High spin structure of the neutron-rich nuclei ^{137}I and ^{139}Cs

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(Received 8 July 2009; published 14 October 2009)

High spin excited states in the neutron-rich nuclei ^{137}I and ^{139}Cs were investigated from a study of the prompt γ rays emitted in the spontaneous fission of ^{252}Cf with the Gammasphere detector array. Ten new excited levels with 18 new deexciting transitions were observed in ^{139}Cs and the level scheme of ^{139}Cs was extended up to 4670 keV. Spins and parities of levels in ^{139}Cs were firmly assigned up to $25/2^+$. Three new levels were found in ^{137}I. Shell model calculations were performed to interpret the experimental results. A good agreement between theory and experiment in both nuclei was found.

DOI: 10.1103/PhysRevC.80.044314 PACS number(s): 23.20.Lv, 23.20.En, 21.10.Hw, 27.60.+j

I. INTRODUCTION

Studies of the structure of neutron-rich nuclei near the $Z = 50$, $N = 82$ doubly-magic ^{132}Sn core provide an important test for shell model calculations employing realistic effective interactions. In particular, these data may be used to find out how far a shell model interpretation is adequate for neutron-rich nuclei. Therefore, with five valence protons outside the $Z = 50$ closed shell and two valence neutrons beyond the $N = 82$ major shell, the ^{139}Cs nucleus is a good candidate for this purpose. An additional motivation for the present study in ^{139}Cs is a work reported by Nowak *et al.* [1] in 1999, where a level scheme of ^{139}Cs, different from that reported by Hwang *et al.* [2] in 1998, was proposed.

The β decay [3], fission of ^{252}Cf [2] and fission of ^{248}Cm [1] have been used to populate excited states in the ^{139}Cs nucleus. Thirteen transitions and eleven levels up to high spin in ^{139}Cs were identified by Nowak *et al.* [1]. In the present work, we confirmed the yrast band of ^{139}Cs reported in Ref. [1] and extended it up to 4670 keV by adding ten new excited levels with 18 new deexciting transitions. Spins and parities of levels in ^{139}Cs were firmly assigned up to $25/2^+$. The level pattern of ^{139}Cs indicates the validity of a shell model description. Realistic shell model calculations were performed, as discussed in Sec. III, to interpret the spectrum of ^{139}Cs and a good agreement between theory and experiment was found.

The energy levels in ^{137}I, an isotone of ^{139}Cs, were also extended with three new excited levels added on the top of the level scheme reported in Ref. [4] and our calculations gave better results than those obtained in Ref. [4].

II. EXPERIMENTAL RESULTS

Studies of the spontaneous fission of ^{252}Cf with multi-gamma-detector arrays provide a powerful approach for the identification of high spin states in neutron-rich nuclei [5]. Data for this work were obtained by using the Gammasphere detector array at Lawrence Berkeley National Laboratory. A ^{252}Cf spontaneous fission source with an α activity of 62 μCi was sandwiched between two 10 mg/cm^2 iron foils, which were used to stop the fission fragments and eliminate the need for a Doppler correction. A plastic sphere, 7.62 cm in diameter, surrounded the source to absorb β rays and conversion electrons, as well as to partially moderate and absorb fission neutrons. A total of 5.7×10^{11} triple- and higher-fold γ-ray coincidence events were recorded. Data were analyzed with the RADWARE software package [6].

It is known that more than 150 nuclei are populated in the spontaneous fission of ^{252}Cf and many transitions from various nuclei overlap even in triple- or higher-fold coincidence spectra. Furthermore, in the binary spontaneous fission of ^{252}Cf, two complementary fragments are formed from a ^{252}Cf nucleus and there are always multiple pairs of related partners of a specific nucleus. Thus, it is not easy to assign a new γ-ray transition or a cascade of several new γ-ray transitions to a specific nucleus. By double gating on the known transitions in each of its partners, one can identify the transitions in a given nucleus in principle. The fission partners of ^{139}Cs are the Tc isotopes, namely $^{108-110}$Tc.

Hwang *et al.* [2] claimed that the 218.6, 408.6, 618.4, 387.5, and 503.0 keV transitions compose the yrast cascade of ^{139}Cs based on the fact that the 218.64 keV transition was found from the β decay of ^{139}Xe to ^{139}Cs [3], whereas Nowak *et al.* [1] reported that the transitions out of the yrast levels in ^{139}Cs have energies of 595.5, 601.5, 475.2, 468.5, 544.3, 428.2, 589.9, 236.6, 740.3, 756.3, and 727.6 keV and also supported the existence of the low-lying 218.6 keV transition.

To clarify the above dilemma, measurements to determine the mass number assignments of the transitions were performed. One way to substantiate a mass number assignment of a fission fragment transition is to determine the correlated pair yield functions for its partners because it is common that

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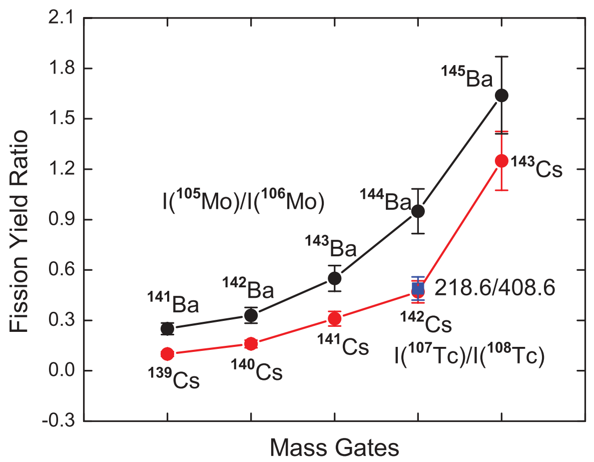

FIG. 1. (Color online) Fission yield ratios of ^{107}Tc to ^{108}Tc in Cs gates along with those of ^{105}Mo to ^{106}Mo in Ba gates. The same ratio of ^{107}Tc to ^{108}Tc in the 218.6/408.6 keV double gate is indicated with a solid square. Data are taken from Refs. [1–3,12–15]. For the data points of ^{139}Cs and ^{140}Cs, the uncertainties are smaller than the size of the solid circles.

the three- or four-neutron channel has the largest yield in most cases [8]. However, it is not feasible to obtain accurate results in this way in the present work. This is because how all the high spin states in odd-odd Cs isotopes such as ^{138}Cs, ^{140}Cs, and ^{142}Cs and odd-odd Tc isotopes like ^{106}Tc, ^{108}Tc, and ^{110}Tc decay to their ground states is not known. Thus, an alternative method, which has been used for our work in ^{137,138}Cs [9], ^{143,144}La [10], and ^{134}I [11], was adopted here, described as follows. In the 595.5/475.2 keV (^{139}Cs) [1], 594.3/640.9 keV (^{140}Cs) [2], 369.5/481.0 keV (^{141}Cs) [2,12], 205.4/404.7 keV (^{142}Cs) [2], and 282.3/397.2 (^{143}Cs) [2,12] double gates, the fission yield ratios of the 292.6 keV transition in ^{107}Tc [2,13,14] to the 154.1 keV transition in ^{108}Tc [2,15] were measured to be 0.10(1), 0.16(2), 0.31(4), 0.47(7), and 1.25(18), respectively, as shown in Fig. 1. The variation of these ratios follows that of similar ratios of ^{105}Mo to ^{106}Mo in $^{141-145}$Ba double gates [3], which indicates that the mass number for the 475.2 → 595.5 keV cascade is below 140. Because the level schemes of ^{137,138}Cs have been well established [9,16,17], we argue that the 475.2 → 595.5 keV cascade belongs to the ^{139}Cs nucleus. In addition, we need to point out that the same ratio of ^{107}Tc to ^{108}Tc in the 218.6/408.6 keV [2] double gate was measured to be 0.49(7) which is consistent with the value in the ^{142}Cs gate, as shown in Fig. 1. That means that the 408.6 → 218.6 cascade forms a band in ^{142}Cs. The details regarding the level structure of ^{142}Cs will be discussed in another report [18]. Here, it is also worth mentioning that the authors in Ref. [2] did not perform any measurement to determine the mass number of the 408.6 → 218.6 cascade. Rather, the assignment of this cascade to ^{139}Cs was solely based on the observation of the 218.64 keV transition in the β decay of ^{139}Xe to ^{139}Cs [3]. Because the spin-parity of the 218.64 keV level was assigned to be $5/2^+$ [19], it may not be populated in our fission data.

To demonstrate how we identified new transitions in ^{139}Cs, two coincidence spectra, created by double gating on the transitions reported in Ref. [1], are shown in Fig. 2, where the transition energies used for double gating are indicated. Both of these two spectra clearly show the coincidence relationships among transitions in ^{139}Cs and its partners ^{108}Tc [2,15], ^{109}Tc [2,13], and ^{110}Tc [20]. All of the previously known transitions in ^{139}Cs, except the 914.9 and 1126.5 keV transitions feeding the 595.5 keV level reported in Ref. [1], were confirmed and those coincidence transitions, marked with an asterisk in Fig. 2, are newly observed in the present work. Another two coincidence spectra are shown in Fig. 3, which provide additional support for our placement of the new transitions. The gate transitions are indicated in the spectra. The effort of extensive crosschecking with many other coincidence spectra led to the final level identifications and placements in the ^{139}Cs nucleus. Ten new excited levels with 18 new deexciting transitions were found to allow us to establish the level scheme of ^{139}Cs, as presented in Fig. 4, where excited states are extended up to 4670 keV. We have included the 218.6 keV level in our scheme, Fig. 4, because it was seen in the β dacay [3] and we will compare it with the corresponding calculated level energy in the next section.

The spin-parity of the ground state of ^{139}Cs was reported as $7/2^+$ [3]. Spins and parities of the excited levels, as presented in Fig. 4, were determined by measuring the γ-γ angular correlations with the Gammasphere detector array and the internal conversion coefficient of the 236.9 keV transition. More details of the new technique of angular correlation measurements developed for our high statistics data can be found in Ref. [21]. Three examples of our angular correlation measurements in ^{139}Cs are shown in Figs. 5–7, where the angular correlation function is expressed in the form of $W(\theta) = 1 + A_2(\delta)P_2(\cos\theta) + A_4(\delta)P_4(\cos\theta)$. Theoretical A_2 and A_4 values of γ-γ angular correlations are $A_2 = 0.10$ and $A_4 = 0.0$ for a pure quadrupole-quadrupole cascade, $A_2 = -0.07$ and $A_4 = 0.0$ for a pure quadrupole-dipole cascade, and $A_2 = 0.05$ and $A_4 = 0.0$ for a pure dipole-dipole cascade [22]. The measured A_2 and A_4 values for the 428.2 → 475.3, 740.4 → 428.2, 727.9 → 740.4, 544.4 → 601.64, and 589.8 → 544.4 keV cascades, listed in Table I, are all consistent with the theoretical ones for a pure quadrupole-quadrupole cascade. Therefore, these transitions are of pure quadrupole character. We propose that their multipolarities are $E2$ rather than $M2$ because the spontaneous fission process populates predominantly yrast levels and high spin states and $E2$ transitions have been observed in the yrast bands in the neighboring even-even ^{138}Xe [23] and ^{140}Xe nuclei

TABLE I. Angular correlations measured in the present work. Theoretical values of A_2^{the} and A_4^{the} of γ-γ angular correlations for a pure quadrupole-quadrupole cascade are included.

Cascade (keV)	A_2^{exp}, A_4^{exp}	A_2^{the}, A_4^{the}
428.2 → 475.3	0.11(1), 0.00(2)	0.10, 0.0
740.4 → 428.2	0.11(2), −0.02(3)	0.10, 0.0
727.9 → 740.4	0.11(3), −0.01(4)	0.10, 0.0
544.4 → 601.6	0.09(2), 0.01(3)	0.10, 0.0
589.8 → 544.4	0.10(4), −0.00(7)	0.10, 0.0
475.3 → 595.4	−0.10(1), −0.01(2)	see text

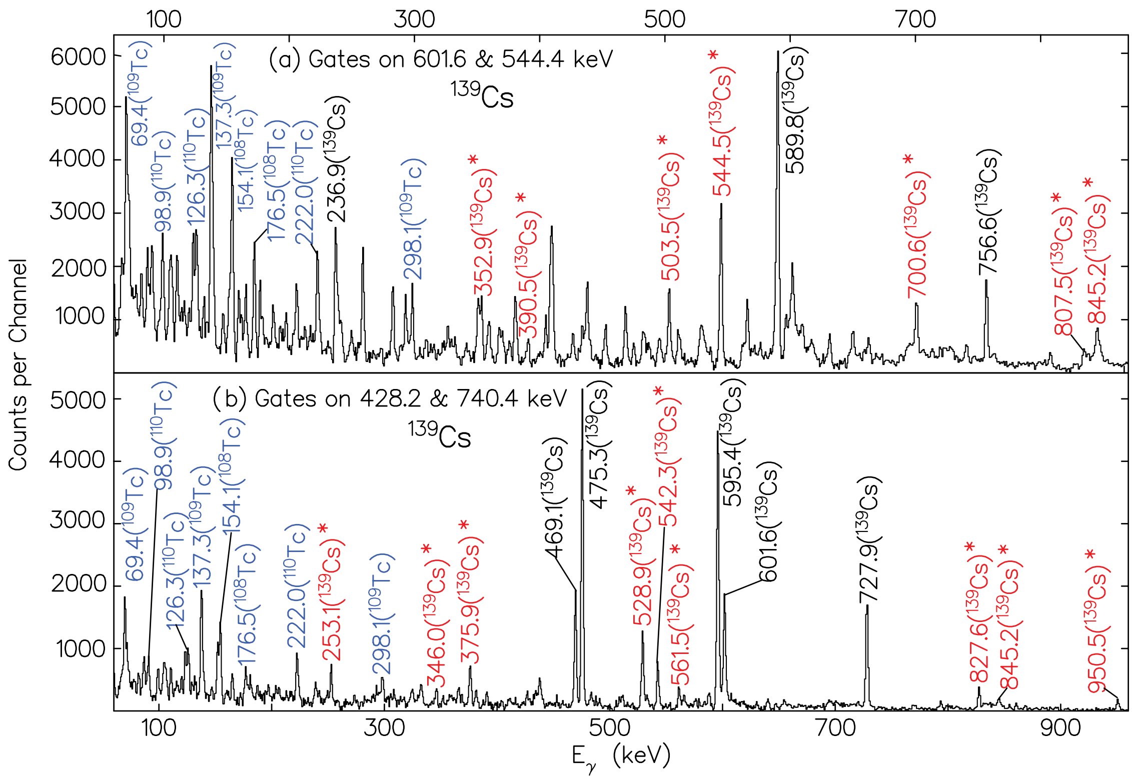

FIG. 2. (Color online) Coincidence spectra gated on the known transitions in ^{139}Cs [1]. The newly observed transitions in the present work are marked with an asterisk.

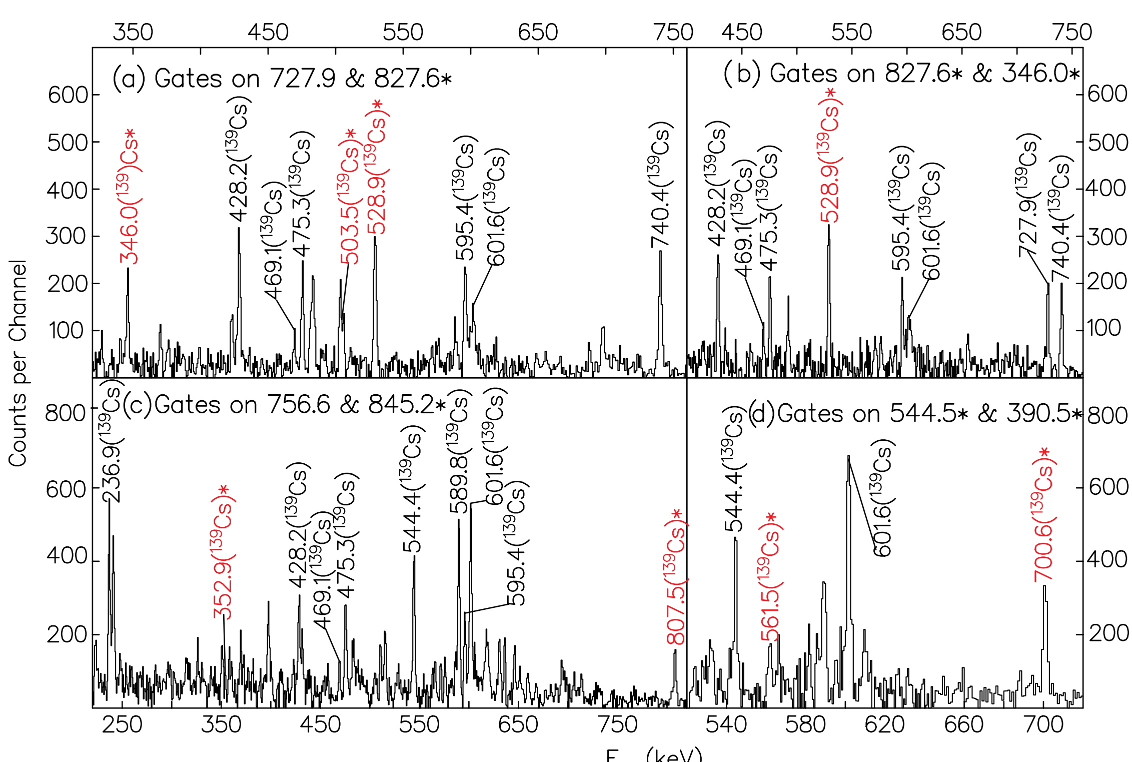

FIG. 3. (Color online) Coincidence spectra gated on new transitions in ^{139}Cs. The newly observed transitions in the present work are marked with an asterisk.

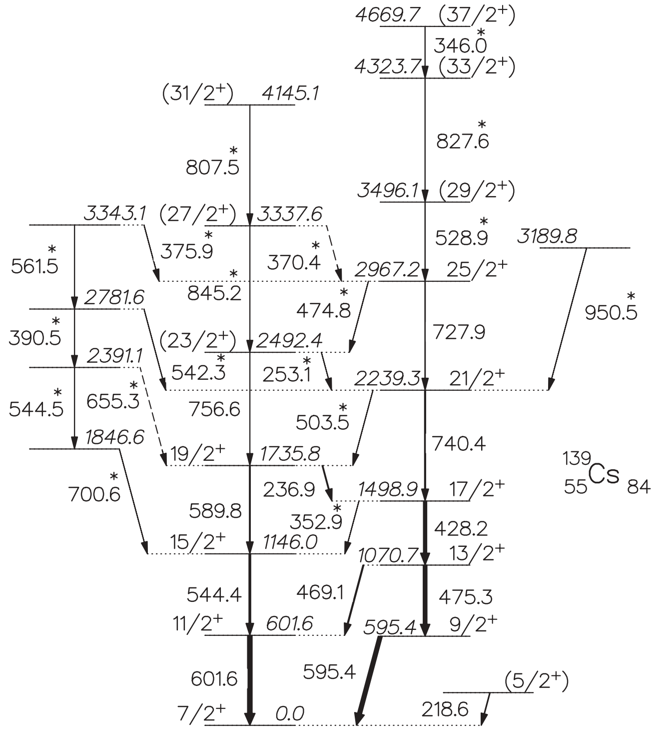

FIG. 4. Partial level scheme of ^{139}Cs identified in the present work. Energies are in keV and the width of the arrow is proportional to the corresponding γ-ray intensity. Transitions marked with an asterisk are newly observed. The 218.6 keV level is based on the β-decay study of Ref. [3].

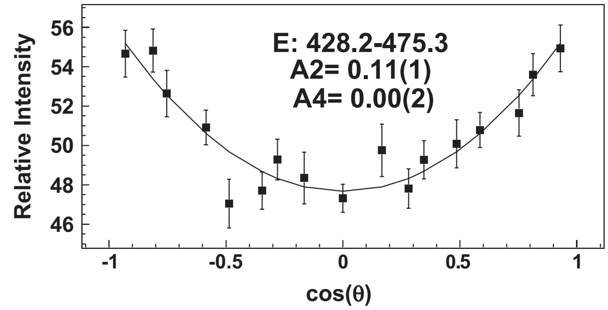

FIG. 6. Angular correlation for the 428.2 → 475.3 keV cascade in ^{139}Cs.

[24]. Another support for our proposal is from the half-life measurements, as described in Ref. [25], for the levels which the above transitions depopulate. No half-lives of more than 4 ns were observed for any of these levels in our data because no time effect on the transition intensities was found in our minimum 4 ns time window. Therefore, $11/2^+$, $15/2^+$ and $19/2^+$ were assigned to the 601.6, 1146.0 and 1735.8 keV levels, respectively.

Because the spin of the 601.6 keV level was assigned as 11/2, the spin of the 595.4 keV level should be either 9/2 or 11/2 due to its high spin feature and yrast structure. If the spin was 11/2, the spin difference between this level and the ground state would be 2, which results in a conclusion that the multipolarity of the 595.4 keV transition is $E2$, $M2$, $E3$, or $M3$. However, the very low transition probabilities of $E3$ and $M3$ rule out the possibility of their existence. The impossibility of $E3$ and $M3$ is also supported by the experimental A_2 value because the minimum theoretical A_2 value -0.05 [22] for the $15/2(Q)11/2(Q,O)7/2$ cascade is not nearly as large negatively as the experimental A_2 value $-0.10(1)$ as shown in Fig. 5. If the 595.4 keV transition was of pure quadrupole character for an 11/2 assignment, then the A_2 and A_4 values should be 0.10 and 0.0 for a pure quadrupole-quadrupole 475.3 → 595.4 cascade, which conflicts with these experimental results of $A_2 = -0.10(1)$ and $A_4 = -0.01(2)$. Thus, the spin of the 595.4 keV level was assigned as 9/2. Then, the parity of levels in the 475.3 → 595.4 cascade was obtained from the total internal conversion coefficient (α_T) of the 236.9 keV transition. The measured α_T of a specific transition can be used to determine its multipolarity and thus the spin-parity of the two levels connected by this transition. The α_T of a low-energy transition can be measured from the intensity balance in and out of a state which this transition feeds or depopulates, by double gating on other two transitions in the same cascade. The total internal conversion coefficient of the 236.9 keV transition was measured to be 0.086(12) by double gating on the 756.6 and 475.3 keV transitions and then calculating the difference between the relative γ-ray intensity of the 236.9 keV transition and that of the 428.2 keV transition, with an assumption that the α_T of the 428.2 keV transition is negligible. Theoretical values were computed as $\alpha_T(E1) = 0.020$, $\alpha_T(M1) = 0.083$, $\alpha_T(E2) = 0.094$, and $\alpha_T(M2) = 0.42$, respectively, by using the BRICC v2.2b Conversion Coefficient Calculator [26]. Comparisons of the experimental α_T value with the calculated

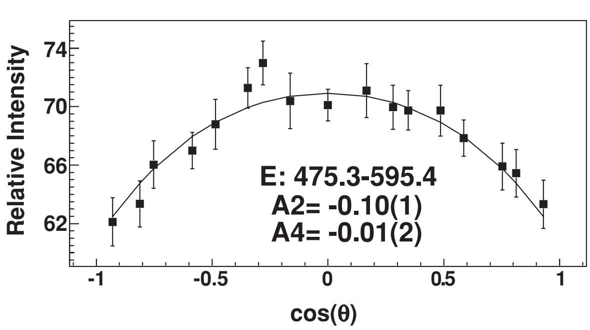

FIG. 5. Angular correlation for the 475.3 → 595.4 keV cascade in ^{139}Cs.

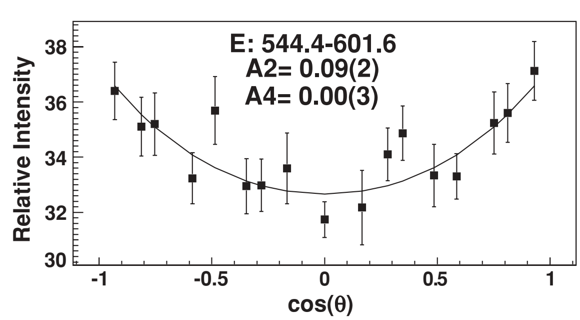

FIG. 7. Angular correlation for the 544.4 → 601.6 keV cascade in ^{139}Cs.

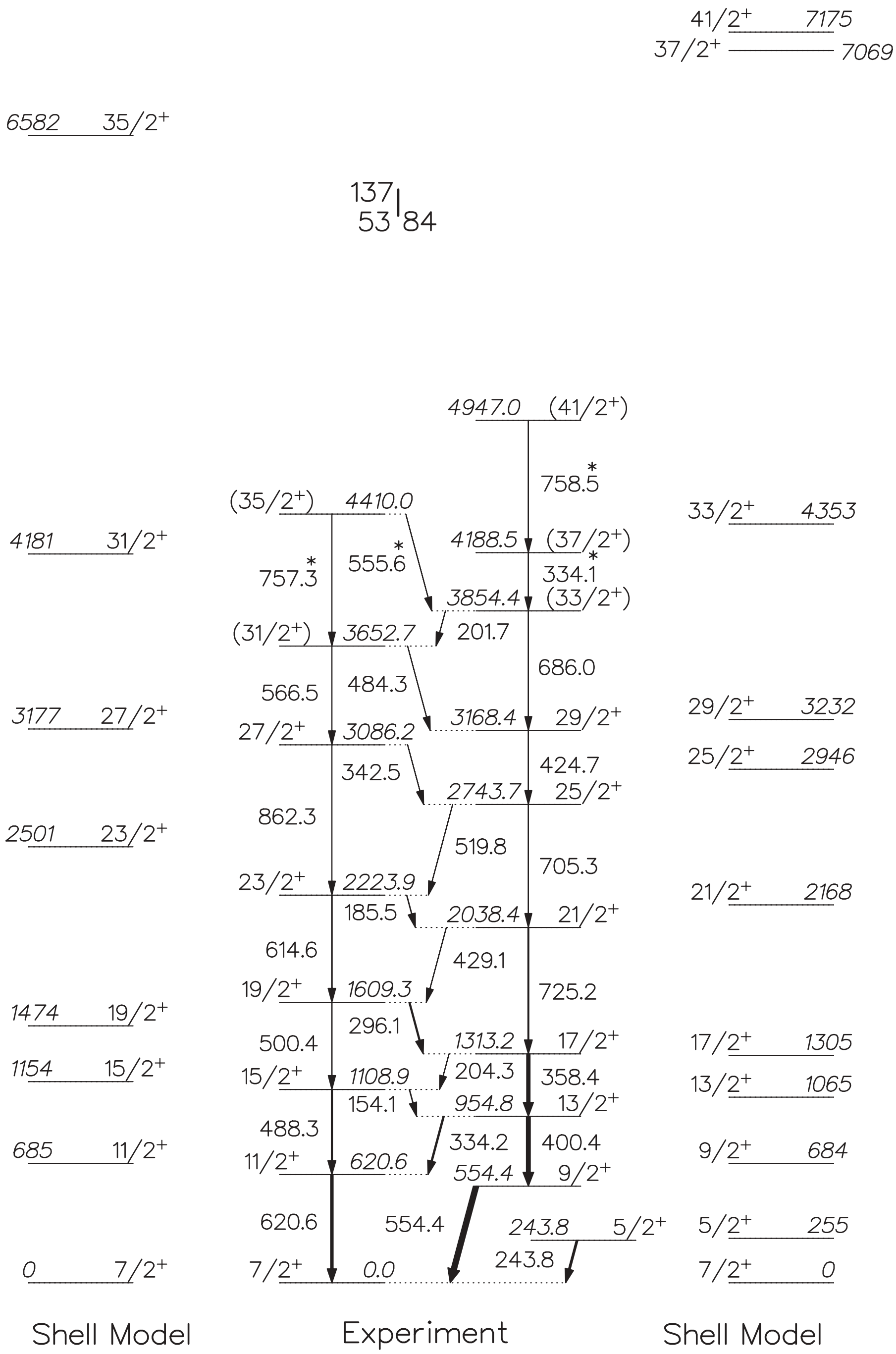

FIG. 8. Level scheme of ^{137}I identified in the present work. Energies are in keV and the width of the arrow is proportional to the corresponding γ-ray intensity. Four new transitions observed here are marked with an asterisk. Predictions from our shell model calculation are shown.

ones indicate that the multipolarity of the 236.9 keV transition is $M1$ and/or $E2$. So, the parity of the 1498.9 keV level is the same as that of the 1735.8 keV level. With an eye to the results in the above paragraph, the parity of levels in the 475.3 → 595.4 cascade should be positive. Thus, a $J^{\pi} = 9/2^{+}$ was assigned to the 595.4 keV level, which agrees with the tentative assignment in Ref. [1]. The $M1/E2$ mixture of the 595.4 keV transition, consistent with the character of the 554.4 keV transition in its isotone ^{137}I [4], will be discussed below. Finally, the spins and parities of the levels of energies 1070.7, 1498.9, 2239.3 and 2967.2 keV were assigned as $13/2^{+}$, $17/2^{+}$, $21/2^{+}$, and $25/2^{+}$, respectively.

The spins and parities of other upper yrast levels were tentatively assigned by assuming that the spin values increase with increasing excitation energy in the spontaneous fission and the transitions are of $E2$ character. As we shall discuss in Sec. III B, our shell model calculations confirm these assignments. In the same subsection, a tentative identification is made for those states whose spins and parities cannot be assigned in our experimental data.

Figure 8 shows the level scheme of ^{137}I observed in the present work. The level scheme is almost the same as the one reported by A. Korgul *et al.* [4], except that we added three new excited levels with four new deexciting transitions on

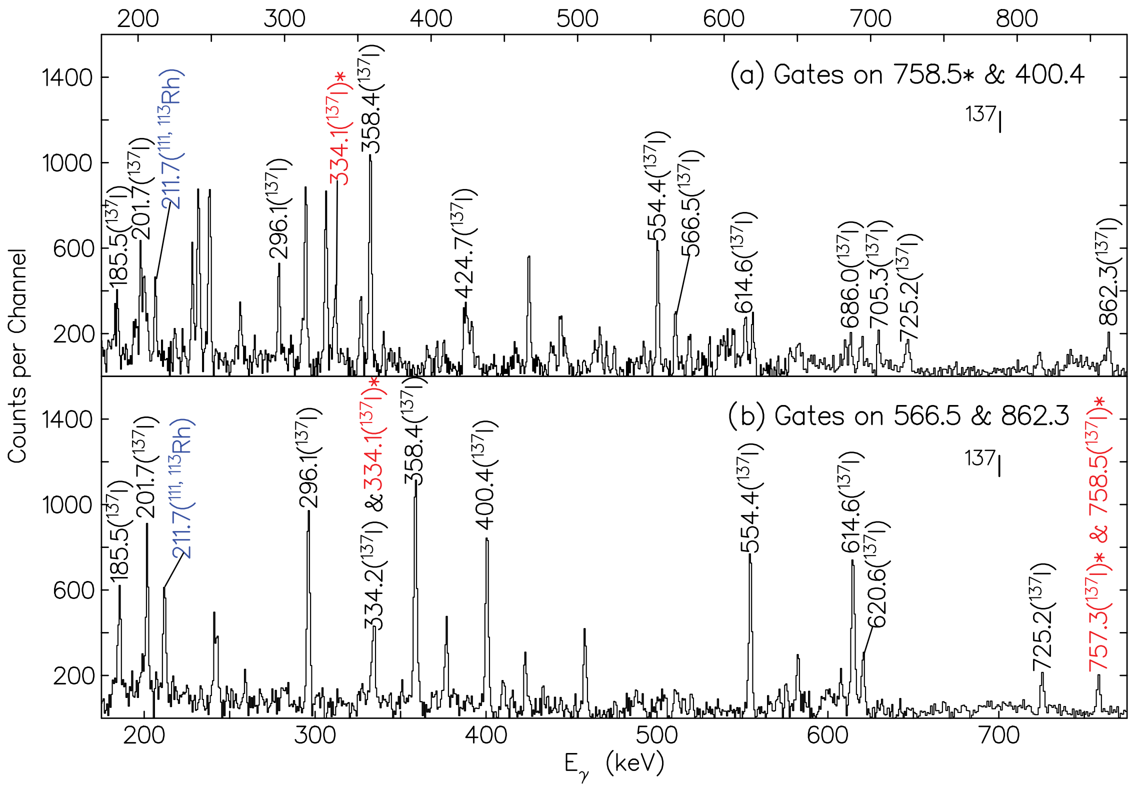

FIG. 9. (Color online) Coincidence spectra gated on transitions in ^{137}I. The gate transition energies are indicated in the spectra. The newly observed transitions in the present work are marked with an asterisk.

the top. In this figure, we have also reported the results of our shell model calculations, which will be discussed in the next section. The spectra in Fig. 9 indicate the coincidence relationships among the known and new transitions in ^{137}I, where the gate transitions are also shown. We adopted the spin-parity assignment in Ref. [4], where angular correlation measurements were performed. The spins and parities of the three new levels were assigned by assuming that the transitions linking these levels are of $E2$ character.

Because both the 595.4 keV transition in ^{139}Cs and 554.4 keV transition in ^{137}I [4] are of a $M1/E2$ mixture, it is worth measuring their mixing ratio (δ) values. As shown in Fig. 5, the measured A_2 and A_4 values for the 475.3 → 595.4 keV cascade in ^{139}Cs are −0.10(1) and −0.01(2), respectively, which produce two minimum values of the mixing ratio of the 595.4 keV transition ($9/2^+ \rightarrow 7/2^+$) as $\delta = -4.2^{+0.4}_{-0.5}$ and $\delta = -0.07 \pm 0.02$, respectively, by using the DELTA program from the National Nuclear Data Center [3]. The measured A_2 and A_4 values for the 400.4 → 554.4 keV cascade in ^{137}I are −0.24(1) and −0.01(1), respectively, as presented in Fig. 10, which are consistent with the experimental results of $A_2 = -0.233(6)$ and $A_4 = -0.033(7)$ in Ref. [4]. Our A_2 and A_4 values also give two minimum δ values for the 554.4 keV transition ($9/2^+ \rightarrow 7/2^+$)in ^{137}I, as $\delta = -1.3^{+0.2}_{-0.1}$ and $\delta = -0.55^{+0.07}_{-0.10}$, respectively. As will be seen in the next section, the δ values, which favor $E2$ character for both the 595.4 (^{139}Cs) and 554.4 (^{137}I) keV transitions, are reproduced very well by our shell model calculations.

III. SHELL MODEL CALCULATIONS

A. Introductory discussion

The systematics of the odd-$A^{133-141}$Cs nuclei [2,3,12] is presented in Figs. 11 and 12. Excitation energies of the first excited states, with $J^\pi = 5/2^+$, and some other yrast states in these isotopes are shown in Fig. 11. Their level patterns indicate a strong shell effect in ^{137}Cs ($N = 82$). Variations of the excitation energies of the $11/2^+$ states in these odd-A Cs isotopes versus the excitation energies of the first 2^+ states in the corresponding even-even Xe cores [3] are shown in Fig. 12. We see a nearly linear relationship, which indicates that yrast states in these odd-$A^{133-141}$Cs are formed from coupling the valence proton to the corresponding Xe core.

The systematics of the odd-A $N = 84$ isotones, ^{135}Sb [27], ^{137}I [4], ^{139}Cs, and ^{141}La [3], is presented in Figs. 13 and 14.

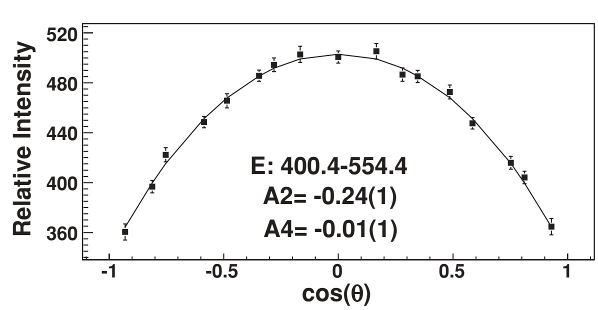

FIG. 10. Angular correlation for the 400.4 → 554.4 keV cascade in ^{137}I measured in the present work.

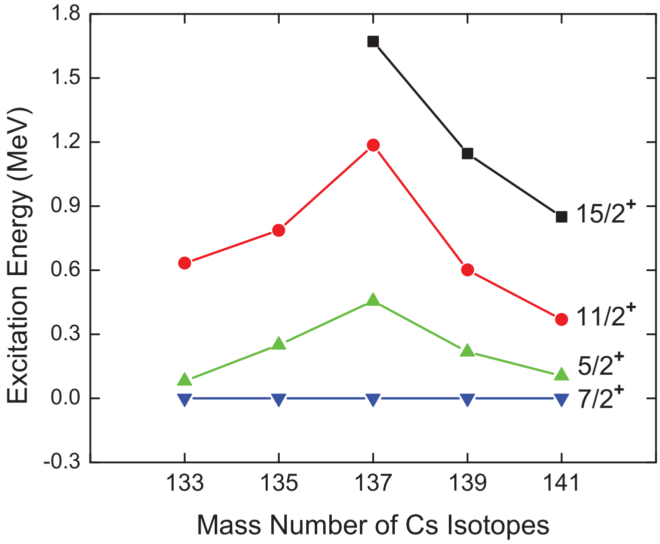

FIG. 11. (Color online) Excitation energies of the first excited $5/2^+$ states and some other yrast states in odd-$A^{133-141}$Cs. Data are taken from Refs. [2,3,12] and the present work.

Excitation energies of the same yrast states as shown in Fig. 11 are presented in Fig. 13, where a similarity is observed in their level patterns. Variations of the excitation energies of the $11/2^+$ states in ^{135}Sb, ^{137}I, and ^{139}Cs versus the excitation energies of the first 2^+ states in the corresponding ^{134}Sn, ^{136}Te, and ^{138}Xe cores [23], as presented Fig. 14, show an almost linear relationship, which also indicates that yrast states in ^{135}Sb,^{137}I, and ^{139}Cs are formed from coupling the valence proton to the corresponding even-even core. Although the $11/2^+$ state of ^{141}La has not been observed so far, one can predict its position as roughly at 600 keV, based on the excitation energies of the same state in ^{135}Sb, ^{137}I, ^{139}Cs, and of the first 2^+ state in ^{140}Ba [28].

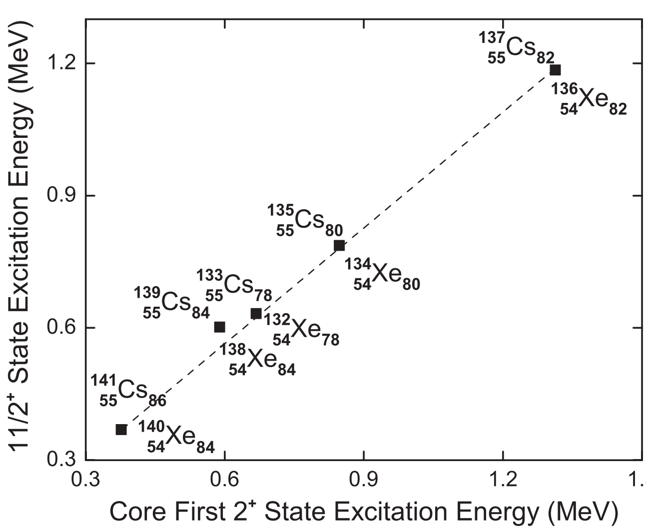

FIG. 12. Excitation energies of the $11/2^+$ states in the odd-$A^{133-141}$Cs nuclei versus those of the first 2^+ states in the corresponding even-even Xe cores. A dashed line is drawn to indicate the linear relationship of these data. Data are taken from Refs. [2,3,12] and the present work.

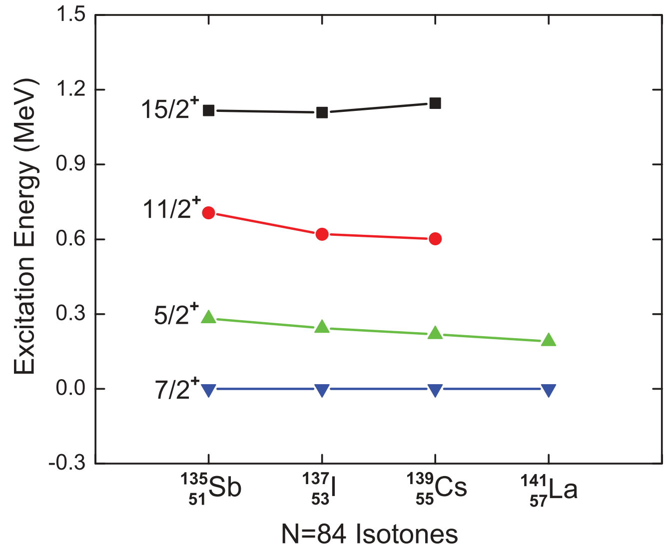

FIG. 13. (Color online) Excitation energies of the first excited $5/2^+$ states and some other yrast states in ^{135}Sb, ^{137}I, ^{139}Cs, and ^{141}La. Data are taken from Refs. [3,4,27] and the present work.

On the above grounds, a shell model study has been conducted here for ^{139}Cs, with five valence protons outside the $Z = 50$ closed shell and two valence neutrons beyond the $N = 82$ major shell. Levels in ^{139}Cs are spaced somewhat more evenly than in ^{137}I, which may suggest that the addition of two protons to ^{137}I induces a change toward a collective motion. However, as we shall see in the next subsection, a shell model description of ^{139}Cs turns out to be quite successful.

B. Results and comparison with experiment

We have performed a shell model study for the two $N = 84$ isotones ^{137}I and ^{139}Cs. In this subsection we

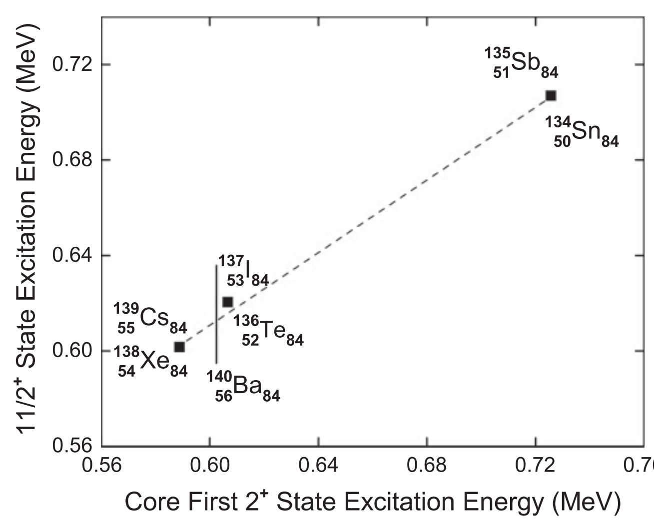

FIG. 14. Excitation energies of the $11/2^+$ states in ^{135}Sb, ^{137}I, and ^{139}Cs versus those of the first 2^+ states in the corresponding even-even ^{134}Sn, ^{136}Te, and ^{138}Xe cores. The excitation energy of the first 2^+ state in ^{140}Ba is also indicated. A dashed line is drawn to indicate the linear relationship of these data. Data are taken from Refs. [3,4,23,27,28] and the present work.

compare the results with those obtained in the present experiment.

We consider ^{132}Sn as a closed core, with the valence protons occupying the five levels $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $1s_{1/2}$, and $0h_{11/2}$ of the 50–82 shell, and the two valence neutrons the six levels $0h_{9/2}$, $1f_{7/2}$, $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$, and $i_{13/2}$ of the 82–126 shell. The same shell model Hamiltonian is used as that employed in recent studies on ^{132}Sn neighbors with $N > 82$, which yielded results in very good agreement with experiment [29]. Here we only mention that the two-body effective interaction contained in this Hamiltonian is derived from the CD-Bonn nucleon-nucleon potential with the inclusion of the Coulomb force for protons. A brief discussion of the derivation of the two-body matrix elements can be found in Ref. [30], where the adopted values of the single-proton and -neutron energies were also given. These were taken from the experimental spectra [3] of ^{133}Sb and ^{133}Sn, respectively, with the exception of the proton $s_{1/2}$ and the neutron $i_{13/2}$ levels, which are still missing. The calculations have been carried out using the OSLO shell model code [31].

Let us start by considering the three-valence-proton nucleus ^{137}I. As mentioned above, the level scheme observed in the present experiment is almost the same as that of Ref. [4] but with three new levels as shown in Fig. 8, where the calculated levels are also reported. From Fig. 8, one sees that the agreement between theory and experiment is very good up the $29/2^+$ state, the discrepancy ranging from a few keV to 280 keV, while for the $31/2^+$ and $33/2^+$ states, the theoretical energies are higher by about 500 keV. We see that the three highest-spin levels are predicted to lie more than 2 MeV above the experimental ones. This may indicate that excitations outside the chosen model space play an important role for such states.

In the work of Ref. [4], a shell model calculation was also performed to interpret the observed spectrum of ^{137}I. The significant discrepancies occurring between some theoretical and experimental energies were seen as an indication that the excitation pattern of ^{137}I deviates from the shell model scheme. This was essentially based on the prediction of a $29/2^+$ isomer, which was not observed in their experiment.

The present calculation differs from that of Ref. [4] in that a modern realistic two-body interaction and a larger model space are used. This produces on the whole a better agreement with experimental data. On this ground, we come to the conclusion that an accurate description of ^{137}I may be obtained within the shell model. As for the $29/2^+$ state, we find that this state, dominated by the $\pi(g_{7/2})^2(d_{5/2})\nu(f_{7/2})^2$ configuration, lies above the $27/2^+$ and $25/2^+$ and decays to the latter with a transition probability of $5 \times 10^9\,\mathrm{s}^{-1}$. This corresponds to a $B(E2; 29/2^+ \rightarrow 25/2^+) = 317\ e^2\mathrm{fm}^4$, obtained with $e_\pi^{\mathrm{eff}} = 1.55e$ and $e_\nu^{\mathrm{eff}} = 0.7e$ [32]. It turns out that the transition to the $27/2^+$ state is hindered by a factor of about 100, which is mainly due to the small energy gap. In this case, we have $B(E2) = 18\,e^2\mathrm{fm}^4$ and $B(M1) = 0.005\ \mu_N^2$, the latter being obtained with the effective $M1$ operator of Ref. [30]. Note that this operator and the above effective charges are just the same as those used in all the studies on ^{132}Sn neighbors (see, for instance, Ref. [33]).

In the same way, we have also calculated the mixing ratio, δ, for the $9/2^+ \rightarrow 7/2^+$ transition (the 554.4 keV transition).

TABLE II. Experimental and calculated excitation energies (in MeV) for ^{139}Cs.

J^π	E_{exp}	E_{calc}	J^π	E_{exp}	E_{calc}
$7/2^+$	0.00	0.00	$21/2^+$	2.239	2.338
$5/2^+$	0.219	0.159	$23/2^+$	2.492	2.691
$9/2^+$	0.595	0.710	$25/2^+$	2.967	3.100
$11/2^+$	0.602	0.688	$27/2^+$	3.338	3.406
$13/2^+$	1.071	1.141	$29/2^+$	3.496	3.472
$15/2^+$	1.146	1.192	$31/2^+$	4.145	4.464
$17/2^+$	1.499	1.426	$33/2^+$	4.324	4.593
$19/2^+$	1.736	1.607	$37/2^+$	4.670	5.824

We find $\delta = -3.9$, which comes rather close to the value $-1.3^{+0.2}_{-0.1}$ obtained in the present experiment, indicating that this transition is mainly of $E2$ character.

It is worth noting that between the $9/2^+$ and $7/2^+$ states a $5/2^+$ state is observed at 243.8 keV excitation energy. We predict the first $5/2^+$ state at 255 keV and find $B(E2; 9/2^+ \rightarrow 5/2^+) = 81\ e^2\mathrm{fm}^4$ corresponding to a transition probability of about $3 \times 10^8\,\mathrm{s}^{-1}$. This makes the feeding of this state not competitive with respect to that of the $7/2^+$ state, in agreement with the finding of the present work. A second $5/2^+$ state is predicted by our calculation at only 130 keV above the yrast one, for which the $B(E2; 9/2^+ \rightarrow 5/2^+)$ value turns out to be $270\ e^2\mathrm{fm}^4$. However, the deexcitation of the $9/2^+$ state to this state is also unlikely owing to the small energy of the γ ray involved.

Before starting to discuss our results for ^{139}Cs, we would like to mention the work of Ref. [30], where it was reported on a shell model study on the lighter $N = 84$ isotone ^{135}Sb having only one valence proton. In recent years, this nucleus has been the subject of much theoretical and experimental interest (see, for instance, Ref. [32]). A low-lying $5/2^+$ state was identified [34,35], whose position appeared to be anomalous when looking at the systematics of the odd-even lighter Sb isotopes. In Ref. [30], it was shown that a shell model calculation with the same effective Hamiltonian of the present study accounts for the observed properties of the yrast $5/2^+$ state in ^{135}Sb as well as for the energies of the other observed levels.

It is interesting to note the similarity between the ^{135}Sb and ^{137}I levels. In fact, a low-energy $5/2^+$ state is present in both nuclei and a correspondence can be established between the $7/2^+$, $11/2^+$, $15/2^+$, $19/2^+$, and $23/2^+$ states of ^{135}Sb identified in the ^{248}Cm fission experiment [27] and the members with the same angular momentum and parity of one of the two $\Delta J = 2$ cascades observed in ^{137}I. As for the other cascade, the $9/2^+$ state has been identified in ^{135}Sb through β-decay studies of ^{135,136}Sn [36].

Our level scheme of ^{139}Cs is shown in Fig. 4. In Table II, we compare the experimental excitation energies with the calculated values for the levels with assigned spin and parity. As was the case for ^{137}I, the agreement between the calculated and experimental energies is very good for all states up to $J^\pi = 29/2^+$ state, the discrepancies ranging now from few tens of keV up to about 200 keV. As for the $31/2^+$ and $33/2^+$ states, the discrepancies reach about 300 keV, while the $37/2^+$

TABLE III. Calculated excitation energies (in MeV) of the second and third levels with J^π from $15/2^+$ up to $27/2^+$ in ^{139}Cs.

J^π	$15/2^+$	$17/2^+$	$19/2^+$	$21/2^+$	$23/2^+$	$25/2^+$	$27/2^+$
	1.484	1.533	2.345	2.523	2.897	3.265	3.468
	1.753	1.941	2.391	2.682	3.179	3.365	3.673

state is predicted to lie at more than 1 MeV above the observed one. The reason for this large discrepancy may also be that excitations outside the model space we used play an important role for such a state.

It is interesting to see that the structure of the level scheme observed in the two lighter isotones, ^{135}Sb and ^{137}I, persists in ^{139}Cs with two more valence protons. As regards the mixing ratio for the $9/2^+ \rightarrow 7/2^+$ transition (the 595.4 keV transition), our calculated value of $\delta = -3.6$ comes close to that predicted for ^{137}I and to the experimental value $-4.2^{+0.4}_{-0.5}$, which favors $E2$ character for the 595.4 keV transition.

Finally, let us come to the observed levels of ^{139}Cs shown in Fig. 4, to which no spin-parity can be assigned from our experimental data. These cannot be uniquely matched by a sequence of theoretical states. We therefore report in Table III the predicted excitation energies of the second and third states with J^π from $15/2^+$ up to $27/2^+$, which are the most probable candidates for their identification. Based on this table, an attempt at identification can be made if we do not go beyond the second excited states and consider only $M1$ and/or $E2$ transitions. With these assumptions, we may establish a correspondence between the experimental levels at 1.847, 2.391, 2.782, 3.190, 3.343 MeV and the calculated yrare ones from $J^\pi = 19/2^+$ up to $J^\pi = 27/2^+$. In this case, the discrepancy between theory and experiment turns out to be about 100 keV for all levels, except the $19/2^+$ for which it is 498 keV. Clearly, for a safer interpretation more experimental data are needed.

IV. CONCLUSIONS

The high spin structure of the $N = 84$ neutron-rich nucleus ^{139}Cs was investigated in the present work. The yrast levels identified by Nowak *et al.* were confirmed and extended up to 4670 keV, with ten new levels and 18 new deexciting transitions observed. By using a newly developed technique to perform the angular correlation measurements for our high statistics data and the method of the internal conversion coefficient measurement, spins and parities of levels in ^{139}Cs were firmly assigned up to $25/2^+$. The mixing ratio of the 595.4 keV transition in ^{139}Cs was measured and is consistent with our theoretical prediction.

The high spin states in the $N = 84$ neutron-rich nucleus ^{137}I was also studied with three new excited levels and four new deexciting transitions added on the top of the previously known level scheme. The mixing ratio of the 554.4 keV transition in ^{137}I was measured and comes close to the value predicted by our calculations.

Along with our experimental work, we have performed a shell model calculation for ^{137}I and ^{139}Cs employing a two-body effective interaction derived from the CD-Bonn nucleon-nucleon potential. This effective interaction, which does not contain any adjustable parameter, has been used in conjunction with the experimental single-particle energies of ^{133}Sb and ^{133}Sn, consistently with all the recent studies by the Napoli group on ^{132}Sn neighbors with $N \geqslant 82$.

We have compared the states observed in the present experiment for ^{137}I and ^{139}Cs with those predicted by the theory. It turns out that our calculations provide a very satisfactory description of both isotones, with discrepancies not exceeding 150 keV for most of the states up to 3.5 MeV. This shows that the interpretation of the low-energy spectra of these nuclei is well within the shell model framework.

In conclusion, it is worth emphasizing that the present experiment has provided further evidence for the similarity of the spectroscopy of the $N = 84$ isotones, which is clearly born out by our shell model study.

ACKNOWLEDGMENTS

The work at Vanderbilt University, Mississippi State University, and Lawrence Berkeley National Laboratory is supported by the US Department of Energy under Grant and Contract Nos. DE-FG05-88ER40407, DE-FG02-95ER40939, and DE-AC03-76SF00098. The work at Tsinghua University is supported by the National Natural Science Foundation of China under Grant No. 10775078 and by the Major State Basic Research Development Program under Grant No. 2007CB815005.

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