NUCLEAR TRANSFORMATIONS AND THE ORIGIN OF THE CHEMICAL ELEMENTS

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Until the beginning of this century the chemical elements have been considered as certain prime substances, and corresponding atoms as elementary constituent parts from which more complex molecules can be built up. The discovery of radioactive phenomena and their interpretation, due to Rutherford, as the spontaneous disintegration of atomic nuclei has shown, however, that chemical elements can be, under certain circumstances, transformed into one another and such transformations occur spontaneously for the heaviest of the known elements. Rutherford succeeded also, as early as 1919, in producing artificial transformations of light, usually stable, atoms, bombarding them with the intensive beams of fast α-particles. The first element which was disintegrated in such a way was nitrogen, which in the collision with an α-particle emits a proton and is transformed into a heavier isotope of oxygen. The corresponding nuclear reaction can be written in the form:

$$ {}_7N^{14} + {}_2He^4 \rightarrow {}_8O^{17} + {}_1H^1. \tag{1} $$

Further investigations of Rutherford and his school have shown that analogous processes can happen for the most of the light elements and that the probability of disintegration decreases very rapidly with increasing atomic number so that already for $Z > 20$ no emission of protons can be observed. It was also found that the probability of disintegration increases very rapidly with increasing energy of the bombarding α-particles. Both observations can be satisfactorily explained by the theory of artificial nuclear disintegrations worked out by Gamow according to which the probability of such transformations depends on the transparency of the potential barrier surrounding each nucleus and preventing the incident α-particles from entering the nuclear structure. The theoretical expression for the transparency of such barriers for incident α-particles can be worked out on the basis of modern wave-mechanics and is in very good agreement with the detailed results of experiments (*1*).

Gamow concluded from this theory that the transparency of nuclear barriers must be much larger if the bombarding particles are protons. Due to the smaller charge and mass of a proton, the probability of penetration of a proton into a given nucleus is the same as for an α-particle with 16 times larger energy. Remembering that nuclear transformations have been observed by Rutherford only for α-particles with the energies of several million electron-volts, one could conclude that in the case of proton-bombardment one can expect observable results already for energies of a few hundred kilovolts. These considerations encouraged Cockcroft to construct special high-voltage apparatus in which he could produce the beams of protons with the energies up to 500 kilovolts for the use of nuclear bombardment. Bombarding with these protons a target of lithium he was able to observe the expected nuclear transformation at voltages as low as 250 kilovolts (*2*). In this case the proton penetrates into the nucleus of the lithium atom and breaks it up into two α-particles. The reaction can be written in the form:

$$_{3}Li^{7} + {_1}H^{1} \rightarrow {_2}He^{4} + {_2}He^{4}, \qquad (2)$$

with the liberation of a large amount (about 18 x 10^6 e. v.) of energy. Bombarding by his proton-beams different light elements, Cockcroft was able to find other examples of the reactions of the same type and to prove the validity of the theoretical formula for the probability of artificial disintegration. At the present time various ingenious apparatuses producing fast beams of particles have been developed in different laboratories throughout the world, increasing our knowledge concerning different types of artificial transformations of light elements. It has been mentioned above that due to the decreasing transparency of nuclear potential barriers the reactions of such type can be observed by present voltages only in the region of light elements and one requires proton-beams of about 10 x 10^6 e. v. in order to penetrate into the nuclei of such heavy elements as mercury and lead.

Quite a new type of nuclear reactions was recently discovered by Fermi (*3*), who was able to show that the nuclei of different, especially heavy, elements bombarded by neutrons can be transformed into their heavier isotopes. Such "capture" phenomena can only be explained as the sticking of incident neutrons to the bombarded nucleus with the liberation of surplus energy in the form of γ-radiation. It was observed by Fermi that the probability of such radiative capture of neutrons increases with their decreasing energy and that one can observe the maximum effect for those neutrons slowed down by collisions with other nuclei to their ordinary thermal velocities. One can easily understand that such type of nuclear reaction can happen without difficulty also for heavy nuclei since, due to the absence of repulsive forces between the neutron and the nucleus, there is no potential barrier preventing the penetration of the neutron into the nuclear structure. The theory of radiative capture of slow neutrons by heavy nuclei was worked out by Bethe and is in satisfactory agreement with the experimental evidence. The heavier isotope formed as the result of the capture of a neutron by certain nuclei can be unstable and subject to the spontaneous emission of an electron which leads to the formation of a nucleus with larger charge and larger mass than the original one. Thus the radiative capture of neutrons and consequential β-disintegration leads step by step to the formation of more complex nuclei. As the typical Fermi-reaction one can write down the process of radiative capture of a neutron by the nucleus of ${}_{53}I^{127}$:

$$\left.\begin{array}{l} {}_{53}I^{127} + {}_{0}n^{1} \rightarrow {}_{53}I^{128} + h\nu \\ {}_{53}I^{128} \rightarrow {}_{54}Xe^{128} + \bar{\beta} \end{array}\right\} \qquad (3)$$

leading to the nucleus of ${}_{54}Xe^{128}$.

Turning our attention from the experimental evidence obtained in the laboratories to the processes happening in the universe, we may at once conclude that there is not much chance for the nuclear reactions to occur around us on the earth. In fact the probability of nuclear transformation by the velocities corresponding to ordinary temperatures is extremely small and need not be taken into account. Only neutrons can produce nuclear transformations at small velocities, but all neutrons are already hidden inside of different stable nuclei and in order to get them out one must use very fast beams of protons or α-particles. If, however, we consider the processes happening inside of stars, in the hottest places of the universe, the situation might be rather different; in fact, the thermal velocities corresponding to several million degrees centigrade are already sufficient to produce artificial transformations of the lightest elements. Using Gamow's formula for the probability of nuclear transformations by collision, Atkinson and Houtermans (*4*) calculated the chance for a proton, moving with thermal velocity, to penetrate into the nuclei of different elements and estimated the periods of time necessary for 50% transformation of different substances mixed up with hydrogen under the conditions governing inside of our sun (density $\sim$1; temperature $\sim$60 x 10^6 °C.). They obtained the following numbers: for *Li*, 34 min.; for *B*, 14 years; for *Ne*, 1 x 10^9 years; and for *Pb*, 10^{61} years (!), which shows that only the lightest elements are easily transformed by proton-bombardment under the conditions governing in the interior of stars. Making the same calculations for collisions with helium-nuclei (α-particles) one obtains very small probabilities even for the lightest elements so that such processes are very improbable even at intrastellar temperatures; still smaller probabilities are obtained for the disintegrative collisions with heavier particles. Thus the thermal nuclear transformations in stars are of importance only for the lightest elements and are entirely due to the collisions with hydrogen atoms which are always present in large amount in stellar substance.

The discovery of the radiative capture of neutrons by heavy nuclei opens, however, new possibilities for the intrastellar nuclear reactions. The neutrons which can be ejected from the nuclei of light elements by collisions with protons may stick to the nuclei of different heavy elements thus securing the possibility of the formation of still heavier nuclei. It might be that this effect plays a very important role in the formation of different elements in the interior of stars.

We come now to one of the most interesting questions concerning the physical state of the matter deep inside of stars. It is of course clear that due to extremely high temperatures and pressures in these regions all molecules are dissociated into separate atoms and even more all atoms are completely ionized, all electronic shells being torn away from the nuclei by the violent collisions. We may consider the substance inside of a star as the mixture of bare nuclei and free electrons, a mixture which can be treated as the ordinary mixture of two ideal gases: nuclear gas and electronic gas. Now, due to the fact that the average number of electrons in the atom is about fifty per nucleus, the partial pressure of electronic gas will, according to Dalton's law, form about 98% of the total pressure and is the only one which must be taken into account.

The equilibrium problem between the pressure of the electronic gas in the star's interior and the gravitational pressure of the outside layers of the star was considered by Landau (*5*) and we give here a short account of his calculations. The pressure of an ideal gas containing N particles in the cube with the side l is, as is well known, given by:

$$P = \frac{1}{6} \cdot \frac{N}{l^2} \cdot n \cdot p = \frac{1}{6} \cdot \frac{N}{l^2} \cdot \frac{v}{l} \cdot mv, \qquad (4)$$

where v is the velocity of particles, $n = \frac{v}{l}$ the number of collisions of a single particle with the wall per second and p the momentum equal to mv in the nonrelativistic case. For the ordinary isothermic compression $v = const.$ and the pressure P is inversely proportional to l^3; i. e., directly proportional to the density $\rho = \frac{N}{l^3}$. (Boyle-Mariotte law).

If, however, l becomes very small, the motion of different particles of our electronic gas must be quantised and no more than two electrons may stay on the same energy level (Pauli principle). With still decreasing l (increasing density), the distances between quantum levels become larger so that finally all levels will be densely occupied by electrons (this state is called saturated Fermi-gas), and the further compression must be inevitably connected with the increase of the velocity v. According to the fundamental relation of quantum theory, the momentum of the particle moving in the space of linear dimension l is given by:

$$p \sim \frac{h}{l},$$

where h is the quantum-constant; thus for saturated gas the momentum is inversely proportional to l. As far as the momentum is small compared with mc (velocity v small compared with the velocity of light), we can use the relation $v = \frac{p}{m}$, which means that the velocity itself is inversely proportional to l. The formula (4) shows us that in this region of densities the pressure P is inversely proportional to l^5; i. e., directly proportional to $\rho^{5/3}$. For still larger densities the average velocity of the particles approaches the velocity of light. After this limit we must write $n = \frac{c}{l}$ for the number of collisions and still use the formula (5) which is correct also in the relativistic case (the increase of p is here due to the increase of the mass

$$\left(m = \frac{Mo}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}\right)$$

We see that for such large densities the pressure P varies as $\frac{1}{l^4}$ or as $\rho^{4/3}$. The diagrammatic representation of the (p, ρ)-relation for the ideal electronic gas is shown on Fig. 1, by the curve I.

The outside pressure P' due to gravitation is, as is well known, proportional to $\rho^{4/3}$ and the coefficient of proportionality depends on the total mass M of the star. The curves II′, II″ and II‴ represent (P', ρ)-curves for three different masses. We see that if M is small (curve II′) the inside pressure will be always larger and the star will expand and cool down until it will be turned into a large piece of stone. For somewhat larger mass (curve II″) there is a state of stable equilibrium between P and P' and the finite stage of the star will have inside a region filled up with nonrelativistic saturated Fermi-gas. For still larger masses (curve II‴) the inside pressure will never be able to oppose the weight of stellar substance and the star would collapse into a mathematical point (!) unless the further compression would be stopped by intranuclear repulsive forces between the particles of nuclear gas. This will happen when the distance between the particles is of the order 10^{-12} cm.; i. e., when the density approaches the value of 10^{12} relative to water! Thus we come to the conclusion that such a star will have in its center a very dense nucleus differing from the atomic nuclei only by its size which can be several miles in cross section. By calculations still further elaborated Landau was able to show that the limiting mass for which the stellar nucleus must be formed is about one third of the mass of our sun. Consulting astronomical data we find that this corresponds to the lower limit of stellar masses, which means that *all stars possess such nuclei which evidently represent the sources* *of the stellar* energy radiated in such large amounts into interstellar space.

The question of the mechanism of energy-liberation is not yet quite clear but one can easily see that the gravitational energy alone liberated in the compression (Helmholtz's old theory) to such large densities would be enough to secure sufficiently long periods for stellar lives.

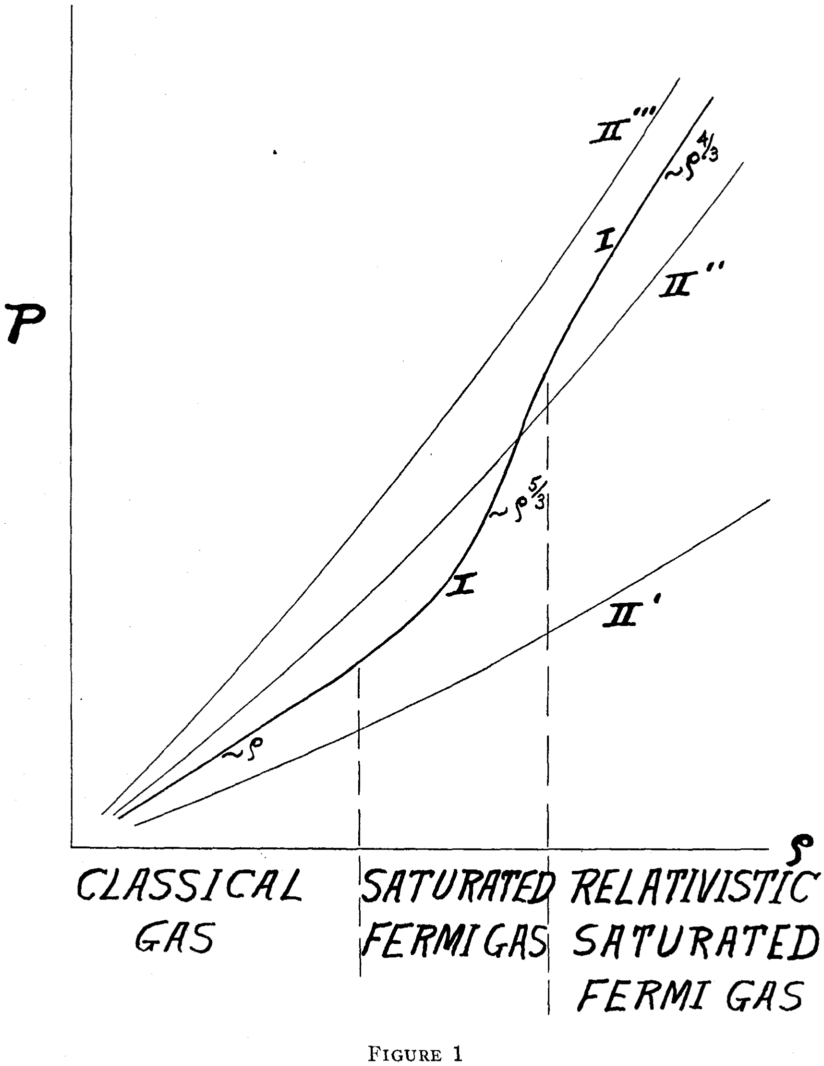

FIGURE 1

In this article we are interested especially in the role played by stellar nuclei in the formation of heavy elements. One can easily imagine that the stellar nucleus may not be considered as an inactive globe. The eruptive processes from its surface will throw out the small pieces of nuclear substance which coming into the outside layer of the star will immediately disintegrate giving rise to the nuclei of different stable and radioactive elements.

We see thus that there are many different phenomena inside of a star giving rise to formation and transformation of different elements and the hope may be justified that further investigation will clarify the relative importance of various processes and lead to a complete explanation of the relative abundance of different elements in the universe.

BIBLIOGRAPHY

(1) For details see G. Gamow, Constitution of Atomic Nuclei and Radioactivity, Oxford University Press, 1931, or the new considerably enlarged edition of the same book due to appear in 1936.
(2) **Cockcroft and Walton.** Proc. Roy. Soc. 136, 619 (1932); 137, 229 (1932).
(3) **E. Fermi.** Proc. Roy. Soc. 146, 483 (1934); 149, 522 (1935).
(4) **R. Atkinson** and **F. G. Houtermans.** Zeits. f. Physik 54, 656 (1929).
(5) **L. Landau.** Phys. Zeits. d. Sowjetunion 1, 88 (1932); 2, 46 (1932).

The Genetic System

This book is a radical departure from the usual genetics text. It is a careful, scholarly, point-by-point analysis of the materials and methods of genetics. One by one the assumptions and principles of heredity are held up to the light of scientific inspection, scrutinized, and evaluated. The formal logic, the one-two-three arrangement of points, and the insistent and almost exclusive use of Drosophila material, become almost monotonous by the time the reading of the volume is completed. One finds himself with the feeling that simple things have at times been made more difficult than necessary.

The distinction between heredity and the mechanism of heredity has been relegated to the past, and the author considers the facts and principles of inheritance under the broad heading of The Genetic System. The book is scantily illustrated, and the use of symbols for genes is far from consistent throughout the book. The mathematical implications of various systems of mating in populations, the question of equilibrium in populations, and their important corollary, the gene-frequency method, are not mentioned. An excellent chapter on the relation of characteristics to the environment provides a welcome break in the didactic presentation. The final two chapters, on chromosomal aberrations and mutations, respectively, are likewise warmer in tone and less painfully formal than the earlier chapters.

In the opinion of the reviewer, the book is unsuitable for an elementary text in genetics, but provides an excellent critique and a good lesson in logic for the more advanced student of genetics who wishes to review and "fix" his knowledge of the subject.—L. H. S.

Genetics, by H. S. Jennings. xiv+373 pp. New York, W. W. Norton & Co. 1935.

Vertebrates Through the Microscope

This volume presents a compact, concisely-written account of vertebrate histology, unique in that it is not centered around man and medical histology. System by system the microscopic anatomy of various forms is taken up on a descriptive basis. Widely varying vertebrate forms are used as examples, and the student is encouraged to discern the variations between the general descriptions given in the text and the specific form he may be studying at the time. The book is fully and excellently illustrated with diagrams and photomicrographs, mostly original. An excellent chapter on the blood cells presents clearly the differential classification based on the new supra-vital technique. Another very worth-while chapter is concerned with the histology of the endocrine glands. The final chapter is a concise outline of general histological technique. References accompany each chapter, with a general text reference at the end of the book.—L. H. S.

The Microscopic Anatomy of Vertebrates, by George G. Scott and James I. Kendall. 306 pp. Philadelphia, Lea and Febiger. 1935.

Pacemakers

This, the first of a proposed new series of monographs on experimental biology, deals with certain mechanisms underlying vital processes. The master reactions, or pacemakers, controlling the dynamic steady state, are presented and analyzed, as keys to the understanding of protoplasmic events. These are of the utmost importance to students of the behavior of living organisms, whether these students call themselves biochemists, biophysicists, physiologists, botanists, zoölogists, behaviorists, or psychologists. To bring out the central idea that a great deal of the overt behavior of organisms is determined by the interrelations of chemical events within cells and groups of cells quite independently of external environmental factors, the work of many investigators is presented and correlated. Chief among these are Osterhout and his colleagues, Parker, Crozier and their students, and the author and his own students. The various phenomena chosen as the basis for the correlated conclusions are permeability, growth, bioelectric effects, rhythmic activity, lateral line effects, sensory adaptation, and the physiology of the sense of time. The author is to be congratulated on bringing together in unified form such a series of interrelated phenomena. We wish success to this new series of monographs.—L. H. S.

Pacemakers in Relation to Aspects of Behavior, by Hudson Hoagland. x+138 pp. New York, the Macmillan Co. 1935.

How Good is Best?

The question of the range of human capacities and the comparative abilities of men becomes of importance in our present attempts at social reorganization. Are the seemingly great differences between men real or only apparent? The author of this unique volume concludes that the differences which separate the mass of mankind from one another are small, the ratios of the extremes of any given trait or ability, whenever measurable, falling within the limits of 1.3 and 2.5. The implications of this fact are discussed in detail. The point is made that genius represents only an added increment of qualities existent in all men, the increment at this point in the scale resulting in more profound changes than at others; much as an added degree of heat applied to water at 99° may profoundly change its characteristics, yet this added degree being no more of a quantitative increment than any other in the process of raising the water to a temperature of 99°. The raw data from which the conclusions of the book are drawn are given in full in appendices. It is quite certain that the responses of various readers of the volume will vary considerably in the degree of acceptance of the treatment and conclusions, yet it is imperative that the book be critically read by biologists, psychologists, sociologists, economists and statisticians.—L. H. S.

The Range of Human Capacities, by David Wechsler. ix+159 pp. Baltimore, the Williams and Wilkins Co. 1935.