RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 41, NUMBER 5 MAY 1990

Evidence for the onset of reflection asymmetry in ^{216}Fr

M. E. Debray, J. Davidson,* M. Davidson,* A. J. Kreiner,* D. Hojman, and D. Santos
Departamento de Física, Comisión Nacional de Energía Atómica, RA-1429, Buenos Aires, Argentina

K. Ahn, D. B. Fossan, Y. Liang, R. Ma, E. S. Paul, W. F. Piel, Jr., and N. Xu
Physics Department, State University of New York at Stony Brook, Stony Brook, New York 11794

(Received 1 September 1989)

States in doubly odd ^{216}Fr have been studied using in-beam α, γ, and e^- spectroscopy techniques through the ^{208}Pb(^{11}B,$3n$) fusion-evaporation reaction. ^{216}Fr shows a band structure with interleaved states of alternating parities connected by enhanced $B(E1)$ transitions. It represents the lowest-mass corner of the region ($Z \geq 87$, $N \geq 129$) in which this phenomenon is observed.

The existence of band structures with interleaved states of alternating parity connected by enhanced $B(E1)$ transitions in the translead region has been related[1,2] to the appearance of reflection asymmetric shapes. This phenomenon has been studied mainly in even-even and odd mass nuclei.[3-9] In order to subject this picture to further testing we have started an investigation of doubly odd nuclei. The first example[10] showing the above-mentioned features was ^{218}Ac. In order to determine the Z and N values for which this phenomenon starts to occur we studied in the present work the next lighter doubly odd isotone of ^{218}Ac, namely ^{216}Fr($Z=87$, $N=129$). In fact, this nucleus turns out to be the lightest one where a band with alternating parities appears.

^{216}Fr has been studied using the ^{208}Pb(^{11}B,$3n$) reaction through experiments performed in two different laboratories. α-particle and γ-ray excitation functions (in the 53–74 MeV bombarding energy range) and e^- spectra (with a mini-orange spectrometer on a 1 mg/cm^2 target at 56 MeV) were obtained at the TANDAR accelerator in Buenos Aires. Compton suppressed (CS), multiplicity filtered γ-γ coincidences, DCO ratios, and γ-beam time distributions were measured at the Nuclear Structure Laboratory in Stony Brook. The latter setup consisted of 5 CS Ge detectors (at angles of 90°, 30°, and 150° to the beam) and a fourteen element BGO multiplicity filter. The DCO ratios (see Table I) are obtained from a coincidence matrix which has on one axis detectors at 90° and on the other, detectors at 30°. The experiment was performed in this case on a thicker $\simeq 8$ mg/cm^2 lead-backed target at 57 MeV ^{11}B energy.

The center part of Fig. 1 shows a partial level scheme obtained for ^{216}Fr showing the features discussed above. The isotopic assignment of lines to ^{216}Fr was done on the basis of α-particle and γ-ray excitation functions, previous knowledge of neighboring odd A ^{215,217}Fr (Refs. 11 and 12), and coincidences of candidate γ lines with x rays of Fr. The stretched $E1$ and $E2$ character of the transitions of this structure follows unambiguously from conversion electron measurements, DCO ratios, and intensity balance in coincidence spectra (see Table I) firmly establishing relative spins and parities.

On the other hand, the spin-parity assignment of the "band head" state is a more delicate matter. So far only a few states in ^{216}Fr were proposed[13] exclusively on the basis of α-particle groups stemming from the ground-state decay of ^{220}Ac with no γ rays observed. The ground state of ^{216}Fr has been assigned as (1^-) because it exclusively α decays to the 1^- ground state[14,15] of ^{212}At with a hindrance factor[5] which fits the systematics. ^{216}Fr is analogous to ^{218}Ac in that it only has one α-emitting state. In contrast, there is a systematic occurrence[14] of two α-emitting isomers in many doubly odd nuclei of this region (mostly with $Z \leq 87$ and/or $N \leq 129$) namely, the $I^\pi = (1^-)$ ground state and a (9^-) excited state which mainly arise from the coupling of the two lowest-lying single-particle orbits ($\pi h9/2$ and $\nu g9/2$) above the double shell closure at $Z=82$ and $N=126$. The fact that the 1^- and 9^- states lie lowest is consistent with the presence of an attractive proton-neutron particle-particle force acting strongly in the antialigned and aligned $\pi h9/2 \otimes \nu g9/2$ configurations, respectively (which have the largest spatial overlap). These states are certainly purest in terms of the $\pi h9/2 \otimes \nu g9/2$ configuration for ^{210}Bi and the particle-particle matrix elments of the p-n force can be extracted from the lowest-lying $I^\pi = J^\pi = 0^-, 1^-, \ldots, 9^-$ multiplet (where J is the two-particle angular momentum) giving[16] the typical inverted-parabola shape for the matrix elements $V_J = \langle (\pi h9/2 \otimes \nu g9/2)_J | V_{p-n} | (\ )_J \rangle$. In ^{210}Bi the lowest-lying members of this multiplet are[14] the 1^- (ground state), the 0^- (46.5 keV), and the 9^- (271 keV), and the 1^--9^- splitting is largest. Moving up in Z (or N) the particle character for the $\pi h9/2$ ($\nu g9/2$) gives way to a mixed particle-hole (quasiparticle) behavior, the residual p-n force is expected to diminish[17] because it becomes an average between the attractive particle-particle and the repulsive particle-hole matrix elements and the splitting of the J multiplet will decrease. In fact, the 1^--9^- energy separation decreases from 271 keV in ^{210}Bi to 37 keV in its isotone ^{216}Ac (Ref. 18), and other states of intermediate spin J start to move into the 1^--9^- gap (see for instance the case[15] of ^{212}At). Eventually the 9^- state, being able to γ decay to the 1^- ground state through a series of low-energy $M1$ and/or $E2$ transitions, may lose its α-emitting character. Since the 9^- state is still expected[10] to be low-lying, it will be on the yrast line receiving strong feeding in a heavy-ion-induced fusion reaction. These arguments provide a basis for the tentative

TABLE I. γ-ray energies, intensities, and DCO ratios [DCO (d) is the average value of $I_\gamma(90°)/I_\gamma(30°)$] in coincidence spectra gated by dipole transitions at 30° and 90°, respectively; DCO(q) is the same average value but gated on quadrupole transitions, conversion coefficients, total transition intensities, and adopted multipolarities.

E_γ[a] (kev)	I_γ (arb. units)	DCO(d)	DCO(q)	α_K^{th} $E1$[b] α_K^{th} $E2$ α_K^{th} $M1$	α_K^{exp}	α_L^{th} $E1$ α_L^{th} $E2$ α_L^{th} $M1$	α_L^{exp}	I^{tot} (arb. units)	Mult.
121.9	2.2(4)	0.97(12)	1.63(25)					2.8(4)	$E1$
138.2	1.7(5)	0.91(12)	1.59(14)					2.1(8)	$E1$
175.2	5.9(6)		1.74(22)					6.4(6)	$E1$
206.7	8.8(7)	1.10(10)	1.70(10)					9.3(7)	$E1$
235.0[c]	38(3)	0.86(5)	1.68(9)			0.0091 0.159 0.20	0.009(2)	39(3)	$E1$
276.8	21(2)	1.02(8)	1.85(8)	0.0334 0.0833 0.700	0.018(10)			21(2)	$E1$
291.5[c]	13.7(9)		1.49(7)	0.0299 0.075 0.612	0.030(6)	0.005 0.0635 0.11	0.006(2)	13.7(9)	$E1$
313.0	7.3(8)	0.65(6)	1.03(5)	0.0254 0.0643 0.501	0.14(6)			7.1(8)	$E2$
398.9	7.9(9)	0.58(4)	0.99(9)					8.2(9)	$E2$
414.0	45(4)	0.53(3)	1.01(3)					47(4)	$E2$
441.6	72(8)	0.56(3)	0.97(3)	0.0122 0.0317 0.198	0.039(9)			74(8)	$E2$
451.3[c]	6.2(9)							6.3(9)	$E2$
498.6	52(6)		1.20(8)	0.0095 0.0249 0.143	0.030(15)	0.0016 0.0096 0.025	0.012(6)	53(6)	$E2$
527.7	100(6)		0.93(3)	0.0085 0.0223 0.123	0.044(10)			100(6)	$E2$

[a] Errors in E are about 0.2 keV.

[b] Theoretical values from Ref. 26.

[c] Contaminated lines. Relative intensities were deduced from coincidence spectra.

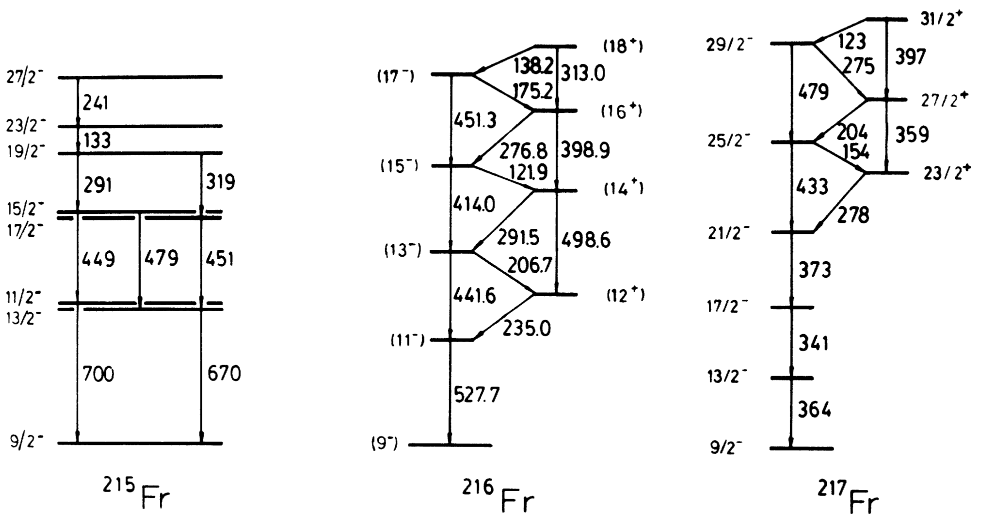

FIG. 1. Partial level scheme of ^{216}Fr compared to Yrast structures in ^{215,217}Fr (Refs. 11 and 12).

TABLE II. $B(E1)/B(E2)$ ratios in ^{216}Fr and in ^{217}Fr (Ref. 12) from states of initial spin I_i^{π}.

$I_i\pi$	^{216}Fr $B(E1)/B(E2)$ (10^{-6} fm^{-2})	I_i^{π}	^{217}Fr $B(E1)/B(E2)$ (10^{-6} fm^{-2})
(13^-)	0.23(3)	$25/2^-$	1.1(4)
(14^+)	1.9(3)	$27/2^+$	0.9(2)
(15^-)	0.32(8)	$29/2^-$	1.0(3)
(16^+)	1.3(2)	$31/2^+$	1.0(4)
(17^-)	2.6(6)	. . .	. . .
(18^+)	0.21(6)	. . .	. . .

spin-parity assignment in ^{216}Fr.

^{216}Fr is shown in Fig. 1 along with ^{215}Fr and ^{217}Fr (Refs. 11 and 12). The lower part of the scheme of ^{215}Fr can be interpreted as an $h9/2$ proton weakly coupled to the noncollective ^{214}Rn core. No positive parity states related to the ground "band" configuration ($h9/2$) are known. On the other hand, ^{217}Fr clearly shows collective features both in the quadrupole (slowly increasing $E2$'s) and in the reflection asymmetric (positive-parity states strongly connected by $E1$'s to the negative-parity states) degrees of freedom. It is interesting to note that the first quadrupole transition in ^{216}Fr (528 keV) interpolates quite well between the first quadrupole transitions in ^{215,217}Fr[$(670+364)/2=517$ keV].

The $B(E1)/B(E2)$ ratios found here in ^{216}Fr are similar to those measured in ^{217}Fr (see Table II). A similar pattern repeats itself for the isotopic chain ^{216,217,218}Ra and ^{217,218,219}Ac (Ref. 10). A more detailed examination of these ratios leads, however, to the following interesting observation. While in ^{217}Fr the $B(E1)/B(E2)$ ratios are similar for transitions from negative-parity states to positive-parity states as for transitions from positive to negative, in ^{216}Fr these ratios are larger for states with positive parity (up to the 16^+ state). This implies that in the even-even core the transitions from negative to positive are larger than the transitions from positive to negative. For pure vibrations[19] (and if only s, d, and f bosons are considered) the $E1$ transitions from positive (I^+) to negative-parity $[(I-1)^-]$ states are forbidden because these transitions require a change of four units in core angular momentum and hence the simultaneous annihilation of two d bosons. A similar argument holds for an octupole vibration coupled to a deformed core. For stable reflection asymmetric shapes, on the other hand, these ratios should be similar[20] for transitions starting either from positive- or from negative-parity states. The $B(E1)/B(E2)$ ratios observed for ^{216}Fr [and also for its isotones ^{217}Ra and ^{218}Ac (Refs. 7 and 21)] show an intermediate behavior between the two extremes just discussed. This adds a strong point for the case of a smooth development in the reflection asymmetric character in these nuclei.

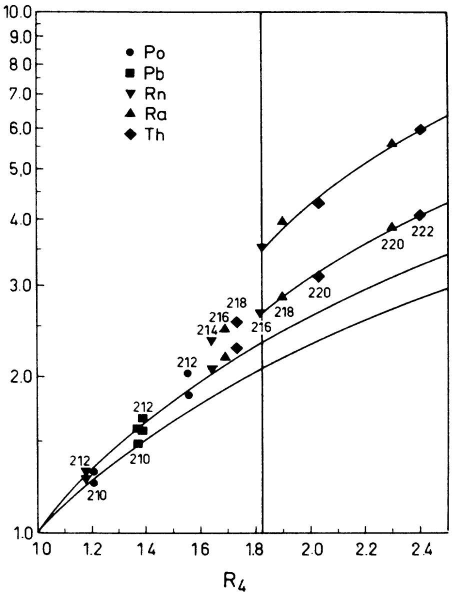

FIG. 2. Mallmann (R_I vs R_4) plot for even-even, $208<A\leq 222$ ($Z\geq 82$; $N\geq 126$) nuclei. Data from Refs. 3, 4, 14, and 25.

In fact, the transition between a spherical shell model (or single particle) and a collective regime[22,23] seems to occur precisely at $N=129$. All the known even $N=128$ isotones, from ^{210}Pb to ^{218}Th (Ref. 14), have $R_4(=E_{4^+}/E_{2^+})$ ratios less than the critical value 1.82 in a Mallman plot[22,24] (see Fig. 2) showing a compression of the transition energies as one goes up the ground-state band while the known odd Z, $N=128$ isotones are essentially an $h9/2$ proton weakly coupled to the A-1 even-even core. On the other hand, the even $N=130$ isotones from ^{216}Rn on, clearly show collective features; their R_4 ratios lie beyond $R_4=1.82$ and R_6 and R_8 fall nicely on the collective branch of the variable moment of inertia curves. It is interesting to note that ^{216}Rn (Ref. 25) falls exactly (see Fig. 2) on the end point of the upper family of curves having a spectrum which goes approximately[24] as $R_I=[I(I+1)/6]^{1/2}$ [which gives $R_4=(\frac{10}{3})^{1/2}=1.82$]. (Incidentally one may note that the nuclei with $R_4<1.82$ do not adapt too well to the lower family of curves showing a smoother transition to the upper family.) From all the nuclei falling on the upper VMI curves, the only one where no interleaved states of negative parity are known is ^{216}Rn.

Hence, so far the lightest nucleus showing evidence for reflection asymmetry is ^{216}Fr, defining a lower boundary for this kind of phenomenon as $Z>86$ and $N>128$. This boundary approximately coincides with the criterium for collectivity given by the VMI curves for even-even nuclei (namely $Z\geq 86$ and $N\geq 130$).

We kindly acknowledge interesting comments, particularly on the behavior of the $B(E1)/B(E2)$ ratios by M. Gai.

[*] Also at Departamento de Física, Facultad de Ciencies Exactas y Naturales, Universidad de Buenos Aires, RA-1428 Buenos Aires, Argentina.

[1] G. A. Leander *et al.*, Nucl. Phys. **A388**, 452 (1982).

[2] F. Iachello and A. D. Jackson, Phys. Lett. **108B**, 151 (1982).

[3] J. Fernández Niello *et al.*, Nucl. Phys. **A391**, 221 (1982).

[4] M. Gai *et al.*, Phys. Rev. Lett. **51**, 646 (1983); Y. Gono *et al.*, Nucl. Phys. **A459**, 427 (1986).

[5] N. Schulz *et al.*, Phys. Rev. C **28**, 435 (1983).

[6] P. D. Cottle *et al.*, Phys. Rev. C **30**, 1768 (1984); J. F. Shriner, Jr., *et al.*, Phys. Rev. C **32**, 1888 (1985).

[7] N. Roy *et al.*, Nucl. Phys. **A426**, 379 (1984).

[8] S. Khazrouni *et al.*, Z. Phys. A **320**, 535 (1985).

[9] W. Bonin *et al.*, Z. Phys. A **322**, 59 (1985), and references therein.

[10] M. E. Debray *et al.*, Phys. Rev. C **39**, 1193 (1989).

[11] N. Schulz *et al.*, J. Phys. G **10**, 1201 (1984).

[12] M. Aiche *et al.*, J. Phys. G **14**, 1191 (1988).

[13] J. Borggreen *et al.*, Phys. Rev. C **2**, 1841 (1970).

[14] *Table of Isotopes,* 7th ed., edited by C. M. Lederer and V. S. Shirley (Wiley, New York, 1978).

[15] T. Lönnroth, V. Rahkonen, and B. Fant, Nucl. Phys. **A376**, 29 (1982).

[16] J. P. Schiffer and W. W. True, Rev. Mod. Phys. **48**, 191 (1976).

[17] A. J. Kreiner, Phys. Rev. C **22**, 1570 (1980).

[18] M. J. Martin, Nucl. Data Sheets **49**, 83 (1986).

[19] A. Arima and F. Iachello, Ann. Phys. (N.Y.) **99**, 253 (1976).

[20] G. A. Leander *et al.*, Nucl. Phys. **A453**, 58 (1986).

[21] M. Debray *et al.* (unpublished).

[22] A. J. Kreiner, Phys. Rev. C **30**, 371 (1984).

[23] A. J. Kreiner and C. Pomar, Phys. Rev. C **36**, 463 (1987), and references therein.

[24] M. A. J. Mariscotti, Phys. Rev. Lett. **24**, 1242 (1970).

[25] P. D. Cottle *et al.*, Phys. Rev. C **35**, 1939 (1987).

[26] F. Rösel *et al.*, At. Data Nucl. Data Tables **21**, 293 (1978).