Phy 11

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Radioactivity Induced by Nuclear Excitation*

I. Excitation by Neutrons

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It is shown that the 4.1-hr. period of indium can be produced by nuclear excitation of indium and is to be attributed to an excited metastable state, $In^{115,*}$ of the stable In^{115}. This result is obtained by studying the radioactivity produced in indium by neutrons of different energy distributions and by studying the chain reactions produced in cadmium by fast neutrons. It is found that In^{115*} can be produced from In^{115} by 2.5-Mev neutrons, but not noticeably by strong sources of photoneutrons which have energies of a few hundred thousand electron volts. A radioactive Cd^{115} of 2.5-day half-life time is found to transform with emission of negative electrons into In^{115*}. Cd^{115} was produced by neutron loss from Cd^{116} and by neutron capture from Cd^{114}.

WHEN indium is bombarded with fast neutrons from a Rn-Be source, a radioactive indium isotope, of 4.1-hr. half-life time, is produced which emits negative electrons.[1] So far, it has been assumed, that when an element is transformed by neutron bombardment into its own radioactive isotope, the radioactive isotope is generated either through neutron capture or through neutron loss from the bombarded element. The present experiments, however, indicate that this radioactive In isotope is generated through a new type of nuclear process—nuclear excitation leading to a metastable isomer of the stable In^{115}. For this metastable isomer we introduce the symbol In^{115*}.

As it was known that more than two radioactive isotopes of indium could be generated by neutron bombardment from the two stable isotopes of indium, a further investigation of their generation appeared to be of interest. Two of these radioactive isotopes, of 13-sec. and 54-min. half-life time, have been assigned to mass number 116. They are isomers produced from In^{115} by radiative capture of the neutron. In order to learn more about the generation of the 4.1-hr. period, which did not appear to be water-sensitive, we made the following experiments.

§1. GENERATION OF In^{115*} FROM INDIUM

A thick indium foil was bombarded with Rn-α-Be neutrons, and showed the 4.1-hr. period more strongly than the 54-min. capture period. A similar indium foil irradiated with photoneutrons from a strong radium-beryllium source (0.5 g Ra-260 g Be) did not show the 4.1-hr. period, though the photoneutron source was so strong that it produced the 54-min. capture period with an initial activity of 1200 impulses per minute recorded by a Geiger-Müller counter. Control experiments showed that this large activity was caused by the primary photoneutrons and not by slower scattered neutrons which would obviously produce a large activity of the 54-min. period by resonance capture. If the 4.1-hr. period, which is strongly produced by the fast Rn-α-Be neutrons, belonged to an isomer of In^{116}, it would be difficult to understand why this period is not appreciably produced from In^{115} by capture of the photoneutrons which have energies of a few hundred thousand electron volts. We conclude therefore that this period must not be attributed to In^{116}.

We made further experiments with neutrons from a radon-boron source. It was found that

* Some of these experiments have been reported at the Washington Meeting of the American Physical Society, April 1938, and at the British Association Meeting in Cambridge, August 1938. (See Nature **142**, 521 (1938)).

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[1] Szilard and Chalmers, Nature **135**, 99 (1935); Amaldi, d'Agostino, Fermi, Pontecorvo, Rasetti and Segrè, Proc. Roy. Soc. **A149**, 522 (1935); Lawson and Cork, Phys. Rev. **52**, 531 (1937).

these neutrons excite the 4.1-hr. period more strongly than either the 25-min. period of I, or the 54-min. period of In, which are both caused by neutron capture; and also much more strongly than other investigated periods which are known to require fast neutrons for their excitation, such as the 10-min. and 15-hr. periods of Al, the 2.3-min. period of Si, and the 2.3-min. period of P. The 170-min. period of P which does not require very fast neutrons for its excitation is, however, more strongly activated than the 4.1-hr. period of In. These results are in accord with the fact that a radon-boron source is deficient in very fast neutrons compared with a Rn-α-Be source. The strong activation of the 4.1-hr. period in the present experiment cannot be attributed to a neutron loss reaction from either In^{113} or In^{115} for such a reaction requires very fast neutrons.

Nor can the strong activation of this period by radon-boron neutrons be attributed to neutron capture from In^{113}, since the relative abundance of this isotope is only five percent. The capture cross section of In^{113}, corrected for the half-value thickness of the β-rays, would have to be 100 times larger than the capture cross section of iodine. In the absence of slow neutrons we cannot expect such large differences of capture cross sections among the strongly absorbing elements of odd atomic number of such similar atomic weight. This is borne out by an unpublished survey of the relative capture cross sections of elements for Ra+Be photoneutrons which was made by J. H. E. Griffiths, Oxford, in collaboration with one of us.

Finally indium was irradiated with neutrons of about 2.5-Mev energy, produced by bombarding heavy ice with deuterons of 250 kev.

TABLE I. *Stable and some radioactive isotopes of cadmium, indium and tin in the mass range 112 to 117. For stable isotopes the relative abundance in percent is given in heavy type. For radioactive isotopes the half-life periods are given in italics.*

M	$_{48}$Cd		$_{49}$In	$_{50}$Sn
117	*4h*	→	*2.3h*	**9.1**
116	**7.3**		*13s*	**15.5**
			54m	
115	*2.5d*	→	*4.1h*	**0.4**
			95.5	
114	**28.0**			**0.8**
113	**12.3**		**4.5**	
112	**24.2**			**1.1**

The 4.1-hr. period was found to be strongly activated. Obviously this cannot be caused by a neutron loss reaction, since the available energy is certainly less than the binding energy of the neutron in an In isotope.

The experiments described rule out the possibility that this radioactive indium isotope is generated from a stable indium isotope by neutron capture, or neutron loss, and therefore exclude an indium isotope of mass number 112, 114 or 116 as the carrier of the 4.1-hr. period. Moreover, the fact that photoneutrons from a Ra-Be source do not excite the 4.1-hr. period, while neutrons from the D+D reaction do so, suggests that its carrier might arise through a process which has a real or apparent energy threshold.

These results forced us to assume that the 4.1-hr. period is generated by a new type of process. In order to explain this period we assumed that the In^{115} nucleus may be excited by neutron impact and left in a metastable excited state, In^{115*}. This metastable In^{115*} may be radioactive and transform either by β-disintegration into its stable isobar Sn^{115}, or by emission of γ-rays and internal conversion electrons into the stable In^{115}.

If this assumption is correct it should be possible to produce this radioactive indium isotope by other methods of nuclear excitation from indium, e.g. by proton impact. S. W. Barnes and P. W. Aradine, Rochester, will report in the following paper on the nuclear excitation of indium by protons.

It is conceivable that the existence of a metastable state of In^{115} is connected with the high nuclear spin (9/2) of In^{115}. If the metastable In^{115*} has a small spin it will be difficult to reach the metastable state from the ground state by a direct transition. As a rule, a higher excited state of indium will have to be produced, from which the metastable state can be reached by one or more spontaneous transitions. The apparent energy threshold of In^{115*} may therefore be considerably above the level of the metastable state.

§2. GENERATION OF In^{115*} FROM CADMIUM

Other methods of producing In^{115*} can be devised, and we have isolated In^{115*} from cadmium bombarded by neutrons from Li+D,

thus confirming our assignment of the 4.1-hr. period.

As can be seen from Table I, cadmium has an isotope of mass number 116 having a relative abundance of 7.3 percent. By bombarding cadmium with fast neutrons of the Li+D reaction, one could hope to produce a radioactive Cd^{115} by the neutron loss reaction Cd^{116} $(n, 2n)$. Such a radioactive isotope could be expected to emit negative electrons and it might transform partly into the stable In^{115} and partly into the metastable In^{115*}.

We bombarded metallic cadmium for several hours with neutrons from Li+D using deuterons of 950 kev and currents averaging 30μa. The irradiated cadmium was dissolved in nitric acid and a small quantity of indium was added. Indium was precipitated by adding ammonia. The indium which was separated from the cadmium solution two days after the irradiation showed a single activity decaying with a 4.1-hr. period. By successive separations of indium from the cadmium solution it was found that this radioactive indium isotope grew from a parent substance of 2.5-day half-life period. This indium isotope was found to emit negative electrons.

We have compared the half-life period and the electron absorption curve of this radioactive indium isotope with the half-life period and the electron absorption curve of the radioactive indium isotope produced by fast neutrons from indium. The result confirms our assumption that the two are identical and that the carrier of the 4.1-hr. period is In^{115*}. The range of the electrons in Al was found to be 0.15 g/cm^2. This corresponds to an energy of 550±100 kev.

Our experiments show that In^{115*} grows from the parent Cd^{115} which decays with a half-life time of 2.5 days. We find by magnetic analysis that Cd^{115} emits negative electrons, thus transforming into In^{115*} and perhaps also into the stable In^{115}.[2]

To investigate whether Cd^{115} can also be obtained by slow neutrons we irradiated with neutrons a cadmium sheet which was enclosed between two similar cadmium sheets and placed inside a paraffin block. We found that the two outer sheets showed a stronger activity of the 2.5-day period than the inner sheet. This indicates that Cd^{115} is produced by slow neutron capture from Cd^{114}. The activity produced in this way is small compared with the activity produced by the neutron loss reaction from Cd^{116}.

The properties of In^{115*} are of great interest both from the point of view of the nature of isomeric nuclei and of isobaric pairs. A detailed investigation of the radiations emitted by In^{115*} is now being carried out. An account of some preliminary experiments has been given at the British Association Meeting.[3]

We wish to thank all those who have cooperated in this work: Dr. F. M. Brewer, Old Chemistry Laboratory, Oxford, who in the early stages of this work identified the carrier of the 4.1-hr. period as an isotope of indium; Mr. P. I. Dee, Cavendish Laboratory, Cambridge, who made it possible for us to use strong Li+D neutron sources; Drs. E. T. Booth, C. H. Collie and C. Hurst, Clarendon Laboratory, Oxford, who carried out the irradiations with D+D neutrons. Our thanks are also due to Professor F. A. Lindemann, F.R.S. and to Dr. J. D. Cockcroft, F.R.S. for their kind interest in this work. We are much indebted to the Anaconda Wire and Cable Company who very generously enabled us to work with large quantities of indium.

[2] A radioactive Cd isotope of similar half-life time (58 hr.) has been previously reported to exist by Cork and Thornton (Phys. Rev. **51**, 608 (1937)), but assigned by them to mass number 117. They also reported a radioactive isotope of In of 2.3-hr. half-life time which they ascribed to In^{117} and which appeared to grow from a 58-hr. Cd parent. We find this indium isotope only when we precipitate indium from the cadmium solution in a time less than two days after irradiation. By successive separations we find that it grows from a 4-hr. Cd parent, a radioactive isotope which has been previously reported by Cork and Thornton and at the time assumed to be Cd^{115}.

[3] See Nature **142**, 521 (1938).

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