The Radioactive Isotopes of Indium

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Although there are but two stable isotopes of indium whose mass numbers are 113 and 115, seven radioactive periods are shown to exist. Six of these whose half-life periods are 13 seconds, 72 seconds, 54 minutes, 2.3 hours, 4.1 hours and 50 days emit negative electrons, and one period of 20 minutes is radiopositive. By bombarding indium with slow neutrons, deuterons and very fast neutrons, and by bombarding cadmium with deuterons it is possible to assign with considerable confidence each period to a certain indium isotope. The conclusions are that the 54 minute and 13 second activities are both due to In^{116}, the 4.1-hour and 50-day periods are both In^{114} and the 20-minute, 72-second and 2.3-hour periods are from isotopes of mass 111, 112, and 117, respectively. Beta-ray energy limits are approximately 2.15 Mev for the 50-day period and 1.75 Mev for the 20-minute positive period.

THERE are at present two known stable isotopes of indium, their relative abundance being 4.5 percent and 95.5 percent for mass numbers 113 and 115, respectively. Fermi[1] and his co-workers have exposed indium to slow neutrons and have observed radioactive half-life periods of 13 seconds and 54 minutes with a very weak activity of a few hours. When slow neutrons produce a radioactive isotope of the bombarded element, the process is considered to be simply the capture of the neutron. Thus one should expect only two radioactive isotopes of indium, 114 and 116, to be formed by this process. The correct assignment of the observed activities to definite isotopes cannot be made from this type of bombardment alone.

The discovery[2, 3] that very energetic neutrons such as those emitted by lithium bombarded by

[1] Amaldi, D'Agostino, Fermi, Pontecorvo, Rasetti and Segrè, Proc. Roy. Soc. **149**, 522 (1935).

[2] Heyn, Physica, **4** 160 (1937).
[3] Pool, Cork and Thornton, Phys. Rev. **51**, 890 (1937).

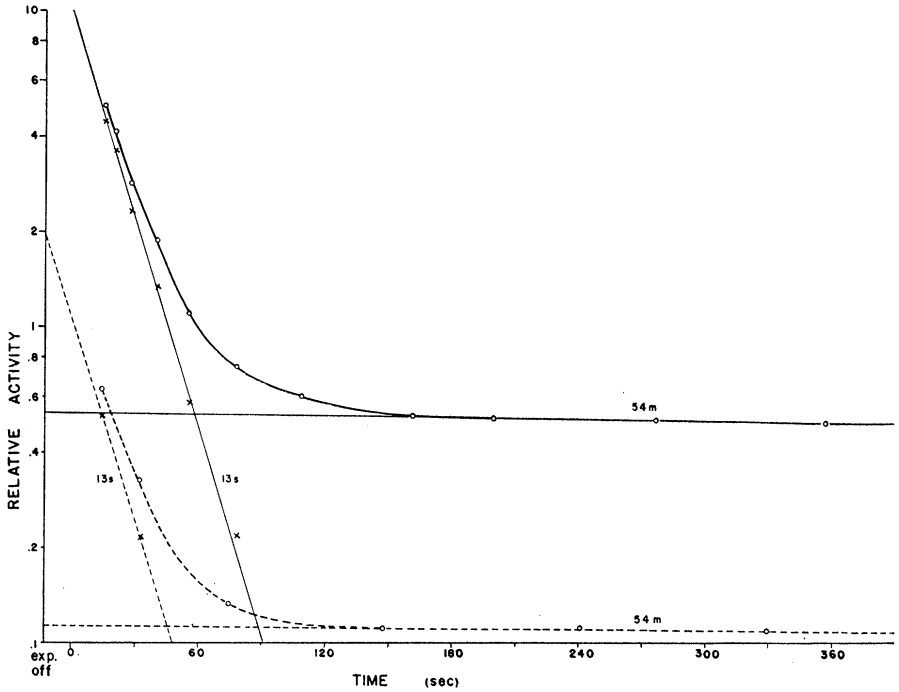

FIG. 1. Decay curves for beta-activity from indium activated by slow neutrons; dotted curves show resolution of gamma-ray activities from a similarly activated indium target.

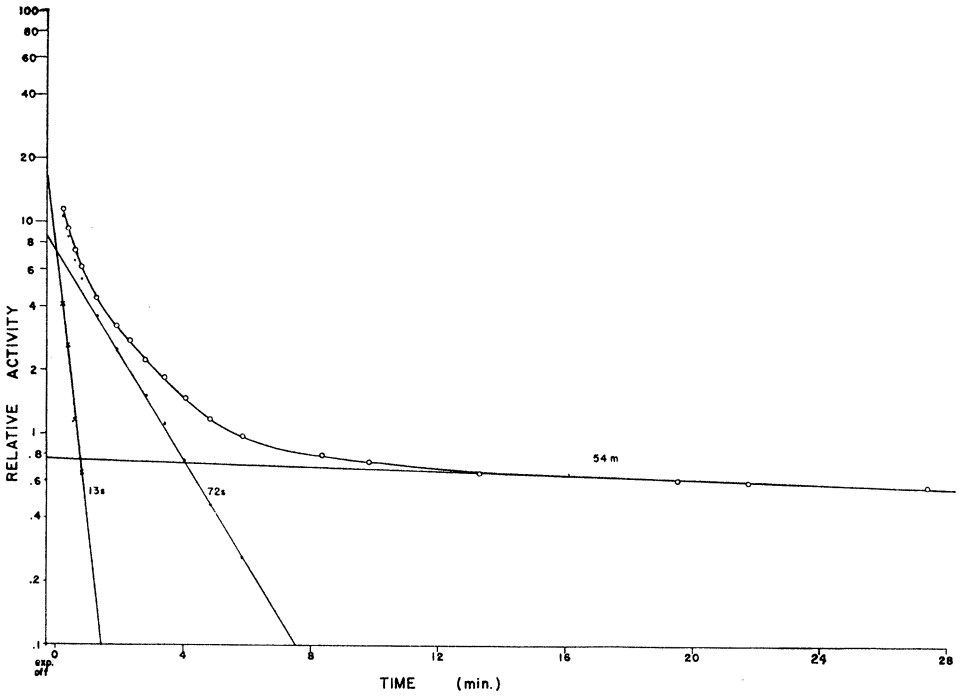

FIG. 2. Decay curves for indium activated by fast neutrons (showing short periods).

deuterons will eject neutrons from the bombarded nucleus allows a more exact assignment of these radioactive periods. Moreover the bombardment of a target directly by very high energy deuterons has been shown to induce the same reactions that are observed when the target is bombarded by slow neutrons except that the intensity of the radioactivities produced may be very greatly increased. To make the assignment of the indium isotopes more complete this investigation includes the results obtained by bombarding the neighboring element, cadmium, with deuterons and subsequently making a chemical separation of the resulting product. Silver has also been radiated with 13 Mev alpha-particles in an attempt to produce one of the active indium isotopes.

RESULTS

Slow neutrons and deuterons

The results obtained with slow neutrons and deuterons are very similar except that the observed activities are much stronger in the latter case. Slow neutron activation was accomplished by imbedding the specimen in a block of paraffin, placed as close as possible to a beryllium target, bombarded by deuterons. Fig. 1 shows a composite decay curve of this activity. This curve resolves satisfactorily into the three periods 13 seconds, 54 minutes and one of a few hours (all negative active). The results with deuterons are not shown but they yield a similar curve except that the increased intensity allows the longer period to be more definitely evaluated as 4.1 hours.

Fast neutrons

Bombardment with the energetic (14→20 Mev) neutrons from lithium exposed to 6.3 Mev deuterons, gave results with indium as shown in Figs. 2 and 3. These results are presented in two figures in order to show more clearly the very different periods. It is quite apparent that certain new periods; namely, 72 seconds and 50 days, both negative, are present in addition to those previously observed. The period of 72 seconds undoubtedly is the same as the period of 1 minute reported by Bothe[4] and Gentner and others[5] induced by means of high energy

[4] Bothe and Gentner, Naturwiss **25**, 284 (1937).
[5] Chang, Goldhaber and Sagane, Nature **139**, 962 (1937).

gamma-rays. A fraction of the high energy neutrons slowed down by scattering always gives a trace of the slow neutron reactions. An estimate of the relative intensities of the various activities at the end of bombardment shows definitely that with fast neutrons or slow neutrons the 13 second and 54 minute periods always have the same ratio with respect to each other. This suggests the assignment of these periods to a single isomeric isotope. The 4.1-hour period appears very strongly with fast neutrons and only very weakly with slow neutrons or deuterons. Since the relative abundance of the isotopes 113 and 115 is about one to twenty such a variation in activity would be expected if it were due to isotope 114. Hence, although the 13-second and 54-minute periods could have been associated with either 114 or 116 they are undoubtedly due to 116. This is substantiated by the fact that they are less strongly excited by fast than by slow neutrons. The 72-second period appears only with fast neutrons and hence must be associated with isotope 112. The 50-day period has so far been observed only when the activation has been with fast neutrons. This therefore might be placed as either an isomer of 112 or 114. It has been tentatively placed as 114. This can be checked by sufficient slow neutron bombardment, but exposures so far have not been sufficient to settle this definitely.

TABLE I. *Stable and radioactive isotopes.*

AT. WT.	106	107	108	109	110	111	112	113	114	115	116	117	118
47 AG		52.2	2m	47.5	20s	7.5d							
48 CD	1.5		1.0		15.2	15.2	21.8	14.9	23.7	4.3h	15.9	58h	
49 IN						20m	72s	4.5	4.1h 50d	95.5	13s 54m	2.3h	
50 SN							1.1		0.8	0.4	15.5	9.1	22.5

Deuterons on cadmium

When 6.3 Mev deuterons are allowed to bombard cadmium certain radioactive isotopes of indium may be formed by the capture of the deuteron with the expulsion of a neutron (i.e., proton capture). One case of this has been reported in the investigation[6] of cadmium. The stable isotopes in this part of the periodic table are shown in Table I. It may be seen from this table that the process of a proton capture might yield many indium isotopes but not 116, and hence not the 13-second and 54-minute periods. The composite decay curve of the indium chemical separation from the bombarded cad-

[6] Cork and Thornton, Phys. Rev. **51**, 608 (1937).

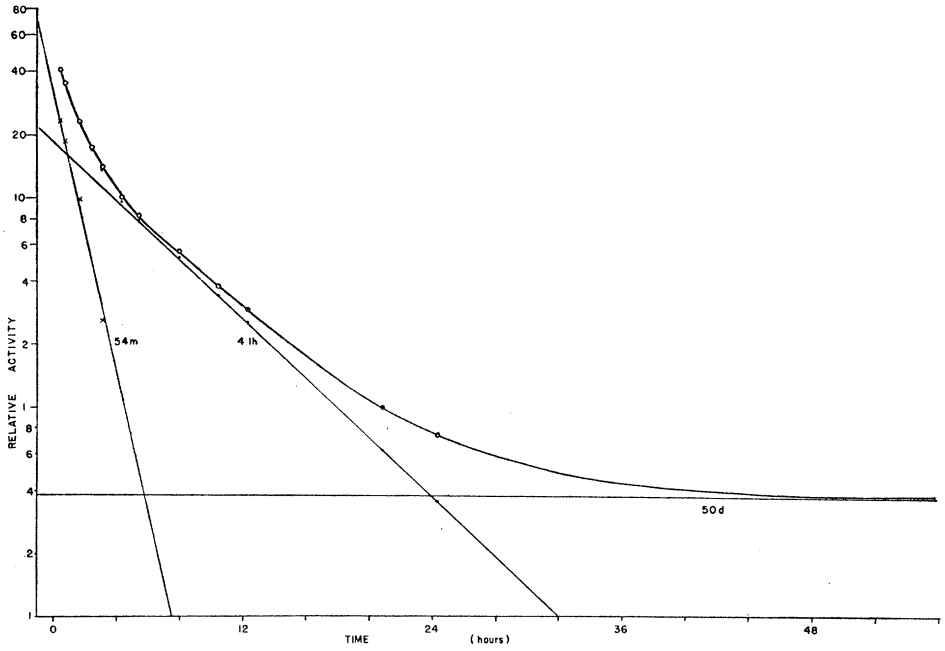

FIG. 3. Decay curves for indium activated by fast neutrons (showing long periods).

mium is shown in Fig. 4. This curve may be resolved into the already well-known periods of 4.1 hours and 2.3 hours, giving in addition a new period of 20 minutes. This 20-minute period was shown to be radiopositive and is accordingly assigned to isotope 111. Other possibilities would be isotopes of mass 107 and 109. These are not probable because of the low relative abundance of the parent cadmium isotopes. Since the minimum time for the chemical separation was about 10 minutes, the period of 72 seconds could not be observed.

Alpha bombardment of silver

By accelerating doubly ionized helium atoms in the cyclotron a beam of alpha-particles of 12 to 13 Mev is obtained. This was allowed to fall on silver, hoping that the reaction corresponding to the absorption of an alpha-particle with the ejection of a neutron might occur. This would lead to the formation of In^{110} and In^{112} from Ag^{107} and Ag^{109}. No evidence of this reaction was observed.

Summary of Probable Reactions

The probable reactions for the various activities are as follows:

(a) Slow neutrons

$$_{49}In^{N}+{}_{0}n^{1}\rightarrow{}_{49}In^{N+1}$$

$$_{49}In^{N+1}\rightarrow{}_{50}Sn^{N+1}+{}_{-1}e \text{ (13 sec., 54 min., 4.1 hr., 50 da.)}$$

(b) Fast neutrons

$$_{49}In^{N}+{}_{0}n^{1}\rightarrow{}_{49}In^{N-1}+{}_{0}n^{1}+{}_{0}n^{1}$$

$$_{49}In^{N-1}\rightarrow{}_{50}Sn^{N-1}+{}_{-1}e \text{ (72 sec., 4.1 hr., 50 da.)}$$

(c) Deuterons on cadmium

$$_{48}Cd^{N}+{}_{1}H^{2}\rightarrow{}_{49}In^{N+1}+n^{1}$$

$$_{49}In^{N+1}\rightarrow{}_{50}Sn^{N+1}+{}_{-1}e, \text{ 72 sec., 2.3 hr., 4.1 hr., 50 da.)}$$

$$\rightarrow{}_{48}Cd^{N+1}+{}_{+1}e \text{ (20 min.).}$$

Beta- and Gamma-Spectra

There are now shown to be seven radioactive periods in indium. It is evident that a knowledge of the energies of the beta- and gamma-radiations associated with each of these periods should be of value, particularly those relating to the isomeric isotopes. In order to obtain this information it is necessary to isolate each activity for the cloud chamber exposures. This is not easy in every case, and will require much further work. In Fig. 1 is shown in dotted lines the

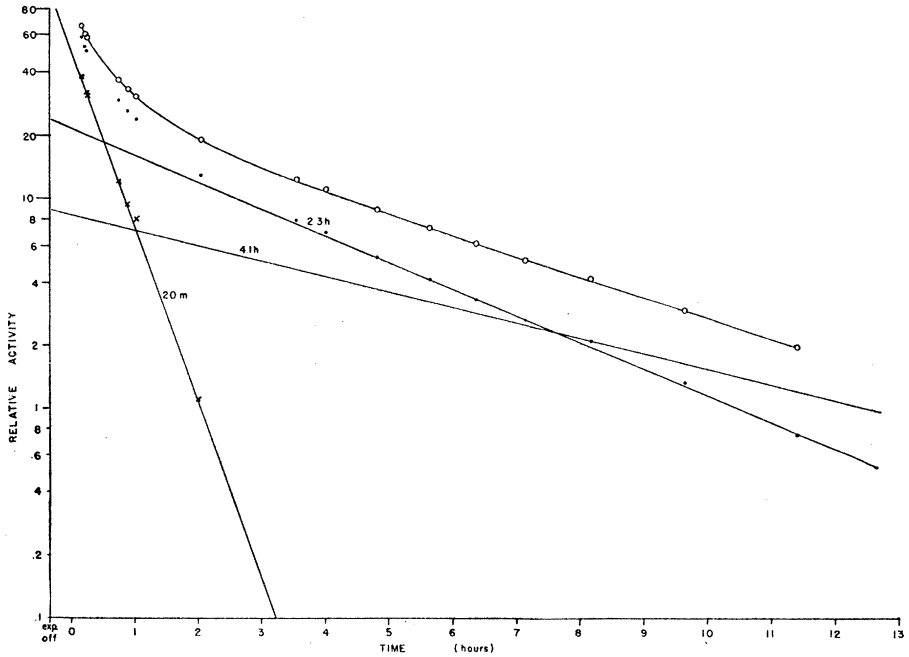

FIG. 4. Decay curves for the indium separation from cadmium bombarded with deuterons.

decay of the gamma-ray activity excited by neutron bombardment. It is apparent that there are gamma-ray periods for the 13-second and 54-minute activities. The energy of each of these has not yet been determined. The energies of the upper limits of the beta-radiations from the 54-minute and 13-second activities have been reported[7] as 1.3 Mev and 3.2 Mev, respectively. In the present investigation about 750 tracks have been measured for the 50-day period and about 100 tracks for the positive 20-minute period. These measurements indicate energies at the upper limit of 2.15 Mev and 1.75 Mev, respectively. Measurements are in progress to determine as far as possible the beta- and gamma-energies for the remaining activities.

We are greatly indebted to Mr. D. W. Stewart for aid in carrying out the necessary chemical separations.

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[7] Gaerttner, Turin and Crane, Phys. Rev. **49**, 793 (1937).

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The Magnetic Moment of the Proton

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The magnetic moment of the proton was measured by the method of the magnetic deflection of molecular beams employing H_2 and HD. The result is $\mu_P = 2.46\mu_0 \pm 3$ percent.

THE magnetic moment of the proton was first measured by Estermann, Frisch and Stern in Hamburg in 1932–33.[1] These measurements gave the surprising result that the proton moment was not one but 2.5 nuclear magnetons with the limit of error of about 10 percent. We have repeated these measurements with the aim of obtaining as great an accuracy as possible. The knowledge of this numerical value is important for several reasons: It allows a check on any theory of the heavy elementary particles, because the theory must give just this numerical value; but it is, of course, also important for the theory of the nuclei and for the theory of the forces between elementary particles.

In addition to the experiments with H_2, we have employed beams of HD[2] and have removed certain sources of error contained in the previous measurements.

I. METHOD

The principle of the method used is the measurement of the deflection of a beam of hydrogen molecules in an inhomogeneous magnetic field. From this measurement the magnetic moment of the proton is obtained in the following way:

Normal hydrogen is composed of 25 percent parahydrogen and 75 percent orthohydrogen. We neglect, at first, the rotation of the molecule. Then in the case of parahydrogen, the two proton spins are antiparallel and the total spin and magnetic moment of the molecule are consequently 0. In the case of orthohydrogen, the two proton spins are parallel, resulting in a total spin of the molecule of 1 and a magnetic moment of twice the proton moment. An infinitely narrow beam of orthohydrogen molecules of a definite velocity should, therefore, be split by the magnetic field into three components corresponding to the deflections 0, $+2s_P$ (H_2) and $-2s_P$ (H_2), where s_P (H_2) would be the deflection under the conditions of our experiment of a H_2 molecule having one proton moment. A beam of parahydrogen would give only the one undeflected component.

In addition to this splitting due to the magnetic moment of the protons, we have to consider the magnetic moment due to the rotation of the molecule as a whole. At very low temperatures all the parahydrogen molecules have the

[1] R. Frisch and O. Stern, Zeits. f. Physik **85**, 4 (1933); U. z. M. 24; I. Estermann and O. Stern, Zeits. f. Physik **85**, 17 (1933); U. z. M. 27. (U. z. M., Untersuchungen zur Molekularstrahlmethode, refers to a series of papers concerning the molecular ray method.)

[2] We wish to express our sincere thanks to Dr. F. G. Brickwedde of the National Bureau of Standards who kindly prepared the HD.