Rapid Communications

Observation of a μs isomer in $^{134}_{49}In_{85}$: Proton-neutron coupling "southeast" of $^{132}_{50}Sn_{82}$

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We report on the observation of a microsecond isomeric state in the single-proton-hole, three-neutron-particle nucleus ^{134}In. The nuclei of interest were produced by in-flight fission of a ^{238}U beam at the Radioactive Isotope Beam Factory at RIKEN. The isomer depopulates through a γ ray of energy 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 $I^\pi = 5^-$ member of the $\pi 0g_{9/2}^{-1} \otimes \nu 1f_{7/2}^3$ multiplet, decaying to the $I^\pi = 7^-$ ground state with a reduced-transition probability of $B(E2; 5^- \to 7^-) = 0.53(6)$ W.u. Observation of this isomer, and lack of evidence in the current work for a $I^\pi = 5^-$ isomer decay in ^{132}In, provides a benchmark of the proton-neutron interaction in the region of the nuclear chart "southeast" of ^{132}Sn, where experimental information on excited states is sparse.

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Atomic nuclei are many-body quantum systems which, except for the few cases of light nuclei with up to four nucleons, cannot yet be solved exactly [1]. Within the shell-model approach, the Hamiltonian of nuclear systems is replaced by the sum of a common single-particle potential and a two-body residual interaction acting only between the valence nucleons moving in a reduced space. This interaction

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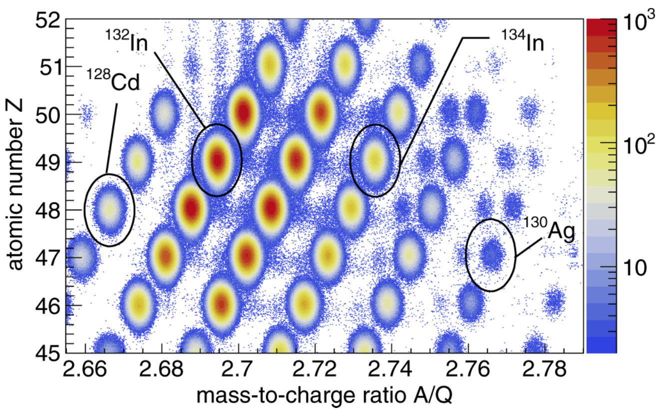

FIG. 1. Section of the particle identification plot showing all events recorded in the experiment, and accordingly to the reconstructed atomic number Z and mass-to-charge ratio A/Q. The labeled isotopes are the ones discussed in the text.

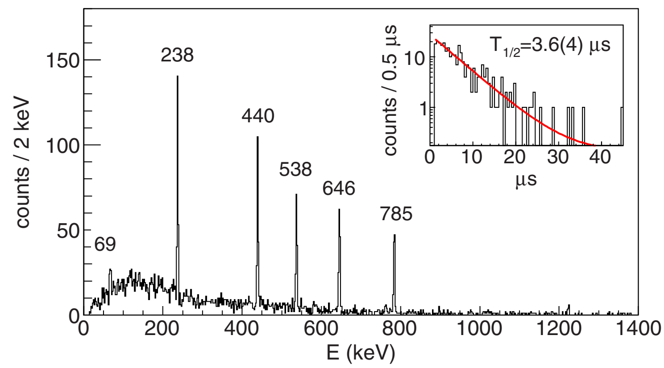

FIG. 2. Energy spectrum of γ rays correlated with implantation of ^{128}Cd ions, stemming from the previously reported $I^{\pi} = 10^{+}$ isomer of ^{128}Cd [16]. This spectrum represented correlated γ-ray events recorded between between 1 and 10 μs after the ion implantation. The time distribution of the 538 keV γ ray is shown in the inset.

should take into account, in an effective way, all the degrees of freedom that are not explicitly included. 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 such effective 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 proton-neutron channel [5]. The present work is part of the BRIKEN experimental campaign, an international collaborative effort to study β-delayed neutron emission at RIKEN [6], and was aimed at the search for low-energy isomeric states in the odd-odd nuclei ^{132}In, ^{134}In, and ^{130}Ag, which were predicted in Ref. [7].

Excited states in nuclei with few proton holes and few neutron particles "southeast" of ^{132}Sn (i.e., of nuclei with proton number $Z < 50$ and neutron number $N > 82$) are crucial to testing effective Hamiltonians in this region of the nuclear chart. In particular, the predicted isomerism is very sensitive to the details of the proton-neutron interaction [7]. However, from the experimental point of view, excited states in this region are challenging to access due to low production rates. Indeed, the only reports of characteristic γ rays were presented very recently, emitted from excited states in ^{132}Cd [8] and ^{132}In [9]. In the latter case, γ rays allowed the observation of most of the member states of the $\pi 0g_{9/2}^{-1} \otimes \nu 1f_{7/2}$ multiplet in ^{132}In; all of the other expected multiplets in this nucleus remain unobserved. The aim of the current work is to continue the exploration of the region, and provide new experimental information on the residual interaction related to proton-hole neutron-particle couplings in ^{132}In and its near neighbors.

The nuclei of interest were produced following the in-flight fission of a 345 MeV/u ^{238}U beam on a 4 mm beryllium target and then separated using the BigRIPS fragment separator and the ZeroDegree spectrometer [10]. The primary beam intensity was ≈60 pnA. The particle identification of the secondary beam (see Fig. 1) was performed on an event-by-event basis using the standard ΔE-TOF-$B\rho$ method [11], where ΔE is the energy loss in the beam-line ionization chamber, TOF is the time-of-flight between positions F3 and F7 of the BigRIPS spectrometer [10], and $B\rho$ the magnetic rigidity measured from the ion positions and angles at position F3, F5, and F7. In 3.5 days of measurement, approximately 1.5×10^{6} ions of ^{132}In, 2.3×10^{5} ions of ^{134}In, and 7.6×10^{3} ions of ^{130}Ag were transmitted to the experimental station 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 Advanced Implantation Detector Array (AIDA), which consisted of a stack of six double-sided silicon strip detectors [12]. A plastic scintillator downstream of AIDA provided a veto signal for light particles traveling with the beam. The active stopper was surrounded by the BRIKEN neutron detector [13,14] composed of 140 proportional counters filled with ^{3}He gas embedded in a high-density polyethylene moderator. In addition, two segmented clover-type HPGe detectors [15] were installed at about 6 cm from the center of AIDA for high-resolution γ-ray detection. Events detected by the HPGe crystals were correlated offline on an event-by-event basis to events detected in BigRIPS and AIDA. The full-energy peak γ-ray detection efficiency of the system measured using a ^{133}Ba and a ^{152}Eu source was 1.53(9)% at 1332 keV. With inclusion of an add-back algorithm, designed to add together the energy of signals detected in neighboring crystals within a time interval of 1 μs, the efficiency was 2.13(5)% at 1332 keV. Events with signals in all four crystals of the same detector were rejected because they were background dominated.

The isomer spectroscopy setup was validated measuring the 10^{+} isomer of ^{128}Cd, which was previously reported to decay with a half-life of 3.56(6) μs and producing a cascade of six γ rays decaying to the ground state [16]. Figure 2 shows the energy spectrum of the isomer decay recorded in our experiment, between 1 and 10 μs after the implantation. Using this time range removed the large γ-ray background which arises from implantation of ions in AIDA. Six γ rays can be observed with energies and half-lives in very good agreement with the previous report. The isomer half-life 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 ions implanted.

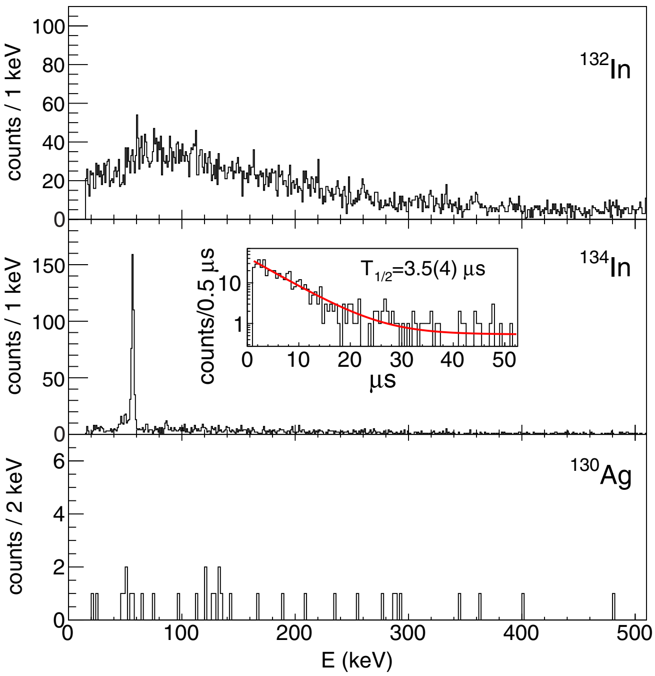

FIG. 3. γ-decay energy spectra for ^{132}In, ^{134}In, and ^{130}Ag. The time distribution of the 56.7 keV γ ray (inset) was fitted with a function including an exponential decay and a constant background. The ion-γ correlation-time window was varied between 1–200 μs; the figure shows the case of 1–15 μs. These spectra were generated following implantation of 1.4×10^6, 2×10^5, and 6.6×10^3 fully stripped ions of ^{132}In, ^{134}In, and ^{130}Ag, respectively, in the AIDA active stopper.

Finally, the isomeric-production ratio was determined as in Ref. [17] and found to be 8.0(15)% in agreement with the previous report of 6.5(3)% determined in the same facility [18].

Figure 3 shows the energy spectra of the events detected by the HPGe detectors and correlated with implantation of fully stripped ^{132}In, ^{134}In, and ^{130}Ag ions. A single γ ray of energy 56.7(1) keV is visible in the case of ^{134}In, while no evidence is found of decays from isomeric states in ^{132}In and ^{130}Ag. The time distribution of the 56.7(1) keV γ ray yields a half-life of 3.5(4) μs. The latter was determined from the data, by maximizing a Poisson probability log-likelihood function that considered an exponential decay and a time-independent background. Weisskopf single-particle estimates for the γ-ray partial decay branch for a transition of energy 56.7 keV for multipole order 1 and 2 decays are shown in Table I. Of these, only an $E2$ assignment is consistent with the expected single-particle decay transition strength.

To understand the single-particle or single-hole nature of the observed isomer in ^{134}In, it is worth considering first the simplest odd-odd nucleus in the region, i.e., ^{132}In ($Z = 49$, $N = 83$). The coupling of a $0g_{9/2}$ proton hole and a $1f_{7/2}$ neutron particle is expected to result in a multiplet of eight states with spins from 1^- to 8^-. The quadrupole component of the residual interaction should split the multiplet with energies distributed as a Paar's parabola in $I(I+1)$, with 6^- and 7^- being the lowest lying members [20]. 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 $\nu 1f_{7/2}$ (0 keV), $\pi 1p_{1/2}^{-1}$ (365 keV), $\nu 2p_{3/2}$ (853 keV), and $\pi 1p_{3/2}^{-1}$ (1353 keV), which are inferred from ^{131}In [21,22] and ^{133}Sn [23,24]. In the case of ^{134}In and ^{130}Ag, two more neutron-particles and two more proton-holes contribute, respectively, thereby increasing the number of possible configurations and the mixing between them. However, the lowest excited states are expected to be the same multiplets of states as in ^{132}In with two neutron particles or two proton holes coupled to $I^\pi = 0^+$. An estimate of the excitation energies of the same multiplet when two neutrons are coupled to $I^\pi = 2^+$ can be determined from the 2^+ state in ^{134}Sn (725.6 keV), and from the 2^+ state in ^{130}Cd (1325 keV) for the case of two proton holes. Besides generating more configurations, the two holes or two particles can also change slightly the order and energy of the multiplets as observed in ^{132}In.

TABLE I. Weisskopf estimated half-lives ($T_{1/2}$) for different multipolarities of ^{134}In isomer decay in the case of bare nuclei and neutral atoms. The latter includes the effect of internal-electron conversion that was accounted for by the coefficient α_{ic} of the *BrIcc* database [19]. The isotopes that we measured after implantation were neutral atoms. The value that best agrees with the experimental half-life of 3.5(4) μs is obtained assuming $E2$ multipolarity. The table also shows the theoretical reduced-transition probability in Weisskopf units. The uncertainty in the final W.u. values is 12% dominated by the experimental uncertainty in the measured half-life.

Multipolarity $^E_M\lambda$	Bare nuclei $T_{1/2}$ (μs)	Neutral atoms $T_{1/2}$ (μs)	$B(^E_M\lambda)$ W.u.
$E1$	1.4×10^{-6}	7.6×10^{-7}	2.2×10^{-7}
$M1$	1.2×10^{-4}	3.3×10^{-5}	9.6×10^{-6}
$E2$	23.7	1.9	0.53
$M2$	2.0×10^{3}	43.7	12.5

In view of these considerations, a single transition with energy lower than the single-particle energies above most likely connects two states of the yrast multiplet. This rules out $E1$ and $M2$ transitions because they would require a change of parity, and leaves the $E2$ as the most likely transition multipolarity. An $E2$ isomeric transition is, however, incompatible with the parabolic dependence of energy to spins, because any multiplet's member decays to the ground state via strong $M1$ cascade. The existence of the isomer would then be due to the fine details of the residual interaction, which leads to a departure from the parabolic dependence. Further insight comes from two different shell models developed southeast of ^{132}Sn. In both cases the model space 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. Excited states with energy of less than 2 MeV are well described in this space. The first shell model (SM-I) uses an effective Hamiltonian

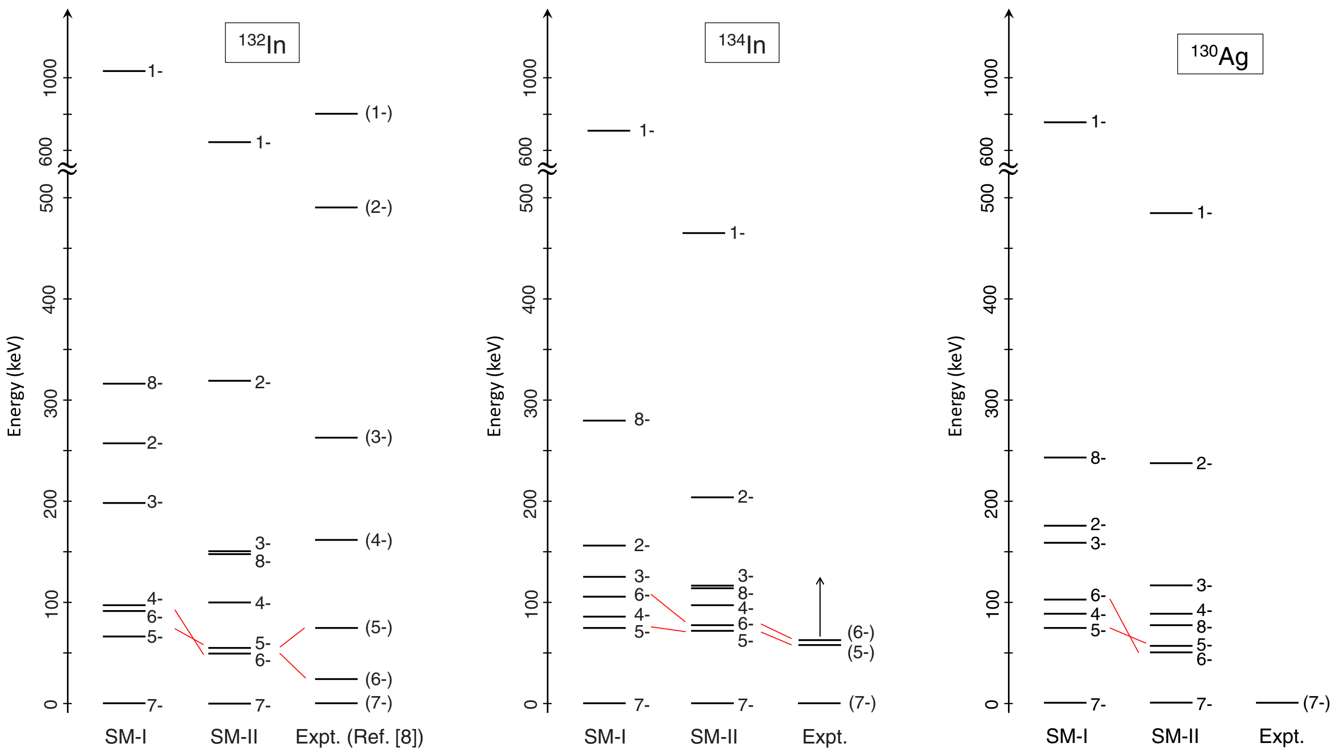

FIG. 4. Comparison between level schemes of the yrast multiplet from shell-model calculations (see text for details) and the one determined from available experimental data for excited states in ^{132}In, ^{134}In, and ^{130}Ag. The ground-state spin 7^- for the three isotopes is assigned based on shell-model calculations. The level scheme drawn for ^{132}In is uncertain due to one or more unobserved transitions [9]. Our data suggest that the 5^- state in ^{132}In lies above the 6^- and that the ordering of these two states is inverted in ^{134}In.

with proton-proton and neutron-neutron interactions obtained through the existing CD-Bonn G-matrix results, while proton-neutron interactions across two major shells are derived from the monopole-based universal interaction plus the M3Y spin-orbit force [7]. In the second shell model (SM-II), a two-body effective interaction is derived within the framework of the $\hat{Q}$-box folded diagram expansion [9,25] starting from the high-precision CD-Bonn *NN* potential. The neutron-proton effective interaction has been explicitly derived in the particle-hole formalism as described in Ref. [5].

The results of both calculations are consistent with the general arguments above, and are shown in Fig. 4 for the lower energy states. They both predict for the three isotopes a ground-state spin of 7^- and in ^{134}In the yrast 5^- states lies below the 6^- states. This causes the 5^- state to decay to the 7^- ground state, with a $B(E2)$ value which makes the 5^- state isomeric. The calculated half-life of such a 5^- isomer agrees with the experimental one. For example, SM-I calculates a $B(E2; 5^- \rightarrow 7^-) = 0.65$ W.u. (26.6 e^2 fm^4) corresponding to a half-life for neutral nuclei of 2.85 μs in good agreement with our experimental result of 3.5(4) μs. Based on these shell model calculations we assigned tentatively the ground state of the three isotopes to be 7^-, and the isomer in ^{134}In to be the yrast 5^- state. In this assumption, the isomeric-production ratio measured for the ^{134}In would be 46(6)%, i.e., the isomeric level and the ground state were populated with similar intensities. Notice that as shown in Fig. 4, the gaps between the calculated low-lying energy levels are often smaller than 50 keV. It is possible, therefore, that one or more low-energy transitions escaped observation. This leaves open a few other possibilities for a different interpretation for the observed isomer. For example, it is possible that the 5^- state lies above the 4^- and that one of the transitions of the cascade $4^- \rightarrow 6^- \rightarrow 7^-$ was not observed. Under these circumstances the 4^- state could be isomeric with a half-life in the microsecond regime. To firmly assign the isomer, an experimental setup capable of detecting low-energy x rays and conversion electrons is necessary.

The SM-I also predicts, in contrast with SM-II, the yrast $I^\pi = 5^-$ state to be isomeric in ^{132}In and ^{130}Ag. Our work shows no evidence of μs isomerism in these isotopes. Given that ^{132}In was implanted at a higher rate than ^{134}In, and that it is reasonable to assume a similar isomer production rate for the two isotopes, the existence of a 5^- isomer in ^{132}In appears unlikely; consequently the ordering of the 5^- and 6^- states is likely inverted in these two isotopes. Further investigation of SM-I showed that a reduction of the p-n interaction strength obtained reducing a single two-body matrix element by 100 keV resulted in the inversion of the 5^- and 6^- states in ^{132}In and ^{130}Ag (with disappearance of the predicted isomer) without changing the ordering for ^{134}In. This shows that (a) isomerism of this kind is very sensitive to the details of the p-n interaction, (b) as expected, ^{134}In has a less pure hole-particle coupling nature than ^{132}In, and (c) the present data can also aid shell-model development. In the case of ^{130}Ag, our observations are complicated by the relatively small implantation rate.

Assuming for this case a similar isomer population as for ^{134}In ($\approx$50%), one would expect to detect about 20 γ rays from a potential 5^- isomer. This was at the limit of the sensitivity of our current setup.

To summarize, we have investigated isomerism southeast of ^{132}Sn in the three odd-odd nuclei ^{132,134}In and ^{130}Ag. Energy and ordering of excited states in these three isotopes are key to building an effective Hamiltonian in the region. We have identified for the first time an isomeric state in ^{134}In, which based on both general arguments and two shell-model calculations we have tentatively 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 only a handful of excited states identified in nuclei southeast of ^{132}Sn. A similar 5^- isomeric state in the less exotic nucleus ^{132}In with configuration $\pi 0g_{9/2}^{-1} \otimes \nu 1f_{7/2}^{1}$ was not observed, suggesting that the ordering of the 5^- and 6^- states in these two isotopes is inverted. We did not find evidence in the current work in the 3-proton-hole, 1-neutron-particle system ^{130}Ag.

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