PHYSICAL REVIEW C **78**, 021305(R) (2008)

# Possible chirality in the doubly-odd $^{198}$Tl nucleus: Residual interaction at play

E. A. Lawrie,[1] P. A. Vymers,[1,2] J. J. Lawrie,[1] Ch. Vieu,[3] R. A. Bark,[1] R. Lindsay,[2] G. K. Mabala,[1,4] S. M. Maliage,[1,2] P. L. Masiteng,[1,2] S. M. Mullins,[1] S. H. T. Murray,[1] I. Ragnarsson,[5] T. M. Ramashidzha,[1,2] C. Schück,[3] J. F. Sharpey-Schafer,[1,2] and O. Shirinda[1,2]

[1]*iThemba LABS, P.O. Box 722, 7129 Somerset West, South Africa*
[2]*University of the Western Cape, Private Bag X17, 7535 Bellville, South Africa*
[3]*Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, IN2P3, F-91405 Orsay, France*
[4]*Department of Physics, University of Cape Town, Private Bag, 7701 Rondebosch, South Africa*
[5]*Division of Mathematical Physics, LTH, Lund University, SE-221 00 Lund, Sweden*

(Received 11 April 2008; published 20 August 2008)

A candidate for chiral bands was found in $^{198}$Tl for the first time in a mass region of oblate (or nonaxial with $\gamma \geqslant 30^\circ$) deformed nuclei. Two bands show very similar quasiparticle alignments, moments of inertia, and $B(M1)/B(E2)$ ratios. They have a relative excitation energy of about 500 keV and different patterns of energy staggering. Calculations using the two-quasiparticle-plus-triaxial-rotor model with residual proton-neutron interaction included show that a triaxial deformation with $\gamma \sim 44^\circ$ agrees very well with all the experimental observations. Furthermore, considerable energy staggering for both partner bands was calculated for this $\pi h_{9/2} \otimes \nu i_{13/2}^{-1}$ configuration at $\gamma \sim 30^\circ$, suggesting that chiral bands may have substantial energy staggering.

DOI: 10.1103/PhysRevC.78.021305 PACS number(s): 23.20.Lv, 21.60.Ev, 27.80.+w, 29.30.Kv

Although it is well known that many molecules form three-dimensional structures with well-defined chirality (or handedness), no chiral systems are yet confirmed beyond doubt for nuclear matter. The question about the existence of nuclear chirality is thus of great interest. It is, however, not always easy to interpret the experimental observations and to draw conclusions about possible chirality of the nucleus. For an ideal nuclear chiral system two degenerate $\Delta I = 1$ rotational bands are expected with identical properties [1]. The difficulty in proving the existence of nuclear chirality is caused by difficulties in interpreting differences in some of the properties of the observed partner bands; e.g., often the bands do not have the same staggering pattern, or they are not degenerate and do not reach energy degeneracy even at higher spins. It is often not clear if the observed differences rule out a chiral interpretation for the partner bands or if they are a consequence of other nuclear properties. Some calculations that suggest fingerprints of chirality can be found in Refs. [1–4]. Thus, it is important to obtain extensive experimental data for nuclei that may show chirality, and preferably for different nuclear configurations and in different mass regions. In this publication we report on the observation of a pair of bands in $^{198}$Tl that are associated with a particle-hole configuration suitable for a chiral system. This work indicates a new mass region, and for the first time among nuclei on the oblate side ($\gamma \geqslant 30^\circ$) in the ($\epsilon_2$, $\gamma$[1]) plane, which is suitable for investigations of nuclear chirality. Two-quasiparticle-plus-triaxial-rotor model calculations are used to study the effect of the nonaxiality of the nuclear core. We also studied the effect of the residual proton-neutron interaction on the partner bands, which we believe have not been reported for chiral band candidates before.

[1]Where all possible quadrupole shapes are described by $0^\circ \leqslant \gamma \leqslant 60^\circ$.

The excited $^{198}$Tl nuclei were produced with the $^{197}$Au($\alpha$,3n)$^{198}$Tl reaction at a beam energy of 40 MeV in two complementary experiments. The first employed the electron spectrometer [5] at the tandem accelerator laboratory at Orsay. The data analysis involved a search for low-energy transitions in the electron-$\gamma$ and $\gamma$-$\gamma$ matrices and measurements of the internal conversion coefficients. This allowed the assignment of multipolarities to many new transitions. The second experiment was performed at iThemba LABS, South Africa, with the AFRODITE array [6,7], consisting of eight clover and six LEPS detectors. An analysis of $\gamma$ coincidences, directional correlations from oriented states (DCO ratios), and linear polarization anisotropies was carried out. More details about the experiments can be found in Ref. [8].

The level scheme of $^{198}$Tl [9] is considerably extended with two new bands and several other transitions. It has been confirmed that the yrast band shows signature inversion and spins and parities are assigned to the new levels. The detailed level scheme will be published in a subsequent publication. A partial level scheme showing the extended yrast band and a new side band is plotted in Fig. 1 (also published in Ref. [8]).

The yrast band has been assigned a high-K proton and a low-K neutron $\pi h_{9/2} \otimes \nu i_{13/2}^{-1}$ configuration [9]. The new side band has the same parity as the yrast band and a relative excitation energy of about 500 keV (see Fig. 2). No configuration involving two quasiparticles from shells lying close to the Fermi surfaces and from other than $\pi h_{9/2}$ and $\nu i_{13/2}$ orbitals can match the spin and parity of this side band. The numerous links between the two bands also suggest similarities in their single-particle configurations. Thus, the same $\pi h_{9/2} \otimes \nu i_{13/2}^{-1}$ configuration is associated with the side band. It is important to investigate whether the side band could result from a coupling with the $\gamma$-vibrational band of the even-even core. This scenario does not look very likely, however, because although a low-lying $2_2^+$ state was discovered in $^{198}$Hg, it has $B(E2; 2_\gamma^+ \to 2_{\rm g.s.}^+)/B(E2; 2_\gamma^+ \to 0_{\rm g.s.}^+) = 30$ [10].

 

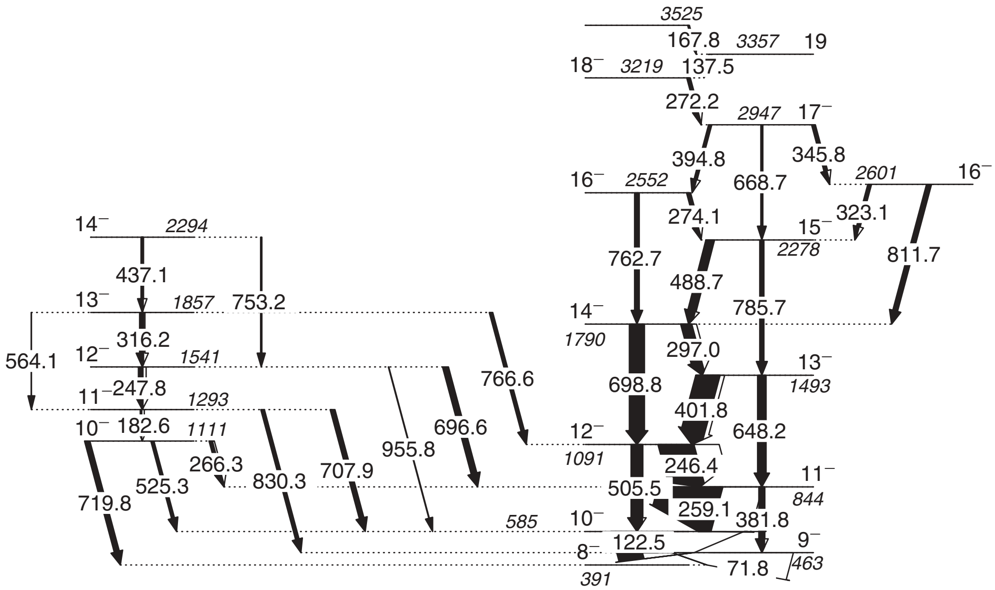


FIG. 1. Partial level scheme showing the pair of bands in $^{198}$Tl.

This value deviates considerably from the value of 1.4 expected for a good vibrator (in terms of the rotation-vibration model). Thus, in the following we investigate whether the side band could be interpreted as a chiral partner of the yrast band.

The $\pi h_{9/2} \otimes \nu i_{13/2}^{-1}$ nucleon configuration is favorable for a chiral system, because the proton particle occupies the lowest $h_{9/2}$ orbital (with $\Omega = 9/2$ in the oblate limit), while the neutron hole is located at the top of the $i_{13/2}$ shell, as observed in the neighboring odd-$Z$ and odd-$N$ nuclei [10]. The measured quasiparticle alignments, kinematic moments of inertia, and $B(M1)/B(E2)$ transition probability ratios are very similar for these two bands (shown in Fig. 3), which also supports the chirality scenario. Vanishing energy staggering is suggested for chiral bands. This is a result of a uniform rotation, which is a basic assumption in the Tilted Axis Cranking model [1]. An alternative argument claims that the Coriolis interaction is small for a chiral system with total angular momentum constructed by three mutually perpendicular angular momenta and, thus, the energy staggering should also be small [11]. However, the effect of the residual proton-neutron interaction, which can also contribute to energy staggering, seems not to be taken into account in the latter argument.

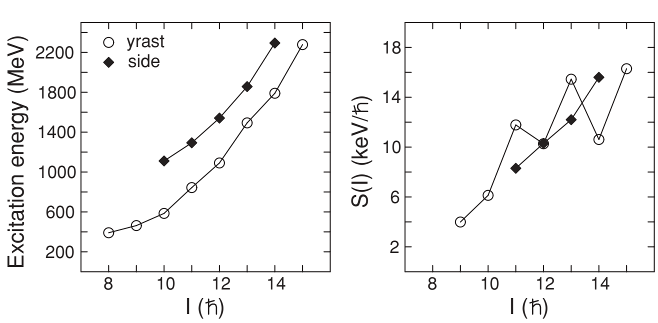


FIG. 2. Excitation energy (left panel) and staggering, $S(I) = [E(I) - E(I-1)]/(2I)$ (right panel), in the yrast and side bands in $^{198}$Tl.

The description of these bands in terms of chirality depends crucially on the nonaxiality of the nuclear shape. However, theoretical models differ when predicting the axiality parameter of this nucleus. The total Routhian surface (TRS) [12,13] calculations performed for the three lowest-lying negative parity bands in $^{198}$Tl with configurations eA and fA, eB and fB, and gA and hA (where the proton Routhians e, f, g, and h have major contributions from the $h_{9/2}$ orbitals with $\Omega = 9/2$ and 7/2, respectively, and the neutron Routhians A and B originate from the $i_{13/2}$ orbital with $\Omega = 1/2$) show nearly

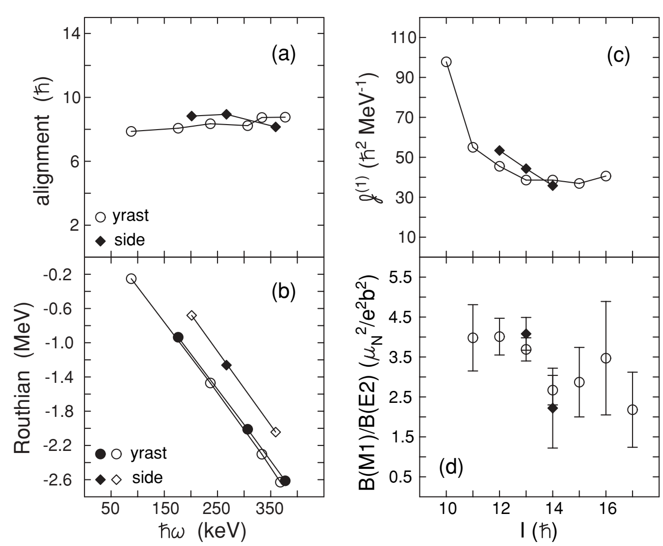


FIG. 3. Experimental quasiparticle alignments (a) and Routhians (b) (calculated with reference parameters $J_0 = 8\hbar^2$/MeV and $J_1 = 40\hbar^4$/MeV$^3$), kinematic moments of inertia (c), and $B(M1)/B(E2)$ transition probabilities (d) for the yrast and side bands in $^{198}$Tl.

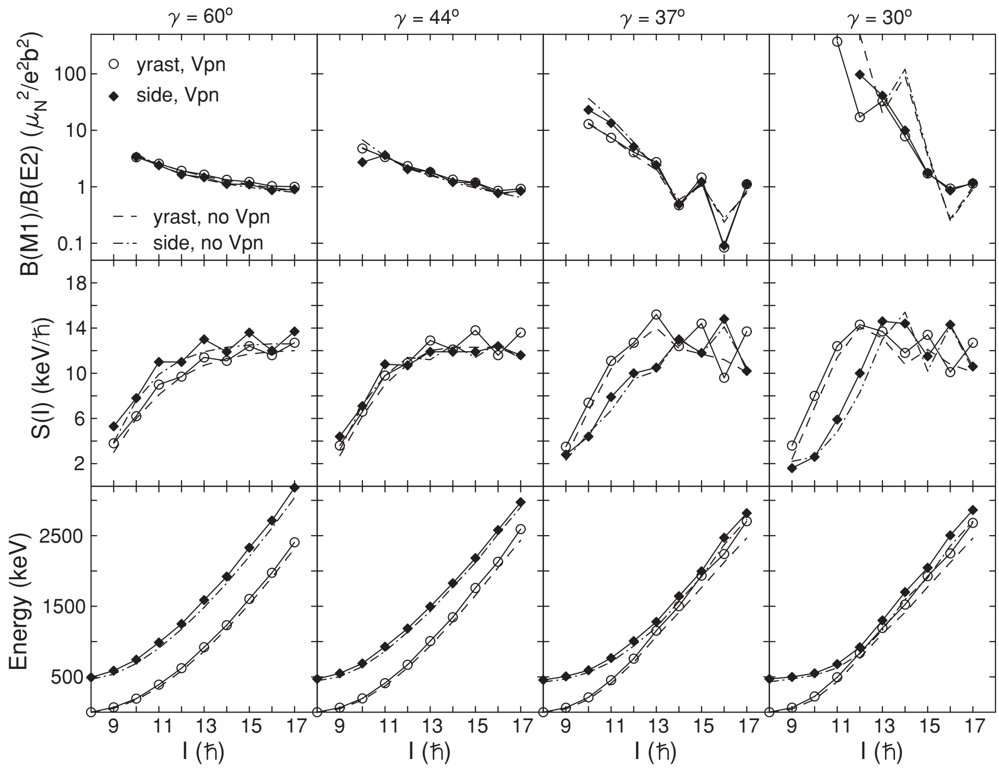


FIG. 4. Calculated excitation energies, staggering $S(I) = [E(I) - E(I-1)]/(2I)$, and $B(M1)/B(E2)$ transition probability ratios for the yrast and side bands in $^{198}$Tl at different $\gamma$ deformations.

axially symmetric oblate shapes with $-65^\circ \geqslant \gamma \geqslant -62^\circ$.[2] This model also predicts axially symmetric oblate shapes for the neighboring Tl and Hg isotopes. However, low-lying $\gamma$ bands were found in the even-even Hg isotopes and large nonaxialities were derived from the excitation energies, and independently from the $B(E2)$ transition probabilities (e.g., $\gamma \sim 36^\circ$ for $^{198}$Hg) in the framework of the rigid-triaxial-rotor model [15]. Furthermore the excitation energies of the low-lying states in the odd Tl nuclei in this mass region could not be reproduced if the rotation of an axially deformed nucleus was assumed or by interpreting the data in terms of harmonic vibrations (for $^{199}$Tl see Ref. [16]). A very good description of these states was, however, achieved by assuming a nuclear shape with the same $\gamma$ deformation as derived for the neighboring even-even core (i.e., for $^{199}$Tl $\beta_2 = 0.15, \gamma = 36^\circ$) [16,17]. Thus, conflicting results for the axiality of the Tl nuclei in the 190 mass region are suggested by these theoretical models.

Several calculations using the particle-plus-rotor model have been carried out for the yrast band in $^{198}$Tl [18,19]. These calculations have been performed with and without proton-neutron interaction and for axially symmetric or triaxial nuclear shapes. To investigate both partner bands we performed calculations with the two-quasiparticle-plus-triaxial-rotor model [20]. The focus was placed on investigating the effects on the partner bands caused by (i) a possible nonaxial shape and (ii) a residual proton-neutron interaction. A quadrupole deformation of $\epsilon_2 = 0.15$ and variable moments of inertia were used. No Coriolis attenuation factor was introduced and the parameters for the residual interaction, $V_{pn} = \sqrt{8\pi^3}(\hbar/m\omega)^{3/2}\delta(\mathbf{r}_p - \mathbf{r}_n)(u_0 + u_1\sigma_p \cdot \sigma_n)$, were set to $u_0 = -4.95$ MeV and $u_1 = -0.55$ MeV as previously used [21]. Standard parameters were used for the Nilsson potential [22] and for the pairing gap (corresponding to $\Delta_p = 0.525$ MeV and $\Delta_n = 0.759$ MeV). Results from the calculations with and without residual proton-neutron interaction and for different values of the nonaxiality parameter $\gamma$ are shown in Fig. 4. The residual proton-neutron interaction has a very strong effect on the energy staggering in the bands. Indeed, it is impossible to reproduce the signature inversion in the yrast band of $^{198}$Tl (for any value of $\gamma$), unless the residual proton-neutron interaction is considered. For $\gamma \sim 30^\circ$ this interaction has a strong effect also on the $B(M1)/B(E2)$ ratios.

The magnitude of the divergence from axiality strongly affects all characteristics of the bands. For instance, for an axially symmetric oblate shape the relative excitation energy of the side band increases with increasing spin, from 552 keV at $I = 10\hbar$ to 689 keV at $I = 14\hbar$. When the nuclear shape becomes nonaxial the relative excitation energy of the side band starts decreasing, and for large nonaxiality the partner bands reach energy degeneracy. For a shape with $\gamma = 44^\circ$ the relative excitation energy of the side band is nearly constant in the spin range where this band is observed experimentally,

[2]Note that in the cranking model $\gamma = -60^\circ$ corresponds to collective rotation of the oblate deformed nucleus [14].

i.e., 496 keV at $I = 10\hbar$ and 482 keV at $I = 14\hbar$. For axial deformation the calculations with proton-neutron interaction suggest staggering in both partner bands, with the same phase (which corresponds to signature inversion) and with slightly larger magnitude for the side band. The staggering pattern in the partner bands, however, shows different behavior when the deformation becomes triaxial. While in the yrast band the staggering amplitude simply increases keeping the same phase, the amplitude in the side band decreases and changes phase for larger nonaxialities. It should be noted that substantial energy staggering, not necessarily with the same phase, occurs in the partner bands for $\gamma \sim 30^\circ$, where excellent conditions for a chiral system occur. This shows that chiral bands may have substantial energy staggering, contrary to the suggestion that the staggering vanishes for such a system.

The calculated $B(M1)/B(E2)$ transition probability ratios are found to decrease slowly as a function of spin for both bands and to show no staggering for axial deformation. The magnitude of these ratios increases rapidly for larger nonaxialities and when $\gamma$ approaches 36° a strong staggering develops.

The excellent agreement that is observed between the experimental data and the calculations obtained with $\gamma = 44^\circ$ is worth noting. Not only the nearly constant relative excitation energy and the smooth dependence of the $B(M1)/B(E2)$ ratios but also the signature inversion in the yrast band and the absence of signature staggering in the side band are all well reproduced by the calculations. This indicates that the nuclear shape in $^{198}$Tl is most likely not axially symmetric, with $\gamma \sim 44^\circ$.

The most interesting question, i.e., are these bands chiral, still remains. The projections of the angular momenta of the proton, neutron, and collective rotation for $\gamma = 30^\circ$ and $\gamma = 44^\circ$ for both bands are plotted in Fig. 5. It is clear that these angular momenta have major components along the short ($x$), long ($z$), and intermediate ($y$) nuclear axes, indicating an aplanar (i.e., pointing out of the planes defined by the major nuclear axes) orientation of the total angular momentum. The average angles between these three angular momenta, $\alpha(\mathbf{p}, \mathbf{R})$, $\alpha(\mathbf{n}, \mathbf{R})$, and $\alpha(\mathbf{p}, \mathbf{n})$, defined in the usual manner, e.g., $\alpha(\mathbf{p}, \mathbf{R}) = \arccos[\langle \mathbf{p}.\mathbf{R}\rangle/(|\mathbf{p}|.|\mathbf{R}|)]$, are close to 90° for $I = 8\hbar$, $\gamma = 44^\circ$, and for both bands. At higher spins these angles start decreasing slowly. However, even at spin $I = 16\hbar$ they are larger than 40° for both bands, indicating that,

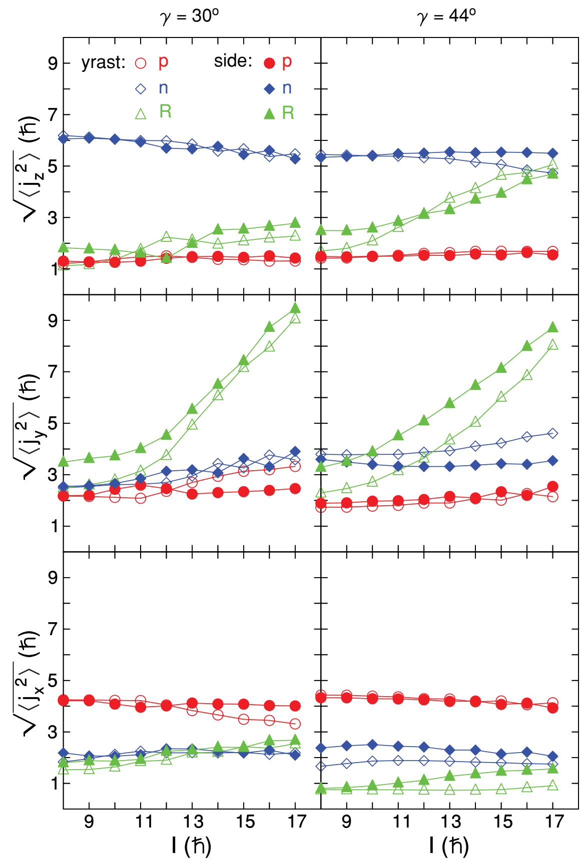


FIG. 5. (Color online) Calculated projections of the angular momenta of the proton (p), the neutron (n), and the collective rotation (R) for the partner bands and for $\gamma = 30^\circ$ (left panels) and $\gamma = 44^\circ$ (right panels).

although the three angular momenta are not strictly mutually perpendicular at high spin, they still form an aplanar system, as expected in a chiral scenario. Thus, the partner bands in $^{198}$Tl may represent a chiral system.

We thank the crews of the iThemba LABS separated sector cyclotron and the tandem accelerator of Orsay for their help and assistance. This work is based upon research supported by the National Research Foundation and was also partially funded under a CNRS/NRF exchange agreement.

[1] S. Frauendorf and J. Meng, Nucl. Phys. **A617**, 131 (1997).
[2] K. Starosta *et al.*, Phys. Rev. C **65**, 044328 (2002); Phys. Rev. Lett. **86**, 971 (2001).
[3] T. Koike, K. Starosta, and I. Hamamoto, Phys. Rev. Lett. **93**, 172502 (2004).
[4] S. Q. Zhang, B. Qi, S. Y. Wang, and J. Meng, Phys. Rev. C **75**, 044307 (2007).
[5] J. S. Dionisio *et al.*, Nucl. Instrum. Methods A **362**, 122 (1995).
[6] R. T. Newman *et al.*, Balkan Phys. Lett. **Special Issue**, 182 (1998).
[7] J. F. Sharpey-Schafer, Nucl. Phys. News **14**, 5 (2004).
[8] E. A. Lawrie *et al.*, Acta Phys. Pol. B **38**, 1417 (2007).
[9] A. J. Kreiner, M. Fenzl, S. Lunardi, and M. A. Mariscotti, Nucl. Phys. **A282**, 243 (1977).
[10] R. B. Firestone, *Table of Isotopes*, edited by V. S. Shirley, 8th ed. (Wiley, New York, 1996).
[11] C. Vaman, D. B. Fossan, T. Koike, K. Starosta, I. Y. Lee, and A. O. Macchiavelli, Phys. Rev. Lett. **92**, 032501 (2004).
[12] R. Wyss, W. Satula, W. Nazarevicz, and A. Johnson, Nucl. Phys. **A511**, 324 (1990).
[13] W. Nazarewicz, G. A. Leander, and J. Dudek, Nucl. Phys. **A467**, 437 (1987).

[14] G. Andersson *et al.*, Nucl. Phys. **A268**, 205 (1976).
[15] L. Esser, U. Neuneyer, R. F. Casten, and P. von Brentano, Phys. Rev. C **55**, 206 (1997).
[16] Y. Tanaka and R. K. Sheline, Nucl. Phys. **A276**, 101 (1977).
[17] J. Meyer-ter-Vehn, Nucl. Phys. **A249**, 141 (1975).
[18] A. J. Kreiner, Z. Phys. A **288**, 373 (1978); Phys. Rev. C **22**, 2570 (1980).
[19] H. Toki, H. L. Yadav, and A. Faessler, Phys. Lett. **B71**, 1 (1977); Z. Phys. A **292**, 79 (1979).
[20] P. B. Semmes and I. Ragnarsson, in *Proceedings of the International Conference on High-Spin Physics and Gamma-Soft Nuclei, Pittsburg, 1990*, edited by J. X. Saladin, R. A. Sorenson, and C. M. Vincent (World Scientific, Singapore, 1991), p. 500; in *Future Directions in Nuclear Physics with 4$\pi$ Gamma Detection Systems of the New Generation*, edited by J. Dudek and B. Haas (AIP Conf. Proc. 259, 1992), p. 566.
[21] R. A. Bark *et al.*, Phys. Lett. **B406**, 193 (1997); **B416**, 453(E) (1998).
[22] T. Bengtsson and I. Ragnarsson, Nucl. Phys. **A436**, 14 (1985).