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β decay of ^{133}In: γ emission from neutron-unbound states in ^{133}Sn

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Excited states in ^{133}Sn were investigated through the β decay of ^{133}In at the ISOLDE facility. The ISOLDE Resonance Ionization Laser Ion Source (RILIS) provided isomer-selective ionization for ^{133}In, allowing us to study separately, and in detail, the β-decay branch of ^{133}In $J^{\pi} = (9/2^{+})$ ground state and its $J^{\pi} = (1/2^{-})$ isomer.

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Thanks to the large spin difference of the two β-decaying states of ^{133}In, it is possible to investigate separately the lower and higher spin states in the daughter, ^{133}Sn, and thus to probe independently different single-particle and single-hole levels. We report here new γ transitions observed in the decay of ^{133}In, including those assigned to the deexcitation of the neutron-unbound states.

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I. INTRODUCTION

Simple nuclear systems around doubly magic nuclei in exotic regions of the Segré chart are key to our understanding of nuclear structure. The observable evolution of the nuclear single-particle (s. p.) levels sequence far from stability has been postulated to arise from tensor and central forces [1,2], as the occupation of valence orbitals changes with the addition (or removal) of nucleons. Theoretical calculations predicting the evolution of shell structure require as an input complete information on s. p. states close to the core. In this context, the structure of ^{133}Sn, only one neutron above the doubly magic ^{132}Sn ($Z = 50$, $N = 82$), provides essential information on neutron s. p. energies, allowing us to predict properties of more complex nuclei in the ^{132}Sn region when moving further away from stability.

Moreover, nuclear astrophysics has a global interest in properties of neutron-rich nuclei, since they are used as input for modeling nucleosynthesis processes such as the *r* process. When no experimental data are available, theoretical predictions are used. So far, all calculations assume that when states above the neutron-separation energy (S_n) are populated in β decay, they deexcite through β-delayed neutron emission. Nonetheless this assumption is known to be not correct [3]. Recently, a strong competition between neutron and γ decay of levels above S_n was observed both in the ^{78}Ni and in the ^{132}Sn regions [4,5]. The fact that the γ deexcitation of neutron-unbound states can be observed and studied opens the possibility to hunt for those s. p. as well as single-hole (s. h.) states that are neutron unbound and were so far unobserved.

The study of ^{133}Sn provides excellent conditions to investigate single-particle transitions relevant in the neutron-rich ^{132}Sn region due to the simplicity of its nuclear structure. The applicability of the shell-model approach to interpret its nuclear structure arises from the doubly magic nature of ^{132}Sn. Such nature is evident from the high energy of its first excited state, $E(2^+,{}^{132}\mathrm{Sn}) = 4041$ keV [6,7], and the large spectroscopic factors determined for known states in ^{133}Sn ($S \approx 1$), revealing the purity of single-neutron excitations [8]. Simple configurations corresponding to neutron s. p. orbitals were assigned to low-lying states in ^{133}Sn, which were found at excitation energies of 854 keV ($\nu p_{3/2}$), 1367 keV ($\nu p_{1/2}$), 1561 keV ($\nu h_{9/2}$), and 2005 keV ($\nu f_{5/2}$) relative to the ($\nu f_{7/2}$) ground state of ^{133}Sn [5,8–12]. In view of the importance of the s. p. energies for predicting the properties of more complex nuclei, when moving away from the $N = 82$ and $Z = 50$ shell closures, different experimental techniques were adopted to confirm these values and find the last missing s. p. state corresponding to the $\nu i_{13/2}$ orbital. At higher excitation energies, states based on the two-particle single-hole ($2p1h$) configurations with respect to the ^{132}Sn core are expected. At present, information about them is limited to a tentatively deduced neutron-hole $\nu h^{-1}_{11/2}$ state [5,9].

β-decay studies seem to be a natural choice to investigate the nature of neutron-unbound states in ^{133}Sn, since there is a large energy window for their population in the β de-

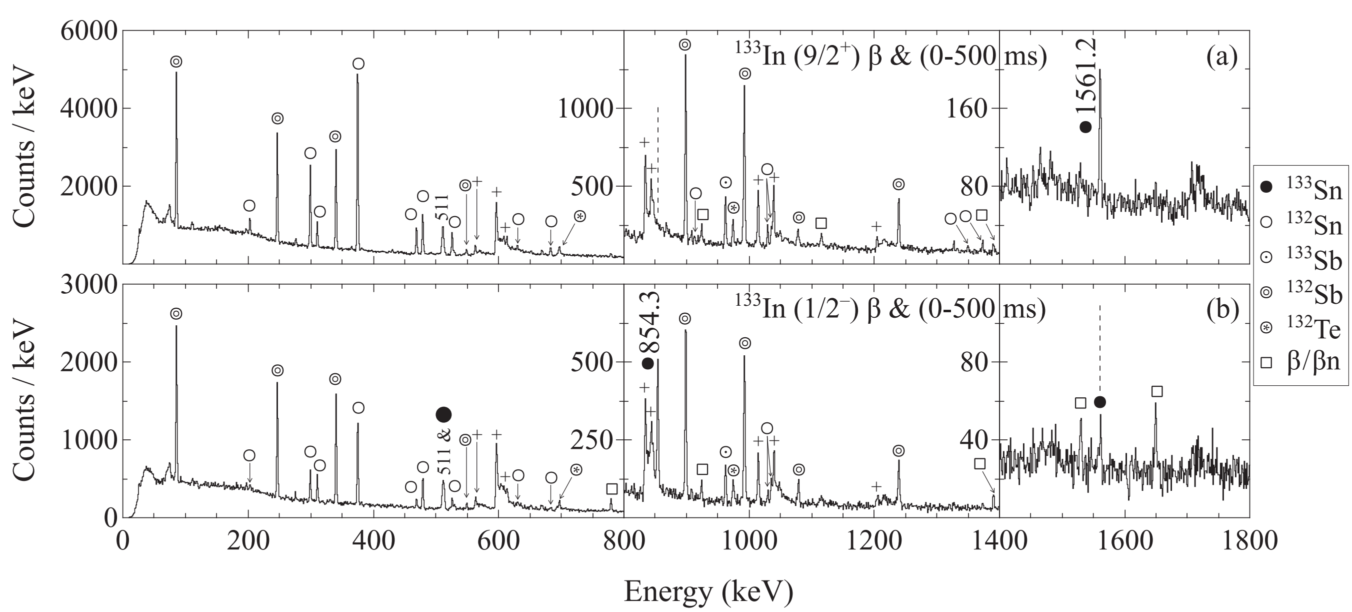

FIG. 1. Portions of β-gated γ-ray spectra within a time window of 500 ms after the proton impact, showing corresponding 854 keV and 1561 keV transitions in ^{133}Sn, which uniquely decay from the (a) ($9/2^+$) ground state or (b) ($1/2^-$) isomeric state of ^{133}In. Lines marked with a cross (+) arise from the neutron-induced activity.

cay of ^{133}In, determined by the high decay energy $Q_\beta = 13.4(2)$ MeV (based on systematics) and the low neutron-separation energy $S_n = 2.4$ MeV [13]. Previous β-decay studies of ^{133}In provided information about the energy of delayed neutrons, $E_n = 1.26$ MeV, associated with decay of the $(11/2^-)$ neutron hole state, positioning it at an excitation energy of ~3.7 MeV in ^{133}Sn [9,10]. According to recent work, the decay of this state proceeds not only via neutron emission, but also, with significant contribution, via electromagnetic decay leading to the emission of 3570(50) keV γ rays [5].

The purpose of this work is to reexamine β decay of ^{133}In, taking advantage of recent experimental developments, which open new possibilities to study this β decay. Until recently, β decay studies of ^{133}In were limited by the inability to perform independent studies of β decay of the ^{133}In ground state (^{133g}In), $I^\pi = (9/2^+)$, and isomeric state (^{133m}In) with $I^\pi = (1/2^-)$ and $E_{\mathrm{level}} = 330$ keV, both having similar half-lives. Only one half-life of $T_{1/2} = 180(15)$ ms was observed in the experiment with beam containing both ^{133g}In and ^{133m}In [9]. Recent advances in resonance ionization laser ion sources for on-line isotope separators (ISOL) result not only in increased beam production yields, but also enhanced their purity. In the case of measurements using a ^{133}In beam produced at ISOL facilities, the delivery of a beam free from isobaric contamination is not the only requirement. In order to investigate specific s. p. and s. h. levels in ^{133}Sn populated in β decay of ^{133}In, the possibility to study separately the decay of the ground state and of the isomeric state is needed and was achieved via selective laser ionization in this work for the first time.

II. EXPERIMENTAL TECHNIQUE

The β decay of ^{133}In was studied at the Isotope Separator On-Line (ISOLDE) facility [14] at CERN. Indium ions were produced by fission induced in a UC_x target by fast neutrons. Those were generated by a proton-to-neutron converter [15], with a beam of 1.4-GeV protons from the Proton Synchrotron Booster (PSB) having an average beam intensity of 1.9 μA. The fission products then diffuse from the target material to the hot ion source. The indium isotopes were ionized using a Resonance Ionization Laser Ion Source (RILIS) [16]. The application of isomer-selective ionization employing a titanium:sapphire (Ti:Sa) laser in narrow-band mode [17] allowed us to study separately the β decay of the ground- or the isomeric-state of ^{133}In [18]. Following extraction and acceleration by an electrostatic potential of 40 kV, the beam of ^{133}In was separated using the High-Resolution Separator (HRS) [14] and then implanted on a movable aluminized mylar tape in the middle of the ISOLDE Decay Station (IDS) [19]. Pulses from the PSB were separated in time by multiples of 1.2 s, while the indium beam was implanted continuously for 200 ms after each proton pulse. To suppress the long-lived daughter activities, the tape was moved after every 34–35 proton pulses, matching the duration of the CERN PSB supercycle.

In order to measure the β-decay products of ^{133}In, the detection setup at IDS consisted of β and γ detectors arranged in a close geometry surrounding the beam-implantation position. β particles were detected by a 3-mm thin plastic placed directly behind the ion collection point. For γ-rays detection we used four high-purity germanium Clovers ensuring high-resolution γ-ray spectroscopy up to 7.6 MeV

TABLE I. Relative γ-ray intensities (I_{rel}) following the β and βn decays of ^{133}In $(9/2^+)$ ground state and its $(1/2^-)$ isomeric level, normalized to the 4041-keV transition. It should be noted that, for the βn-decay channel, there might be some contribution coming from the beam impurity to the I_{rel} values presented below.

Decay channel	E_γ (keV)	I_{rel}[a] ^{133g}In $(9/2^+)$	^{133m}In $(1/2^-)$
β	513(1)	–	[b]
β	854.3(5)	–	33(2)
β	1561.2(5)	7.3(7)	–[c]
β	3181.1(5)	4.1(8)	–
β	3563.9(5)	38(4)	–[c]
β	6088(2)	4.8(7)	–[c]
βn	132(1)	[d]	
βn	203.0(5)	5.7(5)	2.9(5)
βn	299.4(5)	28(2)	13(1)
βn	310.4(5)	7.9(6)	11.0(9)
βn	375.1(5)	77(4)	43(2)
βn	469.0(5)	12.8(9)	5.8(7)
βn	478.9(5)	19(1)	18(1)
βn	526.0(5)	10.5(9)	6.9(7)
βn	630.1(5)[e]	<3	<3
βn	683.1(5)	5.6(5)	1.7(7)
βn	913.1(5)	1.6(3)	–
βn	1029.8(5)	3.9(8)	2.4(7)
βn	1035.8(5)	3.5(5)	6(1)
βn	1349.6(5)	1.3(4)	–
βn	1373.9(5)	2.3(5)	1.9(4)
βn	4041.1(5)	100(11)	100(11)
βn	4351.5(5)	54(6)	69(8)
βn	4416.2(5)	10(1)	8(1)
β and/or βn	779.4(5)[f]	2.4(8)	10(1)
β or βn	924.1(5)	4.0(6)	5(1)
β or βn	1115.6(5)	2.1(5)	–
β or βn	1390.6(5)	2.3(5)	4.7(7)
β or βn	1529.9(5)	–	2.9(9)
β or βn	1649.5(5)	–	6(1)
β or βn	3597(1)	3.5(9)	–
β or βn	5132(1)	–	6(1)
β or βn	5437(1)	–	9(1)
β or βn	5949(2)	–	7.7(9)
β or βn	6065(2)	–	5.5(8)

[a] For intensity per 100 decays of the parent, multiply by 0.122(15) and 0.109(13), for ^{133g}In and ^{133m}In, respectively.
[b] Seen in coincidence with 854 keV line.
[c] Beam impurity. The observed intensity is compatible with the amount of the $(9/2^+)$ ground state component in the ^{133}In $(1/2^-)$ isomeric beam.
[d] Seen in γ-γ coincidence spectra.
[e] Most probably a doublet line.
[f] Most probably a doublet line (780.8-keV transition reported in ^{132}Sn) [30].

and two $LaBr_3$(Ce) detectors, which were employed to measure lifetimes by applying the fast timing technique [20,21]. The Nutaq [22] digital data acquisition system (DAQ) was employed to read out the signals from the detectors and timing signals to correlate the activity with the proton impact on target. The fast plastic and $LaBr_3$(Ce) detector signals were preprocessed before being input into the digital DAQ [21]. Data were collected in triggerless mode. In the off-line analysis events were reconstructed, correlated with the time of arrival of the proton and coincidence gates as well as Clover add-back corrections were imposed.

Neutron-induced activity is a source of background that needs to be well understood for a consistent data analysis. Neutrons contributing to background activity can have two origins in this experiment: they may be produced by proton impact and emitted from the target area, or they may arise from the β decay of neutron-rich nuclei as delayed particles. The neutrons induce both (n,γ) and $(n,n'\gamma)$ reactions on the surrounding materials [23–25]. Particular attention was paid to the identification of γ transitions arising from these reactions. The neutron-induced peaks originating from interactions of neutrons from the target area are observed within the first 30 ms after the proton arrival. They were used to cross check the energy calibration at high energies. Their contribution can be removed by imposing a coincidence with the β detector and/or a time condition from the proton impact on target. The identification of γ rays following interactions of β-delayed neutrons is more complicated, since their time correlation is consistent with the half-life of ^{133}In, and they are also in coincidence with β particles.

III. EXPERIMENTAL RESULTS

In order to identify transitions following the β decay of ^{133}In, we studied β-gated γ-ray spectra within a time window from the proton impact on target, ranging from two to three half-lives of ^{133g}In and ^{133m}In. With such conditions, the contribution from daughters' activities, whose half-lives amount to 1.46(3) s for ^{133}Sn [26] and 39.7(8) s for ^{132}Sn [27], is significantly reduced.

In these spectra, we identified transitions corresponding to $^{133}\mathrm{In} \rightarrow {}^{132}\mathrm{Sn}$ βn decay and subsequent $^{132}\mathrm{Sn} \rightarrow {}^{132}\mathrm{Sb}$ β decay as the most intense ones. The quality of isomer selective laser ionization achieved in our experiment was demonstrated in Ref. [18], where we discussed the population of previously reported low-lying states in ^{133}Sn. An indication of the presence of the $(1/2^-)$ isomeric state of ^{133}In in the implanted beam is the detection of the 854 keV γ ray emitted from $(3/2^-)$ state in ^{133}Sn, whereas the line at 1561 keV, corresponding to depopulation of the $(9/2^-)$ state in ^{133}Sn, is the signature of the $(9/2^+)$ ground-state content. In Fig. 1 we present portions of β-gated γ-ray spectra showing relevant known transitions uniquely decaying from the $(9/2^+)$ or $(1/2^-)$ state of ^{133}In.

Although the ^{133m}In beam contained impurity originating from ^{133g}In of the order of $\sim$30%, it is always possible to determine whether a new line is present in the spectrum due to the one or the other states of ^{133}In. It can be clarified by comparing relative γ-ray intensities, significantly influenced when the RILIS was set to provide ^{133g}In versus ^{133m}In beam. The relative intensities (I_{rel}) of the γ rays assigned to β or

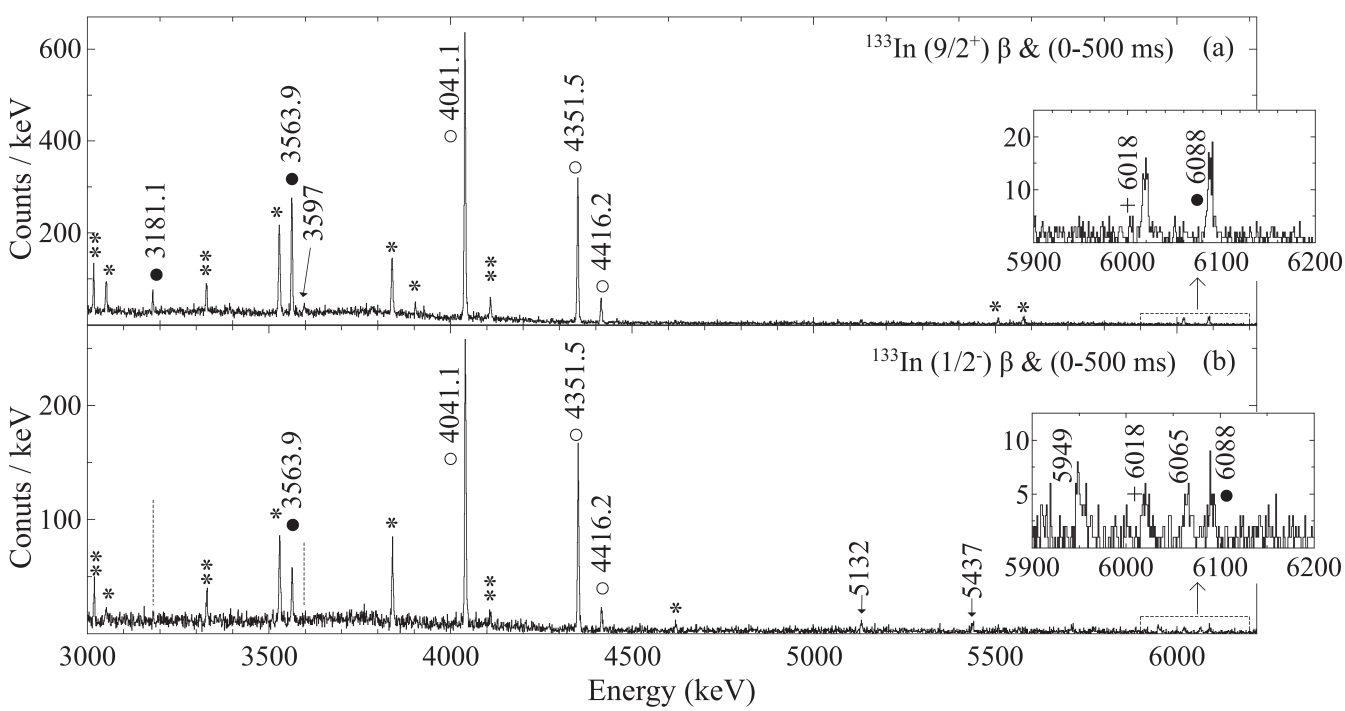

FIG. 2. Portions of the β-gated γ-ray spectra for the decay of the (a) ground and (b) isomeric state of ^{133}In recorded in the first 500 ms after the proton pulse occurrence. In the inserts, the zoom of the higher energy part is shown. Transitions in ^{133}Sn (•) and ^{132}Sn (○) are labeled by their energies. Lines marked with star symbols correspond to escape peaks (" * " first or " ** " second escape peak, respectively). The line at 6018 keV (marked with "+") was identified as originating from a neutron-induced background.

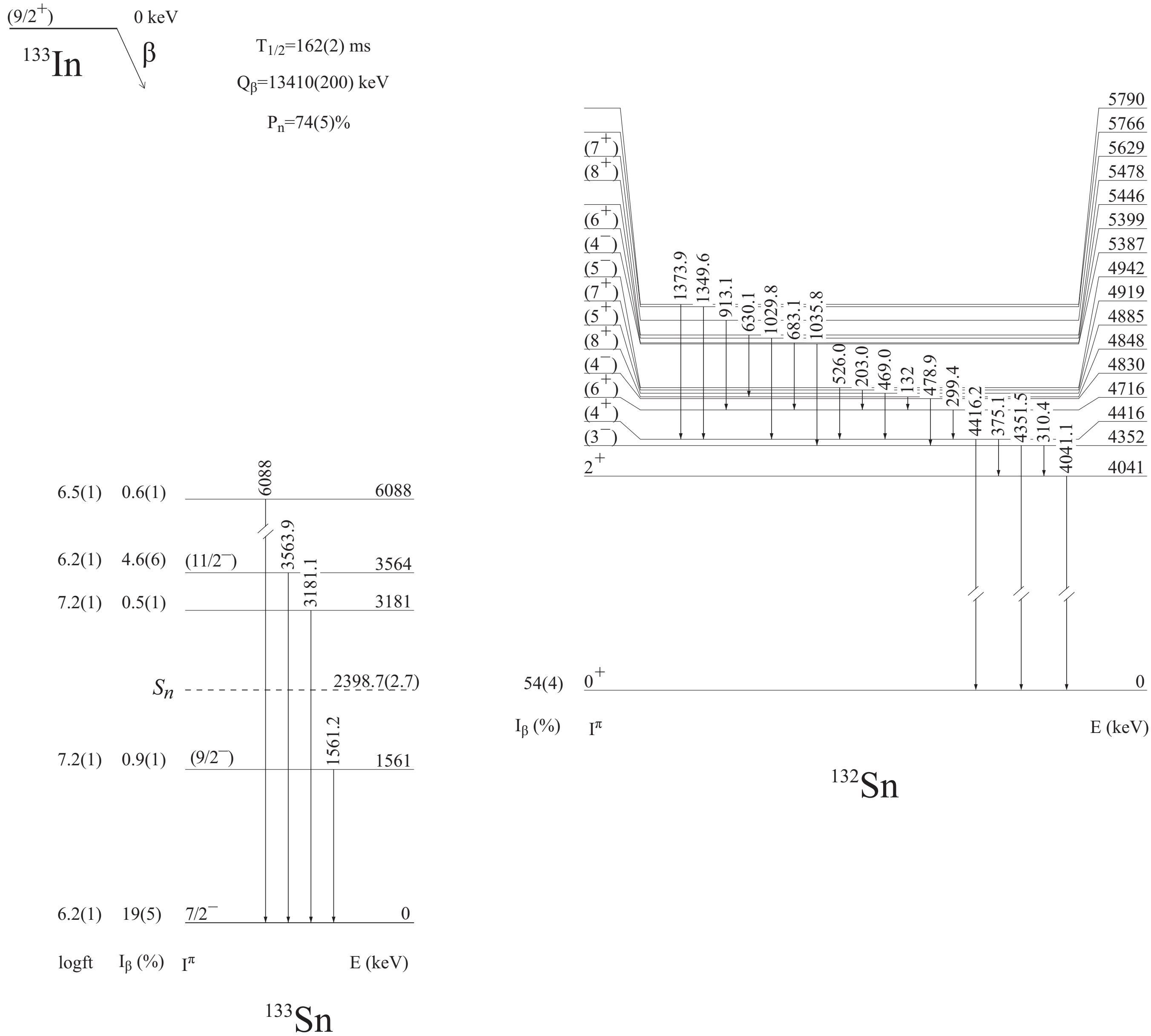

FIG. 3. Decay of ^{133g}In, $I^{\pi} = (9/2^{+})$, and apparent β feeding (I_{β}) to levels in ^{133}Sn. The β feeding to levels above S_n energy in ^{133}Sn is deduced only from γ transitions (see the text for more details). The spin-parity assignments of states in ^{132}Sn were adopted from Ref. [30]. The Q_{β} and S_n energies were taken from Ref. [13].

βn-decay branches of the $(9/2^{+})$ ground and $(1/2^{-})$ isomeric state of ^{133}In are given in Table I. Transition de-populating the $(5/2^{-})$ state in ^{133}Sn, 2004.6 keV [9,10], is not evident neither in the spectra of ^{133g}In nor ^{133m}In. We can estimate upper limits of its I_{rel}, $I_{rel} < 1$, and $I_{rel} < 0.7$ for the β decay of ^{133g}In and ^{133m}In, respectively.

A. β decay of the ground state of ^{133g}In, $I^{\pi} = (9/2^{+})$

The most intense transitions following the decay of $(9/2^{+})$ ground state of ^{133}In belong to its βn-decay channel (see Table I). Besides the known 1561.2-keV transition assigned to ^{133}Sn, we identified new transitions following the decay of the $(9/2^{+})$ ground state at energies 924.1(5), 1029.8(5), 1115.6(5), 1349.6(5), 1373.9(5), 1390.6(5), 3181.1(5), 3563.9(5), 3597(1), and 6088(2) keV [see Figs. 1(a) and 2(a)]. Their assignment is justified by the analysis of their time dependences relative to the proton pulses. Their belonging to the neutron-induced background was excluded. Analysis of the β-γ-γ data allowed us to construct the decay scheme of ^{133g}In. Three new transitions, 3181 keV, 3564 keV, and 6088 keV, could be placed in the level scheme of ^{133}Sn, see Figs. 2(a) and 3. Note that they deexcite levels above the neutron-separation energy. A half-life of $T_{1/2} = 167(7)$ms was obtained for the 3564 keV transition (Fig. 4). In order to determine ^{133g}In half-life value, three γ transitions were considered: the new γ transition at 3563.9 keV and known β-n-γ transitions at 375.1 keV and

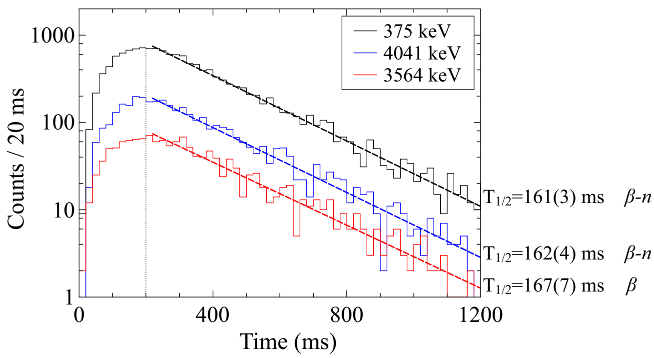

FIG. 4. Time distribution of the 375.1-, 4041.1-, and 3563.9-keV γ rays in coincidence with β particles with respect to the proton pulse. The fit of decay pattern is shown as a dashed line corresponding to the ^{133g}In decay. The vertical line indicates the end of the implantation.

4041.1 keV (see Fig. 4). We adopt the weighted average of 162(2) ms as the ^{133g}In half-life. This value is consistent with two recent results known from the literature, 165(3) ms [28] and 163(7) ms [29]. For the 3181 keV and 6088 keV transitions, the time analysis gave low-precision results because of the limited statistics, but still in accordance with the half-life of ^{133g}In. The analysis of the β-γ-γ coincident data allowed us to assign three new transitions, 1030 keV, 1350 keV, and 1374 keV, to ^{132}Sn since they are observed in coincidence with 375 keV and 4041 keV γ rays. Analysis of the β-γ-γ and γ-γ matrices does not indicate any coincidences for other new transitions.

B. β decay of the isomeric state of ^{133m}In, $I^\pi = (1/2^-)$

The analysis of the β-γ-γ data confirmed that the 854-keV and 513-keV transitions are in coincidence with each other and therefore follow the decay of the $I^\pi = (1/2^-)$ isomer [18]. The observed $(1/2^-) \rightarrow 3/2^- \rightarrow 7/2^-$ cascade supports the low-spin assignment for the decaying state in the progenitor (see Fig. 5) [8]. Several new transitions at energies 924.1(5), 1029.8(5), 1373.9(5), 1390.6(5), 1529.9(5), 1649.5(5), 5132(1), 5437(1), 5949(2), and 6065(2) keV were observed in spectra [see Figs. 1(b) and 2(b)] and assigned to this decay. The low statistics did not allow us to measure the half-life of the individual new transitions, but we could confirm that they are consistent with the half-life of ^{133m}In, $T_{1/2} = 167(11)$ ms (Fig. 6), and therefore it is excluded that they belong to the decay of the granddaughter or any other nucleus in the isobaric mass chain. In the spectra collected with RILIS set on the $(1/2^-)$ isomeric state [Figs. 1(b) and 2(b)] weak transitions originating from the ground-state decay can be observed, due to a small ^{133g}In beam component.

C. Analysis of the apparent β feeding

The absolute intensities of the γ rays following the β decay of ^{133}In daughters, ^{132}Sn and ^{133}Sn, were used to calculate the number of ^{133}Sn and ^{132}Sn nuclei produced in the ^{133g}In and ^{133m}In decay. We adopted absolute γ-ray intensities of relevant transitions, I_{abs}(962 keV, ^{133}Sn $\rightarrow$ ^{133}Sb) = 12(2)% and I_{abs}(340 keV, ^{132}Sn $\rightarrow$ ^{132}Sb) = 48.8(12)% from Refs. [31,32], respectively. Corrections to account for the tape movement and different half-lives of ^{132}Sn and ^{133}Sn were included in the calculations. The determination of the number of nuclei produced both following the β and βn decays of ^{133}In allows us to calculate the βn emission probability, which was found to be $P_n = 74(5)\%$ for the $(9/2^+)$ ground state and $P_n = 80(5)\%$ for the $(1/2^-)$ isomeric level. The apparent β feeding intensities (I_β) to levels in ^{133}Sn are summarized in Fig. 3. When no γ rays were detected the remaining intensity arising from both the β and βn decays was assigned to apparent ground-state feeding. Since some decays could proceed to states deexcited by weak, undetected γ-ray transitions, β feeding intensities should be taken as apparent. In particular, for levels located at excitation energies exceeding S_n in ^{133}Sn, they should be considered only as a lower limit, since the population of neutron unbound states followed by neutron emission cannot be accounted for.

D. Lifetime measurement of 854 keV state in ^{133}Sn

The fast timing technique was applied in order to measure the half-life of the $3/2^-$ level at 854 keV in ^{133}Sn. Despite the fact that the 854 keV and 513 keV transitions are in coincidence, it was not possible to apply triple (β-γ[HPGe detector]-γ[$LaBr_3$(Ce)]) coincidences because of the limited statistics. Instead double (β-γ[$LaBr_3$(Ce)]) coincidences were employed, by means of the centroid-shift method [20,21], using as a reference point the centroid position of the time-delayed spectrum gated by the 1561 keV γ transition, which is assumed to be prompt. In this way, an upper limit on the lifetime was obtained, $T_{1/2} < 34$ ps, which appears to be consistent with the value of 21(11) ps recently reported [5]. It was not possible to determine lifetimes of other states because of the high energy of the deexciting transitions and the low efficiency of the $LaBr_3$(Ce) detectors at these energies.

IV. DISCUSSION

The wave functions of states at low excitation energies in ^{133}Sn, a nucleus with only one valence neutron outside the ^{132}Sn core, should be dominated by s. p. neutron orbitals between $N = 82$ and $N = 126$ shells (Fig. 7). At higher excitation energies, states built on the neutron $(\nu f^2_{7/2})\nu^{-1}$ or proton $\nu^1\pi^1\pi^{-1}$ two-particle one-hole configurations are expected. Due to the low neutron-separation energy of ^{133}Sn, the majority of those excited states are neutron unbound. Thanks to the large spin difference of the two β-decaying states of ^{133}In, it is possible to investigate separately the lower and higher spin states in ^{133}Sn and thus to probe independently different s. p. and $2p1h$ levels relevant in the ^{132}Sn region.

The knowledge about neutron s. p. states above $N = 82$ is almost complete. The only still unobserved s. p. state in this region, $13/2^+$ $(\nu i_{13/2})$, has been hypothesized to be neutron unbound in ^{133}Sn as it is expected at excitation energy about 2.5 MeV [33]. This state would be populated in the second-forbidden decay of the $(9/2^+)$ ^{133g}In, making it a rather hindered transition; it is not observed in this study. All

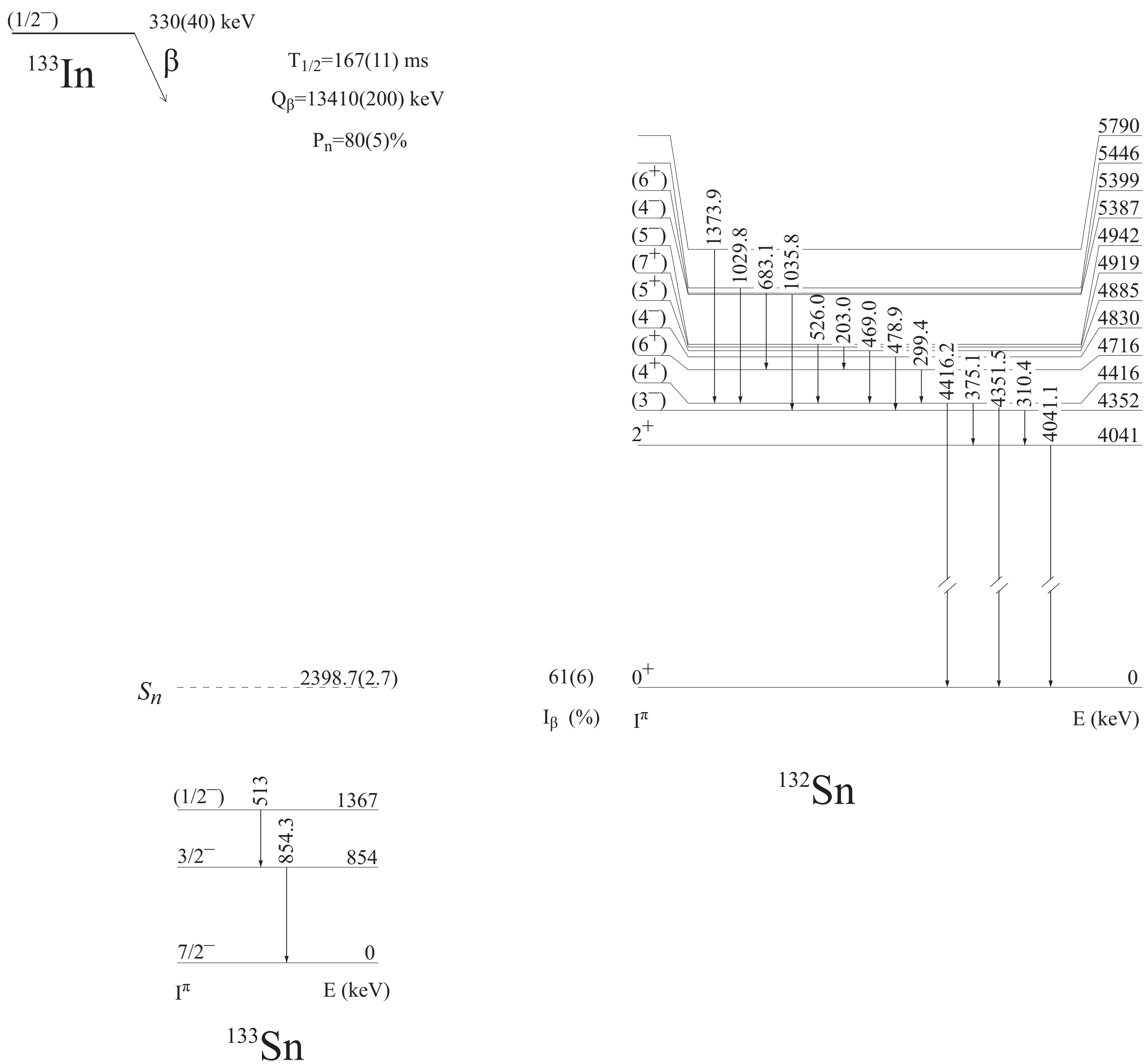

FIG. 5. Decay of ^{133m}In, I$^\pi$ = (1/2$^-$). The spin-parity assignments of states in ^{132}Sn adopted from Ref. [30]. The Q$_\beta$ and S$_n$ energies were taken from Ref. [13], the energy of the $I^\pi = (1/2^-)$ isomeric state of ^{133}In was adopted from Ref. [26]. The determination of the apparent β feeding to the levels in ^{133}Sn was not possible due to unresolved contribution of the 511-keV annihilation γ-ray in the 513-keV photopeak.

known transitions depopulating excited states with I$^\pi = 1/2^-$ ($\nu p_{1/2}$), $3/2^-$ ($\nu p_{3/2}$), and I$^\pi = 9/2^-$ ($\nu h_{9/2}$) assignments in ^{133}Sn were confirmed in this work. On the other hand, β feeding to the ($5/2^-$) ($\nu f_{5/2}$) level was not evident neither in the decay of ($9/2^+$) nor ($1/2^-$) state of ^{133}In.

A. Neutron single-hole excited states in ^{133}Sn

The relevant s. p. levels in the ^{132}Sn region are depicted in Fig. 7. Strong population of the $11/2^-$ ($\nu h^{-1}_{11/2}$) and $7/2^+$ ($\nu g^{-1}_{7/2}$) neutron single-hole ($2p1h$) states in ^{133}Sn is expected in the β decay of the ($9/2^+$) ground state of ^{133}In. The β decay of its ($1/2^-$) isomeric state would instead proceed by feeding the $1/2^+$ ($\nu s^{-1}_{1/2}$) and $3/2^+$ ($\nu d^{-1}_{3/2}$) states, which also have a neutron-hole nature. The spin-parity selection rules favor population of $7/2^+$ level via the $\nu g_{7/2} \to \pi g_{9/2}$ Gamow-Teller transition resulting in the $\nu f^2_{7/2}\, g^{-1}_{7/2}$ daughter configuration (see Fig. 7). The corresponding $\nu g^{-1}_{7/2}$ hole state in ^{131}Sn was found at an excitation energy of 2434 keV with receiving the overwhelming majority of the β feeding, as demonstrated by the very low $\log ft = 4.4$ [34]. Only one level in ^{131}Sn located at lower excitation energy [$E_{\rm level} = 65.1(3)$ keV] than

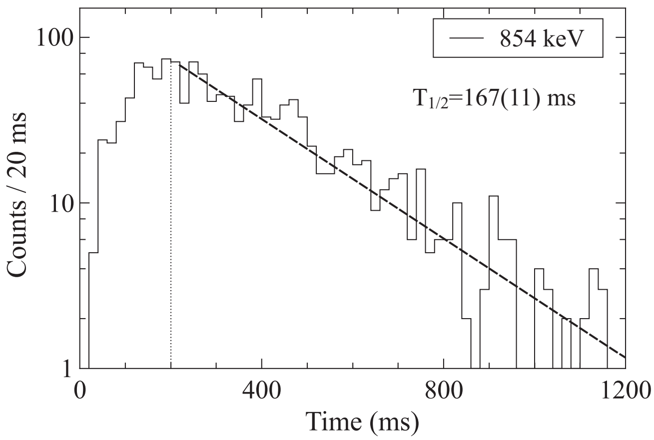

FIG. 6. Time distribution of the 854.3-keV γ-rays in coincidence with β particles with respect to the proton pulse. The fit of decay pattern is shown as a dashed line. The vertical line indicates the end of the implantation.

the $7/2^+$ state, which was assigned $I^\pi = 11/2^-$ spin-party, is fed in the decay of the $(9/2^+)$ ^{131}In ground-state ($\log ft > 5.6$) [34]. The systematics of neutron hole states in the lighter odd $^{125-131}$Sn isotopes follow a smooth trend, see Fig. 8. The excitation energies of the single-hole configurations increase

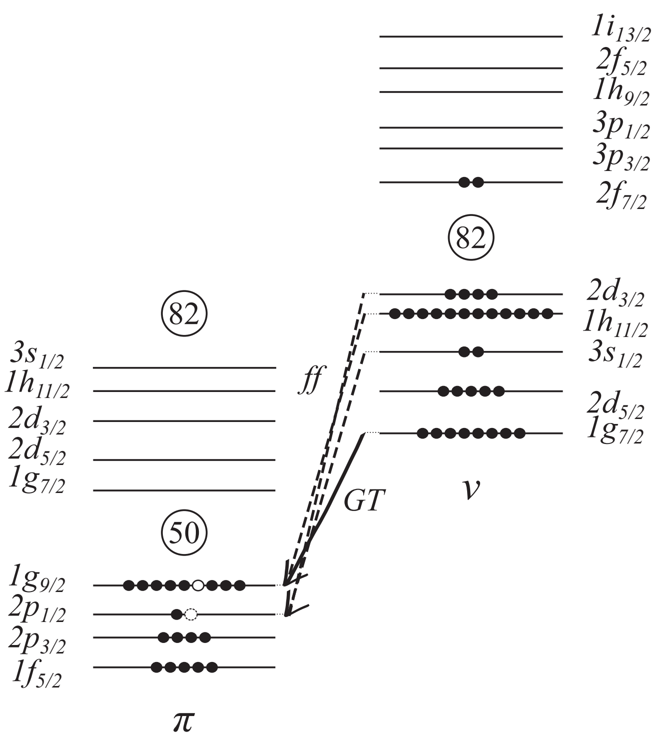

FIG. 7. Schematic view of single-particle states involved in Gamow-Teller (GT) and first forbidden (ff) decays resulting in the population of neutron hole states in ^{133}Sn. Configurations of ^{133}In are represented by circles corresponding to two neutron particles occupying the $\nu f_{7/2}$ orbital and the proton hole located on $\pi g_{9/2}$ (the ground state, solid stroke) or $\pi p_{1/2}$ orbital (isomeric state, dashed stroke).

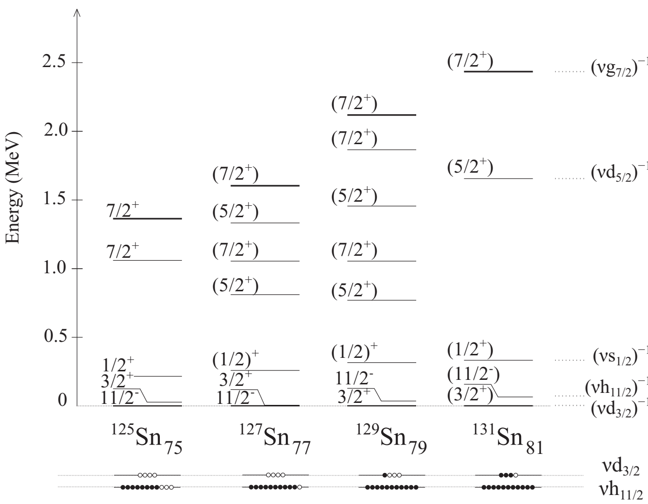

FIG. 8. Systematics of $1/2^+, 3/2^+, 5/2^+, 7/2^+$, and $11/2^-$ states in odd $^{125-131}$Sn isotopes observed in β-decay studies of $^{125-131}$In isotopes [34–36]. Bold levels with $I^\pi = 7/2^+$ assignments have the biggest feedings following the β decays of $9/2^+$ states of indium isotopes.

with the addition of the next pair of neutrons. According to the systematics of the lowest-energy levels in odd $^{125-131}$Sn nuclides, the two lowest-energy levels having s. h. nature in ^{133}Sn are expected to be the $3/2^+$ and $11/2^-$ states.

The identification of s. h. states in ^{133}Sn is more complicated than in lighter Sn isotopes, since the neutron-separation energy is drastically reduced just after crossing the $N = 82$ magic number. Consequently, β-delayed neutron emission is the main decay mode of ^{133}In, involving also s. h. states in ^{133}Sn, which are all expected to be neutron unbound. However, the high excitation energy of the first 2^+ state in ^{132}Sn, $E(^{132}\mathrm{Sn}, 2^+) = 4041$ keV [6,7], leads to favorable circumstances to observe γ emission from at least some of the neutron unbound states in ^{133}Sn. In the case of the decay of neutron unbound states in ^{133}Sn located at excitation energies up to ~6.4 MeV, the kinematics of β-delayed neutron emission ($E_i^\star = S_n + E_f^\star + E_n$) would limit the final level that can be fed in ^{132}Sn to its ground state. If neutron unbound states of ^{133}Sn such as $7/2^+$ and $11/2^-$ are located below this energy threshold, their decay via neutron emission would have to proceed with $\ell = 4$ or $\ell = 5$, respectively. Due to centrifugal barrier hindering the neutron from leaving the nucleus, the contribution of electromagnetic decay of those unbound states would be significant. The observation of this phenomenon in the ^{132}Sn region was reported recently by Vaquero *et al.* [5] for the level found in ^{133}Sn at 3570(50) keV. This competition between neutron and γ decay of unbound states was attributed to a nuclear structure effect. In the case of lower spin states expected to be populated at excitation energies exceeding S_n of ^{133}Sn, such as $1/2^+$ $(\nu s_{1/2}^{-1})$ and $3/2^+$ $(\nu d_{3/2}^{-1})$, the aforementioned scenario would not be valid, since neutron emission with lower ℓ would not be hindered. Hence, the identification of lower spin states in ^{133}Sn is more complicated, since the γ-ray emission from them is not significant enough a decay mode to compete with neutron emission.

Owing to the isomer selectivity the observation of new transitions following only the decay of the $(9/2^+)$ ground state of ^{133}In gives the opportunity to connect them with missing higher spin states in ^{133}Sn, including those corresponding to the $\nu h_{11/2}^{-1}$ and $\nu g_{9/2}^{-1}$ configurations. We indicate here new transitions deexciting high spin states in ^{133}Sn at energies 3181, 3564, and 6088 keV.

The new γ-ray transition identified in this work at 6088 keV is assigned to the de-excitation of the 6088 keV level in ^{133}Sn. Other placement of this transition in the decay scheme of of ^{133}In is not supported by β-γ-γ coincidences. For this level, we calculated β feeding resulting from γ-ray contribution and $\log ft = 6.5$ was obtained, see Fig. 3. It is worth noting that this level ($\sim$3.7 MeV above S_n) may deexcite also by neutron emission to the ground state of ^{132}Sn. If we assumed that the I_β intensity determined for the ground state of ^{132}Sn (Fig. 3) was entirely due to the decay of this 6088 keV level, $\log ft = 4.5$ would be obtained. This suggests that the level is fed by a Gamow-Teller transition, and consequently $I^\pi = (7/2^+)$ assignment is proposed for it. As a cross check the energy of the $7/2^+$ neutron-hole state in ^{133}Sn can be estimated using the energies of the 6^- and 7^- states in ^{132}Sn, which provide empirical information about the $\nu f_{7/2}\, g_{7/2}^{-1}$ interaction. These states were identified in β-decay studies of ^{132}In and their energies were deduced to be 7210 keV (6^-) and $\sim$7550 keV (7^-) [7]. Using these values together with the known s. p. and s. h. energies from this region, the energy of $7/2^+$ state in ^{133}Sn was calculated to be about 6.1 MeV. This value, even if it is a rough estimate, led to the conclusion that the γ ray deexciting this state should be observed.

The next s. h. level in ^{133}Sn, which is expected to be populated in the β decay of the $(9/2^+)$ ground state of ^{133}In, is the $I^\pi = (11/2^-)$ state. Such a state was identified by Hoff *et al.* at an excitation energy of about 3700 keV [9]. Recently, a 3570(50) keV transition was assigned as the deexcitation of the same level [5]. In this work we provide improved accuracy of the energy of the $(11/2^-)$ state, 3563.9(5) keV. This level, located $\sim$1.1 MeV above the S_n energy of ^{133}Sn, decays also through neutron emission. Hoff *et al.* observed 1.26 MeV neutrons following the decay of ^{133}In and related them to the decay of $(11/2^-)$ state populated in ^{133}Sn [9,10]. Since the contribution of neutrons in the decay of this state was clearly manifested in their spectra, real β feeding to the 3564 keV level is bigger than determined from our data, hence $\log ft = 6.2$ should be treated as an upper limit.

Concerning the 3181 keV state, shell-model calculations predict a $11/2^-$-$19/2^-$ multiplet corresponding to the configuration $\nu f_{7/2}^2\, h_{11/2}^{-1}$ between about 3.5 and 4.5 MeV and a $3/2^+$-$15/2^+$ multiplet corresponding to $\nu f_{7/2}^2\, d_{3/2}^{-1}$ between 3.3 and 5 MeV [37]. The only states that can be expected below 3.5 MeV are those from the $3/2^+$-$15/2^+$ multiplet. Taking into account that the 3181 keV level is populated in the decay of the $9/2^+$ ground state and that the calculated energies of the levels depend on monopole corrections, we propose a tentative spin-parity assignment of $I^\pi = (7/2^+,\ 9/2^+,\ 11/2^+)$ for 3181 keV level in ^{133}Sn. This β feeding transition from the $9/2^+$ ground state of ^{133}In is similar to the $9/2^+ \rightarrow (7/2^+)$ transition in the decay of ^{129}In feeding the 1047-keV state in ^{129}Sn [36].

B. Proton single-hole excited states in ^{133}Sn

Population of states having proton-hole nature, $\nu f_{7/2}\, \pi g_{7/2}\, g_{9/2}^{-1}$, should also be considered in studies of ^{133}In decay, since first forbidden $\nu f_{7/2} \rightarrow \pi g_{7/2}$ transition to orbitals above the $Z = 50$ shell closure can also occur (see Fig. 7). On the basis of empirical calculations using the experimental interactions for $\pi g_{7/2}\, g_{9/2}^{-1}$, $\nu f_{7/2}\, \pi g_{7/2}$, and $\nu f_{7/2}\, \pi g_{9/2}^{-1}$ deduced from corresponding states in ^{132}Sn, ^{134}Sb, and ^{132}Sb [30], the excitation energy of such level is expected at about 4.8 MeV. Taking into account the value of $\log ft = 5.6$ for an analog state in ^{132}Sn, $\pi g_{7/2}\, g_{9/2}^{-1}$ at 5.6 MeV [30], the β feeding to the presumed 4.8 MeV state in ^{133}Sn was estimated to be about 2%. It is worth noting that this level would depopulate both by neutron and by γ decay. The nonobservation of candidates for the decay of such levels is compatible with the low branching.

Gamow-Teller decay from deeply bound neutrons in ^{133}In (e.g., $\nu 2d_{5/2} \rightarrow \pi 2d_{5/2}$ and $\nu 1g_{7/2} \rightarrow \pi 1g_{7/2}$) would lead to highly excited states for which γ deexcitation is not competing with neutron emission. The initial and final wave functions would have, e. g., configurations $\nu f_{7/2}^2\, \pi g_{9/2}^{-1}$ or $\nu f_{7/2}^2\, \pi p_{1/2}^{-1}$ and $\nu f_{7/2}^2\, g_{7/2}^{-1}\, \pi g_{7/2}\, g_{9/2}^{-1}$ or $\nu f_{7/2}^2\, g_{7/2}^{-1}\, \pi g_{7/2}\, p_{1/2}^{-1}$. A hint of the fact that this happens in the decay of both ^{133g}In and ^{133m}In is given by observation of almost the same transitions assigned to ^{132}Sn in both decays.

V. SUMMARY AND CONCLUSIONS

The structure of ^{133}Sn has been studied from the β decay of ^{133}In. By taking advantage of the isomer selectivity capabilities of the ISOLDE RILIS, independent investigation of the β decay of the ^{133}In $(9/2^+)$ ground state and the ^{133}In $(1/2^-)$ isomer could be performed.

Three states above the neutron-separation energy have been identified in the ^{133}Sn nucleus, some of them for the first time. They all decay by electromagnetic radiation to the ground state. The high-lying γ-decaying states have predominant two-particle one-hole neutron configurations. The 6088-keV state is proposed to have $(7/2^+)$ spin-parity and be predominantly the neutron single-hole state based on the $\nu f_{7/2}^2\, g_{7/2}^{-1}$ configuration, while the 3564-keV state is proposed to be built on the $\nu f_{7/2}^2\, h_{11/2}^{-1}$ configuration, with assigned $(11/2^-)$ spin-parity. A spin-parity assignment of $I^\pi = (7/2^+, 9/2^+, 11/2^+)$ is tentatively proposed for the 3181-keV level.

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