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High-spin structures of $^{136}_{55}\text{Cs}_{81}$

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Odd-odd ^{136}Cs nuclei have been produced in the $^{18}\text{O} + ^{208}\text{Pb}$ and $^{12}\text{C} + ^{238}\text{U}$ fusion-fission reactions and their γ rays studied with the Euroball array. The high-spin level scheme has been built up to ~ 4.7 MeV excitation energy and spin $I \sim 16\hbar$ from the triple γ -ray coincidence data. The configurations of the three structures observed above ~ 2 MeV excitation energy are first discussed by analogy with the proton excitations identified in the semi-magic $^{137}\text{Cs}_{82}$ nucleus, which involve the three high- j orbits lying above the $Z = 50$ gap, $\pi g_{7/2}$, $\pi d_{5/2}$ and $\pi h_{11/2}$. This is confirmed by the results of shell-model calculations performed in this work.

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I. INTRODUCTION

Being less bound than its two even-even neighbors, ^{136}Xe and ^{136}Ba , the odd-odd $^{136}_{55}\text{Cs}_{81}$ nucleus cannot be populated by β decay, at variance to most of the odd-odd nuclei in the nuclide chart. Thus, the ^{136}Cs nuclei were produced for the first time by spallation of La and by fission of U, induced by 600 MeV proton beams [1, 2]. This led to the identification of two states, the ground state with $T_{1/2}=13.16$ d decaying to excited states of ^{136}Ba and an isomeric state with $T_{1/2}=19$ s. The latter was measured from the Cs x-rays, meaning that the isomeric state decays to the ground state via one converted transition at least. Moreover the spin values of these two states were obtained from laser spectroscopy, $I = 5\hbar$ for the ground state and $I = 8\hbar$ for the isomeric state.

Very recently, the excitation energy of the isomeric state was determined thanks to the measurement of its decay to the ground state by means of a 518-keV $E3$ transition [3]. Moreover a very weak branch (a 413 keV $M4$ transition) populating an intermediate state at 105 keV has been also measured. The ground state and the first excited state were then assigned to belong to the multiplet of states with the $\pi g_{7/2}\nu d_{3/2}$ configuration, while the isomeric level would be the 8^- state from the $\pi g_{7/2}\nu h_{11/2}$ configuration [3].

The high-spin structures built above the $I = 8\hbar$ isomeric state remain unknown, while such structures with only one neutron hole in the $\nu h_{11/2}$ orbit, i.e., the unique high- j orbit lying below the $N = 82$ gap, are expected

to be simple enough to provide important tests for shell-model calculations. A first candidate for this purpose is $^{134}\text{I}_{81}$, unfortunately such a test is very limited as a unique structure comprising five excited states was measured and discussed in this odd-odd nucleus [4, 5].

In the present paper, we report on the first identification of the high-spin states of ^{136}Cs , produced as fission fragment in two fusion reactions, $^{18}\text{O} + ^{208}\text{Pb}$ and $^{12}\text{C} + ^{238}\text{U}$, and studied with the Euroball array. The level scheme has been built up to ~ 4.7 MeV excitation energy and up to spin values around $16\hbar$. The yrast states are first discussed in comparison with the proton excitations already identified in $^{137}\text{Cs}_{82}$ [6]. Then the predictions from shell-model calculations using the SN100PN effective interaction [7] are presented, showing a good agreement with experimental results.

II. EXPERIMENTAL DETAILS

A. Reaction, γ -ray detection and analysis

The ^{136}Cs nuclei were obtained as fission fragments in two experiments. First, the $^{12}\text{C} + ^{238}\text{U}$ reaction was studied at 90 MeV incident energy, with a beam provided by the Legnaro XTU Tandem accelerator. Second, the $^{18}\text{O} + ^{208}\text{Pb}$ reaction was studied with a 85 MeV incident energy beam provided by the Vivitron accelerator of IReS (Strasbourg). The gamma rays were detected with the Euroball array [8]. The spectrometer contained 15 cluster germanium detectors placed in the backward hemisphere with respect to the beam, 26 clover germanium detectors located around 90° and 30 tapered single-crystal germanium detectors located at forward angles. Each cluster detector consists of seven closely packed large-volume Ge crystals [9] and each clover detector consists of four smaller Ge crystals [10]. In order to get rid of the

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Doppler effect, both experiments have been performed with thick targets in order to stop the recoiling nuclei (47 mg/cm² for ²³⁸U and 100 mg/cm² for ²⁰⁸Pb targets, respectively).

The data of the C+U experiment were recorded in an event-by-event mode with the requirement that a minimum of five unsuppressed Ge detectors fired in prompt coincidence. A set of 1.9×10^9 three- and higher-fold events was available for a subsequent analysis. For the O+Pb experiment, a lower trigger condition (three unsuppressed Ge) allowed us to register 4×10^9 events with a γ -fold greater than or equal to 3. The offline analysis consisted of both multigated spectra and three-dimensional 'cubes' built and analyzed with the Radware package [11].

More than one hundred nuclei are produced at high spin in such fusion-fission experiments, and this gives several thousands of γ transitions which have to be sorted out. Single-gated spectra are useless in most of the cases. The selection of one particular nucleus needs at least two energy conditions, implying that at least two transitions have to be known. The identification of transitions depopulating high-spin levels which are completely unknown is based on the fact that prompt γ -rays emitted by complementary fragments are detected in coincidence [12, 13]. For the reactions used in this work, we have studied many pairs of complementary fragments with known γ -ray cascades to establish the relationships between their number of protons and neutrons [14, 15]. This was taken into account for identifying the γ -ray cascades emitted by the ¹³⁶Cs nucleus, as shown in the forthcoming section.

III. EXPERIMENTAL RESULTS

In order to identify the unknown transitions depopulating high-spin levels located above the 8^- isomeric state of the odd-odd ¹³⁶Cs isotope, we have first looked into spectra gated by the first transitions of its main complementary fragments, ^{85,86}Br in the O+Pb reaction and ^{103–105}Tc in the C+U reaction. In addition to the γ rays known in ^{85,86}Br and ^{103–105}Tc respectively, new transitions are observed and assigned to ¹³⁶Cs. As an example, the spectra of Fig. 1 show the high-energy part of coincidence spectra gated on two transitions belonging to ⁸⁵Br [spectrum (a)], ⁸⁶Br [spectrum (b)], ¹⁰⁵Tc [spectrum (c)]. These three spectra exhibit the 1184 keV transition of ¹³⁷Cs [6] and a new transition at 1398 keV which is assigned to ¹³⁶Cs.

Secondly, we have analyzed spectra in double coincidence with the 1398 keV transition and one transition of either ^{85,86}Br in the O+Pb reaction or ^{103–105}Tc in the C+U reaction. This allowed us to identify unambiguously two other transitions emitted by the high-spin states of ¹³⁶Cs, at 262 and 730 keV, which are also weakly observed in spectra gated by two transitions belonging to the complementary fragments. Then the coincidence

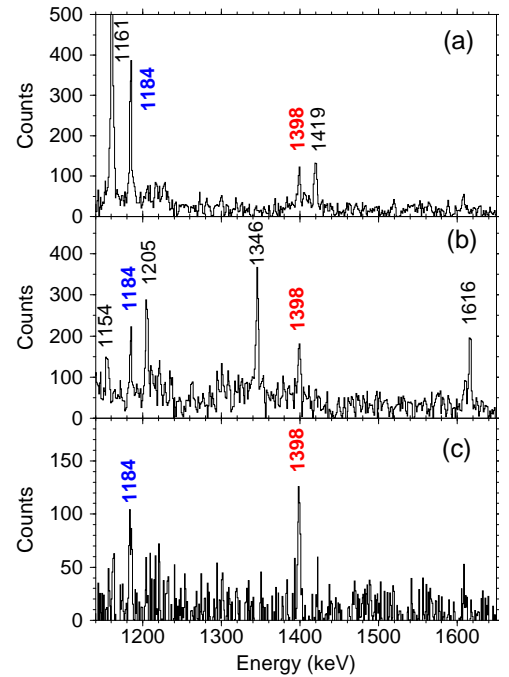


FIG. 1. (Color online) High-energy part of coincidence spectra gated on transitions belonging to the complementary fragments of ¹³⁶Cs: (a) spectrum double-gated on the 345- and 1227-keV transitions of ⁸⁵Br [16], built from the ¹⁸O + ²⁰⁸Pb data set, (b) spectrum double-gated on the 190- and 331-keV transitions of ⁸⁶Br [17], built from the ¹⁸O + ²⁰⁸Pb data set, (c) spectrum double-gated on the 63- and 84-keV transitions of ¹⁰⁵Tc [18], built from the ¹²C + ²³⁸U data set. The 1184-keV transition (in blue) belongs to ¹³⁷Cs [6] and the new 1398-keV one (in red) is assigned to ¹³⁶Cs.

relationships of the 262-, 730-, and 1398-keV transitions have been carefully analyzed in order to identify the other transitions having lower intensity. Finally all the coincidence relationships have been looked for. The obtained level scheme is shown in Fig. 2.

In addition to the three transitions mentioned above, a 66 keV line is observed in all the double-gated spectra [see for instance the spectrum shown in Fig. 3(a)]. These four transitions in cascade have been located just above the 8^- isomeric state. The order of the four transitions is obtained thanks to their relative intensities measured in various spectra, in agreement with the existence of several lines which are observed in coincidence with only two or three of the four transitions (such as the lines at 945, 1014, and 1318 keV). Nevertheless the order of the 66- and 1398-keV transitions could not be disentangled unambiguously, as the uncertainty on $I_\gamma(66)$ obtained in spectra gated by transitions belonging to the complementary fragments is too large. We have chosen to put the 66-keV transition at the bottom of the cascade, as discussed below.

Above 3 MeV excitation energy, the level scheme comprises two cascades, in parallel to the main one. The structure (2) built on the 2928 keV state is very irregular

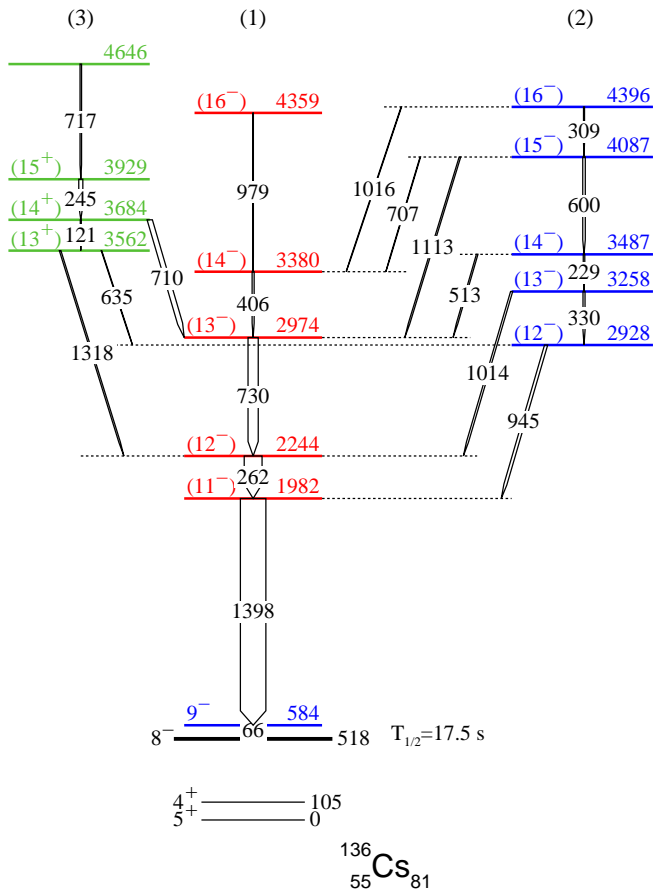


FIG. 2. (Color online) Level scheme of ^{136}Cs established in this work. The excitation energies of the long-lived 8^- state and the 4^+ state are from Ref. [3]. The width of the arrows is proportional to the γ -ray intensity. The colored states are new. The color code is the same as that of Fig. 4.

in energy. All its states decay towards states belonging to the main structure. The 3563-keV level is the bottom of a new structure, structure (3), which starts with two low-energy transitions. It decays mainly towards the 2244-keV state and weakly to the 2928-keV one by means of the 635-keV transition. The latter can be seen in the spectrum of Fig. 3(b).

We have extracted the internal conversion electron coefficients of the 66- and 121-keV transitions by analyzing the relative intensities of transitions in cascade. The intensity imbalance of the 66-keV γ ray measured in spectra in double coincidence with transitions located above it leads to $\alpha_{tot}(66) = 2.8(10)$, which is in good agreement with the theoretical value for a $M1$ multipolarity (see Table I). Regarding the 121-keV transition, we have obtained $\alpha_{tot}(121) = 0.45(10)$, which is also close to the value expected for a $M1$ multipolarity.

As mentioned in the introduction, the 8^- isomeric level of ^{136}Cs belongs to the configuration $\pi g_{7/2}\nu h_{11/2}$ which gives a multiplet of states with spin values ranging from 2^- to 9^- . This means that the 9^- fully-aligned state lies

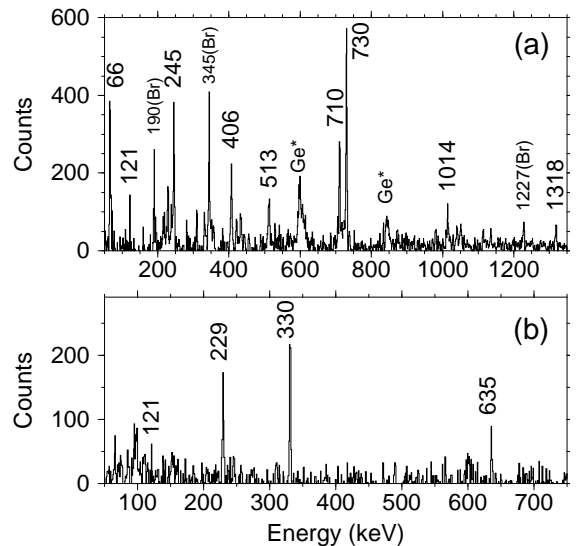


FIG. 3. Coincidence spectra gated on transitions belonging to ^{136}Cs : (a) spectrum double-gated on the 1398- and 262-keV transitions, built from the $^{18}\text{O} + ^{208}\text{Pb}$ data set [transitions emitted by $^{85,86}\text{Br}$, the complementary fragments of ^{136}Cs , are labeled by (Br)], (b) spectrum double-gated on the 1398- and 945-keV transitions, built from the $^{12}\text{C} + ^{238}\text{U}$ data set.

TABLE I. Values of conversion coefficients for the 66.0 and 121.4 keV transitions, the theoretical values come from the *BrIcc* database [19].

$E(\text{keV})^a$	$\alpha_{tot}(\text{exp})^a$	$\alpha_{tot}^{th}(E1)^a$	$\alpha_{tot}^{th}(E2)^a$	$\alpha_{tot}^{th}(M1)^a$
66.0(5)	2.8(10)	0.69(2)	8.3(3)	3.0(1)
121.4(5)	0.45(15)	0.128(2)	0.94(2)	0.52(1)

^a the number in parenthesis is the error in the last digit.

above the isomeric level and would belong to the yrast line. Afterwards the increase of angular momentum has to involve the breaking of proton pairs. In the neighboring ^{137}Cs [6] the first sign of the breaking is an $E2$ transition of 1184 keV, which is close to the energy of the $2_1^+ \rightarrow 0^+$ transition of the two even-even isotones, 1313 keV in ^{136}Xe and 1435 keV in ^{138}Ba . All these facts would be in favor of putting the 1398-keV transition above the 66-keV one in the yrast cascade of ^{136}Cs , thus defining the spin and parity values of the 584-keV state, $I^\pi = 9^-$ (see Fig. 2). The reverse order of the two transitions will be discussed in Sec. IV B.

The statistics of our ^{136}Cs data is too low to perform γ - γ angular correlation analyses. Therefore the spin assignments of all the states, given in parentheses in Fig. 2, are based on the following assumptions: (i) In the yrast decays, spin values increase with excitation energy and are similar for the states located within the same energy range, (ii) Most of the transitions are dipole. In addition, because of the numerous links, the parity of structure (2) is assumed to be the same as the one of structure (1), i.e. negative. On the other hand, the parity of structure (3)

is assumed to be positive.

We have gathered in Table II the properties of all the transitions assigned to ^{136}Cs from this work.

TABLE II. Properties of the transitions assigned to ^{136}Cs observed in this work.

E_γ^a (keV)	$I_\gamma^{a,b}$	$I_i^\pi \rightarrow I_f^\pi$	E_i	E_f
66.0(5)	- ^c	$9^- \rightarrow 8^-$	583.9	517.9 ^d
121.4(5)	3.3(8)	$(14^+) \rightarrow (13^+)$	3684.1	3562.6
229.0(4)	6.0(15)	$(14^-) \rightarrow (13^-)$	3486.8	3257.8
245.1(3)	15(4)	$(15^+) \rightarrow (14^+)$	3929.2	3684.1
261.6(2)	70(10)	$(12^-) \rightarrow (11^-)$	2243.9	1982.3
309.4(4)	4(2)	$(16^-) \rightarrow (15^-)$	4396.1	4086.7
330.2(3)	8(2)	$(13^-) \rightarrow (12^-)$	3257.8	2927.6
513.2(4)	6(2)	$(14^-) \rightarrow (13^-)$	3486.8	2973.7
406.4(3)	8(2)	$(14^-) \rightarrow (13^-)$	3380.1	2973.7
599.8(5)	9(3)	$(15^-) \rightarrow (14^-)$	4086.7	3486.8
635.0(5)	2.5(12)	$(13^+) \rightarrow (12^-)$	3562.6	2927.6
706.5(5)	1.0(5)	$(15^-) \rightarrow (14^-)$	4086.7	3380.1
710.4(3)	19(5)	$(14^+) \rightarrow (13^-)$	3684.1	2973.7
716.7(4)	5(2)	$\rightarrow (15^+)$	4645.9	3929.2
729.8(3)	40(8)	$(13^-) \rightarrow (12^-)$	2973.7	2243.9
945.3(4)	12(3)	$(12^-) \rightarrow (11^-)$	2927.6	1982.3
979.1(5)	2(1)	$(16^-) \rightarrow (14^-)$	4359.2	3380.1
1013.7(5)	8(3)	$(13^-) \rightarrow (12^-)$	3257.8	2243.9
1015.9(5)	2(1)	$(16^-) \rightarrow (14^-)$	4396.1	3380.1
1113.2(5)	5(2)	$(15^-) \rightarrow (13^-)$	4086.7	2973.7
1318.5(5)	5(2)	$(13^+) \rightarrow (12^-)$	3562.6	2243.9
1398.4(3)	100(15)	$(11^-) \rightarrow 9^-$	1982.3	583.9

^a The number in parentheses is the error in the last digit.

^b The relative intensities are normalized to $I_\gamma(1398) = 100$.

^c see text

^d from Ref. [3]

IV. DISCUSSION

A. General features

The various configurations of the yrast states of ^{136}Cs having $I > 8\hbar$ can be easily derived from the proton configurations identified in the $^{137}\text{Cs}_{82}$ core, given that the neutron configuration is unique, $(\nu h_{11/2})^{-1}$. Several proton configurations have been recently identified in ^{137}Cs [6], which can be sorted out as a function of (i) the orbit occupied by the odd proton and (ii) the number of broken pairs in the $\pi g_{7/2}$ and $\pi d_{5/2}$ orbits. They are listed in the left part of Table III. It is worth recalling that all the fully-aligned states indicated in the third column were identified in $^{137}\text{Cs}_{82}$ [6]. Regarding the $(\pi h_{11/2})^1$ state, the 1867-keV level is a good candidate as it was populated with $L = 5$ in the proton-transfer reaction ($^3\text{He}, d$), but its spin value was chosen to be $9/2^-$ because of its decay towards the $7/2^+$ ground state [20]. Nevertheless a $M2$ $11/2^- \rightarrow 7/2^+$ transition cannot be excluded, since such a transition is observed in the neighboring $^{139}\text{La}_{82}$ isotone [6].

TABLE III. Various proton configurations having zero, one and two broken proton pairs in the $\pi g_{7/2}$ and/or $\pi d_{5/2}$ orbit identified in ^{137}Cs [6, 20]. By coupling the $(\nu h_{11/2})^{-1}$ configuration to each proton one, one obtains the value of $I_{max}^\pi(\text{tot})$ expected for some excited states of ^{136}Cs .

Proton configuration	Proton seniority	I_{max}^π	$E(\text{keV})_{^{137}\text{Cs}}$	$I_{max}^\pi(\text{tot})_{^{136}\text{Cs}}$
$(\pi g_{7/2})^1(\pi g_{7/2}d_{5/2})^4$	1	$7/2^+$	0	9^-
	3	$15/2^+$	1671	13^-
	5	$23/2^+$	3464	17^-
$(\pi d_{5/2})^1(\pi g_{7/2}d_{5/2})^4$	1	$5/2^+$	455	8^-
	3	$17/2^+$	1893	14^-
	5	$21/2^+$	2783	16^-
$(\pi h_{11/2})^1(\pi g_{7/2}d_{5/2})^4$	1	$11/2^-$	1867 ^a	11^+
	3	$23/2^-$	3495	17^+
	5	$31/2^-$	5492	21^+

^a see text

In all the configurations expected to be involved in the yrast states of $^{136}\text{Cs}_{81}$, the odd nucleons have opposite characters: The neutron is a hole while the protons are particles. Thus, the residual interactions lift the degeneracy of each multiplet so that the states with medium spin values¹ are lowered in energy as compared to the $I_{max}^\pi(\text{tot})$ state. As a result, the yrast states of ^{136}Cs are expected to be formed from the fragments of each multiplet which comprise the states having spin values between I_{medium} and I_{max}^π . Then, the states of structure 1 with $I^\pi = (11^-)$ to (16^-) and those of structure 2 with $I^\pi = (12^-)$ to (16^-) (see Fig. 2) have one of the two configurations, $(\pi g_{7/2})^1(\pi g_{7/2}d_{5/2})^4$ and $(\pi d_{5/2})^1(\pi g_{7/2}d_{5/2})^4$, with a proton seniority of 3 or 5. Regarding the states of structure 3, they likely have the $(\pi h_{11/2})^1(\pi g_{7/2}d_{5/2})^4$ configuration with a proton seniority of 3.

B. Results of shell-model calculations

To get a deeper insight into the configurations of the yrast states of ^{136}Cs measured in this work, we have performed shell-model calculations, using the interaction SN100PN taken from Brown *et al.* [7] and the NuShellX@MSU code [21]. The calculational details are exactly the same as those described in Ref. [3] dealing with the energy and decay of the 8^- isomeric state of ^{136}Cs .

The left part of Fig. 4 shows the excitation energy above the 5^+ ground state (from the $(\pi g_{7/2})^1(\nu d_{3/2})^{-1}$

¹ The spin of the lowest member of the multiplet corresponds to the perpendicular coupling of the two angular momenta, i.e., $I_{medium}^\pi(\pi\nu) \sim I_{max}^\pi(\pi) + I^2(\nu)$

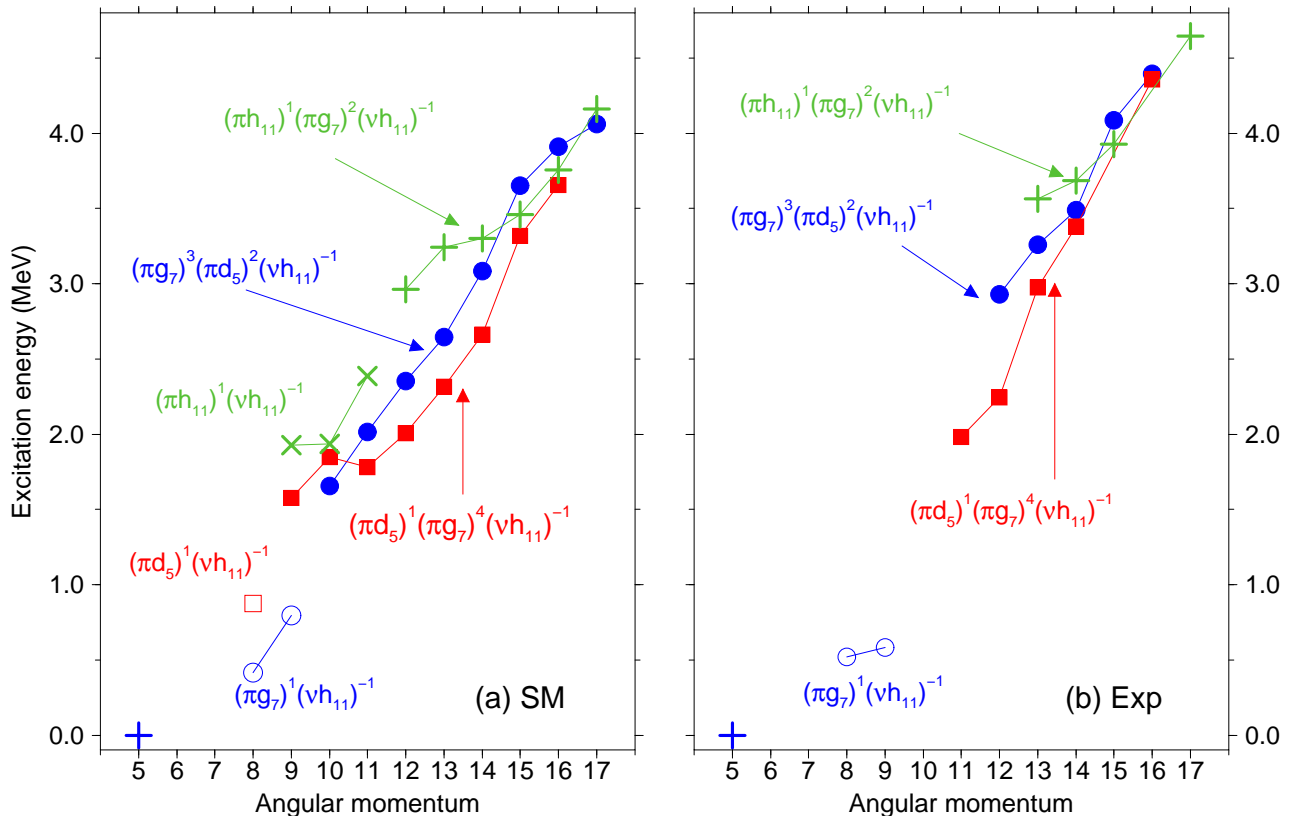


FIG. 4. (Color online) (a) Excitation energy as a function of angular momentum of the ^{136}Cs states having $I \geq 8\hbar$, predicted by the SM calculations to lie above the 5^+ ground state (see text). The first two or three states for each spin value are drawn. The states having the same main configuration are linked by a solid line. (b) Experimental states of ^{136}Cs drawn using the same symbols as in (a).

configuration) as a function of angular momentum of the ^{136}Cs states with $I \geq 8\hbar$. Those having the same main configuration are drawn with the same symbol and linked by a solid line.

As reported in Ref. [3], the 8^- isomeric state belongs to the $(\pi g_{7/2})^1(\nu h_{11/2})^{-1}$ configuration. The $I_{max}^\pi = 9^-$ state lies above it. Then to increase the angular momentum, a proton pair has to be broken. At this point, the SM calculation predicts two sets of levels lying between ~ 1.7 MeV and ~ 4.0 MeV excitation energy. For the yrast states with $I^\pi = 11^-$ to 16^- [see the red filled squares in Fig. 4(a)], the odd proton is located in the $\pi d_{5/2}$ orbit and one or two $\pi g_{7/2}$ pairs are broken. On the other hand, the states having an odd number of protons in the $\pi g_{7/2}$ orbit have higher excitation energies [see the blue filled circles in Fig. 4(a)]. Thus the states of structure 1 with $I^\pi = (11^-)$ to (16^-) (see Fig. 2) have likely the $(\pi d_{5/2})^1(\pi g_{7/2})^4(\nu h_{11/2})^{-1}$ configuration (noted 1), while the states of structure 2 with $I^\pi = (12^-)$ to (16^-) have the $(\pi g_{7/2})^3(\pi d_{5/2})^2(\nu h_{11/2})^{-1}$ one (noted 2).

It is worth pointing out that, taking into account the fact that the 10^- state of configuration 2 is predicted to lie below the 11^- state of configuration 1, one could infer that this 11^- yrast state mainly decays towards the 10^- state of configuration 2 instead of towards the 9_1^-

state. Such an assumption would be in agreement with the experimental results provided that the order of the 66- and 1398-keV transitions is reversed (as mentioned in Sec. III). Nevertheless, since the configuration of the 11_1^- state is different from both the 10_1^- and 9_1^- states, its decay to the lowest state (9_1^-), very favored by the large transition energy, is more likely, meaning that the 1398-keV transition is located above the 66-keV one.

The fact that the 12^- state of the configuration 2 decays towards the 11^- state of the configuration 1 can be explained by the high energy of the transition. Thus the predicted 11^- and 10^- states of the $(\pi g_{7/2})^3(\pi d_{5/2})^2(\nu h_{11/2})^{-1}$ configuration could not be observed experimentally in this work.

The promotion of one proton to the $\pi h_{11/2}$ orbit leads to multiplets of states with positive parity. While the predicted $9^+ - 11^+$ states of the $(\pi h_{11/2})^1(\nu h_{11/2})^{-1}$ configuration have a too large excitation energy to be populated in our experiment, we can expect to observe the $13^+ - 17^+$ states due to the breaking of a proton pair, i.e., from the $(\pi h_{11/2})^1(\pi g_{7/2})^2(\nu h_{11/2})^{-1}$ configuration with a proton seniority of 3 [see the green plus symbols in Fig. 4(a)]. This is in agreement with the experimental states of structure 3 (see Fig. 2).

In conclusion, the use of the SN100PN effective in-

interaction gives a good description of the yrast states of the odd-odd ^{136}Cs . Nevertheless it has to be mentioned that the predicted spectrum is slightly more compressed than the experimental one [compare Figs. 4(a) and (b)]. As examples, the 11_1^- state is calculated(measured) at 1779(1982) keV, the 13_1^+ state at 3243(3562) keV. However similar differences are also observed in the semi-magic ^{137}Cs isotope. The SM calculations of its excited states have been recently published using the same effective interaction [22]. For instance, when selecting levels having the same proton-excitation content as the 11_1^- and 13_1^+ states of ^{136}Cs (see Table III and Fig. 4), we notice that the $17/2^+$ state is calculated(measured) at 1706(1893) keV and the $23/2^-$ state at 3103(3495) keV.

V. SUMMARY

The odd-odd ^{136}Cs nuclei have been produced as fission fragments in two fusion reactions, $^{12}\text{C} + ^{238}\text{U}$ and $^{18}\text{O} + ^{208}\text{Pb}$, the γ -rays being detected using the Euroball array. The high-spin level scheme has been built up to ~ 4.7 MeV excitation energy by analyzing triple γ -ray coincidence data. The yrast structures, identified in this work, have been firstly discussed in comparison with the general features known in the mass region, particularly the proton excitations already identified in $^{137}\text{Cs}_{82}$, which involve the three high- j orbits lying above

the $Z = 50$ gap, $\pi g_{7/2}$, $\pi d_{5/2}$ and $\pi h_{11/2}$. Then shell-model calculations using the SN100PN effective interaction have been successfully compared to experimental results. They confirm that three high-spin structures observed above ~ 2 MeV are due to the odd proton lying in one of the three orbits coupled to one or two broken proton pairs in the two close orbits ($\pi g_{7/2}$ and $\pi d_{5/2}$), the odd neutron being a spectator. The SN100PN effective interaction could be further tested using the high-spin states of $^{138}_{57}\text{La}$. Such a work is in progress.

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