Reflection symmetry of the near-yrast excitations in ^{145}Ba

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Excited states in ^{145}Ba, populated in spontaneous fission of ^{248}Cm, have been studied by means of γ spectroscopy, using high-fold γ coincidences measured with the EUROGAM2 array of Ge detectors. The 507.7-keV level, which has been assigned in this work spin and parity $9/2^+$, belongs to the $i_{13/2}$ intruder band. We have identified in ^{145}Ba a new $9/2_2^-$ level at 346.3 keV and a band on top of it. The negative parity indicates that it is not due to an octupole excitation. The position of the $5/2^-$ ground state, relative to the positive-parity band, could be reproduced by calculations with a reflection-symmetric potential and we do not observe a parity doublet to the ground state. Therefore we conclude that octupole excitations in ^{145}Ba are most likely due to octupole vibrations coupled either to the reflection-symmetric ground state or to the $i_{13/2}$, decoupled neutron configuration.

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I. INTRODUCTION

In a recent study of ^{143}Xe [1] we have found a band based on the $9/2_2$ level at 322.9 keV, which could not be reproduced by the quasiparticle rotor model (QPRM) with a reflection-symmetric potential. This raised the question if the 322.9-keV level may be due to octupole correlations, which are expected and observed in this part of the nuclear chart [2–6]. The final conclusion about the nature of the 322.9-keV excitation and the presence of octupole correlations in ^{143}Xe could not be drawn in Ref. [1] because we could not determine the parity of the 322.9-keV level. To progress, we have undertaken studies of the neighboring $N = 89$ isotones in order to find similar excitations and to explain their nature. In this work we report on the search for an analogous $9/2_2$ excitation in ^{145}Ba, a nucleus where one expects strong octupole correlations, considering the fact that its even-even neighbors ^{144}Ba and ^{146}Ba may have static octupole deformation in their ground states [3,6,7].

Octupole correlations in ^{145}Ba were first studied in β^- decay of ^{145}Cs [8]. Although no parity doublets were found, the authors concluded that low-energy levels in ^{145}Ba cannot be described by a standard Nilsson model with quadrupole deformation only, and suggested that octupole effects are present in ^{145}Ba. In a measurement of prompt-γ rays from spontaneous fission of ^{248}Cm [9] clear band structures have been observed, which has facilitated spin and parity assignments. For example, the 112.5-keV level in ^{145}Ba reported in Ref. [8] with spins 3/2 ($5/2^-$) has been assigned in Ref. [9] spin and parity $7/2^-$, etc. Considering significantly different spin assignments in the two works one may question the interpretation of the ^{145}Ba nucleus proposed in Ref. [8].

Spin assignments from Ref. [9] have been adopted in another study of prompt-γ rays from spontaneous fission of ^{252}Cf [10], replacing their previous assignments [11]. Importantly, in Ref. [10] a band of positive parity, based on the $11/2^+$ level at 671.1 keV, has been proposed and another new band (band 5 in Ref. [10]) has been assigned negative parity. Bands in ^{145}Ba, observed in prompt-γ works, were arranged in Ref. [10] into simplex $s = +i$ and $s = -i$ branches of the $I = 5/2$ parity doublets. These results were analyzed theoretically by Chen *et al.* [12], using their model [13], which has been well tested in octupole-deformed actinides. The authors concluded that while the $s = -i$ branch of the $I = 5/2$ parity doublet can be reproduced by calculations (though no $7/2^+$ level is known), the proposed $s = +i$ branch includes levels which probably belong to reflection-symmetric configurations. We note that the prominent 507.7-keV level, reported with spin and parity $11/2^-$ [9,10] has not been explained in the studies so far.

To learn more about the degree of octupole correlations in ^{145}Ba it is necessary to verify the existing information on spins and parities and obtain additional experimental data for this nucleus. Therefore, we have analyzed prompt-γ, triple coincidences from fission of ^{248}Cm, obtained with the EUROGAM2 Ge array [14], the same data which has been used in Ref. [9], but using now improved analysis techniques [15]. More details about the experiment and data analysis can be found in Refs. [16,17].

II. EXPERIMENTAL RESULTS

The present work confirms most of the coincidence relations and, therefore, excited levels and their arrangement into bands in ^{145}Ba, as reported in Refs. [9,10]. Some of the levels and transitions, reported previously, are not seen in our data. On the other hand we could add several new transitions and lines, as discussed below.

We do not observe the tentative 197.9-keV transition from the 2924.0-keV level and the 632.6- and 701.8-keV transitions in band (5) of Ref. [10], which may be due to lower statistics in our data. We also do not see the 126.5-, 256.2-, and 249.5-keV decays from the 1098.6-, 1640.4-, and 1889.9-keV levels, respectively, reported in Ref. [10]. We cannot confirm the

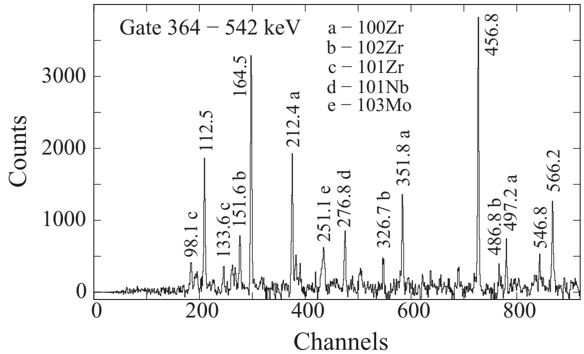

FIG. 1. γ spectrum doubly gated on lines in ^{145}Ba obtained in the present work. Lines are labeled in keV. Major contaminating lines (a–e) are identified.

2429-keV level as well as the 231.6-keV decay from the 1098.6-keV level, reported in Ref. [10], which should be seen in our data. We also do not see the 546.1-keV transition on top of the 1394.5-keV level, reported in Ref. [10] and, therefore, do not confirm the 1940.6-keV level.

On the other hand we could extend band (2) of Ref. [10] placing a new, 546.8-keV transition on top of the band. Figure 1 shows a γ spectrum doubly gated on the 364.4- and 542.0-keV lines in this band. In the spectrum there is a new line at 546.8 keV. Other gates confirm that this line belongs to the band. This is an important observation, indicating the presence of a backbend in the band.

In Fig. 2(a) we show a spectrum doubly gated on the 112.5-keV line of ^{145}Ba and the 212-keV line of ^{100}Zr, the main complementary fission fragment to ^{145}Ba. In the spectrum a new line at 233.8 keV can be seen. The spectrum, doubly gated on the 112.5- and 233.8-keV lines is shown in Fig. 2(b). In this spectrum one can see major lines of ^{100}Zr, ^{101}Zr, and ^{102}Zr, which indicates that the 233.8-keV line belongs to ^{145}Ba. Because there is no line at 164.5 keV in Fig. 2(b), the new 233.8-keV transition should feed the 112.5-keV level. In Fig. 2(b) there are new lines at 294.8 and 361.1 keV and the known line at 456.8 keV. The two new lines belong to ^{145}Ba. In the spectrum doubly gated on the 233.8- and 294.8-keV lines, shown in Fig. 3, there are the 456.8-, 542.0-, and

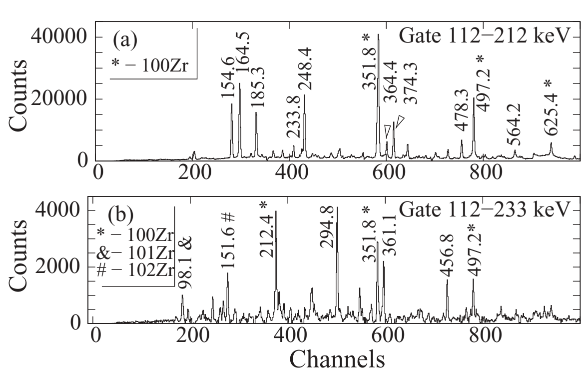

FIG. 2. γ spectra doubly gated on lines in ^{145}Ba as obtained in the present work. Lines are labeled in keV. The spectra show the presence of new, 233.8- and 361.1-keV lines in ^{145}Ba.

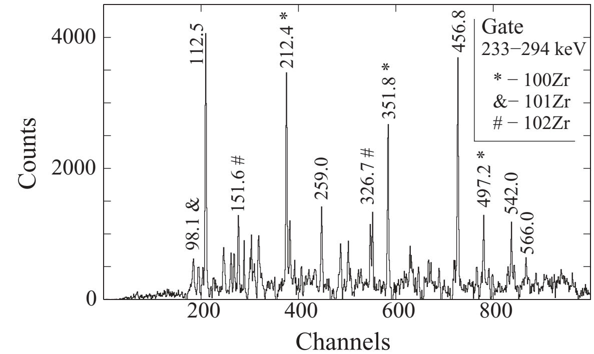

FIG. 3. γ spectrum doubly gated on 233.8- and 298.4-keV lines in ^{145}Ba, as observed in the present work. Lines in the spectrum are labeled in keV. The spectrum documents the presence of a new level at 346.3 keV in ^{145}Ba.

566.0-keV lines of the ground state (g.s.) band of ^{145}Ba. Thus, the new 233.8- and 294.8-keV transitions define a new level at 346.3 keV in ^{145}Ba. The 361.1-keV line seen in Fig. 2(b) feeds the 346.3-keV level. In the spectrum doubly gated on the 233.8- and 361.1-keV lines, shown in Fig. 4, there are new lines at 263.5-, 477.2-, and 536.0-keV. The 361.1-, 477.2-, and 536.0-keV lines could be arranged into a band based on the 346.3-keV level. This is shown in Fig. 5, where we display the scheme of excited levels in ^{145}Ba, populated in spontaneous fission of ^{248}Cm, as observed in the present work. In the scheme there are also two new levels at 1213.0 and 1678.8 keV, which are defined by the new 170.2-, 313.0-, and 465.8-keV transitions observed in this work. We could not determine parities of these two levels, which prevents further discussion. Properties of transitions and excited levels in ^{145}Ba, observed in this work, are listed in Table I.

Spins and parities of levels shown in Fig. 5 have been, generally, adopted from Refs. [9,10] but some values have been altered and some are new. Multipolarities of transitions in ^{145}Ba have been deduced in this work from angular correlations, conversion coefficient estimates, and from the observed intensity branching ratios. In assigning spins to excited levels, we also assumed that spins are growing with

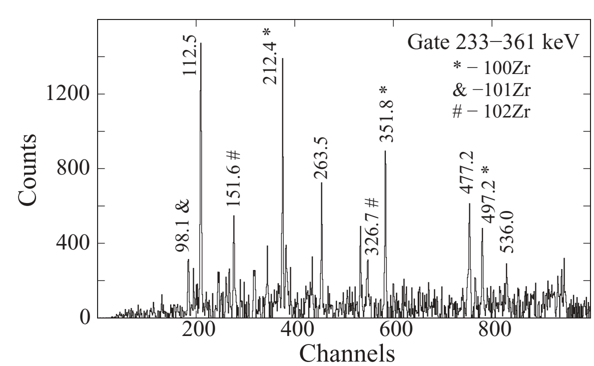

FIG. 4. γ spectrum doubly gated on 233.8- and 361.1-keV lines in ^{145}Ba, obtained in the present work. Lines in the spectrum are labeled in keV. The spectrum shows the presence of new, 263.5-, 477.2-, and 536.0-keV lines in ^{145}Ba.

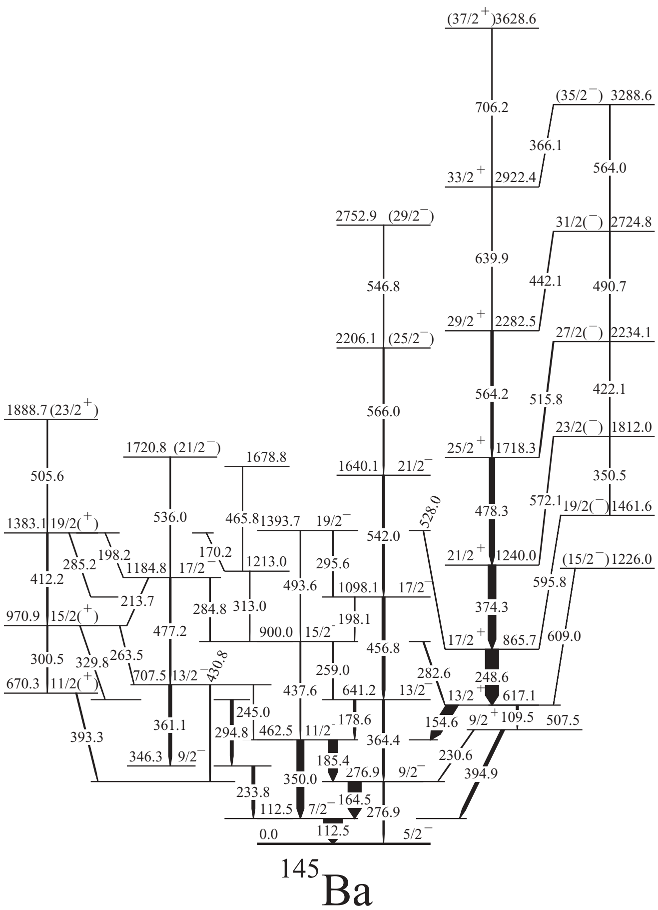

FIG. 5. Scheme of excited levels in ^{145}Ba, populated in spontaneous fission of ^{248}Cm, as observed in the present work.

excitation energy, as commonly observed for excited states populated in spontaneous fission [18].

We assume, as was done in Refs. [9,10,12], that the band on top of the 617.1-keV level corresponds to a decoupled $i_{13/2}$ neutron configuration. This is consistent with the plot of the total aligned angular momentum I_x in this band, shown in Fig. 6. The I_x alignment for bands in ^{145}Ba have been calculated using energies of the in-band, $\Delta I = 2$ transitions. For a transition with energy $E_\gamma = E_i - E_f$, between levels with energies E_i and E_f and spins I_i and I_f, the I_x value was calculated using the prescription of Ref. [19],

$$I_x = \sqrt{(I_a + 1/2)^2 - K^2},$$

where $I_a = (I_i + I_f)/2$ and K is the projection on the symmetry axis of the spin of the band head. The rotational frequency $\hbar\omega$ was calculated as [19]

$$\hbar\omega = (E_i - E_f)/\left(I_x^i - I_x^f\right),$$

where

$$I_x^{i,f} = \sqrt{(I_{i,f} + 1/2)^2 - K^2}.$$

The $i_{13/2}$ shell starts to be populated at the neutron number $N = 89$. Therefore, we assumed a $K = 3/2$ value for the band on top of the 617.1-keV level (the decoupled nature of this band supports a low-K value). The aligned angular momentum in

TABLE I. Properties of γ transitions and excited levels in ^{145}Ba, as observed in ^{248}Cm fission in this work.

E_γ (keV)	I_γ (rel.)	$E_{\text{lev}}^{\text{ini}}$ (keV)	$I_{\text{lev}}^{\text{ini}}$	Multipolarity
109.5 (1)	110(10)	617.1	$13/2^+$	$E2$, $\Delta I = 2$
112.5 (1)	1000(40)	112.5	$7/2^-$	$M1 + E2$, $\delta = -0.40(9)$
154.6 (1)	560(30)	617.1	$13/2^+$	$E1$, $\Delta I = 1$
164.5 (1)	700(35)	276.9	$9/2^-$	$M1 + E2$, $\delta = -0.22(7)$
170.2 (2)	15(4)	1383.1	$19/2^{(+)}$	
178.6 (2)	51(5)	641.2	$13/2^-$	
185.4 (1)	490(25)	462.5	$11/2^-$	$M1 + E2$, $\delta = -0.30(8)$
198.1 (3)	12(4)	1098.1	$17/2^-$	
198.2 (3)	12(5)	1383.1	$19/2^{(+)}$	
213.7 (2)	15(5)	1184.8	$(17/2^-)$	
230.6 (2)	25(5)	507.5	$9/2^+$	
233.8 (1)	150(20)	346.3	$9/2^-$	$M1 + E2$, $\delta = -0.10(4)$
245.0 (2)	76(5)	707.5	$1/2^-$	
248.6 (1)	710(30)	865.7	$17/2^+$	$E2$, $\Delta I = 2$
259.0 (2)	25(9)	900.0	$15/2^-$	
263.5 (2)	20(5)	970.9	$15/2^{(+)}$	
276.9 (1)	190(15)	276.9	$9/2^-$	$E2$, $\Delta I = 2$
282.6 (2)	15(5)	900.0	$15/2^-$	
284.8 (2)	10(5)	1184.8	$(17/2^-)$	
285.2 (3)	20(7)	1383.1	$19/2^{(+)}$	
294.8 (1)	66(8)	641.2	$13/2^-$	$E2$, $\Delta I = 2$
295.6 (3)	15(5)	1393.7	$(19/2^+)$	
300.5 (2)	15(5)	970.9	$15/2^{(+)}$	
313.0 (2)	25(5)	1213.0		
329.8 (1)	35(5)	970.9	$15/2^{(+)}$	
350.0 (2)	370(20)	462.5	$11/2^-$	
350.5 (2)	15(3)	1812.0	$19/2^{(-)}$	
361.1 (1)	50(5)	707.5	$13/2^-$	
364.4 (1)	210(15)	641.2	$13/2^-$	$E2$, $\Delta I = 2$
366.1 (2)	210(15)	3288.6	$(35/2^-)$	
374.3 (1)	420(20)	1240.0	$21/2^+$	$E2$, $\Delta I = 2$
393.3 (2)	55(3)	670.3	$11/2^{(+)}$	$E1$, $\Delta I = 1$
394.9 (1)	170(20)	507.5	$9/2^+$	
412.2 (2)	70(15)	1383.1	$19/2^{(+)}$	
422.1 (2)	14(3)	2234.1	$23/2^{(-)}$	
430.8 (2)	28(3)	707.5	$13/2^-$	
437.6 (2)	92(6)	900.0	$15/2^-$	
442.1 (2)	24(4)	2724.8	$31/2^{(-)}$	
456.8 (1)	260(50)	1098.1	$17/2^-$	$E2$, $\Delta I = 2$
465.8 (2)	35(8)	1678.8		
477.2 (2)	24(6)	1184.8	$(17/2^-)$	
478.3 (1)	280(10)	1718.3	$25/2^+$	$E2$, $\Delta I = 2$
490.7 (2)	35(5)	2724.8	$31/2^{(-)}$	
493.6 (3)	16(4)	1393.7	$(19/2^+)$	
505.6 (3)	30(10)	1888.7	$(23/2^+)$	
515.8 (1)	43(5)	2234.1	$27/2^{(+)}$	$\Delta I = 1$
528.0 (2)	18(3)	1393.7	$(19/2^+)$	
536.0 (4)	10(5)	1720.8	$(21/2^-)$	
542.0 (1)	150(25)	1640.1	$21/2^-$	
546.8 (3)	40(15)	2752.9	$(29/2^-)$	
564.0 (2)	30(5)	3288.6	$(35/2^-)$	
564.2 (1)	120(10)	2282.5	$29/2^+$	

TABLE I. (*Continued.*)

E_γ (keV)	I_γ (rel.)	E_{lev}^{ini} (keV)	I_{lev}^{ini}	Multipolarity
566.0 (2)	85(35)	2206.1	$(25/2^-)$	
572.1 (1)	22(5)	1812.0	$23/2^{(-)}$	
595.8 (2)	7(3)	1461.6	$19/2^{(-)}$	
609.0 (3)	14(4)	1226.0	$(15/2^-)$	
639.9 (2)	12(3)	2922.4	$33/2^+$	
706.2 (4)	8(4)	3628.6	$(37/2^+)$	

the band on top of the 617.1-keV level, measured relative to the ground-state band of ^{144}Ba (with $K = 0$) is $5.7\hbar$ (it is 5.9 when assuming $K = 1/2$), which is only consistent with a low-K orbital of the $i_{13/2}$ shell.

The most important change, as compared to previous works, concerns the 507.5-keV level, to which we assign spin and parity $I^\pi = 9/2^+$. This result is based on angular correlations between the 109.5- and 248.6-keV transitions, where the 248.6-keV transition is known to be stretched $E2$ in character. The correlation is shown in Fig. 7(a), where for comparison we show angular correlations of the 248.6-keV transition with the known, stretched $E1$ (154.6-keV) and stretched $E2$ (374.3-keV) transitions. Experimental data points are compared here to theoretical predictions of Refs. [6,17] for various multipolarities of transitions in $\gamma\gamma$ cascades, where D denotes a stretched dipole and Q denotes a stretched quadrupole. Clearly, the 109.5-keV transition is not stretched $E1$ in character, as reported before. The correlation for the 109.5–248.6-keV cascade is consistent with both transitions being stretched quadrupole in character. In Fig. 7(b) we show angular correlation for the 109.5–394.9-keV cascade, which is consistent with the stretched quadrupole-dipole case (for comparison we show angular correlations for the 364.4–276.9-keV cascade of two stretched quadrupole transitions). The combined results for the 109.5-keV transitions indicate its stretched quadrupole character.

This result is consistent with the estimates of the α_K conversion coefficient obtained by comparing intensity of the 109.5-keV line and the intensity of the X_K line of Ba, as seen in

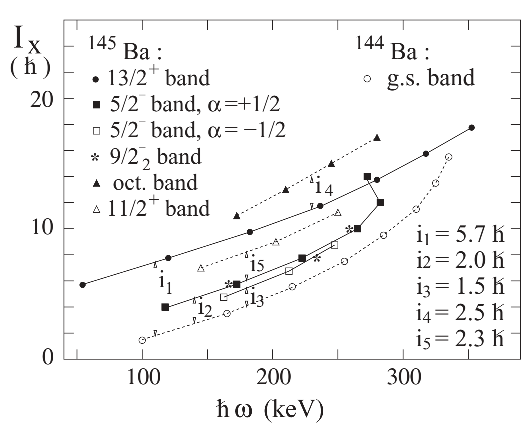

FIG. 6. Total aligned angular momenta in bands of ^{145}Ba and in the g.s. band of ^{144}Ba. The label "oct. band" refers to the band on top of the 1226.0-keV level.

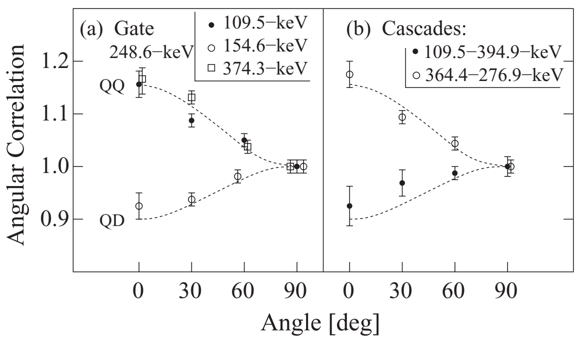

FIG. 7. Angular correlations in ^{145}Ba, as measured in this work.

the spectrum measured by a low-energy photon spectrometer (LEPS), four of which were attached to the EUROGAM2 array. The spectrum, shown in Fig. 8, is doubly gated on the 248.6- and 394.9-keV lines. In this particular gate the total intensity of the 109.5- and 112.5-keV transitions should be equal. The observed γ intensities may differ due to different values of the conversion coefficients for the two transitions. In Fig. 8 the γ intensity of the 109.5-keV line is lower than the γ intensity of the 112.5-keV line. Therefore, the internal conversion for the 109.5-keV transition must be higher than for the 112.5-keV, $M1 + E2$ transition. Thus, again, the 109.5-keV transition cannot be $E1$. To check the procedure we show in Fig. 9 a LEPS spectrum doubly gated on the 248.6- and 350.0-keV lines. Here the γ intensity of the 112.5-keV line is lower than the γ intensity of the 154.6-keV line (this difference is more pronounced when corrected for the LEPS detector efficiency, which is 50% lower at 154 keV than at 112 keV). Thus the internal conversion for the 154.6-keV transition is lower than for the 112.5-keV transition, in accord with their reported multipolarities of $E1$ and $M1 + E2$, respectively.

Taking intensities of the barium x-ray lines from Fig. 9 along with a theoretical value $\alpha_K = 0.058$ of the K-conversion coefficient for a pure $E1$ transition at 154.6 keV, we have estimated the contribution to the x-ray line due to the conversion of the 154.6-keV transition, and were able to estimate the α_K conversion coefficient for the 112.5-keV transition. The obtained value of $\alpha_K(112.5) = 0.63(3)$ is consistent with a $M1 + E2$ multipolarity for this transition, considering that the theoretical α_K values [22] calculated at 112.5 keV yield 0.14, 0.60, and 0.85 for pure $E1$, $M1$, and $E2$ multipolarities,

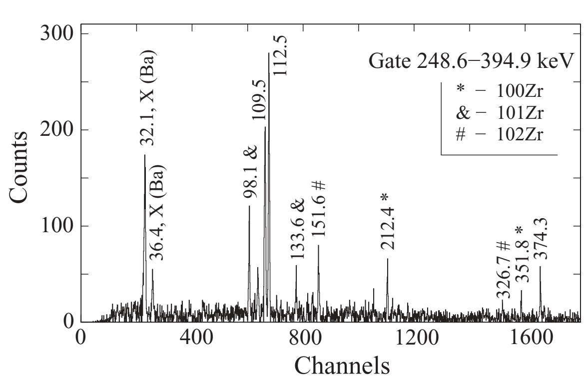

FIG. 8. Gate 248.6–394.9 keV projected on LEPS.

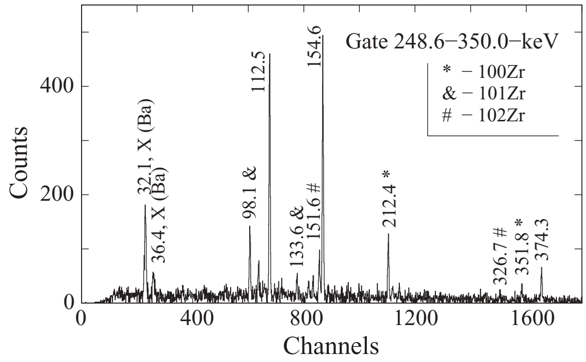

FIG. 9. Gate 248.6–350.0 keV projected on LEPS.

respectively. Similarly, taking a theoretical value $\alpha_{tot} = 0.068$ of the total conversion coefficient for a pure $E1$ transition at 154.6 keV we calculated the total intensity of the 154.6-keV line and then used it to estimate the total conversion coefficient for the 112.5-keV transition. The obtained value of $\alpha_{tot}(112.5) = 0.76(7)$ is again consistent with a $M1 + E2$ multipolarity for the 112.5-keV transition.

Using the $\alpha_K(112.5) = 0.63(3)$ value together with γ intensities from Fig. 8 we estimated the α_K conversion coefficient for the 109.5-keV transition. The obtained value, $\alpha_K(109.5) = 0.85(11)$, compared against theoretical α_K values of 0.15, 0.65, and 0.92 [22], calculated at 109.5 keV for pure $E1$, $M1$, and $E2$ multipolarities, respectively, indicates an $E2$ multipolarity for the 109.5-keV transition. Similarly, using the $\alpha_{tot}(112.5) = 0.76(7)$ value obtained from Fig. 9 and γ intensities from Fig. 8 we estimated the total conversion coefficient for the 109.5-keV transition to be $\alpha_{tot}(109.5) = 1.18(13)$. This value is closest to the $E2$ solution, considering the theoretical values of 0.18, 0.76, and 1.39 calculated at 109.5 keV for pure $E1$, $M1$, and $E2$ multipolarities.

The above data indicate that the 507.5-keV level has spin $9/2^+$, which agrees with the systematics of the $9/2^+$ excitations, drawn in Fig. 10 relative to the $5/2^-$ excitations in the $N = 89$ isotones. We cannot explain why some conversion coefficient values reported in Ref. [9] are so much different from the present results. Because of this discrepancy, we have double checked our results. We also note that not all results are different. The α_K conversion coefficient of 0.63(3), calculated in this work for the 112.5-keV transition in ^{145}Ba, is consistent with the value reported in Ref. [9]. Similarly, the α_K coefficient

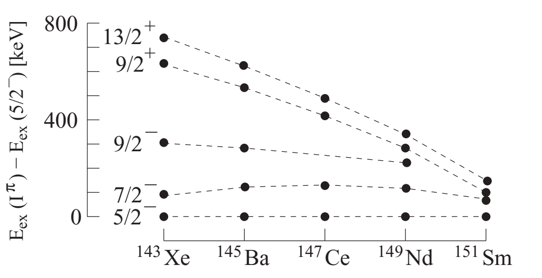

FIG. 10. Systematics of selected yrast levels in $N = 89$ isotones. The data are taken from this work and from Refs. [1,20,21]. See text for further explanation.

TABLE II. Experimental angular-correlation coefficients $(A_2/A_0)_{exp}$ and $(A_4/A_0)_{exp}$ for cascades of γ transitions in ^{145}Ba populated in fission of ^{248}Cm, as determined in the present work.

$E_{\gamma1}$-$E_{\gamma2}$ (keV)	$(A_2/A_0)_{exp}$	$(A_4/A_0)_{exp}$
109.5–248.6	0.100(12)	0.021(21)
109.5–394.9	−0.053(19)	−0.011(31)
112.5–164.5	0.416(44)	0.073(56)
112.5–233.8	0.276(41)	0.095(57)
112.5–350.0	−0.146(30)	−0.012(40)
112.5–394.9	0.171(24)	−0.010(36)
154.6–185.4	0.163(17)	0.021(30)
154.6–248.6	−0.058(13)	0.000(21)
164.5–185.4	0.405(18)	0.083(31)
164.5–364.4	−0.353(34)	−0.089(42)
185.4–276.9	−0.172(31)	0.030(41)
185.4–437.6	−0.084(24)	−0.029(35)
233.8–294.8	−0.052(24)	0.023(35)
248.6–374.3	0.112(12)	0.005(21)
276.9–364.4	0.113(14)	0.021(28)
364.4–456.8	0.089(20)	−0.030(38)
374.3–478.3	0.098(16)	−0.011(30)
478.3–515.8	−0.058(18)	0.000(25)

of 0.67(13) for the 109.7-keV transition in ^{147}Ba, calculated in this work, agrees with the result of Ref. [9].

For the band on top of the 1226.0-keV level previous interpretations are somewhat confusing. In Ref. [10] this band (their band 5) has been assigned negative parity, based on systematics, and incorporated into the $s = +i$ branch of the proposed $I = 5/2$ parity doublet. The same band has been also discussed as an example of a pairing-free structure or a new type of superdeformed band [10]. The mean alignment in this band ("oct. band" in Fig. 6) is about $2.5\hbar$ relative to the $13/2^+$ band. It is the same as the mean alignment in the octupole band of ^{144}Ba, calculated relative to the ground-state band (see Fig. 12 in Ref. [6]). In Table II we list experimental angular correlation coefficients $(A_2/A_0)_{exp}$ and $(A_4/A_0)_{exp}$, for several cascades of γ transitions in ^{145}Ba populated in fission of ^{248}Cm which were obtained in the present work. The angular correlation for the 515.8–478.3-keV cascades indicates a $\Delta I = 1$ multipolarity for the 515.8-keV transition, supporting the spins proposed in Ref. [10]. We therefore propose that the band on top of the 1226.0-keV level is due to an octupole vibration coupled to the $13/2^+$ band.

Following the same arguments as in Refs. [10,12] we assume, tentatively, that the 670.3-keV level has positive parity. The alignment in this band, relative to the $5/2^-$, ground-state band is $2.3\hbar$, which is consistent with the assumption of an octupole phonon coupled to the ground-state band.

The cascade of 294.8- and 233.8-keV transitions, depopulating the 641.2-keV level to the 112.5-keV level via the 346.3-keV level constraints spin and parity of the 346.3-keV level to $9/2^-$ or $11/2^-$. To distinguish between these two possibilities we have analyzed angular correlations for the 233.8- and 294.8-keV transitions. In Fig. 11 we show angular correlations for the various cascades involving the 346.3-keV level as well as for other cascades, shown for comparison.

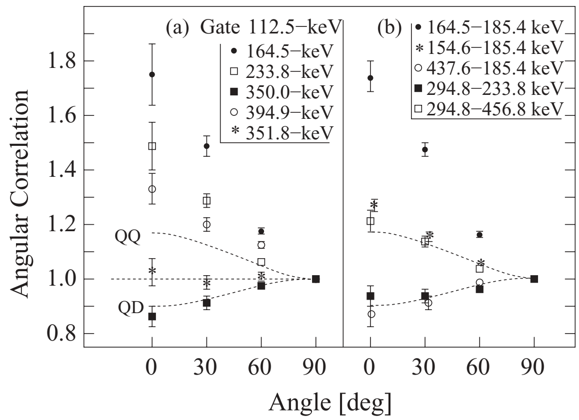

FIG. 11. Angular correlations in ^{145}Ba, as measured in this work. The 351.8-keV transition belongs to ^{100}Zr and is shown as a reference. It should show isotropic angular correlation in cascade with the 112.5-keV transition of ^{145}Ba.

The high anisotropy for the 112.5–164.5- and 164.5–185.4-keV cascades is characteristic of $M1 + E2$ transitions with sizable mixing ratio δ. In order to make a conclusion about the 233.8-keV transition from angular correlations for the 112.5–233.8-keV cascade, we have to determine the mixing ratio for the 112.5-keV transition, first. However, in the 112.5–164.5-keV cascade both transitions may have a nonzero δ. It is also well known that there are usually two solutions for δ of a given transition. This is because the constraint put on it by the A_4 coefficient of angular correlations is usually much weaker than the constraint put by the A_2 coefficient. This significantly increases the number of possible solutions but can be helped by analyzing other cascades involving the 164.5-keV transition (the 164.5–364.4-keV and 164.5–185.4-keV cascades). We note that some of the transitions involved in the discussed correlations are of a stretched character (154.6, 350.0, 364.4, and 394.9 keV). In such cases one of the two δ values in the cascade is zero. Furthermore, conversion coefficients determined experimentally for some of these transitions also limit the number of solutions. For instance, for the 112.5-keV transition the other solution from angular correlations is $\delta = -2.9(7)$. However, this is eliminated by the value of the conversion coefficient for the 112.5-keV transition α_K=0.63(3), which corresponds to $|\delta| = 0.35(-0.35, +0.20)$ [22]. In this way, combining all the available data, we have found a set of common δ values for the 112.5-, 164.5-, 185.4-keV, and other transitions, which are listed in Table I.

With the $\delta = -0.40(9)$ value for the mixing ratio of the 112.5-keV transition, angular correlations for the 112.5–233.8-keV cascade give an $M1 + E2$, $\delta = -0.10(5)$ solution for the 233.8-keV transition with the $\chi^2 = 1.9$ value for the fit. The same angular correlation data fitted assuming a stretched quadrupole character for the 233.8-keV transition results in $\chi^2 = 141$. This clearly indicates spin 9/2 for the 346.3-keV level. Angular correlations for the 294.8–457.8-keV cascade, shown in Fig. 11(b), are consistent with both transitions in the cascade being stretched quadrupole in character, which confirms the 9/2 spin for the 346.3-keV level. We note that in Fig. 11(b) the 294.8–233.8-keV cascade shows correlations consistent with the quadrupole-dipole case.

Due to the observed branchings, spins of the new 707.5- and 1184.8-keV levels in ^{145}Ba are restricted to 13/2 and 17/2, respectively. Because of the 430.8-keV decay of the 13/2,707.5-keV to the 276.9-keV level the parity of the 707.5-keV level should be negative. Consequently, because of the 477.2-keV decay, the parity of the 1184.8-keV levels should also be negative.

III. DISCUSSION

As found in our study of ^{143}Xe [1], its near-yrast structure could be reproduced by quasiparticle-rotor model (QPRM) calculations using a reflection-symmetric potential, without invoking octupole effects to additionally alter relative positions of orbitals. The only unknown was the nature of the second 9/2 level at 322.9 keV. In this work we have shown that an analogous $9/2_2$ level in ^{145}Ba has negative parity. It is likely that the $9/2_2$ level in ^{143}Xe is of the same origin and that these levels in both ^{143}Xe and ^{145}Ba do not require the presence of octupole correlations to explain their nature. In Fig. 6 the alignment in the band based on the $9/2_2^-$ level is similar to the alignment in the band based on the $5/2^-$ ground state. The total alignment (in both α branches) in the g.s. band is $3.5\hbar$, which is consistent either with the $f_{7/2}$ or $h_{9/2}$ origin of this band. The $9/2_2^-$ band, strongly mixed with the g.s. band, is most likely due to the other of the two orbitals.

Similarly as for ^{143}Xe, we have performed in this work the QPRM calculations with a reflection-symmetric potential for ^{145}Ba, using the codes GAMPN, ASYRMO, and PROBI [23]. In the calculations we used a deformation of $\epsilon_2 = 0.16$ for the positive-parity levels and $\epsilon_2 = 0.17$ for the negative-parity levels, an inertia parameter $a = 23.3$ keV, and a Coriolis attenuation parameter $\xi = 0.6$. Standard values for the κ and μ parameters of the ls and l^2 terms were used [24]. More information on such calculations can be found in Refs. [25,26].

The low position of the $5/2^-$ level at $N = 89$ is unexpected, as discussed in Ref. [8], where it has been proposed that octupole correlations are responsible for lowering the $5/2^-[523]$ configuration, an effect predicted by Leander *et al.* [2]. In Fig. 12 we compare the experimental and calculated energies of states in ^{145}Ba. An interesting result is that the position of the $5/2^-$ level relative to the $13/2^+$ level can be reproduced with the reflection-symmetric potential, similarly as in ^{143}Xe. Therefore, there is no need for introducing an octupole shape at the ground state to explain the low position of the $5/2^-$ ground-state level in ^{145}Ba. It seems that it is the interaction between the four orbitals 1/2[541], 1/2[530], 3/2[532], and 3/2[521] in a reflection-symmetric potential which can produce a low-energy $5/2^-$ solution, corresponding to the ground state in ^{145}Ba.

The present calculation also provides candidates for the $9/2_2^-$ and $13/2_2^-$ levels, newly observed in this work at 346.3 and 707.5 keV, respectively. These levels are members of the mixed $3/2[532] + 3/2[521]$ configuration in a reflection-symmetric potential. One should note, however, that the reproduction is of moderate quality. Furthermore, the model

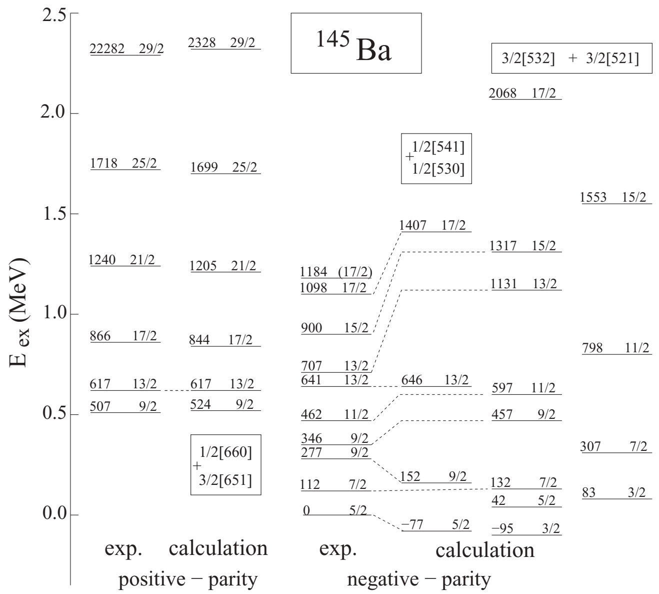

FIG. 12. Comparison of the experimental and calculated energies of excited states in ^{145}Ba, as obtained in the present work. Calculations are normalized to the experiment at the $13/2^+$ level at 617 keV.

used predicts the $3/2^-$ member of the discussed, mixed configuration as the ground state, which is not observed in the experiment.

Among other levels predicted by the present calculations is a $5/2^-_2$ level, calculated at 42 keV, and a $7/2^-_2$ level calculated at 132 keV. One of them could correspond to the 198.9-keV level reported in β decay [8], with the 5/2 or $7/2^-$ assignment.

The reproduction of the negative-parity levels, shown in Fig. 12 could be improved by changing the parameters of the calculations, in particular, by increasing the value of the Coriolis attenuation parameter. Its low value applied in this work was chosen in order to reproduce properly the positive-parity band and, most importantly, the position of the $13/2^+$ level relative to the $5/2^-$ ground state. The description of the intruder configuration, like $i_{13/2}$ in ^{145}Ba, imposes important constraints on model parameters because such a band has a simple configuration, unlike the negative-parity bands which are strongly mixed. Increasing the Coriolis attenuation parameter allows for an improvement in the description of the negative-parity band at the expense, however, of a worse reproduction of the positive-parity band and, interestingly, further lowering the position of the $5/2^-$ ground state.

Another parameter which allows one to manipulate positions of band heads is the deformation. The $\epsilon_2 = 0.17$ value taken for the negative-parity levels, is similar to that used in Ref. [2]. Some improvement is obtained when increasing the ϵ_2. However, it is causing an unrealistic lowering of the characteristic $11/2^-[505]$ configuration, which is not observed experimentally.

It seems that the predictive powers of the present model are exhausted and more sophisticated calculations should be performed to verify the proposed picture of the four negative-parity orbitals in a reflection-symmetric potential producing the low-lying $5/2^-$ level and a variety of other negative-parity levels, newly observed in ^{145}Ba. Particularly interesting would be the verification, both theoretical and experimental, of the low-lying $3/2^-$ level predicted by the present calculations.

The backbending observed in the ground-state band of ^{145}Ba is an indication that in this nucleus octupole correlations, though probably present, are weaker than in the ^{144}Ba core where a slow upbend is observed in the ground-state band. Such a delayed and attenuated backbending has been interpreted as due to an extra binding between positive- and negative-parity orbitals in a reflection-asymmetric potential [7]. It is possible that in ^{145}Ba the odd neutron blocks octupole correlations and one observes near the yrast line bands with properties characteristic of a reflection-symmetric potential. These are the $13/2^+$ band and the $5/2^-$ ground-state band.

Octupole excitations in ^{145}Ba could be of a vibrational character with rotational bands on top of them. The bands on top of the 670.3- and 1226.0-keV levels are candidates for such excitations. It is of high interest to verify if there is any low-spin level with positive parity below the proposed $11/2^+$ level. Such levels could be populated in β decay of ^{145}Cs. There is an intriguing possibility that the 491.2-keV level reported in Ref. [8] has spin and parity $7/2^+$, which would be consistent with its population in β decay and its decay branchings. (We note that spins proposed in the previous β-decay work [8] have been significantly changed by the prompt-γ works). In our calculations the $7/2^+$ level, belonging to the $i_{13/2}$ configuration, appears well above, at 970 keV. Thus the 491.2-keV level could correspond to an octupole excitation, expected at this energy, when extrapolating the proposed $11/2^+$ band to lower spins.

It should be also noted, that the positive parity of the 670.3-keV level is only tentatively assigned. In the case of a negative parity being assigned to the 670.3-keV level in a future study, this level could be explained within the mixture of the four negative-parity orbitals present near the Fermi level in ^{145}Ba. This complex structure contains four solutions for each spin higher than 1/2. In Fig. 12 we have shown the two lowest solutions for a given spin. The $11/2^-$ level calculated at 798 keV could correspond to the experimental 670.3-keV level. Clearly, more advanced calculations and more accurate measurements should be performed to explain the nature of this level.

Finally, it is worthwhile to remark that the 277.1-keV level reported in Ref. [8] corresponds, obviously, to the $9/2^-$ excitation seen in this work at 276.9 keV. Its population in β decay, if confirmed, could raise a question about the spin of the ground state in ^{145}Cs. This spin seems to be firmly determined as $3/2^+$ in atomic-beam magnetic-resonance measurements [27,28]. The available γ spectroscopy data [29] is consistent with spin $3/2^+$ but would also allow spin $5/2^+$ for the ground state of ^{145}Cs.

IV. SUMMARY

We have reinvestigated excited states in ^{145}Ba, populated in spontaneous fission of ^{248}Cm. The 507.5-keV level has been assigned spin and parity $9/2^+$ and is now interpreted as a member of the band originating from the $i_{13/2}$ neutron intruder.

A new band based on the $9/2^-_2$, 346.3-keV level has been identified, which is analogous to the band on top of the $9/2_2$

level at 322.9 keV in ^{143}Xe. We propose that in both nuclei this band originates from the $f_{7/2}$ or $h_{9/2}$ neutron orbital. The ground-state band, strongly mixed with the $9/2_2$ band in both nuclei, is most likely due to the other of the two orbitals.

The yrast bands in ^{145}Ba can be, as in ^{143}Xe, reproduced satisfactorily assuming a reflection-symmetric potential. In particular, the position of the $5/2^-$ ground state, relative to the $i_{13/2}$ neutron intruder, can be reproduced without involving octupole correlations.

The present work suggests that there is no octupole deformation in the ground state of ^{145}Ba, though octupole effects are present at medium spins. Bands on top of the 670.3- and 1226.0-keV levels can be explained as octupole bands coupled to the $5/2^-$ ground state and the $13/2^+$ level, respectively. A detailed reinvestigation of low-spin excitations populated in β decay of ^{145}Cs could help in identifying the eventual positive-parity excitations, in particular, a $7/2^+$ excitation expected below the proposed $11/2^+$, 670.3-keV level. The observation of such a level would help in further clarifying the nature of octupole effects in ^{145}Ba, answering the question if there are only bands due to octupole vibrations or if there there is a parity doublet associated with the ground state in ^{145}Ba. The evidence available at present does not support the presence of octupole deformation in the ground state of ^{145}Ba.

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