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# The nuclear theory of the origin of the elements[1]

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*Abstract*

*The science of nucleosynthesis is the attempt to understand the natural abundances of the nuclear species in terms of their nuclear properties and naturally occurring circumstances in which the nuclei would be assembled. In this talk I hope to discuss the highlights of the current status of this theory. The abundances of the prominent nuclear species in the solar system can be successfully reproduced by a few major epochs of thermonuclear fusion within stars or star-like objects, although the lightest species up to atomic mass* $A = 4$ *perhaps reflect the ashes of a primeval fireball in the cosmological expansion of the universe. The abundance variations observed in other stars support this view by displaying many abundance features that are consistent with it. Many of the fascinating details, however, remain to be solved.*

The nuclear theory of the origin of the elements, commonly called *nucleosynthesis*, is the attempt to interpret the abundances of the nuclear species in terms of their nuclear properties and naturally occurring circumstances in which the nuclei would be assembled. A very sizeable body of data is available to guide the construction of the theory and to test its success. There are 81 stable elements having numbers of stable isotopes ranging from one for the element sodium, for example, to ten for the element tin, and comprising a total of 280 stable nuclear species. The abundances of these species in the solar system constitute 280 data points for the theory, to which must be added all observable abundance ratios in other stars. Another large body of information has been obtained in the nuclear laboratory. Not only have the properties of the 280 stable nuclei been studied in considerable detail, but also the more than 1000 artificially produced radioactive nuclei have been studied to the degree feasible in the laboratory, and thousands of nuclear reaction cross sections resulting in the production or destruction of the 280 stable species have been measured. This body of nuclear facts has been augmented by a semiempirical structure of nuclear systematics and nuclear

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theory and thereby made into a powerful tool for the investigation of nucleosynthesis. Decades of painstaking astronomical observations with modern techniques have been interpreted with the aid of untold thousands of calculations relating to the structure and evolution of the stellar interior. Insufficient though it may be, we nonetheless have all of this with which to contemplate our basic question—have the elements been assembled by thermonuclear reactions. In this paper I hope to recount the nature of this advancing knowledge and to illustrate the current degree of success of the theory.

The abundances of the elements are imperfectly known. The data has been difficult to obtain and even harder to interpret. The most extensively studied object is, of course, the solar system, whose composition is inferred primarily from the sun, the meteorites, and the earth. The sun is the most attractive sample in the sense that was originally a homogeneous sample and is chemically unfractionated, but it has the disadvantage that one can use only those atomic lines that the spectrum provides and that the isotopic composition of each element is generally unmeasurable. The line spectrum from the solar photosphere has been studied for half a century, and several solar abundance compilations have been published [1, 2, 3, 4, 5]. The line strengths relative to those of hydrogen, the most abundant element, are interpreted with the aid of model atmospheres and the theory of radiative transfer to yield the abundances relative to hydrogen.

In recent years, it has also been discovered [6] that the ratio of abundances of elements heavier than hydrogen in the solar cosmic rays is substantially constant and equal to known photospheric abundance ratios. Inasmuch as these particles are presumably accelerated by flares in the photosphere, their abundance ratios have been used to augment the photospheric data. It is especially interesting, as I will discuss later, that the abundance ratio $H/He \approx 16$ inferred in this way is in reasonable agreement with the time average $H/He \approx 20$ observed in the solar wind [7], because both values for this ratio, which is of crucial importance to both the solar-neutrino experiment and to bigbang cosmology, are considerably and significantly larger than the value $H/He \approx 10$ that has been assumed correct for many years.

Ultraviolet spectra obtained with rockets fired above the earth's atmosphere have provided information about the composition of the solar corona. Analyses of these spectra by Pottasch [8] and Jordan [9] have shown a puzzling feature: the abundances of iron, nickel, and cobalt relative to hydrogen seem to be about an order of magnitude greater than in the solar photosphere. Cameron [10] suggested that radiation pressure on the metals would be sufficient to enrich the corona and deplete the photosphere in metal content, but Lambert [11] finds that mechanism to be ineffective.

Inasmuch as many element abundances cannot be obtained from photospheric lines, the possibility of a complete table of solar abundances was aided by the idea that the chondritic meteorite or some subclass thereof constitutes a representative sample of the abundances of the nonvolatile elements. SUESS and UREY [12] used this idea in the construction of their historic review paper which was so instrumental to the development of the science of nucleosynthesis, and many subsequent investigations have amplified and tested that idea [13]. The fact is, however, that the meteorites show evidence of a fairly complicated but unknown chemical history, so that they cannot give definitive values for the element abundances until that history is understood. The major puzzle again involves the element iron [13] which is roughly an order of magnitude more abundant relative to silicon in meteorites than in the solar photosphere. Indeed, the meteorite abundances bear similarity to those of the solar corona [14]. The meteorites are nonetheless a much better sample of nonvolatile elements than it the earth, whose chemical history is much more extensive. The many accurate terrestrial measurements of the isotopic composition of the elements have proved most useful for the theory. The physics and chemistry of the solar system has not, with only a few exceptions which are reasonably well understood, been able to alter the isotopic composition. A large and significant portion of the isotopic chemistry has been performed in Switzerland by F. G. HOUTERMANS, his colleagues and his students.

In summary, one can say that our knowledge of different solar abundances continues to improve, but these important questions now cloud interpretation: (1) are the solar photosphere, the solar corona, the solar wind, and the solar cosmic rays fractionated with respect to composition? (2) What is the chemical history of the meteorites and how shall we interpret their composition?

The absorption spectra of the stars are very different from that of the sun. The differences are primarily due to the wide range of temperatures found in stellar photospheres and to some extent due to variations in surface gravity, and after interpretation of the line strengths it is found that the average composition of stars is similar, but not identical, to the composition of the sun. It is in the differences from the solar composition, all of which are difficult to establish quantitatively, that we discover some of the most exciting tests of the nuclear theory of the origin of the elements. These important differences are basically of the two following types: (1) The oldest known stars formed from material that was much less rich in the elements heavier than helium than have the stars formed recently. This fact suggests that most of the elements have not always been with us but have, on the contrary, been manufactured during the history of the universe; (2) Many stars showing very unusual abundances seem to have exposed material on their surfaces that had previously been modified by nuclear reactions within their own interiors. These abundance modifications should show evidence of specific nuclear processes.

The most metal deficient star yet found is HD122563. Extensive studies of it [15] have shown that all of the heavy elements are less abundant relative to hydrogen than they are in the sun by factors between $10^2$ and $10^3$. As I shall describe below, the first low mass stars formed in the universe are expected in big-bang cosmologies to have formed from material in which the heavy elements are virtually absent, so this observation is not surprising. All of the Population II objects (primarily globular clusters and high-velocity stars) show substantial underabundances of this type, so HD122563 is special only in the extreme degree of the underabundance. If, however, one supposes that the universe was once metal poor, it follows that at least 99% of the heavy elements have been synthesized between the early formation of the first Population II objects and the formation of young stars. The logical site for this synthesis is in the natural sequences of thermonuclear epochs encountered in the thermal evolution of the stellar interior.

With the discovery by PENZIAS and WILSON [16] that the universe appears to be filled with a photon gas having a temperature of about 3 °K, there have been detailed recalculations of element abundances that will survive the early expansion in a big-bang universe. These calculations [17, 18, 19] assume that the 3 °K gas is the same photon gas that existed when the originally dense universe had expanded sufficiently to be transparent to an average thermal photon, but that the high-temperature photon gas of that epoch has been diluted and redshifted by the general relativistic expansion of the universe. The observed Hubble expansion [20] for the scale factor $R(t)$ of the universe

$$\mathrm{H} = \frac{1}{R}\frac{\mathrm{d}R}{\mathrm{d}t} \approx (10^{10}\ yr)^{-1}$$

when coupled with the observed average density of matter in the universe [21]

$$3 \times 10^{-31}\ \mathrm{gmcm}^{-3} < \varrho_0 < 3 \times 10^{-30}\ \mathrm{gmcm}^{-3}$$

and the present temperature of the thermal photon background allows one to calculate the thermal history of the universe. The connection is made by choosing a theory of gravitation. If general relativity is correct, which is what is assumed by most people, an isotropic universe expands according to [22]

$$\frac{1}{V}\frac{\mathrm{d}V}{\mathrm{d}t} = (24\,\pi G \varrho)^{\frac{1}{2}}$$

The expansion of the dense hot early universe, when the composition is known because it is in thermal equilibrium, can be followed subject to the demand that it yield today's density. Explicit calculation of the rate of each nuclear reaction yields the evolution of the abundances, and the results of a detailed calculation are shown in figure 1. The final abundances, shown as fraction of the total mass, depend upon the expansion rate, which can in turn be related to $\varrho_0/\theta^3$, where $\varrho_0$ is the present average density and $\theta$ is $T/3$ °K. The value of $\varrho_0/\theta^3$ appears to be between $10^{-30}$

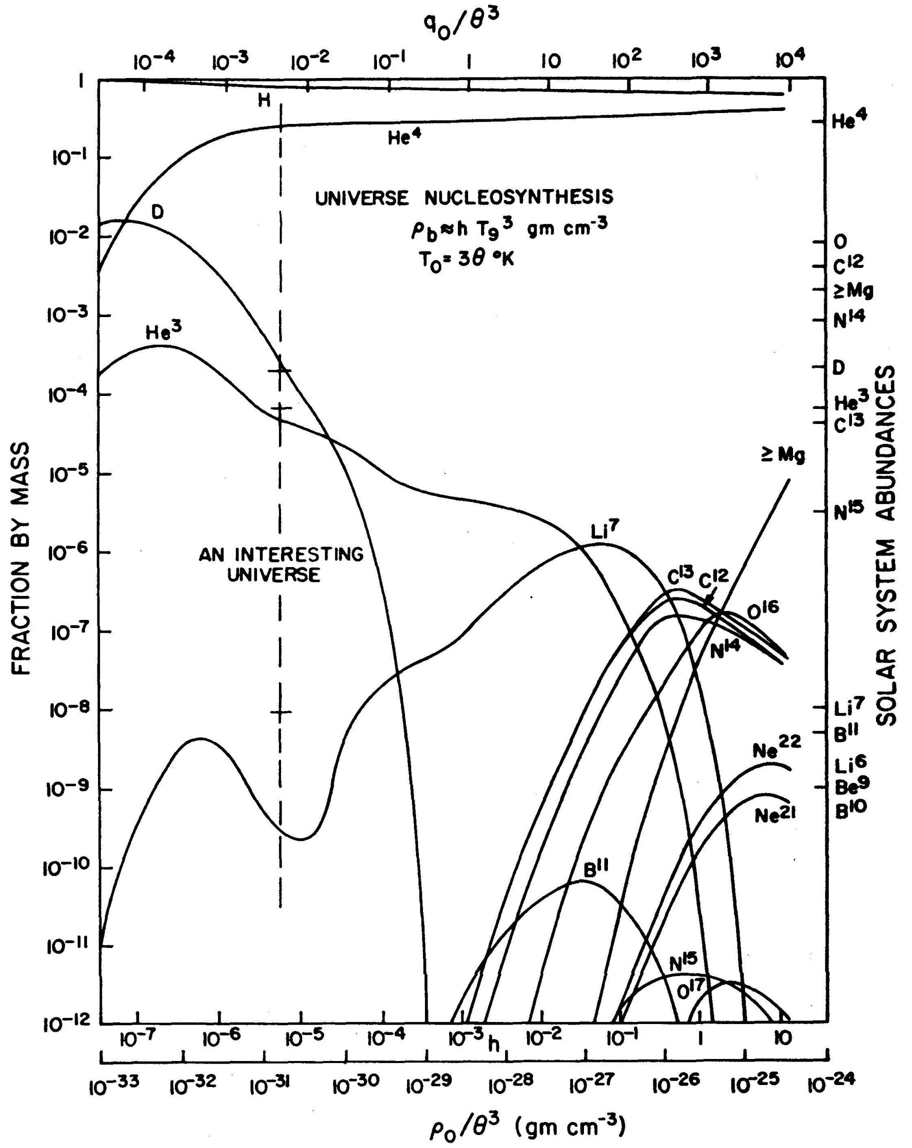


*Figure 1*

The final abundances by mass fraction of a universe which has expanded from an initial dense fireball are displayed against the ratio of the present average mass density $\varrho_0$ to the cube of the present temperature $\theta = T/3°$ of the thermal background radiation [19, 32]. The solar abundances are shown on the right-hand ordinate. For the apparent properties of our universe, only H, D, $^3$He, $^4$He, and $^7$Li seem to be produceable in the cosmic fireball in quantities as large as are observed

and $10^{-31}$ gmcm$^{-3}$. It is quite interesting that for such a universe the abundances of H, D, $^3$He, $^4$He, and perhaps $^7$Li are similar to their average observed values. How fascinating to think that these nuclei may be the ashes of the beginnings of our knowable universe! It seems equally clear that all heavier nuclei are now much too abundant to be understood in this way, so it is gratifying that the globular clusters, which may have been the first massive objects to condense during the expansion [23], are so very underabundant in heavy elements.

The correctness of these ideas are difficult to check because the concentrations of D, $^3He$, $^4He$, and $^7Li$ cannot be measured directly in the surfaces of the oldest mainsequence stars. The concentrations of D and $^7Li$ are too small whereas the surface temperatures are too cool to excite lines of helium. The helium situation is more promising in evolved Population II stars, however. Computations of the pulsation of RR Lyrae stars by CHRISTY [24] and of evolutionary tracks of stars in the HR diagram by FAULKNER and IBEN [25] suggest vary strongly that even very old horizontal-branch stars of the halo Population II have a He/H ratio near $^1/_{10}$ by number (a helium mass fraction $Y = 0.27$). Inasmuch as the $^4He$ production in the simplest big bangs is very near the value $Y = 0.27$ for the observed properties of the universe, these results lend support to the big-bang model. On the other hand, the startling observations of SARGENT and SEARLE [26] and J. GREENSTEIN and MUNCH [27] show an abnormally low helium abundance in the old horizontal branch B stars, whereas younger stars of the same type show normal helium abundance. This evidence suggests that helium has also been synthesized largely within the interiors of stars of starlike objects and that the simplest big bang is not correct. However, G. GREENSTEIN, TRURAN and CAMERON [28] point out that the horizontal branch B stars are the only general class of star in which it can be expected that helium will gravitationally settle out of the photosphere. Astronomy can therefore not yet claim to have settled this question which is so important for the nuclear origin of helium and the general understanding of the universe. It is also apparent that one must interpret the small values of He/H inferred from solar cosmic rays and from the solar wind with caution, because it seems quite impossible that the sun should have *less helium* than the oldest stars. The resolution of this helium mystery is perhaps the most important problem in astronomy today.

If the universal concentration of helium was in fact low when the first stars formed, we may be forced to abandon big-bang cosmology unless one of the following statements [19, 29] is true:

(1) The correct theory of gravitation is not general relativity. The most investigated alternative is the scalar-tensor theory, which can yield small helium production [29].

(2) The universe was highly anisotropic in the past. The large anisotropy required to reduce the helium to a low level is probably excluded by the isotropy of the 3 °K radiation [30].

(3) Most of the mass of the universe was not in the form of known particles during element building.

(4) The universe contains degenerate neutrinos.

There is yet another intriguing aspect of the mystery. The observed average density of helium in the universe is about $10^{-31}$ gmcm$^{-3}$. If that density is the result not of a big bang but rather of the fusion of hydrogen to helium in stars at an energy release of $6 \times 10^{18}$ erggm$^{-1}$, the universe must contain $6 \times 10^{-13}$ ergcm$^{-3}$ of radiant energy density. Such an average energy density of starlight is not observed in the night sky, but if physical processes of absorption and reemission [31] have thermalized that energy density the resulting photon temperature would be 3 °K. Is it a curious accident that the observed microwave background has a temperature of 3 °K? Supporters of a big-bang origin for helium must answer "yes", because the energy released from the big-bang formation of helium is completely lost today. In the big-bang model the density of helium decreases as $R^{-3}$ as the scale factor $R(t)$ of the universe increases, whereas the thermal photon temperature decreases as $R^{-1}$; thus the accidental equality mentioned above must from that point of view, be regarded as a truth of the present epoch only [32].

If the galaxy formed with a small mass fraction for helium ($Y \approx 0$), it follows that the galactic luminosity must have been much larger in its early years than today, because the present galactic luminosity converts only 3 to 5% of hydrogen to helium in $10^{10}$ years. Ordinary stars do not easily provide the required early galactic fusion, and it may well be that supermassive stars [32], formed in association with the galactic disk, are responsible. In their explosions from high density (little bangs) the density is higher for a given temperature than in the expansion of the universe and the expansion is faster. About 40% of the mass expanded from temperatures in excess of $20 \times 10^9$ °K will appear as helium. This phase of high galactic luminosity might be manifest as the quasi-stellar objects (provided they are not local).

In awarding the 1967 Nobel Prize in physics to Hans Bethe, the Swedish Academy of Science cited especially Bethe's discovery [33] of the reaction cycles capable of fusing hydrogen into helium in the interiors of stars. His work successfully developed the details of the general ideas described in 1929 by Atkinson and Houtermans [34] following Gamow's [35] discovery of the role of quantum penetration of coulomb barriers. Even if helium is primarily a remnant of the cosmic fireball, the proton-proton chains and the CN cycle [36] nonetheless provide the internal power for the main-sequence stars, and will, as a consequence, necessarily convert at least several percent of the galactic mass of hydrogen into helium. At the conclusion of World War II, C. C. Lauritsen and W. A. Fowler of the California Institute of Technology decided that a substantial portion of the effort of their nuclear laboratory would be directed toward the investigation of the nuclear details suggested by Bethe's work. Many individuals and laboratories have followed their lead, with the result that the hydrogen burning cycles are today the most thoroughly studied area of laboratory nuclear astrophysics [37, 38]. The required experiments have involved long hours of particle bombardment at low energies. The cross sections are among the smallest that have been measured in the nuclear laboratory, requiring painstaking attention to properties of beam, target, and background counts. Even so the results have to be extrapolated to the even lower energies at which the reactions should occur in the thermal environment of the stellar interior. Two very profound tests of this cornerstone of astrophysical theory have been devised, and I would like to review them now.

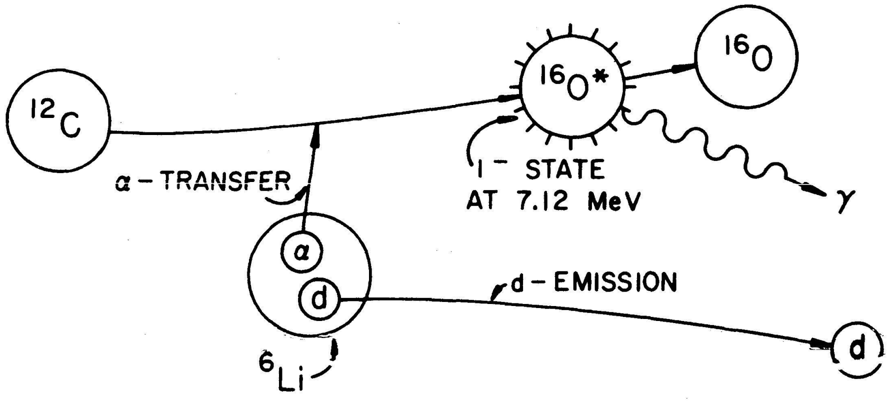
In 1958 FOWLER [39] described the possibility of detecting the neutrinos emitted by the decay of $B^8$ in the center of the sun. Their very weak interaction with matter allows the neutrinos to emerge directly from the solar center but, by the same token, prevents them from being easily detected. The unique opportunity to test the theory results from the fact that there is no other known technique for viewing the center of a star. If the details of the nuclear reactions are correctly known, and if the theory of stellar structure is correct, the flux of $B^8$ neutrinos can be calculated. As early as 1955 DAVIS [40] had studied the $^{37}Cl\ (\nu, e^-)\ ^{37}A$ reaction capable of detecting these neutrinos, and aided by BAHCALL's [41] theoretical study of the neutrino-absorbing reaction, DAVIS undertook the observation. His results [42] obtained at the Brookhaven Solar Neutrino Observatory deep in the Homestake Mine of South Dakota indicate that the average $^{37}Cl$ nucleus is absorbing neutrinos at a rate less than or equal to $3 \times 10^{-36}$ $sec^{-1}$, which is about a factor of two less than the most probable estimates derived from nuclear physics and stellar structure [43]. At the present time it is unclear whether DAVIS' upper limit will become, with further counting, an actual measurement or whether it will remain an upper limit. Because total uncertainties of a factor of two yet remain in the calculated value, furthermore, it is too early to tell if a real discrepancy exists, but the future of this research program will be followed with cautious excitement. The helium puzzle rears its head again, because if the details of the nuclear physics and of the theory of stellar structure are correct, the $B^8$ neutrino flux becomes a measure of the initial helium content of the sun. If DAVIS' limit is taken to be an actual measurement the inferred value of the helium mass fraction would be $Y = 0.16$, which is near the values inferred from the solar wind and from the solar cosmic rays.

Solar neutrino astronomy [42] has already demonstrated that less than 9% of the sun's power is provided by the carbon-nitrogen cycle:

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

It is believed [36], however, that this cycle, in which the carbon and nitrogen isotopes play the role of nuclear catalyst for an overall process in which $4\,^1H \rightarrow {}^4He + 2\,e^+ + 2\,\nu$, is the dominant power source for main-sequence stars whose masses exceed about 1.5 solar masses. The thermonuclear rates of these proton induced reactions have been the object of large numbers of investigations [37], and it now appears that their rates are known with sufficient accuracy for astrophysical needs. The stars shining on this source of power are too distant to affect the neutrino astronomy experiment, so the confirmation of our understanding of this cycle has been provided by the abundance ratios produced by it. Although the total number of CN isotopes is unaltered by the cycle, their relative abundances are redistributed in proportion to their lifetimes against nuclear interactions with the free protons in the stellar interior. The lifetimes measured in the laboratory are such that the catalysts are driven to abundance ratios near C/N = $^1/_{100}$ and $^{13}C/^{12}C = ^1/_4$. Both ratios are, of course, quite different from the solar values C/N = 5.5 and $^{13}C/^{12}C = ^1/_{90}$ [44], which are regarded to be a superposition of all of the nuclear processes that have contributed to nucleosynthesis. It is not possible to isolate a pure sample of the CN cycle, because it occurs in the central portions of stars. Highly evolved stars, however, have in many cases mixed material from their interiors to their surfaces, in which case the surface abundance ratios should be equal to those obtainable by diluting the CN-cycle ratios with varying amounts of the surface CN nuclei, primarily $^{12}C$. On this basis one expects variable abundance ratios which have, however, the values $^{13}C/^{12}C \approx ^1/_4$ and $N/C \approx 100$ as upper limits. This is exactly what is observed. Carbon is one of the few elements whose isotope ratio can be measured in stars, in this case by the spectra of the molecule $C_2$ which forms in cool stellar surfaces. The different reduced mass of those molecules containing one $^{13}C$ nucleus results in a shifted wavelength of the molecule's absorption lines. The observed abundance ratios [45] are found to be variable, but the largest observed values are near $^{13}C/^{12}C = ^1/_4$. Nitrogen rich stars have also been found [46, 47]. Because the CN cycle is the only known thermonuclear situation capable of producing a large overabundance of nitrogen relative to carbon, the large value of N/C observed in these stars is convincing evidence of our understanding of the CN cycle.

The fact that $^{16}O$ and $^{12}C$ are the next most important species after H and $^4He$ has long been believed [36] to be related to the fact that the fusion of $^4He$, which is the thermonuclear epoch to be expected following the exhaustion of hydrogen during hydrogen burning has those two nuclei as its major products. Salpeter [48] showed in 1952 that the burning process would be initiated by the buildup in the gas of a small equilibrium concentration of unstable $^8Be$, but it is only recently that Staub and coworkers [49] have been able to clarify the nuclear parameters with a direct measurement of the properties of $^8Be$ by the low-energy scattering of alpha particles on helium. The capture of a third alpha particle by $^8Be$ forms $^{12}C$, although some moderate uncertainty in the rate of that process remains. Another sophisticated experiment has been performed recently to obtain the rate of the subsequent $^{12}C(\alpha, \gamma)\,^{16}O$ reaction, which is presumeably responsible for the large $^{16}O$ abundance. The rate of this reaction at low energies has never been directly measurable because, surprisingly enough, it depends upon the reduced alpha-particle width of a state in $^{16}O$ that is stable against breakup into $^{12}C + {^4He}$. Thus $^{12}C + {^4He}$ has, even at zero kinetic energy, more energy than the relevant state of $^{16}O$. Loebenstein *et al.* [50] have been able to simulate that reaction by the direct transfer of an alpha particle from the $^6Li$ nucleus into a $^{12}C$ nucleus. The reaction mechanism is illustrated in figure 2. The binding energy of the alpha particle to the deuteron in $^6Li$ affects the energetics in such a way that the desired state of $^{16}O$ can be formed. The net result is that the rates of the helium burning reactions




SIMULATION OF $^{12}C(\alpha)^{16}O^*(\gamma)^{16}O$ BY $^{6}Li(^{12}C,d)^{16}O^*(\gamma)^{16}O$

COMPLICATION: INTERFERENCE WITH COMPOUND NUCLEUS FORMATION

RESULT: $\theta_\alpha^2 = 0.085 \pm 0.04$, LOEBENSTEIN, ET. AL, NUCL. PHYS. A91, 481(1967)

*Figure 2*

Schematic of a reaction mechanism capable of adding an alpha particle to $^{12}C$ to produce directly a state $^{16*}O$ having less mass than $^{12}C + ^{4}He$. This ingenious experiment [50] has improved our nuclear knowledge of nucleosynthesis in helium burning. It is typical of the care with which the nuclear details are being explored in the attempt to obtain the facts needed for nuclear astrophysics

are now known with sufficient accuracy that we know that the fusion of helium in stars will in fact result in comparable yields of $^{12}C$ and $^{16}O$. Nature seems to concur, on the average, with that conclusion, but the cool carbon stars present convincing evidence that this ratio has been somewhat variable [51]. After the formation of CO, one finds oxide bands such as TiO and ZrO if $O/C > 1$, whereas one finds carbide bands such as CH and CN if $O/C < 1$. The ratio O/C formed in the stellar interior increases somewhat with the stellar mass, so this variability is not surprising; indeed, the variability of the observed ratios lends support to the hypothesis of stellar nucleosynthesis.

Although hydrogen burning and helium burning support most of the lifetimes of the stars, it is the later thermonuclear epochs that are responsible for most of the element synthesis. Carbon burning is the next to occur. Recent measurements by PATTERSON, WINKLER, and ZAIDINS [52] have greatly improved our knowledge of the rates of the reactions

$$\begin{aligned} ^{12}C + ^{12}C &\rightarrow ^{20}Ne + ^{4}He \\ &\rightarrow ^{23}Na + p \\ &\rightarrow ^{23}Mg + n \\ &\rightarrow ^{24}Mg + \gamma \end{aligned}$$

which initiate carbon burning. To understand the composition of the final products, however, one must include the reactions of $p$, $n$, $\alpha$, and $\gamma$

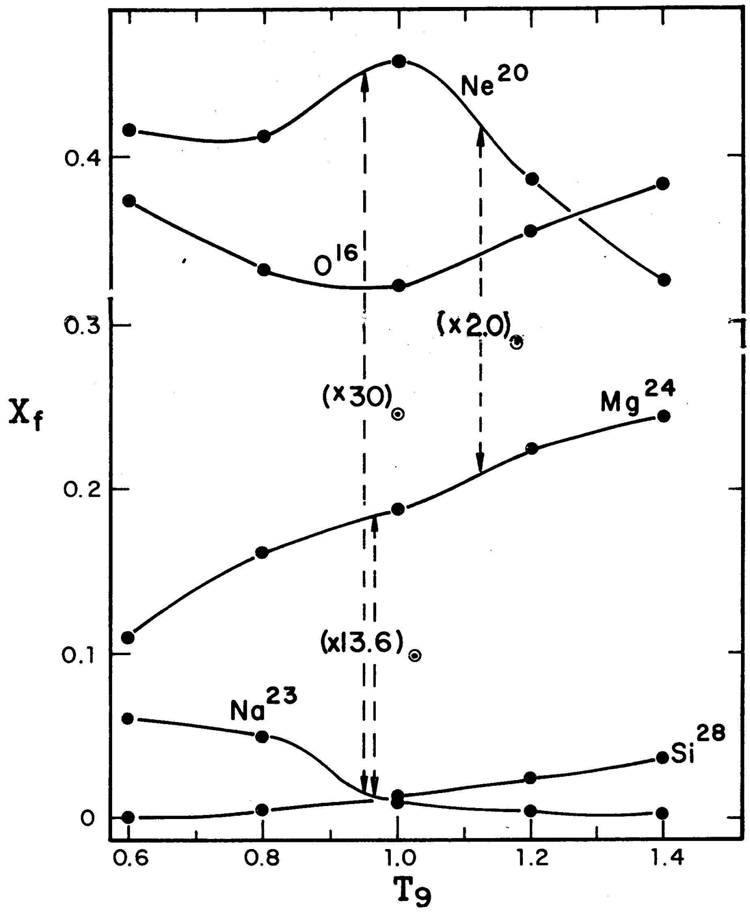



*Figure 3*

The final fraction by mass of the most abundant species produced by carbon burning at constant temperature as a function of temperature, which is expressed in billions of degrees [53]. The abundance ratios observed in the solar system are indicated by dashed arrows at the temperature where that ratio is obtained. It sems clear that $^{20}$Ne, $^{24}$Mg, and $^{23}$Na are the result of carbon burning near $10^9$ °K. The composition was initially half oxygen and half carbon

with each constituent of the gas. The rates of most of these reactions are known with limited accuracy, but ARNETT and TRURAN [53] have numerically computed the results of this network of reactions and their results are striking. Figure 3 shows the final abundances as a function of burning temperature for an initial composition containing equal amounts of $^{12}$C and $^{16}$O. The major species produced are $^{20}$Ne, $^{24}$Mg, and $^{23}$Na. Near $1.0 \times 10^9$ °K, moreover, which is the expected carbon burning temperature in stars, they are produced in relative amounts almost exactly equal to their relative proportions in the solar system. There can really be little reasonable doubt that carbon burning has been the primary source of these three nuclei. The situation is even more dramatic if one considers carbon heated quickly to high temperature followed by a rapid expansion and cooling, such as might occur in a supernova envelope heated by a

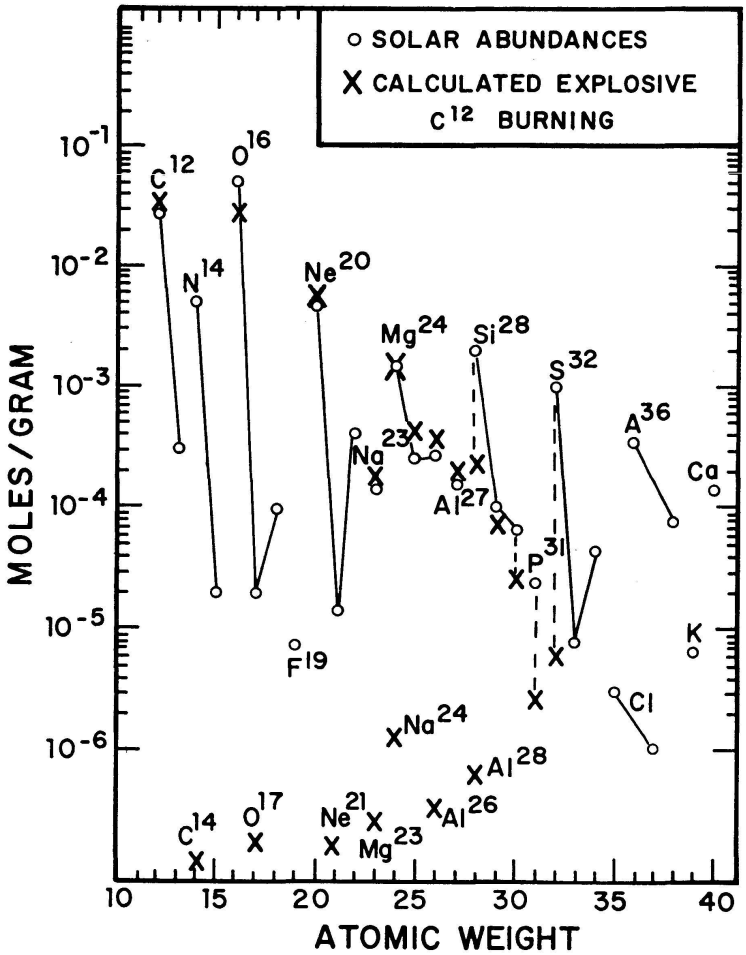



*Figure 4*

Abundance products of the explosive partial burning of carbon. After being quickly heated to $T_9 = 1.8$ the gas is expanded and cooled to $T_9 = 0.5$ in 1.25 sec, during which time 22% of the $^{12}C$ has been burned. The calculated abundances bear dramatic similarity to the solar abundances [unpublished calculation by W. D. ARNETT]

compressional wave [54] or in explosive ignition [55] of carbon. In the example shown in figure 4, the nuclei $^{12}C$, $^{16}O$, $^{20}Ne$, $^{23}Na$, $^{24}Mg$, $^{25}Mg$, $^{26}Mg$, $^{27}Al$ and $^{29}Si$ each have final values near the solar abundances.

When $^{28}Si$, which is the major nuclear species remaining after oxygen burning, is heated to temperatures above $3 \times 10^9$ °K, a free bath of alpha particles is established such that capture reactions come into equilibrium with the reverse photodisintegration reactions [56]:

$$^{28}Si + ^{4}He \Leftrightarrow ^{32}S + \gamma$$
$$^{32}S + ^{4}He \Leftrightarrow ^{36}A + \gamma$$
etc.

The nuclei heavier than $^{28}Si$ come into equilibrium with $^{28}Si$ and the free densities of $p$, $n$, and $\alpha$. In these circumstances the abundances are easily calculable, and, as shown in figure 5, the quasiequilibrium abun-

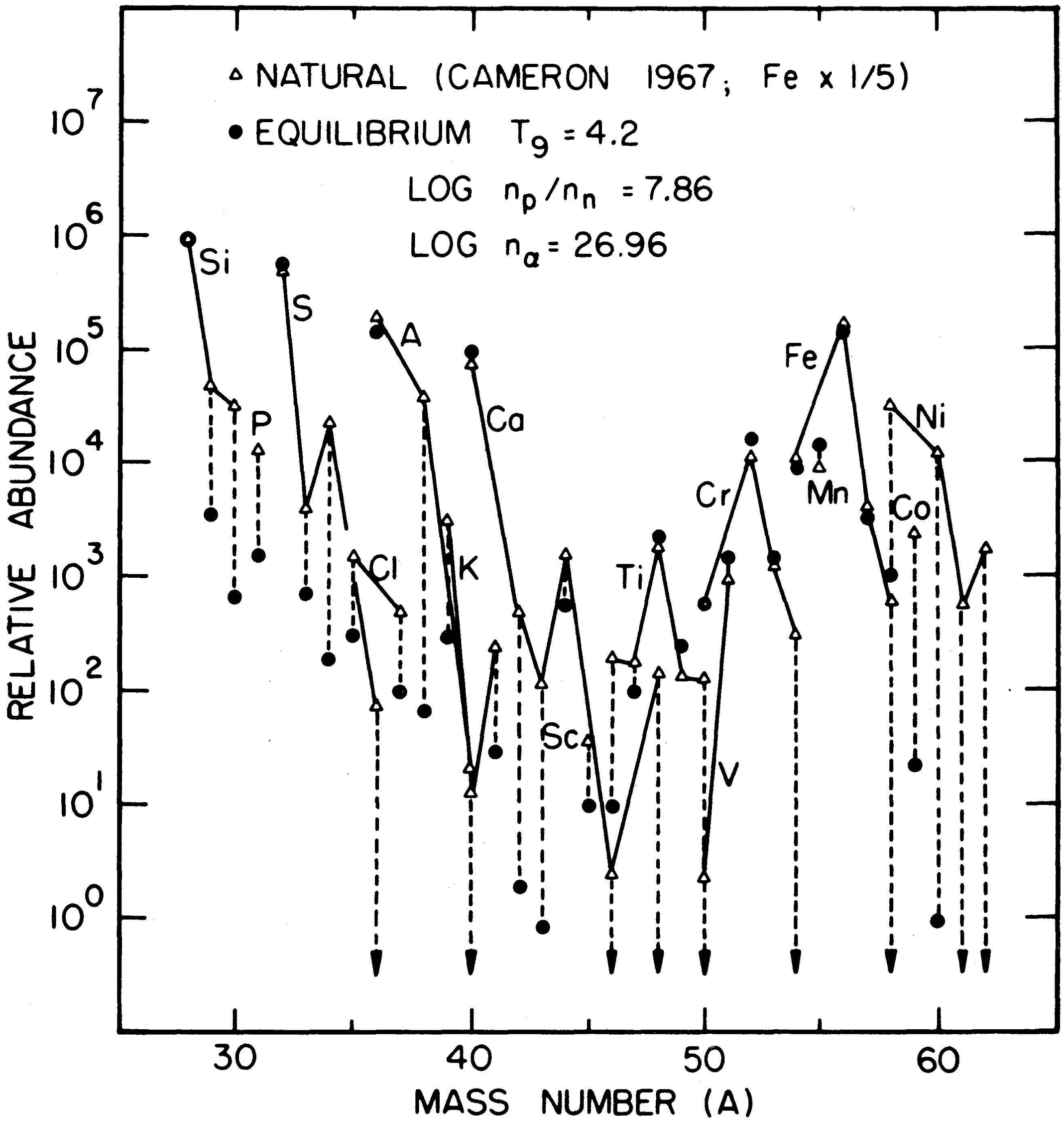



*Figure 5*

Comparison of the solar abundances, shown as triangles, with the abundances of nuclei in equilibrium with $^{28}$Si, shown as solid circles. The good agreement for the most abundant species suggests that the silicon quasiequilibrium [56, 57] is largely responsible for nucleosynthesis in the range $28 \leq A \leq 57$

dances of the $A = 4\,n$ nuclei and of the iron-peak nuclei dramatically reproduce the solar abundances. We have concluded [57], therefore, that silicon burning is primarily responsible for nucleosynthesis between $A = 28$ and $A = 57$. This conclusion will, moreover, be subject to a direct observational check [58]. The natural abundances of $^{56}$Fe, $^{52}$Cr, $^{48}$Ti and $^{44}$Ca shown in figure 5 are compared with the abundances of radioactive $^{56}$Ni, $^{52}$Fe, $^{48}$Cr, and $^{44}$Ti established in the equilibrium. After expulsion from the supernova, these radioactive species decay to the stable daughters and in doing so emit characteristic lime gamma rays

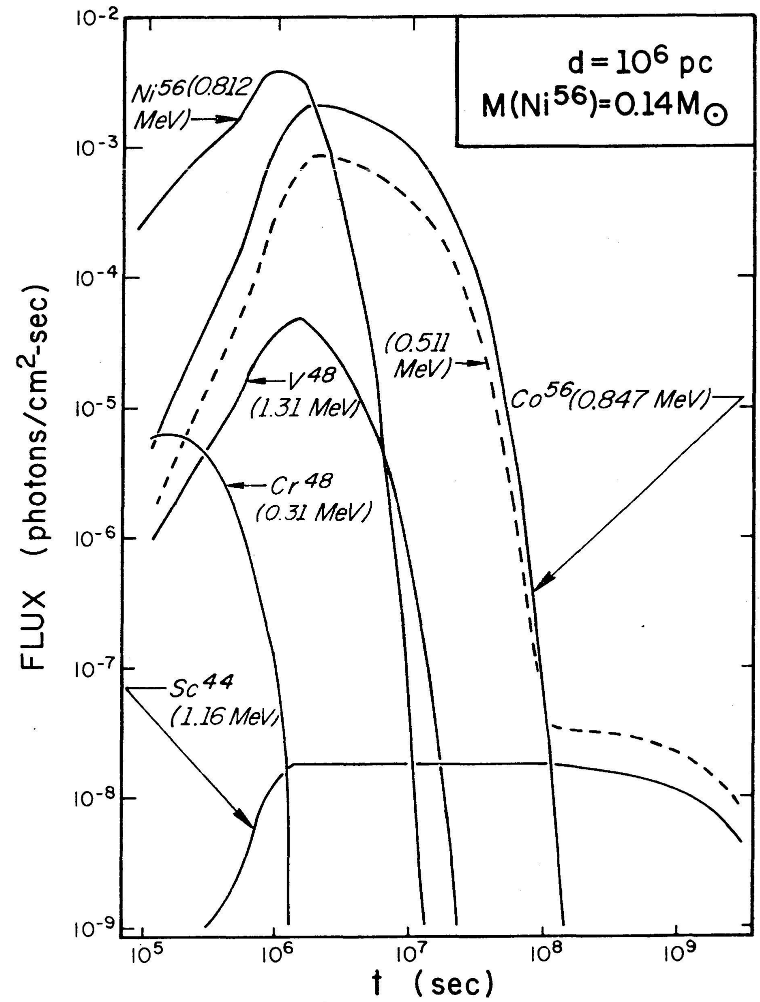



*Figure 6*

The gamma-ray line fluxes as a function of time from a hypothetical supernova at a distance of $10^6$ parsec [58]. It has been assumed that about ½ of a solar mass of silicon-quasiequilibrium material has been ejected. The prospect of detecting these lines from an earth satellite are very good

that may be detected in young supernova remnants. Figure 6 shows the fluxes at earth as a function of time from a hypothetical supernova which has exploded at the considerable distance of $10^6$ parsec ($3 \times 10^6$ light years). Such events are expected to be observable from gamma-ray telescopes in earth satellites [58], and their direct observation will be a clear confirmation of nuclear events within stars. Successful detection of such radioactivity rivals the solar neutrino experiment in profundity of implications, and we hopefully await the chance to make the observation.

I should not conclude this summary paper without a few words concerning the synthesis of the elements more massive than iron, for it is a subject on which I have worked continuously for the past 10 years. The primary mechanism for this synthesis is the capture of free neutrons

[59] which are not hindered by a large coulomb barrier in their interaction with nuclei of large atomic number. The process of slow neutron capture [60] has been especially successful as a quantitative theory. The abundances produced by this *s-process* capture chain are, because of the simple sequential chain of captures, inversely proportional to the thermal averages of the neutron-capture cross sections of the nuclei along the chain. MACKLIN and GIBBONS at the Oak Ridge National Laboratory are making a systematic study of the quantitative success of this theory and they have recently [61] summarized the situation. The degree of success is best illustrated by two isotopes of samarium, $^{148}$Sm and $^{150}$Sm. The measured values for the products of the abundance and the neutron-capture cross section are

$$\frac{N(^{148}Sm)}{N(^{150}Sm)}\,\frac{\sigma(^{148}Sm)}{\sigma(^{150}Sm)} = 0.98 \pm 0.06$$

which is dramatically near the expected equality. I was enabled by the success of this theory to invent a technique [62] for measuring the time when nucleosynthesis occurred. By a situation exactly analogous to the samarium isotopes it happens that about 60% of the abundance of $^{187}$Os has been due to the decay of $^{187}$Re *before the formation of the solar system*, and an even more accurate measure will be available when the separated samples of $^{186}$Os and $^{187}$Os have been accumulated in quantities suitable for measurement of their neutron-capture cross sections. This measurement, which is of great cosmological importance, would have been of little significance without your work here [63, 64] on the $^{187}$Os/$^{187}$Re isochrones of the iron meteorites, on the half-life of $^{187}$Re, and on the near constancy of the Re/Os abundance ratio. I know of no finer example of the profound influence of cosmochemistry on cosmology.

It is an exciting time for nuclear astrophysics and cosmology. Almost all of the results I have described today are quite recent ones, and I have had to omit reference to as many more. In closing I would only cite the extinct radioactivities $^{129}$I and $^{244}$Pu, whose complicated trail is now so actively pursued in meteorites [65], and the transuranic charges discovered by FOWLER [66] in the cosmic rays. The existence of heavy radioactive nuclei in substantial numbers is our surest proof that the chemical elements have not been a permanent part of the universe. The quantitative success of our theory leaves little doubt that the elements have had a primarily thermonuclear origin. The question is *where* and *when*.

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