The Radioactive Isotopes of Indium

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(Received March 28, 1940)

It is shown that radioactive isotopes of indium may be formed possessing ten distinct half-lives ranging from 13 seconds to 50 days. By producing the various isotopes with different methods of excitation and measuring the energies of the beta- and gamma-radiations emitted by each, it now becomes possible to assign with reasonable certainty each radioactivity to an isotope of a particular mass number. Energy level diagrams can be constructed for certain of the excited nuclei. Increased resolution of the magnetic beta-ray spectrometer now makes it possible to identify positively the element in which internally converted gamma-rays are emitted. This is accomplished by observing the differences in the K-, L- and M-conversion electron energies and comparing with known binding energies obtained from x-ray analysis. The total conversion coefficients are observed in several cases, and the ratios of K- to L-conversion coefficients for individual gamma-rays are used to compute the probable energy level spin values on the basis of present theory. A radioactivity of 50-day half-life assigned to In^{114} is shown to consist of a gamma-ray emission followed by a beta-ray of half-life 72 seconds and energy 1.98 Mev. It thus becomes possible to observe the form of this beta-spectrum in the magnetic spectrometer, and since it is an allowed transition it is significant to compare it with the present theory of beta-decay which has been developed only for transitions of this type and until now always tested by measurements on forbidden spectra. Within the probable errors the experimental results conform with the theoretical predictions of the Fermi theory.

INTRODUCTION

THE element indium has proven to be especially interesting in regard to its radioactive properties. Although there are only two stable isotopes of mass numbers 113 (4.5 percent) and 115 (95.5 percent) there now appear to be radioactive isotopes having ten distinct half-lives. This investigation is a continuation of the work previously reported.[1] New information has been obtained regarding the beta- and gamma-ray energies associated with the decay of each radioactivity, as well as the yield of each when different modes of excitation are employed, and it now appears reasonably certain that every radioactivity can be correctly assigned to a particular indium isotope.

In Table I are shown the percentages of the stable isotopes in indium and the neighboring elements. In Table II are listed collectively the half-lives and radiations of the various radioactivities observed, as well as the reactions by which they have been produced and the probable isotope responsible for each activity. In order to arrive at this final assignment it is necessary in many cases to combine our own results with the findings of other investigators on the same subject. It has therefore seemed preferable to treat each radioactivity separately, showing fully the reasons for the assignment. In certain cases it has been possible to construct energy level diagrams for the excited nuclei.

In addition to the string electrometer and ionization chamber, Geiger-Müller counter and cloud chamber, the magnetic beta-ray spectrometer has proven to be an invaluable aid in solving this problem. Not only does it yield the forms and upper limits of the beta-spectra but very precisely gives the energies of internally converted gamma-rays. Moreover by observing the decay of electrons having a particular energy one can often obtain the value of a particular half-life entirely independent of other activities which may be present.

Bombardments have been made in the cyclotron with deuterons up to 10 Mev and alpha-particles up to 20 Mev in energy. In order to obtain a slow neutron bombardment the sample is placed in a thick paraffin block and exposed to neutrons from a beryllium target bombarded with deuterons. For exposure to fast neutrons the sample is wrapped in cadmium and placed directly back of a lithium target bombarded with deuterons. This gives a beam of neutrons ranging beyond 20 Mev in energy.

[1] J. M. Cork and J. L. Lawson, Phys. Rev. **56**, 241 (1939).

13-second activity

This is one of the activities first observed by Amaldi *et al.*[2] in irradiating indium with slow neutrons. It is probably produced by several reactions, but unfortunately the half-life is so short that adequate chemical separation is usually impossible. So far it has not been observed in reactions involving deuterons and protons, since traces of oxygen, etc. cause very short-lived activities. The 13-second activity is obtained more strongly by bombarding indium with slow neutrons than with very energetic neutrons;[3] hence it is assigned to In^{116}. Gaerttner, Turin and Crane[4] have measured the electron spectrum with a cloud chamber, and reported a beta-ray with an upper energy limit of 3.2 Mev. It was originally reported[3,4] that gamma-rays accompanied this beta-radiation. However, Mitchell and Langer[5] did not observe any gamma-radiation of 13 seconds half-life. Absorption measurements in aluminum taken with an electrometer are shown in Fig. 1. Each point on the curve was obtained with an individual sample of indium foil which had been irradiated in paraffin with beryllium neutrons for a bombardment time of 5 seconds. The strong background of the 54-minute activity was subtracted for each absorber thickness. It is apparent that the slight residual radiation able to penetrate more than 0.5 cm of aluminum is only about 0.1 percent of the initial beta-activity, and is probably due to bremstrahlung accompanying the beta-absorption. "Pure" beta-ray emitters such as P^{32} show a similar penetrating radiation when measured with the same apparatus.

54-minute activity

This radioactivity, emitting both beta- and gamma-radiation, has been produced by several means: In (n,γ), In (d,p)[3] and Cd (p,n).[6] The gamma-radiation was first reported by Mitchell and Langer[5] to be monochromatic and of energy 1.4 Mev. Curtis and Richardson[7] in observing Compton and photoelectrons in a cloud chamber reported five gamma-rays of energies 1.8, 1.3, 1.0, 0.4 and 0.2 Mev with intensities 0.3, 1.0, 1.0, 0.3 and 0.1, respectively. In this work it was also reported that more than one gamma-

TABLE I. *Shows the percentages of stable isotopes occurring in indium and its neighboring elements.*

Element	Atomic Weight												
	106	107	108	109	110	111	112	113	114	115	116	117	118
$_{47}Ag$		52.5		47.5									
$_{48}Cd$	1.5		1.0		15.2	15.2	21.8	14.9	23.7		15.9		
$_{49}In$								4.5		95.5			
$_{50}Sn$							1.1		0.8	0.4	15.5	9.1	22.5

TABLE II. *Showing activities observed in indium, their radiations, formation reactions and probable responsible isotope.*

Activity	Radiations	Reactions	Isotope
13-sec.	β^- 3.2 Mev	In (n,γ)	116
54-min.	β^- 0.8 Mev β^- 1.2 Mev γ 0.2 Mev γ 0.4 Mev γ 1.0 Mev γ 1.3 Mev γ 1.8 Mev	In (n,γ) In (d,p) Cd (p,n)	116
50-day	γ 0.192 Mev β^- 1.98 Mev (see 72 sec.)	In (d,p) Cd (d,n) In $(n,2n)$ In (n,γ) Cd (p,n)	114
72-sec.	β^- 1.98 Mev	In $(n,2n)$ In (γ,n) Cd (p,n)	114
65-hr.	K capt. γ 0.173 Mev γ 0.247 Mev	Cd (d,n) Cd (p,n) In $(n,2n)$ Ag $(\alpha,n$	112
117-min.	β^- 1.73 Mev	Cd (d,n) (also grows from Cd^{117} by β^-)	117
105-min.	γ 0.393 Mev	Cd (d,n) (also grows from Sn^{113} by K capt.)	113
4.5-hr.	γ 0.338 Mev	Cd (p,γ) Cd (d,n) (excitation of In by n, γ, p, α) (grows from Cd^{115} by β^-)	115
23-min.	β^+ 1.7 Mev γ 0.16 Mev	Ag $(\alpha,2n)$ Cd (d,n) Cd (p,n)	111
66-min.	β^+ 2.0 Mev	Ag (α,n) Cd (p,n) Cd (d,n)	110

[2] E. Amaldi *et al.*, Proc. Roy. Soc. **149**, 522 (1935).
[3] J. L. Lawson and J. M. Cork, Phys. Rev. **52**, 531 (1937).
[4] E. Gaerttner, J. J. Turin and H. R. Crane, Phys. Rev. **49**, 793 (1936).
[5] A. C. G. Mitchell and L. M. Langer, Phys. Rev. **53**, 505 (1938).
[6] S. W. Barnes, Phys. Rev. **55**, 241 (1939).
[7] B. R. Curtis and J. R. Richardson, Phys. Rev. **53**, 942 (1938).

quantum per beta-particle was emitted. The beta-rays have been measured in the cloud chamber by Gaerttner, Turin and Crane[4] to have an upper energy limit of 1.3 Mev. The magnetic beta-ray spectrometer however showed[1] an end-point of only 0.85 Mev with a probable error of perhaps 0.1 Mev. Langer, Mitchell and McDaniel[8] show an absorption curve in aluminum which indicates a complex spectrum having components of 0.8 and 1.2 Mev. However, these authors point out that the upper energy group may be due to Compton electrons from high energy gamma-radiation. In this work the coincidences between beta- and gamma-rays were investigated, the results indicating about 2 gamma-rays per beta-particle.

The fact that the 54-minute activity is made by deuteron or slow neutron bombardment more strongly than by bombardment with very energetic neutrons is evidence for assigning it to In^{116}. This postulates isomerism of this activity with the 13-second activity. Both periods seem to be produced with the same relative intensities when activation by neutrons of various energies is effected.[5] Both beta-transitions lie on the "allowed" Sargent curve,[9] and hence take place between levels differing by 0 or 1 unit of angular momentum. It is at present rather difficult to propose a probable energy level diagram which includes the levels in Sn^{116} from which the gamma-ray transitions presumably take place.

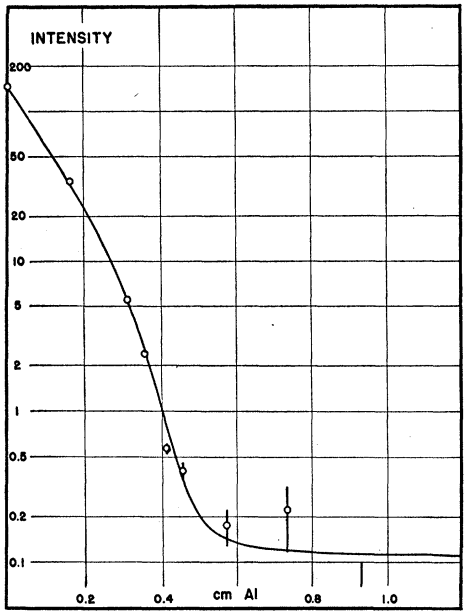

FIG. 1. Absorption in aluminum of the 13-second activity.

50-day activity

This activity has been produced by In (d,p), Cd (d,n), In $(n,2n)$,[3] In (n,γ)[10] and by Cd (p,n)[11] reactions. Since it is produced by slow neutrons it must belong to an isotope of mass 114 or 116. When very energetic neutrons are used it is enhanced by a factor of 1000 with respect to the 13-second activity, presumably due to an $(n,2n)$ reaction. Therefore it can be assigned to In^{114} with reasonable certainty.

Barnes[11] found the spectrum of this activity to consist of K- and L-conversion electrons of nearly equal intensity arising from a gamma-ray of energy 0.19 Mev. Lawson and Cork,[3] however, observed electrons in the cloud chamber up to an energy limit of 2.15 Mev. Both spectra actually exist. To prepare a very strong sample for use in the magnetic beta-ray spectrometer cadmium was bombarded with 10-Mev deuterons for 60 microampere hours in the cyclotron. The active indium was then precipitated on a filter paper as hydroxide using only one mg of indium as carrier. This was mounted in the magnetic spectrometer after one month and the spectrum shown in Fig. 2 obtained. The low energy conversion electrons are so intense that it is impossible to draw them on the same scale as the continuous beta-ray spectrum, but they may be seen on the lowest curve in Fig. 5 and in Fig. 6. The beta-ray spectrum below the conversion electron energy is not drawn because it is distorted by the scattered and absorbed conversion electrons in the source itself. The beta-rays have an inspection upper end point of 1.98 $\pm$0.03 Mev in rough agreement with the previous cloud-chamber measurements. Due to the long life of this activity a rather accurate spectrum was obtainable, although the number at the maximum on the continuous part was only 25 counts per minute above a background of about 4 counts per minute. In order to properly correct for slow fluctuations in the

[8] L. M. Langer, A. C. G. Mitchell and P. W. McDaniel, Phys. Rev. **56**, 380 (1939).
[9] N. Feather and E. Bretscher, Proc. Roy. Soc. **165**, 530 (1938).
[10] A. C. G. Mitchell, Phys. Rev. **53**, 269 (1938).
[11] S. W. Barnes, Phys. Rev. **56**, 414 (1939).

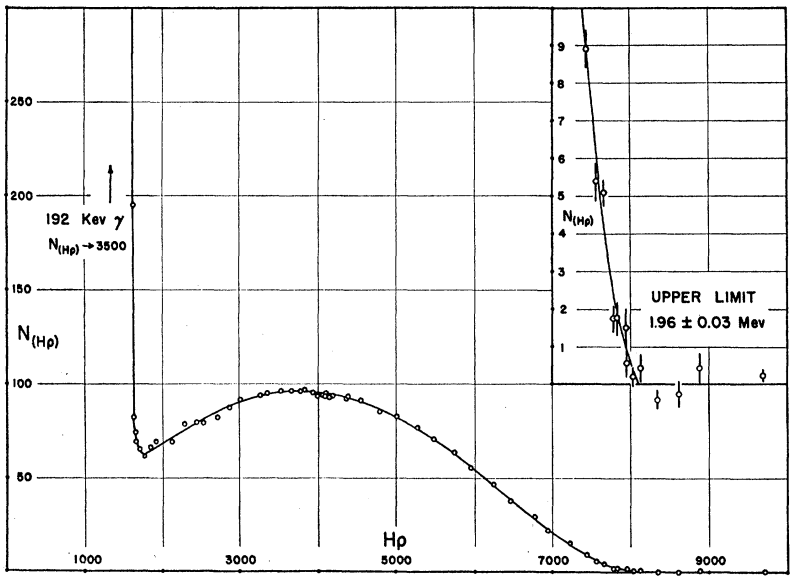

FIG. 2. Electron spectrum of the 50-day activity in indium.

background rate a gate was swung into and out of the electron beam every 30 seconds. At the same time the pulses from the Geiger-Müller counter were switched from one Cenco recorder to another. In this fashion the background readings on one meter were continuously recorded along with the gross count on the other meter. To check the apparatus the source was removed, and over a 12-hour interval the two recorders agreed within statistics. They also agreed when the background was increased by external means to 30 times the normal value. In the course of these experiments the "normal" background of the counter was observed to vary as much as 10 percent.

72-second activity

This activity has been formed by In $(n,2n)$, In (γ,n)[3,12] and by Cd (p,n)[11] reactions. Since it is not observable by In (n,γ) it was originally assigned[3] to In^{112}. However, in this location it should be formed by the reaction Ag (α,n) but King and Henderson[13] did not find such a radioactivity. Their results have been substantiated by experiments in this laboratory in which silver was bombarded by a 0.2-microampere beam of alpha-particles of energy 20 Mev. Therefore it is necessary to assign this activity to In^{114} as isomeric with the 50-day activity. To test this possibility the energy of the beta-particles was compared to that of the beta-radiation in the 50-day activity. Because of the short life of the 72-second activity it was necessary to make this comparison by absorption methods. Fig. 3 shows the absorption in aluminum of both activities, the solid points indicating the 50-day period and the open points(with vertical lines indicating the estimated errors) the 72-second period. It can be seen that after the initial absorption of the soft conversion electrons from the 50-day period the absorption of the beta-rays emitted from each activity is identical. One may now postulate an energy level diagram as shown in Fig. 4 for isotopes of mass 114. In this diagram it is obvious that the half-life of the gamma-ray transition must actually be 50 days, hence, must occur between levels differing by several units of angular momentum. This is necessary because it is the only way that the theoretical lifetime of the transition may be made long enough[14] unless the transition is one having a $0-0$ spin change between states of different parity. Sachs[15] has worked out some of the expected conditions for such transitions, and concludes that the electrons which are converted will not be monochromatic, but will be distributed over a large range in

[12] W. Bothe and W. Gentner, Naturwiss. **25**, 284 (1937).
[13] L. D. P. King and W. J. Henderson, Phys. Rev. **57**, 71 (1940).
[14] M. H. Hebb and G. E. Uhlenbeck, Physica **5**, 605 (1938).
[15] R. G. Sachs, Phys. Rev. **57**, 194 (1940).

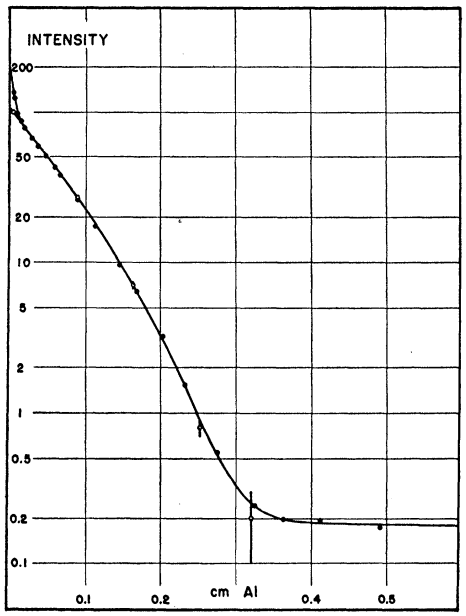

FIG. 3. Absorption in aluminum of the 50-day activity (solid points) and the 72-second activity (open points).

energy. Also the absolute value of the conversion coefficient is much lower than is expected from the Weizsäcker theory for equivalent lifetimes. Because the conversion electron lines are quite sharp (see Fig. 6), and the conversion coefficient is quite large (see below) it can be concluded that the two indium states between which the gamma-ray transition takes place differ by several units of angular momentum.

The conversion coefficient for the gamma-ray can be obtained by counting the number of conversion electrons produced, and comparing this result with the number of electrons emitted in the subsequent beta-transition which is in equilibrium with the gamma-radiation. Two methods are possible: One involves the extrapolation of the absorption curve of the 50-day beta-rays to zero absorber thickness (see Fig. 3) to obtain a value which represents the number of beta-rays emitted. This number can be compared to the total number of beta-rays and conversion electrons represented by the extrapolation to zero thickness of the total intensity curve. The result obtained in this fashion is subject to extrapolation errors, and yields a value for the conversion coefficient of 100 ± 30 percent. This represents the total conversion coefficient $(\alpha_K+\alpha_L+\cdots)$. The other more accurate method of evaluating the conversion coefficients is to integrate the beta-ray spectrum obtained on the magnetic spectrometer (Fig. 2) to obtain the number of beta-particles emitted, and compare this result with the integrated number of conversion electrons also obtained on the spectrometer. In this manner the total conversion coefficient of the 50-day half-life gamma-ray is found to be 105 ± 15 percent. This result

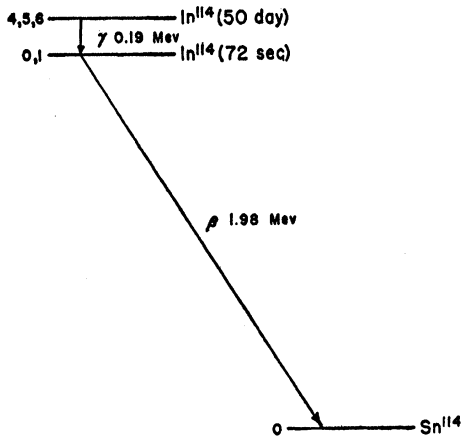

FIG. 4. Energy level scheme in In^{114}.

is in agreement with the observation that very little external gamma-radiation is present (see Fig. 3).

Hebb and Nelson have calculated[16] the conversion coefficients for the K and L shells for the nonrelativistic case. In this calculation the results show that the ratio of the K- to L-conversion coefficients, α_K/α_L, is quite sensitive to the order of multipole radiation. This is of value because this ratio can be found experimentally, whereas the actual conversion coefficients themselves are very difficult to obtain. These calculations are probably good only in the very low energy regions but may be used at least to estimate the spin changes which take place. The experimental ratio α_K/α_L is 1.0 ± 0.1 (see Table III). Hebb's calculations predict α_K/α_L to be 2.3 for spin changes of 3 units, and 1.4 for spin changes of 4 units. Therefore it is likely that for this gamma-ray transition a spin change of 4 or

[16] The authors are indebted to Mr. M. H. Hebb and Mr. E. Nelson for the availability of these calculations before their final publication.

5 units occurs, which also is necessary to explain its long lifetime.

Since the 72-second beta-transition of energy 1.98 Mev lies on the "allowed" Sargent curve and therefore represents an angular momentum change of 0 or 1 unit, one may assign probable spin values to the various levels. These are shown in small figures at the left of the levels in Fig. 4. Since In^{113} probably has a spin of $\frac{9}{2}$ it is easy to see that in contrast to the production of the 50-day level, the formation of the 72-second level might require energetic neutrons to effect the necessary momentum change, which is in line with experimental findings.

65-hour activity

This activity was first discovered on the magnetic beta-ray spectrometer[1] and was found to consist of two internally converted gamma-rays. These gamma-rays have been more carefully investigated, and some of the results are shown in Fig. 5. In order to obtain the intensities of the various electron groups the observed counting rate (through the spectrometer) is divided by H to obtain $N_{(H\rho)}$, due to the manner in which the momentum is selected in the magnetic semi-circular focusing spectrometer.[17] This is then integrated over $H\rho$ and the area obtained is proportional to the total number of electrons. But this integration over an electron group is proportional to $\Delta(H\rho)N_{(H\rho)}$ where $\Delta(H\rho)$ is the spread of selected momenta. But $\Delta(H\rho)$ is proportional to H;[17] therefore the intensity is proportional to $H\cdot N_{(H\rho)}$. In Fig. 5 therefore the ordinates represented are proportional to $H\cdot N_{(H\rho)}$ and the heights of the peaks thus represent the intensities of the various electron groups. The three curves shown were taken at intervals of about one week, and demonstrate the relatively rapid decay of certain of the peaks, finally leaving peaks for the K- and L-conversion electrons of the 50-day gamma-ray which has already been discussed. The ordinates of the two lower curves have been shifted in order to separate the drawings. The half-life of the decay of this activity agrees within allowable error with the value previously given as 65 hours.[1]

In order to separate the conversion lines more completely and thus more surely identify the parent isotope, the resolution of the spectrometer

[17] J. L. Lawson and A. W. Tyler, Rev. Sci. Inst. **11**, 6 (1940).

TABLE III. *Shows experimental ratios of conversion coefficients for 5 gamma-rays in indium. The element in which the transition takes place is found from the difference in energy between the K- and L-conversion electrons observed in source A. The half-lives have been determined in the spectrometer and are therefore relatively free from other disturbing radioactivities which may be present. Source A—1 mm wide, 0.02 mg evaporated on 0.005-inch glass; Source B—1 mm wide, 0.1 mg filtered on 0.007-inch paper; Source C—3 mm wide, 0.2 mg filtered on 0.007-inch paper.*

SOURCE *A*	SOURCE *B*	SOURCE *C*	ELEMENT	γ-RAY ENERGY (KEV)	HALF-LIFE
$\frac{\alpha_K}{\alpha_L}=5.4\pm0.8$		$\frac{\alpha_K}{\alpha_L+\alpha_M}=4.0\pm0.4$	In	392.7 ± 1	104 ± 2 min.
$\frac{\alpha_K}{\alpha_L}=4.8\pm0.6$ $\frac{\alpha_K}{\alpha_M}=23\pm10$	$\frac{\alpha_K}{\alpha_L}=5.3\pm0.8$	$\frac{\alpha_K}{\alpha_L+\alpha_M}=4.0\pm0.5$	In	337.7 ± 1	272 ± 2 min.
$\frac{\alpha_K}{\alpha_L}=5.9\pm0.5$ $\frac{\alpha_K}{\alpha_M}=30\pm10$	$\frac{\alpha_K}{\alpha_L}=5.3\pm0.6$	$\frac{\alpha_K}{\alpha_L+\alpha_M}=5.0\pm1.0$	Cd	246.7 ± 1	
$\frac{\alpha_K}{\alpha_L}=1.0\pm0.1$ $\frac{\alpha_K}{\alpha_M}=4.6\pm0.8$		$\frac{\alpha_K}{\alpha_L+\alpha_M}=0.9\pm0.1$	In	191.7 ± 1	50 ± 4 day
$\frac{\alpha_K}{\alpha_L}=6.6\pm0.6$ $\frac{\alpha_K}{\alpha_M}=35\pm10$			Cd	172.8 ± 1	

was increased by a factor of about three. Fig. 6 shows the results obtained with a very thin sample mounted on glass 0.005 inch thick, for the same momentum region as that indicated in Fig. 5. It can be seen that many peaks are now resolved which are readily ascribable to the various conversion lines from three gamma-rays. The energies of the gamma-rays are: 191.7±1 kev (50-day), 172.8±1 kev (65-hour) and 246.7 ±1 kev (65-hour). The K-, L- and M-conversion lines from the 192-kev gamma-ray are labeled K_{192}, L_{192}, M_{192} and similarly for the other gamma-rays. The resolution is now so good that it is possible with certainty to tell the element in which the gamma-ray transition takes place, since this is revealed by the difference in energy between the K- and L-conversion electron lines. The results indicate that the 50-day gamma-ray occurs in indium, in agreement with the proposed level scheme just presented (Fig. 4). However, it appears that both 65-hour gamma-rays have $K-L-M$ differences characteristic of cadmium, which means that either K-electron capture or positron emission takes place before the observed gamma-rays are emitted. The half-life of 65 hours is then to be associated with the K capture or positron emission process, and not to the observed internally converted gamma-rays. The observed ratios of K- to L-conversion coefficients α_K/α_L (see Table III) indicate according to Hebb's calculations probable spin changes of 1 and 2 units, respectively, for the 173- and 247-kev gamma-rays. It is not yet possible to tell whether transitions from both of the excited levels in cadmium go directly to the ground state, or whether the transitions occur in cascade.

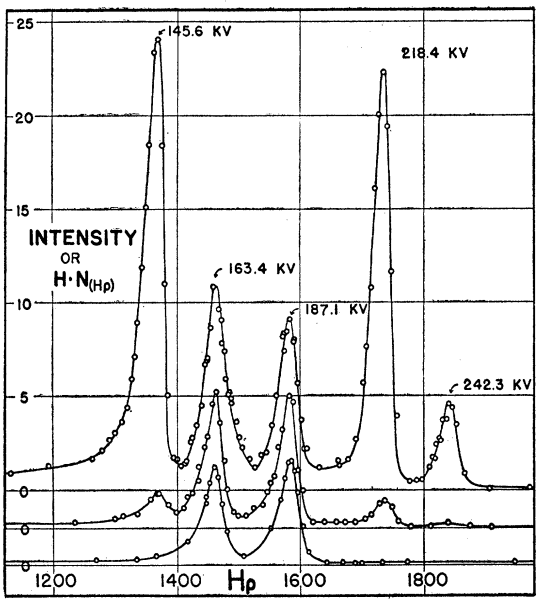

FIG. 5. Conversion electron spectrum of 3 gamma-rays showing the decay of certain electrons with a half-life of 65 hours. The lower curves taken approximately one and two weeks later than the top curve are shifted in ordinates in order to separate the drawings.

Positrons are not found in the magnetic spectrometer. It is possible to assign an upper limit to the probability of their occurrence. For positrons having an upper energy limit of 100 kev to 1.5 Mev this has been found to be not greater than 0.005 times the number of conversion electrons observed. Therefore the ratio of the number of K-capture processes to the number of positron emission processes which occur is at least as high as 200 divided by the average conversion coefficient of the gamma-rays. Since the absolute conversion coefficients are probably small due to the small spin changes which take place, the ratio of K quanta to positrons must be a very large number—perhaps 10^4.

An attempt was made to observe the K radiation of cadmium (which should be present following the K-electron capture in indium) by critical absorption methods. The sample was placed a short distance from a Geiger-Müller counter so that absorbing layers of various materials could be interposed. The electrons emitted by the source were swept out of the counter by a magnetic field, and the absorption of the remaining radiation observed using foils of palladium, rhodium and ruthenium. The Ru foil was made by cementing together a very thin layer of Ru powder with collodion. The experimental absorption coefficients of the soft radiation for the three foils were 12, 11.5 and 50 g^{-1} The theoretical values for indium K radiation are 11.0, 67 and 63 g^{-1} and for cadmium K radiation are 13.0, 11.3 and 72 g^{-1}, respectively. The experimental findings therefore indicate the existence of cadmium K radiation. The low experimental value for the absorption in the ruthenium foil can be accounted for by the uneven quality of the foil itself. It should be pointed out that the presence of cadmium K radiation is not in itself definite proof of K

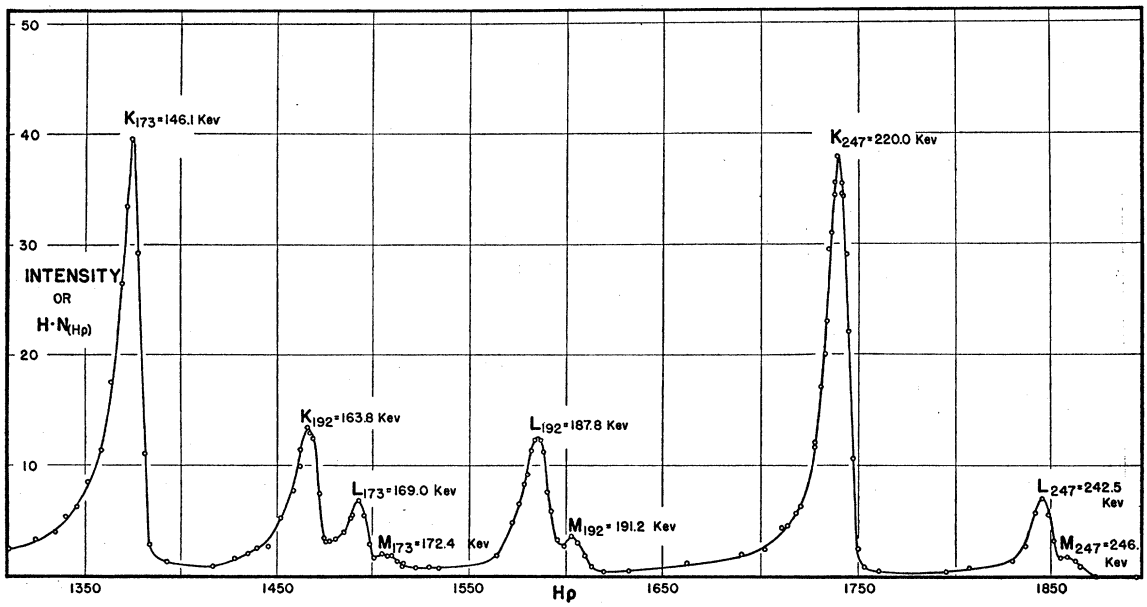

FIG. 6. Conversion electron spectrum over the same region as that in Fig. 5, but with increased resolution showing K-, L- and M-conversion electrons of 3 gamma-rays of energies 173 kev, 192 kev and 247 kev, respectively.

capture, because the conversion of the two gamma-rays following the supposed K capture takes place in a cadmium atom. Cadmium K radiation would result from the filling of the empty K-conversion shells. However the high intensity of the observed K radiation, together with the absence of positrons suggests the probability of the K-capture process.

The 65-hour activity can be produced by In $(n,2n)$, Cd (d,n),[1] Cd (p,n) [11] and Ag (α,n) reactions. The existence of the last reaction was established by bombardment of a silver sample with 20-Mev alpha-particles for an exposure of 2-microampere hours in the cyclotron. The In $(n,2n)$ and Ag (α,n) reactions make the assignment of this activity to In^{112} most reasonable.

117-minute activity

This beta-ray emitter was one of two indium activities observed to grow from radioactive cadmium. If the parent cadmium isotopes are not metastable forms of normally stable atoms then this activity must be assigned to one or the other of the two indium isotopes, 115 or 117. The choice is made by an observation upon the formation of the responsible cadmium parent. It was reported[1] that the 117-minute indium period grew from a cadmium parent of 3.7 hours half-life, which was placed at Cd^{117} due to the intensity of production by neutrons of various energies. The half-life of the parent substance was obtained by a careful analysis of the total decay curve of a cadmium specimen bombarded with deuterons which unfortunately contains other radioactivities. The use of the beta-ray spectrometer now allows a more accurate evaluation of the half-life of this parent cadmium isotope quite independent of any disturbance from the other activities that are always present; namely, the 56-hour half-life beta-emitter and the 4.5-hour indium gamma-ray in equilibrium with it (to be discussed below) and short-lived position emitters. A sample of cadmium strongly activated by a deuteron bombardment was subjected to a chemical separation in order to remove all indium immediately after bombardment. It was then placed in the magnetic beta-ray spectrometer and a decay curve was made of electrons having a momentum of 5800 $H\rho$. This corresponds to an energy of 1.3 Mev which is above the upper energy limit of the 56-hour beta-particles[1] (see Fig. 11). The points in Fig. 7 represent the experimentally observed values. Since the daughter indium is a beta-emitter of energy 1.73 Mev the observed points should

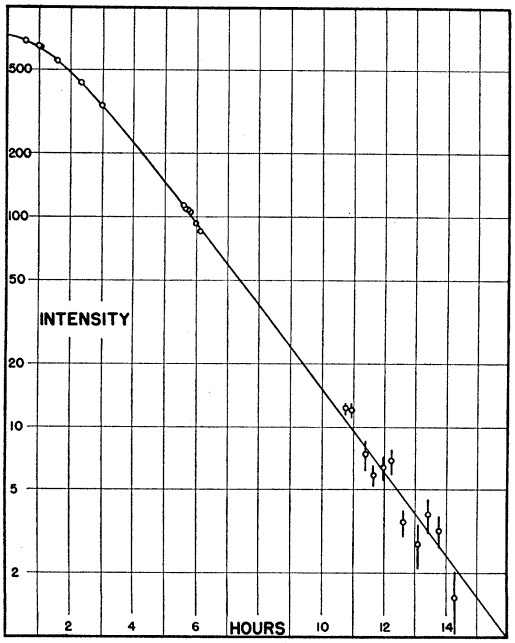

FIG. 7. Decay curve of Cd^{117} electrons and growth of In^{117} electrons of momentum 5800 $H\rho$. Solid line is theoretical for a parent half-life of 170 minutes.

represent both the decay of the parent and the build-up of the daughter in amounts depending upon their relative intensities at 1.3 Mev. The half-life of the daughter is 117±3 minutes (see Fig. 8); therefore it is possible to calculate from the experimental points the half-life of the cadmium parent, and the relative numbers of electrons of parent and daughter emitted in equal $H\rho$ intervals at 5800 Hρ. The full line in Fig. 7 is the theoretical decay of a parent of half-life 170 minutes into a daughter substance of half-life 117 minutes. The intensity ratio of parent to daughter at equilibrium has been adjusted to 0.48 at this energy. The half-life of Cd^{117} is therefore 170±10 minutes, and the energy of its beta-particles is greater than 1.3 Mev. If equal numbers of electrons are emitted by the parent and daughter substances at equilibrium, the upper energy limit of the parent cadmium beta-rays is less than the end-point of the indium beta-rays, i.e., less than 1.7 Mev.

To obtain the half-life of the daughter indium a sample of cadmium was bombarded with deuterons for three hours. The indium was removed and mounted in the spectrometer. Decay curves were taken of electrons of two energies, 435 kev and 402 kev, respectively. These are shown in the inset of Fig. 8 and indicate a half-life of 117±3 minutes.

Originally[1] an internally converted gamma-ray was observed in indium which, because of its rather similar half-life (about 2 hours), was also assigned to In^{117}. However, Barnes[11] found the same gamma-ray in indium recovered from aged radioactive tin, which was assigned rather conclusively to isotopes of mass 113. This gamma-ray was measured in the magnetic spectrometer (Fig. 8) and found to have a half-life of 104±2 minutes (see below). To show that this gamma-ray was definitely not connected with the beta-radiation due to In^{117} a sample of cadmium was activated and the indium removed. After two hours indium was again extracted, and mounted in the spectrometer. With this source the beta-rays of In^{117} were indeed found, but the converted gamma-ray was not observable.

105-minute activity

An indium radioactivity of half-life 105 minutes was extracted from aged radioactive tin by

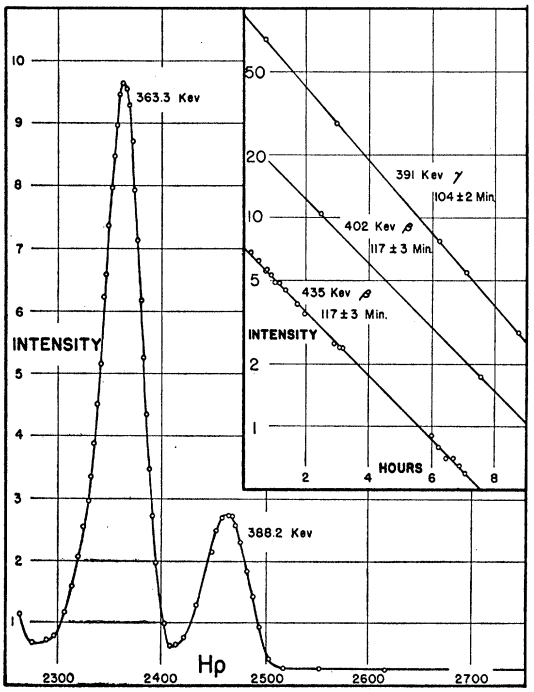

FIG. 8. Conversion electron spectrum of 0.39-Mev gamma-ray. In the inset are shown decay curves taken of the peak of the K-conversion electron line, and of the electrons emitted by In^{117} of nearly the same energy.

Barnes.[11] The tin had been formed by bombarding indium with protons, and could be attributed only to the isotope of mass 113 since all other possible isotopes of tin are stable. The tin was observed to decay to indium only by K capture with a half-life of 100 days. When placed in a photographic spectrometer the sample showed two internally converted gamma-rays of energies 85 kev and 390 kev, respectively. The process was considered to be the following: tin decays to indium by 100-day K capture, the indium decays by the 85-kev gamma-ray of presumably short half-life to metastable In^{113*}, and the 390-kev gamma-ray of half-life 105 minutes is emitted in the transition between In^{113*} and the ground state. The total conversion coefficient for this gamma-ray was found by Barnes to be 70 ± 10 percent.

The 390-kev gamma-ray has been obtained on the magnetic spectrometer in indium extracted from cadmium bombarded with deuterons. The conversion electrons from the gamma-ray are shown in Fig. 8. The decay of the gamma-ray is shown in the top curve of the inset in this figure, and the observed half-life of 104 ± 2 minutes agrees with Barnes' results. An attempt was made to observe the 85-kev gamma-ray with the same source but it was not found. This lends support to the level scheme proposed by Barnes, to which we have attached tentative spin and parity values to the left of the energy levels as shown in Fig. 9. The parity change in the 390-kev gamma-ray transition is required in order to explain its long lifetime. The assignment of spin to Sn^{113} follows from its ease of production by a (p,n) reaction from In^{113}, which has a probable spin of $\frac{9}{2}$.

4.5-hour activity

The 4.5-hour period in indium has been formed by many reactions: Cd (p,γ),[11] Cd (d,n) and by excitation of indium by neutrons,[18] x-rays,[19] protons[20] and alpha-particles.[21] It also grows from cadmium made radioactive by deuterons and neutrons.[1] It has been ascribed[18] to gamma-

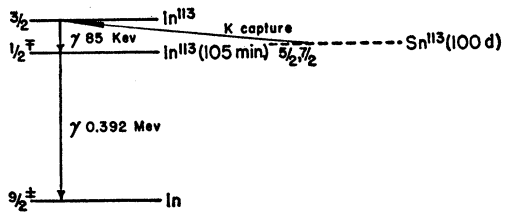

FIG. 9. Energy level scheme in In^{113}.

radiation occurring in the transition from metastable In^{115*} to stable In^{115}. The conversion electrons have been measured on the magnetic spectrometer,[22] and indicated a gamma-ray of energy 336 kev. Recent measurements with the spectrometer set for higher resolution give the energy of the gamma-ray as 337.7 ± 1 kev, and show it to occur definitely in the element indium (see Table III).

It was shown[18,1] that this activity grew from a cadmium parent of half-life 56 hours by beta-emission. In activated cadmium, aged one day to remove Cd^{117} and its daughter product In^{117}, in addition to the 56-hour beta-rays, a gamma-ray of the same lifetime was observed.[1] The energy of this gamma-ray was first determined from cloud-chamber studies of the Compton electrons ejected from a thin carbon radiator. Fig. 10 shows a family of absorption curves in lead of the cadmium gamma-radiation at frequent time intervals after bombardment. It is apparent that after the initial decay of a high energy gamma-ray probably due to some other isotope of cadmium, each curve is resolvable into two components whose absorption coefficients are 3.2 cm^{-1} and 1.5 cm^{-1}, respectively. The lowest curve shows the absorption in lead of the 4.5-hour indium gamma-radiation obtained from a source of indium extracted from the aged cadmium sample. This shows a single gamma-ray absorption coefficient of 3.2 cm^{-1}. The theoretical gamma-ray absorption coefficient for an energy of 338 kev is 3.18 cm^{-1}, which is in good agreement with the experimental result. This proves that the 4.5-hour gamma-ray is not entirely converted, but that considerable external gamma-radiation is present.

The hard component of the cadmium gamma-radiation has an absorption coefficient which is

[18] Goldhaber, Hill and Szilard, Phys. Rev. **55**, 47 (1939).
[19] Collins, Walsman, Stubblefield and Goldhaber, Phys. Rev. **55**, 507 (1939).
[20] S. W. Barnes and P. W. Aradine, Phys. Rev. **55**, 50 (1939).
[21] Lark-Horovitz, Risser and Smith, Phys. Rev. **55**, 878 (1939).
[22] J. L. Lawson, Phys. Rev. **56**, 131 (1939).

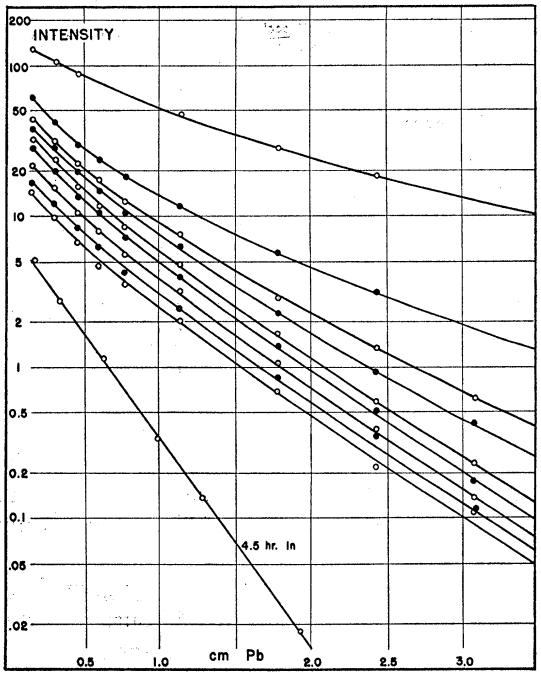

FIG. 10. Shows a family of absorption curves in lead of the activity induced in cadmium by deuteron bombardment taken at various times after bombardment. Lowest curve shows the absorption of the 4.5-hour In^{115} gamma-radiation.

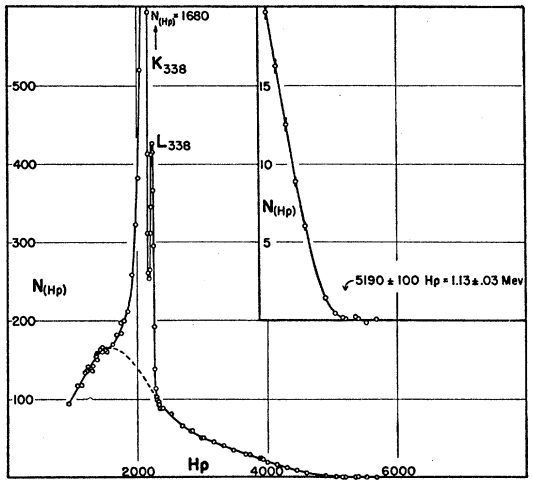

FIG. 11. Electron spectrum of the 56-hour half-life Cd^{115} beta-rays in equilibrium with the 4.5-hour In^{115} converted gamma-ray.

characteristic of an energy of 0.54 Mev. Because this is in contradiction to the previous cloud-chamber measurements,[1] more cloud-chamber pictures were taken. These now show two gamma-rays of energies 0.35 and 0.55 Mev, the lower energy radiation presumably being due to transitions from In^{115*}. The other gamma-ray of about $\frac{1}{3}$ the external intensity is probably short-lived, and in equilibrium with the 56-hour beta-rays. The original cloud-chamber measurements undoubtedly contained another short-lived high energy gamma-ray whose existence is shown in the beginning curves of Fig. 10.

In order to evaluate the conversion coefficient of the 4.5-hour gamma-ray, the beta-ray spectrum of the 56-hour parent cadmium was investigated. A thin cadmium foil was bombarded with 10-Mev deuterons for 50-microampere hours. After removing the indium completely and allowing the sample to age 48 hours to remove Cd^{117} and In^{117} the spectrum shown in Fig. 11 was obtained. The weight of cadmium present was about 2 mg. The very intense conversion electron line due to In^{115*} can easily be seen. Due to scattering within the source the beta-ray spectrum below this energy is somewhat distorted. However, it is still possible to make a rather good estimate of the number of conversion electrons and the number of beta-particles present. The ratio of these numbers presumably yields $\alpha/(1-\alpha)$ for the 4.5-hour gamma-ray. The value of the total conversion coefficient α obtained in this manner is 49 ± 10 percent. The upper energy limit for the 56-hour beta-particles is 1.13 ± 0.03 Mev, which is in agreement with the value originally given.[1] One may now postulate an energy level diagram as shown in Fig. 12. It is not possible to tell with certainty from the beta-ray spectrum (Fig. 11) whether the beta-rays are complex, but because the intensity of the 0.54-Mev gamma-ray is only $\frac{1}{6}$ of the intensity of the 0.338 Mev gamma-ray, the scheme shown in Fig. 12 is necessary. As a matter of fact the shape of the distribution in Fig. 11 actually does suggest a double beta-ray spectrum of upper limits about 0.6 and 1.13 Mev, respectively. One may assign probable spin values and parity to the states, and these are shown in small figures to the left of the levels. The spin of In^{115} in the ground state is known to be $\frac{9}{2}$. The long lifetime of In^{115*} makes necessary a spin assignment of $\frac{1}{2}$ and parity opposite to that of the ground state. Collins and

Waldman[23] in examining the formation of In^{115*} by excitation of indium with x-rays of different energies report a level in In^{115} at about 1.2 Mev above ground which must have a probable spin of $\frac{7}{2}$. It is likely therefore that the 0.54-Mev gamma-ray level has a spin of $\frac{3}{2}$ or possibly $\frac{5}{2}$. Both beta-rays from Cd^{115} as shown are forbidden. The level in cadmium probably has a spin of $\frac{1}{2}$ as it is easily formed by slow neutrons from Cd^{114} which probably has a spin of 0.

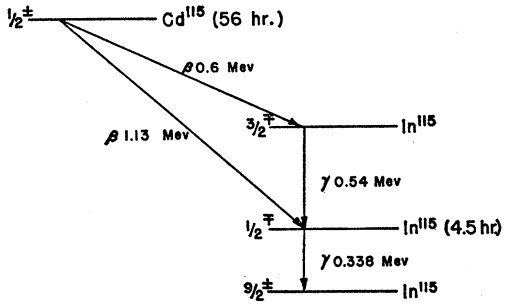

Fig. 12. Energy level scheme in In^{115}.

Therefore both beta-rays probably take place between states of opposite parity, if the spin values shown are correct.*

23-minute activity

A positron emitter in indium formed by bombarding cadmium with deuterons was reported[1] whose half-life was determined from an analysis of the total indium activity. In order to separate this activity from all negative electron emitters a sample of activated indium was mounted in the spectrometer and the decay of the positrons of momentum 4750 $H\rho$ measured. The results are shown in Fig. 13 in curves A and B for two samples of indium, obtained using deuterons of energies 9.6 and 8.8 Mev, respectively, on cadmium. Both decay curves are resolvable into two half-lives of durations 23.0 ± 1.0 minutes and 66 minutes. The 23-minute activity also emits an internally converted 160-kev gamma-ray.[11] The spectrum of the positrons was investigated on the magnetic spectrometer but the determination of the end-point was impossible due to the presence of the 66-minute positron activity. However it is of the order of magnitude of 1.7 Mev.

This activity has been formed by Ag $(\alpha,2n)$ [13] (also confirmed with 20-Mev alpha-particles in this laboratory), by Cd (d,n) [1] and by Cd (p,n) [11] reactions. These place it at In^{111}.

66-minute activity

Barnes[11] first observed this activity, which emits positrons with a half-life of 66 minutes. The upper limit of the positron energy was set at 1.6 ± 0.3 Mev. This isotope has since been formed by Ag (α,n)[13] (also confirmed by alpha-particle bombardment of silver in this laboratory) and now by Cd $(d,2n)$ reactions (see Fig. 12). The $(d,2n)$ reaction is evidently very critical with respect to the bombarding energy, for a reduction of the deuteron energy from 9.6 to 8.8 Mev reduced the intensity of the 66-minute activity by a factor of 10 with respect to the 23-minute activity. This is rather conclusive evidence that the 66-minute period is due to In^{110}. It was

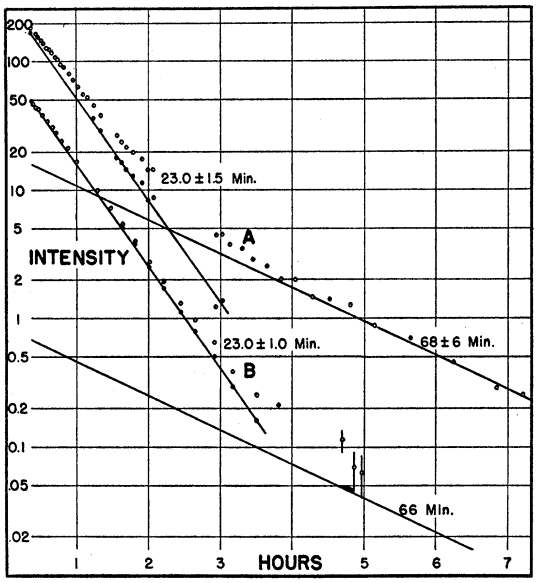

FIG. 13. Spectrometer decay curves of the indium positron activity of momentum 4750 $H\rho$ bombarding cadmium with deuterons. Curve A is for a bombarding energy of 9.6 Mev and curve B is for a bombarding energy of 8.8 Mev.

[23] G. B. Collins and B. Waldman, private communication.

* *Note added in proof.*—Present theory would predict a short half-life for the 0.54-Mev gamma-ray with spin and parity changes as shown in the scheme of Fig. 12 and hence coincidences between the 0.6 Mev-beta-particle and the following short-lived gamma-radiation. Professors A. C. G. Mitchell and L. M. Langer, of the University of Indiana, kindly examined the radioactive cadmium for these coincidences, with negative results for gamma-radiation of half-life shorter than 10^{-4} sec., thus indicating a need for revision of the level diagram of Fig. 12 or of the theory regarding the half-life of gamma-ray emission.

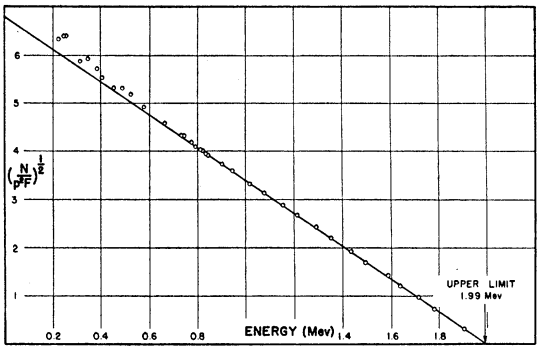

FIG. 14. Kurie plot for the electrons emitted in the 50-day indium activity. These are also the electrons emitted in the 72-second activity.

possible to estimate the upper energy limit of the emitted positrons in the magnetic spectrometer. This yielded a value of 2.0 ± 0.1 Mev in rough agreement with the cloud-chamber determination.

COMPARISON OF EXPERIMENTAL BETA-RAY SPECTRA WITH THEORY

Most experimental work on the shape of beta-ray spectra has been compared to the theory of Fermi[24] and the modification of this theory proposed by Konopinski and Uhlenbeck.[25] The usual comparison has been made by means of a Kurie plot[26] in which the validity of the Fermi prediction is tested by the grouping of the experimental points into a straight line when $(N/p^2F)^{\frac{1}{2}}$ is plotted against the energy W of the emitted beta-particle. N is the number of electrons of momentum p and energy W observed in equal momentum intervals. F is a function given explicitly by Fermi and approximated for light elements by Kurie.[26]

However in all of the cases so far accurately presented, experimental beta-ray spectra for "forbidden" transitions have been compared to theories which had been developed for "allowed" transitions. The theory for forbidden transitions is not yet published. It is difficult to measure beta-ray spectra of the allowed type because the energy of such beta-rays is either low (and hence instrumental corrections are large) or the lifetime of the transition is so short that it is not possible to secure accurate measurements. However, it is now possible to measure the beta-ray spectrum of an allowed transition of high energy, and still secure a long period in which to make measurements. This is possible because of the characteristics of In^{114}, for the beta-rays observed in the 50-day period and mapped in Fig. 2 are really the allowed beta-rays of the 72-second activity. The apparent half-life of 50 days is due to the equilibrium existing between these beta-particles and the 50-day gamma-ray. Therefore the data shown in Fig. 2 down to the energy of the gamma-ray was substituted in a Kurie plot (Fig. 14). The approximation for the Fermi function given by Kurie *et al.* is not valid for indium, so the original function was used. (This makes a difference of about 15 percent between the low and high regions of the spectrum.) The disagreement between the experiment and theory is now not great enough to be real, and one can say that the predictions of the Fermi theory regarding the shape of allowed beta-ray spectra is substantiated by In^{114}. Further accuracy is now being attempted.

ACKNOWLEDGMENTS

The chemical separations required in this investigation were carried out by Mr. W. H. Sullivan. Mr. R. J. Bessey has performed certain of the numerical calculations in connection with the Fermi theory of beta-decay. It is a pleasure to acknowledge the helpful suggestions received in discussions with Professor G. E. Uhlenbeck. This work was made possible by the financial aid of the Horace H. Rackham Fund.

[24] E. Fermi, Zeits. f. Physik **88**, 161 (1934).
[25] E. J. Konopinski and G. E. Uhlenbeck, Phys. Rev. **48**, (1935).
[26] F. N. D. Kurie, J. R. Richardson and H. C. Paxton, Phys. Rev. **49**, 368 (1936).