^{124}In levels populated in the β decay of ^{124}Cd

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The β decay of ^{124}Cd into levels in ^{124}In was reinvestigated at the Holifield Radioactive Ion Beam Facility. Fifty-MeV protons were bombarded on uranium targets and the induced fission products were mass separated and deposited on a moving tape in the center of an array of γ detectors. The resulting γ-γ coincidences revealed appreciable disagreement with previous work and has resulted in a revised ordering of the low-energy states in ^{124}In. The resulting partial decay scheme has four energy levels, three of which are new.

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I. INTRODUCTION

β decay is one of the best ways to populate low-lying and low-spin levels far from stability. The low-lying states of the neutron-rich odd-odd In nuclei can be described as a $g_{9/2}$ or $p_{1/2}$ proton hole coupled to an $h_{11/2}$, $g_{7/2}$, $d_{3/2}$, $d_{5/2}$, or $s_{1/2}$ neutron particle (hole). In most cases the In ground and isomeric states are describable as $\pi(g_{9/2})^{-1} \otimes \nu(g_{7/2})$. The ground states J^π of the even mass In from 114 to 122 are all 1^+ [1,2], with the result that the β decays of the 0^+ ^{118,120,122}Cd [1,2] nuclei have only been observed to decay to the ground states of the corresponding In isotopes (^{114,116}Cd are stable).

For the case of the β decay of ^{124}Cd, Folgelberg *et al.* [3] reported observing a total of four γ transitions deexciting levels at 36.5 keV (1^+), 179.9 keV (1^-), and 242.7 keV (1^+) based on γ and conversion electron data. They assigned a J^π equal to 2^+ to the ground state of ^{124}In. The resulting partial decay scheme of ^{124}Cd from Ref. [3] is displayed in Fig. 1. Later work [4] assigned a value of 3^+ to the ground state of ^{124}In based on a $\pi g_{9/2} \otimes \nu d_{3/2}$ configuration. As the ground state of ^{124}Cd is 0^+, most of the β-decay strength would be expected to populate levels above the ground state.

A high-spin isomer was identified in ^{124}In [3,5]. The assigned J^π of the isomer is (8^-) from collinear fast-beam laser spectroscopy [6] and the systematics of odd-odd In isotopes. The large difference in spin-parity between the 0^+ ground state of ^{124}Cd and (8^-) precludes any β decay to this isomeric state. The only other studies that have provided any information on the excited states of ^{124}In have been from a ^{124}Sn(t,^{3}He) study [7] and a study of low-lying high-spin yrast states in ^{124}In from the reaction of a 1.29-GeV ^{238}U beam on a Be target [8]. The former study reported levels at 122(15), 178(15), 365(20), and 555(20) keV. It should be noted that the 178-keV peak in that work is not resolved from the larger peak at 122 keV (see Fig. 2 in Ref. [7]). The yrast states study [8] reported high-spin states built on the high-spin isomer of ^{124}In and has no levels that would be expected to be populated in β decay.

As part of an investigation into the β decays of ^{124,126}Ag [9], we produced a large amount of the isotope ^{124}Cd directly from the fission of uranium and as the β daughter of ^{124}Ag [9]. This paper reports on the observed β decay of this isotope. We report significant disagreements with the previously published decay scheme [3].

II. EXPERIMENTAL METHOD

Fission products were produced via the proton-induced fission of ^{238}U at the Holifield Radioactive Ion Beam Facility. Fifty-MeV protons with an intensity of $\approx$15 μA from the ORIC cyclotron were used to bombard a ^{238}UC$_x$ target [10] in a plasma ion source installed at the IRIS-2 [11]. The proton-induced fission products were then mass-separated via a high resolution ($\Delta m/m \approx 10\,000$) magnet and delivered to the LeRIBSS (Low-Energy Radioactive Ion Beam Spectroscopy Station) detector array, where they were embedded on a moving tape located in the center of the array [11]. The beam of mass 124 was pulsed via electrostatic plates with the beam on for the first 2 s and then turned off for 1 s for a total of 3 s to allow the half-life measurements. The tape cycle time was chosen to enhance the observation of the short-lived ^{124}Ag isomers (144(20) and 191(28) ms for the high- and low-spin isomers, respectively [9]). Cadmium-124 is present in this data set both from being deposited on the tape directly and as the β daughter of ^{124}Ag.

At LeRIBSS the detector setup consisted of four segmented clover Ge detectors and two plastic scintillators surrounding the tape. The γ-γ coincidences were used to construct the decay scheme in ^{124}In after β decay. More details on the experimental setup may be found in Refs. [9,12,13]. Overall, very high statistics were collected for these nuclei compared to previously published results. The number of events observed

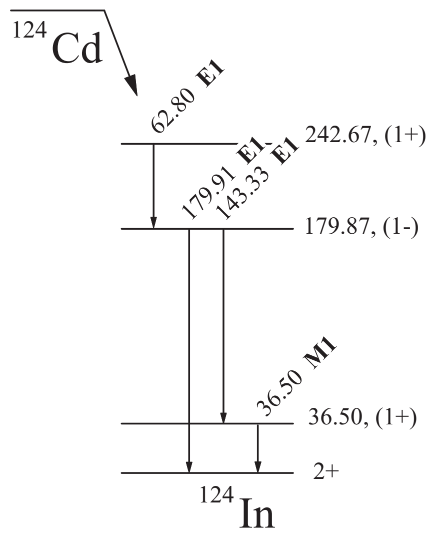

FIG. 1. Previously published partial decay scheme of the β decay of ^{124}Cd [3].

in the 62-keV peak was ≈500 000 (more than an order of magnitude more than previously published work [3]) in the singles γ spectra.

III. EXPERIMENTAL RESULTS

We have observed a total of five γ rays that are assigned to the decay of ^{124}Cd. The energies of the γ rays, 36.5(2), 62.2(1), 143.0(2), 179.6(1), and 242.0(3) keV, observed in this work match well with those of Ref. [3]: 36.50(5), 62.8(1), 143.33(5), and 179.91(5) keV. The low-energy portion of the ungated γ spectrum is shown in Fig. 2. Peaks assigned to the decay of ^{124}Cd are labeled with their respective energies and peaks from the decays of ^{124}Ag and ^{124}In are labeled by their parent nucleus.

Figures 3(a)–3(d) show the three spectra resulting from the γ rays coincident with the 179.9, 36.5, 143.0, and 62.2 keV γ transitions, respectively. The relevant part of the decay scheme from the previous work [3] is shown in the inset on the right side of each panel in Fig. 3.

Gating on the 179-keV transition [Fig. 3(a)] gives clear coincidence only with the 62-keV γ ray. Gating on the 36.5-keV transition [Fig. 3(b)] only shows a clear coincidence with the 62.2-keV γ line, while the expected 143-keV γ line is absent, indicating that the 36.5–62.2 cascade does not go through the intermediate 143-keV transition. Figure 3(c) shows the γ rays in coincidence with the 143.0-keV γ transition. The 62.2-keV γ line is clearly present, while the 36.5-keV γ line is absent, indicating that the 179-keV γ ray transition cannot be feeding a 36.5-keV level. Figure 3(d) shows the 179-keV γ ray is in coincidence with the 62.2 keV transition. The 36.5-, 143.0-, and 179.6-keV transitions are all in coincidence with the 62.2-keV γ ray. Gating on the 242.0-keV γ ray produces no coincident γ transitions. These discrepancies with the previous decay scheme [3] in the 36.5- and 143.0-keV γ-γ coincidence spectra indicate that the previous ordering of the γ transitions and their consequent levels are incorrect.

IV. DISCUSSION AND CONCLUSIONS

The observed γ transitions in the decay of ^{124}Cd are of low energy and have significant values of α_{tot} that must be taken into account to get the total intensity of a given transition. In the previous work [3], α_K values were determined by measuring conversion electrons in a Si(Li) detector. The values of 0.7(2), <0.07, and 0.028(10) were determined for the 62.8-, 143.3-, and 179.9-keV transitions, respectively. These values all compare well to the calculated values from the conversion coefficient calculator BRICC [14] for $E1$ transitions. The corresponding conversion electron intensity for the 36.5-keV transition was not measured directly, instead its α_K was "obtained from the K x-ray intensity after correcting for the K-shell conversion of other transitions and for the fluorescence yield" [3], resulting in a value of 5.9(25). This value falls between the calculated values for $E1$ (2.9) and $M1$ (9.5). Fogelberg *et al.* [3] assigned this transition a multipolarity of $M1$. In our data, using $\alpha_{\text{tot}} = 9.5$ (or 5.9) results in more

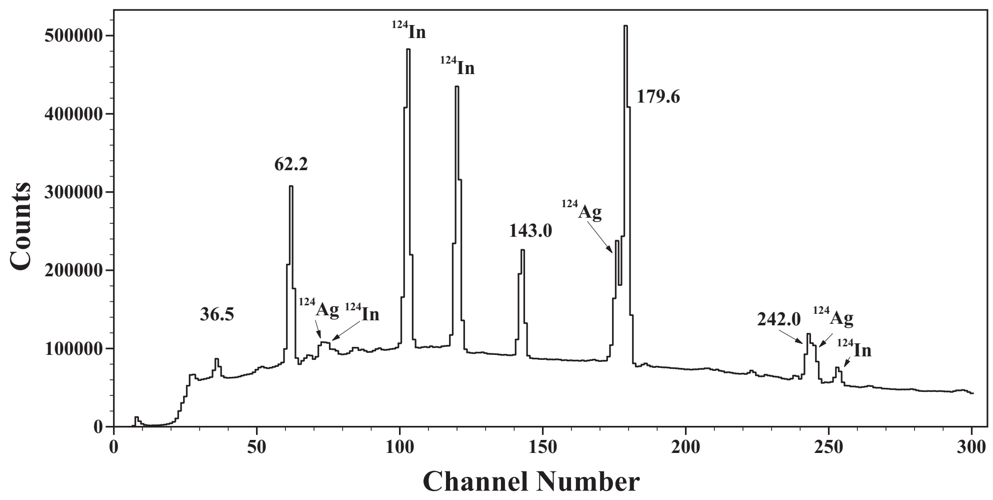

FIG. 2. Ungated γ spectrum showing the five peaks assigned to the decay of ^{124}Cd. Peaks resulting from the β decay of other nuclei are labeled as their respective β-decaying parent.

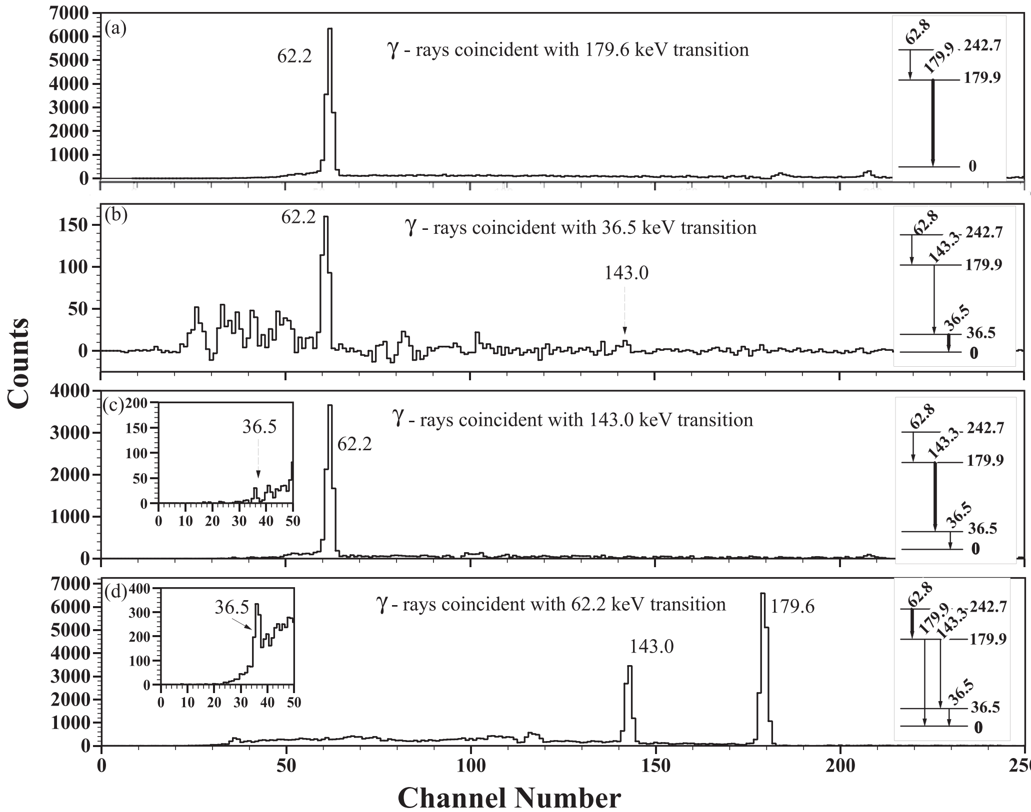

FIG. 3. The γ spectra coincident on the transitions (a) 179.6 keV, (b) 36.5 keV, (c) 143.0 keV, and (d) 62.2 keV. The insets on the right side of the figure correspond to previous work [3], with energy values taken from that work. The insets on the left side of the figure are enlargements of the 0- to 50-keV portion of the respective spectrum.

feeding into the 62.2-keV state than can be accounted for from the decay of a 62.2-keV $E1$ transition deexciting this state. The possibility of the 62.2-keV state decaying by β decay is excluded because the state that is deexcited by the 62.2-keV transition has been measured by Fogelberg *et al.* to have a lifetime of 50(6) ns [3]. We therefore assign a multipolarity of $E1$ to the 36.5-keV transition.

The properties of the observed transitions from the decay of ^{124}Cd are shown in Table I. We use the calculated values from Ref. [14] for the α_{tot} values. A new partial decay scheme that satisfies the observed coincidences for the β decay of ^{124}Cd is shown in Fig. 4. Note that the intensity balance of the 36.5-, 143.0-, and 179.6-keV γ rays feeding the 62.2-keV level minus the intensity of the 62.2-keV transition gives a value of 0 (within error bars) for the β feeding to this state. This is consistent with the assigned J^π value of 2^- that we assign to this level. For the higher-lying levels, the resulting β branches to the 98.7-, 205.2-, and 241.8-keV states are 16.5(6)%, 15.8(3)%, and 67.7(9)% respectively. These values should be considered as upper limits as higher-energy levels are likely to be weakly populated (the value for Q_β is 4170(40) keV [15]). The levels populated are listed in Table II. The level J^π values are assigned as a result of the multipolarities of the observed transitions. It was not possible to observe any ground-state-to-ground-state decays in this experiment. However, if the assignment of 3^+ to the ground state of ^{124}In is correct, this decay would be a second forbidden decay with a very small branching ratio.

TABLE I. List of γ rays resulting from the β decay of ^{124}Cd. The I_{tot} intensities in column 3 are normalized to 100%. The γ intensities are based on singles. The I_γ values are uncorrected for α_{tot}, and the corrected I_{tot}values use the theoretical α_{tot} [14] based on the multipolarities reported in Ref. [3], except for the case of the 36.5-keV γ ray (see text).

E_γ (keV)	I_γ	I_{tot}	Multipolarity	α_{tot}	E_i	E_f
36.5(2)	2.3(2)%	8.7(6)%	$E1$	2.85(6)	98.7(2)	62.2(1)
62.2(1)	28.2(5)%	47.0(10)%	$E1$	0.664(10)	62.2(1)	0.0
143.0(2)	7.8(5)%	8.3(5)%	$E1$	0.063	205.2(2)	62.2(1)
179.6(1)	29.2(5)%	30.3(4)%	$E1$	0.033	241.8(2)	62.2(1)
242.0(3)	5.3(2)%	5.7(2)%	$E2$	0.07	241.8(2)	0.0

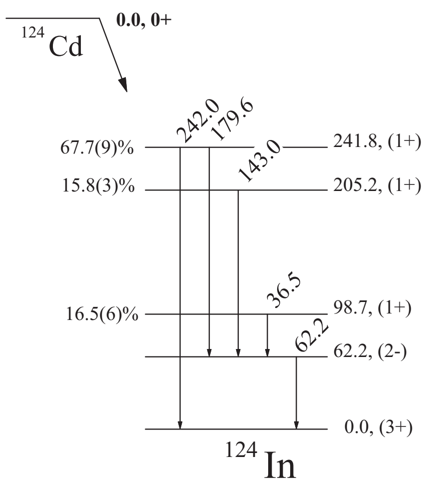

FIG. 4. Proposed partial decay scheme of ^{124}In.

The resulting partial decay scheme has four levels, three of which are new. As noted above, the likely configuration of the 3^+ ground state is $\pi g_{9/2} \otimes \nu d_{3/2}$ [4]. The first excited state at 62.2 keV decays via an $E1$ [3] transition to the 3^+ ground state and is therefore assigned a J^π value of 2^-. This state is likely based on a $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration. The three states at 98.7, 205.2, and 241.8 keV are apparently directly populated by β decay and are observed to decay to the (2^-) 62.2-keV level. They are all assigned as 1^+ based on the observed $E1$ multipolarities from Ref. [4] to the 62.2-keV 2^- state. These states likely arise from $\pi g_{9/2} \otimes \nu d_{3/2}$ or $\pi g_{9/2} \otimes \nu s_{1/2}$ configurations.

TABLE II. List of levels populated in the β decay of ^{124}Cd.

E_{level} (keV)	Branching ratio	J^π
0.0	0%	(3^+)
62.2(1)	0%	(2^-)
98.7(2)	<16.5(6)%	(1^+)
205.2(2)	<15.8(3)%	(1^+)
241.8(1)	<67.7(9)%	(1^+)

In conclusion, we have reinvestigated the β decay of ^{124}Cd into levels in ^{124}In. Significant disagreement with previous work has been observed, resulting in a revision of the low-energy states in ^{124}In.

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