Persisting Domination of the Octupole over the Quadrupole Degrees of Freedom and the New Type of Transitional Nuclei: High-Spin Behavior of ^{218}Ra

N. Schulz, V. Vanin,[a] M. Aïche, A. Chevallier, J. Chevallier, and J. C. Sens
Centre de Recherches Nucléaires et Université Louis Pasteur, 67037 Strasbourg, France

Ch. Briançon, S. Cwiok,[b] and E. Ruchowska[c]
Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, 91406 Orsay, France

J. Fernandez-Niello[d] and Ch. Mittag
Sektion Physik, Universität München, 8046 Garching, Federal Republic of Germany

J. Dudek
Centre de Recherches Nucléaires et Université Louis Pasteur, 67037 Strasbourg, France and Joint Institute for Heavy Ion Research, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

(Received 28 November 1988)

High-spin states up to $I=(31^-)$ have been studied in the ^{218}Ra nucleus and the staggering sequence of levels of positive and negative parity persists up to the highest level. This observation supports the idea that in some nuclei the high-spin excitations may primarily be dominated by deformations which do not conserve the intrinsic parity (such as octupole, $\lambda=3$, and higher odd-λ multipolarities) rather than by the "usual" quadrupole ($\lambda=2$) and possibly higher even-λ multipolarities.

PACS numbers: 21.10.Re, 21.10.Ft, 23.20.Lv, 27.80.+w

As the number of nucleons gradually exceeds the proton and neutron magic numbers, the primarily noncollective high-spin excitation pattern in the corresponding nuclei evolves towards a collective one. The latter sets in when the number of valence particles exceeds typically 6 to 8 for protons and 4 to 6 for neutrons, in both medium-heavy and heavy nuclei. This collective excitation pattern is characterized by the presence of rotational bands with the regular energy-E vs spin-I dependence. On the contrary, a very irregular E vs I dependence and an apparently random ordering of the electromagnetic $E\lambda$ and $M\lambda$ transitions characterize the noncollective pattern.

The rotational bands, as studied extensively in the past, preserve the intrinsic symmetries of signature and parity,[1] often to an extremely good approximation. These symmetries are a property of the triaxial-shape geometry and produce the typical spin sequences $I^\pi=0^\pm, 2^\pm, 4^\pm, \ldots$ and $I^\pi=1^\pm, 3^\pm, 5^\pm$ for even-even nuclei.

In many nuclei a different pattern, namely the one characterized by the intrinsic simplex symmetry[2] (the mirror symmetry with respect to a plane containing the symmetry axis), dominates. In these cases the regular band structures are composed of the spin-parity sequences $I^\pi=0^+, 1^-, 2^+, 3^-, \ldots$ and $I^\pi=0^-, 1^+, 2^-, 3^+, \ldots$ for even-even nuclei, and analogous half-integer-spin sequences for odd-A nuclei. The electromagnetic decay proceeds then via $E1$ *and* $E2$ transitions with the $B(E1)/B(E2)$ ratio being large relative to normal.[3] The interpretation of this phenomenon frequently employs the stable octupole-shape deformation β_3 or, alternatively, the octupole-shape susceptibility with large-amplitude collective β_3 oscillations.

The great majority of the so-called transitional nuclei, i.e., those spanning the transition between the noncollective and collective motion, exhibit relatively well pronounced band structures with the symmetries of the first kind discussed above. It is the purpose of this Letter to provide evidence that a special type of transitional nuclei exists in nature. They are characterized by an enhanced octupole susceptibility (decay pattern dominated by odd multipolarity components in nuclear shapes) while the quadrupole-type influence, which usually dominates, plays only a secondary role. In the following the experimental results[4] for the transitional nucleus ^{218}Ra are presented, and it will be argued that this nucleus produces the discussed special transitional behavior up to the highest observed spin.

In order to strongly populate high-spin states, the nucleus ^{218}Ra was produced via the ^{208}Pb(^{14}C,4n) reaction with an incident beam energy of 80 MeV provided by the 18-MV MP tandem Van de Graaff accelerator at Strasbourg. The self-supporting lead target, enriched in ^{208}Pb ($>99\%$), had an effective thickness of 2.5 mg cm^{-2}. The ^{14}C beam had an intensity of 4 particle nA and was dumped several meters behind the target in a Faraday cup. The investigation of ^{218}Ra was made with the multidetector 4π array called "Château de Cristal."[5] In the present experiment it consisted of (i) ten Ge detectors, each surrounded by an anti-Compton shield, the γ-ray entering from the side; with seven detectors positioned at 30° or 150° with respect to the beam, and the others at 90°; (ii) two planar Ge detectors with Be windows, axially positioned at 90° and 30°, respectively; and (iii) 38 BaF_2 crystals constituting an inner array which was used as a γ-ray multiplicity filter. Requiring that at least three BaF_2 (fold 3) were triggered, 4×10^8 $\gamma\gamma$ events detected in Ge counters were registered.

The relative yield of the highest spin states of ^{218}Ra was enhanced in the data analysis by imposing a fold greater than or equal to 6. This condition also affected the relative yields of the different xn exit channels ($x=3,4,5$). Especially, it lowered the $5n$ (^{217}Ra) channel to 2.6%, diminishing thereby the contamination of several γ rays in ^{218}Ra. The level scheme of ^{218}Ra deduced from the present work is presented in Fig. 1. Spin assignments were established from the measured γ-ray anisotropies $I(30°)/I(90°)$ and from the directional correlation ratios extracted from the $\gamma\gamma$ coincidence data, assuming that the considered transitions are stretched. The electric character of the quadrupole transitions was deduced from the absence of delayed components in the γ-γ time spectra, and the electric or magnetic decays for dipole transitions were inferred from intensity balance arguments.

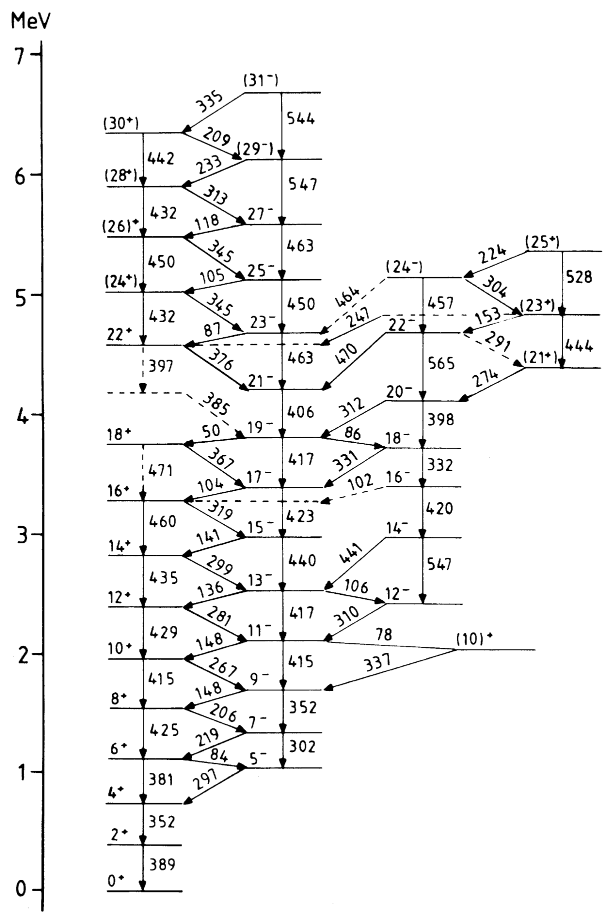


FIG. 1. Level scheme of ^{218}Ra obtained in the present work. Transition energies are given in keV.

The positive- and negative-parity bands previously known[6-8] up to spins 16^+ and 17^- were confirmed and extended to higher spins. It was found that the 417-keV γ peak corresponds to two transitions and therefore the 19^- and 21^- states differ from those proposed earlier.[8] The relatively large $B(E1)/B(E2)$ ratios persist up to the highest levels observed and the slightly decreasing trend of these ratios with increasing spins[7,8] is confirmed at higher spins by the present work: The values (in units of 10^{-6} fm^{-2}) range from 2.6 to 0.4. A second negative-parity band, observed up to $I=(24)$, is connected by $M1$ transitions to the first negative-parity band. At high excitation energy, its states are interconnected by dipole transitions with the members of a new band, presumably a second positive-parity band.[9]

Calculations of the potential energies using the Strutinsky method with the deformed Woods-Saxon potential[10] give the results presented for $I=0$ in Fig. 2. In these calculations, for each β_3 value the energy is minimized over the other deformation parameters[11] β_λ ($\lambda=2$, 4, 5, 6, and 7) whose values are shown in the bottom part of the figure. For increasing spins, the theoretical results for ^{218}Ra predict[12] the evolution of the octupole susceptibility (up to $\beta_3\sim0.11$), which is close to the maximum predicted for nuclei in this range[12,13] and which dominates over all other deformations in ^{218}Ra. The coexisting $E1$ and $E2$ transitions (Fig. 1) signify the simplex symmetry in this nucleus as implied by the average field theories when the odd-λ shape multipolarities are present.[2] However, at the same time the bands in ^{218}Ra do not show any clear regularity of the $E\sim I(I+1)$ type, which corresponds well with the negligible elongation of $\beta_2\simeq0.07$.

To give further support to the idea of the special transitional behavior of ^{218}Ra, manifested in theory by the predominance of octupole over quadrupole degrees of freedom and in experiment by the simplex symmetry and irregular E vs I pattern, the spin responses to rotation in the form of I vs ω curves are illustrated in Fig. 3 for $^{218-220}$Ra and compared to the analogous results in the well-known transitional nuclei $^{152-154}$Dy. The similarities in the decay characteristics of the compared nuclear pairs are evident, while the Ra nuclei produce, in addition, a clear simplex symmetry pattern (see Fig. 1). There the regular-collective pattern in ^{220}Ra can qualitatively be understood in view of both the $\sim30\%$ larger elongation ($\beta_2\sim0.10$) and the well developed twin octupole minima with the pronounced (~800 keV) separating barrier.

The unusually strong effects of the $E1$ transitions observed in experiment can be qualitatively understood in terms of the spontaneous parity breaking in the intrinsic nuclear frame at deformations predicted for this nucleus by theory. Indeed, the calculated quasiparticle wave functions have comparable contents of both positive- and

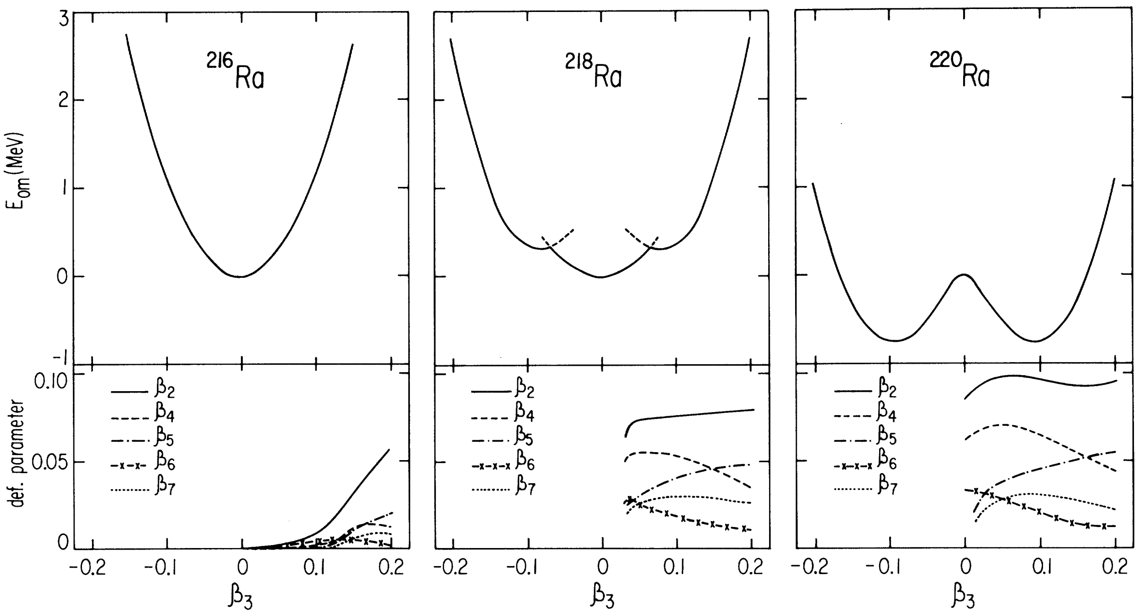
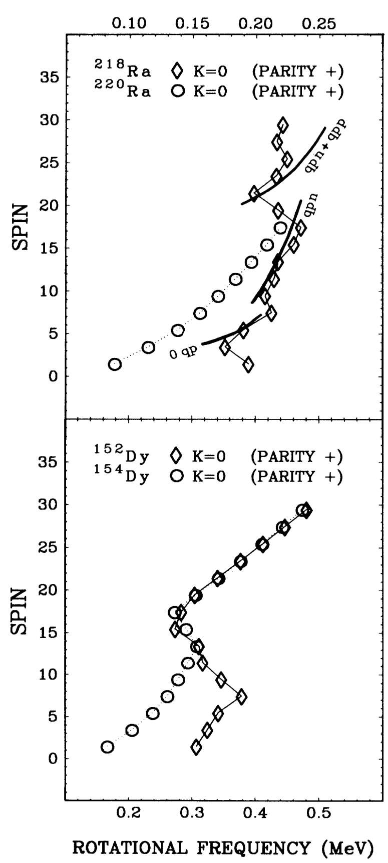


FIG. 2. Total potential energies along the steepest-descent lines after minimization within the six-dimensional space of multipoles β_2–β_7 at $I=0$, as a function of β_3 (top). The corresponding values of all multipolarities but β_3 are given at the bottom. The developing octupole character of the equilibria when N changes from 128 to 132 and most importantly the domination of β_3 over all other deformations in ^{218}Ra deserve noting. (In the latter nucleus a coexistence with the spherical minimum and/or large-amplitude dynamical octupole oscillations is a likely picture.)



negative-parity contributions as shown in Fig. 4. This provides a clear necessary condition for the $E1$-type matrix elements $(\sim\langle f|rY_{10}|i\rangle\sim\langle f|z|i\rangle)$ being nonzero and often large. In addition, the reduction of the pairing gap at $\hbar\omega_{cr}\simeq 0.20$ MeV (see bottom of Fig. 4) corresponds to the neutron alignment most likely seen for spins $8\leq I\leq 18$ (cf. Fig. 3).

In short, the experiment on the ^{218}Ra nucleus gives evidence that the simplex symmetry persists up to the highest spins observed, while the E vs I relation remains very irregular. This is in good qualitative agreement with the theoretical results yielding a very large octupole deformation ($\beta_3\sim 0.09$), close to the maximum predicted for this mass region, and simultaneously a markedly less significant β_2 value. All these facts are presented as evidence for a new type of transitional nuclei where the octupole-type deformation dominates over all other shape components.

The authors thank G. Heng and the staff of the Stras-

FIG. 3. Comparison between the octupole-transitional ^{218}Ra and collective ^{220}Ra (top) and the well-studied "usual" transitional nuclei of ^{152}Dy and ^{154}Dy in terms of the spin projection on the axis of rotation as a function of ω. Thick lines present the results of the cranking calculations with pairing for the ground state [zero quasiparticles (0 qp)], two-quasiparticle neutron s band (qp n), and four-quasiparticle (two-quasiparticle neutron and two-quasiparticle proton) band (qp n+qp p), respectively.

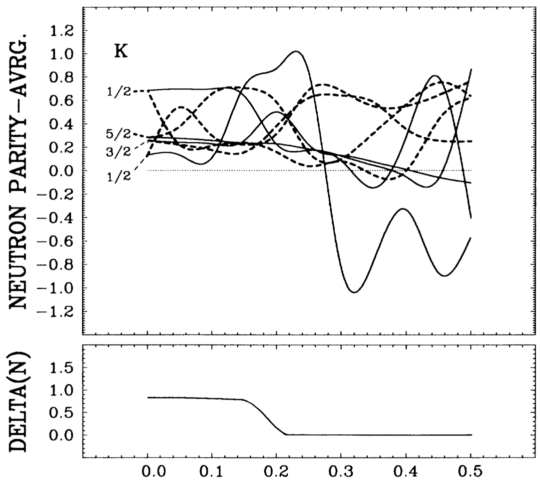


FIG. 4. The parity content ($\langle \nu | \hat{\pi} | \nu \rangle$) of a few neutron orbitals closest to the Fermi level in ^{218}Ra as a function of rotational frequency (top). The bottom part displays the corresponding change in the pairing gap. Curves are labeled by the K quantum number and full (dashed) lines correspond to $s=-i$ $(+i)$. $\beta_2=0.075$, $\beta_3=0.090$, and $\beta_4=0.054$.

bourg MP tandem for developing and providing the ^{14}C beam. One of us (V.V.) acknowledges financial support from Fundação de Amparo e Pesquisa do Estado de São Paulo (Brazil). This work has partially been done in the framework of the Institut National de Physique Nucléaire et de Physique des Particules–Polish Laboratories collaboration agreement.

[a]Permanent address: Instituto de Física da Universidade de São Paulo, 01000 São Paulo, Brazil.

[b]Permanent address: Institute of Physics, Warsaw Technical University, 00-622 Warsaw, Poland.

[c]Permanent address: Institute of Experimental Physics, University of Warsaw, 00-681 Warsaw, Poland.

[d]Permanent address: Departemento de Física, Comisión Nacional de Energía Atómica, Buenos Aires, Argentina.

[1]A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, New York, 1975), Vol. 2.

[2]W. Nazarewicz *et al.*, Phys. Rev. Lett. **52**, 1272 (1984).

[3]G. A. Leander *et al.*, Nucl. Phys. **A453**, 58 (1986), see also references therein.

[4]M. Aïche *et al.*, in *Proceedings of the Conference on High Spin Nuclear Structure and Novel Nuclear Shapes, Argonne, 1988* (Argonne National Laboratory Report No. ANL-PHY-88-2).

[5]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 Permanente, Suppl. No. 56, 1987).

[6]J. Fernandez-Niello *et al.*, Nucl. Phys. **A391**, 221 (1982).

[7]M. Gai *et al.*, Phys. Rev. Lett. **51**, 646 (1983).

[8]Y. Gono *et al.*, Nucl. Phys. **A459**, 427 (1986).

[9]I. N. Mikhailov *et al.*, J. Phys. G **15**, L19 (1989).

[10]J. Dudek *et al.*, Phys. Rev. C **23**, 920 (1981); S. Cwiok *et al.*, Comput. Phys. Commun. **46**, 379 (1987).

[11]A. Sobiczewski *et al.*, Nucl. Phys. **A485**, 16 (1988).

[12]W. Nazarewicz *et al.*, Nucl. Phys. **A467**, 437 (1987).

[13]W. Nazarewicz *et al.*, Nucl. Phys. **A429**, 269 (1984).