On the Hypothesis of the Instability of the Deuteron

Our attention has been called by Dr. C. C. Lauritsen to a possible alternative explanation of the experiments recently reported by us.¹ In these experiments pairs of targets containing respectively light and heavy hydrogen were bombarded by hydrogen molecule ions. Protons having ranges up to 20 cm were observed from both targets but in greater numbers from the targets containing heavy hydrogen and this difference was attributed to the disintegration of the deuterons of the targets by the protons of the beam. The fact that both targets yielded these particles was attributed to a small contamination (about 1 part in 30,000) of H^2 in the H^{1+2} beam.

The point raised by Dr. Lauritsen is that the contamination of H^2 in the apparatus must be largely increased when the beam is playing on the target containing heavy hydrogen and this added contamination might produce just the effect observed by us, since all of the hydrogen in the chamber contributed to the beam.

It had been our intention to employ in this experiment not the H^{1+2} beam but the simple H^{1+} beam which could contain no such contamination; however, this experiment was delayed owing to the rather extensive readjustments of the apparatus that would be required. Now owing to the obvious ambiguity of the experiments which we reported, we recognize that for a final settlement of this question experiments with a pure H^{1+} beam are essential.

We now think it altogether possible however that the results of such an experiment will be negative. For recently alternative and reasonable explanations have been found for those phenomena which originally led us to the hypothesis of the instability of the deuteron. There is evidence^{2, 3} in the important case of carbon under deuteron

bombardment that two nuclear reactions occur:

At least at low voltages, these reactions appear to account for the long range protons and neutrons observed. It appears not unlikely that similar reactions with other nuclei and the possibility of carbon and oxygen contamination⁴ of targets will ultimately account completely for our observations.

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¹ G. N. Lewis, M. S. Livingston, M. C. Henderson and E. O. Lawrence, *Phys. Rev.* **45**, 242-244 (1934).

² C. C. Lauritsen and H. R. Crane, *Phys. Rev.* **45**, 345-346 (1934). C. C. Lauritsen, H. R. Crane and W. W. Harper, *Science* **79**, 234 (1934).

³ M. C. Henderson, M. S. Livingston and E. O. Lawrence, *Phys. Rev.* **45**, 428 (1934).

⁴ We are indebted to Dr. J. D. Cockcroft for communicating to us evidence that the long range protons observed when tungsten is bombarded by deuterons are in fact due to a contamination.

Further Experiments with Artificially Produced Radioactive Substances

C and B_2O_3 bombarded with protons

After having observed induced radioactivity in a number of substances bombarded with deuterons,¹ it seemed desirable to bombard the same targets with protons. This led to the striking observation that two of the targets, namely carbon and boron oxide, showed an appreciable activity which decayed at the same rate as did the activity produced by deuterons. The intensity of the activity produced by protons, as compared to that produced by deuterons under similar conditions was, in the case of carbon, about 10 percent, and in the case of the boron oxide, about 20 percent. That the ion beam could contain 10 to 20 percent deuterons due to contamination of the tube with H^2 (adsorbed on the walls, etc.) seems highly improbable, since on other occasions we have changed from deuterons to protons and have observed no more of the deuteron effect than could be accounted for by the normal amount of H^2 in ordinary hydrogen—about one part in 6000. The fact that the decay periods of the active substances produced by protons and by deuterons are quite exactly the same suggests strongly that the same radioactive products are formed. In the case of deuteron bombardment the radio-

active substances are supposedly N^{13} and C^{11} , respectively, and hence for the case of proton bombardment we may suggest the following alternative reactions which would involve the same radioactive products:

where the excess energy calculated from the change in mass in the overall reaction is given, and

where in accordance with the presumable mass of the neutron the excess energy from the change in mass is nearly negligible and might be either positive or negative.

One hesitates to accept the first type of proposed reaction, mainly because the probability of a particle being

¹ Lauritsen, Crane and Harper, *Science* **79**, 234 (1934); Crane and Lauritsen, *Phys. Rev.* **45**, 430 (1934).

added to a nucleus without the ejection of some other particle to carry away the excess energy is extremely small. So far no example of it has been established.

The second type of reaction seems more attractive, since any excess energy could easily be carried away by the neutron. If we take the masses of the proton, neutron and positron as 1.0072, 1.0067 and 0.0005, respectively, then the only kinetic energy available for the neutron and the positron is the kinetic energy contributed by the incident proton (in this case 0.9×10^6 e.v.). Nevertheless, we may not be justified in expecting to find the energies of the positrons limited to 0.9×10^6 e.v., since the known phenomena of the continuous β -ray spectrum have already indicated that the strict law of the conservation of energy may not hold in the case of electron emission. It might be reasonable to expect, however, that the energies of the positrons plus those of the neutrons would satisfy the conservation of energy statistically, and therefore have 0.9×10^6 e.v. as a mean energy.

In a preliminary set of cloud-chamber photographs taken by Dr. Carl D. Anderson and Mr. Seth H. Neddermeyer of carbon after proton bombardment, tracks appear having energies distributed up to above 10^6 e.v. It is interesting to note that the positron energy spectrum is continuous, as in the case of the β -rays, and that some of the positrons come off with energy in excess of the 0.9×10^6 e.v. which would be available on the above assumptions as to reaction and mass. More detailed data regarding the energy spectrum will be published by Anderson and Neddermeyer. A more precise knowledge of the mass of the neutron will be necessary for the further study of the energy relations—both elementary and statistical—in these processes.

Radioactive gases from C and B_2O_3

In observing the activity of a B_2O_3 target in a cloud chamber after deuteron bombardment, it was noticed after a short time that a large number of tracks appeared which originated in the gas. Although it has been assumed that the radioactive substance in this case is C^{11} , the above observation would indicate that the active material is a

gas which rapidly diffuses out of the B_2O_3 . As further evidence, we found that warming the active B_2O_3 to about 200°C in air completely drove off the radioactive constituent. It therefore seemed desirable to collect, and if possible, determine the nature of the active gas. To do this we warmed a small amount of the activated B_2O_3 in a flask containing air, and transferred the air into an ionization chamber, through a liquid air trap. As long as the chamber was protected by the liquid air, no activity was recorded. However, upon removing the liquid air and allowing the trap to rise to a temperature considerably above that of liquid air, a large amount of the active material then made its appearance in the chamber. The B_2O_3 which was left in the flask was afterwards tested and found to have no activity. From this we conclude that after the B_2O_3 is bombarded, nearly all the C^{11} exists in the target as CO or CO_2 , and very little, if any, as carbon. It should be noted that in measuring the period of decay of this substance, any method in which the gas is not prevented from escaping will lead to an apparent period which is considerably shorter than the real period. In order to make certain that the effect observed from B_2O_3 was due to the boron, and not to the oxygen, a target of SiO_2 was bombarded with deuterons and tested for activity. No measurable effect was found, so it can be assumed that the oxygen contributes little, if any, of the effect.

A graphite target after bombardment with deuterons, which supposedly contained N^{13} , was also heated in an effort to drive off the active constituent, but after heating to a red heat, about half the activity remained in the target. This result does not necessarily cast doubt upon the belief that the active substance is N^{13} , because we know that nitrogen, as well as other gases, is very strongly adsorbed on carbon.

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Energy Spectra of Positrons Ejected by Artificially Stimulated Radioactive Substances

Curie and Joliot¹ have reported that under the bombardment by α -particles from Po, several of the light elements, *viz.*, B, Mg, Al undergo transmutations which result in the production of radioactive isotopes which have half-lives of the order of several minutes and disintegrate by the ejection of positrons. Lauritsen, Crane and Harper² have produced such radioactive substances artificially by the bombardment of various light elements with deuterons and protons accelerated to 900,000 e-volts energy. They have very kindly supplied us with several samples of C, B, Be and Al freshly subjected to proton or deuteron bombardment. By inserting these samples in a cloud chamber operating in a magnetic field of 800 gauss it was shown that in all cases so far tested the disintegration results in the ejection of positrons of varying energies up to about

1.5 million e-volts. No α -particles or protons are observed and no tracks which can with certainty be ascribed to disintegration negatrons. For convenience we refer in the following to the element bombarded rather than to the supposed radioactive product. A discussion of the various nuclear reactions is being given by Dr. C. C. Lauritsen and H. R. Crane.

The samples so far tested are given in Table I.

When the activated B_2O_3 target was inserted in the chamber a large number of tracks were observed which did not originate in the target itself. Stereoscopic photographs taken with the magnetic field adjusted to the high value of

¹ Curie and Joliot, *Comptes Rendus* **198**, 254 (1934).

² Lauritsen, Crane and Harper, *Science* **79**, 234 (1934).