Isomeric states in neutron-rich $^{129}$In and the $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}^{-1}$ multiplet

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Abstract. Within the RISING stopped beam campaign the neutron-rich indium isotopes with masses $A=125-130$ have been studied using the method of isomer spectroscopy. The decays of several isomeric states have been observed and here we compare our results for $^{129}$In to previous measurements for this nucleus. The isomeric states were populated in the fragmentation of a $^{136}$Xe beam at 750 MeV/u and in the relativistic fission of a $^{238}$U beam at 650 MeV/u at the accelerator facility GSI (Darmstadt, Germany).

1. Introduction
In the last decade a large number of theoretical studies and experiments have been performed to investigate the region around the doubly magic $^{132}$Sn. This region is of particular interest on one hand for testing the interactions used in shell model calculations and on the other, because its relevance for nuclear astrophysics, especially for nucleosynthesis calculations.

Results are presented for isomeric states in neutron-rich indium nuclei. Information on isomeric states in neutron-rich Ag, Cd, In and Sn isotopes, deduced from the same dataset, have already been presented in Refs. [1, 2, 3, 4, 5, 6, 7], including the first observation of a high-spin, core-excited isomer in $^{131}$In. Here we focus on the results obtained for $^{129}$In.

2. Experimental setup
The neutron-rich indium isotopes were studied with the RISING stopped beam setup employing the method of isomer spectroscopy. Two different reactions were used to produce these neutron-rich nuclei, namely the fragmentation of a $^{136}$Xe primary beam at an energy of 750 MeV/u and relativistic fission of a $^{238}$U beam at 650 MeV/u. The primary beams were provided by the accelerator facility at the Gesellschaft für Schwerionenforschung (Darmstadt, Germany) consisting of the linear accelerator LINAC and the heavy ion synchrotron SIS. Beryllium production targets with thicknesses of 4 and 1 g/cm$^2$, respectively, were used at the entrance of the fragment separator FRS.

The reaction products were separated and the ions of interest selected and identified on an event-by-event basis using the information from the different beam detectors, placed at the focal planes of the separator, and the $B\rho - \Delta E - B\rho$ method. The mass-to-charge ratio $A/Z$ was determined from the measured time-of-flight through the second half of the fragment separator.
and several position measurements using plastic detectors and multi-wire proportional chambers (MWPC). The nuclear charge \(Z\) is determined from two independent energy-loss measurements performed with ionisation chambers called MUSIC. Figure 1 shows the nuclear charge measured in the first ionisation chamber, MUSIC41, plotted against the same quantity determined from the energy-loss in the second, MUSIC42. The different nuclear charges are clearly separated and a gate on \(Z = 49\) can be set. Figure 2 shows the different \(A/Z\) values, gated on \(Z = 49\), against the measured horizontal position \(x\) at the second focal plane to separate the different masses \(A\) and select the isotopes of interest in the offline analysis.

The ions which pass through the FRS are then stopped in a passive stopper at the final focal plane of the FRS which is surrounded by 15 former EUROBALL cluster detectors, each consisting of 7 encapsulated Ge-crystals to measure the \(\gamma\)-rays following isomeric decays. The Ge signals are split up into two separate electronic branches, one equipped with digital-gamma-finders (DGF) which processes the signal to obtain energy and time information, but have a limited time granularity of 25 ns/bin. The other electronic branch consists of a conventional analog timing electronic chain with two different time-to-digital converters TDC with ranges of 1 and 800 \(\mu s\) and granularities of 0.31 ns/channel and 0.73 ns/channel, respectively.

3. Experimental results

In this section, the results obtained for the nucleus \(^{129}\)In are presented. In \(^{129}\)In, several isomeric states were known previous to this work. Fogelberg et al. [8] identified two ms isomeric states, which are connected by a 281-keV transition, and assigned spin/parity of \((29/2^+\)) and \((23/2^-)\) to the higher and lower isomeric state, respectively. Those isomeric states can not be observed in our experiment due to their long half-lifes of 110 and 700 ms, respectively. The presence of a \(\mu s\) isomer was first reported by Genevey et al. [9] who observed four \(\gamma\)-rays with energies of 334-, 359-, 995- and 1354-keV following the decay of this isomeric state to the ground state. Its half-life was measured in three independent experiments to 8.5(5) \(\mu s\) [9], 11(1) \(\mu s\) [10, 11] and 2.2(3) \(\mu s\) [12].

All four \(\gamma\)-rays reported by Genevey et al. [9] are observed in the delayed spectrum obtained in our experiment as shown in Figure 3 (time range 200 ns to 25 \(\mu s\) after implantation). The 334-, 359- and 995-keV transitions are observed in mutual prompt coincidence and in addition the 334-keV transition is found to be in prompt coincidence with the 1354 keV \(\gamma\)-ray. As an example the prompt coincidence spectrum for the 334-keV transition is presented in Figure 4.

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**Figure 1.** Calculated nuclear charge \(Z_1\) from the energy loss in MUSIC41 in comparison to \(Z_2\) from MUSIC42. The gate used for the offline analysis to select the Indium isotopes is shown in red.

**Figure 2.** Measured position \(x_2\) at the second focal plane as a function of the mass-to-charge ratio \(A/Z\) gated on \(Z = 49\) (Indium), as shown in Figure 1.
Figure 3. $\gamma$-ray spectrum in delayed coincidence with the implanted $^{129}$In ions. The full time range of the DGF (25 $\mu$s) is used, excluding however the prompt flash after the implantation. The transitions marked with a star have been assigned to background radiation.

Note that the energy sum of the 359- and 995-keV transitions equals 1354-keV, the energy of the fourth transition, thus confirming the level scheme proposed in [9]. In that reference a spin and parity assignment of $17/2^-$ was made for the isomeric state on the basis of a conversion electron measurement for the 334-keV transition.

Figure 4. Prompt coincidence spectrum gated on the 334-keV transition in $^{129}$In.

Figure 5. DGF time distribution gated on the 334-keV transition in $^{129}$In and the least-square fit to the data (red line) to determine the half-life, $T_{1/2}$.

The half-life of the isomeric state was determined by least-square fits of the time distributions obtained for the four $\gamma$ rays. As an example the time distribution of the 334-keV transition is shown in Figure 5. A mean half-life of $T_{1/2}=11.2(2)$ $\mu$s was calculated from the individual values. This value agrees perfectly with the value published in [10, 11] and is only slightly higher as compared to the half-life reported in [9]. In contrast, no agreement is found with the value obtained in [12]. All measured half-lifes and the relative intensities of the four $\gamma$ rays are
summarized in Table 1. The relative intensities are in good agreement with the ones quoted in [9].

Table 1. Summary of the $\gamma$-ray energies $E_\gamma$, half-lifes $T_{1/2}$, obtained from the individual fits, relative intensities $I_\gamma$, and coincidence relations observed in this work for the $\gamma$-rays emitted in the decay of the $17/2^-$ isomer in $^{129}$In. The relative intensities $I_{\gamma,\text{lit}}$ from [9] are listed for comparison.

| $E_\gamma$ [keV] | $T_{1/2}$ [$\mu$s] | $I_\gamma$ [%] | $I_{\gamma,\text{lit}}$ [%] | obs. coinci. |
|-----------------|---------------------|-----------|-----------------|-------------|
| 333.6           | 11.5(3)             | 100(2)    | 100             | 358.9, 995.0, 1354.0 |
| 358.9           | 11.0(3)             | 82(3)     | 83              | 333.6, 995.0 |
| 995.0           | 11.3(4)             | 86(3)     | 82              | 333.6, 358.9 |
| 1354.0          | 10.7(9)             | 25(2)     | 28              | 333.6       |

4. Conclusion
The RISING stopped beam setup has been used to observe the decay of isomeric states in neutron-rich indium isotopes. Here we presented the re-measurement of the half-life of the $17/2^-$ isomer in $^{129}$In. Our results are in good agreement with the previously published half-life values, coincidence relations and relative intensities.

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