PHYSICAL REVIEW VOLUME 81, NUMBER 5 MARCH 1, 1951

Radioactivity of Ag^{111}, Cd^{111}, In^{111}, and Sn^{111}

C. L. McGinnis
Department of Physics, University of California, Berkeley, California

(Received November 7, 1950)

By considering the 111-isobars as a unit it has been possible to specify the spin and parity of the ground states of Ag^{111}, Cd^{111}, In^{111}, and Sn^{111}, and of four excited states of Cd^{111}. The characteristics of the transitions between these levels are given. The electron spectra associated with a 5-hr In^{110}, 4.2-hr In^{109}, and 50-min In^{108} are also given.

I. INTRODUCTION

THE 111 isobars have been separately studied by many investigators.[1] Here, they are considered as a unit with the result that it has been possible to characterize their disintegration scheme uniquely and, in particular to make a definite assignment of spin and parity to the several states.

II. THE ISOBARS OF MASS NUMBER 111

Ag^{111}

This activity was first observed[2] in the silver fraction from palladium bombarded with deuterons. It was assigned to Ag^{111} and characterized by a 7.5-day half-life with 0.8 Mev β^-. Subsequently, the maximum beta-energy of 1.06 ± 0.03 Mev was spectrographically measured.[3] By absorbing $\beta\gamma$-coincidences Storruste[4] detected a 0.33-Mev γ-ray occurring in 6.5 percent of the disintegrations. More recently the photoelectric spectrum[5] has shown the presence of 340 ± 2- and 243 ± 2-kev π-rays in the ratio 8:1 and a complex β^- spectrum. Johansson gives 7.50 ± 0.12 days as the half-life. We have produced Ag^{111} by the reaction $Ag(\alpha,pp)Ag^{111}$.

Cd^{111}

A 50 ± 5-min activity chemically identified as belonging to cadmium was first produced by neutron bombardment of cadmium.[6] X-rays of 1.5 Mev on cadmium excited this activity[7,8] showing that it is an isomer. The capture of thermal neutrons by enriched Cd^{110} assigned the activity[9] to Cd^{111m}. We have also produced it[10] by fast neutron bombardment of enriched Cd^{111} and Cd^{112}, from $Ag(\alpha,pn)$ and $Pd(\alpha,n)$. Our half-life measurement of 48.6 ± 0.3 min agrees with the previously reported value.[8] Spectrographically we found internal conversion electrons from 149- and 247-kev γ-rays, the former highly converted and the latter the same as observed[10] in the decay of In^{111}. By means of delayed coincidences with[11] Cd^{111m} and[12] In^{111} Deutsch and his co-workers measured $8\pm1\times10^{-8}$ sec for the half-life of this latter γ-ray. Hole[13] has also observed the electron spectrum using a rather thick source (10 mg/cm^2), and found internal conversion electrons from 146 ± 4- and 235 ± 5-kev γ-rays with K/L ratios of 1.8 ± 0.2 and >10, respectively. From the photoelectric spectrum he estimates that the intensity of the 146 quanta is <10 percent of that of the 235-kev ray, and from this he computes that the former is >92 percent converted and the latter 16 ± 3 percent. Hole found the ratio of the 146 to 235 electrons to be 5.7 and concluded that the former is responsible for the isomeric state.

Slow neutron bombardment of cadmium has failed to reveal the presence of an isomer with a half-life[14] between 10^{-3} and 1 sec.

In^{111}

A 2.7-day indium activity was first produced[15] by bombardment of cadmium with deuterons. Lawson and Cork[16] found this activity to be characterized by two internally converted 172.8 ± 1- and 246.7 ± 1-kev γ-rays with K/L and K/M ratios of 6.6 ± 0.5, 35 ± 10 and 5.6 ± 0.5, 30 ± 10, respectively. From the high intensity of the Cd K x-rays, observed by critical absorption, they concluded that it decays by K-capture. They also set an upper limit to the occurrence of positrons at <0.005 of the electrons. This activity was assigned to mass number 111 by $Ag+\alpha$ excitation functions,[17,18] the threshold being 15 ± 0.5-Mev $\gamma\gamma$-coincidence measurements showed that these two γ-rays are in cascade.[19] By measuring ee, $e\gamma$, and $\gamma\gamma$-coincidences Boehm *et al.*,[20] find α_k and α_L for the 172 and

---

[1] For a list of references see G. T. Seaborg and I. Perlman, Revs. Modern Phys. **20**, 611 (1948).

[2] J. D. Kraus and J. M. Cork, Phys. Rev. **52**, 763 (1937).

[3] Helmholz, Hayward, and McGinnis, Phys. Rev. **75**, 1469 (1949).

[4] A. Storruste, Phys. Rev. **79**, 193 (1950).

[5] S. Johansson, Phys. Rev. **79**, 896 (1950).

[6] M. Dode and B. Pontecorvo, Compt. rend. **207**, 287 (1938).

[7] J. R. Feldmeier and G. B. Collins, Phys. Rev. **59**, 937 (1941).

[8] M. L. Wiedenbeck, Phys. Rev. **67**, 92 (1945).

[9] M. Goldhaber and C. O. Muehlhause, Phys. Rev. **74**, 1248 (1948).

[10] A. C. Helmholz and C. L. McGinnis, Phys. Rev. **74**, 1559 (1948).

[11] M. Deutsch and W. E. Wright, Phys. Rev. **77**, 139 (1950).

[12] M. Deutsch and D. T. Stevenson, Phys. Rev. **76**, 184 (1949).

[13] N. Hole, Arkiv Mat. Astron. Fysik **36A**, No. 9 (1948).

[14] Holmes, Mei, and Turgel, Phys. Rev. **75**, 889 (1949).

[15] J. M. Cork and J. L. Lawson, Phys. Rev. **56**, 291 (1939).

[16] J. L. Lawson and J. M. Cork, Phys. Rev. **57**, 982 (1940).

[17] D. J. Tendam and H. L. Bradt, Phys. Rev. **72**, 527 (1947).

[18] S. N. Ghoshal, Phys. Rev. **73**, 417 (1948).

[19] Bradt, Gugelot, Huber, Medicus, Preiswerk, and Scherrer, Helv. Phys. Acta **19**, 77 (1945).

[20] Boehm, Huber, Marmier, Preiswerk, and Steffen, Helv. Phys. Acta **22**, 69 (1949).

TABLE I. Experimental results.

Activity	Half-life	γ-ray (kev)	K/L	$\frac{\text{conv. } e^-}{247e^-}$	Percent conv.
Cd^{111m}	48.6±0.3 min	149.6±0.3 246±2	1.99±0.3 5.12±0.22	14.5±1.0 <0.014 for any others >100 kev	87±13
In^{111}	2.84±0.03 d	172.1±0.5 246.6±0.7 330±10 93±10	6.6±0.4 5.19±0.01	1.73±0.03 2.5±0.1×10^{-2} 1.3±0.5×10^{-2} <2.5×10^{-4} for any others >100 kev	10.4±0.9 6.0±0.5
		β^+ <4×10^{-3} of the electrons ratio transitions 172/247 =0.97±0.10			
Sn^{111}	35±1 min	1.51±0.03 Mev β^+	K/β^+ =2.50±0.25		

247 γ-rays to be 0.081±0.008, 0.009±0.001 and 0.036 ±0.005, 0.006±0.001, respectively, and the ratio of the conversion electrons to be 2.1±0.1. We have observed 2.84±0.03 days for the half-life[3] of In^{111} and have produced this activity from the bombardment of cadmium as well as of silver with alphas. Mallary and Pool[21] report a measurable number of positrons associated with the 2.84-day activity of In^{111}.

Sn^{111}

By the bombardment of enriched cadmium isotopes with α-particles Hinshaw and Pool[22] produced a 35.0±0.5-min positron activity (1.45 Mev by absorption), in the tin fraction and assigned it to Sn^{111}.

III. EXPERIMENTAL RESULTS

The experimental results are summarized in Table I. The electron spectra were investigated with a magnetic lens spectrometer similar to one described by Siegbahn.[23] In computing the K/L ratios and the ratios of the conversion electrons the areas under the lines were used.

Using a 0.16- and a 0.48-mg/cm² Ag radiator, the ratio of the photo-electrons of the two In^{111} γ-rays was measured to be 2.32±0.24. According to the experimental data of Jones[24] for a silver radiator and these energies the 172 γ-ray is 2.51 times more efficient than the 247. Thus, the γ-ray ratio is 0.93. With the percent the two γ's are converted, the ratio of the transitions is, thus, 0.97±0.10.

The percent by which each In^{111} γ-ray is converted was measured by absorbing in aluminum the electron-electron coincidences at 180°. After subtracting the background coincidences ($e\gamma$, e-x-ray, etc.), Fig. 1, curve B, presents N_{ee}, the number of e^-e^- coincidences, divided by the total number of electrons, $N_{e172}+N_{e247}$, counted in the G-M tube with zero absorber as a function of the mg/cm² of Al over the other counter. Curve A represents N_{ee} divided by the electrons counted in the tube covered with absorber. Thus, between the range of the 172-kev γ-ray conversion electrons (35 mg/cm²), and that of the 247 γ-ray electrons (60 mg/cm²), we have

$$N_{ee}/N_{e247}=\Omega\times(1-e^{-\lambda t})=(3.88\pm0.20)\times10^{-3} \quad (1)$$

and at zero absorber

$$N_{ee}/(N_{e172}+N_{e247})=\Omega xy(1-e^{-\lambda t})=(2.35\pm0.10)\times10^{-3}. \quad (2)$$

x and y are the percentages by which the 172 and 247 γ-rays are converted. t is the resolving time of the coincidence counter $=2.5\times10^{-7}$ sec. λ is the decay constant for the 247-kev γ-ray. Ω is the percentage of the total solid angle subtended by the source equal to 3.8±0.2. Ω was measured by aluminum absorption of the $\beta\gamma$ coincidences of Co^{60}. Thus,

from (1), $x=11.5\pm1.7$ $y=6.64\pm1.0$,
from (2), $x=9.5\pm1.4$ $y=5.48\pm0.8$.

Therefore, $x=10.4\pm0.9$ and $y=6.0\pm0.5$.

As the Co^{60} β-spectrum has the allowed shape[25] the angular correlation is isotropic.[26] The theoretical treatment of the directional correlation of successive internal conversion electrons only includes the case of electric multipole radiation.[27] According to this theory, if the 172-kev γ-ray were pure electric quadrupole, the measured x and y would then be increased by a factor of 5.5. However, no correction of this type has been made.

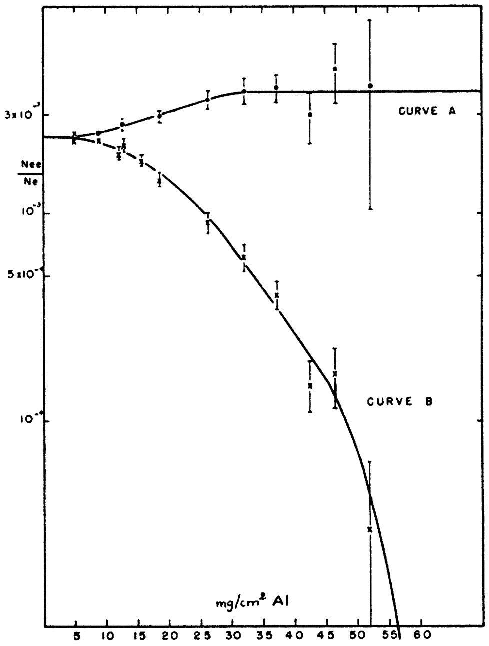

FIG. 1. Aluminum absorption of the In^{111} electron-electron coincidences.

---

[21] E. C. Mallary and M. C. Pool, Phys. Rev. **76**, 186 (1949).
[22] R. A. Hinshaw and M. L. Pool, Phys. Rev. **76**, 358 (1949).
[23] K. Siegbahn, Phil. Mag. **37**, 181 (1946).
[24] M. T. Jones, Phys. Rev. **50**, 110 (1936).
[25] Deutsch, Elliot, and Roberts, Phys. Rev. **68**, 193 (1945).
[26] D. L. Falkoff and G. E. Uhlenbeck, Phys. Rev. **79**, 334 (1950).
[27] J. W. Gardner, Proc. Phys. Soc. (London) **62A**, 763 (1949).

Comparison between our measurements and the theoretical internal conversion coefficients (see below) show that the 172-kev γ-ray is probably pure magnetic dipole, and the 247-kev γ is pure electric quadrupole.

N_{ee} as a function of the mg/cm^2 of Al placed over both counters was also measured, which showed that <1 percent of the 247-kev conversion electrons are in coincidence with those of any γ-ray more energetic than 172 kev.

The ratio of the 172/247 conversion electrons was measured to be 1.70 ± 0.03 through a 0.4 mg/cm^2 Nylon window in the magnetic spectrograph (Fig. 2). Using a Nylon window 0.8 mg/cm^2 the ratio was decreased 2 percent. Hence, the absorption is estimated to have been 2 percent, making the ratio 1.73 ± 0.03. For Cd^{111m} the measured ratio of 149/247 electrons was 13.8 ± 1.0. The absorption correction is estimated as 5 percent, and so this ratio is 14.5 ± 1.0.

A search was made for the conversion electrons from a possible excited state of In^{111} by observing spectrographically the indium fractions obtained from Ag bombarded with alphas of several different energies. It is not possible to ascribe any of the observed lines (see below), to an excited level of In^{111}, and, thus, between 50 and 700 kev there are no conversion electrons due to an isomeric state of In^{111} with a half-life >20 min or <100 days.

The Sn^{111} was obtained from Cd bombarded with 39.6-Mev alphas. The β^+ spectrum produced a straight-line FK plot with an upper energy of 1.51 ± 0.03 Mev. The ratio K/β^+ was computed to be 2.50 ± 0.25 from the relative area under the 247-kev line and that under the β^+ spectrum and from the fact that this γ-ray is 6 percent converted. The major portion of the error is due to the uncertainty in knowing exactly when $t=0$ in the chemical separation of In from Sn. No conversion electrons caused by an excited state of Sn^{111} or In^{111} were observed.

By counting the activity produced in stacked cadmium foils bombarded with 9.67-Mev protons from the 60-in. cyclotron and 3.75-Mev from a Van de Graaff generator we find the threshold for the production of In^{111} occurs at a proton energy of 2.35 ± 0.20 Mev (Fig. 3). With the n-p difference[28] as 0.79 Mev the 2.84-day In^{111} is, thus, 1.56 ± 0.20 Mev above the ground level of Cd^{111}. The 48-day In^{114m} was also produced in the same foils, and we find this level is 2.26 ± 0.20 Mev above the ground state of Cd^{114}. As discussed below this is a reasonable value for the In^{114} threshold indicating that the In^{111} threshold is probably correct. In absolute magnitude the cross sections shown in Fig. 3 are believed to be accurate within a factor of two.

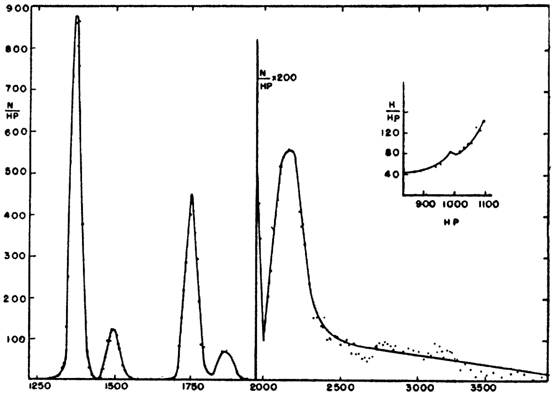

FIG. 2. Composite electron spectrum of the In^{111} activity showing conversion electrons from 172-, 247-, 340-, and (insert) 93-kev γ-rays.

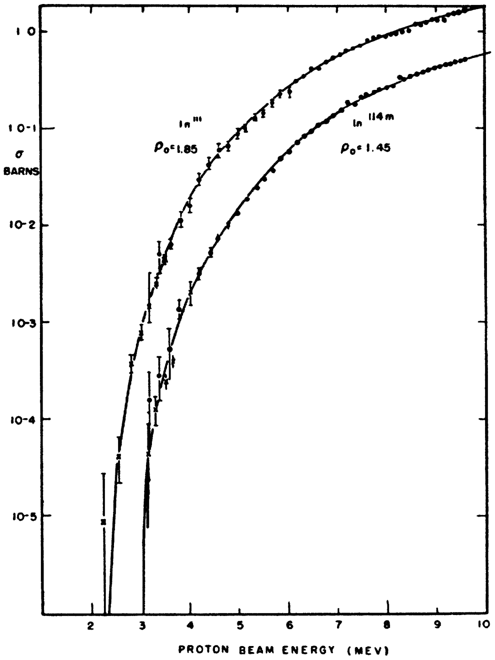

FIG. 3. Cd$^{111}(p,n)$In^{111} and Cd$^{114}(p,n)$In^{114} excitation functions. The solid curves are the theoretical shapes for the indicated radii.

According to Stephens, Spruch, and Schiff,[29] near the threshold the yield of the (p,n) reaction varies as $(E_p-E_t)^{\frac{1}{2}}$, where E_p and E_t are the proton beam and threshold energies, respectively. Below 3×10^{-4} barns the curves of Fig. 3 have been drawn in this shape.

Applying statistical methods to the theory of the compound nucleus Weisskopf and Ewing[30] have computed the cross section for (p,n) reactions. The shape of the excitation curves can be fitted best by assuming $r_0=1.85$ for Cd^{111} and 1.45 for Cd^{114}, the nuclear radius being $r_0A^{\frac{1}{3}}\times10^{-13}$ cm. With these radii the theoretical cross sections for the production of In^{111} and In^{114m} are 1/6 and 1/18, respectively, of those observed. Although the absolute magnitude of the nuclear radius is not too accurate, their relative magnitude, probably, is substantially correct.

---

[28] Franzen, Halpern, and Stephens, Phys. Rev. **76**, 317 (1947).

[29] Quoted by Shoupp, Jennings, and Sun, Phys. Rev. **75**, 2 (1940).

[30] V. F. Weisskopf and P. H. Ewing, Phys. Rev. **57**, 472 (1940).

TABLE II. $100N_e/(N_e+N_\gamma)$ computed from Rose's value of $(N_e/N_\gamma)_K$ and the measured K/L ratio.

γ-ray	Expt.	Elect. 1	Elect. 2	Elect. 3	Mag. 1	Mag. 2	Mag. 3
172.1	10.4±0.9	3.50	16.95	48.8	9.85	41.0	79.2
246.6	6.0±0.5	1.36	5.88	19.8	4.18	17.2	51.1

TABLE III. Theoretical ratio 172/247 conversion electrons.

172-kev γ-ray	Elect. 1	Elect. 2	Mag. 1	Experiment
172/(247 elect. 2)	0.60	2.88	1.67	1.73±0.03
172/(247 mag. 1)	0.84	4.05	2.35	

In light of the single-particle model of the nucleus it is interesting to note that the even-odd nucleus has a radius about 25 percent greater than the even-even nucleus.

IV. CALCULATIONS

In evaluating the "Fermi Coulomb correction factor," F_c, we used the approximation of Bethe and Bacher as given by Feister.[31] The latter has shown that for β^- emission this approximation deviates from the accurate computation by less than 0.4 percent for $Z=50$.

In computing f_+ for positrons the "screening correction factor" as given by Reitz[32] has been applied to F_c. For capture, Marshak's formulas[33] for the Fermi function, f_c, were used. The f values tabulated below have been multiplied by the factor $(2I_f+1)/(2I_i+1)$ for those cases in which it was found that the spin of the parent I_i is less than that of the final nucleus I_f.

The γ-ray half-lives were computed from the formula given by Axel and Dancoff[34] and the K internal conversion coefficients, $(N_e/N_\gamma)_k$, from the table privately distributed by Rose *et al.*[35]

V. DISCUSSION

From hyperfine structure the ground-state spin of Cd^{111} has been found[36] to be 1/2. According to the shell structure model of the nucleus[37] this is a $3s_{1/2}$ state, i.e., even parity.

As only the 247-kev γ-ray is common[3] to the activity of In^{111} and Cd^{111m}, the first excited state of the latter is thus at 247 kev. Comparison between theory and experiment (Tables II and III), clearly indicates that this γ-ray is electric quadrupole. On this basis the possibility of a small admixture of magnetic dipole cannot be eliminated. Thus, the spin of this level can be either 5/2 or 3/2 with even parity. The 172-kev γ-ray is likewise clearly magnetic dipole with the possibility of a slight admixture of electric quadrupole. Hence, this latter transition involves a spin change of one unit.

If the 247-kev level has a spin of 3/2, then the 419-kev level would have a spin of 5/2 making the theoretical ratio of 419/172 transitions 8×10^2, whereas it is observed to be $<10^{-4}$. Hence, the 247-kev level must have spin 5/2, i.e., this γ-ray is pure electric quadrupole, and the 419-kev level has spin 7/2 and even parity. The computed ratio of 419/172 transitions is, then, 3×10^{-7} in agreement with the measurements (Table VII).

The screening correction factor increases Rose's value of $(N_e/N_\gamma)_k$ by 3.6 percent for the 172-kev magnetic dipole and by 3.9 percent for the 247-kev electric quadrupole γ-rays. The observed $(N_e/N_\gamma)_k$ and the theoretical values with the screening correction applied are given below.

γ-ray	experiment	theory
172.1	0.10 ±0.010	0.0982±0.0013
246.6	0.054±0.005	0.0544±0.0008.

The error listed for the theoretical value arises from an uncertainty of 1 kev in the γ-ray energy.

The theoretical half-lives of the 172- and 247-kev γ-rays are 4×10^{-8} and 7×10^{-10} sec, respectively. The latter has been measured[12] to be $8\pm1\times10^{-8}$ sec.

This assignment, spins 7/2, 5/2 both even parity, agrees with the $\gamma\gamma$ angular correlation experiment of Boehm and Walter,[38] who found the distribution given by $1-(0.07\pm0.04)\cos^2\theta$. Theoretically,[39] the coefficient for the first-transition dipole and the second quadrupole is -0.103 for spins 7/2 and 5/2; and -0.074 for spins 5/2 and 3/2.

The recent work of Johansson[5] on Ag^{111} also agrees with this assignment. The ft values (Table IV) for the decay of Ag^{111} to the ground state and to the 340-kev level of Cd^{111} are empirically[40] classified as first forbidden. $ft=2.59\times10^9$ for the decay to the 247-kev level is usually characteristic of a second-forbidden transition. However, Shull and Feenberg[41] have pointed out that in the case of a first-forbidden transition involving a spin change of 2 with a change of parity, and, conse-

TABLE IV. Values of ft for Ag^{111} and Sn^{111}.

Activity	Transition	W_0	%	$T_{\frac{1}{2}}\times10^{-4}$ sec	f	$ft\times10^{-5}$	$(W_0^2-1)ft10^{-10}$
Ag^{111}	to ground	3.08	91[a]	73.6	34.5	254	0.0216
	to 247 level	2.59	1[a]	6690	37.5	25,900	1.43
	to 340 level	2.41	8[a]	589	15.9	936	0.045
Sn^{111}	capture	3.95	72	0.294	38.9	1.14	$\frac{f_c}{f_+}=2.89\pm0.12$
	positrons	3.95	28	0.732	13.5	0.99	

[a] The percentage (%) values for the Ag^{111} transitions are taken from Johansson (reference 5).

---

[31] I. Feister, Phys. Rev. **78**, 375 (1950).
[32] J. R. Reitz, Phys. Rev. **77**, 10 (1950).
[33] R. E. Marshak, Phys. Rev. **61**, 446 (1942).
[34] P. Axel and S. M. Dancoff, Phys. Rev. **76**, 892 (1949).
[35] See also Rose, Goertzel, Spinrad, Harr, and Strong, Phys. Rev. **76**, 1883 (1949).
[36] Schüler and Brück, Z. Physik **56**, 291 (1929).
[37] M. Mayer, Phys. Rev. **78**, 16 (1950).
[38] F. Boehm and M. Walter, Helv. Phys. Acta **22**, 379 (1949).
[39] D. R. Hamilton, Phys. Rev. **58**, 122 (1940).
[40] E. J. Konopinski, Revs. Modern Phys. **15**, 209 (1943).
[41] F. P. Shull and E. Feenberg, Phys. Rev. **75**, 1768 (1949).

TABLE V. In^{111} f values.

					Ratio of transitions from In^{111} to Cd^{111} levels			
					Theory			
Transition	W_0	f^0	$f^1\times10^3$	$f^2\times10^7$	$\frac{f^0}{565}$	$\frac{f^1\times10^4}{5.65}$	$\frac{f^2\times10^8}{5.65}$	Experiment
to 419 level	1.23	5.65	1.09		1.00			0.97 ± 0.10
to 396 level	1.28	8.34	1.61	1.09	1.48	2.85	1.93	$<10^{-4}$
to 340 level	1.39	6.55	1.34	1.04	1.16	2.37	1.84	0.0082
to 247 level	1.57	7.55	1.83	1.57	1.33	3.24	2.78	0.03 ± 0.10
β^+ to 419 level	1.23	7.3×10^{-5}			1.3×10^{-5}			$<6\times10^{-4}$

quently, having a β-spectrum of forbidden shape, the product $(W_0^2-1)ft$ is about 10^{10}. For the transition to the 247-kev level this product is 1.43×10^{10} indicating that it is of this type. These results combined with the known spin and parity, 1/2 and 5/2 both even, of the ground and 247-kev level of Cd^{111} serve to fix the spin of Ag^{111} as 1/2 with odd parity.

From the relative intensity in the Ag^{111} decay of the 247- and 340-kev γ-rays (1:8), it is seen that the latter goes directly to the ground state of Cd^{111}. Thus, the 340-kev level may have a spin of 3/2 or 1/2 with even parity. The value of $(W_0^2-1)ft$ is more than a factor of ten too low for this transition to involve a spin change of two.

Although the ft of In^{111} for an allowed transition, 1.38×10^6 (Table V) is about a factor of 10 higher than the empirical classification, that for first forbidden, 2.67×10^2, is too low by a factor of 10^5. Hence, it is concluded that this is an allowed transition. The results on the photoelectric spectrum show that no measurable number of decays go directly to the 247-kev level. This fixes the ground state of In^{111} with spin 9/2 and even parity, which is in agreement with the shell model.[37] Also in agreement is the fact that both stable isotopes of indium, 113 and 115, have measured ground state spins of 9/2.

We have observed the internal conversion electrons of a 330 ± 10 kev γ-ray in the decay of In^{111} (Fig. 2). This is undoubtedly the same as the 340-kev γ-ray that is reported by Johansson[5] in the decay of Ag^{111}. This 330 ± 10-kev γ-ray can, thus, originate either by a direct capture decay of the In^{111} ground state or from the dual decay of the Cd^{111} 419-kev level. If the former is the case, the ft value for an allowed transition is 1.6×10^8, a factor of 10^3 higher than the empirical classification. It it originates from a first-forbidden transition the ft, 3.3×10^4, is a factor of 10^3 lower than the empirical classification. Moreover, with the spin and parity assignments possible under these circumstances the observed number of 330-kev transitions is 10^7 less than that permitted by the theoretical γ-ray half-lives. Therefore, the assumption that it originates by a direct transition from the ground level of In^{111} is not justified by the experimental evidence.

TABLE VI. Theoretical ratio of 149/247-kev conversion electrons and the percentage by which the 149-kev γ-ray is converted.

149.6-kev γ-ray	Elec. 3	Elec. 4	Elec. 5	Mag. 2	Mag. 3	Mag. 4	Expt.
Ratio	11.4	15.7	16.6	10.2	15.3	16.7	14.5 ± 1.0
% converted	66.8	92.0	98.3	59.8	89.7	98.2	87 ± 13

We, thus, conclude that a 340-kev γ-ray arises from the dual decay of the 419-kev level of Cd^{111}. Our work limits the spin of this level to either 3/2 or 5/2 with even parity. For example, with spin 1/2 and even parity there are 10^8 more of these transitions observed than are permitted by the theoretical γ-ray half-lives. Combining this result with Johansson's work uniquely fixes the spin of the 340-kev level at 3/2 with even parity.

In addition to decaying to the ground state this 340-kev level can also decay to the 247-kev level. The expected 93-kev γ-ray conversion electrons were observed (Fig. 2). Theoretically the ratio of 93/340 transitions is 0.005, which is consistent with the observed value of 0.085, since other assumptions of spin and parity give ratios differing by factors of 10^6.

Although we have been unable to observe spectrographically any positrons associated with the 2.84-day In^{111}, it can only be stated that they must occur by a factor of 4×10^{-3} smaller than the electrons, i.e., in less than 6×10^{-4} of the disintegrations. The theoretical value of f_+/f_e is 1.3×10^{-5} in agreement with the measurement.

According to Axel and Dancoff's classification[34] the 149-kev transition is characterized by $\Lambda=4$. The half-lives given below for the indicated Λ are to be compared to the experimental half-life of 2916 sec.

Λ	3	4	5
half-life	8×10^{-4}	117	2×10^7.

By comparison of the measured percentage by which this π-ray is converted and the ratio of the 149/247 conversion electrons with the theoretical values (Table VI), it is also seen that the best agreement is obtained by assigning $\Lambda=4$ to this transition.

Thus, the 396-kev level has even parity and may have a spin of either 11/2 or 13/2. We have been unable to extract chemically any 48-min Cd from the 2.84-day In and can, thus, state that transitions to this level must occur in less than 10^{-4} of the total. Hence, the In^{111} decay to this level is second forbidden, which fixes the spin of the 396-kev level at 13/2 with even

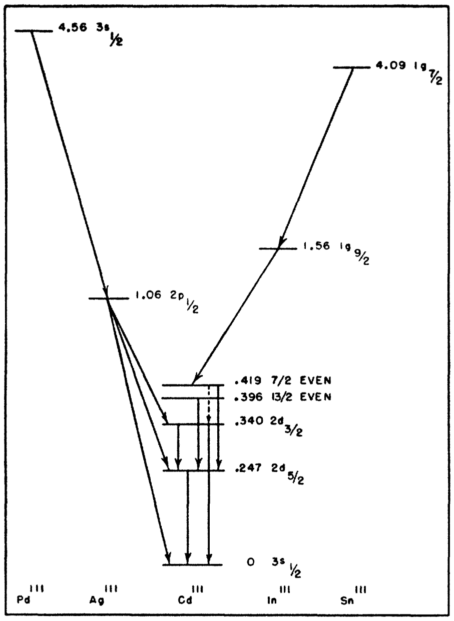

FIG. 4. Decay scheme of the 111-isobars.

parity; i.e., the 149-kev γ-ray is pure electric 2^4 pole (Table VI).

The ft values for Sn^{111} (Table IV) show that this decay is allowed. The screening correction increased the f_+ by 4 percent. As no conversion electrons from an excited state of either the parent or daughter were observed, it is concluded that the transition takes place between the ground states. Thus, Sn^{111} may have a spin of either 7/2, 9/2, or 11/2 with even parity. According to the shell structure model of the nucleus the 61st neutron is expected to be in either the $1g_{7/2}$ or $2d_{5/2}$ state. On this basis the spin of Sn^{111} is taken as 7/2 with even parity.

The 26-min Pd^{111} activity[42] has a value $ft = 7.9\times 10^6$, which is characteristic of a first-forbidden transition. The spin can thus be 1/2 with even parity. The resulting disintegration scheme of the 111 isobars is shown in Fig. 4.

The spin and parity assignments are all in agreement with Mayer's spin-orbit coupling model of the nucleus with the exception of the 396-kev metastable level of Cd^{111m}. The single-particle model would only permit a level with spin 11/2 and odd parity; i.e., the 149-kev transition would have to have $\Lambda = 3$. As discussed above such an assignment is not in agreement with the experimental evidence. This suggests that the single-particle model is not valid for the higher excited states (Table VII).

TABLE VII. Theoretical and experimental transition ratios for Cd^{111}.

Transition ratio	$\frac{22.5}{172}$	$\frac{79}{172}$	$\frac{419}{172}$	$\frac{56}{149}$	$\frac{396}{149}$	$\frac{93}{340}$
Theory	10^{-14}	9×10^{-1}	3×10^{-7}	10^{-15}	7×10^{-8}	5×10^{-3}
Experiment	$<10^{-4}$	8.2×10^{-3}	$<10^{-4}$	$<8\times 10^{-4}$	$<10^{-3}$	8.5×10^{-2}

TABLE VIII. γ-rays associated with the 5.0±0.2-hr In^{110}.

γ-ray energy in kev	119	590?	661	885	935
Relative intensity of conversion electrons	1.0±0.2	0.02±0.01	1	0.13±0.03	0.11±0.01

VI. OTHER RESULTS

Incidental to the main investigation the following results were also obtained.

Cd^{107}, Cd^{109}

In the Cd fraction from Ag bombarded with 39.6-Mev alphas the conversion electrons of a long-lived 88-kev γ-ray and those from a 6.7-hr 93-kev γ-ray were spectrographically observed. These well-known lines[1] are associated with the activity of Cd^{109} and Cd^{107}, respectively. It is suggested that the former was produced for the main part by $Ag^{107}(\alpha,pn)Cd^{109}$ and the latter from the decay[43] of the 33-min In^{107} produced by $Ag^{107}(\alpha,4n)In^{107}$. The relative yield Cd^{107}/Cd^{109} is estimated to have been 1 percent.

TABLE IX. γ-rays associated with the 4.2±0.2 hr In^{109}.

γ-ray energy in kev	58	205	347	427
Relative intensity of conversion electrons	0.6±0.1	1	0.080±0.003	0.016±0.005
K/L ratio	0.9±0.1	3±1		

Sn^{108}, In^{108}

In the tin fraction obtained by bombarding Cd with 39.6-Mev alphas we found, in addition to the Sn^{111} activity, both the K and L conversion electrons from a long-lived 159-kev γ-ray which has already been assigned to an isomeric transition[44] in Sn^{117} and those from the well-known[1] 390-kev γ-ray of In^{113m} belonging to the 105-day K-capture activity of Sn^{113}.

We also observed a 50±5-min build-up and a 4.0±0.3-hr decay of positrons which from the FK plot have an upper energy of 2.31±0.02 Mev. Conversion electrons of a 285-kev γ-ray, which has not been previously reported, decayed with a 4.0±0.3 hr half-life. The K/L ratio is estimated to be 3 or greater. The ratio, positrons to conversion electrons, is 20:1. As none of the lines associated with the decay of In^{107}, In^{109}, or In^{110} were detected (see below), comparable with that expected from the observed number of positrons, the activity is limited to mass number 106 or 108. Identifying this activity with Sn^{108}, 4-hr K-capture, In^{108}, 50-min positrons, agrees with the assignment of Mallary and Pool,[43] who obtained a similar activity from the bombardment of enriched Cd isotopes with alphas and deu-

---

[42] E. Segrè and G. T. Seaborg, Phys. Rev. 59, 212 (1941).

[43] E. C. Mallary and M. L. Pool, Phys. Rev. 76, 1454 (1949).

[44] E. C. Mallary and M. L. Pool, Phys. Rev. 77, 75 (1950); J. W. Mihelich and R. D. Hill, Phys. Rev. 79, 781 (1950).

terons. If the 285 γ-ray belongs to Cd^{108}, it is 6.4 percent converted with theory giving 1.1, 8.7, and 3.3 percent for electric dipole, quadrupole, and magnetic dipole respectively. From the linearity of the FK plot[45] the positron branching between the 285-kev level and ground state is smaller than 5 percent.

In^{110}

In the indium fractions from Ag bombarded with alphas of different energies we observed in addition to the conversion electrons associated with the activity of Cd^{109} and In^{111} those corresponding to the γ-rays shown in Tables VIII and IX. These have not been reported previously as belonging to the assigned activities. Owing to the similarity of the half-lives the mass assignments were made by noting the correlation of their conversion electrons with each other and with those belonging to In^{111}.

In the decay of the 270-day Ag^{110} Siegbahn[46] has observed 116-, 935-, 885-, and 656-kev γ-rays, the latter three being in cascade in that order to the ground level of Cd^{110}. He did not observe any coincidences between the 116-kev electrons and the β-spectrum and so ascribes this γ-ray to the isomeric transition, which occurs about 3 percent of the time, between the 270-day level and the 24-sec ground state of Ag^{110}. For the 116-kev line he found a K/L ratio of about 1.3 and for the 656-kev γ-ray $N_e/N_\gamma = 2.5\times 10^{-3}$.

The conversion electrons from 119-, 935-, 885-, and 661-kev γ-rays, having a 5.0±0.2-hr half-life, are associated with the decay of In^{110}. The latter three are, thus, the same that Siegbahn observed. In^{110} is known to have a 65-min 1.6-Mev positron decay.[1] Hence, the 5-hr activity must result from the decay of an isomeric level of In^{110}. It is suggested that the 119-kev π-ray is the isomeric transition. The K/L ratio for this line is 4.5±1.0 showing that it is not the same as the 116 line reported by Siegbahn. Although this ratio is more characteristic of $\Lambda = 4$ than $\Lambda = 5$, the former has a theoretical half-life of 5 min and the latter 195 days. From the experimental data this 119-kev transition occurs about 0.3 percent of the 5-hr capture decay, giving it a half-life of 75 days, i.e., $\Lambda = 5$ for the isomeric transition in In^{110}.

In^{109}

From the bombardment of enriched Cd isotopes with alphas and deuterons Mallary and Pool[43] find a 4.30±0.15-hr indium activity which they assign to In^{109}. We find four γ-rays decaying with a 4.2±0.2-hr half-life (Table IX), which are the product of $Ag(\alpha,2n)In$. They may thus be associated with either In^{109} or In^{111}. If assigned to the latter the expected growth of the ground level would be less than 10 percent, which growth it was not possible to detect.

The 58-, 205-, and 427-kev γ-rays are associated together on the basis of their better internal correlation than their correlation with the In^{111} radiation and, hence, are ascribed to In^{109}.

The 347-kev γ-ray has a half-life of 5±1 hr and could be the same as the 340-kev transition that occurs in Cd^{111}. If this were the case, it would have originated from the direct capture decay of an excited state of In^{111} having spin 1/2 and even parity. The isomeric transition to the ground level of In^{111} would be favored compared to decay to the 340-kev level of Cd^{111} unless the energy difference between the ground and excited states of In^{111} were of the order of 30 kev, in which case the isomeric transition could have a half-life 100 times that of capture. However, such long half-lives are characteristic of $\Lambda = 5$ transitions, not $\Lambda = 4$. For example, the half-life of Sb^{124}, a 20-kev isomeric transition[47] with $\Lambda = 4$, is 21 min. It, thus, seems more reasonable to ascribe this line to In^{109}.

In^{114}

Boehm and Preiswerk[48] proved that In^{114} decays not only by β^- to Sn^{114} but also to Cd^{114} with the emission of 715- and 548-kev γ-rays. Mei *et al.*[49] have shown that they are in cascade by observing the combination 1.27-Mev γ-ray. Positrons of 650±100 kev have also been detected occurring about 10^{-4} of the β^- which is of the order of magnitude to be expected from bremsstrahlung pair production.[48]

Our threshold measurements show that the 72-sec ground state of In^{114} is 2.07±0.20 Mev above the ground state of Cd^{114}, which, thus, permits the emission of 1.05-Mev positrons. With this energy difference the Fermi theory yields $f_e/f_- = 8\pm 2$ percent compared to 3 ± 1 percent observed[48] and $f_+/f_- = 3.6\pm 0.6\times 10^{-3}$ compared to the measured ratio of about 10^{-4}. This disagreement between theory and experiment is of the order of magnitude to be expected due to the difference in the nuclear matrix elements, e.g., for Cu^{64} $f_e/f_- = 0.1$ and $f_+/f_- = 8.9$ and experiment[50] gives 1.75 and 2.0, respectively. Our threshold measurement is, thus, not in disagreement with these experiments indicating that the true energy differences $In^{114} - Cd^{114}$ and $In^{111} - Cd^{111}$ probably lie within our observed limits.

It is a pleasure to express my appreciation to Professor A. C. Helmholz for his helpful guidance during the course of this work. I also express my thanks to Mr. Bernie Rossi and the 60-in. cyclotron crew for making the many bombardments and to the Radiation Laboratory for assistance throughout the work.

---

[45] H. Brown and V. Perez-Mendez, Phys. Rev. **78**, 812 (1950).

[46] K. Siegbahn, Phys. Rev. **77**, 233 (1950).

[47] der Mateosian, Goldhaber, Muehlhause, and McKeown, Phys. Rev. **72**, 1271 (1947).

[48] F. Boehm and P. Preiswerk, Helv. Phys. Acta **22**, 331 (1949).

[49] Mei, Mitchell, and Zaffarano, Phys. Rev. **76**, 1883 (1949).

[50] Bradt, Gugelot, Huber, Medicus, Preiswerk, Scherrer, and Steffen, Helv. Phys. Acta **19**, 219 (1946); M. Deutsch. Phys. Rev. **72**, 729 (1947).