and for the solutions of which only physical and chemical conceptions apply. Even though the application of physical and chemical methods may not at once reveal the ultimate nature of life processes it constitutes an essential step in an interpretation of the dynamics of biological phenomena.

In conclusion, I wish to express, on the part of my colleagues and myself, the sincere appreciation of the thought and painstaking interest which President Merriam has given to the development of the organization and plans of this division, of the liberal support of the trustees of the Carnegie Institution and of the opportunity and splendid cooperation given by Stanford University.

SURFACE STRUCTURE AND ATOM BUILDING. II

By Professor W. D. HARKINS

UNIVERSITY OF CHICAGO

(5) *Graphical representation of the new periodic system.* A complete atom contains as many electrons as protons. If the weight of one proton (p) plus one electron (e) is taken as unity, then the atomic weight (W)[9] is supposed to give the number of protons and of electrons in the atom. That is, the symbol $(pe)_W$ represents the composition of any complete atom of atomic weight W. If P is the number of protons in the atom, then $P = W$. Let N represent, not the total number of electrons in the atom, but the number in the nucleus, then $P - N = Z$ is the *atomic number*, and $2N - P$ is the *isotopic number*, for any known or unknown atomic species.

An entirely new periodic system was revealed when two of the above variables were plotted on a two-dimensional diagram, but by far the simplest form of this system was found to be given with the isotopic number on one (Y) axis, and the atomic number on the other (X) axis. If even numbers are represented by heavy lines, and odd numbers of these variables by light lines, an extremely remarkable pattern is found to emerge (Fig. 8).

The isotopic number for any atomic species other than hydrogen gives the number of the isotope according to a system in which the lowest possible isotope of any element is given the number *zero*. For example the isotopic numbers for the known species of a few elements are: He, 0; Li, 0 and 1; Be, 1; B, 0 and 1; C, 0; Mg, 0, 1 and 2; Al, 1; Si, 0, 1 and 2; Fe, 2 and 4. If the empirical formula of any nucleus is written $(p_2e)_z\ (pe)_n$, then the subscript n gives the *isotopic number*, just as the subscript Z gives the atomic number.

The isotopic number is as important to distinguish the species as the atomic number to distinguish the element.

[9] Actually W is very close to, but in general is not exactly, a whole number. P is this whole number.

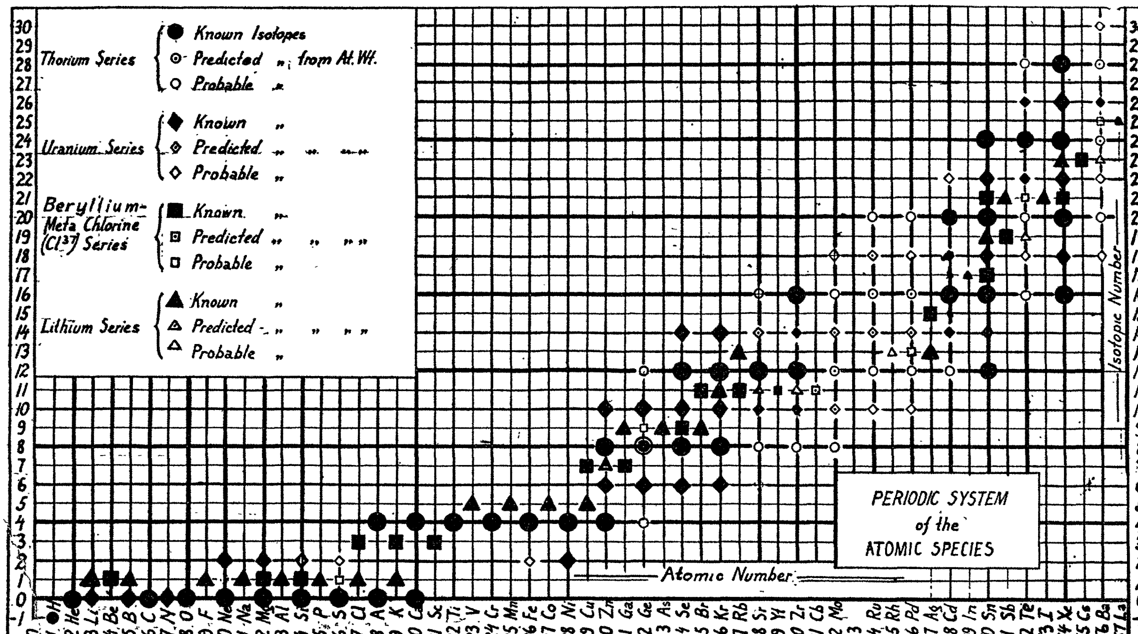

FIG. 8

As has been stated the *heavy coordinates in Fig. 8 represent even numbers and the light lines odd numbers.* Now it is remarkable that where heavy lines meet heavy lines the greatest number of species occur (sixty-seven known species in the figure), and these are also by far the most abundant. Where light lines intersect light lines the number of known species is less (thirty-two), and the atoms of these species are in general far less abundant. Where heavy vertical lines intersect light horizontal lines the number of known species is again reduced by about one half to fourteen species.

By far the fewest species occur where light vertical meet heavy horizontal lines (Class IV). It is indeed remarkable that only three species (Li_0, B_0 and N_0) of this type are known in the whole system of 92 elements, and it is even more remarkable that all three lie on the *lowest heavy* line of the diagram, that of isotopic number 0. If their production were governed by pure chance, 1 atom in 4 should belong in this class, while actually it contains only 1 atom in 160,000 in the earth's crust. Thus *there are almost no atoms in which the number of nuclear electrons is odd and the number of protons even.* Thus there is a certain matching of P and N. Thus if N is even, P is usually even, and if N is odd, P is almost always odd.

TABLE I

CLASSIFICATION OF ATOMIC SPECIES ACCORDING TO EVEN AND ODD NUMBER OF ELECTRONS

	Abundance in atomic percentage: Earth's crust	Meteorites
Class I, N = even, P = even, z = even	87.4	95.4
Class II, N = even, P = odd, z = odd	10.8	2.1
Class III, N = odd, P = odd, z = even	1.8	2.5
Class IV, N = odd, P = even, z = odd	0.0007	0.0

The new periodic system requires for its proper representation a figure in at least three dimensions. Suppose that Fig. 8 lies in a horizontal plane, and that the abundance of each species is represented by the height of a peak which lies vertically above the point which represents it. The height of these peaks is represented in Fig. 9.

(6) *Fourth periodic relation: high stability and abundance for atoms of isotopic number divisible by 4, and a secondary periodicity of 2.* Among the light elements (atomic numbers 6 to 28) there is a periodicity of 4 in the abundance of the atomic species as related to the isotopic number. This is apparent in Fig. 9.

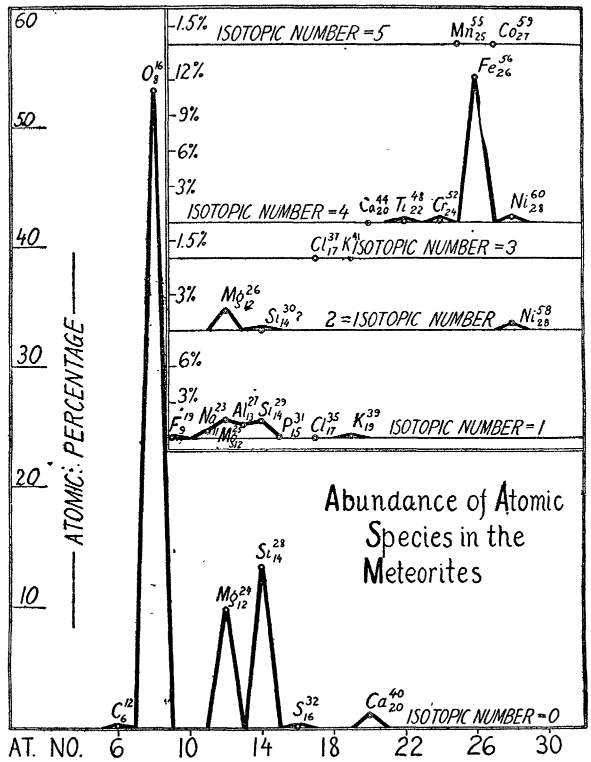

FIG. 9

Furthermore, as is shown plainly by Fig. 10, there is a periodicity of 2 in the *number of species now known* with respect to the isotopic number. The appearance of the plot represented by Fig. 8 seems

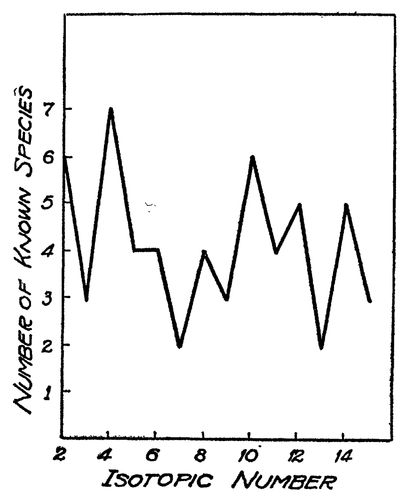

FIG. 10

to indicate that this periodicity will remain, at least between isotopic numbers 2 and 10, even after much more thorough investigations have been carried out.

(7) *General theory of nuclear stability.* The periodic relations of atom nuclei show that special

types of composition with respect to evenness and oddness of number are very much preferred to others, and that evenness of number is much the more common.

There is in addition a general, non-periodic relation which determines the general bounds of the region of atomic stability.

First, no nucleus (other than the proton) is known in which the ratio of electrons to protons (N/P) is less than ½ or 0.5.

Second, the net positive charge on the nucleus of an atom may rise as high as 20 while the relative negativeness (ratio of negative to positive electrons) remains at its most general value of 0.5, but in order that the nucleus may be stable and attain a higher net positive charge, the relative negativeness must increase to an extent which increases with increase in the net positive charge. Thus the atom nucleus, in order to be stable, must have a relative negativeness (N/P) which matches its net positiveness (Z).

The band of stability is shown in Fig. 11. It is of great interest that the small number of atomic species contained in the rectangle in the lower left-hand corner of this figure constitute 99.9 per cent. of all known material.

The usefulness of the relationship between stability and the relative negativeness (N/P) of the nucleus is illustrated by the fact that before the discovery of the isotopes of lithium four predictions were made by various workers concerning their existence, and the only one of these found to be correct was that made on the basis of this relation.

If the nucleus of the atom is considered as consisting of an aggregation of positively charged groups, then by the principles of electrostatics alone a mutual repulsion is to be expected. This indicates that other, probably magnetic, forces are involved. However, there might well be limits beyond which such forces could not go in holding positive groups together. It is well in this connection to consider certain facts:

a. The most abundant atomic species are those in which $\frac{N}{P}$ is ½.

b. No atomic species for which $\frac{N}{P}$ is equal to ½ has a positive charge on the nucleus which is greater than 20.

c. All atomic species of nuclear charge greater than 29 are very rare. According to the data less than one atom in a thousand has a nuclear charge higher than 29.

If it is assumed that the positive groups in atom nuclei exhibit a certain amount of mutual electrostatic repulsion, which increases with the positive nuclear charge Z, then it may also be assumed that with nuclei for which Z is large, this repulsion may be

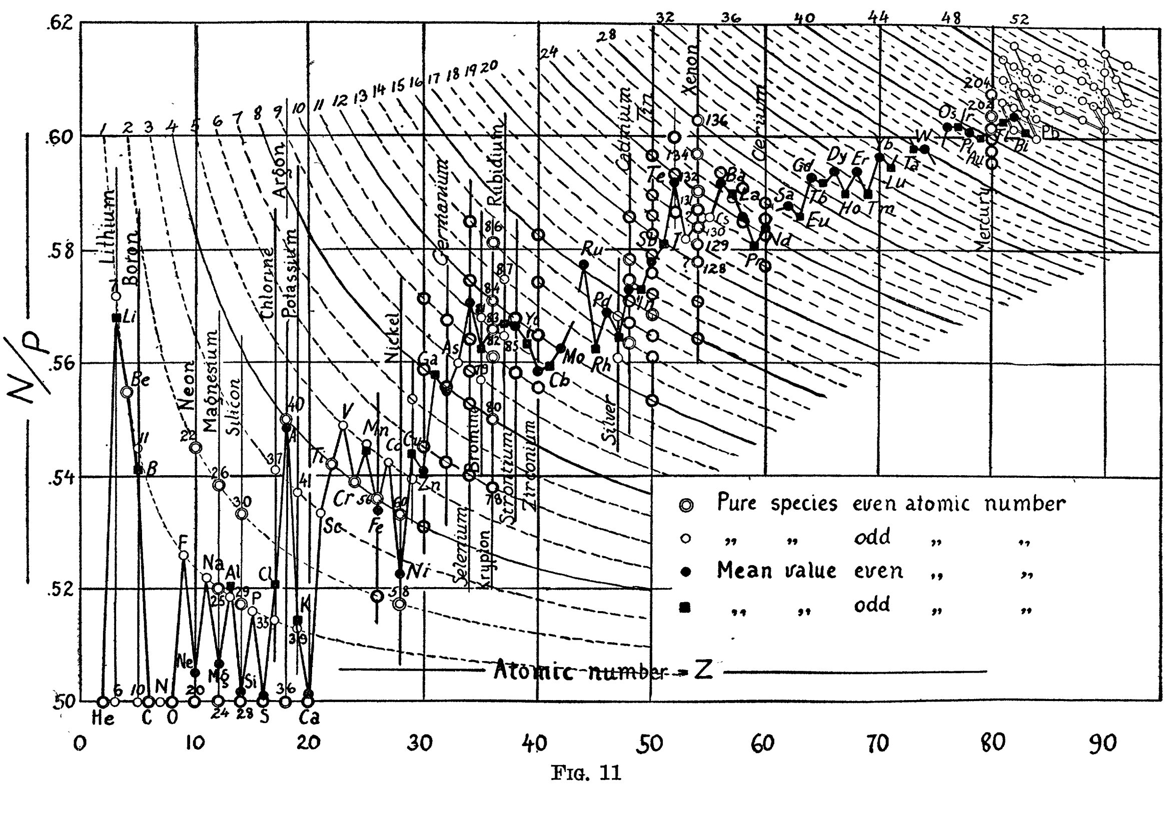

FIG. 11

decreased by an increase of $\frac{N}{P}$, the relative negativeness of the nucleus.

(8) *The whole number rule and the packing effect in the formation of complex atoms from hydrogen.* If four atoms of hydrogen unite to form one of helium, then atomic mass is lost in the process. The amount of this mass which thus disappears is equal to 0.76 per cent. of the mass of the hydrogen utilized. The amount of energy which thus escapes, presumably as energy of radiation, was calculated by Harkins and Wilson (1915) as 2.8×10^{-19} ergs per 4 g of helium formed, by the use of Einstein's equation,

$$-\Delta E = -c^2 \cdot \Delta m$$

in which $-\Delta E$ is the energy loss in ergs, $-\Delta m$ the loss of mass in grams and c the velocity of light.

If the packing effect is almost constant, the true atomic weights on the basis of oxygen as 16 must be very close to whole numbers. This rule (Harkins and Wilson, 1915) is commonly known as the "whole number rule."

If the energy of emission of alpha and beta particles in radioactive transformations comes from the nucleus itself, then the packing effect should increase as the complexity of the nucleus decreases. Harkins and Wilson considered, however, that the evidence of the chemical atomic weights indicated that the departures from whole numbers are not in general over 0.1 per cent.

Recent work by Costa and by Aston indicates that, as is to be expected from the above considerations, there is a maximum for the packing effect, and it is found to occur at atomic weights between 50 and 80.

The values (Fig. 12) for light elements of odd and even number exhibit agreement with the *second*

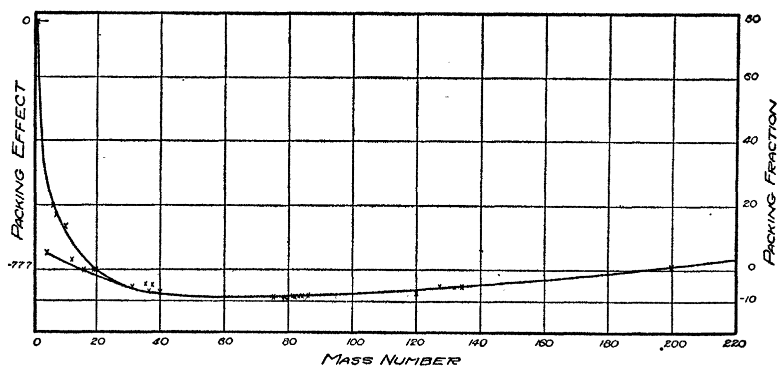

FIG. 12

Thus the formation of 1 pound of helium from 1.0078 pounds of hydrogen would give as much energy as the combustion of ten thousand tons of coal. The wave-length (λ) which would correspond to this amount of energy if one quantum of radiation is emitted when one atom of helium is formed is 4.3×10^{-4} Ångstrom units, according to Planck's law:

$$E = h\gamma = \frac{hc}{\lambda},$$

in which the frequency $\gamma = \frac{c}{\lambda}$ and h is Planck's constant. This is in the general region of the cosmic rays.

It was found that the loss of mass or the "packing effect" in the formation of any heavier atom from hydrogen has almost the same percentage value (0.76 per cent.). If this percentage were exactly constant, then all atomic species would have whole numbers for their atomic weights, provided the atomic weight for helium is taken as 4, that of carbon as 12, that of oxygen as 16, etc.

periodic relation in that the stability is indicated to be greater for elements of even than for those of odd atomic number. For higher atomic numbers, however, the packing effect does not give at present a sufficiently sensitive method to detect differences which may be found in other ways.

(9) *Experimental demonstration of the synthesis of atoms, and the hydrogen-helium theory.* The four fundamental periodic relations of atom nuclei thus far discussed were discovered in connection with development of the "hydrogen-helium theory" of the structure of complex atoms (1915). A careful study of the relations exhibits the fact that they are in remarkable accord with the theory.

Whether or not atom nuclei are built from alpha particles, their existence and stability are related in a most striking way to the composition of the alpha particle. For example, the upper part of Fig. 13 gives a plot of the thorium disintegration series from thorium (atomic number 90) to lead (82). For each disintegration in which an alpha particle is emitted, the atomic number is lowered by 2.

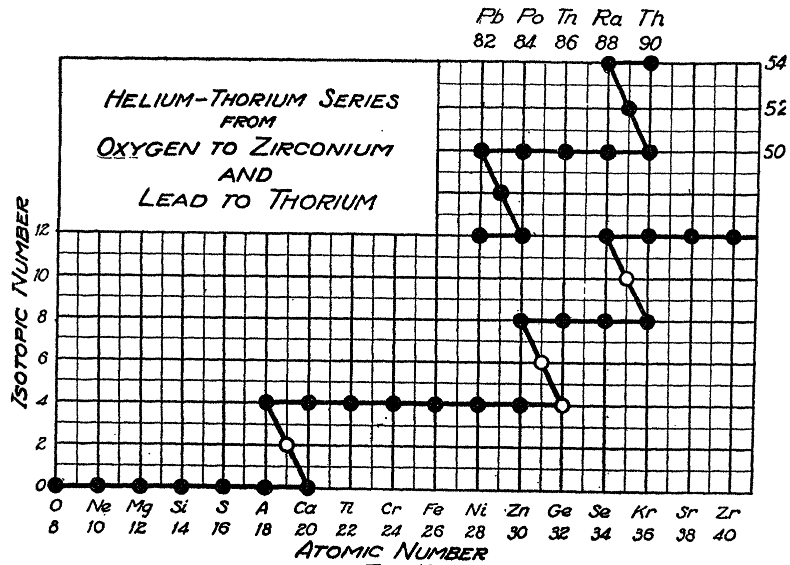

FIG. 13

The lower part of the figure shows the lower end of the same series in which no disintegrations have been found to occur. It is, indeed, extremely worthy of attention that the lower part of the series for ordinary atoms exhibits the same pattern as that for the radioactive elements. Thus only the species of even atomic number are found in either series. The plot of the series for low atomic numbers shows that no species of odd atomic number which belongs on one of the horizontal lines has as yet been discovered, although there are vacancies which correspond to 20 species. In contrast, 22 of the 23 positions for even atomic number are filled, and these include the most abundant species of atoms which exist.

One of the evident suggestions of this figure is that the light atoms are built up from helium. In order to test the helium theory of atom building, experiments were begun in 1921 by Ryan and the writer to determine by the photography of Wilson Cloud tracks what occurs when very fast alpha particles collide with the nucleus of the atom. The method thus applied was adopted by Blackett and by Harkins and Shadduck. It was shown that in some of the collisions an alpha particle attaches itself to the nucleus of a heavier atom and thus increases the atomic weight. This is the only synthesis of a heavier from a lighter atom which has been observed. Up to the present time the addition of the alpha particle has been demonstrated only in the case in which a proton (hydrogen nucleus) is almost simultaneously emitted. However, this limitation is due to the method employed, since the emission of the hydrogen particle is used as the test for the synthesis.

If the fast alpha particle merely collides with the nucleus of the heavy atom, a fork is obtained (Fig. 14 *A*). If the alpha particle collides with the nucleus at b (Fig. 14 *B*) and adheres to it, the photograph shows only a straight line which is

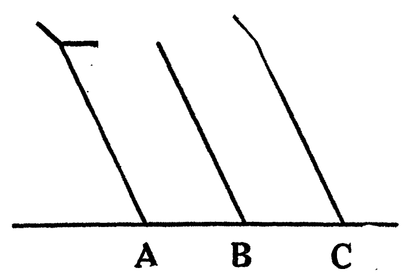

FIG. 14 A, B, C

exactly like the track of the alpha particle, except that it is shorter. It is extremely difficult to prove that the track has not been shortened by some other cause. If, however, the alpha particle adheres, and a hydrogen particle is emitted almost simultaneously, a fork is found in the photograph (Fig. 14 *D*) which resembles that for an ordinary collision, but whose distinguishing features give sufficient evidence of the union of the alpha particle with the nucleus of the heavier atom.

Thus one of the three tracks is about 10 times thinner than the other two, but appears as a continuous straight line in the photograph. Such a track is definitely characteristic of a hydrogen particle, since all heavier atoms give the broad tracks, and an electron gives a dotted track, commonly curved, unless it is much shorter.

In the only synthesis thus far found, a helium nucleus unites with the nucleus of an atom of nitrogen, to form one of fluorine, which at once dis-

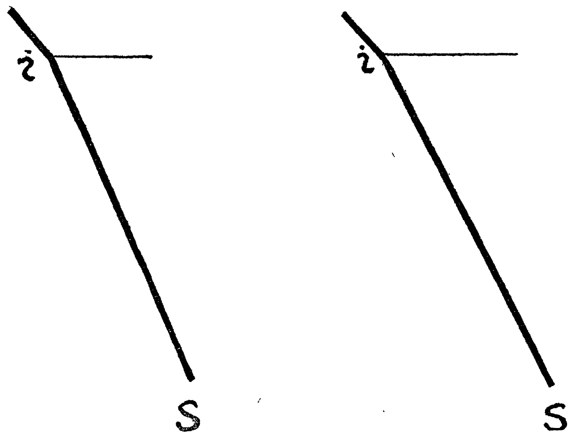

FIG. 14 D. Disintegrative-Synthesis of Atoms. Tracing taken from a photograph of two views at right angles of the tracks of atoms. The long heavy straight line in each view represents the track of a doubly charged helium atom, formed at (s) by the disintegration of an atom of thorium C′. The initial velocity of the helium atom is thirteen thousand miles per second. At the point (i) the helium atom, with a velocity of 11,600 miles per second, unites with a nitrogen atom in the air. A hydrogen atom (H+) (faint track) is emitted at a velocity of 17,000 miles per second, and an oxygen atom (short heavy track) of mass 17 is found. This has an initial velocity of 3,300 miles per second.

integrates into hydrogen and oxygen of atomic mass 17.

If the faint track of the hydrogen nucleus shown in Fig. 14 *D* is too dim to be seen, a deflection such as that shown in Fig. 14 *C* is found.

Photographs of the natural disintegration of atoms of certain radioactive substances are much easier to obtain, and a tracing of one of these is shown in Fig. 15.

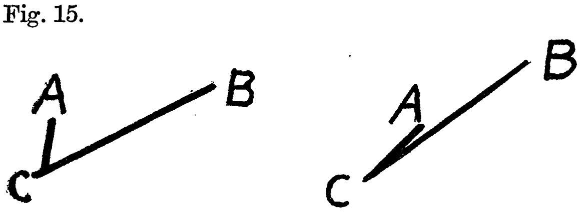

FIG. 15

FIG. 15. The Natural Disintegration of Atoms. Tracing taken from a photograph of two views, at right angles, of the tracks produced in air by the disintegration of radioactive atoms. An atom of one of the rare gases of the atmosphere (Thoron) disintegrates at C and shoots off a doubly charged helium atom (Track A). The atom left at C is an atom of bismuth. This disintegrates to give another helium atom (Track B), and an atom of lead. The track of the lead atom is shown by the very short stub at C. Since the mass of the atom of lead is 53 times larger than that of the helium atom, its velocity is 53 times smaller, so it has a much smaller range in air.

(10) *Fifth periodic relation.* It has been shown that if the atomic species are classified into four sets or classes (Table II) the number of possible species for each class is the same as for the others. However, the actual number of stable species is very high for Class I and decreases with the class number, until in Class IV only three species are known, and the abundance of these is very slight.

With the single exception of these three species a study of Fig. 8 (or Fig. 13) shows that along (horizontal) lines of even isotopic number every position which represents an element of even atomic number is filled (if in the general region of stability with reference to N/P), while every position of odd atomic number is vacant.

Thus from left to right the difference of composition of two adjacent known species is always that of a single alpha particle (α or p_4e_2).

The same difference is found for species of odd isotopic number, but here the positions which are filled correspond with odd atomic numbers. However, there is this important modification: in many regions every corner is filled, that is, the difference in composition from one species to the next is often that of a half-alpha particle of p_2e. In general a species of Class III lies in the plot either (*a*) between two species of Class II, or (*b*) adjacent along the horizontal line to a single species of Class II. At low atomic numbers condition (*a*), and at higher values condition (*b*) holds in general. It is possible that some species of low abundance may be found for which this rule does not hold, but there is a general apparent relation between the species of Classes II and III which is of great interest.

(11) *Are atom nuclei built up largely from alpha particles?* The data presented in this paper strongly suggest the idea, either that (1) The nuclei of atoms are formed largely by the aggregation of α-particles, or (2) the nuclei of atoms are largely composed of α-particles.

A few of the facts and relations which favor one or both of these ideas are recapitulated below.

(1) α-particles are given off in the disintegration of heavy atoms.

(2) α-particles are taken up in the synthesis of light atoms.

(3) Atoms whose nuclei have a composition which is the same as a whole number (j) of alpha particles (α_j) are by far the most abundant of all the types of atoms.

(4) They form also all the most abundant species.

(5) The elements of even number have been found on bombardment by fast α-particles to be more stable than those of odd number.

(6) The very light elements of even number exhibit a greater packing effect than those of even number.

(7) Fig. 13 gives very strong evidence for this point of view.

There is, however, evidence which seems to indicate that atom nuclei, even if they have been built up from α-particles, can not contain α-particles whose stability is not affected by their environment. Thus the packing effect or loss of energy in the formation of hydrogen from helium is large (0.77 per cent.). The additional packing effect in the formation of heavier atoms is not very great.

Therefore, the high stability of "non-radioactive" atom nuclei with reference to their disintegration into α-particles indicates that if the α-particle exists as a group inside the nucleus, it has nevertheless lost a part of its individuality.

The idea that the nucleus is built up by the aggregation of α-particles meets a certain difficulty with the nuclei of high charge, since it is difficult to see how the α-particles can obtain sufficient velocity to drive it through the region of mutual repulsion.

However, this difficulty is lessened by the fact that very few nuclei of high charge have been formed; that is, all elements of atomic number greater than 28 are extremely rare. Also the newer quantum mechanics cooperates in removing this difficulty, since it gives to the alpha particle, which has on the old basis too low a kinetic energy to pass through the repulsive region, a small chance of penetration.

On the whole, *there is very strong evidence that the α-particle plays a primary rôle in atom building.* Just what this rôle is it is difficult to say.

The question as to the existence of other proton-electron groups and their relation to atom building has been discussed in other papers, and need not be repeated here. If a half α-particle (p_2e) exists, the explanation of some of the relations would be simplified. However, since it is not found free in nature as an isotope of hydrogen, such half α-particles, if they exist at all, must have a great tendency to unite with other like particles to form a whole α-particles. Also, if neutrons (pe) or (pe_1) exist they would not be affected by a repulsive effect of the nucleus, since they have no net charge. If atoms grow heavier by the addition of neutrons, then only isotopes are formed, and atoms of higher atomic number can be formed only by the subsequent emission of beta-particles. Among other possible groups p_3e_2 is suggested, since this is the most common difference in composition between an atom of even atomic number and one of the next higher odd number.

(12) *Atom building and the composition of the earth.* A study of books on the composition of the earth exhibits the fact that the chemical and physical nature of the substances involved is looked upon as the primary factor in the determination of the composition. Or, if this is not the point of view, the general topic is entirely avoided.

A more fundamental point of view is that expressed in section (9): The composition of the earth is determined most largely by atomic stability and by the processes by which elements are built and disintegrate. The chemical and physical properties have, however, an important secondary effect. That oxygen is an extremely abundant element in the crust of the earth is not due in a primary sense, as was formerly supposed, to the low density of its compounds, but to the fact that its atoms are very stable, and probably to the ease with which it is formed.

(13) *The building of the earth.* The composition of the earth's crust has not been thought to exhibit evidence concerning the origin of the earth. Nevertheless, there seems to be a relation between the two.

The rarest (Fig. 16) of all classes of elements is known by the designation the rare gases. These gases are chemically and physically very much alike. However, there is no known relation between abundance and chemical or physical characteristics.

The abundance of the elements is related to the nuclear or non-chemical relations of the atomic species and elements as expressed by the new periodic system.

According to the second periodic relation, elements of even number, such as the rare gases, have a relatively high nuclear stability, and as a class should be abundant.

The obvious deduction is that the abundance of the rare gases on earth is much less than corresponds with the extent to which they were formed in the material from which the earth was built.

Thus, either: (1) In the process by which the earth was built the rare gases were not condensed, or (2) The rare gases have escaped from the earth since it has been formed.

Thus the gravitational energy of the mass or masses of material involved has at some time been insufficient to hold gaseous substances; that is, at some period the velocity of the molecules of the rare gases has exceeded what is termed the velocity of escape.

Only those elements which are held by chemical rather than physical forces are now present in the earth to any considerable extent.

Accurate determinations of the atomic weight of meteoric and terrestrial nickel (Baxter) and chlorine (Harkins and Stone) show that there is no appreciable difference between the atomic weights of the element in either case. This indicates either that the material of the earth's surface and of the meteorites has a common origin or else that the relative proportions of the isotopes in an element are determined

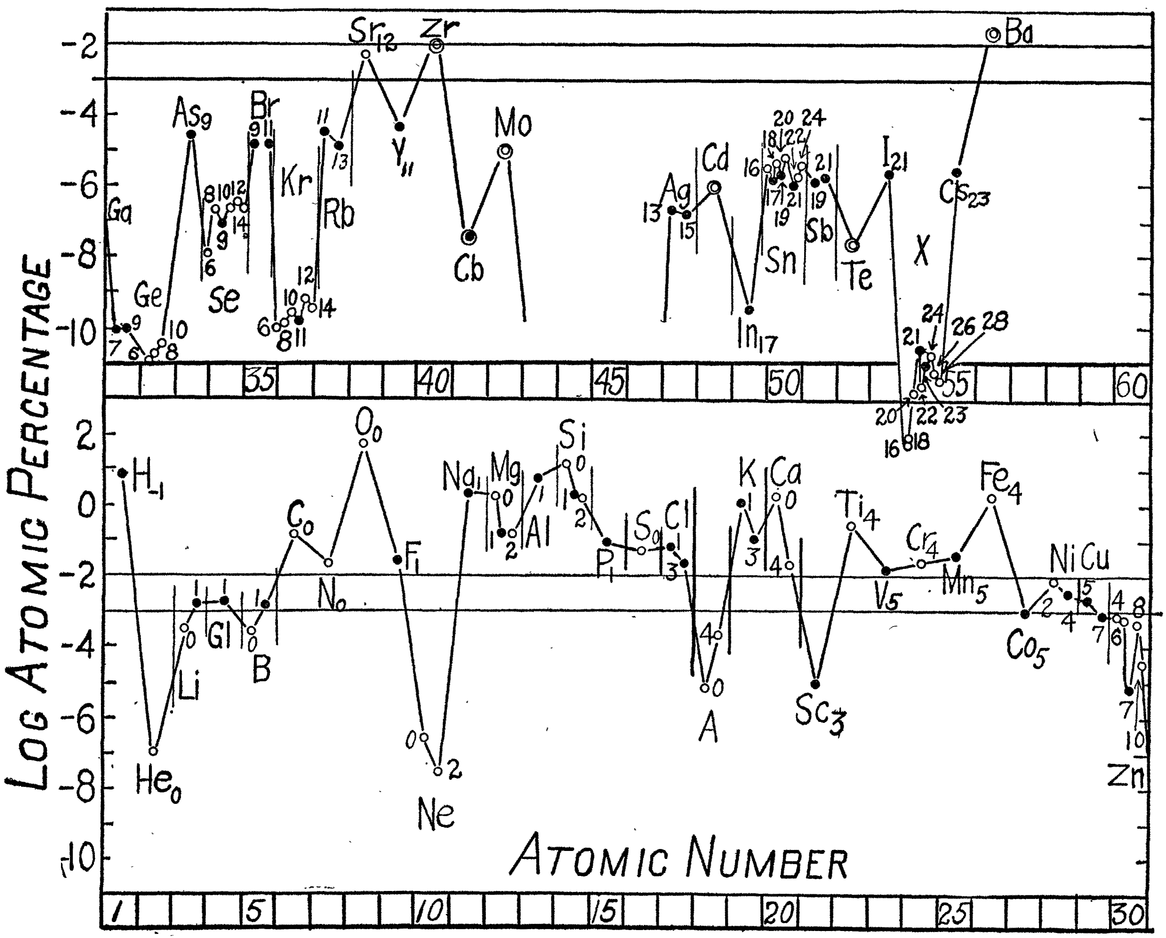

Fig. 16

by their relative stability and method of formation with reference to their source.

In addition this work seems to show that the natural processes which occur on earth and in the meteorites have not sufficed for their separation. This is not on the whole surprising, since the work of this laboratory indicates that the experimental separation of the isotopes of chlorine is a moderately slow process under favorable conditions, and thus far nickel has not been separated at all. Nevertheless, if the earth's surface is as old as it is commonly supposed to be, the above facts are somewhat remarkable. They agree with the idea obtained from other sources, that isotopes can not be separated by chemical means, and they indicate that conditions on earth and in the meteorites are not favorable for their separation by diffusion.

While these relations do not lead to any definite theory of the origin of the earth, they are entirely in accord with the planetesimal theory, which supposes that the earth at one time had a much smaller mass than at present, and that it has grown to its present size by the addition of small bodies such as meteorites or planetesimals. Whether or not they are in agreement with other theories depends upon the specifications of each of the theories. On the whole, it seems difficult to reconcile these facts with the theory that the earth has been formed by the condensation of a gaseous system of about the same mass as the earth of the present period.

THE AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

THE PRESENT ENROLMENT

This is the time of year when a report on the number of members enrolled in the American Association is most significant, for the association year closes on September 30, for which date the official count of members is made for the year. The following notes on the enrolment of September 30, 1929, will surely be of considerable interest to all readers of Science.