Deuteron-Induced Radioactivities

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Bombardment of several elements with 5-MEV deuterons produces the following radioactivities. Commercial *copper* decays with a half-life of 130±10 days, emitting gamma-rays and very slow electrons. Attempts at chemical identification of probable radioactive products have been inconclusive, and the activity may be due to some unknown impurity in the copper. *Zinc* emits electrons with half-lives of 97±10 hours, 25±2 hours, 12±1 hours and 1±0.3 hours; the third of these is possibly due to radio Cu^{64} which has the same period. *Antimony* exhibits electron activities with half-lives of 50±4 days, 68±2 hours (confirming the 2.5 day period found by Fermi with neutrons) and 24±2 hours. *Ruthenium* shows half-lives of 46±3 days, 11±2 days, 39±1 hours and 4±1 hours, all due to electrons. *Bismuth* yields electrons of 5 days half-life and alpha-particles which increase in number for three weeks and then remain practically constant. This is interpreted as the synthesis of radium E through the reaction $_{83}Bi^{209}+{}_1H^2\rightarrow{}_{83}Bi^{210}$ (i.e., Ra E)$+{}_1H^1$, followed by its natural decay to polonium and thence to lead. The range of the alpha-particles agrees with that of the alphas from natural polonium to within 0.5 mm, and the time required to reach maximum alpha-activity is consistent with the 140 day half-life of polonium.

BOMBARDMENT of the elements herein reported has been made with the cyclotron of Lawrence and Livingston.[1] The targets were mounted in the bombardment chamber which was roughly evacuated with a Hyvac pump, the deuterons entering this region through a window of thin platinum foil supported on a brass grid. The magnitude of current was read by rotating a tungsten or platinum target into the beam near the inner side of the window; during the bombardment this target was turned aside and a small fraction of the current, employed as an indicator of correct synchronization, was picked up on an internal probe wire. The transmission factor of the window was approximately 50 percent, and the bombarding currents given below are therefore one-half of the current actually produced. The energy of the deuterons was observed by visual observation of the range in air across the bombardment chamber after passage through aluminum foils of known stopping power. Most of the targets were wrapped in aluminum foil as a protection against contamination from recoil atoms distilled onto the window during previous use. Correction for the stopping power of these wrappers has been made in the data given.

The observations of radioactivity were made on a quartz-fiber electroscope of the Lauritsen type. The yields of active atoms per impinging deuteron have all been computed for an infinite duration of bombardment, when equilibrium would be reached between the production of the nuclei and their spontaneous decay. Due to a number of uncertainties, such as the calibration of the electroscope, the transparency of the window through which the deuterons pass, etc., the absolute values of the yields are not to be taken too seriously, but the relative values are probably quite good, particularly among the activities of a single element, in which fluctuations in bombarding current would effect all isotopes equally. The errors given in the periods of decay have been obtained from inspection of the curves and are limits of error of generous size.

COPPER

Extended observations[2] have been made on filings scraped from the copper deflecting plate in the interior of the cyclotron. This is subjected to bombardment by stray deuterons of probably the full 5 MEV energy. The first sample was examined after about one month's intermittent use, and for the first 200 hours of observation showed a radioactivity with half-life of 14 hours. This is doubtless a combination of the 12.8-hour activity of radio Cu^{64} (originally given as 10 hours by Fermi but more recent observations by Van Voorhis[3] quote the former figure) and the 15.5-hour activity of radio Na^{24}. After this interval the sample exhibited a half-life of 25 days,

[1] Lawrence and Livingston, Phys. Rev. **45**, 608 (1935).

[2] Presented before the Physical Society at Seattle, June 18, 1936.

[3] Van Voorhis, Phys. Rev. **49**, 876 (1936).

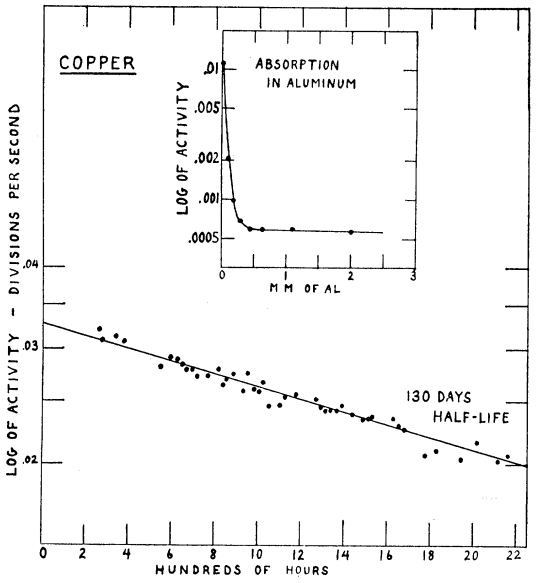

FIG. 1.

the observations extending over an additional 42 days time.

Assuming that it is really copper and not some impurity that has been transmuted, the radio isotope responsible must be one that can be attained by some known or hypothetical deuteron reaction. The known types may be classified as follows:

$$\text{(I)} \quad {}_zX^A + {}_1H^2 \rightarrow {}_zX^{A+1} + {}_1H^1,$$

$$\text{(II)} \quad \rightarrow {}_{z+1}X^{A+1} + {}_0n^1,$$

$$\text{(III)} \quad \rightarrow {}_{z-1}X^{A-2} + {}_2He^4.$$

The first of these, the net effect of which simply is to add a neutron to the target nucleus (Oppenheimer-Phillips[4] transmutation), would here be ruled out, since only two stable copper isotopes are known, Cu^{63} and Cu^{65}, and the resulting radio isotopes Cu^{64} and Cu^{66} have half-lives of 12.8 hours and 6 minutes, respectively. The second type must also be discarded, since it leads to Zn^{64} or Zn^{66}, both of which are stable; while if Cu^{62} existed, the result would be radio Zn^{63}, which should be positron active, whereas (see below) the observed activity is of negative electrons. The third case would seem to fit the present situation:

$$_{29}Cu^{65} + {}_1H^2 \rightarrow {}_{28}Ni^{63} + {}_2He^4$$

$$_{28}Ni^{63} \rightarrow {}_{29}Cu^{63} + e^-.$$

In spite of the unlikelihood of all of these possibilities except that of nickel, a chemical analysis for nickel, copper and zinc was attempted on a second set of copper filings. A little zinc and nickel was added to an acid solution of the irradiated copper; CuS was precipitated out with H_2S, then Ni $(OH)_2$ was precipitated from alkalinity, and finally ZnS was brought down with more H_2S.

The results of this showed that the previously found 25 day half-life, was entirely spurious; the Ni (OH_2) has been followed for three months and shows an apparent half-life of 130 ± 10 days; the CuS decayed with the 14.5 days activity characteristic of the omnipresent radio phosphorous (probably occluded or brought down as some phosphate); while the ZnS had an initial activity only one-seventh that of the nickel hydroxide and was consequently discarded. The sum of the Ni $(OH)_2$ and CuS (P^{32}) activities showed the original false 25 day half-life, which emphasizes very clearly the necessity for caution when contaminants may be present and when only a relatively short time of observation is employed to compute a half-life.

The character of the radiation from the Ni $(OH)_2$ has been observed to be negative electrons accompanied by gamma-rays, through visual observation with a Wilson chamber equipped with Helmholtz coils. For the use of this instrument I am grateful to Dr. F. N. D. Kurie and Mr. H. Paxton. The absorption curve is shown in Fig. 1. The beta and gamma-rays are both evident, the latter about one-twentieth as strong as the former, with no absorber. According to Feather's rule,[5] the energy of the electrons, as determined from the maximum range of 0.05 cm of aluminum, is about 0.4 MEV.

Although these results favored the hypothesis of the creation of Ni^{63}, it was felt desirable to use a test that would be more specific for nickel than merely precipitating its hydroxide. In collaboration with Mr. Philip Abelson further chemical analysis has been carried on with a third sample of filings. The result has been to

[4] Oppenheimer and Phillips, Phys. Rev. **48**, 500 (1935).

[5] Feather, Phys. Rev. **35**, 1559 (1930).

shake our faith in the Ni^{63} supposition and to suggest that possibly the reaction is

$$_{29}Cu^{65}+{}_{1}H^{2}\rightarrow{}_{26}Fe^{59}+{}_{2}He^{4}+{}_{2}He^{4}$$

$$_{26}Fe^{59}\rightarrow{}_{27}Co^{59}+e^{-}.$$

However, the analysis is still very inconclusive with regard to both hypotheses and more work must be carried on. It is quite possible that the activity is due to some unknown impurity in the commercial copper. The Ni^{63} interpretation is also improbable on other grounds: the production[6] of an activity of half-life 3 hours$\pm$10 minutes when nickel is bombarded with slow neutrons. If this latter radiation is of electrons, it is very probably due to the production of radio Ni^{63} through neutron capture by Ni^{62} (present to 3.8 percent abundance), although a similar capture by Ni^{64} (0.9 percent) to form electron emitting radio Ni^{65} must not be overlooked. On the other hand, if the 3 hours period is due to positrons, it is probably due to the formation of radio Ni^{59} out of Ni^{58}, of 68.1 percent abundance.

The longer range of the 130 days' activity and the presence of a gamma-ray are sufficient to distinguish it from the 3 months activity observed by McMillan[7] in deuteron activated brass and molybdenum.

Zinc

The bombardment of zinc for 2 hours with 3.5 microamperes of 3.2 MEV deuterons yields[8] a

[6] Rotblat, Nature **136**, 515 (1935); Naidu, Nature **137**, 578 (1936).

[7] McMillan, Phys. Rev. **49**, 876 (1936).

[8] Presented before the Physical Society at Berkeley, Dec. 20, 1935.

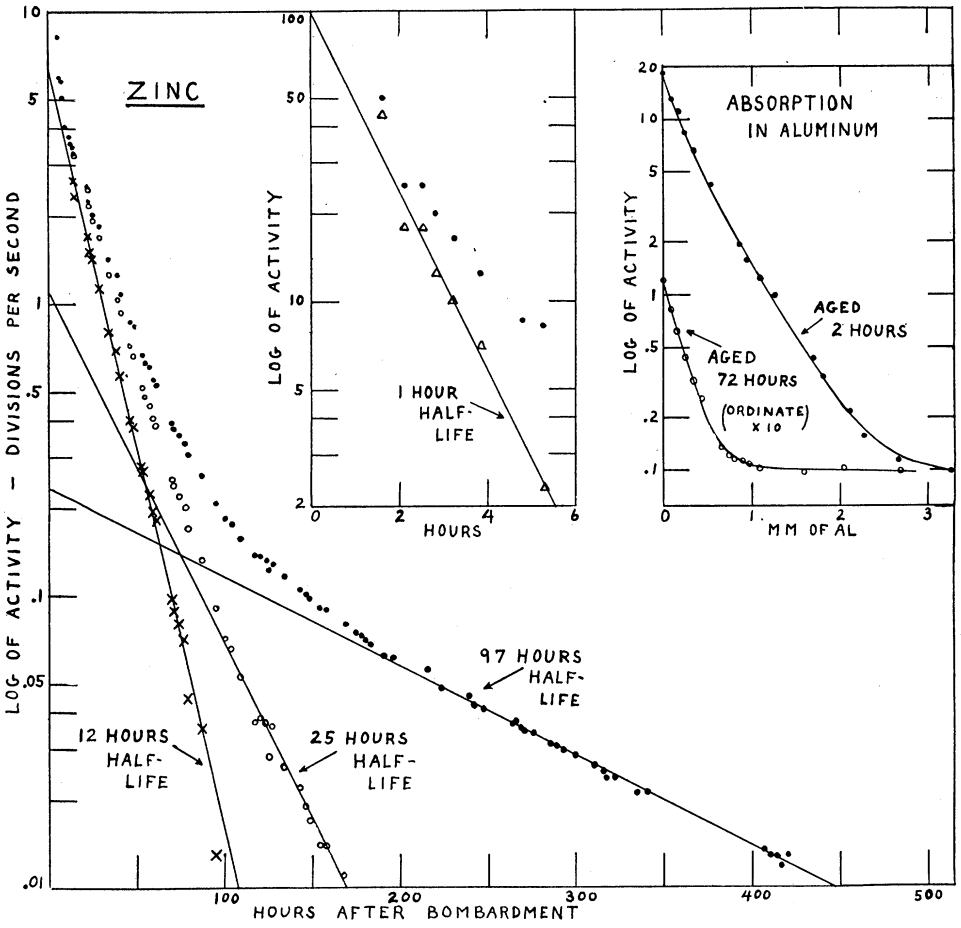

FIG. 2.

radioactivity of which the decay curve is shown in Fig. 2. The longest period, followed for about two half-lives, shows a half-life of 97 ± 10 hours. Subtraction of this activity from the experimental readings gives the open circles of the figure, in which a definite curvature precludes the possibility of but a single period. It is feasible to fit a 25 ± 2 hour line to the later points and on subtraction of this, the earlier readings are seen to fall on a fairly well established activity of 12 ± 1 hours half-life. The insert reveals an additional radiation of 1 ± 0.3 hours half-life. The thick target yields, computed for equilibrium by correcting for the finite length of the exposure, are as follows:

Half-life	Yield (H^2 per active atom)
97 ± 10 hours (negative electrons)	1.2×10^8
25 ± 2 hours (negative electrons)	1.5×10^8
12 ± 1 hours (negative electrons)	0.5×10^8
1 ± 0.3 hours (? ?)	0.2×10^8

The sign of the charges were determined from visual examination with a cloud chamber in a magnetic field. Absorption curves taken 2 hours and 72 hours after activation, are shown in Fig. 2, and indicate at least one gamma-ray as well as a complex of electron groups.

The stable isotopes of copper, zinc, gallium and germanium are:[9]

$_{29}$Cu		63		65				
$_{30}$Zn	64		66	67	68		70	
$_{31}$Ga				69		71		
$_{32}$Ge			70		72	73	74	76

Under neutron bombardment zinc exhibits[10] the 6-minute and 12-hour activities characteristic of radio Cu^{66} and Cu^{64}, while an additional activity with 100 minutes half-life has been observed by McLennan, Grimmet and Read;[11] gallium shows[10] a 20-minute radiation that has been chemically identified as due to a gallium isotope and also a 23-hour activity that is slightly water sensitive. These two periods may probably be assigned to radio Ga^{70} and Ga^{72}.

No usual reaction with deuterons could transmute zinc to an electron-emitting form of gallium; if the observed 25 ± 2-hours period were identified with the 23-hours activity of radio gallium, recourse would have to be made to the type of reaction as yet unestablished for deuterons:

$$_{30}Zn^{68,\,70}+{}_1H^2\rightarrow{}_{31}Ga^{70,\,72}+\text{gamma-ray}$$

$$_{31}Ga^{70,\,72}\rightarrow{}_{32}Ge^{70,\,72}+e^-.$$

(A reaction of this type, but with the proton as projectile, is known[12] in the case of $_6C^{12}+{}_1H^1\rightarrow$radio $_7N^{13}+$gamma.) The only possible electron-emitting isotopes of zinc, Zn^{69} and Zn^{71}, may be called on to explain two of the observed activities. If the one-hour radiation is of positrons, its origin could be in

$$_{30}Zn^{64}+{}_1H^2\rightarrow{}_{30}Zn^{65}+{}_1H^1$$

$$_{30}Zn^{65}\rightarrow{}_{29}Cu^{65}+e^+.$$

or

$$_{30}Zn^{66,\,67}+{}_1H^2\rightarrow{}_{31}Ga^{67,\,68}+{}_0n^1$$

$$_{31}Ga^{67,\,68}\rightarrow{}_{30}Zn^{67,\,68}+e^+.$$

One would be tempted to identify the 12 hour activity with the 12.8-hour period of radio Cu^{64}, through

$$_{30}Zn^{66}+{}_1H^2\rightarrow{}_{29}Cu^{64}+{}_2He^4$$

$$_{29}Cu^{64}\rightarrow{}_{30}Zn^{64}+e^-$$

were it not for the fact that this isotope has recently been shown by Van Voorhis[3] to decay both to stable Zn^{64} by the emission of an electron and also to stable Ni^{64} by emitting a positron. More careful examination must be made to establish whether or not the 12-hour period of zinc does exhibit positrons as well as electrons.

Antimony

A piece of metallic antimony, wrapped in thin aluminum foil, was exposed for 1 hour to 1 microampere of 5 MEV (net) deuterons.[13] The subsequent radioactive decay curve can be analyzed into three well-defined components, as shown in Fig. 3. The half-lives and the thick target saturation yields (corrected for the finite time of exposure) are as follows.

[9] Aston, *Mass Spectra and Isotopes* (1933).
[10] Amaldi, d'Agostino, Fermi, Pontecorvo, Rasetti and Segrè, Proc. Roy. Soc. **A149**, 522 (1935).
[11] McLennan, Grimmet and Read, Nature **135**, 505 (1935).
[12] Cockcroft, Gilbert and Walton, Proc. Roy. Soc. **A148**, 225 (1935).
[13] Presented at the Seattle meeting of the Physical Society, June 18, 1936.

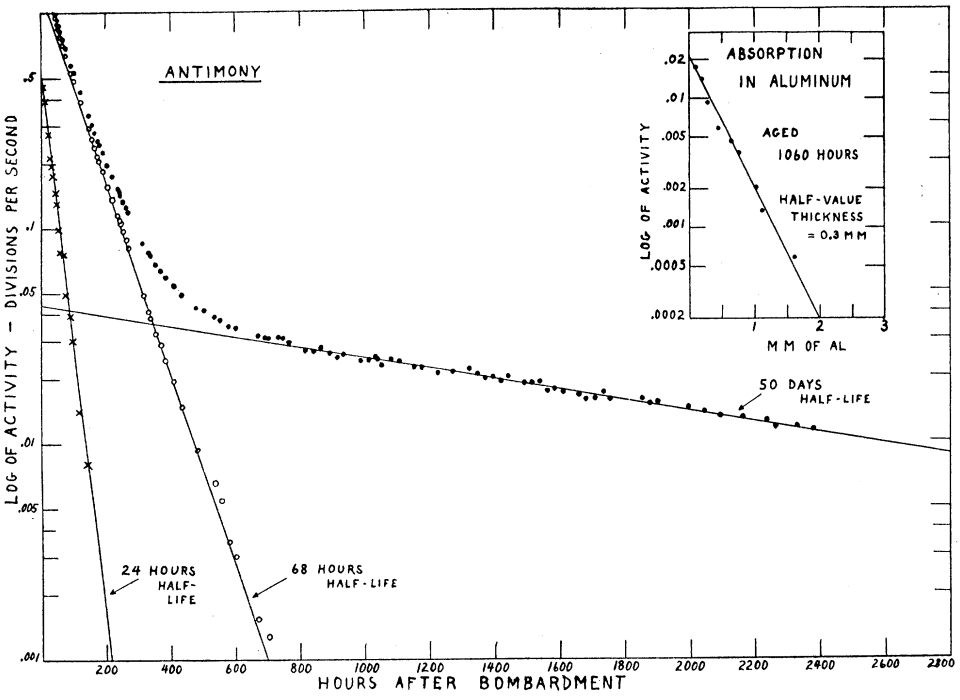

FIG. 3.

Half-life	Yield (H^2 per active atom)
50±4 days (negative electrons)	1.4×10^7
68±2 hours (negative electrons)	0.7×10^7
24±2 hours (negative electrons)	1.2×10^8

A residual activity of about 2.5 minutes, not very well established, is probably due to adsorbed oxygen and nitrogen, which yield radio F^{17} and O^{15} with half-lives of 1 minute 10 seconds and 2 minutes 6 seconds, respectively. Observation with a Wilson chamber in a magnetic field has shown that these three longer period activities are due to negative electrons. An absorption curve in aluminum, taken 44 days after the bombardment when only the longest period remained, is shown in Fig. 3. This apparently indicates a single distribution of electrons, with a half-value thickness of 0.03 cm Al. If there is a gamma-ray present, it is too weak to be detected.

The antimony, tellurium and relevant tin isotopes are[14]

$_{50}$Sn···118	119	120		122	124		
$_{51}$Sb	121		123				
$_{52}$Te 122	123	124	125	126	128	130	

[14] Aston, *Mass Spectra and Isotopes* (1933), and Nature **137**, 613 (1936); Bainbridge and Jordan, Phys. Rev. **49**, 416 (1936).

It is evident that no radio tellurium can be formed by deuteron bombardment of antimony, for deuteron capture, whether followed by neutron emission or not, would yield stable tellurium in every case. The two possibilities involving radioactive antimony are

$$_{51}Sb^{121,\,123}+{}_1H^2\rightarrow{}_{51}Sb^{122,\,124}+{}_1H^1$$

$$_{51}Sb^{122,\,124}\rightarrow{}_{52}Te^{122,\,124}+e^-.$$

Only one possibility exists for the production of radio tin:

$$_{51}Sb^{123}+{}_1H^2\rightarrow{}_{50}Sn^{121}+{}_2He^4$$

$$_{50}Sn^{121}\rightarrow{}_{51}Sb^{121}+e^-.$$

Fermi[10] has observed a 2.5 days half-life activity when antimony is bombarded with neutrons, and has shown the isotope to be one of antimony, necessarily either Sb^{122} or Sb^{124}. It seems reasonable to identify this with the 68-hour activity reported in the present paper. The 50-day and 24-hour periods are then to be assigned to the other radio-antimony isotope and to Sn^{121}, or *vice versa*. No chemical test has yet been made. It is tempting to assign the 24±2-

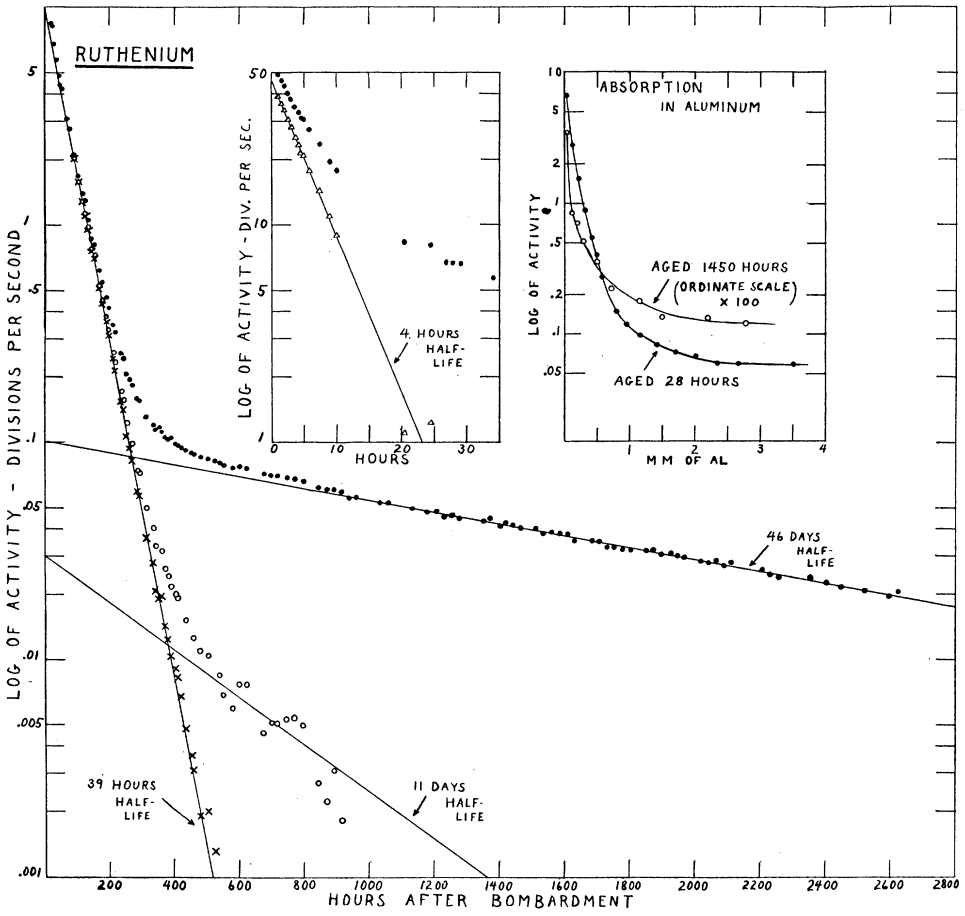

FIG. 4.

hour period to Sn^{121} and to identify it with the 28 ± 2-hour activity found when tin is transmuted to radio tin by deuteron bombardment.[15]

RUTHENIUM

Ruthenium was bombarded[16] for 2 hours with 2.5 microamperes of deuterons at a net energy of 5.3 MEV, the sample being wrapped in very thin aluminum foil to prevent deposition on it, by recoil, of the sodium and phosphorus generally present in the bombardment chamber of the cyclotron. The metal had previously been heated red hot with a blow torch and thoroughly washed, being handled only with tweezers. The radioactive decay curve is shown in Fig. 4.

The longest period, of half-life 46 ± 3 days, appears to be well established, having shown no deviation for almost two half-lives. A shorter period, with half-life 39 ± 1 hours, is apparent from the early data. An intermediate activity, of half-life around 9 to 13 days, may be detected only by the fact that when the 46-day data are subtracted from the original experimental points, the 39-hour activity shows a persistent flattening out as time goes on. These points (open circles in Fig. 4, in the region along the time axis from 400 to 900 hours) are too badly scattered to determine the slope and intensity of this middle activity, but by working backward one can adjust the slope and intensity to such values that when the resulting 11-day period is subtracted, the earlier points fall well along the 39-hour line without any consistent deviation. It is then seen that the 11-day line fits reasonably well along the points from which it could, in theory, be located.

[15] Livingood and Seaborg. See following paper.

[16] Presented before the Physical Society at Seattle, June 18, 1936.

This activity is so weak that whether or not it is included makes no noticeable difference in the half-life of the 39 hours radiation. The insert of Fig. 4, on a more open time scale, reveals a further short period activity with half-life 4 ± 1 hours.

Visual cloud chamber observations, made 20 hours after bombardment, showed only negative electrons and gamma-rays. If the 11-day activity were of positrons, they probably would not have been noticed since the intensity of this component is so weak.

The thick target yields, calculated for infinite exposure, are given below:

Half-life	Yield (H^2 per disintegration)
46 ± 3 days (negative electrons)	2.5×10^7
11 ± 2 days ? ?	1×10^{10}
39 ± 1 hours (negative electrons)	0.8×10^7
4 ± 1 hours (negative electrons)	1.5×10^7

Fig. 4 also exhibits the absorption curves in aluminum, one taken when the sample was 28 hours old, the other at the age of 60 days. The former is complex, as would be expected, since three and possibly four electron activities are contributing, with at least one associated gamma-ray. The rather similar curve obtained when only the 46-day activity is appreciable is somewhat surprising. There would be little physical significance in an analysis of these complex curves into components, since the determination of energy distributions from absorption curves is notoriously erroneous.

The isotopic constitution of ruthenium and of neighboring elements, as given by Aston[9] and Dempster[17] are

$_{42}$Mo	92	94	95	96	97	98	100	
$_{43}$Ma								
$_{44}$Ru	96	98	99	100	101	102	104	
$_{45}$Rh					103			
$_{46}$Pd		102		104	105	106	108	110

Masurium has been identified only by its x-ray spectrum, but one of its stable isotopes is surely Ma^{99}, since molybdenum has been activated[10, 18] with slow neutrons to give two periods, of 25 to 30 minutes and 36 hours half-lives. As slow neutron capture usually leads to the formation of a heavier isotope of the element hit, and since Mo^{99} is unknown while Mo^{98} is the most prevalent, it seems likely that one of these periods is due to the production of radio Mo^{99} which emits an electron and becomes stable Ma^{99}.

The possible radioactivities of ruthenium bombarded with deuterons are therefore

$$_{44}Ru^{104}+{}_1H^2\rightarrow{}_{44}Ru^{105}+{}_1H^1$$

$$_{44}Ru^{105}\rightarrow{}_{45}Rh^{105}+e^-$$

$$_{45}Rh^{105}\rightarrow{}_{46}Pd^{105}+e^-$$

$$_{44}Ru^{102}+{}_1H^2\rightarrow{}_{44}Ru^{103}+{}_1H^1$$

$$_{44}Ru^{103}\rightarrow{}_{45}Rh^{103}+e^-$$

$$_{44}Ru^{101,\,104}+{}_1H^2\rightarrow{}_{45}Rh^{102,\,105}+{}_0n^1$$

$$_{45}Rh^{102,\,105}\rightarrow{}_{46}Pd^{102,\,105}+e^-.$$

Reaction similar to the last couplet, but starting from $Ru^{98,\,99,\,100}$, would give rise to positron active rhodium isotopes decaying into stable ruthenium, since there are no stable palladium isotopes to which the rhodium could go by electron emission. If the only stable masurium isotope is Ma^{99}, there are several paths by which radio masurium could be formed:

$$_{44}Ru^n+{}_1H^2\rightarrow{}_{43}Ma^{n-2}+{}_2He^4$$

$$_{43}Ma^{n-2}\rightarrow{}_{44}Ru^{n-2}+e^-,$$

where $n=98$, 100, 102, 104.

Summing up, there are possible four radio isotopes of masurium, two of rhodium and two of ruthenium which could be formed directly by deuteron bombardment of ruthenium and which would be electron emitters; there are at least three possible positron emitters. As yet, no chemical analysis has been attempted in an endeavor to assign the four observed activities to various of these possibilities.

Kurtschatow, Nemenow and Selenow[19] have reported four activities when ruthenium is bombarded with slow neutrons, with periods of 40 seconds, 100 seconds, 11 hours and 75 hours, the intensity ratios being 100, 100, 10, 40, respectively. (Whether these are the observed

[17] Dempster, Nature **135**, 65 (1935).
[18] McLennan, Grimmet and Read, Nature **135**, 147 (1935).
[19] Kurtschatow, Nemenow and Selenow, Comptes rendus **200**, 2162 (1935).

initial ratios or whether they have been corrected for the finite exposure time is not stated.) Because of the equal intensity of the first two, they suggest as the relevant reaction the double disintegration listed above. These two shortest periods could not have been observed in the present work with deuterons, for observation did not begin until 20 minutes after the exposure was finished. The failure to observe 11-hour and 75-hour activities suggests that these may be due to masurium or molybdenum isotopes accessible with neutron bombardment but not with deuterons. On the other hand, the 75-hour period might have been deduced erroneously if observations had ceased during the transition interval just before the 46-day activity would have made itself known.

The interpretation of the deuteron induced activities is complicated further by the fact that rhodium, under neutron bombardment yields[10, 20] two periods of half-lives 35 to 44 seconds and 3.8 minutes. One of these must be due to radio Rh^{104} and the other to either radio Ru^{103} or radio Ma^{100}, these three isotopes being formed respectively, by neutron capture, capture plus proton emission, and capture plus alpha-emission.

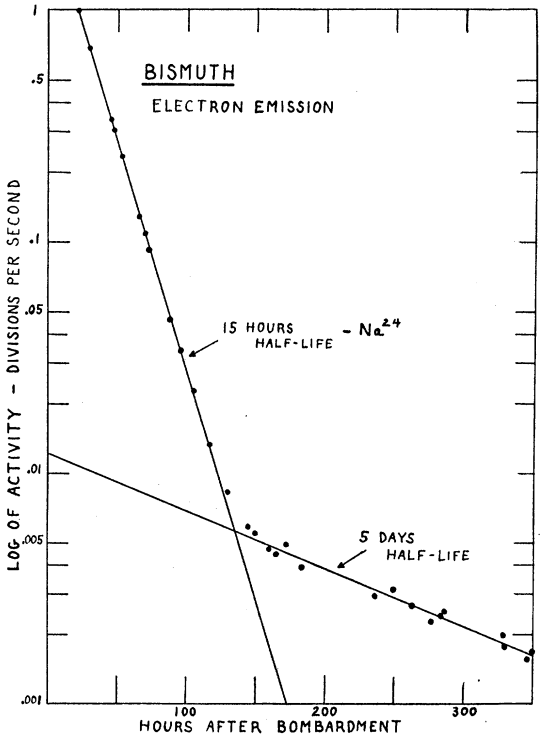

FIG. 5.

BISMUTH[21]

Since it is well known that radium *E*, which emits electrons with a half-life of five days, is isotopic with bismuth, several attempts have been made to convert bismuth into this radioactive form by neutron bombardment, the expected reaction being

$$_{83}Bi^{209}+{}_{0}n^{1}\rightarrow{}_{83}Bi^{210}(\text{Ra E})$$

$$_{83}Bi^{210}\rightarrow{}_{84}Po^{210}+e^{-}.$$

Fermi and his collaborators,[10] and McLennan, Grimmet and Read[11] have found no detectable activity after such an attempt. Sosnowski[22] has reported an electron activity with a half-life of about 1 hour, and since a chemical analysis showed no radioactive thallium or lead, concluded that a bismuth isotope must be responsible and hence that the synthetic Ra E must have a different internal arrangement of its constituent parts than the natural variety, because of the lack of agreement in the decay periods. Subsequently, Preiswerk and von Halban[23] using a much stronger source of neutrons (1200 mc of Rn+Be and 300 mc of Rn+B) have not confirmed Sosnowski's findings. More recently Andersen[24] has reported no activity in bismuth after neutron bombardment.

Following the successful attempt of Cork and Lawrence[25] to produce disintegrations in platinum by deuteron bombardment in the neighborhood of 5 MEV, it was felt that the available deuteron energy was perhaps sufficient to effect a transmutation in bismuth, through the Oppenheimer-Phillips[4] type of reaction

$$_{83}Bi^{209}+{}_{1}H^{2}\rightarrow{}_{83}Bi^{210}(\text{Ra E})+{}_{1}H^{1}.$$

It was hoped that the almost universal negative result with neutrons was due to a relative insuf-

[20] Dopel, Physik. Zeits. **37**, 96 (1936).
[21] Presented before the Washington meeting of the Physical Society, May 2, 1936.
[22] Sosnowski, Comptes rendus **200**, 1027 (1935).
[23] Preiswerk and von Halban, Comptes rendus **201**, 722 (1935).
[24] Andersen, Nature **137**, 457 (1936).
[25] Cork and Lawrence, Phys. Rev. **49**, 788 (1936).

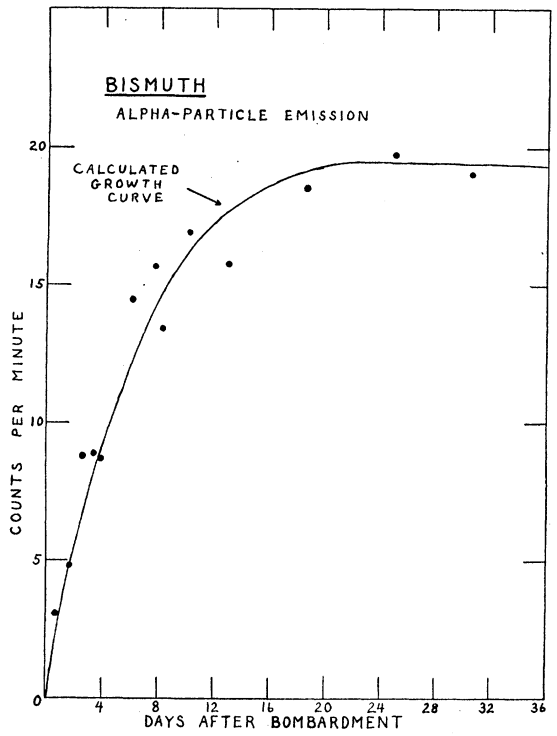

FIG. 6. (Ordinate of calculated curve adjusted to fit at the maximum.)

ficiency of their numbers and that the much greater bombarding currents of deuterons might give a detectable effect.

To prevent its melting during the exposure, a thick layer of bismuth was soldered to a heavy copper plate; this was wrapped in aluminum foil in an effort to prevent contamination with radio sodium present in the bombarding chamber of the cylotron due to a recent preparation of this material. An exposure of 4 hours to 1.2 microamperes of deuterons with a net energy of 4.4 MEV was made, and the subsequent radioactivity observed with an electroscope. The decay curve is shown in Fig. 5. In spite of the precautions to avoid it, a very strong activity with the 15-hour half-life of radio sodium was present, and only after 150 hours (when the net activity was about equal to the background) did a departure from this period occur. The following feeble activity decayed at a rate which was quite consistent with the 5 days half-life of Ra E. By correcting for the time of exposure, the equilibrium thick target yield was found to be 2×10^9 deuterons per active nucleus.

If the manner of formation of this isotope is immaterial to its subsequent behavior, then a confirmatory test of its production would be the detection of alpha-particles with the range of 3.9 cm of air characteristic of polonium, through the natural decay of this into lead:

$$_{84}Po^{210}\rightarrow{}_{82}Pb^{206}+{}_{2}He^{4}.$$

Furthermore, as the Ra E is gradually converted into Po, the alpha-particle activity of the latter should first increase with time up to a maximum value and then die away with the 140 days half-life of natural polonium. The well-known theory of radioactive growth and decay shows that this time of maximum activity, after the preparation of the parent substance, is given by

$$t_{\max}=\frac{1}{\lambda_2-\lambda_1}\log_e\frac{\lambda_2}{\lambda_1},$$

where λ_1 and λ_2 are the decay constants ($\lambda=0.693/$ half-life) of the parent and product. For the case of Po growing in fresh Ra E, this time works out as 23 days.

Consequently, a search for alpha-particles was made with a linear amplifier, commencing on the day after bombardment. During the following two weeks counts greater than background were obtained on nine days, but the greatest net activity was only 1.5 alpha-particles per minute and no consistent rise in activity was noticeable. (The background was taken by replacing the irradiated bismuth with another sample from the same supply and mounted on copper in an identical manner, in order to eliminate any possible natural radioactive contamination.)

In an endeavor to strengthen this activity, if it were genuine, a second bombardment was made, for a total of 13 microampere hours at 5.4 MEV, and to further increase the yield, the aluminum foil wrapper was omitted. The resulting 5-day period of Ra E was completely masked by the 15 hours radio sodium and 14.5 days radio phosphorus contamination activities, but the alpha-particle emission was established as genuine from the outset. The growth curve is indicated in Fig. 6, and is seen to follow the theoretical curve not too badly, a maximum being reached in approximately 3 weeks. Since the calculation of this interval involves the 140-

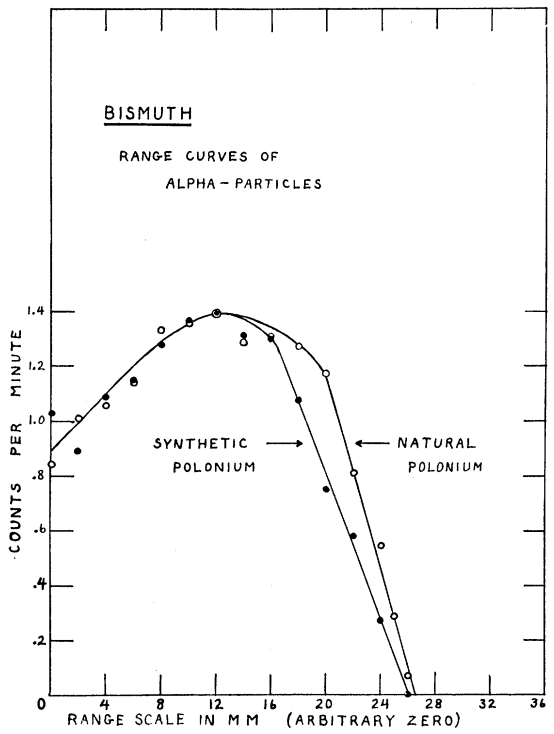

FIG. 7.

day half-life of polonium, it was not felt necessary to establish this period by direct continued observation.

After the attainment of this very nearly constant yield of the maximum activity, a measurement of the range of the alpha-particles was made, not on an absolute basis, but by comparison with that of the alphas from natural polonium deposited onto a silver plate, the two samples being alternately attached to a frame mounted on a micrometer screw and counts being taken at varying distance from the amplifier. The resulting curves are shown in Fig. 7, after a geometrical correction has been made for change in solid angle with distance. The scale of ordinates for the much stronger natural sample has been reduced to a fit at the maximum activity, to facilitate comparison. The extrapolated ranges are seen to agree to within 0.5 mm, which is as good as could be expected with the simple procedure used.

If the chance of transmutation were markedly increased for particular deuteron energies, the range curve would show a series of steps, corresponding to the emission of alpha-particles from layers more densely populated with active atoms at particular distances below the surface. Such a resonance phenomenon with deuterons has been found by Cork and Lawrence[25] in the transmutation of platinum into radio iridium, wherein the deuteron is captured and an alpha-particle emitted. On the other hand, the observed smooth range curve, of somewhat lesser slope than that of the natural particles, indicates the emission of alphas in gradually decreasing numbers at greater depths below the surface; this is consistent with the postulated Oppenheimer-Phillips type of disintegration, the chance of the deuteron being split, into a repelled proton and a captured neutron, diminishing with reduced deuteron energy.

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