Proton Induced Radioactivities

II. Nickel and Copper Targets

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Nickel bombarded with 6.3-Mev protons shows activities of half-lives of 10.5±0.6 min., 3.4±0.3 hr., and 12.8±0.8 hr., corresponding to known periods of Cu^{62}, Cu^{61} and Cu^{64}, respectively. The reactions are principally of the *p-n* type but there is evidence that in the case of Cu^{62} proton capture occurs at energies below the *p-n* threshold. The maximum β-ray energies obtained by absorption method are 2.8, 1.2 and 0.68 Mev for Cu^{62}, Cu^{61} and Cu^{64}, respectively. Thick target excitation curves are given. Copper bombarded with 6.3-Mev protons shows two activities of half-lives 38.3±0.5 min. and 235±20 days due to Zn^{63} and Zn^{65}, respectively. Both must be formed by *p-n* reactions. The Zn^{63} positrons have a maximum energy of 2.3±0.15 Mev. Thick target excitation curve shows a threshold proton energy of 4.1±0.1 Mev in good agreement with the energy relations. Average (thick target) cross section for the $Cu^{63}(p\text{-}n)Zn^{63}$ reaction is 0.28×10^{-25} cm². For protons of energy 6.1 Mev it is 0.95×10^{-25} cm.

INTRODUCTION

THIS work is a continuation of the studies[1] being made in this laboratory of the nuclear reactions produced by high energy protons. The present paper summarizes the results obtained when targets of nickel and copper are bombarded by protons of energies up to 6.3 Mev accelerated in the cyclotron. The proton beam currents were of the order of 0.5μa which is sufficient to produce large activities. Thus a 30-minute bombardment of a copper target by this beam produces an initial activity of about one millicurie and with the ionization chamber and d.c. amplifier this activity (38 min.) can be followed for about 16 half-lives.

I. RADIOACTIVE CU FROM NI TARGETS

Periods

Nickel bombarded with 6.3-Mev protons shows Cu activities with half-lives of 10.5±0.6 min., 3.4±0.3 hr., and 12.8±0.8 hr. (cf. Fig. 1). The 10.5-minute positron emitting activity has been shown by Heyn,[2] Bothe and Gentner[3] and Ridenour and Henderson[4] to be due to Cu^{62}. The 3.4-hour positron emitting activity has been shown by Ridenour and Henderson[4] to be due to Cu^{61}. Each of these could be formed either by a proton-neutron (*p-n*) reaction or by proton capture. The 12.8-hour period is known[5] to be assigned to Cu^{64} which can be formed only by the *p-n* reaction.

The absorption curves in aluminum of the positrons emitted by Cu^{62} and Cu^{61} show maximum positron energies[6] of 2.8±0.3 and 1.2±0.2 Mev respectively (cf. Figs. 2 and 3). Cu^{64} decays as a branch reaction,[5] emitting either a positron going to Ni^{64} or an electron going to Zn^{64}. Cloud-chamber photographs of the β-rays from an aged sample showed 210 electron tracks and 138 positron tracks giving a branching ratio of 1.5 electrons per positron, in agreement with VanVoorhis'[5] data. Absorption measurements (Fig. 3) show a maximum energy of 0.68±0.1 Mev, also in agreement with VanVoorhis' cloud-chamber data, which showed about the same energy for positrons and electrons.

Excitation curves

Thick target excitation data were obtained by bombarding identical targets for the same length of time with known proton currents, reducing the beam energy in steps by aluminum foils of known stopping power. The decay curves were followed

[1] L. A. DuBridge, S. W. Barnes, J. H. Buck and C. V. Strain, Phys. Rev. **53**, 447 (1938).
[2] F. A. Heyn, Nature **138**, 723 (1936).
[3] W. Bothe and W. Gentner, Naturwiss. **25**, 90 (1937).
[4] L. N. Ridenour and W. J. Henderson, Phys. Rev. **51**, 1102 (1937).
[5] S. N. VanVoorhis, Phys. Rev. **50**, 895 (1936).
[6] The relation obtained by E. E. Widdowson and F. C. Champion, Proc. Phys. Soc. **50**, 185–195 (1938), was used to obtain the maximum energies from the aluminum ranges of the beta-rays.

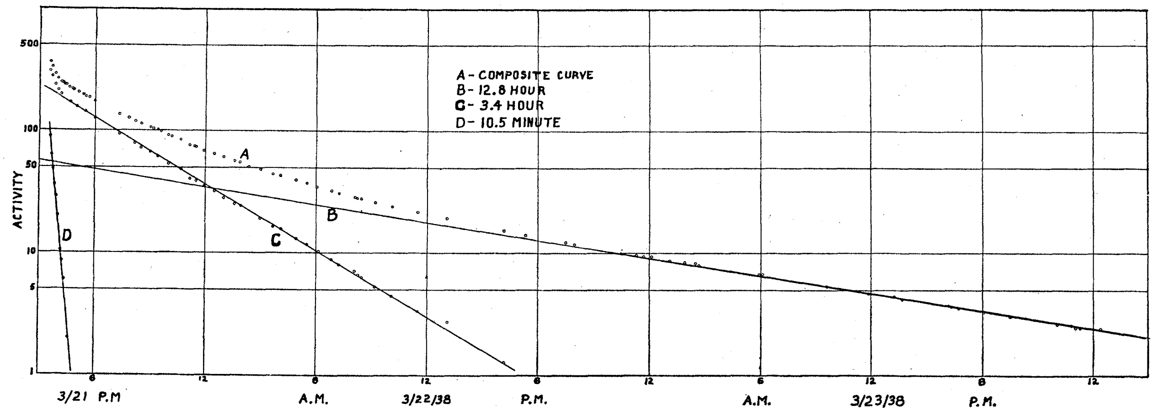

FIG. 1. Decay of radioactivity induced by protons in Ni targets.

to obtain the activity associated with each period. The initial activities corrected to infinite bombardment are shown as a function of proton energy in Fig. 4. Since Cu^{64} can be formed only by a proton-neutron reaction in this case the excitation curve is that for the single process, Ni^{64} (p-n) Cu^{64}. The theoretical threshold[7] for this reaction is rather low (2.5 Mev). Some activity could be detected below three Mev but it was weak because of the low penetration factor and the low abundance of Ni^{64}. A consideration of the stable isotopes of nickel shows that both Cu^{61} and Cu^{62} might be formed by either a proton-neutron reaction or by simple proton capture. Although at sufficiently high energy the p-n reaction seems more probable, it is interesting to determine whether the capture process does occur. This can be done by determining whether Cu^{62} is formed below the p-n threshold. In the case of Cu^{62} the positron energy is 2.8 ± 0.3 Mev and hence the threshold[7] for the p-n reaction must be 4.6 ± 0.3 Mev. However, the excitation curve for this period (Fig. 4) shows activity at proton energies below three Mev. This must be ascribed either to the occurrence of proton capture or to contamination. Carbon impurity from which N^{13} (11.0-min. half-life) is formed is suggested and no other impurity of the correct half-life seems possible. The positron absorption curves, however, for samples activated at four Mev and at six Mev were the same within limits of error (Fig. 2), and showed no evidence of the much softer (1.25-Mev) positrons from N^{13}. It is evident then that the Cu^{61} (p-γ) reaction is occurring at low energies, though the activity rises sharply above 4.6 Mev where the p-n reaction sets in. The cross section for capture at four Mev is approximately 0.7 percent of the total cross section at 6.3 Mev when corrected for isotopic abundance.

In the case of Cu^{61} the predicted threshold is 2.9 Mev (positron energy 1.1 Mev) and our data show no detectable activity below three Mev. However, White, Delsasso, Sherr and Ridenour[8]

[7] For a discussion of the energy relation see reference 1.

[8] M. G. White, L. A. Delsasso, Rubby Sherr and L. N. Ridenour, Phys. Rev. 54, 314 (1938).

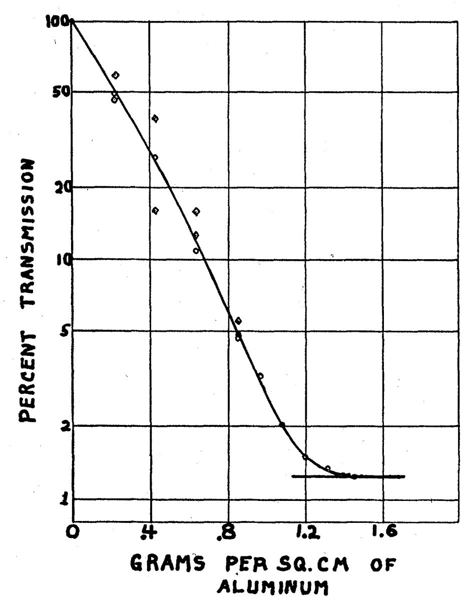

FIG. 2. Absorption curve in Al for Cu^{62} positrons. Circles are for nickel sample bombarded at 6.3 Mev. Squares are for nickel sample bombarded at 4.0 Mev.

find that Cu^{61} (3.4 hr.) is formed by protons of energy less than 1.9 Mev. However, they also report a low value (2.1 Mev) for the threshold of the Ni^{64} (*p-n*) Cu^{64} reaction which has a computed threshold of 2.5 Mev, which is difficult to understand. However, even if one assumes that their energy values are 0.4 Mev low there is still evidence that proton capture is effective in forming Cu^{61}.

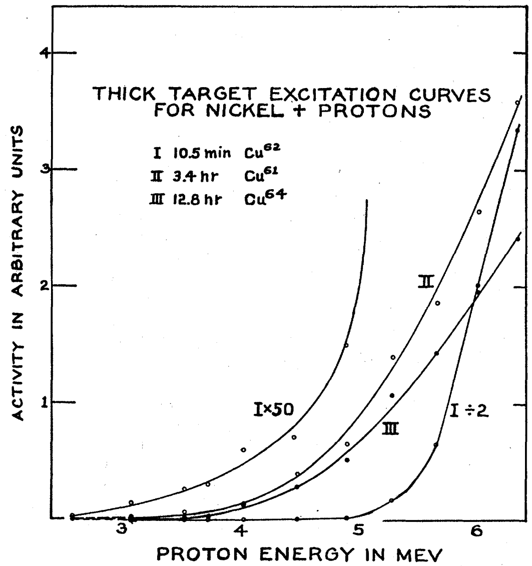

FIG. 4. Thick target excitation curves for Cu isotopes.

Cross section

The d.c. amplifier and ionization chamber were calibrated as follows. The deflection produced by one beta-particle per second traversing the chamber was computed from the depth of the chamber, the specific ionization of the particle and the measured current sensitivity of the amplifier. The effective solid angle subtended by the chamber was measured and the number of beta-particles per second, emitted in all directions, required to produce a centimeter deflection was computed. This ranged from 80 to 160 β/sec. depending upon the β-ray energy. This value was checked with a standard uranium source. With this calibration and with the value of the stopping power of nickel for protons computed from the data of Livingston and Bethe[9] the cross sections for the reactions for protons of energy between 0 and 6.3 Mev and also for energy between 6.0 and 6.3 Mev were computed. The results are given in Table I.

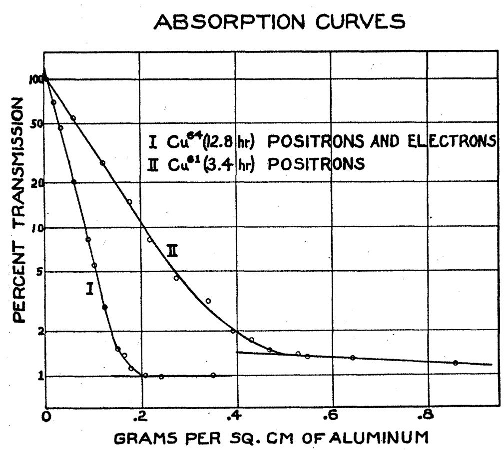

FIG. 3. Absorption curve in Al for Cu^{61} and Cu^{64} β-rays.

The value for Cu^{61} and Cu^{64} are uncertain since the isotopic abundances of Ni^{61} and Ni^{64} are not well known. Also it is assumed that proton capture plays a negligible role. Consequently the values for Cu^{61} and Cu^{62} may be high. Cu^{61} will be affected most since the isotopic abundance of Ni^{60} is approximately 30 times that of Ni^{61}.

RADIOACTIVE Zn ISOTOPES FROM Cu TARGETS

For short proton bombardments of copper a strong activity is observed with a half-life of

[9] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 261–272 (July, 1937).

TABLE I. *Proton induced radioactivities in* Cu *and* Zn.

Assumed Process	Half-life	Yield* Rad. atoms per 10^6 protons: Obs.	Yield* Rad. atoms per 10^6 protons: For single isotope	Cross section† $\times 10^{25}$ cm²: Av.	Cross section† $\times 10^{25}$ cm²: 6.3–6.0 Mev
Ni^{61}(*p-n*)Cu^{61} (and Ni^{60}(*p*-γ)Cu^{61})	3.4 hr.	0.48	29.	0.29	1.05
Ni^{62}(*p-n*)Cu^{62} (and Ni^{61}(*p*-γ)Cu^{62})	10.5 min.	1.11	30.	0.30	1.50
Ni^{64}(*p-n*)Cu^{64}	12.8 hr.	0.24	26.	0.26	0.78
Cu^{63}(*p-n*)Cn^{63}	38.3 min.	18.4	27.	0.28	0.95

* For a thick target at 6.3 Mev.

† Assuming *p-n* reactions.

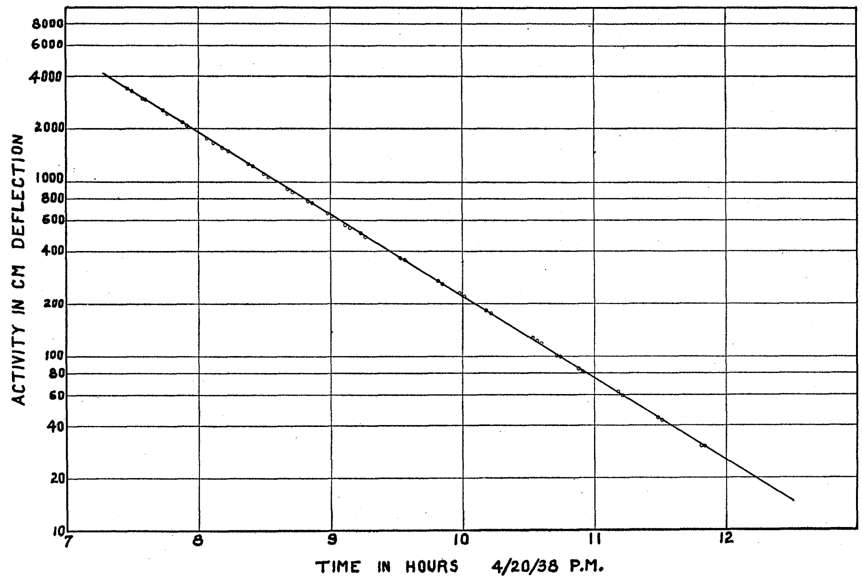

FIG. 5. Decay curve for Zn^{63}. Copper+protons.

38.3±0.5 min. (cf. Fig. 5). The absorption curve for the positrons emitted (cf. Fig. 6) show a maximum energy of 2.3±0.15 Mev. This activity has been shown by Pool, Cork and Thornton[10] and by Bothe and Gentner[11] to be due to either Zn^{63} or Zn^{65}. However, a long lived activity has since been definitely assigned to Zn^{65} and consequently the 38-minute activity can be assigned to Zn^{63}.

The thick target excitation curve is shown in Fig. 7. The samples showed no detectable contamination and only the Zn^{63} period is excited in short bombardments so that it was possible to fix the proton threshold energy at 4.1±0.1 Mev. This is in agreement with the computed threshold of 4.17±0.17 Mev. The cross section for this

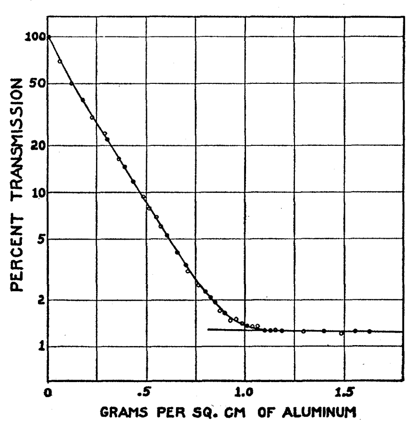

FIG. 6. Zn^{63} positron absorption curve.

[10] M. L. Pool, J. M. Cork and R. L. Thornton, Phys. Rev. 52, 239 (1937).

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

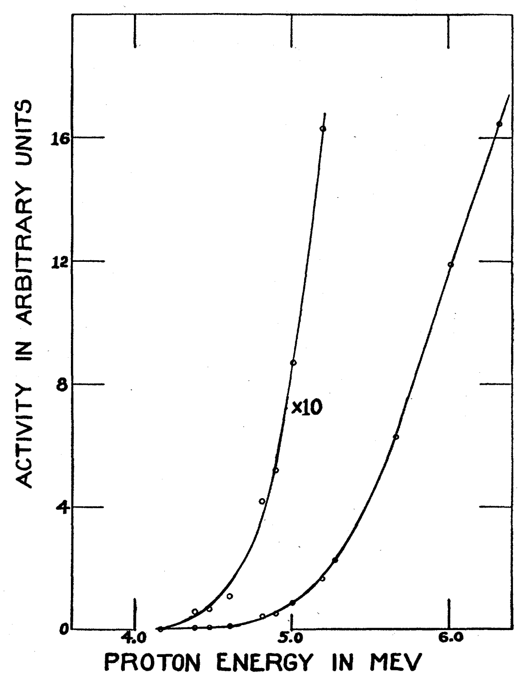

FIG. 7. Thick target excitation curve for $Cu^{63}(p\text{-}n)Zn^{63}$.

reaction for proton energies ranging from 6.0 to 6.3 Mev is 0.95×10^{-25} cm^2 (cf. Table I).

A long lived activity is observed in copper samples which have been subjected to long bombardments. The decay curve (cf. Fig. 8) shows a single half-life of 235 ± 20 days. A cloud-chamber investigation made by Mr. George Valley[12] shows that the radioactive decay takes place either by positron emission of K electron capture. The negative electrons which are observed are identified as internal conversion electrons. This same activity has been obtained by bombarding zinc with deuterons[13] and consequently must be assigned to Zn^{65}.

[12] A preliminary report was made by S. W. Barnes and George Valley, Phys. Rev. **53**, 946 (1938). A more detailed report will be published soon.

[13] J. J. Livingood and G. T. Seaborg, Phys. Rev. **54**, 239 (1938).

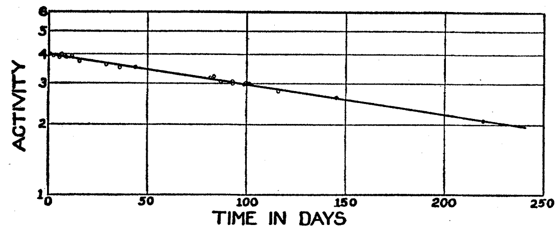

FIG. 8. Decay curve for Zn^{65}.

I wish to express my thanks to Professor L. A. DuBridge and Professor S. W. Barnes for advice given during the investigations, to Dr. J. H. Buck for help in bombarding samples and taking data, and to Mr. George Valley for the cloud-chamber photographs. The work has been supported in part by a grant from the Research Corporation.

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Proton Induced Radioactivities

III. Zinc and Selenium Targets

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Zinc bombarded with 6.5-Mev protons shows activities of half-lives 18.0 ± 0.5 min., 72 ± 4 min., 9.4 ± 0.2 hr., and 84.4 ± 2.0 hr., corresponding to the known periods of Ga^{70}, Ga^{68}, Ga^{66}, and Ga^{67}, respectively. In addition, a new period of 48 ± 2-min. half-life is observed and assigned to Ga^{64}. Thick target excitation curves are given for Ga^{64}, Ga^{68}, and Ga^{70}. Selenium bombarded with 6.3-Mev protons shows activities of half-lives 6.3 ± 0.2 min., 17.4 ± 0.5 min., 4.4 ± 0.3 hr., and 33 ± 1 hr., corresponding to the known periods of Br^{78}, Br^{80} (2) and Br^{82}, respectively. The previously observed discrepancy between the thresholds for the two Br^{80} activities and their maximum β-ray energies has been confirmed. Thick and thin targets excitation curves were obtained. The cross section for the production of the Br^{80} isomers by the Se^{80} (p-n) reaction are 0.82 and 0.22×10^{-25} cm^2 for the short and long periods, respectively, at a proton energy of 6.3 Mev. The ratio of these two cross sections rises from 3.6 at 6.3 Mev to over 200 at 3.2 Mev.

INTRODUCTION

THIS work is a continuation of the studies[1] made in this laboratory of the nuclear reactions produced by high energy protons. The present paper concerns the results obtained when targets of zinc and selenium are bombarded by protons of energies up to 6.5 Mev. Results with these targets have already been reported[1] for proton energies up to 3.8 Mev. Much larger yields are obtained with the higher energy beam and additional periods are produced. Further studies of the excitation functions have therefore been made, particularly for the Br^{80} isomers produced from Se.

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[1] DuBridge, Barnes, Buck and Strain, Phys. Rev. **53**, 447 (1938).

RADIOACTIVE Ga ISOTOPES FROM Zn

The complete decay curves for the radioactivity produced by 6.3-Mev protons in a pure