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The American Association for the Advancement of Science:
Nuclear Chemistry, the Neutron and Artificial Radioactivity: PROFESSOR WILLIAM D. HARKINS 533
Obituary:
Charles Velmar Green: C. C. L. 543
Scientific Events:
The British National Human Heredity Committee; The Summer Symposium on Theoretical Physics at the University of Michigan; National Research Fellowships in Physics, Chemistry and Mathematics; Award of the Chandler Medal to Professor Giauque; In Honor of Professor Osborn; Award of the Two Hundred and Fifty Thousandth Bausch and Lomb Microscope to Professor Novy 543
Scientific Notes and News 547
Discussion:
Is Geology a Science?: DR. CHESTER K. WENTWORTH. *A Plea to Publishers of Scientific Books:* M. GRAHAM NETTING. *Notice of Possible Suspension of Rules of Nomenclature in Certain Cases:* DR. C. W. STILES 550
Scientific Books:
The Migrations of Animals: DR. ROBERT CUSHMAN MURPHY. *North American Fossils:* PROFESSOR B. F. HOWELL. *A Book of Wonder Plants:* DR. FREDERICK V. COVILLE 553
Societies and Meetings:
The Southwestern Division of the American Association for the Advancement of Science: VEON C. KIECH. *The Minnesota Academy of Science:* PROFESSOR H. K. WILSON. *The Ohio Academy of Science:* WILLIAM H. ALEXANDER 555
Reports:
Report of the President of the National Research Council of Canada 556
Special Articles:
Synthesis of Substances of Possible Physiological Activity: PROFESSOR L. F. FIESER and OTHERS. *Potassium: A Basal Factor in the Syndrome of Corticoadrenal Insufficiency:* PROFESSOR R. L. ZWEMER and DR. RICHARD TRUSZKOWSKI. *Dietary Production and Prevention of Anemia in Larval Amblystoma:* ESTHER M. PATCH 558
Scientific Apparatus and Laboratory Methods:
Differential Staining of Thick Sections of Tissues: MADELINE KNEBERG. *A Convenient Resistance for Determination of Redox Potentials in Biological Fluids:* MONROE E. FREEMAN 561
Science News 10

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NUCLEAR CHEMISTRY, THE NEUTRON AND ARTIFICIAL RADIOACTIVITY[1]

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(1) INTRODUCTION

NUCLEAR chemistry is just a decade old, yet it is now the most active of all the special branches of science. Nuclear reactions are very similar to ordinary chemical reactions, except that they deal with matter which is a million million times more dense than ordinary matter, and on this account the forces are extremely high and the energies involved are a million times greater than those of ordinary atomic chemistry.

[1] Address presented before Section C of the American Association for the Advancement of Science, and the St. Louis Section of the American Chemical Society, St. Louis, January 1, 1936. The section on deuterium (heavy hydrogen) has been omitted, and in its place an abstract of a paper "Deuterium as a Reagent in Nuclear Chemistry" presented at the April meeting of the American Chemical Society, has been substituted.

The purpose of this address is to outline some of the nuclear work done at the University of Chicago and especially to emphasize the point of view developed during the last few years, which is that only reactions of the chemical type occur among nuclei. Thus atoms may be artificially synthesized, but not artificially disintegrated.

Thus when two atomic nuclei meet they first combine to form a new nucleus, which on account of its large content of energy is unstable and therefore has a life which is short in large scale time, but not excessively short on a nuclear time scale. This intermediate product nucleus may then disintegrate in any one of a number of ways, which depend upon the nature and state of the metastable nucleus. Thus the disintegration is a step separate from the synthesis which precedes it.

(2) Mass, Energy and Fundamental Particles

The most obvious property of matter is mass. According to present theory all substances are built up from four fundamental particles: the proton, the neutron, and the negative and positive electron. There is, in addition, another particle, the little neutron, or neutrino, which is supposed by current theory to play a part in nuclear chemistry, but no definite evidence of its existence has been obtained.

TABLE I

Elementary Particles

One unit of Mass = 1.65×10^{-24} gram

Particle	Charge	Mass	Spin
Proton	Unit +	1.0075	½
Neutron	Zero	1.00856	½
Negative electron	Unit −	0.00055	½
Positive electron	Unit +	0.00055	½
Neutrino	Zero	Very small	½
Photon	Zero	Varies as frequency	0
(b) Light nuclei used as projectiles			
Deuterium or Heavy Hydrogen	Unit +	2.0142	1
Helium	+ +	4.0034	0

According to Einstein mass (M) and energy (E) may be considered as identical, so the equation

$$E = M$$

may be used. Since, however, it is customary to express energy and mass in different units, a conversion constant, found to be the square of the velocity of light (c^2), must be used with such units, or

$$E = c^2M = 9 \times 10^{20}$$

Thus a weight of one gram contains an energy of 9×10^{-20} ergs.

This equation was used by Swinne (1914) to calculate the mass lost in radioactive disintegrations, and by Harkins and Wilson (1915) to calculate the energy liberated by a nuclear reaction of hydrogen. The energy liberated by one pound of hydrogen, when it unites with a heavier atom was found by them to be of the order of a million times greater than that of a chemical reaction of atoms, since it was found to give as much heat as the burning of ten thousand tons of coal.

The photon is a particle assumed in the modern corpuscular theory of light. Its mass is a constant $\left(\frac{h}{c^2}\right)$ times the frequency (ν) of the light. When the energy of the photon is very high, as it commonly is when emitted by a radioactive substance, it is designated as a γ-ray. The mass of a γ-ray of high energy has recently been found to be as high as 0.010, and in experiments on lithium it has been claimed that a mass of 0.017 has been observed. Thus the remarkable result has been obtained that "particles" of light have been discovered which have a mass twenty (possibly even thirty) times greater than that of an electron at rest. This gives the peculiar relation that the mass associated with a unit of light may be greater than that of a material particle.

(3) Fast Atoms

Atoms of helium are shot out from radioactive substances with velocities as high as 12,800 miles per second. These fast atoms pull at least one negative electron from each atom through which they pass. The result is that the track of every fast atom is defined in a gas by a sharp line of many thousands of positive and negative ions. Now in 1911 C. T. R. Wilson found that if the gas is supersaturated with water vapor, each ion becomes the center of a minute water droplet. If a brilliant light shines through the gas the track of the atom becomes visible as a fine bright, continuous line of white fog or cloud, and almost always such a line is straight.

The tracks of electrons, except those from cosmic rays, are, on account of the small mass of the electron, very crooked, and dotted, that is non-continuous. The track of a hydrogen atom (charge +) is straight, but commonly only about one fourth as broad as that produced by a helium atom (charge ++).

By means of photographs of these Wilson cloud or fog tracks the characteristics of fast atoms may be determined and in Table II these are compared with those of slow atoms.

TABLE II

Behavior of Slow and Fast Atoms of Helium in Air

Slow atoms, velocity 7/10 mile per second	Fast atoms, velocity 10,000 miles per second
1. Average velocity constant over large intervals of time.	1. Velocity decreases with extreme rapidity.
2. Deflected several times in each smallest microscopic region.	2. Move several inches in a straight line until velocity is lost.
3. Collides with another atom on average each $\frac{1}{300,000}$ inch.	3. Would need to travel about a mile to give a sharp collision.
4. Apparent diameter 2×10^{-8} cm.	4. Apparent diameter 7×10^{-13} cm.

Thus atoms at very high relative velocities behave in their relations toward collision as though they are extremely small in comparison with slow atoms. Thus a fast atom acts as if it has a diameter ten thousand times, an area a hundred million times and a volume a million million times smaller than a slow atom.

(4) THE NUCLEUS

These anomalous relations are explained very simply by the theory of Rutherford. This considers that in slow collisions the outer parts of the two atoms come in contact. At high relative speeds the atoms pass through each other (not, however, without a partial loss of individuality), but collisions occur only when their dense central portions, called nuclei, happen to meet. The nucleus of the atom as so defined has a diameter about one ten thousandth that of the atom as a whole. A cubic centimeter of lightly packed nuclei would thus weigh about ten million tons, or a thimble could contain the material of a hundred battleships. This illustrates the great density of material in nuclei.

The outer part of the atom according to this current style of theory is an aura or cloud of relatively tenuous nature which consists entirely of negative electrons.

The number attributed to this cloud, commonly called the number of electrons in the neutral atom, determines the chemical and physical behavior of the material made up of these neutral atoms or what is considered as an element. The same number gives the position of the element in the ordinary periodic system of the elements.

Thus in the most abundant of all atoms, that of the most common kind of oxygen, there are eight negative electrons in the non-nuclear aura, and, if the atoms are to be neutral, there must be a charge (Z) equal to that of 8 electrons, but positive, on the nucleus.

(5) THEORY OF THE COMPOSITION OF ATOMIC NUCLEI

In 1923 the writer suggested that all atomic nuclei have a composition represented by the formula

$$(np)_Z\, n_I$$

Where n is a neutron with a zero charge, p is a proton with a single positive charge, so Z is the number of positive charges in the nucleus as a whole. The values of Z (atomic number) range from 0 to 92 (-1 is included for the negative electron), and I (isotopic number) varies from -1 to 54.

For ordinary oxygen the value of Z is 8 and that of I is zero, so the oxygen nucleus consists of 8 neutrons and 8 protons.

The mass of this oxygen atom is 16 by *definition.* Each non-nuclear electron has a mass of 0.00055, so the mass of the nucleus is 15.99945, and the average mass of a neutron or proton is 0.999725. In the free state a proton has a mass of 1.0075, and a neutron of 1.0085, as nearly as is known.

Thus if 8 neutrons and 8 protons could be packed together into an oxygen nucleus they would lose 0.82 per cent. of their mass. This is called the packing effect.

It is simpler, and gives the same numerical result, if it is considered that eight neutrons and eight hydrogen atoms give a complete atom of oxygen. Thus 8 neutrons each when free of mass 1.0085 and 8 hydrogen atoms of mass 1.00807 are present in an oxygen atom of mass 16.0000, or the packing effect is 0.8217 per cent. That is 1/122 of the mass of the initial particles has been lost as energy. It must not be supposed that such a complicated reaction as this can be made to take place in a single step.

Nearly all atoms, except the lightest, have masses which are expressed with moderate accuracy as whole numbers. The light atoms—neutrons, atoms of hydrogen, heavy hydrogen, lithium, beryllium and boron—have masses in which the decimal fraction may rise as high as 0.014. Thus if two light atoms were to form an atom heavier than oxygen, in general the mass expressed by the decimal would disappear as ordinary mass of the atom which is formed. If, however, a light atom is formed its decimal mass must be given to it. Atoms of high decimal mass undergo reactions more readily in general than those of low decimal mass. Thus beryllium of mass 9.*0136* undergoes nuclear reactions in general much more readily than oxygen of mass 16.*0000,* since it contains more available energy.

(6) HYDROGEN FROM NITROGEN

The first artificial transmutation of atoms was obtained by Rutherford, who in 1919 formed hydrogen from nitrogen. The apparatus which he used was extremely simple, since it consisted of a spinthariscope, invented by Sir William Crookes (1903). A radioactive salt or deposit on a piece of metal sends alpha particles against a screen of zinc sulphide, which gives bright scintillations, but not at distances greater than the range of the α-particles, which in general is not over 8.6 cm in air. In nitrogen, however, the scintillations were visible at distances as high as 28 cm, which indicated that a lighter particle, assumed and later proved to be hydrogen, was emitted. Rutherford therefore assumed that the nitrogen nucleus is disintegrated to give hydrogen and carbon by the blow delivered by the helium atom, which immediately escapes.

$${}_7N^{14} \rightarrow {}_6C^{13} + {}_1H^1$$

This is just as though in a collision of two billiard balls one of them should break into two pieces.

(7) NUCLEAR CHEMISTRY

This is called "nuclear disintegration without capture." To reveal the details of such an event it was essential to adopt a more refined experimental method. That suggested and used by Harkins and Ryan was to take as a source of high speed helium atoms a deposit of thorium C′, which gave the fastest known atomic projectiles. These are helium atoms with an initial velocity of 0.0688 that of light, or 12,800 miles per second. Such an atom has an energy of 8.761 million volts. These atoms were allowed to shoot into nitrogen at about atmospheric pressure in a Wilson Cloud Chamber, and the tracks were photographed. The first twenty thousand photographs did not show a single disintegration, but further thousands of photographs, by the use of exactly this method, were taken by Blackett in Cambridge and Harkins and Shadduck in Chicago. These showed that the earlier interpretation of Rutherford's experiment was erroneous, since the photography demonstrated that the projectile was captured.

Thus the primary action was found to be the formation of a new atom. The reaction is exactly analogous in form to those most commonly found in chemistry in which A and B react to form C and D.

For example:

$$\underset{\text{Nitrogen}}{{}_7N^{14}} + \underset{\text{Helium}}{{}_2He^4} \rightarrow \underset{\text{Fluorine}}{{}_9F^{*18}} \rightarrow \underset{\text{Oxygen 17}}{{}_8O^{17}} + \underset{\text{Hydrogen.}}{{}_1H^1}$$

This indicates that the primary action is the union of nitrogen and helium to form fluorine. The fluorine atom, however, contains the energy of not only the mass of the nitrogen and the helium atoms, but also the kinetic energy of the helium atom. This is more energy than represents a stable state of an atom of fluorine, so this "excited" nucleus disintegrates into an atom of oxygen and one of hydrogen which fly off in two different directions.

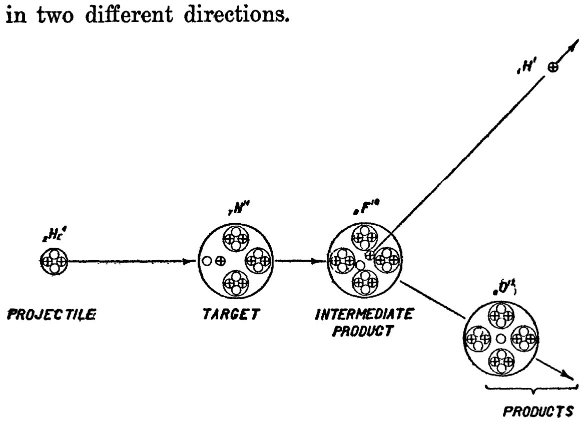


FIG. 1. A helium nucleus strikes the target nucleus of nitrogen and unites with it to form an intermediate fluorine nucleus. This moves at high speed and finally disintegrates after a short life into hydrogen and oxygen. In this case the oxygen nucleus is stable but often such a nucleus is unstable and a second disintegration ensues. If the projectile is a proton and the target carbon of mass 12 the intermediate product nitrogen 13 has a life of 10.5 minutes and the final products are carbon 13 (instead of oxygen 17) and a negative electron (instead of hydrogen ${}_1H^1$).

Thus this reaction was proved to be a disintegrative synthesis, or disintegration by capture, instead of a pure disintegration or disintegration without capture.

The discovery of this reaction gave birth to nuclear chemistry.

(8) Atoms Disintegrate Only by Use of Their Own Internal Energy

In natural radioactivity an atomic nucleus suddenly disintegrates into two parts, which fly apart at high velocities. Thus a radium nucleus disintegrates into a helium nucleus and a radon nucleus.

$$\text{Radium} \rightarrow \text{Helium} + \text{Radon}$$

The kinetic energy of the helium and radon atoms comes from the internal or mass energy of the radium nucleus.

As many as five helium nuclei may be emitted in succession in five steps, in each of which a nucleus splits into two parts. It is probable that when by "artificial disintegration" the nucleus seems to split into three or four particles, the disintegration more frequently occurs in steps in which two particles separate in each step, with a short life for each intermediate metastable atom.

Until 1933, while as indicated in the last section it had been known for some years that many disintegrations occur by capture, it was believed that many others occur by non-capture. In this year, however, Harkins and Gans developed the mechanics of disintegration without capture, that is the simple physical type of disintegration, and were able to show that such disintegrations do not occur, that is, in all artificial disintegrations the energy is transmitted to the nucleus, for example, that of fluorine, only when the projectile is captured, as follows:

$${}_9\text{Fluorine}^{19} + {}_0\text{Neutron}^1 \rightarrow {}_9\text{Fluorine}^{*20} \rightarrow {}_7\text{Nitrogen}^{16} + {}_2\text{Helium}^4$$

and not

$${}_9\text{Fluorine}^{19} \rightarrow {}_7\text{Nitrogen}^{15} + {}_2\text{Helium}^4$$

Thus this disintegration is, like those of natural radioactivity, brought about by the high internal en-

TABLE III

Projectile	Product	
α-particle	Primary from AB* Proton or Neutron	Secondary from C* + electron – "
Proton	α-particle, deutron, + electron	+ electron
Neutron	α-particle, proton, – electron	– electron
Deuteron	α-particle, proton, neutron, H^3	+ electron – electron

ergy (mass) of the fluorine nucleus of approximate mass 20. This atom contains not only the masses of the initial fluorine atom and of the neutron, but in addition all the mass it obtains from the kinetic energy of the neutron.

A summary of all known nuclear reactions gives the relations between the projectile and the products of disintegration, as shown in Table III.

An attempt has been made to obtain some information in regard to the life period of the intermediate nucleus AB* when massive particles are emitted. It is well known that in the reaction

$$ {}^{0}_{6}C^{12} + {}^{-1}_{1}H^{1} \rightarrow {}^{-1}_{7}N^{*13} \rightarrow {}^{1}_{6}C^{13} + {}^{-2}_{-1}\varepsilon^{0} $$

where ${}^{-2}_{1}\varepsilon^{0}$ is the positive electron, the intermediate nitrogen nucleus has a half life of about 10.3 minutes. For cases in which an α-particle is emitted by a fast neutron the writer has been able to show that the total life does not exceed 10^{-7} seconds, but has not been able to determine the actual value of the life period, which probably lies between 10^{-7} and something of the order of 10^{-17} to 10^{-19} or 10^{-20} seconds. It may be assumed that the period depends upon the structure of A, B, AB*, the nature of the products of the disintegration of AB*, and that it decreases, in general, with the velocity of the projectile B.

The idea that the synthesis, and not the disintegration, is the primary action, changes the view-point in connection with the nuclear stability. For example, the oxygen 16 nucleus, when used as a target, gives in general the smallest variety of disintegrations of any of the light nuclei. Also, carbon 12 gives an even smaller number of disintegrative-synthesis than oxygen with fast neutrons from beryllium and thorium C′. Thus the oxygen nucleus, with 8 neutrons and 8 protons, seems to be specially complete or stable with reference to the addition of other particles, and carbon, with 6 neutrons and 6 protons, toward the addition of a neutron. If, however, such additions occur, there is usually for the addition product some type of disintegration which gives a favorable energy balance. The importance of the synthesis has been emphasized by the specific action between slow neutrons, and certain nuclei, such as those of boron, cadmium and silver (also gadolinium), since these nuclei have a peculiarly great affinity, presumably due to resonance, for neutrons at certain low velocities. This is said to be due to the wave characteristics of the system.

The simplest assumption which can be made concerning the capture of the projectile, and the subsequent disintegration, is that the part of the energy which does not remain as, or change into, kinetic energy is largely transformed, provided the nucleus is analogous to a molecular system, into vibrational energy of the parts of the intermediate nucleus AB*, although some of it may be stored in the potential form.

While it may not be essential at the present time to know what particles in the nucleus are vibrating, it is nevertheless interesting in connection with the development of a more refined theory. As a preliminary measure it may be assumed that the vibrating particles are only protons, and neutrons, *e.g.,* 8 of each in the oxygen nucleus. Even on this assumption the emission of an α-particle seems probable from the energy standpoint alone, since usually 4 or 5 million e-volts more energy is required for the emission of a proton or a neutron, on account of the mass relations. However, the problem arises as to how the energy necessary for emission is to be transmitted to the two particular protons and neutrons which are emitted.

There are several types of evidence which indicate the probability that groups with a mass of 4, which may consist of 2 protons and 2 neutrons, or more rarely of 4 neutrons (possibly 2 pairs of neutrons) exist to some extent in such nuclei. These may be designated as α-groups, with a mass of 4, and a charge of 2, with more rarely a charge of zero.

Thus (1) the abundance of atoms of an approximate mass 4 m and a charge 2 m, where m is a whole number, is very much greater, up to atomic number 30, than all other types of atoms; (2) the atomic masses indicate that such nuclei are the most stable, that is, they exhibit the smallest values of M/m, where M is the exact atomic mass; (3) the relations of disintegrative syntheses themselves give some support to this theory.

In some reactions, as in the first of these two:

$$ {}_{5}B^{11} + {}_{1}H^{1} \rightarrow {}_{6}C^{*12} \rightarrow 3\,{}_{2}He^{4} \qquad (1) $$

$$ \text{or} \rightarrow {}_{4}Be^{8} + {}_{2}He^{4} \qquad (2) $$

three, instead of two particles are given as distintegration products, because energy is liberated by such a reaction, while an absorption of energy would accompany any other two-particle disintegration. Probably reaction 2 is commonly the first step in (1). Usually, however, the input of energy increases with the number of particles emitted, so in general increase of kinetic energy of the projectile favors an increase in the number of particles. Cosmic ray projectiles, with energies up to 10^{11} volts, have enough energy to cause the nucleus to split into a large number of particles.

As an example let a deuteron be added to a nitrogen nucleus. This would give, neglecting the kinetic energy of the deuteron, an excess of 20.5 million e-volts in the intermediate oxygen nucleus 0^{*16}. This would be sufficient energy to dissociate this into helium and carbon, which requires 5.6 million e-volts, into 4 helium atoms, (which uses up 12.5 million), into a proton and nitrogen 15 (also 12.5 millions), but is very far from being able to supply the 124 million e-volts necessary for complete conversion into protons and neutrons. This last process would also in general involve supplying a much larger amount of kinetic energy.

(9) Negative and Positive Electrons

Negative and positive electrons have the same mass, about 1/1830 that of a hydrogen atom, but differ in having opposite charges, though these have the same magnitude. The most remarkable difference is that negative electrons make up the outer part of all atoms (except neutrons, which are bare nuclei), while positive electrons seem to have only a very temporary existence.

Positive electrons were discovered by Carl Anderson (1932) in cosmic rays in which they occur in not very different numbers from negative electrons.

Theories of the atom leave no place for the existence of positive electrons inside atoms, but such electrons are known to come out of atoms. Thus in the nuclear reaction

$$A + B \rightarrow AB^*$$

if AB^* has a low isotopic number (I), such as -1, it may have a moderately short life (as 10 minutes) and lose its instability by the loss of a positive electron. In this case the atomic number decreases by one (nitrogen changes to carbon) and the isotopic number increases by 2.

Commonly, however, AB^* will dissociate into two nuclei C^* and D. If C^* is excited, it may lose either a negative electron (if I is relatively high) or a positive electron if I is relatively low, as compared with the value of I in the band of high stability.

If a positive electron is found to be emitted from an atom, a proton in the nucleus changes into a neutron

$$p \rightarrow n + \varepsilon^+$$

while if a negative electron comes out from the nucleus a neutron changes to a proton inside the nucleus.

$$n \rightarrow p + \varepsilon^-$$

If a positive and negative electron meet they mutually annihilate each other's charge, and the energy goes off as a photon or γ-ray with a mass of .00110 or the mass of two electrons, that is the energy of the γ-ray is $.00110 \times .93 \times 10^9$ volts, or one million volts.

A γ-ray of a million volts energy may in a nuclear electrical field be transformed into a positive and a negative electron. The reactions are

$$\varepsilon^+ + \varepsilon^- \rightarrow \gamma$$
$$\gamma \rightarrow \varepsilon^+ + \varepsilon^-$$

Thus particles may change into light and light into particles.

No one has as yet been successful in causing either a positive or negative electron to unite with any atomic nucleus.

Although either negative or positive electrons are produced in nuclear reactions, neither of them is supposed to exist in any nucleus. While a proton may give birth to a positive electron, and a neutron to a negative electron, neither the proton nor the neutron is supposed to contain an electron.

According to classical theory, an electron has a diameter 2,000 times larger than a proton, and modern theory, while it does not directly accept this idea, does implicitly assume that an electron is too large to be present in either a proton or a neutron, and is thus not found in any nucleus.

(10) Success and Failure of Helium as a Nuclear Projectile

Protons, neutrons, deuterons heavy hydrogen nuclei), and helium nuclei (α-particles) are now used as nuclear projectiles for the disintegrative-synthesis of atoms. Of all these the α-particle has the highest positive charge, that of 2. Since the repulsion between nuclei varies as the product of the charges, and inversely as the square of the distance, the repulsion is equal to a constant times $\frac{2Z}{r^2}$ where Z is the atomic number of the other nucleus.

The highest energy of α-particles found from radioactive substances is 8.761 million e-volts, which has been found insufficient to cause the α-particle to penetrate nuclei of charge higher than 19, that of potassium, often enough to give a detectable number of disintegrations. A very few faster α-particles are actually emitted, but their number is too small to be effective in this sense.

The energy necessary to cause a nuclear projectile to strike another nucleus is greatly reduced if instead of an α-particle, a nucleus of an atom of light hydrogen (a proton) or of heavy hydrogen (a deuteron) is used, since each of these nuclei has a unit charge, and the repulsion force between the two nuclei at any given distance is reduced to one half. This also reduces to one half the energy necessary for the projectile to reach any definite distance (r) from the other nucleus.

Thus protons of the same energy as α-particles are able to penetrate nuclei of much higher atomic number. However, with the energy now available they are not able to disintegrate nuclei of very high charge.

(11) The Neutron

The question may be asked: if even ten million volts of energy is not sufficient to shoot any positively charged particle into a heavy nucleus, then how can heavy nuclei be built up from the lighter ones? A very simple answer to this question was given by the writer (April, 1920) by the assumption of the existence of atoms of zero nuclear charge, or neutrons, with a unit mass equal approximately to that of a hydrogen atom, and of heavier neutrons, particularly the double neutron, which were supposed to be present in other nuclei.

It was predicted that neutrons would contain no non-nuclear electrons, and would have no chemical, and almost none of the ordinary physical properties, aside from mass. It was considered that they would pass readily through the outer part of atoms, and through the region close to the nucleus in which α-particles are repelled, and attach themselves to the nucleus. Thus they were supposed to not be affected by what is now considered as the potential wall toward positive particles.

In addition it was assumed that isotopic atoms are formed by the addition of the neutron. This prediction has received recent confirmation by Fermi.

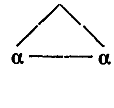
These predictions, including as they do the effects of neutrons in nuclear synthesis, cover all the important properties of neutrons, found within two years of the discovery of the existence of the neutron. Somewhat similar predictions were made two months later by Rutherford.

That the beryllium nucleus consists of two α-particles (helium nuclei) and one neutral nuclear particle, or neutron, was a part of the theory of nuclear composition developed by Harkins and Wilson (1915). Thus the beryllium nucleus should have, according to the simple theory, a mass of 8, but atomic weight determinations gave it the mass of 9. According to this theory the atomic weight of an element of even number should be a multiple of 4, since their nuclei were supposed to be represented by the formula $\alpha_{z/2}$, that is of a number of α-particles equal to half the atomic number.

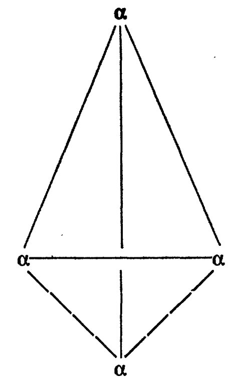
Thus the atomic weights should be:

α	α_2	α_3	α_4	α_5	α_6	α_7	α_8	
4	8	12	16	20	24	28	32	etc.
	Helium	Beryllium	Carbon	Oxygen	Neon			
		Magnesium	Silicon	Sulphur				

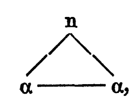
All these are correct except in the case of beryllium. This suggested the theory that a combination of two α-particles α-α is unstable, but



or



etc., stable. That is 3 particles or more are essential for stability. To change 8 to 9 and keep the charge constant a neutron must be added. Thus it was supposed that the system α_2 could be stabilized as in carbon by adding a third α-particle, but in beryllium the only possibility would be the addition of a neutron to form



or the ordinary formula for beryllium is α_2n. From this point of view a beryllium nucleus is a carbon nucleus in which one α-particle has been replaced by a neutron.

When beryllium is bombarded by α-particles from polonium radiations of the γ-ray type seem to appear, as was discovered by Bothe and Becker (1930). It was found by Curie and Joliot that the radiation formed in this way, if it is allowed to strike paraffin, or another material which contains hydrogen, ejects very fast protons, with ranges up to 26 cm in air, which corresponds to a velocity of nearly 3×10^9 cm per second, or one tenth the velocity of light. The energy is 5.7 million volts.

They suggested that the photons of the γ-rays strike the protons and by a process similar to the Compton effect, transfer energy to the protons. It was found that to do this the energy of the γ-rays must be 50 million volts, or an altogether surprising amount of energy since it is nearly 20 times larger than that of the most energetic rays from radioactive materials.

According to current opinion at the time, this was much more energy than could be released from the beryllium or any other atom when struck by an α-particle with an energy of five million volts.

If, however, it is assumed that the projectile which propels the proton forward is not a photon, but an atom, then the energy of this atom could be very much less. The natural assumption that the atom released from the beryllium nucleus is a neutron was made by Chadwick (1932) who very quickly, by a remarkable set of experiments, demonstrated that his assumption is justified. This would mean that the neutron is released by the following reactions:

$$\underset{\text{Beryllium}}{{}_4Be^9} + \underset{\text{Helium}}{{}_2He^4} \rightarrow \underset{\text{Carbon}}{{}_6C^{12}} + \underset{\text{neutron}}{{}_0n^1}$$

Since the mass of the neutron was supposed to be equal to that of the proton, the maximum velocity of the protons should be equal to that of the neutrons or 3.3×10^9 cm per second. Suppose now that these particles, supposedly neutrons, are shot into nitrogen. It is possible to calculate the maximum velocity which should be given by a head-on collision of neutron of mass 1 against a nitrogen nucleus of mass 14. This is found to be 4.4×10^8 cm per second, or an energy of 1.4 million volts, and a range of 3.3 mm in air. Photographs in nitrogen by Feather showed tracks of this length, in agreement with the assumption of the existence of a neutron.

It is possible to calculate the mass of the particle which would give these results. If m and v are the mass of the neutron, then since 1 and 14 are the masses of the proton and nitrogen nucleus respectively: the velocity of the proton

$$u_p = \frac{2m}{m+1} v$$

and of the nitrogen atom

$$u_N = \frac{2m}{m+14}$$

or

$$\frac{m+14}{m+1} = \frac{u_p}{u_n} = \frac{3.3 \times 10^{19}}{4.7 \times 10^9}$$

or

$$m = 1.15$$

That is, the result obtained from the early experimental work was that the mass of the neutron is 1.15 times that of the proton, while the most recent value of this ratio is 1.002.

(12) Properties of Neutrons

The most striking properties of neutrons are just those predicted in 1920, *i.e.,* first the ability at high velocities to penetrate very much greater distances through matter than any other atoms; second, notwithstanding this, to set other atoms in motion, and third, to unite readily with the nuclei of other atoms.

Neutrons dissipate their kinetic energy by collisions with atomic nuclei, while on the average charged nuclei such as fast protons, helium nuclei, etc., lose almost their entire energy by the work done in removing electrons from other atoms. This causes a great difference in their ranges. Thus with a velocity of 3×10^9 cm per second an α-particle travels about a foot in air, a hydrogen nucleus about the same distance, while a neutron goes about a quarter of a mile before it experiences a sharp collision with another atom, and may travel several miles before its velocity is reduced to that of ordinary molecules. The extremely great range of the neutron is due to its lack of any electrical charge. Its range indicates that while it collides with a nucleus much more often than with an electron, the nuclear collision is itself a rare event. Fast neutrons pass easily through a thick wall of metal, or of stone if the stone contains no water.

(13) Fast Neutrons

Neutrons have been found with velocities over 30,000 miles a second, but a more usual velocity if half of this. Fast neutrons form an isotope of the atom used as a target with a mass one unit greater, as

$${}_7N^{14} + {}_0n^1 \rightarrow {}_7N^{*15}$$

With light nuclei such as this, the next step is to emit helium

$${}_7N^{*15} \rightarrow {}_5B^{11} + {}_2He^4$$

Much more rarely a proton is emitted. Since the helium nucleus has a double charge, the proton a single charge, and the potential wall for such charged particles increases with the charge on the intermediate nucleus, more hydrogen and less helium is emitted as the charge on the intermediate nucleus becomes higher.

The principal experiments on disintegration by fast neutrons are those of Feather; Harkins, Gans and Newson; Meitner and Kurie.

Remarkable work on the scattering of neutrons has been carried out by Dunning and his collaborators.

(14) Slow Neutrons

At the present time practically all neutrons as they are initially produced have very high velocities, that is velocities expressed as thousands of miles, up to 30 thousand miles, per second. This is because they are produced from heavy hydrogen, beryllium, boron or some other atom with a high decimal mass. This gives a large amount of mass available for conversion into kinetic energy. The only chance for slower neutrons to be ejected is for a part of this mass to be converted into a photon (gamma-ray energy).

The question arises: how can these fast neutrons be slowed down? The obvious answer is by collisions with other nuclei. If, however, they are not slowed down rapidly, they may be captured by some of the nuclei before their velocity becomes low. Thus the problem is solved by passing neutrons through material which will slow them down the most rapidly. Now it is a well-established relation of mechanics that in an elastic collision between a light body in motion and a heavy body at rest, only a small part of the kinetic energy of the light body is given to the heavy one.

Thus lead, with heavy atoms, slows down neutrons very slowly, while hydrogen, with atoms of the same mass as the neutron, slows them down very rapidly.

In elastic collisions both the momentum (MV) and the kinetic energy ($\frac{1}{2}$ MV^2) of the two particles are kept constant. The equations for the maximum velocity imparted have already been given.

The maximum velocity imparted to a hydrogen atom (U_H) is

$$U_H = \frac{2M}{M+1} V = V$$

and to a lead atom (U_{lead})

$$U_{lead} = \frac{2M}{M+217} V = \frac{1}{104} V$$

and the kinetic energies are

$$E_H = \tfrac{1}{2} V^2$$

$$E_{lead} = \tfrac{1}{2} \times 207 \left(\frac{V}{104}\right)^2 = .00957 V^2$$

$$= \frac{1}{207} V^2$$

Thus it is possible for a neutron to lose practically all its kinetic energy in a single collision with a hydrogen nucleus, but it can not lose as much as a thousandth of its energy in a single collision in lead. Thus in lead it is usually captured before it has become slow.

These relations have been recognized since the earliest work was done on the scattering of neutrons in gases which contain hydrogen, but attracted general attention only after the remarkable behavior of slow neutrons was discovered.

If another solar system should pass through our own with a sufficiently high velocity, then barring too close approach of the bodies (suns and planets) themselves, the effects on both systems could be negligible. A slow passage would, however, produce very disastrous effects, since sufficient time would be given for the forces to act.

If, when a neutron passes moderately close to a nucleus in its passage through an atom, and if there is an attraction between the nucleus and the neutron, then the chance that the neutron be captured should increase with the time of interaction of the forces, that is as the velocity decreases. From this point of view slow neutrons should be captured much more often than the fast ones. This simple deduction has had ample experimental verification, although its quantitative form, that the chance of capture varies inversely as the velocity, is only approximately true. Not only are slow neutrons captured more frequently, but they are also more often deviated from their straight line path when they pass close to an atomic nucleus. That is both the absorption and the scattering of neutrons are greatly increased when the neutrons are made slow.

The customary method of expressing this is to say that in nuclear encounters the cross section of the neutron is much greater for slow than for fast neutrons, but not in the same ratio for capture and for scattering.

When the neutron was first discovered there seemed to be no possible means of protecting any region, close to a source of neutrons, from their great penetrating action. Now this can be done by putting up a wall of water or paraffin, either of which contains hydrogen. Such a wall converts the fast neutrons into slow ones. When the farther side of the wall is covered with a sheet of cadmium about a millimeter thick or a similar thickness of boron which absorbs the neutrons since the nuclei of these two elements, as well as those of a few others, attract slow neutrons at remarkably great distances as compared with other nuclei.

Thus, even near a powerful source of neutrons a room surrounded by such a wall is almost free from neutrons.

The work of Fermi on slow neutrons is discussed in the section on artificial radioactivity.

(15) THE HYDROGEN NUCLEUS OR THE PROTON AS A PROJECTILE

On account of the positive charge on the hydrogen nucleus or proton it is repelled, except at very minute distances by an atomic nucleus. Thus only fast protons are able to come into contact with a nucleus. The principal reactions of protons (${}_1H^1$) are given below as represented by specific disintegrations. The most general reaction is for a hydrogen nucleus to go in and a helium nucleus to come out, as

$${}_9F^{19} + {}_1H^1 \rightarrow {}_{10}Ne^{*20} \rightarrow {}_8O^{16} + {}_2He^4 \qquad (1)$$

If the target is carbon this may be converted into radioactive nitrogen 13, which disintegrates directly into a carbon nucleus of mass 13 with emission of a positive electron (ε^+) with a half period of 10.3 minutes.

$${}_6C^{12} + {}_1H^1 \rightarrow {}_7N^{*13} \rightarrow {}_6C^{13} + {}_1\varepsilon^0 \qquad (2)$$

In a reaction of type (1) the intermediate nucleus, represented above by ${}_{10}Ne^{*20}$, always breaks up into a helium nucleus and the remainder or residue of this nucleus. This residue is in some cases a new isotype of great interest to workers in this field. Thus with lithium of mass 6

$$_3Li^6 + {}_1H^1 \rightarrow {}_4Be^{*7} \rightarrow {}_2He^3 + {}_2He^4$$

a new lighter isotope of helium of mass 3 is formed, while with beryllium 9 both a new isotope of beryllium, of mass 8, and heavy hydrogen ($_1H^2$) are formed.

$$_4Be^9 + {}_1H^1 \rightarrow {}_5B^{*10} \rightarrow {}_4Be^8 + {}_1H^2$$

(16) Heavy Hydrogen (Deuterium) as a Reagent in Nuclear Chemistry

During the last two years deuterium has been the most widely used reagent in nuclear chemistry. That this is true is due to the remarkable combination of characteristics outlined below. Much of this work has been done by Lawrence and his collaborators, who have obtained deuterons with energies as high as six million volts. Crane and Lauritsen, in Pasadena, and the workers in Cambridge, England, have done important work, but with a much lower kinetic energy of the projectiles. The work of Tuve and Hafsted has been of interest, both with deuterons and with protons.

(1) The positive charge on the deuteron causes it to be accelerated in an electrical, and if in motion in a magnetic, field.

(2) The smallness of its charge, equal to that of the proton, enables it to penetrate the potential wall of a nucleus more easily than more highly charged positive particles, and in this it is excelled only by the neutron.

(3) The deuteron is a loose combination of a neutron (n) and a proton (p), of formula (pe), while the general formula for any nucleus is $(pe)_Z \, n_I$ in which Z is the atomic, and I the isotopic number. In the reaction, which has not been demonstrated to occur,

$$-{}^{1}_{1}H^1 + {}^{1}_{0}n^1 \rightarrow {}^{0}_{1}H^2 + E \qquad (1)$$
$$1.0081 + 1.0084 = 2.0142 + 0.0023$$

the energy of binding would be only 0.0023 or 2.15 MEV, which indicates that a single proton and a single neutron are only loosely bound, in the nuclear sense, in the nucleus of the atom of heavy hydrogen.

(4) The energy of combination of the deuteron with another nucleus, particularly if the atomic number is low and odd, is very high. Thus with itself, where E is the kinetic energy:

$${}^{0}_{1}H^2 + {}^{0}_{1}H^2 + E \rightarrow ({}^{0}_{2}He^4 + (Q) + E) \qquad (1)$$
$$2.01449 + 2.01449 + E \rightarrow (4.00336 + 0.02562) + E$$

Thus, unless the helium nucleus disintegrates or gives off a gamma ray, it must hold 0.02562 grams or 23.9 million electron volts (MEV) of excess energy. This causes it to disintegrate by (3) or (4)

$${}^{0}_{2}He^{*}4 \rightarrow {}^{1}_{1}H^3 + \; -{}^{1}_{1}H^1 + Q \qquad (3)$$
$$4.02898 \rightarrow 3.01664 + 1.00807 + 0.00427$$

$${}^{0}_{2}He^{*}4 \quad -{}^{1}_{2}He^3 + \; {}^{1}_{0}n^1 + Q \qquad (4)$$
$$4.02898 \quad 3.01664 + 1.00885 + 0.00339$$

The reaction between boron 10 and deuterium to give carbon 12 gives a carbon atom of mass 12.0290, which can not exist with its great excess of 23.7 MEV of energy so it disintegrates in one of three ways: (1) gives off a proton, (2) gives off a neutron, or (3) breaks up into 3 alpha particles (presumably in two steps).

By (3) the deuteron can give either (a) a proton or (b) a neutron to another nucleus. In (a) a charged particle must penetrate the other nucleus; in (b) the neutron may be captured and the charged particle escape. In (a) the charge of the other nucleus must be low unless the deuteron has an extremely high velocity, in (b) the charge may be either low or high since the neutron has no charge, (theory of Oppenheimer).

(17) Artificial Radioactivity

According to the point of view of this address, all nuclear disintegration is due to a radioactivity of the unstable intermediate nucleus.

The term artificial radioactivity has been used by others in a more specific sense to represent the possession of radioactivity of a measurable period by one of the products of a nuclear synthesis, and is commonly of the type in which a positive or negative electron is emitted, although the term includes delayed emission of γ-rays.

The first artificially radioactive atom to be discovered was nitrogen of mass 16 produced by action of a neutron, found by Harkins, Gans and Newsom, who assumed that it would give a delayed emission of a negative electron and change into oxygen 16. Although this was later proved to be true, the amount of material available was too small to demonstrate this at the time.

Curie and Joliot, by use of a large amount of polonium, were able to produce a different type of radioactivity, from α-rays, in sufficient quantity to give a direct experimental proof. Their work is of great importance, since they were the first to produce atoms of negative isotopic number.

Fermi, Amaldi, Agostino, Rosetti and Segre produced a large number of radioactive nuclei by the action of neutrons as in the experiment of Harkins, Gans and Newsom, and found slow neutrons to be specially effective in giving the property of radioactive emission of negative electrons or γ-rays to the atoms of almost any element.

It is well known that considerable amounts of radioactive sodium has been obtained by Lawrence by deuteron bombardment in a cyclotron.

Since a neutron in a nucleus when it changes to a proton emits a negative electron, and since a positive particle always contains at least one proton, and this may change to a neutron and a positive electron, the following relations are what is to be expected whenever an electron is emitted.

1. When a neutron is captured the radioactive disintegration gives a negative electron.
2. When a proton is captured a positive electron is emitted.
3. When deuterons or α-particles are captured either a positive or a negative electron is emitted.
4. In electron emission the isotopic number does not fall below zero.
5. When a positive electron is emitted the isotopic number rises to $+1$ or higher.
6. A low isotopic number, as compared with the position of the band of stability, favors the emission of a positive, and a high isotopic number, the emission of a negative electron.

At the present time almost any element may be produced in a radioactive form, and it is probable that some or many of these will be useful in medicine and surgery. The effects of neutrons upon tissues should be much more intense than those of γ-rays. On account of the large water content of the body fast neutrons which penetrate the tissues are rapidly converted into slow neutrons, which are then captured. Thus nuclear chemistry enters the realm of physiology.

OBITUARY

CHARLES VELMAR GREEN

ON April 18, 1936, two days after his thirty-fourth birthday, Charles Velmar Green, a research associate and one of the Board of Directors of the Roscoe B. Jackson Memorial Laboratory, was accidentally drowned while fishing near Bar Harbor, Maine.

This sudden end to an all too brief career, marked by superior ability and great industry, had in it elements of tragedy lacking in the foreseen termination of the activities of those of advanced age.

The years of quiet, patient effort that had marked Green's progress from his birthplace on a farm in Ashley, Michigan, through school, Michigan State College and the University of Michigan, left their mark on his character. They had been distinguished throughout by self-reliance and independence of thought, by tenacity of purpose and by the highest ideals of personal integrity.

When in 1927, two years after his B.S. degree, he received an M.S. under the friendly guidance of Professor Harrison Hunt, of Michigan State College, he had already developed a calm maturity of intellect and an unfailing soundness of scientific judgment far in advance of his years.

These qualities he continued to show in increased measure during the work for his doctorate and in the years which followed it (1930–36). By concentration and tireless effort he obtained and analyzed a sufficient mass of data to establish for the first time linkage between genes for size and a gene for color in mammals. His grasp of this subject was demonstrated, not only in the initial presentation of his results but in the extended discussion of them which followed.

In the course of the development of his work he also contributed notably to research in the field of differential growth, to changes in crossing-over correlated with age and to many other interesting and important phases of mammalian genetics. He had already published more than thirty scientific papers covering a wide range of research.

His chief happiness lay in research rather than in teaching. Each succeeding year saw broader and more important advances in his methods of approach. To these advances two factors contributed greatly. One was the contentment and inspiration of his home life and the completely adjusted companionship with his wife, Sybil Kent Green. The other was the joy that he derived from fishing and other recreation inherent in the environment of Mount Desert Island.

One may fairly say that happiness, creative activity and a balanced integration of purpose filled his own life so abundantly that, to an unusual degree, he transferred these qualities to those around him. In the face of these inspiring facts the deep personal sorrow of his friends and associates must quickly be recognized as selfish, and must give place to a willing determination to carry on as he would have done had he lived.

C. C. L.

SCIENTIFIC EVENTS

THE BRITISH NATIONAL HUMAN HEREDITY COMMITTEE

A LETTER to the editor of the London *Times* of May 6, signed by R. Ruggles Gates; Humphry Rolleston; Grafton Elliot-Smith; R. A. Fisher; Arthur Keith; E. Farquhar Buzzard; Moynihan; F. Gowland Hopkins, members of the British National Human Heredity Committee (115 Gower Street, London, W. C. 1), reads as follows:

Problems of national health have reached a point where the hereditary element can no longer be neglected. The leaders of the medical profession are no longer satisfied with the alleviation of disease, but are acutely conscious of the need for fuller knowledge of heredity in connection