High-energy excited states in $^{98}$Cd

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Abstract. In $^{98}$Cd a new high-energy isomeric $\gamma$-ray transition was identified, which confirms previous spin-parity assignments and enables for the first time the measurement of the $E2$ and $E4$ strength for the two decay branches of the isomer. Preliminary results on the $^{98}$Cd high-excitation level scheme are presented. A comparison to shell-model calculations as well as implications for the nuclear structure around $^{100}$Sn are discussed.

1. Introduction

Studies of isomerism in the neutron-deficient $N \simeq Z$ nuclei around $^{100}$Sn give important insights into the role of proton-neutron pairing, serve as testing grounds for nuclear models and give input for understanding the astrophysical $rp$-process [1, 2]. Previous studies of $^{98}$Cd [3, 4] have revealed the existence of a high-energy core-excited state of $(12^+)$ decaying by a 4207 keV $E4$ transition to the $(8^+)$ state [4]. Large-scale shell-model (LSSM) calculations done in the $gds$-model space could reproduce the energy of the $(12^+)$ state [4]. The LSSM calculations have also suggested the existence of a $14^+$ state below the $12^+$ state resulting in a spin-gap isomer, which
is supposed to decay by $\beta$ or proton emission, and a $10^+$ state lying above the $12^+$ isomer [4]. These predictions together with the long-standing prediction of the $16^+$ and $25/2^+$ spin-gap isomeric states in $^{96}\text{Cd}$ and $^{97}\text{Cd}$, respectively, [5] have been motivation to continue studies in this very exotic region of the nuclidic chart.

2. Experimental details
In summer 2008 an experiment on $^{96,97,98}\text{Cd}$ was performed at the GSI Darmstadt using the FRS fragment separator [6] and the RISING germanium array in the “Stopped Beam” configuration [7]. These exotic nuclei of interest were produced using fragmentation of a 850 MeV/u $^{124}\text{Xe}$ beam on a 4 g/cm$^2$ $^9\text{Be}$ target and finally implanted into an active stopper consisting of nine double-sided silicon strip detectors [8]. The active stopper was surrounded by the RISING Ge-array with a photopeak efficiency of $\sim$10% at 1.3MeV [7], which collected $\gamma$ rays correlated with ion implantation and/or particle decays registered in the active stopper. Using the FRS detectors all ions were identified on an event-by-event basis allowing for a clean selection of the fragment of interest.

3. First results
While the analysis of this complex experiment is still in progress first results are already available. In several isotopes like $^{98}\text{Cd}$, $^{96}\text{Ag}$ [9] and $^{94}\text{Pd}$ [10] new $\gamma$-ray sub-$\mu$s isomeric transitions were discovered. This work reports preliminary results in $^{98}\text{Cd}$ where a new high-energy isomeric transition was identified.

In the $\gamma$-ray spectrum sorted in delayed coincidence with implanted $^{98}\text{Cd}$ ions, beside the known transitions [3, 4] with energies 4207(2), 147, 198, 688 and 1395 keV representing the cascade $(12^+) \rightarrow (8^+) \rightarrow (6^+) \rightarrow (4^+) \rightarrow (2^+) \rightarrow 0^+$ in $^{98}\text{Cd}$, a new transition with an energy of 4157(3) keV was identified. Figure 1 presents a spectrum gated on the new $\gamma$-ray, showing that this transition is in coincidence with the $(8^+) \rightarrow (6^+) \rightarrow (4^+) \rightarrow (2^+) \rightarrow 0^+$ cascade in $^{98}\text{Cd}$. A time spectrum of the 4157 keV $\gamma$-ray transition is shown in Fig. 2. A least-squares fit was performed using a single exponential decay plus a constant background (see Fig. 2). The preliminary result for the half-life is $T_{1/2} = 0.23(8)$ $\mu$s, which agrees with the known halflife $T_{1/2} = 0.23(\pm 3)$ $\mu$s of the $(12^+)$ isomeric state [4].

In our previous work [4] the assignment of the $E4$ character to the 4207 keV transition as well as the $(12^+)$ spin and parity to the 6635 keV state was discussed at length. Also in that work [4]
the lower observational limit for $E2$ transitions was 80 keV, and consequently we concluded that a hypothetical $(10^+)$ state would lie less than 80 keV below or above the $(12^+)$ state not changing the $E4$ assignment to the 4207 keV transition.

Both the $\gamma-\gamma$-coincidence relations as well as the halflife suggest that the new transition is part of an alternative cascade connecting the $(12^+)$ state with the $(8^+)$ state. Therefore, we suggest the existence of a state with an energy of 6585 keV, tentatively assign spin and parity of $(10^+)$ to this new state, and suggest an $E2$ character to this new 4157 keV high-energy
transition (see Fig. 3 column “EXP”). This also implies an experimentally non-observed 50 keV E2 isomeric transition depopulating the (12\(^+\)) state and feeding the (10\(^+\)) state. With this assignment from the measured half-life and the observed branching the preliminary transition strengths \(B(E2; 12^+ \rightarrow 10^+) = 2.1(13)\) W.u. and \(B(E4; 12^+ \rightarrow 8^+) = 3.0(10)\) W.u. are inferred.

4. Shell-model calculations

On the basis of the above discussed experimental evidence for a (10\(^+\)) state lying 50 keV below the excited (12\(^+\)) state in \(^{98}\)Cd the deficiencies of the previous SM calculations [4] became obvious (see Fig. 3, column “LSSM t=5”). Therefore, new SM calculations have been performed in order to account for the experimental level scheme. Figure 3 shows the new experimental level scheme of \(^{98}\)Cd (EXP) compared to two revised SM calculations, “3n-ph” and “pgdg”, which reproduce the correct ordering of the 10\(^+\) and 12\(^+\) states.

The 12\(^+\) is a core-excited state with a main component of the neutron configuration \(\nu (t_5/2, d_{5/2})\). On the other hand the leading configuration of the 10\(^+\) state is the \(\nu (t_9/2, g_{7/2})\). Thus changing the relative position of the neutron \(d_{5/2}\) and \(g_{7/2}\) orbitals with respect to each other may help in reproducing the experimental observation. The absolute single particle energies of the \(d_{5/2}\) and \(g_{7/2}\) orbitals relative to \(^{100}\)Sn are unknown and up to now their values have only been extrapolated. According to Ref. [11] in \(^{101}\)Sn the \(\nu d_{5/2}\) orbital is 80 keV lower than \(\nu g_{7/2}\). Therefore, a small variation in these single-particle energies can result in the reversal of the order of these two orbitals. A recent experiment on \(^{101}\)Sn has reported a \(\gamma\)-ray transition of 172 keV [12], which most probably connects the 5/2\(^+\) and 7/2\(^+\) states. The authors discuss and give good arguments that the 5/2\(^+\) state should be the ground state of \(^{101}\)Sn [12]. In the extreme single-particle shell-model this would mean that \(\nu d_{5/2}\) is 172 keV lower than \(\nu g_{7/2}\), but when accounting for the configuration mixing, in this case especially core-excitations, the situation changes.

The SM calculation labeled “3n-ph” (see Fig. 3) is performed with the m-scheme code NuShell@MSU [13, 14] in the SNE model space \(\pi \nu (f_{5/2}, p_{3/2}, p_{1/2}, g_{9/2}, g_{7/2}, d_{5/2}, s_{1/2}) + \nu (h_{11/2})\) using the SNET interaction [14, 15]. The following truncation was used: \(\pi (f_{5/2}, p_{3/2})\) and \(\nu (f_{5/2}, p_{3/2}, p_{1/2})\) were considered fully occupied, allowing for proton \(\pi (p_{1/2}, g_{9/2})\) configurations and up to 3 neutron particle-hole excitations (“3n-ph”) from the \(\nu g_{9/2}\) to \(\nu (d_{5/2}, g_{7/2})\) orbitals. As shown in Fig. 3 the “3n-ph” calculation reproduces the experimental ordering of the 10\(^+\) and 12\(^+\) states in \(^{98}\)Cd and their close position relative to each other. The calculation “3n-ph” presents a case where the single-particle orbital \(\nu d_{5/2}\) is 50 keV higher than \(\nu g_{7/2}\), i.e. “reversed” order. That means that in the case of \(^{101}\)Sn, one neutron outside the closed N=50 shell, and no core-excitations, i.e. the “On-ph” calculation, the 5/2\(^+\) state is 50 keV above the 7/2\(^+\). But once the neutron \(ph\)-excitations are taken into account the ordering of the calculated levels 5/2\(^+\) and 7/2\(^+\) in \(^{101}\)Sn is again “normal”. At “1n-ph” the calculated 7/2\(^+\) state is about 50 keV above the 5/2\(^+\), at “2n-ph” - 110 keV, and at “3n-ph” - 112 keV above the 5/2\(^+\) state, showing a converging trend and fairly reproducing what is believed to be experimentally observed [12]. Calculations with higher number of neutron \(ph\) core-excitations were not performed due to computational limitations.

The calculation labeled “pgdg” (see Fig. 3) is performed with another m-scheme code OXBASH [15] in the SN model space \(\pi \nu (f_{5/2}, p_{3/2}, p_{1/2}, g_{9/2}, g_{7/2}, d_{5/2}, s_{1/2}) + \nu (h_{11/2})\) using the GF interaction [16] for \(\pi \nu (p_{1/2}, g_{9/2})\) and the SNA interaction [15] for the rest. The calculation was truncated to \(\pi (p_{1/2}, g_{9/2})\) and \(1p1h \pi g_{9/2}^{-1} \nu d_{5/2}, g_{7/2} + \nu g_{9/2}^{-1} \nu d_{5/2}, g_{7/2}\) excitations across Z, N = 50 shell gaps. A “normal” sequence of the neutron \(d_{5/2}\) and \(g_{7/2}\) orbitals was assumed, i.e. \(d_{5/2}\) below the \(g_{7/2}\), and the proton-proton monopole part of the interaction was tuned to reproduce proton separation energies in \(^{88}\)Sr, \(^{90}\)Zr and \(^{100}\)Sn. Meaning that in the “pgdg” stronger proton particle-hole excitations across the shell gap are allowed and as shown in
Fig. 3(right) this calculation also reproduces the relative position of the $10^+$ state below the $12^+$, although currently the calculated splitting considerably exceeds the experimentally observed one. The existence of stronger proton-core excitations across the $Z = 50$ shell gap has been discussed also in the work of Vaman et al. [17] when trying to explain the increased $B(E2)$ strength in the yrast $2^+ \rightarrow 0^+$ transitions in the very neutron-deficient Sn isotopes. Therefore, the experimental $B(E2)$ and $B(E4)$ strengths from the core-excited state in $^{98}$Cd provide a crucial test of the SM calculations.

A detailed assessment of the level scheme and transition rates will be given in a forthcoming paper after the experimental analysis and the universal shell-model interaction tuning are completed.

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