FAST-TIMING INVESTIGATION OF $A = 128$ ISOBARS POPULATED IN THE β-DECAY OF ^{128}Cd*

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The excited structure of $A = 128$ isobars populated in the β decay of ^{128}Cd has been investigated by means of high-resolution γ-spectroscopy and fast-timing measurements. The experiment was performed at the ISOLDE facility at CERN profiting from the production of intense and pure Cd beams by means of a temperature-controlled quartz transfer line, capable of suppressing surface-ionized species. The production yields and purity of Cd beams are presented. Results on sub-nanosecond lifetimes for excited states in ^{128}In and ^{128}Te are discussed.

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1. Introduction

The evolution of shell structure far from stability is one of the current important topics in nuclear structure research. The region around the doubly-magic ^{132}Sn isotope [1, 2] is one of the most thoroughly studied, since it is within reach of current experimental facilities. Understanding of nuclear structure in this region requires systematic investigation of nuclei around the double $Z = 50$ and $N = 82$ shell closure, where collective effects set in with only few extra nucleons. Exotic nuclei in the vicinity of ^{132}Sn are also relevant due to the potential impact of nuclear properties on the astrophysical r-process path, which influences the predicted isotopic abundances.

Shell-model calculations have been developed to describe the nuclear structure around ^{132}Sn [3–5] and they are able to achieve a good description, in particular, below the $N = 82$ shell gap. One of the missing pieces of information are reduced transition probabilities, which are key measurements for probing nuclear wave functions, and can be obtained from the direct measurement of excited state lifetimes.

In this work, we are presenting the results obtained on nuclei populated in the $A = 128$ β-decay chain, starting from a high-intensity and pure Cd ion beam produced at the ISOLDE facility. The production yields and the purity of the delivered Cd beams are presented. In addition, selected results on sub-nanosecond lifetimes of excited states in ^{128}In and ^{128}Te are discussed.

2. Experimental details

The data-taking campaign was part of the IS685 experiment [6] which was performed at the Isotope Separator On-Line (ISOLDE) facility at CERN. High-purity Cd beams were extracted from the target unit, ionized, selected in mass by the GPS separator, and transported to the ISOLDE Decay Station (IDS) where the ion beam was implanted onto a movable tape. An array of six 6 High-Purity Germanium (HPGe) clover detectors, three β detectors surrounding the implantation point, and two $LaBr_3(Ce)$ detectors in a compact geometry for fast-timing measurements were used at IDS. A XIA Pixie16 data-acquisition system was employed to digitize detector signals. Fast-timing signals underwent analog processing through constant fraction discriminators and time-to-amplitude converters before being fed to the digitizers. The excited structure of nuclei populated in the ^{128}Cd β-decay chain was studied by means of γ-spectroscopy and fast-timing methods [7–9]. Calibrations of the γ-ray detectors were performed using ^{140}Ba, ^{152}Eu, ^{138}Cs, ^{88}Rb sources and internal γ-rays in the decay chain. The absolute efficiency and resolution of the HPGe detectors was of $\sim 6\%$ and 2.7 keV at 1332 keV.

One of the key elements for the success of the experiment are the high-intensity and purity Cd beams produced at ISOLDE. We profit from the combination of three prominent features, which ensures good selectivity. The first one is the use of a uranium–carbide/graphite (UC_x) as a target material in a unit equipped with a neutron converter. Protons from the CERN PSBooster accelerated to 1.4 GeV impinge on the converter and produce spallation neutrons that irradiate the target, inducing fission, which suppresses the production of neutron-deficient caesium isobars compared to direct production by protons on (UC_x) [10].

The second element is a temperature-controlled transfer line used as a chemical selector between the target and the ion source. It consists of a quartz tube that acts as a retainer for elements with low volatility, compared to more volatile ones that go through, such as Zn, Hg, and of course Cd. The quartz transfer line delays the release of alkali elements such as Cs [11, 12], effectively reducing background.

The third feature contributing to the delivery of pure and high-intensity Cd beams is the use of selective laser ionization via the ISOLDE resonance-ionization laser ion source (RILIS) [13]. It provides fast and selective ionization of many metallic elements with high efficiency, and not only it is capable of isotopic selectivity but also of isomeric selectivity, profiting from the distinct hyperfine splitting [14] of nuclear states of different angular momenta.

In the experiment, the ISOLDE target unit #756 was used. In order to investigate its performance, the radioactive Cd ion beam intensity and purity was assessed. The measurements were performed by γ-ray spectroscopy using the detector system previously described. The production is given as the yield normalized to the incident proton beam current. The yields are derived from the observed γ-ray intensities, using the experimental detection efficiency and the available γ-ray branching ratios from the literature. Yields are corrected for the transmission to the IDS and the released fraction from the target.

For each mass, data were collected with and without RILIS ionization. While Cd ionization cannot be achieved without RILIS, surface-ionized species can still emerge if they are not delayed by the quartz transfer line. The measured production yields for the even masses ranging from $A = 124$–130 are summarized in Table 1, while Fig. 1 shows the $A = 128$ case. Detection limits are provided at 1σ of the observed background at the relevant γ-ray energies. In the measurements with RILIS on, the observed amount of In is consistent with β decay from the produced Cd, and thus no direct production is quoted. The production limit is given using the measurements with RILIS off. Based on the present data, we can conclude that

the delivered Cd beams are of high purity with no Cs nor In contamination. The release of possible isobaric contaminants is at least three orders of magnitude lower than that of the Cd isotopes under these conditions.

Table 1. Measured yields for Cd and possible isobaric contaminants released from the UC_x target with a quartz transfer line, with and without resonant ionization.

Isotope	Yield (ions/μC) RILIS on	Yield (ions/μC) RILIS off
^{124}Cd	$1.39(11) \times 10^5$	$\leq 1.1 \times 10^2$
^{124}In	—	$\leq 2.3 \times 10^2$
^{124}Cs	≤ 9	$\leq 1.2 \times 10^2$
^{126}Cd	$3.0(2) \times 10^4$	≤ 3
^{126}In	—	≤ 20
^{126}Cs	≤ 6	≤ 5
^{128}Cd	$1.59(13) \times 10^4$	≤ 0.4
^{128}In	—	≤ 38
^{128}Cs	≤ 5	≤ 1
^{130}Cd	$7.3(5) \times 10^2$	≤ 0.7
^{130}In	—	≤ 3
^{130}Cs	≤ 7	≤ 9

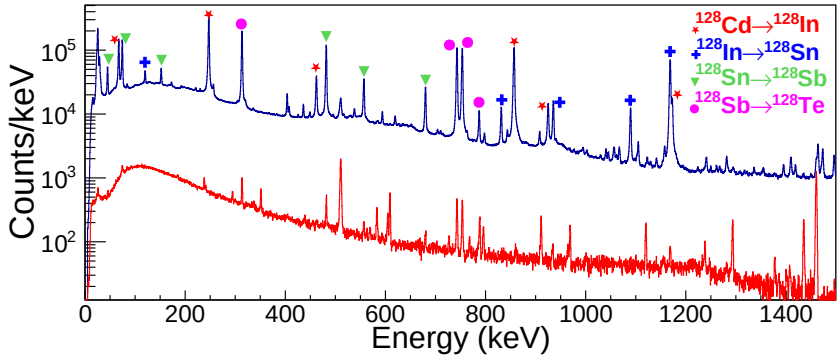

Fig. 1. γ-ray spectra obtained in a saturation mode for the mass $A = 128$ with (blue/black) and without (red/gray) laser ionization. Both data sets were collected for the same amount of time. The strongest peaks associated with the β decay of ^{128}Cd and its daughters are identified and labeled.

3. Lifetime measurements in the ^{128}Cd β-decay chain

Sub-nanosecond lifetimes in the $A = 128$ isobars were extracted from the time distributions between the β particle and $LaBr_3(Ce)$ scintillators, and from the pair of $LaBr_3(Ce)$ detectors. An additional gate on γ rays measured with HPGe detectors was applied for enhanced selectivity. Timing calibrations for the full-energy and Compton response of the $LaBr_3(Ce)$ scintillator detectors have been performed using ^{138}Cs and ^{140}Ba sources.

3.1. Lifetime of the 315 keV state in ^{128}In

Data acquired in the experiment allowed us to extract lifetimes of excited states in ^{128}In for the first time, as illustrated by the 315 keV level lifetime using triple $\beta\gamma\gamma(t)$ coincidences. A partial scheme of excited states in ^{128}In is shown in Fig. 2 along with the fast-timing analysis performed using the β–$LaBr_3(Ce)$ time-delayed distributions selected on the weak 315 keV de-exciting transition. The stronger 68 keV decay was not chosen due to the limitations of obtaining a proper calibration of the $LaBr_3(Ce)$ time response below 100 keV. A coincidence with the 857 keV or 315 keV transitions in the HPGe detectors was required to have a better selection.

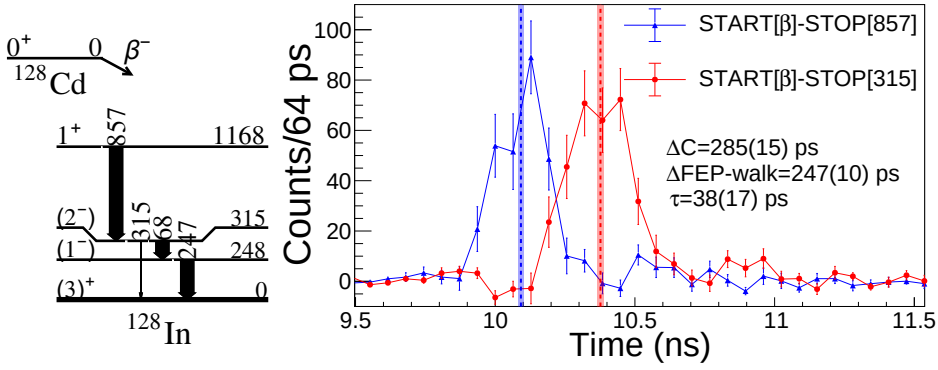

Fig. 2. Left: A partial decay scheme of ^{128}Cd β decay. Right: Time-delayed $\beta\gamma\gamma(t)$ spectra used to measure the lifetime of the 315 keV (2^-) state in ^{128}In.

The centroid-shift method was employed to derive the lifetime, yielding a value of $\tau = 38(17)$ ps. Using the γ-ray intensities from our analysis, the tabulated internal conversion coefficients [15] and the proposed spin-parity values (Fig. 2), the reduced transition probabilities for both de-exciting transitions were derived. For the 68 keV transition, $B(\mathrm{M1}) = 1.0(^{+0.9}_{-3})$ W.u. is obtained, while for the 315 keV transition, our measurement suggests an E1 character with $B(\mathrm{E1}) = 19(^{+16}_{-6}) \times 10^{-5}$ W.u. An M2 component is discarded

based on the large $B(\mathrm{M2}) = 8(^{+7}_{-3}) \times 10^2$ W.u. if a pure M2 character is assumed. The E1 multipolarity of the 315 keV transition supports the (2^-) spin-parity assignment for the 315 keV state.

3.2. Lifetimes of excited states in ^{128}Te

The β decay of the ^{128}Sb 5^+ isomer populated in the decay chain of ^{128}Cd, strongly feeds the 6^+ state in ^{128}Te. The lifetimes of the yrast 4^+ and 6^+ states have been measured. The half-life of the 6^+ state was measured from triple $\beta\gamma\gamma(t)$ events from the time distributions between the β detector and the $LaBr_3$(Ce) ones, where the three strongest 314, 754, and 743 keV γ-ray transitions were selected. A third coincidence was imposed in the HPGe detectors with each of the other two transitions in the $6^+ \rightarrow 4^+ \rightarrow 2^+ \rightarrow 0^+$

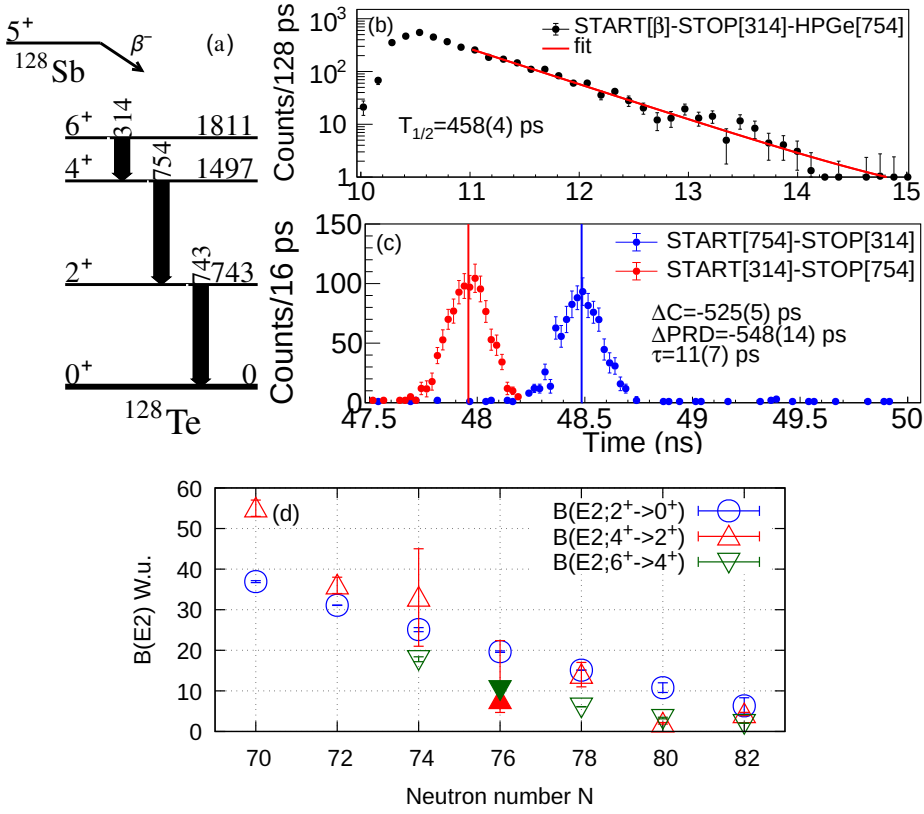

Fig. 3. (a) Partial β-decay scheme of the 5^+ isomer in ^{128}Sb. Lifetime analysis for the 6^+ (b) and 4^+ (c) states in ^{128}Te, respectively. See the text for details. (d) Systematics of B(E2) rates for Te isotopes (data taken from [18]). The B(E2) probabilities for the decay of the 6^+ and 4^+ states in ^{128}Te ($N = 76$) were measured in this work.

cascade. The analysis is illustrated in Fig. 3 for the β–$LaBr_3$[314]–HPGe[754] combination. We adopt a $T_{1/2} = 458(4)$ ps value calculated as the weighted average of the different combinations of γ rays selected in the $LaBr_3$(Ce) and HPGe detectors. The result is in accordance with the previously reported values of 420(30) ps [16] and 480(30) ps [17], but has a much better precision.

The lifetime of the 4^+ state is measured from the time-delayed coincidences between the 314 and 754 keV transitions selected in the $LaBr_3$(Ce) detectors using triple $\gamma\gamma\gamma(t)$ coincidences, since an extra coincidence in the HPGe detector at 743 keV was required in order to avoid mixing with the 754 keV γ ray in the $LaBr_3$(Ce) spectra. Applying the mirror-symmetric method [9] with timing calibrations derived from the $\beta\gamma(t)$ coincidences [14], $\tau = 11(7)$ ps was measured. No prior measurement was reported in the literature. A transition rate of $B(\mathrm{E2}; 4^+ \rightarrow 2^+) = 297(^{+561}_{-117})\ e^2\mathrm{fm}^4$ is deduced. Within its limited precision, it is consistent with the B(E2) values of the even–even Te isotopes, as depicted in Fig. 3.

4. Summary and conclusions

Pure and intense Cd beams were produced at the ISOLDE facility at CERN by the combination of a UC_x target equipped with a neutron converter and a temperature-controlled quartz transfer line, the RILLS system. The enhanced purity allowed access to nuclei populated in the β decay of neutron-rich Cd isotopes without isobaric contamination. Here, we report on selected results of fast-timing measurements in the $A = 128$ β-decay chain. The first measurement of the lifetime of the 315 keV (2^-) excited level in ^{128}In has been presented. For ^{128}Te, the lifetimes of the 6^+ and 4^+ states have been measured, the latter for the first time.

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