Near-yrast structure of neutron-rich, $N=85$ isotones

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Excited states in ^{139}Xe, populated in the spontaneous fission of ^{248}Cm, were studied by means of prompt-γ spectroscopy, using the EUROGAM2 multidetector array. Spins and parities of excited levels were determined experimentally. New information was also obtained for the ^{141}Ba nucleus. These data and a reevaluation of the data available in the literature on ^{141}Ba and ^{143}Ce show that the near-yrast structures of the ^{139}Xe, ^{141}Ba, and ^{143}Ce nuclei are similar to that in the heavier $N=85$ isotones. The presence of strong octupole correlations in the ^{139}Xe and ^{141}Ba nuclei, reported in another recent study, is not supported by the present work. The observed excitations in the $N=85$ isotones are interpreted as being due to quadrupole and octupole vibrations coupled to the valence-neutron levels.

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I. INTRODUCTION

Neutron-rich lanthanides exhibit features characteristic of nuclei with octupole deformation. The features are observed in an ''island'' of nuclei located on the nuclear chart around $N=88$ and $Z=60$ [1–3]. Studies performed up to now demonstrate that the strongest octupole correlations in the lanthanides are observed in nuclei with $N=88$ neutrons. In nuclei closer to the $N=82$ closed shell, octupole effects are smaller, while for $N>90$ quadrupole effects dominate. It has been also observed that octupole effects are weaker at the $Z=64$ subshell closure [4] as well as close to the $Z=50$ shell [5]. The 3^- octupole-phonon energy is expected to increase when approaching proton number $Z=50$ along constant neutron number N, if the $Z=50$ closed shell is well defined at this neutron number. It is expected to be so for $N=85$.

In previous works on ^{145}Nd and ^{147}Sm [6] and ^{149}Gd [7] $N=85$ isotones, located at the edge of the lanthanide region of octupole deformation, the structure of these nuclei was interpreted as being due to quadrupole and octupole vibrations coupled to single-particle excitations. It was concluded that although excited levels can be classified as simplex $s=\pm i$ bands, octupole deformation is not present at the neutron number $N=85$.

In contrast to the above interpretation, very pronouced octupole effects have been proposed in the $N=85$, ^{141}Ba, and ^{139}Xe nuclei, with indications that the effect increases when going towards proton number $Z=50$ [8]. Consequently, we investigated the ^{137}Te, $N=85$ isotone, where, according to Ref. [8], strong octupole correlations should be observed. No strong effects were observed in this nucleus [9].

The systematics of excited levels in the $N=85$ isotones, updated with the new data for ^{137}Te, suggest that some spin and parity assignments reported in Ref. [8] are not correct. To examine this suggestion we reinvestigated the ^{139}Xe and ^{141}Ba nuclei and reviewed the available information on the ^{143}Ce nucleus. The present work reports on this study. Partial results of this work were presented in Ref. [10].

II. EXPERIMENT, DATA ANALYSIS, AND THE RESULTS

Medium-spin, yrast, and near-yrast levels in ^{139}Xe and ^{141}Ba were populated in the spontaneous fission of ^{248}Cm [11]. Prompt γ rays, following fission were measured using the EUROGAM2 array of anti-Compton spectrometers [12]. About 2×10^{10} $\gamma\gamma\gamma$ coincidence events were measured and arranged into various three-dimensional histograms of high dispersion, which allowed studies of γ rays with intensities as low as 10^{-8} of the total intensity [13,14]. The geometry of EUROGAM2 provided double and triple angular correlations, and the CLOVER detectors of EUROGAM2 enabled directional-polarization measurements [15,16]. Details of the EUROGAM2 experiment and the data analysis techniques have been described in a number of previous works (see, e.g., Ref. [13]).

A. ^{139}Xe

The nucleus ^{139}Xe has been previously studied via the β^- decay of ^{139}I [17] and as a fission product observed in the spontaneous fission of ^{248}Cm [18] and ^{252}Cf [8]. The ^{252}Cf work reported two bands built on the 1086 keV and 1512 keV levels, which were both assumed to have positive parity. No experimental data to support those assignments were given. In the present work we aimed at the experimental verification of spins and parities in the two bands observed.

Our coincidence data obtained from the EUROGAM2 measurement allowed construction of the partial decay scheme of ^{139}Xe as shown in Fig. 1. Properties of γ transitions in ^{139}Xe obtained in the present work are listed in Tables I and II.

We confirm all the levels reported in Refs. [8,18]. An important new datum concerns the 1085.8 keV level, for which new 407.4 keV and 526.4 keV γ decays were found. Figure 2(a) displays a spectrum double gated on the 527 keV and 491 keV lines, where a peak at 527 keV is seen. This

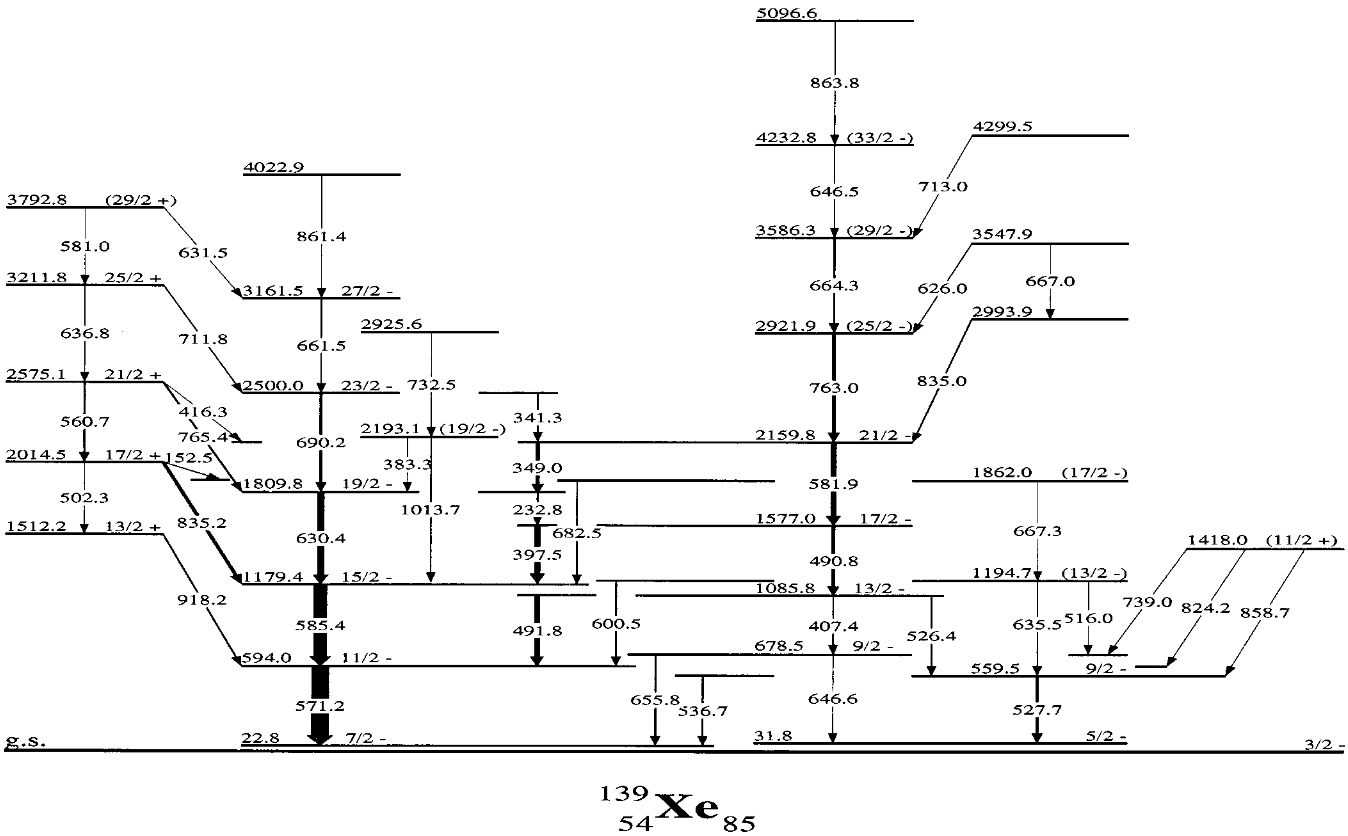

FIG. 1. Partial decay scheme of ^{139}Xe as obtained in this work.

indicates that the 527 keV line is a doublet corresponding to two transitions of 527 keV in a cascade. A spectrum double gated on the 527 keV line and displayed in Fig. 2(b) shows γ lines feeding the 1085.8 keV level and lines corresponding to transitions in the ^{104}Mo and ^{106}Mo nuclei, which are the most pronounced fission partners of ^{139}Xe. The new 526.4 keV transition links the 1085.8 keV level with the 559.5 keV level. This level decays further via the 527.7 keV and 536.7 keV transitions to the 31.8 keV and 22.8 keV levels, respectively, as first reported in Ref. [17]. The new 407.4 keV decay branch of the 1085.8 keV level populates the 678.5 keV level reported in Ref. [17]. The 407.4 keV transition is observed in the spectrum double gated on the 491 keV and 656 keV lines, as shown in Fig. 2(c).

Spin and parity of the ground state, the 22.8 keV level, and the 31.8 keV level in ^{139}Xe were found to be $3/2^-$, $7/2^-$, and $5/2^-$ [17], respectively. This is strongly supported by the systematics shown in Fig. 3. The 22.8 keV and the 31.8 keV levels in ^{139}Xe fit well the smooth variation of the excitation energies of the $7/2^-$ and $5/2^-$ states in the $N=85$ isotones. Spin and parity assignments to other excited levels were made using angular correlations and directional-polarization correlations, as described in Refs. [15,16]. Coefficients for these correlations are listed in Tables I and II. Figure 4 shows examples of angular correlations.

Theoretical values of the coefficients for γ-γ correlations for stretched transitions are $A_{22}/A_{00}=0.102$ and $A_{44}/A_{00}=0.009$ for a quadrupole-quadrupole cascade, $A_{22}/A_{00}=-0.071$ for a quadrupole-dipole cascade, and $A_{22}/A_{00}=+0.050$ for a dipole-dipole cascade. The data shown in Fig. 4 indicate a stretched quadrupole character for the 571.2, 585.4, 630.4, 690.2, 560.7, 527.7, 526.4, 490.8, and 581.9 keV transitions and a $\Delta I=1$ character for the 491.8, 397.5, 349.0, 341.3, 918.2, 835.2, 765.4, and 711.8 keV transitions.

The directional-polarization coefficients are consistent with electric quadrupole ($E2$) multipolarity for the 571.2, 585.4, 630.4, 527.7, 526.4, 490.8, and 581.9 keV transitions and $\Delta I=1$, $M1+E2$ multipolarity of the 397.5 keV transition. For the 918.2, 835.2, and 711.8 keV transitions linear polarization is consistent with the positive parity assignment to the band on top of the 1512.2 keV level, though it is not fully conclusive.

Adopting spin and parity $3/2^-$, $7/2^-$, and $5/2^-$ for the ground state, the 22.8 keV level, and the 31.8 keV level, respectively, and considering the experimentally determined multipolarities of transitions, we assigned spins and parities to the excited levels in ^{139}Xe as shown in Fig. 1. It was assumed here that spin values in bands are increasing with the increasing excitation energy. This is based on the observation that fission predominantly populates yrast levels.

Spin and parity assignments are crucial for the conclusions of this work. Therefore some of these assignments are discussed below in more detail. The negative parity assignments to the 559.5, 1085.8, 1577.0, and 2159.8 keV levels are particularly important here since they differ from the assumptions made in Ref. [8]. Our assignments are based on the measured angular correlations and linear polarizations,

TABLE I. Properties of γ transitions in the ^{139}Xe nucleus, as measured in this work. In the last column energies of correlating transitions used to measure directional polarization are shown.

E_{exc} (keV)	I^{π}	E_{γ} (keV)	I_{γ} [relative]	Polarization	E_{γ}^{corr} (keV)
559.5	$9/2^-$	527.7	6(1)		
		536.7	4(1)		
594.0	$11/2^-$	571.2	100(5)		
678.5	$9/2^-$	646.6	1.5(5)		
		655.8	4(1)		
1085.5	$13/2^-$	407.8	6(1)		
		491.8	25(3)	−0.22(11)[a]	585.4
		526.4	3(1)		
1179.4	$15/2^-$	585.4	75(5)	+0.25(6)	571.2
1194.7	$(13/2^-)$	516.0	1.0(5)		
		635.5	3(1)		
		600.5	6(2)		
1418.0	$(11/2^+)$	739.0	0.7(3)		
		824.2	1.2(4)		
		858.7	1.0(5)		
1512.2	$13/2^+$	918.2	5(1)		
1577.0	$17/2^-$	397.5	24(2)	−0.10(6)	585.4
		490.8	13(2)		
1809.8	$19/2^-$	232.8	5(1)		
		630.4	33(3)	+0.17(8)	571.2
1862.0	$(17/2^-)$	667.3	1.0(5)		
		682.5	4(1)		
2014.5	$17/2^+$	152.5	1.1(3)		
		502.3	1.2(4)		
		835.2	8(1)	−0.2(2)	585.4
2159.8	$21/2^-$	581.9	30(3)		
		349.0	14(2)		
2193.1	$(19/2^-)$	1013.7	2.8(7)		
		383.3	1.2(4)		
2500.0	$23/2^-$	341.3	3(1)		
		690.2	10(1)		
2575.1	$21/2^+$	416.3	1.0(5)		
		560.7	7(1)		
		765.4	6(1)		
2921.9	$(25/2^-)$	763.0	15(3)		
2925.6		732.5	0.8(4)		
2993.9		835.0	5(1)		
3161.5	$27/2^-$	661.5	4(1)		
3211.8	$25/2^+$	636.8	2.9(7)		
		711.8	3(1)		
3547.9		626.0	2.5(8)		
		667.0	1.2(6)		
3586.3	$(29/2^-)$	664.3	5(1)		
3792.8	$(29/2^+)$	581.0	0.9(5)		
		631.5	1.0(5)		
4022.9		861.4	0.8(4)		
4232.8	$(33/2^-)$	646.5	2.0(4)		
4299.5		713.0	0.6(3)		
5096.6		863.8	0.8(4)		

[a]Value obtained for the 491 keV doublet line.

TABLE II. Coefficients of γ-γ angular correlations for pairs of γ transitions in the ^{139}Xe nucleus, as measured in this work. Transitions in "sum" are listed in the last column (see text for the definition of "sum").

E_{γ}-E_{γ} pair (keV)	A_2/A_0	A_4/A_0	Transitions in "sum"
918.2–571.2	−0.13(3)	0.01(1)	
585.4–571.2	0.09(1)	0.02(1)	
630.4–571.2	0.10(1)	0.01(1)	
690.2–571.2	0.10(1)	0.00(3)	
491–571.2	−0.03(1)	0.01(1)	
397.5–571.2	0.08(1)	0.00(1)	
397.5–581.9	−0.10(2)	−0.04(4)	
341.3–581.9	−0.12(4)	−0.01(4)	
491–527	0.08(1)	−0.03(5)	
835.2–sum	−0.04(1)	0.02(1)	571.2, 585.4
835.2–560.7	−0.04(2)	0.02(2)	
349.0–sum	−0.09(2)	0.02(2)	571.2, 585.4, 630.4
765.4–sum	−0.07(2)	0.00(2)	571.2, 585.4, 630.4
711.8–sum	−0.06(3)	0.02(4)	571.2, 585.4, 630.4

and on the observed decay properties of the 1085.8 keV level. The $17/2^-$ spin and parity assignment to the 1577.0 keV level is based on a $\Delta I=1$, $M1+E2$ multipolarity, measured for the 397.5 keV transition, and is consistent with other observations.

Though the 491 keV line is a doublet which could not be resolved in our multipolarity measurement, meaningful conclusions can still drawn from the linear polarization and angular correlations measured for the doublet, since the intensity the 491.8 keV transition is two times larger than that of the 490.8 keV component. The 571.2 keV–491 keV angular

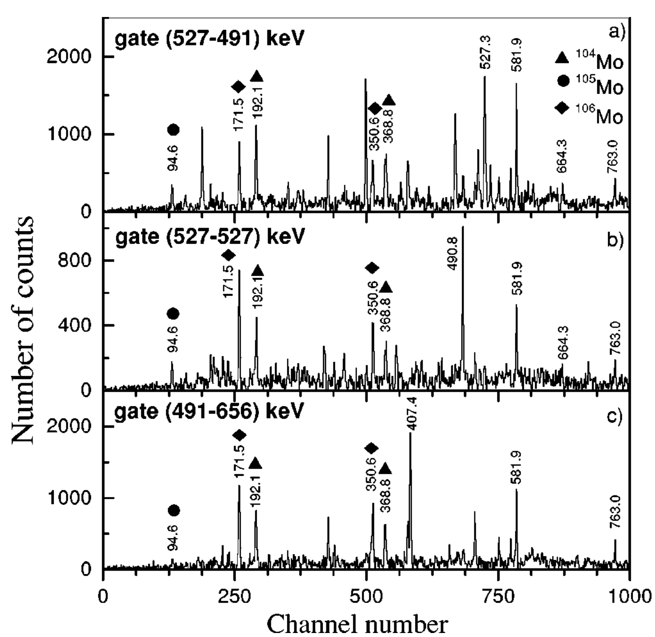

FIG. 2. Coincidence spectra double gated on lines from ^{139}Xe. See text for more explanations.

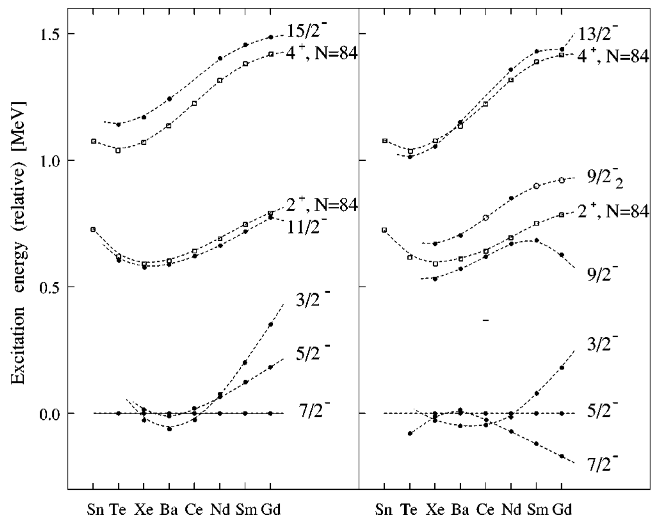

FIG. 3. Systematics of low- and medium-spin excitations in the $N=85$ isotones. Dashed lines are drawn to guide the eye. The data are taken from this work and Refs. [4–9,17,18].

correlation is consistent with a $\Delta I=1$ character for the 491.8 keV transition. This, and the negative polarization for the 491 keV doublet, indicate that the 491.8 keV transition has a $M1+E2$ character. Consequently the spin and parity of the 1085.8 keV level are $13/2^-$. This is further confirmed by the 526.4 keV–490.8 keV angular correlation, which is consistent with a stretched quadrupole character for both transitions and thus spin 13/2 for the 1085.2 keV level, in view of the 9/2 and 17/2 spin assignments to the 559.5 keV, and 1577.0 keV levels, respectively. Negative parity of the 1085.8 keV level is a consequence of the observation that the 490.8 keV, 526.4 keV, and 527.7 keV decays are of a prompt character. In our experiment we could measure lifetimes in the range from 10 to a few hundred nanoseconds [19]. No half-life longer than 10 ns was observed in ^{139}Xe in the present experiment, indicating that none of the transitions with energy lower than 800 keV observed presently in ^{139}Xe has magnetic quadrupole ($M2$) multipolarity. Consequently, the 490.8 keV, 526.4 keV, and 527.7 keV transitions, which correspond to $\Delta I=2$ spin changes, are of stretched $E2$ character and we can assign negative parity to the 1085.8 keV and 559.5 keV levels, based on the $5/2^-$ and $17/2^-$ spin and parity assignments to the 31.8 keV and 1577.0 keV levels, respectively. Similar arguments allow the $I^{\pi}=9/2^-$ assignment to the 678.5 keV level.

The 594.0 keV and 1179.4 keV levels, of the yrast band on top of the $7/2^-$, 22.8 keV level, fit well the regular systematics of the $11/2^-$ and $15/2^-$ excitation energies in the $N=85$ isotones, as shown in the left-hand panel of Fig. 3. Their excitation energies, displayed relative to their $7/2^-$ bandheads, follow closely the energies of the 2^+ and 4^+ excitations in the corresponding core nuclei with $N=84$ neutrons. This observation supports the conclusion of Ref. [6] that excitations in the $N=85$ isotones can be viewed as vibrations of the core nuclei coupled to the valence-neutron states.

A clear correlation between the excitation energies of the $13/2^-$ levels, calculated relative to the $5/2^-$ levels, with the 4^+ excitation energies in the corresponding $N=84$ core nuclei, shown in the right-hand panel of Fig. 3, supports further the $13/2^-$ spin and parity assignment to the 1085.8 keV level. This level probably corresponds to the $5/2^-\otimes 4^+$ configuration. The correlation observed between the $9/2^-$, yrast excitations, displayed relative to the $5/2^-$ levels and the 2^+ excitation energies in the corresponding $N=84$ core nuclei, is weaker. The deviation becomes more evident at ^{149}Gd and, probably, for ^{135}Sn. It may be caused by the fact, discussed in Ref. [7], that in the $N=85$ isotones the yrast $9/2^-$ level may have large components from both the 2^+ core excitation coupled to the $5/2^-$ level and the single-particle excitation of the odd neutron to the $\nu h_{9/2}$ orbital. Close to proton numbers $Z=50$ and $Z=64$, where the 2^+ energies increase, the yrast $9/2^-$ level may be dominated by the $\nu h_{9/2}$ excitation. If the $9/2^-$ excitation results from such a mixture, one expects another $9/2^-$ excitation close in energy. Indeed, the nonyrast $9/2^-_2$ level is observed systematically in the $N=85$ isotones. One may see in Fig. 3 that it correlates better with the 2^+ excitation of the $N=84$ core. This nonyrast $9/2^-$ may therefore be dominated by the 2^+ excitation of the core.

The 1512.2 keV level was assumed to have spin and parity $13/2^+$ in Ref. [8]. This level is populated rather weakly in fission and our polarization measurements are inconclusive. However, angular correlation measurements clearly indicate $\Delta I=1$ character for the 918.2, 835.2, 765.4, and 711.8 keV transitions, and hence spins 13/2, 17/2, 21/2, and 25/2 for the 1512.2, 2014.5, 2575.1, and 3211.8 keV levels, respectively. The fact that such a nonyrast 13/2 level is populated in fission suggests that it probably has an opposite parity to the $13/2^-$, 1085.8 keV level. In the heavier $N=85$ isotones, $13/2^+$ excitations are systematically observed and were interpreted as due to octupole vibrations. Figure 5 shows their energies as a function of the corresponding 3^- excitation energies in the corresponding $N=84$ cores. The data for ^{145}Nd, ^{147}Sm, and ^{149}Gd were taken from Refs. [6,7] and for ^{141}Ba from the reevaluation of the β decay studies [20], done in this work and discussed in detail in the next subsection. A distinct correlation observed in Fig. 5 strongly supports the interpretation of the 1512.2 keV level in ^{139}Xe as an octupole excitation coupled to the $7/2^-$, 22.8 keV level. The 3^- excitation in the ^{138}Xe core is not known, and in Fig. 5 an energy of 2050 keV was used, estimated from the systematics of these excitations in the region [10].

A number of other levels with energies 1194.7, 1862.8, 2193.1, 2925.6, 2993.9, 3547.9, and 4299.5 keV are observed, which decay to the bands built on the $5/2^-$ and $7/2^-$ levels. The 2193.1 keV and 2925.6 keV levels were reported previously [8]. For these levels we could not establish spins and parities, because of their low population. Nonyrast excitations with such decay properties are, however, expected in the $N=85$ isotones [6].

Characteristic $11/2^+$ excitations are observed systematically in heavier $N=85$ isotones [6]. They were interpreted as due to an octupole phonon coupled to the $5/2^-$ member of the $\nu(f7/2^3)_j$ multiplet [7]. It is interesting to ask if such excitations are present in lighter $N=85$ isotones. If observed, they would give additional information about octupole ef-

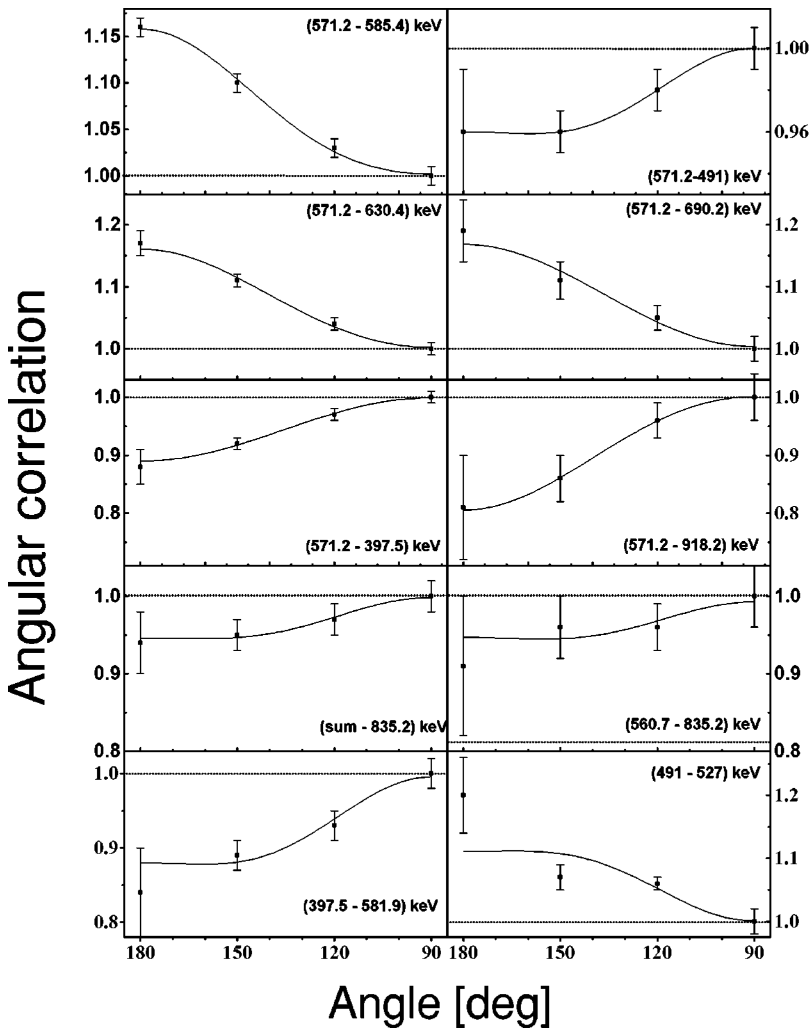

FIG. 4. γ-γ angular correlations for transitions in ^{139}Xe, as obtained in the present work.

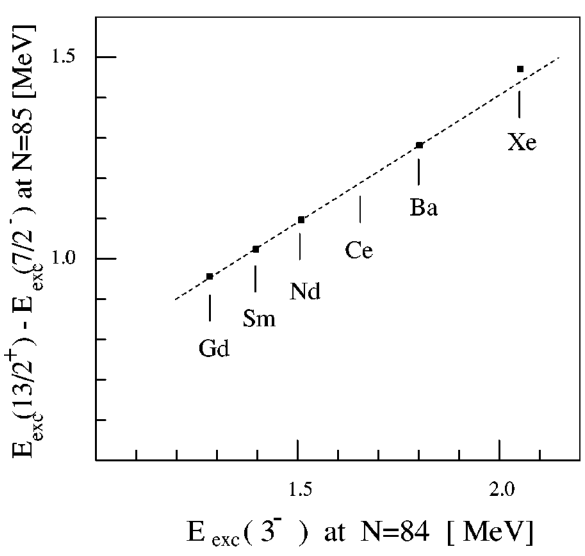

FIG. 5. Systematics of $13/2^+$ excitation energies calculated relative to the $7/2^-$ levels in the $N=85$ isotones as a function of the 3^- excitation energies in the $N=84$ core nuclei. The data are taken from this work and Refs. [4–9,17,18]. The data for ^{143}Ce are not available.

fects at $N=85$. The $11/2^+$ excitation should decay to the $11/2^-$ member of the band built on the $7/2^-$ state and to the $9/2^-$ levels. In our data we observe a level at 1194.7 keV, which has such decay properties. Therefore in Ref. [10] we suggested that it might be a candidate for the $11/2^+$, octupole excitation built on top of the $5/2^-$ state. This can be verified now, utilizing the correlation between octupole excitations in the $N=85$ nuclei and the corresponding 3^- excitations in $N=84$ cores. One expects that a correlation, similar to the one observed for $13/2^+$ octupole excitations, holds also for the $11/2^+$ excitations.

Indeed, the $11/2^+$ excitation energies, displayed relative to the $5/2^-$ levels, show a strong correlation with the 3^- excitation energies in the corresponding $N=84$ cores, as illustrated in Fig. 6. The data for ^{145}Nd, ^{147}Sm, and ^{149}Gd are taken from Refs. [6,7]. For ^{141}Ba and ^{143}Ce we reevaluated β-decay data from Refs. [20,21], as discussed in the next two subsections. Taking 2050 keV for the 3^- excitation energy in the ^{138}Xe core nucleus, as discussed above, we expect the $11/2^+$ excitation in ^{139}Xe to be about 1450 keV. Consequently, the 1194.5 keV level is an unlikely candidate for the $11/2^+$, octupole excitation.

The expected $11/2^+$ octupole excitation is of a nonyrast character and may be populated only weakly in fission. A

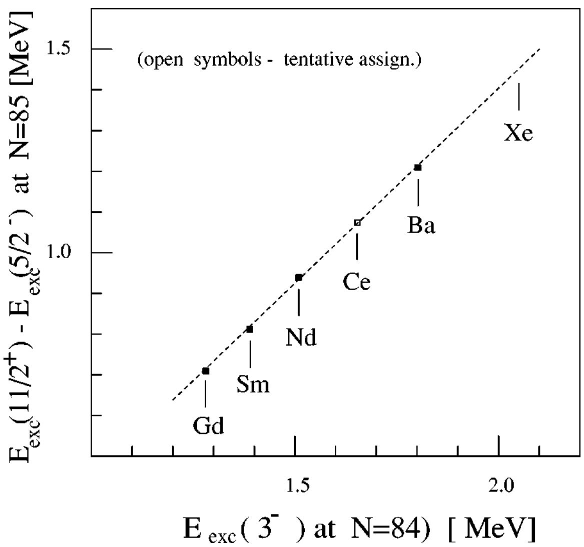

FIG. 6. Systematics of $11/2^+$ excitation energies relative to the $5/2^-$ levels in the $N=85$ isotones as a function of the 3^- excitation energies in the $N=84$ core nuclei. The data are taken from this work and Refs. [4–9,17,18].

new search for such an excitation in ^{139}Xe, performed in this work, revealed the 1418.0 keV level, with excitation energy and decay properties as expected for the $11/2^+$ octupole excitation. The present measurements could not establish the multipolarities of transitions depopulating this level. Another study is required to answer this question and to identify a band on top of this level, analogous to vibrational bands observed on top of $11/2^+$ levels in ^{145}Nd, ^{147}Sm, and ^{149}Gd [6,7].

B. ^{141}Ba

The nucleus ^{141}Ba has been studied previously via the β^- decay of ^{141}Cs [20] and as a fission product observed in the spontaneous fission of ^{252}Cf [8]. The latter work reported two excited bands built on the 1187 keV and 1341 keV levels, respectively, which were both assumed to have positive parity. No experimental data were given to support this assumption. Levels at 610 keV and 747 keV, with $9/2^-$ tentative spin and parity assignments, were also reported in Refs. [8,20].

Properties of γ transitions in ^{141}Ba as observed in the present work are listed in Table III. Our coincidence data confirm all the levels reported in Ref. [8], except the 2929 keV, the population of which may be too low in our measurement. Important new observations made in the present work are the 440.6 keV and 577.9 keV γ decays of the 1187.6 keV level to the 747.0 keV and 609.7 keV levels, respectively. Figure 7 displays spectra double gated on the 532.3 keV, 692.0 keV, and 561.4 keV lines, respectively, which show the newly found, 440.6 keV and 577.9 keV transitions. The partial decay scheme of ^{141}Ba obtained in this work is shown in Fig. 8.

The coefficients which best fit the angular correlations for pairs of γ transitions in ^{141}Ba are shown in Table III. They are consistent with the spin values shown in Fig. 8. In par-

TABLE III. Properties of γ transitions in the ^{141}Ba nucleus, as measured in this work. In the last column an energy of the correlating transition is given. "sum" denotes an average correlation with the 588.6 and 658.5 keV transitions.

E_{exc} (keV)	I^π	E_γ (keV)	I_γ (relative)	A_2/A_0	A_4/A_0	E_γ^{corr} (keV)
0.0	$3/2^-$					
48.4	$5/2^-$					
55.0	$7/2^-$					
609.7	$9/2^-$	561.4	3(1)			
		554.7	2(1)			
643.6	$11/2^-$	588.6	100(5)			
747.0	$9/2^-$	692.0	4(1)			
		698.5	1.0(5)			
1187.6	$13/2^-$	440.6	4(1)			
		543.8	11(2)			
		577.9	2(1)			
1256.7	$(11/2^+)$	509.8	1.5(5)			
		613.0	0.8(4)			
		646.7	1.5(5)			
1302.1	$15/2^-$	658.5	50(5)	0.12(3)	−0.01(2)	588.6
1341.3	$13/2^+$	697.7	0.5(2)			
1719.8	$17/2^-$	417.7	15(3)	−0.06(2)	0.01(3)	658.5
		532.3	18(3)			
1836.5	$(17/2^+)$	495.0	2(1)			
		534.4	15(2)	−0.05(2)	0.01(2)	sum
2114.7	$19/2^-$	812.6	12(2)	0.09(4)	−0.03(4)	658.5
2329.6	$21/2^-$	214.9	1.5(5)			
		609.8	10(2)			
2433.3	$21/2^+$	318.5	5(1)			
		596.9	14(2)			
3127.9	$(25/2^+)$	694.6	6(1)			
3176.0	$(25/2^-)$	846.4	4(2)			
3834.9	$(29/2^-)$	707.0	2(1)			

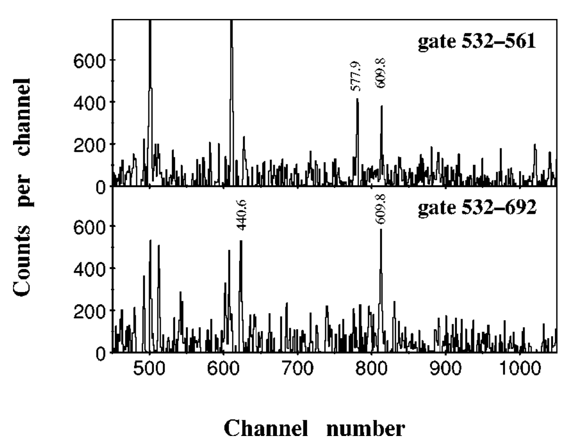

FIG. 7. Coincidence spectra double gated on lines from ^{141}Ba. See text for more explanations.

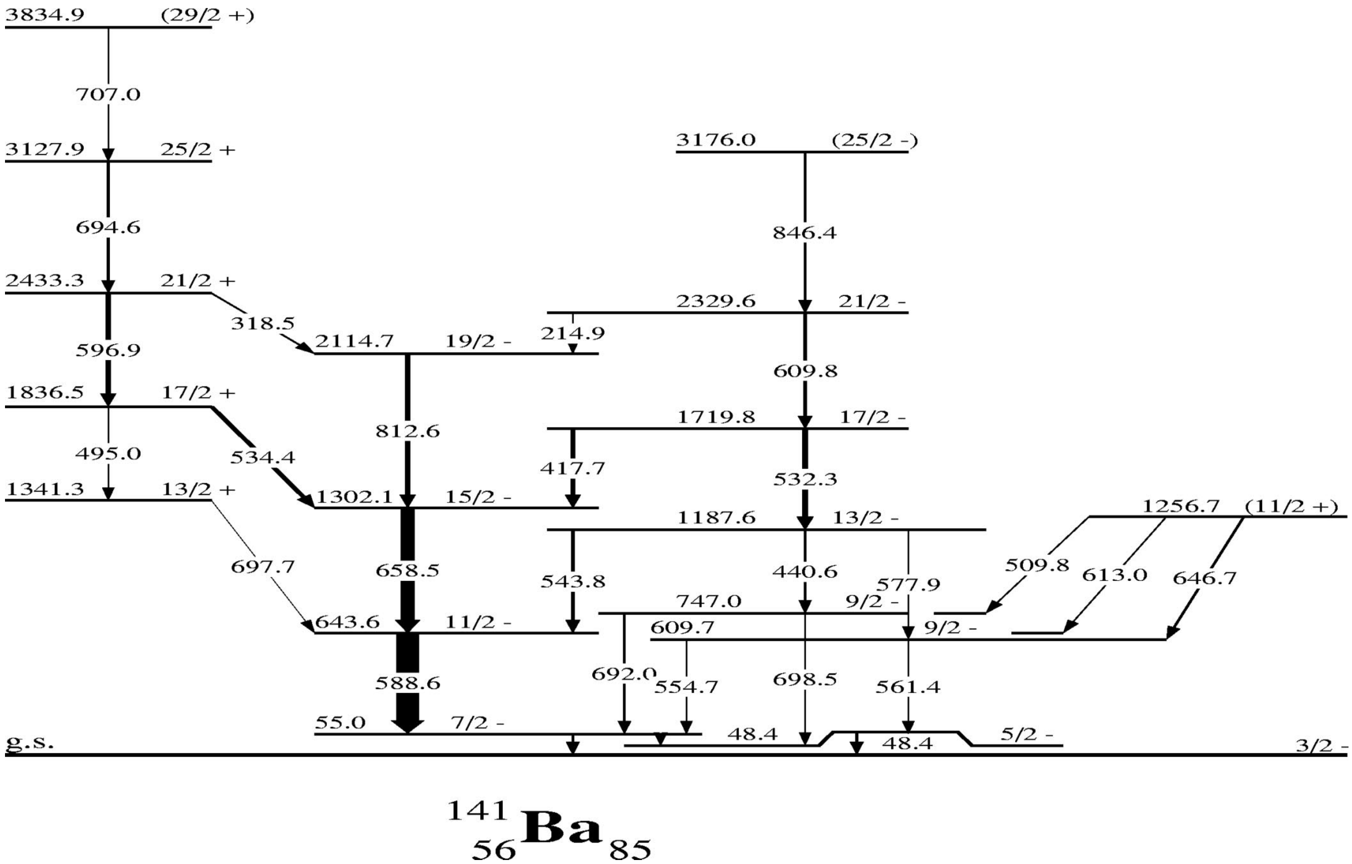

FIG. 8. Level scheme of ^{141}Ba as obtained in this work.

ticular, spins 13/2 and 17/2 are assigned to the 1187.6 keV and 1719.8 keV levels, respectively, because of the $\Delta I=1$ character of the 543.8 keV and 417.7 keV transitions. The new 440.6 keV and 577.9 keV decays determine negative parity for the 1187.6 keV level, since they are $E2$ rather than $M2$, in view of their prompt character.

Similar arguments allow the 17/2 spin assignment to the 1836.5 keV level. The parity could not be determined. In Ref. [8] the 1341.3 keV level was assigned, tentatively, spin and parity $13/2^+$. The decay of the 1836.5 keV level to the 1341.3 keV level was marked as tentative there. In our data we see a weak 495.0 keV line, but it is contaminated by decays in fission-partner nuclei. Therefore the spin and parity of the 1341.3 keV level could not be determined. The systematics shown in Fig. 5 is strongly in favor of a $13/2^+$ excitation present at this energy.

It may be noted that a level at 1341.5 keV has been also seen in the β^- decay of ^{141}Cs [20]. It is surprising, though not impossible, that a level with spin $13/2^+$ could be populated indirectly, following β^- decay of ^{141}Cs, which has spin and parity $7/2^+$ in its ground state. It is also possible that there is another excited level around 1300 keV in ^{141}Ba, which corresponds to the $13/2^+$ octupole excitation in this nucleus.

In Ref. [20] a 1256.7 keV level has been reported, which was assigned spin and parity $11/2^+$ or, tentatively, $13/2^-$. Considering the systematic trends of $11/2^+$ and $13/2^-$ excitations in $N=85$ isotones, shown in Figs. 3 and 6, the $11/2^+$ spin and parity assignment to this level is strongly favored.

C. ^{143}Ce

The ^{143}Ce nucleus has been studied via the β^- decay of ^{143}La [21]. A partial level scheme from that study, relevant to the present discussion of the $N=85$ isotones, is shown in Fig. 9. In addition to the characteristic $3/2^-$, $5/2^-$, and $7/2^-$ levels originating from the $(\nu f^3_{7/2})_j$ coupling, and the $9/2^-$ level at 662.7 keV, which were assigned their spins and parities uniquely, we show levels at 640.3, 817.0, and 1116.8, which fit well the systematic behavior of the $11/2^-$, $9/2^-_2$, and $11/2^+$ excitations in the $N=85$ isotones, respectively, as shown in Figs. 3 and 6. It would be very interesting to verify experimentally these expectations.

III. SYSTEMATICS OF EXCITATIONS IN THE $N=85$ ISOTONES

With three neutrons outside the $N=82$ closed shell, the $N=85$ isotones show an excitation pattern characteristic of transitional nuclei, i.e., multiparticle levels and vibrationlike excitations coupled to them. The near-yrast excitation patterns in ^{139}Xe, ^{141}Ba, and most likely also in ^{143}Ce are remarkably similar to each other and to decay schemes in the heavier $N=85$ isotones. This suggests that the structure of yrast levels is similar in all these nuclei and allows a systematic comparison of ^{139}Xe, ^{141}Ba, and ^{143}Ce with ^{145}Nd,

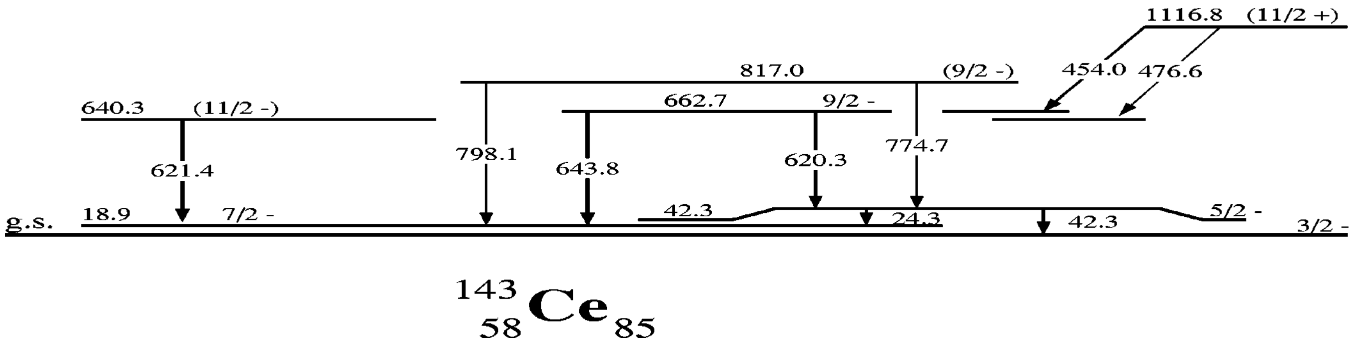

FIG. 9. The partial level scheme of ^{143}Ce as reevaluated in this work.

^{147}Sm, and ^{149}Gd, for which detailed studies have been performed previously [6,7].

At low excitation energy all three neutrons occupy the $f_{7/2}$ orbital, producing a $\nu(f_{7/2}{}^3)_j$ multiplet with the $3/2^-$, $5/2^-$, and $7/2^-$ multiplet members lowest in energy [22]. This characteristic configuration appears systematically in the $N=85$ isotones, as illustrated in Fig. 3. The $(\nu f^3)_j$ cluster was introduced in Ref. [22] to describe the multiplet of the three lowest states in the $N=85$ isotones by analogy to the so-called "$\nu f_{7/2}$ nuclei" with $Z=23$ or $N=23$, where a similar $(\nu f^3)_j$ cluster is present. It should be mentioned here that in the $N=85$ isotones the $\nu p_{3/2}$ orbital is much closer to the $\nu f_{7/2}$ than it is at $N=Z=23$. Therefore the $3/2^-$ level has at $N=85$ a significant admixture of the $\nu f^2_{7/2}p_{3/2}$ configuration, as discussed in detail in Ref. [22].

The $I^\pi=11/2^-$ and $15/2^-$ yrast levels in the $N=85$ isotones were interpreted as higher-spin members of the $\nu(f_{7/2}{}^3)_j$ multiplet [22]. The $\nu(f_{7/2}{}^3)_j$ multiplet origin of these excitations is manifested by a significant decrease of the in-band transition intensities above spin $15/2^-$. In Fig. 3 the $I^\pi=11/2^-$ and $15/2^-$ yrast levels are compared to the 2^+ and 4^+ excitations in the corresponding $N=84$ cores. It is apparent from Fig. 3 that the points for the $N=85$ isotones follow closely the $N=84$ points. In the cluster-vibration model of Ref. [22] the $I^\pi=11/2^-$ and $15/2^-$ yrast levels were reproduced by coupling the $f^3_{7/2}$ cluster to the quadrupole vibration. The resulting configuration was called a *collective* quasi-$f_{7/2}$ multiplet.

The $9/2^-$ excitations at $N=85$ can be viewed either as members of the collective quasi-$f_{7/2}$ multiplet or as a result of promoting the odd neutron to the $\nu h_{9/2}$ orbital. Observation of two $9/2^-$ levels close in energy in the $N=85$ isotones indicates that two mechanisms compete here. The $\nu h_{9/2}$ neutron excitation manifests its presence by a characteristic sequence of $13/2^-$, $17/2^-$, and $21/2^-$ levels, forming on top of the $9/2^-$ level a cascade of transitions with energies decreasing with spin. Such cascades are observed in the heavier $N=85$ isotones and were interpreted as the $\nu[(f^2_{7/2})_{0^+,2^+,4^+,6^+}\otimes h_{9/2}]_j$ configuration [6,7], with $j_{max}=21/2$. In the lighter $N=85$ isotones studied in the present work, the $\nu[(f^2_{7/2})_{0^+,2^+,4^+,6^+}]$ sequence, with its characteristic energy spacing, is not present and the band on top of the 9/2 level shows more collective, quasirotational character. Let us note that the quasi-$f_{7/2}$ multiplet, with one quadrupole phonon [22] cannot generate spin 21/2.

Not all the $9/2^-_2$ levels are known in the $N=85$ isotones. In Fig. 3 the $9/2^-_2$ levels in ^{143}Ce, ^{147}Sm, and ^{149}Gd are drawn tentatively (open circles). The 1085 keV level in ^{139}Xe is a good candidate for the $9/2^-_2$ state, as discussed in Refs. [20,22] and it follows the systematics of Fig. 3. The 1108 keV level in ^{147}Sm, however, proposed as the $9/2^-_2$ excitation [22], deviates from the systematics as illustrated in Fig. 10(a), which shows the $9/2^-_2$ excitation relative to the $5/2^-$ level with the 1108 keV level included. This level also does not follow the trend of the energy difference between the $9/2^-_2$ and $9/2^-_1$ levels. Figure 10(b) shows the energy differences between the $9/2^-_2$ and $5/2^-$ levels and the $13/2^-_1$ and $9/2^-_2$ levels, respectively, as a function of the corresponding core 2^+ excitation energy. Once more the 1108 keV level does not fit the trend. One may notice that the 1020 keV level in ^{147}Sm [23] fits better the systematics but its decay properties are not known [23]. Based on systematics we suggest that the 817 keV level in ^{143}Ce corresponds to the $9/2^-_2$ excitation. The decay properties of the 817 keV level are in favor of this assignment.

In Refs. [20,22] it has been suggested that the $9/2^-_1$ and $9/2^-_2$ levels in the $N=85$ isotones, one of a more collective and the other of a more single-particle nature, exchange their properties when the proton number increase from $Z=60$ to $Z=62$. The $9/2^-_2$ levels in ^{141}Ba, ^{143}Ce, and ^{145}Nd were interpreted as single-particle states, and the $9/2^-_2$ levels in ^{147}Sm and ^{149}Gd as collective excitations. Figure 3 shows a strong correlation between the excitation energies of the $13/2^-_1$ levels (measured relative to the $5/2^-$ level) and the 4^+ excitations in the corresponding $N=84$ cores, suggesting a collective nature for the $13/2^-_1$ levels. Therefore the $9/2^-_2$ levels in ^{139}Xe and ^{141}Ba, which are strongly linked to the $13/2^-_1$ levels, should also have collective character, contrary to the conclusion of Refs. [20,22]. More experimental information is needed to clarify this situation.

Let us note that the $\nu h_{9/2}f^2_{7/2}$ multiplet can mix with the collective quasi-$f_{7/2}$ band on top of the $5/2^-$ level. If there was a clear distinction between the $\nu f^N_{7/2}$ cluster and $9/2^-$ collective, quasi-$f_{7/2}$ excitations, as suggested in Ref. [20], one should also see a third $9/2^-$ level nearby.

In the course of this study new theoretical calculations became available for 9/2 levels in the $N=85$ isotones [24]. The calculations confirm the presence of the $\nu(f_{7/2}{}^3)_{9/2^-}$ and $\nu[(f_{7/2}{}^2)h_{9/2}]_{9/2^-}$ configurations but they also suggest the

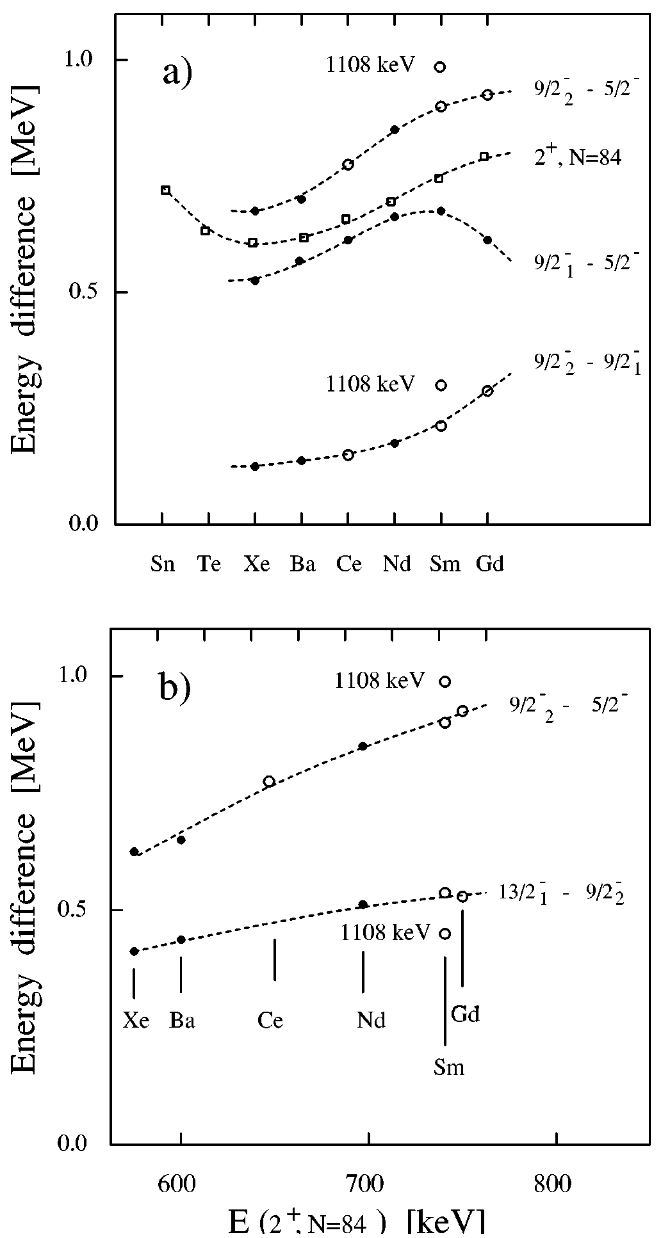

FIG. 10. Systematics of $9/2^-$ excitations in the $N=85$ isotones. Open circles represent tentative assignments. Dashed lines are drawn to guide the eye. The data are taken from this work and Refs. [4–9,17,18].

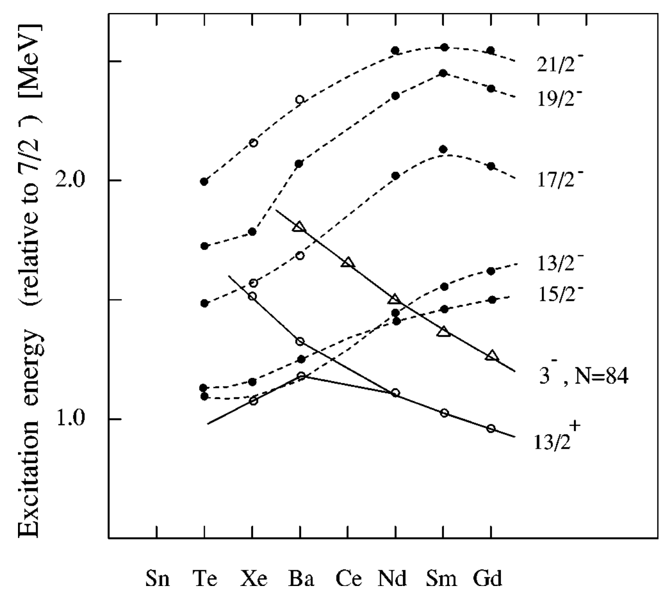

FIG. 11. Systematics of energies of medium-spin levels in $N=85$ isotones. See text for more explanations. Lines are drawn to guide the eye. The data are taken from this work and Refs. [4–9,17,18].

presence of a third $9/2^-$, near-yrast excitation corresponding to the $\nu[(f_{7/2}{}^2)p_{3/2}]_{9/2^-}$ configuration, which comes as the lowest $9/2^-$ level in their calculations. Verificaton of the nature of the observed $9/2^-$ excitations in $N=85$ isotones will require further studies. In particular, one should identify experimentally the expected third $9/2^-$ excitation, which up to now was not observed in the discussed nuclei.

Figure 11 displays energies of medium-spin excited states in $N=85$ isotones relative to the $7/2^-_1$ level. It can be seen that members of the $\nu(f_{7/2}{}^3)_j$ and $\nu[(f^2_{7/2})h_{9/2}]_j$ multiplets follow rather smooth systematics in contrast to the $19/2^-$ level. In Ref. [7] it was suggested that the $19/2^-$ level in ^{149}Gd may be due to double octupole-phonon excitation coupled to the $\nu(f^3)_{7/2^-}$ level. Similar excitations were observed in ^{147}Sm and ^{145}Nd nuclei [6]. In a recent study of the ^{148}Gd nucleus [25], there are even suggestions of the presence of a three octupole-phonon excitation. The picture may be more complicated, however, since the trend for the $19/2^-$ levels is quite different from the trend of octupole excitations in the $N=85$ isotones, as shown in Fig. 11.

At higher excitation energies the odd neutron can be promoted to the $i_{13/2}$ orbital giving rise to the $13/2^+$ excitation. As pointed out in Ref. [20], the presence of such a contribution is supported by the observation of $13/2^+$ levels in ^{145}Nd and ^{147}Sm in (d,p) and $(\alpha,{}^3\mathrm{He})$ reaction studies [26,27]. Another $13/2^+$ excitation expected in $N=85$ isotones is due to an octupole phonon coupled to a $\nu(f^3)_{7/2^-}$ level. This expectation of two $13/2^+$ levels led the authors of Ref. [8] to the conclusion that in ^{139}Xe and ^{141}Ba two bands of the same simplex based on the $I^\pi=13/2^+$ levels are present, one of which has a single-particle $\nu i_{13/2}$ nature and the other, lower in energy, is due to an octupole phonon coupled to the $\nu(f_{7/2}{}^3)_{7/2^-}$ state. This is illustrated in Fig. 11, where, according to Ref. [8], the systematics for the $I^\pi=13/2^+$ excitation (solid line) splits into two branches below proton number $Z=60$. Due to its predicted yrast character, the lower $I^\pi=13/2^+$ level should be clearly seen in ^{137}Te at an excitation energy of about 1 MeV. We could not see such a level in ^{137}Te where, instead, a strongly populated $I^\pi=13/2^-$ level was identified at 1100.8 keV [9]. As seen in Fig. 11, levels proposed in ^{139}Xe and ^{141}Ba as $I^\pi=13/2^+$ excitation follow closely the systematics for the $I^\pi=13/2^-$ levels, which includes the newly found $13/2^-$ level in ^{137}Te. In this work (cf. Secs. II A and II B) we have shown that the discussed $I=13/2$ levels in ^{139}Xe and ^{141}Ba have negative parity and belong to either the $\nu(f_{7/2}{}^3)_j$ or $\nu[(f^2_{7/2})h_{9/2}]_j$ multiplet. In Figs. 5 and 6 we have shown that there is a clear correlation

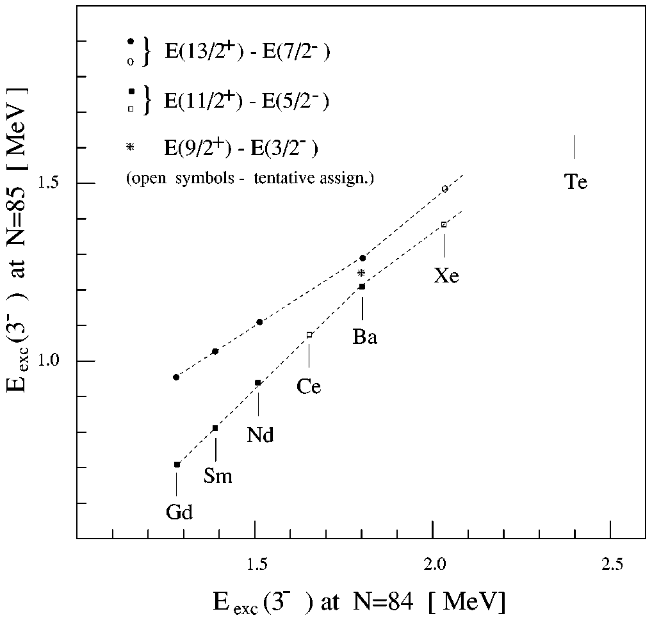

FIG. 12. Octupole excitations in the $N=85$ isotones.

between the energies of the $13/2^+$ levels in the $N=85$ isotones and the 3^- octupole excitations in their $N=84$ cores. Moreover, excitation energies of the $I^\pi=13/2^+$ levels relative to the $7/2^-$ level are systematically lower than the corresponding 3^- core excitations. These observations indicate a large contribution to the $13/2^+$ level originating from the octupole vibration coupled to the odd particle in the $f_{7/2}$ orbital as well as the contribution from the $\nu i_{13/2^+}$ single-particle excitation. On the other hand, it is likely that the second $13/2^+$ level with a dominant contribution from the $\nu i_{13/2}$ neutron excitation is pushed to higher energies and is too nonyrast at $N=85$ to be populated in fission.

The presence of octupole excitations in the $N=85$ isotones is clearly manifested by the systematic observation of $11/2^+$ and $13/2^+$ excitations in these nuclei. In Fig. 12 the combined data from Figs. 5 and 6 are displayed. The energy of octupole excitations in $N=84$ and $N=85$ isotones decreases with increasing proton number. This observation contradicts recent suggestions of Ref. [8] that octupole correlations increase with decreasing proton number. The trend shown in Fig. 12 reflects the increasing proton contribution to the octupole phonon. As their number increases from $Z=50$ towards $Z=64$, protons fill the $\pi(d_{5/2})$ and $\pi(g_{7/2})$ orbitals, both of which can couple by the octupole interaction to the $\pi(h_{11/2})$ orbital, giving rise to strong octupole correlations in the region [28]. For Gd to Ba $N=85$ isotones the variation of octupole excitation energy in $N=85$ isotones is very regular and could be used to predict energies of the yet unknown octupole excitations. The data shown in Fig. 12 suggest that the expected excitation energy of the $13/2^+$ level in ^{143}Ce is 1190 keV. Below $Z=56$, the observed trends change. The interaction of the 3^- core excitation with valence neutrons grows for the $11/2^+$ levels, while for $13/2^+$ levels it decreases. Identification of the $11/2^+$ and $13/2^+$ levels in ^{137}Te would significantly enrich the systematics. With linear extrapolations of the data in Fig. 12, one predicts excitation energies of 1650 keV and 1850 keV for the two levels, respectively, taking the 3^- octupole excitation energy in ^{136}Te to be 2450 keV, as estimated in Ref. [10].

There may be more octupole excitations present in the $N=85$ isotones than seen so far. One possibility is an $I=9/2$ coupling of an octupole phonon to the $3/2^-_1$ excitation. The 1249.0 keV level in ^{141}Ba [20] is a good candidate for such an excitation, considering its decay properties and excitation energy. It is marked by an asterisk in Fig. 12. Indeed, the authors of Ref. [20] assigned spin and parity $9/2^+$ to the 1249.0 keV level or, as a less likely solution, $11/2^-$ (the 1256.8 keV level in ^{141}Ba observed in Ref. [20] was assigned spin $11/2^+$ or, as a less likely solution, spin $13/2^-$). It is likely that $9/2^+$ excitations may be also present in other $N=85$ isotones. The $9/2^+$ excitations are too nonyrast in character to be populated in fission but should be seen in β^- decay experiments. Figure 12 gives hints about their excitation energies.

It seems that the correct calculations of octupole excitation energies at $N=85$ will require going beyond the shell-model scheme. In particular the effect of polarization of cores towards octupole instability has to be taken into account, similarly as proposed for coupling of quadrupole phonon to valence neutrons at $N=85$ [22]. To describe properly such excitations the energy of the quadrupole phonon was taken at 1 MeV in Ref. [22], which is significantly lower than energies of 2^+ excitations in the corresponding $N=82$ cores. This arbitrary selection takes care of the effect of "softening" of the $N=82$ cores towards quadrupole distortions, when neutrons are added.

IV. THE EXPECTED YRAST EXCITATIONS IN ^{135}Sn

The obtained systematics of excitation energies in the $N=85$ isotones, shown in Fig. 3, helps to predict properties of the nearyrast excitations in ^{135}Sn and ^{137}Te. The ^{135}Sn nucleus is located on the path of the astrophysical *r* process and its properties are important for the r-process calculations. For instance, the excitation pattern of ^{135}Sn can provide information about neutron level energies and about the strength of the $Z=50$ shell closure at $N=85$.

For ^{137}Te the systematics suggests spin $7/2^-$ for the ground state. Two excited states with spins $5/2^-$ and $3/2^-$ are predicted close to each other at around 100 keV. The $9/2^-_1$ level is expected at around 700 keV above the $7/2^-$ state. It is of great interest to verify experimentally predictions for ^{137}Te, to enrich the systematics.

The existing systematics suggests that spin and parity of the ground state in ^{135}Sn are $7/2^-$. For the first excited state spin $5/2^-$ and excitation energy of about 200 keV are expected, while for the second excited state spin $3/2^-$ is expected at around 400 keV. Further up, the $9/2^-_2$ and $11/2^-_1$ levels are expected to be between 700 keV and 800 keV above the $7/2^-$ level, while the $15/2^-$ level is expected to be around 1200 keV above the $7/2^-$ level.

These predictions can be compared with theoretical estimates obtained for ^{135}Sn using the OXBASH code [31] with the same input data as used to successfully describe the ex-

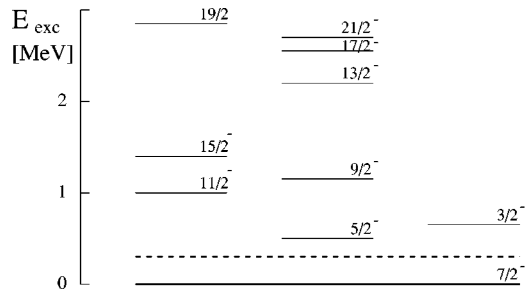

FIG. 13. OXBASH prediction for ^{135}Sn. See text for explanations.

citation pattern in ^{134}Sn in Refs. [29,30]. The results, shown in Fig. 13, confirm the expected pattern, though the ground state produces calculations about 300 keV lower than expected. If it was at the level marked in Fig. 13 by the dashed line, the agreement between energies calculated with OXBASH and estimated from systematics would be very satisfactory up to 1.5 MeV of excitation. The above results are now confirmed by more detailed shell-model calculations of Ref. [24].

V. CONCLUSIONS

In summary, medium-spin, near-yrast excited states in ^{139}Xe and ^{141}Ba, populated in the spontaneous fission of ^{248}Cm, were studied using the EUROGAM2 array. Spin and parity assignments based on measured angular correlations and linear polarizations, as well as new decay branches observed for the 1085.8 keV level in ^{139}Xe and the 1187.6 keV level in ^{141}Ba, have shown that both levels have negative parity. This result, together with our recent study of the ^{137}Te nucleus, indicates that the structures of ^{137}Te, ^{139}Xe, and ^{141}Ba are similar to the heavier $N=85$ isotones and do not support recent proposals that octupole correlations increase in these nuclei. A similar structure is suggested for ^{143}Ce, based on a reevaluation of the data available in the literature.

A very strong correlation between the excitation energies of $13/2^+$ octupole excitations in the $N=85$ isotones, and the energies of the 3^- octupole vibrations in the corresponding $N=84$ core nuclei, was found. A similar correlation, expected for $11/2^+$ octupole excitations, enables predictions to be made of the excitation energies of the $11/2^+$ levels in the ^{139}Xe, ^{141}Ba, and ^{143}Ce nuclei.

The systematics of octupole excitations in the $N=85$ isotones is qualitatively explained as resulting from various octupole couplings between the $\Delta j=\Delta I=3$ orbitals active in the region. Based on this picture we suggest that there is a $9/2^+$ octupole excitation present in the $N=85$ isotones discussed. The 1249.0 keV level in ^{141}Ba is the first candidate for this new octupole excitation.

Excitations observed in the $N=85$ isotones were explained as the result of coupling between levels formed by three valence neutrons in the $f_{7/2}$ and $h_{9/2}$ orbitals and quadrupole and octupole vibrations. These excitations can be classified using the simplex quantum number as $s=+i$ and $s=-i$ levels. The classification shows that the underlying, single-particle structure contains orbitals necessary to build octupole deformation but the clear vibrational character of the observed excitations indicates that octupole deformation is not present in the $N=85$ isotones with $50\leqslant Z\leqslant 64$.

Extensive systematics of energies of identified levels obtained in this work serves as a guide for searches for several new, suggested excitations in the $N=85$ isotones, possibly via β^- decay studies. In ^{137}Te the $3/2^-$, $5/2^-$, and $9/2^-$ yrast levels, predicted by the systematic trends of energy levels, are still not known. A confirmation of the proposed $11/2^+$ levels in ^{139}Xe, ^{141}Ba, and ^{143}Ce is of great interest as would identification of further $9/2^+$ levels. It is also of interest to find $13/2^-_1$ to $9/2^-_2$ decay branches in ^{143}Ce$-^{149}$Gd, $N=85$ isotones in order to clarify the nature of the $9/2^-$ levels in these nuclei.

Various octupole vibrations coupled to three valence neutrons in the $N=85$ isotones, presented in this work, provide an excellent testing ground for models describing the coupling between single-particle and collective excitations in this region. Equally interesting is to obtain a more accurate description of quadrupole modes coupled to the $h_{9/2}$ and $i_{13/2}$ neutron orbitals not considered in previous calculations.

ACKNOWLEDGMENTS

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