Half-lives of neutron-rich $^{128-130}$Cd

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The $\beta$-decay half-lives of $^{128-130}$Cd have been measured with the newly commissioned GRIFFIN $\gamma$-ray spectrometer at the TRIUMF-ISAC facility. The time structures of the most intense $\gamma$ rays emitted following the $\beta$ decay were used to determine the half-lives of $^{128}$Cd and $^{130}$Cd to be $T_{1/2} = 246.2 (21)$ ms and $T_{1/2} = 126 (4)$ ms, respectively. The half-lives of the $3/2^+$ and $11/2^-$ states of $^{125}$Cd were measured to be $T_{1/2} (3/2^+) = 157 (8)$ ms and $T_{1/2} (11/2^-) = 147 (3)$ ms. The half-lives of the Cd isotopes around the $N = 82$ shell closure are an important ingredient in astrophysical simulations to derive the magnitude of the second $r$-process abundance peak in the $A \sim 130$ region. Our new results are compared with recent literature values and theoretical calculations.

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I. INTRODUCTION

The $\beta$-decay properties (half-lives and $\beta$-delayed neutron-branching ratios) of nuclei below doubly magic $^{132}$Sn [i.e., $N \approx 82$, $Z < 50$] are key input parameters for any astrophysical $r$-process scenario because they play an important role in the formation and shape of the second abundance peak at $A \sim 130$ [1]. This is despite the fact that the astrophysical site, or sites, where rapid neutron capture nucleosynthesis [2–6] takes place remain(s) elusive.

In both the high- and low-entropy hot neutrino-driven-wind scenarios, the most important nuclei in this mass region are the $N = 82$ isotones with $Z = 40–50$ because the enhanced neutron binding energy compared with their isotopic neighbors leads to a barrier for the $r$-process reaction flow toward heavier masses. After the breakout of the $N = 82$ shell, isotopes with $N = 84, 86$, and 88 also become important, such as $^{134,136,138}$Sn, $^{133,135}$Ag, $^{132,134,136}$Cd, $^{131,133}$Rh, and $^{130}$Pd [1].

At the so-called “waiting-point nuclei,” an accumulation of $r$-process material occurs (under given astrophysical conditions) and material can be transferred to the next elemental chain via $\beta$ decay. The half-lives of these waiting points thus determine how much material is accumulated and, therefore, the amplitude and shape of the resulting $r$-process abundance peaks after decay back to stability. The prominent $r$-process abundance peaks at $A \sim 80$, 130, and 195 correspond to waiting-point isotopes at the closed neutron shells $N = 50, 82$, and 126 where, due to nuclear-shell-structure effects, the reaction flow is hindered.

More neutron-rich “cold” $r$-process scenarios, such as neutron-star mergers [7,8], drive the reaction path towards the neutron dripline into regions that will only be partially accessible to experiments at the new generation of radioactive-beam facilities. Since most nuclei involved in $r$-process calculations are currently experimentally inaccessible, one has to rely heavily on the predictive power of theoretical models for the $\beta$ decay of these nuclei. The relative $r$-process abundances of nuclei around neutron shell closures are particularly sensitive to the half-lives, and it is thus critical to have models that can accurately reproduce these decay properties.

In particular, shell-model calculations for the waiting-point nuclei near the $N = 82$ neutron shell closure [9,10] have been performed by adjusting the quenching of the Gamow–Teller (GT) operator to reproduce the $^{130}$Cd half-life reported in Ref. [11] and are known to yield systematically large values for the half-lives of other nuclei in the region [10]. A new, shorter, half-life for $^{130}$Cd as measured by the EURICA collaboration [12] would resolve this discrepancy by scaling the GT quenching by a constant factor for all nuclei in this region.
Distinguishing between these discrepant half-life measurements for $^{130}$Cd [11,12] is thus of critical importance since the as-yet-unknown half-lives of other $N = 82$ waiting-point nuclei with $40 \leq Z \leq 44$ play a key role for the reproduction of the second abundance peak in $\tau$-process calculations.

A recent experimental campaign with the EURICA detector [13] at RIKEN measured the $\beta$-decay half-lives of 110 neutron-rich isotopes between Rb and Sn; among them, $^{128-130}$Cd [12]. While the previously reported half-life value for $^{128}$Cd of $T_{1/2} = 280(40)$ ms [14] was in agreement with the much more precise value of $T_{1/2} = 245(5)$ ms reported in Ref. [12], large discrepancies were found for $^{129,130}$Cd.

$^{129}$Cd $\beta$ decays from both a $3/2^+$ and an $1/2^-$ state but it is presently unknown which of the two states is the ground state and which is the isomeric state. In an experiment at ISOLDE, Arndt et al. [15,16] measured the half-lives of both states by using $\beta$-delayed neutrons. They reported $T_{1/2} = 104(6)$ ms for the “$11/2^-$ ground state” and $T_{1/2} = 242(8)$ ms for the “$3/2^+$ isomer” but gave no explanation of how the ground state was assigned.

The ground-state-spin assignments for many neutron-rich odd-A Cd isotopes have recently been confirmed via laser spectroscopy [17]. The odd-A Cd isotopes $^{121,123,125,127}$Cd have a well-established ground-state spin of $3/2^+$ but the exact position of the $11/2^-$ isomer is not known for $^{125,127}$Cd. Shell-model calculations [18] suggest that this order is inverted at $^{129}$Cd compared with the lighter odd-A Cd isotopes; however, there is no direct experimental evidence for this inversion. We thus label the two states only according to their spin and parity.

The recent measurements of the EURICA collaboration [18] did not resolve the issue of the ground-state spin-parity assignment in $^{129}$Cd. However, the half-lives for the $3/2^+$ and $11/2^-$ states were determined separately via the $\gamma$ transitions at 1423 and 1586 keV in the daughter nucleus to be $T_{1/2}(3/2^+) = 146(8)$ ms, and via the $\gamma$-ray transitions at 359, 995, 1354, 1796, and 2156 keV to be $T_{1/2}(11/2^-) = 155(3)$ ms. These results are in clear contradiction with the previous measurements [15,16].

In the case of the $^{130}$Cd half-life, the value of 127 (2) ms reported in Ref. [12] also differed from the previously accepted value of 162 (7) ms [11] by more than 5σ. The measurement of Ref. [11] was performed with the same technique using $\beta$-delayed neutrons as the $^{129}$Cd measurements of Refs. [15,16]. In an earlier paper, the $^{130}$Cd half-life was reported as 195 (35) ms [19].

In this paper we report an independent determination of the half-lives of $^{128-130}$Cd which, in general, confirm the recent EURICA results [12,18,20] but disagree with the previous measurements [11,15,16]. We report an improved precision for the $^{128}$Cd half-life, and revised half-lives for the two $\beta$-decaying states of $^{129}$Cd based on more detailed $\gamma$-ray spectroscopy.

II. EXPERIMENT

The half-lives of $^{128-130}$Cd were measured with the newly commissioned GRIFFIN $\gamma$-ray spectrometer [21,22] at the TRIUMF-ISAC facility [23]. Many of the nuclei in this neutron-rich region below doubly magic $^{132}$Sn have complicated decay chains, including significant $\beta$-delayed neutron-emission branches, as well as the presence of $\beta$-decaying isomeric states. A measurement of the temporal distribution of characteristic $\gamma$ rays emitted from the excited states of the daughter nucleus following $\beta$ decay of the parent isotope is a powerful method to reduce the complex background contributions to the measurement. This method requires the use of a high-efficiency $\gamma$-ray spectrometer because of the low production rates and short half-lives.

The isotopes of interest were produced by using a 500 MeV proton beam with $9.8 \mu$A intensity from the TRIUMF main cyclotron incident on a UC$_3$ target. The ion-guide laser ion source (IG-LIS) [24] was used to suppress surface-ionized isobars such as In and Cs, while the neutral Cd atoms of interest were extracted and selectively laser ionized in a three-step-excitation scheme. The Cd isotopes of interest were then accelerated to 28 keV, selected by a high-resolution mass separator, and delivered to the GRIFFIN spectrometer. GRIFFIN is comprised of 16 high-purity germanium (HPGe) clover detectors [21,22]. The radioactive-ion beam (RIB) was implanted into an aluminized mylar tape of the moving tape collector at the mutual centers of SCEPTAR, an array of 20 thin plastic scintillators for tagging $\beta$ particles [25], and GRIFFIN. The longer-lived background activity, either from isobaric contaminants in the beam or from daughters following the decay of the Cd isotopes, could be removed by moving the tape following a measurement. A typical cycle for the $^{128-130}$Cd runs consisted of a background measurement for 0.5 s, followed by a collection period (beam-on) with the beam being implanted into the tape for 10 s, followed by a collection period (beam-off) with the beam blocked by the ISAC electrostatic beam kicker downstream of the mass separator. The beam-off period consisted of a decay time of typically two to three half-lives, the movement of the tape for 1 s to a shielded position outside of the array, and the start of the new cycle with the background measurement.

The high efficiency of the GRIFFIN array coupled with the SCEPTAR $\beta$ detector allowed for the sensitive detection of the $\gamma$ rays following the $\beta$ decay of interest. All of the analyses reported here were performed by using add-back algorithms in which all of the detected energy in a clover within a 400 ns coincidence timing window was summed in order to increase the photopeak efficiency of GRIFFIN, as well as reduce the contribution of Compton background to the $\gamma$-ray spectrum [21,22].

III. DATA ANALYSIS

The data were analyzed by using $\beta$-$\gamma$ coincidences requiring a $\beta$ particle to be detected in SCEPTAR within a coincidence window of 400 ns of a $\gamma$ ray detected in GRIFFIN, resulting in a strong suppression of room-background $\gamma$ rays. Cycles in which the RIB dropped out for a portion of the cycle were rejected in order to increase the signal-to-background ratio. In the case of $^{128}$Cd, this resulted in the removal of 30% of the cycles, but only 1% of the total data.

A. $^{128}$Cd decay

Approximately 7 h of $^{128}$Cd data were collected with a beam intensity of $\sim$1000 pps. The 857 keV $I_{\gamma,rel} = 95 \, (10)$% and
the 925 keV transition [$I_{\gamma,\text{rel}} = 12.4(12\%)$] in the daughter nucleus $^{128}\text{In}$ [26] were used to determine the half-life. The strongest transition at 247 keV ($I_{\gamma,\text{rel}} = 100\%$) was not used because it is emitted from a 23 (2) $\mu$s isomeric state. The population of this isomer generally causes the emitted $\gamma$ ray to fall outside of the selected $\beta$-$\gamma$ time window of 400 ns.

The data were grouped into 10 ms bins and fit with an exponential plus constant background, as shown for the 857 keV $\gamma$ ray in Fig. 1. Sources of systematic uncertainties were investigated, including the re-binning of the data as well as a “chop analysis” [27,28]. The chop analysis was performed by changing the fit region that was used in order to investigate rate-dependent effects. By starting the fit at a later time, rate-dependent effects such as pileup [29] and dead time are gradually reduced. If these effects are statistically significant, they can be seen as a correlation between the half-life and time of the first bin used. The measured half-life did not change significantly as the first bin in the fit region was increased, nor did the measured half-life change as the last bin in the fit region was decreased.

The data were also re-binned into 20 and 40 ms per bin with no statistically significant change in the fitted half-life. The half-lives deduced from the 857 and 925 keV $\gamma$ rays were 245.8 (21) and 257 (11) ms, respectively, while the fit to the sum of these two $\gamma$ rays resulted in a half-life of 246.2 (21) ms. This result is consistent with the previous measurements of 245 (5) [12] and 280 (40) ms [14] and improves the precision of the $^{128}\text{Cd}$ half-life by a factor of 2.4.

### B. $^{129}\text{Cd}$ decay

Approximately 13 h of $^{129}\text{Cd}$ data were collected with a beam intensity of $\sim$250 pps. The beam of $^{129}\text{Cd}$ delivered to GRIFFIN consisted of both the ground state and the isomeric state. A portion of the $\gamma$-ray spectrum is shown in Fig. 2, and the partial level scheme showing the important transitions for the measurement of the half-life is depicted in Fig. 3.

The half-life of the 11/2$^-$ state was deduced in Ref. [18] by using the summed time distribution of the $\gamma$ transitions at 359, 995, 1354, 1796, and 2156 keV to be $T_{1/2}(11/2^-) = 155 (3)$ ms. Similarly, the half-life of the 3/2$^+$ state [$T_{1/2}(3/2^+) = 146 (8)$ ms] was measured by using the sum of the 1423 and 1586 keV $\gamma$ rays because they are known to be directly fed by the decay of the 3/2$^+$ state in $^{129}\text{Cd}$.

The high statistics of our measurements with GRIFFIN have made it possible to extract the half-life of the 11/2$^-$ state from just the 359, 1796, and 2156 keV $\gamma$ rays, yielding $T_{1/2}(11/2^-) = 147 (3)$ ms. For the half-life of the 3/2$^+$ state, the two transitions at 1423 and 1586 keV were used, resulting in $T_{1/2}(3/2^+) = 157 (8)$ ms (Fig. 4). A summary of the half-lives measured from each of the individual $\gamma$ rays is given in Table I. The same sources of systematic uncertainties as in the $^{128}\text{Cd}$ analysis were also studied for $^{129}\text{Cd}$ and

**FIG. 3.** A portion of the $^{129}\text{Cd}$ decay scheme (adapted from Ref. [18]) that shows the transitions relevant to the measurement of the half-life (see text for details). The $\gamma$ rays that were used in the half-life analysis are shown in red. Note that the ordering of the ground state and isomeric state in $^{129}\text{Cd}$ is unknown; in this context “x” can be $<0$ keV.
found to have negligible influence compared with the statistical uncertainties.

Unlike Ref. [18], in this work we do not use the strong 995 keV $\gamma$ ray in the analysis of the half-life of the 11/2$^-$ state of $^{129}$Cd due to the previously observed feeding from the 3/2$^+$ state of $^{129}$Cd via the 1222 keV transition in $^{128}$In [18]. We also do not include the 1354 keV $\gamma$ ray in this analysis because it is contaminated by a $\gamma$ ray of the same energy from the decay of the 611 ms ground state of $^{129}$In [30].

Based on the relative intensities of the observed $\gamma$ rays from $^{129}$In and $^{129}$Sn, we estimate that approximately 20% of the total 1354 keV photopeak intensity in our experiment was from $^{129}$In decay, which, if included, would bias the measured half-life to longer values.

The half-lives for the 11/2$^-$ and 3/2$^+$ $\beta$-decaying states of $^{129}$Cd measured in this work agree with the general conclusion of Ref. [18] that the half-lives of the two states are very similar and do not differ by a factor of $\approx 2$, as reported in Ref. [15,16,31]. A direct comparison of the results from the individual $\gamma$-ray transitions between this work and those of Ref. [20] is given in Table I. For statistical reasons, in Ref. [20] the counts in the 1423 and 1586 keV photopeaks were summed, and the fit of the summed decay curve resulted in the published value of 146 (8) ms [18] for the 3/2$^+$ state which is consistent with the value of 157 (8) ms reported here. The weighted average of these two independent measurements is 151.5 (57) ms. For the half-life of the 11/2$^-$ state we do not average with Ref. [18] but recommend the value of 147 (3) ms reported here due to the exclusion of contaminant $\gamma$-ray photopeaks in the current work.

### C. $^{130}$Cd decay

For $^{130}$Cd, approximately 38 h of data were collected with a beam intensity of 15–30 pps. Figure 5 shows a portion of the $\beta$-coincident $\gamma$-ray spectrum obtained during the $^{130}$Cd experiment.

The 451.0 $\gamma$ rays following the decay of $^{130}$Cd [32] were used to measure the half-life, yielding 123 (5), 138 (20), and 126 (6) ms, respectively. The transition at 951 keV $\gamma$ rays following the decay of $^{130}$In [33]. Fitting the sum of the time distributions of these three $\gamma$ rays yields a half-life of 126 (4) ms for the decay of $^{130}$Cd (Fig. 6), in excellent agreement with the value of 127 (2) ms recently reported in Ref. [12] and in strong disagreement with the previous half-life measurement of 162 (7) ms [11]. The study of systematic uncertainties was performed as discussed above and did not reveal any statistically significant effects on the measured half-life.

![FIG. 5. A portion of the $\beta$-gated $\gamma$-ray energy spectrum for the $^{130}$Cd experiment. The strongest peaks in the spectrum are labeled, including the doublet at 951 keV. The three strong $\gamma$ rays at 451, 1170, and 1669 keV were used for the half-life analysis. $\gamma$ rays following the $\beta$ decay of $^{130}$In are labeled with *.]
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FIG. 6. Sum of the 451, 1170, and 1669 keV $\gamma$-ray time distributions. The half-life obtained from the fit is 126 (4) ms. Note that the time represents the amount of time that has elapsed since the start of a cycle.

IV. DISCUSSION AND CONCLUSION

The half-lives of $^{128}$Cd, of the $11/2^-$ and the $3/2^+$ states of $^{129}$Cd, and of the $N = 82$ isotope $^{130}$Cd were measured at TRIUMF-ISAC by using the GRIFFIN $\gamma$-ray spectrometer. The $^{128}$Cd half-life measured in this work of 246.2 (21) ms is in excellent agreement with the previous measurement of Ref. [12], but a factor of 2.4 more precise. The measured half-lives of the two known $\beta$-decaying states in $^{129}$Cd, 147 (3) ms for the $11/2^-$ state and 157 (8) ms for the $3/2^+$ state, are found to be similar, in agreement with the recent work of Ref. [18], but in disagreement with the results of Refs. [15,16,31]. We recommend the revised value for the $11/2^-$ state reported here rather than averaging with Ref. [18] due to the exclusion of potential contaminants in the current analysis. Finally, the half-life of the $N = 82$ waiting point nucleus $^{130}$Cd was measured to be 126 (4) ms, in excellent agreement with the value of 127 (2) ms reported in Ref. [12] but in strong disagreement with the measurements of 162 (7) and 195 (35) ms from Refs. [11,19].

The confirmation of the shorter half-life for the $N = 82$ isotope $^{130}$Cd has significant implications for nuclear structure calculations in this region, as well as for $r$-process nucleosynthesis simulations. As shown in Fig. 7, the Fayans energy-density functional (DF3) + continuum quasiparticle random-phase approximation (CQRPA) model [34] and the relativistic Hartee–Bogoliubov (RHB) + relativistic quasiparticle random-phase approximation (RQRPA) [35] in general do a reasonable job of describing the systematic trend of the half-lives of neutron-rich Cd isotopes but slightly overestimate the absolute values.

As discussed in Ref. [12], the systematic overestimate of the half-lives for the $N = 82$ isotones can be traced to the scaling of the Gamow–Teller quenching to the previously reported longer half-life for $^{130}$Cd [11]. Increasing the GT quenching factor from $q = 0.66$ to $q = 0.75$ in order to reproduce the shorter half-life of $^{130}$Cd reported in Ref. [12] and confirmed in the current work resolves this discrepancy. This directly affects the predicted half-lives for the yet-unmeasured $N = 82$ isotones $^{127}$Rh, $^{126}$Ru, and $^{125}$Tc. As demonstrated in Refs. [1,12], the decrease in the calculated half-lives for these nuclei has a major influence on the shape of the rising wing of the $r$-process abundance peak at $A \sim 130$.

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