PHYSICAL REVIEW C VOLUME 27, NUMBER 6 JUNE 1983

Half-lives and emission probabilities of delayed neutron precursors $^{121-124}$Ag

P. L. Reeder and R. A. Warner
Pacific Northwest Laboratories, Richland, Washington 99352

R. L. Gill
Brookhaven National Laboratory, Upton, New York 11973
(Received 10 February 1983)

Half-lives and delayed neutron emission probabilities have been measured for $^{121-123}$Ag. The new isotope ^{124}Ag has been identified by its delayed neutron decay. Its half-life is 0.54 ± 0.08 s and its neutron emission probability is $> 0.1\%$. From beta decay measurements, a half-life of 2.07 ± 0.03 s was found at mass 123 and assigned to the previously unknown ^{123}Cd. An improved half-life for ^{124}Cd of 1.2 ± 0.1 s is reported.

[RADIOACTIVITY $^{121-124}$Ag, $^{122-124}$Cd [from $^{235}U(n,f)$]; measured $t_{1/2}$, P_n, on-line mass separation, n, β multiscaling.]

We report here the first measurements of delayed neutron emission probabilities (P_n) from three isotopes of Ag and also the first observation of the new isotope ^{124}Ag. Delayed neutron emission from isotopes of Ag has been reported previously by Lund and Rudstam.[1] In their work, weak neutron activity was seen at masses 121 and 122, but good half-life data could not be obtained. A half-life of 0.39 ± 0.03 s was measured for ^{123}Ag. No measurements of delayed neutron emission probabilities were made.

At the TRISTAN on-line isotope separator facility at Brookhaven National Laboratory, an ion source of the forced electron bombardment induced arc discharge (FEBIAD) type has recently become operational.[2,3] This source provides Ag, Cd, and In fission products (among others) with appreciable yields. During a recent survey of neutron count rates as a function of mass number, we observed sufficient activity at mass numbers 121–124 to permit measurements of half-lives and P_n values. These neutron activities are assigned to Ag isotopes because Rh and Pd fission products are not produced by this ion source and delayed neutron emission is energetically forbidden for Cd and In fission products at these mass numbers.

A single mass ion beam from TRISTAN passed through a slit at the focal plane of the magnetic separator and was deposited on a movable tape about 4 m downstream from the slit. This deposition point was surrounded by a high efficiency neutron counter consisting of 40 ^{3}He proportional tubes embedded in polyethylene. This counter has been described in detail elsewhere.[4,5] The neutron counting efficiency decreases only slightly in the energy region from 100–1200 keV and is about 59%. The neutron energy spectra of the precursors studied here are not known so we have assumed the same efficiency for all precursors. This assumption contributes, at most, a 10% uncertainty to the P_n measurements.

The P_n experiments were made by simultaneously measuring neutron and beta decay curves. The beta particles were counted with a 450 mm^2 totally depleted surface barrier Si detector 1000 μm thick. This detector was located behind the ion beam deposition point but outside the vacuum system. Beta particles penetrated the 25 μm thick Mylar tape and 75 μm thick Al vacuum window before reaching the detector. All the Ag isotopes of interest here have $Q_\beta > 6$ MeV. High energy beta particles completely pass through the Si counter and leave about 370 keV. A discriminator was set at 250 keV in the valley between this broad peak and the noise pulses. For the P_n measurements, we assumed that the beta efficiency was the same for all precursors.

The neutron and beta decay curves were analyzed for the saturation activity for each component. The P_n was determined from the neutron saturation activity (A^n_{sat}) corrected for neutron counting efficiency (ϵ_n) divided by the beta saturation activity (A^β_{sat}) corrected for beta counting efficiency (ϵ_β), as shown in Eq. (1):

$$P_n = \frac{A^n_{\text{sat}}/\epsilon_n}{A^\beta_{\text{sat}}/\epsilon_\beta} \quad . \tag{1}$$

The P_n depends only on the ratio of efficiencies. This ratio can be determined from decay curve measurements on a precursor for which the P_n value is already known. In this mass region ^{127}In is the nearest precursor with a measured P_n value.[6]

In a single set of experiments, we measured neutron and beta growth and decay curves at masses 120–124 and at 127 by means of the pulsed beam technique. The ion beam was switched by electrostatic deflection plates located immediately after the mass selection slit. Neutron and beta multiscalers were started before the ion beam was switched on to provide a background measurement. Cycle times were adjusted to give about two precursor half-lives for beam on and more than ten half-lives for beam off. At the end of a multiscaling scan, the tape was moved to reduce the buildup of long-lived activity.

The growth and decay curves were analyzed by the least squares fitting program MASH.[7] This code analyzes the growth and decay curves simultaneously and accounts for parent-daughter-granddaughter relationships. Branching to isomeric states was included in the analysis whenever data were available from the literature.[8–17]

The neutron decay curves consisted of a single component plus a constant background of about 3 counts/s. The MASH program determined the best half-life as well as the saturation activity.

The mass 127 neutron and beta decay curves were analyzed to obtain the efficiency ratio $\epsilon_\beta/\epsilon_n$ to be used in Eq. (1). The neutron decay curve gave a half-life of 3.69 ± 0.05 s which was assigned to $^{127}In^m$. The neutron and beta saturation activities for $^{127}In^m$ along with the P_n value of (0.68 ± 0.06)% from Ref. 6 were used in Eq. (1) to give an efficiency ratio of 0.302 ± 0.027. Even though the 1.1 s $^{127}In^g$ was the most prominent component in the beta decay, there was only marginal evidence for a 1.1 s component in the neutron decay curve. A limit of ≤ 0.002% was determined for the P_n of $^{127}In^g$, which is lower than the limit of 0.04% given in Ref. 6.

The half-lives and P_n values for the Ag precursors are given in Table I. The uncertainties given in Table I for the P_n include the statistical uncertainties of the neutron and beta saturation activities as obtained from the MASH program. The uncertainties do not include the systematic error of 9% in the efficiency ratio which is due to the uncertainty in the P_n value of $^{127}In^m$, nor do they include possible variations of a few precent in the neutron and beta counting efficiencies for different precursors. We estimate that the total systematic error on the P_n values is about 15%, although this does not include the possibility that unknown isomers may distort these results. Both our neutron and beta decay curves could be fitted with a single Ag component, so we have no evidence for additional isomers except possibly at mass 121.

TABLE I. Half-lives, P_n values, and energy windows for Ag delayed neutron precursors.

Mass	n sat. activity (counts/s)	Half-life (s)	Method for $t_{1/2}$	P_n (%)	$Q_\beta - B_n$ (MeV)
120	0.21 ± 0.09	1.25 ± 0.03 [a]	β	<0.003	0.10 ± 0.12 [b]
		1.17 ± 0.05 [c]	γ		
121	1.98 ± 0.07	0.78 ± 0.01 [a]	β	0.080 ± 0.013	1.42 ± 0.18 [b]
		0.91 ± 0.06 [a]	n		
		0.8 ± 0.1 [d]	γ		
		0.72 ± 0.10 [e]	β		
122	2.99 ± 0.08	0.57 ± 0.03 [a]	n	0.186 ± 0.006 [f]	1.1 [g]
		0.48 ± 0.08 [h]	γ		
		1.5 ± 0.5 [c]	γ		
123	3.83 ± 0.09	0.30 ± 0.01 [a]	n	0.55 ± 0.02 [f]	1.8 [g]
		0.39 ± 0.03 [i]	n		
124	0.85 ± 0.06	0.54 ± 0.08 [a]	n	>0.1	2.2 [g]
127 [j]	107.3 ± 0.7	3.69 ± 0.05 [a]	n	0.68 ± 0.06 [k]	1.1 ± 0.2 [l]
		3.76 ± 0.03 [i]	n		
		3.7 ± 0.1 [d]	β		

[a]Present work.
[b]Reference 18.
[c]Reference 9.
[d]Reference 10.
[e]Reference 17.
[f]Statistical uncertainty only; see text for systematic uncertainty.
[g]Reference 19.
[h]Reference 11.
[i]Reference 1.
[j]$^{127}In^m$ (used for efficiency determination).
[k]Reference 6.
[l]Ground state mass from Ref. 18 + isomer mass difference from Ref. 12.

The neutron decay curve at mass 120 gave a very weak neutron activity but the half-life could not be determined. If we assume the neturon activity seen at mass 120 is all due to 1.25 s $^{120}Ag^{g}$, we obtain the upper limit for the P_n shown in Table I.

At mass 121, the neutron and beta decay curves gave half-lives for ^{121}Ag which disagreed with each other outside the estimated uncertainties. The beta decay curve could not be fitted with the 0.91 s half-life obtained from the neutron decay curve unless an extra component of about 0.5 s was included. The P_n values for ^{121}Ag was calculated assuming either the 0.91 s half-life from the neutron decay curve or the 0.78 s half-life from the beta decay curve. The P_n values were $(0.093 \pm 0.002)\%$ and $(0.067 \pm 0.002)\%$, respectively. In Table I, the P_n is given as the average of these two values and the uncertainty is half their difference.

At mass 122, the neutron decay curve gave a single component with a half-life of 0.57 ± 0.03 s, which is consistent with the half-life of 0.48 ± 0.08 s reported by Shih, Hill, and Williams[11] for ^{122}Ag. At mass 122 and 123 the beta decay curves were dominated by the Cd and In activities which made it difficult to determine the half-life of the Ag component. The beta decay curves were therefore analyzed with the half-life of the Ag component fixed at the value determined by neutron counting.

The neutron decay curve at mass 124 is shown in Fig. 1. The observed half-life is 0.54 ± 0.08 s and is assigned to a new isotope of Ag. The beta decay curve at mass 124 was dominated by the In activity which meant that the magnitude of the ^{124}Ag beta activity could not be determined unambiguously. We therefore report in Table I a lower limit to the P_n based on the maximum ^{124}Ag activity which gave a reasonable fit to the beta decay curve.

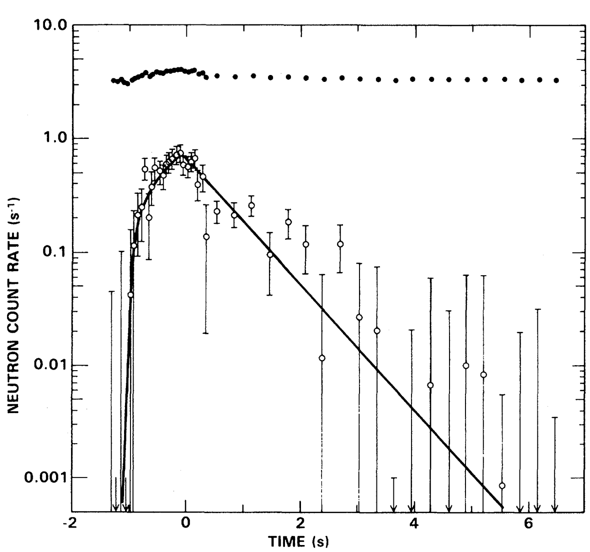

FIG. 1. Growth and decay curve for neutron activity at mass 124. Upper points = total activity. Lower points = total activity − background. Solid line = calculated component with 0.54 s half-life.

To get good fits to the beta decay curves, it was sometimes necessary to adjust the half-lives of the major components. Since Cd is prominent in the mass 122−124 decay curves, we present our values for the Cd half-lives in Table II. No other experimental value for the ^{123}Cd half-life is available in the literature. At mass 124, the uncertainty on the Cd half-life has been adjusted to account for the uncertain magnitude of the Ag beta component.

The assignment of the observed neutron activities at masses 121−124 to Ag precursors is supported by calculations of the energy window available for delayed neutron emission. The energy window is the difference between the total beta decay energy (Q_β) and the neutron binding energy (B_n). We have calculated energy windows for Ag and In nuclides based on the 1981 experimental mass table.[18] For In, delayed neutron emission cannot occur until mass 127. The mass excess data for Cd are not measured above mass 121 so we have used mass formula predictions from Monahan and Serduke[19] for Cd precursors. These calculations indicate that ^{129}Cd would be the lightest mass Cd precursor. The energy windows for Ag precursors are given in Table I. The very low limit reported here for delayed neutrons from ^{120}Ag is consistent with the vanishingly small energy window calculated from the mass table. The heavier Ag isotopes all have positive energy windows. The observation of ^{124}Ag was possible because of its delayed

TABLE II. Half-lives of Cd isotopes.

Mass	Half-life (s)	Method
122	5.10 ± 0.13 [a]	β
	5.24 ± 0.03 [b]	β
	5.78 ± 0.09 [c]	β
	3.13 ± 0.12 [d]	β
123	2.07 ± 0.03 [a]	β
124	1.2 ± 0.1 [a]	β
	0.9 ± 0.2 [e]	γ
	1.7 ± 0.6 [b]	β

[a]Present work.
[b]Reference 13.
[c]Reference 14.
[d]Reference 10.
[e]Reference 15.

neutron emission even though it could not be conclusively seen in the beta decay curve.

We wish to acknowledge the support of the entire staff of TRISTAN for establishing and maintaining this facility. In particular, we thank R. E. Chrien, M. L. Stelts, and H. I. Liou for their work on the TRISTAN data acquisition system. We also thank F. K. Wohn for providing us with the computer program MASH and P. E. Haustein for providing us with mass excess numbers. This work was prepared for the U.S. Department of Energy under Contracts No. DE-AC06-76RL0-1830 and No. DE-AC02-76CH00016.

[1]E. Lund and G. Rudstam, Phys. Rev. C 13, 1544 (1976).

[2]R. E. Chrien, M. L. Stelts, V. Manzella, R. L. Gill, F. K. Wohn, and J. C. Hill, in *Nuclear Spectroscopy of Fission Products—1979*, edited by T. von Egidy, IOP Conf. Proc. No. 51 (IOP, Bristol and London, 1980), p. 44.

[3]R. Kirchner and E. Roeckl, Nucl. Instrum. Methods 127, 307 (1975).

[4]P. L. Reeder, J. F. Wright, and L. J. Alquist, Phys. Rev. C 15, 2098 (1977).

[5]P. L. Reeder and R. A. Warner, Nucl. Instrum. Methods 180, 173 (1981).

[6]E. Lund, P. Hoff, K. Aleklett, O. Glomset, and G. Rudstam, Z. Phys. A 294, 233 (1980).

[7]F. K. Wohn, K. D. Wünsch, H. Wollnik, R. Decker, G. Jung, E. Koglin, and G. Siegert, Phys. Rev. C 17, 2185 (1978).

[8]*Table of Isotopes,* 7th ed., edited by C. M. Lederer and V. Shirley (Wiley, New York, 1978).

[9]B. Fogelberg, A. Bäcklin, and T. Nagarajan, Phys. Lett. 36B, 334 (1971).

[10]B. Grapengiesser, E. Lund, and G. Rudstam, J. Inorg. Nucl. Chem. 36, 2409 (1974).

[11]L. L. Shih, J. C. Hill, and S. A. Williams, Phys. Rev. C 17, 1163 (1978).

[12]K. Aleklett, E. Lund, and G. Rudstam, Phys. Rev. C 18, 462 (1978).

[13]G. Rudstam, P. Aagaard, P. Hoff, B. Johansson, and H. U. Zwicky, Nucl. Instrum. Methods 186, 365 (1981).

[14]O. Scheidemann and E. Hagebö, J. Inorg. Nucl. Chem. 35, 3055 (1973).

[15]B. Fogelberg, T. Nagarajan, and B. Grapengiesser, Nucl. Phys. A230, 214 (1974).

[16]L.-E. De Geer and G. B. Holm, Phys. Rev. C 22, 2163 (1980).

[17]B. Fogelberg and P. Hoff, Nucl. Phys. A391, 445 (1982).

[18]A. H. Wapstra and K. Bos, October, 1981 midstream atomic mass adjustment, available from the National Nuclear Data Center, Brookhaven National Laboratory, Upton, New York 11973.

[19]J. E. Monahan and F. J. D. Serduke, Phys. Rev. C 17, 1196 (1978).