Observation of a μs isomer of $^{134}_{49}\text{In}_{85}$ and hole-particle structures south-east of $^{132}_{50}\text{Sn}_{82}$

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In the BRIKEN campaign aimed at exploration of the $^{132}\text{Sn}$ region, an isomeric state of $^{134}_{49}\text{In}_{85}$ was discovered via γ-ray spectroscopy. The nuclei of interest were produced by in-flight fission of a $^{238}\text{U}$ beam at the Radioactive Isotope Beam Factory at RIKEN. The isomer decays through a γ ray of 56.7(1) keV and with a half-life of $t_{1/2} = 3.5(4)$ μs. Based on the comparison with shell-model calculations, we interpret the isomer as the $5^{-}$ member of the $\pi f_{7/2}^{1} \otimes \nu f_{7/2}^{1}$ multiplet, decaying to the $7^{-}$ ground state with a reduced-transition probability of $B(E2; 56.7 \text{ keV}) = 6.8 \text{ W.u.}$ Observation of this isomer, along with the non-observation of a similar $5^{-}$ isomer of $^{132}\text{In}$ provides a benchmark of the proton-neutron interaction in a region where experimental information on excited states is sparse.

Atomic nuclei are many-body quantum systems that except for the few cases of nuclei with up to four nucleons, cannot yet be solved exactly [1]. The Hamiltonian of such systems is usually approximated by replacing the sum of the two-body interaction between all the nucleons by a common single-particle potential and a two-body residual interaction acting only between the valence nucleons. Nuclei with two particles, two holes, or one particle and one hole with respect to a core, offer one of the best opportunities to constrain the residual interaction [2–4]. Odd-odd and odd-A nuclei with few valence nucleons provide important additional information for a more comprehensive test of the residual interaction [5]. The present work is part of the BRIKEN project [6], and was aimed at the search for low-energy isomeric states in the odd-odd nuclei $^{132}\text{In}$, $^{134}\text{In}$, and $^{130}\text{Ag}$, which were predicted in Ref. [7]. With few valence nucleons outside the $^{132}\text{Sn}$ core, excited states in these nuclei are fundamental to test effective Hamiltonians in the region of the nuclear chart south-east of $^{132}\text{Sn}$ (i.e., of nuclei with proton number $Z < 50$ and neutron number $N > 82$). In particular, the predicted isomerism is very sensitive to the details of the proton-neutron interaction [7]. From the experimental point of view, excited states in this region are very difficult to access due to low production

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The only observation of γ rays was presented very recently, emitted from excited states in 132In [8]. These γ rays allowed the observation of most of the member states of the π0q_{9/2}^{-1} ⊗ ν1f_{7/2} multiplet in 132In while all the other important multiplets in this nucleus remain unobserved. Along these lines, the aim of this work was to continue the exploration of the region, and provide new experimental information on 132In and its neighbours.

The nuclei of interest were produced by in-flight fission of a 345 MeV/u 238U beam on a 4 mm beryllium target and then separated using the BigRIPS fragment separator and the ZeroDegree spectrometer [9]. The primary beam intensity was \~60 pA. Two aluminium wedge-shaped energy degraders with thicknesses of 3 mm and 2 mm were placed at the intermediate focal planes of BigRIPS (F1 and F5, respectively) for purification of the beam. The secondary beam energy was tuned using two planar Al degraders, one of 2 mm in F7 and one adjustable between 4 mm and 5.5 mm at F11. This energy degrader setting proved best to minimise the neutron background in the experimental area. The particle identification of the secondary beam (see Fig. 1) was performed on an event-by-event basis using the ∆E – TOF – Bρ method [10], where ∆E is the energy loss in the F7 ionisation chamber, TOF is the time-of-flight between F3 and F7, and Bρ the magnetic rigidity measured from the ion positions and angles at F3, F5, and F7. In 3.5 days of measurement, approximately 6.5 \times 10^{5} ions of 132In, 1.5 \times 10^{5} of 134In and 5 \times 10^{3} of 130Ag were implanted in the detectors described below.

In the experimental area located at the final focal point F11, a plastic scintillator provided the timing signal of heavy ions that were implanted in the stack of silicon detectors AIDA (Advanced Implantation Detector Array) [11]. A plastic scintillator downstream of AIDA provided a veto signal for light particles travelling with the beam. The active stopper was surrounded by the BRIKEN neutron detector [13, 14] composed of 140 proportional counters filled with 3He gas embedded in a high-density polyethylene moderator. In addition, two segmented clover-type HPGe detectors from ORNL [15] were installed at about 6 cm from the center of AIDA for high-resolution γ-ray detection. γ-rays detected by the HPGe crystals were correlated on an event-by-event basis to events detected in BigRIPS and AIDA. The efficiency, measured using a 152Eu source, was 1.55% at 1332 keV, or 2.13% at the same energy when an add-back algorithm was implemented, designed to add together the energy of signals detected in neighbouring crystals within a time interval of 400 ns. Events with signals in all four crystals of the same detector were rejected because background dominated. The isomer spectroscopy setup was validated measuring the 10+ isomer of 128Cd, which was previously reported to decay with a half-life of 3.56(6) μs and originating a cascade of six γ rays [12]. Fig. 2 shows the energy spectrum of the isomer decay recorded in our experiment. Six γ rays can be observed with energy and half-life in very good agreement with the previous report. The isomer half-life that we measured gating on the 538 keV γ ray was 3.6(4) μs. The lower precision of our result is the combined effect of lower γ efficiency (a factor \~4), and the 5 times smaller number of ion implantations.

Fig. 3 shows the energy spectra of the events detected by the HPGe detectors and correlated with implantation of 132In, 134In, and 130Ag, respectively. A single γ ray of 56.7(1) keV is very clear in the case of 134In, while we found no evidence of isomers of 132In and 130Ag. The time distribution of the 56.7(1) keV γ ray has a half-life of 3.5(4) μs, corresponding to a B(E2; 56.7 keV) = 6.8 W.u. The half-life was determined from the data, maximising a Poisson probability log-likelihood function that considered an exponential decay and a time-independent background.

The Weisskopf estimated half-lives for a transition of 56.7 keV and different multipolarities are shown in Tab. 1. The E2 transition is the one that best agrees with the experimental data but M2 is also to consider.
TABLE I. Weisskopf estimated half-lives ($t_{1/2}$) for different possibilities of $^{134}$In isomer decay. The internal conversion coefficient $\alpha_{ic}$ for the 56.7 keV transition was calculated using the Brückner database [16]. The value that best agrees with the experimental half-life of 3.5(4) $\mu$s is highlighted in bold font.

<table>
<thead>
<tr>
<th>Multipolarity</th>
<th>$\Delta\pi$</th>
<th>$\alpha_{ic}$</th>
<th>$t_{1/2}$ ($\mu$s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E1$</td>
<td>yes</td>
<td>0.86</td>
<td>$7.6 \times 10^{-7}$</td>
</tr>
<tr>
<td>$M1$</td>
<td>no</td>
<td>2.60</td>
<td>$3.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>$E2$</td>
<td>no</td>
<td>11.69</td>
<td>1.9</td>
</tr>
<tr>
<td>$M2$</td>
<td>yes</td>
<td>45.20</td>
<td>43.7</td>
</tr>
<tr>
<td>$E3$</td>
<td>yes</td>
<td>282</td>
<td>$2.1 \times 10^{6}$</td>
</tr>
<tr>
<td>$M3$</td>
<td>no</td>
<td>619</td>
<td>$8.3 \times 10^{7}$</td>
</tr>
</tbody>
</table>

To understand the nature of the observed isomer of $^{134}$In, it is worth considering first the simplest case of odd-odd nucleus in the region, i.e., $^{132}$In. The coupling of a $0g_{9/2}$ proton hole and a $1f_{7/2}$ neutron particle results in a multiplet of eight states with spins from $1^{-}$ to $8^{-}$. The quadrupole component of the residual interaction is expected to split the multiplet with energies distributed as a parabola in $J(J + 1)$, with $6^{-}$ and $7^{-}$ being the lowest lying members [17]. Three more multiplets should rise from the simplest excited configurations: two positive-parity states $\pi 1p_{1/2}^{-1}$ $\otimes$ $\nu 1f_{7/2}$, four negative-parity states $\pi 0g_{9/2}^{-1}$ $\otimes$ $\nu 2p_{3/2}$, and four positive-parity states $\pi 1p_{3/2}^{-1}$ $\otimes$ $\nu 1f_{7/2}$. The location in energy of these excited multiplets should reflect the single-particle energies $\pi 1p_{1/2}$ (365 keV), $\nu 2p_{3/2}$ (853 keV), and $\pi 1p_{3/2}$ (1553 keV), which are experimentally known from $^{130}$In [18, 19] and $^{133}$Sn [20, 21]. In the case of $^{134}$In and $^{130}$Ag, two more neutrons and two more holes contribute increasing the number of configurations and of the configuration mixing. However, the lowest energies are expected to be dominated by the simplest configurations, i.e., the same multiplets of states as in $^{132}$In with two neutron particles or two proton holes coupled to $J^* = 0^+$. For a rough estimate of the excitation energies of the same multiplet when two neutrons are coupled to $J^* = 2^+$ one can refer to the $2^+$ state in $^{134}$Sn (725.6 keV), and to the $2^+$ state in $^{130}$Cd (1325 keV) for the case of two proton holes. Besides originating more configurations, the two holes/particles can also change slightly the order and energy of the multiplets as observed in $^{132}$In.

In view of these considerations, a single $\gamma$ ray with energy lower than the single particle energies above, most likely connects two states of the yrast multiplet. This rules out $M2$ transitions because they require a change of parity, and leaves the $E2$ as the most likely transition. The parabolic dependence of energy to spins, however, is not compatible with a $E2$ isomer because any multiplet’s member decays to the ground state via $M1$ cascades.

A very important insight comes from shell-model calculations detailed in Ref. [7] that compatibly with the general arguments above, predicted the yrast $5^{-}$ states to lie below the $6^{-}$ states. This causes the $5^{-}$ state to decay to the $7^{-}$ ground state with a low $B(E2)$ value, which makes the $5^{-}$ state isomeric (see Fig. 4). The model space used in these calculations consists of the four proton orbits $0f_{5/2}, 1p_{3/2}, 1p_{1/2}, 0g_{9/2}$, and the six neutron orbits $1f_{7/2}, 2p_{3/2}, 2p_{1/2}, 0h_{9/2}, 1f_{5/2}, 0i_{13/2}$, corresponding to the $Z = 28 − 50$ and $N = 82 − 126$ major shells. This parameter space is, therefore, suitable to study states below 2 MeV. The model uses an effective Hamiltonian with proton-proton and neutron-neutron interactions obtained through the existing CD-Bonn G matrix results, while proton-neutron interaction across two major shells are derived from the monopole based universal interaction plus the M3Y spin-orbit force [7].

Ref. [7] also highlighted that the $4^{-}$ state could be isomeric if it lies below the $5^{-}$ decaying to the ground state with an $M3$ transition. An $M3$ transition is, however, expected to be much-longer lived than the observed transition as confirmed by SM calculation that for the $M3$ multipolarity yields the value of $B(M3; 4^- \rightarrow 7^-) = 2215 \, \mu^2 fm^4$ corresponding to a half-life of 42 s, orders
of magnitude larger than the experimental half-life. On the other hand, SM calculates a \( B(E2; 5^- \rightarrow 7^-) = 26 \, e^2 fm^4 \) corresponding to a half-life of 2.85 \( \mu s \) in very good agreement with our result of 3.5(4) \( \mu s \). We assign therefore the observed isomer to be the yrast 5\(^-\) state of \(^{134}\)In.

Notice that SM predicts the 5\(^-\) also to be isomeric in \(^{132}\)In and \(^{130}\)Ag. Our experimental data shows no evidence of isomerism in these isotopes. Given that \(^{132}\)In was implanted at a higher rate than \(^{134}\)In, and that it is reasonable to assume similar isomer production rate for the two isotopes, the existence of a 5\(^-\) isomer of \(^{132}\)In appears unlikely; the ordering of the 5\(^-\) and 6\(^-\) is likely inverted in these two isotopes. This, however, is not surprising. Due to the lack of experimental information on the proton–neutron interaction in this quadrant of \(^{132}\)Sn, large uncertainties related to the isomerism in these odd-odd nuclei are to be expected in shell-model calculations. In case of \(^{130}\)Ag, our observation are complicated by the small implantation rate. Assuming also in this case, a similar isomer population as for \(^{134}\)In, one would expect to detect about 20 \( \gamma \) rays from a potential 5\(^-\) isomer. This is within but at the limits of the sensitivity of our setup.

To summarise, we have investigated isomerism south-east of \(^{132}\)Sn in the three odd-odd nuclei \(^{132,134}\)In and \(^{130}\)Ag. We have identified for the first time one isomer of \(^{134}\)In, which based on shell-model calculations is assigned to be the yrast 5\(^-\) state with a dominant configuration \( \pi 0g_{9/2}^{-1} \otimes \nu 1f_{7/2}^{3} \). To date, this is the most exotic and, one of the handful of known excited states south-east of \(^{132}\)Sn. A similar 5\(^-\) isomeric state in the less exotic nucleus of \(^{132}\)In with configuration \( \pi 0g_{9/2}^{-1} \otimes \nu 1f_{7/2}^{3} \) was not observed, suggesting that the ordering of the 5\(^-\) and 6\(^-\) states in these two isotopes is inverted. We did not find evidence of isomerism in \(^{130}\)Ag. Since the energy and ordering of the low-energy states in these three isotopes depends strongly on the details of the proton-neutron interaction, and since the yrast states are still dominated by simple multiplet configurations, these three isotopes are key to build an effective Hamiltonian in this region, and should be the focus of future studies. Our new data is a step forward in that direction.

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