PHYSICAL REVIEW C **80**, 011304(R) (2009)

Parity doubling in ^{219}Th and the onset of collectivity above $N = 126$

W. Reviol,[1] D. G. Sarantites,[1] C. J. Chiara,[1,2,*] M. Montero,[1,†] R. V. F. Janssens,[2] M. P. Carpenter,[2] T. L. Khoo,[2] T. Lauritsen,[2] C. J. Lister,[2] D. Seweryniak,[2] S. Zhu,[2] O. L. Pechenaya,[3,‡] and S. G. Frauendorf[4]

[1]*Department of Chemistry, Washington University, St. Louis, Missouri 63130, USA*

[2]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*

[3]*Department of Physics, Washington University, St. Louis, Missouri 63130, USA*

[4]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*

(Received 21 May 2009; published 15 July 2009)

Excited states in ^{219}Th have been observed for the first time in an experiment using the ^{26}Mg + ^{198}Pt reaction and evaporation-residue-gated γ-ray spectroscopy. Two structures of interlinked alternating-parity levels with simplex quantum numbers $s = \pm i$ are observed, reminiscent of similar sequences in heavier odd-mass isotopes, but only three mass units away from the $N = 126$ neutron closed shell. The emergence of quadrupole-octupole collectivity in this mass region and the trend for parity-doublet bands are discussed.

DOI: 10.1103/PhysRevC.80.011304 PACS number(s): 21.10.−k, 23.20.Lv, 21.60.Ev, 27.80.+w

Indications of the onset of octupole collectivity in the actinide region just above magic neutron number $N = 126$ can be inferred, for example, from the marked difference between the level schemes of ^{218}Th [1] and ^{220}Th [2]. The $N = 128$ isotope exhibits a single $E2$ sequence with decreasing energy spacings between levels as a function of spin. This behavior is attributed to excitations associated with the $(g_{9/2})^2$ valence-neutron multiplet. In contrast, the yrast structure of the $N = 130$ isotope consists of a sequence of successive even- and odd-spin states with alternating parity, similar to those of the heavier even-mass isotopes. However, the spacing corresponding to the $E2$ transitions is approximately constant, a behavior that has been interpreted as due to a reflection-asymmetric tidal wave moving over the nuclear surface. In the heavier isotopes, the spacing increases with spin, i.e., the motion becomes more rotational in character. It is carried by a combination of the collective quadrupole and octupole modes, of which $B(E1)/B(E2)$ ratios of transition probabilities on the order of 10^{-6} fm^{-2} are a benchmark. Traditionally, the collective degree of freedom has been described as static quadrupole-octupole deformation [3]. Recently, the author of Ref. [4] argued that an interpretation in terms of the condensation of octupole phonons may be more appropriate, and supporting evidence has recently been proposed in the case of ^{240}Pu [5]. In this framework, the tidal-wave motion and octupole rotation are two expressions of the same general phenomenon [4].

As discussed in Ref. [6], the symmetry of the collective distortion (mean field) dictates the spin-parity sequence of the bands. If the angular momentum is perpendicular to a reflection plane of the octupole shape, the band consists of an alternating-parity sequence, labeled by the simplex quantum number s,[1] which fixes the parity for a given spin. For the even-N nuclei under consideration, $s = 1$. If the angular momentum is not perpendicular to the reflection plane, s is no longer a good quantum number. Then, so-called parity doublets are present, i.e., pairs of states nearly degenerate in energy with the same spin but opposite parity [3]. This evidence for octupole correlations occurs in odd-N and odd-Z nuclei, where the unpaired nucleons may carry an angular momentum component parallel to the symmetry plane (the component K along the symmetry axis in the case of axial symmetry). In this instance, to demonstrate the presence of parity doublets, it is important that both sequences belonging to the simplex quantum number be observed (for half-integer spin, $s = \pm i$), and the $B(E1)/B(E2)$ benchmark introduced above provides an additional means to confirm that octupole correlations are, indeed, strong. The best example thus far for parity-doublet bands is the ^{223}Th ($N = 133$) nucleus [7], and there are two additional clear cases in ^{225}Th [8] and ^{221}Ra [9]. These three examples can be contrasted with the situation in the nearby nuclei ^{221}Th [7] and ^{219}Ra [10] where parity doublets are absent. In ^{221}Th, only one band with strong $E1$ transitions has been reported, while in ^{219}Ra several such bands are observed, one being yrast. The latter two examples can be viewed as cases where simplex is a good quantum number.

Here, we present a level scheme for ^{219}Th and discuss its $s = -i$ and $+i$ sequences. With 129 neutrons, the ^{219}Th nucleus is found to exhibit transitional character. Evidence is found for the onset of the quadrupole-octupole collectivity that becomes prominent in the heavier Th isotopes, while manifestations of few-nucleon excitations characteristic of the lighter isotopes is recognizable as well. Surprisingly, the parity doublets absent in ^{221}Th reappear in ^{219}Th.

Prior to this work, no excited states had been reported in the ^{219}Th nucleus. Here, the 128-MeV ^{26}Mg + ^{198}Pt → ^{224}Th* reaction was used, leading to ^{219}Th in the 5n evaporation channel. The measurement is a by-product of an experiment aimed at studying ^{220}Th and described in detail in Ref. [2]. The

*Present address: Department of Chemistry and Biochemistry, University of Maryland, College Park, Maryland 20742, USA.

†Present address: Department of Physics, Stanford University, Stanford, California 94305, USA.

‡Present address: Department of Radiation Oncology, Washington University School of Medicine, St. Louis, Missouri 63130, USA.

[1] $s = p\, e^{i\pi I}$, where p and I represent parity and spin, respectively.

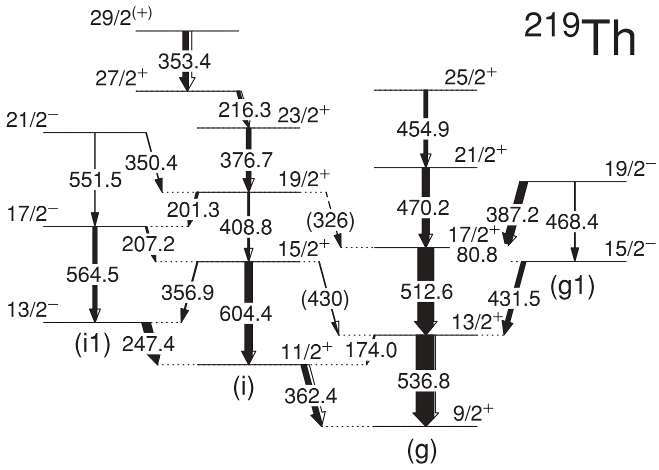

FIG. 1. Partial level scheme for ^{219}Th. Transitions indicated as dashed arrows and parities given in parentheses are tentative. The transition energies are given in keV. The widths of the filled and open parts of the arrows are proportional to the γ-ray and internal conversion intensities, respectively. Labels for level sequences are introduced to ease the discussion in the text.

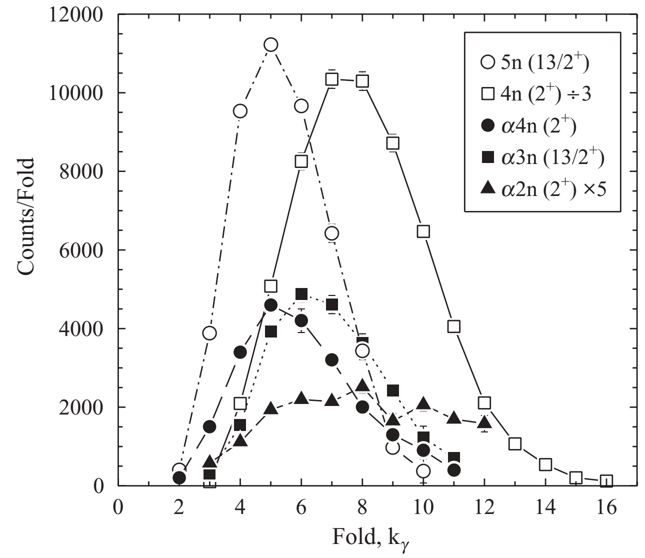

FIG. 2. Total γ-ray fold distributions for the ground-state transitions of ^{219,220}Th and $^{216-218}$Ra. The distributions for ^{220}Th + $4n$ and ^{218}Ra + $\alpha 2n$ are normalized to ease the comparison with the other channels.

detector setup consisted of the Gammasphere spectrometer [11,12], comprising 98 HPGe detectors with BGO Compton suppression shields, and the 64-element evaporation-residue (ER) detector HERCULES [13]. An early account of the structure of ^{219}Th can be found in Ref. [14].

Figure 1 provides a partial level scheme of ^{219}Th containing the strongest transitions in this nucleus. The isotopic assignment of prominent γ rays, such as the 536.8-keV $13/2^+ \rightarrow 9/2^+$ transition, relies on the yield of coincident x rays. The mass assignment is based on two analyses with consistent results: (1) the total γ-ray fold (k_γ) distribution, a quantity that includes the hits in both HPGe and BGO elements of the array and provides an indication of the γ-ray multiplicity, and (2) the γ-ray yields of representative transitions for different HERCULES time-of-flight ranges. The former result is presented in Fig. 2, while the latter was discussed in Ref. [14]. From Fig. 2, it can be seen that the 536.8-keV line in ^{219}Th has the lowest mean k_γ value. Compared with the ^{220}Th case, an additional neutron is evaporated, leaving the ER nucleus with less excitation energy and a lower entry spin, leading to a lower average γ-ray multiplicity. A consistent picture emerges from the analysis which also includes the $\alpha 2n$ to $\alpha 4n$ channels, the other strong reaction products [2].

The ground state of ^{219}Th is proposed to have spin-parity $9/2^+$, an assignment also reported for the $N = 129$ isotones ranging from ^{217}Ra to ^{211}Pb and attributed to the $(g_{9/2})^3$ seniority-one state [15]. Further support for this assignment comes from the observation that the ground-state spin-parities of the neighboring Th isotopes ($N = 127$ and $N \geqslant 131$) match those of the corresponding Ra isotones, and it is unlikely that ^{219}Th would break this trend.

The level scheme is based on the observed coincidence relationships, transition intensities, and transition-energy sums. For most transitions, γ-ray angular distributions were measured and spins firmly established assuming stretched $E1$, $M1$, and $E2$ transitions only. The full account of this work, including the complete level scheme, is forthcoming [16]. Sample coincidence spectra for ^{219}Th are given in Fig. 3. The spectrum in panel (a) represents the ground-state sequence labeled "g" and a set of states labeled "g1" in Fig. 1. Spectra (b) and (c) provide justification for the level sequences labeled "i" and "i1". Notably, the 362.4-keV transition is not coincident with the 536.8-keV ground-state transition. The 564.5-keV γ ray is one of the next higher lying transitions and is not coincident with the prominent 207.2, 408.8, and 604.4-keV transitions. The negative-parity assignment for sequence "i1" is based on features described in the next paragraphs. The structure composed of "i" and "i1" resembles, at medium spin, the characteristic pattern of $E1$ and crossover $E2$ transitions indicative of octupole correlations, i.e., the characteristic "zigzag" pattern. Sequences "g" and "g1" also give rise to an octupole-type structure, although the zigzag pattern is less obvious because of the large parity splitting ($\delta E \sim 180$ keV.[2]) Note that the high-spin transitions between the states with $I \geqslant 23/2$ feed both the "i" and "g1" sequences, but the feeding of the latter occurs in multiple steps (not shown in Fig. 1).

The following three characteristic features are worth noting about the "i1" sequence:

(i) *Absence of E2 transitions to sequence "g"*. The significance of the spectrum extension shown in the inset of Fig. 3(a) is the absence of a $E_\gamma \sim 677$-keV transition (around channel 1354). If the $21/2^-$ state was of positive parity, such a transition would be expected to connect this level to the $17/2^+$ state that decays with the 512.6-keV transition. A related aspect is the absence of a $E_\gamma \sim 610$-keV line (around channel 1220) in the spectrum of Fig. 3(c). If the $13/2^-$ state was of positive parity, such a

[2] $\delta E = E(I^-) - E_{\rm ref}(I^+)$ with $E_{\rm ref}(I^+) = [(I+1)(E(I-1)^+) + I(E(I+1)^+)]/[2I+1]$.

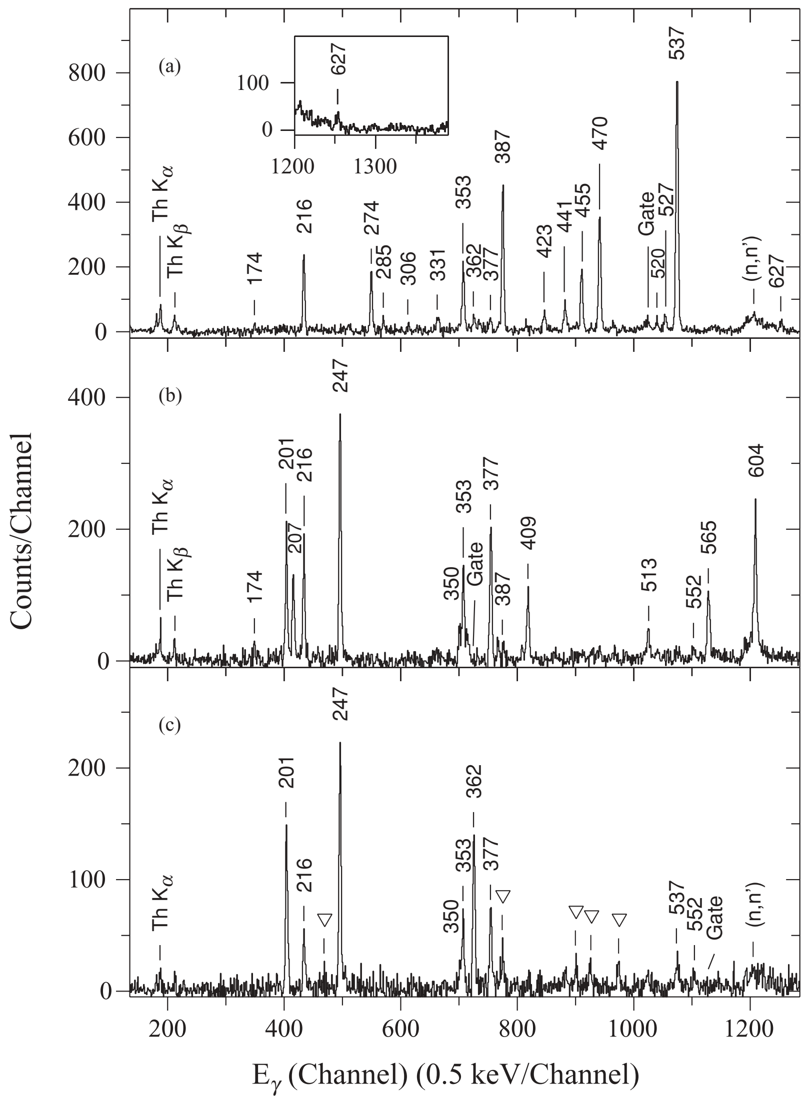

FIG. 3. Representative ER-gated γ-ray coincidence spectra for ^{219}Th. The gating γ-ray transitions have the respective energies of (a) 512.6, (b) 362.4, and (c) 564.5 keV. The inset in panel (a) displays a spectrum extension relevant to the discussion in the text. The spectrum in panel (c) is contaminated by ^{220}Th γ rays. These are labeled by triangles. Note that not all γ rays assigned to ^{219}Th are shown in the level scheme of Fig. 1.

transition would be expected as a direct link to the ground state. As these scenarios are ruled out, the sequences "i1" and "g" have opposite parity.

(ii) *Total-intensity balance for the* $13/2^-$ *state.* For the low-lying 247.4-keV dipole transition, the $E1$ assignment is supported further by considering the balance between the total feeding and decay intensities, as a transition of $M1$ character would result in a decay intensity for the second 13/2 state exceeding the feeding strength by an unlikely factor of 3.

(iii) *Linear-polarization measurement.* Following the technique of using the Gammasphere segmented Ge detectors as a γ-ray polarimeter [12], a linear-polarization effect was measured for some crucial transitions in ^{219}Th. An algorithm has been devised[3] to obtain two subsets of γ-ray events: those with their energy deposited in one side of the segmented detector, called "confined" (C), and those where the photon energy is shared between the two sides, called "shared" (S). The corresponding spectra, obtained with an ER coincidence gate and a gate on the 564.5-keV transition in the "i1" sequence, are presented in Figs. 4(a) and 4(b). The difference spectrum $\eta C - S$ of Fig. 4(c), where η is an energy-dependent normalization, represents the polarization and, as shown in Ref. [12], is positive for electric transitions, negative for magnetic ones, and consistent with zero for mixed $E2/M1$ cases. Among the crucial dipole transitions, the 201.3 and 247.4-keV transitions display the anticipated $E1$ behavior, while the 362.4-keV γ ray has $M1$ character. Figure 4(d) presents the function $\eta = S/C$, obtained from a fit to ^{152}Eu source data, together with the η values for the ^{219}Th transitions under discussion. From this plot, the distinction between $E1$ and $M1$ character is also obvious.

The combinations of the sequences "i", "i1" and "g", "g1" can be grouped into simplex bands with $s = -i$ and $s = +i$, respectively. These simplex bands are characterized by $B(E1)/B(E2)$ ratios of the same order of magnitude as

[3]The algorithm is similar to the one providing the hit position of the γ ray incident on the segmented Ge detector, used for reducing Doppler broadening, and will be reported in Ref. [16].

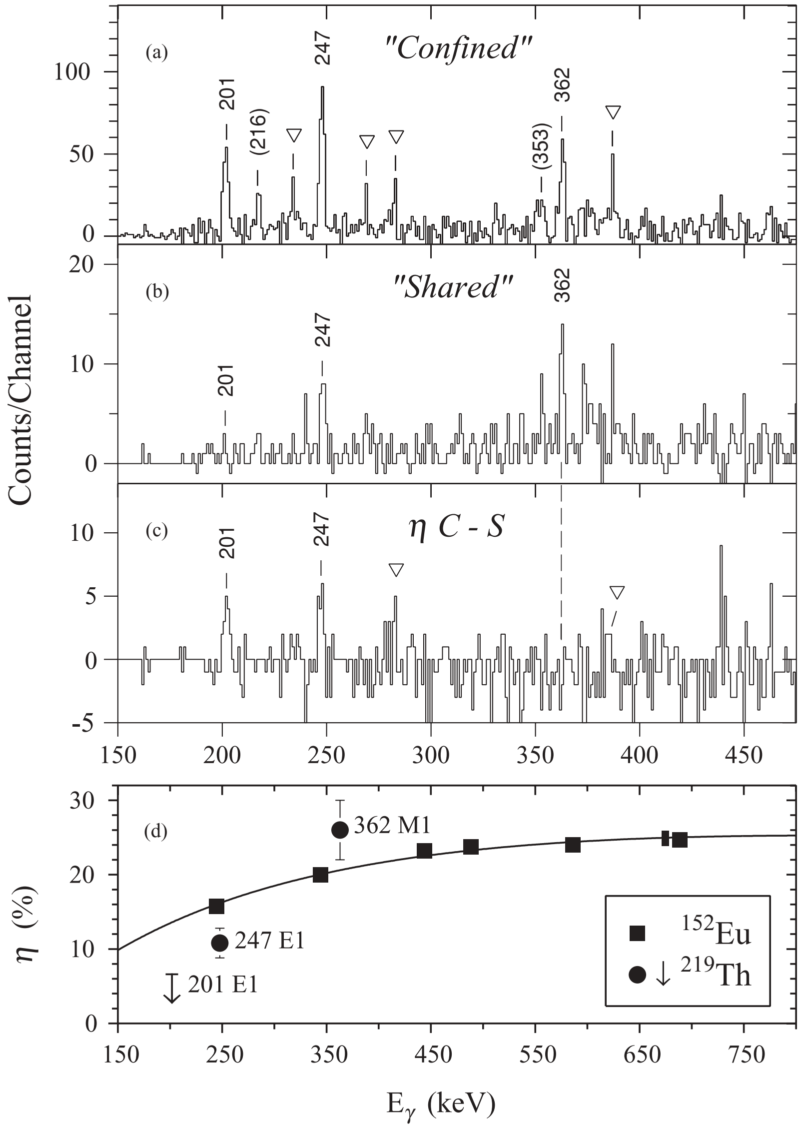

FIG. 4. Linear polarization analysis for ^{219}Th γ rays coincident with the 564.5-keV transition. Spectra (a) and (b) contain the "confined" events C and "shared" events S, respectively, (c) is the difference spectrum $\eta C - S$. Panel (d) provides the normalization function $\eta(E_\gamma)$, based on ^{152}Eu source data, together with the η values for the 201.3, 247.4, and 362.4-keV transitions in ^{219}Th. The data point for $E_\gamma = 201.3$ keV is an upper limit. See text for further details.

those in the heavier Th isotopes. For the $s = -i$ structure, the average value of these ratios is $1.2(2) \times 10^{-6}$ fm^{-2} and, in fact, the $B(E1)/B(E2)$ ratio for the 15/2$^+$ state is only 1/4 of those for the higher lying states, which scatter around 1.6×10^{-6} fm^{-2}. For the $s = +i$ structure, the average value is $2.4(9) \times 10^{-6}$ fm^{-2}. For reference, the ratios for the 15/2$^+$ and 17/2$^-$ states in ^{221}Th scatter around a value of 2.4×10^{-6} fm^{-2}. Any decrease of these ratios, when approaching neutron magicity, should be associated with a loss in dipole strength reflecting a gradual loss in quadrupole-octupole collectivity.

To provide an interpretation of the ^{219}Th level structure, the reader is referred to Fig. 4 of Ref. [17], in which the energies of neutron levels are given as a function of the quadrupole and octupole deformations. In the absence of static octupole deformation, at $N = 129$, the lowest lying configurations are $(g_{9/2})^3$ and $i_{11/2}(g_{9/2})^2$, which give rise to the positive-parity members of the $s = +i$ and $s = -i$ bands, respectively. The negative-parity states in both cases are then proposed to result from the coupling of these two configurations with the octupole phonon. The observation that the "i" sequence, based on the $i_{11/2}(g_{9/2})^2$ configuration, displays energy spacings decreasing in energy with spin as in ^{218}Th ($N = 128$) and extends to the maximally aligned 27/2$^+$ state is consistent with this interpretation. Similarly, the fact that the other main sequence of $E2$ transitions, based on the $(g_{9/2})^3$ configuration, exhibits essentially constant spacings as in ^{220}Th ($N = 130$) and exceeds the maximum spin of 21/2 for that configuration through a "vibration-like" structure is consistent with this interpretation as well.

Further support for this interpretation comes from the absence of a simplex partner in the ^{217}Ra isotone [18]. The ^{219}Th and ^{217}Ra schemes are compared in Fig. 5. While the positive-parity levels are nearly the same, the sequence "i1" in ^{219}Th, i.e, the simplex partner of "i", has no counterpart in ^{217}Ra. This difference is understood as resulting from the decrease with Z of the softness of the octupole mode for $Z < 90$ (see Fig. 7 of Ref. [3]). Thus, there is no low-lying octupole vibration in ^{217}Ra, and the simplex partners of the positive-parity states cannot be generated at energies similar

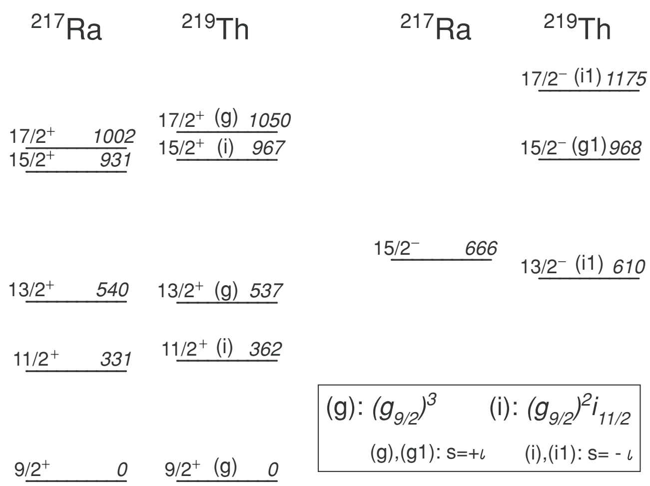

FIG. 5. Comparison of the lowest lying states in the isotones ^{217}Ra and ^{219}Th. States are displayed separately according to parity. Excitation energies are given in keV. Additional labels for ^{219}Th and assignments in the figure legend are discussed in the text.

to those in ^{219}Th. Note that the $15/2^-$ state in ^{217}Ra corresponds, instead, to the occupation of the $j_{15/2}$ neutron orbital (cf. Ref. [18]).

However, two additional observations suggest that the present interpretation needs to be complemented by further considerations. These observations are (1) the presence of $M1$ transitions deexciting the levels of sequence "i" toward states of sequence "g" in competition with the $E1$ transitions linking the same "i" states to the "i1" levels and (2) the presence of parity doublets in a range of states $13/2 \leqslant I \leqslant 19/2$ in ^{219}Th. The $M1$ transitions indicate that the angular momentum must have a component within the symmetry plane. This tilt of the rotational axis breaks the simplex symmetry and generates the parity doublets, as mentioned in the introductory paragraphs. It is the odd neutron occupying an orbital with a substantial $K = 3/2$ component emanating from the $g_{9/2}$ state that is responsible for the tilt. Since ^{219}Th does not exhibit rotational-like behavior, the emerging picture is that of a tidal wave running across the surface of the nucleus. The appearance of parity doublets at $N = 129$, 133, and 135, but not at $N = 131$, can be explained as follows. From Fig. 4 of Ref. [17], the odd neutron should, at moderate axial quadrupole-octupole deformation ($\beta_2 \sim 0.1$, $\beta_3 \sim 0.1$), be expected to occupy orbitals with $K = 3/2$ at $N = 135$, $K = 5/2$ at $N = 133$, $K = 1/2$ at $N = 131$, and $K = 3/2$ at $N = 129$. The $K = 3/2, 5/2$ orbitals naturally tilt the rotational axis with respect to the normal to the symmetry plane and generate parity doublets. This tilt is absent for $K = 1/2$ with the implication that simplex is a good quantum number and no parity doublets occur at $N = 131$.

The interpretation of the ^{219}Th level scheme requires invoking two complementary aspects. On the one hand, the pattern characteristic of the quadrupole-octupole collective mode (parity doublets and strong $E1$ linking transitions) seen in the heavier isotopes can already be recognized in this nucleus. On the other, the pattern is not completely regular, and the distortions (irregular level spacing and the presence of $M1$ transitions) can be seen as a signature of generating angular momentum within the limited space of a few valence neutrons. Such ambivalent behavior is expected for a transitional nucleus at the borderline of the region where the collective pattern emerges.

In conclusion, the ^{219}Th nucleus exhibits features indicative of the presence of significant octupole correlations and marks the onset of octupole collectivity in the light-actinide region. The parity doublets, characteristic of ^{223,225}Th and absent in ^{221}Th, reappear, just three units away from $N = 126$. The symmetries of the rotating mean field impact the level structure already at the very onset of collective motion, while the underlying single-particle structure can still be recognized. Parity doublets occur in odd-N and odd-Z octupole nuclei, because there is an angular momentum component within one of the reflection planes. The exceptions are the $K = 1/2$ band structures (and $K = 0$ bands in even-even and odd-odd nuclei) without such component, which appear as single alternating-parity sequences.

The authors thank J. Elson (WU) and J. Rohrer (ANL) for technical support and J. P. Greene (ANL) for the preparation of the target. One of the authors (W.R.) acknowledges inspiring discussions with I. Y. Lee. This work was supported by the US Department of Energy, Office of Nuclear Physics, Grant Nos. DE-FG02-88ER-40406, DE-AC02-06CH11357, and DE-FG02-95ER40934.

[1] W. Bonin, H. Backe, M. Dahlinger, S. Glienke, D. Habs, and E. Hanelt, Z. Phys. A **322**, 59 (1985).
[2] W. Reviol *et al.*, Phys. Rev. C **74**, 044305 (2006).
[3] P. A. Butler and W. Nazarewicz, Rev. Mod. Phys. **68**, 349 (1996), and references therein.
[4] S. Frauendorf, Phys. Rev. C **77**, 021304(R) (2008).
[5] X. Wang *et al.*, Phys. Rev. Lett. **102**, 122501 (2009).
[6] S. G. Frauendorf, Rev. Mod. Phys. **73**, 463 (2001).
[7] 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).
[8] J. R. Hughes *et al.*, Nucl. Phys. **A512**, 275 (1990).
[9] F. Fernandez-Niello, C. Mittag, F. Riess, E. Ruchowska, and M. Stallknecht, Nucl. Phys. **A531**, 164 (1991).
[10] M. Wieland *et al.*, Phys. Rev. C **45**, 1035 (1992).
[11] I. Y. Lee, Nucl. Phys. **A520**, 641c (1990).
[12] G. J. Schmid *et al.*, Nucl. Instrum. Methods A **417**, 95 (1998).
[13] W. Reviol, D. G. Sarantites, R. J. Charity, C. J. Chiara, J. Elson, M. Montero, O. L. Pechenaya, S. K. Ryu, and L. G. Sobotka, Nucl. Instrum. Methods A **541**, 478 (2005).
[14] W. Reviol, D. G. Sarantites, C. J. Chiara, M. Montero, and O. L. Pechenaya, Acta Phys. Pol. B **38**, 1547 (2007).
[15] *Table of Isotopes*, 8th ed., edited by R. Firestone and V. Shirley (Wiley, New York, 1996), Vol. II.
[16] W. Reviol *et al.* (in preparation).
[17] G. A. Leander and Y. S. Chen, Phys. Rev. C **37**, 2744 (1988).
[18] N. Roy, D. J. Decman, H. Kluge, K. H. Maier, A. Maj, C. Mittag, J. Fernandez-Niello, H. Puchta, and F. Riess, Nucl. Phys. **A426**, 379 (1984).