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The Quest for the Origin of the Elements

William A. Fowler

All life on Earth depends on the energy in sunlight, which comes initially from the nuclear fusion of hydrogen into helium deep in the solar interior. But the sun did not produce the chemical elements which are found in the earth and in our bodies. The first two elements and their stable isotopes, hydrogen and helium, emerged from the first few minutes of the early high-temperature, high-density stage of the expanding Universe, the so-called big bang. A small amount of lithium, the third element in the periodic table, was also produced in the big bang, but the remainder of the lithium and all of beryllium, element 4, and boron, element 5, are thought to have been produced by the spallation of still heavier elements in the interstellar medium by the cosmic radiation. These elements are in general very rare, in keeping with this explanation of their origin (*1*).

Where did the heavier elements originate? The generally accepted answer is that all of the elements from carbon, element 6, up to long-lived radioactive uranium, element 92, were produced by nuclear processes in the interior of stars in our own Galaxy. The stars which synthesized the heavy elements in the solar system were born, aged, and eventually ejected the ashes of their nuclear fires into the interstellar medium over the lifetime of the Galaxy before the solar system itself formed 4½ billion years ago.

The lifetime of the Galaxy is thought to be more than 10 billion but less than 20 billion years. The ejection of the nuclear ashes or newly formed elements took place by slow mass loss during the old age of the stars, called the giant stage of stellar evolution, or during the relatively frequent outbursts which astronomers call novae, or during the final spectacular stellar explosions called supernovae.

In any case the sun, the earth, and all the other planets in the solar system condensed under gravitational and rotational forces from a gaseous solar nebula in the interstellar medium consisting of big-bang hydrogen and helium mixed with the heavier elements synthesized in earlier generations of galactic stars.

This idea can be generalized to successive generations of stars in the Galaxy, with the result that the heavy-element content of the interstellar medium and the stars which form from it increases with time. The oldest stars in the galactic halo—those we believe to have formed first—are found to have heavy-element abundances less than 1 percent of that of the solar system. The oldest stars in the galactic disk have approximately 10 percent. Only the less massive stars among those first formed can have survived to the present as so-called Population II stars. Their small concentration of heavy elements may have been produced in a still earlier but more massive generation of stars, Population III, which rapidly exhausted their nuclear fuels and survived for only a very short time. Stars formed in the disk of the Galaxy over its lifetime are referred to as Population I stars.

We speak of this element building as nucleosynthesis in stars. It can be generalized to other galaxies, such as our twin, the Andromeda Nebula, and so this mechanism can be said to be universal. We refer to the basic physics of energy generation and element synthesis in stars as nuclear astrophysics.

The field of nuclear astrophysics has two main goals. First, it attempts to understand energy generation in the sun and other stars at all stages of stellar evolution. Energy generation by nuclear processes requires the transmutation of nuclei into new nuclei with lower mass. The small decrease in mass is multiplied by the velocity of light squared, as Einstein taught us, and a relatively large amount of energy is released.

Thus the first goal is closely related to the second goal, that of understanding the nuclear processes which produced under various astrophysical circumstances the relative abundances of the elements and their isotopes in nature. Figure 1 shows a curve of atomic abundances as a function of atomic weight. The data for this curve were first systematized from a plethora of terrestrial, meteoritic, solar, and stellar data by Suess and Urey (*2*) and have been periodically updated by Cameron (*3*). Major contributions to the experimental measurement of atomic transition rates needed to determine solar and stellar abundances have been made by Whaling (*4*).

The curve in Fig. 2 is frequently referred to as "universal" or "cosmic," but it primarily represents relative atomic abundances in the solar system and in main-sequence stars similar in mass and age to the sun. In current usage the curve is described as "solar." How this curve serves as a goal can be simply put. Calculations of atomic abundances produced under astronomical circumstances at various postulated stellar sites are almost invariably reduced to ratios relative to "solar" abundances.

Early Research on Element Synthesis

George Gamow and his collaborators Alpher and Herman (*5*) attempted to synthesize all of the elements during the big bang by using a nonequilibrium theory involving neutron (n) capture with gamma-ray (γ) emission and electron (e) beta-decay by successively heavier nuclei. The synthesis proceeded in steps of one mass unit, since the neutron has approximately unit mass on the mass scale used in all the physical sciences. As they emphasized, this theory meets grave difficulties beyond mass 4 (^{4}He) because no stable nuclei exist at atomic mass 5 and 8. Enrico Fermi and Anthony Turkevich attempted valiantly to bridge these "mass gaps" without success. Seventeen years later Wagoner *et al.* (*6*), armed with nuclear reaction data accumulated over the intervening years, succeeded only in producing ^{7}Li at a mass fraction of at most 10^{-8} compared to hydrogen plus helium for acceptable model universes. All heavier elements totaled less than 10^{-11} by mass. Wagoner *et al.* (*6*) did succeed in producing ^{2}D, ^{3}He, ^{4}He, and ^{7}Li in amounts in reason-

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able agreement with observations at the time. More recent observations and calculations are frequently used to place constraints on models of the expanding universe, and in general favor open models in which the expansion continues indefinitely unless there exists an abundance of so-called "missing mass."

It was in connection with the gap at mass 5 that the W. K. Kellogg Radiation Laboratory first became involved, albeit unwittingly, in astrophysical and cosmological phenomena. At the laboratory, in 1939, Staub and Stephens (*7*) detected resonance scattering by ^{4}He of neutrons with orbital angular momentum equal to one in units of $\hbar$ (Planck's constant divided by 2π) and energy somewhat less than 1 MeV. This confirmed previous reaction studies by Williams *et al.* (*8*) and showed that the ground state of ^{5}He is unstable—as fast as ^{5}He is made it disintegrates. The same was later shown to be true for ^{5}Li, the other candidate nucleus at mass 5. The Pauli exclusion principle dictates for fermions that the third neutron in ^{5}He must have at least unit angular momentum, and not zero as permitted for the first two neutrons with antiparallel spins. In classical terminology, the attractive nuclear force cannot match the outward centrifugal force. Still later, at the laboratory, Tollestrup *et al.* (*9*) confirmed, with improved precision, the first quantitative proof by Hemmendinger (*10*) that the ground state of ^{8}Be is unstable. The Pauli exclusion principle is again at work in the instability of ^{8}Be. As fast as ^{8}Be is made it disintegrates into two ^{4}He nuclei. The latter may be bosons, but they consist of fermions. The mass gaps at 5 and 8 spelled the doom of Gamow's hopes that all nuclear species could be produced in the big bang one unit of mass at a time.

The eventual commitment of the Kellogg Radiation Laboratory to nuclear astrophysics came about in 1939, when Bethe (*11*) brought forward the operation of the CN cycle as one mode of the fusion of hydrogen into helium in stars (since oxygen has been found to be involved the cycle is now known as the CNO cycle). Charles Lauritsen, his son Thomas Lauritsen, and I were measuring the cross sections of the proton bombardment of the isotopes of carbon and nitrogen which constitute the CN cycle. Bethe's paper (*11*) told us that we were studying in the laboratory processes which are occurring in the sun and other stars. It made a lasting impression on us. World War II intervened, but in 1946, on returning the laboratory to nuclear experimental research, Lauritsen decided to continue in low-energy, classical nuclear physics with emphasis on the study of nuclear reactions thought to take place in stars. In this he was strongly supported by Ira Bowen, a Caltech professor of physics who had just been appointed director at the Mount Wilson Observatory, by Lee DuBridge, the new president of Caltech, by Carl Anderson, Nobel Prize winner in 1936, and by Jesse Greenstein, newly appointed to establish research in astronomy at Caltech.

Although Bethe (*11*) and others still earlier had previously discussed energy generation by nuclear processes in stars, the grand concept of nucleosynthesis in stars came from Fred Hoyle (*12*). In two classic papers the basic ideas of the concept were presented within the framework of stellar structure and evolution with the use of the then known nuclear data.

Again the Kellogg Laboratory played a role. Before his second paper Hoyle was puzzled by the slow rate of formation of ^{12}C nuclei from the fusion of three alpha particles (α's) of ^{4}He nuclei in red giant stars. Hoyle was puzzled because work with Schwarzschild (*13, 14*) had convinced him that helium burning through $3\alpha \rightarrow {}^{12}\mathrm{C}$ should commence in red giants just above 10^8 K rather than at 2×10^8 K as required by the reaction rate calculation of Salpeter (*15*). Salpeter made his calculation while a visitor at Kellogg in 1951 and used the Kellogg value (*9*) for the energy of ^{8}Be in excess of two ^{4}He to determine the resonant rate for the process ($2\alpha \leftrightarrow {}^8\mathrm{Be}$) which takes into account both the formation and decay of ^{8}Be. However, in calculating the next step, $^8\mathrm{Be} + \alpha \rightarrow {}^{12}\mathrm{C} + \gamma$, Salpeter had treated the radiative fusion as nonresonant.

Hoyle realized that this step would be speeded up by many orders of magnitude, thus reducing the temperatures for its onset, if there existed an excited state of ^{12}C with energy 0.3 MeV in excess of $^8\mathrm{Be} + \alpha$ at rest and with the angular momentum and parity ($0^+, 1^-, 2^+, 3^-, \ldots$) dictated by the selection rules for these quantities. He came to Kellogg early in 1953 and questioned the staff about the possible existence of his proposed excited state. Whaling and his visiting associates and graduate students (*16*) decided to go into the laboratory and search for the state, using the $^{14}\mathrm{N}(d,\alpha)^{12}\mathrm{C}$ reaction (d = deuteron). They found it almost exactly where Hoyle had predicted. It is now known to be at 7.654 MeV excitation in ^{12}C, or 0.2875 MeV above $^8\mathrm{Be} + \alpha$ and 0.3794 MeV above 3α. Cook *et al.* (*17*) then produced the state in the decay of radioactive ^{12}B and showed that it could break up into 3α and thus by reciprocity could be formed from 3α. They argued that the spin and parity of the state must be 0^+, as is now known to be the case.

The $3\alpha \rightarrow {}^{12}\mathrm{C}$ fusion in red giants jumps the mass gaps at 5 and 8. This process could never occur under big-bang conditions. By the time ^{4}He was produced in the early expanding Universe the density and temperature were too low for helium fusion to carbon. In contrast, in red giants, after hydrogen conversion to helium during the main-sequence stage, gravitational contraction of the helium core raises the density and temperature to values where helium fusion is ignited. Hoyle and Whaling showed that conditions in red giant stars are just right.

Fusion processes can be referred to as nuclear burning in the same way we speak of chemical burning. Helium burning in red giants succeeds hydrogen burning in main-sequence stars and is in turn succeeded by carbon, neon, oxygen, and silicon burning to reach the elements near iron and somewhat beyond in the periodic table. With these nuclei of intermediate mass as seeds, subsequent processes similar to Gamow's involving neutron capture at a slow rate (s-process) or at a rapid rate (r-process) continued the synthesis beyond ^{209}Bi, the last stable nucleus, up through short-lived radioactive nuclei to long-lived ^{232}Th, ^{235}U, and ^{238}U, the parents of the natural radioactive series. This last requires the r-process, which actually builds beyond mass 238 to radioactive nuclei which decay back to ^{232}Th, ^{235}U, and ^{238}U rapidly at the cessation of the process.

The need for two neutron-capture processes was explained by Suess and Urey (*2*). With the adroit use of relative isotopic abundances for elements with several isotopes, they demonstrated the existence of the double peaks (r and s) in Fig. 1. It was immediately clear that these peaks were associated with neutron shell filling at the magic neutron numbers N = 50, 82, and 126 in the nuclear shell model of Hans Jensen and Maria Goeppert-Mayer.

In the s-process the nuclei involved have low capture cross sections at shell closure and thus large abundances to maintain the s-process flow. In the r-process it is the proton-deficient radioactive progenitors of the stable nuclei which are involved. Low capture cross sections and small beta-decay rates at shell closure lead to large abundances,

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but after subsequent radioactive decay these large abundances appear at lower values of the mass number A than for the s-process, since the atomic (proton) number Z is less and thus $A = N + Z$ is less. In Hoyle's classic papers (*12*) stellar nucleosynthesis up to the iron-group elements was attained by charged-particle reactions. Rapidly rising Coulomb barriers for charged particles curtailed further synthesis. Suess and Urey (*2*) made the breakthrough which led to the extension of nucleosynthesis in stars by neutrons unhindered by Coulomb barriers all the way to ^{238}U.

The complete run of the synthesis of the elements in stars was incorporated into a paper by Burbidge, Burbidge, Fowler, and Hoyle (*18*), commonly referred to as B^{2}FH, and was independently developed by Cameron (*19*). Notable contributions to the astronomical aspects of the problem were made by Greenstein (*20*) and many other observational astronomers. Since that time nuclear astrophysics has developed into a full-fledged scientific activity including the exciting discoveries of isotopic anomalies in meteorites. The following account will highlight some of the experimental and theoretical research under way at present or carried out in the past few years. It cannot include details of the nucleosynthesis of all the elements and their isotopes, which would involve discussing all the reactions producing a given nuclear species and all those which destroy it. The reader will find some of these details for ^{12}C, ^{16}O, and ^{55}Mn.

It is noted that the measured cross sections for the reactions are customarily very small at the lowest energies of measurement, for ^{12}C(α,γ)^{16}O even less than 1 nanobarn (10^{-33} cm^2) near 1.4 MeV. This means that experimental nuclear astrophysics requires accelerators with large currents of well-focused, monoenergic ion beams, thin targets of high purity and stability, detectors of high sensitivity and energy resolution, and experimentalists with great tolerance for long running times and with patience in accumulating data of statistical significance. Classical Rutherfordian measurements of nuclear cross sections are required, and the results are essential to our understanding of the physics of nuclei.

A comment on nuclear reaction notation is necessary at this point. In the reaction ^{12}C(α,γ)^{16}O discussed above, ^{12}C is the laboratory target nucleus, α is the incident nucleus (^{4}He) accelerated in the laboratory, γ is the photon produced and detected in the laboratory, and ^{16}O is the residual nucleus, which can also be detected if it is desirable to do so. If ^{12}C is accelerated against a gas target of ^{4}He and the ^{16}O products are detected but not the gamma rays, the laboratory notation is ^{4}He(^{12}C,^{16}O)γ. The stars could not care less. In stars all the particles are moving and only the center-of-momentum system is important for the determination of stellar reaction rates. In ^{12}C(α,n)^{15}O($e^+\nu$)^{15}N, n is the neutron promptly produced and detected and e^+ is the beta-decay positron, which can also be detected.

Stellar Reaction Rates from Laboratory Cross Sections

Thermonuclear reaction rates in stars are customarily expressed as $N_A\langle\sigma\sigma\rangle$ reactions per second per mole per cubic centimeter, where $N_A = 6.022 \times 10^{23}$ mole^{-1} is Avogadro's number and $\langle\sigma v\rangle$ is the Maxwell-Boltzmann average as a function of temperature for the product of the reaction cross section σ (in square centimeters) and the relative velocity of the reactants v (in centimeters per second). Multiplication of $\langle\sigma v\rangle$ by the product of the number densities per cubic centimeter for the two reactants is necessary to obtain rates in reactions per second per cubic centimeter. The N_A is incorporated so that mass fractions can be used (*21*).

Early work on the evaluation of stellar reaction rates from experimental laboratory cross sections was reviewed in Bethe's Nobel lecture (*11*). Fowler *et al.* (*21*) have provided detailed numerical and analytical procedures for converting laboratory cross sections into stellar reaction rates. It is first necessry to accommodate the rapid variation of the nuclear cross sections at the low energies which are relevant in astrophysical circumstances. For neutron-induced reactions this is accomplished by defining a cross-section S-factor equal to the cross section (σ) multiplied by the interaction velocity (v) in order to eliminate the usual v^{-1} singularity in the cross section at low velocities and low energies.

For reactions induced by charged particles such as protons, alpha particles, or ^{12}C, ^{16}O, . . . nuclei it is necessary to accommodate the decrease by many orders of magnitude from the lowest laboratory measurements to the energies of astrophysical relevance. This is done in the way first suggested by Salpeter (*22*) and emphasized in Bethe's Nobel lecture (*11*). A relatively slowly varying S-factor can be defined by eliminating the rapidly varying term in the Gamow penetration factor governing transmission through the Coulomb barrier. Stellar reaction rates can be calculated as an average over the Maxwell-Boltzmann distribution for both nonresonant and resonant cross sections. Expressions for reaction rates derived from theoretical statistical model calculations are given by Woosley *et al.* (*23*).

Although the extrapolation from cross sections measured at the lowest laboratory energies to cross sections at the effective stellar energy can often involve a decrease by many orders of magnitude, the elimination of the Gamow penetration factor, which causes this decrease, is based on the solution of the Schroedinger equation for the Coulomb wave functions, in which one can have considerable confidence. The main uncertainty lies in the variation of the S-factor with energy, which depends primarily on the value chosen for the radius at which formation of a compound nucleus between two interacting nuclei or nucleons occurs (*18*). The radii used by my colleages and me in recent work are given in (*23*). There is, in addition, an uncertainty in the "intrinsic nuclear factor" used in the definition of σ, and this can be eliminated only by recourse to laboratory experiments. The effect of a resonance in the compound nucleus just below or just above the threshold for a given reaction can often be ascertained by determining the properties of the resonance in other reactions which are easier to study.

Hydrogen Burning in Main-Sequence Stars and the Solar Neutrino Problem

Hydrogen burning in main-sequence stars has contributed only about 20 percent more helium than resulted from the big bang. However, hydrogen burning in the sun has posed a problem for many years. In 1938 Bethe and Critchfield (*24*) proposed the proton-proton or pp chain as one mechanism for hydrogen burning in stars. From many cross-section measurements at Kellogg and elsewhere it is now known that the pp chain, rather than the CNO cycle, is the mechanism which operates in the sun.

Our knowledge of the weak nuclear interaction tells us that two neutrinos are emitted when four hydrogen nuclei are converted into helium nuclei. Detailed elaboration of the pp chain (*25, 26*) showed that a small fraction of these neutrinos, those from the decay of ^{7}Be and ^{8}B, should be energetic enough to be detectable through interaction with the nucleus ^{37}Cl to form radioactive ^{37}Ar (*27, 28*). Davis (*29*) and his collaborators have attempted for more than 25 years to

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detect these energetic neutrinos by employing a 380,000-liter tank of perchloroethylene ($C_2{}^{35}Cl_3{}^{37}Cl_1$) located 1 mile deep in the Homestake Gold Mine in Lead, South Dakota. They find only about one-third of the number expected on the basis of the model-dependent calculations of Bahcall *et al.* (*30*).

Something is wrong—either the standard solar models or the relevant nuclear cross sections are in error, or the electron-type neutrinos produced in the sun are converted in part into undetectable muon neutrinos or taon neutrinos on the way from the sun to the earth. There indeed have been controversies about the nuclear cross sections which have been for the most part resolved (*31, 32*).

It is generally agreed that the next step is to build a detector which will detect the much larger flux of low-energy neutrinos from the sun through neutrino absorption by the nucleus ^{71}Ga to form radioactive ^{71}Ge. This will require 20 to 50 tons of gallium at a cost (for 20 tons) of approximately $10 million. An international effort is being made to obtain the necessary amount of gallium. We are back at square one in nuclear astrophysics. Until the solar neutrino problem is resolved, the basic principles underlying nuclear processes in stars are in question.

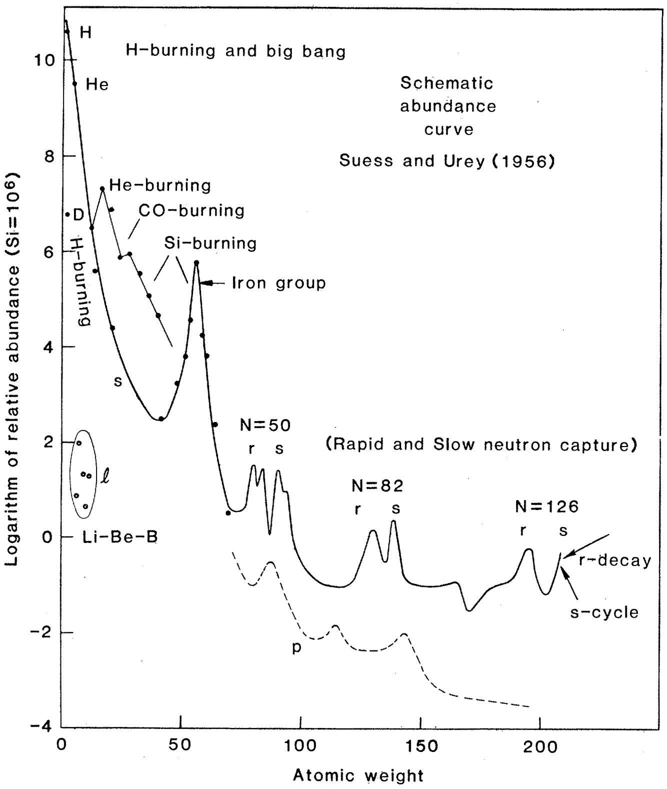
The CNO cycle operates at the higher temperatures which occur during hydrogen burning in main-sequence stars somewhat more massive than the sun, because the CNO cycle reaction rates rise more rapidly with temperature than do those of the pp chain. The cycle is important because ^{13}C, ^{14}N, ^{15}N, ^{17}O, and ^{18}O are produced from ^{12}C and ^{16}O as seeds. The role of these nuclei as sources of neutrons during helium burning is discussed next.

Synthesis of ^{13}C and ^{16}O and Neutron Production in Helium Burning

The human body is 65 percent oxygen and 18 percent carbon by mass; with the remainder mostly hydrogen. Oxygen (0.85 percent) and carbon (0.39 percent) are the most abundant elements heavier than helium in the sun and similar main-sequence stars. It is little wonder that the determination of the ratio $^{12}C/^{16}O$ produced in helium burning is a problem of paramount importance in nuclear astrophysics. This ratio depends in a fairly complicated manner on the density, temperature, and duration of helium burning, but it depends directly on the relative rates of the $3\alpha \rightarrow {}^{12}C$ process and the $^{12}C(\alpha,\gamma)^{16}O$ process. If $3\alpha \rightarrow {}^{12}C$ is much faster than $^{12}C(\alpha,\gamma)^{16}O$ then no ^{16}O is produced in helium burning. If the reverse is true then no ^{12}C is produced. For the most part the subsequent reaction $^{16}O(\alpha,\gamma)^{20}Ne$ is slow enough to be neglected.

There is general agreement about the rate of the $3\alpha \rightarrow {}^{12}C$ process (*33*). However there is a lively controversy about the laboratory cross section for $^{12}C(\alpha,\gamma)^{16}O$ and about its theoretical extrapolation to the low energies at which the reaction effectively operates. Data obtained at Caltech in the Kellogg Laboratory (*34*) and data obtained at Münster (*35*) have been compared with theoretical calculations, and the theoretical curves which yield the best fit to the two sets of data are from Langanke and Koonin (*36*). The crux of the situation is made evident in Fig. 2, which shows the extrapolations of the Caltech and Münster cross-section factors from the lowest measured laboratory energies (~1.4 MeV) to the effective energy ~0.3 MeV, at $T = 1.8 \times 10^8$ K, a representative temperature for helium burning in red giant stars. The extrapolation in cross sections covers a range of 10^{-8}. The rise in the cross-section factor is due to the contributions of two bound states in the ^{16}O nucleus just below the $^{12}C(\alpha,\gamma)^{16}O$ threshold. These contributions plus differences in the laboratory data produce the current uncertainty in the extrapolated *S*-factor.

With so much riding on the outcome it will come as no surprise that both laboratories are engaged in extending their measurements to lower energies with higher precision. In the discussion of quasi-static silicon burning that follows it will be found that the abundances produced in that stage of nucleosynthesis depend in part on the ratio of ^{12}C to ^{16}O



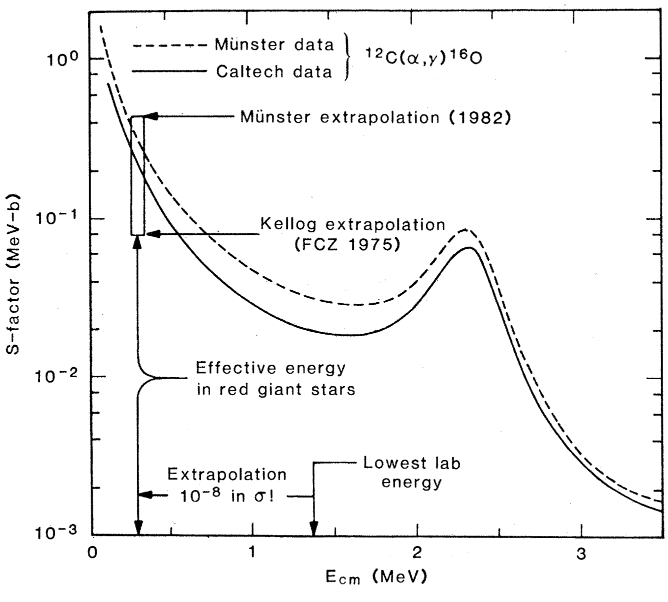


Fig. 1 (left). Schematic curve of atomic abundances relative to Si = 10^6 versus atomic weight for the sun and similar main-sequence stars. Fig. 2 (right). Cross-section factor *S* (in MeV-barns) versus center-of-momentum energy (in MeV) for $^{12}C(\alpha,\gamma)^{16}O$. The dashed and solid curves are the theoretical extrapolations of the Münster and Kellogg Caltech data by Langanke and Koonin (*36*). [Taken with some modification from Kettner *et al.* (*35*)]

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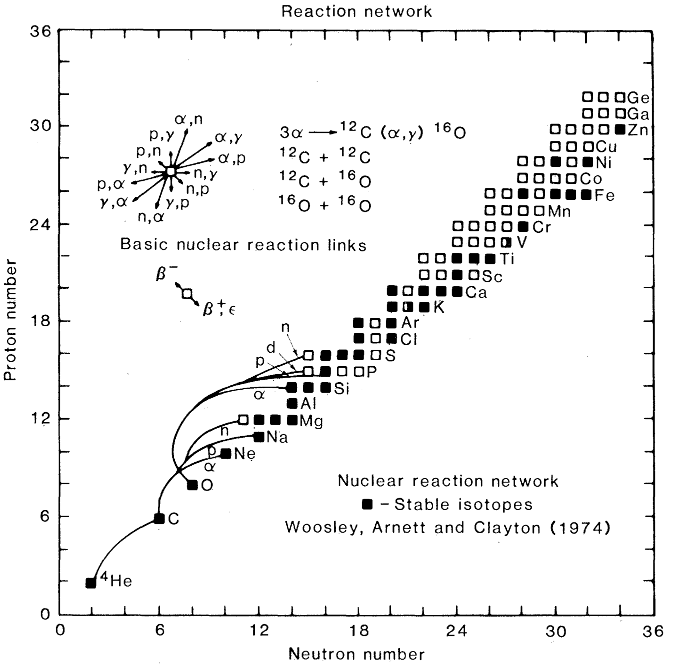

Fig. 3. Reaction network for nucleosynthesis involving the most important stable and radioactive nuclei with $N = 2$ to 34 and $Z = 2$ to 32. Stable nuclei are indicated by solid squares. Radioactive nuclei are indicated by open squares.

produced in helium burning and that the different extrapolations shown in Fig. 2 are in the range crucial to the ultimate outcome of silicon burning. These remarks do not apply to explosive nucleosynthesis.

Recently, the ratio of ^{12}C to ^{16}O produced under the special conditions of helium flashes during the asymptotic giant phase of stellar evolution has become of great interest. The hot blue star PG 1159-035 has been found to undergo nonradial pulsations with periods of 460 and 540 seconds and others not yet accurately determined. The star is obviously highly evolved, having lost its hydrogen atmosphere, leaving only a hot dwarf of about 0.6 solar mass (0.6 $M_\odot$) behind. Theoretical analysis of the pulsations (*37*) requires substantial amounts of oxygen in the pulsation-driving regions where the oxygen is alternately ionized and deionized. Carbon is completely ionized in these regions and only diminishes the pulsation amplitude. It is not yet clear that sufficient oxygen is produced in helium flashes, which certainly involve $3\alpha \rightarrow {}^{12}C$ but may not last long enough for $^{12}C(\alpha,\gamma)^{16}O$ to be involved. The problem may not lie in the nuclear reaction rates, according to (*37*). We shall see.

In what follows in this article β^+-decay is designated by $(e^+\nu)$, since both a positron (e^+) and a neutrino (ν) are emitted. Similarly, β^--decay will be designated by $(e^-\bar{\nu})$, since both an electron (e^-) and an antineutrino $(\bar{\nu})$ are emitted. Electron capture (often indicated by ϵ) will be designated by $e^-,\nu)$, the comma indicating that an electron is captured and a neutrino emitted. The notations $(e^+,\bar{\nu})$,(ν,e^-), and $(\bar{\nu},e^+)$ should now be obvious.

Neutrons are produced when helium burning occurs under circumstances in which the CNO cycle has been operative in the previous hydrogen burning. When the cycle does not go to completion, copious quantities of ^{13}C are produced in the sequence of reactions $^{12}C(p,\gamma)^{13}N(e^+\nu)^{13}C$. In subsequent helium burning, neutrons are produced by $^{13}C(\alpha,n)^{16}O$. When the cycle goes to completion the main product (>95 percent) is ^{14}N. In subsequent helium burning, ^{18}O and ^{22}Ne are produced in the sequence of reactions $^{14}N(\alpha,\gamma)^{18}F(e^+\nu)^{18}O(\alpha,\gamma)^{22}Ne$, and these nuclei in turn produce neutrons through $^{18}O(\alpha,n)$ $^{21}Ne(\alpha,n)^{24}Mg$ and $^{22}Ne(\alpha,n)^{25}Mg$. However, the astrophysical circumstances and sites under which the neutrons produce heavy elements through the s-process and the r-process are, even today, matters of some controversy and much study.

Carbon, Neon, Oxygen, and Silicon Burning

The advanced burning processes discussed in this section involve the network of reactions shown in Fig. 3. Because of the high temperature at which this network can operate, radioactive nuclei can live long enough to serve as live reaction targets. Excited states of even the stable nuclei are populated and also serve as targets. Determination of the nuclear cross sections and stellar rates of the approximately 1000 reactions in the network has involved and will continue to involve extensive experimental and theoretical effort.

The following discussion applies to stars massive enough that electron degeneracy does not set in as nuclear evolution proceeds through these various burning stages. In less massive stars electron degeneracy can terminate further nuclear evolution at certain stages, with catastrophic results leading to the disruption of the stellar system.

Figure 4, taken from Woosley and Weaver (*38*), applies to the pre-supernova stage of a young (Population I) star of 25 $M_\odot$ and shows the result of various nuclear burnings in the following mass zones: (i) >10 $M_\odot$, convective envelope with the results of some CNO burning; (ii) 7 to 10 $M_\odot$, products mainly of H burning; (iii) 6.5 to 7 $M_\odot$, products of He burning; (iv) 1.9 to 6.5 $M_\odot$, products of C burning; (v) 1.8 to 1.9 $M_\odot$, products of Ne burning; (vi) 1.5 to 1.8 $M_\odot$, products of O burning; and (vii) <1.5 $M_\odot$, products of Si burning in the partially neutronized core (these are not shown in detail but consist mainly of ^{54}Fe and other neutron-rich nuclei such as ^{48}Ca, ^{50}Ti, ^{54}Cr, and ^{58}Fe). Figure 4 has been evaluated shortly after photodisintegration has initiated core collapse, which will then be sustained by the reduction of the outward pressure through electron capture and the resulting almost complete neutronization of the core.

It must be realized that the various burning stages took place originally over the central region of the star and finally in a shell surrounding that region. Subsequent stages modify the innner part of the previous burning stage. For example, in the star of Fig. 4, C burning took place in the central 6.5 $M_\odot$ of the star but the inner 1.9 $M_\odot$ were modified by subsequent Ne, O, and Si burning.

Helium burning produces a stellar core consisting mainly of ^{12}C and ^{16}O. After core contraction the temperature and density rise until carbon burning through $^{12}C + {}^{12}C$ fusion is ignited. The main product of carbon burning is ^{20}Ne, produced primarily in the $^{12}C(^{12}C,\alpha)^{20}Ne$ reaction. When the ^{12}C is exhausted, ^{20}Ne and ^{16}O are the major remaining constituents. As the temperature rises from further gravitational contraction, the ^{20}Ne is destroyed by photodisintegration, $^{20}Ne(\gamma,\alpha)^{16}O$. This occurs because the alpha particle in ^{20}Ne is bound to its closed-shell partner, ^{16}O, by only 4.731 MeV (for comparison, the binding of an alpha particle in ^{16}O is 7.162 MeV).

The next stage is oxygen burning through $^{16}O + {}^{16}O$ fusion. The main product is ^{28}Si through the primary reaction $^{16}O(^{16}O,\alpha)^{28}Si$ and a number of sec-

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ondary reactions. Under some conditions neutron-induced reactions lead to the synthesis of significant quantities of ^{30}Si. Oxygen burning can result in nuclei with a small but important excess of neutrons over protons.

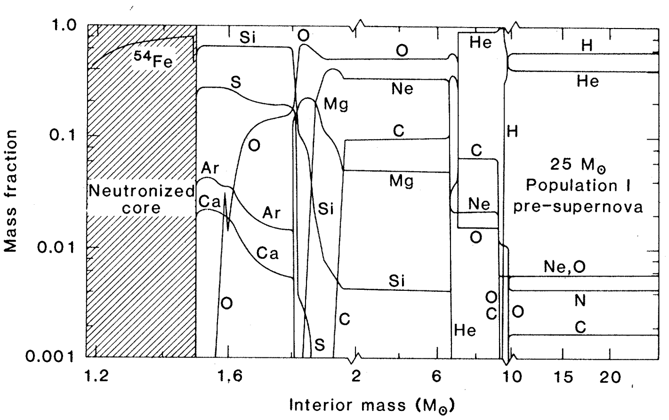

Fig. 4. Pre-supernova abundances by mass fraction versus increasing interior mass in solar masses, $M_\odot$, measured from zero at the stellar center to 25 $M_\odot$, the total stellar mass from Woosley and Weaver (*38*) for a Population I star.

The onset of Si burning signals a marked change in the nature of the fusion process. The Coulomb barrier between two ^{28}Si nuclei is too great for fusion to produce the compound nucleus, ^{56}Ni, directly at the ambient temperatures and densities. However, the ^{28}Si and subsequent products are easily photodisintegrated by (γ,α), (γ,n), and (γ,p) reactions. As Si burning proceeds, more and more ^{28}Si is reduced to nucleons and alpha particles, which can be captured by the remaining ^{28}Si nuclei to build through the network in Fig. 3 up to the iron-group nuclei. The main product in explosive Si burning is ^{56}Ni, which transforms eventually through two beta-decays to ^{56}Fe.

In quasi-static Si burning the weak interactions are fast enough that ^{54}Fe, with two more neutrons than protons, is the main product. Because of the important role played by alpha particles (α) and the inexorable trend to equilibrium (e) involving nuclei near mass 56, which have the largest binding energies per nucleon of all nuclear species, B^{2}FH (*18*) broke down what is now called Si burning into their α-process and e-process. Quasi-equilibrium calculations for Si burning were made by Bodansky *et al.* (*39*), who cite the original papers in which the basic ideas of Si burning were developed. Modern computers permit detailed network flow calculations to be made (*38*, *40*).

The extensive laboratory studies of Si burning reactions are reviewed in (*33*). The laboratory excitation curves for ^{54}Cr$(p,n)^{54}$Mn and ^{54}Cr$(p,\gamma)^{55}$Mn are discussed here as examples. The neutrons produced in the first of these reactions will increase the number of neutrons available in Si burning but will not contribute directly to the synthesis of ^{55}Mn as does the second reaction. In fact, above its threshold at 2.158 MeV the (p,n) reaction competes strongly with the (p,γ) reaction, which is of primary interest, and produces a pronounced competition cusp in the excitation curve. The rate of the ^{54}Cr$(p,\gamma)^{55}$Mn reaction at very high temperatures will be an order of magnitude lower because of the cusp than would otherwise be the case.

The element manganese has only one isotope, ^{55}Mn, and in nature is produced in quasi-static Si burning, probably through the ^{54}C$(p,\gamma)^{55}$Mn reaction. The reactions ^{51}V$(\alpha,\gamma)^{55}$Mn and ^{52}V$(\alpha,n)^{55}$Mn may also contribute, especially in explosive Si burning. The overall synthesis of ^{55}Mn involves a balance in its production and destruction. In quasi-static Si burning the reactions which destroy ^{55}Mn are probably ^{55}Mn$(p,\gamma)^{56}$Fe and ^{55}Mn$(p,n)^{55}$Fe, which are discussed and illustrated in (*41*). ^{55}Mn$(\alpha,\gamma)^{59}$Co, ^{55}Mn $(\alpha,p)^{58}$Fe, and ^{55}Mn$(\alpha,n)^{58}$Co may also destroy some ^{55}Mn in explosive Si burning. Calculations of the overall synthesis of ^{55}Mn yield values that are in fairly close agreement with the abundance of this nucleus in the solar system. Unfortunately, the same cannot be said about many other nuclei.

Laboratory measurements on Si burning reactions have covered only about 20 percent of the reactions in the network of Fig. 3 involving stable nuclei as targets. Direct measurements on short-lived radioactive nuclei and the excited states of all nuclei are impossible at present, although the production of radioactive ion beams, pioneered by Richard Boyd and Haight *et al.* (*42*), hold great promise for the future.

In any case, it has been clear for some time that experimental results on Si burning reactions must be systematized and supplemented by comprehensive theory. Fortunately, theoretical average cross sections will suffice in many cases, because the stellar reaction rates integrate the cross sections over the Maxwell-Boltzmann distribution. For most Si burning reactions resonances in the cross section are closely spaced and even overlapping, and the integration covers a wide enough range of energies that the detailed structure in the cross sections is averaged out. The statistical model of nuclear reactions developed by Hauser and Feshbach (*43*), which yields average cross sections, is ideal for the purpose. Accordingly, Holmes *et al.* (*44*) undertook the task of developing a global, parametrized Hauser-Feshbach theory and computer program for use in nuclear astrophysics (*23*). The free parameters are the radius, depth, and compensating reflection factor of the blackbody, square-well equivalent of the Woods-Saxon potential characteristic of the interaction between n, p, and α with nuclei having $Z \geq 8$. Two free parameters must also be incorporated to adjust the intensity of electric and magnetic dipole transitions for gamma radiation. Weak interaction rates must also be specified, and ways of doing this will be discussed later.

It is well known that the free parameters can always be adjusted to fit the cross sections and reaction rates of any one particular nuclear reaction. This is not done in a global program. The parameters are, in principle, determined by the best least-squares fit to all reactions for which experimental results are available. This lends some confidence in predictions for cases where experimental results are unavailable.

The original program (*23*, *44*), has produced reaction rates in numerical or analytical form as a function of temperature. Ready comparison with integrations of laboratory cross sections for target ground states are possible. Using the same global parameters which apply to reactions involving the ground states of stable nuclei, the theoretical program calculates rates for the ground states of radioactive nuclei and the excited states of both stable and radioactive nuclei. Summing over the statistically weighted contributions of the ground and known excited states or theoretical level density functions yields the stellar reaction rate for the equilibrated statistical population of the nuclear states. After summing, division by the partition function of the target nucleus is necessary.

Sargood (*45*) compared experimental results from a number of laboratories for protons and alpha particles reacting with 80 target nuclei (which are, of course, in their ground states) with the theoretical predictions of (*23*). Ratios of statistical model calculations to laboratory mea-

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surements for 12 cases are shown in Table 1 for temperatures in the range 1×10^9 to 5×10^9 K. The double entry for ^{27}Al(p,n)^{27}Si signifies ratios of theory to measurements made in two different laboratories. The theoretical calculations match the experimental results within 50 percent with a few marked exceptions. For the rather light targets in Table 1, especially at low temperature, the global mean rates can be in error whenever more and stronger resonances or fewer and weaker resonances than expected on average occur in the excitation curve of the reaction at low energies.

Sargood (*45*) also compared the ratio of the stellar rate of a reaction with target nuclei in a thermal distribution of ground and excited states with the rate for all target nuclei in their ground state. The latter is determined from laboratory measurements. In many cases, notably for reactions producing gamma rays, the ratio of stellar to laboratory rates is close to unity. In other cases the ratio can be high by several orders of magnitude. This frequently occurs when the ground state can interact only through partial waves of high angular momentum, resulting in small penetration factors and thus small cross sections and rates. This makes clear that it is frequently not valid to assume that a statistical theory which does well predicting ground state results will do equally well in predicting excited state results. Bahcall and Fowler (*46*) have shown that in a few cases laboratory measurements on inelastic scattering involving excited states can be used indirectly to determine reaction cross sections for those states.

Ward and Fowler (*47*) have investigated in detail the circumstances under which long-lived isomeric states do not come into equilibrium with ground states. When this occurs it is necessary to incorporate into network calculations the stellar rates for both the isomeric and ground states. An example of great interest is the nucleus ^{26}Al. The ground state has spin and parity $J^\pi = 5^+$ and isospin $T = 0$, and has a mean lifetime for positron emission to ^{26}Mg of 10^6 years. The isomeric state at 0.228 MeV has $J^\pi = 0^+$, $T = 1$, and mean lifetime of 9.2 seconds. Ward and Fowler (*47*) showed that the isomeric state effectively does not come into equilibrium with the ground state for temperatures $< 4 \times 10^8$ K. At these low temperatures both the isomeric state and the ground state of ^{26}Al must be included in the network of Fig. 3.

Astrophysical Weak Interaction Rates

Weak nuclear interactions play an important role in astrophysical processes, as indicated in Fig. 3. Only through the weak interaction can the overall proton number and neutron number of nuclear matter change during stellar evolution, collapse, and explosion. The formation of a neutron star requires that protons in ordinary stellar matter capture electrons. Gravitational collapse of a type II supernova core is retarded as long as electrons remain to exert outward pressure.

Many years of theoretical and experimental work on weak interaction rates in the Kellogg Laboratory and elsewhere have culminated in the calculation and tabulation by Fuller *et al.* (*48*) of electron and positron emission rates and continuum electron and positron capture rates, as well as the associated neutrino energy loss rates, for free nucleons and 226 nuclei with mass numbers between 21 and 60. Extension to higher and lower values of A is under way.

The detailed nature and the difficulty of the theoretical aspects of the combined atomic, nuclear, plasma, and hydrodynamic physics problems in type II supernova implosion and explosion were brought home to us by Hans Bethe during his stay in our laboratory early in 1982. His visit resulted in the preparation of two seminal papers (*49, 50*).

Current ideas on the nuclear equation of state predict that early in the collapse of the iron core of a massive star the nuclei present will become so neutron-rich that allowed electron capture on protons in the nuclei is blocked. Allowed electron capture, for which $\Delta l = 0$, is not permitted when neutrons have filled the subshells having orbital angular momentum, l, equal to that of the subshells occupied by the protons. This neutron shell blocking phenomenon, and several unblocking mechanisms operative at high temperature and density, including forbidden electron capture, have been studied in terms of the simple shell model by Fuller (*51*). Typical conditions result in a considerable reduction of the electron capture rates on heavy nuclei, leading to significant dependence on electron capture by the small number of free protons and a decrease in the overall neutronization rate.

Recent work on the weak interaction has concentrated on making the previously calculated reaction rates as efficient as possible for users of the published tables and computer tapes. The stellar weak interaction rates of nuclei are in general very sensitive functions of temperature and density. For electron and positron emission, most of the temperature-dependence is due to thermal population of parent excited states at all but the lowest temperatures and highest densities. In general, only a few transitions will contribute to these decay rates and hence the variation of the rates with temperature is usually not so large that rates cannot be accurately interpolated in temperature and density with standard grids (*48*). The density-dependence of these decay rates is minimal. In electron emission, however, there may be considerable density-dependence; but this does not present much of a problem for practical interpolation since the electron emission rate is usually very small under these conditions.

The temperature- and density-dependence of continuum electron and positron capture is a much more serious problem. In addition to temperature sensitivity introduced through thermal population of parent excited states, there are considerable effects from the lepton distribution functions in the integrands of the continuum-capture phase-space fac-

Table 1. Statistical model calculations versus measurements. Ratio of reaction rate (ground state of target) from Woosley *et al.* (*110*) to reaction rates from experimental yield measurements (1970–1982) at Bombay, Caltech, Colorado, Kentucky, Melbourne, and Toronto.

Reaction	$T_9 = T/10^9$ K				
	1	2	3	4	5
^{23}Na(p,n)^{23}Mg	1.4	1.2	1.1	1.1	1.0
^{25}Mg(p,γ)^{26}Al	1.2	1.1	1.0	0.9	0.8
^{25}Mg(p,n)^{25}Al	1.1	1.0	0.9	0.8	0.8
^{27}Al(p,γ)^{28}Si	3.7	2.1	1.5	1.3	1.1
^{27}Al(p,n)^{27}Si	1.8	1.4	1.3	1.3	1.2
	0.9	0.9	0.9	1.0	1.0
^{28}Si(p,γ)^{29}P		1.2	1.3	1.2	0.9
^{29}Si(p,γ)^{30}P		1.0	1.6	1.6	1.5
^{39}K(p,γ)^{40}Ca	15	4.5	3.0	2.6	2.5
^{41}K(p,γ)^{42}Ca	0.5	0.5	0.5	0.4	0.4
^{41}K(p,n)^{41}Ca	0.8	1.0	1.1	1.2	1.3
^{40}Ca(p,γ)^{41}Sc				0.1	0.2
^{42}Ca(p,γ)^{43}Sc	1.3	1.4	1.4	1.4	1.3
	0.8	1.1	1.3	1.4	1.4

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tors. This means that interpolation in temperature and density on the standard grid to obtain a rate can be difficult, especially for electron capture processes with threshold above zero energy.

We have found that the interpolation problem can be greatly eased by defining a simple continuum-capture phase-space integral, based on the value for the transition from the parent ground state to the daughter ground state, and then dividing this by the tabulated rate (*48*) at each temperature and density grid point to obtain values that are much less dependent on temperature and density. This procedure requires a formulation of the capture phase-space factors which is simple enough to use many times in the inner loop of stellar evolution nucleosynthesis computer programs. Such a formulation in terms of standard Fermi integrals has been found, along with approximations for the requisite Fermi integrals. When the chemical potential (Fermi energy) which appears in the Fermi integrals goes through zero these approximations have continuous values and continuous derivatives.

We have recently found expressions for the reverse reactions to e^-, e^+-capture, (that is, $\nu,\bar{\nu}$-capture) and for $\nu,\bar{\nu}$-blocking of the direct reactions when $\nu,\bar{\nu}$-states are partially or completely filled. These reverse reactions and the blocking are important during supernova core collapse when neutrinos and antineutrinos eventually become trapped, leading to equilibrium between the two directions of capture. General analytic expressions have been derived and approximated with computer-usable equations. All of these new results will be published in Fuller *et al.* (*52*) and new tapes including $\nu,\bar{\nu}$-capture will be made available to users on request.

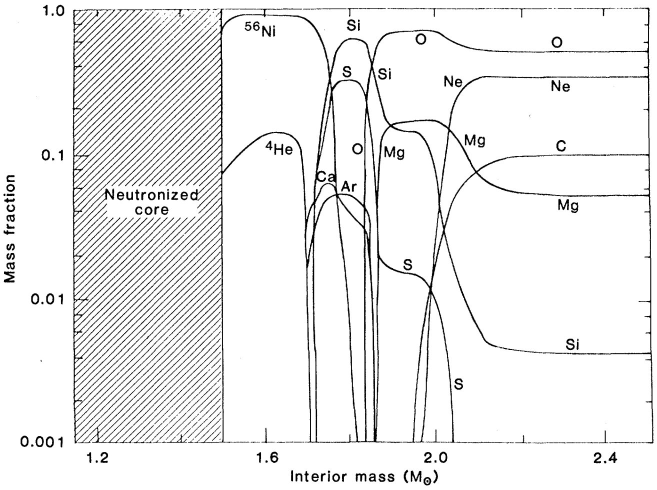

Fig. 5. Final abundances by mass fraction versus increasing interior mass in solar masses, $M_\odot$, in Type II supernova ejecta from a Population I star with total mass equal to 25 $M_\odot$, from Woosley and Weaver (*38*).

Calculated Abundances for $A \lesssim 60$ and Comments on Explosive Nucleosynthesis

Armed with the available strong and weak nuclear reaction rates which apply to the advanced stages of stellar evolution, theoretical astrophysicists have attempted to derive the elemental and isotopic abundances produced in quasi-static pre-supernova nucleosynthesis and in explosive nucleosynthesis occurring during supernova outbursts. Although there is reasonably general agreement on nucleosynthesis during the various preexplosive stages, explosive nucleosynthesis is still an unsettled matter, subject to intensive study (*53*).

The abundances produced in explosive nucleosynthesis must depend on the detailed nature of supernova explosions. Ideas concerning the nature of type I and type II supernova explosions were published many years ago (*54, 55*). It was suggested that type I supernovae of small mass were precipitated by the onset of explosive carbon burning under conditions of electron degeneracy, where pressure is approximately independent of temperature. Carbon burning raises the temperature to the point where the electrons are no longer degenerate and explosive disruption of the star results. For type II supernovae of larger mass it was suggested that Si burning produced iron-group nuclei, which have the maximum binding energies of all nuclei, so that nuclear energy is no longer available. Subsequent photodisintegration and electron capture in the stellar core lead to core implosion and ignition of explosive nucleosynthesis in the infalling inner mantle, which still contains nuclear fuel. These ideas have "survived" but, to say the least, with considerable modification over the years (*56*). Modern views on type II supernovae are given in (*40, 49, 50, 57*), and on type I supernovae in (*58*).

We can return to the nuclear abundance problem by reference to Fig. 5, which shows the distribution of final abundances by mass fraction in the supernova ejecta of a 25-$M_\odot$ Population I star. The pre-supernova distribution is that shown in Fig. 4. The modification of the abundances for mass zones interior to 2.2 $M_\odot$ is very apparent. Mass exterior to 2.2 $M_\odot$ is ejected with little or no modification in nuclear abundances. The supernova explosion was simulated by arbitrarily assuming that the order of 10^{51} ergs was delivered to the ejected material by the shock generated in the bounce or rebound of the collapsing and hardening core.

Integration over the mass zones of Fig. 5 for 1.5 $M_\odot < M < 2.2\ M_\odot$ and of Fig. 4 for $M > 2.2\ M_\odot$ yielded the isotopic abundances ejected into the interstellar medium by the simulated supernova (*38*). The results relative to solar abundances are shown in Fig. 6. The relative ratios are normalized to unity for ^{16}O, for which the overproduction ratio was 14; that is, for each gram of ^{16}O originally in the star, 14 grams were ejected. This overproduction in a single supernova can be expected to have produced the heavy-element abundances in the interstellar medium just prior to formation of the solar system, given the fact that supernovae occur approximately every 100 years in the Galaxy. The ultimate theoretical calculations will yield a constant overproduction factor of the order of 10.

The results shown in Fig. 6 are disappointing if one expects the ejecta of 20-$M_\odot$ Population I supernovae to match solar system abundances with a relatively constant overproduction factor. The dip in abundances from sulfur to chromium is readily apparent. However, calculations must be made for other stellar masses and properly integrated over the mass distribution for stellar formation, which is roughly inversely proportional to mass (*38*). Woosley *et al.* (*53*) discuss their expectations of the abundances produced in stellar explosions for stars in the mass range 10 to $10^6\ M_\odot$. They show that a 200-$M_\odot$ Population III star produces abundant quantities of sulfur, argon, and calcium, which may compensate for the dip in Fig. 6. Population III stars are massive stars in the range 100 $M_\odot < M < 300\ M_\odot$ which are thought to have formed from hydrogen and helium early in the history of the Galaxy and evolved very rapidly. Since their heavy-element abundance was zero they have no counterparts in presently forming Population I stars or among old, low-mass Population II stars.

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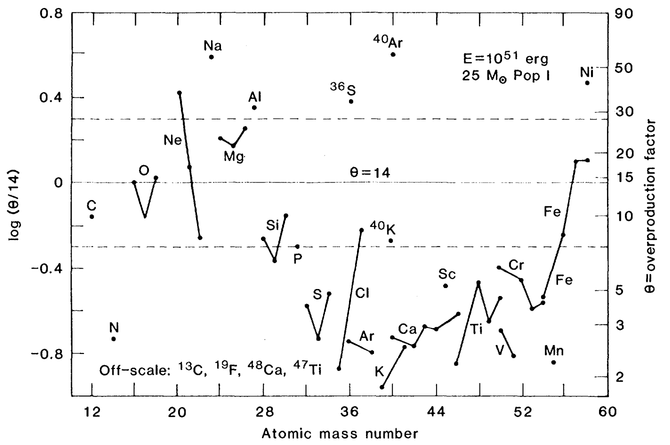

Fig. 6. Overabundance (ϑ) relative to 14 times solar abundances versus atomic mass number for nucleosynthesis resulting from a Type II, Population I supernova with total mass equal to 25 $M_\odot$, from Woosley and Weaver (*38*).

Other authors have suggested a number of solutions to the problem depicted in Fig. 6. Nomoto *et al.* (*59*) calculated the abundances produced in carbon deflagration models of type I supernovae and, by adding equal contributions from type I and type II supernovae, obtained a result which is somewhat more satisfactory than Fig. 6. Arnett and Thielemann (*60*) recalculated quasi-static pre-supernova nucleosynthesis for $M \approx 20\ M_\odot$, using a value for the $^{12}C(\alpha,\gamma)^{16}O$ rate equal to three times that given in (*21*); this would seem to be justified by the recent analysis of $^{12}C(\alpha,\gamma)^{16}O$ data, as discussed earlier. They then assumed that explosive nucleosynthesis would not substantially modify their quasi-static abundances and obtained results in which the average overproduction ratio is roughly 14. However, their assumption of minor modification during explosion and ejection is questionable.

I feel that the results discussed in this section and those obtained by numerous other authors show promise of an eventual satisfactory answer to the question where and how the elements from carbon to nickel originated.

Isotopic Anomalies in Meteorites and Evidence for Ongoing Nucleosynthesis

Almost a decade ago it became clear that nucleosynthesis occurred in the Galaxy up to the time of formation of the solar system or at least up to several million years before the formation. For slightly over a year it has been clear that nucleosynthesis has continued up to the present time or at least within several million years of the present. The decay of radioactive ^{26}Al ($\bar{\tau} = 1.04 \times 10^6$ years) is the key to these statements, which bring great satisfaction to most experimentalists, theorists, and observers in nuclear astrophysics.

Isotopic anomalies in meteorites produced by the decay of short-lived radioactive nuclei were first demonstrated in 1960 by Reynolds (*61*), who found large enrichments of ^{129}Xe in the Richardson meteorite. Jeffery and Reynolds (*62*) demonstrated that the excess ^{129}Xe was correlated with ^{127}I in the meteorite and that it resulted from the decay in situ of ^{129}I ($\bar{\tau} = 23 \times 10^6$ years). Quantitative results indicated that $^{129}I/^{127}I \approx 10^{-4}$ at the time of meteorite formation. On the assumption that ^{129}I and ^{127}I were produced in roughly equal abundances in nucleosynthesis (most probably in the r-process) over a period of $\sim 10^{10}$ years in the Galaxy prior to formation of the solar system, and taking into account that only the ^{129}I produced over a period of the order of its lifetime survives, Wasserburg *et al.* (*63*) suggested that a period of free decay of the order of 10^8 years or more occurred between the last nucleosynthetic event which produced ^{129}I and its incorporation in meteorites in the solar system. There remains evidence for such a period in some cases, notably ^{244}Pu, but probably not in the history of the nucleosynthetic events which produced ^{129}I and other "short-lived" radioactive nuclei such as ^{26}Al and ^{107}Pd ($\bar{\tau} = 9.4 \times 10^6$ years).

The substantial meteoritic anomalies in ^{26}Mg from ^{26}Al, in ^{107}Ag from ^{107}Pd, in ^{129}Xe from ^{129}I, and in the heavy isotopes of Xe from the fission of ^{244}Pu ($\bar{\tau} = 117 \times 10^6$ years; fission tracks also observed) as well as searches in the future for anomalies in ^{41}K from ^{41}Ca ($\bar{\tau} = 0.14 \times 10^6$ years), in ^{60}Ni from ^{60}Fe ($\bar{\tau} = 0.43 \times 10^6$ years), in ^{53}Cr from ^{53}Mn ($\bar{\tau} = 5.3 \times 10^6$ years), and in ^{142}Nd from ^{146}Sm ($\bar{\tau} = 149 \times 10^6$ years; α-decay) are discussed exhaustively by Wasserburg and Papanastassiou (*64*). They espouse in situ decay for the observations to date, but Clayton (*65*) argues that the anomalies occur in interstellar grains preserved in the meteorites and originally produced by condensation in the expanding and cooling envelopes of supernovae and novae. Wasserburg and Papanastassiou write (*64*, p. 90), "There is, as yet, no compelling evidence for the presence of preserved presolar grains in the solar system. All of the samples so far investigated appear to have melted or condensed from a gas, and to have chemically reacted to form new phases." With mixed emotions I accept this.

Before turning to some elaboration of the $^{26}Al/^{26}Mg$ case it is appropriate to return to a discussion of the free decay interval mentioned above. It is the lack of detectable anomalies in ^{235}U from the decay of ^{247}Cm ($\bar{\tau} = 23 \times 10^6$ years) in meteorites (*66*) coupled with the demonstrated occurrence of heavy Xe anomalies from the fission of ^{244}Pu ($\bar{\tau} = 117 \times 10^6$ years) (*67*) which demands a free decay interval of the order of several times 10^8 years. This interval is measured from the "last" r-process nucleosynthesis event (supernova?) which produced the actinides, Th, U, Pu, Cm, and beyond, up to the "last" nucleosynthesis events (novae?, supernovae with short-run r-processes?) which produced the short-lived nuclei ^{26}Al, ^{107}Pd, and ^{129}I before the formation of the solar system. The fact that the anomalies produced by these short-lived nuclei relative to normal abundances all are of the order of 10^{-4} despite the wide range in their mean lifetimes (1.04×10^6 years to 23×10^6 years) indicates that this anomaly range must be the result of inhomogeneous mixing of exotic materials with much larger quantities of normal solar system materials over a short time rather than the result of free decay. The challenges presented by this conclusion are manifold. Figure 14 of (*64*) shows the time scale for the formation of dust, rain, and hailstones in the early solar system and for the aggregation into chunks and eventually terrestrial planets. The solar nebula was almost but not completely mixed when it collapsed to form the solar system. From ^{26}Al it becomes clear that the mixing time down to an inhomogeneity of only one part in 10^3 was the order of 10^6 years.

Evidence that ^{26}Al was alive in interstellar material in the solar nebula which condensed and aggregated to form the parent body (planet in the asteroid belt?) of the Allende meteorite is shown in Fig. 7, taken with some modification from Lee *et al.* (*68*). The Allende meteorite fell near Pueblito de Allende in Mexico on 8 February 1969 and is a carbonaceous chondrite, a type of meteorite

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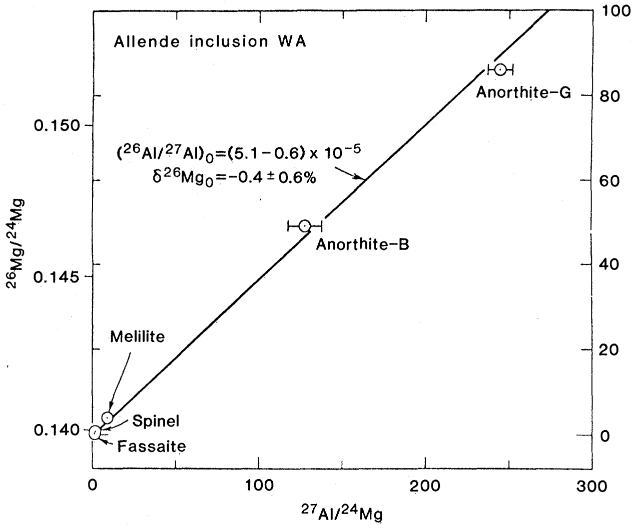

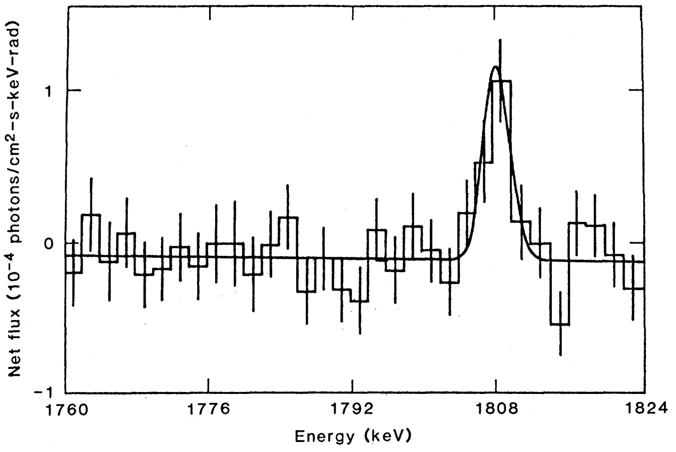

Fig. 7 (left). Evidence for the in situ decay of ^{26}Al in various minerals in inclusion WA of the Allende meteorite, from Lee *et al.* (*68*). The linear relation between ^{26}Mg/^{24}Mg and ^{27}Al/^{24}Mg implies that ^{26}Al/^{27}Al = $(5.1 \pm 0.6) \times 10^{-5}$ at the time of formation of the inclusion with ^{26}Al considered to react chemically in the same manner as ^{27}Al. Fig. 8 (right). The High Energy Astrophysical Observatory (HEAO 3) data on gamma rays in the energy range 1760 to 1824 keV emitted from the galactic equatorial plane, from Mahoney *et al.* (*69*). The line at 1809 keV is attributed to the decay of radioactive ^{26}Al ($\bar{\tau} = 1.04 \times 10^6$ years) to the excited state of ^{26}Mg at this energy.

thought to contain the most primitive material in the solar system, unaltered since its original solidification.

Figure 7 depicts the results for ^{26}Mg/^{24}Mg versus ^{27}Al/^{24}Mg in different mineral phases from a Ca-Al-rich inclusion called WA obtained from a chondrule found in Allende. The excess ^{26}Mg is linearly correlated with the amount of ^{27}Al in the mineral phases. Since ^{26}Al is chemically identical with ^{27}Al, it can be inferred that phases rich in ^{27}Al were initially rich in ^{26}Al, which subsequently decayed in situ to produce excess ^{26}Mg. Aluminum-26 existed with abundance 5×10^{-5} that of ^{27}Al in one part of the solar nebula when the WA inclusion aggregated during the earliest stages of the formation of the solar system. The unaltered inclusion survived for 4.5 billion years to tell its story. Other inclusions in Allende and other meteorites yield ^{26}Al/^{27}Al from zero up to $\sim 10^{-3}$, with 10^{-4} a representative value. The reader is referred to (*68*) for the details of the story and the significance of non–accelerator-based contributions to nuclear astrophysics.

Evidence that ^{26}Al exists in the interstellar medium today appears in Fig. 8 from Mahoney *et al.* (*69*), which shows the gamma-ray spectrum observed in the range 1760 to 1824 keV by instruments aboard the High Energy Astronomical Observatory HEAO 3, which searched for diffuse gamma-ray emission from the galactic equatorial plane. The discrete line in the spectrum at 1809 keV, detected with a significance of nearly 5 standard deviations, is without doubt due to the transition from the first excited state at 1809 keV in ^{26}Mg to its ground state. Radioactive ^{26}Al decays by $^{26}\mathrm{Al}(e^{+}\nu)^{26}\mathrm{Mg}(\gamma)^{26}\mathrm{Mg}$ to this state and thence to the ground state of ^{26}Mg. Given the mean lifetime (1.04×10^6 years) of ^{26}Al, this shows that ^{26}Al was produced no more than several million years ago and is probably being produced continuously. It is no great extrapolation to argue that nucleosynthesis in general continues in the Galaxy. Quantitatively, the observations indicate that ^{26}Al/^{27}Al $\sim 10^{-5}$ in the interstellar medium. This average value was probably much the same when the solar system formed, but the variations in ^{26}Al/^{27}Al in meteoritic inclusions show that there were wide variations in the solar nebula about this value ranging from zero to 10^{-3}.

The question immediately arises, what is the site of synthesis of the ^{26}Al? Since the preparation of (*47*) I have been convinced that ^{26}Al could not be synthesized in supernovae at high temperatures where neutrons are copiously produced because of the expectation of a large cross section for $^{26}\mathrm{Al}(n,p)^{26}\mathrm{Mg}$. This expectation has been borne out by measurements on the reverse reaction $^{26}\mathrm{Mg}(p,n)^{26}\mathrm{Al}$ in the Kellogg Laboratory by Skelton *et al.* (*70*). There is little doubt that the stellar rate for $^{26}\mathrm{Al}(n,p)^{26}\mathrm{Mg}$ is very large indeed.

It has been suggested that ^{26}Al is produced in novae (*65, 70, 71*). This is quite reasonable on the basis of nucleosynthesis in novae (*72*). In current models for novae, hydrogen from a binary companion is accreted by a white dwarf until a thermal runaway involving the fast CN cycle occurs. Similarly, a fast MgAl cycle may occur with production of ^{26}Al/^{27}Al $\gtrsim 1$, as shown in figure 9 of (*47*) and substantiated by the recent experiental measurements cited in (*47*). Clayton (*65*) argues that the estimated 40 novae occurring annually in the galactic disk can produce the observed ^{26}Al/^{27}Al ratio of 10^{-5} on average. He assumes that each nova ejects $10^{-4}\ M_\odot$ of material containing an ^{26}Al mass fraction of 3×10^{-4}.

Another possible source of ^{26}Al is spallation induced by irradiation of protoplanetary material by high-energy protons from the young sun as it settled on the main sequence. This possibility was discussed very early by Fowler *et al.* (*73*), who also attempted to produce D, Li, Be, and B in this way, requiring such large primary proton and secondary neutron fluxes that many features of the abundance curve in the solar system would have been changed substantially. A more reasonable version of the scenario was presented by Lee (*74*) but without notable success. I find it difficult to believe that an early irradiation produced the anomalies in meteorites. The ^{26}Al in the interstellar medium today certainly cannot have been produced in this way.

Anomalies have been found in meteorites in the abundances compared with normal solar system material of the stable isotopes of many elements: O, Ne, Mg, Ca, Ti, Kr, Sr, Xe, Ba, Nd, and Sm. The possibility that the oxygen anomalies are nonnuclear in origin has been raised by Thiemens and Heidenreich (*75*), but the anomalies in the remaining

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elements are generally attributed to nuclear processes.

One example is a neutron-capture/beta-decay (nβ) process studied by Sandler *et al.* (*76*). The seed nuclei consist of all of the elements from Si to Cr with normal solar system abundances. With this process at neutron densities of $\sim 10^7$ mol cm^{-3} and exposure times of $\sim 10^3$ seconds, small admixtures ($\lesssim 10^{-4}$) of the exotic material produced are sufficient to account for most of the Ca and Ti isotopic anomalies found in the Allende meteorite inclusion EK-1-4-1 by Niederer *et al.* (*77*). The anomalies in stable isotope abundances are of the same order as those for short-lived radioactive nuclei and strongly support the view that the solar nebula was inhomogeneous, with regions containing exotic materials up to 10^{-4} or more of normal material.

Agreement for the ^{46}Ca and ^{49}Ti anomalies in EK-1-4-1 was obtained only by increasing the theoretical Hauser-Feshbach cross sections for ^{46}K(n,γ), and ^{49}Ca(n,γ) by a factor of 10 on the basis of probable thermal resonances just above threshold in the compound nuclei ^{47}K and ^{50}Ca, respectively. Huck *et al.* (*78*) reported an excited state in ^{50}Ca just 0.16 MeV above the ^{49}Ca(n,γ) threshold which can be produced by s-wave capture and fulfills the requirements of (*76*).

Sandler *et al.* (*76*) suggest that the exposure time scale of $\sim 10^3$ seconds is determined by the mean lifetime of ^{13}N (862 seconds), produced through ^{12}C$(p,\gamma)^{13}$N by a jet of hydrogen suddenly introduced into the helium-burning shell of a red giant star where a substantial amount of ^{12}C has been produced by the $3\alpha \rightarrow {}^{12}$C. The beta-decay ^{13}N$(e^+\nu)^{13}$C is followed by ^{13}C$(\alpha,n)^{16}$O as the source of the neutrons. All of this is very interesting, if true. More to the point, Sandler *et al.* (*76*) predict the anomalies to be expected in the isotopes of chromium, and attempts to measure these anomalies are under way by Wasserburg and his colleagues.

Observational Evidence for Nucleosynthesis in Supernovae

Over the years there has been considerable controversy concerning elemental abundance observations at optical wavelengths on galactic supernova remnants. To my mind the most convincing evidence for nucleosynthesis in supernovae has been provided by Chevalier and Kirshner (*79*), who obtained quantitative spectral information for several of the fast-moving knots in the supernova remnant Cassiopeia A (approximately dated 1659, but a supernova event was not observed at that time). The knots are considered to be material ejected from various layers of the original star in a highly asymmetric, nonspherical explosion. In one knot, KB33, the following ratios relative to solar were observed: S/O = 61, Ar/O = 55, Ca/O = 59. It is abundantly clear that oxygen burning to the silicon-group elements in the layer in which KB33 originated has depleted oxygen and enhanced the silicon-group elements. Other knots and other features designated as filaments show different abundance patterns, albeit not so easily interpreted. The moral for supernova modelers is that spherically symmetric supernova explosions may be the easiest to calculate but are not to be taken as realistic.

Most striking of all has been the payoff from the NASA investment in the High Energy Astronomy Observatory HEAO 2, now called the Einstein Observatory. With instruments aboard this satellite Becker *et al.* (*80*) observed the x-ray spectrum in the range 1 to 4 keV of Tycho Brahe's supernova remnant (1572), showing the *K*-level x-rays from Si, S, Ar, and Ca. Shull (*81*) has used a single-velocity, non–ionization-equilibrium model of a supernova blast wave to calculate abundances in Tycho's remnant relative to solar and finds Si = 7.6, S = 6.5, Ar = 3.2, and Ca = 2.6. With considerably greater uncertainty he gives Mg = 2.0 and Fe = 2.1. He finds different enhancements in Kepler's remnant (1604) and in Cassiopeia A. One more lesson for the modelers: no two supernovae are alike. Nucleosynthesis in supernovae depends on their initial mass, rotation, mass loss during the red giant stage, degree of symmetry during explosion, initial heavy-element content, and probably other factors. These details aside, it seems clear that supernovae produce enhancements in elemental abundances up to iron and probably beyond. Detection of the much rarer elements beyond iron will require more sensitive x-ray detectors operating at higher energies. The nuclear debris of supernovae eventually enriches the interstellar medium, from which succeeding generations of stars are formed. It becomes increasingly clear that novae also enrich the interstellar medium. Sorting out these two contributions poses interesting problems for research in all aspects of nuclear astrophysics.

Explosive Si burning in the shell just outside a collapsing supernova core primarily produces ^{56}Ni, as shown in Fig. 5. It is generally believed that the initial energy source for the light curves of type I supernovae is electron capture by ^{56}Ni ($\bar{\tau}$ = 8.80 days) to the excited state of ^{56}Co at 1.720 MeV with subsequent gamma-ray cascades to the ground state. The subsequent source of energy is electron capture and positron emission by ^{56}Co ($\bar{\tau}$ = 114 days) to a number of excited states of ^{56}Fe with gamma-ray cascades to the stable ground state of ^{56}Fe. Both the positrons and gamma rays heat the ejected material. If ^{56}Co is an energy source there should be spectral evidence for cobalt in newly discovered type I supernovae, since its lifetime is long enough for detailed observations to be possible after the initial discovery.

The cobalt has been observed. Axelrod (*82*) studied the optical spectra of SN1972e obtained by Kirshner and Oke (*83*) and assigned the two emission lines near 6000 Å to Co III. The lines are clearly evident in spectra obtained at 233 and 264 days after Julian day 2441420, assigned as the initial day of the explosive event, but are only marginally evident at 376 days ($\sim \bar{\tau}$ later). The lines decay in reasonable agreement with the mean lifetime of ^{56}Co.

Branch *et al.* (*84*) studied absorption spectra during the first hundred days of SN1981b. Deep absorption lines of Co II are clearly evident near 3300 and 4000 Å.

It is my conclusion that there is substantial evidence for nucleosynthesis of elements produced in oxygen and silicon burning in supernovae. The role of neutron capture processes in supernovae will be discussed next.

Neutron-Capture Processes in Nucleosynthesis

In an earlier section I discussed the need for two neutron-capture processes for nucleosynthesis beyond $A \gtrsim 60$: the s-process and the r-process. For a given element the heavier isotopes are frequently bypassed in the s-process and produced only in the r-process; thus the designation r-only. Lighter isotopes are frequently shielded by more neutron-rich stable isobars in the r-process and are produced only in the s-process; thus the designation s-only. The lightest isotopes are frequently very rare because they are not produced in either the s- or the r-process and are thought to be produced in what is called the p-process, involving positron production and capture, proton capture, neutron photoproduction, and/or (p,n)-reactions (*85*).

The s-process has the clearest phenomenological basis of all processes of nucleosynthesis, primarily as a result of the correlation of s-process abundances

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(N) (*86*) with a beautiful series of measurements on neutron capture cross sections (σ) in the range 1 to 100 keV (*87*). In first-order approximation the product σN should be constant in s-process synthesis: a nucleus with a small (large) neutron capture cross section must have a large (small) abundance to maintain continuity in the s-capture path. When σN is plotted against atomic mass, this is demonstrated in plateaus found from $A = 90$ to 140 and from $A = 140$ to 206. Nuclear shell structure introduces the precipices shown in such a plot at $A \sim 84$, ~ 138, and ~ 208, which correspond to the s-process abundance peaks in Fig. 1. At these values of A the neutron numbers are "magic," $N = 50$, 82, and 126; the cross sections for neutron capture into new neutron shells are very small, and with a finite supply of neutrons the σN product must drop to a new plateau as observed. Iben has argued convincingly that the site of the s-process is the He-burning shell of a pulsating red giant (*88*) and the neutron source is the $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$ reaction. Critical discussions have been given in (*89*) and (*90*).

The r-process has been customarily treated by the waiting point method of B^{2}FH (*16*). Under explosive conditions a large flux of neutrons drives nuclear seeds to the neutron-rich side of the valley of stability where the (n,γ)-reaction and the (γ,n)-reaction reach equality. The nuclei wait at this point until electron beta-decay transforms neutrons in the nuclei into protons and further neutron capture can occur. At the cessation of the r-process the neutron-rich nuclei decay to their stable isobars. In first order, this means that the abundance of an r-process nucleus multiplied by the electron beta-decay rate of its neutron-rich r-process isobar progenitor will be roughly constant. At magic neutron numbers in the neutron-rich progenitors, beta-decay must open the closed neutron shell in transforming a neutron into a proton and there the rate will be relatively small. Accordingly, the abundance of progenitors with $N = 50$, 82, and 126 will be large. The associated number of protons will be less than in the corresponding s-process nuclei with a magic number of neutrons. It follows that the stable daughter isobars will have smaller mass numbers, and this is indeed the case, the r-process abundance peaks occurring at $A \sim 80$, ~ 130, and ~ 195, all below the corresponding s-process peaks as illustrated in Fig. 1.

A phenomenological correlation of r-process abundances with beta-decay rates by Becker and Fowler (*91*) is too phenomenological to satisfy critical nuclear astrophysicists, who wish to know the site of the high neutron fluxes demanded for r-process nucleosynthesis and the details of the r-process path through nuclei far from the line of beta-stability. There is also a general belief at present that the waiting point approximation is a poor one and must be replaced by dynamical r-process flow calculations taking into account explicit (n,γ),(γ,n), and beta-decay rates with time-varying temperature and neutron flux.

Many suggestions have been made for possible sites of the r-process, almost all in supernova explosions where the basic requirement of a large neutron flux of short duration is met. These suggestions are reviewed in Schramm (*92*) and Truran (*90*). To my mind the helium core thermal runaway r-process of Cameron *et al.* (*93*) is the most promising. These authors do not rule out $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$ as the source of the neutrons, but their detailed results are based on $^{13}\mathrm{C}(\alpha,n)^{13}\mathrm{O}$ as the source. They start with a star formed from material with the same heavy-element abundance distribution as in the solar system but with smaller total amount. They assume that the helium core of the star after hydrogen burning contains a significant amount of ^{13}C, which was produced by the introduction of hydrogen into the core which had already burned half of its helium into ^{12}C. The electrons in the core are initially degenerate, but the rise in temperature with ^{13}C burning lifts the degeneracy, producing a thermal runaway with expansion and subsequent cooling of the core. This event is the second helium-flash episode in the history of the core, and if it occurs only a small amount of the r-process material produced need escape into the interstellar medium to contribute the r-process abundance in solar system material. It is my belief that a realistic astrophysical site for the thermal runaway, perhaps with different initial conditions, will be found.

Nucleocosmochronology

Armed with r-process calculations of the abundances of the long-lived parents of the natural radioactive series, ^{232}Th, ^{235}U, and ^{238}U, and with the then-current solar system abundances of these nuclei, B^{2}FH (*18*) determined the duration of r-process nucleosynthesis from its beginning in the first stars in the Galaxy up to the last events before the formation of the solar system. The abundances used were those observed in meteorites, assumed to be closed systems since their formation, taken to have occurred 4.55 billion years ago. It was necessary to correct for free decay during this period in order to obtain abundances for comparison with calculations based on r-process production plus decay before the meteorites became closed systems. The calculations required only the elemental ratio Th/U in meteorites, since the isotopic ratio $^{235}\mathrm{U}/^{236}\mathrm{U}$ was assumed to be the same for meteoritic and terrestrial samples. The Apollo Program added lunar data to the meteoritic and terrestrial data.

B^{2}FH considered a number of possible models, including r-process nucleosynthesis uniform in time and an arbitrary time interval between the last r-process contribution to the solar nebula and the closure of the meteorite systems. A zero value for this time interval indicated that uranium production started 18 billion years ago. When this time interval was taken to be 0.5 billion years, the production started 11.5 billion years ago. These results are in remarkable, if coincidental, concordance with current values.

It is appropriate to point out that nucleocosmochronology yields, with additional assumptions, an estimate for the age of the expanding Universe independent of astronomical redshift-distance observations of distant galaxies. These assumptions are that the r-process started soon (<1 billion years) after the formation of the Galaxy and that the Galaxy formed soon (<1 billion years) after the big-bang origin of the Universe. Adding a billion years or so to the start of r-process nucleosynthesis yields an independent value, based on radioactivity, for the age or time back to the origin of the expanding Universe.

Much has transpired over recent years in the field of nucleocosmochronology. I have kept my hand in most recently in (*94*). Sophisticated models of galactic evolution were introduced by Tinsley (*95*). A method for model-independent determinations of the mean age of nuclear chronometers at the time of solar system formation was developed by Schramm and Wasserburg (*96*). The most recent results are those of Thielemann *et al.* (*97*), who calculated that r-process nucleosynthesis in the Galaxy started 17.9 billion years ago, with uncertainties of +2 billion and −4 billion years. This is to be compared with my value of 10.5 ± 2.3 billion years (*94*). Thielemann and I are now recomputing the new value for the duration, using an initial spike in galactic synthesis plus uniform synthesis thereafter.

The results of Thielemann *et al.* (*97*)

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indicate that the age of the expanding Universe is 19 billion years, give or take several billion years. This is to be compared to the Hubble time or reciprocal of Hubble's constant, given by Sandage and Tammann (*98*) as 19.5 ± 3 billion years. However, the Hubble time is equal to the age of the expanding Universe only for a completely open Universe with mean matter density much less than the critical density for closure, which can be calculated from the value for the Hubble time just given to be 5×10^{-30} g cm^{-3}. The observed visible matter in galaxies is estimated to be 10 percent of this, which reduces the age of the Universe to 16.5 billion years. Invisible matter, neutrinos, black holes, and so on may add to the gravitational forces which decrease the velocity of expansion and may thus decrease the age to that corresponding to critical density, which is 11.1 billion years. If the expansion velocity was greater in the past, the time to the present radius of the Universe is correspondingly less. Moreover, others have obtained results for the Hubble time equal to about one-half that of Sandage and Tammann (*98*), as reviewed in van den Bergh (*99*).

A completely independent nuclear chronology involving radiogenic ^{187}Os produced during galactic nucleosynthesis by the decay of ^{187}Re ($\bar{\tau} = 65 \times 10^9$ years) was suggested by Clayton (*100*). Schramm (*92*) discusses still other chronometric pairs. Clayton's suggestion involves the s-process even though ^{187}Re is produced in the r-process, as it requires that the abundance of ^{187}Re be compared to that of its daughter, ^{187}Os, when the s-only production of this daughter nucleus is subtracted from its total solar system abundance. This was to be done by comparing the neutron capture cross section of ^{187}Os with that of its neighboring s-only isotope ^{186}Os, which does not have a long-lived radioactive parent, and using the $N\sigma$ = constant rule for the s-process. However, Fowler (*101*) pointed out that ^{187}Os has a low-lying excited state at 9.75 keV which is practically fully populated at the temperature (3.5×10^8 K) at which the s-process is customarily assumed to occur. Moreover, with spin $J = 3/2$ this state has twice the statistical weight of the ground state with spin $J = 1/2$, so that measurements of the ground state neutron capture cross section yield only one-third of what one needs to know.

All of this led to a series of beautiful and difficult measurements for neutron-induced reactions on the isotopes of osmium, yielding values for the cross-section ratio of ^{186}Os(n,γ) relative to ^{187}Os(n,γ). This ratio must be multiplied by a theoretical factor to correct the ^{187}Os cross section for that of its excited state. Woosley and Fowler (*102*) obtained estimates for this factor in the range 0.8 to 1.10, which translate into a time for the beginning of the r-process in the Galaxy in the range 14 to 19 billion years. Measurements of the cross sections for neutron scattering off the ground state of ^{187}Os to its excited state at 9.75 keV (*103, 104*) supported the lower value of the Woosley and Fowler (*102*) factor and thus a value for the time back to the beginning of r-process nucleosynthesis in the range 18 to 20 billion years. This is concordant with the latest value from Th/U nucleocosmochronology. Measurements of the neutron capture cross section on the ground state of ^{189}Os might be helpful, since ^{189}Os has a ground state with the same spin and Nilsson numbers as the excited state of ^{187}Os and an excited state corresponding to the ground state of ^{187}Os. Such measurements have been made by Browne and Berman (*105*) but are now being checked.

It will be clear that the lifetime of ^{187}Re comes directly into the calculations under discussion, and there has been some discrepancy in the past between lifetimes measured geochemically and those measured directly by counting the electrons emitted in the 2.6-keV decay ^{187}Re($e^- \nu$)^{187}Os. This is treated in considerable theoretical detail by Williams *et al.* (*106*), who found that the direct measurements by Payne and Drever (*107*), which agree with the geochemical measurements of Hirt *et al.* (*108*), are correct. There is also the vexing problem of a possible decrease in the effective lifetime of ^{187}Re in the galactic environment, where ^{187}Re is subject to destruction by the s-process as well as being produced by the r-process. This decreases all times based on the Re/Os chronology (*109*). The time back to the beginning of r-process nucleosynthesis could be as low as 12 billion years. It is appropriate to end this section with the considerable uncertainity in nucleocosmochronology, indicating that, as in all nuclear astrophysics, there is much exciting experimental and theoretical work to be done for many years to come.

Conclusion

In spite of the past and current research in experimental and theoretical nuclear astrophysics, the ultimate goal of the field has not been attained. Hoyle's grand concept of element synthesis in the stars will not be truly established until we attain a deeper and more precise understanding of many nuclear processes operating in astrophysical environments. Hard work must continue on all aspects of the cycle: experiment, theory, observation. It is not just a matter of filling in the details. There are puzzles and problems in each part of the cycle which challenge the basic ideas underlying nucleosynthesis in stars. Not to worry—that is what makes the field active, exciting, and fun. It is a great source of satisfaction to me that the Kellogg Laboratory continues to play a leading role in experimental and theoretical nuclear astrophysics.

And now permit me to pass along one final thought. My major theme has been that all of the heavy elements from carbon to uranium have been synthesized in stars. Our bodies consist for the most part of these heavy elements. Apart from hydrogen, we are 65 percent oxygen and 18 percent carbon, with smaller percentages of nitrogen, sodium, magnesium, phosphorus, sulfur, chlorine, potassium, and traces of still heavier elements. Thus it is possible to say that each one of us and all of us are truly and literally a little bit of stardust.

References and Notes

1. J. Audouze and H. Reeves, in *Essays in Nuclear Astrophysics*, C. A. Barnes, D. D. Clayton, D. N. Schramm, Eds. (Cambridge Univ. Press, Cambridge, 1982), p. 355.
2. H. E. Suess and H. C. Urey, *Rev. Mod. Phys.* **28**, 53 (1956).
3. A. G. W. Cameron, in *Essays in Nuclear Astrophysics*, C. A. Barnes, D. D. Clayton, D. N. Schramm, Eds. (Cambridge Univ. Press, Cambridge, 1982), p. 23.
4. W. Whaling, in *ibid.*, p. 65.
5. R. A. Alpher and R. C. Herman, *Rev. Mod. Phys.* **22**, 153 (1950).
6. R. V. Wagoner, W. A. Fowler, F. Hoyle, *Astrophys. J.* **148**, 3 (1967).
7. H. Staub and W. E. Stephens, *Phys. Rev.* **55**, 131 (1939).
8. J. H. Williams, W. G. Shepherd, R. O. Haxby, *ibid.* **52**, 390 (1937).
9. A. V. Tollestrup, W. A. Fowler, C. C. Lauritsen, *ibid.* **76**, 428 (1949).
10. A. Hemmindinger, *ibid.* **73**, 806 (1948); *ibid.* **74**, 1267 (1949).
11. H. A. Bethe, *ibid.* **55**, 434 (1939); in *Les Prix Nobel 1967* (Almquist & Wiksell, Stockholm, 1968).
12. F. Hoyle, *Mon. Not. R. Astron. Soc.* **106**, 343 (1946); *Astrophys. J. Suppl.* **1**, 121 (1954).
13. ______ and M. Schwarzschild, *Astrophys. J. Suppl.* **2**, 1 (1955).
14. A. R. Sandage and M. Schwarzschild, *Astrophys. J.* **116**, 463 (1952). In particular, see last paragraph on p. 475.
15. E. E. Salpeter, *ibid.* **115**, 326 (1952).
16. D. N. F. Dunbar, R. E. Pixley, W. A. Wenzel, W. Whaling, *Phys. Rev.* **92**, 649 (1953).
17. C. W. Cook, W. A. Fowler, C. C. Lauritsen, T. Lauritsen, *ibid.* **107**, 508 (1957).
18. E. M. Burbidge, G. R. Burbidge, W. A. Fowler, F. Hoyle, *Rev. Mod. Phys.* **29**, 547 (1957); hereafter referred to as B^{2}FH (*18*). Also see F. Hoyle, W. A. Fowler, E. M. Burbidge, G. R. Burbidge, *Science* **124**, 611 (1956).
19. A. G. W. Cameron, *Publ. Astron. Soc. Pac.* **69**, 201 (1957).
20. J. L. Greenstein, in *Modern Physics for the Engineer*, L. N. Ridenour, Ed. (McGraw-Hill, New York, 1954), chapter 10; in *Essays in Nuclear Astrophysics*, C. A. Barnes, D. D. Clayton, D. N. Schramm, Eds. (Cambridge Univ. Press, Cambridge, 1982), p. 45.

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21. W. A. Fowler, G. R. Caughlan, B. A. Zimmerman, *Annu. Rev. Astron. Astrophys.* **5**, 525 (1967); *ibid.* **13**, 69 (1975). Also see M. J. Harris *et al.*, *ibid.* **21**, 165 (1983); G. R. Caughlan *et al.*, *At. Data Nucl. Data Tables*, in press.
22. E. E. Salpeter, *Phys. Rev.* **88**, 547 (1957); *ibid.* **97**, 1237 (1955).
23. S. E. Woosley, W. A. Fowler, J. A. Holmes, B. A. Zimmerman, *At. Data Nucl. Data Tables* **22**, 371 (1978).
24. H. A. Bethe and C. L. Critchfield, *Phys. Rev.* **54**, 248 (1938).
25. W. A. Fowler, *Astrophys. J.* **127**, 551 (1958).
26. A. G. W. Cameron, *Annu. Rev. Nucl. Sci.* **8**, 249 (1958).
27. B. Pontecorvo, *Chalk River Lab. Rep. PD-205* (1946).
28. L. W. Alvarez, *Univ. Calif. Radiat. Lab. Rep. UCRL-328* (1949).
29. R. Davis, Jr., in *Science Underground*, M. M. Nieto *et al.*, Eds. (American Institute of Physics, New York, 1983), p. 2.
30. J. N. Bahcall, W. F. Huebner, S. H. Lubow, P. D. Parker, R. K. Ulrich, *Rev. Mod. Phys.* **54**, 767 (1982).
31. R. G. H. Robertson, P. Dyer, T. J. Bowles, R. E. Brown, N. Jarmie, C. J. Maggiore, S. M. Austin, *Phys. Rev. C* **27**, 11 (1983); J. L. Osborne, C. A. Barnes, R. W. Kavanagh, R. M. Kremer, G. J. Mathews, J. L. Zyskind, *Phys. Rev. Lett.* **48**, 1664 (1982)
32. R. T. Skelton and R. W. Kavanagh, *Nucl. Phys. A* **414**, 141 (1984).
33. C. A. Barnes, in *Essays in Nuclear Astrophysics*, C. A. Barnes, D. P. Clayton, D. N. Schramm, Eds. (Cambridge Univ. Press, Cambridge, 1982), p. 193.
34. P. Dyer and C. A. Barnes, *Nucl. Phys. A* **233**, 495 (1974); S. E. Koonin, T. A. Tombrello, G. Fox, *ibid.* **220**, 221 (1974).
35. K. U. Kettner, H. W. Becker, L. Buchmann, J. Gorres, H. Kräwinkel, C. Rolfs, P. Schmalbrock, H. P. Trautvetter, A. Vlieks, *Z. Phys. A* **308**, 73 (1982).
36. K. Langanke and S. E. Koonin, *Nucl. Phys. A* **410**, 334 (1983); private communication (1983).
37. S. G. Starrfield, A. N. Cox, S. W. Hodson, W. D. Pesnell, *Astrophys. J.* **268**, L27 (1983); S. A. Becker, private communication (1983).
38. S. E. Woosley and T. A. Weaver, in *Essays in Nuclear Astrophysics*, C. A. Barnes, D. D. Clayton, D. N. Schramm, Eds. (Cambridge Univ. Press, Cambridge, 1982), p. 381.
39. D. Bodansky, D. D. Clayton, W. A. Fowler, *Astrophys. J. Suppl.* **16**, 299 (1968).
40. T. A. Weaver, S. E. Woosley, G. M. Fuller, in *Proceedings of the Conference on Numerical Astrophysics*, R. Bowers, J. Centrella, J. LeBlanc, M. LeBlanc, Eds. (Science Books International, Boston, 1983).
41. L. W. Mitchell and D. G. Sargood, *Aust. J. Phys.* **36**, 1 (1983).
42. R. N. Boyd, in *Proceedings of the Workshop on Radioactive Ion Beams and Small Cross Section Measurements* (Ohio State Univ. Press, Columbus, 1981); R. C. Haight, G. J. Mathews, R. M. White, L. A. Avilés, S. E. Woodward, *Nucl. Instrum. Methods* **212**, 245 (1983).
43. W. Hauser and H. Feshbach, *Phys. Rev.* **78**, 366 (1952).
44. J. A. Holmes, S. E. Woosley, W. A. Fowler, B. A. Zimmerman, *At. Data Nucl. Data Tables* **18**, 305 (1976).
45. D. G. Sargood, *Phys. Rep.* **93**, 61 (1982); *Aust. J. Phys.* **36**, 583 (1983).
46. N. A. Bahcall and W. A. Fowler, *Astrophys. J.* **157**, 645 (1969).
47. R. A. Ward and W. A. Fowler, *ibid.* **238**, 266 (1980). For recent experimental data on the production of $^{26}\mathrm{Al}$ through $^{25}\mathrm{Mg}(p,\gamma)^{26}\mathrm{Al}$, see A. E. Champagne, A. J. Howard, P. D. Parker, *ibid.* **269**, 686 (1983). For recent experimental data on the destruction of $^{26}\mathrm{Al}$ through $^{26}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$, see L. Buchmann, M. Hilgemaier, A. Krauss, A. Redder, C. Rolfs, H. P. Trautvetter, in press.
48. G. M. Fuller, W. A. Fowler, M. J. Newman, *Astrophys. J. Suppl.* **42**, 447 (1980); *ibid.* **48**, 279 (1982); *Astrophys. J.* **252**, 715 (1982).
49. H. A. Bethe, A. Yahil, G. E. Brown, *Astrophys. J. Lett.* **262**, L7 (1982).
50. H. A. Bethe, G. E. Brown, J. Cooperstein, J. R. Wilson, *Nucl. Phys. A* **403**, 625 (1983).
51. G. M. Fuller, *Astrophys. J.* **252**, 741 (1982).
52. ———, W. A. Fowler, M. J. Newman, in preparation.
53. S. E. Woosley, T. S. Axelrod, T. A. Weaver, in *Stellar Nucleosynthesis*, C. Chiosi and A. Renzini, Eds. (Reidel, Dordrecht, 1984).
54. F. Hoyle and W. A. Fowler, *Astrophys. J.* **132**, 565 (1960).
55. W. A. Fowler and F. Hoyle, *Astrophys. J. Suppl.* **9**, 201 (1964).
56. J. C. Wheeler, *Rep. Prog. Phys.* **44**, 85 (1981).
57. G. E. Brown, H. A. Bethe, G. Baym, *Nucl. Phys. A.* **375**, 481 (1982).
58. K. Nomoto, *Astrophys. J.* **253**, 798 (1982); *ibid.* **257**, 780 (1982); in *Stellar Nucleosynthesis*, C. Chiosi and A. Renzini, Eds. (Reidel, Dordrecht, 1984).
59. ———, F.-K. Thielemann, J. C. Wheeler, *Astrophys. J.* **279**, L23 (1984); erratum **283**, L25 (1984).
60. W. D. Arnett and F.-K. Thielemann, in *Stellar Nucleosynthesis*, C. Chiosi and A. Renzini, Eds. (Reidel, Dordrecht, 1984).
61. J. H. Reynolds, *Phys. Rev. Lett.* **4**, 8 (1960).
62. P. M. Jeffery and J. H. Reynolds, *J. Geophys. Res.* **66**, 3582 (1961).
63. G. J. Wasserburg, W. A. Fowler, F. Hoyle, *Phys. Rev. Lett.* **4**, 112 (1960).
64. G. J. Wasserburg and D. A. Papanastassiou, in *Essays in Nuclear Astrophysics*, C. A. Barnes, D. D. Clayton, D. N. Schramm, Eds. (Cambridge Univ. Press, Cambridge, 1982), p. 77.
65. D. D. Clayton, *Astrophys. J.* **199**, 765 (1975); *Space Sci. Rev.* **24**, 147 (1979); *Astrophys. J.* **268**, 381 (1983). Also see D. D. Clayton and F. Hoyle, *Astrophys. J. Lett.* **187**, L101 (1974); *Astrophys. J.* **203**, 490 (1976).
66. J. H. Chen and G. J. Wasserburg, *Earth Planet. Sci. Lett.* **52**, 1 (1981).
67. D. S. Burnett, M. I. Stapanian, J. H. Jones, in *Essays in Nuclear Astrophysics*, C. A. Barnes, D. D. Clayton, D. N. Schramm, Eds. (Cambridge Univ. Press, Cambridge, 1982), p. 144.
68. T. Lee, D. A. Papanastassiou, G. J. Wasserburg, *Astrophys. J. Lett.* **211**, L107 (1977).
69. W. A. Mahoney, J. C. Ling, W. A. Wheaton, A. S. Jacobson, *Astrophys. J.* **278**, 784 (1984); see also W. A. Mahoney, J. C. Ling, A. S. Jacobson, R. E. Lingenfelter, *ibid.* **262**, 742 (1982).
70. R. T. Skelton, R. W. Kavanagh, D. G. Sargood, *ibid.* **271**, 404 (1983).
71. M. Arnould, H. Nørgaard, F.-K. Thielemann, W. Hillebrandt, *ibid.* **237**, 931 (1980).
72. J. W. Truran, in *Essays in Nuclear Astrophysics*, C. A. Barnes, D. D. Clayton, D. N. Schramm, Eds. (Cambridge Univ. Press, Cambridge, 1982), p. 467.
73. W. A. Fowler, J. L. Greenstein, F. Hoyle, *Geophys. J.* **6**, 148 (1962).
74. T. Lee, *Astrophys. J.* **224**, 217 (1978).
75. M. H. Thiemens and J. E. Heidenreich, *Science* **219**, 1073 (1983).
76. D. G. Sandler, S. E. Koonin, W. A. Fowler, *Astrophys. J.* **259**, 908 (1982).
77. F. R. Niederer, D. A. Papanastassiou, G. J. Wasserburg, *Astrophys. J. Lett.* **228**, L93 (1979).
78. A. Huck, G. Klotz, A. Knipper, C. Miéhé, C. Richard-Serre, G. Walter, *CERN 81-09* (1981), p. 378.
79. R. A. Chevalier and R. P. Kirshner, *Astrophys. J.* **233**, 154 (1979).
80. R. H. Becker *et al.*, *Astrophys. J. Lett.* **234**, L73 (1979).
81. J. M. Shull, *Astrophys. J.* **262**, 308 (1982); private communication (1983).
82. T. S. Axelrod, thesis, University of California, Berkeley (1980).
83. R. P. Kirshner and J. B. Oke, *Astrophys. J.* **200**, 574 (1975).
84. D. Branch, C. H. Lacy, M. L. McCall, P. G. Sutherland, A. Uomoto, J. C. Wheeler, B. J. Wills, *ibid.* **270**, 123 (1983).
85. J. Audouze and S. Vauclair, *An Introduction to Nuclear Astrophysics* (Reidel, Dordrecht, 1980), p. 92.
86. P. A. Seeger, W. A. Fowler, D. D. Clayton, *Astrophys. J. Suppl.* **11**, 121 (1965).
87. R. L. Macklin and J. H. Gibbons, *Rev. Mod. Phys.* **37**, 166 (1965). Also see B. J. Allen, R. L. Macklin, J. H. Gibbons, *Adv. Nucl. Phys.* **4**, 205 (1971).
88. I. Iben, Jr., *Astrophys. J.* **196**, 525 (1975).
89. J. Almeida and F. Käppeler, *ibid.* **265**, 417 (1983).
90. J. W. Truran, *International Physics Conference Series No. 64* (Institute of Physics, London, 1983), p. 95.
91. R. A. Becker and W. A. Fowler, *Phys. Rev.* **115**, 1410 (1959).
92. D. N. Schramm, in *Essays in Nuclear Astrophysics*, C. A. Barnes, D. D. Clayton, D. N. Schramm, Eds. (Cambridge Univ. Press, Cambridge, 1982), p. 325.
93. A. G. W. Cameron, J. J. Cowan, J. W. Truran, in *Proceedings of the Yerkes Observatory Conference on "Challenges and New Developments in Nucleosynthesis,"* W. D. Arnett, Ed. (Univ. of Chicago Press, Chicago, 1984).
94. W. A. Fowler, in *Proceedings of the Welch Foundation Conferences on Chemical Research, XXI, Cosmochemistry*, W. D. Milligan, Ed. (Robert A. Welch Foundation, Houston, 1977), p. 61; also see W. A. Fowler, in *Cosmology, Fusion and Other Matters*, F. Reines, Ed. (Colorado Associated Universities Press, Boulder, 1972), p. 67.
95. B. M. Tinsley, *Astrophys. J.* **198**, 145 (1975).
96. D. N. Schramm and G. J. Wasserburg, *ibid.* **163**, 75 (1970).
97. F.-K. Thielemann, J. Metzinger, H. V. Klapdor, *Z. Phys. A* **309**, 301 (1983); private communication.
98. A. Sandage and G. A. Tammann, *Astrophys. J.* **256**, 339 (1982).
99. S. van den Bergh, *Nature* (*London*) **229**, 297 (1982).
100. D. D. Clayton, *Astrophys. J.* **139**, 637 (1964).
101. W. A. Fowler, *Bull. Am. Astron. Soc.* **4**, 412 (1972).
102. S. E. Woosley and W. A. Fowler, *Astrophys. J.* **233**, 411 (1979).
103. R. L. Macklin, R. R. Winters, N. W. Hill, J. A. Harvey, *ibid.* **274**, 408 (1983).
104. R. L. Hershberger, R. L. Macklin, M. Balakrishnan, N. W. Hill, M. T. McEllistrem, *Phys. Rev. C* **28**, 2249 (1983).
105. J. C. Browne and B. L. Berman, *ibid.* **23**, 1434 (1981).
106. R. D. Williams, W. A. Fowler, S. E. Koonin, *Astrophys. J.* **281**, 363 (1984).
107. J. A. Payne, thesis, University of Glasgow (1965); R. W. P. Drever, private communication (1983).
108. B. Hirt, G. R. Tilton, W. Herr, W. Hoffmeister, in *Earth Sciences and Meteorites*, J. Geiss and E. D. Goldberg, Eds. (North-Holland, Amsterdam, 1963).
109. K. Yokoi, K. Takahashi, M. Arnould, *Astron. Astrophys.* **117**, 65 (1983).
110. S. E. Woosley, W. A. Fowler, J. A. Holmes, B. A. Zimmerman, *At. Data Nucl. Data Tables* **22**, 371 (1978).
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