ARTIFICIAL RADIOACTIVITY

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HISTORICAL INTRODUCTION

On January 15, 1934, I. Curie and F. Joliot[1] presented the first good evidence for the phenomenon which, under the name of "induced" or "artificial" radioactivity, had been sought since the discovery of the natural activity of uranium by Becquerel in 1896. In the course of their investigations of the positive electron discovered less than two years previously, they found that when certain light elements (B, Mg, Al) were bombarded with the alpha-particles from polonium, they emitted positrons in large numbers. Their discovery of artificial radioactivity was made when they observed that this positron emission did not cease immediately on the removal of the source of alpha-particles, but instead decayed according to an exponential law, with a half-life characteristic of the substance bombarded, and of several minutes duration. They found that the growth of the activity under alpha-particle bombardment followed the usual exponential curve, the transformation constant being the same for growth and decay. After irradiation for a period long compared with the half-life, the induced activity observed in a sample reached a saturation value which could not be increased by further irradiation. Curie and Joliot ascribed the radioactivity induced in boron to N^{13}, an isotope of nitrogen not known in nature, and predicted that the same isotope could be formed by the bombardment of carbon by deuterons, according to the reaction

$$_6C^{12} + _1H^2 \rightarrow _7N^{13} + _0n^1.$$

This prediction proved to be correct, and led to the first production of radioelements by totally artificial means, without the use of a naturally radioactive source of alpha-particles. Crane and Lauritsen,[2] Henderson, Livingston, and Lawrence,[3] and later Cockcroft,[4] verified that an artificial radioelement

was produced by the deuteron bombardment of carbon, but the half-life as measured by them differed markedly from that reported by Curie and Joliot for the product of the alpha-particle bombardment of boron. This discrepancy was later shown to have been false, the radioelement being N^{13} in each case. Cockcroft, Gilbert, and Walton[5], and Crane and Lauritsen,[6] had meanwhile demonstrated that the same N^{13} was formed by the proton bombardment of carbon, while Crane and Lauritsen had also found that boron displayed a radioactivity under deuteron[2] and proton[6] bombardment which they correctly attributed to C^{11}.

It was apparent that at the voltages available (up to about 3 mev.) for accelerating protons and deuterons, and with the energies possessed by alpha-particles obtainable from naturally radioactive sources, the nuclear transformations necessary to produce artificial radioelements could be stimulated only in the lightest elements; viz, those having the lowest potential barriers opposed to the entry of charged particles into the nucleus. Fermi,[7] therefore, tried the effect of neutron bombardment of various elements in the hope of producing artificial radioactivity. From the first, this method was successful, and he and his co-workers were able to produce transmutations leading to artificial radioelements in many elements, including even uranium.

In a communication[8] dated October 22, 1934, Fermi and his co-workers reported a great increase in the activation of silver under neutron bombardment when the source and the silver were surrounded by quantities of water or paraffin. This was shown to be a specific effect of a substance containing hydrogen, although exhibited in a lesser degree by carbon, iron, lead, and silicon. It was correctly attributed by Fermi to the slowing down of the neutrons by collision with hydrogen nuclei, the resulting slow neutrons having a greater probability of capture than fast neutrons. This phenomenon has proved to be of great importance in the study of nuclear reactions.

During the past year, the investigations in the field of artificial radioactivity have been concerned with the discovery of new radioelements made

in the three ways mentioned above, and the correlation of data concerning them. Advances in our understanding of the effects due to slow neutrons have also been made, although this subject is by no means closed as yet. The present paper is an attempt to treat in detain the knowledge of the whole subject down to the end of August, 1935.

THE ARTIFICIAL RADIOELEMENTS

1. General Stability Considerations: It has long been a subject of remark that in a diagram whose ordinate is atomic weight, or the difference between atomic weight and atomic number, and whose abscissa is atomic number, the points representing the stable isotopes found in nature and measured in the mass-spectrograph lie in a well-defined region (Figure 1.) As this can hardly be regarded as being fortuitous, we should consider the stable isotopes as defining a region of nuclear stability outside of which lie nuclei which can be formed by the expenditure of energy, but which, once formed, tend to return to the region of stability by the expulsion of an alpha-particle, by the transformation of a nuclear neutron into a proton with the consequent expulsion of a beta-particle, or by the reverse transformation of a nuclear proton into a neutron, with the emission of a positron. The rules of isotopic statistics,[9] particularly those concerning the paucity of isotopes of elements with odd atomic number and that of isotopes with odd A - Z, where A is mass-number and Z is charge-number, doubtless have an important bearing, whose meaning has not been completely elucidated as yet, on the matter of nuclear stability. The problems of stability of nuclei have been examined in detail by Heisenberg,[10] and by Gamow;[11] here a brief and completely qualitative discussion will suffice.

In Figure 2 the stable isotopes up to Cl are plotted as circles, and the artificial radioelements in this region of the periodic table are plotted as squares, the arrows indicating their mode of formation. The diagram will be better understood after reference to Section 3, below, which it is designed to

illustrate, but here it should be noted that the stable isotopes lie in an extremely regular grouping, and that all of the known artificial radioelements lie in such a position that they can transform themselves into stable isotopes by the emission of a positron or of an electron, and that in every case they do emit the appropriate particle. It is also to be noted that those unstable nuclei which lie above and to the left of the line defining the stable isotopes emit electrons to return to the region of stability, while those below and to the right emit positrons, as is indeed demanded by their positions on the diagram. Among the heavier elements are known cases in which the emission either of a positron or an electron would return the artificial radioelement to a stable form; such cases are pointed out in Section 5.

2. Chemical Identification of the Radioactive Isotope: It is obviously of the utmost importance to determine the chemical nature of an artificial radioelement. Manifestly, it must be an isotope of an already known element in almost all cases, for the chemical properties of an atom are determined almost entirely by the charge on its nucleus, without regard to the structural stability of this nucleus. It is equally clear that the moment a disintegration leading to the formation of a new and unstable nucleus takes place, the newly-born atom has properties determined by its new charge-number and will behave in all chemical respects like the element of which it is an isotope.

The chemical identification of artificial radioelements is based on the well-known fact that isotopes are not appreciably separated by ordinary chemical reactions. Thus, if an element consists of the fraction A of isotope a, and (1 - A) of isotope b, and if the fraction B of the total enters into a chemical reaction, then BA and B(1 - A) will be the fractions of each isotope that have reacted. While the chemical behavior of the few hundred thousands or few millions of atoms of an artificial radioelement formed in a nuclear reaction may be erratic and uncertain, if a quantity of the element with which the radioelement

is suspected of being isotopic is added, and then completely separated out chemically and examined for activity, it can be definitely established whether or not the radioelement is isotopic with the element in question; for, if the isotopy exists, all of the activity will have been separated out in the removal of the element under examination. The procedures involved may best be illustrated by means of examples; the radioactive products of the bombardment of carbon by deuterons and of boron by deuterons were carefully investigated by Yost, Ridenour, and Shinohara,[12] and their results are given below.

Experimental Method

Carbon was bombarded in the form of graphite and boron in the form of fused boric oxide by 0.8 and 0.9 mev. deuterons accelerated in the tube developed by Crane and Lauritsen for nuclear investigations.[15] Currents of about 40 microamperes were usually employed. The presence, amount, and half-life of the radioactive material were determined by quartz-fiber electroscopes constructed and kindly loaned by Professor Lauritsen, or by means of a Geiger counter whose cylindrical electrode was of aluminum about 0.2 mm. thick.

The experiments were always conducted on a gaseous form of the radioelement; in the case of boron this was prepared simply by heating the boric oxide target to about 600° in a closed vessel and washing the resulting gases into a gasometer with air. In the case of carbon, a thin layer containing practically all the activity was scraped off the upper surface of the target and burned with about 200 cc. of air in a platinum boat in a quartz combustion tube. Air for the combustion was supplied from a specially constructed gas pipette. Small amounts of other gases could be added to the air used to burn the carbon or to the gases present in the gasometer in the experiments on boron. The following experiments were carried out; when any gas other than air was present, the fact is so stated.

Carbon bombarded by deuterons: The gases from the combustion of the carbon were passed first over heated copper oxide in all cases. They were subsequently passed through a train of solid or liquid absorbents, or they were collected over concentrated sulfuric acid in a second gas pipette similar to the first.

(1) The exit gas was passed through a train consisting of solid KOH (or soda lime), potash bulbs filled with 50 percent KOH, $CaCl_2$ and P_2O_5. The gas not absorbed was active. The solid KOH and $CaCl_2$ showed no activity. This experiment eliminates H, Li, Be, B and C as the active substances. The hydrogen would have been burned to H_2O and this would have mixed with the water of the KOH solution. The small amount of water vapor from the KOH solution would have been absorbed by $CaCl_2$ or P_2O_5. The oxides of Li, Be and B are not volatile at room temperatures. The hydrides of boron are burned by heated air and decomposed by alkali with the formation of B_2O_3 or its salts.[16] Carbon was present as CO_2 and this is readily absorbed by the alkalis present in the train.

(2) The exit gases were passed through alkaline pyrogallol and then collected in the pipette. The resulting gas was active. This result eliminates oxygen as O_2, since it is absorbed by the alkaline pyrogallol. If the oxygen were present as NO_2, it would undergo complete absorption in the potash.

(3) The gases resulting from the combustion of the graphite by a helium-air mixture were collected over concentrated sulfuric acid in the pipette. By passing the gas repeatedly (10 to 15 times) through alkaline pyrogallol it was freed from O_2 and CO_2. The gas so treated was strongly radioactive. It was next passed into an evacuated tube containing metallic calcium shavings and the calcium was then heated with a Bunsen burner. Extensive absorption of the gases took place. The tube was again evacuated to remove the helium and any other gases not absorbed by the calcium. After the contents of the tube had cooled and air had been admitted, the solid contents were removed and ground to a powder in a mortar. The powder showed strong activity. This result eliminates helium

as the source of the activity, since it would be removed with the ordinary helium when the tube was evacuated.

The powder was then placed in a glass tube equipped with a dropping funnel containing water. The gases evolved on adding water were radioactive. This result eliminates oxygen (if originally present as NO) and fluorine if present as the very unreactive CF_4 or C_2F_6. The oxygen would not be liberated as a gaseous substance in this procedure. If the fluorides of carbon were originally present, they would have been pumped out if they had not reacted with calcium, and they would have been converted to calcium fluoride and carbide had they so reacted; the calcium fluoride does not yield a volatile product in the alkaline solution such as existed on addition of water to the powder. Nitrogen would have absorbed as Ca_3N_2, and this substance, on treatment with water, yields ammonia.

The combined results of the chemical experiments eliminate not only all the elements of the first row of the periodic system except nitrogen as the source of the radioactivity, but also all others. On physical grounds it is possible to state that the activity must be due to one of the elements H, He, Li, Be, B, C or N (unless the possibility of the emission of an electron from the carbon nucleus during bombardment is admitted, in which case O must be a possibility; no example of such a reaction has been established), since the total nuclear charge entering into the reaction producing the radioactive substance is 7. The total mass entering into the reaction is probably 14 and possibly 15 (although the abundance of C^{13} is very small), and we may certainly presume from the experiments on recoil radioactive nuclei[4] that the mass number of the radioactive product is surely not larger than 14 and is probably 13. Inasmuch as the only particles emitted from carbon under deuteron bombardment in observable numbers are known to be neutrons and protons, the radioactivity is probably due to C or N. Since we may assume in analogy with all cases of artificial radioactivity that the active substance is an isotope of mass number different from those known

by mass spectra, it is likely to be C^{14} or N^{13}, and the latter is the more probable on the ground of the rarity of C^{13}, as well as from the fact that it emits positrons. The present experiment seems definitely to have established that it is nitrogen, and we may then infer that it is likely to be N^{13}.

Measurements on the half-life of the active gas at various stages in the chemical treatment yielded concordant values around 10.5 minutes, indicating that the activity is due to a single substance.

Boron bombarded by deuterons: The total mass entering into this reaction may be 12 or 13, corresponding to B^{10} or B^{11}. The total charge is 6, and we may again for safety admit the possibility of the emission of a negative electron from the nucleus. On physical grounds, the activity may, then, be due to H, He, Li, Be, B, C or N. Since a heavy particle must be emitted in the creation of the radioelement,[5] the total mass of the product must be 12 or smaller. The chemical experiments were as follows:

(1) A small amount of carbon dioxide was added to a sample of gas collected in the gasometer. One-half of the gas was tested and found to be active. The other half was passed repeatedly through KOH solution, and the resulting gas showed an activity of about one-third that of the first half, after correcting for known decay which took place while the operation was carried out. Some of the active materials evidently had been absorbed by the potash. Since Li and Be compounds are involatile, these elements are eliminated as possible sources of all the activity.

(2) To a 150 cc. sample of gas in the gasometer about 10 cc. of carbon monoxide were added, and the mixture was then passed over heated cupric oxide. Half of the resulting gas was tested with an electroscope and found to be active. The other half was passed several times through 50 percent KOH solution and then into the electroscope. The resulting gas was inactive. These two results eliminate B, N_2 and O_2 as possibilities, since the volatile hydrides of B would burn to B_2O_3 on the hot CuO or be decomposed by the alkali,[16] and N_2 and O_2 would

not be absorbed by KOH.

(3) Experiment 2 was repeated after 10 cc. of helium had been added to the gas sample in the gasometer. The activity was absorbed by KOH. This result excludes He as the source of the activity since it is not absorbed by alkalies.

(4) A sample of gas to which CO and NO_2 had been added was passed over hot CuO and through a strong solution of $KMnO_4$ in 3 N sulfuric acid. The resulting gas was active. The experiment was repeated but without passing over hot CuO. The result was the same. These results excluded H_2, and N as NO or NO_2, for hydrogen would burn to water and be mixed with the water in the permanganate solution; NO or NO_2 would be oxidized completely to HNO_3 by the acidified permanganate.[17] Fluorine, if present as BF_3, would be completely hydrolyzed and absorbed by the aqueous solution. Boron, if present as volatile hydrides, would be oxidized and decomposed by the heated CuO or hydrolyzed by the solution.

The results of the chemical experiments eliminate all elements in the first row of the periodic system except carbon. The gas driven from the boric oxide target has the properties of a mixture of carbon dioxide and carbon monoxide. Just why the newly formed carbon atoms should be oxidized partly to monoxide and partly to dioxide is not evident. It was not determined whether the two compounds were always formed in the same proportions.

Measurements on the half-life of the radioactive gas both before and after chemical treatment yielded the value 20.5 minutes in all cases, indicating that the activity is due to a single substance. Since C^{12} is stable, on the physical grounds outlined above, this substance is probably C^{11}.

When the artificial radioelement produced in a nuclear reaction is an isotope of a completely unknown element, or of one which is so rare that none can be added to the radioelement to stabilize its chemical properties, the matter of chemical identification is a great deal more difficult. Such a

case occurs in the bombardment of uranium by neutrons; Fermi, who first studied this reaction, early concluded [18] that at least one of the half-lives observed belonged to an element of charge-number 93, for its chemical reactions did not seem to be those of any of the known elements from 86 to 92 incluside. This point of view was criticized by v. Grosse and Agruss,[19] who thought that the experiments of Fermi did not exclude the possibility that the radioelement in question might be isotopic with element 91, whose isotopes occuring in nature -- protactinium and UX_2 -- are both very rare. New experiments by Fermi,[20] and Hahn and Meitner [21] seemed to indicate that not only element 93 was formed, but also elements 94 and 95 were formed in the disintegration of uranium by neutrons, a chain of radioactive products apparently being initiated. Interesting results have been obtained also in the bombardment of thorium by neutrons,[20,22] and our whole knowledge of the effects of neutron bombardment of the natural radioactive elements, sketchy as yet (see Section (5), where the reactions for each element are treated in detail),may be expected to shed some light on the problems of the uranium, actinium, and thorium series, and perhaps on the missing elements 85 and 87.

3. Concentration of the Artificial Radioelements: It is evident that if the radioelement produced in a nuclear reaction is not isotopic with the bombarded element, a very effective concentration of the radioactivity can be performed by separating out the active element by means of an appropriate chemical reaction, a few milligrams of the element with which the radioelement is isotopic having been added to stabilize the chemical behavior of the small number of active atoms. This self-evident procedure has often been employed.

Another useful means of concentration of a radioelement differing chemically from its parent, which has a much more limited range of application, is that of electrochemical deposition. This has been employed by Haissinsky [23] in the concentration of radiocopper, produced by neutron bombardment of zinc. In order that this means may be applicable, the radioelement must be electro-

chemically more noble than its parent.

In the case which has occurred most frequently to date in the production of artificial radioelements -- that in which the radioelement is isotopic with its parent -- the situation is by no means so hopeless as is the chemical separation of ordinary isotopes. Szilard and Chalmers [24] first showed that active iodine could be separated from ordinary iodine by making use of the fact that when I^{128} is formed by the capture of a neutron by I^{127}, the struck nuclei may have been removed from the compound containing the I being irradiated. Whether the atoms freed in this way will interchange with their isotopes bound in the irradiated chemical compound will depend on the nature of the chemical compound with which we are dealing. To prevent such interchange, Szilard and Chalmers first worked with non-ionizing organic compounds, such as ethyl iodide and bromoform, with a trace of free halogen added to protect the radioactive isotope. After the irradiation, the free iodine or bromine was reduced and precipitated as a silver halide. Fermi[20] has prevented the interchange of radioactive and ordinary chlorine atoms by irradiating a compound in which the chlorine is bound in a radical which, once destroyed, has a negligible probability of being rebuilt. If sodium chlorate is irradiated, a trace of Cl^- added, and AgCl precipitated, care being taken to prevent the precipitation of $AgClO_3$, from 70% to 90% of the activity is concentrated in the precipitate. Similar results can be obtained with bromates and iodates. Manganese dioxide precipitated from irradiated potassium permanganate solution carries a large part of the activity due to radiomanganese.

Physical methods of separation depending on the fact that the atom is likely to have lost one or more extranuclear electrons at the moment of formation, and hence can be collected by an electrostatic field, have also been employed by Fermi[20] and by Paneth[25] for the concentration of radioactive isotopes of the bombarded element.

The phenomenon of recoil of the struck nucleus at the moment of formation of an artificially radioactive nucleus was first observed by Werten-

stein[26] in the case of radiofluorine formed from atmospheric nitrogen by alpha-particle bombardment, and has since been observed in many cases where a heavy particle is emitted in the formation of an artificial radioelement.[4, 27]

The possibility of concentrating an artificial radioelement makes artificial radioactivity useful as a detector of neutrons which can be observed only in the presence of gamma-radiation so intense that electrical methods of neutron detection are not feasible. This procedure was used by Ridenour, Shinohara, and Yost[28] in their experiments on the disintegration of Be^9 by x-rays; their results are given below in illustration of the value of the method.

The Disintegration of Beryllium by Photons and its Possible Bearing on the Mass of Be^9

Szilard and Chalmers[29] found that when beryllium was bombarded with the gamma-rays of radium in equilibrium with its decay products, neutrons were liberated, and could be detected by means of the radioactivity they excited in iodine. Meitner[30] showed that these neutrons excited radioactivity in I, Au and Ag, but not in Na, Si and Al. The former reactions involve the capture of a neutron, which, as Fermi[20] has shown, is most probable when the neutrons have little energy; while the latter three reactions involve the emission of an alpha-particle or proton, and probably have a higher probability when the bombarding neutrons have greater energies. Brasch and others,[31] working with x-rays, have obtained this disintegration at voltages between 1.5 and 2 mev.

In the present experiment, beryllium was bombarded with the x-rays from the tube in the Kellogg Radiation Laboratory. The tube is self-rectifying, and was supplied with 50 cycle ac. at 0.9 mev. peak. The electron current to the target was 2 m.a. The beryllium was located directly behind the tungsten target, in a bomb which was lowered inside the electrode. The ethyl iodide used as a detector for the neutrons was also in the bomb, just above the beryllium and in

a Dewar vessel to prevent the heat generated at the target from reaching the ethyl iodide in the course of the irradiation, which lasted 40 minutes. The active iodine was separated from the ethyl iodide by the method of Szilard and Chalmers.[24] 200 g. of beryllium and 375 cc of ethyl iodide were employed; the inside diameter of the bomb was 6.2 cm., and its overall length 25 cm. The intensity of radiation at 1 cm. behind the target is calculated to be 2.5×10^4 r/min., on the basis of the measured intensity at 50 cm. from the target and the known filtration in both cases.

The samples of iodine separated after irradiation were tested for activity with a quartz-fiber electroscope loaned by Professor C. C. Lauritsen. There was no increase over the background on the introduction of a sample. To check the sensitivity of the method, a test run was made with 370 mg. of radium placed under the bomb in the position occupied by the target of the x-ray tube in the first experiment. The activation of the iodine in this case was easily measurable, initially more than doubling the cosmic-ray background. This poor yield in the case of the radium is to be attributed to the unfavorable geometrical conditions of necessity offered by the bomb; a much larger effect can be obtained by increasing the solid angles of irradiation.

Taking into consideration the relative intensities of the two sources of radiation, it may be said that an activation produced by the x-rays of one-one-thousandth the magnitude of that produced by the gamma-rays of radium would have been detected in this experiment. This may be perhaps reconciled with the statement of Gentner,[32] that 0.9 mev. radiation is most effective in the disintegration of beryllium, if one presumes that the efficiency of the process falls off sharply on the low-energy side of 0.9 mev., for the number of 0.9 mev. quanta in the radiation produced in an x-ray tube excited with a.c. at 0.9 mev. peak is very small.

Of one is to suppose that beryllium is disintegrated into two alpha-particles and a neutron by a high energy photon, and that the enormously reduced yield just below a million volts found in this experiment indicates the existence of

a genuine threshold for the phenomenon, then it seems possible that the mass of Be^9 is too high. If we fix the threshold at 0.9 mev. and take the mass of the neutron as 1.0080, then, on our assumptions, the mass of Be^9 must be 9.0114, a result which explains the anomaly of the stability of Be^9, as well as Bonner and Brubaker's [33] results on the energy of the neutrons from Be bombarded with deuterons.

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4. The Reactions Leading to the Formation of Artificial Radioelements:

There are only eight type-reactions which need be adduced to explain the formation of about 100 artificial radioelements known to date, with one possible exception which will be considered under the paragraph on bromine in the next Section. Each reaction has been studied in sufficient detail so that there can be little doubt that it is an established one. It should be always explicitly borne in mind that in all these reactions the conservation of energy in the broad sense is satisfied, so that in reaction VIII, for example, a gamma ray of the appropriate energy must always be emitted.

A. REACTIONS PRODUCED BY ALPHA PARTICLE BOMBARDMENT:

I. Capture of the alpha particle with emission of a neutron.

$$_{Z}X^{A} + {}_{2}He^{4} \rightarrow {}_{Z+2}Y^{A+3} + {}_{0}n^{1} \quad \text{followed by} \quad {}_{Z+2}Y^{A+3} \rightarrow {}_{Z+1}W^{A+3} + {}_{1}e$$

This is historically the first reaction of artificial radioactivity, and being that observed by Curie and Joliot[1] in the cases of boron and aluminum bombarded by alpha-particles. They thought that this reaction also led to the 2.3 minute period observed in magnesium bombarded with alpha-particles, and although this reaction doubtless does take place in Mg+n, the period of the positron emission is unknown, the 2.3 minute period being due to Al^{28}, formed in accordance with reaction II, below. (See the paragraph on magnesium in Section 5.)

In all the cases known in which reaction I takes place, the alternative emission of a proton, leading at once to the stable isotope

$_{Z+1}W^{A+3}$, also takes place, and with a much greater probability. The successive emission of a neutron and a positron, or the immediate emission of a proton on alpha-particle bombardment may be thought of as alternative routes between the two stable isotopes $_{Z}X^{A}$ and $_{Z+1}W^{A+3}$, and the energy expended along both routes must be equal.

II. Capture of the alpha particle with emission of a proton.

$$_{Z}X^{A} + _{2}He^{4} \rightarrow _{Z+1}W^{A+3} + _{1}H^{1}, \text{ followed by } _{Z+1}W^{A+3} \rightarrow _{Z+2}Y^{A+3} + e^{-}$$

This reaction which was discussed in the last paragraph for the case where it gives rise to a stable isotope, is known in one case to give rise to an artificial radioelement.

B. REACTIONS PRODUCED BY DEUTERON BOMBARDMENT

III. Capture of the deuteron with emission of a neutron.

$$_{Z}X^{A} + _{1}H^{2} \rightarrow _{Z+1}W^{A+1} + _{0}n^{1}, \text{ followed by } _{Z+1}W^{A+1} \rightarrow _{Z}X^{A+1} + e^{+}$$

This is historically the earliest reaction involving deuterons. It gives rise in the case of carbon bombarded by deuterons to N^{13}, the same radioelement which is produced in boron by alpha-particle bombardment. Only two cases of this reaction may be regarded as certain, the radioactivity reported by early investigators,[2, 3] in Be, Al, etc., being probably due to contamination.

IV. Capture of the deuteron with emission of a proton.

$$_{Z}X^{A} + _{1}H^{2} \rightarrow _{Z}X^{A+1} + _{1}H^{1}, \text{ followed by } _{Z}X^{A+1} \rightarrow _{Z+1}W^{A+1} + e^{-}$$

This reaction, first studied by Lawrence,[28] gives rise, in the elements of smaller charge-number, to the same radioelements that are formed by reaction VIII, below. There is no reason for doubting that, given sufficiently high voltages, it would do so for all elements. Reaction IV has been examined theoretically by Oppenheimer.[35] Elements as high in the periodic

table as copper (Z = 29) have been disintegrated in this manner, while our information regarding the beta-radioactive elements of the shortest half-lives and most energetic spectra known,[36, 37] also comes from this reaction.

C. THE REACTION PRODUCED BY PROTON BOMBARDMENT

V. Radiative capture of the proton.

$$ {}_{Z}X^{A} + {}_{1}H^{1} \longrightarrow {}_{Z+1}W^{A+1} \text{ , followed by } {}_{Z+1}W^{A+1} \longrightarrow {}_{Z}X^{A+1} + e^{+} $$

There has in the past been considerable confusion concerning this reaction in the reports emanating from different laboratores.[4, 6, 38] This confusion is to be attributed to the failure to recognize that we have here a case of "resonance" penetration of the target nucleus by the proton, with no third particle to carry off any excesses of energy of momentum. An appreciable yield in the reaction will result only near certain very definite resonance levels which may be supposed to correspond roughly to quantized states of the proton in the field of the target nucleus. This fact, when taken in connection with the differences in the voltage scales at different laboratories, makes it by no meaus surprising that Cockcroft, Gilbert, and Walton[4] have failed to find an effect in boron bombarded by protons, and that Hafstad and Tuve[38] at first failed completely to find the activity, due to N^{13}, induced in carbon by proton bombardment. This reaction has been treated theoretically by Breit and Yost.[39]

D. REACTIONS PRODUCED BY NEUTRON BOMBARDMENT

VI. Capture of the neutron with emission of an alpha-particle.

$$ {}_{Z}X^{A} + {}_{0}n^{1} \longrightarrow {}_{Z-2}Q^{A-3} + {}_{2}He^{4} \text{, followed by } {}_{Z-2}Q^{A-3} \longrightarrow {}_{Z-1}R^{A-3} + e^{-} $$

This reaction, where it leads to the formation of an artificial radioelement, is usually endothermic, so that it will take place only when the neutron has a certain minimum energy. There are cases (B, Li) in which

a stable nucleus is formed in a similar reaction, and here the reactions are exothermic and seem to require neutrons of almost zero energy.[20, 40] Such cases will be discussed more fully later.

VII. Capture of the neutron with emission of a proton

$$_{Z}X^{A} + {}_{0}n^{1} \longrightarrow {}_{Z-1}R^{A} + {}_{1}H^{1}, \text{ followed by } {}_{Z-1}R^{A} \longrightarrow {}_{Z}X^{A} + e^{-}$$

This reaction, like VI, involvesthe emission of a heavy charged particle from the struck nucleus, and hence as a rule requires energetic neutrons for its production. It should also be remarked in connection with reactions VI and VII that, since the emergent heavy charged particle must escape from the attractive field at the center of the nucleus, which becomes stronger with increasing charge-number of the nucleus involved, these reactions are found only among the light elements; viz., those of charge-number less than about 30.

VIII. Radiative capture of the neutron

$$_{Z}X^{A} + {}_{0}n^{1} \longrightarrow {}_{Z}X^{A+1} + h\nu, \text{ followed by } {}_{Z}X^{A+1} \longrightarrow {}_{Z-1}R^{A+1} + e^{-}$$

This is, to date, the most frequently occuring reaction encountered in the production of artificial radioactivity, and it takes place in a larger number of elements than any other nuclear reaction. When it was first observed that a radioelement isotopic with its parent could be formed by neutron bombardment, there were theoretical difficulties in accepting the idea of simple capture of a neutron of an initial energy of several million volts by a stationary nucleus, without the emission of any heavy particles whatever. Incontrovertible evidence that this process was indeed occurring, however, made it necessary to abandon these objections. The discovery by Fermi[8, 20] that this reaction was greatly enhanced by slowing down the incident neutrons in paraffin surrounding the source enabled the theoretical treatment of the phenomenon by Bethe[41] and Perrin and Elsasser[42] to be made on the basis that only very slow neutrons could be captured with the

emission of a gamma ray.

Reaction VIII is by no means limited to cases in which the product nucleus is unstable, as is shown by the enormous absorption of slow neutrons by such substances as cadmium and mercury, which are only feebly activated by neutron bombardment. In such cases, the next heavier stable isotope of Cd, Hg, et al., is formed by the radiative capture of the neutron. Gamma rays emitted in such neutron capture, in the production of both stable and unstable nuclei, have been observed by Fermi[20] and others.[42, 44]

It should be remembered that, while the emission of gamma rays is demanded in reactions V and VIII , it may also occur for any of the other reactions. Until such gamma rays have been sought for and their energy determined, if they exist, it will not be possible unambiguously to balance mass and energy in any of the reactions just discussed. In attempting to strike such a balance, one should also bear in mind that ordinarily the tables of isotopic masses are tables of <u>atomic</u> masses, and hence include the masses of all the extra-nuclear electrons. The reason for this is obscure, but this defect in the tables does not make trouble save in cases of artificial radioactivity. In the case of beta-particle emission, the mass of the emitted electron should <u>not</u> be taken into account in the computation, for its loss from the radioactive atom is compensated for by the gain of a new extra-nuclear electron demanded by the fact that the charge-number of the nucleus has been raised by one owing to the loss of the disintegration electron. In the case of positron emission, on the other hand, <u>twice</u> the electron rest-mass energy should be added to the energy of disintegration, for not only has the positron escaped, but an extra-nuclear electron will be lost owing to the reduction of the nuclear charge-number by one.

It seems clear from the investigations of Henderson,[45] and of Crane, Delsasso, Fowler, and Lauritsen,[36] that the maximum energy of the continuous electron spectrum, and <u>not</u> the mean energy, should be taken as the energy of

electron or positron disintegration. This result, which is a natural consequence of the neutrino hypothesis, seems now to rest on a fairly firm experimental foundation.

5. Detailed Discussion of the Artificial Radioelements: In this section the reactions producing artificial radioactivity are treated for the case of each element. The listing has been made according to the bombarded element, although it will be noted that in many cases the same artificial radioelement can be made in a variety of ways; for example, Al^{28} is produced from Mg^{25} by reaction II, from Al^{27} by reaction IV and reaction VIII, from P^{31} by reaction VI, and from Si^{28} by reaction VII. The number of the reaction which is probably the one responsible for the formation of the radioelement being discussed will be found in the margin to the left of the discussion. The sign of the disintegration electron emitted from each radioelement, where not explicitly stated, can be determined from the type of nuclear reaction involved; we have seen that reactions I, III, and V lead to radioelements which emit positrons in their decay, while reactions II, IV, VI, VII, and VIII yield electron-emitting bodies. No case is known in which bombardment by neutrons produces a radioactive emission of positrons. At the end of the paragraph on each element is a complete list of references to the work bearing on that element; the most important ones have been mentioned specifically in the paragraph.

The half-value thickness for the absorption of the beta-rays emitted from an artificial radioelement is often given below in g/cm^2 of aluminum; the mean energy of the electron or positron spectrum can be obtained roughly in mev. by multiplying the half-value thickness by 8.

1.) Hydrogen

No artificial radioactivity has been excited in this element by neutron, proton, deuteron, or alpha-particle bombardment. (7,20)

2.) Helium

The technical difficulties of irradiating and testing for subsequent activity sufficiently large volumes of the noble gases has prevented their careful investigation for artificial radioactivity.

Ridenour, Shinohara, and Yost[46] bombarded 300 cc of argon at atmospheric pressure with neutrons from Be bombarded by deuterons, but failed to find any detectable activity. The noble gases will be omitted from this list.

3.) Lithium

I(?) Meitner[47] reported observing the radioactive emission of positrons from Li bombarded with alpha-particles. The upper energy limit was 0.3 mev., and the half-life several minutes. These she attributed to B^9. She also reports a beta-particle emission of energy and half-life not stated. This was attributed to Be^{10}. This work has not been confirmed.

II(?)

IV Crane, Delsasso, Fowler, and Lauritsen[37] have found a beta-activity in Li bombarded with deuterons. The half-life is about 0.5 seconds, and the upper limit of the electron energy spectrum about 10 mev. The activity is probably to be attributed to Li^8 and possibly to H^4. Strong bombardment of Li with neutrons,[7, 20] has yielded no detectable activation, although one might expect the same Li^8 mentioned above to be formed in reaction VIII.

4.) Beryllium

An extremely weak activity probably due to impurities was exhibited by Be after strong irradiation with slow neutrons.[20]

5.) Boron

I The formation of N^{13} by alpha-particle bombardment of boron is one of the three original reactions of artificial radioactivity. The half-life first measured by Curie and Joliot[1] and Ellis and Henderson[14] was wrong, being given as 14 minutes instead of about 10.5. More accurate measurements due to Ellis and Henderson[50] cleared up the difficulty, mentioned earlier in this paper, regarding the identity of the N^{13} formed by B and alpha-particles with that formed by bombarding carbon with deuterons or protons; N^{13} emits positrons, the upper limit of whose energy spectrum is about 1.3 mev. References: 13, 51, 52, 82, 85.

IV Emission of beta-particles from B following deuteron bombardment has been observed by Crane, Delsasso, Fowler, and Lauritsen.[36] The half-life is about 0.02 seconds, and the upper limit of the energy spectrum in the neighborhood of 11 mev. The activity is presumed to be due to B^{12}.

III Crane and Lauritsen[2] and Cockcroft[4] have reported a positron activity with half-life 20 minutes, produced by the deuteron bombardment of boron. The radioelement involved was shown to be C^{11} by Yost, Ridenour, and Shinohara.[12] The upper limit of the positron spectrum is about 1.3 mev., according to Neddermeyer and Anderson.[48]

V Crane and Lauritsen[6] found that C^{11} could also be formed in boron by proton bombardment. The reason for Cockcroft's[4] disagreement with this finding has been discussed in Section 4. Ridenour and Shinohara[49] have measured the voltage excitation curve for the reaction (Figure 3)

but the evidence for resonance is doubtful owing to lack of extreme accuracy in the measurements and the fact that the proton beam contains particles of all energies. References: 48.

6.) Carbon

III Crane and Lauritsen,[2] Cockcroft, Gilbert, and Walton,[4] and Henderson, Livingston, and Lawrence[3] have found a positron activity of about 10.1 minutes half-life in carbon bombarded by deuterons. Yost, Ridenour, and Shinohara[12] showed that the radioelement was N^{13}.

V Lauritsen and Crane[6] found that the same element was formed in the bombardment of carbon by protons, as had Cockcroft, Gilbert, and Walton,[4, 5] and Henderson, Livingston, and Lawrence.[3] Hafstad and Tuve[38] could not at first find evidence of such activity, but the discrepancy has been cleared up, and Hafstad and Tuve[55] have now made the best measurements of the voltage excitation function for this resonance reaction. The radiative capture of protons by carbon has been treated theoretically by Breit and Yost.[39]

7.) Nitrogen

I The phenomenon of recoil of active nuclei formed by alpha-particles bombardment of atmospheric nitrogen, leading to a slight radioactive emission of positrons in all targets when bombarded by alpha-particles in air, was first interpreted correctly by Wettenstein[26] as being due to the formation probably of F^{17} according to reaction I. The half-life is 1.1 minutes. Ellis and Henderson[14] have also studied this radioelement. References: 83, 85.

III Livingston and McMillan[27] have observed the collection by recoil on to a Pt target bombarded by deuterons in air of a radioelement whose parent is nitrogen. This radioelement emits positrons with a half-life of 126 seconds, and has been chemically shown to be oxygen; it is no doubt O^{15}. The upper limit of the positron energy spectrum is 1.7 mev.

8.) Oxygen

No radioelement has been formed from oxygen by bombardment with alpha-particles, protons, deuterons, or neutrons.

9.) Fluorine

I(?) The emission of neutrons on the alpha-particle bombardment of fluorine is well known. This reaction would lead to Na^{22}, which might be expected to decay to Ne^{22} with the emission of positrons. Meitner[47] has observed the emission of positrons from bombarded fluorine, and gives the half-life as "very short," and the upper limit of the spectrum as 0.4 mev. Fahlenbrach[85] attributes this activity to recoil of F^{17} produced in atmospheric nitrogen between source and target.

IV Crane, Delsasso, Fowler, and Lauritsen[37] have observed the formation of F^{20} in the bombardment of F with deuterons. The upper limit of the beta-particle spectrum is about 5 mev., and the half-life 12 seconds.

? Fermi et al.[7, 20] have observed a 9 second and a 40 second activity in F bombarded with neutrons. Neither is sensitive to hydrogen (see Section 6.) Both emit negative electrons.. Neither can be identified with certainty; one is probably N^{16}, but the identity of the other radioelement is at present obscure. References: 54, 55.

11.) Sodium

I Frisch[56] has observed a positron emission with a half-life of 7 seconds, produced in Na by alpha-particle bombardment. It is doubtless to be attributed to Al^{26}. The upper spectral limit is about 1.8 mev.

IV Lawrence[34] has produced Na^{24} by the deuteron bombardment of sodium. Its half-life is 15 hours, and the upper limit of its electron spectrum about .2 mev. It gives off about 1 gamma-ray per disintegration, the energy of the gamma rays being tentatively given as 5.5 mev.

VII ? A 40-second beta-activity found by Fermi[7, 20] in sodium after neutron bombardment is possibly to be attributed to Ne^{23}. References: 30.

VIII A fifteen-hour half-life for the emission of electrons is found in Na after neutron bombardment,[24, 54] and is due to the same Na^{24} discussed above.

12.) Magnesium

I Positrons, known to be emitted from Mg after bombardment with alpha-particles,[1] probably come from Si^{27}. The half-life for positron emission is not known, however,[51, 57] because of the fact that the negative electrons emitted are four times as numerous. These come from reaction II. References: 13, 14.

II Alichanow, Alichanian, and Dzelepow[57] were the first to point out that the measured half-life of about 2.3 minutes for Mg- was that that of electron emission. The electrons have a maximum energy of 3 mev.[51, 57] and the radioelement involved is Al^{28}. References: 82.

? Fahlenbrach[59] has found an half-life of 7 or 8 minutes in magnesium bombarded with the alpha-particles of ThC', in addition to that of 2.3 minutes mentioned above. This has been confirmed by Eckardt.[86, 87] This may be attributed to the positrons from Si^{27} (see above,) in which case we have an example of reaction I; alternatively, the activity can be attributed to Al^{29} formed in accordance with reaction II, the parent nucleus being Mg^{26}. A determination of the sign of the electrons emitted would serve to decide which is the true reaction.

VI Mg, when bombarded with neutrons,[4, 20] exhibits a 40 second period which may be tentatively identified with that shown by Na and attributed to Ne^{23}. References: 78.

VII A fifteen-hour period observed in Mg[4, 20] is doubtless to be attributed to Na^{24}.

VIII A weak and water-sensitive (Vide infra) period[7, 20] of ten minutes observed in Mg is probably that of Mg^{27}.

13.) Aluminum

I One of the three elements in which artificial radioactivity was first discovered by Curie and Joliot[1] is Al. The positron emission from this element is due to P^{30}, as has been shown chemically.[13] The half-life is about 3.3 minutes, and the upper limit of the energy spectrum is 2.74 mev. Ellis and Henderson[14] have studied the yield of this P^{30} and as a function of alpha-particle energy, and find a pronounced flattening beyond 8 mev., this corresponding to the height of the potential barrier of the Al nucleus for alpha-particles. References: 51, 81, 82, 85, 86.

IV Lawrence[34, 58] has reported that bombardment of Al with high-energy deuterons gives a beta-particle radioactivity with a half-life of 2.5 minutes, which is without question to be attributed to Al^{28}.

VI Under neutron bombardment, Fermi[7, 20] has found a period of 15 hours excited in Al. This he chemically showed to be due to an isotope of Na, so it is clear that we have again to deal with Na^{24}.

VII Another period for electron emission observed in Al bombarded with neutrons is a 10 minute one which Fermi[7, 20] has shown to be due to an isotope of Mg, necessarily Mg^{27}. References: 30, 43, 55, 78.

VIII Al bombarded with neutrons exhibits a period of 2.3 minutes[20] which is quite strong when the Al is irradiated under water. This is clearly due to Al^{28}.

14.) Silicon

II Fahlenbrach[59] has found that an electron-emitting radioelement of about 17 days half-life is formed in the bombardment of silicon with the alpha-particles from a source of ThB+C. An effect of double his background was found after 18 days' bombardment with a source of 6 mc. which was renewed each morning. The radioelement is probably P^{32}, owing to the agreement in half-lifes.

VII Si bombarded with neutrons has been found by Fermi[7, 20] to have a 2.3 minute beta-activity which has been chemically demonstrated to be due to Al^{28}. References: 30, 43, 41, 60, 78.

VIII Under neutron bombardment Si also exhibits a weak and water-sensitive activity of half-life several hours. This is probably due, according to Fermi,[20] to Si^{31}.

15.) Phosphorus

I Frisch[56] has reported positron emission from P bombarded with alpha-particles. Its half-life is about 40 minutes and the upper limit of the energy spectrum about 1.8 mev. The activity has been chemically shown to be due to an isotope of Cl, doubtless Cl^{34}.

VI Curie, Joliot, and Prieswerk[60] first noticed a decay period of 2.3 minutes in P bombarded by neutrons, which Fermi[20] has chemically demonstrated to belong to Al^{28}. Reference: 51.

VII Fermi[7, 20] showed by chemical tests that a 2.4 hour period found in P -

neutrons was that of Si^{31}. Half-value thickness of the beta-rays in Al is 0.15 g/cm^2. References: 44, 60.

16.) Sulphur

VII P^{32}, formed in the bombardment of S with neutrons, has been chemically identified by Fermi.[7] It has a half-life of 14 days, and the half-value thickness for absorption of the electrons in Al is 0.10 g/cm^2. Reference: 80

17.) Chlorine

VI P^{32} may also be formed by bombardment of Cl by neutrons. References: 7, 20, 80.

VIII A water-sensitive period of 35 minutes has been shown by Fermi[20] to be due to a Cl isotope, either Cl^{36} or Cl^{38}. References: 79,

19.) Potassium

I Alpha-particle bombardment of potassium gives a positron emitter of 3 hour half-life, which Zyw[61, 84] and demonstrated to be an isotope of Sc, probably Sc^{44}.

VIII An indiced activity found by Fermi[20] in K irradiated by neutrons is strongly water-sensitive, and chemical tests show it to be an isotope of potassium, probably K^{42}. The half-life is 16 hours.

20.) Calcium

VII Hevesy and Levi[62] report having found and identified chemically a 16-hour activity belonging to K^{42}, produced in Ca by neutron bombardment. Fermi on the other hand,[20] using sources of neutrons twice as strong as that employed by the former investigators, finds no activity.

VIII Hevesy and Levi[62] also report a 4 hour activity due to an isotope of Ca. This was not found by Fermi.[20]

21.) Scandium

VI Hevesy[63] reports that K^{42} was shown by his chemical tests to be the radioelement of 16 hour period formed by neutron bombardment of Sc. The maximum energy of the beta-rays emitted is given as about 1.2 mev.

22.) Titanium

? A very weak effect, with a period of a few minutes, was observed by Fermi[7] after neutron bombardment, and may possibly be accounted for by the presence of impurities.

23.) Vanadium

VIII The half-value period of the activity[7, 20] produced in V by neutron bombardment is 3.75 minutes; the half-value thickness for the beta-rays 0.17 g/cm^2 Al. The beta rays are accompanied by a gamma radiation. The activation is strongly sensitive to the presence of substances containing hydrogen. The radioelement is V^{32}.

24.) Chromium

VII The activity[7, 20] induced in Cr by the action of neutrons is also due to V^{52}.

25.) Manganese

VI V^{52} is also formed by the neutron bombardment of manganese.[7, 20]

VIII A water-sensitive activity of 2.5 hours half-life is formed in Mn by irradiation with neutrons; this can be shown chemically to be due to an isotope of Mn, and it must therefore be Mn^{56}. References: 20, 78.

26.) Iron

VII Mn^{56} is formed in the action of neutrons on Fe.[7, 20] References: 43, 60, 78.

27.) Cobalt

VI Co bombarded with neutrons is transformed into Mn^{56}. [7, 20]

VII (?) Co also shows a strong absorption for the slow neutrons, this absorption being accompanied by the emission of a gamma-radiation.[20] Since there is only one stable isotope of Co known, and since this absorption of slow neutrons must then be concerned in the formation of Co^{60}, the fact that no beta-radiation corresponding to this unknown isotope is observed should be investigated. It may be that the half-life of Co^{60} is so short as not to have been observed, or so long that two few atoms disintegrate per second to permit their observation. On the other hand, it is possible, though not likely, that Co^{60} is stable.

28.) Nickel

? Fermi reports a dubious trace of activity in Ni strongly irradiated with neutrons.[20]

29.) Copper

IV Lawrence[64] has observed the production of the two radioactive isotopes of copper (Cu^{64}, Cu^{66}) by the bombardment of copper with deuterons. This is the heaviest nucleus in which transmutation has been accomplished by means of artifically accelerated particles. The periods are 5 minutes and 10 hours.

VIII Both copper neutron-capture reactions giving rise to the radioelements mentioned above are strongly enhanced by the presence of water. The periods given above are those of Fermi;[20] for the long period Bjerge and Westcott[54] report 6 hours. References: 23, 55, 78.

30.) Zinc

VII The long period due to radiocopper (see above) is found in zinc[54] which has been subjected to neutron bombardment. The active copper has been separated chemically[20] and electrochemically.[23] The same remarks apply to the short-period radiocopper. References: 60, 71.

? McLennan, Grimmett, and Read report a 100 minute period in zinc bombarded with neutrons.[65] The origin of this is not known.

31.) Gallium

VIII Two half-lives corresponding to neutron capture by the two known isotopes of Ga are observed.[20] The stronger is the shorter; its half-life is 20 minutes. Half-value thickness for the beta-rays is 0.17 g/cm^2 Al. The longer period is 23 hours, and the beta-particles are accompanied by a rather strong gamma-radiation.

32.) Germanium

? A very weak activity produced by neutron bombardment of Ge, having a half-life of around 2 hours, has been reported by Sugden.[66] The identity of the radioelement is not known.

33.) Arsenic

VIII Neutron capture in this element results in the formation of As^{76}, whose half-life is 26 hours. The beta-particles are half absorbed in 0.16 g/cm^2 of Al.[20] References: 25,

34.) Selenium

VIII The 35 minute activity produced in this element by irradiation with neutrons has been shown to be due to an isotope of Se.[20].

35.) Bromine

VIII Two neutron-capture reactions have been known for bromine for some time. These lead to Br^{80} and Br^{82}, whose half-lives are 18 minutes and 4.2 hours.[20] Half-value thickness for the beta-rays of both radioelements is 0.12 g/cm^2 Al, and each radioelement emits fairly strong gamma radiation. References: 31, 79.

? Recently, Kourtschatow, Kourtschatow, Myssowsky, and Roussinow[67] have reported a longer-period activation of Br by neutron bombardment, which they have shown by chemical tests to be carried by an isotope of Bromine. The half-life is about 36 hours, and the new radiobromine emits very feebly-penetrating beta-particles, together with a strong gamma radiation. The upper limit of the electron spectrum is 0.6 mev. and the energy of the gamma radiation is about 0.65 mev. The existence of this radioelement has been checked by Fermi[68] and the fact that only two stable isotopes exist makes the identity of the third type of radiobromine an interesting puzzle. The original discoverers regarded this as a case where the incident neutron, without being captured, expelled another neutron from the nucleus of Br^{79}, so that the radioelement in question is Br^{78}. This seems very unlikely indeed, as all three reactions involving Br and neutrons go best at small neutron energies, and the likelihood of a very slow neutron expelling another from a nucleus would seem small.

A possibility which does not seem to have been suggested is that one of the periods of Br represents that for positron decay, since both of the possible radiobromine isotopes are so located in the periodic table that either the emission of an electron or that of a positron would return them to stable isotopes, of Kr or Se, respectively.

37.) Rubidium

? Fermi[7] has reported a very weak activity with a period of about 20 minutes in Rb bombarded with neutrons. Its source is unknown.

38.) Strontium

Fermi[20] reports finding no activity after strong neutron irradiation.

39.) Yttrium

VII (?) This element has one known stable isotope; namely, Y^{89}. It strongly absorbs slow neutrons with the emission of gamma-radiation. Since only a weak and doubtful activity has been observed in Yt bombarded with neutrons, the case of this element presents a problem similar to that of Co. (q.v.). Either a heavy particle is emitted in the neutron capture, which seems not likely because of the emission of gamma rays at the moment of neutron capture, or the decay period of Yt^{90} is such that its activity has not been observed, or Yt^{90} is stable. The last alternative seems doubtful because of the observed arrangement of isotopes of all other elements of odd charge-number.

40.) Zirconium

VIII Hevesy and Levi[62] report an activity of 40 hours half-life in Zr bombarded by neutrons. This they attribute to Zr^{97}. Half-value thickness for the beta-particles is 0.13 g/cm^2 Al.

41.) Columbium

? Strong irradiation with neutrons[20] produces only a doubtful activity probably due to impurities.

42.) Molybdenum

? A very weak activity is exhibited after neutron bombardment. There are at least two periods, one of 15 minutes and one longer than a day. The radioelements responsible have not been identified.[7] McLennan, Grimmett, and Read[65] give the half-lives as 25 minutes and 36 hours.

43.) Masurium

Owing to its rarity, this element has never been tested for artificial radioactivity.

44.) Ruthenium

? Kourtschatow, Nemenow, and Selinow[90] report that on bombardment of Ru with slow neutrons, they were able to excite activity showing at least four periods of decay, these being 40 seconds, 100 seconds, 11 hours, and 75 hours. The intensities in equilibrium of these activities are respectively 100, 100, 10, and 40. All periods are extremely water-sensitive, the activity of Ru irradiated in air not being observable. The identity in intensity of the two short periods suggests that they are products of successive decay, but none of the radioelements concerned has been identified.

45.) Rhodium

VIII Rhodium can be strongly activated[20] by bombardment with slow neutrons. It has two periods, of which the shorter, 44 seconds, is water-sensitive and hence is probably that of Rh^{104}. Half-value thickness for the electrons emitted by this radioelement is 0.15 g/cm^2 Al.

? A longer period of 3.9 minutes[20] is observed (0.10 g/cm^2); this may indicate the existence of an unknown isotope of Rh, or may possibly be a case of alternative beta- and positron-decay of Rh^{104}. The shorter period is much the stronger.

46.) Palladium

VIII This element displays at least two periods under neutron bombardment. Both are sensitive to water. The half-lives are given as about 15 minutes, and about 12 hours by Fermi.[20] McLennan, Grimmett and Read[65] give 14 hours for the longer period. The radioelements are probably isotopes of Pd, whose mass-numbers are not known because of the existence of several stable isotopes of Pd.[69]

47.) Silver

VIII Neutron capture in the two known isotopes of this element gives rise to radiosilver isotopes with half-lives of 22 seconds and 2.3 minutes. They are both very sensitive to water. The chemical nature of the longer period has been shown to be that of silver.[7, 30] References: 30, 44, 55, 60, 66, 78.

48.) Cadmium

? The great absorption of slow neutrons in Cd apparently does not correspond to a strong activation. Several weak activities of different periods have been reported by Fermi, but none has been identified.[20]

49.) Indium

VIII A 13 second period and a 55 minute period in Indium irradiated by neutrons are very water sensitive and doubtless correspond to the disintegration of the radioelements In^{114} and In^{116}. The electrons from the 54-minute isotope are known to be negative. A third activity of about 3½ hours was discovered by Szilard and Chalmers;[76] it is either not sensitive to water or only moderately so. Fermi[20] has performed experiments which seem to indicate that the two longer periods of In are due to radioactive isotopes of In, so that the radioelement responsible for the 3½ hour period is not known. This is another case in which alternative positron and beta decay might occur in the case of either In^{114} or In^{116}, so far as the positrons of stable isotopes are concerned.

50.) Tin

Fermi[20] reports that Sn strongly bombarded with slow neutrons remained inactive.

51.) Antimony

VIII An activity in Sb induced by neutron bombardment and decaying with a

period of 2.5 days has been found by Fermi.[20] The half-value thickness for the beta-particles is 0.09 g/cm^2 Al. Chemical tests have shown the activity to be carried by an isotope of Sb.

52.) Tellurium

VIII A weak activity in Te irradiated with neutrons has a period of 45 minutes and is water-sensitive. It is probably due to an isotope of Te.[20]

53.) Iodine

VIII I^{128} is almost certainly responsible for the period excited in I by neutron bombardment, as numerous chemical tests have shown. The period is given by Fermi as 25 minutes; it is about 23 minutes according to Ridenour and Yost. Half-value thickness 0.11 g/cm^2 Al.
References: 24, 30, 44, 60, 66, 78, 79.

54.) Caesium

? The half-life of a weak activity produced by neutron bombardment of Cs has been given by McLennan, Grimmett, and Read as 75 minutes.[61] Fermi[7] indicates that other periods may exist.

56.) Barium

? A weak activity found by Fermi in Ba after neutron bombardment has a period of 3 minutes and is not water-sensitive. Its identity is not known.[7]

VIII A water-sensitive 80 minute period has been shown by chemical tests to be due to an isotope of Ba. It is no doubt Ba^{139} formed by neutron capture.[20]

57. Lanthanum

VIII Although Fermi has been unable to find any activity in La irradiated with neutrons,[20] Sugden[72] reports an activity of half-life 1.9 days which is water-sensitive and no doubt belongs to La^{140}. It could have been missed by Fermi because of the brevity of his irradiation.

58.) Cerium

Marsh and Sugden[72] and Fermi[20] agree in finding no activity in Ce after neutron bombardment.

59.) Praseodymium

VIII Fermi,[7] Sugden,[72] and Hevesy and Levi[73] agree in finding a 19-hour period which is water-sensitive and doubtless corresponds to neutron capture in Pr. Half-value thickness for the beta-rays 0.12 g/cm^2.

? An activity of 5 minutes half-life was early reported by Fermi.[7] It is not water-sensitive, and its carrier is not known.

60.) Neodymium

? Fermi[7] reports a very weak activity of 1 hour half-life in this element, which was not found by Sugden,[72] but was by Hevesy and Levi.[73]

61.) Illinium

This element has never been tested for artificial radioactivity.

62.) Samarium

? A weak activity with a period of about 40 minutes has been found after neutron bombardment by Fermi,[7] and confirmed by Sugden[72] and Hevesy and Levi.[73] An addition, Sugden reports a much longer period. The identity of the radioelements is unknown.

63.) Europium

VIII An extremely intense activation apparently due to neutron-capture to form Eu^{152} or Eu^{154}, which has a half-life of 9.2 hours, has been found by Sugden[66, 72] and confirmed by Hevesy and Levi.[73] Half-value thickness for the beta-particles is 0.11 g/cm^2.

64.) Gadolinium

? Although this element absorbs slow neutrons very strongly, only a very weak activity has been found by Fermi[7] and Hevesy and Levi.[73] The period was 8 hours. Since Sugden[66, 72] found no activity, the possibility of Eu contamination of the former authors' Gd samples should be borne in mind.

65.) Terbium

VIII The 3.9 hour activity discovered by Sugden[66, 72] and confirmed by Hevesy and Levi[73] is apparently to be attributed to Tb^{160} formed by neutron capture.

66.) Dysprosium

VIII The strongest artificial radioactivity found to date in reactions involving neutron bombardment is the 2.5 hour activity of Ds. The reaction is strongly water-sensitive, and no doubt is due to Ds^{165}. This radioelement has been investigated by Hevesy and Levi[73] and by Marsh and Sugden.[72] Half-value thickness for the emitted electrons is 0.07 g/cm^2 Al.

67.) Holmium

VIII Hevesy and Levi[73] report an activity of 35 hours shown by one of their samples which had undergone neutron bombardment. Since dysprosium is one of the most abundant of the rare earths, and since it shows such an enormous activity under neutron bombardment, one must regard with caution the statement of Marsh and Sugden[72] that carefully purified holmium, free
? from Ds, exhibited a period of 2.6 hours, since it may so readily have been caused by contamination of the Ho with a few hundredths of a milligram of Ds. The intensity of the 35 hour period is very high, and the half-value thickness of Al for the beta-particles is 0.11 g/cm^2. The radioelement is Ho^{166}.

68.) Erbium

? Reports on the neutron-produced radioactivity of this element are in conflict. Marsh and Sugden[72] report periods of about 7 minutes and 1.6 days, the latter being about ten times as intense as the former. Hevesy

and Levi[73], on the other hand, report a period of 12 hours. Nothing is known about the carriers of the activity.

69.) Thulium

Artificial radioactivity has never been sought in this element.

70.) Ytterbium

? Marsh and Sugden[72] and Hevesy and Levi[73] are in agreement in finding an activity of 3.5 hour half-life in Yb bombarded with neutrons. The identity of the radioelement is not known. The activity is weak.

71.) Lutecium

? Here another serious disagreement exists. Hevesy and Levi[73] report an activity induced in Lu by neutron bombardment whose period is about 5 days. Marsh and Sugden[72] report finding a 4-hour period, and no other.

72.) Hafnium

VIII Hevesy and Levi[62] have reported an activity with a half-life of several months to be excited in Hf by neutron bombardment. This is probably a reaction involving neutron capture, the radioelement being Hf^{181}. This is the longest period reported todate.

73.) Tantalum

? Fermi[20] reports having found only a dubious activity after 12 hours' irradiation of Ta with 500 mc. of Rn-Be. This is confirmed by McLennan, Grimmitt, and Read.[65]

74.) Tungsten

VIII Fermi[20] found an activity excited in W. by neutron bombardment. It is watersensitive and the carrier of the activity has been chemically shown to be a tungsten isotope. McLennan, Grimmett, and Read[65] give 23 hours for the period.

75.) Rhenium

VIII Fermi[20] discovered a water-sensitive activity produced in Re by neutron bombardment, and showed chemically that it is borne by an isotope of rheium. Half-life is 20 hours, and the emitted beta particles are half absorbed in 0.12 g/cm^2 /Al.

76.) Osmium

Fermi[7] found that this element, irradiated 15 hours with 450 mc of Rn-Be, was inactive.

77.) Iridium

VIII A 19-hour period reported by Fermi[20] in Ir bombarded with neutrons is much enhanced by water, and is probably due to an isotope of Ir.

Sosnowski,[74] on the other hand, finds periods of 50 minutes and 3 days, the shorter one being accompanied by the emission of gamma rays.

78.) Platinum

? Fermi[20] found a very weak 50-minute activity in Pt bombarded with neutrons. The half-life according to McLennan, Grimmett, and Read[65] is 36 minutes. Sosnowski[75] reports a half-life of 100 minutes, this value being probably the least accurate.

79.) Gold

VIII Fermi[20] found a water-sensitive period of 2.7 days in Au bombarded by neutrons. The half-value thickness for the beta-rays, which have been shown to be electrons, is 0.04 g/cm^2 Al. The radioelement is doubtless Au^{198}. Sosnowski[76] has confirmed the half-life and penetration measurements on the electrons emitted, and has claimed to find a gamma-radiation with a half-life of about 5 hours, to which corresponds no known period of beta-decay. This surprising result may be readily explained by the skeptical as being a consequence of the very weak initial intensity of his gamma rays. References: 30, 78.

80.) Mercury

Fermi[20] has failed to find any activity after strong irradiation with slow neutrons, in spite of the large absorption (v. Sect. 8) shown by Hg. for slow neutrons.

81.) Thallium

? McLennan, Grimmett, and Read[71] report an activity with a 97-minute half-life to produced in the bombardment of Ti with neutrons.

82.) Lead

The same as Thallium.[20]

83.) Bismuth

? A weak activity of 100 minute period observed by Sosnowski[77] in Bi bombarded with neutrons must be regarded as doubtful, as it has been denied by Fermi[20], and by McLennan, Grimmett, and Read.[71] Bi has only one known isotope, Bi^{209}, while Bi^{210} is RaE, a beta-active body of 5 days half-life. The existence of the 100-minute activity in bombarded Bi was regarded by Sosnowski as being a case of nuclear isomerism.

90.) Thorium

Fermi[20] reports periods of 1 minute and 24 minutes in Th bombarded with neutrons, and states that these activites are "scarcely sensitive to water."

Hahn and Meitner[22] report that the period of 1 minute is not water-sensitive, and that it is the parent of an 11-minute activity. They have further found a period of about 30 minutes which is water-sensitive, which is identical with Fermi's 24-minute body, and has been chemically shown to be to an isotope of Th. Hahn and Meitner regard

the 1 minute body as being a product of reaction VI. The radioelements are then: 1 minute, Ra^{229}; 11 minutes, Ac^{229}; 30 minute, Th^{233}.

Curie, v. Halban, and Preiswerk[89] report that activities of half-lives 1 minute, 15 minutes, 25 minutes, and 3.5 hours are produced on neutron bombardment of Th. The 25 minute activity is due to an isotope of Th, and its production is enhanced by the presence of paraffin. It is doubtless Th^{233}. The 3.5 hour body is not chemically similar to Th, Pa, Ra, or U, but behaves like La, and is hence probably an isotope of Ac. The 15 minute activity seems also to be carried by an isotope of Ac. They agree with Hahn and Meitner that the 1 minute activity is probably due to an isotope of Ra. In a later communication, the same authors have chemically shown that the activity of 1 minute period is due to an isotope of Ra, and have found an isotope of Pa having a period of 2.5 minutes which they consider to be a decay product of the active isotope whose half-life is 25 minutes. See also Reference 88.

92.) Uranium

Fermi[20] has found periods of activity, induced in U by neutrons, of 15 seconds, 40 seconds, 13 minutes, and 100 minutes. The reactions creating all these radioelements save the one of 40-second half-life seem to be water-sensitive. For the 15 second, 13 minute, and 100 minute activities, the increase in activation produced by irradiation under water instead of in air is the same in each case. This led Fermi to the conclusion that the 40-second period is due to one primary process, while the other three are chain or branching products arising from another primary phenomenon. The identity of the radioelement with the 40-second period is unknown, but the 15-second, 13-minute and the 100-minute products are regarded by Fermi as radioelements of mass-number 239, and charge-number 92, 93, and 94, respectively.

Hahn and Meitner[21] concluded that the 13-minute and 100-minute activity were probably due to elements beyond uranium and different from one another. In a later communication, they reported[21] that the longest-lived activity reported by Fermi was in fact due to a mixture of the two radioelements of periods about 1 hour and 2 to 3 days. All the three radioelements studied by Hahn and Meitner were shown by their chemical tests to have properties different from any of the known elements. The properties one would predict for elements 93 and 94 have been stated by v. Grosse.[19]

SLOW NEUTRONS

6. Reactions Involving Slow Neutrons: No treatment of artificial radioactivity would be complete if it did not include a discussion of the effects due to "slow" neutrons. In October, 1934, Fermi and his co-workers[20] found that the activation of silver by the neutrons from a Rn-Be source could be increased several fold by surrounding source and detector with large quantities of water or paraffin. The

effect was shown to be specifically due to the hydrogen content of the water or paraffin. The most obvious explanation for the phenomenon was that the neutrons from the source, initially having all energies from zero to about 7 mev.[91] lost energy in collisions with the hydrogen nuclei present in water or paraffin, and that these slowed-down neutrons were much more effective in producing radioactivity in silver than were the neutrons of higher velocities. When the effect of substituting such materials as silica and iron for the paraffin or waterwas examined, it was found that a small increase in the activation was produced by surrounding the source and detector with these materials, but the magnitude of the effect was not comparable with that attained by the disposition of large masses of paraffin about the source during irradiation. This lends added weight to the hypothesis that the slowing-down of the neutrons is responsible for the observed effect, as a neutron can lose more energy in a collision with a hydrogen nucleus than in one with a heavier nucleus. Other detectors were substituted for the silver, and the striking discovery was made that all the reactions of type VIII and only these reactions, showed an enhancement when the incident neutrons were slowed down.

The assumption was early made by Fermi[20] that the energies of the neutrons conventionally called "slow" were of the order of magnitude of thermal energies of agitation; that is, about 1/40 of a volt. It can be shown that the impact of a neutron against a proton reduces the energy of the neutron, on the average, by a factor of 1/e. From this it follows that in the course of ten impacts, the energy of a neutron is reduced to about 1/20,000 of its original value. With a neutron of an initial energy of 4 mev., less than 20 impacts would be necessary to reduce the energy to thermal values. Experiments designed to measure the energy of slow neutrons will be discussed in Section 8.

The intense activation observed in many elements bombarded with slow neutrons suggests that the absorption of slow neutrons in these elements must be correspondingly large. This proved to be the case,[20] but the discovery was also

made that many elements which did not show pronounced radioactivity under neutron bombardment exhibited large absorption for slow neutrons. In the cases of heavier elements, (Cd, Hg, and others) this is to be attributed to the capture of a slow neutron with the emission of a gamma ray, in accordance with reaction VIII, except that the nucleus formed by such neutron capture is in this case a stable isotope of the bombarded element, so that no radioactivity is observable. The emission of the gamma rays accompanying the capture of slow neutrons has been observed by Fermi[20] for several of the elements showing large absorption, both with and without the consequent production of radioactivity.

In his studies of the absorption of slow neutrons, Fermi[20] further found that certain light elements (B and Li) exhibited large absorption for slow neutrons, without becoming radioactive or emitting gamma rays at the moment of neutron capture. This has been shown to be due to the capture of the neutron in the B or Li nucleus, and the subsequent disintegration of the product nucleus with the emission of heavy particles.[40] This latter phenomenon (viz., the emission of heavy particles) may be regarded as an alternative to the emission of a gamma ray at the moment of neutron capture; the energy balance in the reaction can be preserved either way.

7. Absorption of Slow Neutrons: The earliest measurements of absorption of slow neutrons were made by Fermi,[20] with the experimental arrangement shown in Figure 4. The absorption curves he obtained with this arrangement were not exponentials, as indeed the geometry would lead one to expect, even though the absorption measured in a parallel beam might follow an exponential law. A theoretical treatment of the absorption curve to be expected with such a distribution of source, absorbers, and detectors is to be found in Appendix A, where the assumption is made that the absorption is exponential when measured in a parallel beam. Experimental evidence that this is the case has been obtained for absorption in Cd by Dunning[92] and Ehrenberg and Hu Chien Shan,[93] and for absorption in Ag by the latter investigators.[93]

Table I, below, shows the cross sections for absorption of slow neutrons obtained by Dunning[92] with the experimental arrangement shown in Figure 5. It will be observed that Dunning used for the detection of slow neutrons the alpha-particles emitted in the Li reaction mentioned in Section 6.

- Neutron-nucleus collision cross sections -

Element	Atomic No.	Atomic Wt.	Compound used	G/cm^2	Fraction Transmitted P	Cross Section $X10^{24}$ CM^{-2} Slow	Fast
H	1	1.008	$(CH_2)_n$	0.131	0.673	35	1.68
D	1	2.014	D_2O	1.36	.631	4.0	1.71
Li	3	6.94	LiF	.24	.765	45	1.84
Be	4	9.02	Be	.703	.780	5.3	1.65
B	5	10.82	B_4C	.0557	.418	360	1.60
C	6	12.00	C	2.86	.549	4.1	1.65
N	7	14.01	NaN_3	1.30	.630	11.3	1.76
O	8	16.00	SiO_2	3.78	.709	3.3	
F	9	19.00	NaF	1.94	.827	2.5	
Na	11	23.00	Na	1.48	.847	4.2	
Mg	12	24.32	Mg	4.67	.669	3.5	
Al	13	26.97	Al	7.24	.788	1.5	2.4
Si	14	28.06	Si	2.23	.867	2.5	
P	15	31.03	P	1.69	.615	14.7	
S	16	32.06	S	6.6	.840	1.4	2.6
Cl	17	35.46	NaCl	1.35	.541	39	
K	19	39.10	K	1.60	.816	8.2	
Ca	20	40.07	CaO	1.87	.751	11.0	
Ti	22	48.1	TiO_2	1.97	.760	11.9	
V	23	50.96	V_2O_5	2.41	.751	10	
Cr	24	52.01	Cr	5.82	.718	4.9	
Mn	25	54.93	Mn	3.69	.558	14.3	
Fe	26	55.84	Fe	3.87	.605	12.0	3.0
Co	27	58.94	Co	1.41	.602	35	
Ni	28	58.69	Ni	3.03	.637	15.4	
Cu	29	63.57	Cu	6.22	.642	7.5	3.2
Zn	30	65.38	Zn	10.7	.627	4.7	3.3
Ge	32	72.60	GeO_2	.08	.93	est. 75	
As	33	74.96	As	5.28	.692	8.6	
Se	34	79.2	Se	3.47	.606	19	
Br	35	79.92	KBr	3.43	.705	11.9	
Sr	38	87.63	$SrCrO_4$	2.21	.832	est. 9	
Y	39	88.9	Y_2O_3	.18	.463	800	
Zr	40	91	ZrO_2	1.87	.807	16.7	
Cb	41	93.1	Cb_2O_5	1.01	.90	est. 14	
Mo	42	96.0	Mo	1.70	.926	7.1	

Table I (con't.)

Element	Atomic No.	Atomic Wt.	Compound used	G/cm^2	Fraction transmitted P	Cross Section $X10^{24}$ Cm^{-2} Slow	Fast
Ru	44	101.7	Ru	6.1	.647	12.5	
Rh	45	102.9	Rh	0.62	.664	115	
Pd	46	106.7	Pd	6.2	.715	10-	
Ag	47	107.88	Ag	1.88	.557	55	
Cd	48	112.41	Cd	.0416	.524	3300	
Sn	50	118.70	Sn	18.8	.678	4.0	4.3
Sb	51	121.77	Sb	7.26	.745	8.1	
Te	52	127.5	Te	5.52	.790	8.2	
I	53	126.93	I	6.78	.738	9.4	4.6
Ba	56	137.37	BaO	.662	.680	140	
La	57	138.90	La_2O_3	.214	.933	80	
Ce	58	140.25	CeO_2	.98	.896	est. 25	
Pr	59	140.9	Pr_2O_3	2.43	.77	25	
Nd	60	144.27	Nd_2O_3	.72	.559	220	
Sm(Sa)	62	150.43	Sa_2O_3	.04	.525	4700	
Eu	63	152	Eu-Gd-Al	.02	.647	est.1000	
Gd	64	157.6	Gd_2O_3	.0068	.590	30,000	
Tb	65	159.2	Tb-Al	.06	.919	est.1000	
Dy	66	162.5	Dy-Al	.27	.685	700	
Ho	67	163.4	Ho-Al	.144	.877	est. 400	
Er	68	167.7	Er_2O_3	.666	.780	120	
Tm	69	169.4	Tm-Al	.07	.987	est. 500	
Yb	70	173.6	Yb_2O_3	.315	.912	90	
Lu	71	175.0	Lu-Al	.045	.93	est. 400	
Ta	73	181.5	Ta	4.56	.663	27	
W	74	184.0	W	7.05	.592	23	5.3
Re	75	186.31	Re	2.39	.501	89	
Os	76	190.6	Od	5.35	.643	27	
Ir	77	193.1	Ir	.785	.509	285	
Pt	78	195.2	Pt	4.30	.769	25	
Au	79	197.2	Au_u	2.52	.508	88	
Hg	80	200.61	HgO	.545	.556	380	5.8
Tl	81	204.39	Tl	10.5	.710	11	
Pb	82	207;20	Pb	22.7	.568	8.6	5.7
Bi	83	209.00	Bi	9.07	.805	8.2	
Th	90	232.15	ThO_2	2.75	.772	32	
Ur	92	238.17	UrO_2	2.52	.83	43	

In Bethe's[41] theoretical treatment of the absorption of slow neutrons, it is predicted that the elastic scattering by the elements showing large absorption for slow neutrons will be at least as important a factor as neutron capture in removing slow neutrons from a beam. The experiments of Dunning[92] in Cd, and of Ridenour and Yost (see below) in Ag, indicate that elastic scattering of slow neutrons in these elements is negligible compared with capture. This indicates that the extremely large cross sections for capture exhibited by certain elements are not adequately explained by the assumptions made by Bethe.

It seemed possible that the measured absorption of an element for slow neutrons might depend on the reaction whereby the slow neutrons are detected. Experiments on this point were performed by Ridenour and Yost,[94] and show that such an effect does exist. Their technique and results are given below.

The geometrical conditions under which irradiation of samples was conducted is shown in Figure 6. The detectors of slow neutrons were discs 5 cm. in diameter, the absorbers discs 7 cm. in diameter. The Ag and Cu detectors were metal sheets; the I, Br, and V detectors consisted of compounds (cf. Table II) held on stiff paper with thin collodion. The source of neutrons was beryllium (or boron) and radon in amounts usually between 100 and 200 millicuries. The activity of the detectors after irradiation was measured with a quartz-fiber electroscope of the Lauritsen type, provided with a window of thin aluminum. The procedure was to irradiate the detector, either bare or between two equal layers of an absorber, for a length of time standard for that detector; then to commence readings one minute after the removal of the detector from the neutron source. The reading was terminated at a time, also standard for each detector, depending on the half-life of the activity under measurement. In Br, for example, the irradiation lasted for 25 minutes, and the measurement for 15 minutes, so that only the short-lifed activity was measured in these experiments. Frequent readings on the background were taken in precisely the way the measurements were made, except that the detector had not been exposed to the neutron source. The activities

found were always easily measurable, being from twice to about twenty-five times the background due to cosmic and local radiation.

The results are shown in Table II. The absorber was in all cases silver, and the numbers in the table under the heading Percent Activity are referred in each case to the no-absorber value for that detector as 100%, so that they are measures of the transmission through the absorber of neutrons having the proper energy to activate the detector.

Table II. Absorption of slow neutrons in silver.

SOURCE OF NEUTRONS	DETECTOR Element	DETECTOR Thickness (g/cm^2)	PERCENT ACTIVITY (TRANSMISSION) WITH ABSORBER OF 0 g/cm^2 Ag	0.46 g/cm^2 Ag	0.81 g/cm^2 Ag	1.72 g/cm^2 Ag
B-Rn	Silver	1.195	100	60 ± 1	42 ± 3	26 ± 4
Be-Rn	Silver	1.195	100	59 ± 1	44 ± 1	27 ± 1
Be-Rn	Silver	0.094	100	46 ± 4	30 ± 1	17 ± 2
Be-Rn	Copper	0.717	100	42 ± 2	28 ± 3	12 ± 2
Be-Rn	Vanadium (as NH_4VO_3)	0.146	100	47 ± 2	35 ± 1	17 ± 2
Be-Rn	Bromine (as NH_4Br)	0.305	100	62 ± 1	56 ± 1	38 ± 1
Be-Rn	Iodine (as CHI_3)	0.143	100	57 ± 2	48 ± 1	37 ± 2

The fact, already mentioned, that the absorption curves obtained with such an arrangement of paraffin as was used in the present experiment are not exponential, but that the absorption decreases with increasing thickness of absorber, would seem to explain the result, clearly shown in the Table, that the absorption measured with a thick detector is much smaller than that measured with a thin detector. The disintegration electrons measured in the case of a thick detector come from a layer on the surface whose thickness is equal to the maximum range, in the material of the detector, of the electrons emitted by the radioelement formed in the reaction concerned. The thickness of this layer is seen to depend

on the density of the bombarded material and the electron spectrum of the radio-element. For an effect of detector thickness on measured absorption to be observable, it is necessary that the absorption of neutrons in the material composing the detector be appreciable. The optimum detector thickness, if the absorption of neutrons in the material concerned is less than that of electrons, will be that which is just equal to the range of the beta-particles in the substance. If a detector of this optimum thickness and one of greater thickness be irradiated equally on both sides by neutrons, the thinner detector will display the greater activity, because the neutrons from the opposite side of the thick detector reaching the side under measurement have suffered an appreciable absorption in the material composing the detector, whereas all the neutrons absorbed in the detector of optimum thickness give rise to electrons which may escape from the detector on the side under measurement. Since, as we have seen, the absorption becomes less with increasing absorber thickness, and since the effect of a thick detector is to commence the absorption measurements farther out on the absorption curve in the direction of increasing absorber thickness, the observed absorption with a thick detector will be less than that with a thin detector, as is indeed found experimentally.

So long as the absorption of neutrons in the thickness of the detector can be neglected, the effect of detector thickness will not complicate the results, and the other detectors are apparently thin enough, relative to the half-value thickness of each for slow neutron absorption,[20] so that the results obtained with them can be intercompared, and compared with those for a thin silver detector. None of the detectors employed in the present experiment gave a half-value thickness of silver as large as that (1.2 g/cm^2) measured by Fermi with a Rh detector, but his value cannot properly be compared with the present ones because of differences which may have been introduced by detector thickness and the disposition of paraffin about the source and detector.

The differences between Br, I, and the other detectors employed in the

present experiment seems necessarily to be due to the fact that neutrons captured by different detectors lie in different ranges of energy. The sense of the differences among the detectors in the energy range of neutrons most likely to be captured by each cannot be determined from these results alone, but further investigations using various absorbers might serve for such a determination.

In order to gain an insight into the distribution of neutrons in the paraffin during irradiation of a detector, experiments were performed with the thin and the thick silver detector under the conditions of irradiation and measurement shown in Figure 2. The results are shown on the figure, and demonstrate (1) that the numbers of slow neutrons incident on the top and bottom surfaces of the detector are the same; i.e. that the distribution of neutrons inside the paraffin is uniform;(2) that the absorption of neutrons in the thick detector is quite appreciable, being of the order of %; (3) that there is no appreciable elastic scattering of slow neutrons from silver, the placing of a sheet of silver absorber on top of the detector actually reducing the intensity of activation of the detector, owing to the reduction in the number of slow neutrons scattered to the back of the detector by the paraffin still above it (compare 7c and 7e in the case of the thick detector); and (4) that the detector thickness has a pronounced effect on the total activation of the detector (see 5a).

The selective effect found here in the absorption of slow neutrons has also been observed by Moon and Tillman,[95] and indications of such an effect have been reported in connection with other experiments by Bjerge and Westcott[96] and Artsimovitch and others.[97]

8. Velocities of the Slow Neutrons: The idea that slow neutrons possess thermal velocities seems to be susceptible to an experimental test, and such a test was made first by Fermi,[20] with negative results. He compared the activity of a sheet of rhodium activated first in a mixture of liquid hydrocarbons at room temperature, and then at 200° in another mixture of hydrocarbons which had, at that temperature, the same density and elementary composition as the former medium. The geometrical

conditions of irradiation were the same in the two experiments. No difference in activity could be observed. Another inconclusive experiment was performed by McLennan and others,[98] first at room temperature, and then at liquid hydrogen temperature.

The first positive evidence of a temperature effect on the properties of slow neutrons was offered by Dunning and others,[92, 99] the absorption of "cold" (90° K.) neutrons in Cd. being about 4% greater than that of "warm" neutrons (room temperature.) The effect, though small, is regarded by Dunning as being well above probable error. A much larger effect of temperature has been announced by Moon and Tillman[95,100] and confirmed in part by Fermi.[68] The activation of silver, rhodium, iodine, and copper was found by the former investigators to increase by about 10 - 20% when a layer of paraffin 2.5 cm. thick surrounding the detector was cooled from room temperature to liquid air temperature, the temperature of the neutronsource, which was located outside of a Dewar flask containing the cetector and the paraffin being cooled, remaining constant at that of the room.

Ridenour and Yost sought to measure thiseffect in silver, bromine, and indium. The experimental setup for irradiation is shown in Figure 8, and measurement of the activated sample was carried with the same electroscope and by the same procedure used in the previous experiments. Measurements using the same Rn-Be neutron source were carried out, first with the paraffin warm, and then with the Dewar flask and its contents at liquid air temperature. A layer of Cd 1 mm. thick was placed behind the detector, with the intention of preventing neutrons from passing through the detector more than once. The results for silver and bromine are shown in Table III.

Moon and Tillman[95, 100] report a 17% effect in the case of silver, while the effect observed by Ridenour and Yost is certainly much smaller, and cannot be said to be a great deal larger than the errors of measurement. The results for Br seem more definitely to show that there is an effect of the s ort observed by Moonand Tillman.

The most precise measurements made by Ridenour and Yost on the temperature effect employed the 55 minute activity of In for the detection of the slow neutrons. Eight similar circular sheets of 7 cm. diameter and 0.125 mm. thickness were prepared from pure indium and irradiated in a stack. Since the thickness of of each sheet was the same, the activities found in the sheets could be intercompared. After the stack of eight sheets had been radiated for an appropriate length of time, the sheets were separated and measured one by one, the readings on each being subsequently corrected for decay of the activity. A carefully measured decay curve from which the corrections were made is shown in Figure 9, demonstrating that the errors introduced by correcting for the decay cannot be large, and that only the 55-minute activity was involved in these measurements. The first run with these sheets indicated that there might possibly be an effect of temperature on the activation of the one closest to the detector (see Figure 10). Accordingly, two sheets of a thickness of 0.05 mm. were prepared and placed closest the source. Behind them were two of the 0.125 mm. sheets used in the previous experiment. The results of this experiment, which was made with a stronger neutron source than that used in the previous one, and is hence more accurate, seem conslusively to show that in indium there is no effect of temperature either on the abs lute value of the activation or on the absorption exhibited for slow neutrons.

The situation regarding our knowledge of the energies of the s low neutrons is still far from satisfactory, principallyfor the reason that these energies lie in a region which is extremely difficult to investigate. Dunning[92] and Bonner and

Brubaker[101] have demonstrated that the energies of slow neutrons are below those measurable with an amplifier and counter or with a cloud chamber; viz., lower than about 50,000 or 100,000 electron volts. Measurements made by means of neutron-produced radioactivity are still extremely inconclusive.

It does not seem to have been pointed out that since the concentration of an active isotope by the method of Szilard and Chalmers (see Section 3) depends on the removal from its chemical bond of the atom struck and made radioactive by a neutron, the neutron must have a certain minimum energy in order so to remove the struck atom and make it available for the subsequent separation of the radioactive atoms from the inactive balance of the compound irradiated. In ethyl iodide, for example, the energy required to remove the I atom fromthe ethyl radical is about 1 electron volt, and if the collision between the neutron and the I nucleus is regarded as elastic, from a classical point of view the I atom can take only 1.6% of the energy of the incident neutron. This means that for the separation of active iodine from ethyl iodide to be effective, the neutrons activating the iodine atoms must have energies of at least fifty volts, or two hundred times the velocities of thermal agitation. It would seem that careful measurements of the yield of isotopic separations made by the method of Szilard and Chalmers on compounds in which the I is bound with various energies would give valuable information about the energies of the "slow" neutrons effective.

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Mass and Atomic Numbers of the Isotopes

Naturally Occurring Stable Nuclei Known December, 1934

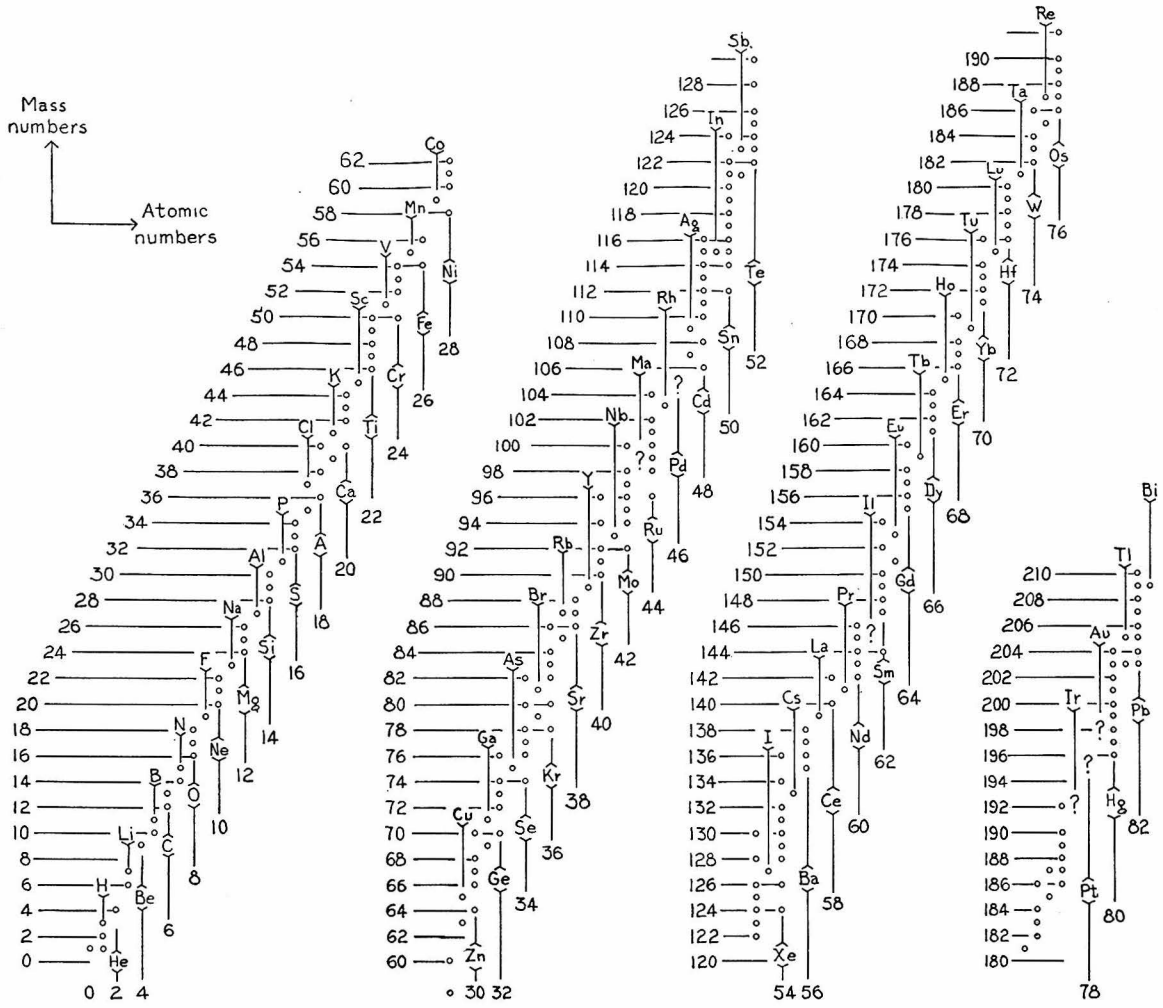


FIGURE 1

THE STABLE ISOTOPES

For details see References 9, 69, 102

FIGURE 2

ARTIFICIAL RADIOACTIVITY IN THE LIGHT ELEMENTS

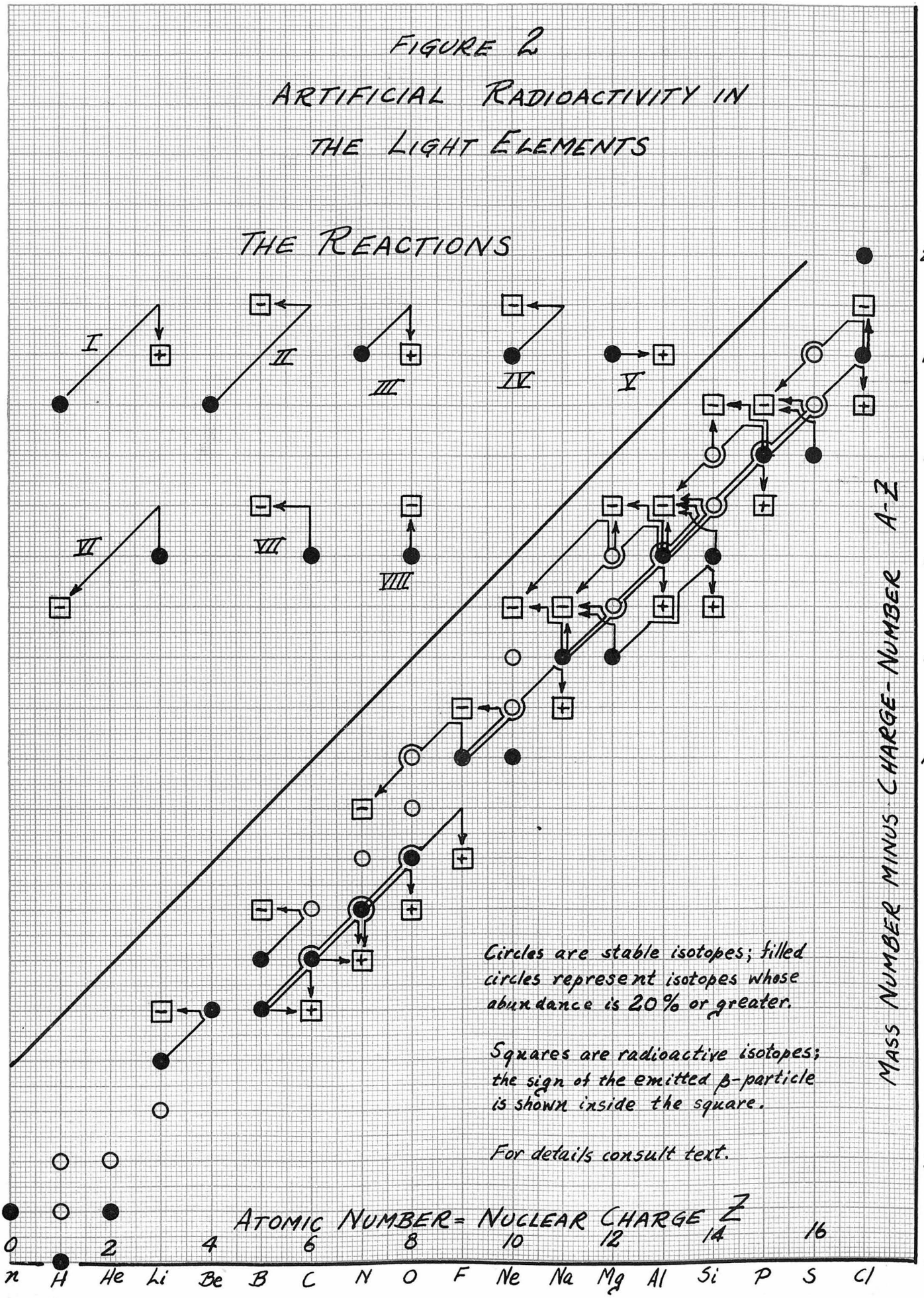
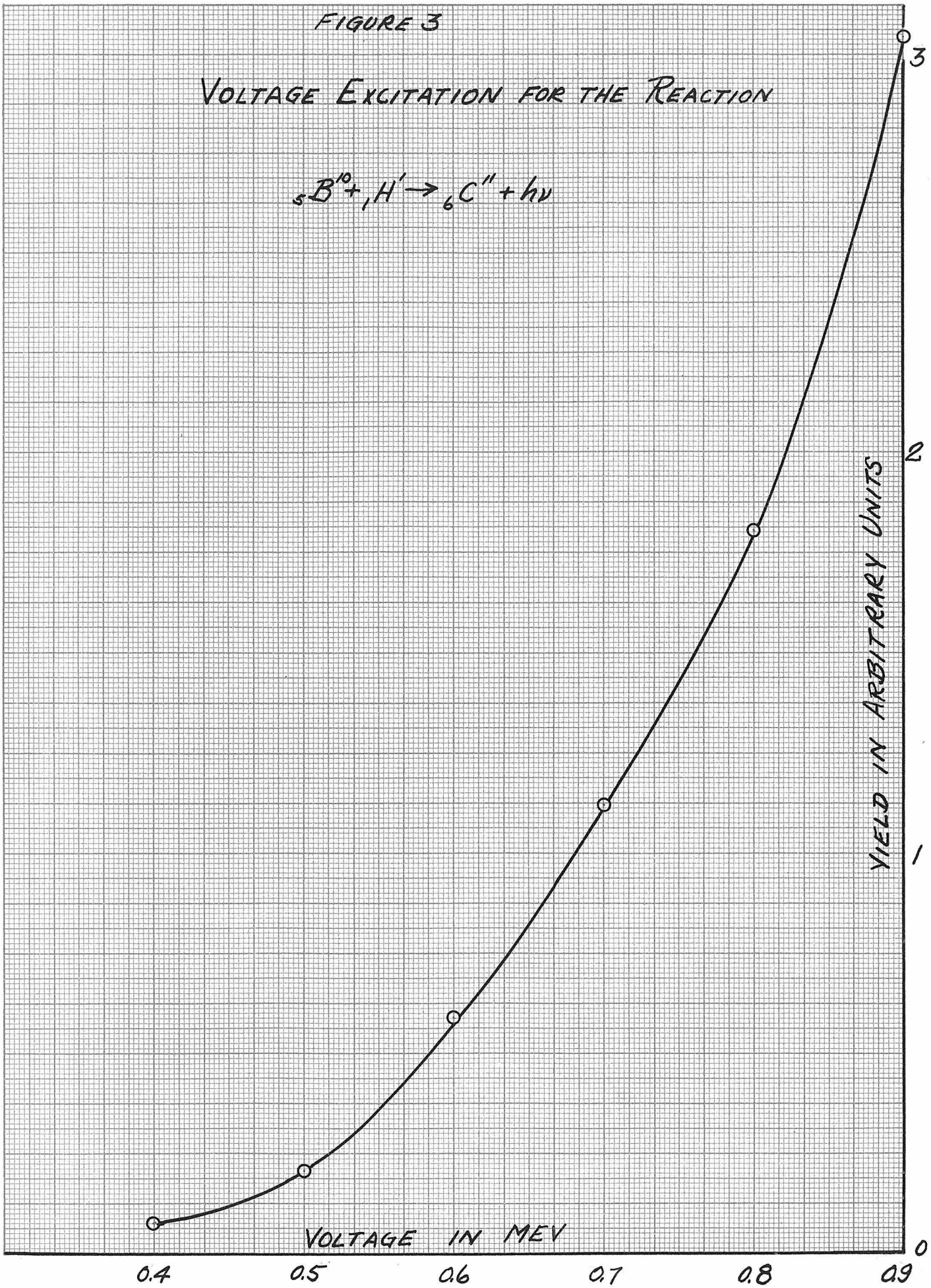


FIGURE 3

VOLTAGE EXCITATION FOR THE REACTION

$${}_5B^{10} + {}_1H^{1} \rightarrow {}_6C^{11} + h\nu$$



Slow Neutron Absorption Measurements

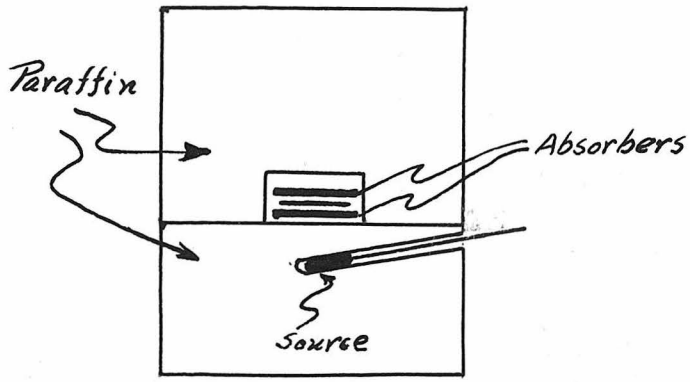


FIGURE 4 - FERMI'S ARRANGEMENT

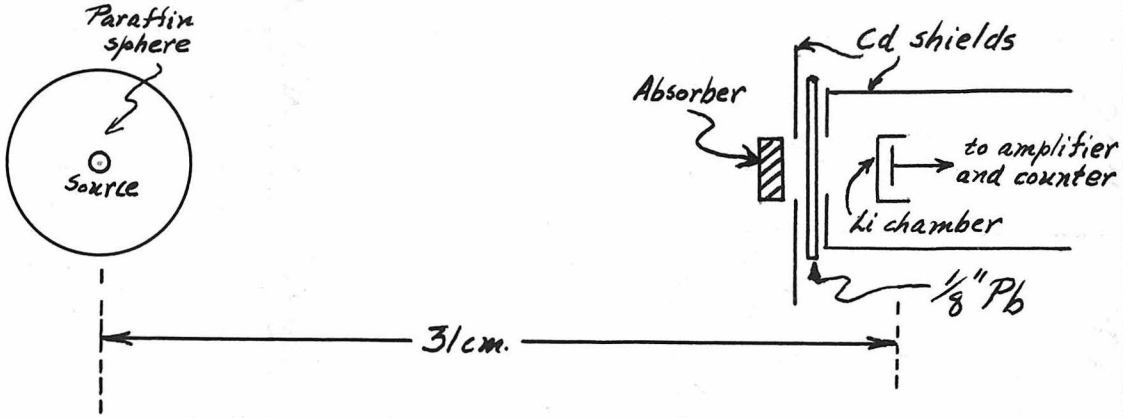


FIGURE 5 - DUNNING'S ARRANGEMENT

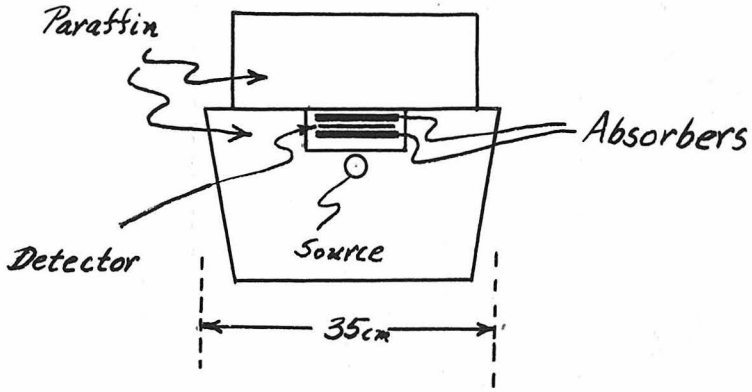
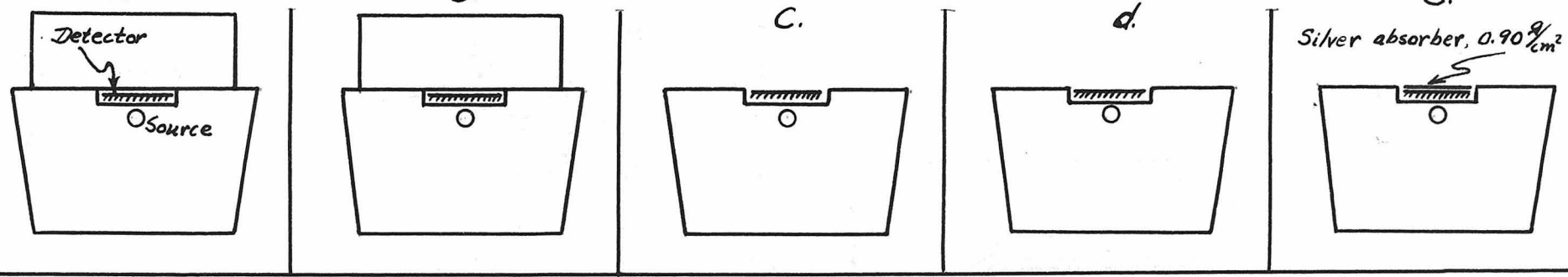
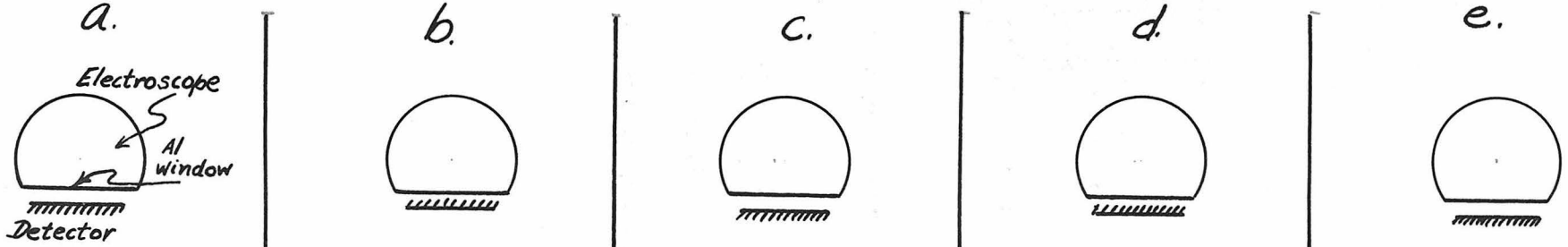


FIGURE 6 - RIDENOUR AND YOST'S ARRANGEMENT

CONDITIONS OF ACTIVATION



CONDITIONS OF MEASUREMENT



MEASURED ACTIVITY

a. Detector		b. Detector		c. Detector		d. Detector		e. Detector	
Thick	Thin	Thick	Thin	Thick	Thin	Thick	Thin	Thick	Thin
4.9	5.6	5.3	6.0	1.3	1.4	2.1	1.2	1.1	1.3
5.1	5.5	5.2	5.7	1.3	1.3	2.1	1.4	1.0	1.3
5.5	5.7	5.5	5.7	1.4	1.3			1.1	
5.3	5.7			1.5	1.5				
5.5	5.8			1.3					
	6.0								
5.26	5.72	5.33	5.80	1.36	1.38	2.1	1.3	1.07	1.3

FIGURE 7 - EFFECT OF DETECTOR THICKNESS, ETC. (see text)

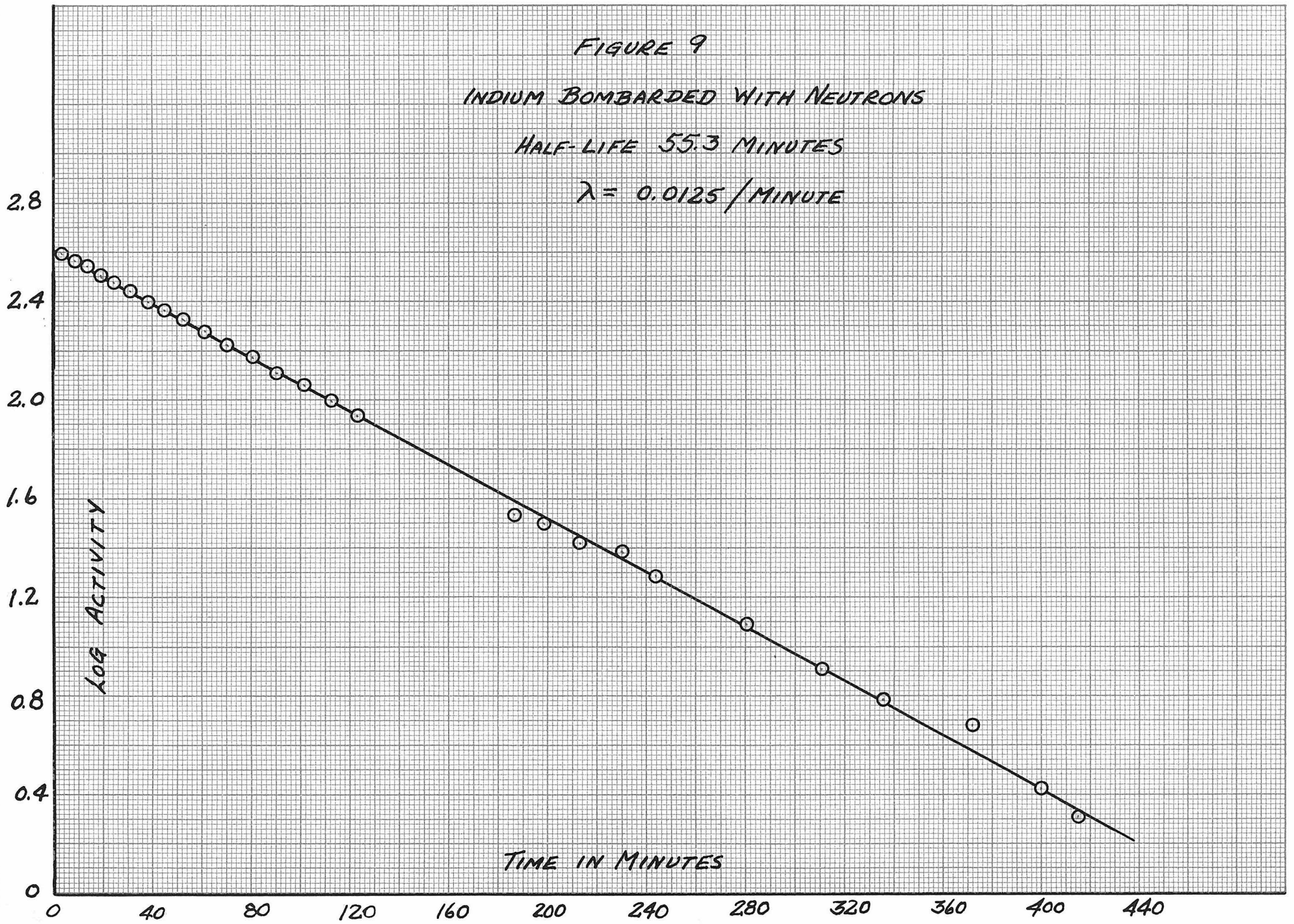


FIGURE 9
INDIUM BOMBARDED WITH NEUTRONS
HALF-LIFE 55.3 MINUTES
λ = 0.0125 / MINUTE
LOG ACTIVITY
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0
TIME IN MINUTES
0
40
80
120
160
200
240
280
320
360
400
440

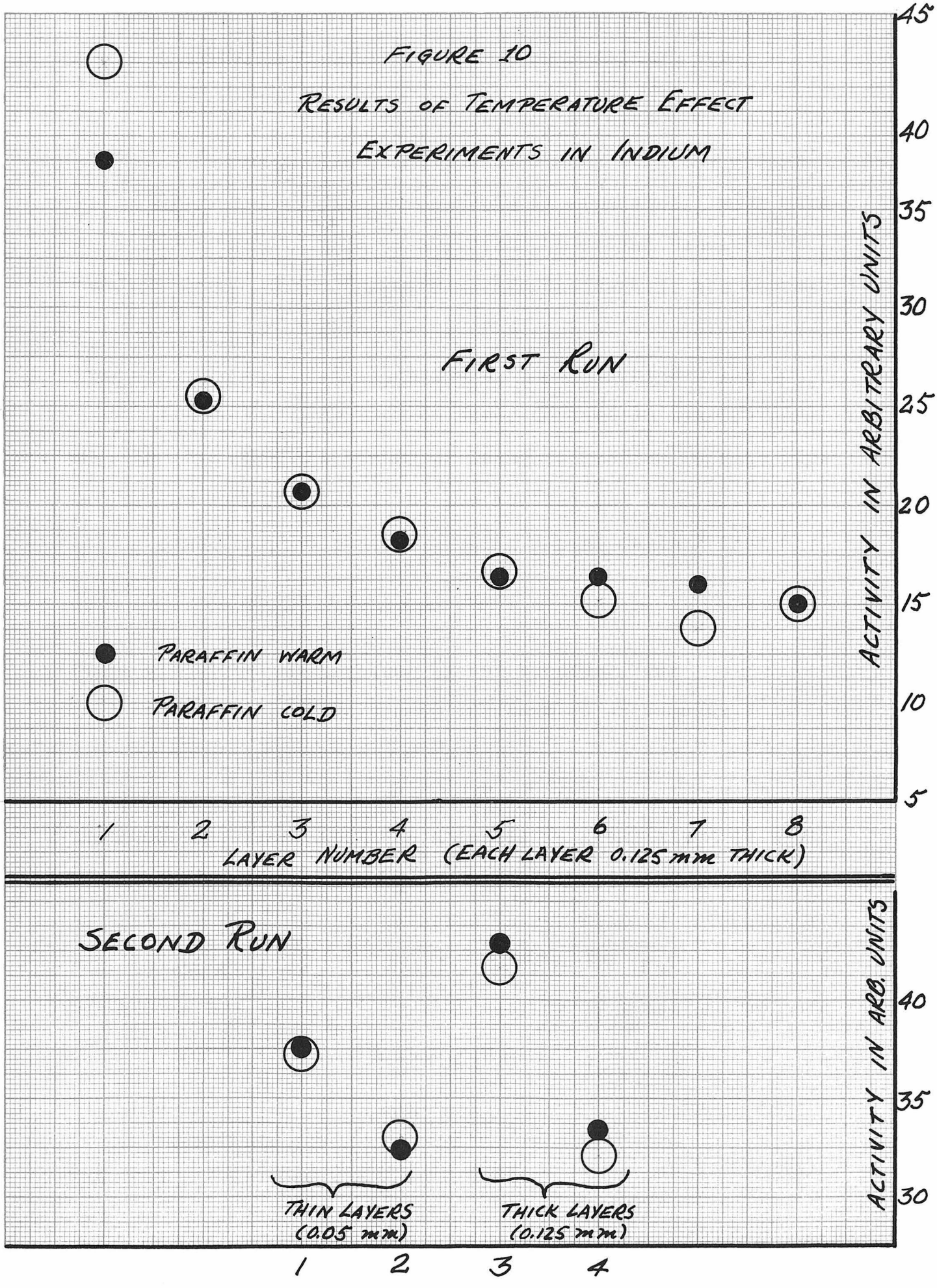
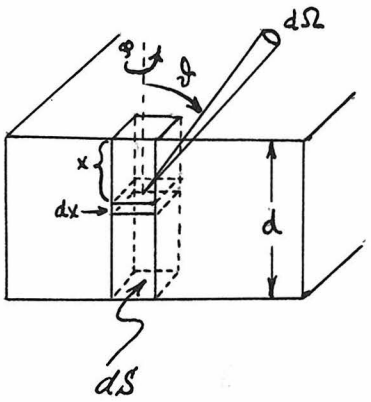


FIGURE 10
RESULTS OF TEMPERATURE EFFECT EXPERIMENTS IN INDIUM
FIRST RUN
PARAFFIN WARM
PARAFFIN COLD
ACTIVITY IN ARBITRARY UNITS
45
40
35
30
25
20
15
10
5
1
2
3
4
5
6
7
8
LAYER NUMBER (EACH LAYER 0.125 mm THICK)
SECOND RUN
ACTIVITY IN ARB. UNITS
40
35
30
THIN LAYERS (0.05 mm)
THICK LAYERS (0.125 mm)
1
2
3
4

APPENDIX A

LAW OF ABSORPTION OF NEUTRONS FROM A NON-PARALLEL BEAM



The assumption is explicitly made in the following treatment that the absorption of neutrons is exponential when measured in a strictly parallel beam.

Neutrons are incident at all angles on one side of a slab of absorbing material of thickness d, whose cross-section for neutron capture, defined in the ordinary way, is σ. Then the number of neutrons passing in unit time through an area dS, normal to the surface and at a depth x, having come from the cone of opening $d\Omega$ and angle ϑ from the normal, is

$$N_0 \, d\Omega \, dS \cos\vartheta \, e^{-\frac{\sigma N x}{\cos\vartheta}}$$

where N = nuclei/unit volume in the absorber, and

N_0 = neutrons/steradian/second incident on unit area.

Writing $d\Omega = \sin\vartheta \, d\vartheta \, d\varphi$,

we have $N_0 \, dS \sin\vartheta \cos\vartheta \, d\vartheta \, d\varphi \, e^{-\frac{\sigma N x}{\cos\vartheta}}$.

The number of these neutrons absorbed in a thickness dx will be $N_0 \, dS \sin\vartheta \cos\vartheta \, d\vartheta \, d\varphi \, e^{-\frac{\sigma N x}{\cos\vartheta}} \cdot \frac{\sigma N dx}{\cos\vartheta}$,

so that the total number absorbed in the slab of thickness d will be $N_0 \, dS \int_0^{2\pi} d\varphi \int_0^{\pi/2} \sin\vartheta \cos\vartheta \int_0^{d} \frac{\sigma N dx}{\cos\vartheta} e^{-\frac{\sigma N x}{\cos\vartheta}} \, d\vartheta$

Performing the integrations with respect to x and φ, we have

$$-2\pi N_0 \, dS \int_0^{\pi/2} \sin\vartheta \cos\vartheta \, d\vartheta \, e^{-\frac{\sigma N x}{\cos\vartheta}} \Big]_{x=0}^{x=d}$$

$$= 2\pi N_0 \, dS \int_0^{\frac{\pi}{2}} \left(1 - e^{-\frac{\sigma N d}{\cos\vartheta}}\right) \sin\vartheta \cos\vartheta \, d\vartheta$$

Let $\cos\vartheta = \xi$; then $\sin\vartheta \, d\vartheta = -d\xi$.

The number of neutrons absorbed in a prism of base dS and height d is then $-2\pi N_0 dS \int_1^0 (1-e^{-\frac{\sigma N d}{\xi}})\,\xi\, d\xi$

$$= 2\pi N_0 dS \int_0^1 \xi\, d\xi - 2\pi N_0 dS \int_0^1 \xi e^{-\frac{\sigma N d}{\xi}} d\xi = 2\pi N_0 dS \left[\frac{1}{2} - \int_0^1 \xi e^{-\frac{\sigma N d}{\xi}} d\xi\right].$$

Let $F(d) = \int_0^1 \xi e^{-\frac{\sigma N d}{\xi}} d\xi$, and make the substitution $\xi = 1/\eta$.

Then $F(d) = \int_\infty^1 \frac{1}{\eta} e^{-k\eta}\left(-\frac{d\eta}{\eta^2}\right) = \int_1^\infty \frac{e^{-k\eta}}{\eta^3} d\eta$ where $k = \sigma N d$.

Integrating by parts, $F(d) = \frac{1}{2}\left[-\frac{e^{-k\eta}}{\eta^2} - k\int_1^\infty \frac{e^{-k\eta}}{\eta^2} d\eta\right]_1^\infty$

$$= \frac{1}{2}\left[e^{-k} - k\left\{-\frac{e^{-k\eta}}{\eta}\right]_1^\infty - k\int_1^\infty \frac{e^{-k\eta}}{\eta} d\eta\right\}\right] = \frac{1}{2}\left[e^{-k} - ke^{-k} + k^2\int_1^\infty \frac{e^{-k\eta}}{\eta} d\eta\right].$$

Now let $k\eta = \varsigma$. Then

$$k^2\int_1^\infty \frac{e^{-k\eta}}{\eta} d\eta = k^2\int_k^\infty \frac{e^{-\varsigma}}{\varsigma} d\varsigma \equiv -k^2 Ei(-k)$$

We then have for the number of neutrons absorbed in a prism of base unity and height d:

$$\pi N_0 dS\left[1-2F(d)\right] = \pi N_0 dS\left[1 - e^{-k} + ke^{-k} + k^2 Ei(-k)\right]$$

where $k = \sigma N d$. The number transmitted through unit area of an absorber of thickness d is $\pi N_0\left[1-\{1-2F(d)\}\right] = 2\pi N_0 F(d)$

where $2F(d) = e^{-k} - ke^{-k} - k^2 Ei(-k)$, and $k = \sigma N d$.

The percentage transmission is then

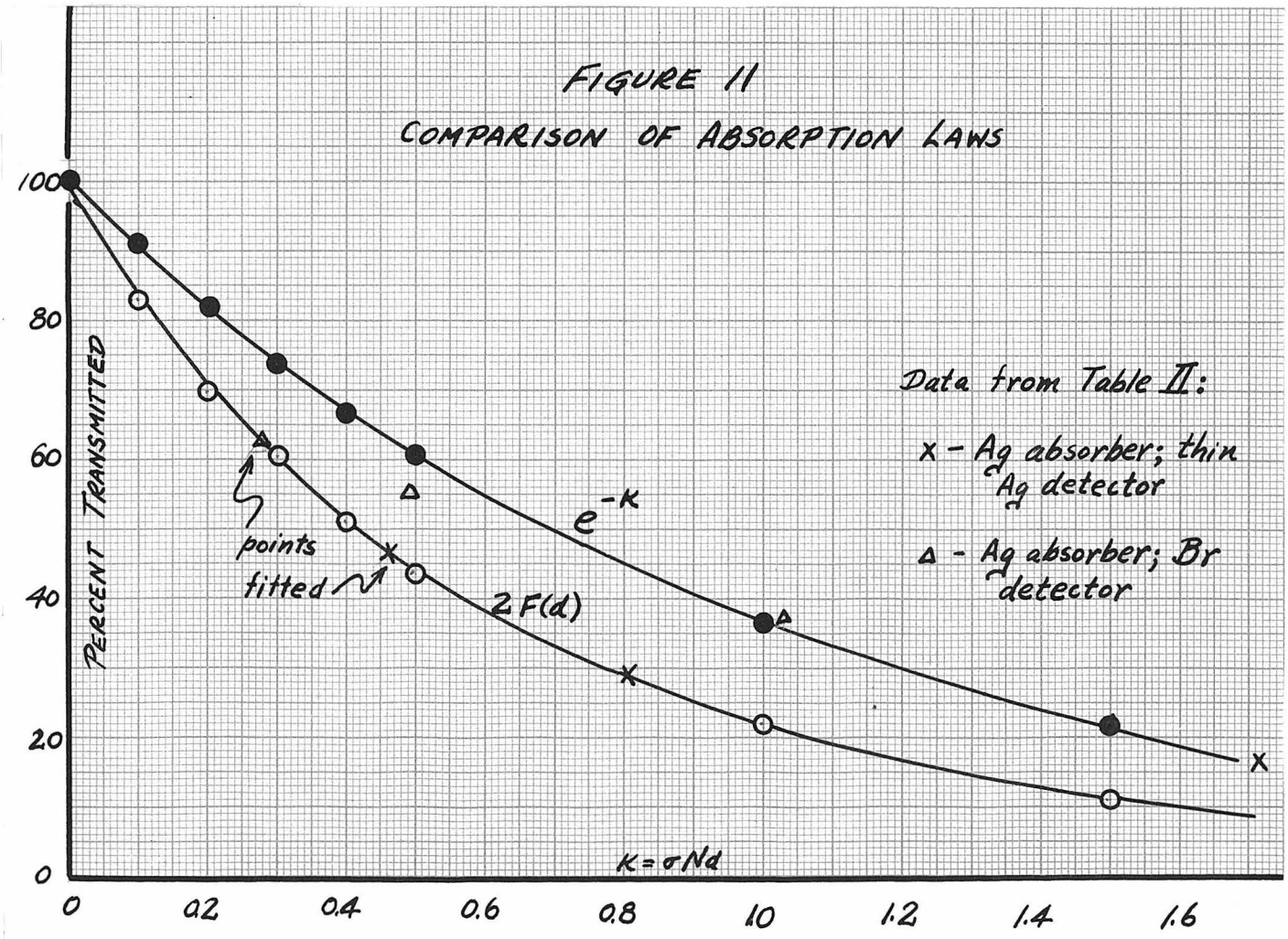
$$\frac{2\pi N_0 F(d)}{\pi N_0} = 2F(d)$$

While it is easy to see that 2F(d) decreases more rapidly for small absorber thickness (i.e. small d and small k) than does e^{-k}, nevertheless this function does not describe the experimental results. See Table IV and Figure 11. Since edge effects are negligible in the experiments of Ridenour and Yost, it may be that this discrepancy is to be explained as being due to the absorption of the neutrons according to a non-exponential law, even in a parallel beam.

TABLE IV

VALUES OF e^{-k} AND OF 2F(d) FOR ROUND VALUES OF k

k	k^2	e^{-k}	ke^{-k}	Ei(-k)	k^2Ei(-k)	2F(d)	log 2F(d)	log e^{-k}
0	0	1	0	$-\infty$	0	1	0	0
0.1	0.01	0.91	0.09	-1.82	-0.018	0.83	9.920	9.957
0.2	0.04	0.82	0.16	-1.22	-0.049	0.70	9.848	9.913
0.3	0.09	0.74	0.22	-0.91	-0.082	0.60	9.779	9.870
0.4	0.16	0.67	0.27	-0.70	-0.112	0.51	9.711	9.826
0.5	0.25	0.61	0.30	-0.56	-0.140	0.44	9.646	9.783
1.0	1.00	0.37	0.37	-0.22	-0.219	0.22	9.340	9.566
2.0	4.00	0.14	0.27	-0.05	-0.196	0.06	8.785	9.131
3.0	9.00	0.05	0.15	-0.013	-0.117	0.017	8.230	8.697
4.0	16	.018	.073	-0.004	-0.061	0.006	7.778	8.263



ERRATA

Page 3, line 4 — For detain read detail.

Page 10 — Insert page number at bottom of page.

line 14 — Omit parentheses around 5.

Page 14, reaction I — In equation, read $_1e^+$ for $_1e$.

line 19 — omit and.

Page 15, line 8 — Insert comma after reaction.

Page 15, line 9 — Insert at least between known in and one case.

reaction II — In equation, read $_{-1}e^-$ for e^-.

reaction III — In equation, read $_1e^+$ for e^+.

reaction IV — In equation, read $_{-1}e^-$ for e^-.

Page 16, reaction V — Read $_1e^+$ for e^+.

Add $+ h\nu$ to end of equation for reaction V.

reaction VI — Read $_{-1}e^-$ for e^-.

Page 17, react. VII — Read $_{-1}e^-$ for e^-.

reaction VIII — Read $_{-1}e^-$ for e^-.

Page 18, line 8 — At end of line, references are [43, 44], not [42, 44].

Page 21, 5th line under Nitrogen: for Wettenstein read Wertenstein.

Page 22, last line in Na VII(?): Reference should be [20], not [30].

Page 23, line 6 — Omit and preceding as a function.

6th line under Silicon: For lifes read lives.

last line: For Fermk read Fermi; also for - read +.

Page 24, 2nd line under Potassium: For and read has.

4th line under Potassium: For indiced read induced.

3rd line under Calcium: Insert comma after Fermi.

Page 25, 2nd line under Cobalt: For VII(?) read VIII(?).

8th line under Cobalt: For twox read too.

Page 27, 1st line under Yttrium: For VII(?) read VIII(?)

MORE ERRATA

Page 8, 5th line from bottom: for electroscope read electroscope.

Page 10, line 4: for incluside read inclusive.

Page 16, reaction VI, in equation: for $Z^{*}Z$ read $Z-2$.

Page 30, 3rd line under Samarium: for An read In.

Acknowledgements, line 8: for discouragement read encouragement.

INSERTION OF FIGURES

Insert Figure	After page
1	3
2	14
3	20
456	35
7	41
8	42
9, 10	43
Appendix A	44

CORRIGENDA

I should like to have what now stands under Fluorine I(?) replaced by the following:

> Frisch[103] has recently reported that a positron emission first observed by Meitner[47] from fluorine bombarded with alpha-particles corresponds to the formation of Na^{22}, whose half-life is extremely long: of the order of 6 months. The half-value thickness for the positrons is 0.03 g/cm^2 of Al. A chemical separation of the active Na has been made. Fahlenbrach[85] mistakenly attributed Meitner's result to the formation of F^{17} from atmospheric nitrogen and its collection by recoil on the target.

Under Calcium one should also add a new paragraph, as follows:

I Frisch[103] has reported that Sc^{43}, a positron emitter of 4.4 hour half-life, is formed by bombarding Ca with alpha-particles. Half-value thickness, 0.06 g/cm^2 Al.