Radioactivity Induced by Nuclear Excitation*

II. Excitation by Protons

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Radioactive indium resulting from proton bombardment of indium exhibits negative electron emission which decays with a 4.1-hr. half-life. Proton bombardment of cadmium does not produce this activity. It is ascribed to a metastable excited state of In^{115} designated by In^{115*} formed by a new type of proton excitation process. Control experiments exclude the possibility of its being formed by stray neutrons. The cross section for protons of 5.8 Mev is about 10^{-29} cm^2.

AT THE present time there are known seven radioactive periods assigned to In isotopes. Of these, six periods have been definitely assigned to five mass numbers, i.e., 111, 112, 114, 116, 116 and 117. The assignment of the seventh period, a 4.1-hr. negative electron emitter, has been subject to doubt.

This activity[1] discovered by Szilard and Chalmers has been found by Lawson and Cork both after fast neutron bombardment of indium and after deuteron bombardment of cadmium. Goldhaber, Hill and Szilard have found that a minimum neutron energy is apparently required to produce this activity. They have suggested[2] that In^{115} can be raised to an excited metastable state by inelastic neutron collisions, in which the neutron is captured and then released with lower energy. They have assumed that the 4.1-hr. period is associated with this metastable excited state which they designate by In^{115*}. This view can be tested by proton bombardment of indium. It is obvious that no previously known type of proton reaction could produce any radioactive In isotope by bombardment of In. Thus if the 4.1-hr. activity is found it is conclusive proof that it is produced by a new type of process, In (p-p).

This may be substantiated in another way. No stable isotope Cd^{115} being known, proton bombardment of Cd should not yield isomers of In^{115} by the Cd (p-n) reaction. In^{114}, however, ought to be formed from Cd^{114}.

We have bombarded Cd and In with 6.7-Mev protons in the cyclotron. Our experiments show (a) that proton bombardment of indium produces the 4.1-hr. activity and (b) that proton bombardment of Cd does not, although it does give the 50-day activity characteristic of In^{114}. These results corroborate the assignment of the 4.1-hr. activity to In^{115*} and show that this metastable state can be produced by exciting the indium nucleus by fast protons.

A sample of "pure" indium was selected for use. A chemical microanalysis showed the following impurities to be present—Pb, Sb and Sn in amounts of 1. to 0.1 percent and Al, Fe, Cd, Bi and Zn in amounts of 0.1 to 0.01 percent. One of us then carried the sample through a chemical procedure calculated to reduce the abundance of these impurities by at least a factor of 10. The purified indium, again in metallic form, was rolled into foil six mil (0.006″) in thickness.

Since the cyclotron chamber is a strong source of neutrons when it is producing protons of over six Mev, it was necessary to separate the effects on the indium of the neutrons and protons. For this purpose two indium foils, separated by a ten-mil (0.01″) foil of Pb were mounted in the vacuum bombardment cup. Foil (1) facing the beam received protons and stray neutrons. Foil (2) immediately behind the lead foil received no protons but the same stray neutrons as struck foil (1).

A ninety-minute bombardment with a $\frac{1}{2}$-μa

* Some of these experiments have been reported at the Washington meeting of the American Physical Society, April, 1938.

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1 L. Szilard and B. Chalmers, Nature **135**, 99 (1 35); J. L. Lawson and J. M. Cork, Phys. Rev. **52**, 531 (1937).

2 See preceding paper.

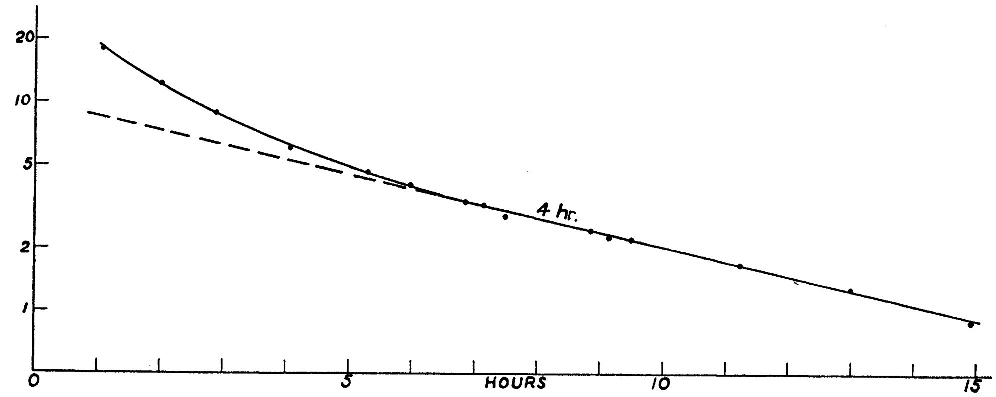

FIG. 1. Decay of indium precipitate from In bombarded by protons. The ordinates when multiplied by 30 give the number of β-particles emitted per sec. in all directions by the sample.

beam of 6.7-Mev protons produced in foil (2) a small activity of the 54-min. period which is caused by neutrons but no activity of a 4.1-hr. period. This latter period did not appear in foil (2) even with much longer exposures.

Samples of In chemically separated from In foil (1) after this foil was exposed to the proton beam showed an activity decaying according to Fig. 1. Six hours after exposure the decay curve shows only a 4-hr. period.

Visual inspection of cloud-chamber tracks from this sample showed that the majority of the emitted electrons were negative, but the activity was too weak for a satisfactory investigation by this method. More definite information as to the sign was obtained in the following way.

A small electromagnet is suspended over the window of the ionization chamber and the active sample placed at the edge of the air gap between the poles in an arrangement which has been described by one of us.[3] A small lead shield between the radioactive sample and the window prevents electrons from entering the chamber in the absence of the magnetic field. Fig. 2 shows the decay curve obtained from a bombarded In foil with a magnetic field which allowed only negative electrons to enter the chamber. It shows the 4.1-hr. period. This period did not appear when the magnetic field was reversed, thus the 4.1-hr. activity does not exhibit an appreciable positive electron emission.

It was not possible to make an accurate determination of the range of the electrons but the values so far obtained are consistent with the value found for the 4.1-hr. period produced from Cd by fast neutrons.[2]

It appears from our results that fast protons can excite the stable In^{115} and produce a metastable In^{115*}. The cross section for the excitation of the In nucleus which leads (not necessarily directly) to In^{115*} is found to be about 10^{-29} cm^2 for 5.8-Mev protons.

This cross section is much smaller than the cross section for *p-n* reactions in this region of the periodic system. For instance if neighbors of In, Cd and Sn, are bombarded by protons, radioactive isotopes of In and Sb are produced respectively and the cross sections for these reactions are about 10^{-26} cm^2. Radioactivities caused by *p-n* reactions can therefore easily overshadow radioactivities caused by nuclear excitation. Fortunately the *p-n* reaction in In^{115}, the more abundant In isotope, apparently leads to a stable isotope Sn^{115}. This pair is one of the three known cases of such stable isobars. In^{113}, however, which has a relative abundance of less than five percent might yield a radioactive Sn^{113} by a *p-n* reaction. One of the activities observed in a sample of Sn which has been separated from bombarded In may be caused by Sn^{113}. This activity is now being investigated along with other activities produced by proton bombardment of In and Cd.

Weisskopf has pointed out that a proton can excite a nucleus in two different ways, i.e., either

[3] S. W. Barnes, Rev. Sci. Inst. in press.

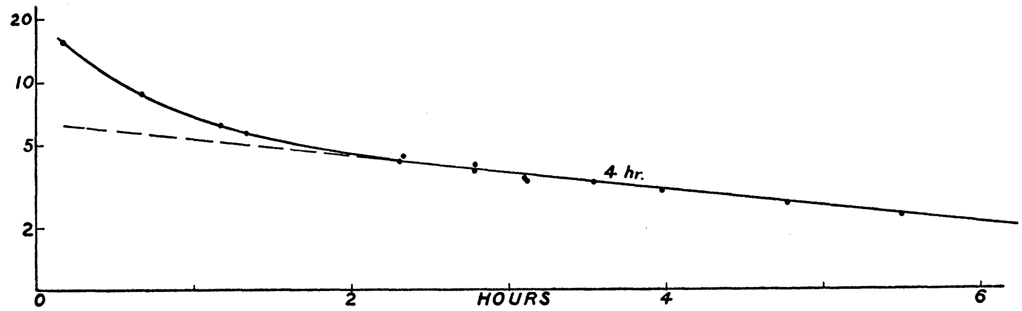

FIG. 2. The decay of the negative electron emission of In bombarded by protons.

by an inelastic collision similar to an inelastic collision of a neutron or through the action of the electric field of the proton.[4]

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[4] V. F. Weisskopf, Phys. Rev. 53, 1018 (1938).

* *Note added in proof.*—Indium has been bombarded with 0.01 μa of 8.5-Mev alpha-particles. No 4.1-hr. activity was observed. According to this result the cross section for excitation of In^{115} with 8.5-Mev alpha-particles cannot be more than twice the cross section for the excitation of In^{115} by 6.5-Mev protons.

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The Quadratic Zeeman Effect

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The Zeeman effects of the principal series lines of sodium and potassium in the range $n=10$ to 35 are observed in absorption, using the new 60-inch cyclotron magnet. With a field of 27,000 gauss, the lines having n in the neighborhood of ten show a normal triplet representing the complete Paschen-Back effect of the narrow ^2P doublet. From about $n=12$ to 20 all components show an increasing displacement toward short wave-lengths proportional to (n^*),[4] the shift of the π components being half that of the center of the two σ components. This is the quadratic Zeeman effect, varying as H^2, and is here measured and compared quantitatively with theory for the first time. The agreement with the simple theory is excellent as far as $n=20$. Beyond this the lines show an additional displacement in the same direction, increasing as a higher power of n. At the same time the lines are broadened toward the red, with indications of an unresolved component whose intensity increases rapidly with n. The displacement is interpreted as a perturbation by the F states, whose separation from the P states in this region becomes comparable with the magnetic energy. The additional lines causing the broadening represent forbidden transitions $^2S \rightarrow {}^2F$. Beyond $n=28$ the broadening increases suddenly and becomes symmetrical, until the lines are no longer distinguishable at $n=35$. All of these perturbation effects are compared with the theoretical results given in the accompanying paper by Schiff and Snyder. Some features are accounted for quantitatively, while the others are satisfactorily explained qualitatively.

THE quadratic Zeeman effect is a displacement toward short wave-lengths of the Zeeman components of a spectral line, proportional to the square of the magnetic field. It is directly related to the diamagnetic term in the theory of magnetism, which contains the square of the "radius" of the atom. In both classical and quantum mechanical theories of the Zeeman