Parity doublet structures in doubly-odd ^{216}Fr

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Parity doublet structures are established in ^{216}Fr, which lies at the lower boundary of enhanced octupole collectivity in the trans-lead region. The newly identified levels are established as the simplex partner of a previously reported band leading to parity doublets with small (~55 keV) average energy splitting, a feature typical of nuclei with near-static octupole deformation. The observed levels do not follow a regular pattern of rotational bands, indicating low quadrupole collectivity. However, enhanced octupole correlations are evident from the small energy splitting and large $B(E1)/B(E2)$ values. Staggering in $E1$ transition energies and $B(E1)/B(E2)$ ratios is noted. The enhancement of octupole correlations in ^{216}Fr is attributed to the availability of a neutron orbital with a $K = 3/2$ component.

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I. INTRODUCTION

Nuclei near doubly-magic ^{208}Pb possess spherical shape, while nuclei with static octupole deformation are predominantly found in the Ra-Th region with $A \approx 220$ [1–4]. The emergence of the octupole deformation is attributed to the presence of proton and neutron orbitals near the Fermi surface which differ by Δj, $\Delta l = 3$. With addition of nucleons to the $Z = 82$ and $N = 126$ magic numbers, the proton $f_{7/2}$, $i_{13/2}$ and neutron $g_{9/2}$, $j_{15/2}$ orbitals approach each other near the Fermi surface for nuclei around $Z = 88$ and $N = 134$, as a result of the deformed nuclear mean field. The region around ^{224}Th ($Z = 90$, $N = 134$) can be considered as a center of stable octupole deformation. As one moves away from the central region towards the heavier nuclei, a transitional region is encountered, where band-like structures built on octupole surface vibrations have been reported in nuclei near ^{236}U ($Z = 92$, $N = 144$) [5]. On the other hand, moving away from ^{208}Pb towards the central region, octupole correlations suddenly emerge, precisely at $N = 129$ [6–8]. In fact, ^{216}Fr ($Z = 87$, $N = 129$) is identified as the lightest nucleus in the trans-lead region which displays characteristic behavior of octupole correlations [6]. However, no simplex partner [9] has been identified earlier [6], as expected if sufficient octupole correlations are present.

The octupole correlations manifest themselves in sequences of alternating-parity levels connected by $E1$ transitions. Furthermore, in the case of odd-A and odd-odd nuclei with stable octupole deformation, so-called parity doublet structures are expected [3,4]. These are pairs of nearly degenerate energy levels of the same spin but opposite parity. Different experimental indicators were further established to understand the degree of octupole correlations [3,4]. Several experimental efforts, with the aim to understand evolution of octupole correlations and to search for stable octupole deformation, were focused mainly on even-even isotopes of Rn, Ra, and Th [1,10–16] and odd-A isotopes of Rn ($Z = 86$) to Th ($Z = 90$) [8,17–25]. The data have revealed that even-even isotopes of radium and thorium with $N = 132$, 134 and odd-A with $N = 133$ provide some of the best examples of nuclei having stable octupole deformation [15,20,23,26–28]. The first experimental evidence of octupole to quadrupole shape change was reported recently for ^{223}Th at the highest spin around rotational frequency $\hbar\omega = 0.23$ MeV [29].

It is evident from the foregoing discussion that experimental data have established a region of octupole deformation. However, very little is known about the excited states in nuclei near the lower edge of this region where the octupole correlations just start developing. Recently, some efforts [30] were made to locate the lower mass boundary of the region of statically octupole-deformed nuclei. A large energy splitting between the simplex partner bands in ^{219}Ra suggests its transitional nature [30], and it was concluded that ^{220}Ra is the lightest radium isotope with stable octupole deformation. High-spin states have revealed parity-doublet structures in ^{220}Ac, which is an isotone ($N = 131$) of ^{219}Ra and provides the first example of a doubly-odd nucleus in which stable octupole deformation has been established [31]. It was found that the measured $B(E1)/B(E2)$ ratios in ^{220}Ac are the largest among all nuclei in

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this region. Only ^{216,218}Fr and ^{218}Ac are examples of other odd-odd nuclei in which alternating-parity sequences connected by $E1$ transitions have been reported [6,7,32,33], and only in the case of ^{218}Ac a simplex partner band has been identified [7]. In view of this, and to understand the evolution of octupole correlations at the lower edge of this region, a high-spin study of ^{216}Fr was performed. The data reveal striking similarity between the values of energy splittings over the range of spins in ^{223}Th and ^{216}Fr, indicating significant octupole correlations. It is particularly interesting to note that, although various theoretical calculations [34–39] were employed to understand and predict region of octupole deformed nuclei, only Ref. [38] lists ^{216}Fr as a nucleus with substantial ocutpole deformation ($\beta_3 = 0.073$). The theoretical results presented in Ref. [38] also indicate much smaller quadrupole deformation, $\beta_2 = 0.019$.

II. EXPERIMENTAL DETAILS AND DATA ANALYSIS

Excited states in ^{216}Fr were populated using the ^{208}Pb(^{11}B,3n) reaction. A self-supporting target of ∼6 mg/cm^2 thickness was bombarded by the beam from the 15-UD pelletron accelerator at IUAC, New Delhi. The excitation function with beam energies in the 54–62 MeV range was determined at the beginning of the experiment. Figure 1 illustrates the singles γ-ray spectra recorded at 54 and 62 MeV. The results reported in this paper are obtained from the data at 57 MeV. The γ rays emanating from the excited states of the residual nuclei were detected using the Indian National Gamma Array (INGA) at IUAC, New Delhi. The array consisted of 14 Compton-suppressed clover detectors which were positioned at 90°, 123°, and 148° with respect to the beam direction. The data in coincidence mode were acquired using CANDLE [40]. These data were sorted into various two- and three-dimensional histograms compatible with RADWARE [41]. The level structure of ^{216}Fr was deduced from coincidence γ-γ matrices and γ-γ-γ cubes, which were analyzed using ESCL8R and LEVIT8R [41], respectively. The γ-ray energies, intensities, and branching ratios were extracted from singles and γ-ray gated spectra from γ-γ matrices. The multipolarity of the γ transitions were deduced from directional correlations of oriented states (DCO) [42] and integrated polarization Directional correlations from oriented nuclei (IPDCO) [43,44] analysis. An asymmetric γ-γ matrix containing γ-ray energies recorded in the detectors at 90° on one axis, while those from the remaining detectors on the other axis was constructed for the DCO measurements. The spectra corresponding to the two axes were generated by projecting a judiciously chosen coincident transition of known multipolarity onto both the axes. The DCO ratio ($R_{\rm DCO}$) for the transition of interest was extracted from these spectra by determining the ratio of the intensity of the transition in the spectrum at backward detectors to that in the detectors at 90°. In the present data analysis, the values of $R_{\rm DCO}$ were found to be ≈0.5 for a dipole transition and ≈1.0 for a quadrupole transition when the spectra were obtained with a gate on a stretched quadrupole transition, while the corresponding values of $R_{\rm DCO}$ are twice as large when the spectra with a gate on a pure dipole transition were used. Furthermore, two asymmetric matrices were constructed with one axis corresponding to the energies of γ rays scattered either in parallel or in the perpendicular segment (with respect to the emission plane) of the 90° detectors while the other axis with the γ ray energies recorded by all the detectors. The ratio (Δ) of the difference between the number of perpendicular and parallel scattered γ rays; and their sum was determined. The positive and negative values of Δ indicate the electric and magnetic nature of the γ transition, respectively.

III. EXPERIMENTAL RESULTS

The partial level scheme of ^{216}Fr deduced from the present work is shown in Fig. 2. The experimental excitation function indicates that the 3n-evaporation channel, leading to ^{216}Fr, carries the maximum cross section at 54 MeV, as illustrated in Fig. 1(a), while the 4n-channel, which yields ^{215}Fr, dominates at 62 MeV [Fig. 1(b)]. A comparison of singles γ-ray spectra at these beam energies (Fig. 1) clearly reveals the presence of

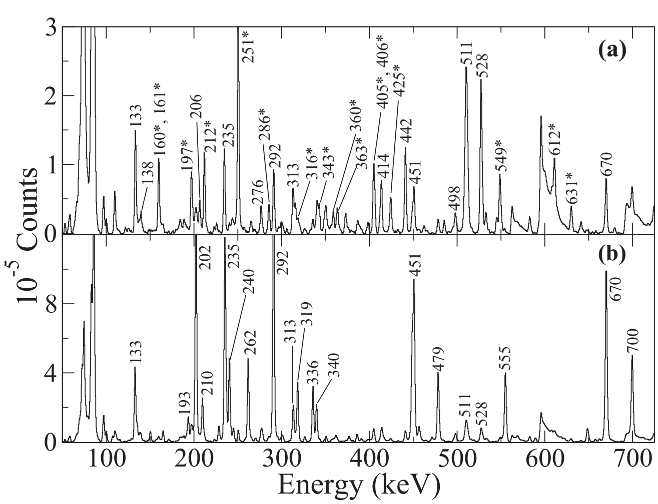

FIG. 1. Smooth Compton-background-subtracted singles γ-ray spectra illustrating transitions observed at (a) 54 MeV and (b) 62 MeV beam energies. The transitions marked with an asterisk are new.

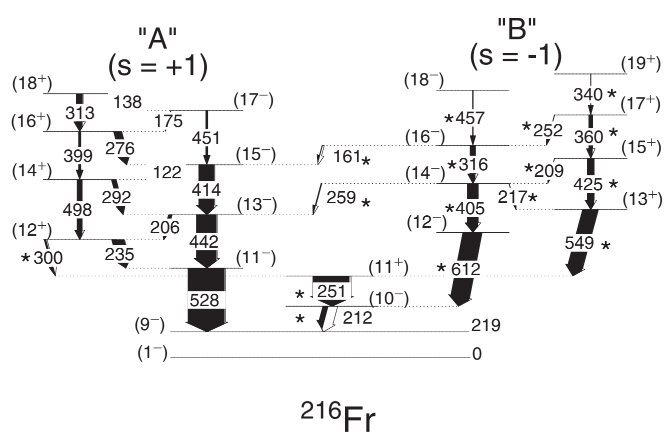

FIG. 2. The partial level scheme of ^{216}Fr obtained from the present work. All the transitions are labeled with their energies in keV. Widths of the solid and open area of the arrows are proportional to intensities of γ rays and internal conversion electrons, respectively. The newly identified transitions are marked with an asterisk.

TABLE I. Table of level energies, spin-parity of the depopulated level (J_i^π), γ-ray energies, and relative γ intensities (I_γ) of ^{216}Fr. The uncertainties in the energies are within 0.5 keV.

E_{level} (keV)	J_i^π	E_γ (keV)	I_γ
Sequence "A"			
747	11^-	527.7	1000.9(36)
982	12^+	235.1	325.1(15)
		300.0	45.4(4)
1189	13^-	206.4	90.2(7)
		441.5	544.8(21)
1480	14^+	291.9	124.7(9)
		498.4	135.9(10)
1603	15^-	122.3	55.7(9)
		414.4	417.7(20)
1879	16^+	276.4	210.0(12)
		399.0	60.7(7)
2054	17^-	174.8	9.02(4)
		451.3	50.8(6)
2192	18^+	138.2	108.8(10)
		313.0	166.6(12)
Sequence "B"			
1043	12^-	611.5	512.3(47)
1231	13^+	549.1	410.3(23)
1448	14^-	216.8	8.0(2)
		405.1	286.5(15)
1656	15^+	208.5	5.6(2)
		425.3	180.2(10)
1764	16^-	316.0	136.9(10)
2016	17^+	252.1	9.3(3)
		359.6	99.4(7)
2221	18^-	457.0	19.1(4)
2356	19^+	340.0	9.6(2)
Remaining transitions			
431	10^-	212.0	141.7(16)
682	11^+	250.7	1000.0(17)
1448	14^-	259.4	11.8(6)
1764	16^-	161.0	12.3(7)

several new transitions in ^{216}Fr. The comparison suggests that the 251 keV transition is the most intense among the newly observed γ rays. Further analysis reveals that the 251 keV transition, in fact, has the same intensity (Table I) as that of the 528 keV transition, which was reported to have the highest intensity in the previous work [6]. A possible explanation for missing such a strong transition in the earlier study could be as follows. The level scheme reported by Debray *et al.* [6] was deduced using only five Compton-suppressed high-purity germanium (HPGe) detectors with the same reaction at 57 MeV of incident beam energy. At this energy, both ^{215}Fr and ^{216}Fr have comparable cross sections, which makes it difficult to uniquely assign the newly observed transitions to either of these isotopes, if the levels are connected via weak linking transitions. It is apparent from the present data analysis that the 251 keV transition is linked to the earlier reported level scheme via a weak 300 keV $M1$ transition with significant conversion coefficient (≈0.65) [45]. Such a transition might have been beyond the observational limit of the earlier γ-ray detection system.

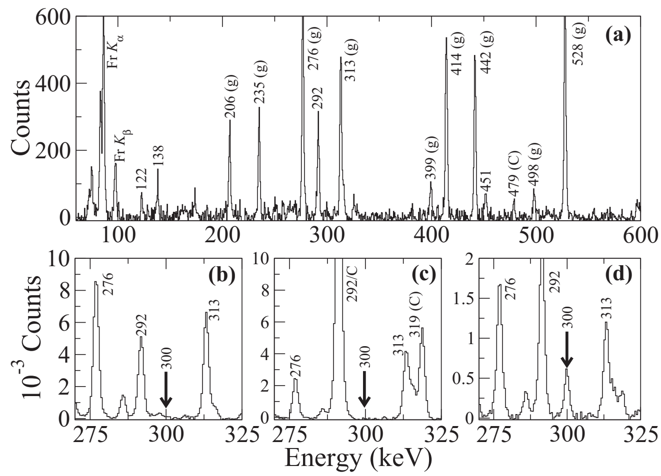

FIG. 3. Coincidence γ-ray spectra illustrating transitions in (a) summed double gates of the transitions in sequence "A" of Fig. 2. The transitions used for the gating are marked with the letter "g". The lower panels show parts of three spectra obtained from gates on the (b) 528, (c) 235, and (d) 206 keV transitions. The transitions marked with "C" are contaminants from ^{215}Fr. Also, note that not all the transitions assigned to ^{216}Fr could be placed in the level scheme of ^{216}Fr in Fig. 2.

Figure 3(a) shows a coincidence γ-ray spectrum obtained from the summed double gates on transitions (528-, 442-, 414-, 498-, 399-, 235-, 206-, and 276 keV) in sequence "A" of the level scheme. All the transitions assigned to ^{216}Fr in the work of Debray *et al.* [6] are clearly visible. It can be seen from the three lower panels of Fig. 3 that the 300 keV transition is coincident with the 206 keV, but not with the 528 and 235 keV transitions. Although the 300 keV γ-ray gated spectrum [Fig. 4(a)] is contaminated by transitions from ^{215}Fr, a strong 251 keV γ ray and coincident transitions from the sequence "A" are visible. This coincidence relationship secures the position of the 300 keV transition as shown in the level scheme (Fig. 2). Furthermore, intensity balance, the DCO and IPDCO ratios [Figs. 5(a) and 5(b), respectively] confirm the $M1$ nature of the 300 keV transition. Coincident spectra illustrating transitions in the negative and positive parity bands of the sequence "B" are shown in Figs. 4(b) and 4(c), respectively. Some of the newly identified transitions such as 160-, 164-, and 343 keV could not be placed in the level scheme. It is evident from the analysis that the states with same spin in the sequences "A" and "B" have opposite parity and constitute simplex partner bands. The level structure of reflection asymmetric nuclei is described in terms of the simplex quantum number (s) [9]. In even-even and odd-odd nuclei $s = +1$ is assigned to a $0^+, 1^-, 2^+, 3^-, \dots$ sequence, and $s = -1$ to the same sequence of spins but with opposite parity. For odd-A nuclei, $s = \pm i$ are used for the $1/2^\pm, 3/2^\mp, 5/2^\pm, 7/2^\mp, \dots$ sequences, respectively.

Since both sequences are based on a 219 keV state with tentative spin-parity [(9^-)] assignments [46], the spin-parity assignments of all the states shown (Fig. 2) above this state are relative and tentative. Therefore, any change in spin and/or parity of the 219 keV state will not affect the conclusions drawn in this paper.

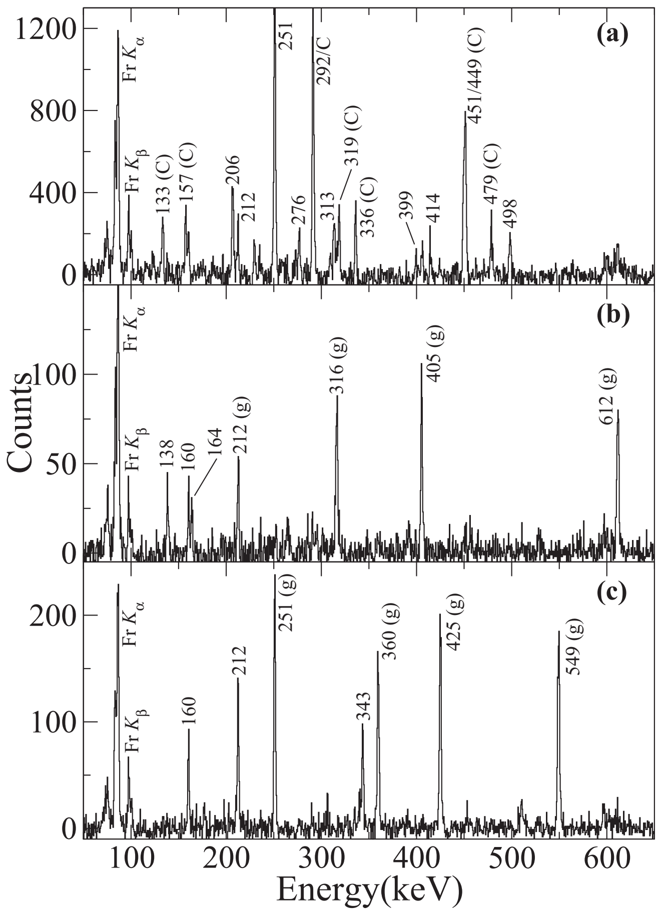

FIG. 4. Coincidence γ-ray spectra illustrating transitions in (a) the 300 keV gate along with (b) negative and (c) positive parity bands of the sequence "B". The spectra are obtained by summing double gates on the transitions which are marked with the letter "g" in the corresponding panels. The transitions marked with "C" are contaminants from ^{215}Fr. Also, note that not all the transitions assigned to ^{216}Fr could be placed in the level scheme of ^{216}Fr in Fig. 2.

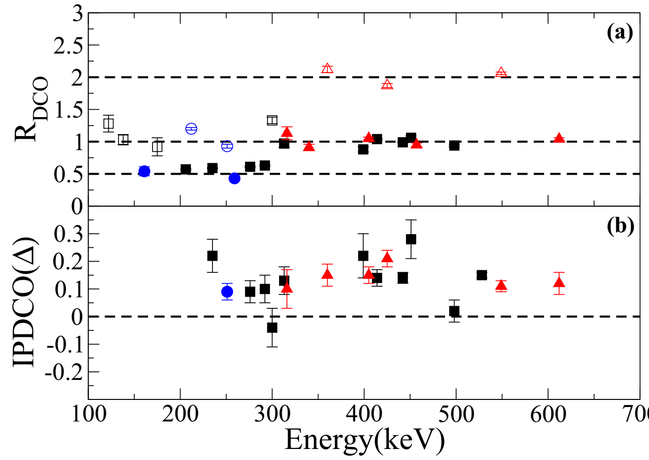

FIG. 5. (a) DCO and (b) IPDCO ratios for the transitions in Fig. 2. The filled (open) symbols in the top panel indicate DCO ratios obtained from the quadrupole (dipole) gates. Further, the transitions belonging to the sequences "A" and "B" are distinguished by using square and triangle symbols, respectively. The remaining transitions, viz., 161, 212, 251, and 259 keV, are shown by circles.

IV. DISCUSSION

A high-spin study of ^{216}Fr was first reported by Debray *et al.* [6], wherein sequences of $E2$ transitions originating from states of opposite parity connected by $E1$ transitions were established. Following this, Sheline *et al.* [47] investigated low-spin states in ^{216}Fr from the α decay of ^{220}Ac in search of reflection asymmetry at low excitation energy. However, no evidence was found.

It is instructive to compare characteristics of the observed bands in ^{216}Fr with different nuclei exhibiting various aspects of quadrupole and octupole collectivity in this region, to understand the underlying nuclear structure. Figure 6 shows systematics of angular momentum versus rotational frequency for the lowest lying sequence and energy splitting in neighboring nuclei. For stable octupole deformation, the magnitude of energy splitting [Fig. 6(a)] should be close to zero. Figure 6(b) can be used to infer about the quadrupole deformation, which manifests itself in the $I(I+1)$ pattern. It is apparent from Fig. 6 that the doubly-odd ^{220}Ac ($N = 131$) displays characteristics of quadrupole as well as

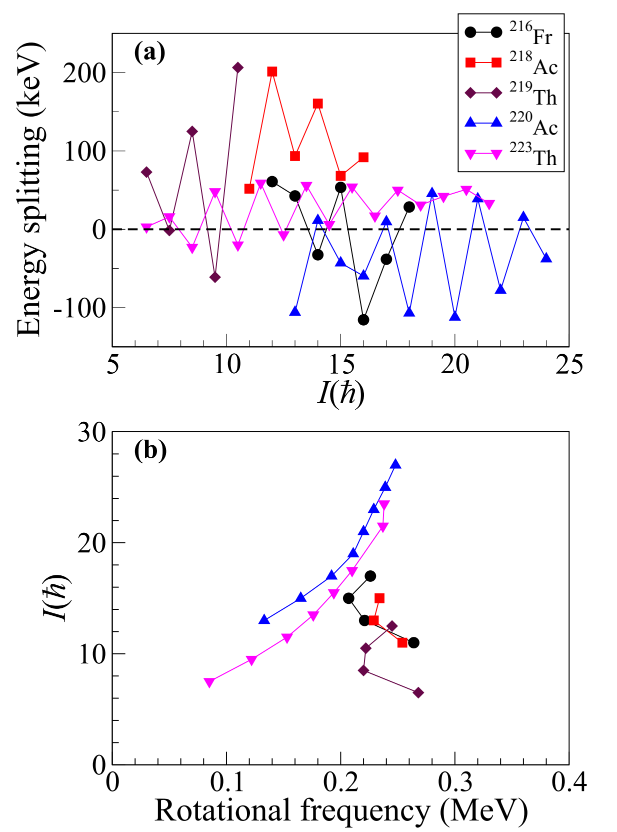

FIG. 6. Comparison of (a) energy splitting $[E(s=-1,-i) - E(s=+1,+i)]$ and (b) spin (I) versus rotational frequency ($\hbar\omega$) in ^{223}Th with $N = 129$ (^{216}Fr, ^{218}Ac, ^{219}Th) and $N = 131$ (^{220}Ac) isotopes for which the parity doublet structures have been reported. See the text for details. The data are taken from Refs. [7,8,29,31] and the present work.

stable octupole deformation, with the average value of energy splitting ~55 keV. Furthermore, all the $N = 129$ isotones (^{216}Fr, ^{218}Ac, and ^{219}Th) show a similar decrease in transition energy with increasing angular momentum [Fig. 6(b)], indicating negligible quadrupole deformation. Also, the magnitude of energy splitting is found to be higher in ^{218}Ac and ^{219}Th than ^{216}Fr, for which it is comparable to ^{223}Th. Therefore, ^{216}Fr is a unique odd-odd nucleus which displays considerably enhanced octupole correlations over quadrupole collectivity. The degree of enhancement is reflected, qualitatively, in the markedly small ($\lesssim$55 keV) average energy splitting and very irregular E versus I relation. The only other nucleus in which dominance of octupole over quadrupole degree of freedom has been reported is ^{218}Ra [48]. However, the average value of energy splitting is large (~120 keV). As mentioned earlier in the introductory paragraphs, it is interesting to note that the theoretical calculations by Möller *et al.* [38] have indeed predicted enhanced octupole deformation. However, their recent work excludes ^{216}Fr from the list of their compilation [39].

Furthermore, experimental $B(E1)/B(E2)$ values can be extracted from the measured γ-ray intensities. For stable octupole deformation, these values (and hence the transition intensities) are expected to be similar for the γ rays originating from either parity state in a given simplex band. On the other hand, for pure vibrational states, the $E1$ transitions from positive $[I^+]$ to negative $[(I-1)^-]$ states are forbidden [49]. This consideration can also be extended to octupole vibrations. It is obvious from the decay scheme presented in Fig. 2 and earlier discussion that neither of the two extremes is realized in ^{216}Fr, but the results present evidence of dominance of octupole correlations over other degrees of freedom.

In the case of ^{218}Fr, it is worth noting that, although the calculations predict comparatively large deformations ($\beta_2 = 0.05$, $\beta_3 = 0.154$) [38], the parity-doublet structures are absent. This can be qualitatively explained using Figs. 3 and 4 of Ref. [35] and adopting a set of deformation parameters (β_2, β_3) mentioned earlier. For both ^{216}Fr and ^{218}Fr, the last unpaired proton is expected to occupy the $K = 1/2$ component of the $1h_{9/2}$ orbital. On the other hand, the odd neutron occupies the $K = 3/2$ component of the $2g_{9/2}$ orbital at $N = 129$ and the $K = 1/2$ component originating from the $1i_{11/2}$ orbital at $N = 131$. The orbitals with $K > 1/2$ provide tilt to the rotational axis such that it does not coincide with the normal to the symmetry axis. This tilt is responsible for breaking the simplex symmetry [8,50] in nuclei. The unavailability of orbitals with $K > 1/2$ accounts for the absence of parity-doublet structures in ^{218}Fr. Similar arguments were employed in Refs. [8,25] to explain the presence (absence) of parity-doublet structures in ^{219}Th (^{221}Th).

A new approach, in terms of reflection-asymmetric nuclear tidal waves, was proposed to interpret the structure of transitional nuclei such as ^{218}Ra and ^{220}Th, where the angular velocity ω remains almost constant (~0.21 MeV/$\hbar$) over a broad spin range [51]. This implies that the nucleus does not rotate faster to gain angular momentum. A similar interpretation may hold for ^{216}Fr, where the angular velocity varies between 0.157 and 0.249 MeV/$\hbar$, with average value ~0.200 MeV/$\hbar$. The spin-dependent staggering of $E1$ transition energies and $B(E1)/B(E2)$ ratios are also considered as signatures of nuclear tidal waves. The staggering of $B(E1)/B(E2)$ ratios, although not as pronounced compared to that of its isotone ^{218}Ac, is apparent in ^{216}Fr (Fig. 7). Nevertheless, it is worth mentioning that the energy splitting is again distinctly higher in ^{218}Ac, ^{218}Ra [48], and ^{220}Th [16] than ^{216}Fr.

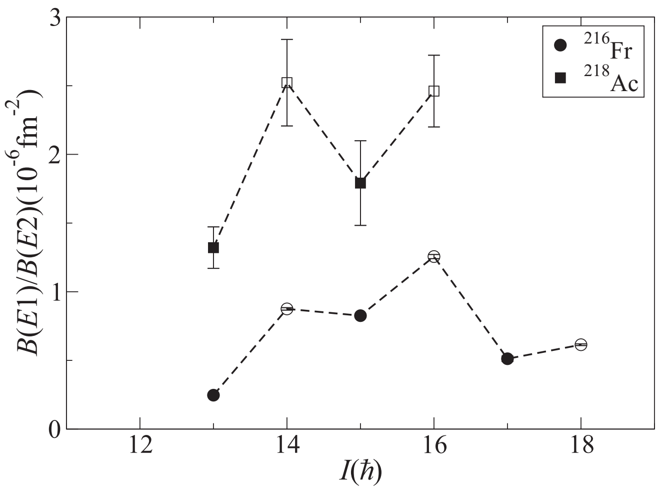

FIG. 7. $B(E1)/B(E2)$ ratios versus initial spin for the transitions in the sequence "A" in Fig. 2 (circles) and corresponding states in ^{218}Ac (squares). The data for ^{218}Ac are taken from Ref. [7]. The positive and negative parity states are further distinguished by open and filled symbols, respectively.

The experimental intrinsic dipole moments (D_0) were deduced from the $B(E1)/B(E2)$ ratios using the formalism prescribed in Ref. [52]. The semiempirical Grodzin's systematic [52] of neighboring even-even nuclei was used to estimate a Q_0 value of 284 e fm^2. The mean dipole moment $|\overline{D_0}| = 0.0833(4)$ e fm for the sequence "A" is approximately 6 times higher than for the sequence "B". This value is about 2 times smaller than that reported in Table 2 of Ref. [52]. The discrepancy can be attributed to erroneous estimation of intensities of some γ-ray transitions in the work of Debray *et al.* [6]. The value (0.0833) is surprisingly similar to that of ^{216}Rn [0.085(2) e fm], while it is approximately factor of 2 lower as compared to ^{218}Ac, ^{217}Fr, and ^{218}Fr [7,33,52]. This observation indicates that octupole correlations become prominent as the central region is approached, with increasing N and Z numbers.

V. SUMMARY

A pair of simplex partner bands have been firmly established in ^{216}Fr. The sequences comprising $E2$ transitions do not follow the $I(I+1)$ pattern, indicating near absence of quadrupole deformation. On the other hand, a very small magnitude of energy splitting is suggestive of strong octupole correlations. Therefore, ^{216}Fr may be regarded as the first doubly-odd nucleus indicating dominance of octupole correlations over quadrupole collectivity. It is noteworthy that the parity-doublet structures which are indicative of strong octupole correlations emerge right at the lower edge of the $A \approx 220$ region. This may be attributed to the availability of $K = 3/2$ neutron orbital. Almost constant angular velocity, staggering of $E1$ transition energies, and $B(E1)/B(E2)$ ratios suggest that the reflection-asymmetric tidal wave approach may be appropriate to describe the structure of ^{216}Fr.

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[1] L. P. Gaffney *et al.*, Nature (London) **497**, 199 (2013).
[2] W. Kurcewicz, Hyperfine Interact. **129**, 175 (2000).
[3] I. Ahmad and P. A. Butler, Ann. Rev. Nucl. Part. Sci. **43**, 71 (1993), and references therein.
[4] P. A. Butler and W. Nazarewicz, Rev. Mod. Phys. **68**, 349 (1996).
[5] H. Ower, Th. W. Elze, J. Idzko, K. Stelzer, E. Grosse, H. Emling, P. Fuchs, D. Schwalm, H. J. Wollersheim, N. Kaffrell, and N. Trautmann, Nucl. Phys. A **388**, 421 (1982).
[6] M. E. Debray, J. Davidson, M. Davidson, A.J. Kreiner, D. Hojman, D. Santos, K. Ahn, D. B. Fossan, Y. Liang, R. Ma, E. S. Paul, W. F. Piel, Jr., and N. Xu, Phys. Rev. C **41**, R1895(R) (1990).
[7] M. E. Debray, A. J. Kreiner, M. Davidson, J. Davidson, D. Hojman, D. Santos, V. R. Vanin, N. Schulz, M. Aïche, A. Chevallier, J. Chevallier, and J. C. Sens, Nucl. Phys. A **568**, 141 (1994).
[8] W. Reviol, D. G. Sarantites, C. J. Chiara, M. Montero, R. V. F. Janssens, M. P. Carpenter, T. L. Khoo, T. Lauritsen, C. J. Lister, D. Seweryniak, S. Zhu, O. L. Pechenaya, and S. G. Frauendorf, Phys. Rev. C **80**, 011304(R) (2009).
[9] W. Nazarewicz, P. Olanders, I. Ragnarsson, J. Dudek, and G. A. Leander, Phys. Rev. Lett. **52**, 1272 (1984).
[10] P. D. Cottle, J. F. Shriner, Jr., F. Dellagiacoma, J. F. Ennis, M. Gai, D. A. Bromley, J. W. Olness, E. K. Warburton, L. Hildingsson, M. A. Quader, and D. B. Fossan, Phys. Rev. C **30**, 1768(R) (1984).
[11] J. F. Shriner, Jr., P. D. Cottle, J. F. Ennis, M. Gai, D. A. Bromley, J. W. Olness, E. K. Warburton, L. Hildingsson, M. A. Quader, and D. B. Fossan, Phys. Rev. C **32**, 1888 (1985).
[12] A. Celler, Ch. Briancon, J. S. Dionisio, A. Lefebvre, Ch. Vieu, J. Zylicz, R. Kulessa, C. Mittag, J. Fernandez-Niello, Ch. Lauterbach, H. Puchta, and F. Riess, Nucl. Phys. A **432**, 421 (1985).
[13] W. Bonin, H. Backe, M. Dahlinger, S. Glienke, D. Habs, E. Hanelt, E. Kankeleit, and B. Schwartz, Z. Phys. A **322**, 59 (1985).
[14] Y. Gono, T. Kohno, M. Sugawara, Y. Ishikawa, and M. Fukuda, Nucl. Phys. A **459**, 427 (1986).
[15] J. F. C. Cocks, D. Hawcroft, N. Amzal, P. A. Butler, K. J. Cann, P. T. Greenlees, G. D. Jones, S. Asztalos, R. M. Clark, M. A. Deleplanque, R. M. Diamond, P. Fallon, I. Y. Lee, A. O. Macchiavelli, R. W. McLeod, F. Stephens, P. Jones, R. Julin, R. Broda, B. Fornal, J. F. Smith, T. Lauritsen, P. Bhattacharyya, and C. T. Zhang, Nucl. Phys. A **645**, 61 (1999).
[16] W. Reviol, C. J. Chiara, M. Montero, D. G. Sarantites, O. L. Pechenaya, M. P. Carpenter, R.V.F. Janssens, T.L. Khoo, T. Lauritsen, C. J. Lister, D. Seweryniak, S. Zhu, and S. G. Frauendorf, Phys. Rev. C **74**, 044305 (2006).
[17] M. Aïche, A. Chevallier, J. Chevallier, S. Hulne, S. Khazrouni, N. Schulz, and J. C. Sens, J. Phy. G: Nucl. Phys. **14**, 1191 (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. A **426**, 379 (1984).
[19] L. A. Riley, P. D. Cottle, M. Fauerbach, V. S. Griffin, B. N. Guy, K. W. Kemper, G. S. Rajbaidya, and O. J. Tekyi-Mensah, Phys. Rev. C **62**, 021301(R) (2000).
[20] J. Fernández-Niello, C. Mittag, F. Riess, E. Ruchowska, and M. Stallknecht, Nucl. Phys. A **531**, 164 (1991).
[21] F. Cristancho, J. X. Saladin, M P. Metlay, W. Nazarewicz, C. Baktash, M. Halbert, I-Y. Lee, D. F. Winchell, S. M. Fischer, and M. K. Kabadiyski, Phys. Rev. C **49**, 663 (1994).
[22] M. Aïche, M. Bentaleb, Ch. Briancon, A. Chevallier, J. Chevallier, J. S. Dionisio, J. Fernandez-Niello, R. Kulessa, E. Lubkiewicz, C. Mittag, F. Riess, E. Ruchowska, N. Schulz, A. Seghour, J. C. Sens, Ch. Vieu, and M. Wieland, Nucl. Phys. A **567**, 685 (1994).
[23] M. Dahlinger, E. Kankeleit, D. Habs, D. Schwalm, B. Schwartz, R. S. Simon, J. D. Burrows, and P. A. Butler, Nucl. Phys. A **484**, 337 (1988).
[24] S. K. Tandel, M. Hemalatha, A. Y. Deo, S. B. Patel, R. Palit, T. Trivedi, J. Sethi, S. Saha, D. C. Biswas, and S. Mukhopadhyay, Phys. Rev. C **87**, 034319 (2013).
[25] W. Reviol, R. V. F. Janssens, S. Frauendorf, D. G. Sarantites, M. P. Carpenter, X. Chen, C. J. Chiara, D. J. Hartley, K. Hauschild, T. Lauritsen, A. Lopez-Martens, M. Montero, O. L. Pechenaya, D. Seweryniak, J. B. Snyder, and S. Zhu, Phys. Rev. C **90**, 044318 (2014).
[26] J. F. Smith, J. F. C. Cocks, N. Schulz, M. Aïche, M. Bentaleb, P. A. Butler, F. Hannachi, G. D. Jones, P. M. Jones, R. Julin, S. Juutinen, R. Kulessa, E. Lubkiewicz, A. Plochocki, F. Riess, E. Ruchowska, A. Savelius, J. C. Sens, J. Simpson, and E. Wolf, Phys. Rev. Lett. **75**, 1050 (1995).
[27] B. Ackermann, H. Baltzer, C. Ensel, K. Freitag, V. Grafen, C. Günther, P. Herzog, J. Manns, M. Marten-Tölle, U. Müller, J. Prinz, I. Romanski, R. Tölle, J. deBoer, N. Gollwitzer, and H. J. Maier, Nucl. Phys. A **559**, 61 (1993).
[28] N. Amzal, J. F. C. Cocks, P. A. Butler, K. J. Cann, P. T. Greenlees, G. D. Jones, S. Asztalos, R. M. Clark, M. A. Deleplanque, R. M. Diamond, P. Fallon, I. Y. Lees, A. O. Machiavelli, R. W. McLeod, F. S. Stephens, P. M. Jones, R. Julin, R. Broda, B. Fornal, J. F. Smith, T. Lauritsen, P. Bhattacharyya, and C. T. Zhang, J. Phys. G: Nucl. Part. Phys. **25**, 831 (1999).
[29] G. Maquart, L. Augey, L. Chaix, I. Companis, C. Ducoin, J. Dudouet, D. Guinet, G. Lehaut, C. Mancuso, N. Redon, O. Stezowski, A. Vancraeyenest, A. Astier, F. Azaiez, S. Courtin, D. Curien, I. Deloncle, O. Dorvaux, G. Duchene, B. Gall, T. Grahn, P. Greenlees, A. Herzan, K. Hauschild, U. Jakobsson, P. Jones, R. Julin, S. Juutinen, S. Ketelhut, M. Leino, A. Lopez-Martens, P. Nieminen, P. Petkov, P. Peura, M.G. Porquet, P. Rahkila, S. Rinta-Antila, M. Rousseau, P. Ruotsalainen, M. Sandzelius, J. Saren, C. Scholey, J. Sorri, S. Stolze, and J. Uusitalo, Phys. Rev. C **95**, 034304 (2017).
[30] T. C. Hensley, P. D. Cottle, Vandana Tripathi, B. Abromeit, M. Anastasiou, L. T. Baby, J. S. Baron, D. Caussyn, R. Dungan,

K. W. Kemper, R. S. Lubna, S. L. Miller, N. Rijal, M. A. Riley, S. L. Tabor, P.-L. Tai, and K. Villafana, Phys. Rev. C **96**, 034325 (2017).
[31] N. Schulz, V. R. Vanin, A. J. Kreiner, E. Ruchowska, M. Aïche, Ch. Briancon, A. Chevallier, J. Chevallier, M. E. Debray, and J. C. Sens, Z. Phys. A **339**, 325 (1991).
[32] M. E. Debray, M. Davidson, A. J. Kreiner, J. Davidson, G. Falcone, D. Hojman, and D. Santos, Phys. Rev. C **39**, 1193 (1989).
[33] M. E. Debray, M. A. Cardona, D. Hojman, A. J. Kreiner, M. Davidson, J. Davidson, H. Somacal, G. Levinton, D. R. Napoli, S. Lenzi, G. de Angelis, M. De Poli, A. Gadea, D. Bazzacco, C. Rossi-Alvarez, and N. Medina, Phys. Rev. C **62**, 024304 (2000).
[34] G. A. Leander and R. K. Sheline, Nucl. Phys. A **413**, 375 (1984).
[35] G. A. Leander and Y. S. Chen, Phys. Rev. C **37**, 2744 (1988).
[36] A. K. Jain, R. K. Sheline, P. C. Sood, and Kiran Jain, Rev. Mod. Phys. **62**, 393 (1990).
[37] S. Ćwiok and W. Nazarewicz, Nucl. Phys. A **529**, 95 (1991).
[38] P. Möller, J. R. Nix, W. D. Myers, and W. J. Swiatecki, At. Data Nucl. Data Tables **59**, 185 (1995).
[39] P. Möller, R. Bengtsson, B. G. Carlsson, P. Olivius, T. Ichikawa, H. Sagawa, and A. Iwamoto, At. Data Nucl. Data Tables **94**, 758 (2008).
[40] B. P. Ajith Kumar, E. T. Subramaniam, K. Rani, and K. Singh, DAE Proc. **44 B**, 390 (2001).
[41] D. C. Radford, Nucl. Instrum. Methods Phys. Res., Sect. A **361**, 297 (1995).
[42] A. Krämer-Flecken, T. Morek, R. M. Lieder, W. Gast, G. Hebbinghaus, H. M. Jäger, and W. Urban, Nucl. Instrum. Methods Phys. Res., Sect. A **275**, 333 (1989).
[43] G. Duchêne, F. A. Beck, P. J. Twin, G. de France, D. Curien, L. Han, C. W. Beausang, M. A. Bentley, P. J. Nolan, and J. Simpson, Nucl. Instrum. Methods Phys. Res., Sect. A **432**, 90 (1999).
[44] K. Starosta, T. Morek, Ch. Droste, S. G. Rohoziński, J. Srebrny, A. Wierzchucka, M. Bergström, B. Herskind, E. Melby, T. Czosnyka, and P. J. Napiorkowski, Nucl. Instrum. Methods Phys. Res., Sect. A **423**, 16 (1999).
[45] T. Kibédi, T. W. Burrows, M. B. Trzhaskovskaya, P. M. Davidson, and C. W. Nestor, Jr., Nucl. Instrum. Methods Phys. Res., Sect. A **589**, 202 (2008).
[46] S.-C. Wu, Nucl. Data Sheets **108**, 1057 (2007).
[47] R. K. Sheline, C. F. Liang, P. Paris, and A. Gizon, Phys. Rev. C **55**, 1162 (1997).
[48] N. Schulz, V. R. Vanin, M. Aïche, A. Chevallier, J. Chevallier, J. C. Sens, Ch. Briancon, S. Cwiok, E. Ruchowska, J. Fernandez-Niello, Ch. Mittag, and J. Dudek, Phys. Rev. Lett. **63**, 2645 (1989).
[49] M. E. Debray, J. Davidson, M. Davidson, A. J. Kreiner, M. A. Cardona, D. Hojman, D. R. Napoli, S. Lenzi, G. de Angelis, D. Bazzacco, S. Lunardi, M. De Poli, C. Rossi-Alvarez, A. Gadea, N. Medina, and C. A. Ur, Phys. Rev. C **73**, 024314 (2006), and references therein.
[50] S. Frauendorf, Rev. Mod. Phys. **73**, 463 (2001).
[51] S. Frauendorf, Y. Gu, and J. Sun, Int. J. Mod. Phys. E **20**, 465 (2011).
[52] P. A. Butler and W. Nazarewicz, Nucl. Phys. A **533**, 249 (1991).

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