ARTIFICIAL RADIOACTIVITY

LOUIS N. RIDENOUR[1] AND DON M. YOST

W. K. Kellogg Radiation Laboratory and Gates Chemical Laboratory, California Institute of Technology, Pasadena, California

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I. HISTORICAL INTRODUCTION

On January 15, 1934, I. Curie and F. Joliot (26) observed for the first time 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, which had been discovered less than two years before, they found that when certain light elements (boron, magnesium, aluminum) were bombarded with the alpha-particles of polonium, they emitted positrons in large numbers. The discovery of artificial radioactivity was made when Curie and Joliot found that the emission of positrons from the bombarded elements did not cease immediately upon the removal of the source of alpha-particles, but instead decayed according to an exponential law, with a half-life of several minutes duration, characteristic of the substance bombarded.[2] 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 a time of irradiation, long as compared with the half-life of the substance under investigation, the activity produced in a sample reached a saturation value which could not be increased by further irradiation. The intensity of the artificial radioactivity was decreased by a reduction in the energy of the bombarding alpha-particles, but the half-life was independent of the energy with which the alpha-particles struck the target being activated. The new type of radioactivity is seen to be precisely the same in character as natural radioactive beta-disintegration, save for the two important differences that (a) the particles emitted are positive, not negative, electrons, and (b) the radioactive nuclei are derived, not from the preceding decay of a naturally radioactive parent, but from a nuclear transmutation

[1] At present at The Institute for Advanced Study, Princeton University.

[2] The half-life is the time required for the activity to decrease to one-half of its initial value.

phenomenon produced by the bombardment of a stable nucleus by a swift alpha-particle.

It was subsequently found that magnesium emitted negative electrons as well as positrons after alpha-particle bombardment, and in such cases there is complete analogy with natural beta-decay, except for the mode of formation of the radioactive nucleus. In what is to follow, the radioactive emission either of positrons or of electrons will be indicated in each case. The energy distribution of the positrons ejected by an artificial radioactive element is, in all cases which have been examined, precisely similar in character to the continuous beta-particle spectrum which has long been known, and there is no reason for regarding radioactive positron emission as a phenomenon essentially different in nature from radioactive electron emission.

In their first paper, Curie and Joliot had ascribed the radioactivity induced in boron by alpha-particle bombardment to N^{13}, an isotope of nitrogen not known in nature, formed in accordance with the nuclear reaction[3]

$$_5B^{10} + {}_2He^4 \rightarrow {}_7N^{13} + {}_0n^1$$

followed by

$$_7N^{13} \rightarrow {}_6C^{13} + {}_1e^+$$

They predicted that the same radioactive nitrogen could be formed by the bombardment of carbon with deutons, 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 (22, 24), Henderson, Livingston, and Lawrence (56), and later Cockcroft (17, 18) verified that an artificial radioelement was produced by the deuton bombardment of carbon. Cockcroft, Gilbert, and Walton (19) and Crane and Lauritsen (23) also 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 deuton (22, 24) and proton (23) bombardment which they correctly attributed to C^{11}.

It was apparent that at the voltages available (up to about 3×10^6) for accelerating protons and deutons, and with the energies possessed (up

[3] The symbol ${}_0n^1$ is used to designate the neutron, a particle with no charge and a mass of 1.0085 (0 = 16.0000). For the present purposes the symbols ${}_ZX^A$, ${}_ZW^A$, etc. mean an element of atomic number Z and atomic mass A.

to about 8.8 m.e.v. (million electron volts)) by alpha-particles obtainable from naturally radioactive sources, the nuclear transformations necessary to produce artificial radioelements could be brought about only in the lightest elements, viz., those having the lowest potential barriers opposed to the entry of charged particles into the nucleus. Fermi (43), therefore, tried the effect of neutron bombardment of various elements, in the hope of producing artificial radioactivity, as there is certainly no Coulomb field opposed to the entry of a neutron into a nucleus. From the first this method was successful, and Fermi and his coworkers have been able to produce transmutations leading to artificial radioelements in almost all of the elements.

In a communication (44) dated October 22, 1934, Fermi and his associates reported a great increase in the activation of silver under neutron bombardment when the source of neutrons 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 to 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 larger 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 and the collection 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 some detail the experimental situation at the end of October, 1935.

II. 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 must consider the stable isotopes as defining a region of 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 one of the three processes: the expulsion of an alpha-particle, the transformation of a nuclear neutron into a proton with the consequent expulsion of a negative electron, or the reverse transformation of a nuclear proton into a neutron, with the emission of a positron. The rules of isotopic statistics (8), particularly those concerning the paucity of isotopes

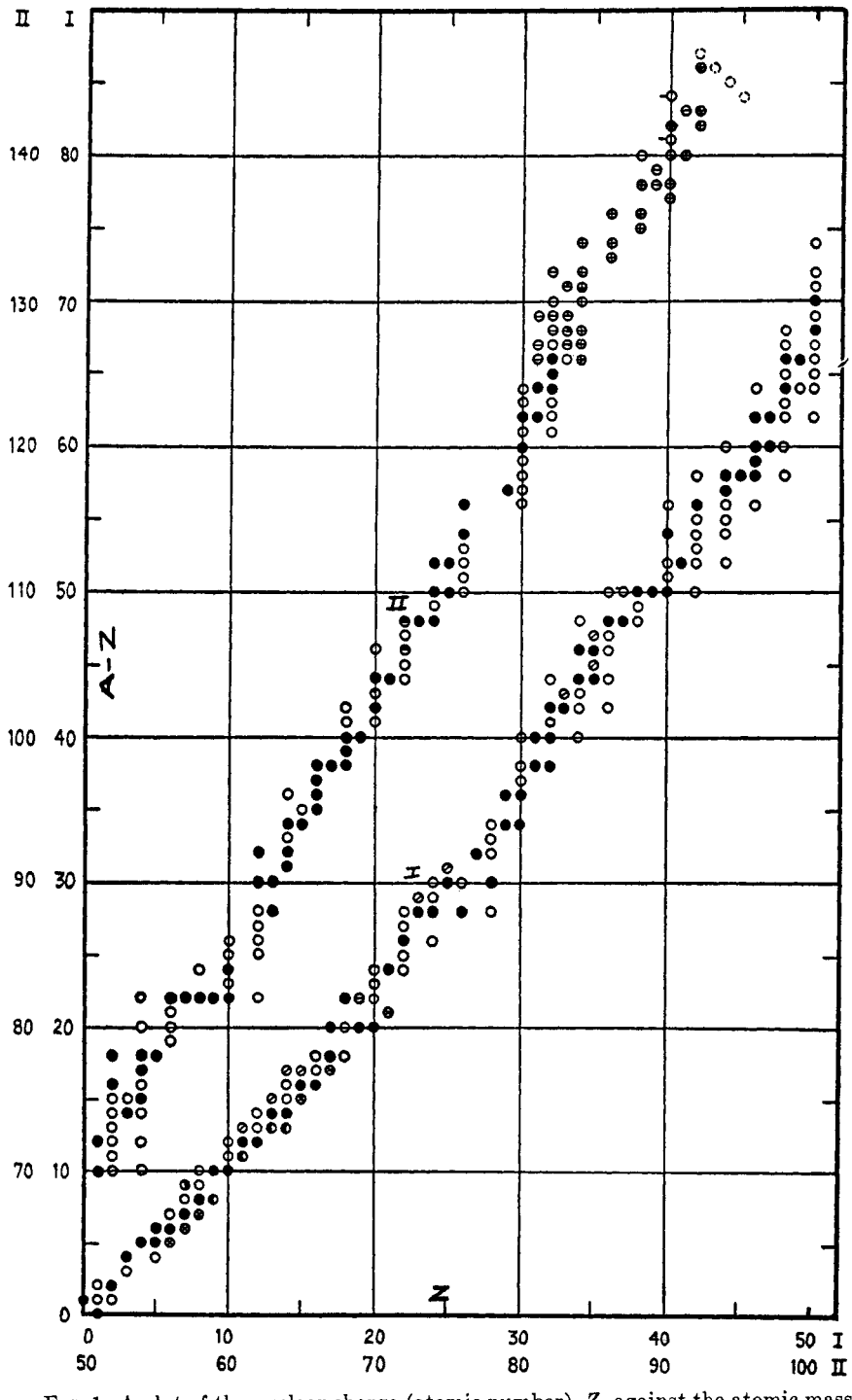

FIG. 1. A plot of the nuclear charge (atomic number), Z, against the atomic mass minus the nuclear charge, $A - Z$, for all the known isotopes. ●, stable isotopes > 20 per cent; ○, stable isotopes < 20 per cent; ⊕, natural α-emitters; ⊖, natural β-emitters; ⊙, artificial β-emitters; ⊗, artificial positron emitters; ◑, artificial positron emitters (?); ◐, artificial positron emitters (?).

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 yet been completely elucidated, on the matter of nuclear stability. The problems of stability of nuclei have been examined in detail by many authors; here a brief and completely qualitative discussion will suffice.

In figure 2 the stable isotopes up to chlorine 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 III, below, which it is intended to illustrate, but here it should be noted that the stable isotopes lie in extremely regular grouping, and that all of the radioactive isotopes lie in such a position that they can transform themselves into stable isotopes by the emission of a positron or 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 of an electron would return the artificial radioelement to a stable form; in all such cases which have been examined, a negative electron is emitted, but it is by no means certain that this is always the case.[4]

III. THE REACTIONS LEADING TO THE FORMATION OF ARTIFICIAL RADIOELEMENTS

There are only eight type-reactions which need be adduced to explain the formation of all (about 100) the artificial radioelements known to date, with one or two possible exceptions which are considered in section IX (paragraphs on indium and bromine). 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 relativistic sense is satisfied, so that in reactions V and VIII, for example, gamma-radiation of the appropriate energy must always be emitted.

[4] The fact that electrons and positrons are emitted in radioactive processes is not to be regarded as evidence for their existence, as such, in the nucleus. Indeed, it can be shown from quite general considerations that it would not be feasible to try to describe the quantum mechanical behavior of an electron located in a region as small as the nucleus. Accordingly it is more profitable, for the present at least, to consider the nuclei as consisting of the heavier particles such as protons, neutrons, and perhaps alpha-particles.

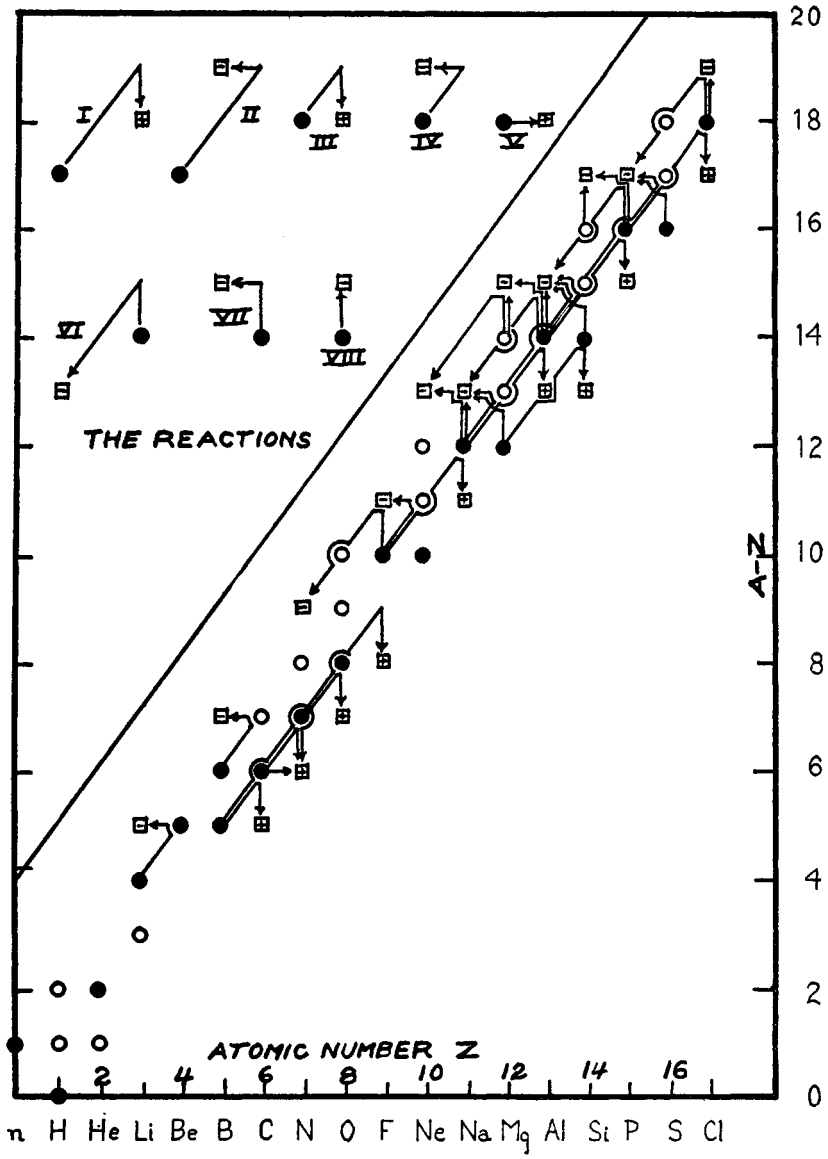

FIG. 2. Artificial radioactivity in the light elements. Z is the atomic number or nuclear charge, and A is the atomic mass. ○, stable isotopes; ●, stable isotopes whose abundance is 20 per cent or greater; □, radioactive isotopes. The sign of the emitted β-particle is shown by + or − in squares.

A. Reactions produced by alpha-particle bombardment

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

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

This is historically the first reaction of artificial radioactivity, being that observed by Curie and Joliot (26) 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. Although this reaction doubtless does take place, 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 paragraph on magnesium in section IX.)

In all the cases known in which reaction I takes place, the alternative emission of a proton at the moment of alpha-particle capture, leading at once to the stable isotope ${}_{Z+1}W^{A+3}$, also takes place, with a much greater probability. The successive emission of a neutron and a positron, or the immediate emission of a proton, from an element bombarded with alpha-particles, 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 either route must be equal to that expended along the other.

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

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

This reaction, which was discussed in the last paragraph for the case in which it gives rise to a stable isotope, sometimes leads to an artificial radioelement. Reaction I is then the alternative one, leading in one step from the stable isotope ${}_{Z}X^{A}$ to the other stable isotope ${}_{Z+2}Y^{A+3}$.

B. Reactions produced by deuton bombardment

Reaction III. Capture of the deuton with emission of a neutron.

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

This is the earliest known reaction involving deutons. It gives rise in the case of carbon bombarded by deutons to N^{13}, the same radioelement which is produced in boron by alpha-particle bombardment. Reactions III and IV may be regarded as alternative in the same manner that reactions I and II have been so regarded above.

Reaction IV. Capture of the deuton with emission of a proton.

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

This reaction, first studied by Lawrence (64), gives rise to the same radioelements that are formed by reaction VIII, below. It is noteworthy that even at energies (up to 5 m.e.v.) far below the height of the potential barrier opposed to the entry of the deuton into heavy nuclei, this reaction has a measurable yield in elements as heavy as platinum ($Z = 78$). The theory of the reaction has been given by Oppenheimer and Phillips (81), and is in substantial agreement with the experimental data. Our information concerning the beta-radioactive elements of the shortest half-lives and most energetic electron-spectra known (20, 21) also comes from this reaction.

C. The reaction produced by proton bombardment

Reaction V. Radiative capture of the proton.

$$ {}_zX^A + {}_1H^1 \rightarrow {}_{z+1}W^{A+1} + h\nu, \text{ followed by } {}_{z+1}W^{A+1} \rightarrow {}_zX^{A+1} + {}_1e^+ $$

There has in the past been considerable confusion in the reports concerning this reaction which have emanated from different laboratories (17, 18, 23, 50). 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 and momentum. An appreciable yield in the reaction will result only near certain definite "resonance levels," which may be supposed roughly to correspond to quantized states of the proton in the field of the target nucleus.

When the yield of artificial radioactivity is plotted as a function of bombarding particle energy, the time of exposure and bombarding ion current being supposed held constant throughout the measurements, the shape of the curve obtained for a reaction of type V will be very different from the shape of the yield–voltage curve obtained for a reaction such as reaction III, where a neutron is emitted at the instant of formation of the artificial radioelement. In the latter case, the probability of disintegration increases in approximately an exponential fashion with the energy of the bombarding particle, while in the former instance, the probability of disintegration is different from zero only when the energy of the bombarding particle is in the neighborhood of a "resonance" value. If the target under bombardment is thicker than the range of the bombarding particles in the material of which it is composed, then a yield–voltage curve for reaction IV will consist of plateaus separated by abrupt rises in the yield which occur each time the energy of the bombarding particles becomes as high as a "resonance" level. The yield–voltage curve measured in a "thin" target (i.e., a target in which each proton in the ion beam loses only a few thousands of volts energy) will consist of the differential of the thick target curve, namely, a series of peaks, each member of which occurs at a "resonance" value of the energy.

Taken in connection with the differences in voltage scales at different laboratories, the foregoing considerations make it by no means surprising that Cockcroft, Gilbert, and Walton (17, 18) have failed to find the radioactivity produced in boron by proton bombardment, and that Hafstad and Tuve (50) at first failed to find the activity produced in carbon by proton bombardment.

The "resonance" character of reactions of this type will no doubt be very useful in the future in standardizing high-voltage outfits used for nuclear investigations, in the same manner that melting points are useful in establishing a scale of temperatures.

Reaction V has been treated theoretically by Breit and Yost (15).

D. Reactions produced by neutron bombardment

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

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

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 (boron, lithium) in which a stable nucleus is formed in a similar reaction, and here the reactions are exothermic and seem to have a greater probability when the neutrons have almost zero energy (4, 16).

Reaction VII. Capture of the neutron with emission of a proton.

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

This reaction, like VI, involves the 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 to take place only among the light elements, viz., those of charge-number less than about 30.

Reaction VIII. Radiative capture of the neutron.

$$ {}_{z}X^{A} + {}_{0}n^{1} \rightarrow {}_{z}X^{A+1} + h\nu, \text{ followed by } {}_{z}X^{A+1} \rightarrow {}_{z+1}W^{A+1} + {}_{-1}e^{-} $$

This is, to date, the most frequently occurring reaction encountered in the production of artificial radioactivity; indeed, it takes place in a larger number of elements than any other known 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 several millions of volts energy by a stationary nucleus, without the emission of any heavy particles whatever. Incontrovertible evidence that the radioelement formed was in fact the next heavier isotope of the bombarded element made it clear that capture of the neutron was indeed occurring, while the discovery, already mentioned in section I, that the slowing-down of neutrons by a substance containing hydrogen greatly enhanced the probability of this reaction, made it seem likely that the energy of the neutrons entering the reaction is always very low. The activity due to this reaction which is observed in the absence of any hydrogen-containing substance surrounding the source of neutrons and target being activated may then be attributed to the neutrons of low energy produced by scattering from nearby objects of the neutrons emitted by the source.

A theoretical treatment of the reaction, made along substantially the same lines and offered about the same time by Bethe (10), Perrin and Elsasser (84), and Fermi (4), seems to have several features that are not in accord with the experimental results.

Reaction VIII is by no means limited to cases in which the product nucleus is unstable, as is shown by the enormous absorption for slow neutrons displayed by such substances as cadmium, mercury, and gadolinium, which are only feebly activated by neutron bombardment. In such cases, the next heavier isotope of cadmium, mercury, gadolinium, etc. is stable and is formed by the radiative capture of the neutron.[5] Gamma-rays emitted in such neutron capture, in the production of both stable and unstable nuclei, have been observed by Fermi (4) and others (45, 61). Their energy has been roughly measured in several cases by Rasetti (86).

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 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 bear in mind that the tabulated isotopic masses ordinarily met are *atomic* masses, and hence include the masses of all the extranuclear electrons. The reason for this seems to be that one of the original purposes of isotopic mass determinations was to enable their comparison with atomic weights measured by the chemists. Now that the chief usefulness of isotopic masses is in balancing the equations of nuclear reactions, it would seem that the masses of the extranuclear electrons might

[5] For example, the known isotopes of cadmium are 106, 108, 110, 111, 112, 113, 114, 115, 116, and since the abundant ones differ by unity, any isotope formed by neutron capture would be one of these and therefore stable. The isotopes 106, 108, and 116 are present in only small amounts in cadmium.

well be subtracted. If one uses a table of *atomic* masses in calculating the energy balance in a reaction in which an electron is emitted, the mass of the emitted electrons should not be taken into account in the computation, for its loss from the radioactive atom is compensated by the gain of a new extranuclear 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, *twice* the electron rest-mass energy should be added to the energy of disintegration, for not only has the positron escaped, but an extranuclear electron will be lost owing to the reduction of the nuclear charge-number by one unit.

It seems clear from the investigations of Henderson (55) and of Crane, Delsasso, Fowler, and Lauritsen (20), that the maximum energy of the continuous beta-particle spectrum, and not the mean energy, should be taken as the energy of electron or positron disintegration.[6]

IV. CHEMICAL IDENTIFICATION OF THE RADIOACTIVE ISOTOPES

Until the discovery of artificial radioactivity, the end-products of nuclear disintegrations were identified only by inferences involving the number and character of particles known to be emitted in the reactions, and the balance of energy in the nuclear reaction postulated to explain the disintegration. The probabilities of the known nuclear disintegrations range from about 10^{-6} to 10^{-11} per incident bombarding particle, and although in an ion-accelerating tube currents of 10^{13} ions per second are by no means unusual, it is immediately obvious that the bombardment time required to make a spectroscopically detectable amount of the product of the most favorable nuclear reaction is impossibly long. The same argument applies to any other means of detecting a gross amount of a stable isotope which may be formed in a nuclear disintegration.

If the product of the reaction is radioactive, however, the situation is entirely changed, for extremely sensitive methods of detection of charged particles in rapid motion are available. By the use of a Geiger counter or a sensitive electroscope, the detection of 10^5 or 10^6 sufficiently radioactive atoms is very easy. Since the chemical character of an atom is determined by the charge on its nucleus, without regard to the structural stability of that nucleus, it is 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.

[6] The fact that the energy spectrum of the beta-particles of a beta-active substance is continuous, and not discrete, has led to the assumption of the existence of the neutrino, a particle of small mass and no charge, introduced to preserve the conservation laws of momentum and energy in beta-ray decay.

The chemical identification of artificial radioelements is based on the 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 AB and $B(1 - A)$ will be the fractions of each isotope that have reacted. While the chemical behavior of the few hundreds of thousands or few millions of atoms of an artificial radioelement formed in a nuclear reaction may be erratic and uncertain, if a quantity of that 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 radioactivity will have been separated out in the removal of the element under examination.

It must be pointed out that failure to separate a radioelement from an added element is not sufficient evidence for the statement that they are isotopic with each other. Also, isotopes may be separated from each other chemically, if they exist in different valence states. If, after a chemical treatment calculated to bring both the radioelement and the known added element to the same valence state, a separation can be effected, one has reasonably good proof that the two are not isotopic. The fact that two elements coprecipitate or are carried along together in some reactions does not establish that they are isotopic, as all chemists know well.

When the artificial radioelement produced in a nuclear reaction is an isotope of a completely unknown element, or of one so rare or itself so radioactive that none can be added to the radioelement to stabilize its chemical properties, the matter of chemical identification becomes a great deal more difficult. Such a case occurs in the bombardment of uranium by neutrons: Fermi, who first studied this reaction, early concluded (42) that at least one of the half-lives observed belonged to an element of charge-number 93, for its chemical properties did not seem to be those of any of the known elements from 86 to 92 inclusive. This point of view was criticized by von Grosse and Agruss (49), 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 occurring in nature—protactinium and UX_2—are both very rare. New experiments by Fermi (4) and Hahn and Meitner (52) seemed to indicate that not only element 93, but also elements 94 and 95 were formed in the bombardment 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, and our knowledge of the effects of neutron bombardment of the naturally radioactive elements, sketchy as yet (see

section IX, where the reactions for each element are treated in detail), may be expected to shed some light on the problems of the uranium, thorium, and actinium series, and perhaps on the missing elements 85 and 87.

For many years the use of the naturally radioactive elements as indicators in chemical reactions involving their stable isotopes has been a well-known technique (82) in chemistry, although it is one drastically limited in scope by the fact that (except for the cases, unimportant in this connection, of potassium, rubidium, and samarium) the naturally radioactive elements are restricted to the atomic numbers 81 to 92, inclusive. The ready availability of radioactive isotopes of almost all the stable elements (see section IX) should make possible many experiments not feasible in any other way in which these radioelements are used as indicators. The application to biochemical studies is also worthy of consideration.

V. 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 method of concentrating a radioelement differing chemically from its parent, which has a much more limited range of application, was that of electrochemical deposition. This has been employed by Haissinsky (54) in the concentration of radiocopper, produced by neutron bombardment of zinc. In order that this means may be applicable, the radioelement must be electrochemically 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 radioactive element is isotopic with its parent—the situation is by no means so hopeless as is the chemical separation of ordinary isotopes. Szilard and Chalmers (94) 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 new nucleus is likely to be removed from its chemical bond in the compound of iodine being irradiated, either by the kinetic energy of the captured neutron or, if this energy is too low, by the recoil produced by the gamma-ray whose emission is demanded according to reaction VIII. Whether the atom freed in this way will interchange with its isotopic atoms bound in the irradiated chemical compound will depend on the nature of the chemical compound dealt with. To prevent such interchange, Szilard and Chalmers 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, which proved to contain almost all of the activity.

Fermi (4) 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 chloride ion added, and silver chloride precipitated, from 70 to 90 per cent of the activity is concentrated in the precipitate. Care must be taken to prevent the precipitation of silver chlorate. Similar results can be obtained with bromates and iodates. Manganese dioxide precipitated from irradiated potassium permanganate carries a large part of the activity due to radiomanganese.

Physical methods of separation depend on the fact that the atom is likely to have lost one or more extranuclear electrons at the moment of formation, owing to the energy imparted to it either by the captured neutron or the emitted gamma-ray. Hence the net electric charge on the atom permits its collection by an electrostatic field. Such methods have been employed by Fermi (4) and by Paneth (83) 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 Wertenstein (96), in the case of radiofluorine formed from atmospheric nitrogen by alpha-particle bombardment, and has since been observed in many cases in which a heavy particle is either captured or emitted in the formation of an artificial radioelement (17, 18, 67).

The possibility of concentrating an artificial radioelement makes artificial radioactivity useful as a detector of neutrons, which can be obtained only in the presence of gamma-radiation so intense that electrical methods of detection are not feasible.

VI. 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 coworkers (4) found that the activation of silver by the neutrons from a radon–beryllium source could be increased several fold by surrounding source and detector by 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 0 to about 7 m.e.v. (31), lost energy in collisions with the hydrogen nuclei present in the 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 and water was 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 lent 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 nucleus of hydrogen than in one with a heavier nucleus. When other detectors were substituted for the silver, the striking discovery was made that all the reactions of type VIII, and only these reactions, showed an enhancement when the neutrons were slowed down.

The assumption was early made by Fermi (4) 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 $\frac{1}{2}$. From this it follows that in the course of fifteen impacts the energy of a neutron is reduced to about 1/30,000 of its original value. With a neutron of initial energy 4 m.e.v., less than thirty 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 VIII.

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, but the discovery was also made (4) that many elements which did not show pronounced radioactivity under neutron bombardment exhibited an extremely large absorption for slow neutrons. In the cases of heavier elements (cadmium, mercury, and others), this is to be attributed to the radiative capture of a slow neutron, in complete accordance with reaction VIII, except that the nucleus formed by neutron capture is in these cases a stable isotope of the bombarded element, so that no radioactivity is observable. The energy of the gamma-rays emitted in the capture of a neutron of nearly zero kinetic energy can be estimated from the fact that Aston (8) has found the mass difference between neighboring isotopes of the same element to be always approximately unity in the region of the periodic table where this phenomenon of large slow neutron absorption without consequent radioactivity occurs. The mass of the neutron (9) is fairly accurately known to be 1.0085 on the "physical" scale of masses ($O^{16} = 16$), so that when a free neutron is captured and bound in a nucleus about 7.5 m.e.v. of energy

must be radiated. The measurements of Rasetti indicate that the energy of the capture radiation is in some cases as small as about 4 m.e.v., so that the possibility must be admitted that there is emission of more than one quantum per capture process, i.e., that the radiation of the 7.5 m.e.v. takes place in two or more steps.

In his studies of the absorption of slow neutrons, Fermi (4) further found that certain light elements (boron and lithium) exhibited large absorption for the slow neutrons, without becoming radioactive and also without emitting gamma-radiation at the moment of neutron capture. This has been shown to be due to the capture of the neutron in the boron or lithium nucleus, and the subsequent disintegration of the product nucleus with the

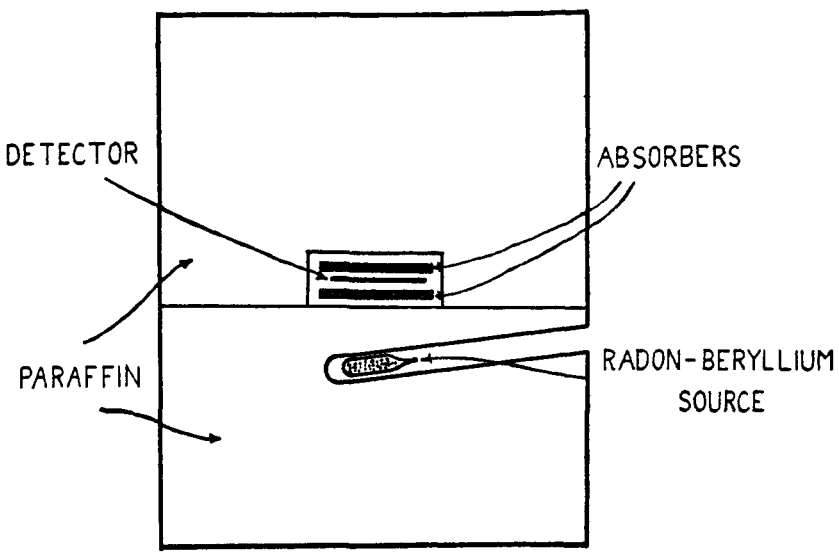

FIG. 3. Fermi's arrangement for measuring absorption of slow neutrons

emission of heavy particles (16). This latter phenomenon (viz., the emission of heavy particles) may be regarded as an alternative to the emission of gamma-radiation at the moment of neutron capture; the energy balance in the reaction can be preserved in either way.

VII. ABSORPTION OF SLOW NEUTRONS

The earliest measurements of the absorption of slow neutrons were made by Fermi (4), with the experimental arrangement shown in figure 3. The absorption curves he obtained with this arrangement were not exponentials, as indeed the geometry would lead one to expect, even though the absorp-

tion measured in a parallel beam might follow an exponential law.[7] Experimental evidence that this is indeed the case has been obtained for absorption in cadmium by Dunning (33) and Ehrenberg and Hu Chien Shan (37), and for absorption in silver by the latter investigators. Fermi used for the detection of the neutrons transmitted through his absorber the radioactivity induced by these neutrons in a sheet of rhodium or of silver.

Another method of slow neutron detection is to count the heavy particles emitted in the disintegration of lithium by slow neutrons. The reaction, mentioned in the last section, is

$$_3Li^6 + {}_0n^1 \rightarrow {}_2He^4 + {}_1H^3$$

the alpha-particles having a range of about 6 mm. and the $_1H^3$ a range of 15 mm. It is not difficult to count the individual particles produced in

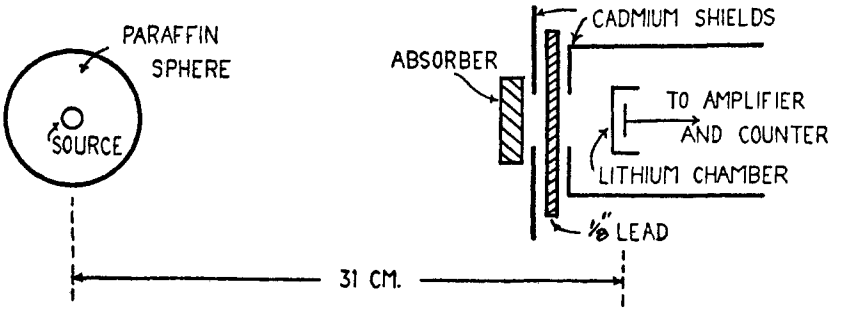

FIG. 4. Dunning's arrangement for measuring the absorption of slow neutrons

this reaction by one of the electrical counting procedures customary for the measurement of alpha-particles from naturally radioactive sources. Dunning and his coworkers (33) have made extensive measurements of the absorption of slow neutrons in various substances, detecting by means of a "linear" amplifier (32) the heavy particles emitted in the lithium reaction. The geometrical arrangement of his source, absorbers, and detector is shown in figure 4, which demonstrates that his absorption measurements were made on a beam of slow neutrons much more nearly parallel than that used by Fermi.

[7] A simple geometrical calculation shows that if the assumptions are made that (a) the absorption of neutrons from a parallel beam is strictly exponential and (b) that the distribution of neutrons in the paraffin is sensibly uniform (which is usually the case), the fraction of neutrons transmitted through an absorber of thickness d is

$$e^{-k} - ke^{-k} - k^2Ei\ (-k)$$

where $k = \sigma Nd$, σ is the cross section for absorption, and N is the number of nuclei per cubic centimeter in the absorber.

TABLE 1

Neutron-nucleus collision cross sections

ELEMENT	ATOMIC NO.	ATOMIC WT.	COMPOUND USED	GRAMS PER SQ. CM.	FRACTION TRANSMITTED	CROSS SECTION × 10^{24}, SQ. CM.	
						Slow	Fast
H	1	1.008	$(CH_2)_n$	0.131	0.673	55	1.68
D	1	2.014	D_2O	1.36	0.631	4.0	1.71
Li	3	6.94	LiF	0.24	0.765	45	1.84
Be	4	9.02	Be	0.703	0.780	5.3	1.65
B	5	10.82	B_4C	0.0557	0.418	360	1.60
C	6	12.00	C	2.86	0.549	4.1	1.65
N	7	14.01	NaN_3	1.30	0.630	11.3	1.76
O	8	16.00	SiO_2	3.78	0.709	3.3	
F	9	19.00	NaF	1.94	0.827	2.5	
Na	11	23.00	Na	1.48	0.847	4.2	
Mg	12	24.32	Mg	4.67	0.669	3.5	
Al	13	26.97	Al	7.24	0.788	1.5	2.4
Si	14	28.06	Si	2.23	0.867	2.5	
P	15	31.03	P	1.69	0.615	14.7	
S	16	32.06	S	6.6	0.840	1.4	2.6
Cl	17	35.46	NaCl	1.35	0.541	39	
K	19	39.10	K	1.60	0.816	8.2	
Ca	20	40.07	CaO	1.87	0.751	11.0	
Ti	22	48.1	TiO_2	1.97	0.760	11.9	
V	23	50.96	V_2O_5	2.41	0.751	10	
Cr	24	52.01	Cr	5.82	0.718	4.9	
Mn	25	54.93	Mn	3.69	0.558	14.3	
Fe	26	55.84	Fe	3.87	0.605	12.0	3.0
Co	27	58.94	Co	1.41	0.602	35	
Ni	28	58.69	Ni	3.03	0.637	15.4	
Cu	29	63.57	Cu	6.22	0.642	7.5	3.2
Zn	30	65.38	Zn	10.7	0.627	4.7	3.3
Ge	32	72.60	GeO_2	0.08	0.93	75*	
As	33	74.96	As	5.28	0.692	8.6	
Se	34	79.2	Se	3.47	0.606	19	
Br	35	79.92	KBr	3.43	0.705	11.9	
Sr	38	87.63	$SrCrO_4$	2.21	0.832	9*	
Y	39	88.9	Y_2O_3	0.18	0.463	800	
Zr	40	91	ZrO_2	1.87	0.807	16.7	
Cb	41	93.1	Cb_2O_5	1.01	0.90	14*	
Mo	42	96.0	Mo	1.70	0.926	7.1	
Ru	44	101.7	Ru	6.1	0.647	12.5	
Rh	45	102.9	Rh	0.62	0.664	115	
Pd	46	106.7	Pd	6.2	0.715	10−	
Ag	47	107.88	Ag	1.88	0.557	55	
Cd	48	112.41	Cd	0.0416	0.524	3300	
Sn	50	118.70	Sn	18.8	0.678	4.0	4.3

TABLE 1—*Concluded*

ELEMENT	ATOMIC NO.	ATOMIC WT.	COMPOUND USED	GRAMS PER SQ. CM.	FRACTION TRANSMITTED	CROSS SECTION × 10^{24}, SQ. CM.	
						Slow	Fast
Sb	51	121.77	Sb	7.26	0.745	8.1	
Te	52	127.5	Te	5.52	0.790	8.2	
I	53	126.93	I	6.78	0.738	9.4	4.6
Ba	56	137.37	BaO	0.662	0.680	140	
La	57	138.90	La_2O_3	0.214	0.933	80	
Ce	58	140.25	CeO_2	0.98	0.896	25*	
Pr	59	140.9	Pr_2O_3	2.43	0.77	25	
Nd	60	144.27	Nd_2O_3	0.72	0.559	220	
Sm	62	150.43	Sm_2O_3	0.04	0.525	4700	
Eu	63	152	Eu–Gd–Al	0.02	0.647	1000*	
Gd	64	157.6	Gd_2O_3	0.0068	0.590	30,000	
Tb	65	159.2	Tb–Al	0.06	0.919	1000*	
Dy	66	162.5	Dy–Al	0.27	0.685	700	
Ho	67	163.4	Ho–Al	0.144	0.877	400*	
Er	68	167.7	Er_2O_3	0.666	0.780	120	
Tm	69	169.4	Tm–Al	0.07	0.987	500*	
Yb	70	173.6	Yb_2O_3	0.315	0.912	90	
Lu	71	175.0	Lu–Al	0.045	0.93	400*	
Ta	73	181.5	Ta	4.56	0.663	27	
W	74	184.0	W	7.05	0.592	23	5.3
Re	75	186.31	Re	2.39	0.501	89	
Os	76	190.6	Os	5.35	0.643	27	
Ir	77	193.1	Ir	0.785	0.509	285	
Pt	78	195.2	Pt	4.30	0.769	25	
Au	79	197.2	Au	2.52	0.508	88	
Hg	80	200.61	HgO	0.545	0.556	380	5.8
Tl	81	204.39	Tl	10.5	0.710	11	
Pb	82	207.20	Pb	22.7	0.568	8.6	5.7
Bi	83	209.00	Bi	9.07	0.805	8.2	
Th	90	232.15	ThO_2	2.75	0.772	32	
U	92	238.17	UO_2	2.52	0.83	43	

* Estimated.

Table 1 is taken from Dunning's paper and gives the cross sections for slow and fast neutron absorption of most of the elements. The cross section σ is defined in the usual way: if a fraction A of the incident number of neutrons is transmitted through a thickness x of absorber, which contains N nuclei per cubic centimeter, then

$$A = e^{-N\sigma x}$$

It will be noted that while for many elements the cross section for slow neutron absorption does not differ appreciably from that for absorption of

fast neutrons, in some cases the former is enormously larger than the latter. While the cross section for fast neutron absorption increases monotonically from boron to lead in a way that is not much different from that in which the nuclear radius is supposed to increase, the cross section for the absorption of slow neutrons varies erratically and unpredictably from one element to the next. The cross section of gadolinium, for example, is about 3×10^{-20} sq. cm., leading to a collision radius of about the size of the K shell of electrons.

Since the detection of slow neutrons is always accomplished by means of a reaction that they produce (viz., either capture of the neutron with subsequent radioactivity of the detector, or disintegration of the nuclei of the detector with the emission of heavy charged particles), it seems likely that the measured absorption of an element for slow neutrons might depend on the particular reaction employed in the detection of the neutrons transmitted through a sample of the absorber. That this is indeed the case has been shown experimentally by Moon and Tillman (78) and by Ridenour and Yost (87). Indications of the same effect have also been obtained in connection with other experiments by Bjerge and Westcott (12) and by Artsimovitch and others (7).

It will be seen from the diagrams of the arrangements used by Fermi and by Dunning for absorption measurements (figures 3 and 4), that the effects of neutron capture and of elastic scattering are not separately evaluated; what is measured is simply the efficacy of an absorber in removing slow neutrons from a beam. It is predicted by the theory of Bethe (10) mentioned above (section III), that elements displaying large cross sections for neutron capture will also present large cross sections for elastic scattering of the slow neutrons. This is apparently in complete disagreement with the available experimental facts. Dunning (33) has shown that there is no appreciable elastic scattering from cadmium, Ridenour and Yost (87) have demonstrated that the same is true of silver, and Mitchell and Murphy (77) have found the same result in mercury. Cadmium, silver, and mercury all have large capture cross sections, and should therefore exhibit large elastic scattering, according to the theory. It is possible that elastic scattering may be an important phenomenon in some of the elements, perhaps in some cases more important than capture, but there is at present no experimental evidence that this is the case.

VIII. THE VELOCITY OF THE SLOW NEUTRONS

It is, of course, a matter of the first importance to know definitely in what velocity range the neutrons conventionally called "slow" lie. Slow neutrons may be thought of as those which are strongly absorbed by cadmium, for definiteness, and it has been shown by Dunning (33) that these

neutrons are not detectable by counting with a linear amplifier the protons knocked on by them (the usual technique for detecting fast neutrons); while Bonner and Brubaker (13) have demonstrated that the recoil protons due to slow neutrons cannot be observed in a cloud chamber (another standard technique for fast neutron measurement). This sets an upper limit of about 50 to 100 electron kilovolts to the energy of the slow neutrons.

If, as was early supposed by Fermi, the energy of the slow neutrons is that of thermal agitation at room temperature (about 1/40 of a volt) it should be possible to detect a difference in their properties when the medium in which they are slowed down—paraffin or water—is cooled to a much lower temperature, say that of liquid air. The neutrons, being at least partially in thermal equilibrium with their surroundings, should have a different energy distribution in the two cases, and hence a different likelihood of capture. After inconclusive temperature-effect experiments had been performed by Fermi (4) and McLennan and others (72), the first positive evidence of such an effect was presented by Dunning and others (33, 34), who found that the absorption of "cold" (90°K.) neutrons in cadmium was about 4 per cent greater than that of "warm" (273°K.) neutrons. A much larger effect of temperature[8] has been announced by Moon and Tillman (78) and confirmed in part by Fermi (5). The activation of silver, rhodium, and iodine by the neutrons from a radon–beryllium source was found by the former investigators to increase by about 10 to 20 per cent 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 neutron source remained constant at that of the room.

More satisfactory than any of these temperature-effect experiments is the result recently announced by Dunning and others (35) for an experiment with a Stern type mechanical velocity selector designed to measure directly and unambiguously the speed of the slow neutrons. In this experiment, four duralumin disks were provided with sectors of sheet cadmium, the sectors subtending 3.7°, the spacing between the sectors being 3.5°. Two of these disks were mounted 54 cm. apart on a shaft which could be rotated, the other two disks being fixed 5 mm. from the rotating ones (figure 5). Since the cadmium is opaque to the slow neutrons and the duralumin transparent, the arrangement forms a velocity selector for the slow neutrons. The results obtained are shown in figure 6, and constitute the most reliable evidence obtained to date that many of the slow neutrons really have thermal velocities.

[8] Lukirsky and Zavewa (68) show that a temperature effect of as high as 45 per cent is attainable. That is, for silver the activity at liquid air temperatures is 45 per cent greater than that at room temperature. In these experiments the cooled paraffin was 0.8 cm. thick.

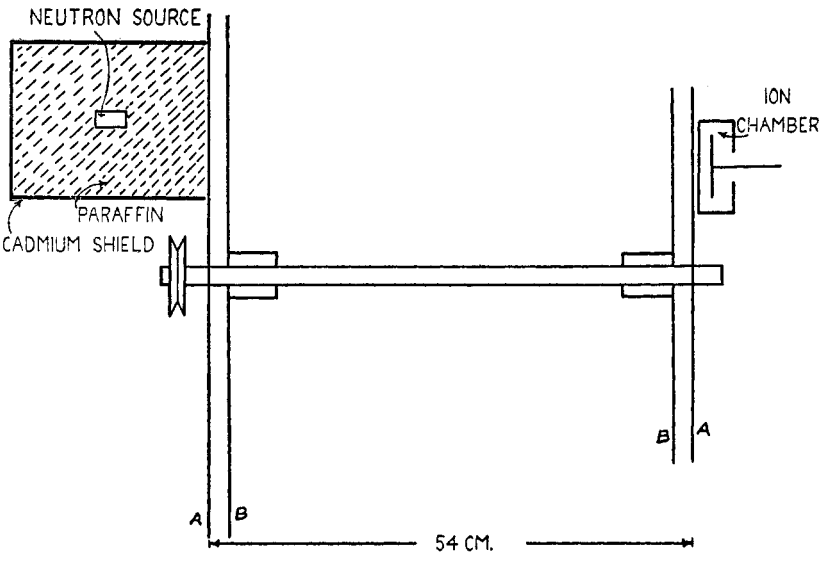

FIG. 5. Schematic drawing of mechanical velocity selector for slow neutrons. A, rotating disk with cadmium sectors; B, fixed disk with cadmium sectors.

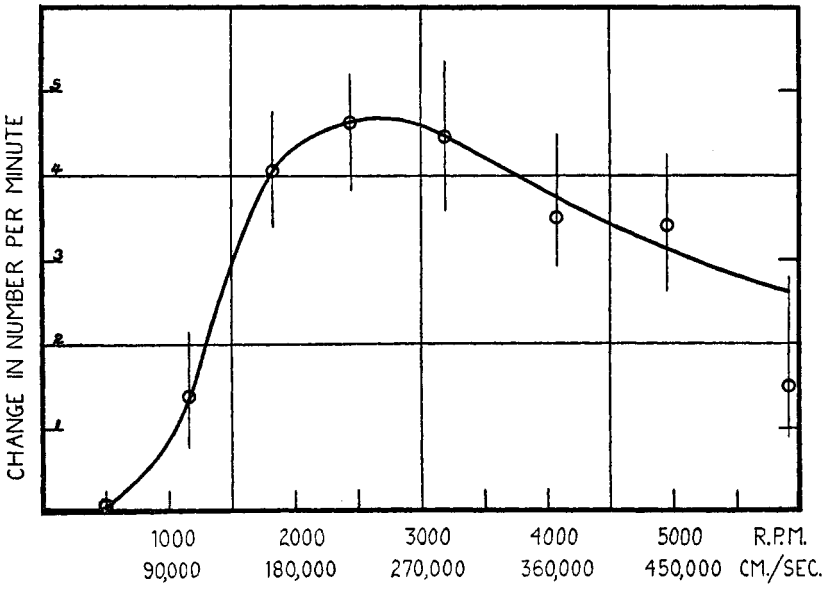

FIG. 6. Curve showing change (decrease) in number of slow neutrons detected after passing through the two shutter systems, as the speed of the sectors was changed. The speed of the sectors is given in revolutions per minute, and the neutron velocity for which the selector is most effective is also indicated.

IX. DETAILED DISCUSSION OF THE ARTIFICIAL RADIOELEMENTS

In this section the reactions producing artificial radioactivity have been treated for the case of each element. The listing is made according to the bombarded element, although it must 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 or reaction VIII, from P^{31} by reaction VI, or from Si^{28} by reaction VII. The number of the reaction-type 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 it is not explicitly stated, can be determined from the type of nuclear reaction involved; we have seen in section III that reactions I, III, and V lead to radioelements which emit positrons in their decay, while reactions II, IV, VI, VII, and VIII give electron-emitting isotopes. No case is known in which bombardment by neutrons produces a radioactive emission of positrons. At the end of the paragraph on each reaction is a list of references to the work bearing on that particular reaction; the most important ones are usually mentioned specifically in the paragraph.

The half-value thickness for the absorption of the beta-radiation emitted by an artificial radioelement is often given below in grams per square centimeter of aluminum; the mean energy of the electron or positron spectrum can be obtained very roughly in m.e.v. by multiplying the half-value thickness by 8.

1. Hydrogen

No artificial radioactivity has been excited in this element by neutron, proton, deuton, or alpha-particle bombardment.

2. Helium

The technical difficulties of irradiating and testing for subsequent activity sufficiently large volumes of the noble gases (66) have prevented their careful investigation for artificial radioactivity.

3. Lithium

I? Meitner (75) reported observing the radioactive emission of positrons from lithium bombarded with alpha-particles. The upper energy limit was 0.3 m.e.v., and the half-life several minutes. These she attributed to B^9. She
II? 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.

IV Crane, Delsasso, Fowler, and Lauritsen (21) have found a beta-activity in lithium bombarded with deutons. The half-life is about 0.5 second, and the upper limit of the electron energy spectrum about 10 m.e.v. The activity is probably to be attributed to Li^8 and possibly to H^4. Strong bombardment of lithium with neutrons (4, 43) 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 beryllium after strong irradiation with slow neutrons (4).

5. *Boron*

I The formation of N^{13} by alpha-particle bombardment of boron is one of the three reactions by which artificial radioactivity was first discovered. The half-life first measured by Curie and Joliot (26) and Ellis and Henderson (38) was wrong, being given as 14 minutes instead of about 10.5. More accurate measurements by Ellis and Henderson (39) cleared up the consequent difficulty regarding the identity of the N^{13} formed by bombarding boron with alpha-particles, with that formed by bombarding carbon with deutons or protons; N^{13} emits positrons, the upper limit of whose energy spectrum is about 1.3 m.e.v. (References 2, 27, 40.)

IV Emission of electrons from boron following deuton bombardment has been observed by Crane, Delsasso, Fowler, and Lauritsen (20). The half-life is about 0.02 second, and the upper limit of the energy spectrum in the neighborhood of 11 m.e.v. The activity is presumed to be due to B^{12}.

III Crane and Lauritsen (22, 24) and Cockcroft (17, 18) have reported a positron activity with a half-life of 20 minutes, produced by the deuton bombardment of boron. The radioelement involved was shown to be C^{11} by Yost, Ridenour, and Shinohara (97). The upper limit of the positron spectrum is about 1.3 m.e.v., according to Neddermeyer and Anderson (79).

V Crane and Lauritsen (23) found that C^{11} could also be formed in boron by proton bombardment. The reason for Cockcroft's (17, 18) disagreement with this finding has been discussed in section IV.

6. *Carbon*

III Crane and Lauritsen (22, 24), Cockcroft, Gilbert, and Walton (17, 18), and Henderson, Livingston, and Lawrence (56) have found a positron activity of about 10.1 minutes half-life in carbon bombarded by deutons. Yost, Ridenour, and Shinohara (97) showed that the radioelement was N^{13}.

V Lauritsen and Crane (23) found that the same element was formed in the bombardment of carbon by protons, as had Cockcroft, Gilbert, and Walton (17, 18, 19) and Henderson, Livingston, and Lawrence (56). Hafstad and Tuve (50) could not at first find evidence of such activity, but the discrepancy has been cleared up, and Hafstad and Tuve (51) 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 (15).

7. *Nitrogen*

I The phenomenon of recoil of active nuclei formed by alpha-particle 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 Wertenstein (96) as being due to the formation probably of F^{17} according to reaction I. The half-life is 1.1 minutes. Ellis and Henderson (38) have also studied this radioelement. (References 29, 40.)

III Livingston and McMillan (67) have observed the collection by recoil on to a platinum target bombarded by deutons 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 m.e.v.

8. Oxygen

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

9. Fluorine

I Frisch (48) has recently reported that a positron emission first observed by Meitner (75) from fluorine bombarded with alpha-particles corresponds to the formation of Na^{22}, whose half-life is extremely long,—of the order of six months. The half-value thickness for the positrons is 0.03 g. per square centimeter of aluminum. A chemical separation of the active sodium has been made.

IV Crane, Delsasso, Fowler, and Lauritsen (21) have observed the formation of F^{20} in the bombardment of fluorine with deutons. The upper limit of the electron spectrum is about 5 m.e.v., and the half-life 12 seconds.

I Fermi and coworkers (4, 43) have observed a 9-second and a 40-second activity in fluorine bombarded with neutrons. Neither is sensitive to hydrogen. 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 11, 57.)

11. Sodium

I Frisch (47) has observed a positron emission with a half-life of 7 seconds, produced in sodium by alpha-particle bombardment. It is doubtless to be attributed to Al^{26}. The upper spectral limit is about 1.8 m.e.v.

IV Lawrence (64) has produced Na^{24} by the deuton bombardment of sodium. Its half-life is 15 hours, and the upper limit of its electron spectrum about 2 m.e.v. It gives off about 1 gamma-ray per disintegration, the energy of the gamma-rays being tentatively given as 5.5 m.e.v.

VII? A 40-second activity found by Fermi (4, 43) in sodium after neutron bombardment is possibly to be attributed to Ne^{23}. (Reference 45.)

VIII A 15-hour half-life for the emission of electrons is found in sodium after neutron bombardment (11, 94) and is due to the same Na^{24} discussed above.

12. Magnesium

I Positrons, known to be emitted from magnesium after bombardment with alpha-particles (26), probably come from Si^{27}. The half-life for positron emission is not known, however (1, 27), because of the fact that the negative electrons emitted are four times as numerous. These come from reaction II. (References 27, 38.)

II Alichanow, Alichanian, and Dzelepow (1) were the first to point out that the measured half-life of about 2.3 minutes for magnesium was that of electron emission. The electrons have a maximum energy of 3 m.e.v. (27, 29), and the radioelement involved is Al^{28}. (Reference 2.)

? Fahlenbrach (41) has found a half-life of 7 or 8 minutes in magnesium bombarded with the alpha-particles of ThC_1, in addition to that of 2.3 minutes mentioned above. This has been confirmed by Eckardt (36). 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 Magnesium, when bombarded with neutrons (4, 43), exhibits a 40-second period which may be tentatively identified with that shown by sodium and attributed to Ne^{23}. (Reference 85.)

VII A 15-hour period observed in magnesium (4, 43) is doubtless to be attributed to Na^{24}.

VIII A weak and water-sensitive period (4, 43) of 10 minutes observed in magnesium 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 (26) is aluminum. The positron emission from this element is due to P^{30}, as has been shown chemically (27). The half-life is about 3.3 minutes, and the upper limit of the energy spectrum is 2.74 m.e.v. Ellis and Henderson (38) have studied the yield of this P^{30} as a function of alpha-particle energy, and find a pronounced flattening beyond 8 m.e.v., this corresponding to the height of the potential barrier of the aluminum nucleus for alpha-particles. (References 2, 27, 40, 74, 80.)

IV Lawrence (64, 73) has reported that bombardment of aluminum with high-energy deutons gives a radioactivity with a half-life of 2.5 minutes, which is without question to be attributed to Al^{28}.

VI Under neutron bombardment, Fermi (4, 43) has found a period of 15 hours excited in aluminum. This he showed chemically to be due to an isotope of sodium, so it is clear that we have again to deal with Na^{24}.

VII Another period for electron emission observed in aluminum bombarded with neutrons is a 10-minute one, which Fermi (4, 43) has shown to be due to an isotope of magnesium, necessarily Mg^{27}. (References 45, 57, 76, 85.)

VIII Aluminum bombarded with neutrons exhibits a period of 2.3 minutes (4), which is quite strong when the aluminum is irradiated under water. This is clearly due to Al^{28}.

14. Silicon

II Fahlenbrach (41) 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-lives.

VII Silicon bombarded with neutrons has been found by Fermi (4, 43) to have a 2.3-minute beta-activity, which has been chemically demonstrated to be due to Al^{28}. (References 28, 45, 76, 85.)

VIII Under neutron bombardment silicon also exhibits a weak and water-sensitive activity of half-life of several hours. This is probably due, according to Fermi (4), to Si^{31}.

15. Phosphorus

I Frisch (47) has reported positron emission from phosphorus bombarded with alpha-particles. Its half-life is about 40 minutes and the upper limit of the energy spectrum about 1.8 m.e.v. The activity has been shown chemically to be due to an isotope of chlorine, doubtless Cl^{34}.

VI Curie, Joliot, and Preiswerk (28) first noticed a decay period of 2.3 minutes in phosphorus bombarded by neutrons, which Fermi (4) has chemically demonstrated to belong to Al^{28}. (Reference 27.)

VII Fermi (4, 43) showed by chemical tests that a 2.4-hour period found in phosphorus bombarded with neutrons was that of Si^{31}. Half-value thickness of the beta-rays in aluminum is 0.15 g. per square centimeter. (References 28, 61.)

16. Sulfur

VII P^{32}, formed in the bombardment of sulfur with neutrons, has been chemically identified by Fermi (43). It has a half-life of 14 days, and the half-value thickness for absorption of the electrons in aluminum is 0.10 g. per square centimeter. (Reference 6.)

17. Chlorine

VI P^{32} may also be formed by bombardment of chlorine by neutrons. (References 4, 6, 43.)

VIII A water-sensitive period of 35 minutes has been shown by Fermi (4) to be due to a chlorine isotope, either Cl^{36} or Cl^{38}. (Reference 3.)

19. Potassium

I Alpha-particle bombardment of potassium gives a positron emitter of a half-life of 3 hours, which Zyw (98) has demonstrated to be an isotope of scandium, probably Sc^{44}.

VIII An induced activity found by Fermi (4) in potassium 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

I Frisch (27) has reported that Sc^{43}, a positron emitter of 4.4-hour half-life, is formed by bombarding calcium with alpha-particles. Half-value thickness is 0.06 g. per square centimeter of aluminum.

VII Hevesy and Levi (59) report having found and identified chemically a 16-hour activity belonging to K^{42}, produced in calcium by neutron bombardment. Fermi, on the other hand (4), using sources of neutrons twice as strong as that employed by the former investigators, finds no activity.

VIII Hevesy and Levi (59) also report a 4-hour activity due to an isotope of calcium. This was not found by Fermi (4).

21. Scandium

VI Hevesy (58) reports that K^{42} was shown by his chemical tests to be the radioelement of 16-hour period formed by neutron bombardment of scandium. The maximum energy of the beta-rays emitted is given as about 1.2 m.e.v.

22. Titanium

? A very weak effect, with a period of a few minutes, was observed by Fermi (43) after neutron bombardment, and may possibly be accounted for by the presence of impurities.

23. Vanadium

VIII The half-value period of the activity (43, 4) produced in vanadium by neutron bombardment is 3.75 minutes; the half-value thickness for the beta-rays is 0.17 g. per square centimeter of aluminum. 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^{52}.

24. Chromium

VII The activity (7, 16) induced in chromium 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.

VIII A water-sensitive activity of 2.5 hours half-life is formed in manganese by irradiation with neutrons; this can be shown chemically to be due to an isotope of manganese, and it must therefore be Mn^{56}. (References 4, 85.)

26. Iron

VII Mn^{56} is formed in the action of neutrons on iron (43, 4). (References 28, 45, 85.)

27. Cobalt

VI Cobalt bombarded with neutrons is transformed into Mn^{56}. (References 43, 4.)

VIII Rotblat (88) has reported a weak and water-sensitive activity in cobalt bombarded with neutrons. This is to be attributed to Co^{60}. The fact that cobalt shows a strong absorption for slow neutrons, this absorption being accompanied by the emission of gamma-rays (4), remains unexplained, since the 20-minute activity found by Rotblat seems too weak to account for the observed slow neutron absorption, while the fact that only one stable isotope of cobalt is known makes it unlikely that radiative capture of slow neutrons to form a heavier stable isotope is the process responsible for the absorption.

28. Nickel

VII The 20-minute activity due to Co^{60} is reported by Rotblat (88) in nickel bombarded with neutrons.

VIII Rotbalt (88) has also found a water-sensitive activity of a few hours' half-life in nickel bombarded by neutrons. It is likely that it is due to Ni^{63}.

29. Copper

IV Lawrence (65) has observed the production of the two radioactive isotopes of copper (Cu^{64}, Cu^{66}) by the bombardment of copper with deutons. This is the heaviest nucleus in which transmutation has been accomplished by means

of artificially accelerated particles.[9] 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 (4); for the long period Bjerge and Westcott (11) report 6 hours. (References 54, 57, 85.)

30. Zinc

VII The long period due to radiocopper (see above) is found in zinc^{59} which has been subjected to neutron bombardment. The active copper has been separated chemically (4) and electrochemically (54). The same remarks apply to the short-period radiocopper. (References 28, 71.)

? McLennan, Grimmett, and Read report a 100-minute period in zinc bombarded with neutrons (70). The origin of this is not known.

31. Gallium

VIII Two half-lives corresponding to neutron capture by the two known isotopes of gallium are observed (4). The stronger is the shorter; its half-life is 20 minutes. Half-value thickness for the beta-rays is 0.17 g. per square centimeter of aluminum. 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 germanium having a half-life of around 2 hours has been reported by Sugden (93). 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. per square centimeter of aluminum (4). (Reference 83.)

34. Selenium

VIII The 35-minute activity (4) produced in this element by irradiation with neutrons has been shown to be due to an isotope of selenium.

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 (4). Half-value thickness for the beta-rays of both radioelements is 0.12 g. per square centimeter of aluminum, and each radioelement emits fairly strong gamma-radiation. (References 3, 14.)

? Recently, Kourtchatow, Kourtchatow, Myssowsky, and Roussinow (62) reported a longer-period activation of bromine by neutron bombardment, which they have shown by chemical tests to be carried by an *isotope of bro-*

[9] This statement must now be modified. Dr. M. G. White has informed one of us that Professor Lawrence and his coworkers have now observed radioactivity, produced by deuton bombardment according to reaction IV, in elements as heavy as platinum. The energy of the bombarding deutons was about 5 m.e.v.

mine. 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 m.e.v., and the energy of the gamma-radiation is about 0.65 m.e.v. The existence of this radioelement has been checked by Fermi (5), 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 bromine 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 is that one of the periods of bromine 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 krypton or selenium, respectively.

37. Rubidium

? Fermi (43) has reported a very weak activity with a period of about 20 minutes in rubidium bombarded with neutrons. Its source is unknown.

38. Strontium

Fermi (4) reports finding no activity after strong neutron irradiation.

39. Yttrium

The large absorption reported by Fermi (4) and by Dunning (33) for slow neutrons in yttrium is now attributed by both these workers to the strong likelihood of contamination of the yttrium sample with a small amount of gadolinium. Only weak and doubtful activity has been found in yttrium strongly irradiated with neutrons.

40. Zirconium

VIII Hevesy and Levi (59) report an activity of 40 hours half-life in zirconium bombarded by neutrons. This they attribute to Zr^{91}. Half-value thickness for the beta-particles is 0.13 g. per square centimeter of aluminum.

41. Columbium

? Strong irradiation with neutrons (4) 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 (43). McLennan, Grimmett, and Read (70) 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

? Kourtchatow, Nemenow, and Selinow (63) report that on bombardment of ruthenium 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 ruthenium 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 (4) 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. per square centimeter of aluminum.

? A longer period of 3.9 minutes (4) is observed (0.10 g. per square centimeter). 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 (4). McLennan, Grimmett, and Read (70) give 14 hours for the longer period. The radioelements are probably isotopes of palladium, whose mass-numbers are not known because of the existence of several stable isotopes of Pd (30).

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 (43). (References 28, 57, 61, 76, 85, 93.)

48. Cadmium

? The great absorption of slow neutrons in cadmium apparently does not correspond to a strong activation. Several weak activities of different periods have been reported by Fermi, but none has been identified (4).

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 55-minute isotope are known to be negative. A third activity of about 3.5 hours was discovered by Szilard and Chalmers (95); it is either not sensitive to water or only moderately so. Fermi (4) has performed experiments which seem to indicate that the two shorter periods of indium are due to radioactive isotopes of indium, so that the radioelement responsible for the 3.5-hour period is not known. This is another case in which alternative positron and electron decay might occur in the case of either In^{114} or In^{116}, so far as the positions of stable isotopes are concerned.

50. Tin

Fermi (4) reports that tin strongly bombarded with slow neutrons remained inactive.

51. Antimony

VIII An activity in antimony induced by neutron bombardment and decaying with a period of 2.5 days has been found by Fermi (4). The half-value thickness for the beta-particles is 0.09 g. per square centimeter of aluminum. Chemical tests have shown the activity to be carried by an isotope of antimony.

52. Tellurium

VIII A weak activity in tellurium irradiated with neutrons has a period of 45 minutes and is water-sensitive. It is probably due to an isotope of Te (4).

53. Iodine

VIII I^{128} is almost certainly responsible for the period excited in iodine by neutron bombardment, as numerous chemical tests have shown. The period is given by Fermi as 25 minutes; half-value thickness is 0.11 g. per square centimeter of aluminum. (References 3, 28, 61, 76, 85, 94.)

54. Cesium

? The half-life of a weak activity produced by neutron bombardment of cesium has been given by McLennan, Grimmett, and Read as 75 minutes (71). Fermi (43) indicates that other periods may exist.

56. Barium

? A weak activity found by Fermi in barium after neutron bombardment has a period of 5 minutes and is not water-sensitive. Its identity is not known (43).

VIII A water-sensitive 80-minute period has been shown by chemical tests to be due to an isotope of barium. It is no doubt Ba^{139} formed by neutron capture (4).

57. Lanthanum

VIII Although Fermi has been unable to find any activity in lanthanum irradiated with neutrons (4), Sugden (69) reports an activity of half-life of 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 (69) and Fermi (4) agree in finding no activity in cerium after neutron bombardment.

59. Praseodymium

VIII Fermi (43), Sugden (69), and Hevesy and Levi (60) agree in finding a 19-hour period which is water-sensitive and doubtless corresponds to neutron capture in praseodymium. Half-value thickness for the beta-rays is 0.12 g. per square centimeter.

? An activity of 5 minutes half-life was early reported by Fermi (43). It is not water-sensitive, and its carrier is not known.

60. Neodymium

? Fermi (43) reports a very weak activity of 1 hour half-life in this element, which was not found by Sugden (69) but was found by Hevesy and Levi (60).

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 (43), and confirmed by Sugden (69), and by Hevesy and Levi (60). In addition, Sugden reports a much longer period. The identity of the radioelement 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 (69, 93) and confirmed by Hevesy and Levi (60). Half-value thickness for the beta-particles is 0.11 g. per square centimeter.

64. Gadolinium

? Although this element absorbs slow neutrons very strongly, only a very weak activity has been found by Fermi (43) and Hevesy and Levi (60). The period was 8 hours. Since Sugden (69, 93) found no activity, the possibility of europium contamination of the former authors' gadolinium samples should be borne in mind.

65. Terbium

VIII The 3.9-hour activity discovered by Sugden (69, 93) and confirmed by Hevesy and Levi (60) 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 dysprosium. The reaction is strongly water-sensitive, and no doubt is due to Dy^{165}. This radioelement has been investigated by Hevesy and Levi (60) and by Marsh and Sugden (69). Half-value thickness for the emitted electrons is 0.07 g. per square centimeter of aluminum.

67. Holmium

VIII Hevesy and Levi (60) 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 (69) that carefully purified holmium, free from dysprosium, exhibited a period of 2.6 hours, since it may so readily have

been caused by contamination of the holmium with a few hundredths of a milligram of dysprosium. The intensity of the 35-hour period is very high, and the half-value thickness of aluminum for the beta-particles is 0.11 g. per square centimeter. The radioelement is Ho^{166}.

68. Erbium

? Reports on the neutron-produced radioactivity of this element are in conflict. Marsh and Sugden (69) report periods of about 7 minutes and 1.6 days, the latter being about ten times as intense as the former. Hevesy and Levi (60), 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 (69) and Hevesy and Levi (60) are in agreement in finding an activity of 3.5-hours half-life in ytterbium 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 (60) report an activity induced in lutecium by neutron bombardment whose period is about 5 days. Marsh and Sugden (69) report finding a 4-hour period, and no other.

72. Hafnium

VIII Hevesy and Levi (59) have reported an activity with a half-life of several months to be excited in hafnium by neutron bombardment. This is probably a reaction involving neutron capture, the radioelement being Hf^{181}. This is the longest period reported to date.

73. Tantalum

? Fermi (4) reports having found only a dubious activity after 12 hours' irradiation of tantalum with 500 mc. of radon–beryllium. This is confirmed by McLennan, Grimmett, and Read (70).

74. Tungsten

VIII Fermi (4) found an activity excited in tungsten by neutron bombardment. It is water-sensitive and the carrier of the activity has been chemically shown to be a tungsten isotope. McLennan, Grimmett, and Read (70) give 25 hours for the period.

75. Rhenium

VIII Fermi (4) discovered a water-sensitive activity produced in rhenium by neutron bombardment, and showed chemically that it is borne by an isotope of rhenium. Half-life is 20 hours, and the emitted beta-particles are half absorbed in 0.12 g. per square centimeter of aluminum.

76. Osmium

Fermi (43) found that this element, irradiated 15 hours with 450 mc. of radon–beryllium, was inactive.

77. Iridium

VIII A 19-hour period reported by Fermi (4) in iridium bombarded with neutrons is much enhanced by water, and is probably due to an isotope of iridium. Sosnowski (91), 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 (4) found a very weak 50-minute activity in platinum bombarded with neutrons. The half-life, according to McLennan, Grimmett, and Read (70), is 36 minutes. Sosnowski (90) reports a half-life of 100 minutes.

79. Gold

VIII Fermi (4) found a water-sensitive period of 2.7 days in gold bombarded by neutrons. The half-value thickness for the beta-rays, which have been shown to be electrons, is 0.04 g. per square centimeter of aluminum. The radioelement is doubtless Au^{198}. Sosnowski (89) 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 a consequence of the very weak initial intensity of his gamma-rays. (References 76, 85.)

80. Mercury

Fermi (4) has failed ts find any activity after strong irradiation with slow neutrons, in spite of the large absorption (see section VIII) shown by mercury for slow neutrons.

81. Thallium

? McLennan, Grimmett, and Read (71) report an activity with a 97-minute half-life to be produced in the bombardment of thallium with neutrons.

82. Lead

No activity has been found by Fermi (4) after neutron bombardment.

83. Bismuth

? A weak activity of 100-minute period observed by Sosnowski (92) in bismuth bombarded with neutrons must be regarded as doubtful, as it has been denied by Fermi (4), and by McLennan, Grimmett, and Read (71). Bismuth 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 bismuth was regarded by Sosnowski as being a case of nuclear isomerism.

90. Thorium

Fermi (4) reports periods of 1 minute and 24 minutes in thorium bombarded with neutrons, and states that these activities are "scarcely sensitive to water."

Hahn and Meitner (53) 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 an isotope of thorium. 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 minutes, Th^{233}.

Curie, v. Halban, and Preiswerk (25) report that activities of half-lives of 1 minute, 15 minutes, 25 minutes, and 3.5 hours are produced on neutron bombardment of thorium. The 25-minute activity is due to an isotope of thorium, 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 thorium, polonium, radium, or uranium, but behaves like lanthanum, and is hence probably an isotope of actinium. They agree with Hahn and Meitner that the 1-minute activity is probably due to an isotope of radium. In a later communication, the same authors have chemically shown that the activity of 1-minute period is due to an isotope of radium, and have found an isotope of polonium 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 46.)

92. Uranium

Fermi (4) has found periods of activity, induced in uranium by neutrons, of 15 seconds, 40 seconds, 13 minutes, and 100 minutes. The reactions creating all these radioelements, save the one of 40-seconds 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 (52) 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 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 von Grosse (49).

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