half an hour of creation...

What happened to ylem in the first one thousand seconds.

by ***George Gamow***

In a very interesting article, "The Composition of Our Universe" (*Physics Today,* April, 1950), Dr. Harrison Brown brings forth convincing evidence which suggests strongly that our cosmos is remarkably uniform in its chemical composition. In fact, apart from a few notable exceptions which can be easily accounted for by local conditions, the relative abundance of various chemical elements is nearly the same on the earth, on the planets, on the sun and other stars of the Milky Way system, in the diffuse interstellar material, and in the distant spiral galaxies which represent the independent stellar systems of their own.

It is only natural that we ask ourselves why the universe is so thoroughly mixed, and why it possesses a particular composition with very high abundance of hydrogen and helium, considerably lower abundance of carbon and oxygen, and practically negligible abundances of such elements as gold or uranium. As long as the atoms were considered as indivisible building blocks of matter, such a question would not make much sense, but the knowledge of today concerning the possibility of transformations between the chemical elements makes it desirable to obtain a rational explanation of the observed relative abundances of various atomic species.

George Gamow is a theoretical physicist whose writings are known to many readers other than physicists. He says of his work on the birth of the elements that he "always thought that the relative abundance of elements must have a simple explanation because it is represented by a simple curve as in the case of alpha decay, or the main sequence of stars. . . . If there is a simple curve, there must be a simple explanation."

The Oldest Archeological Document

We can start our discussion by imagining that once upon a time all the matter of the universe was subjected, more or less uniformly, to certain physical conditions which favored nuclear reactions of all kinds, and led to the present relative numbers of different composite nuclei. It is clear that the physical state of the matter which could have led to such a "nuclear reshuffling" must have been characterized, first of all, by extremely high temperatures of the order of magnitude of a few billion degrees. In fact, in order to make possible free exchange of elementary particles between all kinds of nuclei through the processes of nuclear dissociation and subsequent recombination, the energy of thermal motion must have been comparable with the nuclear binding energy per nucleon, and this corresponds to the temperature of a few billion degrees.

We can also make a guess as to how long ago these extreme temperature conditions must have existed in our universe. Among all the kinds of stable elements existing in nature there are few which are unstable and subject to radioactive decay. Since these unstable nuclei apparently must have been formed during the same epoch as the stable ones, we cannot place that epoch too far back in time if we want to account for the existence of the naturally radioactive elements today.

The natural abundances of Th^{232} and U^{238} are comparable with the abundances of stable elements in the same brackets of atomic weights. Since the mean life of these two unstable isotopes is 13 or 4.5 billion years respectively, we conclude that the date of element-cooking could not have been much farther back in time than a few billion years. On the other hand, natural radioactive isotopes with shorter lifetimes, such as U^{235} ($0.88 \cdot 10^9$ years) and K^{40} ($0.24 \cdot 10^9$ years), are found in nature in considerably smaller amounts (0.0072 and 0.00012 with respect to the main isotopes) which suggests that they have decayed quite considerably since their formation. Assuming that stable and unstable isotopes were formed in comparable quantities at the time of formation, we can easily calculate the date of that epoch: the figure four billion years is from U^{235} data, and one billion years is from K^{40} data. There would be no difficulties with uranium isotope separation if the Manhattan project had been started a few billion years ago!

Our assumption, that all the matter of the universe was subjected to such extremely high temperature a few billion years ago, stands in excellent agreement with astronomical data concerning the past of the stellar universe. The figure of a few billion years for the age of our universe comes out persistently from a large number of seemingly independent astronomical investigations concerning the age of the earth, the moon, the sun, the binary stars, the stellar clusters, and above all, in the age of galactic systems as obtained from the observed phenomenon of the progressing expansion of the universe. The latter studies indicate that the observed expansion must have started a few billion years ago from a presumably uniform state of rather high density and exceedingly high temperature, which is just what we need for cooking various atomic species.

Thus, developing the detailed theory of nuclear processes which must have led to the present abundance of chemical elements, we may also throw some light on the exact conditions which existed in the universe during the early stages of its evolution. The curve of relative abundance of elements represents the oldest archeological document pertaining to the early history of our universe!

It should be noted here that some investigators (Albada; Hoyle; Klein, Bescow, and Treffenberg) prefer the point of view according to which the elements have not been formed in the uniform hot brew existing during the prestellar stage of our universe, but rather in the hot interior of giant prehistoric stars which allegedly populated space during the early development stages and later vanished by exploding and spreading their material all over space. To the present writer such a point of view looks rather artificial and not very probable, and it is his deep conviction that the formation of chemical elements took place in the uniform way described above. It seems, in fact, that the theory of uniform formation, as developed during the recent years by the present writer and some of his colleagues, gives a generally satisfactory and self-consistent explanation of the observed abundances of various elements and their isotopes.

Youth of the Expanding Universe

Before we come to a more detailed study of nuclear reactions which could have taken place in the original highly compressed state of our universe we have to discuss a simple picture of expanding space as it can be formed along the lines of the general theory of relativity.

The relativistic statement that the universe of uniform density must be either in the state of contraction or else in the state of expansion (but never at rest), is equivalent to the self-evident statement of Newtonian theory to the effect that a system of material particles (galaxies), scattered through space, must be either collapsing under the action of mutual gravity or else flying apart if the relative velocities of individual particles are larger than their mutual escape velocities. Observation shows that, in the case of the system of galaxies, the latter is actually the case and, in fact, using the observed galactic masses and velocities, we find that the kinetic energy of their mutual recession is almost one hundred times larger than their mutual potential energy. It follows that the present recession of galaxies will never stop and that our universe is expanding limitlessly into the infinity. (Hyperbolic solution, speaking mathematically.)

Using the fundamental equations of Einstein's general relativity, one can derive an expression similar to the ordinary classical law of the conservation of energy. This expression states that for any part of the universe, considered separately from the rest of it, the sum of the kinetic energy of expansion and the mutual potential energy of masses involved remains constant throughout the expansion.

Curiously enough this generalized conservation law does not contain the term corresponding to the heat content of the expanding masses. Since, as the result of the expansion, the matter filling the universe is adiabatically cooled down, the heat energy seems to disappear tracelessly in violation of the familiar conservation law of classical physics. The explanation of this paradox can be obtained, however, if we notice that during the adiabatic expansion of a gas contained in a cylinder the gas does the work against the receeding piston whereas the expansion of gas filling an infinite (or a closed-on-itself) space does not find any walls to do work against. According to the colorful expression of Enrico Fermi, the loss of heat energy in the expanding universe does not enter into the conservation equation because "that work is done directly into the hands of God (located at infinity) which are pulling the universe asunder".

This being settled we can use the generalized energy equation to study the expansion process, and we find that it starts from a singular state of infinite density, infinite temperature, and infinite expansion velocity, and then gradually slows down to the present rate of expansion. Of course, the expression "infinite density" should be understood only in strictly mathematical sense, since physically we cannot predict what happens to matter when its density becomes larger than the density of atomic nuclei. However, the formula of the general relativity can be safely used through the entire expansion process from the original nuclear density (10^{14} g/cm^3) to the present mean density of the universe (10^{-30} g/cm^3) which corresponds to the linear expansion by a factor of $5 \cdot 10^{14}$. (One micron expands into 500,000 kilometers!)

A very important point concerning physical phenomena in the expanding universe is that at early stages, when all matter was in the form of uniformly distributed hot gas mixed with the black body radiation, the temperature of radiation was dropping faster than that of matter. Indeed we know that in adiabatic expansion the temperature of radiation is inversely proportional to linear dimensions of the container (Wien's first law), whereas the temperature of an ideal monatomic gas drops as the square. Thus, the farther back we go into the past, the more important is the role played by radiation.

At the present epoch, in which the density of matter in the universe is about 10^{-30} g/cm^3, and the temperature is only about 3°K, the density of radiation (according to the Stefan-Boltzmann law) is $7 \cdot 10^{-14} \cdot (3)^4 \cong 6 \cdot 10^{-12}$ erg/cm^3 $\cong 6 \cdot 10^{-32}$ g/cm^3. Thus even now the mass-density of radiation (calculated to mass-energy equivalence law) is only about twenty times smaller than that of matter. That means that during the early stages of expansion the mass density of radiation exceeded that of matter by a very large factor, and that during that epoch the rate of expansion was regulated entirely by radiation density.

Combining this conclusion with the relativistic equation for expansion, one comes to the result that the temperature of the universe during that early period was given by the formula $T = 1.5 \cdot 10^{10}\ °K/t^{1/2}$ where t is the age of the universe expressed in seconds. Thus the temperatures of a few billion degrees, which were necessary for the complete dissociation of the nuclei into their constituent particles (neutrons and protons), must have existed during the first few hundred seconds of the history of the universe. This original mixture of neutrons, protons, and electrons is now known as "ylem", an obsolete noun meaning (according to Webster's dictionary) the primordial substance from which elements were formed. As the temperature of ylem dropped due to progressing expansion, the recombination of neutrons and protons must have started.

What Happened to Ylem—the Light Elements

The first composite nuclei to be formed at that time were, of course, the deuterons. The subsequent capture-collisions between the newly formed deuterons on one side, and the protons and neutrons on the other, lead to the formation of He^3 and tritium nuclei. Next followed the formation of ordinary helium, He^4. In the present state of the theory there still exists the difficulty of understanding the step following He^4. In fact, since it is well known that there is no stable combination of five nucleons, we have to make here a step by at least two units of atomic weight. We can, of course, consider triple collisions of helium, protons, and neutrons, leading to reactions producing lithium such as ${}_2He^4 + p + n \rightarrow {}_3Li^6$, but it seems that for the densities which should be assumed for the epoch of element formation the probability of triple collisions is much too small.

Fermi and Turkevitch, who have studied in much detail thermonuclear reactions between light nuclei during the early expansion period, tried to cover the gap by postulating a reaction between helium and tritium to form lithium and some radiation, where $He^4 + T^3 \rightarrow Li^7 + h\nu$, but they have also found it unsatisfactory.

Still another possibility, which can be called a "nuclear chain bridge", was proposed by Wigner. This possibility can be illustrated by the example of the reaction chain such as:

$$C^{10} + T^3 \rightarrow Li^6 + Be^7 + 2\text{ Mev}$$
$$Li^6 + 4\text{ neutrons} \rightarrow C^{10} + 3e\ (?)$$
$$Be^7 + 3\text{ neutrons} \rightarrow C^{10} + 2e\ (?)$$

Here a single C^{10} nucleus carries T^3 over the "mass-5 crevasse" resulting after several subsequent neutron-captures, in the formation of two C^{10} nuclei. It seems, however, that this particular reaction is not quite suitable for our purpose, since the C^{10} nucleus has a proton-excess and is not likely to be formed by the processes of neutron capture and electron emission as shown in the above transformation scheme.

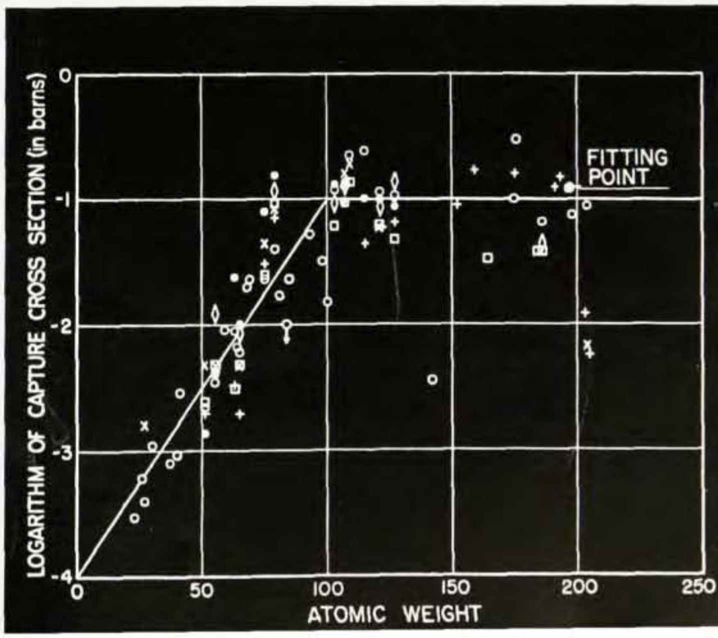
On the other hand there is a possibility that the desired process could be accomplished in a roundabout way through the photoeffect of gamma rays which were plentiful during that stage of element formation. Thus it seems that it is yet too early to know whether the difficulty of the mass-5 crevasse is a decisive one in the development of present theory.

What Happened to Ylem—the Heavy Elements

Whereas in the region of light elements, with comparatively low potential barriers, all kinds of thermonuclear reactions are expected to take place, the situation changes and simplifies quite considerably when we come to the region of heavier elements. Here the nuclei can grow exclusively by the capture of free neutrons intercepted by beta decay processes, and we can write simple equations determining the rate of formation of various atomic species. The only nuclear information which we need to write these equations is the information concerning the capture cross sections of 1 Mev neutrons (which corresponds to the temperature of the universe at that epoch) in different nuclei.

These cross sections are shown in figure 1, from which we see that they increase exponentially up to the atomic weight of 100, and then remain constant for heavier nuclei. The curve also shows that, for certain nuclei, the capture cross sections become ab-

Figure 1: Logarithm of the observed neutron-capture cross section at 1 Mev versus atomic weight. From Rev. Mod. Phys., *22, 2, 184.*



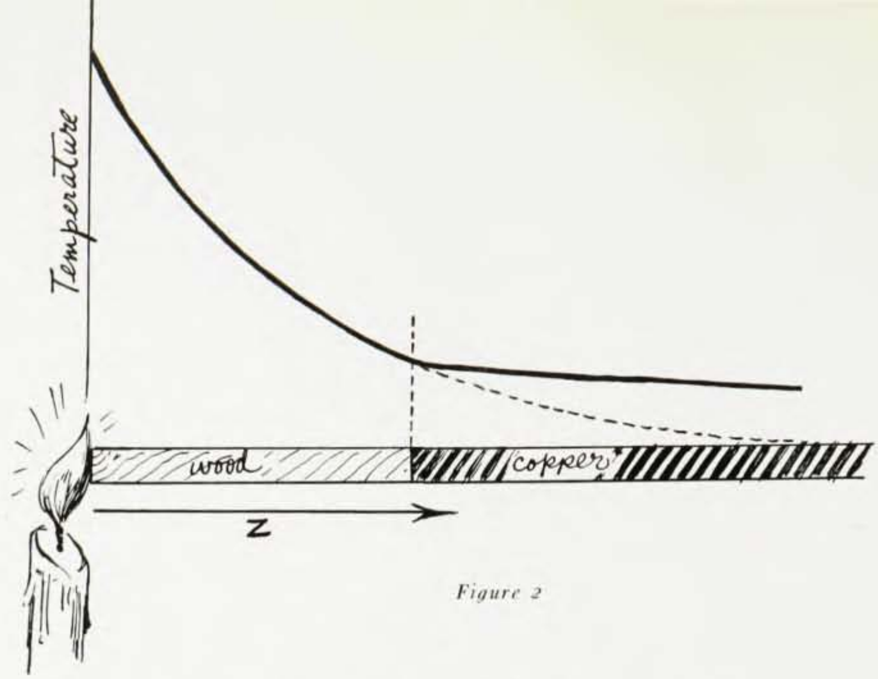


Figure 2

normally small; these are the so called "magic number" nuclei containing the completed neutron shells.

The equations, which describe the building-up process, state essentially that the rate of change of the number of nuclei of any given atomic weight is equal to the difference between the production rate of these nuclei by neutron capture in the previous atomic weight-category, and the rate of disappearance of these nuclei through neutron capture which shifts them into the next atomic weight category. In this sense the equations are similar to those describing the heat conduction along a metal bar (without heat losses through the surface) which state that the rate of change of heat content, in each section of the bar, is equal to the difference between inflow of heat at one end and the outflow of heat at the other.

In this analogy the role of neutron-capture-cross sections is played by the coefficient of heat conductivity. If we now imagine such a bar heated at one end, the temperature distribution at each given moment will be given by an exponential curve, provided the coefficient of heat conductivity remains constant through the entire length of the bar. As time goes on, the temperature distribution along the bar gradually evens up. Similarly, the equation of the nuclear building-up process would lead to an exponential decrease of abundances with increasing atomic weight if the neutron-capture cross section were the same for all nuclei. However, we see from figure 1 that these cross sections, being rather small for light nuclei, become much larger for the heavier ones. In our heat conduction analogy this would correspond to a bar a part of which is made of a poor heat conductor such as wood followed by a much better heat conductor such as copper. It is clear that in this case we will have first a steep temperature gradient, followed by a rather flat temperature distribution in the better heat conductor, as shown.

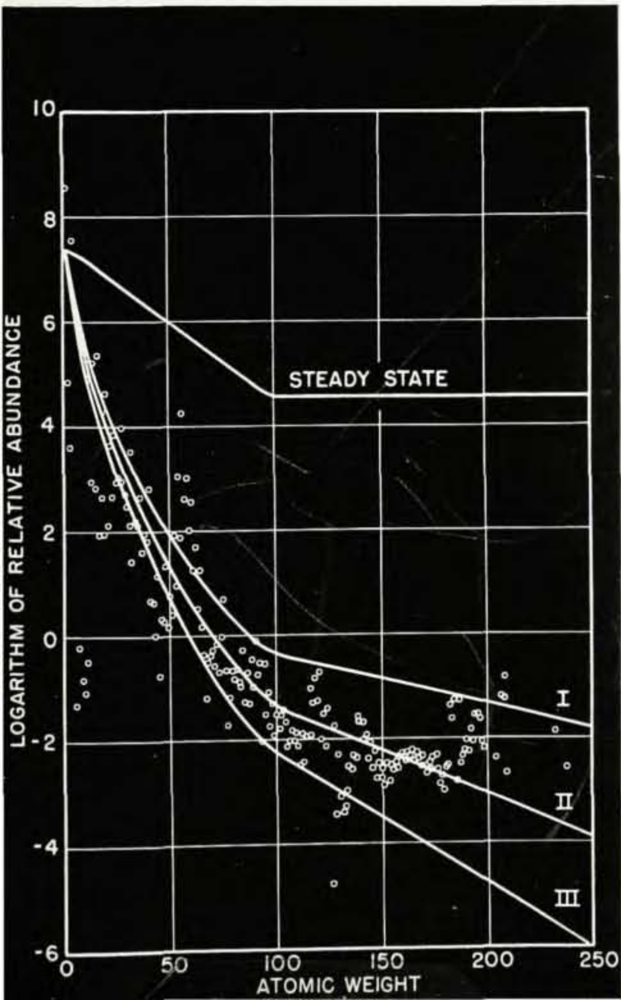
But this is exactly the situation we encounter in studying the curve of the relative abundance of elements: the abundances fall down exponentially up to the atomic number of about one hundred, and they remain more or less constant thereafter. The exact integration of the building-up equations, with the capture cross sections taken from the curve of figure 1, was performed by Alpher and later in some more detail by Alpher and Herman. The result of integration depends, of course, on the assumed neutron density (which determines the number of collisions per second) and on the time (determined by the mean life of free neutrons, and the rate of universal expansion) allowed to the process; the result depends only on the product (density $\times$ time).

The three curves marked I, II, and III in figure 3 show the theoretical abundance curves for density $\times$ time products equal to 1.3, 0.8, and $0.5 \cdot 10^{18}$ sec. neut/cm^3 respectively. We see that the best fit is obtained for the middle curve; whereas the curves corresponding to the other two assumptions show the *overcooking* and *undercooking* of heavy elements. Since the time span of the building-up process given by the mean lifetime of free neutrons must be about 1000 seconds (about 15 minutes), the mean density during the formation process must have been about

10^{15} neuts/cm^3 or 10^{-9} g/cm^3. On the other hand, according to the general theory of expanding universe, the material density decreases as the inverse $3/2^{th}$ power of time and the above result concerning the mean density during the formation process can be obtained if we assume the time dependence of density to be given by the formula $2 \cdot 10^{-3}/t^{3/2}\ g/cm^3$, where t is again the age of the universe in seconds.

In figure 3 we also find the curve marked "steady state" which would represent the relative abundances of elements if the formation process would be permitted to go on indefinitely; in this case the relative abundances of different nuclear species would be simply inversely proportional to the corresponding capture cross sections. The fact that the actually observed abundances do not correspond to the "steady state" curve indicates that the formation of nuclear species took place within the rather short time of about half an hour.

Figure 3: Comparison of relative abundances computed according to the neutron capture theory approximation with no neutron decay or universal expansion. From Rev. Mod. Phys., *22, 2, 190.*



Having established the general validity of the theory ascribing the formation of elements to the varying physical conditions prevailing in the universe during the early stages of its expansion, we may turn now our attention to some minor details. First of all, inspecting the cross section curve given in figure 1, we notice that for certain atomic weights the cross sections for neutron capture become abnormally small. According to the building-up theory, these atomic weights must form the "bottle necks" in the production line so that we should expect the accumulation of nuclei in these regions. And, indeed, careful inspection of the observed abundance curve indicates the abnormally high abundance of nuclei which correspond to the completed nuclear shells.

Another crucial test of the theory is given by the problem of the so called "shielded isobars". Indeed, since we consider the atomic species now existing in the universe as the result of beta disintegration of various neutron-excess nuclei built by the process of successive neutron-capture, it seems rather difficult to understand the formation of isobaric pairs and triplets which, as it is well known, cannot be connected by the simple beta decay processes. This difficulty was, however, recently removed by the work of Smart who has shown that members of the isobar-pairs possessing the excess of protons, can be formed by the nuclear photoeffect in which one or two neutrons are ejected from the nuclei as the result of collision with a hard gamma quantum formed in the radiative neutron-capture processes in another nucleus. It also seems possible that these photoeffect processes could lead to the formation of C^{10} nuclei which are necessary for covering the gap between the atomic weights *4* and *6*.

Summing up, we may say that the theory of the building-up process gives a very satisfactory account of the formation and relative abundances of various atomic species, and also supplies us with the information concerning the time-dependence of temperature and density during the early stages of universal expansion.

We may add that, using this initial condition for the temperature and density of the expanding universe, one can arrive at a number of interesting consequences concerning the formation processes and the masses of stellar galaxies, the present temperature and density conditions in the intergalactic space, etc. But this class of problems falls outside the scope of the present article.