The Artificial Radioactivity of Copper, a Branch Reaction

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The artificial radioactivity of longer half-life produced in copper by deuteron bombardment is studied. It is found to emit both electrons and positrons in the ratio 1.6 to 1. The half-life is found to be 12.8 ± 0.1 hours. The excitation curve of positrons and electrons for deuterons of different energies is studied and found to agree with the theoretical expression of Oppenheimer and Phillips. The upper limits of the energy distribution of the positrons and electrons are obtained from cloud chamber photographs, and are found to be 0.79 and 0.83 Mev, respectively. The results are interpreted as showing that this activity is due to Cu^{64} which branches in disintegrating, going either to zinc or nickel.

WHEN copper is bombarded with high energy deuterons, two radioactive isotopes are produced, one from each of the stable isotopes of copper. The reaction is the capture of a neutron, with the emission of a proton. Lawrence, McMillan and Thornton[1] have measured the excitation curve for deuterons up to 3.1 Mev energy. The same radioactive isotopes may be formed by neutron bombardment of copper. Fermi[2] and others have studied this reaction. In the work to be described, a more detailed study of the isotope of longer half-life has been made.

Deuterons were accelerated to energies of 5 to 6 Mev in the magnetic resonance accelerator or cyclotron. In the first experiment, a solid block of copper was bombarded with 10 μa of deuterons of 25 cm range for fifteen minutes. It showed a large activity with a half-life of about $12\frac{3}{4}$ hours. An absorption curve in lead showed the presence of radiation of about the hardness of annihilation radiation, decaying at the same rate as the electron activity. This absorption curve showed no evidence for any other gamma-radiation. The sample was then placed in a Wilson chamber traversed by a magnetic field. Visual examination showed the presence of both positrons and electrons in roughly equal numbers.

In order to get some quantitative separation of the effect due to positrons and to electrons the following procedure was adopted. Observations were made with a pressure ionization chamber and FP-54 Pliotron, first with the sample directly exposed to the ionization chamber, then with the sample covered with 1.5 cm of paraffin, this being sufficient to stop all electrons encountered here. For calibration purposes two artificial radioactive substances are available, radio-nitrogen produced by deuteron bombardment of carbon which emits only positrons, and radio-phosphorus produced by deuteron bombardment of phosphorus which emits only electrons. Neither substance is known to emit any gamma-rays.

Samples of these two substances were measured with the ionization chamber, first with the sample bare, then covered with paraffin. For the radio-nitrogen (positron emitter) the ratio of ionization with the sample bare to that with it covered was found to be about twenty, while with the radio-phosphorus (electron emitter) this ratio was found to be over a thousand. Therefore if a sample emitting both positrons and electrons but no gamma-rays is examined in this way, the ionization observed with the sample bare is a measure of the sum of the two activities while that observed with the sample covered when multiplied by the factor twenty is a measure of the positron activity alone. For the copper sample, this ratio was found to be about sixty, indicating twice as many electrons as positrons. As mentioned above, the half-life of both positron and electron activities was found to be exactly the same, a more exact measurement giving the value 12.8 ± 0.1 hours.

Next the excitation curves for the two activi-

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[1] Lawrence, McMillan and Thornton, Phys. Rev. **48**, 493 (1935).
[2] Amaldi, d'Agostino, Fermi, Pontecorvo, Rasetti and Segrè, Proc. Roy. Soc. **A149**, 522 (1935).

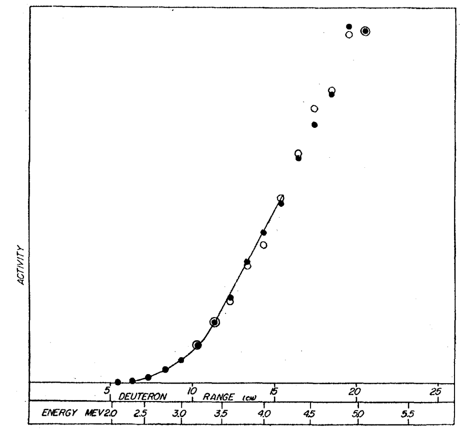

FIG. 1. Excitation curve of Cu^{64} by deuterons. Open circles, positrons; black circles, total (+ and −); line, Oppenheimer and Phillips theory.

ties were determined by the method of bombarding a stack of thin copper foils. The foils used had an average stopping power of 9 mm. They were measured individually with alpha-particles and the corrections given by Mano[3] for the variation of stopping power with velocity were applied. In this case the deuteron beam had a range of 21 cm, the current was 4 μa, and the time of bombardment one hour. Fig. 1 shows the excitation curves so obtained, the open circles representing the positron activity alone, and the solid circles the combined activity. The ordinates have been adjusted to agree at the highest energy point. The curve is the theoretical expression given by Oppenheimer and Phillips[4] with the binding energy of the deuteron set equal to 2.1 Mev. It has been adjusted to fit at its high end, 4.2 Mev, this being the upper limit of the calculations given by Oppenhiemer and Phillips.

Next another solid copper target was bombarded and placed in a hydrogen-filled Wilson chamber which was traversed by a magnetic field. Photographs were taken of the tracks, and their radius was measured by reprojection. These results are shown in Fig. 2 as a histogram, the solid line representing the electrons and the dotted line the positrons. In this series of pictures there were 557 negatives and 353 positives, this ratio agreeing with the ionization chamber analysis as closely as could be expected. These results were analyzed by the method described by Kurie, Richardson and Paxton[5] on the basis of the Konopinski-Uhlenbeck modification of the Fermi theory. The upper limits so found, 0.79 Mev for the positives and 0.83 Mev for the negatives, are indicated on Fig. 2. The straight line plots given by this method of analysis are shown in Fig. 3. It will be noted that the fit is about the same for positives and negatives on these straight line plots but that the histograms are somewhat different in form, that for the positives having its maximum at a slightly higher energy. This is the result of the action of the positive charge of the nucleus, and is noticeable because the emitted particles have comparatively low energy.

Since stable isotopes of both nickel and zinc of mass 64 have been reported,[6] it seems that these observations can best be explained by assuming that radio-copper of mass 64 can disintegrate in either of two ways, going to zinc with the emission of an electron, or to nickel with the emission of a positron. The activity

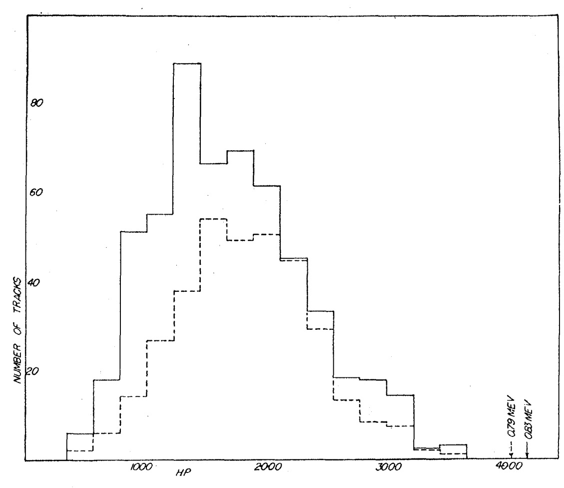

FIG. 2. Distribution of $H\rho$ of positrons and electrons from Cu^{64}. Positrons, broken line; electrons, solid line.

[3] Mano, J. de phys. et rad. **5**, 628 (1934).
[4] Oppenheimer and Phillips, Phys. Rev. **48**, 500 (1935).
[5] Kurie, Richardson and Paxton, Phys. Rev. **49**, 368 (1936).
[6] Aston, *Mass Spectra and Isotopes;* de Gier and Zeeman, Proc. K. Akad. Amsterdam **38**, 8, 810 (1935); Dempster, Phys. Rev. **50**, 98 (1936).

reported by Fermi[2] with a half-life of 5 minutes would then be associated with the disintegration of radio-copper of mass 66, going to zinc 66 with the emission of an electron.

The yield of this reaction is about one atom of Cu^{64} in 5×10^6 deuterons of 5.1 Mev energy.

In conclusion, I wish to express my thanks to Professor Lawrence for the privilege of working in the laboratory, to the other members of the Radiation Laboratory for help and advice, in particular to Dr. Kurie for the Wilson chamber photographs, and to the National Research Council for financial support. Support of the laboratory work by the Research Corporation, the Chemical Foundation, and the Josiah Macy, Jr. Foundation is also gratefully acknowledged.

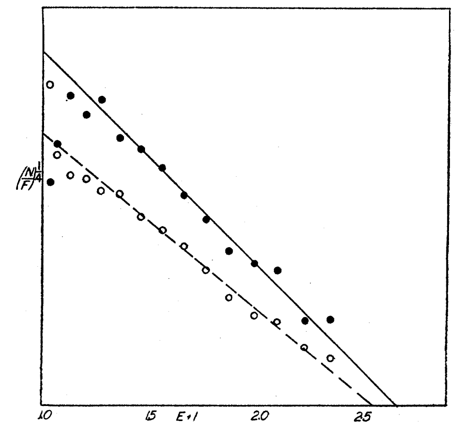

FIG. 3. Analysis of Cu^{64} positrons and electrons for upper limit. Copper K-U plot. Open circles, positrons; black circles, electrons.

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On the Slowing Down of Neutrons in Water

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The diffusion of neutrons in water is considered, and a simple method is given which permits an approximate estimation of initial neutron energies when the final energy and the mean square distance of travel are known.

If we have a source of neutrons in water the escaping particles collide with the surrounding molecules. The free paths between successive collisions form zig-zag trajectories, and there is a tendency to keep the forward direction because the mean scattering angle is small. Fermi[1] has considered this case in detail and found that the relation between distance traveled, r, mean free path, λ, and the number of collisions, a, is given by the formula

$$(r^2)_{\text{av}}=2\Big\{\lambda^2(0)[1+\rho(0)]+\int_0^a\lambda^2(x)[1+\rho(x)]dx+\lambda^2(a)[1+\rho(a)]$$

$$+\frac{\lambda(0)}{1+\rho(0)}\int_0^a\lambda(x)\exp\Big[-x/2-\int_0^x\rho(\xi)d\xi\Big]dx+\frac{\lambda(0)\lambda(a)}{1+\rho(0)}\exp\Big[-a/2-\int_0^a\rho(x)dx\Big]$$

$$+\lambda(a)\int_0^a\frac{\lambda(x)}{1+\rho(x)}\exp\Big[-(a-x)/2-\int_x^a\rho(\xi)d\xi\Big]dx+\int_0^a\frac{\lambda(x)dx}{1+\rho(x)}\int_0^{a-x}\lambda(x+\xi)$$

$$\times\exp\Big[-\xi/2-\int_0^\xi\rho(x+\zeta)d\zeta\Big]d\xi\Big\},\quad\Big(\lambda=\frac{1}{N_H\sigma_H+N_0\sigma_0},\quad\rho=\frac{N_0\sigma_0}{N_H\sigma_H}.\Big)\qquad(1)$$

[1] E. Fermi, Ric. Scient. July, 1936.