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

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The β-decay half-lives of $^{128-130}$Cd have been measured with the newly commissioned GRIFFIN γ-ray spectrometer at the TRIUMF-ISAC facility. The time structures of the most intense γ rays emitted following the β 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 ^{129}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.

I. INTRODUCTION

The β-decay properties (half-lives and β-delayed neutron-branching ratios) of nuclei below doubly magic $^{132}_{150}$Sn$_{82}$ (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 β 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 β 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.

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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 $40 \leqslant Z \leqslant 44$ play a key role for the reproduction of the second abundance peak in r-process calculations.

A recent experimental campaign with the EURICA detector [13] at RIKEN measured the β-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 β decays from both a $3/2^+$ and an $11/2^-$ 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 β-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 γ transitions at 1423 and 1586 keV in the daughter nucleus to be $T_{1/2}(3/2^+) = 146\,(8)$ ms, and via the γ-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 β-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 β-decaying states of ^{129}Cd based on more detailed γ-ray spectroscopy.

II. EXPERIMENT

The half-lives of $^{128-130}$Cd were measured with the newly commissioned GRIFFIN γ-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 β-delayed neutron-

emission branches, as well as the presence of β-decaying isomeric states. A measurement of the temporal distribution of characteristic γ rays emitted from the excited states of the daughter nucleus following β 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 γ-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 μA intensity from the TRIUMF main cyclotron incident on a UC$_x$ 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 β 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 β detector allowed for the sensitive detection of the γ rays following the β 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 γ-ray spectrum [21,22].

III. DATA ANALYSIS

The data were analyzed by using β-γ coincidences requiring a β particle to be detected in SCEPTAR within a coincidence window of 400 ns of a γ ray detected in GRIFFIN, resulting in a strong suppression of room-background γ 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,\text{rel}} = 95\,(10)\%$] and

FIG. 1. Activity of the 857 keV γ-ray photopeak in ^{128}In. The half-life of ^{128}Cd from this transition is determined to be 245.8 (21) ms. The inset shows the gate on the 857 keV γ ray as well as the strong 831.5 keV γ ray following the β decay of ^{128}In. Note that the time represents the amount of time that has elapsed since the start of a cycle. Background data were collected for 1000 ms before the beam was turned on. The beam was turned off at 11.5 s.

the 925 keV transition [$I_{\gamma,\mathrm{rel}} = 12.4\,(12)\%$] in the daughter nucleus ^{128}In [26] were used to determine the half-life. The strongest transition at 247 keV ($I_{\gamma,\mathrm{rel}} = 100\%$) was not used because it is emitted from a 23 (2) μs isomeric state. The population of this isomer generally causes the emitted γ ray to fall outside of the selected β-γ 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 γ 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 γ rays were 245.8 (21) and 257 (11) ms, respectively, while the fit to the sum of these two γ 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}Cd half-life by a factor of 2.4.

B. ^{129}Cd decay

Approximately 13 h of ^{129}Cd data were collected with a beam intensity of $\sim$250 pps. The beam of ^{129}Cd delivered to GRIFFIN consisted of both the ground state and the isomeric state. A portion of the γ-ray spectrum is shown in Fig. 2, and

FIG. 2. A portion of the β-gated γ-ray energy spectrum for the ^{129}Cd experiment. The strongest peaks in the spectrum are labeled. γ rays emitted following the β decay of ^{129}Sn are labeled with * and γ rays following the β decay of ^{128}Sn are labeled with &.

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 γ 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 γ rays because they are known to be directly fed by the decay of the $3/2^+$ state in ^{129}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 transitions, 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 γ rays is given in Table I. The same sources of systematic uncertainties as in the ^{128}Cd analysis were also studied for ^{129}Cd and

FIG. 3. A portion of the ^{129}Cd decay scheme (adapted from Ref. [18]) that shows the transitions relevant to the measurement of the half-life (see text for details). The γ 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}Cd is unknown; in this context "x" can be <0 keV.
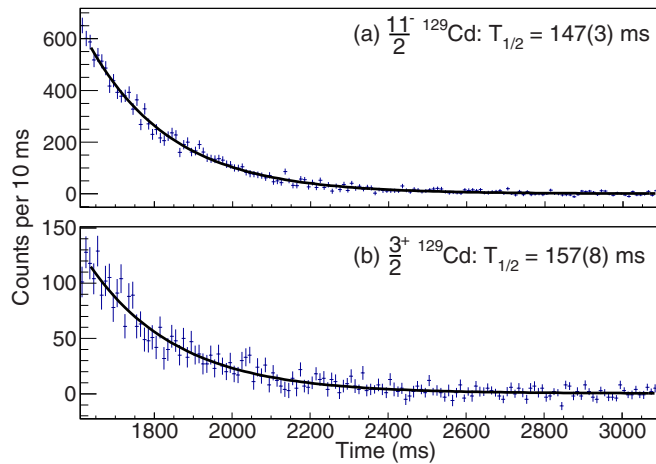
FIG. 4. (a) Fitted activity of the $11/2^-$ state using the 358.9, 1796.5, and 2155.6 keV γ rays. (b) Fitted activity of the $3/2^+$ state using the 1422.9 and 1586.2 keV γ rays. Note that the time represents the amount of time that has elapsed since the start of a cycle.

found to have negligible influence compared with the statistical uncertainties.

Unlike Ref. [18], in this work we do not use the strong 995 keV γ 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 ^{129}In [18]. We also do not include the 1354 keV γ ray in this analysis because it is contaminated by a γ ray of the same energy from the decay of the 611 (5) ms ground state of ^{129}In [30]. Based on the relative intensities of the observed γ 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.

TABLE I. Half-life of ^{129}Cd deduced from individual γ rays in this work and the corresponding results from the measurements of Ref. [20] (see text for details).

E_γ (keV)	Half-life (ms)		Parent state
	This work	Ref. [20]	J^π
358.9	148(3)	155.8(42)	$11/2^-$
1796.5	143(6)	157.9(99)	$11/2^-$
2155.6	136(12)	144(24)	$11/2^-$
Weighted average	146.5(26)	155.8(38)	
Summed value	147(3)	155(3)[a]	
1422.9	158(8)		$3/2^+$
1586.2	157(19)		$3/2^+$
Weighted average	157.9(75)		
Summed value	157(8)	146(8)	
995.1[b]	151.8(23)	152.0(27)	$11/2^- + 3/2^+$
1354.2[c]	192(12)	158.6(81)	Doublet

[a] The value published in Ref. [20] includes the transitions at 995 and 1354 keV.
[b] γ ray was not used in the current analysis due to a potential contamination between the ^{129}Cd and ^{129}Cd^m decays.
[c] Doublet with a γ ray from the decay of ^{129}In.

The half-lives for the $11/2^-$ and $3/2^+$ β-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 ≈ 2, as reported in Ref. [15,16,31]. A direct comparison of the results from the individual γ-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 γ-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 β-coincident γ-ray spectrum obtained during the ^{130}Cd experiment.

The 451.0 [$I_{\gamma,\mathrm{rel}} = 88.6\,(36)\%$], 1170.3 [$I_{\gamma,\mathrm{rel}} = 20.0\,(2)\%$], and 1669.2 keV ($I_{\gamma,\mathrm{rel}} = 100\%$) γ 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 [$I_{\gamma,\mathrm{rel}} = 22.1\,(33)\%$] [32] was not used because it is a doublet with a γ ray from the decay of ^{130}In [33]. Fitting the sum of the time distributions of these three γ 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.
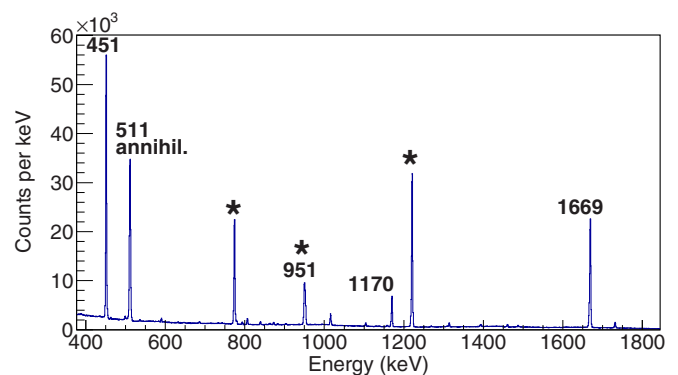

FIG. 5. A portion of the β-gated γ-ray energy spectrum for the ^{130}Cd experiment. The strongest peaks in the spectrum are labeled, including the doublet at 951 keV. The three strong γ rays at 451, 1170, and 1669 keV were used for the half-life analysis. γ rays following the β decay of ^{130}In are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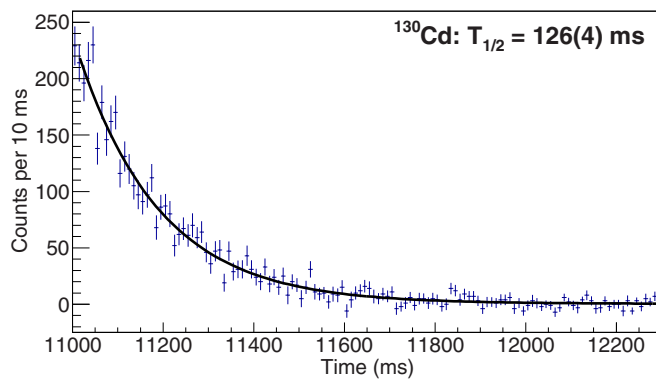
FIG. 6. Sum of the 451, 1170, and 1669 keV γ-ray time distributions. The half-life obtained from the fit is 126 (4) ms. Note that the time represents the amount of time that has elapsed since the start of a cycle.

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 γ-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 β-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 Hartree–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
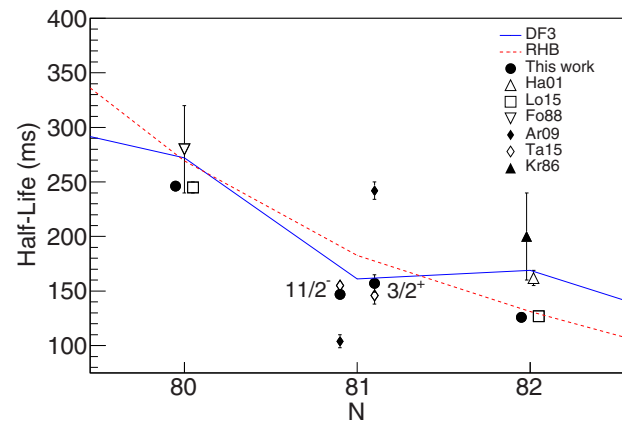

FIG. 7. Comparison between the calculated half-lives using the DF3 + CQRPA [34] and RHB + RQRPA [35] models to the measured half-lives of ^{128}Cd, ^{129}Cd, and ^{130}Cd. The measured half-lives in this work are in good agreement with Ref. [12,18] but do not agree with the previous measurements of Refs. [11,14–16,31]. Some error bars are not visible in the plot because they are smaller than the data points. Ha01: [11], Lo15: [12], Fo88: [14], Ar09: [16], Ta15 [18], Kr86 [19].

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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