THE
PHYSICAL REVIEW
A Journal of Experimental and Theoretical Physics Established by E. L. Nichols in 1893
VOL. 55, NO. 2 JANUARY 15, 1939 SECOND SERIES

Artificial Radioactivity Produced by Protons

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(Received November 7, 1938)

The artificial radioactivity produced in targets of Cu, Ni, Ag, Cr and Mo by bombardment with four-Mev protons has been studied. In Cu, the (p, n) reaction gives rise to the radioelements Zn^{63} (half-life 38.5 min., upper limit of positron spectrum 1.8 Mev) and Zn^{65}. Two new radioactive isotopes of Cu are found in Ni bombarded with protons; they have tentatively been assigned as follows: Cu^{58}, half-life 81 sec., and Cu^{60}, half-life 7.9 minutes. Both emit positrons. Also produced in Ni are Cu^{61}, both by the (p, n) and the (p, γ) reaction (threshold <1.8 Mev), and Cu^{64}, by the (p, n) reaction (threshold apparently 2.1 Mev). Proton bombardment of Ag results in a radioactive Cd isotope which emits very soft negative electrons which are believed to be conversion electrons of a nuclear gamma-ray. The identification of the responsible Cd isotope and the mode of decay is discussed. The half-life of this radioelement is 6.7 hours; the threshold for the reaction is 2.4 Mev. 40-minute Mn^{51} is formed by proton bombardment of Cr. This radioelement emits positrons. Three unassigned activities produced in Mo have half-lives of 45 min., 2.7 hours, and 36.5 hours; the last emits negative electrons.

I. INTRODUCTION

WE HAVE studied in some detail the radioactive isotopes produced by bombarding targets of Cu, Ni and Ag with protons; the results are reported here, together with some incomplete data regarding the activities produced in targets of Cr, Mo and Mg.

The proton beam used in this work was produced by the Princeton cyclotron, the construction of which has been described elsewhere.[1] The mean energy of the beam was about 4.0 Mev (cf. Section II).

The activities are in all cases given in units of divisions per minute on a Lauritsen electroscope. One division per minute corresponds roughly to 6.6×10^{-3} microcurie, if one understands by a microcurie the amount of an artificial radioelement in which 3.7×10^{4} disintegrations per second occur, and neglects corrections which arise from the differences in energy of the electrons and positrons emitted from the various radioelements. These corrections will be of two sorts: the first concerns the absorbing power of the electroscope window for electrons of different velocities, while the second arises from the difference in specific ionization of fast and of slow electrons. No attempt has here been made to evaluate them. The window of the electroscope used here was a sheet of Al foil of thickness 2.4 mg/cm^2.

In several cases, a determination of the sign of the particles emitted by a radioelement was made by the usual method of deflection in a magnetic field, employing a thin-walled Geiger counter as detecting device.

Of the four nuclear reactions which are known to be produced by swift protons; namely, (p, γ),

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[1] M. C. Henderson and M. G. White, Rev. Sci. Inst. 9, 19 (1938).

(p, n), (p, d), and (p, α), only the first two seem to have occurred in the cases we have studied. This is hardly surprising, in view of the fact that we have been working in the region of moderately high atomic number, where the potential barrier against the emission of charged particles is rather large. The energy conditions in the case of the (p, n) reaction are especially simple and interesting, and have been formulated explicitly by DuBridge and his collaborators.[2]

A (p, n) reaction followed by radioactive positron decay results in a final nucleus which is identical with the target nucleus; the energy evolved in the nuclear changes all has been supplied by the kinetic energy of the incident proton. The energy required is then, at the least (the neutron being emitted with negligible kinetic energy, and the emission of no gamma-rays being assumed), the difference between n^1 and H^1 mass (0.8 Mev) plus the mass of two electrons (1.0 Mev) plus the upper limit of the positron energy spectrum from the radioelement formed. The excitation function for such a reaction should then show an energy threshold somewhere above two Mev. Its position is definitely fixed by the positron energy in cases in which no gamma-radiation is emitted.

The case in which the radioactive nucleus formed by a (p, n) reaction decays by the capture of an extranuclear electron (presumably with the simultaneous emission of a neutrino) is somewhat similar to that mentioned above, except that the threshold energy for the reaction may be considerably smaller. Using the notation of DuBridge, we may represent the mass-energy relations in this case as follows:

$$Z^A+H^1+E_p=(Z+1)^A+n^1+E_n+\gamma_1 \\ =Z^A+\nu+E_\nu+n^1+E_n+\gamma_1+\gamma_2, \quad (1)$$

where E_p is the energy of the bombarding proton, E_n the energy of the emitted neutron, ν represents the neutrino rest mass (probably zero), E_ν is the energy of the neutrino, and γ_1 and γ_2 allow, respectively, for the formation of the nucleus $(Z+1)^A$ in an excited state, and for its decay into an excited state of the nucleus Z^A.

The minimum value of E_p will be that for which $E_n=\gamma_1=\gamma_2=0$. In this event,

$$E_{p0}=n^1-H^1+\nu+E_\nu=0.8+\nu+E_\nu \text{ Mev}. \quad (2)$$

When E_ν becomes larger than about one Mev, the process of positron decay will compete with that of extranuclear electron capture, so that we may expect thresholds for the production of radioelements which decay by the latter process alone to lie between proton energies of one and two Mev. At these energies, the penetration of charged particles into any but the lightest nuclei is likely to be rare, so that one may expect observational thresholds at energies higher than those predicted by energy considerations alone. Also, of course, one cannot say *a priori* that a disintegration in which $\gamma_1=\gamma_2=0$ will have a large enough probability to permit its observation. If, on account of selection rules, the transition from the nucleus $(Z+1)^A$ to the ground state of the nucleus Z^A is a "nonpermitted" one, while a transition to an excited state of the nucleus Z^A is "permitted," one may observe an energy threshold for the reaction higher than that given by Eq. (2) by the amount, γ_2, of excitation energy of the final nucleus.

II. "Excitation Function" Measurements

In several instances in the course of the investigation reported here attempts were made to measure the energy-yield curve for nuclear reactions by the method of stacked foils which, introduced at Berkeley, has become a standard technique for use with a cyclotron. In order to evaluate the results of such a measurement, it is necessary to know the distribution of energy of the particles composing the primary beam and the thickness of the foils used.

The distribution in range of the particles comprising the proton beam was determined by measuring the ion current to a collector housed in the main accelerating chamber vacuum as a function of the superficial mass of interposed sheets of Al foil. The curve so obtained is shown in Fig. 1. The conversion from range in Al to air range and from air range to energy is taken from data given by Livingston and Bethe,[3] as is the computation of the normal straggling.

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

[3] Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1927). Cf. pp. 266–85.

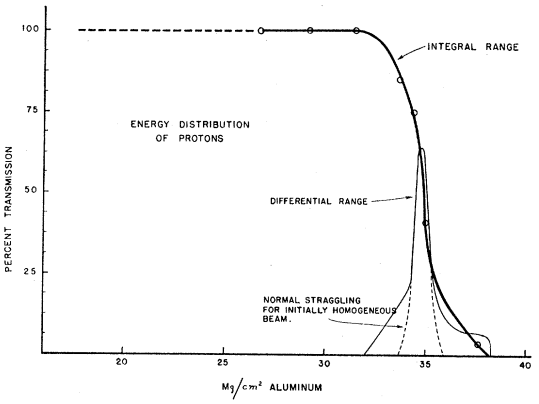

FIG. 1. Range distribution of the proton beam.

It is seen that the energy spread of the beam is a little more than twice that which would be introduced by the straggling of an initially homogeneous beam.

The causes of this broad energy distribution can be divided into two categories: (1) the energy spread inherent in the resonance acceleration method, and (2) irregularities in thickness of the aluminum stopping foils. The latter factor is difficult to evaluate, but visual inspection of the thinnest foils used indicates that a correction to the beam width as measured should be applied. Inhomogeneity of the beam energy due to the cyclotron can arise from the finite size of the ion source, variation of the beam energy with magnetic field setting (see Fig. 1 of reference 2), and broadening of the effective ion source center by magnetic field inhomogeneities. The differential range curve shown in Fig. 1 was obtained by graphical differentiation of the experimental curve, and comparison of it with the curve shown for normal straggling of an initially homogeneous beam suggests that about 75 percent of the particles in the beam are of very nearly the same energy.

Stacked-foil measurements were made in Cu, Ni and Ag; the energy thicknesses of the foils used ranged from 0.1 Mev to 0.2 Mev, depending upon the material of the foil and the energy of the protons incident upon it. The stopping power of the foils was computed from data given by Mano[4] in the case of Ag and Cu; the stopping power for Ni was computed from Mano's formulae to agree with data given by Rosenblum.[5]

Since the actual thicknesses of the rolled foils, as determined by careful weighing, differed somewhat even for foils which were nominally identical, correction for this was made by dividing the activity of any given foil by the superficial mass of the foil, and expressing the corrected activity as divisions/minute per mg/cm². This procedure neglects differences in the self-absorption of the several foils for the electrons each emits, but since the foils were all exceedingly thin and the differences small, the procedure was thought to be justified.

It is clear that the greatest caution must be exercised in interpreting the results of the stacked-foil measurements given here. The initial inhomogeneity of the beam is about 0.25 Mev, and this is rapidly increased by the effect of straggling as the beam passes through the foils; while the thickness of each foil is around 0.15 Mev. This means that, without making any allowance for straggling, the difference in energy between the most energetic proton incident on the front face of a foil and the slowest proton reaching the back face of the same foil is about 400 kev: more than twice as great as the energy thickness of a single foil. During long runs, unavoidable fluctuations in the "tuning" of the cyclotron magnet may introduce still larger variations in the energy distribution of the beam. As already remarked, there is evidence that the beam energy is dependent upon the magnet setting near resonance. Under the circumstances, it did not seem to be necessary to make the customary correction for "recoil" of activated atoms from the rear of one foil to the front of the next. The abscissae of the points actually plotted in the energy-yield curves here given represent the energy in the center of a particular foil of protons which initially had the mean energy of the beam.

One datum, however, can be obtained from the energy-yield curves given here; this is a lower limit for the energy threshold of a particular reaction. Having found the last foil which shows detectable radioactivity, we are fairly safe in saying that the most energetic protons which fell on the first inactive foil were incapable of

[4] Mano, J. de Phys. et Rad. **5**, 628 (1934).

[5] Rosenblum, Ann. de physique **10**, 408 (1928).

producing the reaction in question, within the limits set by the sensitivity of our measuring device. As has been mentioned in the last section, this datum is of particular interest in the case of the (p, n) reaction.

III. Experimental Results

A brief statement of preliminary results has already appeared.[6]

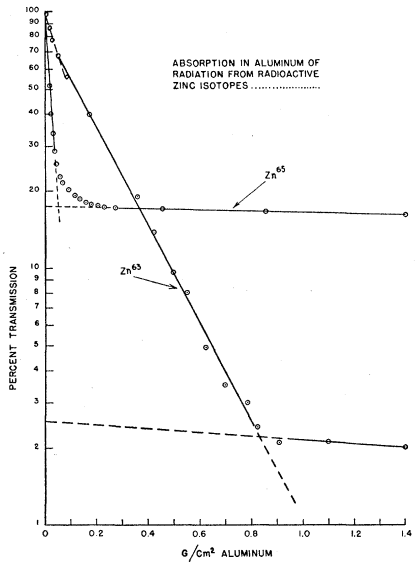

FIG. 2. Absorption curves for the radiation from Zn^{63} and Zn^{65}. The end points are, respectively, 0.82 and 0.20 g/cm², indicating maximum electron energies of 1.77 and 0.55 Mev. Note large intensity of gamma-rays from Zn^{65}.

A. Copper

The production of Zn^{63} by proton bombardment of Cu has already been reported.[6] Its half-life is 38.5 ± 0.8 min. The absorption in Al of the positrons emitted in the decay of Zn^{63} is shown in Fig. 2; their mass range is 0.82 g/cm², leading, by Feather's rule,[7] to an upper energy limit of about 1.8 Mev. The energy threshold to be expected for the reaction Cu^{63} (p, n) Zn^{63} is then 3.6 Mev, by the considerations of Section I. This is in good agreement with the value indicated by the method of stacked foils (see Fig. 3). Since, as mentioned in the preceding section, the points on the energy-yield curves here given represent the mean beam energy in the center of a given foil, while for the threshold energy we shall take the greatest incident energy on the first inactive foil, the threshold energy is somewhat greater than the zero-activity intercept of the line drawn through the plotted points.

Barnes and Valley[8] have found that a long lived radioelement is also produced by the proton bombardment of Cu. They reported the half-life to be about seven months and attributed the activity to Zn^{65}, formed by the reaction Cu^{65} (p, n) Zn^{65}. Both positrons and electrons are emitted, as well as an extremely intense gamma-ray. An absorption curve of the radiation emitted by this radioelement is shown in Fig. 2; the sample of Zn^{65} used for making this curve came from the side of one of the copper dees of the Princeton cyclotron, which had undergone many hours of proton bombardment. The absorption curve shows at least three components. By placing the radioactive sample in a magnetic field it was possible to show that the soft radiation consists largely of charged particles. Fairly intense x-radiation was found to exist in addition to the very intense gamma-ray. Internal conversion of the gamma-ray accounts for the negative electrons observed and the x-rays then arise from the subsequent filling of the K and L shells. Either positron emission or extranuclear

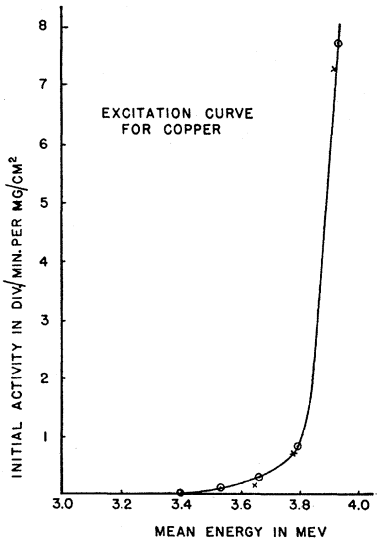

FIG. 3. Energy-yield curve for the reaction Cu^{63} (p, n) Zn^{63}. Crosses and circles represent two different runs. Threshold at 3.6 Mev.

[6] L. N. Ridenour, L. A. Delsasso, M. G. White and R. Sherr, Phys. Rev. **53**, 770 (1938).
[7] Feather, Phys. Rev. **35**, 1559 (1930).
[8] Barnes and Valley, Phys. Rev. **53**, 946 (1938).

electron capture will transform Zn^{65} into Cu^{65}; from the abnormally high ratio of gamma-rays to positrons, both processes seem to occur.

B. Nickel

As has been reported,[6] four different periods are found in the decay of Ni bombarded with protons (see Fig. 4). All have been chemically identified as due to isotopes of Cu. The two longer lived radioelements are readily identifiable as well-known radioactive Cu isotopes.

1. Cu^{64}:—An activity of half-life 12.8 hours, in which both positrons and negative electrons are emitted, is clearly caused by the familiar radioelement Cu^{64}. It can only be formed from Ni by proton bombardment in the reaction Ni^{64} (p, n) Cu^{64}, as the isotope Ni^{63}, from which Cu^{64} could be formed by proton capture, has not been reported to exist as a stable isotope. The energy-yield curve for this radioelement is shown in Fig. 5. The threshold energy for the reaction seems to be between 2.1 and 2.3 Mev, and certainly no higher. This is somewhat puzzling,

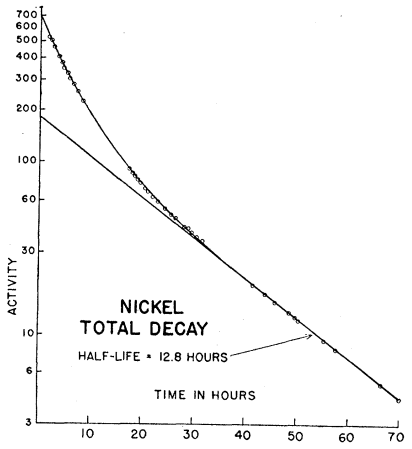

FIG. 4a. Decay curve for Ni bombarded with protons. The long periods—bombardment time 2.5 hours.

as Van Voorhis[9] gives the upper energy limit of the spectrum of the positrons as 0.7 Mev; from the simple considerations already given, one would expect that the energy threshold for this reaction would fall at $1.0+0.8+0.7=2.5$ Mev, at least for those Cu^{64} nuclei which are to emit positrons in their subsequent decay.

We consider the most likely explanation of this result to be the presence in the beam of a small number of high energy protons; protons whose initial energy was 4.2 Mev would reach the foil whose plotted point in Fig. 5 lies at an abscissa of 2.05 Mev with an energy of 2.46 Mev, so that any protons of initial energy higher than 4.2 Mev would contribute to the 12.8-hour activity of that foil. Presence in the bombarded foils of a spurious 13-hour activity caused by

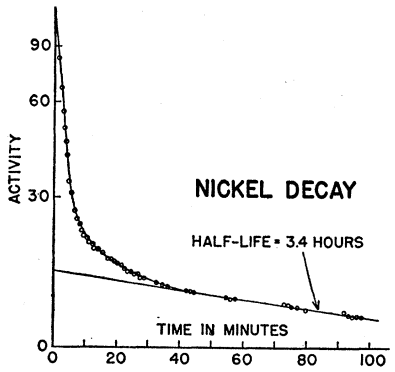

FIG. 4b. Decay curve for Ni bombarded with protons. The short periods—bombardment time 4 minutes.

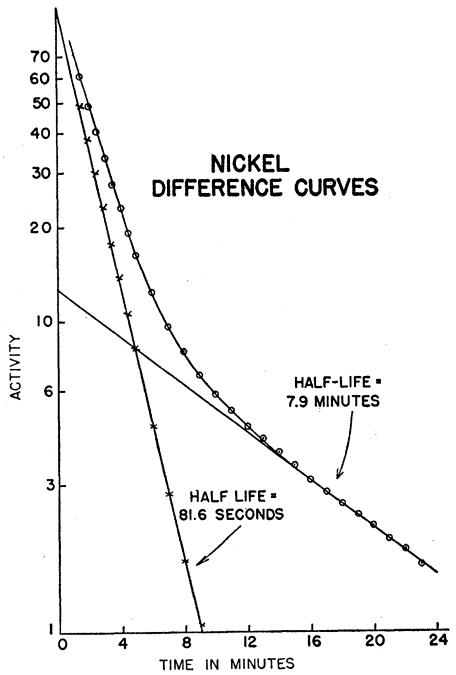

FIG. 4c. Decay curve for Ni bombarded with protons. Difference curves from data of Fig. 4b.

[9] Van Voorhis, Phys. Rev. **50**, 895 (1936).

the presence of a contaminant of unknown nature is considered unlikely.

Because confirmation of this result by other workers has not been made, it is not yet profitable to discuss the possible explanations which could be offered in case the threshold is really too low. Two present themselves at once: (1) Ni^{63} is stable but rare, so that at low energies the Ni^{63} (p, γ) Cu^{64} reaction could take place, and (2) the agreement in half-lives for the emission of positive and negative electrons by Cu^{64} is merely fortuitous, Cu^{64} really being an isomeric nucleus in the usual sense. In this case, a categorical statement regarding the energy threshold for the production of the Cu^{64} nuclei which are to emit negative electrons could not be made on the basis of a measurement of the energy spectrum of the negative beta-particles alone.[2] Below 2.5 Mev, then, one would form the Cu^{64} isomer which emits negative electrons; above 2.5 Mev, both the positron-emitting and the negative electron-emitting isomers would be formed. Both these alternatives seem very unlikely.

2. Cu^{61}:—A nickel target bombarded with protons displays a strong activity of half-life 3.4 hours, in which positrons are emitted. Clearly, this is the well-known radioelement Cu^{61}, chemical tests having demonstrated that it is isotopic with Cu. Both Ni^{60} and Ni^{61} are stable isotopes of nickel, so that this radioelement could be formed either by the reaction Ni^{60} (p, γ) Cu^{61} or by the reaction Ni^{61} (p, n) Cu^{61}. The upper limit of the positron energy spectrum from Cu^{61} is 0.9 Mev,[10] so that the threshold for the (p, n) reaction can be expected to lie at 2.7 Mev. A sharp rise in the energy-yield curve for this reaction at the expected energy (Fig. 5) bears out this interpretation. The production of Cu^{61} below 2.7-Mev proton energy is doubtless entirely because of proton capture in Ni^{60}.

Two short periods for positron emission are also found in the decay of nickel bombarded with protons. These have both been shown chemically to be isotopes of Cu. Their periods are 81 ± 2 seconds and 7.9 ± 0.5 minutes. We have found no evidence of the formation of the radioelement Cu^{62} (half-life 10.0 minutes) by the reaction Ni^{62} (p, n) Cu^{62} or by proton capture in Ni^{61}. Strain and Buck[11] have reported its formation at a proton energy of six Mev, which presumably indicates that the energy threshold for the reaction lies above four Mev and below six Mev.

The short period activities reported here cannot be assigned unambiguously without their discovery in other reactions. They are presumably formed either by proton capture or by the (p, n) reaction, and, neglecting the possibility of nuclear isomerism because none of the known radioactive isotopes of Cu has been found to be isomeric, they may belong to Cu nuclei of mass number 58, 59, or 60. We have suggested[6] the tentative assignment of the 80-second period to Cu^{58} and the 7.9-minute period to Cu^{60}, on the extremely doubtful basis of relating the activity ratio of the two radioelements to the abundance ratio of Ni^{58} to Ni^{60}.

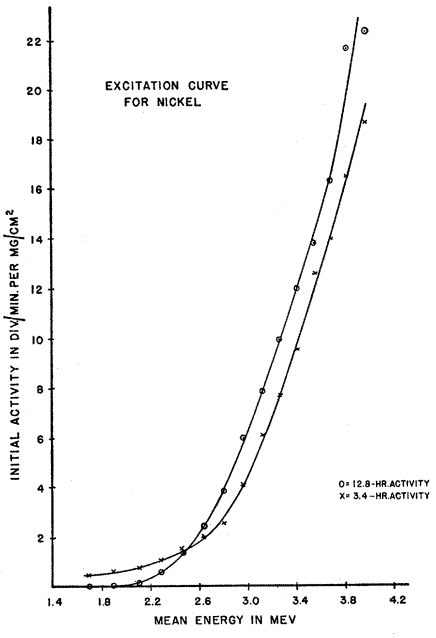

FIG. 5. Energy-yield curves for the long period radioelements produced by proton bombardment of Ni. Crosses —Cu^{61}; circles—Cu^{64}.

C. Silver

The strongest activity we have found to be produced by proton bombardment at our energy of four Mev is the 6.7-hour period in Ag. This activity has been shown chemically to be caused by an isotope of Cd, and the radiation which is

[10] L. N. Ridenour and W. J. Henderson, Phys. Rev. **52**, 889 (1937).

[11] Strain and Buck, Phys. Rev. **53**, 943 (1938).

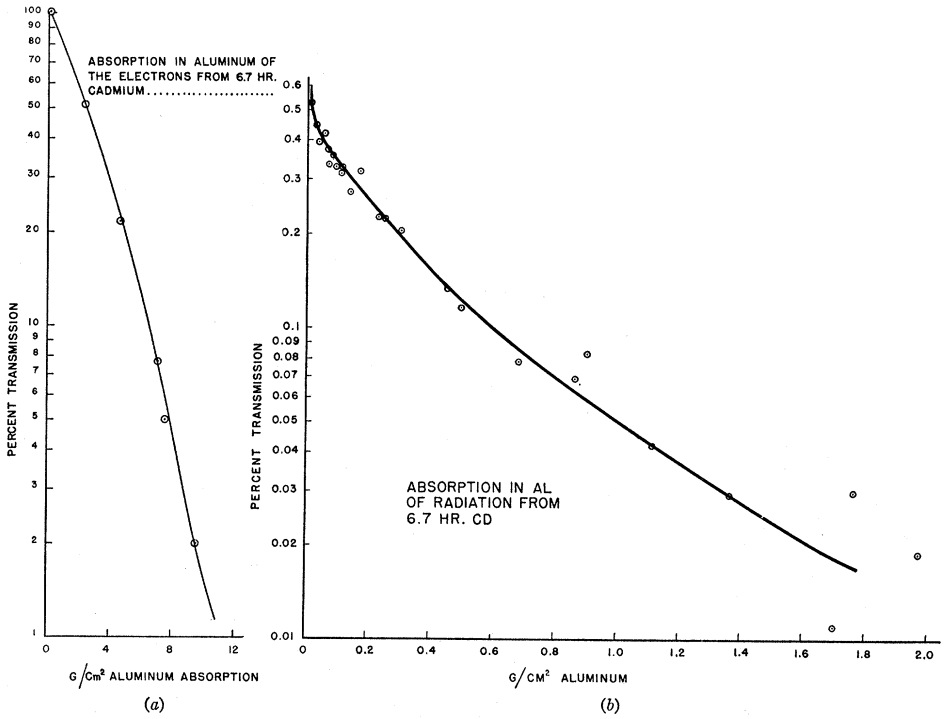

FIG. 6. Absorption in Al of the radiations from the 6.7-hour Cd isotope produced by bombarding Ag with protons. (*a*) Soft component. Mass range of electrons 12 mg/cm², corresponding to an energy of about 90 kev. (*b*) Absorption curve at large absorber thicknesses. While the curve cannot be properly resolved, it is seen to consist of a very weak hard radiation, together with a radiation for which the mass absorption coefficient lies between 2 and 3, corresponding to x-rays of wave-length 0.51 to 0.57A.

emitted is mainly negative electrons of extremely feeble penetrating power. Fig. 6 shows the absorption in Al of this radiation. A weak component of greater penetrating power has a mass absorption in Al which is about that of the *K* radiation of Ag, while there is some indication of a harder radiation still which is of very small intensity.

Now the Cd isotopes which can be formed by proton bombardment of Ag (whose two stable isotopes are Ag^{107} and Ag^{109}) have mass numbers 107, 108, 109 and 110. Indium, to which a radioactive Cd emitting negative disintegration electrons would decay, has stable isotopes of mass numbers 113 and 115. In the absence of any evidence for a chain of disintegrations (see decay curve, Fig. 7), we may assume that the negative electrons emitted are not disintegration electrons, but conversion electrons of a nuclear gamma-ray emitted in some other form of radioactive decay.

Two possibilities may be invoked to explain this case. First, the activity may be caused by the production, by proton capture, of one of the two stable Cd isotopes Cd^{108} or Cd^{110} in a metastable excited state. The subsequent decay of this nucleus to the ground state is accompanied by the emission of a gamma-ray, whose conversion gives rise to the negative electrons observed. The decay of an isomeric Cd^{108} or Cd^{110} by extranuclear electron capture to Ag^{108} or Ag^{110} would be followed by the decay of one of these well-known radioactive Ag isotopes, and since the absorption curve (Fig. 6) shows no evidence of the penetrating electrons associated with these radioelements, we must suppose that gamma-ray decay to the ground state is the only way in which a metastable Cd^{108} or Cd^{110} can be responsible for the activity. A case of this sort has recently been reported.[12]

The second possibility is that the radioactivity is caused by one of the isotopes Cd^{107} or Cd^{109}, produced by the (p, n) reaction. Positron decay

[12] Pontecorvo, Phys. Rev. **54**, 542 (1938).

in a small proportion of cases (< 5 percent) is not ruled out by the rough sign measurements made on the electrons emitted by this radioelement, but the preponderance of negatives shows that the predominating decay process under this assumption would be extranuclear electron capture. Decision between the two identifications suggested may be made by precise identification of the x-rays as being due either to Cd or to Ag. Unambiguous discovery that positrons are emitted would, by the considerations mentioned in the last paragraph, decide in favor of the latter interpretation.

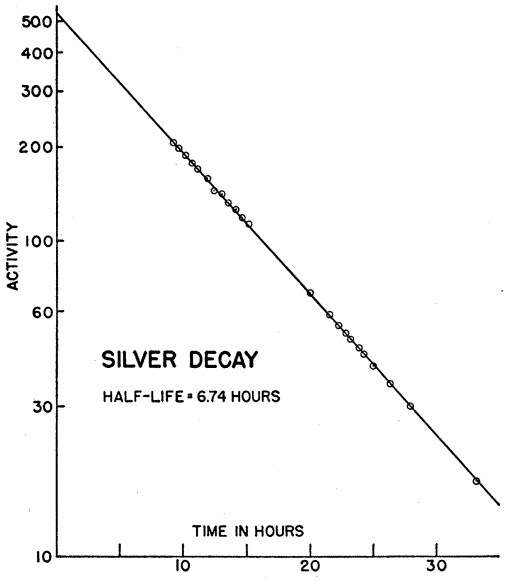

FIG. 7. Decay of radioactive Cd. Bombardment time 3.25 hours.

The threshold for the production of this radioelement seems to be at 2.4 Mev (Fig. 8). The interpretation of this result awaits a decision as to the type of reaction giving rise to the radioactive Cd.

A very much weaker period of about 7 or 8 minutes half-life is produced in Ag bombarded with protons. We have not investigated the radioelement responsible for this activity.

D. Other elements

In our previous note,[6] we reported a positron activity of about 20 minutes half-life to be produced in Mg by proton bombardment, as well as a much weaker activity of some hours half-life. More careful investigations have shown that the longer period is the 107-minute one of F^{18}, caused by oxygen contamination of the target. The shorter period seems also to be caused by a contaminant of unknown nature, since its intensity varies somewhat erratically from one sample of "very pure" Mg to another.

TABLE I. *Summary of the radioactive periods observed.*

TARGET	OBSERVED PERIODS	CHEM.	SIGN OF EMITTED PARTICLES	ASSIGNMENT	μ CURIES PER μAMP.	THRESHOLD Mev	UPPER LIMIT OF β-SPECT. Mev	OTHER REACTIONS	REF.
24 Cr	40 min.	Mn	+	$\left\{\begin{matrix}Cr^{52}\ (p,\gamma)\ Mn^{51}\\ Cr^{53}\ (p,n)\ Mn^{51}\end{matrix}\right\}$	0.17			$Cr^{52}\ (d,n)$	3
28 Ni	81 sec.	Cu	+	$Ni^{58}\ (p,n)\ Cu^{58}$	1.0				
	7.9 min.	Cu	+	$Ni^{60}\ (p,n)\ Cu^{60}$	0.37				
	3.4 hr.	Cu	+	$\left\{\begin{matrix}Ni^{60}\ (p,\gamma)\ Cu^{61}\\ Ni^{61}\ (p,n)\ Cu^{61}\end{matrix}\right\}$	11.2	1.8 2.7	0.9	$Ni^{58}\ (\alpha,p)$ $Ni^{60}\ (d,n)$ $Cu^{63}\ (n,3n)$	2 1 1
	12.8 hr.	Cu	±	$Ni^{64}\ (p,n)Cu^{64}$	12.4	2.1	0.7	many	1
29 Cu	38.5 min.		+	$Cu^{63}\ (p,n)Zn^{63}$	1.6	3.6	1.8	$Ni^{60}\ (\alpha,n)$ $Zn^{64}\ (n,2n)$ $Zn^{64}\ (\gamma,n)$	2 1 1
42 Mo	45 min.		?	?	0.09				
	2.7 hr.		?	?	0.10				
	36.5 hr.		−	?	0.17				
47 Ag	6.7 hr.	Cd	−	see text	33.5	2.4			

[1] M. S. Livingston and H. Bethe, reference 3, pp. 359–360.
[2] L. N. Ridenour and W. J. Henderson, Phys. Rev. **52**, 889 (1937).
[3] J. J. Livingood and G. T. Seaborg, Phys. Rev. **54**, 391 (1938).

It was stated in the earlier note that a chemical separation showed the short period activity to be caused by an isotope of Al; this is not inconsistent with the impurity hypothesis here advanced, as Al was separated in the form of the voluminous $Al(OH)_3$, with which the coprecipitation of a small amount of impurity can easily have taken place. A better half-life value for the short period is about 16 minutes.

Three periods have been identified in the decay of a Mo target bombarded with protons; they are 36.5 ± 5 hours, 2.7 ± 0.4 hours, and 45 ± 5 minutes. The radioelement of longest period emits only negative electrons, while both negatives and positives are emitted by a Mo target soon after bombardment. Presumably either or both of the shorter periods corresponds to the emission of positrons. No identification with known radioelements is proposed for these activities, beyond suggesting that they are isotopes of element 43, because of the potential barrier against the emission of charged particles from a nucleus of such high atomic number.

Two activities have been observed in a target of Cr bombarded with protons; one has a half-life of about 108 minutes for the emission of positrons and is probably to be identified as F^{18} caused by oxygen contamination. The half-life of the other is about 40 minutes; positrons are emitted by this radioelement also, and the result of one chemical separation indicates that it is an isotope of Mn. This confirms the report of this period by DuBridge,[2] who suggested its identification with Mn^{53}. Livingood and Seaborg[13] have recently concluded that this radioelement is best assigned as Mn^{51}. Their half-life value of 46 minutes is doubtless better than that given here, which is quite rough. In addition to the activities already mentioned, there seems to be present a weak period of some days' half-life in Cr bombarded with protons.

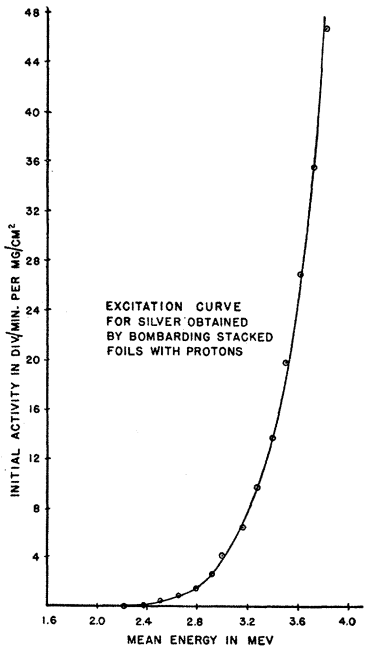

FIG. 8. Energy-yield curve for radioactive Cd.

Table I contains a summary of the radioactive periods reported here, together with some references to other reactions in which are produced known radioelements with which some of them can be identified. A notion of the intensity with which each activity can be produced by four-Mev protons is also given, expressed in terms of microcuries per microampere of ion current on a thick target, corrected to infinite bombarding time.

IV. ACKNOWLEDGMENTS

It is a pleasure to be able to thank Dr. R. C. Newton, of the Department of Chemistry, for suggestions concerning the chemical separations and Mr. John E. Walter for assistance in making the measurements.

[13] J. J. Livingood and G. T. Seaborg, Phys. Rev. **54**, 391 (1938).