Nuclear Transformations Produced in Copper by Alpha-Particle Bombardment

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The radioactivity produced by bombardment of copper with 11 Mev alpha-particles has been investigated. Activities having half-lives of 1.10±0.05 hours and 9.2±0.2 hours have been found to belong, respectively, to the radioactive isotopes of gallium Ga^{68} and Ga^{66}. Both these isotopes have been found to be positron active. Absorption measurements gave values of respectively 1.8 and 3.1 Mev for the maximum energies of the short and long period positrons. Measurements of the positron tracks photographed in a cloud chamber gave, however, corresponding values of 1.9 and 3.9 Mev. The excitation function for alpha-particles and copper has also been investigated.

COPPER has been bombarded with 11 Mev alpha-particles from the cyclotron in the Radiation Laboratory at the University of California. It exhibited a strong consequent radioactivity which decayed with two periods corresponding to half-lives of 1.10±0.05 hours and 9.2±0.2 hours. These values were determined with a quartz fiber electroscope.

Radioactive Products

The only probable reactions which would explain the production of two activities would involve the conversion of each of the isotopes of copper into a radioactive isotope of gallium by the capture of an alpha-particle and emission of a neutron. Such reactions would result in the transformation of Cu^{63} and Cu^{65} into the radioactive isotopes Ga^{66} and Ga^{68}. Accordingly, by the method of ether extraction from hydrochloric acid, a chemical separation was made for gallium from a sample of copper which had been activated by alpha-particle bombardment. Both the 1.10 and the 9.2 hour activities separated out with the gallium precipitate. The copper and zinc were precipitated from solution by hydrogen sulphide and showed no activity. By the following consideration of the results which have already been obtained for the radioactive isotopes of gallium it has been possible to assign the half-lives of 9.2 and 1.10 hours to Ga^{66} and Ga^{68}, respectively. Irradiating gallium with slow neutrons, Fermi and his collaborators[1] found activities having half-lives of 20 minutes and 23 hours. These activities correspond to the radioactive isotopes Ga^{70} and Ga^{72} formed by neutron capture, from the two stable isotopes Ga^{69} and Ga^{71}. It is not possible, however, to assign either of these two periods to the appropriate radioactive isotope. Bothe and Gentner[2] have, however, recently activated gallium using the 17 Mev γ-radiation produced by proton bombardment of lithium resulting in the ejection of a neutron from each of the two stable gallium isotopes. They found activities decaying with half-lives equal to 20 minutes and 60 minutes which must, therefore, correspond to the radioactive isotopes Ga^{70} and Ga^{68}, respectively. It is, therefore, possible to assign the half-life of 9.2 hours to the new radioactive isotope Ga^{66}.

Disintegration Positrons

Both the isotopes of gallium produced by alpha-particle bombardment of copper have been found to be positron active, resulting in the formation of Zn^{66} and Zn^{68}. Absorption measurements were made with the use of aluminum absorbers and the resultant curves are shown in Figs. 1 and 2. The former is for Ga^{68} (1.10 hours) and the end point gives, using Feather's empirical formula, a value of 1.8 Mev for the maximum energy of the positrons. The absorption curve for Ga^{66} (9.2 hours), shown in Fig. 2 gave an end point corresponding to positrons having a maximum energy of 3.1 Mev.

To confirm these results, Dr. H. C. Paxton kindly took a series of Wilson photographs of the positrons emitted, using a cloud chamber fitted with a thin mica window at one side. Immedi-

[1] E. Amaldi *et al*, Proc. Roy. Soc. **A149**, 522 (1935).

[2] W. Bothe and W. Gentner, Naturwiss. **25**, 191 (1937).

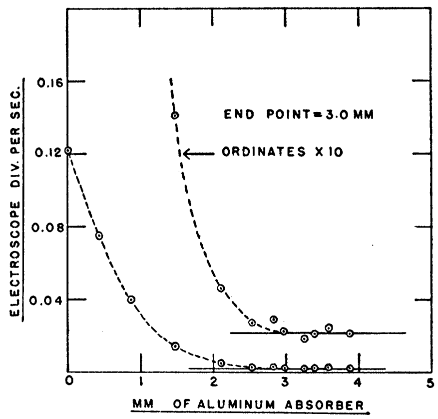

FIG. 1. Copper+11 Mev alpha-particles. Absorption curve for positrons emitted by radioactive Ga^{66} (half-life 1.10±0.5 hours). End point corresponds to an energy of 1.8 Mev.

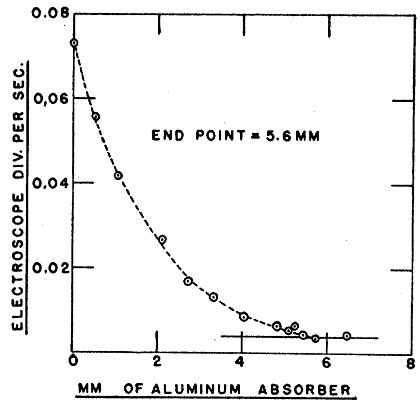

FIG. 2. Copper+11 Mev alpha-particles. Absorption curve for positrons emitted by radioactive Ga^{66} (half-life 9.2±0.2 hours). End point corresponds to an energy of 3.1 Mev.

ately after bombardment the copper specimen, consisting of a small piece of foil, 0.001 in. thick, was placed about 4 cm from the mica window of the cloud chamber; part of the specimen was covered in order to reduce the intensity, and 114 photographs were taken. From these 351 positron tracks were measured and their energy distribution is shown plotted in Fig. 3. No correction for the long period activity has been made. Eighteen minutes were required for taking the photographs during which time the intensity of the short period activity was of the order of ten times the intensity due to the long period activity. The end point shown in Fig. 3 corresponds to positrons of 1.81 Mev energy, which when corrected for the stopping power of the mica window, equivalent to about 0.05 Mev, gives a value of 1.9 Mev for the maximum energy of the disintegration positrons.

Twelve hours after bombardment a further series of 140 photographs was taken, the specimen this time being held close to the mica window of the cloud chamber. The activity due to the short period would now have decayed to about one-fiftieth the intensity of that due to the long period. Three hundred tracks were measured and plotted and gave an end point at $H\rho$ equal to 14,300 gauss cm and a minimum at $H\rho$ equal to about 5000 gauss cm. The end point corresponds to a positron energy of 3.81 Mev. Another series of 150 photographs of these high energy positrons was taken twenty-seven hours after bombardment. From these 450 tracks were measured and the results are given in the histogram shown in Fig. 4. The minimum in the neighborhood of $H\rho$ equal to 5000 gauss cm is still apparent. From these measurements, which were primarily concerned with determining the maximum energy of the positrons, it cannot be said with certainty whether this minimum is real and the spectrum complex. The end point in Fig. 4, at $H\rho$ equal to 14,500 gauss cm, corresponds to a positron energy of 3.87 Mev. Correcting the values of 3.81 and 3.87 Mev for the decrease in energy of about 0.05 Mev, due to the mica window, gives a value in each case of 3.9 Mev. This value is not in very good agreement with the value of 3.1 Mev given by the absorption measurements with the use of Feather's formula. An energy of 3.1 Mev would correspond to an end point at $H\rho$ equal to 11,900 gauss cm. On the other hand, an energy of 3.9

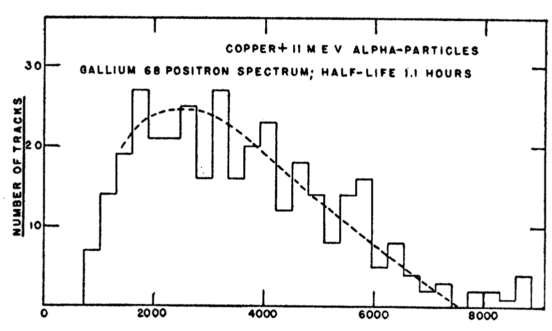

FIG. 3. Positron spectrum for Ga^{68}. End point corresponds to energy of 1.9 Mev.

Mev would correspond to an end point at 7.0 mm of aluminum in Fig. 2.

Excitation Function

Finally measurements were made for the purpose of determining the excitation function of copper. A preliminary experiment was made in which a pile of ten copper foils, each 0.0001 in. thick, were exposed so that the alpha-particle beam fell normally on the first foil. Only the first five foils were found to be active.

A second experiment was performed with five 0.0001 in. copper foils and the activities were followed on an electroscope for 35 hours. The stopping power of the foils was determined by observing visually the decrease in range of the alpha-particle beam in air on introducing the five foils into its path. The range was found to be decreased by 5 cm and, accordingly, it was assumed that each foil was equivalent to 1 cm of air. The range of the beam in air was 11.5 cm.

The results for the short and long periods were corrected to infinite bombardment (after twenty minutes bombardment the first foil showed initial activities of 1.5 and 0.165 electroscope divisions per second for the short and long periods, respectively) and are shown plotted in Fig. 5. The preliminary results are also shown by the diagonal crosses in Fig. 5; these preliminary results have been adjusted by multiplying the ordinates by a factor of 2.39 in order to bring them to the same scale as the subsequent results. A Gamow excitation function of the form

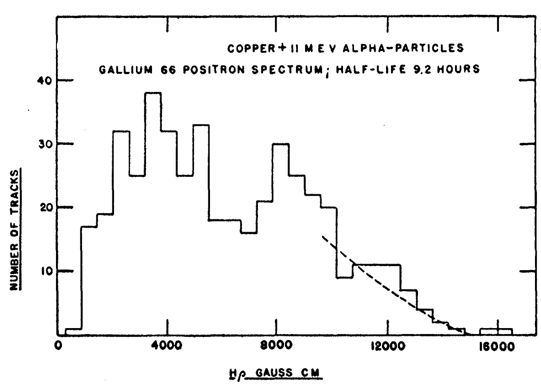

Fig. 4. Positron spectrum for Ga^{66}. End point corresponds to energy of 3.9 Mev.

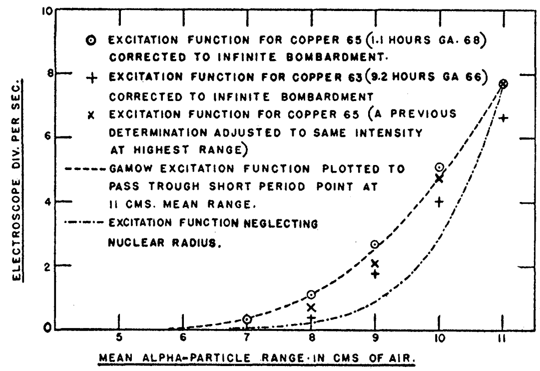

Fig. 5. Excitation function; copper+alpha-particles.

$$G\alpha \frac{1}{E} \exp -\left\{\frac{4Ze^2}{\hbar v}(2u-\sin 2u)\right\},$$

where $\cos^2 u = r_0E/2Ze^2$ has been fitted to the experimental data. E is the energy of the alpha-particles of velocity v while r_0 and Z are the radius and atomic number, respectively, of the bombarded nucleus. The curve shown in Fig. 5 is for r_0 equal to 7×10^{-13} cm. Shown also for comparison is the curve obtained taking r_0 equal to zero. The shape of the curve is quite sensitive to changes in r_0 in the neighborhood of r_0 equal to 7×10^{-13} cm. Thus for r_0 equal to 6×10^{-13} and 8×10^{-13} cm the ordinates at 9 cm mean range are, respectively, equal to 1.9 and 3.9 electroscope divisions per second.

In conclusion I should like to express my thanks to Professor E. O. Lawrence for extending to me the facilities of the Radiation Laboratory and to him, to Professor J. R. Oppenheimer and to the staff of the Radiation Laboratory for so much friendly help and cooperation. I would also thank the Commonwealth Fund of New York for making possible my sojourn here. The research has also been aided by grants to the laboratory from the Research Corporation, the Chemical Foundation and the Josiah Macy, Jr. Foundation.