ARTIFICIAL RADIOACTIVITY

Thesis

In partial fulfillment of the requirements
for the degree of Doctor of Philosophy

Submitted by

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The following thesis is a presentation and discussion of the work done up to date with the artificially produced radioactive substances, in this and in other laboratories. In many instances the product of disintegration is positrons, and this has made possible several experiments concerning the annihilation of positrons and the conversion of their rest mass into radiant energy. The recent work of Fermi on the production of β-ray bodies by neutron bombardment is also described.

Introduction

At the time of this writing, the phenomenon of artificial radioactivity has been known for a little less than three months. It is therefore possible now, as it will undoubtedly not be possible within a short time, to include in a brief paper a reasonably detailed account of the whole of the field. Although attempts to induce radioactivity, and especially to influence the rates of decay of the natural radioactive substances have been made since the discovery of the radioactive substances themselves, not one of the many successes reported has stood the test of closer examination, so it can be said with a great deal of certainty that the history of artificial radioactivity began with the work of Curie and Joliot, published in January, 1934.[1] It had been clear for some time, in the light of experiments on the artificial disintegration of the light elements, that bringing about a change in nuclei as heavy as those of the radioactive series by penetrating them with the projectiles we have available would have a probability so low that it would be hopeless. The only method of attack therefore lay in the transmutation of the light elements, and even this did not seem highly promising, in view of the fact that no natural radioactive substances were known to exist in the region of the low atomic numbers, indicating that perhaps only the very complex nuclei were capable of such behaviour.

If we arrange the elements according to mass number and atomic number, as shown in Fig. 1, we see that they fall along a well defined line, and this we may think of as the region of the stable nuclei.

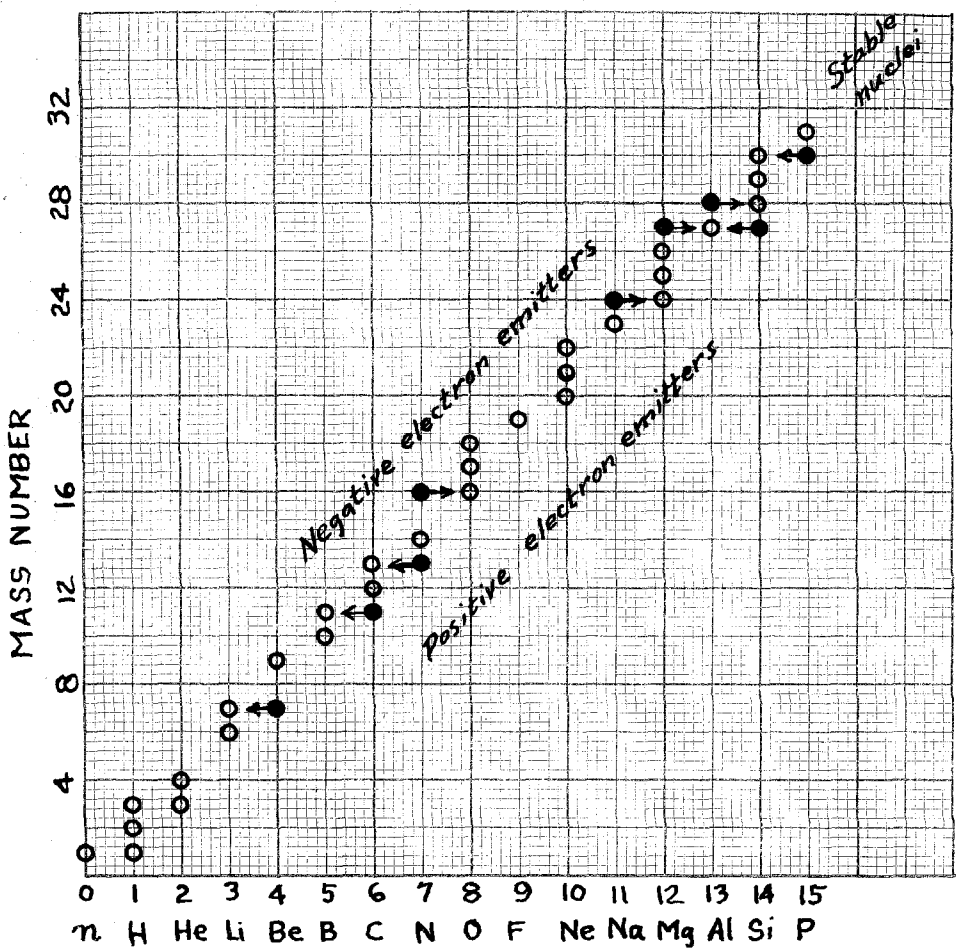


Fig. 1. The nuclei arranged according to mass number and atomic number.
O stable nuclei
←● artificially produced radioactive nuclei.

The total absence of nuclei outside this region is consistent with the idea that the "stable region" is a trough toward which all nuclei rapidly move by means of spontaneous transformations. In the processes going on in nature, especially in parts of the universe where temperatures and pressures are extreme, nuclei of many descriptions must be produced continually, and if there were not a strong tendency for those not in the trough to move into the trough, we should expect to find a detectable number of them in existence. It is not unreasonable to think, however, that in the artificial transmutation of elements, under some conditions products might be formed which would not lie in the stable region of the diagram, but which would

nevertheless have a lifetime long enough to make possible their identification. In order to move into the stable region, a nucleus on the right hand side would have to throw off a positive charge, and a nucleus on the left hand would have to throw off a negative charge, assuming that it would not undergo the more serious change of breaking up into two or more new nuclei.

The fact that β -ray bodies in the radioactive series emit only negative electrons is consistent with the diagram, as we shall see if we extend it upward to the high atomic numbers. For the low atomic numbers (Fig. 1) the slope of the curve is such that the mass number changes just twice as fast as the atomic number, but in the region of the high atomic numbers the curve becomes considerably steeper (Fig. 2). α- particle transformations necessarily cause a shift along a 45 degree line, since the ratio of mass number to atomic number of the α- particle is 2. Therefore after one or more α- transformations an element always finds itself off the curve to the left -- never to the right -- and the emission of a negative electron is required to shift it back onto the curve.

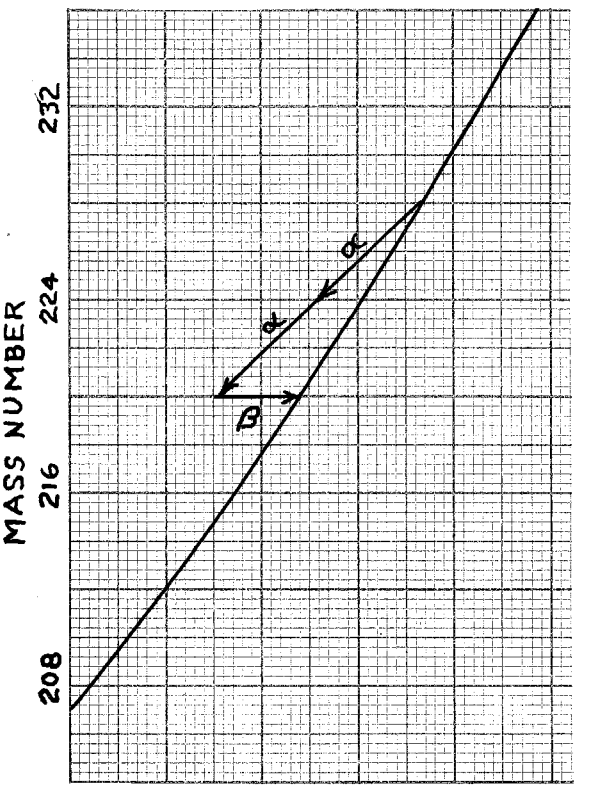


Fig. 2

Experiments

Curie and Joliot[1] made the striking observation that certain of the light elements, namely boron, aluminum and magnesium, continued to eject ionizing particles in large numbers for a considerable length of time after being bombarded with the α-particles from poloniom. They studied the disintegration particles by means of a cloud chamber and also by means of the magnetic analyser used by Thibaud*, and found that they were in all cases positrons. The rates of decay of the active substances, and also the ranges of the positrons in absorbing foils were studied, using a Geiger-Muller counter, and the following results were obtained.

	Decay period**	Upper limit of energy of positrons
B	14 min.	0.7×10^6 e.v.
Al	3¼ min.	2.2×10^6 e.v.
Mg	2½ min.	0.7×10^6 e.v.

H, Li, C, Be, N, O, F, Na, Ca, Ni, and Ag were tried but gave no observable effect. This negative result is not at all conclusive, because if an active substance were produced whose period of decay was either very long or very short, it would escape detection. It may indeed seem fortunate, at first glance, that the decay periods of three or these substances happen to be of such convenient length, when one remembers that the decay periods of the natural radioactive substances range between 10^{10} years and 10^{-11} seconds! Upon closer examination, however, it is seen that, while the α-ray bodies are distributed apparently at random over this wide range, the β-ray bodies fall within a very much narrower range. Of the 17 β-ray bodies in the radioactive

* Described on page
** Time required for unit change in loge intensity.

series (this does not include potassium, of which little is known) the greatest half life is 25 years and the smallest 1 minute, and

β- ray bodies						α- ray bodies	
UX_1	24 days	Ac	13 yrs.	MsTh1	7 yrs.	Th	10^{10} yrs.
UX_2	1 min.	AcB	36 min.	MsTh2	6 yrs.	ThC'	10^{-11} sec.
UY	24 hrs.	AcC	2 min.	ThB	10 hrs.		
RaB	26 min.	AcC^{11}	5 min.	ThC	1 hr.	others at random between these limits	
RaC	19 min.			ThC^{11}	3 min.		
RaC^{11}	1 min.						
RaD	25 yrs.						
RaE	5 days						

9 of the 17 fall between the narrow limits of 1 minute to 1 hour.

In order to account for the production of radioactive substances from the three elements bombarded, Curie and Joliot suggested the following nuclear reactions:

$$(1)\quad B^{10} + He^{4} \longrightarrow N^{13} + n^{1} \longrightarrow C^{13} + n^{1} + E^{+}$$

$$(2)\quad Mg^{24} + He^{4} \longrightarrow Si^{27} + n^{1} \longrightarrow Al^{27} + n^{1} + E^{+}$$

$$(3)\quad Al^{27} + He^{4} \longrightarrow P^{30} + n^{1} \longrightarrow Si^{30} + n^{1} + E^{+}$$

the N^{13}, Si^{27} and P^{30} being the radioactive isotopes. These are indicated as ←● in the diagram (Fig. 1), the small arrows indicating the direction in which they shift as a result of the positron emission.

In suggesting the above reactions, Curie and Joliot pointed out that, if the radioactive substance in the first case were really N^{13}, it should be possible to produce it by bombarding carbon with deutons. The reaction would be

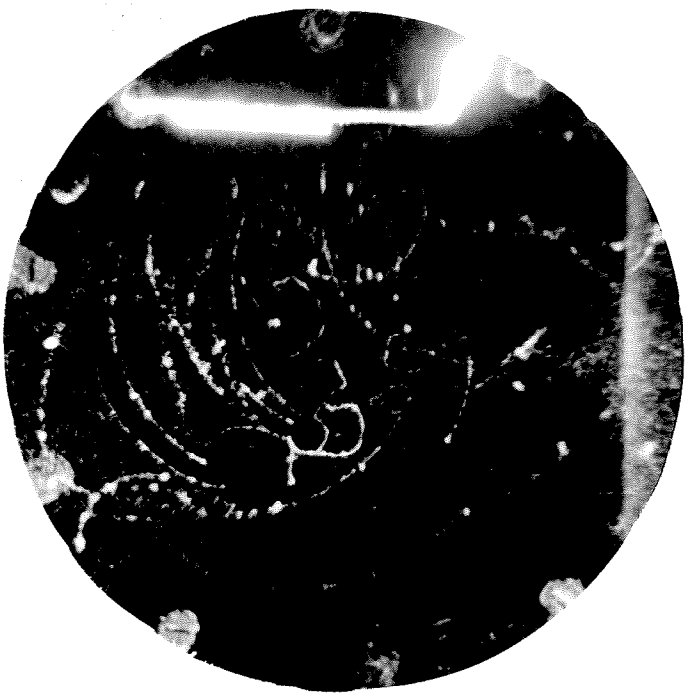
$$C^{12} + H^{2} \longrightarrow N^{13} + n^{1} \longrightarrow C^{13} + n^{1} + E^{+}$$

In order to investigate carbon and other elements under deuton bombardment, Prof. C. C. Lauritsen, Mr. W. W. Harper[2] and the author constructed a multiple target disk to be used in conjunction with the 1,000,000 volt positive ion tube already described[3], on which was fixed targets of a number

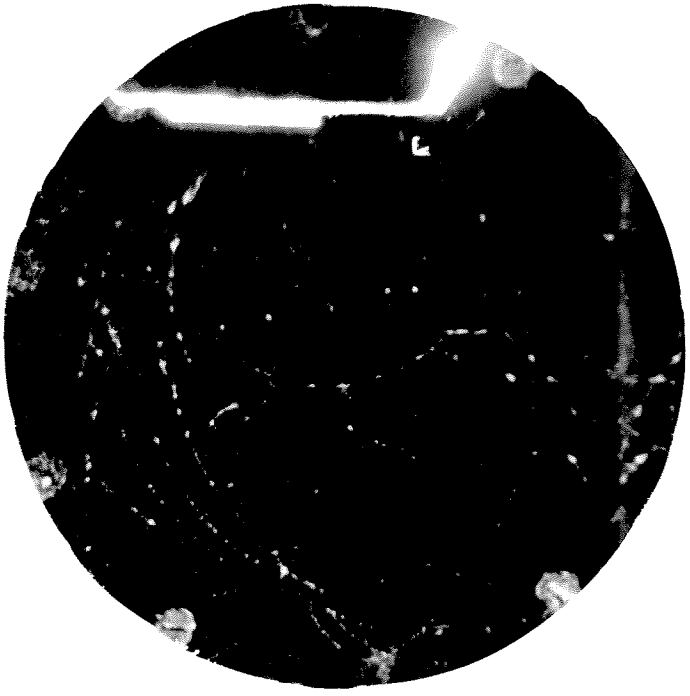
of different substances. The disk could be rotated inside the vacuum by means of a shaft so that it was possible to bring any one of the targets first into the ion beam for bombardment, and then into view of a Geiger counter having a thin window for recording the delayed emission of particles or γ-rays. Targets of LiF, Be, H_3BO_3, C, Mg and Al were subjected to bombardment, each for about 15 minutes with 5 microamperes deuton current, at 900,000 volts, and immediately rotated into view of the Geiger counter. In the case of boron and carbon, a large number of counts was recorded during the first few minutes after bombardment. Carbon gave the largest effect: several hundred counts per second* (calculated for the total solid angle) and decreased at a rate corresponding to a half life of about 10 minutes. The effect from boron was somewhat less intense, and the half life was about 20 minutes. Other substances bombarded gave effects which were appreciable, but which might have been caused by carbon contamination on the surface of the targets. In the case of these small effects a further investigation is to be made, and a knowledge of the rates of decay, especially, will help to decide whether or not they are to be attributed to carbon contamination.

To determine the nature of this delayed activity Dr. Carl D. Anderson and Mr. Seth H. Neddermeyer[4] placed a piece of freshly bombarded carbon in their Wilson cloud chamber and took a series of photographs, extending over a period of about two hours after bombardment. During the first hour each expansion revealed a number of electron tracks, all of which were of positive sign. In addition, a few short negative electron tracks appeared, which originated in the gas, indicating the presence of some gamma rays. Examples of the tracks observed are shown in the following photographs.

* Subsequent measurements with an ionization chamber showed that the total number of positrons emitted, including the very slow ones, was much greater than this -- about 10^4 per second.

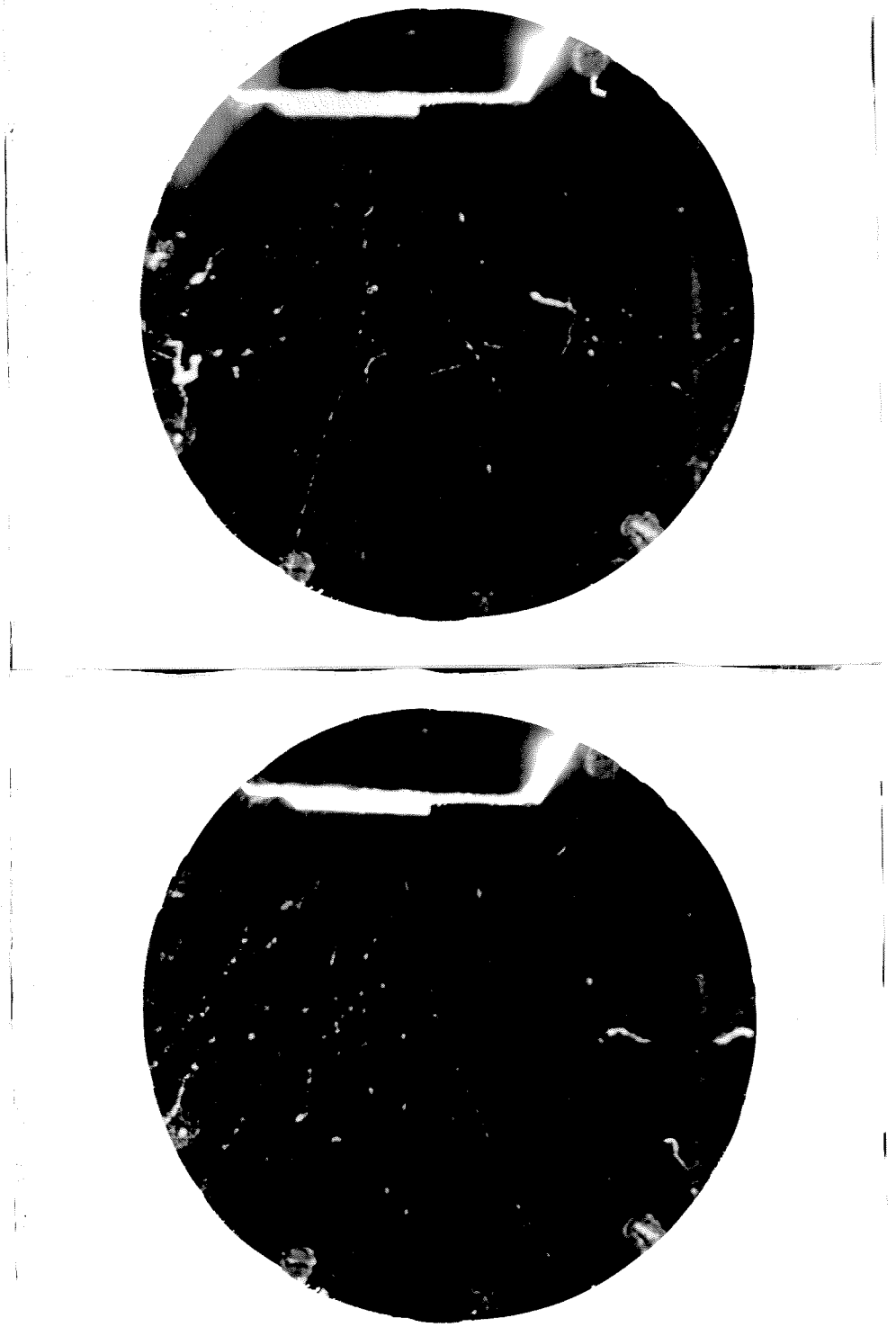


I Carbon target, a few minutes after bombardment with deutons of 900,000 e.v. energy. Magnetic field,780 gauss.



II Same as I, slightly longer time after bombardment.

III Same target as shown in I and II, more than one hour after bombardment, showing the decrease in activity. Two branched tracks appear, which probably represent negatrons set in motion by the positrons near the end of their range. It is interesting that in these close collisions annihilation of the positron does not occur.



IV and V

Two photographs taken without the magnetic field, to give an idea as to the amount of scattering suffered by positrons in this energy range and therefore an idea as to the dependability of the measurements of curvature of the tracks obtained with a magnetic field. Note the uniform curvature of one of the tracks in the upper picture, which is due to a succession of deflections in the same direction.

VI B_2O_3 target after bombardment with deutons of 900,000 e.v. energy, with a 19,000 gauss field, showing a number of tracks which originate in the gas in the chamber. This indicates that the positron-radioactive substance produced in the B_2O_3 is gaseous and diffuses out into the chamber.

Experiments which Give Evidence of the Annihilation of the Positron and the Conversion of its Mass into Radiant Energy

Due to the large amount of radioactive material which it is possible to produce by bombarding carbon and boron with deutons, Prof. Lauritsen and the author[5] found it possible to perform a series of experiments in which the total ionization produced by the positrons and by the γ-rays associated with them was directly made use of, instead of counting the individual particles. This eliminated, for all practical purpooses, statistical fluctuations, and the results obtained were very closely reproducible.

The experimental procedure was as follows: A target of the substance to be investigated was first bombarded for a suitable length of time, generally fifteen minutes, with an ion current of 10 microamperes, consisting principally of H^2, at 0.9×10^6 e.v. energy. The target was then removed

from the tube and placed in the bottom of an ionization chamber, and the rate of production of ionization as a function of time was measured. The ionization observed was attributed to particles which were ejected from the target and traversed the chamber, and also to γ-rays, in case such were present. In order to separate the effect contributed

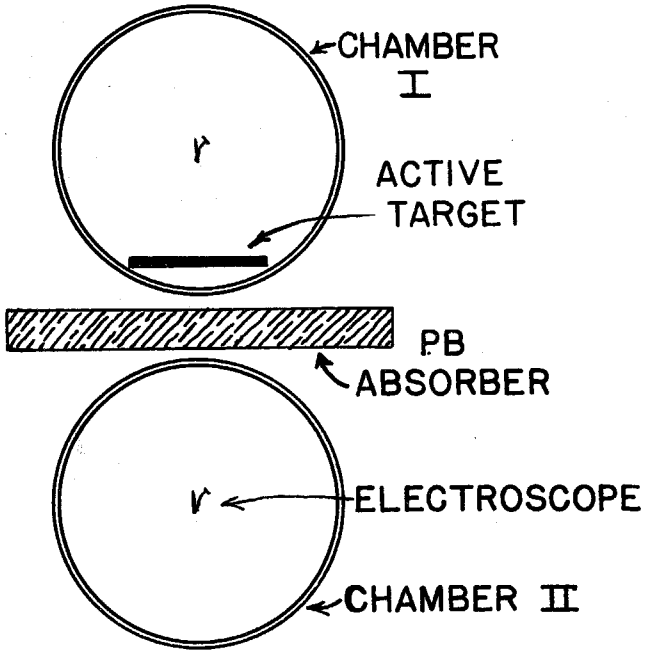


Fig. 3. Arrangement of the ionization chambers and lead absorber used for measuring positron emission and for measuring the absorption of the -rays resulting from the annihilation of the positrons.

by γ-rays alone, a second ionization chamber was placed directly below the first. The walls and linings of the chambers were sufficiently thick to prevent charged particles from entering the lower chamber and giving a direct effect. Therefore any ionization recorded in the lower chamber was attributed to γ-rays.

In Fig. 4 are plotted the log intensities for the two chambers against time after bombardment when a carbon target was placed inside the upper chamber. Curve I refers to the upper chamber and curve II to the lower chamber. It is seen from these plots that the half period (10.3 minutes) is the same within the experimental error, whether determined from the rate of emission of positrons or from the γ-rays associated with the process. This would seem to indicate that the same radioactive process is responsible for both the positrons and the γ- rays, and the most attractive assumption is that the γ-rays have their origin in the annihilation of the positrons together with electrons.

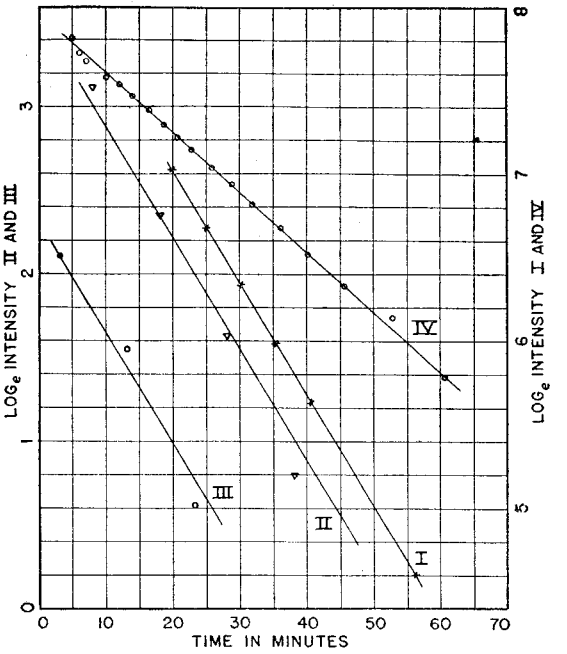


FIG. 4. Intensity of ionization as a function of time after bombardment due to: I, positrons from carbon target; II, γ-rays from carbon; III, γ-rays from carbon after 7.1 cm lead filtration; IV, positrons (?) from B_2O_3 target.

Fig. 4

To determine the absorption coefficient of the γ-rays, we made provision for interposing a sheet of lead 7.1 mm. thick between the two chambers. For the first half hour after bombardment, readings were taken every minute on the lower chamber and the lead was put in and removed at intervals of five minutes. We thus obtained alternately four one-minute readings with lead and four one-minute readings without lead. These are plotted on a log scale in Fig. 4, curves II and III, each set of four one-minute readings being averaged. The log difference between the positrons of the two curves is 1.23, corresponding to a linear absorption coefficient of 1.58 per cm. Since the source was very close to the lead

sheet, a large part of the radiation would necessarily pass through the lead at an angle, tending to compensate the effect of scattering. A calculation from the Gray formula and the Klein Nishina scattering give as the absorption coefficient for 24 x.u. (mc^2) radiation 1.67 per cm., so it seems that the quantum energy of the radiation here observed is, to within our experimental error, equal to mc^2, the energy equivalent of the rest mass of the electron.

In order to ascertain further that the γ-rays originate in the annihilation of the positrons, we performed the following experiment. A piece of freshly bombarded carbon was placed, active side up, directly above one of the chambers, as shown in Fig. 5. Supposedly in this case half the positrons are ejected in the downward direction and are annihilated in the carbon, while the other half escape and are annihilated in the air at a considerable distance away from the target and the ionization chamber. However, by covering the target with a sheet of some dense material, the positrons can be prevented from escaping, and they will all be annihilated in, or very near the carbon. Alternate readings were made on the chamber with the carbon covered with aluminum and with it uncovered. The result was that the rate of production of ionization in the chamber was about twice as great with the carbon covered as with it uncovered.

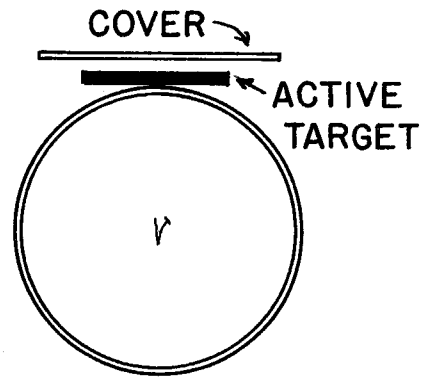


Fig. 5

In Fig. 6, curve I refers to the carbon covered with aluminum; curve II to the carbon without the aluminum cover.

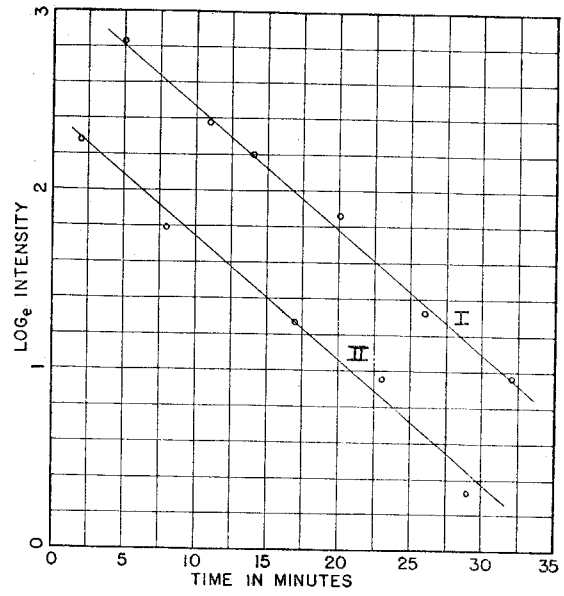


FIG. 2. Intensity of ionization in the chamber: I, with the carbon covered; and II, with the carbon uncovered.

As an additional check, we wished to compare the number of γ-ray quanta emitted with the number of positrons. By calibrating the ionization chamber against a standard radium source, we determined that immediately after bombardment about 6×10^4 photons per second are emitted from the carbon target. Making appropriate allowance for solid angle and considering that half of the positrons die in the target and the other half on the walls of the upper chamber, it turns out that there are 500 ion pairs to be associated with each positron passing through the upper chamber. The mean length of path in the chamber is approximately 5 cm; therefore the positrons would be producing, on the average, 100 ions per cm. of path, which is a reasonable figure and constitutes evidence that the number of photons is very nearly twice the number of positrons.

By comparing this with out previous work on carbon[6], it appears that carbon can be transformed by deutons in the following two ways:

$$C^{12} + H^2 \rightarrow C^{13} + H^1 + \gamma$$

$$C^{12} + H^2 \rightarrow N^{13} + n^1 \rightarrow C^{13} + n^1 + E^+$$

From our estimate of the number of photons obtained in each case, we are led to believe that the first process takes place about 10 times as frequently as the second. This is on the assumption that the annihilation of one positron produces two photons. To account for the radioactivity from boron, we may suggest a completely analogous reaction,

$$B^{10} + H^2 \rightarrow C^{11} + n^1 \rightarrow B^{11} + n^1 + E^+$$

In this case, also, there are alternative reactions which undoubtedly take place more frequently than the one which produces the radioactive substance. These are

$$B^{10} + H^2 \rightarrow 3\,He^4$$

$$B^{10} + H^2 \rightarrow B^{11} + H^1$$

The rate of decay of the activity of a B_2O_3 target, as measured by placing it inside chamber I is shown by curve IV in Fig. 5.

J. Thibaud[7] has performed an experiment, using a technique quite different from that just described, but which also demonstrates clearly that radiation results from the annihilation of positrons. A sketch of his apparatus is shown in Fig. 7.

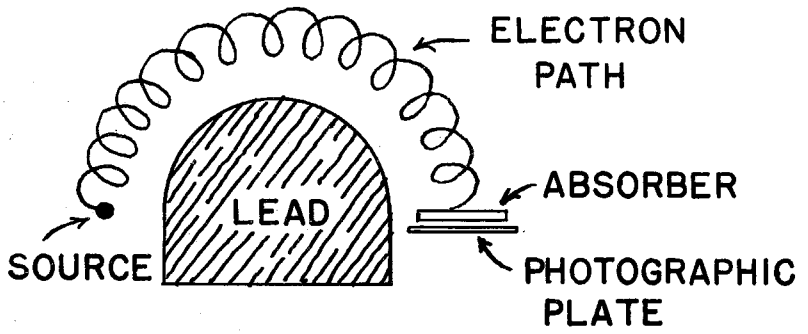


Fig. 7. Thibaud's apparatus for deflecting electrons from a source onto absorbing foils over a photographic plate. The magnetic field is inhomogeneous and perpendicular to the plane of the paper. The large block of lead shields the plate from the source.

Positrons are produced by allowing polonium α-particles to bombard continuously a target of aluminum. The positrons are then bent in a magnetic field so that they will fall on absorbing foils placed directly over a photographic plate. In addition to the bremsstrahlung, or continuous X-radiation which is produced when the positrons are stopped in the foils, there appears a strong monochromatic component of radiation of quantum energy about 0.5×10^6 e.v., which is attributed to the conversion of the positron rest mass into radiation. By replacing the positron source with a radioactive β-ray emitter and reversing the magnetic field, the same experiment was performed with negative electrons. Here the monochromatic component was absent, and only the bremsstrahlung appeared. The curves obtained, showing the intensity of radiation recorded by the photographic plate as a function of the thickness of absorbing foil, for positive and for negative electrons, are shown in Fig. 8. It should be noticed that, for large thicknesses

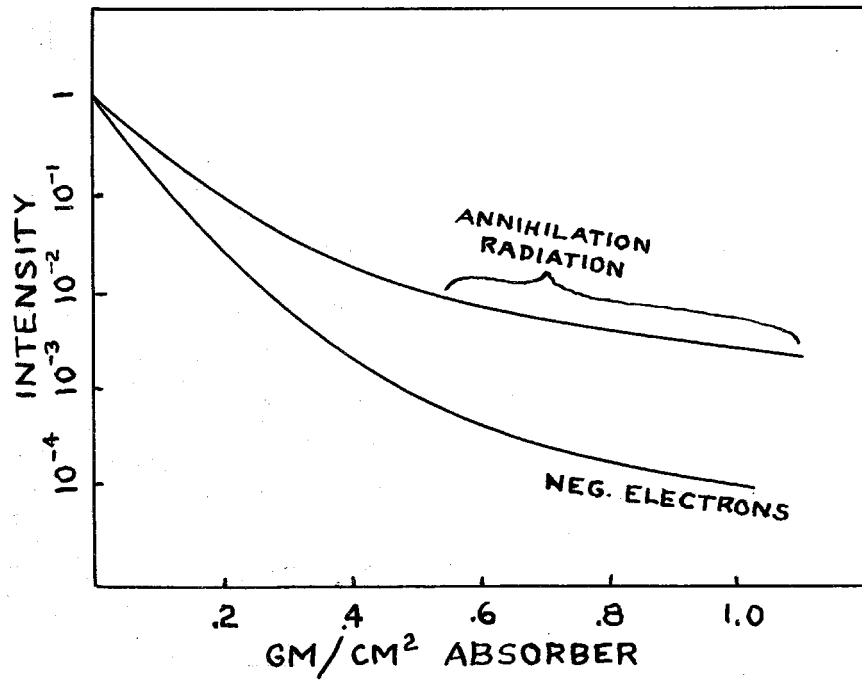


Fig. 8

of absorbing foil* the total amount of radiation resulting from the positrons striking the foil is about 40 times as great as that resulting from an equal number of negative electrons of the same velocity. Thibaud has calculated that this excess is about two quanta per electron, as would be expected on the assumption that the annihilation of a positive electron, together with a negative produces two quanta.

Chemical Tests of the Artifically Produced Radioactive Substances

Due to the rapid disintegration of the positron radioactive substances, extremely small amounts of these materials can be detected and followed through chemical processes. By using 100 millicuries of polonium, Curie and Joliot[8] were able to produce, in the most efficient of the reactions, a total of about 10^5 radioactive atoms, with which to perform chemical experiments, and in this way obtained confirming evidence that the active substances were those which they had at first suggested (see page 5). An example of their chemical experiments will be briefly outlined below.

Boron

Boron nitride powder was bombarded with the -particles from the polonium source until approximate equilibrium was reached between the production of the radioactive substance (supposedly N^{13}) and its decay. The powder was then mixed with soda and heated. This converted the nitrogen into ammonia, which was driven off by the heat. After this operation no activity could be detected in the residue. The ammonia gas was collected in a thin walled glass tube, and found to contain all the active material. The gas was then exposed to a piece of blotting

* The foils were in all cases thick enough to prevent an appreciable number of primary electrons striking the photographic plate.

paper soaked with hydrochloric acid, which very quickly absorbed all the ammonia, converting it into NH_4CL in the blotter. It was found, after this operation that all the active substance had been collected by the blotter. Although these experiments do not constitute a rigorous chemical analysis, they confirm the belief that the active substance is in this case an isotope of nitrogen, and that, in the experiment just described, it existed in the form of $N^{13}H_3^1$, mixed with the $N^{14}H_3^1$, which was known to be present in a large amount, due to the nitrogen in the boron nitride powder used.

Similar chemical experiments were performed with the radioactive substances produced by bombarding aluminum and magnesium with α-particles, and evidence was found indicating that the active substances were isotopes of phosphorous and silicon, respectively.

Radioactive Substances Produced by Deuton Bombardment

In observing the activity of a B_2O_3 target in a cloud chamber after deuton bombardment, Dr. Anderson and Mr. Neddermeyer[4] noticed that after a short time a large number of tracks appeared which originated in the gas (see photograph VI on page 10). Although it had been assumed that the radioactive substance in this case was C^{11}, the above observation indicated that the active material was a gas which rapidly diffused out of the B_2O_3. As further evidence of this, Prof. Lauritsen and the author[9] found that warming the active B_2O_3 to about 200° C in air completely drove off the radioactive constituent. It therefore seemed desirable to collect, and if possible, determine the nature of the active gas. To do this we warmed a small amount of the activated B_2O_3 in a flask containing air, and

transferred the air into an ionization chamber, through a liquid air trap. As long as the chamber was protected by the liquid air, no activity was recorded. However, upon removing the liquid air and allowing the trap to rise to a temperature considerably above that of liquid air, a large amount of the active material made its appearance in the chamber. The $B_2 O_3$ which was left in the flask was afterwards tested and found to have no activity. From this we concluded that after the $B_2 O_3$ was bombarded, nearly all the C^{11} existed in the target as CO or CO_2, and very little, if any, as carbon.

A graphite target after bombardment with deutons, which supposedly contained N^{13}, was also heated in an effort to drive off the active constituent, but after heating to a red heat, about half the activity remained in the target. This result does not necessarily cast doubt upon the belief that the active substance is N^{13}, because we know that nitrogen, as well as other gases, is very strongly adsorbed on carbon.

Production of Radioactive Substances by Proton Bombardment

Very shortly after the first production of radioactive materials by means of deutons, it was found, independently by Cockroft and Walton[10], by Lawrence and his associates[11], and by Prof. Lauritsen and the author[9], that protons directed against some targets, particularly carbon and boron, produced a considerable amount of positron activity, and that the rate of decay was in each case the same as that of the activity produced by deutons. The intensity of the effect produced by protons, as compared to that produced by deutons under similar conditions was, in the case of carbon, about 10 percent, and in the case of boron oxide ($B_2 O_3$), about 20 percent.

The fact that the decay periods of the active substances produced by protons and by deutons are quite exactly the same suggest strongly that the same radioactive products are formed. In the case of deuton bombardment the radioactive substances are supposedly N^{13} and C^{11}, respectively, and hence for the case of proton bombardment we may suggest the following alternative reactions which would involve the same radioactive products:

$$\begin{aligned} C^{12} + H^1 &\longrightarrow N^{13} \longrightarrow C^{13} + E^+ \\ B^{10} + H^1 &\longrightarrow C^{11} \longrightarrow B^{11} + E^+ \end{aligned} \qquad (1)$$

where the excess energy calculated from the change in mass in the overall reaction is given, and

$$\begin{aligned} C^{13} + H^1 &\longrightarrow N^{13} + n^1 \longrightarrow C^{13} + n^1 + E^+ \\ B^{11} + H^1 &\longrightarrow C^{11} + n^1 \longrightarrow B^{11} + n^1 + E^+ \end{aligned} \qquad (2)$$

where in accordance with the presumable mass of the neutron the excess energy from the change in mass is nearly negligible and might be either positive or negative. If we assume that the C^{13} and B^{11} at the beginning and at the end of the process are identical, then the overall process is just equivalent to changing a proton into a neutron and a positron.

One hesitates to accept the first type of proposed reaction, mainly because the probability of a particle being added to a nucleus without the ejection of some other particle to carry away the excess energy is extremely small. So far no example of it has been established.

The second type of reaction seems more attractive, since any excess energy could easily be carried away by the neutron. If we take the masses of the proton, neutron and positron as 1.0072, 1.0067 and 0.0005, respectively, then the only kinetic energy available for the neutron and the positron is the kinetic energy contributed by the incident proton

(in this case 0.9×10^6 e.v.). Nevertheless, we may not be justified in expecting to find the energies of the positrons limited to 0.9×10^6 e.v., since the known phenomena of the continuous -ray spectrum have already indicated that the strict law of the conservation of energy may not hold in the case of electron emission. It might be reasonable to expect, however, that the energies of the positrons plus those of the neutrons would satisfy the conservation of energy statistically, and therefore have 0.9×10^6 e.v. as a mean energy.

Two experiments suggest themselves, the results of which might help in deciding which of the two types of reaction is the correct one. If the latter process is the correct one, it would seem reasonable that a change in the total energy available, or in other words, a change in the energy of the bombarding protons, should have some effect in addition to the usual change in the probability of penetration of the nuclear barrier. The first thing to look for would be some minimum energy below which the reaction could not take place, regardless of the penetration of the proton into the nucleus. An experimental curve which we have obtained, giving the rate of formation of the radioactive substance in a thick carbon target as a function of the voltage used to accelerate the protons is shown in Fig. 9, curve I. The curve obtained by differentiating this curve is also shown (curve II) and this should represent the effect for a thin target, or the true probability of the reaction taking place as a function of voltage. It is seen that the overall probability rises very rapidly between 550 and 650 kv. and is thereafter nearly constant. A decision as to whether this rapid rise reveals anything more than the probability of the penetration of the proton into the nucleus must await more accurate measurements and an investigation of analogous cases.

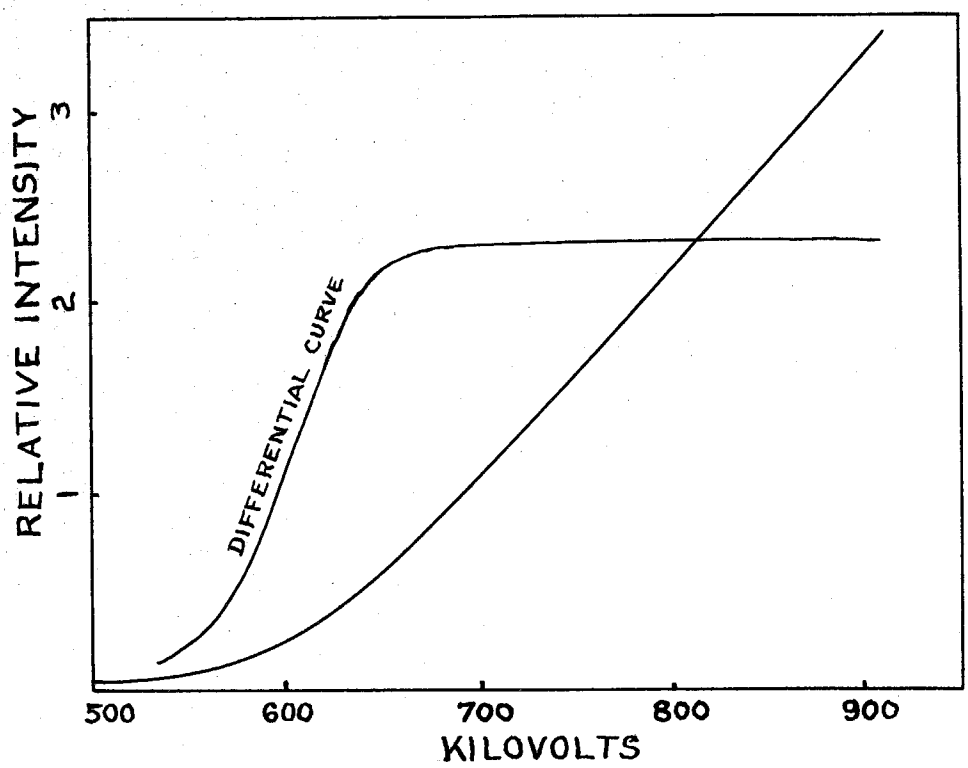


Fig. 9. Efficiency of production of radioactive substance in carbon bombarded with protons, as a function of voltage.

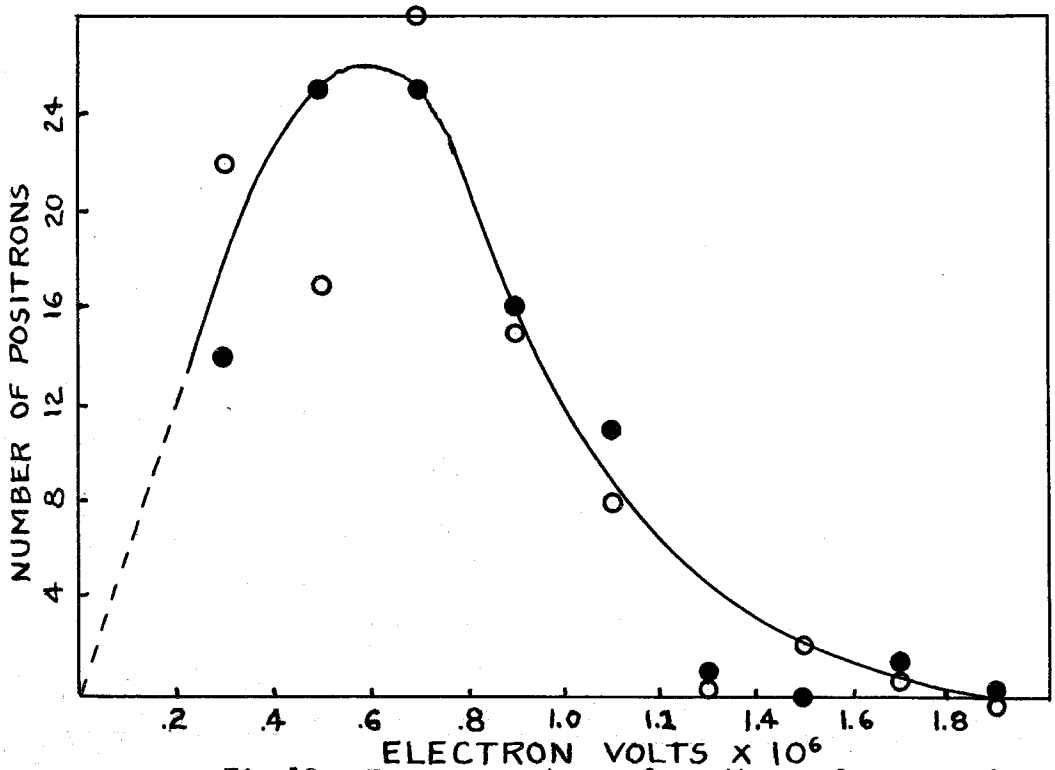


Fig.10. Energy spectrum of positrons from a carbon target bombarded with 700 kv. protons (open circles) and with 900 kv. protons (filled circles).

A second implication of the type of reaction under discussion is that, since the kinetic energy of the positrons must be derived in a large part from the energy of the bombarding protons, a change in the energy of the protons might be expected to influence the energy spectrum of the positrons. This would not be true, however, if the only requirement were that the energy supplied be greater than some minimum value, the excess over this being carried away by the neutron. To test this possibility Dr. Anderson and Mr. Neddermeyer[4] took a large number of cloud chamber photographs of tracks from targets bombarded with protons at 700 and at 900 kv. The results are shown in Fig. 10. No difference in the energy spectrum of the resulting positrons could be established with certainty, and it will be necessary to have a great deal more data to decide the point definitely.

Production of β-active Substances by Neutron Bombardment

Within the last few weeks Fermi[12] has reported the production of a number of radioactive substances by neutron bombardment. In each case he assumes that the neutron is captured and an α- particle emitted, as in the typical reaction

$$F^{19} + n^{1} \longrightarrow N^{16} + He^{4}$$

the N^{16} then emitting a negative electron, becoming O^{16}.

The activity which can be produced by neutron bombardment is very small (of the order of 1 electron per second) compared to the positron activity produced by deuton bombardment, which is of the order of 10^{4} positrons per second. This is due in part to the very small absorption of neutrons in the target, and in part to the relatively small intensity of neutrons

which can be produced. Neutrons have the advantage, however, that they penetrate the very heavy nuclei apparently as easily as they penetrate the light nuclei, and Fermi has already been able to disintegrate barium (at. no. 56). A list of the elements which Fermi has been able to transform into radioactive substances by neutron bombardment is given below, with asterisks to indicate the relative intensities.

Element	Decay period
Fluorine*	
Silicon ***	3 min.
Phosphorous **	3 hr.
Chlorine	
Vanadium	5 min.
Chromium**	6 min.
Iron	2 hr.
Aluminum*	
Arsenic	2 days
Silver **	2 min.
Tellurium	1 hr.
Iodine**	30 min.
Barium	2 min.

Some activity was also obtained with Na, Mg, Ti, Zn, Zr, Se, Sb, Br and La.

The results of the experiments on artifically stimulated electron emitters which have been described in this paper, and especially those stimulated by protons are intimately tied up with the problems of the continuous beta ray emission and the question of the validity of the principle of the conservation of energy, both as applied statistically and to the elementary process. After more experimental data has been made available something of the previous history of the electron emitters will be known as well as the history of their decay, and hence they promise to shed a great deal of light on the general problem of electron disintegration and the apparent failure of the principle of the conservation of energy.

REFERENCES

1. Curie and Joliot, Comptes Rendus 198 254 (1934)
2. Lauritsen, Crane and Harper, Science, 79 234, (1934)
3. Crane, Lauritsen and Soltan, Phys.Rev. 45 507 (1934)
4. Neddermeyer and Anderson, Phys.Rev. 45 498 (1934)
5. Crane and Lauritsen, Phys.Rev. 45 430 (1934)
6. Lauritsen and Crane, Phys.Rev. 45 345 (1934)
7. J. Thibaud, Comptes Rendus 197 1629 (1933)
8. Curie and Joliot, Comptes Rendus 198 ~~254~~ 559 (1934)
9. Crane and Lauritsen, Phys.Rev. 45 497 (1934)
10. Cockroft, Gilbert and Walton, Nature 133 328, (1934)
11.
12. Fermi, La Ricerca Scientifica Vol. I, N 6 Anno V