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Strongly coupled enhanced-deformation band in ^{131}Pr

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An enhanced-deformation (ED) rotational band with unusual characteristics has been discovered in the odd-Z nucleus ^{131}Pr. The dynamical moment of inertia $\mathcal{J}^{(2)}=(50-60)\hbar^2$ MeV^{-1} and the extracted quadrupole moment Q_0 = 5.5 ± 0.8 e b (β_2=0.32±0.05) are comparable with other ED bands (sometimes called "superdeformed") in the mass $A\sim 130$ region. The two signature partners of the ED band are connected by dipole transitions which can be followed down to a K=9/2 bandhead. The nature of this band differs from all other ED bands in the $A\sim 130$ region since the $i_{13/2}$ intruder neutron orbital is unoccupied.

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In the mass 130 region "superdeformed bands" or "enhanced-deformation" (ED) bands seem to be concentrated mainly in even-Z nuclei (Ce-Nd-Sm-Gd). These bands exhibit regular sequences of $E2$ transitions with $\mathcal{J}^{(2)}$ values in the range $(45-60)\hbar^2$ MeV^{-1}. Measured lifetimes indicate quadrupole moments in the range 4.0–7.5 e b [1,2]. To date, it has been widely accepted that the occupation of the highly alignable $i_{13/2}[660]_{1/2}$ neutron intruder orbital plays the crucial role in stabilizing the shape by polarizing the core [3]. Indeed, all such ED bands in this mass region are thought to have at least one $i_{13/2}$ neutron involved in their valence configuration.

In this paper we report the observation of a strongly coupled ED band in the odd-Z nucleus ^{131}Pr. Enhanced deformation was inferred from its high dynamical moment of inertia, $\mathcal{J}^{(2)} = (50-60)\hbar^2$ MeV^{-1}, and was confirmed by measurement of its quadrupole moment, Q_0 = 5.5 ± 0.8 e b. Although these values are comparable to other mass-130 ED bands, we believe that the $\nu i_{13/2}[660]_{1/2}$ orbital is not occupied in ^{131}Pr. This leads us to suggest that the appearance of an ED shape minimum in ^{131}Pr depends only on the existence of an excited ED even-Z,N core (i.e., a strong shell energy correction) since it cannot be caused by the polarization of the $i_{13/2}$ neutron orbital.

A similar band with $\mathcal{J}^{(2)} \simeq 55\hbar^2$ MeV^{-1} was found earlier in ^{129}Pr [4], but neither spin assignments nor lifetime measurements were reported. The estimated spins [$\sim(10-20)\hbar$ if $\mathcal{J}^{(1)} = \mathcal{J}^{(2)}$] were consistent with a configuration that could include $i_{13/2}$ neutrons. A strongly coupled band observed in ^{133}Pm [5] also has similarities with the bands in ^{129,131}Pr but has a lower $\mathcal{J}^{(2)} \sim 45\hbar^2$ MeV^{-1} and no discrete linking transitions were observed and no lifetimes of the states were measured.

High-spin states in ^{131}Pr were populated via the reaction ^{98}Mo(^{37}Cl,4n). A beam of ^{37}Cl ions at a bombarding energy of 155 MeV was provided by the MP tandem of the TASCC facility at Chalk River. This reaction had a grazing angular momentum $L_{gr}=56\hbar$, and left the ^{135}Pr* compound nucleus with an average excitation energy $E^*=74$ MeV. The main channels in the decay of the compound nucleus were 4n into ^{131}Pr (31% of the yield), $p3n$ into ^{131}Ce (29%), $p4n$ into ^{130}Ce (15%), and 3n into ^{132}Pr (8%).

Gamma-ray spectroscopy was performed with the 8π spectrometer. This instrument consists of an inner ball of 71 bismuth germanate (BGO) crystals providing sum energy (H) and fold (K) information and an array of twenty high-resolution Compton-suppressed HPGe detectors. A valid event required a twofold (or higher) Ge coincidence with a condition of $K \geqslant 10$ on the BGO ball. Approximately 2×10^8 events were accumulated with a target of two stacked self-supporting ^{98}Mo foils which each had a thickness of 0.5 mg/cm^2. An additional set of $\sim 2\times10^8$ events were collected with a 1 mg/cm^2 ^{98}Mo foil on a 12 mg/cm^2 lead backing.

Data from the self-supporting target experiment were replayed into a γ-γ coincidence matrix with the condition of $15 \leqslant H \leqslant 30$ (MeV) on the BGO sum energy. The interactive data-analysis codes ESCL8R and LF8R [6] were used to construct a level scheme. With these codes it was possible to analyze the complex coincidence relationships involving many multiple assignments of unresolved γ-ray transitions. A least-squares fit was performed directly on the γ-γ coincidence matrix to extract intensities and energies in the proposed level schemes which included 525 γ-ray transitions distributed amongst several nuclides including ^{131}Pr, ^{132}Pr, ^{130}Ce, and ^{131}Ce. The assignment of transitions to specific nuclides was facilitated by comparison to charged-particle-γ coincidence data from the ^{105}Pd(^{32}S,$xnypz\alpha$) reaction at 155 MeV [7].

The γ-γ lead-backed data were sorted into a matrix with the same H condition described above and containing only coincidences between a $\pm 37°$ detector (closest to the beam axis) and a $\pm 79°$ detector. A directional correlation from oriented states (DCO) [8] analysis was carried out. This allowed the assignment of multipolarities to many transitions. Measurements of the attenuated Doppler shifts for fast transitions that are emitted as the nucleus slows down in a material provide information on the mean lifetimes of nuclear states. Two more γ-γ coincidence matrices from the backed data were made which contained events from detectors at $\pm 79°$ against events in detectors at $+37°$ or $-37°$. A Doppler-shift attenuation method (DSAM) analysis was done to measure lifetimes for the ED band.

Transitions assigned to ^{131}Pr were organized into seven rotational sequences that comprised one decoupled and three strongly coupled bands. A partial level scheme is shown in Fig. 1, where the sequences have been labeled numerically. Some strong transitions in bands 1 and 2/3 have been observed in previous studies [9,10]. Recently, low-energy low-spin level structures have been established from β-decay studies [11]. In this paper the discussion will focus on the properties of the ED band, band 4/5. A spectrum obtained by summing gates chosen to cleanly select the band is shown in Fig. 2. Band 6/7 will be briefly discussed because of its unusual decay (evident in Fig. 2) *into* the ED band. We intend to discuss the remaining bands in a later publication.

In comparison with other "superdeformed" or "enhanced-deformation" bands in the mass-130 region, the ED band has a number of unusual features. These are its low excitation energy, the occurrence of strong dipole transitions between its signature partners, the decay to the proposed bandhead state with $I=K=9/2$, the simple decay pattern of the ED bandhead to "normal-deformed" states, and the decay of a normal-deformed structure (band 6/7) into ED states

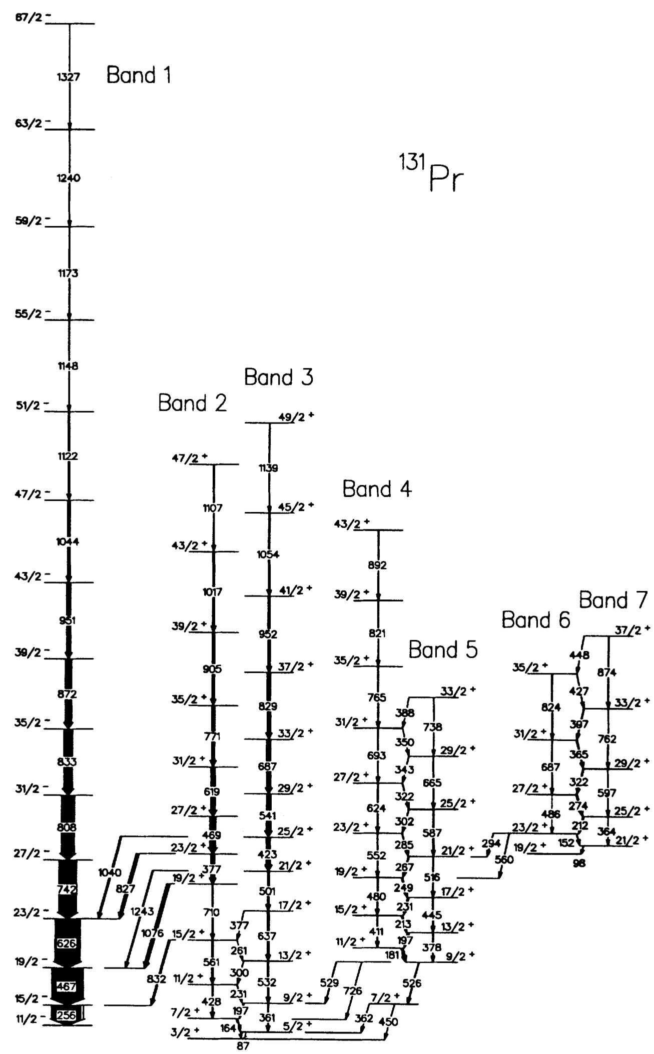

FIG. 1. Proposed partial level scheme for ^{131}Pr.

at high spin. The ED band is not yrast at high spin and its population is too weak to be observed above $\hbar\omega \sim 450$ keV. Typically in this mass region the bands persist to $\hbar\omega \sim 700$ keV or even $\hbar\omega \sim 1000$ keV in the case of ^{132}Ce.

The simple decay of the ED band into band 2/3 has allowed us to determine the excitation energy and spin of the ED bandhead. With reference to Fig. 1, the flux into the bandhead $[I_\gamma(181)+I_\gamma(378)=8\pm1\%]$ equals the flux out $[I_\gamma(529)+I_\gamma(726)+I_\gamma(526)=8\pm1\%]$, where the intensities are relative to $I_\gamma(256)$ ($15/2 \rightarrow 11/2$). DCO ratios for the linking transitions were determined in spectra obtained by summing selected gates on stretched quadrupole transitions of the ED band (namely $E_\gamma=$ 411, 445, 516, and 552 keV). In general only when the DCO ratio ($R_{\rm DCO}$) is less than ~ 0.65 the method does produce an unambiguous assignment and in that case the transition can only be stretched $L2/L1$ with a mixing ratio $\delta=L2/L1 \leqslant 0$ (see Ref. [8]). Among the linking transitions, only the 526 keV transition matches this criterion, $R_{\rm DCO}=0.49\pm0.09$. The transition at 450 keV has $R_{\rm DCO}=0.91\pm0.15$ and is assigned to be of stretched $E2$ character. Since this transition goes to the $3/2^+$ ground state,

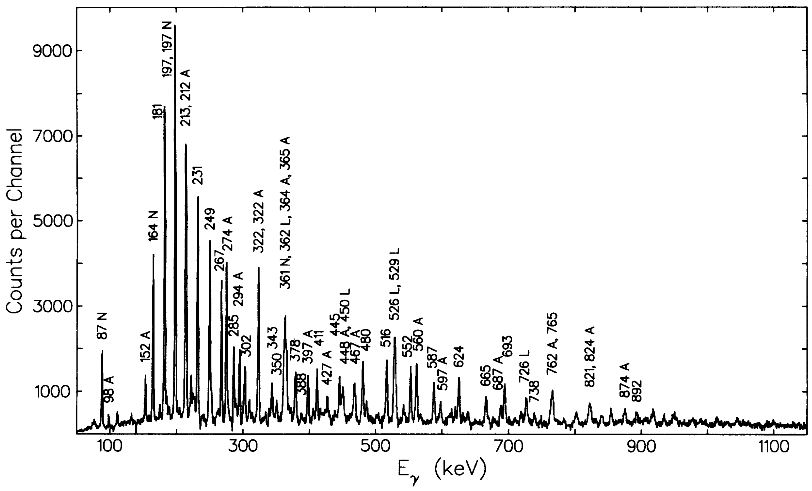

FIG. 2. Coincidence γ-ray spectrum for the sum of gates set on transitions at 181, 213, 231, 249, 411, 526, and 529 keV chosen to select the enhanced-deformation band, band 4/5. Transitions are labeled as follows: Energy (no label) = band 4/5. Energy A = band 6/7. Energy L = link from band 4/5. Energy N = band 2/3 fed by band 4/5.

the spin 9/2 can be assigned to the ED bandhead. The spin and parity of the $3/2^+$ state is consistent with that assigned from β-decay studies [11]. Although the mixing ratio for the 526 keV transition is nearly zero, perhaps suggesting a parity change, the DCO ratios for the other linking transitions, namely $\gamma529$ and $\gamma726$, imply considerable $L2/L1$ mixing, hence a positive parity assignment is indicated.

For such a low spin value, it is most likely that the ED band has a one-quasiparticle rather than a three-quasiparticle structure. This rules out the possibility that the band contains the first pair of aligned $i_{13/2}$ neutrons, since they alone would contribute $\sim 10\hbar$ of angular momentum. The only nearby proton orbital that is signature degenerate over a wide range of rotational frequency is the positive-parity $\pi g_{9/2}[404]_{9/2}$ orbital. Confirmation of the $g_{9/2}$ character is provided by the large $B(M1)/B(E2)$ ratios, which lie in the range 1–2 $(\mu_N/e\ \mathrm{b})^2$ and rule out all other plausible one-proton assignments. The mixing ratios of the intraband $E2/M1$ transitions are positive, and so indicate a prolate shape.

With the lead-backed target data we have performed DSAM analysis of the γ-ray centroid shifts observed in the $\pm 37°$ rings of HPGe detectors, to extract a quadrupole mo-

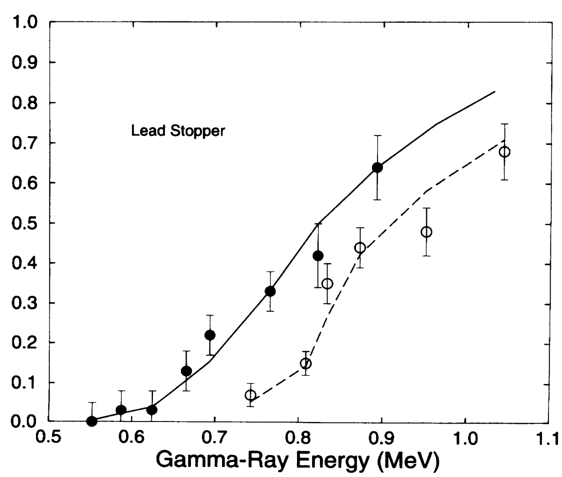

FIG. 3. Fractional Doppler shift of γ rays in the ED band (filled circles) and in band 1 (open circles). The calculated curves have been obtained assuming a constant quadrupole moment Q_0 = 5.5 (solid line) and 3.9 e b (dashed line).

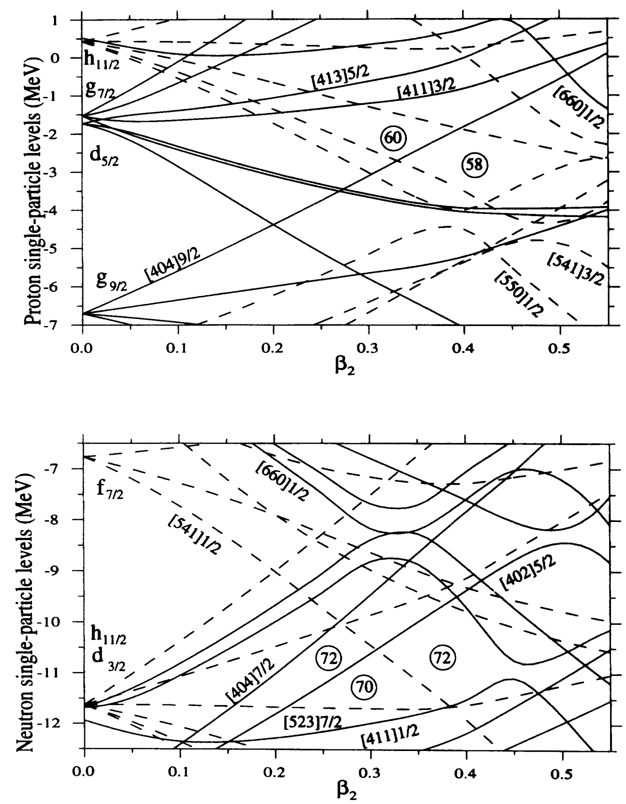

FIG. 4. Proton and neutron single particle levels calculated with a Woods-Saxon potential as a function of quadrupole deformation. Note the shell gaps at $Z=58$ and 60 which are separated by the upsloping $[404]_{9/2}$ orbital. Neutron shell gaps appear at $N=70$ and 72 separated by the downsloping $[541]_{1/2}$ orbital. The following convention is used for the parity: $\pi = +$, solid line; $\pi = -$, dashed line.

ment for the ED band and for band 1. The electronic stopping powers used were those of Northcliffe and Schilling [12] normalized to the α stopping powers of Ziegler and Chu [13]. The nuclear stopping power was calculated from the Lindhard-Scharff-Schiøtt [14] formalism, and large-angle scattering was treated by the Blaugrund [15] method. The data were analyzed assuming a constant quadrupole moment for a given band and the results are shown in Fig. 3. In deriving Q_0 for the ED band, we took into account the $J \rightarrow J-1$ branches with the experimentally determined branching ratios. This enters in two ways: first, the existence of a $J \rightarrow J-1$ branch shortens the lifetime for the state with respect to that calculated with a given Q_0. Second, the $J \rightarrow J-1$ branches constitute a slow side feeding with respect to the feeding down either signature partner band. Band 1 is best represented by a quadrupole moment of 3.9 $\pm$ 0.3 e b. With the relationship of Ref. [16] it corresponds to $\beta_2=0.23\pm0.02$, i.e., "normal" deformation. The data for the ED band are best represented by a quadrupole moment of Q_0 = 5.5 $\pm$ 0.8 e b, indicating an enhanced deformation of $\beta_2=0.32\pm0.05$. At this deformation, in a Woods-Saxon potential the $\pi g_{9/2}[404]_{9/2}$ orbital is expected to lie near the Fermi surface for $Z=59$, as can be seen in Fig. 4.

The same Woods-Saxon potential, but with pairing correlations included, was used in total Routhian surface calculations (TRS [17]). For positive-parity configurations two minima in the (β_2, γ) deformation plane occur over a wide range of frequency. One minimum has $\beta_2=0.24$, $\gamma\sim 1°$ which we associate with the $[411]_{3/2}$ configuration and assign to band 2/3; the other has $\beta_2=0.33$, $\gamma\sim 1°$ which is consistent with the deformation obtained for the ED band from the DSAM analysis. We identify this higher deformation minimum with the $[404]_{9/2}$ configuration assigned to the ED band.

We have performed similar calculations using the modified oscillator potential with the formalism of Ref. [18]. These calculations allow particular configurations to be tracked as a function of spin, but pairing correlations are not included. Both the normal and ED bands can be followed to zero spin in these calculations. For spins $I\sim 15$–20, Fig. 1 shows that the ED band is observed to lie about 750 keV above yrast, whereas the calculation predicts this to be about 700 keV.

The stability and relatively low excitation energy of the ED minimum at zero rotational frequency is most likely associated with the shell-correction energy at $Z=59$, rather than a polarization effect caused by the occupancy of a particular orbital. Both the modified oscillator and the Woods-Saxon calculation at $\hbar\omega=0$, shown in Fig. 4, give substantial shell gaps for $Z=58$ (centered at $\beta_2=0.42$) and $Z=60$ (centered at $\beta_2=0.33$) which are presumably involved in the ED structures of Ce and Nd isotopes. These proton gaps can be reinforced by gaps in the neutron shell energy at $N=70$ and 72. In the calculation it is the more deformed $N=72$ gap (cf. Fig. 4) that is associated with the ED band. At the deformation associated with the ED band, the $i_{13/2}[660]_{1/2}$ neutron intruder orbital is high in energy. A two-particle–two-hole excitation into this intruder orbital would require $\sim$4 MeV of excitation, and hence we rule out this possibility for the ED band.

The ED band exhibits no sharp alignment gain up to a rotational frequency of $\hbar\omega$ $\sim$ 400 keV; this is close to the frequency where the proton $h_{11/2}$ crossing should occur according to our cranked shell model calculations at the appropriate deformation. Presumably we lose sight of the band experimentally at this crossing. A general feature of band crossings which occur off the yrast line is that little intensity flows through the crossing. The behavior of band 2/3 in Fig. 1 illustrates this point.

A remarkable anomaly of the ^{131}Pr case is the observation of the decay of band 6/7 into the ED band. Band 6/7 has an $\mathcal{J}^{(2)}$ consistent with normal deformation. Energetically this is originated by the fact that the ED band gains no angular momentum from aligned particles in the spin range we observe. Therefore, any band that lies reasonably close to yrast and does exhibit an alignment gain can become more close to the yrast line than the ED band. We propose that band 6/7 presents such a case. The measured DCO ratios are consistent with a stretched $E2$ assignment for γ 560 keV and a stretched $E2/M1$ with significant mixing $+0.4 < \delta < +2.5$ for γ 294 keV. Thus, we assign positive parity to band 6/7. Evidently, the decay from band 6/7 to the ED band is caused by mixing of the levels with spin assignment $23/2^+$ at 2600 keV (in sequence "4" of the ED band) and 2609 keV (in sequence "6" of band 6/7), since they have the same spin and parity. These levels are observed to be 9 ± 1 keV apart, and will be strongly mixed by even a weak interaction, e.g., 4.5 keV if the levels were exactly degenerate before mixing.

Band 6/7 has large $B(M1)/B(E2)$ ratios in the range 3–6$(\mu_N/e\,\mathrm{b})^2$, and its dipole transitions have negative $E2/M1$ mixing ratios, which are characteristics of high-K structures. Several such bands are known in ^{133}Pr [19] where they have been described in terms of oblate shapes with a $\nu h_{11/2}^2 \otimes \pi h_{11/2}$ structure. However, these bands have negative parity and therefore cannot be identified with bands 6/7 seen here. An alternative possibility is the prolate structure $\pi h_{11/2} \otimes \nu[404]_{7/2}[523]_{7/2}$ where the neutron quasiparticles form a low lying $K=7^-$ band in the core ^{130}Ce [20]. TRS calculations show that there is a minimum with a β_2 = 0.25 for such a three-quasiparticle configuration. The lack of signature splitting and the calculated $B(M1)/B(E2)$ ratios are in good accord with this assignment. In the Dönau-Frauendorf model, this structure would produce a negative $E2/M1$ mixing ratio for a prolate shape [21].

In summary, we have found a strongly coupled band in ^{131}Pr that has an enhanced-deformation of β_2 = 0.32 $\pm$ 0.05. The low-excitation energy and spin of the bandhead lead us to conclude that the $i_{13/2}[660]_{1/2}$ intruder orbital is neither aligned nor occupied in this structure. This is unlike all the other enhanced-deformation bands in the $A=130$ region. The key aspect is the large gain in shell energy for the $\pi g_{9/2}$ configuration at $Z=59$ when the core deforms out to β_2= 0.33. This provides a stable rotational platform, without aligned particles, which allows us to follow the γ-decay sequence down to the $I=9/2$ bandhead.

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[1] X.-L. Han and C.-L. Yu, At. Data Nucl. Data Tables **52**, 43 (1992).
[2] S. M. Mullins *et al.*, Phys. Rev. C **45**, 2683 (1992).
[3] R. Wyss *et al.*, Phys. Lett. B **215**, 211 (1988).
[4] A. N. James and D. C. B. Watson, in *Nuclei Far from Stability*, Proceedings of the International Conference, Rosseau Lake, Ontario, 1988, AIP Conf. Proc. No. 164, edited by I. S. Towner (AIP, New York, 1988), p. 425.
[5] P. H. Regan *et al.*, Nucl. Phys. **A533**, 476 (1991).
[6] D. C. Radford, in *Proceedings of the International Seminar on The Frontier of Nuclear Spectroscopy*, Kyoto, Japan, 1992, edited by Y. Yoshizawa, H. Kusakari, and T. Otsuka (World Scientific, Singapore, 1993), p. 229.
[7] A. Galindo-Uribarri, Prog. Part. Nucl. Phys. **28**, 463 (1992).
[8] D. Ward *et al.*, Nucl. Phys. **A529**, 315 (1991).
[9] M. J. Godfrey *et al.*, J. Phys. G **13**, 1165 (1987).
[10] P. K. Weng *et al.*, Phys. Rev. C **47**, 1428 (1993).
[11] J. Genevey *et al.*, in *Nuclei Far From Stability and Atomic Masses and Fundamental Constants 1992*, Proceedings of the 6th International Conference on Nuclei Far From Stability and the 9th International Conference on Atomic Masses and Fundamental Constants, Bernkastel-Kues, Germany, 1992, IOP Conf. Proc. No. 132, edited by R. Neugart and A. Wöhr (IOP, London, 1993), p. 671.
[12] L. C. Northcliffe and R. F. Schilling, Nucl. Data Tables A **7**, 233 (1970).
[13] J. F. Ziegler and W. K. Chu, At. Nucl. Data Tables **13**, 463 (1974).
[14] J. Lindhard, M. Scharff, and H. E. Schiøtt, Kgl. Dan. Vidensk. Selsk. Mat. Fys. Medd. **33** (14), (1963).
[15] A. E. Blaugrund, Nucl. Phys. **88**, 173 (1966).
[16] K. E. G. Löbner, M. Vetter, and V. Hönig, Nucl. Data Tables A **7**, 495 (1970).
[17] W. Nazarewicz, R. Wyss, and A. Johnson, Nucl. Phys. **A503**, 285 (1989).
[18] T. Bengtsson and I. Ragnarsson, Nucl. Phys. **A436**, 14 (1985).
[19] D. B. Fossan *et al.*, Nucl. Phys. **A520**, 241c (1990).
[20] D. M. Todd *et al.*, J. Phys. G **10**, 1407 (1984).
[21] F. Dönau and S. Frauendorf, *High Angular Momentum Properties of Nuclei*, edited by N. R. Johnson (Hardwood Academic, New York, 1982), p. 143.