Short-Lived Isotopes of Pd and Ag of Masses 113–117*

J. M. ALEXANDER,† U. SCHINDEWOLF‡, AND CHARLES D. CORYELL
Department of Chemistry and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
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Six new short-lived Pd and Ag isotopes have been isolated from the fission products by fast chemical separations. Their decay properties have been studied by β and γ counting and spectroscopy or by periodic extractions of daughter activities. The nuclides described are: 1.4-min Pd^{113} decaying to 1.2-min Ag^{113m} and 5.3-hr Ag^{113}; 2.4-min Pd^{114} from which 5-sec Ag^{114} was extracted; 45-sec Pd^{115} which decays to about 20-sec Ag^{115m} and 21.1-min Ag^{115}; 2.5-min Ag^{116}; and 1.1-min Ag^{117} which gives rise to the complicated decay chain of Cd^{117} and In^{117}.

I. INTRODUCTION

ISOMERIC states are common in those nuclides which have proton or neutron numbers a few units less than the "magic" or closed shell numbers. This fact is illustrated by the complicated decay chains of Ag, Cd, and In, where isomerism is the usual case rather than the exception. The odd-A isotopes of Ag, with masses 107, 109, and 111, have isomeric states with half-periods between 40 and 75 seconds. Ag^{109m} and Ag^{111m} are formed by β^- decay of the Pd parents; the formation of Ag^{107m} from Pd^{107} is energetically prohibited. It would be expected that Ag^{113} and Ag^{115} might also have short-lived metastable states which are formed by the β^- decay of Pd. This was proposed for Ag^{115} by Wahl and Bonner[1] on the basis of fission yield measurements.

A more complete study is presented here of the expected isomeric states. These species are produced abundantly in the deuteron fission of natural uranium. The yield-mass curve[2] is almost flat in the mass 113 to 117 region and the valley-to-peak ratio in 14-Mev deuteron fission is about 0.2, whereas in the thermal neutron fission of U^{235} it is about 0.0016. However, the relative fission yields of the individual chains studied here may not all be the same, because of problems related to isomerism and distribution of yield along the chain.[3] Rapid chemical procedures have been developed for the separation of Pd and Ag activities from fission products. With these techniques, six new Pd and Ag activities of half-period less than three minutes have been studied.

II. CHEMICAL PROCEDURES AND COUNTING TECHNIQUES

Fission was induced by the bombardment of U foil or UO_3 with 15-Mev deuterons, usually for 1 minute. The chemical procedures used in the experiments were as follows:

(*a*) *Separation of Pd from fission products.*—The bombarded U foil was dissolved in aqua regia containing ~2 mg Pd (II) carrier. After diluting, AgCl was precipitated by the addition of 10 mg Ag carrier, and Pd was extracted into chloroform as the dimethylglyoxime complex (1 ml 1% dimethylglyoxime in methanol per 20 ml chloroform). The organic phase was washed twice with dilute HNO_3 and the Pd was back-extracted into concentrated ammonia. After scavenging with $Fe(OH)_3$, the Pd was reduced with Zn powder, filtered, washed, and counted. (The time required for the chemical separation was three minutes.)

(*b*) *Separation of Ag daughters from Pd.*—(1) The bombarded U metal was dissolved in aqua regia containing ~2 mg Pd (II) and ~10 mg Fe (III). After dilution, $Fe(OH)_3$ and $(NH_4)_2U_2O_7$ were precipitated with ammonia, and the Pd was reduced to the metal with Zn powder. The Pd was then dissolved in aqua regia, diluted, and extracted into chloroform as described in section (*a*). The organic phase, containing Pd, was shaken with an aqueous solution containing a known amount of Ag carrier, and the moment of phase separation was taken as the separation time of Ag formed by the decay of Pd. The Ag solution was washed with chloroform containing dimethylglyoxime, and AgCl was precipitated, washed, and counted. When required, the chemical yield was determined after counting. (The time requirement was five minutes.) Periodic extractions at one-minute intervals were performed in order to determine parent half-periods.

(2) In the search for Ag activities of half-period less than 20 seconds, the Pd was purified as described in section (*a*). The Pd metal was dissolved in aqua regia; the solution was diluted and the Ag was separated by rapid isotopic exchange[4] with Ag foil coated with AgCl. The foil was washed with water and counted immediately.

(*c*) *Periodic separation of Cd daughters from Ag and Pd.*—(1) Bombarded U foil was dissolved in aqua regia containing ~1 mg Pd. After dilution the Pd was extracted into chloroform as the dimethylglyoxime complex. The organic phase was washed twice with

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† Present address: Radiation Laboratory, University of California, Berkeley, California.
‡ Present address: Bundes laboratorium für Kernforschung, Karlsruhe, Germany.
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[2] Sugihara, Drevinsky, Troianello, and Alexander, Phys. Rev. **108**, 1264 (1957); J. M. Alexander, Ph.D. thesis in chemistry, Massachusetts Institute of Technology, October, 1956 (unpublished).
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[4] D. N. Sunderman and W. W. Meinke, Science **121**, 777 (1955).

TABLE I. Experimental results.

A. Pd isolated from fission products

Radiation observed	Observed half-period	No. of half-periods followed
β's>0.2 Mev	2.2±0.2 min	4
β's>3.5 Mev	2.4±0.1 min	6
γ's>0.1 Mev	1.9±0.2 min	4
Photopeaks:		
0.14±0.01 Mev	2.2±0.4 min	4
0.30±0.02 Mev	1.9±0.4 min	5
0.57±0.02 Mev	2.4±0.3 min	5

Unresolved γ's>0.7 Mev present in low intensity
Maximum β energy associated with 2.4±0.1-min Pd: 4.6±0.4 Mev

B. Ag grown from Pd

Radiation observed	Observed half-period	No. of half-periods followed	Relative intensities
β's>0.2 Mev	1.25±0.15 min	5	
β's>1.0 Mev	0.8 ±0.3 min	3	
β's>3.5 Mev	5 ±2 sec	3	
γ's>0.1 Mev	1.15±0.15 min	4	
Photopeaks:			
0.14±0.01 Mev	1.15±0.20 min	4	40
0.31±0.02 Mev	1.15±0.20 min	5	100
0.39±0.02 Mev	1.10±0.20 min	4	30
0.56±0.02 Mev	1.50±0.20 min	3	10
0.70±0.02 Mev	1.35±0.20 min	3	10

Maximum β energy of 1.2-min Ag: <2.0 Mev

C. Ag isolated from fission products

Radiation observed	Observed half-period	No. of half-periods followed	Relative intensities
β's>0.2 Mev	2.25±0.25 min	5	
β's>3.0 Mev	2.5 ±0.1 min	6	
γ's>0.1 Mev	2.0 ±0.25 min	3	
Photopeaks over 0.26 Mev from ⩽3-min Ag:			
0.32 ±0.02 Mev	1.5±0.5 min	3	
0.515±0.015 Mev	3.0±0.5 min	3	100
0.70 ±0.03 Mev	2.6±0.4 min	3	20

Unresolved γ's>0.7 Mev ~2 min present in low intensity
Maximum β energy of 2.5-min Ag: 5.0±0.4 Mev

Measurements on longer-lived Ag:

β's through 900 mg/cm² Al	21.1 ±0.5 min	7	
β's>0.2 Mev	5.3 ±0.2 hr	7	
Photopeaks from long-lived Ag:			
0.138±0.010 Mev	~20 min }	probably but not	20
0.227±0.015 Mev	~20 min }	definitely in coincidence	100
0.310±0.010 Mev	~5 hr		

Maximum β energy of 21.1-min Ag^{115}: 2.9±0.3 Mev
Maximum β energy of 5.3-hr Ag^{113}: 2.2±0.2 Mev

D. Indirect observation of parents by periodic extraction of daughters

Radiation and half-period of daughter observed	Half-period of parent	No. of parent half-periods followed
5.3-hr Ag^{113} (β's>0.1 Mev)	1.43±0.16 min Pd^{113}	3
1.25-min Ag (β's>0.1 Mev)	1.29±0.17 min Pd	3
1.25-min Ag (photopeaks, see Fig. 1)	1.3 ±0.15 min Pd	4
5-sec Ag (β's>3.5 Mev)	3 ±1 min Pd	3
21.1-min Ag^{115} (β's>0.1 Mev)	50 ±12 sec Pd^{115}	4
2.2-day Cd^{115} (β's>0.1 Mev)[a]	44 ± 3 sec Pd^{115}	5
50±20 sec Ag (β's>0.7 Mev)	50 ±20 sec Pd	4
2.2-day Cd^{115} (β's>0.1 Mev)[b]	20 ±10 sec[d] Ag^{115m}	...
2.2-day Cd^{115} (β's>0.1 Mev)[c]	<50-sec Ag^{115m}	...
Cd^{117} (β's>0.1 Mev)[b]	1.1 ±0.1 min Ag^{117}	4
Cd^{117} (β's>0.1 Mev)[c]	1.1 ±0.1 min Ag^{117}	4

[a] 21-min Ag was extracted successively from Pd [Sec. II(*b*)1] and the extracts allowed to decay to Cd, which was counted.
[b] Cd was extracted successively from the combined Pd and Ag parents [Sec. II(*c*)1].
[c] Cd extracted successively from Ag after removal of Pd [Sec. II(*c*)2].
[d] Half-period from curve fitting 45-sec Pd → Ag → 2.2-day Cd (see Fig. 2).

TABLE II. Summary of conclusions.

Nuclide	Half-period	$E_{\beta_{max}}$ (Mev)	E_γ (Mev)	Daughters
Pd^{113}	1.4±0.1 min	...	no prominent γ's	1.2-min Ag^{113m} 5.3-hr Ag^{113} (90%)[a]
Pd^{114}	2.4±0.1 min	...	no observable γ's	5-sec Ag^{114}
Pd^{115}	45 ±3 sec	...	no prominent γ's	~20-sec Ag^{115m} 21.1-min Ag^{115}
Ag^{113m}	1.2±0.15 min	<2.0	0.14±0.01 0.30±0.01 0.39±0.02 0.56±0.02 0.70±0.02	5.3-hr Ag^{113} [b] Stable Cd^{113} 5-yr Cd^{113m} (<5%)[a]
Ag^{113}	5.3±0.2 hr	2.2±0.2	0.30±0.01	Stable Cd^{113}
Ag^{114}	5 ±2 sec	4.6±0.4	0.57±0.02	Stable Cd^{114}
Ag^{115m}	20 ±10 sec		...	21.1-min Ag^{115} [b] 2.2-day Cd^{115}
Ag^{115}	21.1±0.5 min	2.9±0.3	0.138±0.010 0.227±0.015 (both weak, probably coincident)	43-day Cd^{115m} (9%)[c] 2.2-day Cd^{115} (91%)
Ag^{116}	2.5±0.1 min	5.0±0.4	0.515±0.02 0.70±0.03	Stable Cd^{116}
Ag^{117}	1.1±0.1 min	...	...	3-hr Cd^{117m} 50-min Cd^{117}

[a] Yields discussed in the Appendix.
[b] Inferred from decay systematics (see Appendix).
[c] Yields from reference 1.

0.015M HNO_3. Then dithizone (diphenylthiocarbazone) in chloroform[5] containing 1 mg Ag carrier was added to hold in the organic layer the Ag growing from Pd. The organic phase containing Ag and Pd was then shaken with an aqueous solution containing a known amount of Cd carrier in 0.015M HNO_3, and the instant of phase separation was taken as the separation time of Cd formed by the decay of Pd and Ag. The Cd solution was then washed with chloroform and complexing agents, and the Cd purified following a procedure (similar to that of Glendenin[6]) which included an AgCl scavenging, $Fe(OH)_3$ and PdS and Sb_2S_3 scavengings, CdS precipitation, and final Cd precipitation and weighing as the $Cd(NH_4)PO_4$.

(2) In one experiment Pd was removed from the HNO_3 solution by a dimethylglyoxime extraction. Ag then was extracted with dithizone and Cd periodically removed as described in Sec. II(*c*)1. In these experiments the chemical procedures required two to three minutes.

(*d*) *Separation of Ag from fission products.*—Bombarded U metal was dissolved in aqua regia. After dilution with chlorine water, Ag was separated by AgCl precipitation or by isotopic exchange with AgCl coated on Ag foil. The AgCl was dissolved in ammonia and the solution was scavenged with an $Fe(OH)_3$ precipitation. Ag was reduced to the metal with Zn powder, then dissolved in HNO_3, washed with chloroform containing dimethylglyoxime, and precipitated as AgCl which was washed and counted. (The time required was three minutes.)

(*e*) *Counting techniques.*—Gamma spectra of the short-lived species have been measured by scintillation spectrometry making use of a 1-in.×1-in. cylindrical NaI(Tl) crystal and a 20-channel analyzer. The gamma spectra of 21.1-min Ag^{115} and 5.3-hr Ag^{113} were measured on both a gray-wedge analyzer and a single-channel analyzer. Beta spectra were similarly measured using a 0.5-in.×2-in. NaI(Tl) crystal with a 5 mg/cm² Al window. Energy calibration was made with both β and γ standards having maximum energies up to ~3 Mev. Since the samples counted were not weightless, the Kurie plots did not yield straight lines and only the maximum β energy of the hardest component could be estimated. End-window flow-type proportional counters and well-type scintillation counters were used for conventional β and γ counting. Irradiations were obtained from the M.I.T. cyclotron, which delivers 15-Mev deuterons and secondary neutrons from a Be or LiF target.

III. EXPERIMENTAL RESULTS

Because of the number of short-lived nuclides involved and the growth of short-lived Ag daughters from short-lived Pd nuclides, a variety of different observations had to be made, and for reliability of the results, these had to be repeated a number of times. Table I gives a survey of the types of observations made, the half-period correlated with each, and the length of time for which the correlation was followed. Estimates on the reliability of each half-period are given from the inherent precision of the observation and its reproducibility in different preparations. Conclusions are drawn in Sec. IV below from the data in

[5] E. B. Sandell, *Colorimetric Determination of Traces of Metals* (Interscience Publishers, Inc., New York, 1950), pp. 86–112.
[6] L. E. Glendenin, *Radiochemical Studies: The Fission Products*, edited by C. D. Coryell and N. Sugarman (McGraw-Hill Book Company, Inc., New York, 1951), Paper No. 265, National Nuclear Energy Series, Plutonium Project Record, Vol. 9, Div. IV.

Table I, and Table II gives the summary of the conclusions from our work of the decay properties and mass assignments of the ten species of interest. Proposals for decay schemes of the nuclides are given in the appendix.

Part A of Table I gives the observations on Pd isolated directly, the Ag growth time being about 1 min before counting. The data refer largely to 2.4-min Pd^{114} in equilibrium with 5-sec Ag^{114}, except for the γ rays of 0.30 and 0.14 Mev, due to 1.2-min Ag^{113m} coming to equilibrium.

Part B of Table I, which describes short-lived Ag daughters of short-lived Pd parents, gives the decay properties of 1.2-min Ag^{113m} exclusively, except for the experiments with hard β rays.

In Part C of Table I, the species responsible for the different observations are adequately identified by the half-periods observed, and Part D on periodic extraction of known daughters is self-explanatory.

(*a*) *1.4-min* Pd^{113}.—The half-period of Pd^{113} is considered best determined as 1.43 ± 0.16 min from periodic extractions of 5.3-hr Ag^{113} from purified Pd, in agreement with the value of 1.5 min reported by Hicks and Gilbert[7] by a similar experiment. Prompt counting of the silver extracts always showed a 1.2-min component. Plotting the initial specific β activities against time established a half-period of 1.29 ± 0.17 min for its parent, and plotting the intensities of the γ rays of 0.14 and 0.31 Mev gave the value 1.3 ± 0.1 min. Curve 7 of Fig. 1 shows the γ evaluation of the Pd half-period. As shown below, there is no doubt that these data all refer to the same parent, Pd^{113}. The value chosen for the half-period is 1.4 ± 0.1 min. No evidence was obtained for any characteristic γ rays.

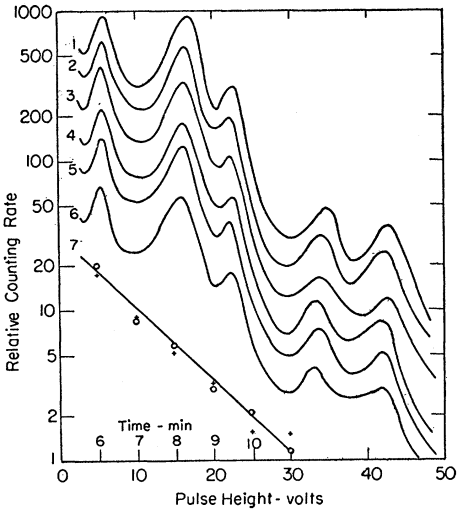


FIG. 1. The γ spectrum of six different Ag samples periodically extracted from Pd. This spectrum is the result of two normalized experiments representing a 35-channel analysis. The photopeaks are at 0.14, 0.31, 0.39, 0.56, and 0.70 Mev with approximate relative abundances 40:100:30:10:10. Curve 7 gives the half-period of the Pd parent, which is 1.3 min (crosses represent the area under the 0.31-Mev peak, circles represent the area under the 0.56-Mev peak).

(*b*) *45-sec* Pd^{115}.—The half-period of Pd^{115} was found by periodic extraction and counting of 21.1-min Ag^{115} to be 50 ± 12 seconds. A more accurate value of 44 ± 3 seconds was found by identical periodic extraction and subsequent purification and counting of 2.2-day Cd^{115} after decay of 21.1-min Ag^{115}. The half-period chosen is 45 ± 3 sec.

(*c*) *1.2-min* Ag^{113m}.—As indicated above, the prominent short-lived Ag isolated from short-lived Pd is the 1.2-min species of relatively low β energy with complex γ spectrum, formed in the decay of 1.4-min Pd^{113}. Only an upper limit of 2.0 Mev could be established for its maximum β energy because of interference of the 2.9-Mev β particles from 21.1-min Ag^{115}. The γ spectrum showed lines at 0.14, 0.31, 0.39, 0.56, and 0.70 Mev (Fig. 1), which are all associated with decay of silver nuclides with half-periods of 1.2 ± 0.25 minutes. These γ's *a priori* may originate from the decay of either Ag^{113m} or Ag^{115m}. To distinguish between these possibilities, six silver samples were extracted from Pd at intervals of 1 minute and the γ spectra observed. Since Pd^{115} has a half-period of 45 sec and Pd^{113} has a 1.4-min half-period, the intensity of γ rays from Ag^{115m} should be depleted by a factor of ~8 with respect to Ag^{113m} in the course of this experiment. Figure 1 shows that the relative intensity of all γ peaks is unchanged in all six Ag samples, indicating a common origin. The half-period of this common parent is 1.3 ± 0.15 min and thus the γ rays are assigned to Ag^{113m}. The energies, with the exception of 0.14 Mev, are in agreement with the energy levels observed[8–10] in Cd^{113} by Coulomb excitation of Cd^{113} and by the $Cd^{112}(d,p)$ reaction.

The half-periods shown for measurements of the different types of radiations are listed in Part B of Table I. The average of all but the curves for $E_\beta>1.0$ Mev and $E_\beta>3.5$ Mev (principally Ag^{115m} and Ag^{114}, respectively) will be taken as 1.2 ± 0.15 min.

(*d*) *5.3-hr* Ag^{113}.—The half-period for Ag^{113} is confirmed,[11] the maximum β energy remeasured[11] as 2.2 Mev, and a γ ray of 0.31 Mev found in low abundance. A comparison of the relative β intensities of the 1.2-min Ag^{113m} and the 5.3-hr Ag^{113} shows that $90\pm5\%$ of the 113 chain passes through 5.3-hr Ag^{113}.

(*e*) $\sim$*20-sec* Ag^{115m}.—Periodic extraction of 2.2-day Cd^{115} from its combined precursors Ag^{115} and Pd^{115} [by methods of Sec. II(*c*)1] gives definite evidence that 2.2-day Cd^{115} is formed by the decay of a short-lived Ag^{115m} as well as 21.1-min Ag^{115}.

[7] H. G. Hicks and R. S. Gilbert, Phys. Rev. **94**, 371 (1954).

[8] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **98**, 1308 (1955); **99**, 617 (1955).

[9] Mark, McClelland, and Goodman, Phys. Rev. **98**, 249, 1245 (1955); **99**, 617 (1955).

[10] P. H. Stelson and F. K. McGowan, Bull. Am. Phys. Soc. Ser. II, **1**, 164 (1956); N. S. Wall, Phys. Rev. **96**, 664 (1954).

[11] Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953).

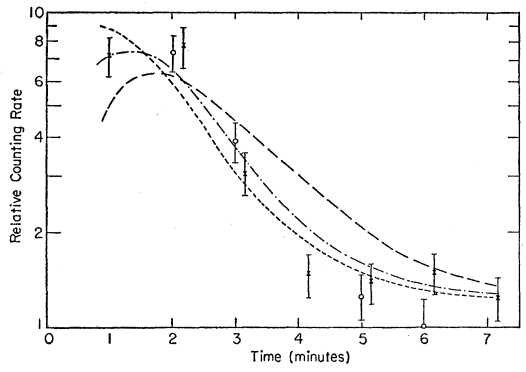
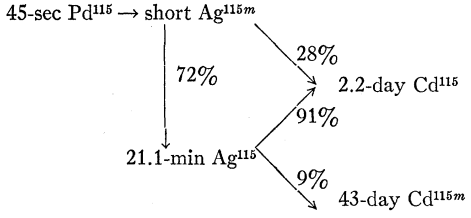


FIG. 2. Delimitation of the half-period of short-lived Ag^{115m} by periodic extraction of 2.2-day Cd^{115} from Pd+Ag sample. At time zero, Pd was isolated by the method of Sec. II(*c*)1 and Ag starts to grow in. In one-minute intervals Cd was separated and counted after purification. Experimental points give relative activities of 2.2-day Cd^{115} extracted 1, 2, 3, ··· minutes after final Pd separation in two runs (× and ○). The curves are the calculated relative Cd activities for successive extracts, assuming that Cd^{115} is formed by the following scheme:



and using for the half-period of Ag^{115m} 10 sec (– – – – –), 20 sec (— · — · —), and 40 sec (— — —). The value 20 sec gives fit with an uncertainty of ±10 sec.

Figure 2 shows the activity of 2.2-day Cd^{115} in successive Cd extracts taken after 1 minute of growth at various times after purification of the mother sample of Pd. The high activity in the first three minutes is good evidence for short-lived Ag^{115m} undergoing β decay. The three curves of Fig. 2 show predictions for the 2.2-day Cd^{115} activity with postulated half-periods of 10, 20, and 40 sec for Ag^{115m}, using the branching ratio 0.28 for β decay determined by Wahl and Bonner[1] from fission yields. The 20-sec curve gives reasonable fit with an estimated uncertainty of ±10 sec.

In another experiment 2.2-day Cd^{115} was periodically extracted from Ag alone, after removal of Pd. Extractions of Cd from Ag were made at 45-second intervals beginning 3.8 minutes after bombardment. None of the Cd samples showed evidence of an Ag^{115} parent other than 21.1-min Ag^{115}. Thus only an upper limit of 50 sec for the half-period of Ag^{115m} could be determined by this method with β counting.

The direct observation of the decay of Ag^{115m} is difficult because of the presence of 1.2-min Ag^{113m}, but discrimination in favor of Ag^{115m} can be obtained by cutting out the lower energy β rays, since Ag^{113m} has a maximum β energy of 2.0 Mev. Periodic separations of Ag were made from Pd, and the extracts counted for β rays above 1 Mev. The gross half-period of 0.8±0.3 min was obtained for the Ag fractions, showing substantial content of Ag^{115m}. Using this half-period without correction for Ag^{113m} contribution, the half-period of 0.8±0.3 min is obtained for the Pd parent, identifying the mass number as 115. The half-period for Ag^{115m} is taken as 20±10 sec.

(*f*) *21.1-min* Ag^{115}.—The half-period of Ag^{115} is confirmed,[11] the maximum β energy remeasured[11] as 2.9 Mev (from absorption measurements), and weak γ rays of 0.138±0.010 and 0.227±0.015 Mev found, which are probably in coincidence.

The discussion so far is based on the assumption that short-lived Ag activities grown from ~1-min Pd are only Ag^{113m} and Ag^{115m}. A rough determination of the maximum β energy of these ~1-min Ag species sets an upper limit of 2.0 Mev. The systematics of β decay[12] predict 2.2 Mev for the maximum β-decay energy of Ag^{113} (observed 2.2 Mev) and 3.2 Mev for Ag^{115} (observed 2.9±0.3 Mev). The predicted maximum β energies of other possible Ag species (114, 116, 117, etc.) are all greater than 4 Mev; therefore, their presence is unlikely. The following discussion of these other mass chains supports this conclusion.

(*g*) *1.1-min* Ag^{117}.—The Cd activity which was periodically extracted from Ag contained in addition to 2.2-day Cd^{115} a much shorter-lived activity which was not observed when Ag and Cd were extracted from Pd. The decay curve was consistent with the complicated growth and decay[13,14] of 3-hr Cd^{117m}, 50-min Cd^{117}, 1.1-hr In^{117}, and 1.9-hr In^{117m}, initially flat and then passing to an apparent half-period of 3.0 hr. The absence[15] of β decay from 75-sec Ag^{111m} eliminates possible contribution of 49-min Cd^{111m}, as verified by the observed Al absorption curve. Also a large contribution[13] of 30-min Cd^{118} could be ruled out by the apparent half-period of the separated Cd.

The Cd decay curves of the successive extracts were analyzed into components of chains of masses 115 and 117. The data correspond to a half-period of 1.1 min for Ag^{117}. Pd^{117} must have a much shorter half-period or a very low yield in the deuteron fission of U^{238}.

(*h*) *2.4-min* Pd^{114} *and 5-sec* Ag^{114}.—Direct observation of the decay properties of Pd^{113} and Pd^{115} was impossible because of the growth of their Ag daughters and of the presence of another Pd activity with a half-period of 2.4 minutes. In the measurement of the β spectrum, this half-period was observed in all channels over 3 Mev for 15 minutes, and the maximum β energy was found to be 4.6 Mev. According to the systematics of β decay,[12] no Pd nuclide of mass number less than

[12] C. D. Coryell, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1953), Vol. 2, p. 305; J. Riddell, "A Table of Levy's Empirical Atomic Masses," Atomic Energy of Canada Limited Report CRP-652, 1956 (unpublished), based on H. B. Levy, Phys. Rev. **106**, 1265 (1957); R. C. Fix, Ph.D. thesis in chemistry, Massachusetts Institute of Technology, 1956 (unpublished).

[13] Coryell, Lévêque, and Richter, Phys. Rev. **89**, 903 (1953).

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[15] Schindewolf, Winchester, and Coryell, Phys. Rev. **105**, 1763 (1951).

117 (with the exception of Pd^{115} which has a half-period of only 45 seconds) is expected to have a maximum β energy of greater than 3.5 Mev. However Ag^{114} or Ag^{116}, which are expected to have very hard β radiation, may be in equilibrium with Pd precursors and be responsible for the observed hard β component. Since no hard-β emitter was observed in the Ag extracted from Pd, it may be concluded that a possible Ag daughter must have a half-period of less than 20 seconds.

Very fast periodic extractions [Sec. II(*b*)2] revealed the existence of an Ag activity of (5±2)-sec half-period having β radiation greater than 3.5 Mev and a Pd parent with half-period ~3 minutes as shown in Fig. 3. The γ spectrum of this Pd, which includes the 5-sec Ag daughter in equilibrium, shows a very intense peak at 0.56 Mev associated with the 2.4-min decay. (The other γ lines listed in Part A of Table I can be assigned to Ag^{113m}.) A level between 0.55 and 0.56 Mev has been found in Cd^{114} by several investigators[8,9,16–18] using Coulomb excitation of Cd^{114} and neutron capture of Cd^{113}, and it has been found in the decay[19] by K capture of 50-day In^{114}. The similarity of the energy levels suggests the mass number 114 for the 2.4-min Pd, 5-sec Ag chain. No other γ radiation was observed that could be assigned to Pd^{114}.

(*i*) *2.5-min* Ag^{116}.—Attempts to observe the decay properties of Ag^{117} by direct separation of Ag from the fission products were unsuccessful due to the presence of a 2.5-min Ag activity. (A short-lived Ag in the fission products was observed before,[20] but mass assignment and characterization of its radiation were not reported.) The γ spectrum of this directly isolated Ag shows photopeaks at 0.515 and 0.70 Mev which are associated with the 2.5-min decay and a relatively weaker peak at 0.310 Mev which is assigned to Ag^{113m} because of its shorter half-period. Coulomb excitation of Cd^{116} reveals the presence of a 0.508-Mev level[8] in this nuclide which is, within the experimental error, identical to the γ line of 0.515 Mev observed for the 2.5-min Ag. Because of the similarity of these energy levels it is proposed to assign the 2.5-min Ag to the mass number 116.

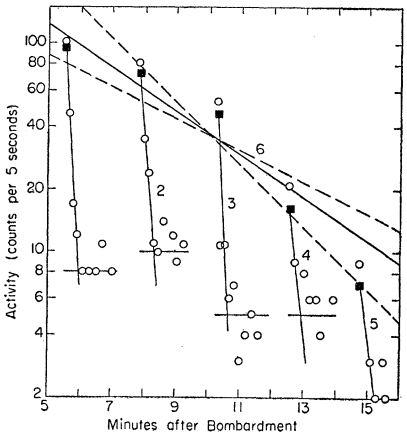

FIG. 3. Decay curve for 5-sec Ag^{114} in five successive extracts from purified Pd. Open circles are observed counts of β particles with energy greater than 3.5 Mev, the curves being analyzed for a 5-sec component and a longer-lived contamination. The half-period is 5±2 seconds as taken from decay curves 1 to 5. Filled squares give the initial 5-sec activity from which a 3±1 minutes half-period (curve 6) for the Pd parent follows, if constant chemical yield is assumed in the silver extractions.

The maximum β energy of the 2.5-min Ag is 5.0 Mev and is definitely greater than that of the 5-sec Ag, as found by a careful comparison of the β spectra of the 2.5-min Ag and the pair 2.4-min Pd, 5-sec Ag. (The quoted uncertainties in Table I arise from the extrapolation of the energy calibration curve.) This difference in maximum β energy gives further evidence that the 2.5-min Ag has a higher mass number than the 2.4-min Pd, 5-sec Ag chain, and that the mass assignments made by comparison of the energies of the decaying nuclides with the energy levels of excited Cd isotopes are correct (if mass numbers greater than 117 are excluded as unlikely).

Duffield and Knight[21] have reported a 2-min Ag activity formed by fast neutron bombardment of enriched Cd^{114}, which they assign to Ag^{114} and which could be identical with the 2.5-min Ag fission product. It could also be an isomer of the 5-sec Ag^{114} not formed in observable quantity in the β decay of 2.4-min Pd^{114}. We have been unable to produce a 2-min Ag with β radiation above 3 Mev by the fast-neutron bombardment of natural Cd or of 10 mg of enriched Cd^{114}.

The 0.170-Mev γ line of 4.8-min Pd^{109m}, which decays[22] by isomeric transition to 13.6-hr Pd^{109}, could not be observed in the γ spectrum of the fission palladium. Its direct formation in fission is unlikely,[3] and its formation by β decay of Rh^{109} is unlikely[22] because of its high spin (11/2−).

APPENDIX. DECAY SCHEMES

The decay data presented in Table II can be represented in reasonable decay schemes presented below for palladium and silver isotopes of mass numbers 113 through 116. The schemes are consistent with the earlier ones presented by Goldhaber and Hill[23] and Dzhelepov and Peker,[24] with due account of more recent information cited in the corresponding sections below. Very little information is available on coincidence of various β groups and γ rays, but the spin assignments were chosen with due regard for β-decay

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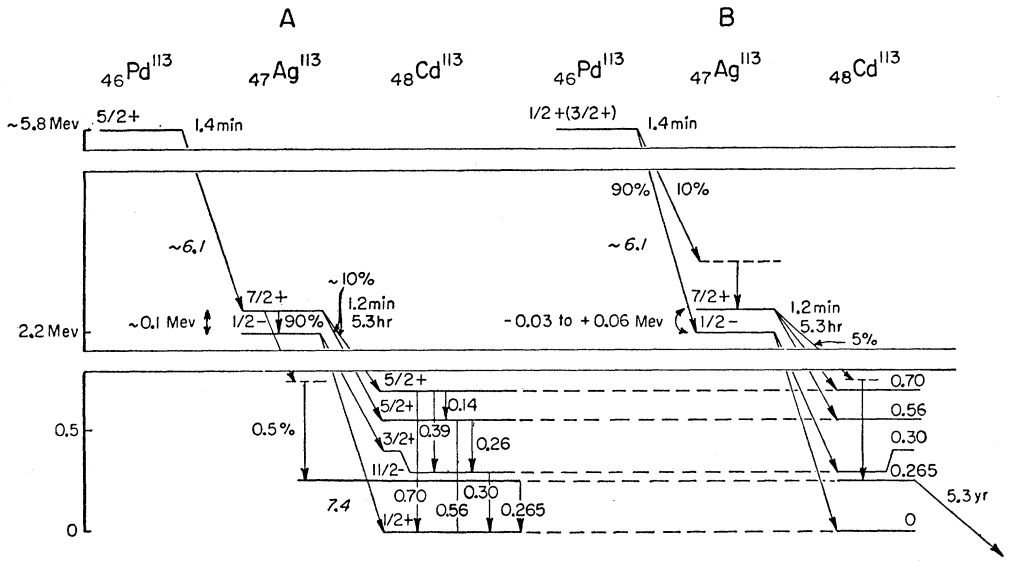

FIG. 4. Decay schemes for $A=113$. Note two alternative possibilities, scheme A and scheme B.

theory[25,26] and logft values,[26,27] and Weisskopf's radiation theory[26,28,29] as modified empirically by Way *et al.*,[30] together with other literature information cited below.

The decay schemes are given for each isobar, followed by discussions below. Wherever possible, branching is noted by percentage of decay, and logft values are given in italics. A firm decision cannot yet be made for two alternative decay schemes A and B for Pd^{113} and Ag^{113}.

Mass Chain 113

The parity and spin assignments made by Goldhaber and Hill[23] and repeated by Dzhelepov and Peker[24] and by Way and co-workers[30] seem quite acceptable. They are $\frac{1}{2}-$ for 5.3-hr Ag^{113}, $11/2-$ for 5.1-yr Cd^{113m}, $\frac{1}{2}+$ for ground-state (natural) Cd^{113}, and $9/2+$ for ground-state In^{113}. Two rather different decay schemes A or B, as shown in Fig. 4, will result according to whether $\frac{5}{2}+$ or $\frac{1}{2}+$, respectively, is assigned to 1.4-min Pd^{113}. It is unlikely that Pd^{113} could be $11/2-$ and decay so readily to Ag without prominent γ radiation.

Determination of the β intensities of 1.2-min Ag^{113} and 5.3-hr Ag^{113} shows that the saturation β activity of the former is 0.1 ± 0.05 of the latter, most of the error coming from the uncertainty in the half-period of the 1.2-min species. One of the isomers is probably $\frac{7}{2}+$ and the other $\frac{1}{2}-$, in the pattern of the well-known[23,24,30] Ag isomers at $A=107$, 109, and 111. The expected Q_β for ground-state Ag^{113} is[12] 2.0 Mev.

With the unlikely assumption that the 1.2-min Ag isomer is the $\frac{1}{2}-$ state, its β transition would go directly to ground-state $(\frac{1}{2}+)$ Cd^{113} (competing with isomeric transition only if the $\frac{1}{2}-$ level fell above $\frac{7}{2}+$ level), and its rich γ spectrum would be unexplained. The 1.2-min isomer is thus identified as $\frac{7}{2}+$.

It can be shown that the $\frac{7}{2}+$ level does not lie appreciably below $\frac{1}{2}-$ (5.3-hr Ag^{113}), because 90% of the β decay of Pd^{113} ultimately leads to the 5.3-hr Ag^{113}. If the 1.2-min level lay more than slightly below the 5.3-hr level (>0.03 Mev), isomeric transition from the 5.3-hr level to the 1.2-min level would occur, giving the easily identifiable γ spectrum of the latter in equilibrium. We conclude that the 5.3-hr level is at most barely above the 1.2-min level, and that it probably is ground state.

For decay scheme A, 1.4-min Pd^{113} will be classed $\frac{5}{2}+$ in accord with the Pd ground states[23,24,30] at $A=103$, 105, 107, and 109. The same value[31] has also been proposed for 22-min Pd^{111}. The predicted β-decay energy[12] of Pd^{113} is ~3.6 Mev corresponding to logft ~6.1, compatible with decay to 1.2-min Ag^{113} $(\frac{7}{2}+)$ without prominent γ radiation.

The chief source of 5.3-hr Ag^{113} in scheme A is isomeric transition. The partial half-period for isomeric transition (90%) of Ag^{113m} is 80 sec, similar[15] to 74 sec for Ag^{111m} (0.087 Mev), 40 sec for Ag^{109m} (0.087 Mev), and 44 sec for Ag^{107m} (0.094 Mev). The transition energy of 1.2-min Ag^{113m} by this scheme would be judged as about 0.10 Mev, about the cutoff of our measurements. It is possible that the γ from isomeric transition, even though weakened greatly by internal conversion, is included in the abundant 0.14-Mev peak we observe.

For decay scheme B, 1.4-min Pd^{113} will be classed as $\frac{1}{2}+$, but $\frac{3}{2}+$ is not excluded. The spin $\frac{1}{2}+$ is recorded[23,24,30] for the ground state of Cd isotopes $A=111$,

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[28] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).
[29] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).
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[31] C. L. McGinnis, Phys. Rev. **87**, 202 (1952).

113, 115, 117, suggested[30] for the ground-state Pd^{111}, and proposed for 45-sec Pd^{115} (see below). The $\frac{1}{2}+$ Pd^{113} would be expected to undergo β decay principally to $\frac{1}{2}-$ Ag^{113} (5.3 hr). It is supposed that the β yield of $\sim 10\%$ of $\frac{7}{2}+$ Ag^{113} (1.2 min) comes from β decay of Pd^{113} to higher energy levels of Ag^{113}, followed by γ de-excitation.

Under scheme B, isomeric transition in Ag^{113} cannot be very prominent and the $\frac{1}{2}-$ level (5.3 hr) would lie in the range <0.03 Mev above the $\frac{7}{2}+$ level to <0.06 Mev below.

The β decay of the two Ag^{113} isomers to Cd^{113} is independent of choice A or B of decay schemes except for the fraction of decay of the 1.2-min Ag^{113m} to give 5.1-yr Cd^{113m}. The 5.3-hr Ag^{113} is expected to decay almost exclusively to ground state Cd^{113}. The β-decay energy of 2.2 Mev corresponds to logft of 7.4 consistent with the assignment. A small branch to the 0.31-Mev level of Cd^{113} is also seen (Table II), suggesting that this level has assignment[8] $\frac{3}{2}+$ rather than $\frac{5}{2}+$.

Inelastic scattering and excitation studies[8,9,10] have established excited states in Cd^{113} at 0.31 ($\frac{3}{2}+$ or $\frac{5}{2}+$), 0.56, and 0.70 Mev and the γ cascade 0.39+0.31 Mev. Our observation (Fig. 1) of a high yield of 0.14-Mev γ rays in the decay of 1.2-min Ag^{113} suggests also the γ cascade 0.14+0.56 Mev. These data lead to the assignment of spins of $\frac{3}{2}+$, $\frac{5}{2}+$, and $\frac{5}{2}+$ for the levels at 0.30, 0.56, and 0.70 Mev.

The use of β-decay theory[25–27] for branching, with ~ 2.3 Mev β-decay energy for 1.2-min Ag^{113}, and the use of Weisskopf's theory[26,28,29] of radiation probabilities as modified empirically by Way *et al.*,[30] leads to reasonable agreement between observed and predicted γ-ray yields in the decay of 1.2-min Ag^{113m}. The spectrum of Ag^{113m} was explored only above 0.10 Mev. It exhibits the components of energy 0.14, 0.30, 0.39, 0.56, and 0.70 Mev (Fig. 1 and Table II). Correcting for scintillator efficiency[32] gives the relative yields 40:100:30:10:10, respectively. The predicted yields, taking the mean life[30] for $E2$ transitions as 0.08 times the single-particle life, are 3:100:30:2:2. This is considered satsifactory agreement.[30]

Fission yield measurements[1] indicate that 0.5% of the 113 chain leads to 5.1-yr Cd^{113m} (11/2−). This occurs most likely in the β decay of Ag^{113m} of high spin through an intermediate state.

Mass Chain 114

Parity and spin in the levels of Cd^{114} and In^{114} have previously been assigned.[23,24,30,33] The proposed decay scheme is shown in Fig. 5. The ground state of Pd^{114} is undoubtedly 0+. The 0.56-Mev γ ray associated with the decay of 2.4-min Pd^{114} is ascribed to a γ transition

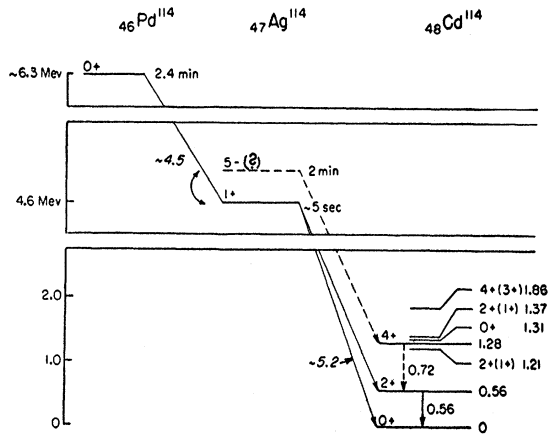

FIG. 5. Decay scheme for $A=114$. The order and energy difference of the two Ag^{114} isomers is unknown, as indicated by the curved double-ended arrow.

following β decay of 5-sec Ag^{114}. The mass assignment depends partly on the agreement of this energy with that observed[8–10,16–19,33] for an excited state in Cd^{114}. The $\sim$5-sec Ag^{114} is very probably 1+, a common ground state[23,24,30] in odd-odd nuclides in this region. This is supported by the logft value for Pd^{114} of 4.5 corresponding to the estimated[12] decay energy of 1.7 Mev. Similarly the decay of $\sim$5-sec Ag^{114} to either the 0+ ground state or the 2+ first-excited state of Cd^{114} should be allowed transitions. No evidence was seen for appreciable decay via the reported[18] excited states at 1.21 and 1.37 Mev (2+ or 1+) and at 1.31 Mev (0+), but the higher γ rays may well have been missed. Assuming 60% β transition to the ground state, the logft value is 5.2.

The $\sim$2-min Ag^{114} reported by Duffield and Knight from the reaction Cd^{114} (n,p) may well be the 5− isomer, another well-known level for odd-odd nuclides, and thus it would not be formed appreciably in β decay or in high yield in a low-energy (n,p) reaction. It should show the 0.72-plus 0.56-Mev γ cascade. Little can be said about the separation of levels for the Af^{114} isomers, and about which is higher. If the high-spin (2-min) level is higher, isomeric transition will compete with β decay for it.

Mass Chain 115

By analogy to Pd^{113}, the ground-state spin of Pd^{115} could be assigned either (A) $\frac{5}{2}+$ or (B) $\frac{1}{2}+$ or $\frac{3}{2}+$. From the following discussions of the spins of Ag and Cd isomers it will become evident that $\frac{5}{2}+$ can be excluded for Pd^{115}, so that $\frac{1}{2}+$ is the best assignment although $\frac{3}{2}+$ is possible. If negative-parity Pd states are considered, $\frac{5}{2}-$ is excluded on the same grounds, but $\frac{3}{2}-$ is permissible. The proposed decay scheme is shown in Fig. 6.

The spins of the two Ag isomers can be expected by analogy[23,24,30] to be $\frac{7}{2}+$ or $\frac{1}{2}-$. The 21.1-min Ag^{115} decays to the extent[1] of 9% to 43-day Cd^{115m} (11/2−)

[32] M. I. Kalkstein and J. M. Hollander, University of California Radiation Laboratory Report UCRL-2764, 1954 (unpublished).
[33] P. H. Stelson and F. K. McGowan, Bull. Am. Phys. Soc. Ser. II, 2, 267 (1957).

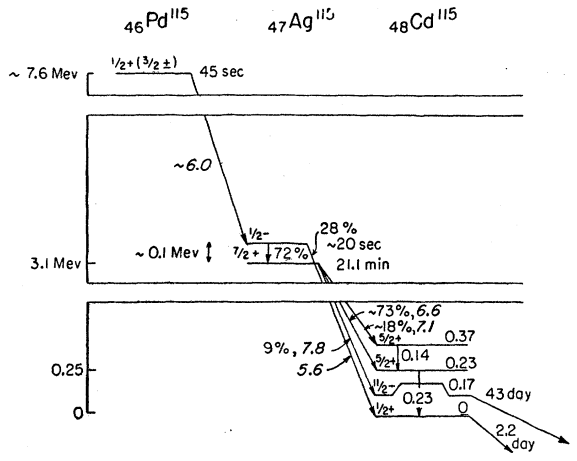

FIG. 6. Decay scheme for $A=115$.

and 91% to 2.2-day Cd^{115} ($\frac{1}{2}+$). This branching cannot be explained by a $\frac{1}{2}-$ assignment, and thus $\frac{7}{2}+$ is assigned to 21.1-min Ag^{115}, contrary to several reviews,[23,24] and $\frac{1}{2}-$ is assigned to 20-sec Ag^{115m}. It has also been established from thermal-neutron fission yields[1] that 28% of the 2.2-day Cd^{115} arises promptly from β decay of the short-lived Ag^{115m} ($\frac{1}{2}-$). If the 45-sec Pd^{115} had spin $\frac{5}{2}+$, direct decay to the $\frac{7}{2}+$ 21.1-min Ag^{115} would be an allowed transition and no mechanism exists for transmitting 28% of the chain through β decay of ~20-sec Ag^{115m} ($\frac{1}{2}-$).

The assumption of $\frac{1}{2}+$ or $\frac{3}{2}+$ for 45-sec Pd^{115} leads to prediction of a first-forbidden transition to the $\frac{1}{2}-$ isomer of Ag^{115}, and second-forbidden transition to the $\frac{7}{2}+$ isomer. The logft for 45-sec Pd^{115} of assumed[12] β-decay energy of 4.5 Mev is 6.0, consistent with the pattern shown.

If the $\frac{1}{2}-$ state of Ag^{115} should be below the $\frac{7}{2}+$ state, there would be negligible population of the latter state. If the $\frac{1}{2}-$ state should be about 0.1 Mev above the $\frac{7}{2}-$ state, the half-period for isomeric transition would be about 1 minute,[22] consistent with the half-period and inferred branching.

It has been shown[1] that β decay of the short-lived Ag isomer leads to 2.2-day Cd^{115} only. If one uses a β-decay energy of 3.2 Mev, the logft for the β decay of ~20-sec Ag^{115m} is ~5.6, in comparison with 6 to 8 expected [26,27] for the direct decay $\frac{1}{2}- \rightarrow \frac{1}{2}+$.

The γ spectrum of 21.1-min Ag^{115} reveals two transitions of 0.23 and 0.14 Mev (probably in coincidence) with relative intensities of 5:1. We therefore postulate energy levels in Cd^{115} at 0.23 and 0.37 Mev, both assigned spin $\frac{5}{2}$. The logft for decay of 21.1-min Ag^{115} ($\frac{7}{2}+$) to a $\frac{5}{2}+$ state would be expected to be 4 to 6, and to a $\frac{5}{2}-$ state 6 to 8. Assuming 80% decay with 2.9 Mev and 20% decay with 2.76 Mev, logft values of 6.6 and 7.1 are determined, not inconsistent with either choice for parity of the Cd states. However, analogy with known excited states of other odd-A Cd isotopes and shell-model considerations favor the choice $\frac{5}{2}+$.

A small fraction (9%) of the 21.1-min Ag^{115} ($\frac{7}{2}+$) leads to the 11/2− state. Assuming this to be a direct transition of 2.9 Mev, a logft of 7.8 is obtained, reasonable for $\Delta I=2$, yes.

Mass Chain 116

The proposed decay scheme for mass chain 116 is shown in Fig. 7. The ground state[23,24,30] of even-even

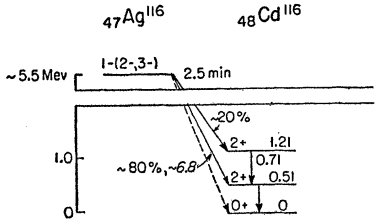

FIG. 7. Decay scheme for $A=116$.

Cd^{116} is 0+. Its first excited state has been found by Coulomb excitation[8,16–18] to be 0.510 Mev and assigned 2+, and the second state at 1.217 Mev identified[33] also as 2+. The γ spectrum of 2.5-min Ag^{116} shows in addition to the 0.515-Mev line another line at 0.70 Mev (relative intensity 0.2), which we assume to be in cascade with the first.

Ignoring possible ground-state decay for lack of evidence, the logft for the 5.0-Mev β transition of 2.5-min Ag^{115} to the 0.51 level in Cd^{116} is 6.8, which is consistent with ΔI, $=0, \pm 1$, yes. Thus the assignments 1−, 2−, or 3− are suggested for the ground state of Ag^{116}. These are all consistent with the relative γ intensities due to branched β decay. The 1− state is a common one[23,24,30] for odd-odd nuclei in this region.

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