INVESTIGATION OF LOW-LYING STATES IN ^{133}Sn POPULATED IN THE β DECAY OF ^{133}In USING ISOMER-SELECTIVE LASER IONIZATION*

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Excited states in the neutron-rich isotope ^{133}Sn were studied via the β decay of ^{133}In. Isomer selective ionization using the ISOLDE RILIS enabled the β decays of ^{133}In$_{\mathrm{gs}}$ ($I^{\pi} = 9/2^{+}$) and ^{133m}In ($I^{\pi} = 1/2^{-}$) to be

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studied independently for the first time. A description of the experimental setup at the ISOLDE Decay Station is presented together with preliminary results from the experiment.

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1. Introduction

In the last two decades technological advances have allowed new experimental studies to extend our knowledge about the neutron-rich nucleus ^{133}Sn. This nuclide, having one neutron above the doubly magic ^{132}Sn core, is the main player to deduce neutron single-particle (SP) states above $N = 82$. The first investigation of ^{133}Sn was performed with β-decay spectroscopy of ^{134}In, for which the large probability of β-delayed neutron emission ($P_n = 65\%$ [1]) opens great possibilities to study the states of interest by measuring γ rays in coincidence with delayed neutrons [2, 3]. These measurements were later followed by reaction studies based on one-neutron transfer reactions [4–7]. The aforementioned investigations provided mutually consistent information about SP energies for $\nu p_{3/2}$ ($E = 854$ keV), $\nu p_{1/2}$ ($E = 1363$ keV), $\nu h_{9/2}$ ($E = 1591$ keV) and $\nu f_{5/2}$ ($E = 2005$ keV) neutron orbitals relative to the $\nu f_{7/2}$ ground state of ^{133}Sn. Nevertheless, the question of the position of the neutron unbound $\nu i_{13/2}$ state remains open for investigation. In addition, recent studies indicate the need to study highly-excited states in ^{133}Sn, for which γ-ray emission was found to be a decay mode, competing with β-delayed neutron emission [7].

Studies of ^{133}Sn via the β decay of ^{133}In, which were not successfully performed so far [2], are a reliable way to provide precise data to clarify the structure of excited states in ^{133}Sn. The ^{133}In β-decay studies can be performed not only for the $I^\pi = (9/2^+)$ ground state ($T_{1/2} = 165(3)$ ms [8]), but also, independently, for the decay of its $I^\pi = (1/2^-)$ isomeric level, which has a similar half-life ($T_{1/2} = 180(10)$ ms [8]).

The purpose of this work was to verify the experimental possibilities to investigate separately the β decay from the ^{133}In $I^\pi = (9/2^+)$ ground state and its $I^\pi = (1/2^-)$ isomeric level. Since there is a large spin difference for the two β-decaying states of the parent-nucleus, they are expected to populate different levels in the daughter nucleus ^{133}Sn.

2. Experiment

Our experiment was performed at the Isotope Separator On-Line facility (ISOLDE) [9] at CERN, where 1.4 GeV protons from the Proton Synchrotron Booster (PSB) were directed on a uranium carbide target equipped with a neutron converter. Fission products were diffused from the target material and then effused via a transfer line to the "hot cavity" ion source for ionization towards the ionizer tube. Ionization of the desired atoms was provided by the Resonance Ionization Laser Ion Source (RILIS) [10]. After extraction and acceleration by an electrostatic potential of 40 kV, ions of ^{133}In were mass separated using the High Resolution Separator (HRS) [11]. Finally, the ion beam was transmitted to the ISOLDE Decay Station (IDS) [12] and implanted on a movable tape. The collection point was surrounded by four HPGe clover detectors, two $LaBr_3$(Ce) detectors and a fast-time response β detector, which consisted of thin plastic scintillator (1 inch in diameter) coupled to a fast PMT. All signals from the detection system, including the proton timing signal from PSB were recorded and sampled in a triggerless mode using the Nutaq digital data acquisition system [13]. This enabled the off-line correlation of the events with the time of the proton pulse impact on the target.

Thanks to the RILIS, which not only offers element selectivity but also allows for isomer selective ionization for odd-mass In isotopes, the β decay of ^{133}In was studied with selective ionization of either ^{133g}In or ^{133m}In. The RILIS was applied to ionize indium with an ionization scheme consisting of a resonant first excitation step and a non-resonant (NR) ionizing step $\{\lambda_1|\lambda_2\} = \{304\text{ nm}|532\text{ nm}^{\rm NR}\}$ [14, 15]. The resonant transition was excited with frequency tripled light from a Titanium:Sapphire (Ti:Sa) laser operated in a "narrowband" mode of operation (fundamental linewidth $\sim$ 800 MHz) [16]. The different hyperfine structures in the atomic energy levels of the $I^\pi = 9/2^+$ ground state and the $I^\pi = 1/2^-$ isomer made it possible to employ the narrowband Ti:Sa laser for isomer selective ionization of indium. The RILIS scan was performed with the less exotic beam of ^{129}In. A schematic drawing illustrating the principle of a RILIS scan is presented in Fig. 1. The number of counts for γ rays that uniquely decay

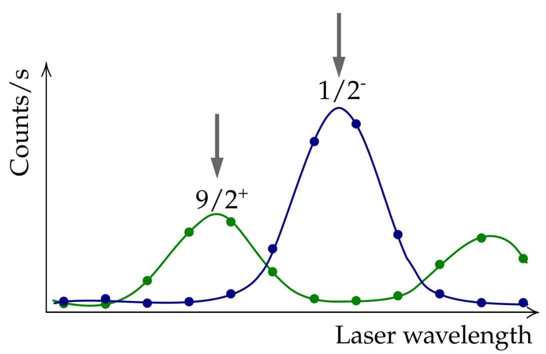

Fig. 1. Schematic drawing behind the idea of the online RILIS-IDS scan for ^{129}In beam, performed to find optimum laser wavelength providing minimum mixing ratio of β-decaying states (see the text for details).

from $I^\pi = 9/2^+$ ground state or $I^\pi = 1/2^-$ isomeric state of ^{129}In are plotted as a function of the wavelength of the narrowband Ti:Sa laser. The evaluation of the ground state/isomer ion beam composition as a function of laser wavelength allowed the selection of the optimum laser frequency to study the decay from a desired state of the parent nucleus with a minimum mixing ratio of ground state *versus* isomer.

3. Results and discussion

In Fig. 2, we present the time-correlated β-gated γ-ray spectra recorded by the HPGe detectors for ^{133}In decay, which were measured independently for the decay of the $I^\pi = (9/2^+)$ ground state and the $I^\pi = (1/2^-)$ isomer. The total duration of the measurement with selective separation for ^{133}In ions in the ground state was 18.5 hours, while for ions in its isomeric state, it lasted for 11.5 hours. We identified γ rays following $^{133}\text{In} \to {}^{133}\text{Sn}$ decay at energies 854 keV and 1561 keV. The 854 keV line was found to be in β–γ–γ coincidence with the 513 keV transition (Fig. 2). Other tran-

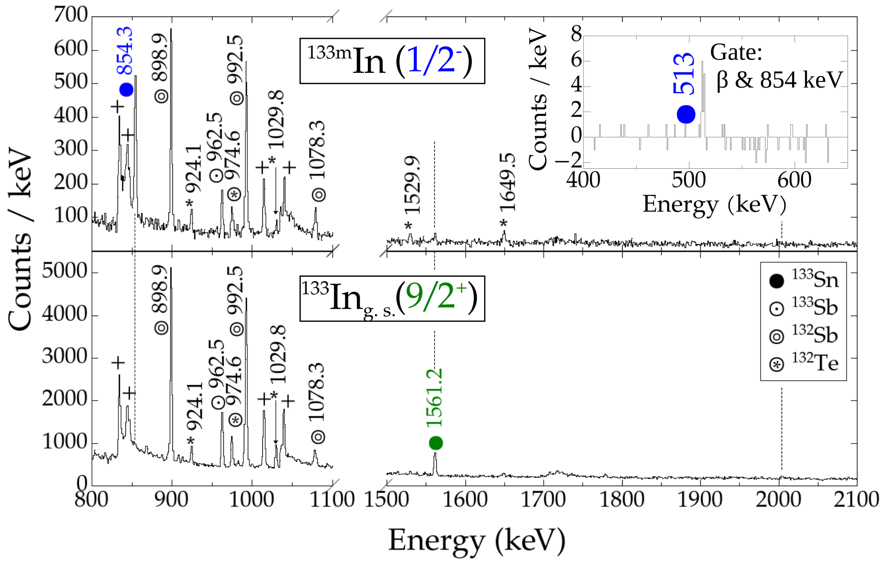

Fig. 2. Portions of the β-gated γ-ray spectra of the ^{133}In decay measured with RILIS set on $I^\pi = (1/2^-)$ isomeric state (upper part) and $I^\pi = (9/2^+)$ ground state (lower part), time-correlated with the proton pulse occurrence. The time gate corresponds to about three half-lives of the ground and isomeric states of ^{133}In, respectively [8]. Part of the β-gated γ-ray spectrum in coincidence with the 854 keV transition is presented in the upper right corner. Lines marked with a star ($*$) are unassigned, while those marked with a cross (+) arise from the neutron-induced activity.

sitions visible in both spectra belong to daughter activities present in the subsequent part of the decay chain of ^{133}In. Dominant lines in Fig. 2 arise from the ^{132}Sn → ^{132}Sb decay [17]. Apart from that, we identified lines corresponding to neutron-induced activity, mainly due to inelastic neutron scattering reactions with stable germanium isotopes in the detectors [18].

The difference in the γ-ray spectra for ^{133}In decay from ground- and isomeric-state can be explained by spin-parity selection rules. Because of the large spin difference between these two states, their decay will populate different groups of levels. In the decay of the $I^\pi = (1/2^-)$ isomeric state, two levels with assigned low-spin values, $I^\pi = 3/2^-$ ($E_\gamma = 854$ keV) and $I^\pi = (1/2^-)$ ($E_\gamma = 513$ keV) are fed in the ^{133}Sn daughter nucleus. It should be noted that in our spectrum there is no line at 2005 keV, which was reported in previous β-decay studies of ^{133}In [2]. Our results confirm previous observations about low-lying states in ^{133}Sn including consistent information about the position of the $I^\pi = (1/2^-)$ state, observed in the β decay of ^{133}In for the first time. A partial decay scheme of ^{133}In is presented in Fig. 3. The presence of a very weak 1561 keV line in the γ-ray spectrum of the decay of isomeric $I^\pi = (1/2^-)$ state is due to a small impurity of the beam. When the laser wavelengths were optimized to selectively ionize ^{133}In atoms in the isomeric state, the ratio of ions in the isomeric state *versus* those in the ground state was not high enough to completely suppress the contribution from the decay of the $I^\pi = (9/2^+)$ ground state. The intensity of the 1561 keV γ ray was used to evaluate the impurity of the beam originating from the presence of ions in the $I^\pi = (9/2^+)$ ground state. The ratio of 1561 keV γ-ray intensities registered when RILIS was set on

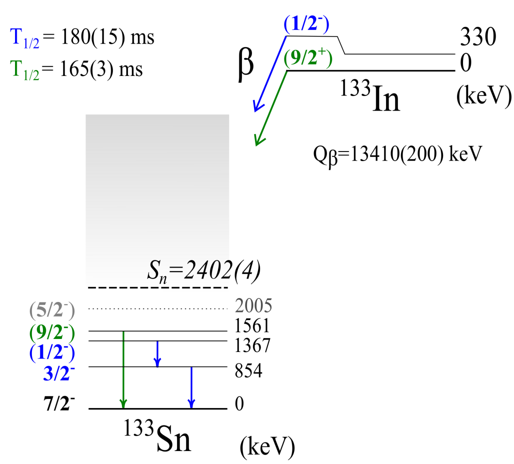

Fig. 3. Schematic representation of ^{133}In β decay. The Q_β and S_n values were taken from [19], $T_{1/2}$ and energy of $I^\pi = (1/2^-)$ level in ^{133}In from [8].

$I^{\pi} = (1/2^{-})$ *versus* when on $I^{\pi} = (9/2^{+})$ was found to be 0.05(1). We do not observe the 854 keV line in the spectrum collected when RILIS was set to separate ions in the $I^{\pi} = (9/2^{+})$ ground state of ^{133}In, indicating a high beam purity.

4. Summary

Low-lying states in ^{133}Sn were studied in the β decay of ^{133}In at the ISOLDE facility. Thanks to the isomer-selective ionization provided by RILIS, we were able for the first time to study separately to study separately the β decay from the ground- and from the isomeric-state of ^{133}In. The impurities of the beam of ^{133}In ions in these two states were found to be negligible. Our data are consistent with the previous results on the low-lying level structure of ^{133}Sn [2–7], and provide further support for the adopted spin assignments of low-lying states in ^{133}Sn.

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