Alternating parity bands in $^{218}_{87}$Fr

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States in doubly odd ^{218}Fr have been studied using in-beam spectroscopy $\alpha-\gamma-\gamma$ coincidence techniques mainly through the ^{209}Bi(^{18}O, $2\alpha n$) reaction at 94 MeV bombarding energy, using the 8π GASP-ISIS spectrometer at Legnaro. ^{218}Fr shows a band structure, with interleaved states of alternating parities connected by enhanced $E1$ transitions. Tentative spin assignment and the relation between the structure of ^{218}Fr and its isotone ^{220}Ac is discussed.

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^{218}Fr has five protons and five neutrons more than the doubly closed-shell nucleus ^{208}Pb. Like the other $N=131$ (and $Z\geqslant87$) isotones, ^{218}Fr is located just on the edge of the region of reflection asymmetric instability. The odd-Z and doubly odd nuclei in this transitional region ($N\leqslant131$), which show quadrupolar and octupolar collectivity, generally display weak-coupling-type schemes, in which the unpaired proton couples to collective states in the neighbors largely preserving their structure. This is true for ^{216}Fr [1], ^{218}Ac [2,3], and ^{217}Ra [4] in which the removal or addition of the odd $h_{9/2}$ proton does not influence significantly the structure already developed in ^{217}Ra. It is also true for the pair ^{219}Ac [5,6] and ^{218}Ra [7,8] and the known $N=131$ isotones ^{219}Ra [9], ^{220}Ac [10], and ^{221}Th [11]. On the other hand, the Fr isotopes are located at the edge ($Z=87$ in number of protons) for which the octupole collectivity starts. The nucleus ^{216}Rn [12] shows evidence of the development of some quadrupole collectivity but no low-lying negative parity states are present. The study of ^{218}Fr provides additional information which hopefully will contribute to the understanding of the onset and evolution of the octupole collectivity in the light actinide region.

The previously known information on ^{218}Fr consists of a few levels obtained from the ^{222}Ac α decay [13]. The ground state of ^{218}Fr has been assigned as (1^-) because it favors the α decay ($E_\alpha=7.867$ MeV) to the (1^-) ^{214}At [14] ground state. The I^π of the excited isomeric ($T_{1/2}=22$ ms) state in ^{218}Fr is unknown.

^{218}Fr has been studied here through the ^{209}Bi(^{18}O, $2\alpha n$) reaction at 94 MeV bombarding energy using the 8π GASP-ISIS spectrometer at Legnaro. With this study, ^{218}Fr becomes the heaviest $Z=87$ isotope studied in-beam with heavy-ion-induced reactions.

A 2 mg/cm^2 self-supporting ^{209}Bi target was bombarded with a 10 pnA ^{18}O beam. For this target-projectile combination the competition of the fission channel is very strong and it is not possible to use conventional $\gamma-\gamma$ coincidence spectroscopy with a multiplicity filter. To reduce the intense γ background originating from fission, we used the ISIS array (40 telescopic $E-\Delta E$ particle detectors) to trigger the GASP spectrometer, selecting the evaporation α particles emitted in coincidence with transitions between excited states in ^{218}Fr. This powerful technique has been used here to identify unambiguously the γ transitions belonging to ^{218}Fr. At the bombarding energy used in the present work to study the ^{209}Bi[^{18}O(94 MeV), $2\alpha xn$] reaction the $2\alpha n$ and $2\alpha 2n$ (^{217}Fr [15]) channels were comparable (the cross sections were estimated to be $\sigma\simeq15$ μb). The predominant transitions could be assigned to ^{218}Fr (and the known ^{217}Fr) from the coincidence with $2\alpha'$s in the E-ΔE matrix of the ISIS array, where the separation between the α's belonging to the $2\alpha n$ (and $2\alpha 2n$) channel and the charged particles arising from other reaction channels was very clear. Approximately a total of 60 000 events were acquired from the $\gamma-\gamma-E-\Delta E$ coincidences ($2\alpha xn$ channels—half of them corresponding to ^{218}Fr).

A positive identification of the γ rays from $Z=87$ nuclei was based on the coincidence between the Fr K x rays and the most intense lines present in the projection spectrum (this is the γ spectrum in coincidence with 2α hits in the ISIS array, two in the BGO multiplicity filter and two in the Ge detectors). Figure 1 shows (a) the γ-ray spectrum corresponding to the projection, (b) the sum of coincidence spectra gated on the 272.9, 323.0, 266.5, 219.0, 380.5, 229.5, 462.7, 150.6, and 492.4 keV transitions assigned to the most intense band in the level scheme obtained for ^{218}Fr (see Fig. 2, band B), and (c) the sum of coincidence spectra gated on the 177.1, 326.6, 367.1, and 439.1 keV transitions labeled as band A on the same level scheme. A very powerful aid in the construction of the level scheme was the cleanliness of the projection spectrum. Only a few transitions belonging to both ^{218}Fr and ^{217}Fr were contaminated (this situation allows an intensity determination for the majority of the transitions and a check of the energy calibration using the known energies of the ^{217}Fr lines).

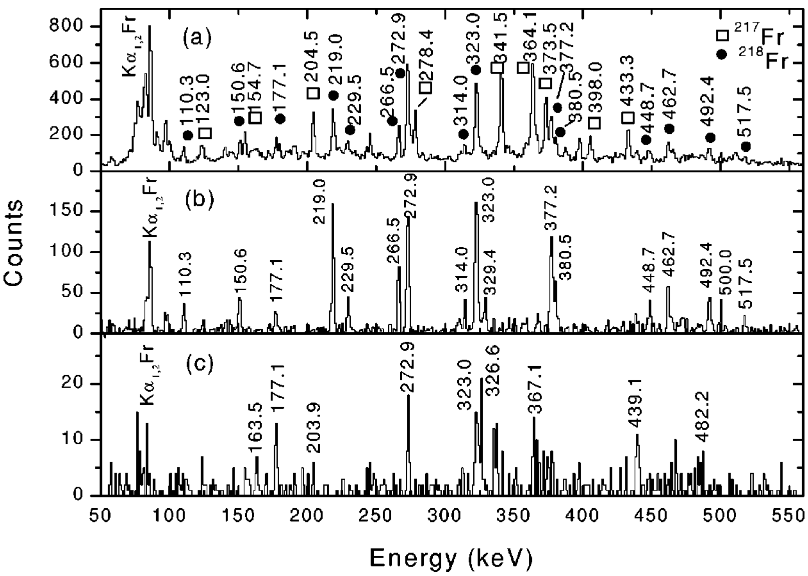

FIG. 1. γ-ray coincidence spectra of Ge detectors corresponding to (a) the projection spectrum, (b) sum of several gates on pairs of transitions of the favored alternating parity band B: (9^-), (11^-), (12^+), (13^-), (14^+), ... and (c) sum of several gates of the unfavored band A: (10^-), (12^-), (14^-), ...

The level scheme (Fig. 2) consists mainly of two bands connected by the 177.1 keV transition, which appears very clear in coincidence with the 272.9 and 326.6 keV lines. Nevertheless, the statistics is too poor to determine unambiguously the character of this transition. The intensity balance seems to indicate that it has $M1(E2)$ character. The assigned order of the transitions in the level scheme is supported by the sum energies and their intensities in the projection spectrum and coincidence spectra. The multipolarities of the transitions belonging to the bands in ^{218}Fr were assigned based on a similar behavior of its neighbor ^{217}Fr (its level scheme (Ref. [15]) is also populated in the present work) and inferred from a comparison with bands in ^{219}Ra, ^{220}Ac, and ^{221}Th. They were hence assumed to be stretched $E2$ and $M1$ (the 177.1 keV) transitions. Only in the cases of the electric dipole transitions and particularly for the low energy lines (150.6 and 110.3 keV), the use of intensity balance in coincidence spectra enabled us to determine the electromagnetic character.

From this result it is assumed that all transitions connecting the two rightmost sequences (band B) have electric dipole character. The resulting level scheme shows an alternat-

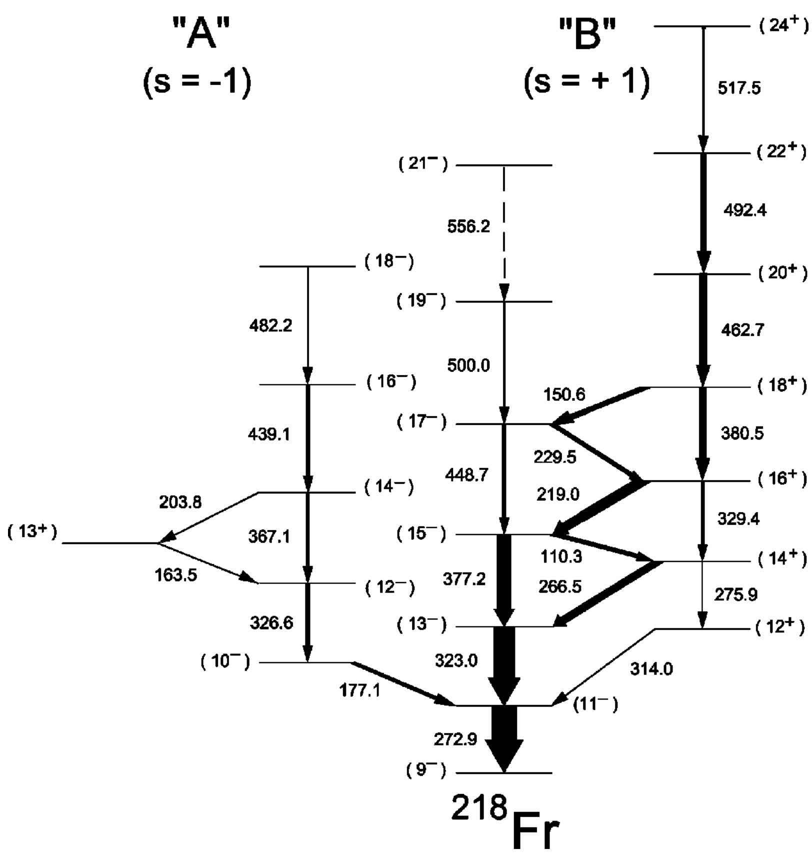

FIG. 2. Level scheme of ^{218}Fr proposed in the present work.

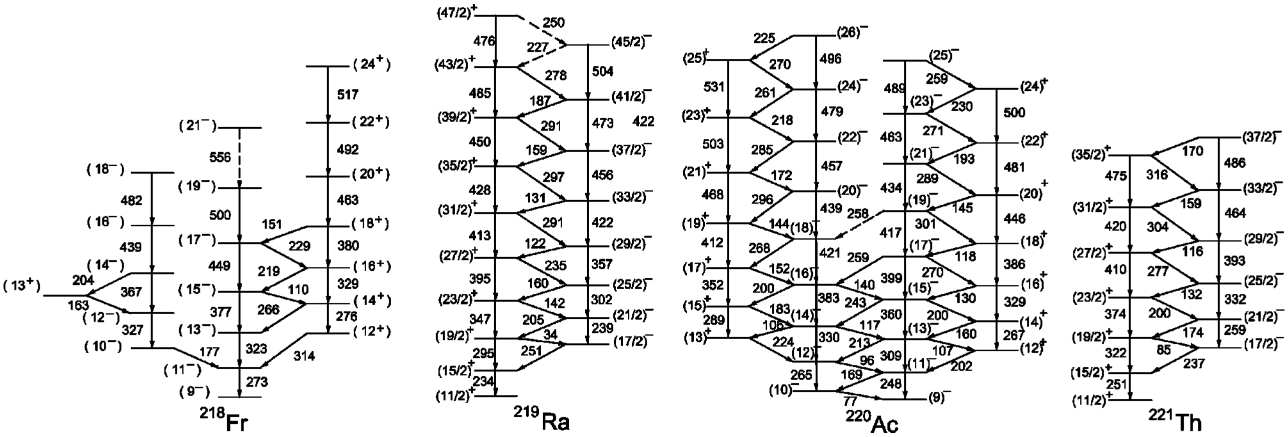

FIG. 3. Level scheme of ^{218}Fr compared to partial level scheme of ^{220}Ac [10] and yrast structures in ^{219}Ra [9] and ^{221}Th [11]. The proposed spin assignments to the levels in ^{218}Fr are discussed in the text. (See Ref. [3] for the spin assignments to the other three nuclei.)

ing parity band structure characteristic of octupole collectivity. In the following discussion the results will be examined on the basis of the reflection asymmetries of the nucleus.

Figure 3 shows the similarity between the bands in the odd-odd isotones ^{218}Fr and ^{220}Ac and the lowest band in the odd isotones ^{219}Ra, and ^{221}Th, resembling also the situation encountered for ^{216}Fr, ^{217}Ra and ^{218}Ac (see Ref. [3]). As discussed in Ref.3, the quasirotational structure observed in ^{219}Ra and ^{221}Th can be interpreted as a decoupled band based on the $i_{11/2}$ orbital with predominant occupation of the $1/2^{+}[640]$ Nilsson state (the dominant $i_{11/2}$ parentage holds at low quadrupole deformation). The unfavored signature band, $I^{\pi}=13/2^{+}$, $17/2^{+}$, ... and its associated octupole phonon band are pushed up in energy and hence not observed. The addition (or removal) of a proton to the odd neutron nucleus (and also of two protons to the neighboring doubly odd isotone) seems to have a small effect on the deformation of the system, possibly due to the quasiparticle character of the proton excitation, which quenches its single-quasiparticle quadrupole moment. This would lead in ^{220}Ac to two relatively degenerate states, the favored $J^{\pi}=10^{-}$ (resulting from the stretched coupling) and $J^{\pi}=9^{-}$ (resulting from the next-to-maximum coupling) of the $\tilde{\pi}h_{9/2}\otimes\tilde{\nu}i_{11/2}$ configuration. Each of these intrinsic states has an alternating parity band built on it. The two-quasiparticle rotor model [16] predicts for the $\tilde{\pi}h_{9/2}\otimes\tilde{\nu}i_{11/2}$ configuration that the even spin states (signature = 0) should be favored. This has to do with the fact that the decoupling parameters of the two $\Omega=1/2$ high-j orbits have opposite sign ($a_p=5$ and $a_n=-6$ for the $h_{9/2}$ and $i_{11/2}$ respectively, see Ref. [17]).

The excited energies of ^{218}Fr fit well into the low-lying yrast-level systematic of the actinide nuclei (see Fig. 4—this fit also helps to confirm that the 272.9 keV transition is the first transition of the yrast band, and that all low-level transitions of this band are observed). It follows from the systematic that the evolution of the positive and negative parity states in the even-even nuclei and the energies of the excited states in the odd and doubly odd nuclei are nearly independent of the particle configuration of the valence nucleons. That is, the smooth transition to stable quadrupole and octupole deformations is mainly related to the collective instead of the particle aspects of these nuclei. The similarity shown in Fig. 3 between the low-lying level schemes of the isotones with $N=131$ reflects just this fact. The in-band transitions

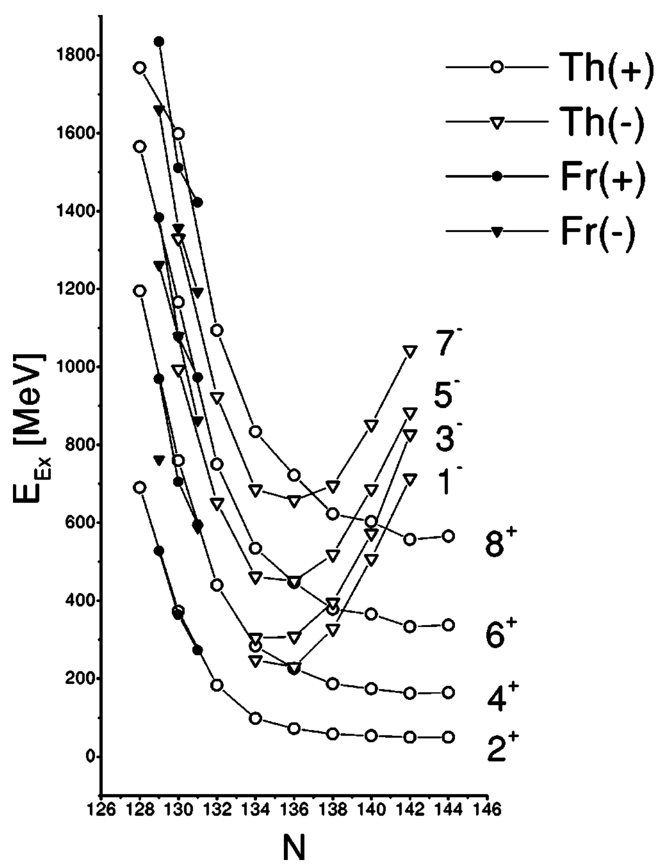

FIG. 4. Low-lying yrast level systematic of the even-even Th, Fr, and Ac isotopes. The states are labeled by $(I-I_g)^{\pi}$ where I represents the spins of the excited levels of the ground-state bands, I_g are the spins of the bandhead states and $\pi=+1(-1)$ for even(odd) spin states, respectively. Data coresponding to empty symbols are taken from Refs. [5,21] and that of full symbols are obtained in this work and from ^{216}Fr [1], ^{217}Fr [15], ^{218}Ac [2,3], ^{219}Ac [5,6], ^{220}Ac [10], and ^{221}Ac [24].

are essentially collective and rather independent of the proton-neutron configurations of the different band heads. Thereby, the sense of the similarity mentioned above (and shown in Fig. 3) is related mainly to the collective character than the particle configuration of these nuclei.

Now the tentative spin-parity $I^\pi=(9^-)$ assignment to the ''bandhead'' state in ^{218}Fr, its intrinsic structure and its relation to the intrinsic structure of ^{220}Ac will be briefly discussed. Many lighter doubly odd nuclei of this region (mostly with $Z\leqslant 87$ and/or $N\leqslant 129$) have two isomeric α-emitting states, the $I^\pi=(1^-)$ ground and a (9^-) excited state, which mainly arise from the coupling of the two lowest-lying single particle orbits $\pi h_{9/2}$ and $\nu g_{9/2}$. The presence of an attractive proton-neutron particle-particle force acting strongly in the antialigned and aligned $\pi h_{9/2}\otimes\nu g_{9/2}$ configurations is consistent with the fact that the (1^-) and the (9^-) states (members of the $J^\pi=1^-,\ 2^-,\ \ldots\ 9^-$ multiplet) lie lowest in energy. On the other hand, other doubly odd nuclei like ^{216}Fr [1] and ^{218}Ac [2] have only one isomeric state, namely, the $I^\pi=(1^-)$ ground state. In these nuclei the particle-hole (quasiparticle) character for the $\pi h_{9/2}$ and $\nu g_{9/2}$ excitations reduces the residual $p-n$ force, and hence the splitting of the J multiplet decreases and other states of intermediate spin J start to move into it. Eventually the 9^- state may decay to the 1^- ground state through a series of low-energy highly converted transitions losing its α-emitting character. Since the 9^- (maximum alignment) state is still expected to be low lying, it will be on the yrast line receiving strong feeding in the heavy-ion induced reaction.

On the other hand, in this region only the $\tilde{\pi}h_{9/2}\otimes\tilde{\nu}g_{9/2}$, $\tilde{\pi}h_{9/2}\otimes\tilde{\nu}i_{11/2}$, and $\tilde{\pi}f_{7/2}\otimes\tilde{\nu}g_{9/2}$ configurations give rise to a possible $J^\pi=1^-$ state. The I^π of the maximum aligned state will be 9^- for the $\tilde{\pi}h_{9/2}\otimes\tilde{\nu}g_{9/2}$, 10^- for the $\tilde{\pi}h_{9/2}\otimes\tilde{\nu}i_{11/2}$ and 8^- for the $\tilde{\pi}f_{7/2}\otimes\tilde{\nu}g_{9/2}$ configuration. In any case the ''maximum aligned'' state is expected to be low lying, and it will also be on the yrast line.

According to the calculations performed by Cwiok and Nazarewicz [18] for deformations $\beta_2\simeq 0.04$, the lowest-lying single proton state in Fr isotopes (two protons less than ^{220}Ac) can be associated with an $\Omega=5/2^-$ (which corresponds at low octupole deformation to the $5/2^-$ [523] Nilsson state originating from the $1h_{9/2}$ subshell), or with an $\Omega=1/2^-$ orbital (corresponds at low octupole and quadrupole deformation to the $1/2^-$ [530] Nilsson state originating from the $2f_{7/2}$ subshell) and the lowest-lying single neutron state can be associated with the $\Omega=5/2^+$ orbital (corresponding at low octupole and quadrupole deformation to the $5/2^+$ [633] Nilsson state originating from the $2g_{9/2}$ subshell) or with the above-mentioned $\Omega=1/2^+$ [640] Nilsson orbit. These single-particle orbitals are restricted to those belonging to the above-mentioned $\tilde{\pi}h_{9/2}\otimes\tilde{\nu}g_{9/2}$, $\tilde{\pi}h_{9/2}\otimes\tilde{\nu}i_{11/2}$ and $\tilde{\pi}f_{7/2}\otimes\tilde{\nu}g_{9/2}$ possible configurations.

In the $\tilde{\pi}f_{7/2}\otimes\tilde{\nu}g_{9/2}$ configuration the decoupling parameters of the two $\Omega=1/2$ orbitals have, as in the $\tilde{\pi}h_{9/2}\otimes\tilde{\nu}i_{11/2}$ case (assumed for ^{220}Ac, see Ref. [3]), different sign ($\pi f_{7/2}$ has $a_p=-4$ and $g_{9/2}$ has $a_n=+5$), and hence also in this case the even-spin values should be favored. This would lead to a level scheme of alternating parity bands (similar to the situation encountered for ^{220}Ac) built on two relatively degenerate states, the favored $J^\pi=8^-$ (resulting from the stretched coupling) and $J^\pi=7^-$ (resulting from the next-to-maximum coupling).

It is very important to point out that while in ^{220}Ac the intensities of both bands (built on the $J^\pi=9^-$ and 10^- states) are similar, that is, both bands are on the yrast line, in ^{218}Fr the observed bands have very different intensities (band B is six times more intense than band A).

If the $\tilde{\pi}h_{9/2}\otimes\tilde{\nu}g_{9/2}$ configuration assignment is correct the relevant decoupling parameters have the same sign ($h_{9/2}$ has $a_p=+5$ and $g_{9/2}$ has $a_n=+5$). In this case states with odd-spin value (signature = 1) should be favored, and these states come down in energy with respect to the even-spin states. This assumption would lead in ^{218}Fr to a level scheme of alternating parity bands built on two low-lying states, the favored $J^\pi=9^-$ (resulting from the stretched coupling) and $J^\pi=8^-$ (resulting from the next-to-maximum coupling) of the $\tilde{\pi}h_{9/2}\otimes\tilde{\nu}g_{9/2}$ configuration. Since the band built on the $J^\pi=8^-$ would not be on the yrast line, it only will receive a weak feeding in the heavy-ion-induced reaction. This argument provides a basis for the tentative $J^\pi=9^-$ bandhead assignment and the explanation of the different intensities observed between the two alternating parity bands in the level schemes of ^{220}Ac and ^{218}Fr.

For a nucleus (which shows nuclear deformation with odd multipole components) with an even number of nucleons, where the spin I is an integer, the possible spin and parity sequences are

$$I=0^+,\ 1^-,\ 2^+,\ 3^-,\ldots \qquad \text{for } s=+1,$$

$$I=0^-,\ 1^+,\ 2^-,\ 3^+,\ldots \qquad \text{for } s=-1,$$

where $s=+$ or -1 are the simplex numbers [19]. Both sequences are observed in the level scheme of ^{218}Fr. Assuming $I=9^-$ for the band-head state of the yrast band (band B), the simplex value is $s=+1$. Band A has a simplex of opposite sign to that of band B (that is, $s=-1$). The presence of low-lying octupole excitations may induce a large $E1$ moment in the intrinsic frame. Thus, states within a band with the same simplex will be connected (besides the electric quadrupole transitions) with strong electric dipole transitions. This situation may lead to the characteristic level scheme of states connected through stretched $E2$ transitions through two parallel (also stretched) $E1$ transitions.

From the $E1$ and $E2$ observed transitions it is possible to deduce the mean value for the absolute magnitude of the intrinsic electric dipole moment $|D_0|$ and the intrinsic quadrupole moment $|Q_0|$. These were extracted from the experimental $B(E1)/B(E2)$ values using the rotational model expression:

$$\left(\frac{D_0}{Q_0}\right)^2=\frac{5}{8}\frac{B(E1)}{B(E2)}\frac{(I+K-1)(I-K-1)}{(2I-1)(I-1)}$$

under the assumption of a constant intrinsic quadrupole moment Q_0. Nevertheless, the use of this formula is questionable since ^{218}Fr is not a good rotor; this is a consistent method to extract D_0 from the data, and allows us to compare our result with other D_0 quoted values obtained in the same way. The $B(E1)/B(E2)$ values were obtained for each excited state measuring the $E1/E2$ γ-ray intensity ratio from a spectrum which was in coincidence with all the transitions lying above the state of interest. The mean value of this ratio is $|\overline{D_0/Q_0}| = 0.36 \pm 0.07 \times 10^{-3}$ fm^{-1}. The experimental mean dipole moment $|\overline{D_0}| = 0.13 \pm 0.03$ e fm was obtained using the known experimental quadrupole moment for ^{218}Ra($Q_0 = 327$ e fm^2) [20] and the semiempirical Grodzins systematic for ^{216}Rn($Q_0 = 294$ e fm^2) [12], ^{218}Rn($Q_0 = 359$ e fm^2) [21] and ^{220}Ra($Q_0 = 492$ e fm^2) [22]. This value of D_0 is approximately a factor of 2 lower than those of ^{218}Ra and ^{219}Ra ([23] and references therein), very similar to that of ^{217}Fr [23] and larger than the value measured for ^{218}Rn [23]. This may indicate that the p-n octupole correlations are larger when the proton number is increasing. However, for this region of light actinides, this statement is more valid for a transition within an octupole vibration picture than for a stable octupole deformed description (as was noticed above, ^{216}Rn does not show evidence of alternating parity structure, indicating probably a lower mass limit for the region in which the development of the reflection asymmetry collectivity starts). Finally, the D_0 value measured in this work is in excellent agreement with the theoretical value $D_0^{th} = 0.14$ e fm deduced from the calculations of Butler and Nazarewicz [23] (using Fig. 1 of this work to calculate the D_0^{shell} contribution). The macroscopic component and the shell correction term are small but of the same sign and similar in magnitude ($D_0^{shell} = D_0^{macr} \simeq 0.07$ e fm resulting in a considerable value of the electric dipole moment in spite of the octupole-vibrational description of this nucleus.

This experiment has shown the extreme power and selectivity of the GASP-ISIS array and demonstrated the feasibility of performing in beam γ-ray spectroscopy in this region of very strong fission competition at the $\sigma \simeq 15$ μb level.

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