First observation of excited states in the ^{138}I nucleus

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Excited states in the ^{138}I nucleus, including $T_{1/2} = 1.3\ \mu s$ isomer decaying by a stretched $E2$ transition of 68 keV, were observed for the first time. The ^{138}I nucleus was populated in the spontaneous fission of ^{248}Cm and studied by means of prompt γ-ray spectroscopy using the EUROGAM 2 array. The microsecond isomer was populated in the neutron-induced fission of ^{235}U and observed at the LOHENGRIN separator. Excitation scheme consists of a low-spin part and a medium-spin, $\Delta I = 1$, band based on the 7^- state with the $(\pi g_{7/2} \nu f_{7/2})_{7^-}$ dominating configuration, as predicted by the shell model. The shell-model calculations of ^{138}I provide the optimum reproduction of the experimental scheme when the $\pi d_{5/2}$ orbital is lowered by 600 keV relative to its position in ^{133}Sb. In the calculation the isomeric level has spin and parity 3^- and deexcites by an $E2$ isomeric transition to the 1^- level, located only 9 keV above the predicted 0^- ground state. Considering additional information on the ground-state spin from the literature, we propose that in ^{138}I the 1^- level corresponds to the ground state and the 0^- is located above. We note, however, that additional measurements are required to resolve this problem.

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I. INTRODUCTION

Recent studies in the region of the doubly magic ^{132}Sn nucleus have revealed an intriguing problem concerning the position of the $d_{5/2}$ proton orbital in the shell-model nuclei around the ^{132}Sn core. In odd-A Sb isotopes the energy of the $5/2^+$ excitation, interpreted as the $d_{5/2}$ proton level measured relative to the $\pi g_{7/2}$ ground states, increases smoothly with increasing neutron number [1], reaching 962 keV in ^{133}Sb. Past $N = 82$ this energy suddenly drops to 283 keV in ^{135}Sb [2]. To reproduce this value using two-body matrix elements (tbme), applied successfully to other nuclei in the region, one has to decrease the position of the $d_{5/2}$ proton level by at least 300 keV [3,4]. This effect was interpreted as due to the formation of the so-called neutron skin [5]. However, we found that also in ^{136}I, which has only one neutron more than ^{133}Sb, one should lower the position of the $d_{5/2}$ proton level by 400 keV to properly describe its excitations [6]. It is unlikely that the neutron skin would form after adding just one neutron to the $N = 82$ core.

Recently it was demonstrated [7] that a suitable change in neutron-proton effective interaction allows good description of the decay scheme of ^{135}Sb without any *ad hoc* decrease of the $d_{5/2}$ proton single-particle energy. Also ^{134}Sb was described well within this approach [7]. We note, however, that ^{134}Sb was also properly reproduced using "conventional" tbme's [8,9] without applying any change to the $\pi d_{5/2}$ position. Thus, the problem seems to grow with the number of valence nucleons (or $\nu\pi$ pairs). If such a correlation is indeed present, it may suggest the need to change some neutron-proton tbme's rather than to decrease the position of the $\pi d_{5/2}$ single-particle energy. For this reason we studied the odd-odd ^{138}I nucleus, having three protons and three neutrons outside the ^{132}Sn core, substantially more than ^{135}Sb. In the present work we report on the first observation of excited states in ^{138}I including a low-spin, microsecond isomer. We note that the ^{138}I nucleus is an isotone of ^{136}Sb, where an analogous microsecond isomer was observed [10], which still awaits a proper explanation.

In the following sections, we present details of the experiment, the data analysis and the experimental results (Sec. II), the shell-model calculations of ^{138}I, their comparison with experimental results and discussions (Sec. III), and, finally, we summarize our results and draw conclusions in Sec. IV.

II. EXPERIMENT, DATA ANALYSIS, AND THE RESULTS

The present study of ^{138}I consists of two kinds of measurements. One is the prompt γ-ray measurement, performed to establish the near-yrast excitations and the other is a measurement of delayed γ-rays where we searched for possible isomers in the micro-to-millisecond range. Both measurements and the resulting data are presented in detail in the following subsections.

A. Prompt γ-ray measurement

We have studied the ^{138}I nucleus populated in spontaneous fission of ^{248}Cm. Prompt γ rays following the fission process were measured using the EUROGAM 2 array [11], equipped additionally with four low-energy photon (LEP) detectors (for more details on the experiment and data analysis techniques see Refs. [12–14]).

In the measurement triple- and higher-fold prompt coincidences between γ rays were measured (time window was about 300 ns). Such events were sorted into three-dimensional histograms, which provided γ-energy spectra double gated on the two coincident γ energies. The quality of such data is usually sufficient to allow selection of γ-ray cascade in a single isotope, from a few hundred various nuclei produced in fission process. As no protons are emitted in spontaneous fission of ^{248}Cm, sum of the atomic numbers, Z_1 and Z_2, of the two fission fragments produced in a certain fission event has to be 96. Therefore iodine nuclei will be produced together with technetium nuclei. Consequently, γ rays of iodine nuclei will appear in prompt coincidence with γ rays of technetium nuclei. In spontaneous fission of ^{248}Cm three neutrons are emitted, predominantly. Therefore one expects that γ rays of ^{138}I will, most likely, appear in coincidence with ^{107}Tc. However, as the number of neutrons may differ from three, one will also observe (with lower probability) coincidences between ^{138}I and other Tc isotopes.

To search for γ rays de-exciting energy levels in ^{138}I we analyzed γ spectra double gated on lines in ^{107}Tc [15]. In the spectrum shown in Fig. 1(a), which is double gated on the

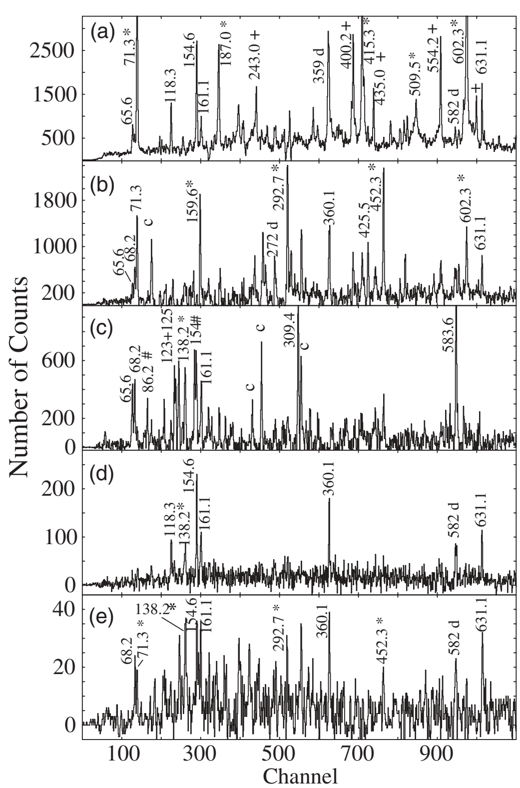

FIG. 1. Coincidence spectra gated on γ lines in ^{107}Tc and ^{138}I. Energies of transitions and are labeled in keV. Energies of gates are given in the text. Symbols used: (+) γ lines in ^{136,137,139}I; (*) γ lines in ^{107}Tc; (#) γ lines in ^{108}Tc; (d) double line; (c) lines from contaminating nuclei.

138.2- and 452.3-keV lines of ^{107}Tc, one observes lines at 118.3, 154.6, and 631.1 keV, assigned neither to ^{107}Tc nor to any of the complementary iodine isotopes. A spectrum double gated on the 138.2- and 154.6-keV lines, shown in Fig. 1(b), contains the 452.3- and 292.7-keV lines of ^{107}Tc, again the 631.1-keV line and new lines at 360.1, 425.5, and 582 keV (double line), now more pronounced than in Fig. 1(a). Figure 1(c) shows a spectrum double gated on the two new lines 154.6 and 631.1 keV. The spectrum is dominated by the new 309.4- and 583.6-keV lines. One also sees lines at 65.6 and 68.2 keV. They are also present in Fig. 1(b), but as less pronounced. This suggests that the two lines belong to the same decay scheme as the 154.6- and 631.1-keV lines. Indeed, in the spectrum double gated on these two lines, which is shown in Fig. 1(d), one observes the dominating 154.6-, 360.1-, 582- (doublet), and 631.1-keV lines. It should be mentioned that there is the 65.6-keV line also in ^{107}Tc. This transition, depopulating the $T_{1/2} = 184$ ns isomer, is strongly suppressed in our data, as can be seen in Fig. 1(a), where its γ intensity is an order of magnitude lower than the intensity of the 71.3-keV transition in ^{107}Tc, populating the isomer. In contrast, γ intensities of the 65.6- and 68.2-keV transitions in Fig. 1(c) are nearly the same (we note that in Fig. 1(a) the intensity of the 65.6-keV transition is about factor of 2 higher than the intensity of the 68.2-keV transition). Finally, in Fig. 1(e) we show a spectrum doubly gated on the 65.6-keV line. Despite low counts, in the spectrum one observes lines from ^{107}Tc (71.3, 138.2, 292.7, and 452.3 keV) and lines from the new cascade (68.2, 154.6, 360.1, and 631.1 keV). This shows that the self-gating, 65.6-keV line is present in both, the ^{107}Tc nucleus and the new cascade.

The coincidence relations observed in Fig. 1 and in further gated spectra, allowed the construction of a cascade of γ transitions, as shown in Fig. 2. The spin assignment, shown in this figure will be discussed later in this work. In Table I we

TABLE I. Properties of γ transitions in the ^{139}I nucleus, as observed in the present work.

E_γ (keV)	I_γ (rel.)	A_2/A_0	A_4/A_0	Correlating E_γ (keV)
43.5	10(5)			
65.6	81(17)			
68.2	100(18)			
118.3	52(5)			
154.6	65(8)			
161.1	14(4)			
251.8	7(2)	−0.14(6)	−0.01(8)	583.6
271.4	14(3)	0.09(6)	−0.01(8)	360.1
273.7	4(1)			
309.4	8(2)	−0.04(6)	0.10(9)	631.1
360.1	39(5)			
425.5	24(4)			
524.5	12(3)			
580.6	18(3)			
583.6	17(3)			
631.1	37(5)			

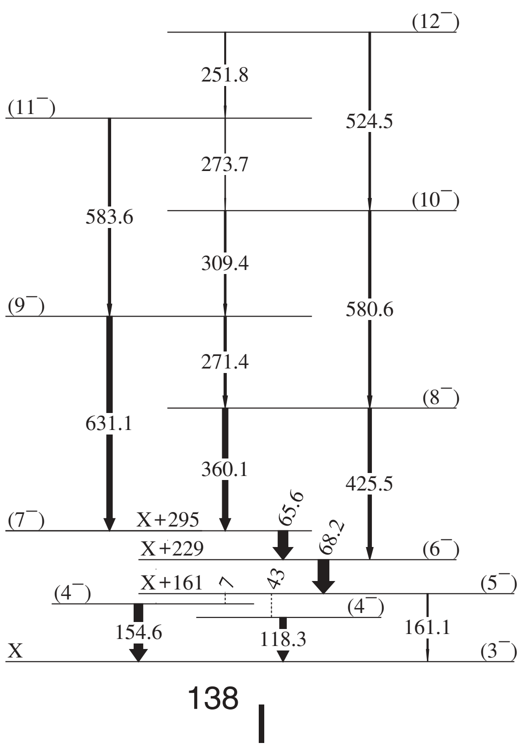

FIG. 2. Partial level scheme of ^{138}I as obtained in the present work.

give the relative intensities of γ transitions placed in the decay scheme of Fig. 2.

We note that, apart from lines of ^{107}Tc, in Fig. 1(c) one can also see lines of ^{108}Tc [16]. This proves that the new cascade belongs to an iodine isotope. As discussed above, the most likely candidate is the ^{138}I nucleus. Indeed, our recent studies of ^{136}I, ^{137}I, and ^{139}I [6,17,18] did not reveal such a cascade in those nuclei. To determine the assignment of the new cascade to an iodine isotope we used the mass correlation technique, proposed by Hotchkis *et al.* [19] and presented in Fig. 3. The application of this technique to the I and Tc complementary fission fragments is described in detail in Refs. [6,20,21], from where we took experimental points for ^{135}I, ^{136}I, ^{137}I, and ^{139}I. The horizontal bar in Fig. 3 represents the average Tc mass, $\langle \text{Tc} \rangle = 106.7(2)$, calculated from intensities of lines of ^{106}Tc, ^{107}Tc, and ^{108}Tc, as observed in the spectra doubly gated on the lines from the new cascade. The intersection of this bar with the straight-line fit to the data points (dashed line in Fig. 3) indicates mass $A(I) = 138.3(2)$, which correlates well the new cascade with the ^{138}I nucleus.

In Fig. 4(a) we show a spectrum measured by LEP detectors, which is doubly gated on the 118.3-keV line (the first gate) and the sum of the 65.6-, 68.2-, 360.1-, and 631.1-keV lines (the second gate). One observes here a peak at 43.5 keV. Due to its low intensity we introduce the 43.5-keV transition to the decay scheme only tentatively. The placement of the 43.5-, 118.3-, 154.6-, and 161.1-keV transitions, and unobserved 7 keV transition, as shown in Fig. 2, is the preferred one, as further discussed in Sec. III, but it is not uniquely determined. It is also not known if the lowest level shown in Fig. 2 is the ground state or an excited state. We mark its energy with X.

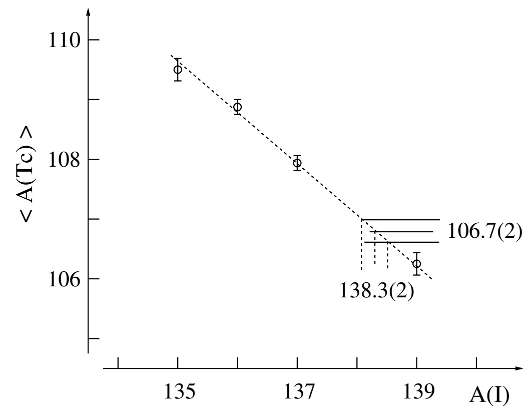

FIG. 3. Mass correlation diagram for Tc and I isotopes and the identification of the γ cascade in ^{138}I. See text for more explanations.

We could estimate the experimental conversion coefficient, α_K for the 65.6- and 68.2-keV transitions, comparing their γ intensities with the intensity of the iodine K_α, X-ray line at 28.5 keV.

Figure 4(b) shows a spectrum measured by LEP detector, which is doubly gated on the 154.6-keV line (the first gate) and the sum of 65.6- and 425.5-keV lines (the second gate). From this spectrum we obtained a value of $\alpha_K = 6(1)$ for the 68.2-keV transition, which indicates its $M1 + E2$ character. Similarly, from the spectrum in Fig. 4(c), which is gated on the 68.2-keV line (the first gate) and the sum of 631.1- and 360.1-keV lines (the second gate), we estimated the conversion coefficient $\alpha_K = 6.5(1.5)$ for the 65.6-keV transition, which

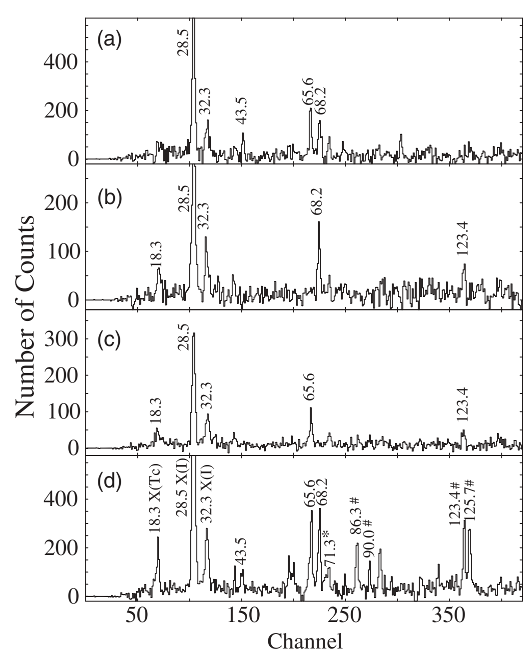

FIG. 4. Coincidence spectra gated on γ lines in ^{107}Tc and ^{138}I, as obtained in this work. The spectra were measured by a LEP detector. Gating energies for the spectra are given in the text. Energies of transitions are labeled in keV. Symbols used: (X(Tc)) K_α line of Tc isotopes; (X(I)) X-ray lines of iodine isotopes; (*) γ lines in ^{107}Tc; (#) γ lines in ^{108}Tc.

indicates an $M1 + E2$ character also for this transition. Figure 4(d) shows an LEP spectrum doubly gated on the 154.6-keV line (the first gate) and the sum of 631.1- and 360.1-keV lines (the second gate), where one can see that both the 65.6- and 68.2-keV lines have similar intensities. This is expected in this spectrum, if both lines have similar values of conversion coefficients.

In Table I we show angular correlations for some of the transitions in ^{138}I, as determined in this work, using techniques described in Refs. [14,22]. These data are consistent with the $\Delta I = 2$ character of the 583.6- and 631.1-keV transitions and the $\Delta I = 1$ character of the 251.8-, 271.4-, 309.4-, and 360.1-keV transitions. The data allow the assignment of spins and parities, relative to spin I^π of the level X+295, populated by the 631.1-keV transition. We assumed that spin values are growing with excitation energies, as commonly observed in nuclei populated in spontaneous fission. Because no half-life longer than 10 ns was observed for any of the levels in Fig. 2, the 583.6- and 631.1-keV transitions have most likely stretched $E2$ multipolarity. Consequently, considering $M1 + E2$ character of the 65.6-keV transition, the 251.8-, 271.4-, 273.7-, 309.4, and 360.1-keV transitions are $M1 + E2$, whereas the 425.5-, 581.6-, and 525-keV transitions are stretched $E2$. As will be discussed in Sec. III, the very probable spin and parity assignment for the X+295 level is $I^\pi = 7^-$. Consequently, the levels above the X+295 keV can be assigned spins and parities, as shown in Fig. 2, based on their multipolarites proposed above and on the assumption that spins are increasing with the excitation energy.

We used the observed branchings to propose spins for the low-lying levels. The nonobservation of the 134-keV decay from the X+295-keV level to the X+161-keV level indicates spin lower than 6 for the latter level. Considering the $M1 + E2$ character of the 65.6- and 68.2-keV transitions, we assign spin 6^- to the X+229-keV level and spin 5^- to the X+161 keV level. Similar arguments based on the observed branchings indicate spin lower than 5 for levels below the X+161-keV level. The assignment shown in Fig. 2 is consistent with the experimental data and is, in our opinion, the most likely one considering also the calculations presented in Sec. III, which predict no low-lying levels of positive parity.

B. Delayed γ-ray measurements

To clear the nature of the lowest level populated in the prompt fission of ^{248}Cm (level X in Fig. 2) we searched for possible long-lived isomers in ^{138}I. Two kinds of measurements were performed, as described in detail below, one in the microsecond range and the other in the millisecond range.

1. The microsecond-range measurement

Microsecond isomers were investigated in the mass chain $A = 138$ at the ILL reactor in Grenoble. These nuclei were produced by thermal-neutron-induced fission of a thin target of about 400 μg/cm^2 of ^{239}Pu. The LOHENGRIN mass spectrometer was used to separate the fission fragments (FFs) recoiling from the target, according to their mass to ionic charge ratios (A/q). Two different setups were used. In the first one the FFs were detected in a gas-filled ionization chamber of 13 cm active length and subsequently stopped in a 1-μm-thin Mylar foil. A few millimeters behind the foil, two cooled adjacent Si(Li) detectors covering an area 2×6 cm^2 were placed to detect conversion electrons and x rays, whereas γ rays were detected by two 60% Ge detectors placed perpendicular to the beam. This setup allows conversion electrons to be detected down to low energy (15 keV) and allows γ-electron coincidences to be obtained. Details on this experimental setup can be found in Ref. [26].

In the second setup the FFs were detected in an ionization chamber, optimized for γ-ray spectroscopy, filled with isobutane at a pressure of 47 mb. This chamber has very good mass resolution and can even be used to assign the proton number to isomeric isotopes in the $Z \sim 40$ region. γ rays de-exciting isomeric states were detected by a Miniball triple cluster detector [24] and a clover detector [25]. These detectors were placed perpendicular to the ion beam in a tightly packed geometry, possible because the ionization chamber was only 6 cm thick. The total efficiency for the γ detection was 20 and 4% for photons of 100 and 1 MeV, respectively. More details on this experimental setup can be found in Ref. [23].

With this setup a new μs isomer de-exciting by a single γ ray of 67.9 keV has been observed in coincidence with ions of $A = 138$. Based on the time spectrum of the isomer, shown in Fig. 5, a half-life-value of 1.26(16) μs was determined. The assignment of the isomer to the atomic number $Z = 53$ was possible thanks to the observation of the K_α and K_β x rays, as illustrated in Fig. 6.

The isomer-delayed spectrum obtained from the Si(Li) detector is shown in Fig. 7. The K, L, and M conversion-electron peaks from the 67.9-keV transition can be observed. The measured intensity ratio of the K-to-L transitions is 1.56(20). The character of this transition can therefore be firmly assigned as $E2$, as the theoretical K-to-L intensity ratios are 7.32, 7.60, and 1.49 for $E1$, $M1$, and $E2$ transitions, respectively. In addition to $A = 138$, isomeric transitions from ions of Sn and Te isotopes with $A = 132$ are also present in this spectrum. They are contaminants with similar A/Q ratios to that of nuclei with $A = 138$. Ions of these two masses passing through the spectrometer could not be resolved by ionization

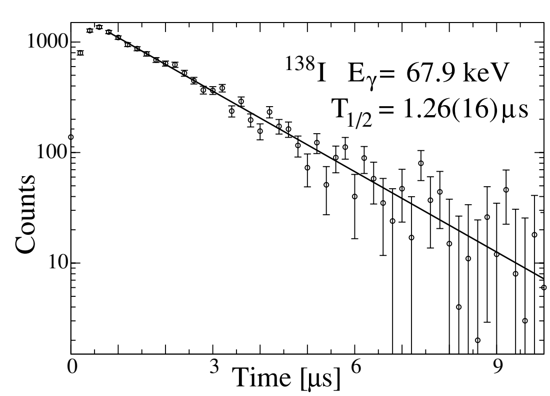

FIG. 5. Time-delayed spectrum of the 67.9 keV γ ray in ^{138}I measured with a Miniball triple cluster and a clover detector.

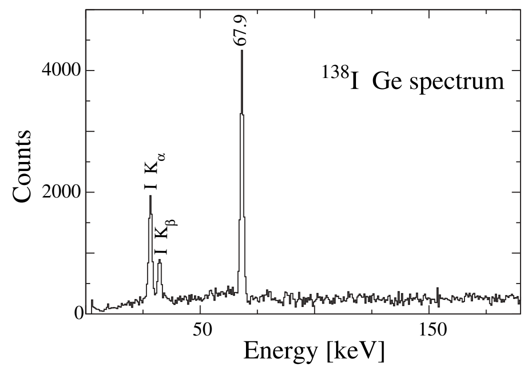

FIG. 6. Gamma spectrum of time-delayed transitions in coincidence with $A = 138$, measured with a Miniball triple cluster and a clover detector.

chamber in the experimental setup used to measure conversion electrons.

2. The millisecond-isomer search

We performed a measurement in the millisecond range, using an electrostatic deflector newly developed for the LOHENGRIN separator [30]. The device was successfully tested on known cases, proving that this technique can be used for millisecond-isomer search in fission fragments [31] in the half-life range from 0.1 ms up.

We used two clover Ge detectors of 120% relative efficiency and one conventional Ge detector of 60% relative efficiency. All detectors were placed at close distance to the exit window of the ion chamber, where ions were collected on a thin tape at a rate of about 2000 ions per second. In the measurement about 7×10^7 ions were collected for mass $A = 138$. In the present run ions were not removed from the collection point. After the saturation, the β-decay activity was on the level providing about 2000 counts per second in each of the Ge detectors. This created some unwanted background. However, as tested on known isomers with half-lives from 0.1 ms in ^{131}Sb up to 140 ms in ^{97}Y, this background could be eliminated to a large extent during the data analysis. The experimental setup and the data analysis techniques used in this run are described in more detail in Ref. [31].

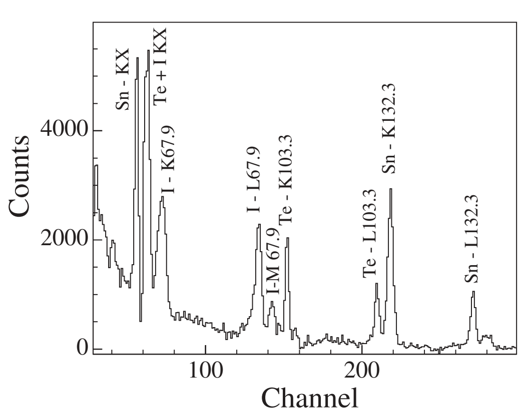

FIG. 7. Si(Li)spectrum obtained in delayed coincidence with the ions of $A = 138$. Transitions are also observed from isomers in Sn and Te nuclei of mass 132, which were contaminants of similar A/Q ratios at the spectrometer setting used.

In the run the electrostatic deflector was operating at a frequency of 100 Hz, allowing a search for isomers in the half-life range from 0.1 to 10 ms. Our Ge detectors registered γ rays in the range from about 20 keV up to 5 MeV. In the indicated energy range we did not observed any γ line corresponding to a possible isomeric decay in the ^{138}I nucleus with a half-life in the range from 0.1 up to 10 ms.

III. DISCUSSIONS

To investigate the structure of the microsecond isomer and other newly observed excited states in ^{138}I, we have performed shell-model calculations. The model space considered for the calculations in this region generally assumes ^{132}Sn as the inert core and ((proton) $\pi(1g_{7/2}, 2d_{5/2}, 2d_{3/2}, 3s_{1/2}, 1h_{11/2})$ and (neutron) $\nu(1h_{9/2}, 2f_{7/2}, 2f_{5/2}, 3p_{3/2}, 3p_{1/2}, 1i_{13/2})$) as valence orbitals. The binding energies, low-lying spectra and transition probabilities were calculated with the SMPN Hamiltonian [4], proposed recently for this region and tested successfully on a number of cases [4,6], using the OXBASH [35] code. The Hamiltonian SMPN [4] was obtained from CW5082 [36] using recent information on the single-particle energies (spe) of the valence orbitals and changing 26 two-body matrix elements (tbme) of it by fitting the binding energies and excitation energies of a few low-lying levels of $A = 134$ isobars of Sn, Sb, and Te. In the present calculations the *spe* of the proton $d_{5/2}$ orbital was varied to test the influence of this parameter, which is an important question in this study.

Unrestricted calculation with six valence nucleons (three neutrons and three protons) occupying all the levels of the above-mentioned valence space is a serious computational problem. Therefore we performed such calculations for $D = 0$ and 600 keV, only, where D denotes the lowering of the *spe* of the $\pi d_{5/2}$ orbital in keV. We have fixed the value of D by performing the calculations at many intermediate values of D in a truncated basis (with $\pi h_{11/2}$ and $\nu i_{13/2}$, high-j orbitals excluded) where we found that the best fit to the experimental spectra is obtained for $D = 600$ keV.

The results for the energy eigenvalues obtained in the unrestricted calculation are compared with the experimental level scheme in Fig. 8. The position of $\pi d_{5/2}$ orbital, relative to its position in the ^{133}Sb nucleus, is marked in Fig. 8 on the scale below the calculated scheme.

The main feature of the calculated scheme, independent of the D value, is a clear distinction between the low-spin multiplet and the medium-spin, quasi-band structure, which reproduces the experimental scheme. On this basis we proposed spin and parity 7^- for the X+295-keV level of Fig. 2. In Fig. 8 the theoretical results are normalized to the experimental energy for spin $I = 7^-$.

In Fig. 8 one observes a significant improvement in the reproduction of the experimental scheme, when the $\pi d_{5/2}$ orbital is lowered relative to its position in ^{133}Sb. The reproduction of the medium-spin excitations with even spins is clearly improved. Their wave functions contain significant

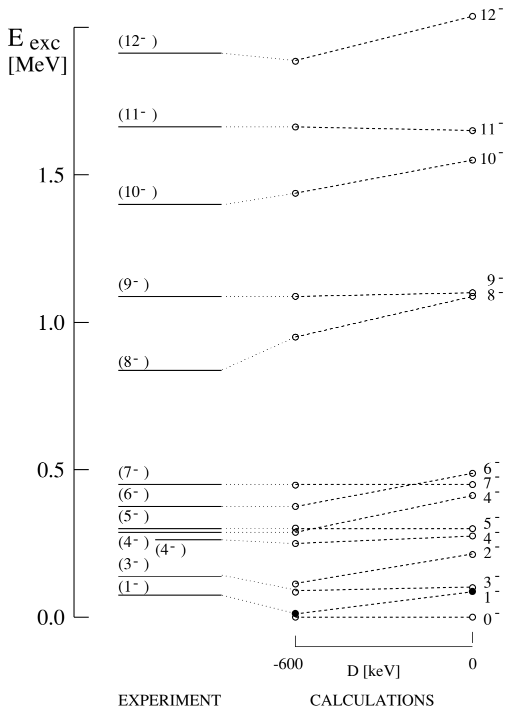

FIG. 8. Energies of excited states in ^{138}I, calculated at different positions of the 5/2 proton level (D denotes the lowering of the $\pi d_{5/2}$ orbital, in keV).

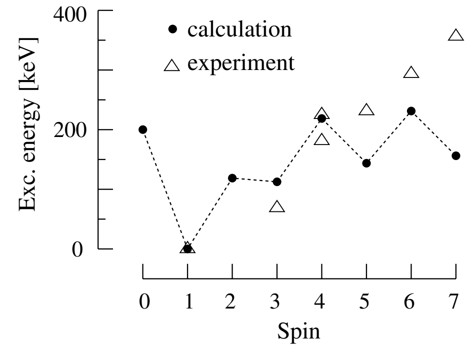

FIG. 9. Energies of excited states within the $(\pi g_{7/2}\nu f_{7/2})_j$ multiplet, as obtained in semiempirical calculations (full dots). Experimental excitations in ^{138}I are marked by triangles (see the text for more comments on the normalization of the the experiment and the calculations).

contributions of the $\pi d_{5/2}$ orbital, which explains the decrease of their excitation energies as a function of D. The agreement for the low-spin excited levels is also improved. The 6^- level, which is located above the 7^- level at $D = 0$, goes below the 7^- excitation at $D = 600$ keV (an analogous effect was observed recently in ^{136}I [6]). Another essential improvement is the decrease of the excitation energy of the second 4^- level. This provides at $D = 600$ keV two 4^- levels located close to each other and close to their experimental counterparts. We note that the reproduction of the remaining levels of the low-spin multiplet is also very good. Finally, with the decreasing position of the $\pi d_{5/2}$ orbital the 1^- level goes down in energy and at $D = 600$ keV it is located 70 keV below the 3^- level. At the same time the 2^- level remains above the 3^- level. The isomeric transition in ^{138}I is thus reproduced as the $3^- \rightarrow 1^-$, $E2$ transition.

Although we can calculate the energy eigenvalues of the 3^- and 1^- levels, the lifetime of the 3^- isomer cannot be computed in our unrestricted calculation due to some computational restrictions. However, we have estimated the lifetime of this isomer in the truncated space calculations. High-$j\pi 1h_{11/2}$ and $\nu 1i_{13/2}$ orbitals are excluded in these calculations. It is interesting to note that unexpectedly large proton and neutron effective charges are needed to reproduce microsecond half-life of this level. But we expect that the $B(E2)$ value for the $3^- \rightarrow 1^-$ transition will be larger (leading to a microsecond half-life for unrestricted calculations with normal [4] effective charges for this region). This is expected on the basis of larger degree of configuration mixing involved in these states in the unrestricted calculations.

The calculation predicts that the ground state in ^{138}I has spin and parity 0^-. For this reason, although the picture presented above is quite convincing, the calculation may need further refinements as there are indications that the spin of the ground state of the ^{138}I nucleus may be different from zero. The measurement of β decay of the ground state of ^{138}I [32] reports a population of the $I^\pi = 3^-$ excitation in ^{138}Xe. On this basis the evaluators of Nuclear Data Sheets adopted $I^\pi = (2^-)$ spin and parity for the ground state of ^{138}I [33]. The tentative character of this assignment reflects the fact that the population of the 3^- excitation in ^{138}Xe is not strong and that it could be accounted for by some unobserved feeding from intermediate states. In contrast, the population of the 0^+ ground state and the 2^+ excitation in ^{138}Xe, observed in β decay of ^{138}I, is strong. This again indicates a nonzero spin for the ground state of ^{138}I but suggests spin $I = 1$ rather than $I = 2$. Such a hypothesis is supported by a semiempirical calculation of the excitation energies within the $(\pi g_{7/2}\nu f_{7/2})_j$ multiplet, as shown in Fig. 9.

In Fig. 9 the experiment was normalized to the calculation at spin 1^-. We assumed that the 68-keV isomeric transition depopulates the 3^- level of Fig. 2 and feeds the 1^- state. We assumed further, that this 1^- level is the ground state in ^{138}I. Therefore it was placed in Fig. 9 at 0 keV, as the calculated 1^- level. In the picture presented in Fig. 9 the experimental 0^- level is missing.

The agreement between the experiment and the calculation at low-spin part of the multiplet is reasonable. So if one expects a predominantly multiplet structure of the states at lower spins, 1^- spin for the ground state appears as a probable option.

Summarizing, we note that in the unrestricted calculation at $D = 600$ keV the 1^- level is located only 9 keV above the 0^- level. One may thus claim that the calculation reproduced well the experimental level spectra in ^{138}I, with the 3^- isomer and the 1^- ground state, whereas the calculated position of 0^- level presents a slight discrepancy with the experiment.

At the end we should mention that further improvement to the calculation will be necessary, most likely concerning the tbme's used. Although lowering the single-particle energy of the $\pi d_{5/2}$ orbital improves the description of excited levels in the discussed region of nuclei, at the same time it causes an overbinding for their ground states. Such an effect is expected when one of the key orbitals is pushed down in energy and was observed already in our study of ^{136}I (see Fig. 5 in Ref. [6]). The overbinding of about 800 keV in ^{138}I, is larger than in ^{136}I, which is due to a larger lowering of the $\pi d_{5/2}$ orbital. These observations suggest once again, that the lowering of the s.p energy of the $\pi d_{5/2}$ orbital, however useful, needs to be investigated more minutely. In Sb isotopes an inversion of the $\pi g_{7/2}$ and $\pi d_{5/2}$ orbitals has been observed around neutron number $N = 70$. It has been shown that the radii of nuclei play an important role in the crossing along with contribution from some proton-neutron interactions [34]. Whether the depression of the $\pi d_{5/2}$ orbital applied in ^{138}I is solely an artifact of improper choice of $\pi\nu$ tbme's or have some real component of depression should be resolved by a suitable experiment sensitive to single-particle energies.

IV. CONCLUSIONS

A satisfactory, overall explanation of the newly observed excitation pattern of ^{138}I was obtained in this work, at the expense of an artificial change to the single-particle energy of the $d_{5/2}$ proton orbital. We found that a lowering of the position of the $\pi d_{5/2}$ orbital by about 600 keV, with respect to its value in ^{133}Sb single-proton nucleus, improves the calculated excitation scheme significantly. In ^{138}I this lowering is larger than the analogous lowering, observed recently in ^{136}I. The value of the depression seems, thus, to correlate with the number of proton-neutron pairs outside the ^{132}Sn core. This suggests the need to change the tbme's used in the region, probably some of the proton-neutron ones, to obtain a good description of ^{136,138}I without any *ad hoc* change to the position of the $\pi d_{5/2}$ orbital. Such an approach may at the same time solve the problem of overbinding observed for the ground states in the region.

Regarding the ground-state spin of ^{138}I, let us summarize our observations and discuss the possible options

(i) SMPN calculations with the unshifted single-particle energies and 600-keV depression of $d_{5/2}$ option predict 0^- as the ground state. This interaction so far has been successful in predicting the ground-state spin and parity of a number of odd-odd and odd-A nuclei in the ^{132}Sn region.

(ii) Calculations with other interactions used in this mass region, namely KH5082 [36] and KH5082 with recent single-particle energies [37] also predict 0^- as the ground state.

(iii) Experimental ground-state spins and parities in $T_z = 0$ (defined with respect to the ^{132}Sn core) odd-odd nuclei above the core, namely, ^{134}Sb $(1n + 1p)$ and ^{142}Cs $(5n + 5p)$ are 0^-. A similar situation may be observed in ^{138}I, the $T_z = 0$ nucleus with $(3n + 3p)$ in this shell. The unobserved 1^- to 0^- transition in ^{138}I may be of very small energy, as seen in both ^{134}Sb and ^{142}Cs (the first excited state is only $\simeq 13$ keV above the 0^- ground state in both cases).

(iv) From the β decay of ^{138}I to ^{138}Xe, the evaluators of Nuclear Data Sheets proposed 0^-, 1^-, 2^- as possible options for the ground state in ^{138}I. But they adopted $I^\pi = (2^-)$ spin and parity solution, considering β decay to the (3^-) level at 2015 keV in ^{138}Xe.

(v) The tentative character of this $I^\pi = (2^-)$ assignment reflects the fact that the population of the 3^- excitation in ^{138}Xe is not strong and that it could be accounted for by some unobserved feeding from intermediate states. In contrast, the population of the 0^+ ground state and the 2^+ excitation in ^{138}Xe, observed in β decay of ^{138}I, is strong, favoring a nonzero option. But it suggests spin $I = 1$ rather than $I = 2$.

(vi) The 1^- option is supported also by a semiempirical calculation of the excitation energies within the $(\pi g_{7/2} \nu f_{7/2})_j$ multiplet, if one expects a predominantly multiplet structure of the low-spin states, unlike that predicted by the full space calculations.

Thus both 0^- and 1^- options seem to have arguments in their favor. Only a conclusive experimental result can resolve this ambiguity.

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