SOVIET PHYSICS USPEKHI VOLUME 2(68), NUMBER 4 JULY-AUGUST, 1959

Physics of Our Day

THE ORIGIN OF THE CHEMICAL ELEMENTS

D. A. FRANK-KAMENETSKIĬ

Usp. Fiz. Nauk **68**, 529-556 (July, 1959)

THE goal of every scientific theory is the interpretation of a certain set of observed facts, which are its empirical basis. Data on the abundances of the chemical elements in the universe (i.e., data on the chemical composition of cosmic matter) serve as the basis of the theory of the origin of the elements. These data cannot, of course, be exact, but even the coarsest analysis permits the determination of certain regularities, whose explanation is the fundamental problem of the theory of the origin of the elements. We shall begin with a review of these experimental data.

THE CHEMICAL COMPOSITION OF COSMIC MATTER

The determination of the average chemical composition of cosmic matter requires the comparison of a vast amount of data. The variety of chemical compositions of various constituent parts of the earth's crust has made the averaging of the results of their analyses exceedingly difficult. Hence, although the basic qualitative characteristics of the curve of abundance of the elements is confirmed by the geological data, this curve has generally been constructed on the basis of analyses of matter of extraterrestrial origin. At present, the average specimen of cosmic matter is generally considered to be the so-called chondritic meteorites.[1] This is the most frequently found type of stony meteorite, and is distinguished by the fact that the structure of these meteorites contains fine stony globules, or chondrules. The chemical composition of chondritic meteorites is distinguished by quite definite characteristic features. On the basis of a large number of analyses of these meteorites, and also taking into account the geological and astrophysical data, Suess and Urey[2] have compiled a table of the relative abundances of the elements. The curve in Fig. 1 is constructed from these data. Here the abscissa is the mass number A, and the ordinate is the logarithm of the abundance, i.e., the relative number of atoms with the given mass number. The unit of abundance is taken such that the abundance of silicon equals one million. Such a unit is convenient because in this scale the abundances of the majority of heavy elements are expressed by numbers of the order of unity.

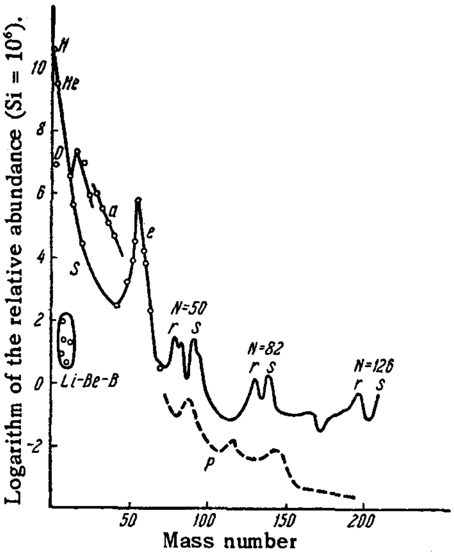

FIG. 1. Curve of the atomic abundances of the elements, according to Suess and Urey.

The basic qualitative features of this curve agree with the results of spectroscopic analysis of stellar atmospheres, geological study of the earth's crust, and the existing data on the composition of the primary cosmic rays, which apparently reflects the composition of the interstellar gas.

The quantitative agreement between the results of chemical analyses of chondritic meteorites and the spectroscopic analysis of stellar atmospheres is not good for all elements. In a number of cases, particularly iron and its neighboring elements, considerable discrepancies have been observed; the reasons for these discrepancies are not yet clear. However, the calculation of the chemical composition from the intensities of the Fraunhofer lines in stellar spectra is not yet sufficiently reliable.

This prevents us from taking the spectroscopic data as the basis for constructing the curve of abundances of the elements.

HYDROGEN AND HELIUM

Of course, the complete curve of abundances cannot be constructed on the basis of analyses of stony (chondritic) meteorites alone. In particular, the most volatile elements, hydrogen and helium, are absent from meteorites. One must roughly estimate their abundances from the total mass of matter in all the stars, nebulas, and interstellar gas. Of course, this estimate is very imprecise, but the qualitative conclusion is undoubtable: hydrogen and helium are the fundamental components of cosmic matter. All the remainder may be considered as a slight impurity. According to the estimate of Suess and Urey, the content of hydrogen in cosmic matter is 40,000 times that of silicon (in number of atoms). Since silicon is one of the most abundant among the remaining elements, the number of atoms of hydrogen and helium is thousands of times greater than the number of atoms of all the remaining elements.

This result is confirmed by the data of theoretical astrophysics. These lead to the conclusion that, to a coarse approximation, the properties of the overwhelming majority of stars can be satisfactorily described by a model consisting only of hydrogen and helium. Thus, a hydrogen-helium model of the sun has been constructed,[3] and shows properties very near those of the actual sun. Hence it follows that the basic features of the internal structure of the sun are determined by the properties of a hydrogen-helium mixture. All the remaining elements may be considered as a slight impurity in this mixture, and their influence on the properties of the star as a slight correction to the hydrogen-helium model. The same conclusion remains valid for the bulk of the stars of the main sequence, to which the overwhelming majority of all stars belong.[4,5] The only group of stars in which the heavy elements play a basic role, hydrogen being completely absent, is that of the white dwarfs, the stars in which all the hydrogen has already been burned up by nuclear reactions. Very few of these stars are known. The fact is that, owing to their low luminosity, it is hard to observe them, and only the nearest ones are known to us. At present it is difficult to judge what the total number of white dwarfs is, or what influence they have on the chemical composition of the universe. However, from the existing data one could hardly expect that this influence is very significant.

The ratio between helium and hydrogen may be estimated only by applying the theory of the internal structure of stars.

The problem of the abundance of deuterium has not at all been clarified. If the content of deuterium in cosmic hydrogen is the same as in terrestrial hydrogen, deuterium must be one of the most abundant elements. However, we possess no direct data on the deuterium content of extraterrestrial matter.

FUNDAMENTAL QUALITATIVE REGULARITIES OF THE ABUNDANCE CURVE

On the curve shown in Fig. 1 one can see immediately a number of distinct qualitative regularities, manifested as more or less sharp maxima and minima in the curve.

After the very high abundance of hydrogen and helium, there follows immediately such a sharp decline that the curve cannot be drawn smoothly in this region on the graph. This decline corresponds to the light nuclei lithium, beryllium, and boron.

Beyond this, the curve rises sharply upward, and shows a smooth, broad maximum in the region of carbon, oxygen, neon, magnesium, silicon, sulfur, and calcium. Characteristic of this region are the especially high abundance of the symmetrical nuclei with $A = 4n$ and $Z = 2n$, which may be obtained from whole numbers of α particles (helium nuclei).

Beyond calcium, a sharp decline follows again to the exceedingly low abundance of the element scandium. This decline, to which insufficient attention has thus far been paid in the literature, we shall call the "scandium gap."

After the scandium gap, the abundance curve rises upward very sharply to the sharpest of all the maxima occurring on it. On this maximum lie iron, nickel, and their neighboring elements; hence it is called the iron maximum.

After the iron maximum, the abundance curve drops sharply as far as the region of mass numbers about 100. This decline is shown linearly on the curve in Fig. 1, but since the logarithm of the abundance is plotted on the graph, the abundance actually falls exponentially with the mass number in this region.

The region of the heavy elements begins with $A = 100$, where the abundance remains of the same order of magnitude on the average over a broad range of mass numbers. On this background, maxima are clearly visible, which are considerably lower than the iron maximum. These maxima correspond to the nuclei with neutron numbers 50, 82, and 126, the so-called "magic numbers," i.e., closed neutron shells. These maxima were noted long ago,[6] and their discovery was the first impetus to the development of the theory of nuclear shells.

Upon this coarse structure of the abundance curve is superimposed a fine structure. Above all, nuclei with even mass numbers show a greater abundance. Besides, the maxima near the magic numbers turn out to be doubled. Finally, on careful examination of the region of heavy nuclei, it is possible to see another smeared-out maximum near A = 160. It is much less clearly marked than the maxima at the magic numbers.

These are the basic qualitative regularities of the abundance curve of the elements, which the theory is required to explain.

POSSIBLE PATHWAYS OF THE SYNTHESIS OF THE ELEMENTS FROM THE VIEWPOINT OF NUCLEAR PHYSICS

The classical physics of the 19th century considered the elements to be eternal and immutable. The clear qualitative regularities in the abundances, which have just been enumerated, admitted of no interpretation whatever from this viewpoint. One might say that the existence of these regularities is one of the pieces of evidence of the insufficiency of the old classical physics, since it could offer nothing in explanation.

In modern nuclear physics, an entire series of processes are known which may lead to the synthesis of atomic nuclei in nature. The analysis of these processes must give a definite, although perhaps qualitative explanation of the abundance curve. All of these processes are nuclear reactions of some type or other.

We may subdivide all the nuclear reactions which can in principle lead to the formation of the elements into the reactions between charged particles and the reactions involving neutrons. All the nuclear particles except the neutron have positive electric charges which lead to Coulomb electrostatic repulsion between them. The approach of these particles is hindered by the Coulomb potential barrier; the height of the barrier increases as the product of the charges of the interacting particles. If the particles obey classical mechanics, they can surmount this barrier only at very high energies of the order of mega-electron volts (Mev). As a rough estimate, when particles of charges Z_1 and Z_2 interact, the mass numbers being A_1 and A_2, the height of the potential barrier is

$$E_B \approx \frac{Z_1 Z_2}{\sqrt[3]{A_1}+\sqrt[3]{A_2}} \text{ Mev}. \tag{1}$$

The proportionality coefficient here is close to unity.

Since nuclear particles obey quantum mechanics, they are able to tunnel under the barrier. That is, they may approach each other with energies less than the height of the barrier. As an estimate of the probability $\mathfrak{P}$ of this tunneling, quantum mechanics gives an approximate formula:

$$\mathfrak{P} \sim \exp\left(4\sqrt{\frac{E_B}{E_R}} - \frac{2\pi Z_1 Z_2 e^2}{\hbar v}\right), \tag{2}$$

where v is the relative velocity of the particles; E is the kinetic energy in the potential well:

$$E_R \approx \frac{10}{A\left(\sqrt[3]{A_1}+\sqrt[3]{A_2}\right)^2} \text{ Mev};$$

A is the reduced mass of the particles, in atomic weight units:

$$A = \frac{A_1 A_2}{A_1 + A_2}.$$

Owing to tunneling under the barrier, nuclear reactions between charged particles may proceed at much smaller energies than the height of the barrier. However, the rate of such a reaction according to formula (2) varies exponentially with the velocity or energy of the particles. For nuclear reactions between charged particles to proceed at a measurable rate, the particles must have sufficient energy. The greater the product of the charges of the particles, the greater this energy must be. In practice, this energy is not measured in Mev, but in units a thousand times smaller: kilo-electron volts (kev). At lower energies, the rate of the reaction declines exponentially.

From what has been stated, it follows that to synthesize nuclei by means of reactions between charged particles, the particles must necessarily have energies of the order of kev or greater (depending on the charges). This energy may be either thermal energy, or may be obtained by acceleration of individual particles by electromagnetic fields or other processes not involving heat. In the first case, one speaks of thermonuclear reactions, and in the second case, of nuclear reactions due to athermal acceleration.

Reactions with neutrons do not require the surmounting of energy barriers, and may proceed at arbitrarily low energies. In fact, the effective cross-sections for interaction of neutrons with nuclei even increase with decreasing energy, as a rule. Actually, the interaction of a neutron with a nucleus at low energies has the character of the capture of the neutron with the emission of a γ quantum. Here one obtains not a new element, but another isotope of the same element. However, processes of this type lead finally to the formation of unstable isotopes — nuclei which are overloaded with neutrons, and which then undergo β decay with the emission of an electron and a neutrino to give nuclei having the higher value of Z corresponding to the next element. Thus, in the presence of neutrons, the combination of successive processes of γ capture and β decay may lead to the synthesis of elements. High energies are not required for this process, provided that they are not necessary in order to produce the neutrons themselves.

We may classify the pathways for the synthesis of the elements which are possible from the viewpoint of nuclear physics as follows:

1. Reactions between charged particles:
   a) thermonuclear reactions,
   b) reactions due to processes of athermal acceleration.
2. Reactions involving neutrons.

The simplest of these processes, from the point of view of the physical conditions that they require, are the thermonuclear reactions, which we shall now discuss.

THERMONUCLEAR REACTIONS

The rate of a thermonuclear reaction is determined by the probability of tunneling by a particle under the Coulomb barrier, according to formula (2). Here we must take into account the distribution of the velocity v among the particles according to thermodynamic equilibrium, i.e., according to Maxwell's law. On multiplying the probability of tunneling at a velocity v by the number of particles having this velocity

$$n(v) \sim e^{-\frac{\mu v^2}{2kT}}$$

(μ is the reduced mass), and integrating over all velocities, we find as the mean probability of tunneling:

$$\overline{\mathfrak{P}} \sim \int \exp\left(-\frac{\mu v^2}{2kT} - \frac{2\pi Z_1 Z_2 e^2}{\hbar v}\right) dv. \tag{3}$$

The integrand of this formula has a sharp maximum at the velocity at which the following quantity has a minimum:

$$\frac{\mu v^2}{2kT} + \frac{2\pi Z_1 Z_2 e^2}{\hbar v},$$

i.e., at the velocity

$$v_m = \sqrt[3]{\frac{2\pi Z_1 Z_2 e^2 kT}{\mu \hbar}}. \tag{4}$$

This is the optimal velocity, at which the reaction basically proceeds. At lower velocities, the probability of tunneling is small, while at higher velocities, there are few particles having the given velocity.

The integrand in (3) expresses the relation of the reaction rate to the Coulomb electrostatic interaction. If the specific nuclear interaction varies smoothly with the energy, then the temperature-dependence of the rate of the thermonuclear reaction will be determined by the integrand of (3) at the value of v given by (4). That is, it is determined by the integrand $e^{-\chi}$, where the temperature barrier exponent χ is equal to:

$$\chi = 3\sqrt[3]{\frac{(\pi Z_1 Z_2 e^2)^2 \mu}{2\hbar^2 kT}}. \tag{5}$$

Upon substitution of the values of the universal constants, we have numerically:

$$\chi = 4248\sqrt[3]{\frac{Z_1^2 Z_2^2 A}{T}} \ (T \text{ in } ^\circ\text{K}) \tag{6}$$

Here the reaction basically proceeds by means of the particles having the optimal energy, which corresponds to the maximum of the integrand in (3):

$$E_m = \frac{\chi}{3} kT. \tag{7}$$

In many cases, the dependence of the specific nuclear reaction on the energy shows resonance maxima corresponding to quasi-stationary energy levels of the compound nucleus. If such a maximum is close to the optimal energy in (7), the thermonuclear reaction will proceed basically at the resonance energy. The character of the temperature dependence will change here, and will be expressed by the function $\exp(-E_r/kT)$, where E_r is the resonance energy.

From the physical considerations presented here, we can estimate the temperature sufficient for thermonuclear reactions to proceed. This temperature is determined by the condition that the index χ must not be too large, and depends on the product Z_1Z_2. For the lightest nuclei, this temperature turns out to be of the order of 1 kev, that is, in customary units, of the order of 10^7 °K. The required temperature increases rapidly with increase in the charges of the particles. A precise estimate of the temperature depends not only on the value of the temperature barrier exponent χ, but also on the coefficient of the exponential.

PHYSICAL CONDITIONS IN THE INTERIORS OF STARS

Of the cosmic objects surrounding us, we may expect to find the highest temperatures in the interior regions of stars. The first question posed by the theory of the origin of the elements is whether thermonuclear reactions that lead to the synthesis of the elements can proceed in the interiors of stars.

This question was first studied twenty years ago by Bethe[7] in his classical paper which launched the development of nuclear astrophysics. As it happened, a negative answer was obtained in this paper. For stars with internal constitutions similar to that of our sun, nuclear reactions may lead only to the transformation of hydrogen into helium; this is the source of the star's energy. The formation of elements heavier than helium in such stars is excluded.

To understand how this result is obtained, we must explain how the temperature at the center of a star is estimated. It is important to emphasize that this estimate depends neither on the law of heat conduction nor on the law of generation of energy. It is based solely on the condition of hydrostatic equilibrium between the pressure and the force of gravity.

Within the accuracy of a dimensionless coefficient, the condition of hydrostatic equilibrium may be obtained from simple considerations of similitude. The force due to the pressure, which tries to expand the star, is

$$F_P = \frac{1}{\rho}\frac{\partial P}{\partial r}, \tag{8}$$

where P is the pressure and ρ is the density.

The force of gravity hindering the expansion is

$$F_G = \frac{G\mathfrak{M}(r)}{r^2}, \tag{9}$$

where G is the gravitational constant, $\mathfrak{M}$ is the mass, and r is the distance from the center of the star. For stars similar in internal structure, it follows from similitude that

$$F_P = \eta\frac{P}{\rho r}, \tag{10}$$

where the values of P, ρ, and r are taken at corresponding points, and η is a structural factor, i.e., a dimensionless number depending on the internal structure of the star. If P and ρ are referred to the center of the star, and r to its surface, the condition of hydrostatic equilibrium acquires the form

$$\eta\frac{P_c}{\rho_c\mathfrak{R}} = \frac{G\mathfrak{M}}{\mathfrak{R}^2},$$

where the index c refers to the center of the star, and $\mathfrak{R}$ is the radius of the star. Hence, the physical state of the matter at the center of the star is characterized in the general case by the condition

$$\frac{P_c}{\rho_c} = \frac{G\mathfrak{M}}{\eta\mathfrak{R}}. \tag{11}$$

Now, let the matter in the center of the star obey the ideal gas law:

$$P = \frac{RT\rho}{\mu}, \tag{12}$$

where R is the gas constant, and μ is the average molecular weight of the stellar matter. Then the condition of hydrostatic equilibrium directly determines the temperature at the center of the star:

$$T_c = \frac{\mu G\mathfrak{M}}{\eta R\mathfrak{R}}. \tag{13}$$

The masses and radii of stars may be conveniently expressed in solar units, equal respectively to the mass and radius of the sun. On transforming to these units and substituting in the values of the universal constants, we obtain

$$T_c = 22.908\cdot 10^6\frac{\mu\mathfrak{M}}{\eta\mathfrak{R}}\ ^\circ\text{K}. \tag{14}$$

Physicists more commonly measure the temperature in energy units. A suitable temperature unit for the central zone of stars is the kilo-electron volt (kev). In these units

$$T_c = 1.98\frac{\mu\mathfrak{M}}{\eta\mathfrak{R}}\ \text{kev}. \tag{15}$$

If the thermodynamic state of the matter varies smoothly with the distance from the center of the star (we shall call such stars homogeneous), we may naturally expect that the structural factor η must be a number of the order of unity. Its exact value may be found by numerical integration of the equation of equilibrium of the star. Here it turns out that for stars similar in their internal structure to our sun, the factor η is very near to unity. Hence, for a rough estimate of the central temperature of homogeneous stars, one may use formula (14) or (15), taking $\eta \approx 1$. Then the central temperature depends only on the mass-radius ratio of the star, and on the average molecular weight of the stellar matter.

At the temperatures of interest to us here, matter is of course completely ionized. The average molecular weight then is equal to the number of atomic weight units per particle (including both nuclei and electrons). The values are the following:

for hydrogen, $\mu = 1/2$,
for helium, $\mu = 4/3$,
for all heavier elements, $\mu \approx 2$.

Thus, if we consider the sun to consist of pure hydrogen, its central temperature will be near 1 kev; if it consists of helium, its temperature will be about 3 kev, and for the heavier elements, about 4 kev. We may consider it firmly established at present that the sun and the homogeneous main-sequence stars similar to it consist basically of hydrogen and helium. The mass radius ratio of such stars varies within rather narrow limits. Hence their central temperatures must lie within 1 or 2 kev. The impurity of heavy atoms may have a considerable influence on the radiative heat conductivity, but has practically no effect on the average molecular weight. Thus, the estimate of the central temperature from the condition of hydrostatic equilibrium is quite reliable.

Temperatures of this order of magnitude are sufficient for the occurrence of nuclear reactions of hydrogen leading to its transformation into helium, and serving as the energy source of the stars. However, they are not at all sufficient for the reactions of synthesis of the heavy nuclei, which require the surmounting of high potential barriers. This conclusion, drawn twenty years ago in Bethe's study,[7] remains in full force today. Hence, as long as all stars are considered to be homogeneous, the formation of elements within them is impossible. Hence, theories have arisen which relate the formation of the elements to a hypothetical prestellar stage in the development of matter.

THE THEORIES OF THE PRESTELLAR FORMATION OF THE ELEMENTS

In so far as we have no factual data on the prestellar state of matter, we may make any assumptions we please about it. Hence the prestellar theories, which were in great vogue until recently, had the possibility of admitting any hypothetical conditions whatever in order to explain the observed abundance curve.

The theories of the prestellar formation of elements are divided into two groups: the theories of thermodynamic equilibrium and the theories of capture of primordial neutrons.

The thermodynamic theory of the origin of the elements was the only possible theory as long as no detailed mechanism of nuclear reactions was known. It is sufficient to assume that in the process of synthesis of nuclei, the temperatures and densities were so high that the direct and reverse reactions proceeded rapidly enough that thermodynamic equilibrium could be attained within the time during which this state endured. If this condition is satisfied, the composition of the equilibrium mixture does not depend on the reaction rates, but is determined by the binding energies and the statistical weights of the nuclei being formed.

If a nucleus consists of Z protons and N neutrons, then by the laws of statistical thermodynamics its equilibrium concentration n_{nuc} is found to be

$$n_{\text{nuc}} = n_p^z n_N^N \frac{\Phi_{\text{nuc}}}{\Phi_p^z \Phi_N^N} e^{\frac{E}{kT}}, \qquad (16)$$

where n_p and n_N are the concentrations of free protons and neutrons, E is the binding energy of the nucleus, and Φ are the partition functions of the particles:

$$\Phi = \sum_i g_i e^{-\frac{\varepsilon_i}{kT}} \approx g \frac{(2\pi MkT)^{3/2}}{h^3}, \qquad (17)$$

where g is the statistical weight, which is equal in the simplest case to $2I+1$, where I is the total angular momentum (nuclear spin). At low temperatures ($kT \ll E$), the exponential factor is so great that at equilibrium, only the nucleus with the greatest binding energy can remain. To obtain all the nuclei in appreciable concentrations, it is necessary that the temperature be no lower than an order of magnitude smaller than the binding energy of the neutron in the nucleus. Thus the equilibrium theory of the formation of the elements requires temperatures of the order of tenths of one Mev, that is, in ordinary units, of the order of billions of degrees Kelvin.

This theory began thirty years ago with the study of the Soviet scientist G. I. Pokrovskiĭ.[8] It was developed further by a number of authors, especially Klein and his associates[9,10] and Hoyle.[11] A summarized presentation of the theory may be found in a series of reviews.[12-14] Since there are no reliable data on the existence of the required temperatures in the heavenly bodies surrounding us, the problem of the theory was to select arbitrary physical conditions at which the composition of the equilibrium mixture would approximate the observed composition of cosmic matter. Here the question remains vague as to how the equilibrium attained at high temperatures is to be frozen. On this equilibrium, there are only some rough qualitative estimates.

Even in his first paper, Pokrovskiĭ[8] came to the conclusion that one cannot select values of the temperature and density such that the observed abundances of all the elements will all fit one equilibrium curve. This conclusion is still valid today.

The further development of the equilibrium theory consisted in representing the observed abundances as the result of the superimposition of a series of equilibrium processes proceeding under differing physical conditions. Thus, hypothetical bodies have been constructed[10] with temperature and density distributions such that the integration of the composition of the equilibrium mixture over this distribution gives a result approximating the observed abundance curve. It is difficult to discuss such models since they are not connected with any observed facts. Extreme physical conditions figure in them: temperatures up to 7×10^9 deg K and densities up to 10^7 g/cm^3. There are no known factual data at present which would indicate the possibility of the actual realization of such conditions.

Recently in the papers of Hoyle,[11] the equilibrium theory has acquired a more realistic character, in that it poses as its problem the explanation, not of the entire abundance curve, but only of a small region of it near the iron maximum. Here, the rpocess of establishment of equilibrium is not referred to a hypothetical prestellar state of matter but to the actually-observed explosions of supernovas. These conceptions have entered as a constituent part of the contemporary scheme of the elements, to which we shall refer below.

As a general scheme, the equilibrium theory had the defect that it had no connection with the other branches of science concerning the universe. More attention has been paid to another theory, which has attempted to connect the problem of the origin of the elements with general cosmology. This is the theory of the capture of primordial neutrons, which is based on the observations of the red shift in the spectra of the extra-galactic nebulae and on the associated theory of the "expanding universe."

In the theory of primordial neutrons, it is assumed that the prestellar state of matter was a neutron state with a very high density. At such a density, the gravitational energy causes the neutron state to be energetically favorable, i.e., stable. Owing to the relativistic expansion of space, the density decreased, and the neutrons became unstable with regard to the β decay that transformed them into protons. The protons which were formed captured neutrons with the formation of deuterium, and thus began a chain of successive processes of γ capture and β decay, which must lead to the formation of all the nuclei up to the heaviest, according to this theory. Neutron capture does not require the surmounting of a potential barrier, so that this theory does not show any rigid temperature requirements. However, it has a very rigid time scale, which is fixed by the half-life of the free neutron, which amounts to only 11.7 minutes.[15] Consequently, according to the theory of primordial neutrons, all of the elements which have existed for billions of years must have been formed during a period of the order of fifteen minutes. After this time had elapsed, none of the primordial neutrons could have remained, and the process of synthesis of nuclei must have ceased.

It is not surprising that a theory involving such spectacular and paradoxical conceptions has made a strong impression and has been pleasing to many. It has even been used as a proof of the correctness of the cosmological conception of the expanding universe. It is understandable that this theory has been pleasing to people of a religious frame of mind, since it is easily associated with religious concepts. As an example, we may give an interesting reference from a message of the late Pope Pius XII to the Papal Academy of Sciences in the Vatican, November 21, 1951:

"Approximately from one to ten billion years ago, the matter of all the stellar systems which we know was compressed into a small space. At that time, all cosmic processes had their origin. The density, pressure, and temperature of matter must have attained then quite colossal values. Only under these conditions can we explain the formation of the heavy nuclei and their content in the periodic system of elements."

The fact alone that some scientific theory may be used as a medium for religious propaganda must not prejudice our relation to it. A scientific theory must be subjected to objective scientific verification by comparison with observed facts. In the present case, as we shall now see, the theory of primordial neutrons did not pass such a test.

THE TEST OF THE THEORY OF NEUTRON CAPTURE

In order to decide on the acceptability of the theory of primordial neutrons, it is necessary to find out how well it agrees with the observed abundances of the elements, on the one hand, and with the data of nuclear physics, on the other hand. The result is satisfactory in the first regard, but not in the second. We shall consider what relations the abundances of the elements must satisfy if they are the result of neutron capture. The concentration n_A of the nucleus with mass number A in the neutron-capture process varies according to the law

$$\frac{dn_A}{dt} = n_N v \left(\sigma_{A-1} n_{A-1} - \sigma_A n_A\right), \qquad (18)$$

where n_N is the concentration of neutrons, v is their mean velocity, and σ is the neutron-capture cross-section of the nucleus with the mass number given by the subscript of σ. If the neutron concentration and the time are sufficient, the process must lead to a steady state, for which

$$\frac{dn_A}{dt} = 0; \tag{19}$$

consequently,

$$\frac{n_A}{n_{A-1}} = \frac{\sigma_{A-1}}{\sigma_A}. \tag{20}$$

Thus, in the steady state, the concentrations of the nuclei must be inversely proportional to their neutron-capture cross-sections.

This conclusion agrees in general quite well with the abundance curve. There is no complete quantitative agreement, but one may always argue that the quantity of neutrons might not have been sufficient to establish a steady state. The fact is of importance that many of the qualitative features of the abundance curve are most simply explained by the rule that the abundance of nuclei decreases as their neutron-capture cross-sections increase. Above all, this relates to such fundamental facts as the increased abundance of nuclei with even mass numbers and the maxima at the magic numbers. In fact, it is known from neutron physics that nuclei with even mass numbers and especially those with filled neutron shells are distinguished by small neutron-capture cross-sections.

Hence it is very likely that most of the nuclei with medium or large mass numbers were formed by neutron capture. However, this does not mean that all the nuclei, including the light ones, were formed in this way, or that the original matter was made of primordial neutrons. On the contrary, a careful study of the problem from the viewpoint of nuclear physics leads to the conclusion that the process of neutron capture cannot begin with the lightest nuclei.

The reason why the theory of capture of primordial neutrons has turned out to be completely useless is the fundamental fact that there are no stable nuclei of mass numbers 5 and 8. In the process of synthesis of nuclei by neutron capture, all mass numbers must be obtained in succession. This process cannot bypass a single mass number. In particular, the nuclei He^5 and Be^8 would have to be necessary steps. However, the lifetime of Be^8 is no greater than 10^{-17} sec, while it has not been possible to observe the bound states of the nucleus He^5 at all. Thus, it has not been possible to get through these two "bottlenecks" of the theory of primordial neutrons.

Thus the facts state that the process of neutron capture must play an important role in the synthesis of the medium and heavy nuclei, but is ruled out for the light nuclei, in any case for those with $A < 9$. As long as it was thought that nuclei heavier than helium are not formed in the interiors of stars, one had to conclude that the theory of the origin of the elements was at an impasse. The way out was shown by the development of astrophysics, the study of the characteristics of particular types of stars.

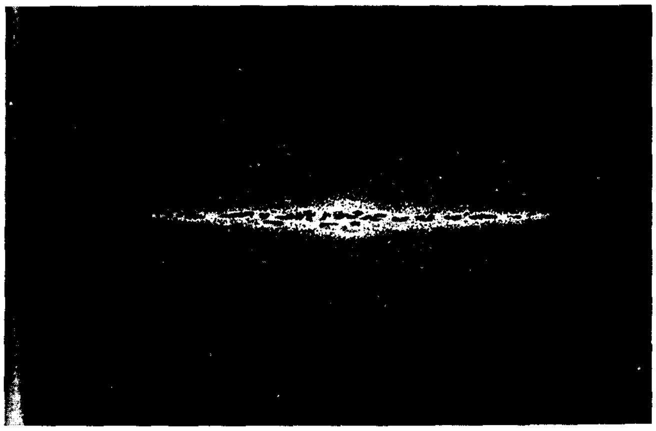

FIG. 2. Diagram of our galaxy.

HETEROGENEOUS STARS

Until recently, astrophysicists classified stars by their purely external characteristics, fundamentally by their color, that is, their surface temperatures. The so-called spectral classification of stars is actually not a classification of stars, but of stellar atmospheres.

Only in the last fifteen years have the essential differences in the internal properties of stars been elucidated. The key to their elucidation was the study of the structure and properties of stellar systems, the most important of which are the galaxies. In Fig. 2 is shown a diagram of our galaxy, which contains about 100 billion stars. One can see distinctly from the diagram that the galaxy consists of two parts, a flat disk and a sphere, which have a common center and partially interpenetrate. One of the most important achievements of observational astrophysics in the last fifteen years has been the elucidation of the fundamental distinction in internal properties between the stars of the flat and the spherical components.

The first indication of this distinction was obtained in 1942 by Baade,[16] who systematically photographed various regions of the galaxy on film sensitized to red light. It turned out that on ordinary film the flat component appears brighter, but on red-sensitive film the spherical component is brighter. Later, the differences in properties of the stars of the flat and spherical components were studied in detail. An especially extensive study in this field has been carried out by the Soviet astronomer B. V. Kukarkin.[17] Without going into detail, we note that in the flat component the majority of the most brilliant stars are white, while in the spherical component, they are red. Herein lies the differences in total brilliance between the different spectral ranges, since this brilliance is determined by the brightest stars. It is obvious that the disk and sphere consist of stars with different internal properties. In our literature they are thus designated as the stars of the flat and the spherical components. In the foreign literature, these two groups of stars are commonly called "populations;" the flat group is called the "disk," while the spherical group is designated by the sonorous name of "halo." Sometimes the flat component is called "population I," while the spherical component is called "population II." These designations are, as we shall see, very unfortunate, since the spherical component consists of the stars of the first generation, while the flat component consists of the second generation. The passion for classification which is inherent to astrophysicists has impelled them in recent years to distinguish even some intermediate "populations," so that now five "populations" may be counted. For our purposes, such fractional subdivisions are not necessary, as they only obscure the heart of the matter. Of importance to us is only the fundamental distiction between the stars of the flat and spherical components.

In order to understand the inner meaning of this distinction, we must use the favorite method of astrophysics of constructing a diagram of the states of stars. The most important of these is the color-luminosity diagram, or as it is otherwise called, the Hertzsprung-Russell diagram. On this diagram, the so-called absolute stellar magnitudes are plotted along the vertical axis. These quantities are proportional to the logarithm of the luminosity, i.e., the amount of energy emitted by the star. On the horizontal axis is plotted the color index which characterizes the color of the star, and hence, the temperature of its surface (but not at all its central temperature). The higher a star lies on the diagram, the brighter it is; the further to the right, the redder it is. However, since the redder the star the lower its surface temperature and the less energy it emits per unit of surface, then, for a given luminosity, the further a star lies to the right on the diagram, the larger its radius must be. This does not mean that the radius of a star has a simple relation to its color, of course; the lines of constant radius on the diagram are by no means vertical straight lines. The relation between the luminosity $\mathfrak{L}$ of the star, the radius $\mathfrak{R}$, and the effective surface temperature T_e has the form

$$\mathfrak{L} = 4\pi\sigma\mathfrak{R}^2 T_e^4, \tag{21}$$

where σ is the Stefan-Boltzmann constant. Hence for a constant radius, the temperature T_e is proportional to the fourth root of the luminosity. The surface temperature T_e is simply related to the color, so that the farther to the right a star lies on the color-luminosity diagram, the lower the temperature T_e is. Thus, at a constant radius, the brighter a star is, the whiter it is, but this relation is so weak that the lines of constant radius do not differ much from vertical straight lines.

In Fig. 3 is shown the classical color-luminosity diagram for the stars near to us, which, like our sun, belong to the flat component of the galaxy. On this diagram the fundamental line of concentration of stars is clearly visible, passing from the upper left to the lower right corner. This is the co-called main sequence, to which the fundamental mass of stars of the flat component belong. The points corresponding to the brightest stars of the main sequence lie in the upper left-hand corner, that is, in the region of white and blue colors. It is just for this reason that the flat component is seen most brightly on ordinary plates, which are sensitive to white and blue light. To the right above the main sequence, there is the branch of the red giants, but the number of these in the flat component is much smaller than the number of white and blue giants

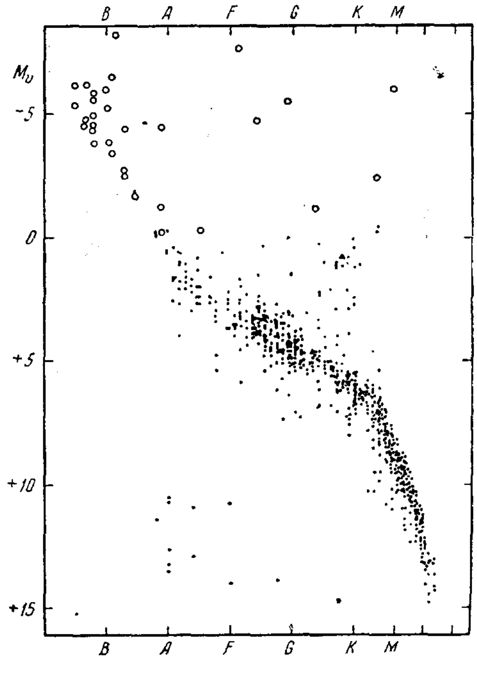

FIG. 3. Classical spectrum-luminosity diagram for the flat component of the galaxy.

and bright stars of the main sequence.

Until recently, the diagram of the type of Fig. 3 was the only known form of the color-luminosity diagram. However, after the distinction between the stars of the flat and spherical components had been elucidated, the question arose of the form of the spectrum-luminosity diagram for stars of the spherical component. It has been possible to construct such diagrams only in recent years. The difficulty here is that the stars of the spherical component are scattered in our field of view among the stars of the flat component. True, it is possible to distinguish them by their kinematic characteristics, i.e., by their velocities of motion. The flat component of the galaxy rotates about its axis, or more exactly, the stars of the flat component revolve about the center of gravity of the disk in Kepler orbits. The stars of the spherical component do not participate in this rotation; hence, we and our sun fly past them, whereas from our point of view they move with high velocities (sometimes they are called "runaway stars"). Very recently, the Soviet astronomer P. P. Parenago[18] was able to distinguish the stars of the spherical component from the background of stars surrounding us on the basis of these kinematic data and to construct the color-luminosity diagram for these stars. However, this had been done much more simply and easily somewhat earlier with the aid of a natural "homogeneous sample" of stars. This sample not only belongs entirely to the spherical component, but all the stars are of the same age. Such a homogeneous sample is the globular cluster. There are many globular clusters in the galaxy. Each contains on the average about 100,000 stars. They all belong to the spherical component. Each globular cluster seems to be a miniature copy of the whole spherical component, which it resembles both in form and in spatial distribution of stars, as characterized by a notable concentration toward the center (the stars of the flat component are concentrated toward the plane of the disk). The globular clusters themselves are also distributed in space in an approximately spherically-symmetrical fashion; many of them are scattered at rather great distances from the galactic center, beyond the main bulk of stars. There is no doubt that the stars of the globular clusters are not distinguished in their internal properties from the stars of the spherical component; this is confirmed also by the presence here and there of characteristic short-period variable stars of the cepheid type (the so-called RR Lyrae type variables, which are called in the American literature "globular-cluster type variables").

A typical form of the spectrum-luminosity diagram for the stars of the spherical component is the beautiful diagram constructed by Sandage[19] for the globular cluster M3, which we have reproduced in Fig. 4. As can be seen by comparison of Figs. 3 and 4, this diagram is sharply distinguished from the diagram for the flat component. The main sequence is almost absent in the spherical component. Only a small "tail" of it remains in the red region, which is called the sequence of subdwarfs. There are no bright white and blue stars in the spherical component. On the other hand, a sequence of red giants is clearly shown, and a new horizontal branch of yellow giants has appeared. It is natural that the spherical component is redder on the average, and hence it is more brightly visible on red-sensitive plates. The thought arises that the points which in the flat component correspond to the white and blue giants and the bright stars of the main sequence

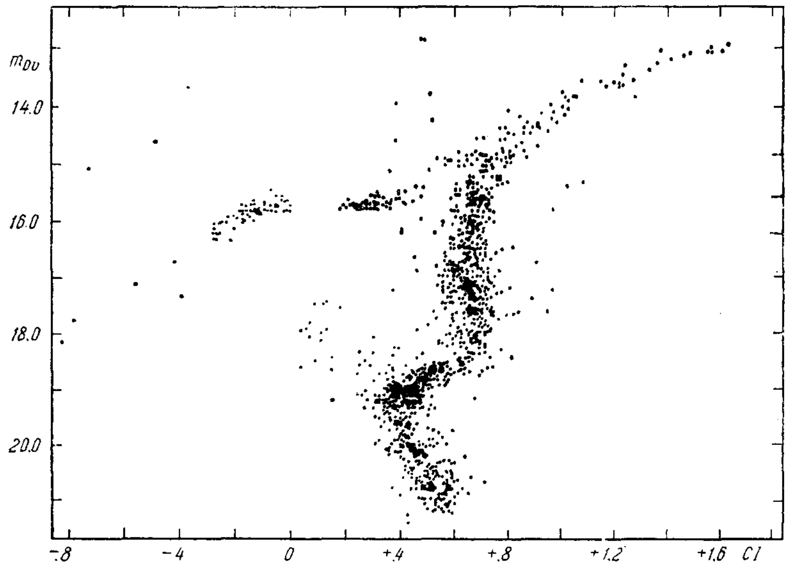

FIG. 4. Spectrum luminosity diagram for the globular cluster M3, according to Sandage.

have been shifted to the right, and the stars which correspond to them have been made into red and yellow giants. When the evolution of the stars has been examined theoretically,[19,20] it turns out that this idea completely corresponds to reality.

The determining factor in the evolution of stars is the combustion of the hydrogen in the central zone. Nuclear reactions of the proton and carbon cycles, which serve as the energy sources of the stars, lead to the transformation of hydrogen into helium. The rate of these reactions increases exponentially with the temperature, and hence the combustion of hydrogen occurs largely at the center of the star, where the temperature is highest. Around the center of the star is formed a burned-out core consisting of helium. The nuclear reactions generating energy proceed thereafter in a thin shell at the surface of the core; there is no nuclear fuel (hydrogen) at deeper levels, while nearer the surface the temperature is too low. At this stage of evolution, the star is described by a model with a shell source of energy. After a burned-out core has been formed inside the star, the properties of the matter may no longer be considered as varying smoothly over the volume of the star. At the boundary of the core, a sharp change in chemical composition from helium to almost pure hydrogen occurs. Further burning of hydrogen leads to a movement of this boundary toward the periphery of the star, the core and the envelope remaining almost constant in composition. In distinction from homogeneous stars, we shall designate such stars with inhomogeneous internal structures as heterogenous stars.

The estimate of the central temperature given above is not applicable to heterogeneous stars. Detailed calculations of the course of the evolutionary process by means of electronic computers[20,21] show that in the course of further evolution, the core must contract, and the envelope must expand. The radius of the star becomes so large that the surface temperature T_e falls according to formula (21). That is, the star becomes a red giant. At the same time, in the burned-out core high densities and temperatures are attained, which are much higher than in homogeneous stars. At this stage the core of the star is degenerate and isothermal.

When the temperature in the helium core of the star rises to about 15 kev, thermonuclear reactions of helium become possible. These reactions become the energy source within the core, which ceases to be isothermal. This moment in the evolutionary process corresponds to the uppermost point on the vertical branch of the red giants on the color-luminosity diagram. After this, the structure of the star abruptly changes again, since electronic degeneracy sets in in the core. The further course of evolution has not been precisely calculated yet, but is is assumed that on the spectrum-luminosity diagram, the star must pass over onto the horizontal branch of yellow giants. The thermonuclear reactions of helium which take place in the burned-out core of the star at this stage of its evolution play a fundamental role in the modern theory of the origin of the elements. We shall now consider these reactions.

HELIUM REACTIONS

At temperatures about 15 kev and sufficiently high densities, the reaction between three α-particles (helium nuclei) to form a nucleus of the fundamental carbon isotope C^{12} becomes possible. This reaction makes it possible to bypass the bottlenecks of the theory of the origin of the elements — the nuclei with mass numbers five and eight. After this reaction may follow the remaining reactions of the helium cycle, which give the nuclei of oxygen O^{16} and neon Ne^{20}. The rates of these reactions have been calculated by a number of authors.[22-24]

The formation of C^{12} takes place by means of the intermediate nucleus Be^8. As we saw above, the lifetime of this nucleus is infinitesimal, not longer than 10^{-17} sec. However, at temperatures of the order of 15 kev, this nucleus occurs in small but appreciable concentrations in thermodynamic equilibrium with helium. Under conditions of thermodynamic equilibrium, the rate of decay is not essential.

The small equilibrium concentration of Be^8 appears to be sufficient for the reaction of C^{12} production, since the energy of the system $Be^8 + \alpha$ is 7.374 Mev higher than the energy of the ground state of C^{12}. That is, it is very near to the energy of the second excited level of C^{12} at 7.65 Mev. Thus, the reaction of formation of C^{12} has a resonance character. The transition of the excited C^{12} nucleus to the ground state takes place by emission of two γ quanta by way of the intermediate level of energy 4.43 Mev.

The possibility of occurrence of the reaction $3\,He^4 \rightarrow C^{12}$, which had been previously predicted from theory, has more recently been confirmed experimentally.[25] The reverse process, the decay of an excited C^{12} nucleus into three α particles, has been observed experimentally, the excited C^{12} being obtained by the decay of the short-lived radioactive nucleus B^{12}. According to the principle of detailed balancing, the probabilities of the direct and reverse processes are identical; the observation of one of them is a proof of the possibility of the other.

SOURCES OF NEUTRONS IN STARS

The helium reactions in the burned-out cores of heterogeneous stars make possible the by-passing of the roadblocks in the processes of formation of the light nuclei. If we assume that the products of the helium reactions may come into contact with hydrogen, then the formation of all the light nuclei may be explained by thermonuclear reactions. The nuclei obtained may serve as the source material for the formation of all the heavy nuclei by the process of neutron capture. However, this process cannot now take place by means of primordial neutrons. Even if matter had originally occurred in a neutron state, all of the primordial neutrons would have long since decayed by the time required for the occurrence of the helium reactions. By the time when nuclei able to capture neutrons had accumulated, nothing could have remained of the primordial neutrons.

Thus the question of the primordial neutron state of matter loses any connection with the theory of the origin of the elements, and completely passes over into the field of general cosmology. Even if matter had ever existed in a neutron state, these primordial neutrons could have played no role in the processes of formation of elements heavier than helium.

On the other hand, as we saw above, a number of characteristic peculiarities of the abundance curve may be well explained by the theory of neutron capture. It is difficult to reject the conception that neutron capture plays an essential role in the processes of synthesis of atomic nuclei. However, these neutrons cannot be primordial. The further development of the theory of the origin of the elements was made possible only after possible pathways had been shown for the generation of free neutrons in thermonuclear reactions in the interiors of stars.[26,27]

The role of such neutron sources in stars may be played by exothermic (α, n) reactions of nuclei with mass numbers $4n+1$.

The stablest light nuclei are constructed symmetrically of an even number of protons and the same number of neutrons. These are He^4, C^{12}, O^{16}, Ne^{20}, Mg^{24}, Si^{28}, S^{32}, Ca^{40}. These nuclei may be considered as consisting of whole numbers of α particles (helium nuclei). If a single extra neutron is added to such a stable symmetrical system, its binding energy turns out to be anomalously low. Such an extra neutron is easily split off, especially if it is replaced by an α particle.

Let us consider for example the carbon isotope C^{13}. This nucleus may be represented as a symmetrical system of three α particles plus one weakly-bound extra neutron. It is energetically favorable for the C^{13} nucleus to combine with a fourth α particle and split off the neutron. This reaction is

$$C^{13}+He^4=O^{16}+n$$

and is an example of an exothermic (α, n) reaction. We note that a similar reaction,

$$Be^9+He^4=C^{12}+n,$$

has led to the discovery of the neutron, and is used in the still widely used radium-beryllium neutron sources.

If the products of helium reactions, C^{12} and Ne^{20} come into contact with hydrogen at temperatures of the order of several kev, they may capture protons, giving respectively N^{13} and Na^{21}. The latter nuclei are β-radioactive, and on emitting positrons are transformed into the stable nuclei C^{13} and Ne^{21}, which may serve as neutron sources by way of exothermic (α, n) reactions. The neutrons which are obtained may be captured by the same products of helium reactions, leading to the sequence of processes of (n, γ) capture and β decay which we have already discussed above. All these reactions do not require temperatures above 15 kev. Thus, thermonuclear reactions in the burned-out cores of heterogeneous stars may provide everything necessary for the synthesis of the heavy nuclei.

It has not yet been established exactly whether these neutron sources are quantitatively sufficient for synthesis of the observed amounts of the heavy nuclei. The theory of thermonuclear neutron sources in stars encounters certain difficulties. Thus, on contact of carbon with hydrogen, the entire chain of the carbon cycle must take place. In this cycle the nucleus N^{14}, in particular, takes part. As everyone who has had anything to do with neutron physics knows, this nucleus actively captures neutrons by an (n, p) reaction, giving the radioactive carbon isotope C^{14}. The presence of N^{14} "poisons" the neutron source using the nucleus C^{13}. This difficulty may be avoided if we ascribe neutron generation to reactions of the nucleus Ne^{21}, but these reactions have their own difficulties.

As we shall see below, neutrons may even be formed, not in the cores, but in the atmospheres

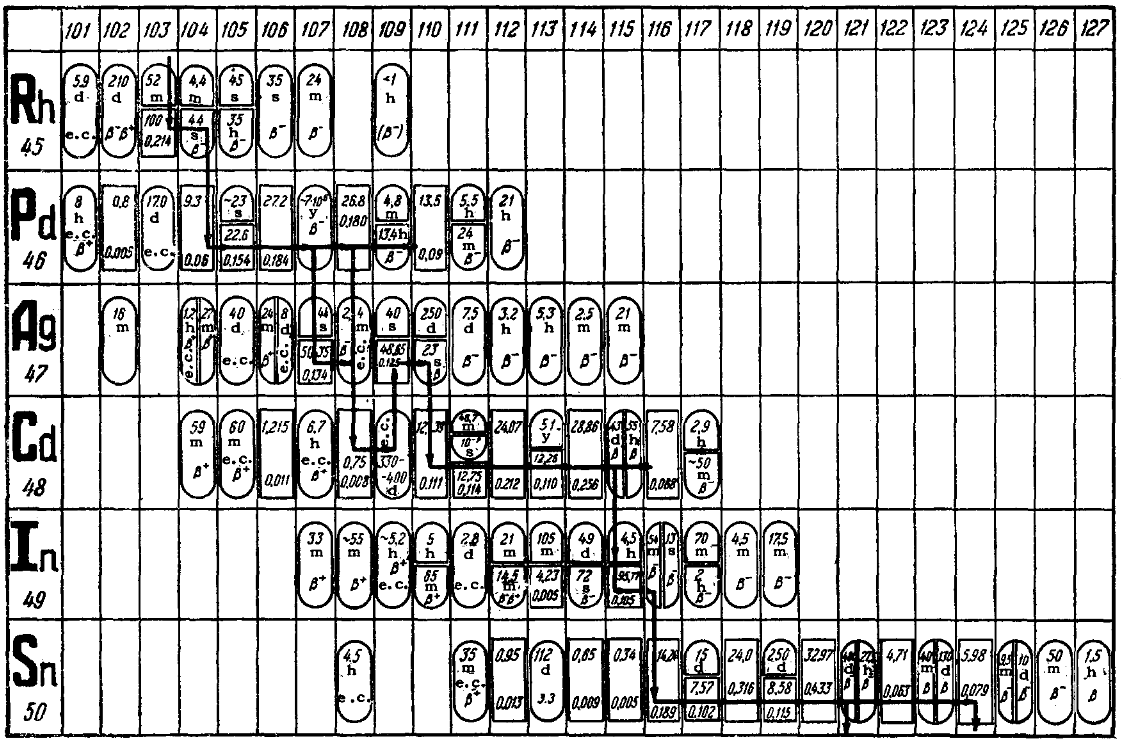

FIG. 5. A portion of the diagram of atomic nuclei.

of stars by means of processes of athermal acceleration, but these processes have not been calculated quantitatively. In any case, it may no longer be doubted that processes of formation of the heavy nuclei are continuing even at present. A direct proof of this is the discovery in the spectra of certain stars of the lines of the unstable element technetium.[28] None of the isotopes of this element have half-lives greater than the order of 10^5 years, nor are they formed by natural radioactive decay. The formation of an element with such a large atomic number as technetium can hardly be explained by any process other than neutron capture. The presence of this element in the atmospheres of stars may be considered as a direct proof of the existence in stars of continuously-active neutron sources.

SLOW AND RAPID PROCESSES OF NEUTRON CAPTURE

Let us consider in more detail how the formation of the elements proceeds by neutron capture. In Fig. 5 is shown a part of the diagram of atomic nuclei. The atomic number is plotted along the vertical axis, and the mass number along the horizontal axis. Neutron capture is shown on this diagram by a horizontal shift to the right, and β decay by a vertical shift, downward when an electron is emitted, and upward for a positron.

If a stable isotope is obtained upon neutron capture, it captures the next neutron and gives the next isotope of the same element. If a β-active isotope is obtained, it emits an electron to give the next element in atomic number, provided that the isotope has not captured another neutron before β decay takes place. The course of the process of synthesis of nuclei by neutron capture depends on the ratio of the times of neutron capture and β decay. If the time between two successive neutron captures is large in comparison with the time for β decay, then the slow process of neutron capture will take place. The pathway of this process is shown in the diagram in Fig. 5 by the solid broken line. As a rule, on this pathway are distributed the stablest and most abundant isotopes. Hence there is every basis for considering the slow process of neutron capture to be the fundamental process of formation of the elements of medium and high atomic weight.

Above the pathway of slow neutron capture lie the nuclei having an excess of neutrons. Such a nucleus may be formed by neutron capture only if the preceding β-active isotope is able to capture a neutron before it undergoes β decay. Hence, in order to form nuclei with an excess of neutrons, a rapid process of neutron capture is required. A rapid process is understood to mean one in which the time between two successive neutron captures is small in comparison with the time for β-decay.

The slow process of neutron capture may take place in stationary stars. In particular, the thermonuclear reactions in the burned-out cores of stars which were discussed above must lead to precisely the slow process of neutron capture, since the duration of the corresponding stage in the evolution of stars is measured in tens of millions of years.

Completely different conditions are necessary for the rapid process: high concentration of neutrons during a short time interval. One might expect to find these conditions during powerful stellar explosions, the so-called outbursts of supernovas. A quantitative theory of stellar explosions has not yet been developed. Hypotheses have been advanced that the same sort of thermonuclear reactions occurs in the explosions as in the stationary processes discussed above, but at the higher temperature of the explosion, these reactions are completed much more rapidly. However, at the present state of the problem, conceptions about the formation of elements in stellar explosions have the character of hypotheses, rather than of quantitatively developed theories.

Recently this hypothesis was unexpectedly corroborated by observations on the outbursts of supernovas. It was found that in certain cases the luminosity of the star after the outburst decayed over a long period of time according to an exponential law, decreasing by half in 55 days. The precision with which this law is obeyed is illustrated by Fig. 6, where the time in days after the moment of outburst is plotted horizontally, and the vertical coordinate is proportional to the logarithm of the luminosity.

Observations of this sort have been known for a long time, and ideas have long since been expressed that the exponential law may be most naturally interpreted as a law of radioactive decay. Then, we must search for a radioactive substance with a half-life of 55 days to serve as the energy source. It was even proposed[29] to consider the radioactive beryllium isotope Be^7 to be such a substance. This suggestion clearly did not stand criticism, since this nucleus decays by electron capture. On the one hand, it liberates a completely insufficient amount of energy, and on the other hand, its half-life is 55 days only when the electron is captured from the K shell. In ionized matter the decay period would be much longer. Hence the discovery of the transuranium element californium aroused great interest, as the the isotope Cf^{254} decays by spontaneous fission with a half-life just equal to 55 days.

Thus the hypothesis[30] has been advanced that the rapid neutron-capture process occurs in the outbursts of supernovas, and leads to the formation of all the atomic nuclei up to the heaviest and most radioactive. It is assumed that the process is terminated by the accumulation of large amounts of californium, whose spontaneous fission is then the energy source of the star during the period immediately following the outburst. A convincing proof of the existence of the rapid neutron-capture process lies in certain details of the abundance curve, namely the fine structure of the maxima at the magic numbers. At each magic number, as may be seen in Fig. 1, are two maxima close together. At one of these is a nucleus having a filled neutron shell, and at the other is the nucleus obtained by β decay of a nucleus having a maximum excess of neutrons and a filled neutron shell. The first corresponds to the slow process, and the second to the rapid process of neutron capture. It was suggested to ascribe the weakly-marked smeared-out maximum at $A = 160$ to fragments from spontaneous fission, but this may not be considered at all as sufficiently substantiated.

We shall now discuss what is meant by a nucleus with the maximum excess of neutrons.

NUCLEI WITH MAXIMUM NEUTRON EXCESS

The rapid neutron-capture process must lead to unstable nuclei, highly overloaded with neutrons. We can discuss the properties of these nuclei only theoretically, since it is impossible to observe them under the experimental conditions available to us.

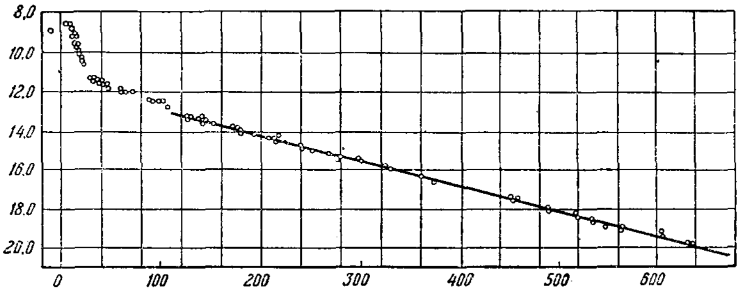

FIG. 6. Logarithm of the luminosity of a supernova as a function of the time.

Neutron capture must terminate for a given atomic number Z with the nucleus having the maximum possible excess of neutrons under the given conditions. In the limiting case of very rapid neutron capture with absence of decay processes, this will be a nucleus which is completely incapable of capturing an extra neutron, since the binding energy of the next neutron would be zero. This is the absolute maximum neutron excess. The absolute maximum ordinarily corresponds to a filled neutron shell or subshell, since the binding energy of the next neutron drops abruptly when such a shell is filled. The absolute maxima of neutron excess in nuclei have been calculated by P. É. Nemirovskiĭ[31] by means of an optical model of the nucleus. According to his results, one of the absolute maxima corresponds to the mass number 56.

Under actual conditions, the process of neutron capture must terminate before the point at which the binding energy of the next neutron becomes zero. In nuclei highly overloaded with neutrons, the time for β decay decreases, and for any given final concentration of neutrons will finally become less than the time between two successive neutron captures. Besides, if the rapid neutron-capture process takes place under the conditions of stellar explosions, then the reverse reactions, the photonuclear (γ, n) reactions, which lead to the ejection of neutrons at the high temperature must take place. Because of these processes, the actually attainable maximum neutron excess may be less than the absolute maximum.

After the nucleus with maximum neutron excess has been obtained by neutron capture, it must undergo one or several β decay processes to give elements of higher atomic number before the neutron-capture process can continue. Under conditions of rapid capture, the times for β decay are large in comparison with the time for capture. Hence, during the time for β decay, the preceding nuclei are able to capture many neutrons, and a large number of the nuclei with maximum neutron excess are formed. These nuclei will subsequently give stable nuclei of the same mass number by way of multiple β decay processes.

In this way the second maxima near the magic numbers on the abundance curve may be explained. Nemirovskiĭ[31] suggests that the iron maximum may be explained in the same way.

THE THERMONUCLEAR THEORY OF THE FORMATION OF THE ELEMENTS

On the basis of the processes discussed above, a group of English and American research workers[32] and the Canadian physicist Cameron[33] have developed a theory of the formation of the chemical elements by thermonuclear reactions in the interiors of stars. In this theory, the original matter is considered to be hydrogen, i.e., the original nuclei are protons. If the original particles of matter were neutrons, they would have transformed into protons by β decay before the fundamental processes of formation of the elements could have begun.

The primordial hydrogen formed stars of the first generation, such as we observe in the spherical component of the galaxy, as a result of condensation due to the force of gravity. From the point of view of the proposed theory, these stars must be considered as being made of hydrogen and helium. And in fact, the content of heavy elements within them is several times smaller than in the stars of the flat component.

In homogeneous stars, the transformation of hydrogen into helium occurs alone (the H-process). In the burned-out cores of heterogeneous stars (yellow or red giants), helium reactions take place to give nuclei with mass numbers $A = 4n$ (the α-process). It is assumed that convective instability arises at a certain stage in the evolution of stars, and leads to the mixing of the core with the envelope. Then the products of the helium reactions come into contact with hydrogen, and the nuclei with mass numbers $A = 4n + 1$ are formed. These are C^{13} and Ne^{21}, which generate free neutrons in exothermic (α, n) reactions. These neutrons form the heavy elements by way of the slow neutron-capture process (the s-process), which takes place under steady-state conditions in the degenerate cores of the stars. The evolution of a star is terminated by explosion (the outburst of a supernova). During the explosion a high neutron concentration appears, and the rapid neutron-capture process (r-process) takes place, leading to the synthesis of nuclei overloaded with neutrons and radioactive nuclei up to californium Cf^{254}. The spontaneous fission of the latter serves as the energy source of the star in the period immediately after the explosion. The products of the explosion are scattered in space in the form of interstellar gas and dust. When these condense, second-generation stars, such as we observe in the flat component of the galaxy, are formed. Actually, the bulk of the gas and dust is associated with the flat component. In the stars of the flat component, the products of the previous reactions are mixed with hydrogen. Hence, the same reactions which took place upon mixing of the burned-out cores of stars with the envelopes occur also in these stars on a larger scale. The remnant after the explosion remains in the form of a white dwarf.

Thus a plausible general scheme of the origin of the elements is obtained, and some of the abovementioned facts are explained: the inverse proportionality between the abundances of many nuclei and their neutron-capture cross-sections, the maxima at the magic numbers, etc.

A number of peculiarities of the abundance curve which do not arise directly from the general scheme must be given special consideration. Among these are the scandium gap, the iron maximum, the by-passed nuclei, and a group of light nuclei which react readily with hydrogen: deuterium, lithium, beryllium, and boron. Burbridge et al.[32] have introduced special processes to explain these peculiarities (except for the scandium gap). These processes, which are not at all clear theoretically, are: the "e-process" for the iron maximum, the "p-process" for the by-passed nuclei, the "X-process" for the light nuclei D, Li, Be, and B. From our point of view, these problems are not yet definitely settled. We shall briefly discuss below the possible ways to solve them.

SCANDIUM, THE COSMOCHEMICAL THERMOMETER

The abrupt decline in the abundance curve from calcium to scandium has not been given sufficient attention in the literature. If we explain the formation of the elements in this region of the curve by thermonuclear reactions or by the rapid neutron-capture process, there is then no reasonable explanation for the low abundance of scandium.

In the slow neutron-capture process, the precursor of scandium is the doubly-magic nucleus Ca^{40}, whose neutron-capture cross-section must be small. However, to explain the very low abundance of scandium, it is also necessary that its capture cross-section be quite large. The only property of the scandium nucleus which might be adduced in explanation is the existence of a neutron resonance at a neutron energy of 4.1 kev. Among the light nuclei, the neutron resonances involve only scattering. However, an appreciable (n, γ) capture takes place for scandium, since the experimentally-measured cross-section for activation is 56 millibarns at an energy of 25 kev, which is considerably higher than the resonance energy.[34] Thus the existence of the scandium gap is a direct factual argument in favor of the view that neutron-capture processes with energies of the order of 4 kev has played an especially large role in the formation of the elements. Such neutrons cannot be obtained directly by any of the nuclear processes. They may be obtained only by slowing of fast neutrons in a medium having a temperature of this order. In the rapid neutron-capture process, the neutrons could not be slowed down before capture. Hence, scandium can be used as a cosmochemical thermometer. Its low abundance is evidence that the fundamental processes of synthesis of the medium and heavy nuclei took place at temperatures about 4 kev. However, this is just the order of magnitude of the temperature required for the formation of neutrons by means of exothermic (α, n) reactions in the burned-out cores of heterogeneous stars.

THE IRON MAXIMUM

The most difficult problem of the theory of the formation of the elements is that of finding a plausible explanation of such a sharply marked feature of the abundance curve as the iron maximum.

Iron and the nuclei near it are distinguished by having maximum binding energies per nucleon, i.e., they are the energetically stablest nuclei. Thus the idea developed of explaining the iron maximum as due to the formation of these nuclei under conditions of thermodynamic equilibrium at very high temperatures, at which both the direct and reverse reactions would proceed quickly enough. It is assumed that such conditions might be realized in stellar explosions (supernovas).

Burbridge et al.[32] calculated that the abundance of six nuclei near iron can be superimposed on the equilibrium curve for a temperature of 3.78×10^9 deg K, with a ratio of the concentration of free neutrons to that of protons of 300. The agreement between the observed abundances and the equilibrium concentrations has hardly any fundamental significance. In order for this to have any meaning, it is necessary to fix the temperature very exactly, for even small changes in temperature would cause very sharp changes in the composition of the equilibrium mixture. We must note also that this agreement was obtained by taking the abundances from data of the spectroscopic analysis of the sun's atmosphere. If we take the results of chemical analysis of meteorites or the earth's crust, the results obtained will be completely different. Finally, the problem remains unclear as to how the equilibrium is frozen upon cooling; a strict quantitative analysis of this question has not yet been carried out.

The process of formation of elements under equilibrium conditions has been designated in the literature as the "e-process." It has been specially introduced in order to explain the iron maximum. Inasmuch as the introduction of this process is rather artificial, it would be very interesting to find any other alternative possibilities for explaining the iron maximum.

THE BYPASSED NUCLEI

In Fig. 5, below the pathway of the slow neutron-capture process lie nuclei with a deficit of neutrons. All of the possible pathways of neutron capture pass by them, and hence they are called the bypassed nuclei. The abundances of the bypassed nuclei are approximately two orders of magnitude smaller than those of the nuclei on the pathway of the slow neutron-capture process. In Fig. 1, the bypassed nuclei are indicated by the dotted line. The low abundance of the bypassed nuclei confirms the idea that neutron-capture processes have played a fundamental role in the processes of formation of the elements. However, in order to explain the origin of the bypassed nuclei, it is necessary to introduce supplementary processes of a different character.

Such processes might be rapid thermonuclear reactions of the (p, γ) or (γ, n) types at high temperatures. Thus, in the general thermonuclear scheme,[32] the "p-process" is introduced in order to explain the formation of the bypassed nuclei. This consists of (p, γ) reactions at temperatures about one billion degrees. It is assumed here that in supernova explosions at temperatures of about four billion degrees, thermodynamic equilibrium sets in in the matter in which all the hydrogen has already been consumed. This leads to the formation of the iron maximum, while after the products are cooled to one billion degrees, they come into contact with hydrogen, and non-equilibrium (p, γ) reactions take place, leading to the formation of the bypassed nuclei.

However, a careful study[35] shows that this is the weakest point in the entire thermonuclear theory of the formation of the elements. In the great majority of cases, not one, but two consecutive (p, γ) or (γ, n) reactions are required for the formation of the bypassed nuclei. Consequently, the times for these reactions must be small in comparison with the β-decay times, that is, the reactions must be rapid. At the temperatures and densities required for rapid reactions, the reactions are already reversible. However, then we are dealing with sequences of rapid, reversible thermal reactions, and by the principle of detailed balancing such a sequence of reactions must unavoidably lead to a state of thermodynamic equilibrium. We mean by this not complete equilibrium, but equilibrium between the bypassed nuclei and their isotopes, isobars, or nuclei with the same number of neutrons which are on the pathway of the slow neutron-capture process. It is easy to test whether such an equilibrium is realized in nature. For this it is sufficient to plot the logarithm of the ratio of abundances (corrected for the statistical weights) against the difference of binding energy. This has been done in Fig. 7. Equilibrium would correspond to a straight line, whose slope would characterize the temperature. One may see from Fig. 7 that the observed abundances have nothing in common with the equilibrium abundances. This compels us to doubt the explanation of the origin of the bypassed nuclei as due to rapid thermonuclear processes.

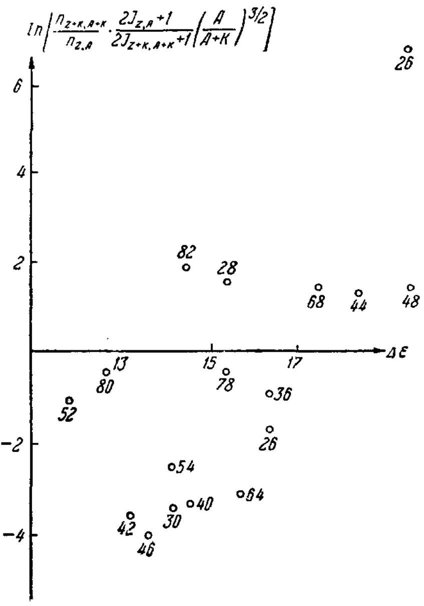

FIG. 7. Comparison of the abundances of the bypassed nuclei with the condition of thermodynamic equilibrium.

We have shown[35] that almost every bypassed nucleus may be obtained from a nucleus lying on the pathway of the slow neutron-capture process by a single (p, 2n) reaction. Here a rapid process is no longer required, but these reactions require protons with energies above 10 Mev. These cannot be thermonuclear, but must originate from processes of athermal acceleration.

THE FORMATION OF ELEMENTS IN PROCESSES OF ATHERMAL ACCELERATION

The necessity of introducing processes of athermal acceleration of particles into the theory of the origin of the elements follows from the fact alone of the existence of deuterium, lithium, beryllium, and boron in nature. The nuclei of these elements react rapidly with hydrogen at thermonuclear temperatures. Their relatively low abundance is evidence that most of the cosmic matter has been cooked in the thermonuclear kettle. However, the amounts of the indicated nuclei that exist in nature have apparently not resulted from thermonuclear reactions. In order to explain their origin, another process[32] has been introduced into the general scheme of the formation of the elements. It is called the "X-process," apparently because not much is known about it. It is assumed that in this process nuclear particles take part, which have been accelerated by variable electromagnetic fields in the atmospheres of stars.

The fact that such an acceleration actually takes place in the atmospheres of stars, the sun in particular, is made obvious by a number of manifestations of solar activity which we observe on the earth. Among these are: the current of particles causing the aurora, magnetic storms, and interruptions of radio communication; non-thermal radio emission, apparently excited by fast electrons in the sun's atmosphere; and finally, the increase in the cosmic ray intensity after chromospheric flares on the surface of the sun. The latter is direct proof of the acceleration not only of electrons, but also of nuclei.

For the accelerated particles to enter into nuclear reactions, the acceleration must take place not in a vacuum, but in a sufficiently dense plasma. However, the acceleration of particles in a plasma is possible only when the particles have a sufficiently high initial velocity. The point is that a charged particle moving in a plasma suffers frictional losses due to electrons. These losses are greater, the lower the velocity of the particle. In order that acceleration may occur, an initial velocity such that the frictional losses are smaller than the energy imparted to the particle by the electromagnetic field is necessary.

Hence,[35] a combination of two processes is required for nuclear reactions in the atmospheres of stars: an initial gas-dynamic injection, and a subsequent electromagnetic acceleration. The injection may be produced by shock waves emerging from inside the star into a medium of lesser density; this will be associated with a progressive increase in velocity. The same shock wave might also produce a disturbance in the plasma, leading to the appearance of alternating electromagnetic fields, such as are necessary for the subsequent acceleration.

The reason for the formation of shock waves must be sought in the turbulent motions which take place in the deep convective zones hidden under the surface of the star. The theory of the internal structure of stars states that a special development of convection should be expected in stars of the red-dwarf type, which lie in the lower right-hand corner of the spectrum-luminosity diagram. This is the type to which the flaring stars belong, in which phenomena similar to the chromospheric flares of the sun occur on a much larger scale. All the conditions exist in the atmospheres of these stars for the occurrence of nuclear reactions due to athermal acceleration.

In the evolution of the more massive stars, there is also a non-stationary stage accompanied by turbulent movements. There are reasons for assuming that similar instability phenomena take place at the end of the horizontal branch of yellow giants (see Fig. 4). It is probable that an analogous branch exists also in the flat component, but it is harder to observe it there. In the corresponding region of the diagram, the magnetic variables are observed; large anomalies of chemical composition are observed in the atmospheres of these stars. These anomalies may be considered as direct evidence of the formation of elements in processes of athermal electromagnetic acceleration.

THE (p, n) AND (p, 2n) REACTIONS

In athermal acceleration, the energy spectrum of the particles does not fall off exponentially at large energies (as it does in the thermal Maxwell distribution), but according to a power law. Hence, a significant role is played here by particles with energies considerably greater than thermonuclear energies. In thermonuclear reactions, protons are captured by nuclei only with emission of γ rays. However, as soon as the energy of the compound nucleus formed by capture becomes sufficient for emission of a neutron, the probability of this process becomes much larger than the probability of emission of a γ quantum. After this point, the basic process of interaction of the nucleus with a proton is the (p, n) reaction.

The energy threshold for the (p, n) reaction cannot be lower than 0.75 Mev (corresponding to the difference in mass between the neutron and the proton). Actually the binding energy of a proton within a nucleus is less than that of a neutron because of electrostatic repulsion, so that in fact the (p, n) reaction becomes possible at proton energies of about 2 Mev. However, if the energy of the proton exceeds this value by the amount of the binding energy of another neutron (about 8 Mev), then the emission of two neutrons may follow the capture of the proton. This is the (p, 2n), reaction, whose energy threshold is correspondingly at about 10 Mev.

(p, 2n) reactions seem to be[35] the most probable pathway for the formation of the bypassed nuclei.

The occurence of these, along with (p, n) reactions, may serve as an additional neutron source for the fundamental pathway for the synthesis of the heavy nuclei, slow neutron capture. If the (p, n) reaction is followed by β decay back to the original nucleus, the final result of these two processes is a pure transformation of a proton into a neutron. Thus, nuclei may serve as catalysts for transformation of protons above the threshold energy into neutrons. The role of these processes in the origin of the elements is far from clarified as yet. In reference 35, the hypothesis is advanced that they may be of significance even as one of the possible explanations of the iron maximum.

(p, n) reactions in the presence of cold hydrogen must be accompanied by the formation of appreciable amounts of deuterium. In this regard, we must note that, if the deuterium content is the same in cosmic hydrogen as in terrestrial hydrogen, the deuteron must be one of the most abundant nuclei. In such a case, the abundance of deuterium would then be near that of iron; this would be a strong argument in favor of the role of processes of athermal acceleration. If we succeed in determining the cosmic abundance of deuterium, this will be a powerful aid in elucidating the roles of athermal and thermonuclear processes in the origin of the chemical elements.

Laboratory experiments on the problem of directed thermonuclear reactions have shown that it is much easier to obtain a nuclear reaction resulting from athermal acceleration than by a true thermonuclear reaction. This result may find a certain analogy in the theory of the origin of the elements.

CONCLUSION

We see that it is possible to explain the formation of all the chemical elements from hydrogen by processes which are qualitatively no different from those taking place at the present time in known stars. Undoubtedly, this is a great forward step in comparison with the theories which made use of arbitrary hypotheses about a prestellar state of matter.

There are still a number of difficulties and unsolved problems. Nothing can be said as yet about the origin of the primordial hydrogen. The final fate of the stars upon cessation of all nuclear processes is not completely clear. The white dwarfs are star "corpses" of this sort, but it has not been shown that there are enough of them.

A good test of the theory of the continuous formation of the elements would be the comparison of the chemical compositions of old and young stars. It has been shown that, in the stars of the spherical component, there is much less of the heavy elements than in the stars of the flat component. However, the comparison of the chemical composition of young and old stars of the flat component does not give such unambiguous results. This has led many astrophysicists to the conclusion that, in the early stages of the development of the galaxy, the processes of nuclear synthesis took place more intensively, although they were qualitatively the same as now.

The problems of explaining the scandium gap, the iron maximum, and the origin of deuterium, lithium, beryllium, and boron, and the bypassed nuclei cannot be considered to be definitely settled.

All these problems require further development and perfection of the theory. Yet, it is important that the theory of the origin of the elements has come into contact with the data of observational astrophysics and with the theory of the evolution of the stars. The theory has already begun to connect the processes of the formation of the elements with definite stages of stellar evolution and with concrete, actually-observed types of stars. This support by real facts is a guarantee of the ultimate success of the theory.

---

[1] V. G. Fesenkov, Современные представления о вселенной (Modern Concepts about the Universe), U.S.S.R. Acad. Sci. M.-L., 1949, p 125.

[2] H. E. Suess and H. C. Urey, Revs. Modern Phys. **28**, 53 (1956) [Usp. Fiz. Nauk **62**, 101 (1957)].

[3] D. A. Frank-Kamenetskiĭ, Астрономический журнал (Astron. J.) **32**, 139, 326 (1955); Usp. Fiz. Nauk **58**, 415 (1956).

[4] D. A. Frank-Kamenetskiĭ, Астрономический журнал (Astron. J.) **31**, 327 (1954).

[5] D. A. Frank-Kamenetskiĭ, Dokl. Akad. Nauk SSSR **104**, 30 (1955).

[6] W. M. Elsasser, J. phys. radium **4**, 549 (1933); **5**, 389, 635 (1934); M. G. Mayer, Phys. Rev. **74**, 235 (1948).

[7] H. A. Bethe, Phys. Rev. **55**, 434 (1939).

[8] G. J. Pokrowski, Physik Z. **32**, 374 (1931).

[9] O. Klein, Revs. Modern Phys. **21**, 531 (1949).

[10] G. Beskow and L. Treffenburg, Arkiv Mat. Astron. Fysik **34A**, No. 13, 17 (1947).

[11] F. Hoyle, Monthly Notices Roy. Astron. Soc. **106**, 343 (1946); **108**, 372 (1948); Astrophys. J., Supplement series **1**, No. 5 (1954); Proc. Phys. Soc. **59**, 972 (1947).

[12] J. Podolansky and D. ter Haar, Russian translation in the collected volume, Ядерные процессы в

звездах (Nuclear Processes in Stars), IL, M. (1957), p. 15.

[13] R. A. Alpher and R. C. Herman, Rev. Modern Phys. **22**, 153, 406 (1950).

[14] D. ter Haar, Revs. Modern Phys. **22**, 119 (1950).

[15] Sosnovskiĭ, Spivak, Prokof'ev, Kutikov, and Dobrynin, J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 1059 (1958), Soviet Phys. JETP **8**, 739 (1959).

[16] W. Baade, Astrophys. J. **100**, 137 (1944).

[17] B. V. Kukarkin, Исследование строения и развития звездных систем на основе изучения переменных звезд (The Study of the Structure and Development of Star Systems Based on the Study of Variable Stars), Gostekhizdat, M., 1949.

[18] P. P. Parenago, Paper given at the 10th International Astronomical Congress, August 1958.

[19] A. R. Sandage, Astronom. J. **58**, 61 (1953).

[20] F. Hoyle and M. Schwarzschild, Astrophys. J., Supplement series **2**, No. 13 (1955).

[21] C. B. Haselgrove and F. Hoyle, Monthly Notices Roy. Astron. Soc. **116**, 515 (1956).

[22] E. E. Salpeter, Revs. Modern Phys. **29**, 244 (1957).

[23] Hayakawa, Hayashi, Imoto, and Kikuchi, Progr. Theor. Phys. (Japan) **16**, 507 (1956).

[24] Nakagawa, Ohmura, Takebe, and Obi, Progr. Theor. Phys. (Japan) **16**, 389 (1956).

[25] Cook, Fowler, Lauritsen, and Lauritsen, Phys. Rev. **107**, 508 (1957).

[26] A. G. W. Cameron, Phys. Rev. **93**, 932 (1954); Astrophys. J. **121**, 144 (1955).

[27] J. Greenstein, in Modern Physics for the Engineer, ed. L. Ridenour, McGraw-Hill, N. Y. 1954, p. 267.

[28] P. W. Merrill, Astrophys. J. **116**, 21 (1952).

[29] L. B. Borst, Phys. Rev. **78**, 807 (1950).

[30] Burbridge, Hoyle, Burbridge, Christy, and Fowler, Phys. Rev. **103**, 1145 (1956).

[31] P. É. Nemirovskiĭ, Paper at the 10th International Astronomical Congress, August 1958.

[32] Burbridge, Burbridge, Fowler, and Hoyle, Revs. Modern Phys. **29**, 547 (1957).

[33] A. G. W. Cameron, Ann. Rev. Nucl. Sci. **8**, 299 (1958).

[34] D. J. Hughes and R. B. Schwartz, Neutron Cross Sections, Brookhaven Natl. Lab., Upton, N.Y., July 1, 1958.

[35] D. A. Frank-Kamenetskiĭ, Paper at the 10th International Astronomical Congress, August 1958.

Translated by M. V. King