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High-spin isomers in $^{96}$Ag: Excitations across the $Z = 38$ and $Z = 50$, $N = 50$ closed shells

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Excited states in $^{96}$Ag were populated in fragmentation of an 850-MeV/u $^{124}$Xe beam on a 4-g/cm$^2$ Be target. Three new high-spin isomers were identified and the structure of the populated states was investigated. The level scheme of $^{96}$Ag was established, and a spin parity of (13$^+$), (15$^+$), and (19$^+$) was assigned to the new isomeric states. Shell-model calculations were performed in various model spaces, including $\pi\nu g_{9/2}$ and $\nu g_{9/2}$ orbits. Detailed shell-model calculations provide the tool to probe specific aspects of the nuclear residual interaction through comparison with key experimental data. Of particular interest are cases in the $^{100}$Sn region where core-excited high-spin isomeric states may be discovered, as there is a limited number of ways of forming these states. The first and so far only known case of such a state was identified in $^{98}$Cd [3]. In fact, this state has a counterpart in $^{96}$Ag, one of which is a core-excited isomer.

Experimentally there is little known about $^{96}$Ag. The existence of such a state was indicated by Grzywacz et al. [5], reporting two $\gamma$-ray transitions. In the experiment presented here, the power of the Rare Isotope Spectroscopic Investigation at GSI (RISING) setup [6] was used to perform detailed isomer spectroscopy of $^{96}$Ag.

II. EXPERIMENT AND RESULTS

The experiment was part of the “stopped beam campaign” of the RISING project [7]. A $^{124}$Xe beam with energy of 850 MeV/u and an intensity of 10$^9$ particles per second was produced at the GSI accelerator complex. The fragmentation reaction on a 4-g/cm$^2$ Be target was investigated at GSI (RISING) setup [6] was used to perform detailed isomer spectroscopy of $^{96}$Ag.

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I. INTRODUCTION

There are many isomeric states predicted and observed near the doubly magic $^{100}$Sn nucleus [1,2]. Their existence and properties are governed by the strong proton-neutron ($\pi\nu$) interaction between identical, but particular in the high-spin $\pi g_{9/2}$ and $\nu g_{9/2}$ orbits. Detailed shell-model calculations provide the tool to probe specific aspects of the nuclear residual interaction through comparison with key experimental data. Of particular interest are cases in the $^{100}$Sn region where core-excited high-spin isomeric states may be discovered, as there is a limited number of ways of forming these states. The first and so far only known case of such a state was identified in $^{98}$Cd [3]. In fact, this state has a counterpart in $^{96}$Ag, one of which is a core-excited isomer.

Experimentally there is little known about $^{96}$Ag. The existence of such a state was indicated by Grzywacz et al. [5], reporting two $\gamma$-ray transitions. In the experiment presented here, the power of the Rare Isotope Spectroscopic

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and temperature and atmospheric-pressure changes during the experiment.

The fragments, including $^{96}$Ag, were slowed down with an Al degrader and implanted into an array of nine double-sided silicon strip detectors (DSSSDs), $5 \times 5$ cm$^2$ each, with $16 \times 16$ $x$-$y$ segmentation. The detectors were arranged in three rows with three detectors in each row. The DSSSDs were surrounded by the RISING HPGe detector array, with a layout described in Ref. [7]. The absolute efficiency of the Ge array in this configuration was 10% at 1.3 MeV. DGF-4C [10] modules were used to process the signals from the Ge array within 90 $\mu$s after the arrival of an ion at S4. The shortest observed half-lives were limited by the flight time through the separator, about 0.33 $\mu$s, and by the background from the prompt bremsstrahlung radiation arising from the implantation of the reaction products in the DSSSDs.

The fragment identification plot obtained in this measurement is shown in Fig. 1 with $2 \times 10^5$ $^{96}$Ag nuclei identified. The correct reconstruction of $Z$ and $A/Q$ was verified by observing the known $\gamma$-ray transitions populated in the isomer decays of $^{96}$Pd [11] and $^{96}$Cd [3].

The delayed $^{96}$Ag $\gamma$-ray spectrum acquired up to 90 $\mu$s after implantation is shown in Fig. 2, where the $\gamma$-ray energies of the $^{96}$Ag transitions are marked. All $\gamma$-ray transitions were observed for the first time in this measurement, except for the 470-keV and 668-keV lines seen by Grzywacz et al. [5]. The inset highlights the region around 4 MeV acquired in 0.6 $\mu$s after the implantation.

A $\gamma$-$\gamma$ coincidence analysis of the $^{96}$Ag data resulted in the level scheme shown in Fig. 3. The isomeric states identified in this experiment are drawn in bold. The level energies, $\gamma$-ray energies, $E_{\gamma}$, relative intensities, $I_{\gamma}$, coincidence relations, isomeric ratios [12], $R$, and the half-lives, $T_{1/2}$, of the measured time distributions are summarized in Tables I and II, respectively. The half-lives for the 2643 + $x$-keV and 2461-keV levels were obtained by maximum likelihood fit of the sum of the time distributions for the 470-, 1506-, 1249-, 743-, 257-, 1719-, and 486-keV $\gamma$ rays (where $"x"$ is the energy of the unobserved transition; see below) with two exponential decay curves. They are consistent with the time distributions of the 630-, 667-, and 743-keV transitions. The half-life of the 6908 + $x$ level was obtained by a fit of the sum of the time distributions for the 4167-keV and 4265-keV $\gamma$ rays with a single exponential decay curve. The summed time distributions are shown in Figs. 4(a) and 4(b), together with the fits. The ordering of the 470-, 1719-, 1976-, and 2461-keV levels is fixed by the cross-over transitions. A $\gamma$-ray spectrum in coincidence with the 667-keV transition and a coincidence time window of $\Delta T_c = 0.15$ $\mu$s is shown in Fig. 5(a). Because of the narrow coincidence window the $\gamma$ transitions above the

![FIG. 1. (Color online) $Z$ versus $A/Q$ identification plot (see text for details).](image)

![FIG. 2. A $\gamma$-ray spectrum observed from 0.075 to 90 $\mu$s after implantation of $^{96}$Ag. The $\gamma$ rays associated with $^{96}$Ag are marked by their energies. The inset highlights the region around 4 MeV acquired in 0.075 to 0.6 $\mu$s after implantation.](image)

![FIG. 3. Proposed level scheme of $^{96}$Ag. The isomeric states identified in this experiment are drawn in bold (see text for details).](image)
1.56 μs isomer are not visible in this spectrum. In Fig. 5(b) a part of the coincidence spectrum is shown, when ΔΤc is increased to 3 μs and one of the γ rays was detected within 0.6 μs of implantation. The 4167-keV and 4265-keV transitions are marked. This indicates the presence of an isomeric state, with a half-life given in Fig. 4(b), which decays into the state at 2643 + x keV.

A coincidence spectrum of the 1249-keV transition with ΔΤc = 0.15 μs is shown in Fig. 5(c). The 743-keV transition depopulating the 2641-keV level is clearly visible. The 486-keV γ-ray is not seen, due to the branching ratios and the observational limit of the RISING array. The 486-keV transition is seen in coincidence with the 257-keV transition. Therefore, it is placed in the level scheme shown in Fig. 3.

The existence of three isomers in 96Ag decaying with high γ multiplicity and partially common cascades, indicates population of high-spin yrast states. In the isotones of 96Ag, 96Rh, and 92Tc, low-lying yrast (8+ ) states were observed. These are identified as the ground state or as an isomer at low excitation energy [13,14]. The shell-model calculations in this work and in Ref. [15] predict a low-lying 8+ state in 96Ag, consistent with the systematics of the (8+) states in 94Rh and 92Tc. Hence, we have assumed that the lowest state populated by the high-spin yrast cascade in Fig. 3 has Iπ = (8+ ).

The spins of the excited states are assigned assuming the observed transitions follow a yrast decay. Based on the coincidence analysis, the 1719-keV transition is parallel to the 470-keV and the 1249-keV transitions. Hence, it is likely that the 1719-keV transition has an E2 character while the 470-keV and 257-keV transitions have a M1 character. Similarly, the 1249-keV and 257-keV transitions form a parallel branch to the 1506-keV transition. There is no isomeric state in between, suggesting E2, M1, and M1 character for the 1506, 1249, and 257 keV transitions, respectively. Therefore, the spins of the 470-keV, 1719-keV, and 1976-keV levels are assigned as (9+ ), (10+ ), and (11+ ). The 630-keV and 667-keV transitions are parallel [see missing coincidence in Fig. 5(a)]. They are in prompt coincidence with the discussed γ rays, and have T1/2 of 1.52(5) and 1.54(15) μs, respectively. Hence, the 2606-keV and 2643-keV states (see Fig. 3), are fed by the 1.56-μs isomer. The isomer half-life is compatible only with E2 multipolarity and a transition energy close to or below the observational limit of 50 keV. Parallel primary decay branches from the isomeric state to the 2606-keV and 2643-keV levels.

### Table I. Level energies, γ-ray energies, relative intensities, and observed prompt coincidences.

<table>
<thead>
<tr>
<th>Eγ (keV)</th>
<th>ΔEγ (keV)</th>
<th>Iγ</th>
<th>Prompt coincidence transitions(keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.56</td>
<td>0.62</td>
<td>0.52</td>
<td>1249, 1506</td>
</tr>
<tr>
<td>2.57</td>
<td>1.25</td>
<td>1.15</td>
<td>1249, 1506</td>
</tr>
<tr>
<td>3.57</td>
<td>2.57</td>
<td>2.47</td>
<td>1249, 1506</td>
</tr>
<tr>
<td>4.58</td>
<td>3.58</td>
<td>3.48</td>
<td>1249, 1506</td>
</tr>
<tr>
<td>5.59</td>
<td>4.59</td>
<td>4.49</td>
<td>1249, 1506</td>
</tr>
</tbody>
</table>

### Table II. Half-lives, T1/2, of isomeric states in 96Ag, isomeric ratios, R, and reduced transition probabilities, B(σλ), of E2, M2, E3, and E4 transitions observed in their decay. One Weisskopf unit (W.u.) corresponds, respectively, to 26.11 e² fm⁴, 34.59 μ² fm², 547.4 e² fm⁴, and 12 144 e² fm⁸ for E2, M2, E3, and E4 transitions. Electric transitions are calculated with two sets of effective charges for protons/neutrons: (1.5/0.5) e (a) and (1.72/1.44) e (b).

<table>
<thead>
<tr>
<th>Jπ</th>
<th>Expt.</th>
<th>GF</th>
<th>FPG</th>
<th>GDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(19+)</td>
<td>6908+χ</td>
<td>0.16(3)</td>
<td>2.0(12)</td>
<td>98</td>
</tr>
<tr>
<td>(15+)</td>
<td>2643+χ</td>
<td>1.56(3)</td>
<td>10.9(6)</td>
<td>4265</td>
</tr>
<tr>
<td>(13−)</td>
<td>2461</td>
<td>100(10)</td>
<td>9.0(14)</td>
<td>486</td>
</tr>
</tbody>
</table>

*Alternative assumption.*
630-keV transition. This assignment is compatible with the measured intensity ratio. Hence, the tentative spin and parity of the 2606-keV, 2643-keV, and 2643 + x keV levels [where “x” is the energy of the unobserved E2 transition connecting the 1.56-μs isomer to the (13+) state] are (12+), (13+), and (15+), respectively.

The core-excited 0.16-μs isomer decays by competing 98-keV E2 and 4265-keV E4 transitions, similar to the core-excited state in 99Cd [16]. This is consistent with the observation of a prompt coincidence between the 98- and 4167-keV transitions. A lower multipolarity for the high-energy transitions is incompatible with the observed half-life and the level scheme. Hence, spins of (17+) and (19+) are assigned to the 6810 + x-keV and 6908 + x-keV levels.

The long decay time of the 100-μs isomer and the transition energy indicate a parity changing transition. If the 2461-keV state had a positive parity or the isomer was because of an unobserved low energy M1 or E2 transition, the 2461-keV state would have been fed from the 2643 + x-keV level. Hence, the data points to a 2461-keV (13−) state, which decays by 743-keV E3 and 486-keV M2 transitions. The strength of the E3 transition of 0.147(17) W.u. is similar to the B[E3; (19+) → (16+)] = 0.3 W.u. transition strength observed in 99Pd [17].

III. DISCUSSION

The standard shell-model approach to nuclei “southwest” of 100Sn employs empirically fitted interactions in the (p3/2, g9/2) proton (π)-neutron (ν) model space (GF) assuming a 76Sr38 core model space FPG [17] by implementing the GF two-body matrix elements (TBME) [18] with realistic interaction TBME obtained from the CD-Bonn nucleon-nucleon potential [21]. To the latter, core polarization corrections were applied assuming a 56Ni56 core following the many-body approach of Ref. [22].

Details of tuning to experimental single-particle energies and correction to the GF TBME to avoid double counting of interaction strength are given in Ref. [17]. These approaches, however, cannot account for core excitations across the N = Z = 50 shell closure. Therefore, in a third approach the πν(g, d, s) space GDS with a realistic interaction inferred according to Refs. [21,22] for a 80Zr40 core was used, as detailed in Refs. [3,16]. However, such a model space cannot describe odd-parity states.

The model spaces and the respective effective interactions employed in the present work in the following are denoted by GF, FPG, and GDS. Shell-model (SM) calculations for GF and FPG were carried out with the code OXBASH [23] while the large-scale shell-model (LSSM) results in the GDS space, allowing for up to 5p-5h excitations (truncation level t = 5), were obtained with the codes ANTOINE and NATHAN [24,25]. Results are shown in Fig. 6 and Table II. Two sets of effective charges were used for electric transitions, namely standard values for large model spaces eπ = 1.5 e, eπ = 0.5 e (a) and

FIG. 4. (a) Summed time distributions for the 470-, 1506-, 1249-, 2461-, and 486-keV γ-ray transitions. (b) Sum of the time distributions of the 4167-keV and 4265-keV γ-ray transitions, populating the state at 6908 + x keV. Half-lives are shown, extracted with the maximum likelihood method.

FIG. 5. (a) and (b) Coincidence spectra with the 667-keV transition within time windows of ΔTc = 0.15 μs and ΔTc = 3 μs, respectively. (c) A spectrum in coincidence with the 1249-keV transition within a time window of ΔTc = 0.15 μs.
FIG. 6. Experimental and shell-model level schemes for $^{96}$Ag. See text for details of the shell-model approaches.

$e_\pi = 1.72\ e,\ e_\nu = 1.44\ e$ (b), which was found to be optimum for the small GF model space [20]. For magnetic transitions quenched single-particle $g_s$ factors with $g_s = 0.7\ g_{s\text{free}}$ were assumed.

The experimental level scheme is very well reproduced by the three approaches within their scope and predictive accuracy. Extension of the GF to the FPG model clearly improves the positions of the $10^+, 11^+$, and $13^-$ levels. The LSSM approach accounts very well for positive parity states and reproduces both the excitation energy and correct order of the $(12-15)^+\ states$ including the core-excited isomer. However, it fails in the correct $17^+-19^+$ sequence which may be because of details of the interaction. A similar effect was observed in $^{98}$Cd for the $12^+-14^+$ states [16]. Inspection of the wave functions reveals that the core-excited states in $^{96}$Ag are dominated by neutron excitations across the $N=50$ gap. Therefore, the excitation energy of the isomer is an indirect measure for the $^{100}$Sn $N=50$ neutron gap. The extracted value of 6.70(15) MeV is in fair agreement with the value of 6.46(15) MeV determined for $^{98}$Cd [3], which establishes a robust $N=50$ shell closure for $^{100}$Sn. The error in the gap size is an estimate of the systematic uncertainties in the residual interaction.

Electromagnetic transition rates were extracted using the half-lives and intensities listed in Tables I and II and the conversion coefficients of Ref. [26]. The 1.56-$\mu$S isomer can be understood as a yrast trap, where a $15^+$ state, the highest spin which can be obtained in the $\pi^3\nu^{-1}(g_{9/2}, p_{1/2})$ space, decays by a low-energy $E2\ \gamma$-ray transition. For the experimentally nonobserved $(15^+)$→$(13^+)$ transition two values are given in Table II. The experimental observational limit of 50 keV and the value of 25 keV, below which the total conversion coefficient increases as $\alpha(E2) \sim E^{-5}_\gamma$, which makes the extracted reduced strength independent from the transition energy. Within these experimental limits good agreement with the various shell-model approaches is obtained. The parity-changing transitions, which are forbidden in the GF space, are remarkably well reproduced in the FPG approach if $E3$ multipolarity is adopted for the $(13^-)$→$(11^+)$ transition. In the extended FPG model space the fairly large $E3$ width is because of excitations from the proton $p_{3/2}$ orbit across the $Z=38$ subshell. The LSSM results in the GDS space using standard effective charges account well for transition strengths between even-parity states including the core-excited $(19^+)$ isomer. The agreement is better than that observed for $^{98}$Cd [3]. In contrast to $^{98}$Cd, in $^{96}$Ag the low-energy $(19^+)$→$(17^+)$ $E2$ dominates over the direct $(19^+)$→$(15^+)$ $E4$ transition owing to the larger $E2$ transition energy and the relative reduced transition strengths.
IV. SUMMARY

In summary, three new high-spin isomers with half-lives of 0.16(3) $\mu$s, 1.56(3) $\mu$s, and 100(10) $\mu$s were discovered in $^{96}$Ag. The level scheme of $^{96}$Ag was built based on coincidence analysis. The 0.16(3)-$\mu$s isomer was identified as the second known core-excited isomer in the $^{100}$Sn region. The 100(10)-$\mu$s isomer is determined as a decay from a negative-parity state, giving a second data point for an $E3$ transition probability in the region. Shell-model calculations were performed in the model space $\pi\nu(\frac{p_1}{2}, \frac{g_9}{2}, \frac{f_9}{2}, \frac{p_3}{2})$, necessary to reproduce the observed $E3$, $M2$ transition probabilities, proving excitations across the $Z=38$ subshell. A large-scale shell-model calculation within the $\pi\nu(gds)$ model space was performed to study the new data on $Z=N=50$ core excitation. The general features of $^{96}$Ag were reproduced, and the excitation energies and the transition probabilities are well described; furthermore, the robustness of the $^{100}$Sn shell gap is confirmed. Fine tuning of the residual particle-hole interaction is needed to reproduce the observed (17$^+$), (19$^+$) level sequence.

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