Probing neutron-rich In and Cd nuclei with isomer spectroscopy

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Abstract

Delayed heavy-ion-tagged γ-ray spectroscopy has been applied to study the decay of relatively long-lived ($T_{1/2}$ in the 100 ns - 100 μs range) isomeric states in selected fragments, including $^{125-130}$In and ^{125,127}Cd, produced in in-flight fission of a 732 MeV/nucleon ^{238}U beam at GSI.

1 Introduction

Some thirty years after it was opened up to observation, the region around doubly magic ^{132}Sn still remains the object of intense interest. The shell structure and effective residual interactions in this part of the nuclidic chart are intimately related to many important issues, such as the proposed quenching of shell-closure strength for extremely neutron-rich nuclei, the development of low-lying deformed intruder configurations, and the astrophysical r-process. The very different predictions for e.g. shell evolution obtained by various theoretical approaches is a clear indication that the detailed understanding of neutron-rich systems far from stability is far from complete, and that new experimental data on global nuclear properties as well as state-dependent ones are urgently needed.

We have performed a search for relatively long-lived (0.1-10 μs) isomeric states in nuclei "south-west" of ^{132}Sn, produced directly in projectile fission of ^{238}U. In addition to the primary goal of obtaining spectroscopic information on the properties of such isomers as well as the intermediate levels populated in their decay, the experiment also forms part of a study aimed at probing the role of angular momentum in projectile fission through observation of the spin distribution of the reaction products.

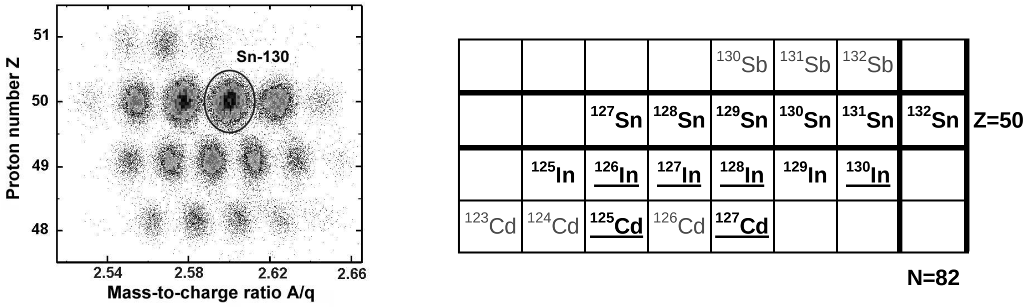

Figure 1: Particle identification spectrum showing proton number Z versus the mass-to-charge ratio A/q for fragments reaching the implantation setup with the FRS optimized for ^{130}Sn, and an overview of the isotopes and isomers (bold type) present in this setting. New isomers are underlined.

2 Experimental details

The nuclei of interest were produced by projectile fission of ^{238}U at the relativistic energy of 732 MeV/nucleon impinging on a 1 g/cm^2 Pb target. The average beam intensity from the SIS heavy ion synchrotron was 4×10^8 ions per cycle, with each cycle consisting of 5 s acceleration and 5 s extraction. The ions of interest were separated by combining magnetic analysis with energy loss in matter in the FRagment Separator FRS [1] and identified event-by-event using standard heavy-ion detectors. A more detailed description of this procedure can be found in, e.g., Refs. [2, 3].

The data presented here were obtained during an effective measurement time of 8 hours with the FRS optimized for the transmission of ^{130}Sn. Figure 1 shows the particle identification spectrum as well as a summary of the isomeric decays observed in this setting.

At the focal plane of the FRS, the transmitted fragments were slowed down in a variable-thickness aluminum degrader and then implanted in a plastic catcher foil viewed by six segmented Clover-type detectors in which delayed γ-rays emitted by the implanted ions were detected. The energy and time of all "first hits" in the Ge detectors within an 80 μs interval following the implantation of an ion were recorded together with the particle identification information for the respective ion. This allowed the construction of heavy ion-gated γ-ray energy versus time matrices for both prompt and delayed ion-gamma coincidences. In addition, ion-gated $\gamma\gamma$ energy matrices were also constructed.

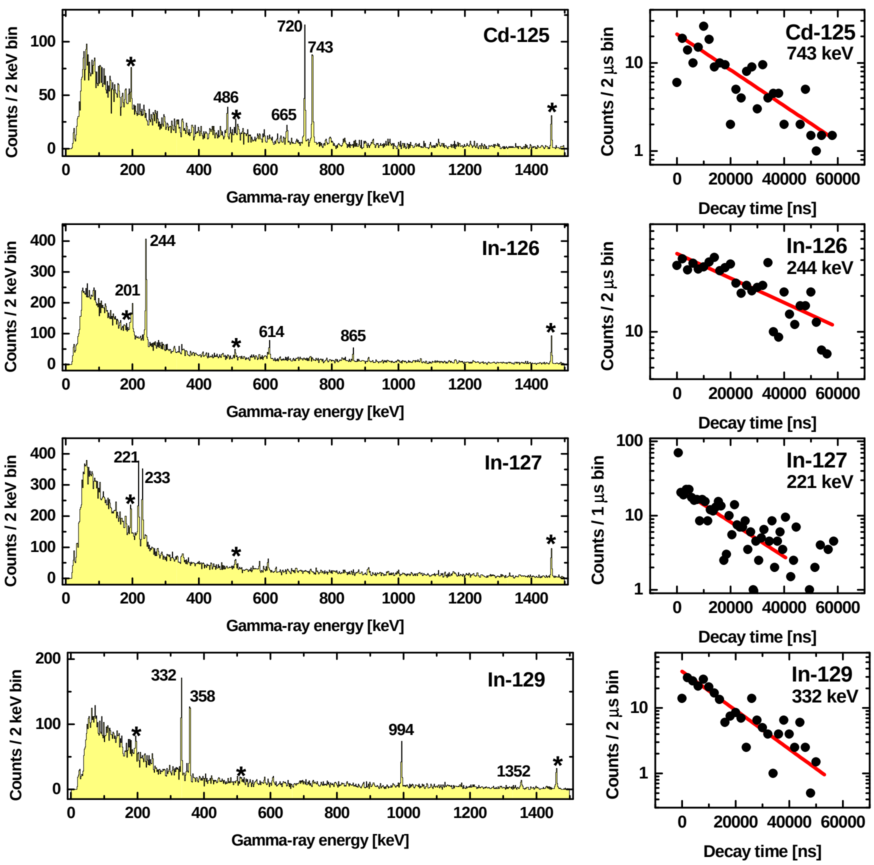

Figure 2: Left: Heavy-ion–gated delayed (1-60 μs after prompt) γ-ray spectra of selected isomers. Asterisks label background activities. Right: Corresponding background-subtracted decay time distributions indicating the one-component exponential fit.

3 Analysis and preliminary results

As the analysis is still in progress, the results presented here should be considered *preliminary.*

The left column of Figure 2 shows delayed γ-ray energy spectra of selected cadmium and indium fragments exhibiting isomeric decays. The γ-ray spectra were obtained by projecting the above mentioned energy versus time matrices for the time interval 1-60 μs after implantation.

By conversely projecting gates on γ-ray energies, decay time distributions for the transitions of interest was obtained. To remove the influence of prompt radiation (produced during the slowing-down process and/or fragments breaking up in the degrader or catcher) as well as room background, time spectra from background gates were subtracted before fitting the resultant distribu-

Table 1: Properties of isomers observed in the present study.

Isotope	I^π	Observed delayed γ-rays* [keV]	Half-life*,† (μs)	
			This work	Previous
^{125}Cd	$(29/2^+)$	486, 665, **720**, **743**	14(2)	
^{127}Cd	?	**820**	1 - 10	
^{126}In	(1^-)	201, **244**, 614, 865	30(3)	
^{127}In	?	**221**, **233**	<0.5 and 13(2)	
^{128}In	(1^-)	**248**, 323	170(80)	>10 [4]
^{129}In	$(17/2^-)$	**332**, **358**, 994, 1352	11(2)	2.0(5) [5]
^{130}In	?	**389**	1 - 10	
^{129}Sn	$19/2^+$	**382**, 570, 1136, 1324	3.9(4)	3.6(2) [5]
^{130}Sn	10^+	97, **391**	1.5(2)	1.61(15) [6]

* Values are preliminary and may change as the analysis progresses.

† From fitting decay time distributions of the γ-rays indicated in bold type.

tions with a simple exponential decay. The right column of Figure 2 illustrates time spectra with fits for some delayed γ-ray transitions of interest, while Table 1 summarizes the properties of the isomers observed in the present study.

The $T_{1/2}$ values obtained for transitions deexciting known isomeric states in ^{129}Sn and ^{130}Sn agree very well with the respective literature values, which gives us confidence in the evaluation procedure.

4 Discussion

In the following, we briefly discuss the preliminary results obtained so far for some of the individual isomers observed in the present study. In several cases the observed properties are difficult to explain by systematics alone without supportive shell model calculations. Such calculations, using various interactions and experimental single-particle energies, are in progress.

^{125}Cd: Two coincident γ-transitions of 720 and 743 keV with similar intensity and half-life follow the decay of this previously unknown isomer. In addition, two much weaker delayed γ-transitions of 486 and 665 keV are observed, but their lifetimes have not yet been evaluated. Comparing with the A=120-130 tin isotopes, where the lowest lying excited state is alternately 2^+ or $15/2^-$, a possible interpretation of this decay would be a cascade starting with a hindered M2 transition deexciting a $19/2^+$ isomer via an $15/2^-$ level down to a known $(11/2^-)$ state, which could be either the ground or an isomeric state (Ref. [7] quotes its energy as 50(70) keV).

^{127}*Cd:* Only one significant delayed γ-transition at 820 keV was observed in coincidence with the implanted ^{127}Cd ions. The very low statistics have thus far only allowed placing the limit 1 μs<$T_{1/2}$ <10 μs on its half-life. The origin of this previously unknown isomer is difficult to interpret, and it is also not known whether the observed γ-ray represents the primary isomeric transition. In analogy to ^{125}Cd, the observed γ-ray could be a hindered M2 $19/2^+$-to-$15/2^-$transition.

^{126}*In:* The decay of this previously unreported isomer exhibits a strong γ-ray at 244 keV, with a half-life of 30(3) μs, as well as two weaker 614 and 865 keV transitions with as of yet undetermined lifetimes. In analogy with ^{128}In (see below), we tentatively interpret this as the primary isomeric M2 (E3) transition connecting the 1^- member of the $\pi g_{9/2}^{-1} \nu h_{11/2}^{-1}$ multiplet with the 3^+ ground state. Evidence for other members of this negative-parity multiplet comes from the proposed (8^-) β-decaying state that has previously been observed [8]. However, the 244-keV γ-ray could possibly also connect a higher-lying isomeric state with the (8^-) level.

^{127}*In:* We observe two coincident delayed γ-rays with 221 and 233 keV, which both exhibit time spectra with an abnormally high number of counts in the first 500 ns interval, followed by a relatively long decay with half-life around of 13(2) μs. This decay pattern, which shows very little resemblance to the odd-A neighbors ^{125,129}In (see Fig. 2 and Table 1), could indicate the presence of two isomeric states above the presumably long-lived $23/2^-$ state [9]. Candidates for the isomeric levels are the high-spin members of the $\pi g_{9/2}^{-1} \nu h_{11/2}^{-2}$ configuration, including the maximally aligned $29/2^+$ state.

^{128}*In:* Our measurement confirms the isomeric (1^-) state observed by Fogelberg [9] to deexcite to the $(3)^+$ ground state by a 248 keV γ-ray with a relatively long half-life. The weaker transition at 323 keV, of yet undetermined half-life, that is also present in our spectrum, could connect a second, higher-lying (1^-) or (5^+) isomeric level to the $(3)^+$ ground state. Such states are indeed expected from the $\pi p_{1/2} \nu h_{11/2}$ and $\pi p_{1/2} \nu d_{3/2}$ configurations.

^{129}*In:* We observe an isomeric decay with the same γ-transitions as reported by Genevey et al. [5] but exhibiting a much longer half-life of 11(2) μs. The deexcitation pattern is consistent with the decay of a $(17/2^-)$ state, as any higher spin would not allow for the known 700 ms $(23/2^-)$ β-decaying isomer at 1900 keV observed by Fogelberg et al. [9], and positive parity would enable a fast E2 transition to the $(13/2^+)$ state at 1352 keV. The existence of an undetected low-energy E1 primary isomeric transition cannot, however, be excluded from our data.

^{130}*In:* A single delayed γ-transition of 389 keV with a half-life $T_{1/2}$ <10 μs was observed in coincidence with the implanted ^{130}In ions, apparently associated with the decay of a previously unreported isomer. Two β-decaying isomers, with I^{π}=(10^-) and 5^+, are known in ^{130}In, and have been assigned as belonging to the $\pi g_{9/2}^{-1}\nu h_{11/2}^{-1}$ and $\pi g_{9/2}^{-1}\nu d_{3/2}^{-1}$ multiplets, respectively [10]. The delayed transition we observe could connect a previously unobserved member of the $\pi g_{9/2}\nu h_{11/2}$ multiplet with the 1^- ground state or another level with the same configuration.

5 Outlook

Although this and other recent studies directed at nuclei close to doubly magic ^{132}Sn have provided a wealth of new data, their interpretation and the details of nuclear structure in this region is not yet clear. A number of outstanding issues remain, including the possibility of shell quenching. At GSI, a continuation of the program of isomer spectroscopy of neutron rich exotic nuclei is planned as part of the stopped-beam phase of the RISING project [11].

In addition to this and further experimental efforts elsewhere, large-scale shell model calculations using realistic interactions and reliable experimental single-particle energies inferred from states with *known* spectroscopic factors are, in our opinion, an indispensable prerequisite to disentangling the roles of shell structure, core excitation and residual interaction in the region around the most neutron-rich doubly magic nucleus known, ^{132}Sn.

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