PHYSICAL REVIEW C VOLUME 45, NUMBER 3 MARCH 1992

Sidebands in ^{219}Ra

M. Wieland, J. Fernández Niello,* and F. Riess
Sektion Physik der Universität München, Am Coulombwall 1, D-8046 Garching, Germany

M. Aïche, A. Chevallier, J. Chevallier, N. Schulz, and J. C. Sens
Centre de Recherches Nucléaires, IN2P3-CNRS,
Université Louis Pasteur, Boite Postale 20, F-67037 Strasbourg, France

Ch. Briançon, R. Kulessa,† and E. Ruchowska‡
Centre de Spectrométrie Nucléare et de Spectrometrie de Mass, IN2P3-CNRS Batiment 104, F-91405 Campus-Orsay, France
(Received 22 October 1991)

Excited states in ^{219}Ra were studied by means of the ^{208}Pb(^{14}C, $3n$) reaction at 65 MeV. The investigation was made with 12 Compton-suppressed Ge detectors and a multicounter array. Transitions in ^{219}Ra were selected by requiring appropriate conditions on fold and sum energy. The proposed level scheme shows two sidebands with alternating parity structure decaying to the ground-state band. It is consistent with a recent description of ^{219}Ra in the framework of the reflection-asymmetric mean-field approach, which predicts a $K = \frac{1}{2}$ ground-state band and two low-lying bands with quantum numbers $K = \frac{3}{2}$ and $K = \frac{5}{2}$.

PACS number(s): 25.70.−z, 23.20.Lv, 27.80.+w

I. INTRODUCTION

Light actinide nuclei are of interest since they present some evidence of breaking the intrinsic reflection symmetry leading to odd multipolarity components in nuclear shapes. This is characterized by the simplex symmetry [1] (mirror symmetry with respect to a plane containing the symmetry axis) which manifests itself by band structures of alternating parity in which the electromagnetic decay proceeds via strongly enhanced $E1$ transitions [2]. Further evidence for the presence of such deformation is provided by the identification of doublets with similar intrinsic configuration (parity doublets) [3].

In this work we report on the study of sidebands in the transitional nucleus ^{219}Ra. This isotope lies at the beginning of the light actinide region where stable octupole deformations are predicted to occur [4]. Its ground-state band shows a vibrational pattern dominated by odd multipole deformations up to high spins [5,6]. The purpose of this investigation was twofold: first, to search for the simplex partner band of the ground-state band as observed in other odd-A nuclei in this region [7–10]; second, to clear up a discrepancy in the low-lying structure of this nucleus between two prior works [5,6].

*Permanent address: Departamento de Física, Comisión Nacional de Energía Atómica, Buenos Aires, Argentina.

†Permanent address: Jagellonian University, Cracow, Poland.

‡Permanent address: Institute of Experimental Physics, Warsaw University, Poland.

II. EXPERIMENTAL PROCEDURE AND DATA ANALYSIS

The ^{219}Ra nucleus was studied using the reaction ^{208}Pb(^{14}C,$3n$) at the MP tandem in Strasbourg with an incident beam energy of 65 MeV. The ^{208}Pb target, enriched to > 99%, had an approximate thickness of 5 mg/cm^2. The experimental setup consisted of 12 Compton-suppressed Ge detectors and the multidetector array "Château de Cristal" [11] as the sum energy and multiplicity filter. In the present experiment it formed an inner array with 26 BaF_2 scintillation counters. The Compton-suppressed Ge detectors were placed at 30°, 90°, and 150° with respect to the beam. The data were registered in an event-by-event mode requiring at least one BaF_2 counter and two Ge detectors to have fired. One event contains the Ge energies, labels, and times with respect to the first BaF_2 fired, the number of BaF_2 fired, and the total energy deposited in these counters. At the chosen bombarding energy the cross section for the $2n$ channel becomes important [12]. Nevertheless, the contribution of ^{220}Ra in the γ spectra could be reduced by setting appropriate conditions on fold and sum energy. Figure 1 shows the emphasis of either ^{219}Ra or ^{220}Ra γ transitions with two choices for the fold condition.

Several new lines could be identified from the γ-γ-coincidence measurement. Table I summarizes the spectroscopic information of the assigned γ rays. The transition multipolarity was established from the extracted directional correlation (DCO) ratios between the spectra measured at 90° and 30° or 150° with respect to the beam. These ratios R were defined as $R = I_\gamma[90° \rightarrow (30°/150°)]/I_\gamma[(30°/150°) \rightarrow 90°]$, where $I_\gamma(\theta_1 \rightarrow \theta_2)$ is the intensity of a γ-ray transition in the detector placed

TABLE I. Spectroscopic information on ^{219}Ra.

$E_{\text{init state}}$	E_γ (keV)[a]	I_γ	DCO ratio
1308.6	79.3	6 (2)	
921.2	84.3	26 (7)	0.81 (0.15) (D)
859.8	96.7	15 (1)	
97.1	97.1	> 5	
1722.0	100.1		
2551.6	108.1	2 (1)	
2136.7	114.0	13 (5)	
1394.9	123.1	193 (9)	0.48 (0.08) (Q)
1240.6	125.9	17 (2)	
587.6	129.0	94 (7)	
1816.7	131.7	76 (3)	0.43 (0.05) (Q)
876.7	141.9	383 (19)	0.51 (0.08) (Q)
2272.9	159.4	27 (5)	
1036.8	160.1	472 (67)	0.42 (0.04) (Q)
1654.8	167.3	4 (1)	0.58 (0.20) (Q)
2750.9	187.2	14 (2)	0.67 (0.11)(Q)
734.8	205.3	670 (33)	0.52 (0.07) (Q)
763.0	223.8	13 (2)	
234.5	234.5	1120 (81)	
1271.8	235.0	320 (41)	
734.8	238.9	26 (1)	
1487.8	247.2	4 (1)	
837.0	249.4	39 (2)	1.08 (0.18) (D)
1114.5	254.9	13 (1)	0.73 (0.15) (Q)
495.8	261.3	225 (12)	
3028.6	277.7		
1685.1	290.2	202 (42)	
2563.7	290.8	44 (7)	
529.5	295.0	1000 (51)	
1409.7	295.2		
2113.6	296.9	98 (8)	0.42 (0.09) (Q)
2022.4	300.4	25 (1)	
1036.8	302.0	123 (6)	1.06 (0.14) (Q)
2444.1	307.4	9 (3)	
1229.3	308.1	29 (3)	
1621.9	313.3	27 (7)	
859.8	320.4	23 (11)	2.13 (0.68) (D)
921.2	333.6	89 (4)	2.17 (0.43) (D)
876.7	347.2	319 (20)	0.98 (0.11) (Q)
1114.5	351.2		0.79 (0.32) (Q)
587.6	353.0	10 (2)	
1394.9	358.1	273 (13)	0.92 (0.11) (Q)
458.6	361.5	81 (4)	1.64 (0.27) (D)
837.0	378.3	14 (3)	
1240.6	381.0	15 (3)	0.45 (0.15) (Q)
1308.6	387.4	85 (4)	2.13 (0.32) (D)
921.2	391.9		
1271.8	395.1	115 (5)	0.88 (0.18) (Q)
2022.4	400.6	8 (2)	
1685.1	413.3	48 (7)	
1722.0	413.4	56 (12)	1.64 (0.26) (D)
1654.8	414.1		
2136.7	415.0	58 (15)	2.33 (0.46) (D)
2551.6	415.1	11 (5)	
1816.7	421.8	209 (10)	0.89 (0.08) (Q)
921.2	425.4	11 (2)	
2113.6	428.5	25 (1)	0.98 (0.15) (Q)
2987.1	435.5	17 (1)	
2563.7	450.2	13 (1)	0.93 (0.09) (Q)
2272.9	456.3	80 (4)	0.93 (0.13) (Q)

TABLE I. (*Continued*).

$E_{\text{init state}}$	E_γ (keV)[a]	I_γ	DCO ratio
458.6	458.6	51 (5)	0.81 (0.16) (D)
3028.6	464.8	14 (1)	
2750.9	478.0	33 (1)	
539.2	539.2	51 (2)	0.50 (0.14) (Q)
1308.6	573.6	14 (2)	
1114.5	619	13 (2)	
859.8	625.4	27 (3)	0.42 (0.13) (Q)
1722.0	685.1	16 (2)	
1240.6	711.1	10 (1)	
2551.6	734.6	13 (2)	
2136.7	741.6	15 (2)	
1487.8	753	17 (3)	

[a]Estimated errors range between 0.1 and 0.3 keV.

at θ_2 when gating on a reference transition in the detector placed at an angle θ_1. The multipolarity of the reference transition used to determine the DCO ratios is given in parentheses in Table I. Following this definition — and assuming an alignment of $\sigma/J < 0.15$— the theoretical directional correlation ratio is $R = 1$ for dipole-dipole (i.e., a dipole transition observed at angle θ_1 in coincidence with a dipole transition observed at angle θ_2) and quadrupole-quadrupole transitions, $R = 0.51$ for quadrupole-dipole transitions, and $R = 1.98$ for dipole-quadrupole transitions.

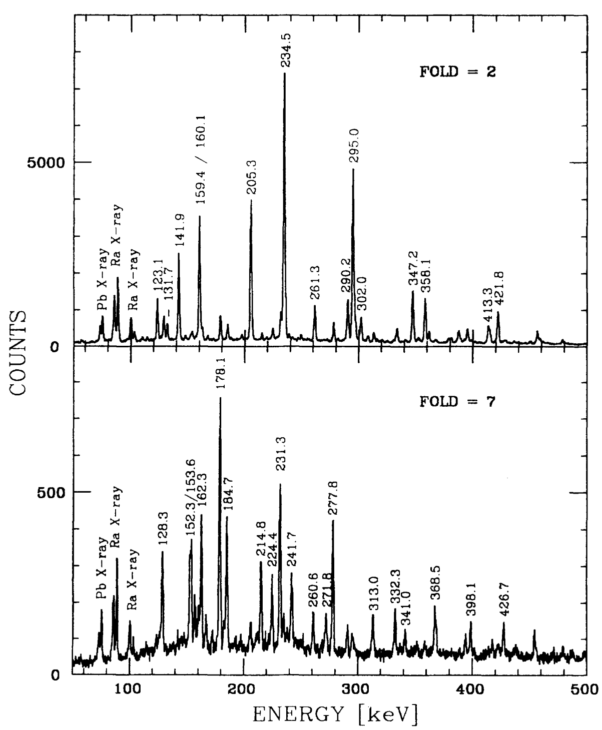

FIG. 1. Gamma-ray spectra measured in the ^{208}Pb(^{14}C,xn) reaction at E_{beam} = 65 MeV. Transitions in ^{219}Ra (^{220}Ra) are marked in the upper (lower) part of the figure.

The level scheme of ^{219}Ra deduced from the present work is presented in Fig. 2. The ground-state spin and parity of this nucleus was suggested to be $\frac{7}{2}^+$ [16], a value which was adopted in this work, although $\frac{11}{2}^+$ could not be ruled out by experiment [13]. No gamma rays with similar energies to those identified in the alpha decay of ^{223}Th [14, 15] were identified with the exception of the 97.1 keV γ ray. The similarity in energy could be fortuitous since both the proposed placement in the level scheme and the proposed nature of the transition differ in all three works. Due to the low bombarding energy the ground-state band could be followed up only to $I = \frac{39}{2}$ at $E^* = 3029$ keV. Two new alternating parity bands were observed in this work and labeled I and II in Fig. 2. Both bands decay to the ground-state band from several excited levels through dipole transitions.

The data allow to extend the band I up to spin $I = \frac{35}{2}$ with approximately the same excitation energy reached by the ground-state band. The tentative placement of the 97 and 362 keV transitions is based solely on intensity arguments in gated spectra and assuming a main $E2$ character for the 97 MeV transition. An indication of the parity of the levels of this band could be obtained from the 459 keV transition. This was measured to be of $M1$ character [6], which automatically determines the character of all other transitions decaying from this band to the ground-state band. Figure 3 shows gates on some of these transitions. The $E1$ nature of the intraband dipole transitions has been deduced from intensity balance arguments.

Band II is weakly populated (see Table I) and could be followed up to spin $I = \frac{21}{2}$. No parity assignment to the levels of this band could be done since the character of the dipole transitions linking this band to the ground-state band is not known. The two sidebands are connected by two nonobserved transitions of 61.4 and 48.4 keV decaying from the 921.2 and 587.6 keV level of band I, respectively.

III. DISCUSSION

All three bands contain states of both parities, which are connected by $E1$ transitions. This suggests a reflection-asymmetric structure. The strength of $E1$ transitions is frequently deduced from the $B(E1)/B(E2)$ branching ratios in this region of octupole instability. The values of these ratios for the ground-state band and the band I in ^{219}Ra are shown in Fig. 4. On the average, the $B(E1)/B(E2)$ values for the ground-state band extracted from this work are smaller than the ones presented in Ref. [5] and no systematic spin dependence can be observed. The average values are 1.7×10^{-6}, 1.1×10^{-6}, and 2.7×10^{-6} fm^{-2} for the ground-state band, band I, and band II, respectively.

The structure of both sidebands is of vibrational character quite similar to that of the ground-state band. This latter band was interpreted in terms of a weak coupling of the $g_{9/2}$ neutron to the soft quadrupole core of ^{218}Ra [5]. It is a $K = \frac{1}{2}$ band according to calculations made by Leander and Chen [16], who coupled single-particle orbits from a deformed shell model including octupole deformation to a reflection-asymmetric core. (The values employed for the quadrupole and octupole parameters are $\beta_2 = 0.1$ and $\beta_3 = 0.1$.) A large negative decoupling factor $a = -6.4$ was calculated, which gives rise to a $I^\pi = \frac{7}{2}^+$ ground state. An improvement of this theoretical approach has been recently done by Ćwiok and Nazarewicz [17] by calculating independently the equilibrium deformation for each low-lying quasiparticle state. They predicted three bands for ^{219}Ra with $K = \frac{1}{2}$, $\frac{3}{2}$

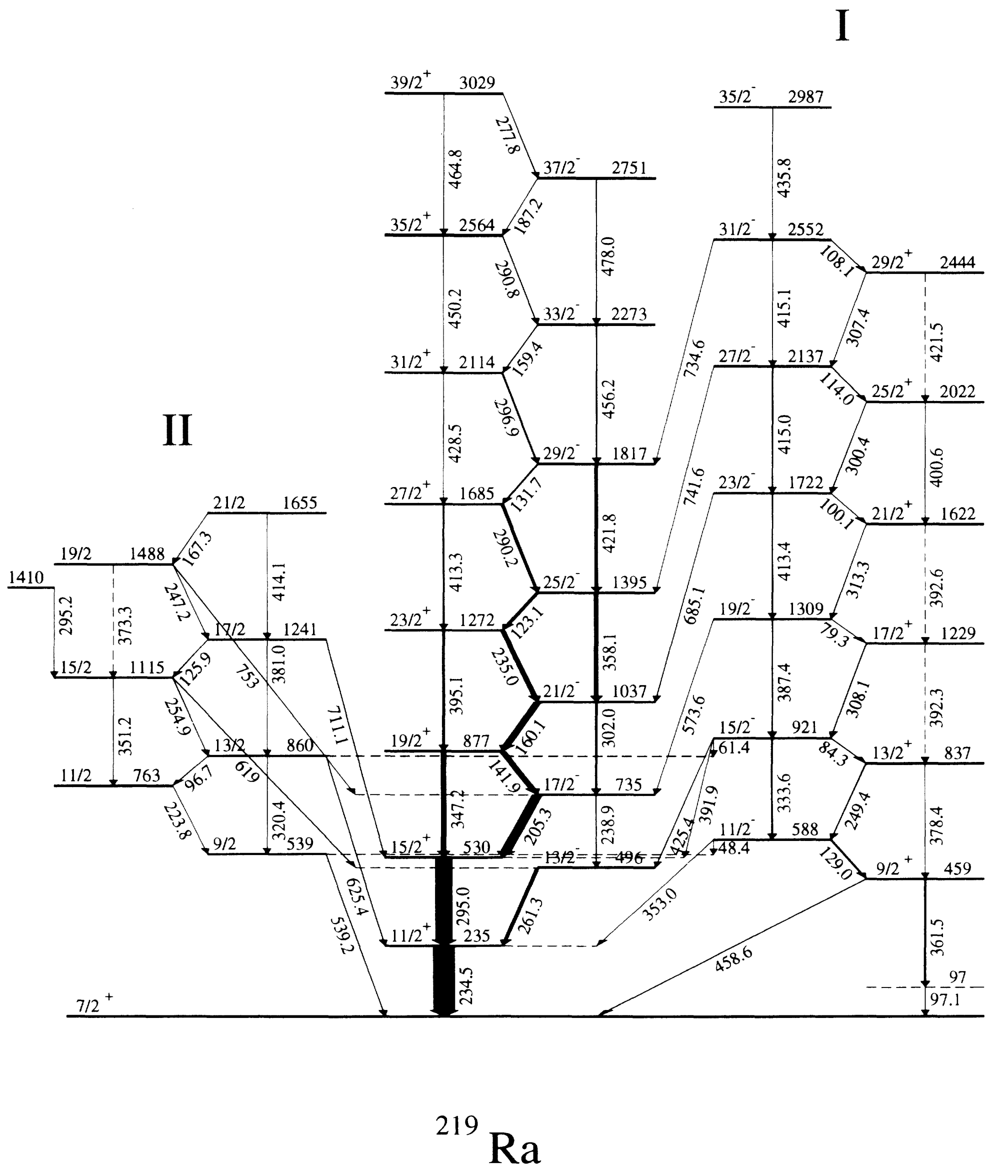

FIG. 2. Level scheme of ^{219}Ra deduced from this work. The ground-state spin and parity is assumed to be $I^\pi = \frac{7}{2}$ (see text).

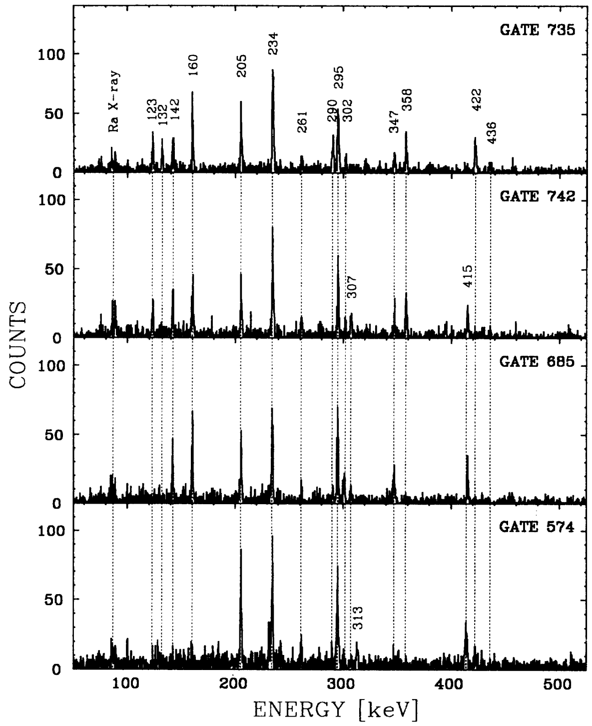

FIG. 3. Gated spectra on some interband transitions. The energies of the gating transitions are given in the figure.

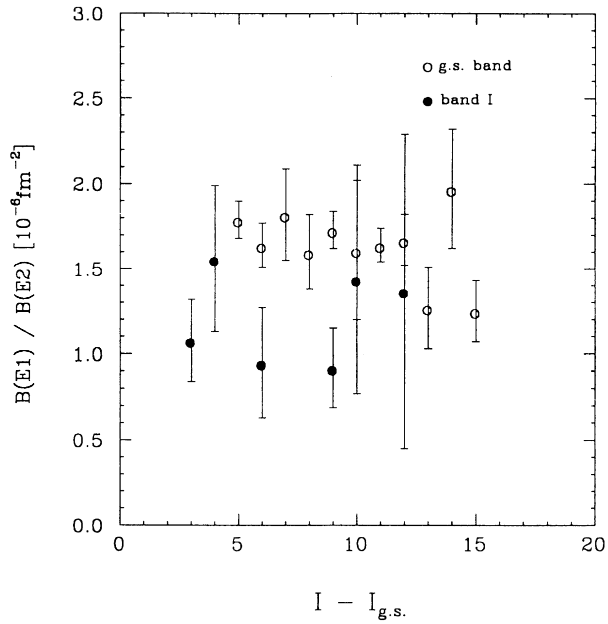

FIG. 4. Branching ratios $B(E1)/B(E2)$ versus spin for the ground-state band (open circles) and the band I (full circles).

and $\frac{5}{2}$ and parity content $\langle\pi\rangle$ between 0.24 and 0.66. If the experimentally observed bands are those predicted, they will not form parity doublets. Support to this interpretation is given by the different average $B(E1)/B(E2)$ ratios for the three bands.

To summarize, the ^{219}Ra nucleus has been studied with a high efficiency detection system. Two sidebands with alternating parity have been found with vibrational-like patterns similar to the ground-state band. The most strongly populated sideband, namely, band I, confirms the structure proposed in [6] and extends it to higher states. Neither of the two new bands appears to be the simplex partner of the ground-state band and so the present level scheme is consistent with the description of ^{219}Ra as composed of three alternating parity bands having different K values.

[1] W. Nazarewicz, P. Olanders, I. Ragnarsson, J. Dudek, and G. A. Leander, Phys. Rev. Lett. **52**, 1272 (1984).

[2] G. A. Leander, W. Nazarewicz, G. F. Bertsch, and J. Dudek, Nucl. Phys. **A453**, 58 (1986).

[3] G. A. Leander and R. K. Sheline, Nucl. Phys. **A413**, 375 (1984).

[4] G. A. Leander, R. K. Sheline, P. Möller, P. Olanders, I. Ragnarsson, and A. J. Sierk, Nucl. Phys. **A388**, 452 (1982).

[5] P. D. Cottle, M. Gai, J. F. Ennis, J. F. Shriner, Jr., D. A. Bromley, C. W. Beausang, L. Hildingsson, W. F. Piel,Jr., D. B. Fossan, J. W. Olness, and E. K. Warburton, Phys. Rev. C **36**, 2286 (1987).

[6] C. Mittag, J. Fernández Niello, F. Riess, and H. Puchta, Ann. Israeli Phys. Soc. **7**, 277 (1984); C. Mittag, Ph.D. thesis, University of Munich, 1989.

[7] S. Khazrouni, A. Chevallier, J. Chevallier, O. Helene, G. Ramanantsizehena, and N. Schulz, Z. Phys. A **320**, 535 (1985).

[8] J. Fernández Niello, C. Mittag, F. Riess, E. Ruchowska, and M. Stallknecht, Nucl. Phys. **A531**, 164 (1991).

[9] M. Dahlinger, E. Kankeleit, D. Habs, D. Schwalm, B. Schwartz, R. S. Simon, J. D. Burrows, and P. A. Butler, Nucl. Phys. **A484**, 337 (1988).

[10] J. R. Hughes, R. Tölle, J. de Boer, P. A. Butler, C. Günther, V. Grafen, N. Gollwitzer, V. E. Holliday, G. D. Jones, C. Lauterbach, M. Marten-Tölle, S. M. Mullins, R. J. Poyntner, R. S. Simon, N. Singh, R. J. Tanner, R. Wadsworth, D. L. Watson, and C. A. White, Nucl. Phys. **A512**, 275 (1990).

[11] C. Bourgeois *et al.*, in *Proceedings of the Twenty-Fifth International Winter Meeting of Nuclear Physics, Bormio, 1987*, edited by I. Iori (Ricerca Scientifica ed. Educazione Permanent, Suppl. No. 56, 1987); F. Beck, in *Conference on Instrument for Heavy-Ion Nuclear Research, Oak Ridge, 1984*, edited by D. Shapira (Harwood Academic, New York, 1985), p. 129.

[12] A. Celler, Ch. Briançon, J. S. Dionisio, A. Lefebvre, C. Vieu, J. Zylicz, R. Kulessa, C. Mittag, J. Fernández Niello, C. Lauterbach, H. Puchta, and F. Riess, Nucl.

Phys. **A432**, 421 (1985).
[13] E. D. Hackett, J. A. Kuehner, J. C. Waddington, and G. D. Jones, Phys. Rev. C **40**, 1234 (1989).
[14] A. M. Y. El-Lawindy, J. D. Burrows, P. A. Butler, J. R. Cresswell, V. Holliday, G. D. Jones, R. Tanner, R. Wadsworth, D. L. Watson, K. A. Connell, J. Simpson, C. Lauterbach, and J. R. Mines, J. Phys. G **13**, 93 (1987).
[15] C. F. Liang, P. Paris, A. Gizon, V. Barci, D. Barneou, R. Beraud, J. Blachot, Ch. Briançon, J. Genevey, and R. K. Sheline, Z. Phys. (to be published).
[16] G. A. Leander and Y. S. Chen, Phys. Rev. C **37**, 2744 (1988).
[17] S. Ćwiok and W. Nazarewicz, Nucl. Phys. **A529**, 95 (1991).