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Half-life measurements for neutron-rich Ag and Cd nuclei

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Half-lives have been measured for the neutron-rich nuclei ^{123}Ag and $^{123-125,127,128}$Cd at an on-line mass separator. The results are compared with recent model calculations. The data near $Z=50$ are consistent with the systematic pattern of discrepancies between the theoretical and new empirical values already observed in the rare-earth region and near $Z=28$. The results imply that additional effects associated with proton shell structure may need to be included in the model.

The ability to determine the properties of neutron-rich nuclei far off the stability line plays an important role in the development of models to describe stellar nucleosynthesis, nuclear structure, and reactor control and cooling processes. The vast number of nuclei which remain inaccessible, but nevertheless constitute a crucial input to the types of studies cited above, has in turn necessitated the use of nuclear models to predict their properties, and most importantly, their half-lives. Recently, a systematic pattern of discrepancies between the predictions of one such model[1] and the experimentally measured half-lives has been observed for neutron-rich nuclei.[2] The results of Ref. 1 are currently considered to be the most detailed and accurate global predictions available for half-lives, and are therefore used in many nucleosynthesis calculations. The identification of systematic deviations may not only point to the true uncertainties inherent in the model, but may also lead to a better understanding of their source, and hence to further improvements in the $T_{1/2}$ estimates. The ratio between the experimental and theoretical half-lives was used as a measure of the predictive power of the model. This ratio when presented as a function of proton number Z appears to follow a sawtooth pattern which decreases monotonically between particular values of Z (turning points) and then jumps suddenly.[2] Furthermore, it has been suggested[2] that the turning points are related to the vicinity of proton closed shells, the evidence for this type of correlation being particularly convincing near $Z=28$. It is thus of interest to search for similar trends in the neighborhood of $Z=50$.

Recently, half-lives of ^{123,124}Ag and ^{123,124,126}Cd were measured.[3–5] However, with the exception of ^{124}Ag and ^{126}Cd, these data were obtained from β and β-delayed neutron counting techniques. The measurement of γ decay curves can provide significantly more precise values for these quantities and, in addition, has the potential to separate ground state and isomeric state decays, which are expected to occur in the odd silver and cadmium isotopes. Consequently, in the current study, we have measured the half-lives for ^{123}Ag and $^{123-125,127,128}$Cd nuclei using γ-ray transitions. While this paper was being prepared for publication we learned of similar work being carried out at the Studsvik ISOL facility.[6]

The measurements were performed at the TRISTAN on-line mass separator at the high flux beam reactor at Brookhaven National Laboratory. The activities of Ag and Cd were produced by thermal neutron fission of highly enriched ^{235}U impregnated on graphite cloth discs in a FEBIAD (Ref. 7) or high temperature plasma[8] type of ion source. The isobaric beam was mass separated by a 90° magnet and deposited onto an aluminized Mylar tape. In the case of the short-lived activities ($T_{1/2}<0.6$ sec), two large Ge detectors viewed the deposition spot (parent port configuration). The beam was collected on the tape for a predetermined period of time before being electrostatically deflected, and the accumulated activity was allowed to decay. During this period of buildup and subsequent decay, a series of consecutive spectra was collected, each for a time period ΔT selected to optimize the activity of interest, after which the deposited activity was moved to a shielded location and a new counting cycle started. For the longer-lived activities ($T_{1/2}>0.6$ sec), the γ detectors were positioned at a "daughter port" about 50 cm away, and shielded from the point of deposition. At the daughter port the multiscaling cycle started with the arrival at the counting station of a new activity. γ-ray singles, γ-multispectrum scaling (GMS), and γ-γ-t coincidences involving the two detectors were simultaneously accumulated at either daughter or parent port. Furthermore, in the latter configuration, γ-ray singles spectra were also taken with the analog to digital converter (ADC) gated by the β signal obtained from a thin plastic detector positioned immediately behind the aluminized tape containing the active sample. The decay curves measured at the parent port were normalized to the counting rate of a precision pulser incorporated into the counting system. No dead time corrections were necessary at the daughter port due to the much lower count rate. Transitions in the energy range from 20 to 3700 keV were identified from a combination of E_γ, I_γ, GMS decay, and coincidence relationships. Furthermore, the key transitions in the $^{123-127}$Cd decay have already been identified by Rudstam *et al.* using a combination of fast chemical separation and an ISOL system.[9]

Table I presents a summary of the half-life measurements obtained for the heavy Ag and Cd nuclei and compares the current results with earlier measurements. The agreement is generally good. Furthermore, there is also reasonable agreement with preliminary half-life measurements for ^{123,125,127}Cd using β decay counting[13] and with the results of Ref. 6.

The decay modes associated with the ground and isomeric states, respectively, are identified in the ^{123,125}Cd isotopes. However, it is clear from Table I that, for ^{125}Cd at least, the measured values of the two half-lives are the same, within the error of the measurement. The justification for nevertheless assuming two distinct decaying states is therefore based on the low energy singles and coincidence γ-ray data, which reveal[14] the existence of two sets of levels with very few connecting transitions, combined with the known[15] systematics of neighboring odd Cd and In nuclei, which all display characteristic decay patterns originating from beta decay of both a low spin and a high spin isomer in each case. It can be seen that, in the case of ^{123}Cd, the earlier measurements did not distinguish these two decay modes. Nevertheless, inasmuch as the two half-lives have similar numerical values in each nucleus, they can still be approximately compared to the $T_{1/2}$ deduced in the earlier work.

The new half-life measurements are also compared in Table I to the theoretical calculations of Takahashi *et al.*[10] and to those of Klapdor *et al.*,[1] the ninth column giving the ratio of experimental half-lives to the latter set of theoretical results. Interestingly, all the results below $Z=50$ are systematically overestimated but are yet within a factor of 2 of the theoretical predictions, and thus somewhat closer than expected from the comparison of previously known nuclei to the model calculations.[1] In contrast, the half-lives for the new nuclei recently studied below $Z=28$ are also systematically overestimated, yet only about a third of them are reproduced by the model calculations within a factor of 2.[2] The sequence of six new Cd isotopes listed in Table I shows a remarkably constant ratio of about 0.55, suggesting that the discrepancies

TABLE I. Observed and predicted half-lives for the new neutron-rich Ag and Cd isotopes.

	This work		Other measurements			Theoretical		
Nuclide[a] and decay	γ transitions used (keV)	$T_{1/2}$ (sec)	$T_{1/2}$ (sec)	Method	Ref.[b]	Takahashi *et al.* (Ref. 10) (sec)	Klapdor *et al.* (Ref. 1) (sec)	$R=\frac{T_{1/2}(\exp)^{c}}{T_{1/2}(\text{calc})}$
^{123}Ag→Cd	116,123, 263,409	0.30±0.02	0.30±0.01	n	3	1.4		
			0.39±0.03	n	11			
^{124}Ag→Cd			0.17±0.03	γ	4	1.0	0.395	0.43±0.08
			0.54±0.08	n	3			
^{123}Cd $\xrightarrow{g}$ In	371	2.11±0.06	2.07±0.03	β	3	5.0	3.20	0.66±0.02
^{123}Cd $\xrightarrow{m}$ In	1027,1165	1.88±0.06						
^{124}Cd→In	62,143,179	1.29±0.03	1.2 ±0.1	β	3	5.6	2.29	0.56±0.01
			0.9 ±0.2	β	12			
			1.7 ±0.6	β	9			
^{125}Cd $\xrightarrow{g}$ In	436	0.64±0.03				2.2	1.22	0.52±0.02
^{125}Cd $\xrightarrow{m}$ In	736,1027, 1173	0.66±0.03						
^{126}Cd→In			0.51±0.01	γ	5	2.3	1.0	0.49±0.01
^{127}Cd→In	377,523	0.30±0.03				1.1	0.56	0.53±0.05
^{128}Cd→In	247,857	0.26±0.02				1.0	0.47	0.55±0.04

[a] *g* and *m* indicate half-lives for the ground and metastable states, respectively.
[b] Either γ, β, or β-delayed neutron decays have been measured.
[c] Calculations of Klapdor *et al.* (Ref. 2) were used in the ratio.

do not depend strongly on the neutron number in these nuclei.

Based on this observation one may offer a very tentative prediction for the half-life of ^{130}Cd. The properties of ^{130}Cd→In decay are of particular importance in nucleosynthesis calculations since ^{130}Cd represents one of the crucial "waiting points" when the *r*-process path crosses a closed shell and the production of the next heavier isotope is inhibited by the consequent drop in neutron binding energy. Thus the half-life plays a crucial role in determining the overall nucleosynthetic cycle time.

If the ratio remains constant up to and including the neutron closed shell at ^{130}Cd, then one would predict $T_{1/2}$ (^{129}Cd)$=0.17$ sec and $T_{1/2}$ (^{130}Cd)$=0.13$ sec. This assumption, of course, is risky but may be useful pending upcoming measurements. Indeed, for ^{129}Cd, we have already observed a transition of $E_\gamma=281$ keV in the A$=129$ isobar with a short half-life consistent with $T_{1/2}\approx 0.2$ sec. Unfortunately, the statistics of the measurement were not sufficient to provide any firm limits of uncertainty.

In the $Z=28$ region, this ratio decreases almost monotonically between Cr and Co nuclei, attaining a value of 0.1 in the latter, and then jumps as the $Z=28$ closed shell is crossed to a value of ≈ 2.5 for Cu nuclei at $Z=29$,[2] subsequently decreasing to 1.1 for ^{80}Zn with $Z=30$.[16] The ratios of roughly 0.4 and 0.6 for the Ag and Cd ($Z=47,48$) isotopes, respectively, would then seem to fit the general pattern noted earlier. It would clearly be of interest to determine how this ratio behaves in the intervening region between $Z=30$ and $Z=47$, and most importantly, to ascertain whether indeed it decreases systematically throughout the $Z=28-50$ shell prior to attaining larger values in the $Z=50-82$ shell. If so, it would seem to imply that additional effects associated with the proton shell structure need to be included in subsequent model calculations.

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