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Induced Radioactivity in Cadmium and Indium

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The artificial activation of cadmium and indium now yields at least three radioactive isotopes of cadmium and eight radioactive isotopes of indium. The probable masses of several of these isotopes have been determined. In cadmium bombarded with deuterons two chain reactions are observed in which the active cadmium decays to radioactive indium. These are Cd (56 hour) to In (4.5 hour), and Cd (3.75 hour) to In (2.1 hour). Evidence is presented for believing that a new 65-hour gamma-radiation is due to an excited state of a normally stable indium isotope of mass 113. The energies and decay constants of many of the radiations have been accurately measured by means of a magnetic spectrometer of high resolving power.

INTRODUCTION

MANY investigations have now been carried out on the artificial activation of cadmium and indium. As shown in Table I there are eight known stable cadmium isotopes and two known stable isotopes of indium. The early experiments of Fermi[1] showed the production of certain activities by the radiative capture of neutrons. By bombarding these elements with deuterons,[2] fast neutrons,[3] gamma-rays,[4] protons[5] and alpha-particles, many other radioactive products have been observed. It is usually possible to assign each radioactivity to a particular isotope by studying its mode of production and the nature of its radiation.

[1] Amaldi, D'Agostino, Fermi, Pontecorvo, Rasetti and Segrè, Proc. Roy. Soc. **149**, 522 (1935).
[2] J. M. Cork and R. L. Thornton, Phys. Rev. **51**, 608 (1937); J. L. Lawson and J. M. Cork, Phys. Rev. **52**, 531 (1937).
[3] Pool, Cork and Thornton, Phys. Rev. **51**, 890 (1937); F. A. Heyn, Physica **4**, 160 (1937); Goldhaber, Szilard and Hill, Phys. Rev. **55**, 47 (1939).
[4] W. Bothe and W. Gentner, Naturwiss. **25**, 284 (1937); Chang, Goldhaber and Sagane, Nature **139**, 962 (1937).
[5] S. W. Barnes and P. W. Aradine, Phys. Rev. **55**, 50 (1939).

CADMIUM

In an earlier experiment by Cork and Thornton,[2] cadmium bombarded with deuterons was found to yield a cadmium radioactivity of peculiar behavior. The chemically separated cadmium was found to increase in activity for a short time before beginning to decay. This suggested the building up of a second radioactive material by a chain reaction. Subsequent chemical separations of indium from the cadmium showed such a daughter activity with a half-life reported as 2.3 hours building up from a radioactive cadmium parent of 58 hours half-life. Goldhaber[3] showed that if the subsequent indium separations were taken from the cadmium fifty or more hours after bombardment, the indium activity decayed with a half-life of not 2+ hours but 4+ hours. This latter is now a well-known period in indium attributed[6] to an excited state of In^{115*}. A further analysis of the chemically separated cadmium activity is shown in Fig. 1. The small circles along curve A are the experi-

[6] M. Goldhaber, Nature **142**, 521 (1938).

TABLE I. *Isotopes of cadmium and indium. Percentages of stable isotopes indicated by vertical figures and half-lives of radioactive isotopes by italic figures. Unassigned activities:* Cd (*3 minute*)? Cd (*40 day*).

AT. WT.	106	107	108	109	110	111	112	113	114	115	116	117	118
$_{47}$Ag		52.5	*2 min.*	47.5	*20 sec.*	*7.5 day*							
$_{48}$Cd	1.5		1.0		15.2	15.2	21.8	14.9	23.7	*56 hr.*	15.9	*3.75 hr.*	
$_{49}$In						*20 min.*	*72 sec.*	*65 hr.* 4.5	*56 day*	*4.5 hr.* 95.5	*13 sec.* *54 min.*	*2.1 hr.*	
$_{50}$Sn							1.1		0.8	0.4	15.5	9.1	22.5

mental points of the composite decay of the cadmium precipitate. If indium separations are made from the cadmium during the first few hours an activity of 2.1 hours half-life is predominant. After 20 hours such separations yield almost no 2.1-hour activity but a fairly pure activity of 4.5 hours half-life. This suggests a double chain reaction in which two active indium isotopes are built up from two active isotopes of cadmium.

The cadmium activity after many days shows a half-life of 40 days. If this 40-day period is subtracted from the composite activity an end-period of 56 hours half-life is observed. Now if it is assumed that this 56-hour cadmium is a parent activity in equilibrium with a 4.5-hour daughter indium, the activity of the former can be evaluated as shown in curve *B*, Fig. 1. The computed build-up of the 4.5-hour activity is shown in curve *C*, Fig. 1. These are both calculated on the assumption that the electrometer is equally sensitive to the radiations from both activities. If curves *B* and *C* are now subtracted, there is left the parent cadmium and daughter indium for the second chain reaction together with any other short period cadmium activity. Since the half-life of the daughter indium is known to be 2.1 hours it is possible by trial to find the half-life of the parent cadmium. The best value has been observed to be 3.75 ± 0.2 hours. Curves *D* and *E* of Fig. 1 show these components. If these resolved curves *B*, *C*, *D* and *E* are added to form curve *A*, a remarkably good agreement is obtained with the observed experimental points except at the very beginning. There is probably an additional cadmium activity of less than three minutes half-life. Since the chemical separation requires a minimum time of about 15 minutes this activity is very difficult to observe.

INDIUM

There are two stable isotopes of indium, their relative abundance being 4.5 percent and 95.5 percent for isotopes of mass 113 and 115, respectively. By various types of bombardment at least eight radioactive isotopes of indium have now been produced. There seems little question regarding the correctness of the assignment of certain of these activities to particular indium isotopes as previously reported.[2, 3] These are as follows: 20-minute positron to In^{111}, 72-second to In^{112}, 13-second and 54-minute to In^{116}, 50-day to In^{114} and 4.5-hour to In^{115*}. Recently the 4.5-hour activity has been studied in a magnetic spectrometer of high resolution.[7] Two monochromatic groups of electrons were observed. Since the experimental difference in energy of these groups corresponds to the difference between the *K* and *L* shell atomic binding energies in indium they were believed to be the internal conversion electrons ejected from the indium atoms by the passage of nuclear gamma-rays through the outer electrons. The energy of this gamma-radiation has thus been found to be very precisely 0.336 ± 0.001 Mev. This indium activity apparently is composed only of this internally converted gamma-ray, as no background of electrons having a continuous spectrum could be detected. The intensity of the sample was sufficiently strong that it is possible to assume at least twenty times as many gamma-ray transitions as beta-ray transitions from the 4.5-hour level. However there also appears to be an indium activity of several days half-life accompanying the 4.5-hour period. Apparently this activity is either built up from the decay of cadmium as a third chain reaction or from the

[7] J. L. Lawson, Phys. Rev. 56, 131 (1939).

4.5-hour gamma-ray decay of the activated indium. The nature of its radiation has not yet been determined and it is impossible to assign it to a particular isotope.

The first indium precipitate from cadmium bombarded with deuterons shows an activity of 65 hours half-life. This was first revealed on the beta-ray spectrometer, since this activity seems to consist almost entirely of electrons due to internally converted gamma-rays. The spectral distribution is shown in Fig. 2. Perhaps not much faith can be placed in the smaller peaks, but the large ones have been substantiated by other sources. They indicate K and L electrons from converted gamma-rays of energies 0.170 and 0.245 Mev. The energy differences between these K and L electrons for the two gamma-rays are 24.0 and 23.4 kev, which agree well with values predicted from x-ray data for indium (23.6 kev). The general background of electrons having a continuous distribution is little more than would be expected from the 50-day activity which is always present. The 65-hour activity is also produced weakly in indium which is exposed to neutrons from lithium bombarded with deuterons. Because there seems to be no beta-radiation connected with the gamma-ray emission, and because the gamma-ray emission probably takes place in indium itself as revealed by the K and L conversion electron energy difference, it seems reasonable to assign the 65-hour activity to an excited state of a normally stable indium isotope, either In^{113*} or In^{115*}. S. W. Barnes[8] reports the production of this activity by a proton-neutron reaction, which would thus rule out the possibility of In^{115*}. The multiplicity of the gamma-rays may be due to various possible transitions from the excited state to the normal state.

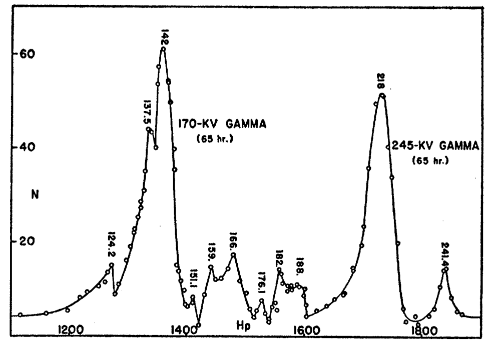

FIG. 2. Long period indium spectrum.

A collection of the observed radioactivities produced in indium and cadmium is shown in Table II. The type of radiation, energy, method of observation and the mass of the most probable isotope responsible for the radiation has been included. In several cases the latter cannot be uniquely determined. Since in the first Cd-In-Sn

[8] S. W. Barnes, private communication.

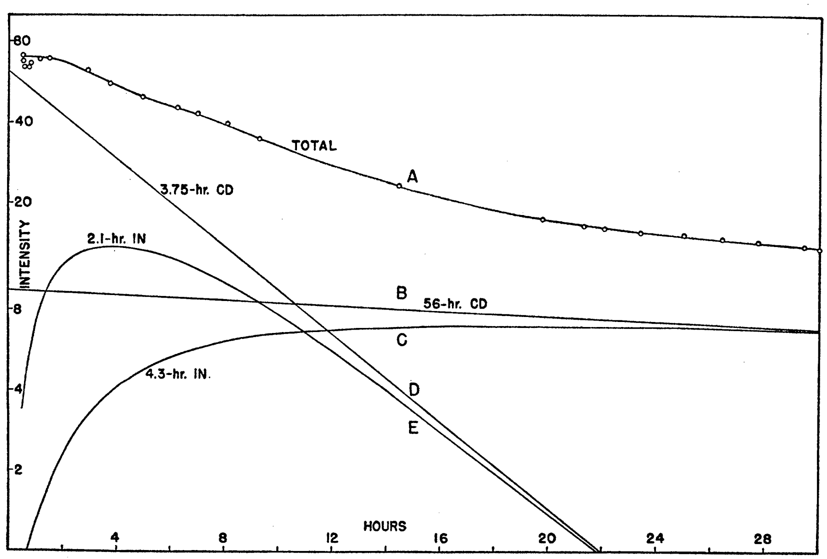

FIG. 1. Resolution of cadmium decay showing growth of two indium activities.

TABLE II. *Radioactive periods in cadmium and indium.*

Element	Activity	Emission	Energy Mv	Probable Isotope	Method
	3 min.(?)				
	3.75 hr.	Electron		117	
$_{48}$Cd	56 hr.	Electron Gamma	1.11 0.8	115	Mag. Spect. Cl. Cham.
	40 day	Electron Gamma	0.95		Cl. Cham.
	13 sec.	Electron Gamma	2.8	116	Cl. Cham.
	72 sec.	Electron		112	
	20 min.	Positron	2.15	111	Cl. Cham.
	54 min.	Electron Gamma	0.85 1.0, 1.3, 1.8	116	Mag. Spect. Cl. Cham.
$_{49}$In	2.1 hr.	Electron Gamma	1.73 0.388	117	Mag. Spect. Mag. Spect.
	4.5 hr.	Gamma	0.336	115	Mag. Spect.
	65 hr.	Gamma	0.170 0.245	113	Mag. Spect. Mag. Spect.
	56 day	Electron	1.75	114	Cl. Cham.

chain reaction the indium is associated with In^{115}, the 56-hour cadmium activity must be due to Cd^{115}. It would seem reasonable then to place the second chain reaction as due to isobars of mass 117, for there are no stable isotopes of either cadmium or indium having this mass. However, S. W. Barnes[8] has recovered from a radioactive tin of 100-day half-life, attributed to Sn^{113}, an active indium of 110-minute half-life. In this activity he observes the same gamma-ray as measured on our beta-ray spectrometer. Unless there are two activities in indium of half-lives nearly two hours, the parent cadmium in the second chain reaction of 3.75-hour half-life must be due to Cd^{113*}, that is, an excited state of normal stable cadmium of mass 113. Further tests on samples produced in other ways can answer this. The long period cadmium activity of

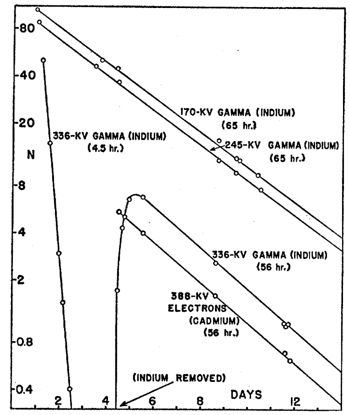

FIG. 3. Spectrometer decay curves.

40-day half-life emits negative electrons and hence might reasonably be due to an isomer of either 115 or 117.

The beta-ray spectrometer is a valuable instrument in determining half-life periods as well as energies of radiations. In Fig. 3 are shown certain decay curves taken with the spectrometer. The half-life of the 0.336-Mev gamma-radiation is shown to be 4.5 hours. The growth and subsequent decay of this same gamma-ray in equilibrium with the 56-hour cadmium activity definitely proves this chain reaction. The half-life for the decay of the two gamma-rays previously mentioned is also shown to be 65 hours. Because of the resolution of the spectrometer it has been possible to separate and study this activity whereas it is nearly impossible to make a good analysis by means of only an ionization chamber.

The chemical separations in this investigation have been performed by Mr. W. H. Sullivan. The work has been made possible by a grant from the Horace H. Rackham fund.