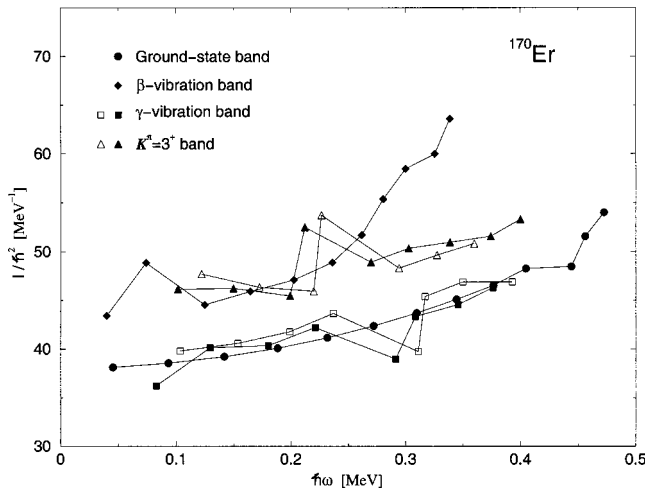


FIG. 4. The moments of inertia as a function of rotational frequency for the ground-state, β -vibrational, γ -vibrational, and $K^\pi = 3^+$ bands. Level repulsion is visible at spin 4^+ for the β - and γ -vibrational bands and at spin 22^+ for the ground-state and the excited $K^\pi = 0^+$ bands. The 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 $-0.96|20_g\rangle_{\text{unpert}} + 0.29|20_{K=0'}\rangle_{\text{unpert}}$ 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 vi-

brational 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 $0.71|12_\gamma\rangle_{\text{unpert}} + 0.70|12_{K=3}\rangle_{\text{unpert}}$, 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.

We thank Dr. I. Ahmad and Dr. J. P. Greene for making and handling the ^{252}Cf source used for the CHICO calibra-

tion. The work by the Rochester group was funded by the National Science Foundation. The work at LBNL and ANL was performed under the auspices of the Department of Energy under Contracts No. DE-AC03-76SF00093 (LBNL) and W-31-109-ENG-38 (ANL).

-
- [1] C.M. Baglin, Nucl. Data Sheets **77**, 125 (1996) and references therein.
- [2] M.W. Simon *et al.*, in *Proceedings of the International Conference on Fission and Properties of Neutron Rich Nuclei*, Sanibel Island, Florida, edited by J.H. Hamilton and A.V. Ramayya (World Scientific, Singapore, 1998), p. 270.
- [3] M.W. Simon, R.W. Gray, D. Cline, C.Y. Wu, and C. Long, Nucl. Instrum. Methods Phys. Res. A (to be published).
- [4] I.Y. Lee, in *Proceedings of the Workshop on Gammasphere Physics*, Berkeley, California, edited by M.A. Deleplanque, I.Y. Lee, and A.O. Macchiavelli (World Scientific, Singapore, 1996), p. 50.
- [5] C.Y. Wu, M.W. Simon, D. Cline, G.A. Davis, A.O. Macchiavelli, and K. Vetter (unpublished).
- [6] C.Y. Wu, M.W. Simon, D. Cline, G.A. Davis, A.O. Macchiavelli, and K. Vetter, Phys. Rev. C **57**, 3466 (1998).
- [7] K. Vetter *et al.*, Phys. Rev. C **58**, R2631 (1998).
- [8] A.O. Macchiavelli *et al.*, Proceedings of the International Conference on Physics from Large γ -Ray Detector Arrays, Berkeley, California, 1994, Vol. II, p. 149, LBL-35687.
- [9] D. Ward *et al.*, Nucl. Phys. **A600**, 88 (1996).
- [10] F. Kearns, G. Varley, G.D. Dracoulis, T. Inamura, J.C. Lisle, and J.C. Willmott, Nucl. Phys. **A278**, 109 (1977).
- [11] F.K. McGowan, W.T. Milner, R.L. Robinson, P.H. Stelson, and Z.W. Grabowski, Nucl. Phys. **A297**, 51 (1978).
- [12] G.B. Hagemann and I. Hamamoto, Phys. Rev. C **46**, 838 (1992).
- [13] T.L. Khoo, F.M. Bernthal, J.S. Boyno, and R.A. Warner, Phys. Rev. Lett. **31**, 1146 (1973).
- [14] D. Ward, R.L. Graham, J.S. Geiger, and H.R. Andrews, Phys. Lett. **44B**, 39 (1973).
- [15] R.M. Lieder *et al.*, Phys. Lett. **49B**, 161 (1974).
- [16] H.R. Andrews, D. Ward, R.L. Graham, and J.S. Geiger, Nucl. Phys. **A219**, 141 (1974).
- [17] P.M. Walker *et al.*, Phys. Lett. **168B**, 326 (1986).
- [18] N.L. Gjorup *et al.*, Proceedings of the International Conference on Nuclear Structure at High Angular Momentum, Ottawa, 1992, Vol. II, p. 160, AECL-10613.
- [19] B. Singh, Nucl. Data Sheets **75**, 199 (1995), and references therein.
- [20] E. Browne, Nucl. Data Sheets **62**, 1 (1991), and references therein.
- [21] I.M. Govil, H.W. Fulbright, and D. Cline, Phys. Rev. C **36**, 1442 (1987).