THE ORIGIN OF THE ELEMENTS

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They [atoms] *move in the void and catching each other up jostle together, and some recoil in any direction that may chance, and others become entangled with one another in various degrees according to the symmetry of their shapes and sizes and positions and order, and they remain together and thus the coming into being of composite things is effected.*

—SIMPLICIUS (6th Century A.D.)

It is my privilege to begin our consideration of the history of the universe during this first scientific session of the Academy Centennial with a discussion of the origin of the elements of which the matter of the universe is constituted. The question of the origin of the elements and their numerous isotopes is the modern expression of one of the most ancient problems in science. The early Greeks thought that all matter consisted of the four simple substances—air, earth, fire, and water—and they, too, sought to know the ultimate origin of what for them were the elementary forms of matter. They also speculated that matter consists of very small, indivisible, indestructible, and uncreatable atoms. They were wrong in detail but their concepts of atoms and elements and their quest for origins persist in our science today.

When our Academy was founded one century ago, the chemist had shown that the elements were immutable under all chemical and physical transformations known at the time. The alchemist was self-deluded or was an out-and-out charlatan. Matter was atomic, and absolute immutability characterized each atomic species. The periodic system of these immutable elements was proclaimed in 1868 by Mendeléev, when the Academy was five years old. Any theory of the origin of the elements was required to account for the formation of each elementary species which remained immutable and unchanged thereafter. An English physician, William Prout, noted that most atomic weights seemed to be integral multiples of that of hydrogen and suggested that all of the heavier elements consisted of the lightest one—hydrogen. However, this was an heretical idea and Prout did not sign the two articles on this suggestion which he published in the *Annals of Philosophy*, 1815–1816. He did sign his concurrent articles on the sap of the vine, the excrement of the boa constrictor, the liquor amnii of the cow, and the ink of the cuttlefish. Like many others he is remembered principally for his heresy and not for his orthodox medical and scientific studies.

The Academy was still young when the twentieth century changed all this. In the first years of this century, Lord Rutherford and his contemporaries showed that the naturally radioactive elements spontaneously broke down through long chains of intermediate elements to lead or bismuth with the emission of helium nuclei (alpha particles), electrons (beta particles), and photons (gamma rays). We now know that antineutrinos are also emitted in these transformations. Rutherford and Bohr showed that the atom consisted of a central nucleus surrounded by satellite electrons in quantized orbits. The chemical properties of an atom depended in high approximation only on the number of satellite electrons; the radioactive transformations were primarily nuclear. A neutral atom of one element changed into that of another when its nucleus changed its positive charge, and the electronic structure made a secondary adjustment in gaining or losing negatively charged electrons. In 1911, the identification of isotopes by Soddy led to the revival of Prout's hypothesis. Those elements which did not have atomic weights approximately equal to an integral multiple of that of hydrogen were shown to consist of mixtures of isotopes which did have this property. By 1919, Rutherford found it possible to induce nuclear transmutations using the energetic alpha particles from natural radioactive sources. Then in the period 1932–1934 came the deluge of experimental results which serve as the foundation for our current ideas of nuclear structure and the origin of the nuclear species. Cockcroft and Walton duplicated Rutherford's results using protons accelerated to moderate energies. Urey discovered the deuteron, Chadwick discovered the neutron, and neutrons were soon produced by accelerated deuterons in the laboratory by Crane, Lauritsen, and Soltan. Anderson discovered the positron (antielectron) and the Curie-Joliots produced "artificial" radioactivity in the laboratory. Pauli suggested the idea of the neutrino and the antineutrino, and Fermi worked out the consequences of this suggestion in the beta-decay processes.

It was immediately realized that the deuteron was the simplest nuclear "molecule"—the deuteron consists of a proton and neutron bound together by the attractive nuclear forces between them. Moreover, all nuclei consist of varying numbers of protons and neutrons, and in this context protons and neutrons soon came to be called nucleons. The neutron was so named because it was found to be electrically neutral. In addition, the neutron was found to have approximately the same mass as the proton. Thus, the charge number of a nucleus is determined only by the number of protons it contains, while the mass number is determined by the total number of nucleons, neutrons as well as protons, which it contains.

The second simplification which sprang from the discoveries made during 1932–1934 concerned the natural and artificial transformations known as the beta decays. The simplest of these decays is that of the neutron which transforms with a half-life of 11.7 min to a proton with the emission of an electron and an antineutrino. The neutron is more massive than its decay products and this excess mass multiplied by c^2 appears as the kinetic energy of these products. In a radioactive nucleus a neutron can also decay to a proton and, moreover, a proton in a higher nuclear energy state than an unfilled neutron state can decay to neutron. In this case the decay involves the emission of a positron and a neutrino or the capture of an atomic electron with the emission of a neutrino.[1] The essential point is that transformations exist by which a nucleon can change from one form to the other—neutron to charged proton or proton to uncharged neutron. This supplements the nuclear transformations in which neutrons or protons or heavier nuclei can be removed or added to a given nucleus. Neutrons and protons are the basic building blocks of nuclei and under appropriate circumstances they can interchange their nucleonic roles.

Experiments in high-energy nuclear physics now show that the neutron and proton also have internal structure and that they can be annihilated by interactions with antineutrons and antiprotons. Furthermore, modern theories in high-energy physics treat the neutron and proton as only two of a great number of strongly interacting particles. At the present time it does not seem necessary to postulate astrophysical circumstances in which excitation energies are so great that these considerations are relevant. We start with neutrons and/or protons and ask how the heavier nuclei species have been synthesized at temperatures up to at most $T \sim 10^{10}$ degrees or interaction energies up to at most $kT \sim 1$ Mev.

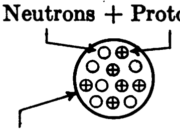
The great simplification which resulted from this concept of neutrons and protons as the fundamental building blocks of nuclei is illustrated most straightforwardly by a consideration of the number of stable and radioactive nuclear species now known, as indicated in Table 1. Ninety elements are found terrestrially and one more, technetium, is observed in stars; only promethium has not been found in nature. Some 280 stable and 66 naturally radioactive isotopes occur on the earth, making a total of 346. In addition, the neutron, technetium, promethium, and the transuranic elements up to number 103, lawrencium, have been produced artificially. The number of radioactive isotopes artificially produced now equals 1,095, and this number is gradually increasing. In regard to atomic mass numbers, all masses from 1 to 238 are found terrestrially with the important exceptions of mass 5 and mass 8. Laboratory processes have extended the radioactive mass numbers beyond 238 to approximately 260. The total number of nuclear species was 1,441 at the end of 1961, with about $^1/_4$ of this number known to occur in nature and with $^3/_4$ having been produced artificially. In the origin of the elements and their isotopes, we shall find that the radioactive forms often play an even more important role than the stable forms to which they decay in nature.

TABLE 1

Elements	
Stable	81
Technetium (stars)	1
Promethium	1
Through bismuth	83
Nat. radioactivity	9
Through uranium	92
Art. radioactivity	11
Through lawrencium	103
Neutron	1
Total	104

Isotopes	
Stable	280
Nat. radioactivity	66
Art. radioactivity	1,095
Total	1,441
December 1961	

Nuclei = Neutrons + Protons



Example: $C^{12} = 6N + 6P$

No Stable Mass 5 or Mass 8

It will be clear that this picture of the structure of nuclei leads quite straightforwardly to an attempt to explain their origin by a synthesis, or buildup, starting with one or the other or both of the basic building blocks. An alternative which has been suggested is that nuclei now in existence resulted from the breakup of a primordial nuclear fluid, with fission and evaporation processes playing a leading role. This point of view has not been quantitatively elaborated in the light of recent evidence on the details of element abundances nor has it been checked in any detail against astronomical observations. The synthesis point of view starts with protons and/or neutrons but does not attempt an answer to the perhaps even more intriguing problem of the origin of these nucleons. Concerning that aspect of the origin problem, we have practically no experimental data except on the

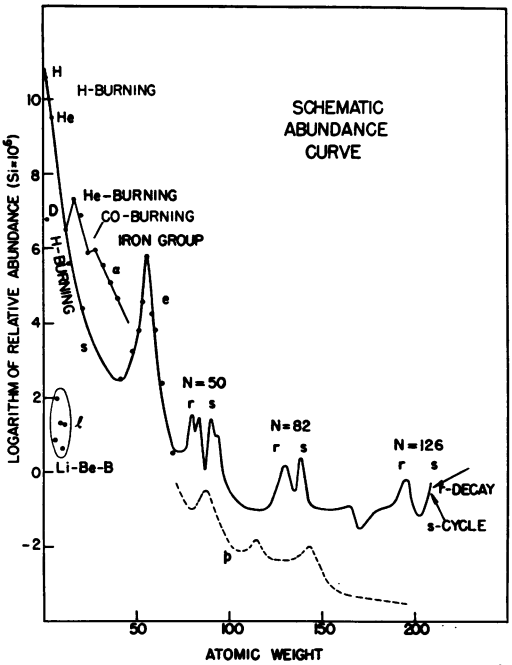


FIG. 1.—Schematic curve of atomic abundances as a function of atomic weight based on the data of Suess and Urey. Suess and Urey have employed relative isotopic abundances to determine the slope and general trend of the curve. There is still considerable spread of the individual abundances about the curve illustrated, but the general features shown are now fairly well established. Note the overabundances relative to their neighbors of the alpha-particle nuclei with $A = 16$, 20,..., 40, the peak at the iron-group nuclei, and the twin peaks at $A = 80$ and 90, at 130 and 138, and at 195 and 208.

creation of nucleon-antinucleon pairs in the high-energy laboratory. Since this creation is inevitably followed by annihilation, it is of little direct application in answering the basic problem—the creation and survival of our immediate astronomical system, the Galaxy, which we know to be composed of particles (protons, neutrons, and electrons) and not antiparticles. There is some evidence that neighboring galaxies in the cluster to which the Galaxy belongs also consist of particles. Concerning galaxies outside our cluster we have little information. All of this is to be contrasted to the growing body of nuclear and astrophysical evidence concerning the synthesis of nuclei from nucleons. It is to this problem that the discussion in this paper is directed.

With an acceptance of the existence of nucleons, this question can be asked, "What has been the nuclear history of the matter, on which we can make observations, which produced the elements and their isotopes in the abundance distribution which observation yields?" To attempt to understand the sequence of events leading to the formation of the elements, it is necessary to study the so-called "universal" or "cosmic" abundance curve. Such a curve in schematic form is shown in Figure 1. This figure gives abundances by number of atoms with 10^6 atoms of silicon taken as an arbitrary standard. It is taken from the analysis of abundances made by Suess and Urey in 1956. Abundance curves are derived mainly from terrestrial, meteoritic, and solar data and, in some cases, from other astronomical sources.

Whether or not this abundance curve is truely universal is not of too great relevance. It is the distribution for the great bulk of the matter on which we have been able to make observations. It must be emphasized that it is heavily weighted by observations on matter in the solar system: the sun, the earth, and the meteorites. Some additional information comes from spectroscopic observations on nearby stars and on the gas and dust which lie between them and which scatter and reflect starlight. All in all, with some exceptions, this material has much the same composition. We can seek the history of this particular matter. We can also ask for the history of the peculiar and abnormal abundances observed in some stars. In time, we may obtain more information of the abundances in other parts of our Galaxy and in other galaxies, and only then shall we be in a position to approach the problem of what part of the average abundances is truly universal or cosmic.

The schematic curve shown in Figure 1 is rich in detail, the complete abundance curve even more so. Superimposed on the figure are certain abbreviations (e.g., H-burning, He-burning, CO-burning) and symbols (e.g., α, e, r, s, l) designating nuclear processes which may have been involved in the synthesis of the relevant nuclear species. At our present state of knowledge it is difficult to see how all of these processes could have occurred in a single astronomical event such as a primordial explosion or "big bang" at the moment of creation of the universe. Moreover, abundances are not universal as discussed above, although there may eventually prove to be some underlying universality in the abundance curves of all astronomical systems. The only single-event theory of element synthesis which has been worked out in detail is that of Gamow, Alpher, and Herman. The restrictions placed on the nuclear processes by the density-temperature conditions assumed for cosmological reasons in this theory lead to an apparently insuperable difficulty at mass 5 at which no stable nuclear form exists. Gamow has phrased the point in the following words: "However, since the absence of any stable nucleus of atomic weight 5 makes it improbable that the heavier elements could have been produced in the first half hour in the abundances now observed, I would agree that the lion's share of the heavy elements may well have been formed later in the hot interiors of stars,"[2] while Salpeter has written: "Thus, for building all elements heavier than helium, the original expansion of the universe is, from the nuclear point of view, simply useless."[3]

In any case, the major developments in recent years have followed the hypothesis that the elements heavier than hydrogen have been synthesized in stars where the varying conditions in stars of different mass and the varying conditions in a given star as it ages and evolves lead to a plethora of circumstances under which nucleosynthesis can take place. Atkinson, Houtermans, Sterne, von Weizsächer, Bethe, Critchfield, and others made important contributions in early studies. Hoyle, Bondi, and Gold accepted stellar nucleosynthesis as a necessity in their steady-state cosmology. The details of many nuclear processes which may occur in stars have been worked out by Salpeter, Lauritsen, Greenstein, and others, and a general account including several new processes has been given by Burbidge, Burbidge, Fowler, and Hoyle. Several groups in Japan and in Russia have made major contributions in this field. The real heroes are the many experimentalists who have painstakingly measured nuclear reaction rates at the excruciatingly low levels which occur in the laboratory when appropriate astrophysical energies ($kT \sim 1$ to 300 kev) are approached and the many observationalists who make difficult spectroscopic studies of element abundances in distant, faint stars. No less heroes are those who measure minuscule abundances of the heavy elements in rocks, meteorites, and tektites.

In what follows, the origin of the elements will be discussed in the context of stellar nucleosynthesis and the illustrative examples will be those most familiar to the author. Before continuing, it is well to emphasize certain points, the chief of which is this: *stellar nucleosynthesis can be incorporated into almost all of the cosmologies which have been studied to date.* In the evolutionary cosmologies which adopt a finite age for the universe, it is necessary in the beginning only to create nucleons but not nuclei. If the red shift observations are taken to indicate an expanding universe, then under the relatively high densities and temperatures at the beginning, the neutron was the predominant nucleon. With time and expansion the neutrons decayed to protons and electrons which could form neutral hydrogen atoms which in turn could aggregate into galaxies and stars because of gravitational forces. Primordial nucleosynthesis need not be necessarily assumed but, on the other hand, some such nucleosynthesis may have occurred. For example, some helium may have been produced in the beginning. Synthesis up to and including mass 4 but not beyond meets no insuperable problems. The astronomical evidence does not exclude the possibility that the Galaxy formed with some helium as well as hydrogen.

In the evolutionary cosmologies which assign an infinite age to the universe by adopting an appropriate value of the cosmological constant, the early form of matter can be taken to be hydrogen which again ultimately formed astronomical systems. In the steady-state cosmology the steady creation is that of neutrons or of protons and electrons (to conserve charge). This is at least the case in our corner of the universe. If antinucleons are being simultaneously created now along with nucleons, the resulting annihilation would in part produce neutral pions which decay with the emission of $\sim$100 Mev gamma radiation. Space probes have not found evidence for such radiation and place a low upper limit on the creation rate for antinucleons in our astronomical neighborhood.

The separate creation of nucleons and leptons now or at some remote time in one or the other cosmological circumstance violates present experimental findings. In the laboratory, nucleons can only be created or annihilated with antinucleons, leptons can only be created or annihilated with antileptons. The problem is common to all cosmologies. There is little inkling of the solution and we must content ourselves with some knowledge of *synthesis* but with little or none concerning *genesis*.

To set the stage for an exposition of current ideas on stellar nucleosynthesis, it is necessary to give some account of the origin and history of the Galaxy and of the solar system. This will be done in succeeding papers by Professors Greenstein and Whipple. Here we give only a brief résumé. When we look out beyond the confines of the planetary system which surrounds the sun, we see our Galaxy as a majestic assemblage of stars which we call the Milky Way. From our position approximately half-way out from its center, the system is viewed edge on. The stars in the Galaxy populate a flat, disk-shaped structure with a spherical nucleus from which radiate several spiral arms trailing the direction of rotation. A few old, high-velocity stars occupy a spherical "halo" above and below the equatorial disk. Twelve to fifteen billion years ago the Galaxy was vastly different. At that time, according to current ideas, it was a rotating mass of turbulent hydrogen gas. Because of statistical fluctuations, the gas in regions of relatively low turbulence and high density condensed into stars under the influence of gravitational forces. As the stellar material contracted, the interior became very hot and dense from the conversion of gravitational potential energy into thermal kinetic energy. These conditions serve to "trigger" exothermic nuclear reactions, beginning with the fusion of hydrogen into helium and going on, as we shall see, into more complicated processes. The energy released from these fusion reactions makes them self-sustaining until the nuclear fuel is exhausted. In addition, this energy release leads to the development of internal pressure which stabilizes the star against further gravitational collapse. This stability lasts for the relatively long periods necessary to consume the interacting nuclei. The burning hydrogen in the sun has lasted for 4.5 billion years and will last as long in the future. We emphasize that this is nuclear, not chemical, burning.

A self-sustaining fusion process has not been successfully accomplished terrestrially in spite of valiant efforts to do so in many countries. In stars, the containment problem, which is so difficult to solve on a terrestrial scale, has been solved automatically by the large mass of these celestial objects. Stars can thus be considered as gravitationally stabilized fusion reactors which release energy through the conversion of one form of nuclear matter into another. Gravitational energy can raise the temperature to the "ignition point" for nuclear processes, but it cannot serve as the source of energy in a stable star which is no longer contracting; the nuclear reactions themselves do this.

As successive nuclear processes take place, the composition of a star changes and the star is said to evolve as its internal structure and external appearance vary in response to these composition changes. It is essential in the point of view of stellar synthesis that instabilities arise during the evolution and aging of a star that return the transmuted material to interstellar space. It is there mixed with the uncondensed hydrogen gas in the Galaxy so that it is available for condensation

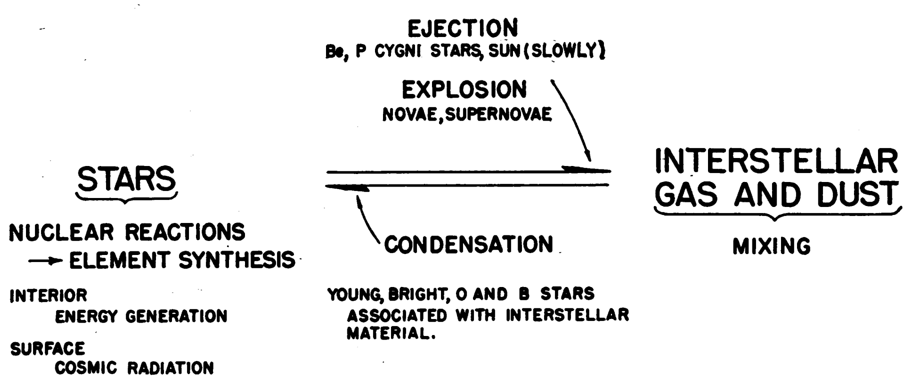


FIG. 2.—Transfer of material between stars and interstellar gas and dust. Synthesis of elements occurs in the stars, and mixing to yield the relative abundance of the elements occurs in interstellar space. Mechanisms for the transfer as observed astronomically are indicated.

into second- and later-generation stars. The general state of affairs in this "equilibrium" between stars and the interstellar gas and dust is illustrated in Figure 2.

Stellar nucleosynthesis demands that there exists this interchange of material between stars and the interstellar medium of gas and dust. The stars are the nuclear furnaces; the space between is the site of the mixing and dilution which result in the average abundance distribution over fairly large astronomical regions. Observations confirm that matter is given off by stars, both slowly and explosively, and that new stars are continually forming from the interstellar material. Giant stars lose mass at a fairly substantial rate; even our sun slowly ejects matter into

FIG. 3.—The "ring" planetary nebula in Lyra showing the spherical shell of gas which is moving away from the central star and was presumably ejected by it. The off-center star within the ring is a field star. (Mount Wilson and Palomar Observatories.)

space. The planetary nebulae, such as that shown in Figure 3, show spherical "smoke rings" moving away from a central star. The "rings" are actually shells. The most spectacular instabilities in stars result in the novae and supernovae that are observed to flare up suddenly and then die away in brightness. For novae, a mass loss of the order of 0.1–1 per cent can suddenly occur. In supernova explosions, all or a substantial fraction of the mass of a star may be ejected with a high velocity, 10^3 to 5×10^3 km/sec, into space. Such an explosion results after years of expansion in an amorphous mass of material such as the Crab nebula (Fig. 4), which is now located in the same region in the sky where Chinese astronomers observed the appearance of a "guest star" in A.D. 1054. Quantitative calculations show that the rate of these mechanisms is such that the heavy-element abundance in the solar system could have been synthesized in earlier stars, which formed and evolved in the Galaxy, if the Galaxy is several billion years older than the sun, which seems to be the case from other evidence.

The reverse process to the breakup of stars, the formation of new stars, also has substantial observational confirmation, albeit somewhat indirect. There are stars in the heavens so bright for their known mass that even nuclear processes cannot have kept them shining for more than a few million years. They are thus much younger than the sun and the Galaxy. The bright stars are "young stars,"

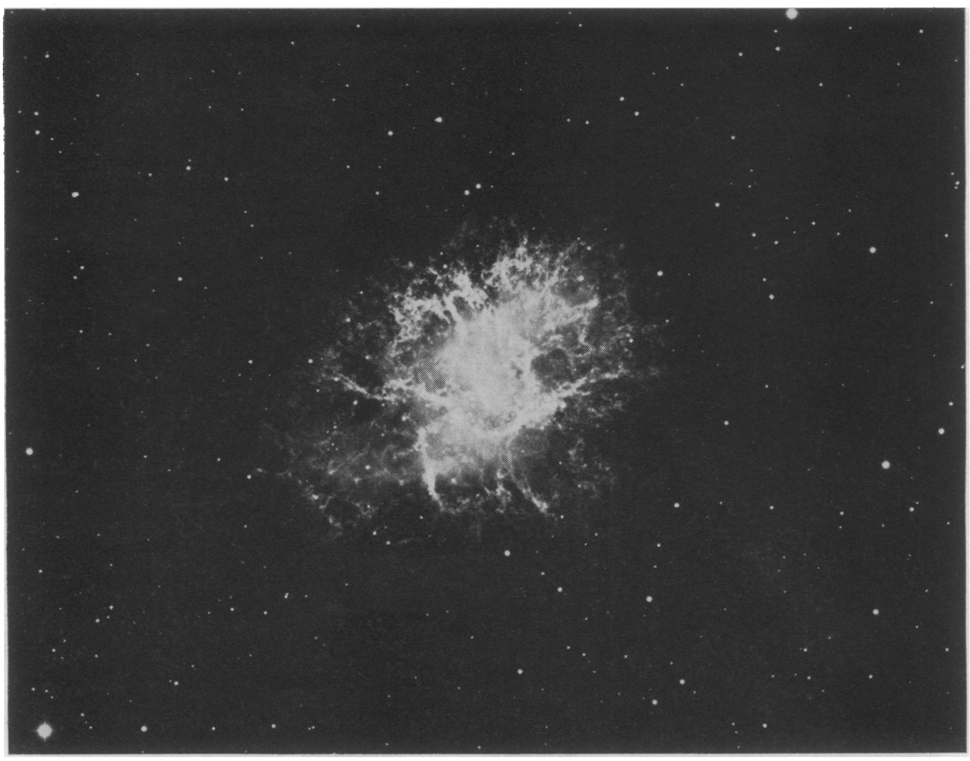


FIG. 4.—The Crab nebula, photographed in the wavelength range λ6300 to λ6750. The filamentary structure stands out clearly at this wavelength, which comprises light mainly due to the H_α line. The nebula consists of the expanding debris of a supernova which was observed to occur at the same point in the sky by the Chinese in A.D. 1054. (Mount Wilson and Palomar Observatories.)

and since they occur only in regions observed to be populated with relatively large amounts of gas, it is reasonable to assume that they condensed from the interstellar material. In regions of no gas and dust, there are few great bright stars; only old stars of low mass, low central temperatures, and low nuclear reaction rates are found there. They are the slow burners from the original and succeeding condensations that cleaned up the vicinity in which they are located.

The process of gravitational contraction of a protostar containing only hydrogen leads to a temperature and density rise in the interior and to a gradient in these quantities such that the temperature and density are highest at the center of the star and drop off rapidly to relatively low values at the stellar surface. When the central temperature reaches 10^7 degrees absolute and the density reaches 100 gm/cm^3, the hydrogen begins to interact through the so-called direct proton-proton or p-p chain which consists initially of the reactions shown in Figure 5. Each of these reactions is exoergic. The reactions proceed with the emission of large amounts of energy even when the reactants have relatively low energies. The reaction products rapidly lose their large energies by atomic (not nuclear) collisions, and thus the reactions are not reversed. The over-all result is $4H^1 \rightarrow He^4$ with the emission of 26.7 Mev or 4.3×10^{-5} ergs of energy from the small fractional difference (0.7%) between the mass of the helium atom and that of four hydrogen atoms. From the standpoint of nucleosynthesis, the p-p chain is important because it is a mechanism by which pure hydrogen can be converted into helium.

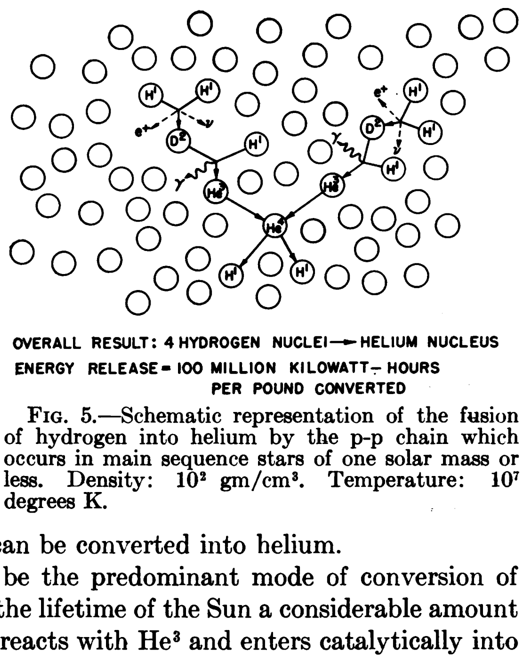


FIG. 5.—Schematic representation of the fusion of hydrogen into helium by the p-p chain which occurs in main sequence stars of one solar mass or less. Density: 10^2 gm/cm^3. Temperature: 10^7 degrees K.

The p-p chain is now thought to be the predominant mode of conversion of hydrogen into helium in the Sun. In the lifetime of the Sun a considerable amount of He^4 has been produced. This He^4 reacts with He^3 and enters catalytically into the production of additional He^4. This can be seen from the complete set of major p-p chain reactions written in modern nuclear notation as follows:

$$H^1(p,\beta^+\nu)D^2(p,\gamma)He^3(He^3,2p)He^4$$

or $$\hookrightarrow (He^4,\gamma)Be^7(e^-,\nu)Li^7(p,\alpha)He^4$$

or $$\hookrightarrow (p,\gamma)B^8(\beta^+\nu)Be^{8*}(\alpha)He^4.$$

In the two last alternatives, the interaction of He^4 with He^3, with the addition of a proton, finally results in the production of two He^4. It will be noted that neutrinos of various energies are emitted in this chain. Those accompanying the production of D^2 have an average energy equal to 0.25 Mev. Those from the decay of Be^7 fall into two approximately monoenergetic groups at 0.88 Mev (90%) and 0.40 Mev (10%). The neutrinos from B^8 have an average energy equal to 7.4 Mev.

The relative production of these various neutrinos depends sensitively on the central temperature of the Sun. Their detection cross sections increase rapidly with energy. Thus a solar neutrino detection experiment such as that under way by Davis at Brookhaven using $Cl^{37} + \nu \rightarrow A^{37} + e^-$ may serve to make an independent determination of the Sun's central temperature which can at the present time be inferred only from models of the Sun's internal structure. It would seem there is available what might be called a *neutrino thermometer*.

The fusion of protons into helium can occur in stars even though protons are all positively charged and mutually repel each other. As a matter of fact, on classical Newtonian mechanics, the fusion cannot occur, because even at stellar temperatures the protons do not have sufficient relative velocities to overcome their mutual repulsion. Sir Arthur Eddington, who proposed hydrogen fusion as the source of energy in stars in 1920, gave a magnificent answer to those who criticized him on classical grounds: "We do not argue with the critic who urges that the stars are not hot enough for this process; we tell him to go and find a hotter place." Eddington's critics were saved from their classical fate by modern quantum mechanics, which governs the behavior of atomic particles and permits fusion to occur even when it is "impossible" on Newtonian mechanics.

Stars which live and shine from energy generated through the process $4H^1 \rightarrow He^4$ fall in a luminosity-color classification called the "main sequence." However, as the hydrogen in the central regions of the star is exhausted, the star ceases to be homogeneous in composition throughout its interior and will move, or "evolve," off the main sequence. The conversion of hydrogen "fuel" into helium "ash" occurs in the core of the star because the temperature and density are highest there. Judging from astrophysical observations, it appears that the reaction product, helium, is mixed with the outer envelope, still hydrogen, with extreme difficulty. Thus, a core of helium develops and gradually increases in size as more and more hydrogen is converted. Because of greater electrostatic repulsions, the doubly charged He^4 does not burn at 10^7 degrees or even at considerably higher temperatures, and so energy generation ceases except in a thin shell surrounding the helium core. This shell now contains the hottest hydrogen in the star. It has been estimated that the shell temperatures reach 3×10^7 degrees, while the density is of the order of 10 gm/cm^3. In the central regions, the nuclear hydrogen furnace goes out for lack of fuel, and one would expect from ordinary experience with furnaces that the temperature would drop. But this is not at all the case in stars because of their great potential gravitational energy. The helium in the core begins to contract and its temperature rises as gravitational energy is converted into kinetic energy.

This "anomalous" behavior of stars is not all pure conjecture, for the sudden rise in temperature of the core also heats up the envelope, which expands enormously and increases the surface area of the star. The increased area means that energy can be radiated at a lower surface temperature, and thus the surface reddens in color. Larger in area and redder in color than main-sequence stars of the same luminosity, these stars are aptly called the "red giants" by astronomers.

Eventually the helium in the core reaches temperatures ($\sim 10^8$ degrees) and densities ($\sim 10^5$ gm/cm^3) at which Coulomb repulsions should no longer critically inhibit nuclear processes between two helium nuclei. What these processes might be constituted for a long time the Gordian knot of nuclear astrophysics. Two helium nuclei, upon interacting, might be expected to form Be^8. However, as noted previously, no nucleus of mass 8 exists in nature, and from this, early investigators inferred that it must be unstable. Shortly after World War II, this was confirmed in quantitative measurements of the Be^8 decay at Los Alamos and the California Institute of Technology. In both laboratories it was found that when Be^8 was produced artificially in nuclear reactions, it promptly broke up into two alpha particles. However, the energy of breakup was found to be relatively small, slightly less than 100 kev. With this last fact in mind, Salpeter of Cornell University then pointed out that, although hot interacting helium in a star will not produce a stable Be^8 nucleus, it will produce, at 10^8 degrees and 10^5 gm/cm^3, a small but real concentration of Be^8 as a result of the equilibrium between the formation and breakup processes. Now, nuclei are found in the laboratory to capture alpha particles with the emission of energy in the form of gamma radiation. Salpeter pointed out that the Be^8 should behave similarly and that if, after its formation from two alpha particles, it collided with a third, the well-known stable carbon nucleus C^{12} should be formed. Because of the low equilibrium concentration of the Be^8, about 1 part in 10 billion at 100 million degrees, Hoyle emphasized that the Be^8 capture process had better be a very rapid one, or a "resonant" reaction in nuclear parlance. Experiments at Stanford, Brookhaven, and Cal Tech have shown that this is the case. It has been possible to show that there exists an excited state of the C^{12} nucleus at 7.656 Mev, with almost the exact energy of excitation and other properties which Hoyle predicted that it must have in order to serve as a thermal resonance for the formation of C^{12} from Be^8 and He^4 in stars.

Thus, there now exists a reasonable experimental basis for the two-state process by which three alpha particles in the hot dense cores of red giant stars can synthesize carbon, bypassing the intervening elements lithium, beryllium, and boron. This process is indicated schematically in Figure 6. The over-all process can, in fact, be looked upon as an equilibrium between three helium nuclei and the excited carbon C^{12*}, with occasional irreversible leakage out of the equilibrium to the ground state of C^{12}. In reaction notation, we have

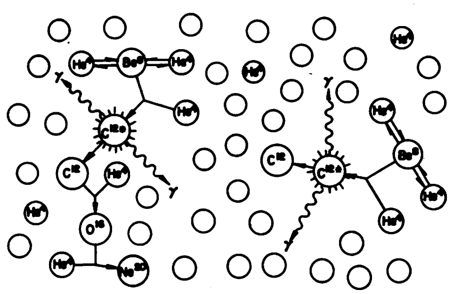
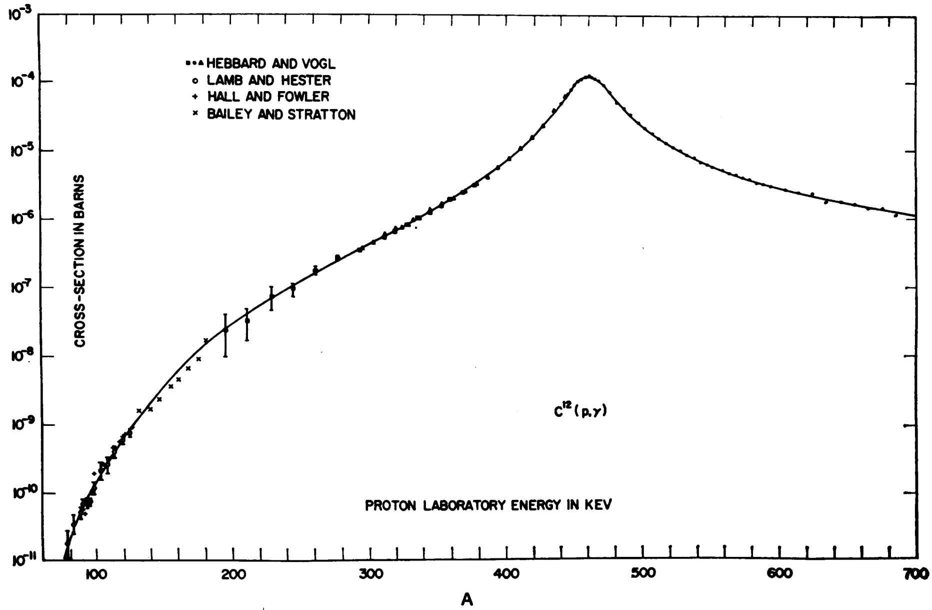


FIG. 6.—Schematic representation of the fusion of helium to form C^{12} which occurs in red giant stars. Density: 10^5 gm/cm^3. Temperature: 1.3×10^8 degrees K.

$$3He^4 \rightleftarrows C^{12*} \rightarrow C^{12}.$$

The C^{12} frequently captures a helium nucleus to form O^{16} before the helium is exhausted. In extreme cases this results in the over-all process $4He^4 \rightarrow O^{16}$. In stars, there is no difficulty at mass 5 and the difficulty at mass 8 has been surmounted. When the central conditions in a red giant reach 10^8 degrees and 10^5 gm/cm^3, the helium begins to burn and energy is released. Because of the small fraction, 0.07 per cent, of mass converted into energy in the above process, the red giant star is not stabilized for any long period after the onset of the helium burning.

The major release in nuclear energy comes in the first process, $4H^1 \rightarrow He^4$. In any case, however, the astronomical evidence indicates that the trend toward catastrophic internal temperatures is stopped and the evolutionary track reversed. Stars that become unstable at this point will eject unburnt hydrogen and helium and the synthesized carbon and oxygen into interstellar matter. Others which remain stable will continue the synthesis process.



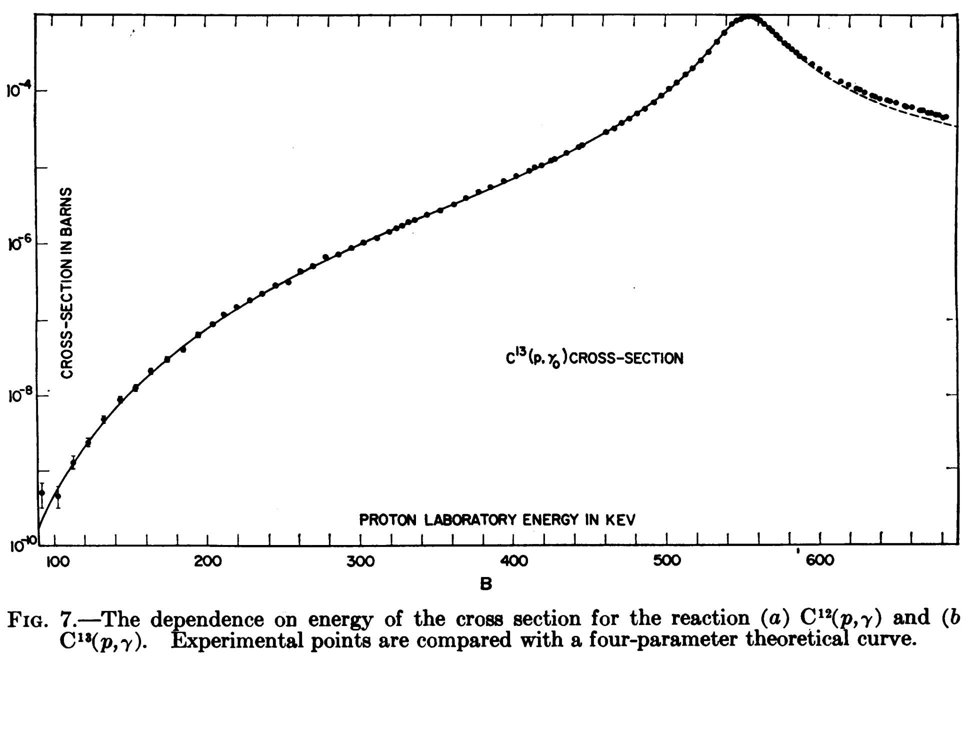


FIG. 7.—The dependence on energy of the cross section for the reaction (*a*) $C^{12}(p,\gamma)$ and (*b*) $C^{13}(p,\gamma)$. Experimental points are compared with a four-parameter theoretical curve.

The C^{12} and O^{16} ejected by stars which become unstable will mix with the primordial interstellar matter and eventually condense into a "second" or later-generation star. In this new star hydrogen can be converted into helium through what is now called the CNO bi-cycle since it incorporates the original CN cycle of Bethe and von Weizsächer and a branch involving O^{16} and O^{17}. In modern nuclear notation the reactions are

$$\rightarrow C^{12}(p,\gamma)N^{13}(\beta^+\nu)C^{13}(p,\gamma)N^{14}(p,\gamma)O^{15}(\beta^+\nu)N^{15}(p,\alpha)C^{12}$$

or

$$\rightarrow N^{14}(p,\gamma)O^{15}(\beta^+\nu)N^{15}(p,\gamma)O^{16}(p,\gamma)F^{17}(\beta^+\nu)O^{17}(p,\alpha)N^{14}$$

These reactions have been extensively investigated experimentally. Recently measured laboratory cross sections for $C^{12}(p,\gamma)$ and $C^{13}(p,\gamma)$ are shown in Figure 7.[4] The solid curves are theoretical cross sections fitted to the data by the adjustment of four phenomenological parameters—the resonance energy, the radius of interaction, and the probabilities at resonance for proton absorption and gamma-ray emission. Effective thermal energies in hydrogen burning in stars correspond to 10–50 kev and fall below the lowest energies at which the reactions are detectable in the laboratory. Even at 100 kev the crcss sections are only $\sim 10^{-34}$ cm^2! The excellent agreement with theoretical expectations leads to some confidence in the extrapolation of the data to stellar energies. This is customarily done by dividing the cross section by the main energy dependence of the Coulomb penetration factor to obtain the so-called cross section factors illustrated in Figure 8. The cross section factor can be accurately extrapolated to zero and can then be integrated over a weighting function consisting of the penetration factor and the Maxwell-Boltzmann distribution in thermal energies.

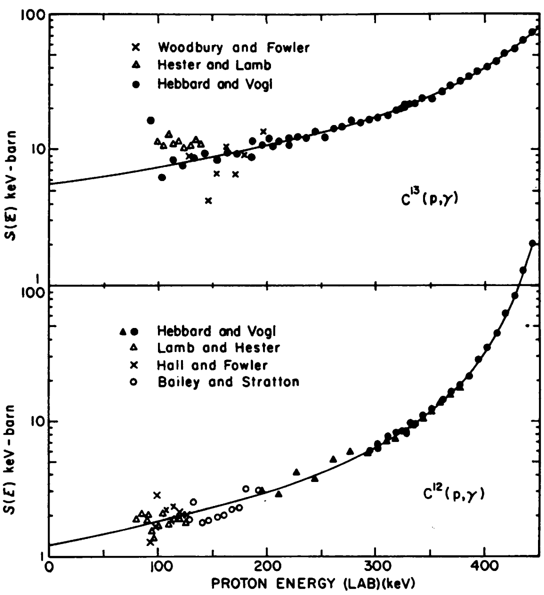


FIG. 8.—The dependence on energy of the cross section factors for the reactions $C^{12}(p,\gamma)$ and $C^{13}(p,\gamma)$.

If resonances occur below the lowest energies measured, then the thermal cross sections and reaction rates would be considerably greater than given by the extrapolation of the laboratory data and still not be directly detectable in the laboratory. Fortunately, separate studies involving the compound nuclei, N^{13} and N^{14} in the cases under consideration, can be made to show that no sharp resonances corresponding to excited states in these nuclei contribute to the cross section in the important but unobservable thermal region.

Returning to helium burning, the nuclear evidence indicates that this process should only rarely proceed beyond oxygen. Thus, C^{12}, O^{16}, or a mixture of both are the products of helium burning. Eventually the helium is exhausted; the core of carbon and oxygen contracts and heats up until the C^{12} and O^{16} begin to burn. The result is the production of a number of intermediate mass nuclei among which Ne^{20}, Mg^{24}, Si^{28}, and S^{32} are the most abundant. This is expected from the great nuclear stability of these nuclei with mass number an integral multiple of 4. The great stability is most simply understood in terms of the model in which these nuclei consist of complexes of the highly stable alpha particle. Indeed, these nuclei are the most abundant among the isotopes of the elements neon, magnesium, silicon, and sulfur. In a star which remains stable, the evolutionary process continues. The Coulomb repulsions between nuclei with $Z = 10$ to 16 are very strong and burning no longer proceeds by the simple fusion of the interacting products. Instead, as the temperature rises, a number of the intermediate nuclei are photodisintegrated in the intense high-energy flux of the tail of the Planck distribution with the emission of alpha particles. For example, a Si^{22} nucleus can be broken down into seven alpha particles at temperatures near 3×10^9 degrees. These alpha particles are captured by other nuclei which escaped photodisintegration. Thus, another Si^{22} nucleus can capture seven alpha particles to form Ni^{56}. The over-all result is $2Si^{28} \rightarrow Ni^{56}$ but the detailed mechanism is not direct fusion but the alpha-process in which buildup of one nucleus to double its original mass and charge occurs upon the breakdown of another into alpha particles. Ni^{56} is radioactive and decays through Co^{56} to Fe^{56} through the successive capture of two electrons from the plasma continuum in a star with the emission in each capture of a neutrino. Many other nuclei near Fe^{56} from V^{50} to Ni^{62} are thought to be produced in this way.

From the standpoint of nuclear physics, it is clear that the sequence of successive burning of heavier and heavier nuclei through charged-particle reactions should terminate at the iron-group nuclei, which are the most "stable" nuclei in the sense that the internal neutron-proton energies are at a minimum and their binding energies are at a maximum in absolute magnitude. Both heavier and lighter nuclei have higher internal energy content and are less stable in this sense than the iron-group nuclei.

Very high temperatures and great densities will be reached at the production of the iron-group elements. Under these conditions, the rates of all possible reactions will be very great indeed and the situation will be best described in terms of a nuclear equilibrium. This appears to be indeed the case, because the shape of the iron-group peak illustrated in the abundance curve of Figure 9 has been found by Burbidge, Burbidge, Fowler, and Hoyle to be in good agreement with the calculated equilibrium distribution at 3.8×10^9 degrees and 3×10^6 gm/cm^3 and with a free proton-to-neutron ratio of 500:1. The temperature and density are consistent with the conditions leading up to equilibrium and the free proton/free neutron ratio is an essential parameter in determining the proton and neutron numbers in the nuclei produced at equilibrium. In the calculation it was necessary to take into account the experimentally known properties of the ground and low-lying excited states of the stable and β-active nuclei involved in the equilibrium and to take into account the β decays on freezing of the mixture. In Figure 9 the process is designated the e process. It is the e process by which the iron-group elements are synthesized. Their overabundance relative to their neighbors can be understood on the basis that enough stars remain stable long enough to develop an iron "ball" in their centers at the end of a long line of energy-generating charged-particle reactions.

The α process and the e process probably occur at a rapidly evolving or even explosive state of stellar evolution. It has been suggested that the collapsing core of a star in its terminal stages as a red giant or in its final catastrophic supernova stage is a possible site for such processes. The collapse of the core is brought about by the fact that no further generation of nuclear energy occurs after the iron-group nuclei are produced. Gravitational contraction takes place unimpeded. The implosion is actually speeded up in the inner regions of the core by the refrigerating action of nuclear processes which transfer some of the iron-group nuclei back into lighter nuclei, mostly He^4 and neutrons, with the absorption of energy.

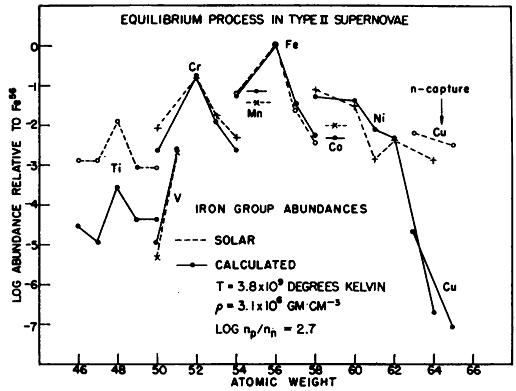


FIG. 9.—The abundance relative to Fe^{56} of nuclei produced in the e process.

The implosion of the core removes the underlying support of the envelope material of the star, which contains unevolved nuclear fuel capable of releasing large amounts of energy on being raised to high temperatures. The gravitational collapse of the envelope material does just this. The energy release by the nuclear reactions in the envelope material further raises its temperature, the collapse is reversed by expansion of the material, and all or part of the envelope material and probably even a portion of core material are blown out from the star at high velocity. The result is observed astronomically as the occurrence of a supernova in which a star is observed in a very short interval to flare up to many times its previous luminosity and to eject a large fraction of its mass into space.

The time scale of the e process has recently been extensively investigated in the light of the large energy losses to be expected on current beta decay theory from the annihilation of electron-positron pairs according to the reaction $e^+ + e^- \rightarrow \nu + \bar{\nu}$. At the high temperature of the e process, many electron-positron pairs are produced in the interaction of radiation and nuclei. Equilibrium is established when production and annihilation are equal. The neutrino emission competes with $e^+ + e^- \rightarrow \gamma + \gamma$ in only about one case in 10^{19}, but the gamma rays are trapped in the star whereas the neutrinos and antineutrinos escape directly with the velocity of light. They escape with the kinetic energy and rest mass equivalent energy of the pair and constitute a critical drain on the dwindling energy resources of the stellar interior. The evolutionary process is speeded up and the burning processes from O^{16} to Ni^{56}, which would otherwise require 10^4 years for completion, take place in approximately one day. The time available for the typical decay, Ni^{56} to Fe^{56}, in the e process is even shorter in the range 10^3 to 10^5 sec. The question arises: How does this short time interval affect the resultant equilibrium process abundances? The term "equilibrium" is applicable only in the sense that ordinary nuclear processes involving nucleons, nuclei, and gamma rays are preceding very rapidly even relative to the short over-all time set by the neutrino loss. On the other hand, the slow electron captures proceed in times comparable to the loss time. In Table 2, a calculation is made under conditions appropriate

TABLE 2

IRON ISOTOPES—PER CENT OF TOTAL e-PROCESS ABUNDANCE BY MASS

$\bar{Z}/\bar{N}$	$\log n_p/n_n$	Fe^{54}	Fe^{56}	Fe^{57}	Fe^{58}	Electron capture time (10^4 sec)
1.000	8.6	1.7	89.1	2.9	0.0	0.0
0.950	6.6	43.4	21.9	7.2	0.0	0.2
0.900	4.0	34.0	29.6	4.7	0.04	1.2
0.872	2.7	4.3	66.6	2.5	0.23	3.2
0.860	1.2	0.2	64.5	3.0	4.0	∞
Solar values		4.1	65.0	1.6	0.23	$M = 30\ M_{\odot}$

to a star with mass equal to 30 solar masses for the final abundances of the isotopes of iron as a function of the time available for electron capture. In the first row, under the heading, the results for "zero" time at equilibrium are given. At this time the α process has produced nuclei with equal number of protons and neutrons so that the averages over all nuclei yield $\bar{Z}/\bar{N} = 1$. It is found that the ratio of free protons to free neutrons in the "gas" surrounding these nuclei is 4×10^8. The most abundant nucleus is Ni^{56} which constitutes 89.1 per cent of the material by mass. If the α process material were immediately ejected from the star at this juncture, the Ni^{56} would eventually decay to Fe^{56} which would then have an abundance equal to 89.1 per cent of the e-process group. The expectations for Fe^{54}, Fe^{57}, and Fe^{58} are also given. These do not agree at all with the observed values for the Sun, given in the last row. Moreover, the complete equilibrium values given in the next-to-the-last row do not agree with observations. These values are calculated for a long time compared to characteristic electron capture times and correspond to the free proton/free neutron ratio expected if all the beta decay processes—electron and positron capture and emission—reach equilibrium. Thus the times available for the decays were neither very short nor very long compared to the decay times. As indicated in Table 2, best agreement with observation is found for a period of 3.2×10^4 sec. This applies to a star with $M = 30\ M_{\odot}$. Type II supernovae are thought to result as the terminal explosive stage of stars in the mass range 10–50 $M_{\odot}$.

Thus, the relative abundances of the iron isotopes (and of the other e-process isotopes) strongly indicate a pre-supernova time scale for the e process of the order of 10^3 to 10^5 sec. This is just what is to be expected if the $e^+ + e^- \rightarrow \nu + \bar{\nu}$ reaction occurs at the rate calculated on the assumption that it is governed by the universal interaction rate found for observable weak interactions including beta decay and muon decay and capture. This process has not been observed in the laboratory and the calculations are guided entirely by theory. The astrophysical evidence strongly implies that the theory is correct or alternatively that some unknown process leads to an energy loss comparable within a factor of 10 to that expected from electron-positron pair annihilation with neutrino-antineutrino emission.

The question is often asked: What becomes of the neutrinos and antineutrinos emitted by a star? The scientist may not know, but the poet does. Witness these lines:

O dark dark dark. They all go into the dark,
The vacant interstellar spaces, the vacant into the vacant, . . .
—T. S. Eliot in "East Coker" (1940)

Beyond the iron-group nuclei, neutron capture processes have played the primary role in the synthesis in stars of the heavy elements. Because of repulsive Coulomb forces, charged particle reactions have been rather ineffective at the temperatures (10^8 to 10^9 degrees) at which the main line of heavy element synthesis has apparently occurred. The small relative abundance (0.1–1%) of the lightest, "charge-rich" isotopes of the heavy elements attests to the infrequent operation of charged particle reactions in the synthesis of these elements. On the other hand, neutrons interact rapidly with heavy nuclei at the "low" energies ($kT \sim$10–100 kev) corresponding to the temperatures just cited. In fact, neutron reaction crcss sections vary roughly as $1/v \sim 1/E^{1/2}$, where v is the neutron velocity and E the energy. Furthermore, at low energies the only reaction other than elastic scattering which is allowed energetically in most cases is the capture of the neutron. This leads to an increase in atomic weight by one unit, a slow but sure mechanism for the synthesis of heavier and heavier nuclei. Eventually, of course, neutron-induced fission becomes possible in the very heaviest nuclei at low energies. This process or alpha particle decay, or even spontaneous fission, depending on circumstances, terminates the synthesis.

Gamow, Alpher, and Herman suggested neutron capture as the mechanism of synthesis of all the elements starting with neutron decay in an early, highly condensed, high-temperature stage of the expanding universe. The density was taken to be $\rho \sim 10^{-7}$ gm/cm^3 and the temperature to be $T \sim 10^{10}$ degrees ($kT \sim 1$ Mev). The measurements of Hughes and his collaborators on the capture cross sections of nuclei for fission spectrum neutrons in the Mev energy range indicated an inverse relationship between these cross sections (σ) and isotopic abundances (N) such that $N \sim 1/\sigma$. This was to be expected in general from the point of view of synthesis in a chain of successive neutron captures. Nuclei with small cross sections would be expected to build up to large abundances in the chain, and vice versa, so that the number of captures per unit time would be uniform over contiguous sections of the chain. However, in recent years it has become clear from nuclear and astrophysical evidence that charged particle reactions must have played a considerable role in the synthesis of the *light* elements. For example, the iron-group abundance peak cannot be understood on the basis of neutron capture since the iron-group nuclei do not have anomalously low capture cross sections.

Gamow's basic idea of neutron capture is incorporated in stellar synthesis, but the difficulties just mentioned are avoided by using charged particle reactions during various stages of stellar evolution to synthesize the elements up to and including the iron group. Neutron production and capture then serves in the intermediate and terminal stages of stellar evolution as the main line of element synthesis beyond iron. In fact a small fraction, slightly over one tenth of one per cent, of the abundant iron-group nuclei are used as the "seed" nuclei at the start of the chain of captures. Mass spectroscopy has shown that the chain is unbroken in atomic mass in this region. (The chain is indeed unbroken beyond $A = 8$.) The abundance curve shows that two quite different and independent neutron capture processes have been necessary to synthesize the abundant isotopes of the heavy elements. In one of these processes, called the *s* process, the neutron captures occur at a *slow* (*s*) rate compared to the intervening beta decays. Thus, the synthesis path lies along the bottom of the valley of mass stability and in general bypasses both the proton-rich, lightest isotopes and the neutron-rich, heaviest isotopes of the elements involved. On the other hand, in the second neutron process, called the *r* process, the neutron captures occur at a *rapid* (*r*) rate compared to beta decay. The captures lead rapidly from stable seed nuclei, predominantly Fe^{56}, to the very neutron-rich side of the mass valley and are stopped only by photoejection of the weakly bound neutrons by the ambient gamma-ray flux associated with the high temperature necessary for the production of the neutrons. Equilibrium between (n,γ) and (γ,n) reactions is established, and progress along the synthesis path occurs only through electron-antineutrino ejection or beta decay which permits further neutron capture. On termination of the synthesizing neutron flux, the neutron-rich isobars at each atomic mass beta decay to the first stable isobar which then "shields" from *r* process production those remaining isobars, if any, having fewer neutrons and more protons. The *s* process and the *r* process account in these ways for the synthesis of *all* the relatively abundant isotopes of the heavy elements. An exposure of a small fraction of the *s*- and *r*-process material to a hot proton flux or an intense photon flux will account for the production of the relatively rare, proton-rich, lighter isotopes of the heavy elements. This infrequent mechanism has been termed the *p* process.

It follows from the evidence for two different neutron capture processes, which occur at quite different rates, that two separate and distinct stages of stellar evolution are demanded. The *s* process has been assigned to the red giant state of stars which were formed from galactic material containing light elements, particularly He, C, O, Ne, and Mg and the intermediate iron-group elements. These elements had been previously synthesized in other stars and ejected into the interstellar medium, mostly primordial hydrogen, of the Galaxy. The He, C, O, Ne, and Mg were required for the production of neutrons by α,n-reactions on C^{13}, O^{17}, Ne^{21}, Ne^{22}, and Mg^{26} during the relatively slow helium burning in the red giant, with lifetimes 10^6 to 10^8 years. Professor Greenstein was the first to suggest a source of neutrons in stars—the exoergic $C^{13}(\alpha,n)O^{16}$ reaction.

The *r* process is thought of as taking place in the exploding envelopes or cores of supernova outbursts. In this case the energy- and neutron-producing processes occur in the short interval of the supernova explosion, 1–100 sec, and the neutron captures accordingly occur at a rapid rate.

To illustrate the general importance of these considerations in determining isotope abundances, Figure 10 is appended. This shows the evidence for the operation of the three separate processes, *p*, *s*, and *r*, in the formation of the stable isotopes of

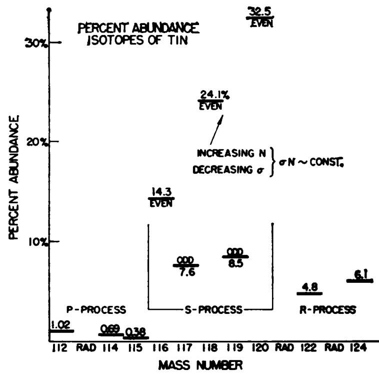


FIG. 10.—Abundance evidence for the operation of three separate processes, p, s, and r, in the formation of the stable isotopes of the element tin. The first three isotopes can only be produced in the relatively rare p process involving charged particles (protons) or radiation, and their abundances are seen to be quite small. The next five isotopes are produced by neutron capture at a slow rate (s process) and exhibit the regularity expected for this process—decreasing capture cross section, hence increasing abundance, with increasing mass number. The last two isotopes are produced only by neutron capture at a rapid rate (r process), and the discontinuity between the s process and the r process is quite apparent.

the element tin. By following through the s-process path shown in Figure 11 and described in the figure caption, it will be seen that the first three isotopes, Sn^{112}, Sn^{114}, and Sn^{115}, cannot be made in the s or the r process. Their low abundances of the order of one per cent or less are consistent with their production only in the p process.

Sn^{116} is the first isotope which can be made in the s process, and the discontinuity in abundance between Sn^{115} and Sn^{116} is quite marked. Similarly, Sn^{120} is the last isotope which can be made in this process, and again there is a discontinuity in going to Sn^{122} and Sn^{124} which can only be made in the r process. The r process apparently produced somewhat lower abundances in this region of atomic weights than the s process. This is a result of the "history" of the synthesis of the elements of the solar system, not of any fundamental nuclear properties of these isotopes. The rising trend in abundances from Sn^{116} to Sn^{120} is consistent with $N\sigma \sim$ constant if we note that $\sigma(n,\gamma)$, in general, decreases as more neutrons are added; and that σ, for odd A isotopes, is higher than σ for even A isotopes because of the tendency to pair up the neutrons. These statements are confirmed by recent measurements at Oak Ridge of 30-kev neutron capture cross sections in separated tin isotopes. Measured cross sections are compared with relative isotopic abun-

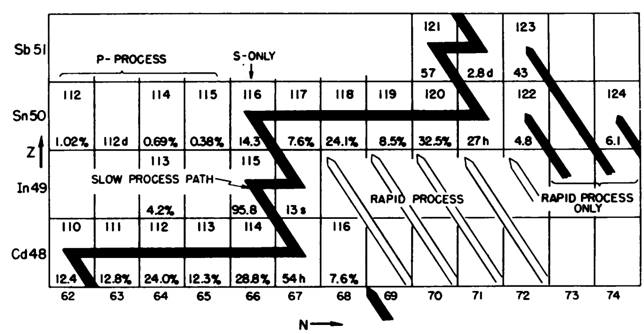


FIG. 11.—The s-process path through the isotopes of tin. The neutron number increases by units of one on a slow time scale until negative beta activity occurs and the path moves to the isobar of higher Z. This path can be determined from empirical evidence on the beta stability of nuclei. Note that the path bypasses the p-process and the r-process nuclei. The r-process nuclei are the end products of an isobaric beta-decay chain, as shown at the far right, from neutron-rich progenitors produced in an intense neutron flux. The p-process nuclei are produced by subjecting a small fraction of s- and r-process nuclei to an intense proton or photon flux.

TABLE 3

σN FOR TIN ISOTOPES

Nucleus	Process	σ (30 kev), (mb)	N (abundance), per cent	σN	N_r	$\sigma N_s = \sigma(N - N_r)$
Sn 116	*s*	92 ± 19	0.142	13.1	0	13.1
117	*sr*	390 ± 82	0.076	29.5	~0.040	13.9
118	*sr*	59 ± 12	0.240	14.2	~0.045	11.5
119	*sr*	243 ± 51	0.086	20.9	~0.040	11.1
120	*sr*	35 ± 7	0.330	11.5	~0.045	10.0
122	*r*	23 ± 5	0.047	1.1	0.047	—
124	*r*	23 ± 4	0.060	0.8	0.060	—

$$\frac{dN_A}{dt} = -\varphi_n(\sigma_A N_A - \sigma_{A-1} N_{A-1}) \approx 0 \qquad A \geq A \text{ (seed nucleus)}$$

dances for Sn^{116} to Sn^{124} in Table 3. The product σN varies over a factor of 2.6 for the first five isotopes and then drops by more than a factor of 10. This drop is explicable on the basis that Sn^{122} and Sn^{124} cannot be produced in the *s* process and their σN should bear no particular relationship to that of the others. The variation in σN for Sn^{116} to Sn^{120} is puzzling until it is noted that Sn^{117} to Sn^{120} can be produced in the *r* process as well as in the *s* process, while Sn^{116} is produced *only* in the *s* process. The *r* production for Sn^{122} and Sn^{124} makes it possible to estimate N_r for Sn^{117} to Sn^{120} as given in the table. Then with $N_s = N - N_r$ it is possible to calculate σN_s which should be at most slowly varying over the range $116 \leq A \leq 120$, and indeed this is seen to be the case. There can be little doubt that the abundances and cross sections of the tin isotopes reveal the nature of the processes by which they were synthesized. Isotopes of tin from red giants and supernovae once mixed together in the interstellar medium have not thereafter been separated and have come down to us as clues to stellar events in the distant past of the Galaxy. In other stars and other galaxies the relative *s*-process abundances will probably be much the same as in the solar system as will the relative *r*-process abundances, but the ratio of $Sn^{122} + Sn^{124}$ to $Sn^{116} + Sn^{117} + Sn^{118} +$

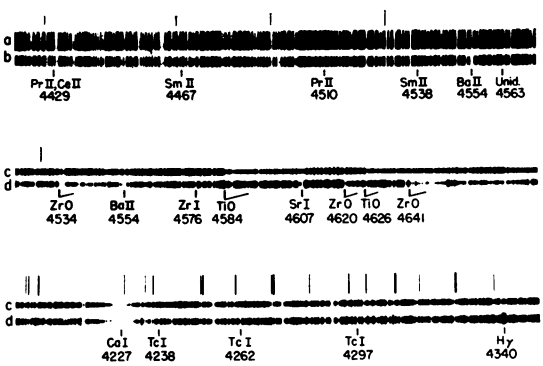


FIG. 12.—Portions of the spectra of stars showing the results of the *s* process. *Top:* (*a*) Normal G-type star, K Geminorum. (*b*) Ba II star, HD46407, showing the strengthening of the lines due to the *s*-process elements barium and some rare earths. *Middle:* (*c*) M-type star, 56 Leonis, showing TiO bands at λλ 4584 and 4626. (*d*) S-type star, R. Andromedae, showing ZrO bands which replace the TiO bands. Lines due to Sr I, Zr I, and Ba II are all strengthened. *Bottom:* (*c*) Another spectral region of the M-type star, 56 Leonis; note that TcI lines are weak or absent. (*d*) R. Andromedae; note the strong lines of TcI. The spectrum of R. Andromedae was obtained by P. W. Merrill, and the upper two spectra by E. M. and G. R. Burbidge.

$Sn^{119} + Sn^{120}$ may show conspicuous variations relating to the past stellar history of the material involved.

The question often arises: Is there evidence that the *s* process is occurring in present-day stars or that it has occurred recently? The most convincing answer is given in Figure 12 which shows spectroscopic evidence for the existence of technetium (Tc) in certain stars. Technetium has no stable isotopes and does not occur naturally on earth, but the isotope Tc^{99} is produced in the *s*-process chain and has a half-life of 2×10^5 years. If it had not been produced in the star and mixed to the surface in the last several hundred thousand years, it would have decayed to Ru^{99} and no technetium line would be observable. Tc^{97} and Tc^{98} have somewhat longer lifetimes but cannot be produced in the *s* process. It is worthy of note that promethium has no long-lived isotopes and has not been observed in stars.

Turning attention for the moment to the *r* process, detailed calculations reveal that it can account quantitatively for the abundance of the nuclei which can be made only or are most probably made in this way. Results of such calculations are shown in Figure 13. Combined calculations for the *r* process and the *s* process are shown in Figure 14. The correspondence between observations and calculations is in general fair although there are many unresolved problems pertaining to both.

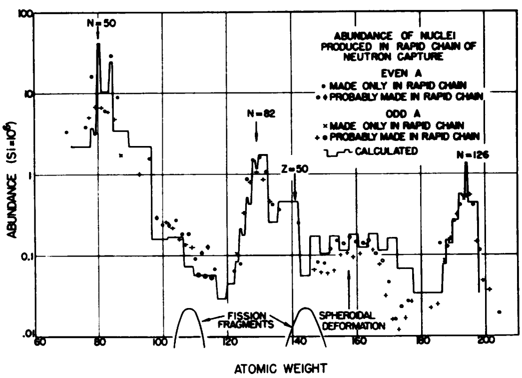


FIG. 13.—Abundances of nuclei produced in the *r* process. The empirical points are taken from Suess and Urey. The histogram is a calculated curve. The free parameters have been adjusted to yield the correct relative heights of the three abundance peaks for magic neutron numbers $N = 50$, 82, and 126.

It is possible to extend the calculations illustrated in Figure 13 into the transuranic region and to calculate the abundance of Th^{232}, U^{235}, and U^{238} produced in each *r*-process event. These nuclei are singled out here because they are the parents of the naturally radioactive series with decay lifetimes comparable to astronomical times. This property has been used to arrive at determinations of the age of the meteorites, $\sim 4.6 \times 10^9$ years, and of terrestrial rocks, $\lesssim 3 \times 10^9$ years. It is also possible to use these chronometers to measure the duration of stellar synthesis in the Galaxy once their production abundances are calculated. An important point is the fact that numerous short-lived progenitors of these nuclei are produced in *r*-process events. Thus, for example, all the material produced at $A = 235$, 239, 243, 247, 251, and 255 contributed to the U^{235} abundance since the nuclei at $A = 239, 243, \ldots 255$ decay relatively rapidly by alpha particle and beta particle emission to U^{235}. At $A = 259$ and beyond, the ultimate fate of the nuclei is spontaneous fission rather than alpha decay and no contribution is made to the abundance of U^{235}. Contributions to U^{235} thus come from six progenitors. The situation is somewhat more complex for U^{238} and Th^{232} but the corresponding numbers are 3.1 and 5.75, respectively, as shown in Table 4. Thus, on the basis of number of progenitors alone, the production ratio for U^{235} relative

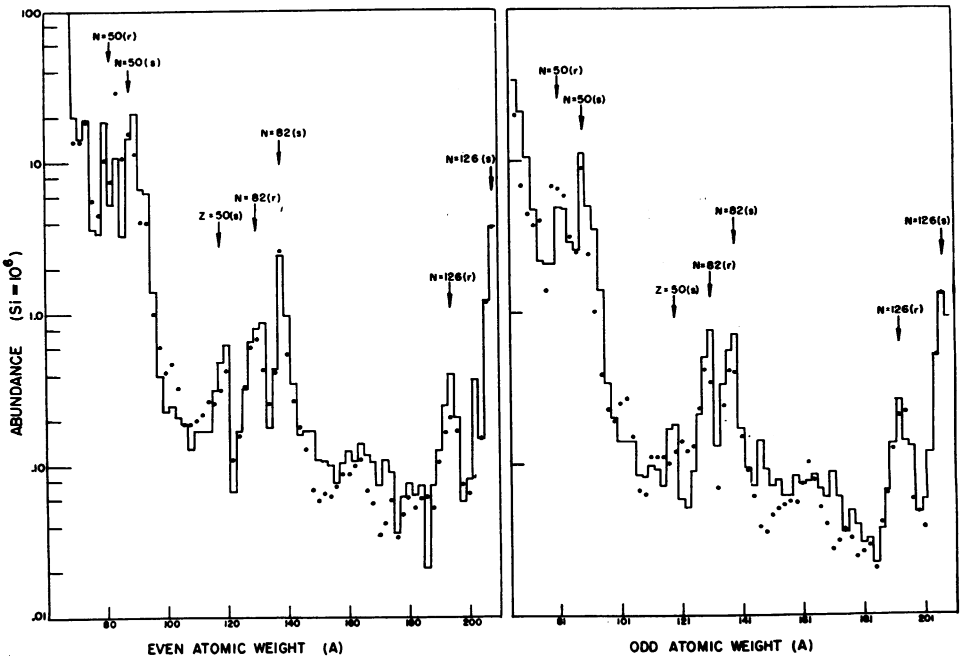


FIG. 14.—The observed meteoritic abundances (points) of the heavy nuclei compared with unsmoothed calculated values (histogram) based on the theory of the r process and the s process.

to U^{238} is 1.93 and that for Th^{232} to U^{238} is 1.85. Detailed calculations yield 1.65 ± 0.15 for each of these ratios, the exact agreement being accidental. Figure 15 shows the use to which these ratios can be put. The present-day observed ratios in meteorites are $Th^{232}/U^{238} = 3.8$ and $U^{235}/U^{238} = 0.0072$, as indicated in the figure. The *differential* mean lifetimes are 9.63×10^9 years for Th^{232} versus U^{238}, and 1.22×10^9 years for U^{235} versus U^{238}. The abundance ratios extended back in time to the origin of the solar system are simply straight lines on the logarithmic abundance scale of Figure 15. For a single sudden synthesis event at some time in the remote past, the extensions to that time are also straight lines back to the relative production ratio 1.65 ± 0.15. The dates so determined are discordant by $\sim 2 \times 10^9$

TABLE 4

PROGENITORS OF U AND TH

Parent	U^{238}	U^{235}	Th^{232}
Great, . . . granddaughter	Pb^{206}	Pb^{207}	Pb^{208}
Mean lifetime (10^9 yr)	6.51	1.03	20.1
Progenitors (A)	238	235	232
	242 (α)*	239 (α)	236 (α)
	246 (α)	243 (α)	240 (α)
	250 (10% α)	247 (α)	244 (α)
		251 (α)	248 (89% α)
		255 (α)	252 (97% α)†
	254 (SF)	259 (SF)	256 (SF)
Total number	3.1	6	5.75
Ratio of progenitors	1	1.93	1.85
Calculated abundance ratio	1	1.65 ± 0.15	1.65 ± 0.15

* In this table, α designates alpha-particle decay, while SF designates decay by spontaneous fission.
† The yield at A = 252 must be multiplied both by 0.97 and by 0.89 to give the fraction which ultimately becomes Th^{232}.

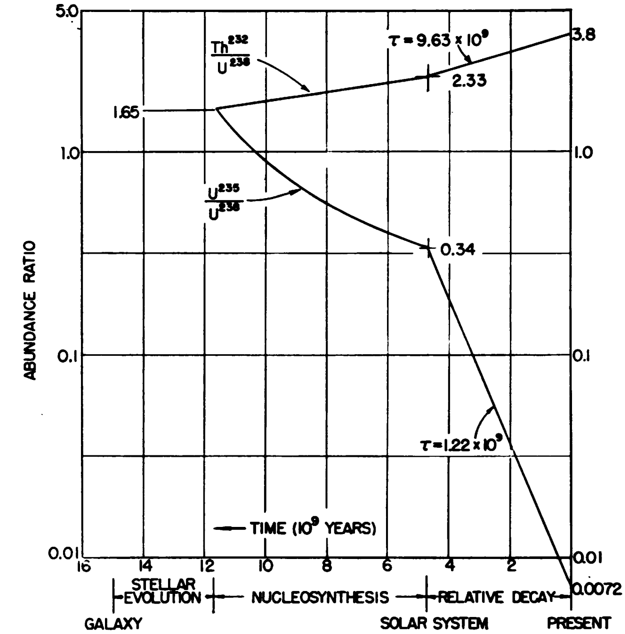


FIG. 15.—The abundance ratios Th^{232}/U^{238} and U^{235}/U^{238} as a function of time for solar system material before and after formation of the system. The curves are adjusted to the present-day ratio and to the calculated ratio for production in each *r*-process event. The calculations indicate continuous synthesis in the Galaxy from 12×10^9 to 4.7×10^9 years ago. Type I supernovae are assigned an evolution lifetime of 3×10^9 years leading to an age for the Galaxy of 15×10^9 years. If the *r* process occurs in rapidly evolving massive condensations, then the age is 12×10^9 years.

years. The curves shown are those expected for uniform synthesis over the nucleosynthesis interval in the Galaxy. Concordant results are obtained from the Th^{232}/U^{238} and the U^{235}/U^{238} ratios at a time for the beginning of *r*-process nucleosynthesis some 12×10^9 years ago. This is a lower limit for the age of the Galaxy since it may be necessary to add an interval of as much as 3×10^9 years for the time for stars to evolve to the supernovae in which the *r* process occurs. On the other hand, the *r* process may have occurred in violent explosions of massive condensations which occurred at the formation of the Galaxy. In spite of this and other uncertainties, the abundances of Th^{232}, U^{235}, and U^{238} found on the earth point to an age of the Galaxy somewhere in the interval from 10 to 15×10^9 years. One must not overlook, however, the comment of Samuel Pepys when the date of Genesis calculated from references in Scripture came under question by the geologists of his time. Said Pepys, "To the Rhenish wine house, and there came Jonas Moore, the mathematician, to us . . . and spoke very many things not so much to prove the Scripture false, as that the time therein is not well computed nor understood."—Diary of Samuel Pepys, 23 May 1661.

In conclusion, it is necessary to mention a new development in astrophysics which almost certainly has important ramifications in regard to nucleosynthesis in the Galaxy. Large radio sources associated with certain galaxies are found to radiate at rates approaching 10^{44} ergs sec^{-1}, some 10^{11} times the optical luminosity of the Sun. If this radiation is due to the synchrotron mechanism, the energy stored in the magnetic field and the high-energy electrons circulating in the field lies in the range 10^{60} to 10^{62} ergs corresponding to the rest mass energy of 10^6 to 10^8 solar rest masses. Hoyle and Fowler have suggested that this energy was made available at the expense of gravitational energy during rapid collapse of objects with masses somewhat greater than the range just indicated. The red shift measured in the optical emission by the so-called radio stars places them at a great distance from the Galaxy and implies total optical luminosities up to 10^{46} ergs sec^{-1} for these objects. Observations on M-82 by Sandage and Lynds show that an explosion involving 5×10^6 solar masses is occurring in that galaxy. The Burbidges have found evidence for "violent events" in numerous galaxies. It can be expected that nuclear reactions will take place during such events. The production of large amounts of helium and lesser amounts of heavier elements may well occur in this way during the formative stages or early history of galaxies. In this way it may be possible to understand the apparent universality of the helium-to-hydrogen ratio, $\sim$10 per cent by number, in the stars of the Galaxy independent of age and position. Massive stars produced helium early in the history of the Galaxy; less massive stars with longer evolution times produced the bulk of the elements heavier than helium. In a way these violent galactic events play a role in the Hoyle-Bondi-Gold cosmology similar to the universal "big bang" in Gamow's cosmology. It may not be too trite to say that the Universe is all things to all men!

Detailed bibliographies may be found in: Burbidge, E. M., G. R. Burbidge, W. A. Fowler, and F. Hoyle, *Revs. Mod. Phys.*, **29**, 547 (1957); Hoyle, F., W. A. Fowler, G. R. Burbidge, and E. M. Burbidge, *Astrophys. J.*, **139**, 909 (1964).

[1] It was, of course, not until 1956 with the fall of the conservation of parity that it became clear that antineutrinos really differ from neutrinos in spite of the fact that both have zero mass, charge, and magnetic moment and both have spin one-half or instrinsic angular momentum equal to $^1/_2\,\hbar$. Antineutrinos move with the velocity of light with their spin vector parallel to their direction of motion as given by the *right-hand* rule. On the other hand, neutrinos move with the velocity of light with their spin vector antiparallel to their direction of motion as given by the *left-hand* rule. Positrons, like antineutronos, are right handed in beta decay; electrons, like neutrinos, are left-handed in beta decay. It is one of the fundamental properties of the beta decay interaction that *handedness* is conserved. If two leptons, as these light particles are collectively known, are emitted in a beta decay, one must be right-handed, the other left-handed. If one is absorbed and one is emitted as in electron capture, they must have the same handedness.

[2] Gamow, G., *Sci. Am.*, **195**, No. 3, 154 (1956).

[3] Salpeter, E. E., *Trans. I.A.U.*, **10**, 661 (1959).

[4] Since 1946, the Office of Naval Research has supported the experimental work in our laboratory by which the cross sections and reaction rates of these and many other reactions have been measured.