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Prompt γ-ray spectroscopy of the neutron-rich ^{124}Cd

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Abstract. Prompt γ-ray spectroscopy of neutron-rich cadmium isotopes has been performed. The nuclei of interest have been populated via a 25-MeV, proton-induced fission of the ^{238}U thick target and prompt γ-rays measured using the multi-detector HPGe array JUROGAM II. New high-spin decays have been observed and placed in the level scheme using triple coincidence gates. The experimental results are compared to shell-model calculations and show good agreement.

1. Introduction

The excited states of the neutron-rich cadmium isotopes lying just two proton holes and a few neutrons away from the doubly magic ^{132}Sn are particularly interesting to study due the possibility of an early onset of quasi-collective behavior. This is illustrated by the unusually low energy of the 2^+_1 states of ^{126,128}Cd [1], in comparison to those of the neighboring Sn and Te isotones. Furthermore, the mid-shell Cd isotopes have long been cited as text-book cases of nuclei possessing excitations described as surface vibrations, though this interpretation has recently been called in to question [2]. It is therefore interesting to see if modern shell-model calculations can reproduce the energies and decay patterns of excited states of the Cd nuclei when removing neutrons from the $N = 82$ shell closure. In the present work medium-to-high spin states in the neutron-rich nucleus ^{124}Cd have been studied and compared to the predictions of shell-model calculations performed using a modern realistic-effective interaction in the full $Z = 28 - 50$ and $N = 50 - 82$ valence space.

Excited states in the nucleus ^{124}Cd have previously been studied following the β-decay of ^{124}Ag, where initially the 2^+_1 state was identified [3]. Later, similar studies at ISOLDE expanded the level scheme up to intermediate-spin states [1]. A prompt γ-ray spectroscopy fission experiment, using the ^{238}U(α, F) reaction, also extended the ground-state band up to spin 12^+ and an additional member of a negative-parity side band was also identified [4]. The fission products of the ^{238}U(α, F) reaction have a symmetric mass distribution centered around $A \sim 120$, making it a good method for populating the

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neutron-rich Pd and Cd nuclei as they are amongst the most strongly produced. Indeed, one notes that in a very recent study performed using a ^{252}Cf source with a much higher fission rate than the one of the ^{238}U(α, F) reaction, level schemes for the nuclei $^{117-120,122}$Cd were reported [5]. A level scheme for ^{124}Cd was not reported and this is likely to be due to the much lower production yield of this nucleus from the fission of ^{252}Cf, which lies in the dip of the double-humped mass distribution. As much of the medium-to-high spin data on nuclei in the neutron-rich mass $80 - 160$ regions comes from prompt γ-ray spectroscopy measurements of spontaneous fission sources then the studies of the symmetric fission region are incomplete. Previous light-ion induced fission reactions have studied the Cd, In and Sn nuclei [6–8] though the target-projectile combination chosen did not give a product distribution as neutron-rich as the one reported in the present work.

The ^{238}U(p, F) reaction has been used in the present work to study excited states in the neutron-rich $A \sim 120$ region. The experimental technique, the results for ^{124}Cd and a comparison with shell-model calculations are described below.

2. Experimental details

Neutron-rich mass ~ 120 nuclei were produced via the 25-MeV, proton-induced fission of a 74-mg/cm^2 thick ^{238}U target. The proton beam was provided by the K130 cyclotron of the Accelerator Laboratory of the University of Jyväskylä (JYFL) with an average intensity of ~ 0.1 pnA. The target was thick enough to stop the majority of the recoiling fission fragments. The proton-beam energy of 25 MeV was chosen as a compromise between a high fission cross section and producing a low-energy compound nucleus, thereby minimizing prompt neutron evaporation. The mass distribution of this reaction is symmetric, centered around mass ~ 120 and an average of 6 neutrons were evaporated [9] per fission. The secondary fission fragments therefore remain neutron rich due to the high N/Z ratio of the compound nucleus.

Emitted γ-rays were detected by the JUROGAM II array which consisted of 39 Compton-suppressed HPGe detectors [10]. 15 tapered single-crystal Ge detectors were located at backwards angles with respect to the beam while 24 Clover Ge detectors, each containing 4 individual crystals, were placed in two rings approximately perpendicular to the beam.

The data acquisition system ran in a total-data-readout, trigger-less mode. Data from each individual Ge crystal were time-stamped and recorded on disk. Event building and data sorting were done offline using the GRAIN software package [11]. An event was defined as a set of three, or more, unsuppressed Ge detectors firing in a time-window of 150 ns. Fission fragments are slowed down and stopped in the target in around 1 ps, which is generally faster than the lifetimes of many γ cascades, then the number of Doppler broadened transitions is minimized.

Three-dimensional $E_\gamma - E_\gamma - E_\gamma$ cubes were built to allow triple γ-ray coincidence analysis with the RADWARE software package [12]. In a such reaction, more than one hundred of nuclei are reasonably well produced, each emitting around 4 γ-rays on average, hence triple coincidences are required to cleanly select transitions in a nucleus of interest. Level schemes can be extended by setting gates on known transitions in a nucleus and observing coincidence relations. The assignment of transitions to a particular nucleus can also be performed by setting gates on the most likely fission fragment partner, knowing that no protons and 6 neutrons are evaporated by the fissioning system, on average, in this reaction.

3. Experimental results

3.1 Mass correlation for Cd-Rh

In order to assign new γ-ray cascades to a particular nucleus, mass correlation plots were made by gating on known transitions in nuclei of an isotopic chain and determining the average mass of

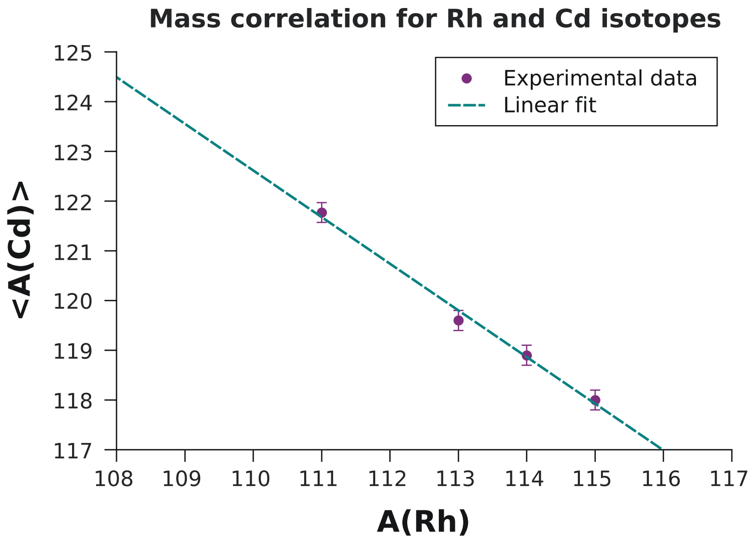

Figure 1. Mass correlation between the cadmium isotopes and their rhodium complementary fragments.

the complementary fission fragment each time. As the fission reaction used here leads to an odd-Z compound nucleus, then the easiest way to determine the relation between complementary fragment masses is to gate on the most intense transitions of the odd-Z fragment. The relative intensity of the observable $2^+ \rightarrow 0^+$ transitions of the complementary even-Z fragments can be extracted as a function of the gated fragment mass and fitted by a Gaussian function. This then allows the determination of the mean mass of a selected transition in given nucleus, as it is presented in Figure 1 for the example given here, the Rh-Cd pairs. The mean number of evaporated neutrons for nuclei of the $A \sim 120$ region was consistently found to be 6. Moreover, the sum of the proton numbers of both complementary fragments was always found to be equal to that of the compound nucleus.

3.2 Level scheme of ^{124}Cd

The level scheme of ^{124}Cd has been reported up to spin 12^+ in previous studies [1, 4]. In order to expand the level scheme, many different combinations of gates were set on the known transitions. An example of a double-gated spectrum is shown in Figure 2. This spectrum was obtained by summing several spectra which were doubly gated on the yrast band and exhibit no, or negligible, contamination from other nuclei. It can be seen that the most intense transitions of the complementary Rh nuclei are present in the low-energy part of the spectrum as well as the uranium X-rays origination from protons interacting with the target. In addition to the known transitions belonging to the ^{124}Cd, four transitions are labeled and marked with a star on the figure. These are assigned to ^{124}Cd in the present work. Careful checks were performed to ensure that they do not belong to other nuclei arising from contaminating coincidences in the gates. Further analysis of the coincidence relations then allowed these transitions to be placed in the level scheme proposed in Figure 3.

In addition, a new transition has been added to the top of the negative-parity side band. In our data set, the 393-keV γ-ray reported by Stoyer *et al.* [4] was not visible, however we have observed the 175-keV previously reported by Kautzsch *et al.* [1] together with a new 415.8-keV transition in coincidence with the lower lying transitions. The very weak relative intensity of the 415.8-keV transition relative to the 175.6- and 538.1-keV ones indicates that it most probably populates the 2559.5-keV state.

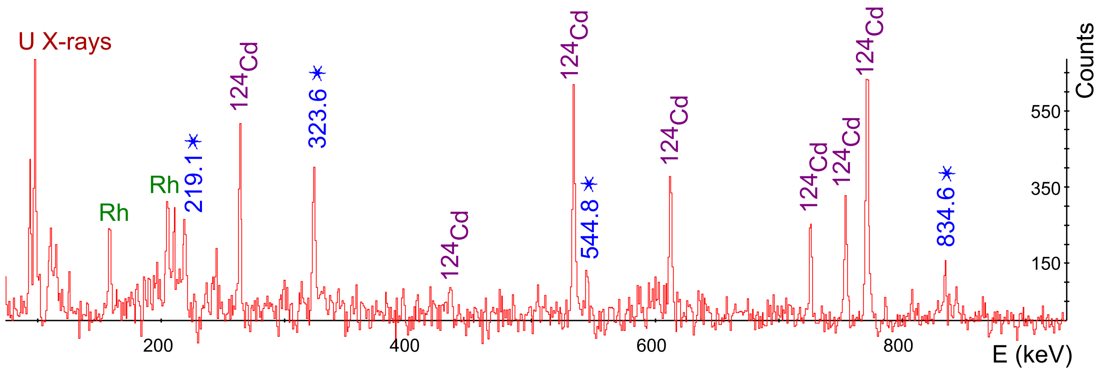

Figure 2. Coincidence spectrum double-gated on yrast transitions of ^{124}Cd. A combination of the cleanest double-gates have been used to highlight the four new transitions marked with a star on the figure (blue). At low energy, uranium X-rays are present, as well as the most intense transitions of the Rh complementary fragments. Lower transitions of the ^{124}Cd yrast band are labeled (purple).

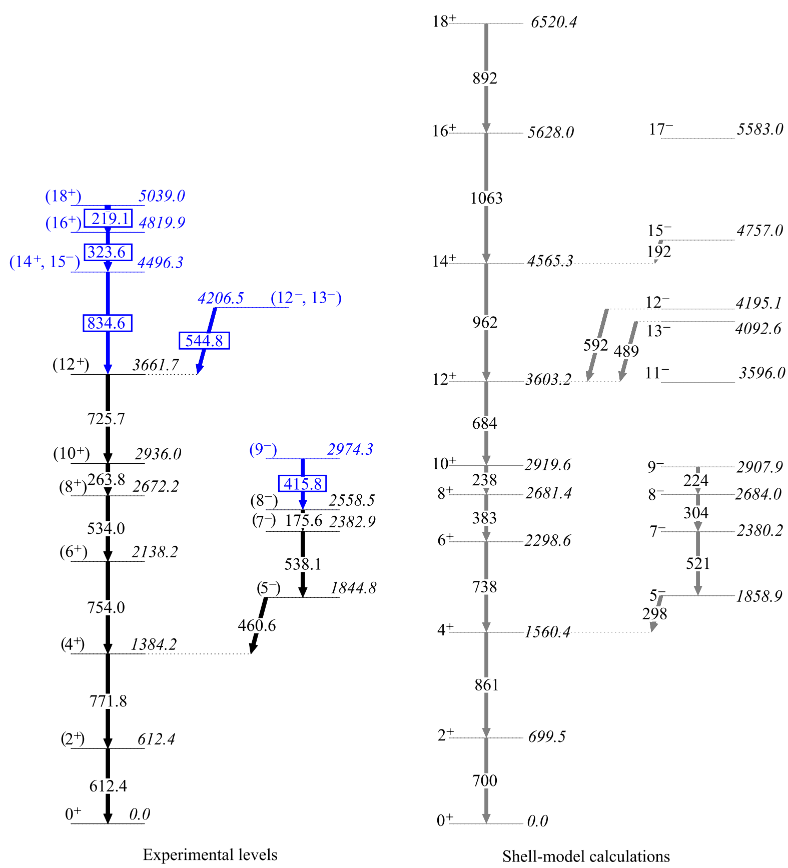

Figure 3. Level scheme of ^{124} Cd established in this work. The new transitions are boxed (blue). On the right part of the figure, the yrast levels predicted by shell-model calculations are shown as well as the deduced transitions (grey).

The spin and parity assignment has been tentatively made from a comparison to the level schemes of the neighboring Cd nuclei, which have a similar structure, and to the shell-model calculations presented in the next section.

4. Discussion

We have performed shell-model calculations using the ANTOINE code and the JJ45 interaction. In our calculation, the nucleus ^{132}Sn has been used as a closed core so that ^{124}Cd is composed of 2 proton- and 6 neutron-holes in the $28-50$ and $50-82$ shells respectively. No truncation was used in the calculations.

The results of our shell-model calculations are presented on the right part of the Figure 3. All the yrast states are plotted for the negative and positive parity states up to $I^{\pi}=18^{+}$. One can see a good overall agreement with the experimental levels for the positive parity states up to the $I^{\pi}=(14^{+},15^{-})$ state. The configurations involve mainly the couplings between neutron hole orbitals, and more precisely the $\nu(h_{11/2})$. The low lying positive parity states up to 10^{+} have a dominant configuration based mostly on the progressive alignment of two neutron holes in the $h_{11/2}$. For the upper part of the positive-parity band, the situation is more complicated with configurations that involve coupling of neutron orbitals but with very fragmented wave functions. One can see from the comparison with experimental results that these configurations do not reproduce the evolution of level energy spacing which is decreasing past the 14^{+} state. This may be explained by the proton-neutron interaction that is maybe not properly taking into account in this region of the nuclear chart. Indeed, one can think that the states above the 10^{+} one is based on the coupling of the two neutron holes in $\nu(h_{11/2})$ with maximum alignment to two proton holes in the $\pi(g_{9/2})$. The progressive alignment of this second pair will lead to a maximum aligned state with $I^{\pi}=18^{+}$ which is in very good agreement with the experimental results.

The negative-parity states are quite well reproduced and are mostly neutron hole configurations. Our shell-model calculation predicts yrast states with negative parity with main configuration being $\nu(h_{11/2}, d_{3/2}s_{1/2})$ in reasonable agreement with the experimental level energies.

5. Summary and conclusions

Decays from high-spin states in ^{124}Cd have been observed from the proton-induced fission of a ^{238}U target at the Jyväskylä accelerator laboratory. The results of the present work show how this reaction can populate states in neutron-rich nuclei up to high spins in the symmetric-fission region. The level scheme of the ground-state band of ^{124}Cd have been extended up to $I^{\pi}=(18^{+})$. A new level was also added to the top of the negative-parity band. Shell-model calculations have been performed and these are in very good agreement for all the states below 4.5 MeV for the positive parity states as well as the negative ones.

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