Level structure of ^{141}Ba and ^{139}Xe and the level systematics of $N=85$ even-odd isotones

Y. X. Luo,[1,2,3] J. O. Rasmussen,[4] J. H. Hamilton,[1] A. V. Ramayya,[1] J. K. Hwang,[1] C. J. Beyer,[1] S. J. Zhu,[3,5] J. Kormicki,[1] X. Q. Zhang,[1] E. F. Jones,[1] P. M. Gore,[1] T. N. Ginter,[4] K. E. Gregorich,[4] I-Yang Lee,[4] A. O. Macchiavelli,[4] P. Zielinski,[4] C. M. Folden III,[4] P. Fallon,[4] G. M. Ter-Akopian,[6] Yu. Ts. Oganessian,[6] A. V. Daniel,[6] M. A. Stoyer,[7] J. D. Cole,[8] R. Donangelo,[9] S. C. Wu,[10] and S. J. Asztalos[11]

[1]*Physics Department, Vanderbilt University, Nashville, Tennessee 37235*
[2]*Institute of Modern Physics, CAS, Lanzhou, China*
[3]*Joint Institute for Heavy Ion Research, Oak Ridge, Tennessee 37830*
[4]*Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[5]*Physics Department, Tsinghua University, Beijing 100084, China*
[6]*Flerov Laboratory for Nuclear Reactions, JINR, Dubna, Russia*
[7]*Lawrence Livermore National Laboratory, Livermore, California 94550*
[8]*Idaho National Environmental and Engineering Laboratory, Idaho Falls, Idaho 83415*
[9]*Universidade Federal do Rio de Janeiro, CP 68528, RG, Brazil*
[10]*Department of Physics, National Tsing Hua University, Hsinchu, Taiwan*
[11]*Massachusetts Institute of Technology, Cambridge, Massachusetts 11830*

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New level schemes of ^{141}Ba and ^{139}Xe are proposed from analysis of the gamma data from ^{252}Cf spontaneous fission in Gammasphere. By analogy with the $N=85$ even-odd isotones ^{149}Gd, ^{147}Sm, and ^{145}Nd, spins and parities were assigned to the observed excited states in ^{141}Ba and ^{139}Xe. Level systematics in the $N=85$ even-odd isotones from Gd ($Z=64$) to Te ($Z=52$) are discussed. The level systematics and comparison with neighboring even-even isotopes indicate that quadrupole and octupole collectivities play a role in ^{141}Ba and ^{139}Xe. From Gd ($Z=64$) to Te ($Z=52$), increasing excitation energies of the $13/2^{+}$ states and lowering relative intensities of the positive-parity bands in the $N=85$ even-odd isotones may indicate that the octupole strength is becoming weaker for the isotones when approaching the $Z=50$ closed shell.

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I. INTRODUCTION

The $N=85$ even-odd nuclei are three neutrons beyond the 82-neutron closed shell. This intermediate region is too close to the closed shell for the simple strong-deformation model, yet far enough from doubly magic ^{132}Sn to make shell-model interpretations difficult. Showing extensive and complex band structure, these so-called "quasi-$f_{7/2}$" nuclei provide a good opportunity to study the interplay between the single-particle excitations and the quasicollective motions. The $N=85$ even-odd isotones are at the border of the predicted quadrupole-octupole correlation island centered at $N=88$, $Z=56$ [1]. Theoretical calculations indicate that octupole excitations may occur in $^{141}_{56}$Ba and $^{139}_{54}$Xe [2]. Because of the octupole strength deduced from the $\nu f_{7/2} i_{13/2}$ transitions, octupole excitations and their trends are of great interest with regard to the structure of $N=85$ even-odd isotones.

Piiparinen *et al.* in 1981 reported high-spin single-particle excitations in $^{149}_{64}$Gd through (α,xn) reactions [3]. Spin and parity assignments for the excited states were made by means of gamma directional correlation from oriented nuclei (DCO) and linear polarization measurements. Levels of $^{149}_{64}$Gd were interpreted as shell model multiplets and multiplets coupled with octupole-phonon excitations, such as $\nu(f_{7/2})^3$, $\nu h_{9/2}(f_{7/2})^2$, $\nu(f_{7/2})^3\otimes 3^-$, $\nu h_{9/2}(f_{7/2})^2\otimes 3^-$, and $\nu(f_{7/2})^3\otimes 3^-\otimes 3^-$. Energies of the $\nu(f_{7/2})^3$ states agree only moderately with those calculated by using empirical two-nucleon interactions taken from $^{148}_{64}$Gd [3]. Urban *et al.* in 1996 presented level schemes for $^{145}_{60}$Nd and $^{147}_{62}$Sm, based largely on their work using heavy-ion reactions [4]. As with $^{149}_{64}$Gd, the excited levels of $^{145}_{60}$Nd and $^{147}_{62}$Sm were assigned to the three-valence-neutron excitations in a spherical potential or with octupole vibrations coupled to them. The $^{143}_{58}$Ce nucleus has many excited levels known from beta-decay studies of its parent ^{143}La [5], but its band structure is not known. Our collaboration in 1997 published first results on level schemes of $^{141}_{56}$Ba and $^{139}_{54}$Xe, based on our 1995 fission data at Gammasphere [6]. When the present work was going on, the first report on $^{137}_{52}$Te, using the data from fission of ^{248}Cm at the Eurogam2 gamma detector array, was reported by Urban *et al.* [7]. No octupole excitations were found in $^{137}_{52}$Te, and the two negative-parity bands observed were interpreted as excitations of the three valence neutrons.

In this paper using our most recent triple-coincidence ^{252}Cf Gammasphere data, we restudied the level structures of $^{141}_{56}$Ba and $^{139}_{54}$Xe to complete the level systematics for $N=85$ even-odd isotones from $Z=64$ to 52. We also present additional analyses on $^{141}_{56}$Ba and $^{139}_{54}$Xe, based on factor-of-2 compressed spectra from our triple-coincidence ^{252}Cf Gammasphere data of 1995. Spin and parity assignments and configuration interpretations are made for the excited levels observed in $^{141}_{56}$Ba and $^{139}_{54}$Xe. Parity doublet bands with both $s=+i$ and $s=-i$ are observed in ^{141}Ba. The level systematics and trends of level structure for $N=85$ even-odd isotones are also discussed.

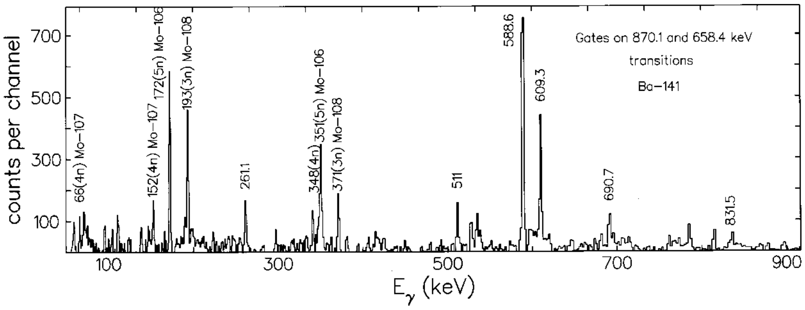

FIG. 1. Double-gated spectrum on 870.1 and 658.4 keV transitions in ^{141}Ba, using the triple-coincidence ^{252}Cf fission data from Gammasphere runs of the year 2000. The new band (4) in ^{141}Ba, consisting of 609.3, 690.7, and 831.5 keV transitions and the interconnecting transition of 261.1 keV, is identified, and the transitions of its fission partners are simultaneously seen.

II. EXPERIMENT AND DATA ANALYSIS

It has been shown that the combination of a multigamma detection array with a fission source provides a powerful tool for the studies of the high-spin structure of neutron-rich nuclei [8]. For two weeks each in August and November 2000, we took fission gamma data in the Gammasphere, which then employed 102 Compton-suppressed Ge detectors. A fission source of ^{252}Cf with a strength of 62 μCi, sandwiched between two Fe foils (10 mg/cm^2) was mounted in a 7.6-cm-diam polyethylene ball centered in the Gammasphere. More than 5.7×10^{11} triple- and higher-fold events were accumulated in about 4 weeks of counting.

The assignments of transitions to the nuclei ^{141}Ba and ^{139}Xe were justified by the simultaneous observations of the complementary fission partners and by careful cross-checks using double gating. Figure 1 shows a double-gated spectrum for ^{141}Ba indicating one of the newly found bands, band (4), observed in ^{141}Ba. It can be seen that the fission partners ^{106,107,108}Mo are simultaneously observed in the spectrum. An effort was made to determine transition energies and relative intensities as accurately as possible. The energy calibration was derived from known, well-determined (usually from beta-decay studies of individual fission fragments) energies of transitions in our own data set. These results are in good agreement with those determined from the separate calibration measurements with familiar standards. From residuals of the energy calibration fit, a systematic error of ± 0.1 keV is assigned. Various double-gated spectra were examined with the least-squares peak-fitting code of Radford's GF3 program [9]. This determined transition energies and relative intensities with statistical standard deviations. Figure 2 shows a gated spectrum based on factor-of-2 compressed data of 1995, showing the better resolution of the factor-of-2 compressed data for the overlapped peaks. Raw data for gamma energies are 16 384 channels from 0 to 5 MeV; the data array created by one of us (A.D.) creates gated spectra with 8192 channels over this range. Tables I and II list the energies with standard deviations and relative intensities obtained from Radford's GF3 program for the assigned $^{141}_{56}$Ba and $^{139}_{54}$Xe transitions, respectively. There are too many complexities of the spectra for the standard deviations on intensities to be meaningful. We estimate that the more intense transitions have standard deviations of around 20% and the weaker transitions as much as 80%.

III. RESULTS AND DISCUSSION

A. New level schemes of ^{141}Ba and ^{139}Xe

Our collaboration, Zhu *et al.* [6], presented a level scheme with three bands in ^{141}Ba. A new level scheme of ^{141}Ba with

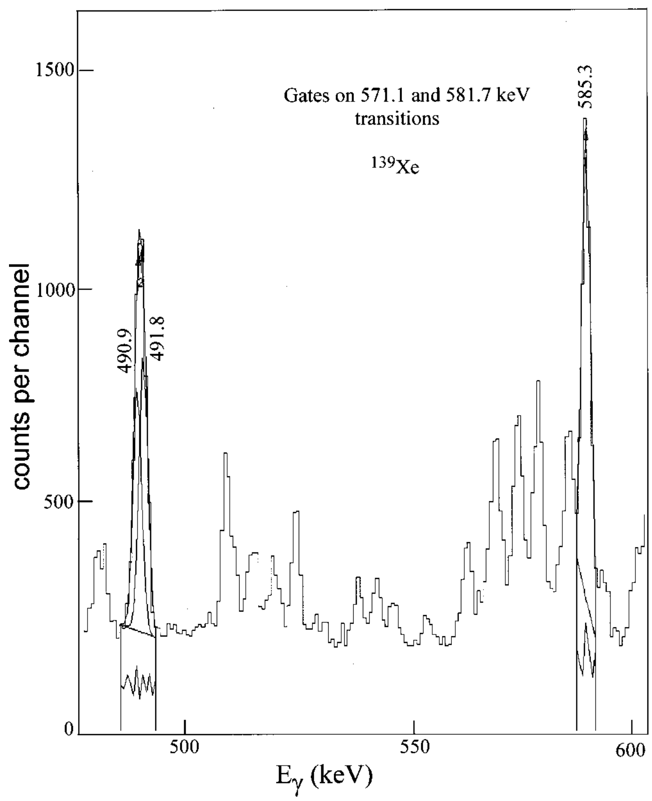

FIG. 2. Double-gated spectrum on 571.1 keV ($11/2^- \rightarrow 7/2^-$) and 581.7 keV ($21/2^- \rightarrow 17/2^-$) in ^{139}Xe, using triple-coincidence with factor-of-2 compressed (16*k* to 8*k*) data array. The cascade through the intermediate $13/2^-$ level generates two transitions of nearly equal energies, so close that they are unresolvable with the compression necessary in our RADWARE cube [9]. This figure shows the nonlinear least-squares fit using Radford's FT2 function in the spectral analysis program GF3 for the complex peak ~491 keV and FT1 for the clean peak ≈585.3 keV. The data and individual and summed peaks are shown, as well as the linear background and the residual errors in the fit. Peak widths were fixed by a formula based on fitting clean peaks, so in the two-peak fit there were six variables, two for the linear background, two peak positions, and two peak heights. The placement of 490.9 and 491.8 keV in the level scheme is fixed by energy sums of alternate paths, and the energy sums agree within 0.1 keV. For visual comparison with the close-doublet fitting the 585.3 keV peak was fit as a single peak. The slanted background subtraction looks peculiar, but it probably approximates the contribution of the leading edge of the adjacent peak at lower energy. Of course, for intensity determinations, as in Tables I and II, we would fit such a peak as a doublet or triplet.

TABLE I. Transition energies, statistical standard deviations, and intensities in ^{141}Ba.

E_γ (keV)	σ (keV)	E_γ [6] (keV)	Relative I_γ	Band	$I_i^\pi \to I_f^\pi$
588.59	0.02	588.9	100	1	$(11/2^-)\to(7/2^-)$
658.42	0.02	658.0	62.0	1	$(15/2^-)\to(11/2^-)$
812.94	0.05	812.9	11.5	1	$(19/2^-)\to(15/2^-)$
835.44	0.13		2.8	1	$(23/2^-)\to(19/2^-)$
869.8	0.4			1	$(27/2^-)\to(23/2^-)$
561.63	0.09	560.9	18	2	$(9/2^-)\to(5/2^-)$
577.26	0.09		3	2	$(13/2^-)\to(9/2^-)$
532.34	0.14	532.3	23	2	$(17/2^-)\to(13/2^-)$
609.49	0.07	609.3	17	2	$(21/2^-)\to(17/2^-)$
845.97	0.09	846.5	7.4	2	$(25/2^-)\to(21/2^-)$
733.34	0.15		1.4	2	$(29/2^-)\to(25/2^-)$
495.17	0.15	495	1.6	3	$(17/2^+)\to(13/2^+)$
596.96	0.14	596.6	12	3	$(21/2^+)\to(17/2^+)$
694.53	0.06	694.4	7	3	$(25/2^+)\to(21/2^+)$
706.42	0.09	706.3	5	3	$(29/2^+)\to(25/2^+)$
784.43	0.14		1.5	3	$(33/2^+)\to(29/2^+)$
609.28	0.11		6.2	4	$(23/2^-)\to(19/2^-)$
690.66	0.17		3.5	4	$(27/2^-)\to(23/2^-)$
831.5	0.12		1.1	4	$(31/2^-)\to(27/2^-)$
549.44	0.08		2.5	5	$(27/2^+)\to(23/2^+)$
751.04	0.11		1.6	5	$(31/2^+)\to(27/2^+)$
687.43	0.14		0.9	5	$(35/2^+)\to(31/2^+)$
555.14	0.11	554.5	12	2-1	$(9/2^-)\to(7/2^-)$
543.72	0.04	543.4	26	2-1	$(13/2^-)\to(11/2^-)$
417.58	0.04	417.9	22	2-1	$(17/2^-)\to(15/2^-)$
395.17	0.22	394.9	0.6	1-2	$(19/2^-)\to(17/2^-)$
214.26	0.26	214.0	1.0	2-1	$(21/2^-)\to(19/2^-)$
697.54	0.24	697.6	3	3-1	$(13/2^+)\to(11/2^-)$
534.22	0.08	534.3	15	3-1	$(17/2^+)\to(15/2^-)$
278.79	0.17		1.4	1-3	$(19/2^-)\to(17/2^+)$
318.34	0.06	317.9	4.2	3-1	$(21/2^+)\to(19/2^-)$
870.14	0.08		6.6	4-1	$(19/2^-)\to(15/2^-)$
452.5	0.1		3.9	4-2	$(19/2^-)\to(17/2^-)$
452.2	0.3			4-2	$(23/2^-)\to(21/2^-)$
335.96	0.16		2.8	4-3	$(19/2^-)\to(17/2^+)$
261.08	0.16		1.2	3-4	$(21/2^+)\to(19/2^-)$
348.44	0.22			4-3	$(23/2^-)\to(21/2^+)$
614.66	0.05		3.2	5-2	$(23/2^+)\to(21/2^-)$
231.42	0.14		0.6	2-5	$(25/2^-)\to(23/2^+)$
318.14	0.09		3.4	5-2	$(27/2^+)\to(25/2^-)$
415.2	0.2			2-5	$(29/2^-)\to(27/2^+)$
335.64	0.22		0.8	5-2	$(31/2^+)\to(29/2^-)$

TABLE II. Transition energies, statistical standard deviations, and intensities in ^{139}Xe.

E_γ (keV)	σ (keV)	E_γ [6] (keV)	Relative I_γ	Band	$I_i^\pi \to I_f^\pi$
571.11	0.02	571.4	100	1	$(11/2^-)\to(7/2^-)$
585.32	0.03	585.2	71	1	$(15/2^-)\to(11/2^-)$
630.38	0.03	630.5	22	1	$(19/2^-)\to(15/2^-)$
690.24	0.09	690.5	8	1	$(23/2^-)\to(19/2^-)$
661.52	0.07	661.7	3.3	1	$(27/2^-)\to(23/2^-)$
861.49	0.15	861.9	1	1	$(31/2^-)\to(27/2^-)$
962	0.4			1	$(35/2^-)\to(31/2^-)$
527.92	0.09	528.1	12	2	$(9/2^-)\to(5/2^-)$
525.24	0.09		3	2	$(13/2^-)\to(9/2^-)$
491.77	0.09	491		2	$(17/2^-)\to(13/2^-)$
581.74	0.07	582.3	18	2	$(21/2^-)\to(17/2^-)$
763.03	0.09	763.3	7.9	2	$(25/2^-)\to(21/2^-)$
664.16	0.09	664.2	4.3	2	$(29/2^-)\to(25/2^-)$
646.53	0.08	646.7	1.4	2	$(33/2^-)\to(29/2^-)$
863.94	0.09	864.3	1.2	2	$(37/2^-)\to(33/2^-)$
995	0.4			2	$(41/2^-)\to(37/2^-)$
502.02	0.2	502.6	0.4	3	$(17/2^+)\to(13/2^+)$
560.27	0.14	560.7	1.1	3	$(21/2^+)\to(17/2^+)$
636.65	0.15	636.2	2.6	3	$(25/2^+)\to(21/2^+)$
580.94	0.15	580.8	0.8	3	$(29/2^+)\to(25/2^+)$
619.63	0.11			3	$(33/2^+)\to(29/2^+)$
732.74	0.16	732.5	1.8	5	
682.3	0.24		0.9	5	
918.54	0.12	918.3	2	3-1	$(13/2^+)\to(11/2^-)$
835.14	0.09	835.4	4.9	3-1	$(17/2^+)\to(15/2^-)$
765.04	0.19	765.6	2.2	3-1	$(21/2^+)\to(19/2^-)$
711.34	0.11	711.7	1.7	3-1	$(25/2^+)\to(23/2^-)$
536.94	0.09	537.2	9	2-1	$(9/2^-)\to(7/2^-)$
490.88	0.09	492		2-1	$(13/2^-)\to(11/2^-)$
397.53	0.05	397.4	17	2-1	$(17/2^-)\to(15/2^-)$
232.78	0.18	233.1	2	1-2	$(19/2^-)\to(17/2^-)$
348.98	0.2	349.2	2.5	2-1	$(21/2^-)\to(19/2^-)$
341.3	0.3	341.3	1.5	1-2	$(23/2^-)\to(21/2^-)$
1013.4	0.4	1013.2	1.6	5-1	
382.67	0.12	383.0	1.2	5-1	
1115.7	0.3	1115.7	0.8	5-1	
425.1	0.3	425		5-1	
805.04	0.2		1.7	6-1	
626.52	0.12		1.6	4-2	$(27/2^+)\to(25/2^-)$

five bands proposed in the present work is shown in Fig. 3. Zhu *et al.* also reported a level scheme of ^{139}Xe, which consisted of four bands [6]. Shown in Fig. 4 is the new level scheme of ^{139}Xe developed in the present work. The energy values given for the levels were derived from a program used by the compilers of the Nuclear Data Sheets [10]. This program takes as input the transition energies and their standard deviations. It then generates the statistically best values for level energies. For the figures we have rounded all level energies and transition energies to the nearest 0.1 keV (our estimated systematic standard deviation.) Therefore, occasionally the difference of initial and final level energies does not quite equal the labeled transition energy. The spin-parity assignments are all tentative, as indicated by the parentheses about all but the ground state. However, the fact that the fission products are formed with an average of six or more units of angular momentum greatly simplifies the construction of bands and assignment of spins, because only yrast or near-yrast states are observed. We are further helped in the

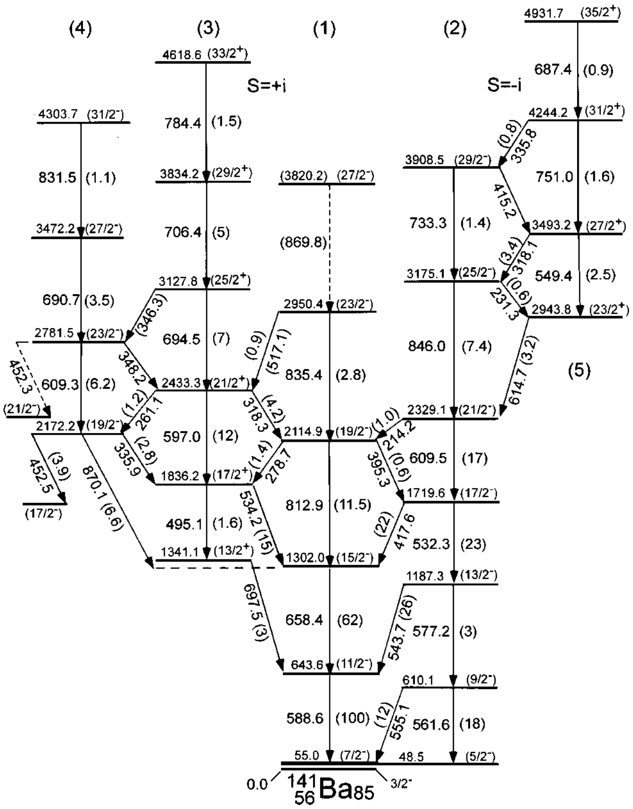

FIG. 3. New level scheme of ^{141}Ba established in the present work. See text.

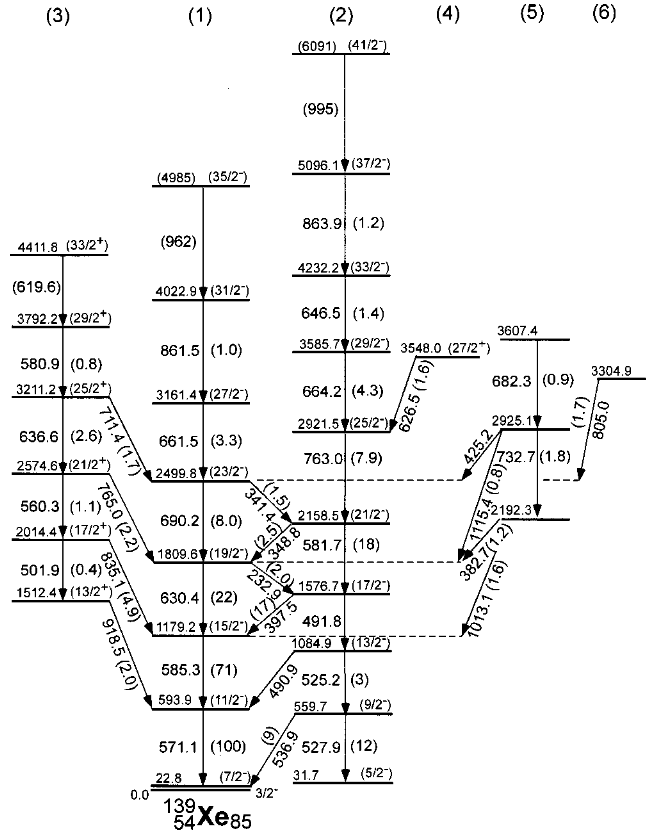

FIG. 4. New level scheme of ^{139}Xe established in the present work. See text.

cases of this paper by the fact that the bands are interlaced with each other. Thus spin and parity assignments are quite constrained, since only $E2$, $M1$, and $E1$ multipolarities are expected to compete. Ideally, one would like to have internal conversion coefficients (ICCs) or directional gamma-gama correlation measurements to confirm multipolarity assignments. Measurement of ICCs for prompt fission gamma radiation is not feasible due to complexity of the large mix of fission product activities. In a few cases where one low-energy (<150 keV) and one high-energy (>200 keV) transitions are present in a cascade, the ICC for the low-energy transition has been extracted by comparing the γ-ray intensities [11]. A Eurogam collaboration, Urban *et al.* [12], has made a few angular correlation measurements. In their case the fission fragments were stopped in a KCl salt pill, a diamagnetic medium in which the perturbing magnetic or electric fields at the stopped fission nuclei should be small. In all our Berkeley Gammasphere experiments we have stopped in metallic stoppers that could leave large residual perturbing fields. We hope that some groups will come forward to greatly expand the work in angular correlations and test the tentative spin-parity assignments proposed here.

Band (1) of ^{141}Ba of Zhu *et al.* is confirmed up to $(19/2^-)$. However, their 814.0 keV transition is not observed. Instead, we place an 835.4 keV and, tentatively, an 869.8 keV transition on the top of this band, extending the spin to $(27/2^-)$. Band (2) of ^{141}Ba is extended up by the 733.3 keV transition, reaching $(29/2^-)$. A 577.2 keV transition is observed in between the 1187.3 and 610.1 keV levels, so band (2) is found to build on the 48.5 keV $(5/2^-)$ level. The interconnecting transitions between bands (1) and (2) are confirmed. Band (3) is extended to spin $(33/2^+)$ by the observation of a 784.4 keV transition. The previously tentatively reported 495 keV transition in band (3) is observed. A new connecting transition between the 2114.9 keV level of band (1) and the 1836.2 keV level of band (3) was observed at 278.7 keV. Of particular interest are the two new bands (4) and (5), which are proposed for the first time in ^{141}Ba. Band (4) is extended to the 4303.7 keV $(31/2^-)$ level with its intertwined transitions of 335.9, 261.1, 348.2, and tentatively 346.3 keV between bands (4) and (3). Band (4) seems to be a bifurcation of band (1), and it is not clear which set of stretched $E2$ cross over transitions above $15/2^-$ is best characterized as the extension of band (1). There are no crossing transitions observed between band (4) and band (1) except for the intense decay-out transition of 870.1 keV found to deexcite the 2172.2 keV $(19/2^-)$ bottom level of band (4) to feed into the 1302.0 keV $(15/2^-)$ level of band (1). In addition, cross over transitions of 452.5 and 452.3 keV were found between bands (4) and (2). So the new band (4) not only decays into bands (1) and (2), but also interconnects with band (3). Consisting of three transitions, the high-lying new band (5) reaches the 4931.7 keV $(35/2^+)$ level, which is the highest excitation energy of any positive-parity band found in the $N=85$ even-odd isotones. Intertwined transitions of 614.7, 231.3, 318.1, 415.2, and 335.8 keV were observed between bands (2) and (5).

Bands (1), (2), and (3) of ^{139}Xe reported by Zhu *et al.* [6] are confirmed and extended tentatively by one level in each band, reaching 4985 keV, $(35/2^-)$, 6091 keV, $(41/2^-)$, and 4411.8 keV, $33/2^-$, respectively; the former two reach the highest excitations observed in all the $N=85$ even-odd isotones. Similar to ^{141}Ba, band (2) is found to be built on the 31.7 keV $(5/2^-)$ level by observation of a 525.2 keV transition. Band (5) is confirmed and extended by observation of a 682.3 keV transition. Two new possible bandheads (4) and (6) are identified. Each consists of only one level.

The three close-lying levels, which lie lowest in the level scheme of ^{141}Ba and ^{139}Xe, were established by several beta-decay studies from 1972 to 1984, as cited in the Table of Isotopes [5]. Their spins and parities are assigned as $(3/2^-)$, $(5/2^-)$, and $(7/2^-)$. They are interconnected by $M1$ and $E2$ transitions, establishing a common parity. This trio of lowest levels is a common feature of the $N=85$ even-odd nuclei, though the level order sometimes changes. Typically, for the $N=85$ even-odd nuclei, there is a gap of 0.6–0.8 MeV above the close trio near the ground state before the onset of a large number of negative-parity excited states, and the higher-spin, near-yrast bands form a sequence of levels connected by $E2$ transitions with about the same spacing as the gap. Such a common feature is seen in ^{141}Ba and ^{139}Xe and other $N=85$ even-odd isotones, although in ^{149}Gd, ^{147}Sm, and ^{145}Nd the bands are seen only to lower excitations and spins.

The assignments of spins and parities to the excited levels of ^{141}Ba and ^{139}Xe are based on the level systematics and analogies to the even-odd isotones ^{149}Gd, ^{147}Sm, and ^{145}Nd, where the assignments were made by means of DCO and linear polarization measurements and shell model calculations or by analogies of level systematics and decay patterns [3,4,7]. The yrast bands (1) in ^{141}Ba and ^{139}Xe are found to be built on the $(7/2^-)$ level, and as mentioned above, band (2) is built on the $(5/2^-)$ level. Keeping this in mind and by analogy to the corresponding levels of the bands of ^{149}Gd, ^{147}Sm, and ^{145}Nd, the bands (1) and (2) of ^{141}Ba and ^{139}Xe are assigned as negative-parity bands, which consist of crossover $\Delta I=2$ $E2$ transitions and form signature partners. The excitation and decay pattern of the newly observed 2172.2 keV level of ^{141}Ba is analogous to the 2704 and 2408 keV $(19/2^-)$ levels in ^{147}Sm and ^{145}Nd, respectively, which suggests a $(19/2^-)$ assignment to this new level and negative parity to band (4) of ^{141}Ba, which consists of $E2$ crossover transitions. Such a band was not well developed in ^{147}Sm and ^{145}Nd [4]. The assignment of spins and positive parity to bands (3) and (5) of ^{141}Ba and to bands (3) and (4) of ^{139}Xe is made also based on the excitation systematics and decay patterns similar to those of the other $N=85$ even-odd isotones. The positive-parity bands (3) and (5) of ^{141}Ba extend to the highest spins and excitation energies, 4618.6 keV $(33/2^+)$ and 4931.7 keV $(35/2^+)$, respectively, among all isotones studied. So parity doublets with both simplex quantum numbers $s=+i$ [bands (1) and (3)] and $s=-i$ [bands (2) and (5)] characteristics of octupole deformation are identified in ^{141}Ba, as seen in ^{149}Gd, ^{147}Sm, and ^{145}Nd, although in the latter three isotopes only lower spins and excitations are observed to be populated. The two parity doublets in ^{141}Ba are interconnected by $E1$ transitions. Note that some parity assignments differ from those of Zhu *et al.* [6]. In ^{139}Xe, however, only one level of 3548.0 keV $(27/2^+)$ is assigned to the higher-lying positive-parity band (4), so only the $s=+i$ parity doublet, bands (1) and (3), is identified. The positive-parity band (3) in ^{139}Xe is pushed up to considerably higher excitation energies, starting from 1512.4 keV, and is very weakly populated (see Fig. 4 and Table II). So between bands (1) and (3) there are only $E1$ transitions de-exciting the levels of band (3) and feeding those of band (1) in ^{139}Xe. Moreover, the positive-parity band (4) in ^{139}Xe starts from the 3548.0 keV $(27/2^+)$ level, the highest level among all the $N=85$ even-odd isotones.

TABLE III. Experimental $B(E1)/B(E2)$ ratios in ^{141}Ba and ^{139}Xe.

	E_γ (keV)	$I_i^\pi \rightarrow I_f^\pi$	$B(E1)/B(E2)$ $(10^{-6}\ \mathrm{fm}^{-2})$
^{141}Ba, $s=+i$	812.9	$(19/2^-)\rightarrow(15/2^-)$	1.54(8)
Bands (1)	278.7	$(19/2^-)\rightarrow(17/2^+)$	
and (3)	835.4	$(23/2^-)\rightarrow(19/2^-)$	0.73(6)
	517.1	$(23/2^-)\rightarrow(21/2^+)$	
	495.1	$(17/2^+)\rightarrow(13/2^+)$	1.41(8)
	534.2	$(17/2^+)\rightarrow(15/2^-)$	
	597.0	$(21/2^+)\rightarrow(17/2^+)$	0.63(5)
	318.3	$(21/2^+)\rightarrow(19/2^-)$	
Bands (3)	597.0	$(21/2^+)\rightarrow(17/2^+)$	0.33(4)
and (4)	261.1	$(21/2^+)\rightarrow(19/2^-)$	
^{141}Ba, $s=-i$	846.0	$(25/2^-)\rightarrow(21/2^-)$	2.18(9)
Bands (2)	231.3	$(25/2^-)\rightarrow(23/2^+)$	
and (5)	549.4	$(27/2^+)\rightarrow(23/2^+)$	1.63(8)
	318.1	$(27/2^+)\rightarrow(25/2^-)$	
	751.0	$(31/2^+)\rightarrow(27/2^+)$	2.43(9)
	335.8	$(31/2^+)\rightarrow(29/2^-)$	
^{139}Xe, $s=+i$	501.9	$(17/2^+)\rightarrow(13/2^+)$	0.52(5)
Bands (1)	835.1	$(17/2^+)\rightarrow(15/2^-)$	
and (3)	560.3	$(21/2^+)\rightarrow(17/2^+)$	0.19(3)
	765.0	$(21/2^+)\rightarrow(19/2^-)$	
	636.6	$(25/2^+)\rightarrow(21/2^+)$	0.15(5)
	711.4	$(25/2^+)\rightarrow(23/2^-)$	

Table III lists the $B(E1)/B(E2)$ ratios calculated from our new data here for levels in ^{141}Ba and the corresponding information for ^{139}Xe. We suggest in the next section that it is difficult to draw conclusions about collectivity from these ratios, even if one has lifetime measurements, which have not been made for these levels.

B. Interpretations for the excited levels of ^{141}Ba and ^{139}Xe

The interpretations of the configurations for the excited levels of ^{141}Ba and ^{139}Xe are made based on the published decay studies as well as systematics and analogies to the other $N=85$ even-odd isotones. These earlier studies based on (heavy-ion, *xn*) reaction gamma work generally do not populate as high spins in the bands as does the spontaneous fission gamma work. Also, these studies were for $Z=60$, 62, and 64, all close to the 64 subshell with filled $g_{7/2}$ and $d_{5/2}$ proton orbitals. The earlier work mainly assigned configurations as excitations of the three valence neutrons, with proton participation entering only indirectly through octupole phonon couplings. We feel that this approach may be quite appropriate for the low end of the main bands, near the $Z=64$ subshell, but we see only small irregularities in the spacing of $Z=54$ and 56 bands when going above the maximum spins of stretched configurations of the three valence neutrons. Invoking double-octupole excitations as in Refs. [3], [4] seems to us questionable for the $Z=54$ and 56 nuclei. Rather, we suggest that the participation of valence protons (four protons in ^{139}Xe and six in ^{141}Ba) gradually increases as one goes up the band to higher spins. The nearly equal spacing of the levels in the bands is characteristic of harmonic vibrational character.

The transition rates among the lowest-lying three levels in ^{141}Ba [5] (cf. Vol. 1, pp. 1316 and 1317, and beta-decay references therein) are slower than the single-proton formula, suggesting they are different couplings of the three valence neutrons, not much involving proton or collective shape phonons. These three levels were proposed [3,4] to be different couplings of the three $f_{7/2}$ neutrons beyond the 82-neutron shell closure, $\nu(f_{7/2})^3$. Couplings allowed by the Pauli principle are $J=3/2$, 5/2, 7/2, 9/2, 11/2, and 15/2. So $\nu(f_{7/2})^3_{3/2}$, $\nu(f_{7/2})^3_{5/2}$, and $\nu(f_{7/2})^3_{7/2}$ are assigned to the ground $3/2^-$, 48.5 keV ($5/2^-$), and 55.0 keV ($7/2^-$) levels of ^{141}Ba, respectively, and the same configurations are assigned to the lowest levels in ^{139}Xe. The $\nu(f_{7/2})^3$ configuration is probably dominant in the lowest $11/2^-$ and $15/2^-$ levels of ^{141}Ba and ^{139}Xe. The beta-decay studies suggested a $\nu h_{9/2}$ single-neutron excitation to the $9/2^-$ level in ^{149}Gd [13], excluding the $\nu(f_{7/2})^3$ assignment, so $\nu h_{9/2}(f_{7/2})^2$ was assigned to this $9/2^-$ level in ^{149}Gd and also to the $9/2^-$ state in ^{147}Sm [14] and ^{145}Nd [15] from single-neutron transfer data. We assume their assignment is applicable also to the $9/2^-$ states in ^{141}Ba and ^{139}Xe. However, the $13/2^-$ state cannot be formed by $\nu(f_{7/2})^3$, so there is likely dominant $\nu(f_{7/2})^2h_{9/2}$ and some contributions from protons. Higher-spin states in bands (1) and (2) probably are a mixture of configurations involving $f_{7/2}$ and $h_{9/2}$ neutrons plus quadrupole phonons.

The $13/2^+$ states in ^{147}Sm and ^{145}Nd were found to be populated with $l=6$ in single-neutron transfer reactions, indicating the contribution to the $13/2^+$ state by the $\nu i_{13/2}$ single-neutron excitations (Ref. [4] and the papers referred to therein). However, Piiparinen *et al.* [3] argued that the $13/2^+$ is predominately due to octupole-phonon excitations coupled to the $\nu(f_{7/2})^3$—that is, $\nu(f_{7/2})^3\otimes 3^-$. The octupole phonon in this case is not the same as the core octupole phonon of ^{132}Sn at 4.351 MeV, composed of nucleon particle-hole states across the closed shells. In ^{141}Ba the $13/2^+$ state lies far lower at 1341 keV and in ^{145}Nd at 1011 keV. The octupole phonon of Piiparinen *et al.* [3] must be composed mainly of valence-shell particle-hole excitations, mainly of the odd neutron, which can be promoted from $f_{7/2}$ to $i_{13/2}$ without the pair breaking needed for proton excitations. Thus there is not a clear-cut choice between assignments of $\nu(f_{7/2})^2i_{13/2}$ and the $\nu(f_{7/2})^3\otimes 3^-$.

In the $Z=60$ (^{145}Nd) isotone the "octupole" band has a bandhead of $11/2^+$ close to the $13/2^+$ and a doublet structure $17/2^+$,$15/2^+$ and $21/2^+$,$19/2^+$ above that. In the case of ^{141}Ba the $19/2^+$, $15/2^+$, and $11/2^+$ are not observed. The $11/2^+$ state presumably arises from a nonstretched ($I_{\mathrm{stretch}}-1$) coupling of $f_{7/2}$ with the octupole phonon.

Band (4) of ^{141}Ba is remarkable in that it is headed by a $19/2^-$ level at 2172.2 keV remarkably close in energy (58 keV) to the level of the same spin and parity in band (1). The energy spacing in band (4) is also smaller than that in band (1), suggesting that band (4) has the greater deformation or quadrupole softness. One of two $19/2^-$ levels in $Z=60$, 62, and 64 isotones has been proposed as a double octupole-phonon state [3,4]. Such an explanation requires considerable anharmonicity of the octupole vibration to bring the state so low. There are alternative and possibly simpler configurations to assign the $19/2^-$, such as $\pi(g^{-2}_{7/2})_2\nu(f^3_{7/2})_{15/2}$, $\nu(f^2_{7/2})_6h_{9/2}$, etc.

The neat picture we might have hoped for would be a family of four interlaced bands, two of positive and two of negative parity. Then we could claim an example of both signature partner and parity doublet bands. However, the presence of five bands in ^{141}Ba spoils the simple picture. Bands (1)–(4) of ^{141}Ba are most tightly interlaced by transitions, while band (5) only seems interconnected with band (2). The lack of $M1$ transitions linking bands (3) and (5) argues against their being signature partners.

We believe it is premature to try to draw definite conclusions about octupole deformations from the $B(E1)/B(E2)$ ratios of Table III. Even when lifetimes are known, the $B(E1)$ strength is not a simple indicator of stable pear-shaped deformation. The $E1$ strength arises from a cross term in the quadrupole and octupole transition matrix elements, which can give a separation of center of charge and center of mass during rotation or vibration. Any significant separation thus requires not only quadrupole and octupole collective motion, but also that the degree of participation of neutrons and protons be unequal. In cluster-model terms, $E1$ strength arises only when the charge-to-mass ratio of the core (such as ^{132}Sn) has a different Z/N ratio than the cluster beyond the core. What is clear is that there is both quadrupole and octupole collective strength in the $N=85$ isotones.

C. Level systematics of the $N=85$ even-odd isotones

Now the systematics, analogies, and trends of the level patterns in $N=85$ even-odd isotones from Gd ($Z=64$) to Te ($Z=52$) are available and can provide important information on the nuclear structure for the isotones, including spin and parity assignments made for the excited levels observed in ^{141}Ba and ^{139}Xe.

Shown in Fig. 5 are the level systematics of the two lowest negative-parity bands [bands (1) and (2) in ^{141}Ba] in the $N=85$ even-odd isotones. As discussed in the previous section, these bands were interpreted [3,4] in the spherical single-particle model near the proton subshell $Z=64$ as consisting of the three-neutron couplings, but in our Ba and Xe

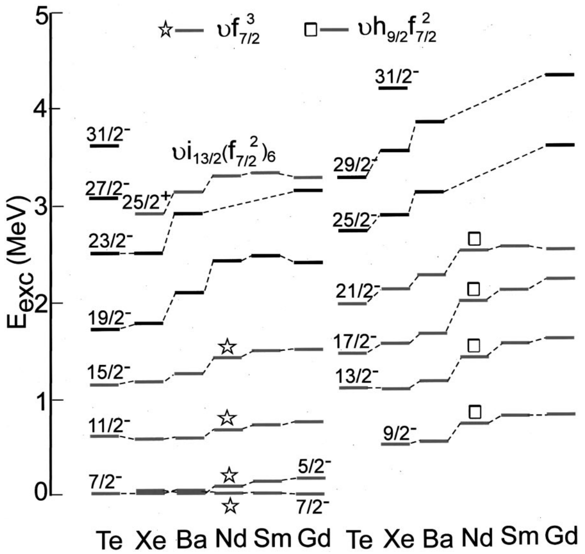

FIG. 5. Level systematics of the two negative-parity bands of the $N=85$ even-odd isotones, which are interpreted in the spherical shell-model basis on single-neutron excitations. Also shown in the figure are systematics for the $25/2^+$ state, which is interpreted as pure neutron excitations. The $19/2^-$ states are interpreted by Piiparinen *et al.* [3] and Urban *et al.* [4] as double-phonon excitations coupled with single neutron states. The star symbol is attached to levels assigned by preceding references to couplings of three $f_{7/2}$ neutrons. The squares are attached to levels assigned by these references to coupling of two $f_{7/2}$ with one $h_{9/2}$. See text for our alternative interpretations.

isotones away from proton shells and subshells may more appropriately be considered signature partners of one band. Level systematics and smooth trends can be seen in Fig. 5 from $_{64}$Gd to $_{52}$Te. It is of interest to note the evolution of the two bands with variation of proton number of the isotones. Moving down from Gd ($Z=64$), the irregularities of the two negative-parity bands are decreasing, and around Ba ($Z=56$) the level spacing becomes more regular. This changing irregularity may be attributed to moving away from the $Z=64$ subshell. Near the proton subshell it is reasonable to assume configurations involving predominantly just excitations of the three neutrons beyond the $N=82$ shell. Indeed, we see a gap in spacing as the spins go above the maximum stretched three-neutron limits. It is obvious that proton excitations must be involved in the higher-spin states. The octupole phonon assignments near the $Z=64$ subshell may be the most appropriate representation there, but midway between $Z=50$ and 64, the band spacings show but little irregularity above the stretched three-neutron limits. Thus it seems reasonable in this middle region to suppose that proton excitations are mixed with neutron excitations throughout the bands. The regular band spacing observed in ^{141}Ba and ^{139}Xe may be an indication that quadrupole collectivity has come into play.

The band spacings in yrast levels of ^{141}Ba and ^{139}Xe are also compared with those for their neighboring even-even isotopes ^{140}Ba [16] and ^{138}Xe [17] in Fig. 6 and 7, respectively. It can be seen clearly that in comparison with ^{140}Ba and ^{138}Xe, respectively, the yrast bands of ^{141}Ba and ^{139}Xe

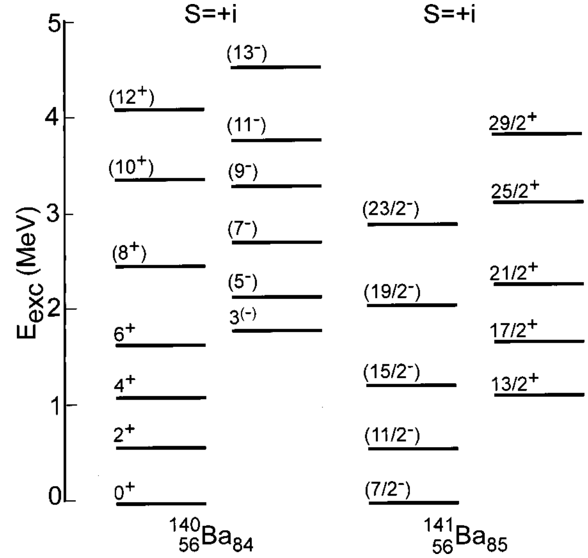

FIG. 6. Comparison of the yrast band of ^{141}Ba with that of the neighboring even-even isotope ^{140}Ba (data taken from [16]). Also shown in the figure is the comparison for the octupole phonon band in ^{140}Ba and the positive-parity band in ^{141}Ba, the latter interpreted as octupole phonon excitations coupled with single-neutron excitations.

are more regular and in fact more like a collective yrast band of vibrational, near-equal spacing. In this transition region between the spherical shell model and spheroidal shell model it seems to us that traditional analyses of moments-of-inertia and particle alignment would not be useful. Likewise, the number of nucleons beyond the ^{132}Sn double closed shell is

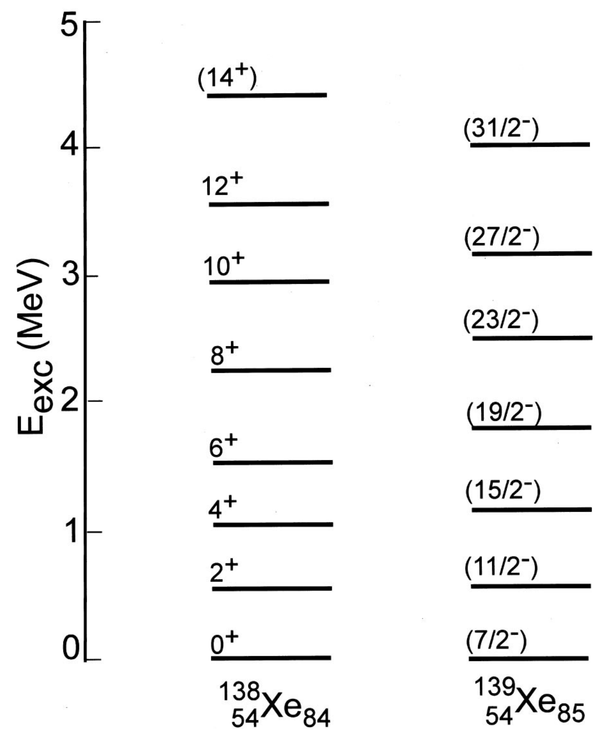

FIG. 7. Comparison of the yrast band of ^{139}Xe with that of the neighboring even-even isotope ^{138}Xe (data taken from [17]).

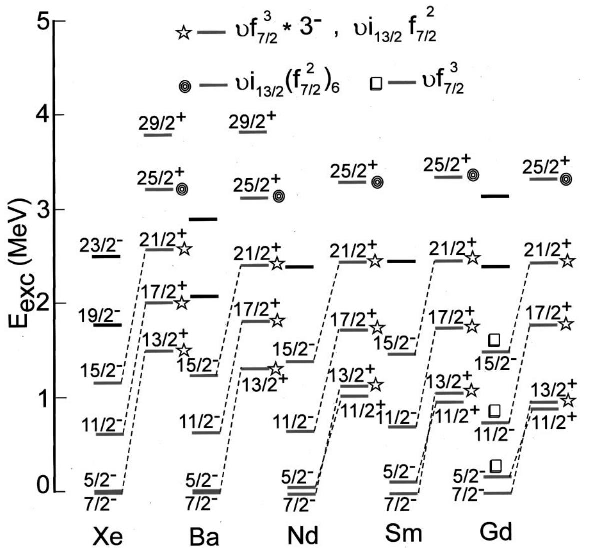

FIG. 8. Level systematics of the lower-lying positive-parity bands of the $N=85$ even-odd isotones, which are interpreted to build on octupole phonon excitations coupled with single-neutron ground states. For the sake of completeness for the bands, the $25/2^+$ member of the bands is also shown in the figure. Explanation of the star, concentric circles, and square symbols is given at the top of the figure. The star symbol denotes a mix of configurations involving an octupole phonon and those with promotion of a neutron from $f_{7/2}$ to $i_{13/2}$.

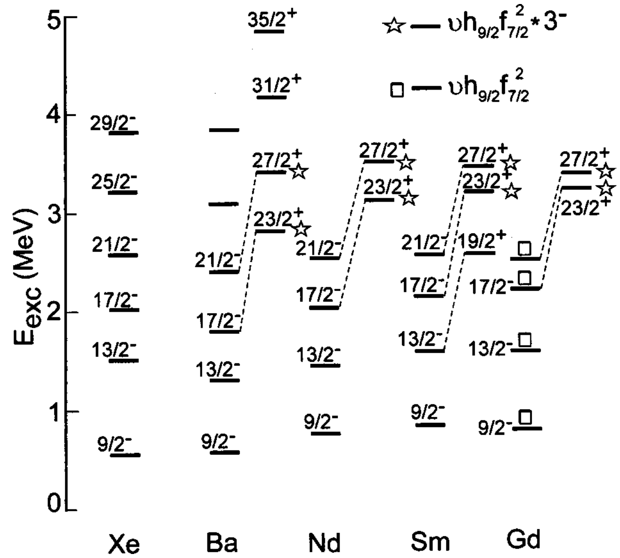

FIG. 9. Level systematics of the higher-lying positive-parity band of the $N=85$ even-odd isotones. This has been interpreted in Ref. [4] as an octupole phonon excitation coupled with single-particle neutron states with one neutron promoted from the $f_{7/2}$ to the $h_{9/2}$ orbital, and such states are labeled by the star symbol. The squares denote the interpretation of Ref. [4] for several states in Gd at the $Z=64$ proton subshell. Note that in Te isotones there is no positive-parity band observed.

too large for simple spherical single-particle shell-model codes. We respectfully invite the nuclear theory community to make further use of the systematics we present.

Figure 8 depicts the systematics of lower-lying positive-parity bands [band (3) in ^{141}Ba, for example] in $N=85$ even-odd isotones, which is considered to build on the octupole phonon excitations coupled to $\nu(f_{7/2})^3$. The positive parity state $25/2^+$ has an almost constant energy as seen in Fig. 8. Figure 9 is drawn for the higher-lying positive-parity bands [band (5) in ^{141}Ba, for example], which are accounted for by Urban *et al.* [4] as the octupole phonon excitations coupled to excited neutron configurations involving the $\nu h_{9/2}(f_{7/2})^2$ orbital. In Fig. 8, of particular interest, is the variation of the excitation energies of the bandheads of the lower-lying positive parity band, $13/2^+$, with changing proton number of the isotopes. It is more clearly seen in Fig. 10 that with decreasing proton number the excitation energies of the $13/2^+$ states are increasing, while those of the $13/2^-$ states, bandheads of the negative-parity band [band (2) in ^{141}Ba, for example], are decreasing in such a way that the $13/2^+$ yrast state in Gd, Sm, and Nd becomes nonyrast in Ba and Xe isotones, and no $13/2^+$ state is observed in the Te isotone. The pronounced trend of the excitation energies of the $13/2^+$ state in the $N=85$ even-odd isotones may account for the decrease of relative intensities of the lower-lying positive-parity band with decreasing proton number of the isotones and for the very weak population of the positive band (3) in ^{139}Xe and the failure to observe a positive-parity band in ^{137}Te. The rising excitation energies and weakening population of the positive-parity band with decreasing proton number of isotones may imply that when approaching the $Z=50$ proton shell, the octupole excitations in the $N=85$ even-odd isotones become weaker.

IV. SUMMARY

New level schemes of ^{141}Ba and ^{139}Xe are proposed here up to an excitation of ≈5 MeV by using the triple- and

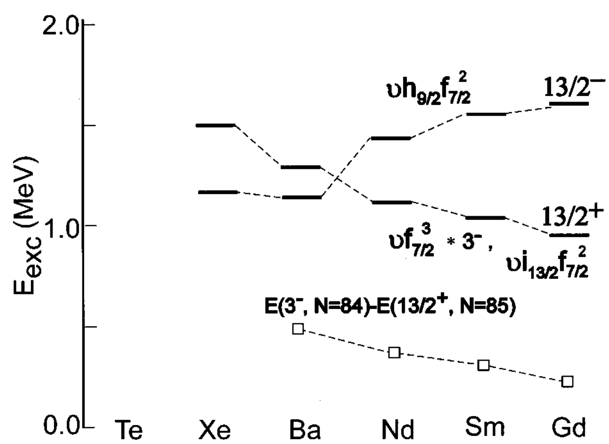

FIG. 10. Trends of the excitation energies of the bandhead, $13/2^+$, of the lower-lying positive-parity bands of the $N=85$ even-odd isotones. Also shown in the figure are the $13/2^-$ states. The $13/2^+$ is rising in excitation energy when proton number is decreasing, becoming nonyrast for Ba and Xe isotones. Also shown in the figure are the energy differences between the 3^- states of the $N=84$ even-even isotones and the $13/2^+$ states of the neighboring $N=85$ even-odd isotones. The data of $N=84$ isotones are taken from [16,18–23]. Also see text.

higher-fold coincidence data from ^{252}Cf spontaneous fission at Gammasphere obtained in the year 2000, supplemented by factor-of-2 compressed spectra from our data of 1995. Spins and parities are proposed for the excited levels. Systematics of the yrast and near-yrast level structure of the $N=85$ even-odd isotones have been extended and expanded from $Z=64$ to 52. Level systematics and analogies of decay patterns for the $N=85$ even-odd isotones support the spin and parity assignments. The level spacings of the observed bands in ^{141}Ba and ^{139}Xe become somewhat more regular in comparison with those of isotones near the $Z=64$ subshell, and this comparative regularity is seen when the yrast bands of ^{141}Ba and ^{139}Xe are compared to those of their neighboring even-even isotopes ^{140}Ba and ^{138}Xe, respectively. This suggests that quadrupole rotation/vibrational motion has come into play in ^{141}Ba and ^{139}Xe. The increasing excitation energies of the $13/2^{+}$ states and the decreasing relative intensities of the positive-parity bands of the $N=85$ even-odd isotones with decreasing proton number of the isotones may be an indication that when approaching the $Z=50$ proton shell, the octupole excitations of the $N=85$ even-odd isotones require more energy, and finally go above yrast and are not observable in the prompt fission gamma spectra.

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