Isomer and $\beta$-decay spectroscopy of $T_z=1$ isotopes below the N=Z=50 shell gap

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Abstract. The RISING setup at the GSI-FRS facility was used to investigate the isomer and beta decays in N~Z~50 Cd, Ag and Pd isotopes. A preliminary analysis of the data has revealed new results on the $T_z=1$, $^{94}$Pd, $^{96}$Ag and $^{98}$Cd isotopes. In $^{94}$Pd a new high-spin isomer was observed, whilst in $^{96}$Ag 3 new isomeric states were identified, including core-excited states. In $^{98}$Cd a new high-energy isomeric $\gamma$-ray transition is observed, thus enabling us to confirm the previous spin assignment for the core-excited 12$^+$ isomer.

1. Introduction
It is expected that for N=Z nuclei the isospin mixing between T=0 and T=1 will be the largest, which will be reflected in the observed $\gamma$ and $\beta$ decays. There are many theoretical shell-model predictions for the nuclei around the N=Z=50 shell closure. The shell-model calculations and the experimental information on spin-gap isomers in the $^{94}$Pd, $^{96}$Ag and $^{98}$Cd isotopes prior to this work is summarized in References [1, 2].

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We studied the region below $^{100}$Sn with the Rare Isotope Spectroscopic INvestigation setup at GSI (RISING). RISING combines the FRagment recoil Separator (FRS) [3] at GSI with a high-efficiency germanium array of 15 EUROBALL cluster detectors [4] and a variety of ancillary particle detectors.

A preliminary analysis of the data revealed new results for some of the $N\sim Z$ nuclei in this region. Here we report on the results for $^{94}$Pd, $^{96}$Ag, $^{98}$Cd.

2. Experimental Setup

We produced nuclei around $^{96}$Cd ($N=Z=48$) with fragmentation of a $^{124}$Xe beam, at 850 MeV/u, on a 4 g/cm$^2$ $^9$Be target. The ions around $^{96}$Cd were selected with the FRS. A/Q was measured by time-of-flight between scintillator detectors at the middle and final focal planes of the separator. Energy loss measurement at the final focal plane was used to determine the charge of the ions. Corrections for different trajectories through the FRS were performed based on position measurements with Time-Projection Chambers. They were positioned at the middle and final focal planes of the separator. An identification spectrum is shown in Figure 1.

![Figure 1. Z vs A/Q plot [5].](image)

After separation and identification the fragments were implanted into an array of 1 mm thick Double Sided Silicon Strip Detectors (DSSSD). This active stopper consisted of 3 rows of 3 DSSSDs each. Each DSSSD was $5\times5$ cm$^2$ and had 16 X-strips and 16 Y-strips. The silicon stopper was surrounded by the RISING gamma-ray spectrometer. A photograph of the stopped beam setup is shown in Figure 2. In this geometry the absolute photo-peak efficiency of the germanium array reaches 11% at 1.3 MeV[6].

3. Results

The analysis of $^{96}$Ag ($Z=47, N=49$) revealed three new isomers. A spectrum of the observed $\gamma$-transitions is shown in Figure 3. The existence of an isomeric state in $^{96}$Ag was indicated by R. Grzywacz et al. [7], where two $\gamma$-transitions were observed. They are marked with open circles in Figure 3.

Based on $\gamma-\gamma$ coincidence relations and the measured half-life a level scheme up to high-spin spherical structures was built [8], including core-excited states. The spin and parity of the states, which do not include core excitation, were tentatively assigned based on systematics of transition probabilities in the region and a shell model calculation. Figure 4 shows partial level scheme of $^{96}$Ag and a comparison to the shell model calculation. The calculation was performed...
Figure 2. A picture of the active stopper surrounded with part of the EUROBALL cluster detectors.

Figure 3. A γ-ray spectrum of $^{96}$Ag isomeric decays. The transitions marked with filled circles were observed for the first time in this experiment. The 470 and 668 keV transitions, marked with open circles were reported in Reference [7]. The insert shows γ-rays de-exciting the core-excited isomer in $^{96}$Ag.

with the Gross-Frenkel(GF) empirical interaction [9] within the $\pi\nu(g_{9/2}, p_{1/2})$ model space. It was consistent with the observed level ordering, but the half-life and γ-decay energies of one of the new isomers marked on Figure 4 indicates E3 and M2 isomeric transitions. At a minimum, this requires the inclusion of the $\pi\nu(p_{3/2}, f_{5/2})$ orbitals in the N=Z=50 shell in order to calculate $B(E3)$ and $B(M2)$ transition probabilities.

Similarly in $^{94}$Pd(Z=46, N=48) a new isomer was discovered [11]. The measured half-life and the γ-γ coincidence relations placed this isomer as a (19$^-$) state decaying by an E3 to the previously known (16$^+$) state in $^{94}$Pd. A spectrum with the γ-transitions from the new isomer and level scheme with transitions observed in the presented experiment are shown in Figure ?? . The existence of the E3 transition prompts as in the case of $^{96}$Ag the necessity to include orbitals deeper in the f-p shell in order to describe the observed γ-transitions. More details can be found in References [11, 12].

The analysis of the $^{98}$Cd(Z=48, N=50) data revealed a new high-energy γ-ray transition [13, 14]. Figure 6 presents a γ-ray spectrum showing the new isomeric transition. The γ-γ-coincidence relations as well as the half-life suggest the existence of an alternative cascade (12$^+$)
Figure 4. Partial level scheme of $^{96}$Ag (right) and calculated energy levels. The arrow points to a new long-lived isomer.

Figure 5. A $\gamma$-ray spectrum of $^{94}$Pd isomeric decays [11, 12]. The transitions marked with filled circles were not reported in previous isomer studies of this nucleus but two of them were observed in $\beta$ decay of the (21$^+$) isomer in $^{94}$Ag [10]. The level scheme shows the transitions observed in the presented experiment. The new E3 $\gamma$ transition depopulating a (19$^-$) isomer is marked in red.

$\rightarrow (10^+) \rightarrow (8^+)$. The $^{98}$Cd level-scheme including the new cascade is shown in Figure 6.

The new experimental results in $^{98}$Cd are inconsistent with the level ordering previously calculated with large-scale shell-model [15]. This may indicate a need to increase the strength of proton particle-hole excitations across the Z=50 shell gap. Further studies are needed to understand the level ordering of the core-excited states in $^{98}$Cd and $^{96}$Ag.
Figure 6. A $\gamma$-ray spectrum of $^{98}$Cd isomeric decays [13, 14]. The transition marked with filled circle was observed for the first time in this experiment. A level scheme including the new transition observed in this experiment is shown.

4. Conclusions
The study of the $^{94}$Pd, $^{96}$Ag and $^{98}$Cd isotopes with RISING revealed new structure information. Isomers were discovered in $^{94}$Pd and $^{96}$Ag. The observation of E3 and E3/M2 transitions in these nuclei requires a larger than previously used shell-model space, in order to calculate $B(E3)$ and $B(M2)$ transition rates.

The new data on the core-excited states in $^{98}$Cd indicates an increase in the strength of proton particle-hole excitations across the $Z=50$ shell gap. Further large scale shell model calculations are needed to understand the structure of the newly discovered core-excited states in $^{96}$Ag and the data in $^{98}$Cd.

Analysis of the data for further isomeric decays and $\beta-\gamma$ correlations is currently in progress.

References
[1] M. Gorska et al., Proceedings of the 8th International Spring Seminar on Nuclear Physics, Key Topics in Nuclear Structure, Paestum, Italy, 2004 (World Scientific, Singapore, 2005) 229.
[2] H. Grawe et al., Eur. Phys. J A27, S01 (2006) 257.
[3] H. Geissel et al., Nucl. Instr. and Meth. B70 (1992) 286.
[4] J. Simpson, Zeitschrift für Physik A358 (1997) 139.
[5] P. Boutachkov et al., GSI Scientific Report (2009) 205.
[6] S. Pietri et al., Nucl. Inst. and Meth. B261 (2007) 1079.
[7] R. Grzywacz et al. Phys. Rev. C55 (1997) 1126.
[8] P. Boutachkov et al., to be published.
[9] R. Gross and A. Frenkel, Nucl. Phys. A267 (1976) 85.
[10] M. La Commana et al., Nucl. Phys. A708 (2002) 167.
[11] R. Wadsworth et al., Acta. Phys. Pol. B40 (2009) 611.
[12] T. S. Brock et al., Phys. Rev. C82 (2010) 061309(R).
[13] A. Blazhev et al., GSI Scientific Report (2009) 206.
[14] A. Blazhev et al., J. Phys.: Conf. Ser. 205 (2010) 012035.
[15] A. Blazhev et al., Phys. Rev. C69 (2004) 064304.