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NUCLEAR REACTIONS IN STARS AND NUCLEOGENESIS*

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INTRODUCTION

It was once thought that the stars and the interstellar matter had a uniform chemical composition except for some of the lighter elements, which were destroyed by thermonuclear reactions in stellar interiors. This view has caused astronomers and physicists to look for extreme physical conditions in which all the matter in the universe was gathered together at high density and raised to a high temperature sufficient to produce the observed abundances of the elements by the nuclear reactions that take place under these conditions. However, in recent years it has become apparent not only that thermonuclear reactions in stellar interiors can produce large abundance changes in even the heaviest elements,[1,2] but also that there are intrinsic differences in the chemical compositions of different classes of stars before thermonuclear reactions have started in them.[3] Stars classed as extreme Population II objects—subdwarfs and members of globular clusters—usually have a much smaller ratio of metals to hydrogen than does the sun, the factor of decrease being commonly about 10 or 20. In certain rare objects this factor may be much larger still.[4] On the other hand, in the O- and B-type stars of extreme Population I the ratio of metals to hydrogen has commonly increased over that in the sun by factors of 2 to 4. Light and heavy elements

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appear to be deficient or overabundant in these stars by about the same factors as the metals.

It has also become apparent that stars are being continually formed from the interstellar medium (the existence of O-associations demonstrates this clearly), and that, after passing through a stage in which thermonuclear reactions take place in their interiors, they return much of their mass to interstellar space, leaving behind white dwarf remnants. Salpeter has estimated that the amount of matter in the Galaxy which has been formed into stars and returned to the interstellar medium is comparable to the amount of matter present in the stars now existing in the Galaxy.[5] There are three ways in which the stars can return material to the interstellar medium:

1. Supernova explosions. Supernovae at the peak of their light curves often outshine the galaxies in which they are situated. A major fraction of the stellar mass is ejected in one of these explosions. A few percent of the stars go through a supernova stage.

2. Nova explosions. These are less spectacular than supernovae by a factor of about 10^4 in light output, and only about 0.1 percent of the stellar mass is ejected in an outburst. However, some novae appear to be recurrent, with an interval between explosions which is quite variable but is of the order of 100 years.

3. Continuous ejection of matter. Many stars are found to be continuously emitting clouds of gas into space. This ejection is possibly associated, at least in some cases, with magnetic activity in the stellar surfaces. Loss of matter can certainly start when a star reaches the M giant stage of evolution. Deutsch has observed a case in which an M-type supergiant is losing matter at a rate of one solar mass in 30 million years or less.[6] Many stars in later stages of evolution are also probably ejecting mass. Greenstein has found continuous emission of material even from white dwarf stars.[7]

It appears that all stars which have reached the white dwarf stage have lost mass by one or more of these mechanisms.

These observations give strong support to the idea that the interstellar medium is being continuously enriched in heavier elements as a result of thermonuclear reactions in stellar interiors. It is tempting to believe that our galaxy may have been originally composed entirely of hydrogen. About 7 billion years ago the Population II stars started condensing; the more massive of these evolved very quickly and ejected heavier elements into the interstellar gases. These heavy elements have been further processed by the stars which have formed since then. In order to test these ideas we must see whether the observed abundances of the elements will be formed as the matter in a stellar interior is raised to high temperatures and densities.

HYDROGEN THERMONUCLEAR REACTIONS

When a mass of gas condenses from interstellar space, there is a release of gravitational potential energy, which manifests itself as a heating of the gas. The rate of contraction of the gas depends on the rate at which heat can be radiated from its surface layers. When the central temperature becomes high enough to support thermonuclear reactions, the contraction of the gas is halted until the thermonuclear fuel is exhausted. For a star like our sun the duration of the contraction up to the point where the main hydrogen thermonuclear reactions commence is of the order of 100 million years.

The first thermonuclear reactions to take place are those that convert the deuterium, lithium, beryllium, and boron into helium. The latter three elements are not very abundant and their conversion does not take long. The sun appears to have been extensively convective during the lithium-consumption stage;[8] it may have been fully convective during the deuterium-consumption stage. If so, then the sun halted its contraction for a period of about 50 million years to destroy deuterium. Its radius was many times its present value and its surface temperature was very low. This was a critical time in the formation of the solar system, and a successful theory of planet formation may have to include the effects of this distended model of the sun.

The main hydrogen thermonuclear reactions are those in the proton-proton chain and in the carbon cycle. The former provide most of the energy generation in less massive stars, including the sun. For stars with central temperatures greater than about

17×10^6 °K, the carbon-cycle reactions become the predominant source of energy generation in stellar interiors. The carbon cycle is more important at higher temperatures because its rate of energy generation varies about as the eighteenth power of the temperature, compared to the fourth power for the proton-proton reaction.

There are three mechanisms by which energy can be transported: conduction, convection, and radiation. In ordinary stars energy transport by conduction is negligible. If the temperature gradient is not very steep, there is no convection, and energy transport takes place by radiation. For steep temperature gradients both radiation and convection take place, but convection is far more important.

Because of the high temperature sensitivity of thermonuclear reactions, there is a steep temperature gradient near the center of the star. Therefore, in hot main-sequence stars, energy transport takes place mainly by convection, and the gases at the center of the star are well mixed. This is the convective core of the star. Outside the core the temperature gradient becomes smaller, and energy transport is by radiation. The gases in this radiative envelope are not mixed. All except the hottest main-sequence stars also have a surface convection zone in which the convection currents are driven by the energy release from the recombination of electrons with ionized hydrogen.

During the course of time the hydrogen in the core becomes converted into helium. Hoyle and Schwarzschild find that a Population II star of mass $1.2\, m_\odot$ takes 5 billion years to exhaust its core hydrogen.[9] The subsequent evolution of the star takes place very rapidly. After the core becomes inert, the burden of energy generation is taken up by the hydrogen surrounding the core. The thermonuclear reactions then take place in a rather thin shell source. The mass of the inert core increases as the shell progresses outward in the star.

During this time the stellar core contracts and the envelope expands. The star becomes a red giant and its luminosity increases substantially. This state of affairs continues until nearly half of the mass of the star is in the inert core. The temperature in the hydrogen-burning shell at this time is 50 or 60×10^6 °K.

It has been pointed out[10,11] that at these high shell temperatures other hydrogen thermonuclear reactions may take place which convert O^{16} into carbon and nitrogen isotopes and Ne^{20} into Ne^{21}. The mean reaction times for these processes are much longer than for those in the carbon cycle, but they may be short enough to allow these reactions to take place once while the carbon cycle is turning over 1000 times.

HELIUM THERMONUCLEAR REACTIONS

When half of the above stellar mass has been converted into helium in the core, the central density has risen to about 10^5 gm/cm^3 and the central temperature is about 100×10^6 °K. At these high central densities the electrons form a partially degenerate Fermi gas.

The course of evolution of the star is now radically altered, owing to the onset of helium thermonuclear reactions at the center of the core. The compound nucleus, Be^8, which is formed when two helium nuclei collide, is unstable and will break up back into two alpha particles. Nevertheless, at a temperature of 100×10^6 °K and a density of 10^5 gm/cm^3, the collisions between helium nuclei are sufficiently rapid to maintain a small amount of Be^8 in the gas. This amount can be calculated from statistical mechanics; for the conditions quoted, nearly one part in 10^9 of the helium exists in the form of Be^8. This concentration is large enough to allow the Be^8 nuclei to undergo reactions with helium nuclei at an appreciable rate.

The main helium thermonuclear reactions consist of alpha-particle captures.[12] They are Be^8 (α,γ) C^{12}, C^{12} (α,γ) O^{16}, O^{16} (α,γ) Ne^{20}, and possibly Ne^{20} (α,γ) Mg^{24}. It has been shown that the first of these can proceed through the second excited state of the C^{12} nucleus.[13,14] The C^{12} (α,γ) O^{16} reaction is nonresonant, but the O^{16} (α,γ) Ne^{20} reaction probably proceeds through the 4.97 Mev state of Ne^{20}. Some calculations by the writer show that for reasonable values of the nuclear parameters involved, it is likely that in the early stages of helium consumption the main product is C^{12}. The later course of the reactions is more sensitive to the nuclear parameters, and some of these parameters are so uncertain that only limits on the behavior of the reactions can be placed from nuclear physical considerations. It is possible that C^{12} may still be the nucleus of greatest abundance when the helium is exhausted, but it is more likely that the abundance of C^{12} is small and those of O^{16} and Ne^{20} are large. Contrary to what one would normally expect, the formation of Ne^{20} is more likely when the helium is consumed at low temperatures than at high temperatures.

However, these helium thermonuclear reactions do not progress very far before rather large readjustments of the stellar model must take place. When the reactions start, the central density is very high and the electrons form a degenerate gas. The behavior of matter under these conditions is opposite to that in an ordinary gas. If a volume element of this gas is compressed, the Fermi level of the electrons is raised. The energy required to do this can only come from the kinetic energy of the ions, and hence the ion temperature must fall. Similarly, if the volume element is expanded, the ion temperature increases. Therefore the condensed core becomes very unstable when helium thermonuclear reactions start in a red giant star, and it must expand.[9,15] It is possible that during the expansion rather a lot of C^{12} will be made by the Be^{8} (α,γ) C^{12} reaction, and a great deal of energy will be released in the core. If this is the case, then an extensive convection zone is likely to exist at the center of the star for a short time, which will tend to mix hydrogen from the envelope into the core.

Let us consider what happens if envelope hydrogen mixes with C^{12} produced in the core. A great deal of energy is released by carbon-cycle reactions taking place at high temperatures. It is not clear whether this large energy release will prevent hydrogen from mixing all the way to the center of the star. If it does not so mix, then, in the region where there are many more protons than C^{12} nuclei, the C^{12} will be transmuted mostly into N^{14}, the most abundant carbon-cycle equilibrium product. However, near the center of the star where there is perhaps only one proton per ten C^{12} nuclei, nearly all these protons will be used up in forming C^{13} out of C^{12}, with very little formation of N^{14}. Another interesting case is that in which hydrogen is mixed throughout the center of the star but is consumed at a temperature above 100×10^{6} °K.

Then the most abundant carbon-cycle equilibrium product is N^{13}, which decays to C^{13} after the hydrogen is exhausted.

NEUTRON PRODUCTION ON A SLOW TIME SCALE

After the star has changed its structure and its central temperature has increased again, the first helium thermonuclear reaction to set in is C^{13} (α,n) O^{16}. This releases a lot of neutrons into the stellar core, which is composed mostly of helium. The helium nuclei cannot capture neutrons (He^5 is unstable), so the neutrons are slowed down until they are in thermal equilibrium with their surroundings. They then have kinetic energies in the vicinity of 10 kev. They are captured by surrounding nuclei in proportion to their capture cross sections in the vicinity of 10 kev. Something like 10 to 100 years will pass between neutron captures in a given typical heavy nucleus, so that neutron-capture products with shorter half-lives for beta emission will decay in the interim. The products of the neutron capture thus lie on a path close to the center of the valley of beta stability on the nuclear mass surface.

From the systematic properties of nuclei the writer has computed neutron-capture cross sections for the members of the capture path at 11 kev. It was found that there is a general increasing trend to the cross sections with nuclear mass number A up to $A \approx 100$, above which they are roughly constant. Superposed on this trend are large decreases in cross section in the vicinity of the closed shells of 50, 82, and 126 neutrons. Nuclides with these particularly low cross sections can be expected to have large abundances when formed by neutron capture.

Numerical calculations have been carried out to find how the initial abundances of the heavier elements are changed by the neutron capture. The initial abundance distribution assumed is shown in Figure 1. This is the abundance distribution of Suess and Urey,[16] but modified in the vicinity of the prominent iron peak (mass number 56) and near lead (mass numbers 204–208), to take account of new solar abundance determinations by Goldberg, Muller, and Aller.[17] The calculations show that only relatively small changes in the abundances of the elements below iron occur during the course of the neutron capture. This is a conse-

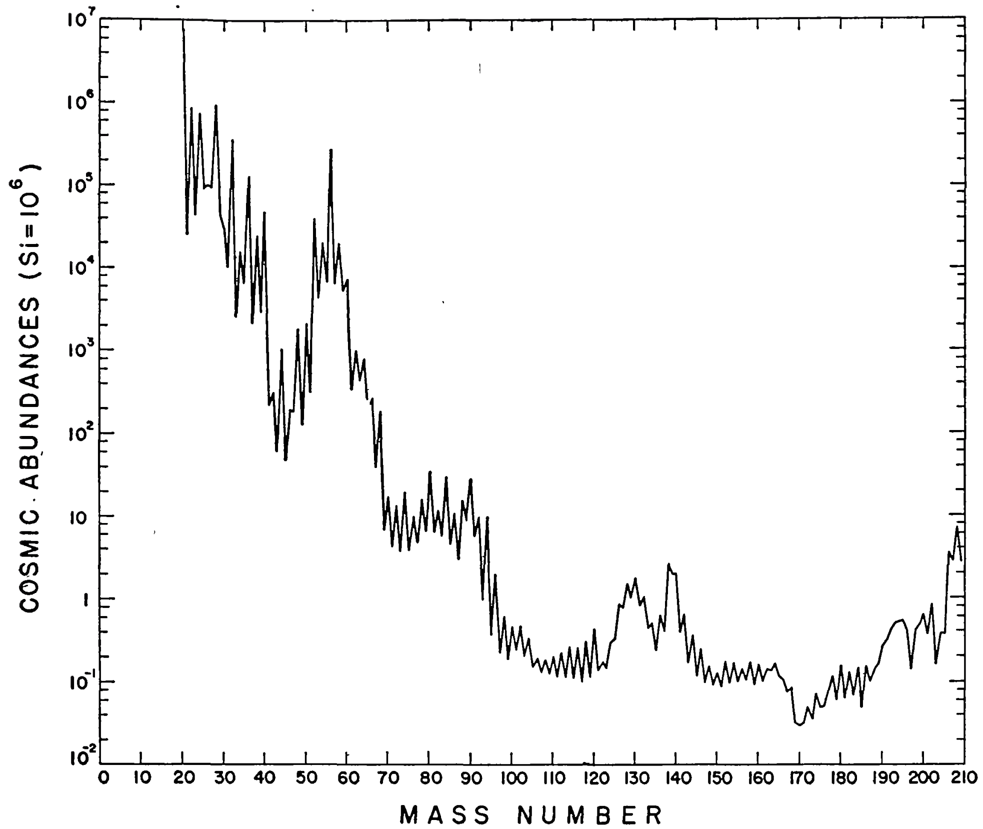

FIG. 1.—The cosmic abundances of the nuclides according to Suess and Urey, slightly modified by the writer as described in the text.

quence of the fact that the abundances of such elements are crudely inversely proportional to their neutron-capture cross sections. Initially most of the neutron capture occurs in the elements of the iron abundance peak. It may be seen in Figure 2 that during the course of the neutron capture the abundance of Fe^{56} drops by a large factor. Also plotted in Figure 2 are the abundances of selected heavier nuclides, expressed as ratios with respect to their initial abundances (called henceforth overabundance factors). These factors are shown as functions of the number of neutrons injected into the core material (per silicon atom of the initial abundance mixture). It may be seen that the heavier nuclides become overabundant by large factors as the nuclei originally in the iron peak move on to larger mass numbers. The heaviest nuclides do not reach overabundance factors of the order of 100 until about 10 neutrons have been injected per initial silicon atom.

The absolute abundances of the heavy nuclides after the injection of 20 neutrons per initial silicon atom are shown in Figure 3. The dots show the initial abundances; the jagged line shows the evolved abundances. The peak at mass number 140 is a reflection of the closed shell of 82 neutrons at this point. It should be noted that the general level of the abundances drops by nearly an order of magnitude in passing above mass number 140.

The heavy elements must compete with the reaction N^{14} (n,p) C^{14} for the neutrons which are produced. Hence, heavy-element synthesis is favored under conditions where there is only a small abundance of N^{14}. The writer has carried out other calculations to determine under what conditions neutron production by the C^{13} (α,n) O^{16} reaction will be followed by the absorption of more than 10 neutrons per initial silicon atom in the heavy elements.[18] In this computation the amount of core helium converted to C^{12} and the amount of hydrogen admixed with the C^{12} were treated as

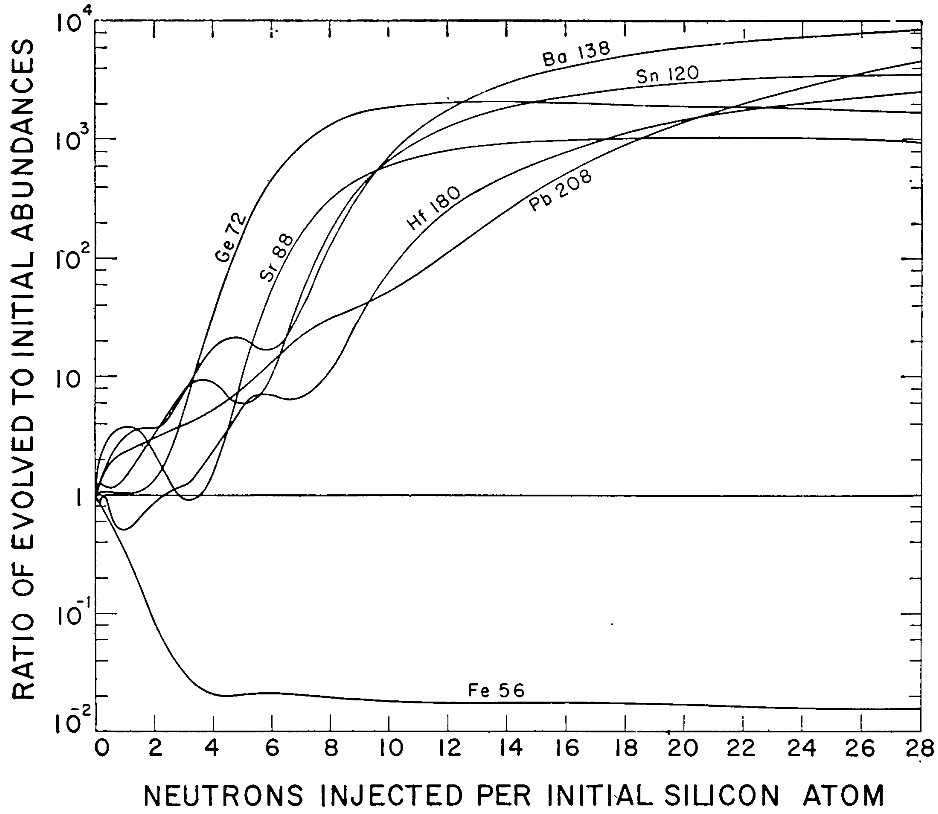

FIG. 2.—Overabundance factors for some selected nuclides as functions of the number of neutrons captured by the heavy elements.

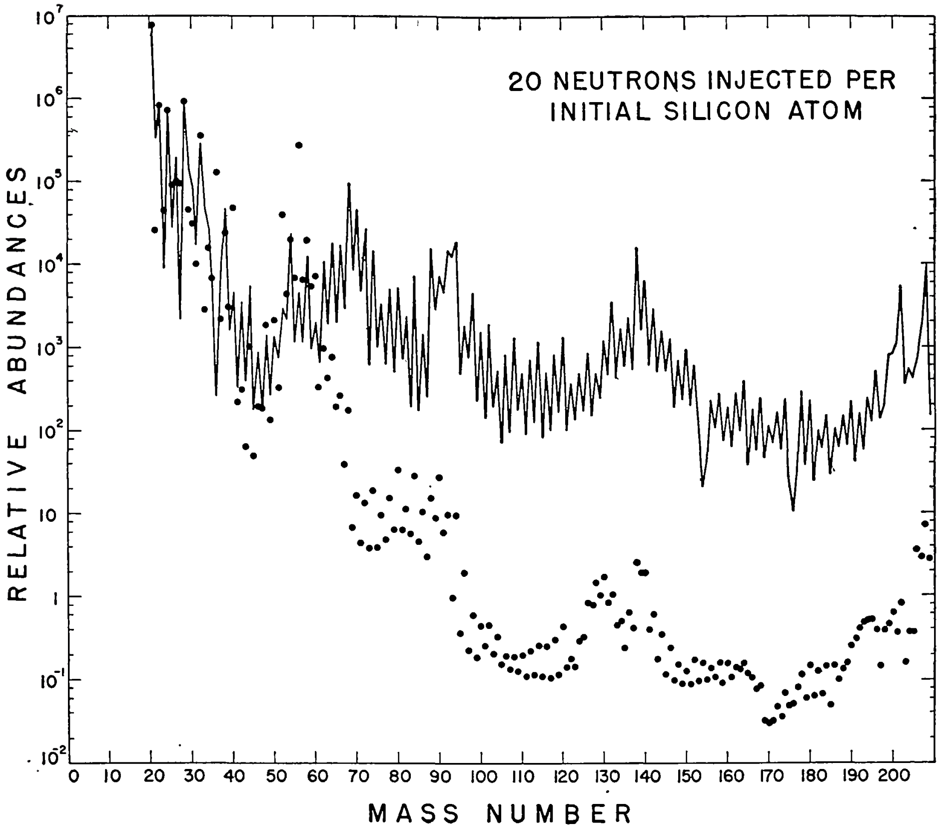

FIG. 3.—The neutron-evolved abundances of the nuclides produced by capture of 20 neutrons injected per initial silicon atom, compared with the initial abundance distribution indicated by solid dots.

variable parameters. Abundance changes were followed as: (1) the protons were allowed to undergo carbon-cycle reactions with the C^{12}; (2) the C^{13} so formed was destroyed by helium reactions; (3) the neutrons produced were absorbed by heavy elements in competition with N^{14}; and (4) the protons produced by the N^{14} (n,p) C^{14} reaction regenerated some C^{13}. The variation of the absorption cross section of the heavy elements as a function of the number of injected neutrons was taken into account. Cases considered included neutron production times long and short compared to the C^{14} half-life (5600 years), the possibility of a thermal resonance in the C^{14} (p,γ) N^{15} reaction, and a solar and a one-tenth solar (Population II) ratio of the abundances of the heavier elements to hydrogen.

It was found for solar abundances that if more than 4 to 8 per-

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cent of the helium had been converted to C^{12} (depending on the time scale), then the heavy elements were built up by overabundance factors of 100 or more when 0.5 to ~0.2 proton was admixed per C^{12} nucleus. A much wider range of acceptable conditions was found for Population II abundances. In the case where the hydrogen is consumed at temperatures above 100×10^6 °K, a large excess of C^{13} over N^{14} can be produced and heavy-element synthesis is limited only by this excess.

Fowler and the Burbidges, disturbed by the problems of mixing and N^{14} competition discussed above, have suggested that an alternate source of neutrons for heavy-element synthesis may be provided by the Ne^{21} (α,n) Mg^{24} reaction.[10] This requires that most of the Ne^{20} present in the initial composition of the star would have been converted to Ne^{21} in the hydrogen shell source, which is at present uncertain.

Stars with S- and Ba II-type spectra appear to show the effects of neutron capture on a slow time scale.[2] Heavy elements have large overabundance factors, but in S-type stars the rare-earth element region is less overabundant than the zirconium region,[4] as would be expected from Figure 3. Strong lines of the unstable element technetium are present in S-type spectra. Tc^{99}, with a half-life of 210,000 years, is a "stable" member of the neutron-capture path, and it appears to be present in R Andromedae in an abundance of the order of magnitude expected from the writer's calculations.[19] Hence in this star not many Tc^{99} half-lives have passed since heavy-element synthesis took place. At the same time the niobium lines are very strong;[4] Nb^{93} is produced by the decay of Zr^{93} with a half-life of 9×10^5 years. Hence an appreciable fraction of this half-life has passed since neutron production ceased in the material which has been mixed to the surface of R Andromedae.

THE APPROACH TO EQUILIBRIUM CONDITIONS

After a star has exhausted both the hydrogen and the helium in its core, it is reasonable to expect that a further core contraction may take place. The star probably continues to gain energy from hydrogen or helium shell sources. When the central temperature passes through the range 0.5 to 1.5×10^9 °K, a great variety of thermonuclear reactions take place.[20] These involve the products of helium thermonuclear reactions and are of two kinds. Heavy ion thermonuclear reactions are those involving C^{12} with C^{12}, C^{12} with N^{14} and O^{16}, O^{16} with itself, and a great many others. These lead to the emission of neutrons, protons, and alpha particles, which react with the other nuclei present. Degenerate instabilities associated with these reactions may cause further internal mixing in the star. The general result of these reactions is the synthesis of elements in the range from neon to calcium.

The other main type of reaction that starts is photodisintegration. Alpha particles are photo-ejected from such light nuclei as O^{16} and Ne^{20}. Neutrons are ejected from the heavy products of neutron capture on a slow time scale when the temperature reaches 1.3×10^9 °K. This will be called photodisintegration on a slow time scale because if the product nuclei are unstable there will usually be time for positron emission or electron capture to take place before further photoneutron emission occurs. The general effect of these reactions is to move heavy nuclei down to the region of the iron abundance peak.

When the central temperature lies in the range 3 to 5×10^9 °K, an extremely large number of nuclear reactions can take place at a very rapid rate. Under these circumstances statistical equilibrium is set up and the abundances of the products of the reactions can be calculated from statistical mechanics. It turns out in this temperature range that the most abundant nuclides in the stellar core are those with the greatest binding energy per nucleon. This gives a narrow peaked distribution centered about Fe^{56}, just of the sort that is observed in the cosmic abundance distribution. Hoyle, Fowler, and the Burbidges obtain good agreement in comparing their computed relative isotopic abundances with those measured in the iron-peak region.[21] Nearly as good agreement is obtained for the abundances of the elements when compared with the solar determinations of Goldberg, Muller, and Aller.[17]

SUPERNOVA EXPLOSIONS

If the central regions of a star reach these high values of temperature and density, it appears that some rather spectacular events become possible. Beta transformations in the interior of

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the star take place at a rapid rate, and the neutrinos emitted escape from the star without appreciable nuclear interaction. This is the Urca process of Gamow and Schönberg.[22] Hoyle has calculated that this process will lead to a slow contraction of the core accompanied by an increasing temperature.[23].

The net result of all the thermonuclear reactions which took place up to the formation of the iron peak was a release of energy. However, when the temperature exceeds about 5 × 10^9 °K, a sort of photodisintegration of the iron peak takes place. The most abundant nucleus now becomes He^4. The combinations of temperature and density at which the transformation from the iron peak to helium takes place[23] are shown in Figure 4. On the left

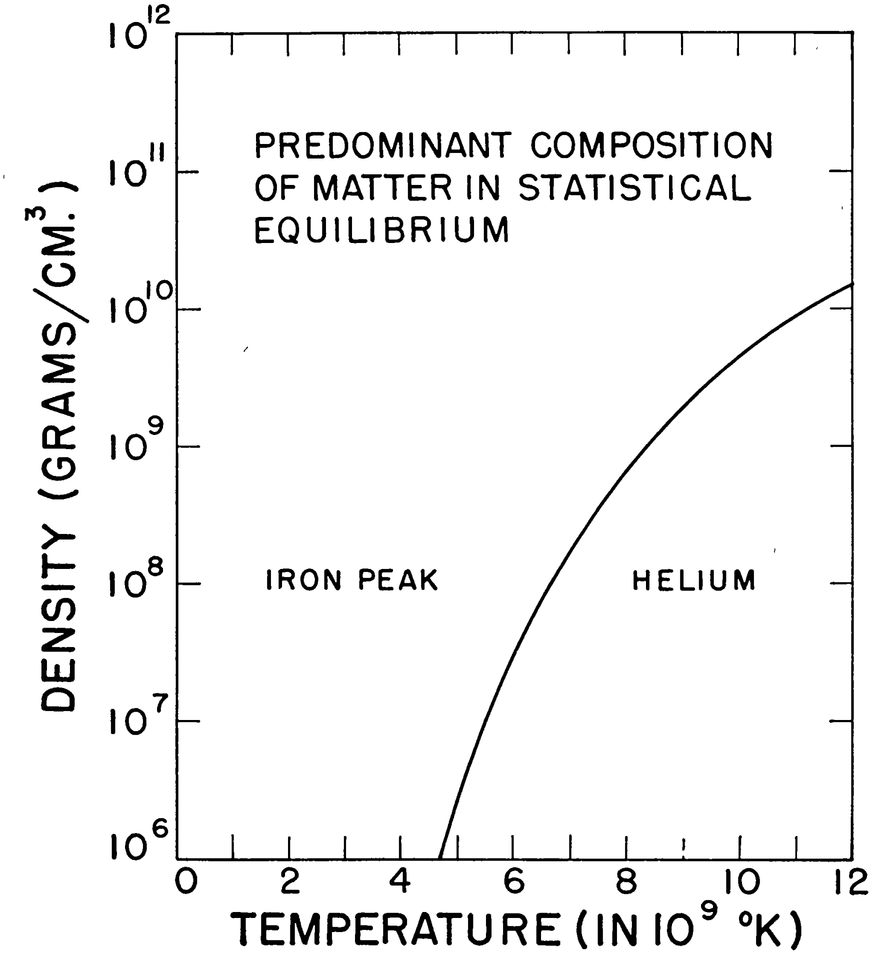

FIG. 4.—The regions of temperature and density in which statistical equilibrium produces predominantly nuclei of the iron peak or helium.

of the line on this diagram the most abundant nuclide is Fe^{56}; the line denotes a very narrow transition region, to the right of which He^4 is the most abundant nucleus.

The transformation from the iron peak to helium requires a large absorption of energy to take place. The only source of energy available to the star for making this transformation is the potential energy of its own gravitational field. Hence the photodisintegration of the iron peak must be accompanied by a collapse of the central regions of the star. Hoyle finds from calculations that this collapse will take a time of the order of 100 seconds.[23]

The outer layers of the star also fall toward the center. These layers contain various products of hydrogen, helium, and heavy-ion thermonuclear reactions. The implosion releases gravitational potential energy in these layers, heating them very quickly to temperatures of the order of a few hundred millions of degrees. A thermonuclear explosion then takes place that releases enough energy to blow the layers off into space with velocities of recession of some thousands of kilometers per second. This is a supernova explosion.

It will evidently be quite a complicated matter to follow in detail the nuclear reactions taking place in supernova explosions, but certain general results are readily apparent.[24,25] Consider first the case in which the number of protons in the reacting layer is comparable to the number of nuclei produced by previous helium and heavy-ion thermonuclear reactions. The protons will be quickly captured by such nuclei, giving a series of reactions of the sort illustrated by the horizontal line at the top of Figure 5. After the hydrogen is exhausted, the products that have been formed undergo decay by positron emission and also take part in helium thermonuclear reactions, following the vertical lines in Figure 5. Some of these products then give exothermic (α,n) reactions, releasing a lot of neutrons into the imploding layers. Some of these neutrons may be used up in (n,p) reactions with the neutron-deficient proton-capture products. However, the imploding layer may contain large abundances of heavy nuclides previously formed by neutron capture on a slow time scale, and these products will readily capture further neutrons on what is now a fast time scale. The mean time between neutron captures

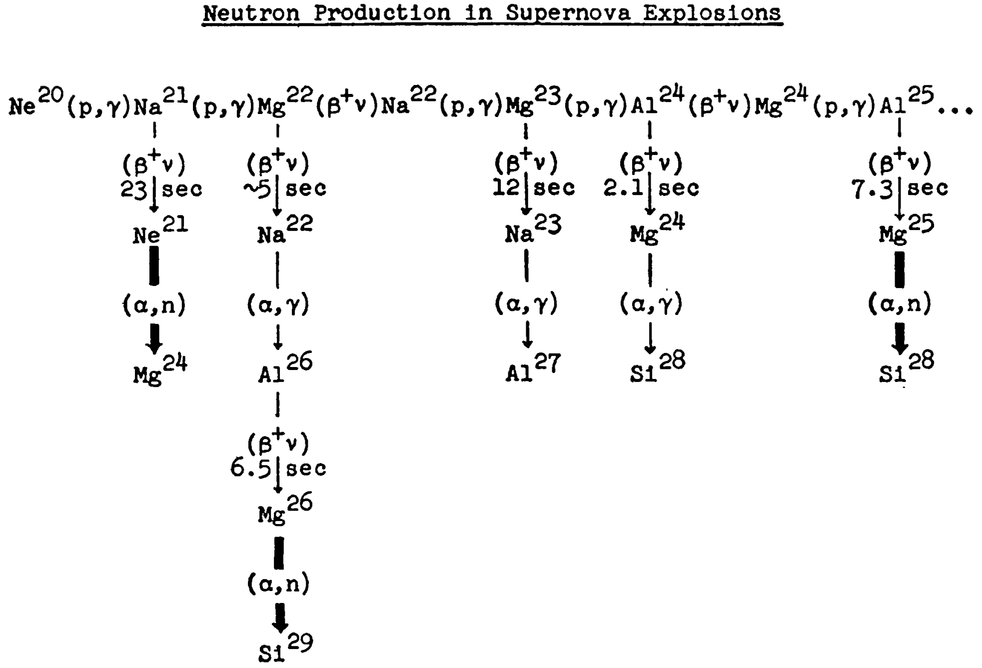

FIG. 5.—Selected nuclear reactions that can occur in supernova explosions.

in a given heavy nucleus will be a small fraction of one second. Neutron capture continues until the neutron binding energy becomes so low that the photoneutron emission rate is equal to the neutron capture rate. The nuclei then wait until beta decay takes place with a half-life of one-tenth to one second. Further neutron addition then takes place until the next photodisintegration limit is reached. This process will build up very heavy nuclei until eventually further neutron addition causes nuclear fission. The writer estimates in a crude preliminary way that fission will terminate the build-up somewhere in the vicinity of the nucleus of atomic number 103 and mass number 287.

After the neutron production ceases, the neutron-rich products that have been formed decay by beta emission until they reach the valley of beta stability. Among the products then formed is the nucleus californium 254. This decays by spontaneous fission with a half-life of 55 days. It has been pointed out that the energy of decay of this nucleus is likely to predominate in the light curves of supernovae for about two years after the explosion,[24,25] and this is indeed observed to be the case in Type I supernovae. Nuclides with mass numbers greater than about 260 which are formed in the explosion will very quickly decay by spontaneous fission, and the writer estimates that the fission products will be mostly formed with mass numbers near 123 and 164.

If, on the other hand, the imploding layer contains many more protons than other light nuclei apart from helium, then the vertical sequences of Figure 5 do not take place and neutron production is negligible. Proton capture will form a variety of nuclei

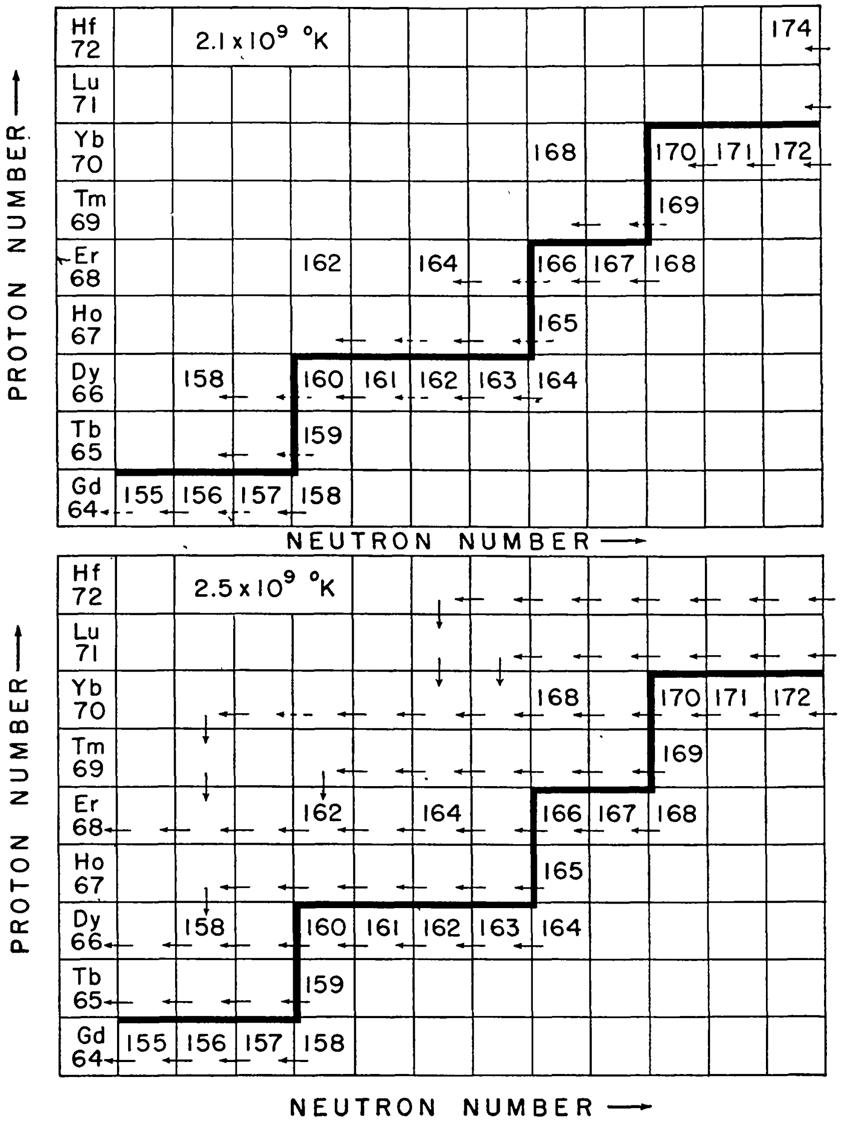

FIG. 6.—Photonuclear reactions in the rare-earth element region. The heavy line shows the positions of products of neutron capture on a slow time scale. The numbers in boxes are mass numbers of beta-stable nuclides.

in the range from neon to calcium, and at higher temperatures beyond calcium. These supernovae would give light curves falling off more rapidly than those of Type I, and this may be the mechanism involved in Type II supernovae in which the light curves do not have a 55-day exponential tail.

In this proton-excess case some important photodisintegration reactions of heavy nuclei may take place. These are illustrated in Figure 6. The heavy line shows the capture path for neutron capture on a slow time scale in the rare-earth element region. Numbers placed in squares are the mass numbers of beta-stable nuclides. Photoneutron and photoproton reactions that can take place with mean times of less than a second are shown by solid arrows; those having mean times between 1 and 10 seconds are shown by broken arrows. It may be seen that a few reactions are possible on the indicated time scales at 2.1×10^9 °K, and at 2.5×10^9 °K there is a rapid emission of nucleons as the heavy nuclei are broken down to the iron peak region. At an intermediate temperature certain heavy nuclides are formed that cannot be formed by neutron capture.

ANALYSIS OF COSMIC ABUNDANCES

It is useful to examine the cosmic abundances of the heavy nuclides to see if they show evidence for formation in the various ways suggested. The cosmic abundances of nuclides with odd mass numbers[16] are shown in Figure 7. The major peaks in the distribution have been interpreted by Coryell as indicating the influence of closed neutron shells in the formation of the heavy elements.[26] Nuclides with closed shells of 50, 82, and 126 neutrons have very small neutron-capture cross sections and would therefore have large abundances if formed by neutron capture. The broad peaks centered about mass numbers 80, 130, and 195 correspond to closed shells of 50, 82, and 126 neutrons in neutron-rich nuclides which may be expected to have beta-decay half-lives of the order of a second. Therefore one can expect that these peaks have resulted from neutron production in Type I supernova explosions. The narrow abundance spikes centered at mass numbers 89 and 139 correspond to stable nuclides with closed shells of 50 and 82 neutrons. They would therefore be products of neu-

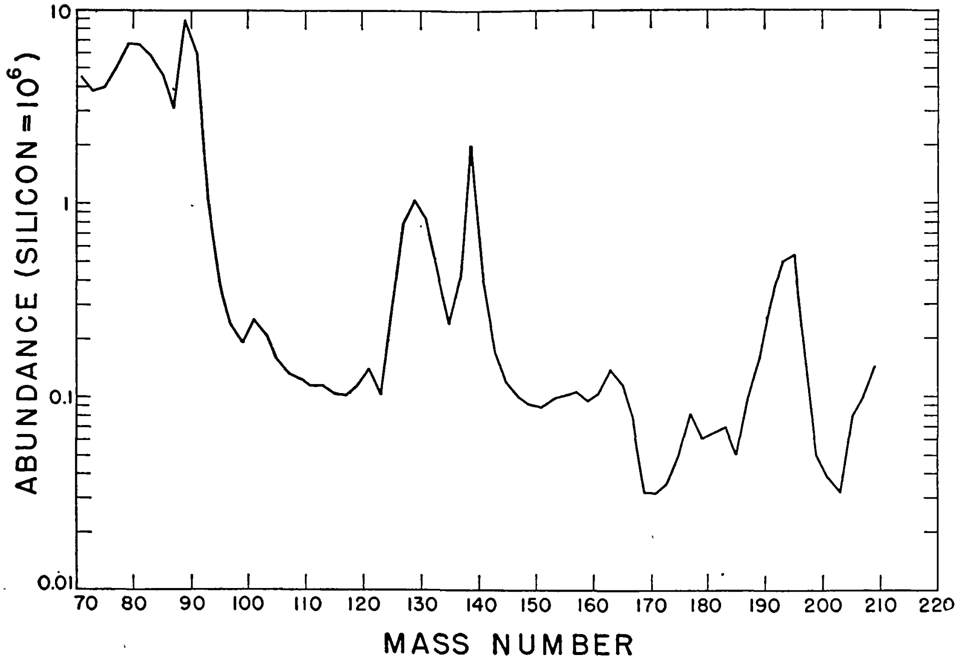

FIG. 7.—The cosmic abundances of nuclides with odd mass number according to Suess and Urey.

tron capture on a slow time scale such as is expected to occur during the early stages of helium consumption in a star. The subsidiary peak at mass number 160 may be formed by the spontaneous fission of very heavy nuclei formed by neutron capture on a fast time scale.

Further conclusions on the mechanisms of nucleogenesis can be obtained by examining the abundances of even-even isobars. A typical section of a nuclide chart is shown in Figure 8. Consider first the pair of isobars $(Z+2, A+2)$ and $(Z, A+2)$. The latter is a beta-decay product from the neutron-rich side of the valley and will be called an "unshielded isobar." On a slow time scale, in which the mean time between neutron captures in a given nucleus is several years, the unshielded isobar $(Z, A+2)$ will not be formed unless the nuclide $(Z, A+1)$ has a half-life of several years or longer, which is seldom the case. On the slow time scale the nuclide $(Z+2, A+2)$ will usually be formed instead. It is called a "shielded isobar." Consider next the pair of isobars $(Z+4, A+4)$ and $(Z+2, A+4)$. The former cannot be made by neutron capture at all, and it is therefore called an

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"excluded isobar." The excluded isobars may be products of proton capture and photonuclear reactions in Type II supernovae.

The cosmic abundances of the three classes of isobars are shown in Figure 9. Isobaric pairs in which the nuclide corresponding to $(Z, A + 1)$ of Figure 8 has a half-life of greater than one year have not been included. It is gratifying to note that the abundances of unshielded isobars display peaks in the vicinity of mass numbers 80, 130, and 195. These are in the same positions as the broad peaks of Figure 7 and demonstrate the closed-shell effects in neutron capture on a very fast time scale. The abundances of the shielded isobars do not show these peaks. It is also gratifying to note that the general level of abundances of the shielded isobars drops by about a factor 5 in passing above mass number 140. This behavior is to be expected for neutron capture on a slow time scale, as can be seen from Figure 3.

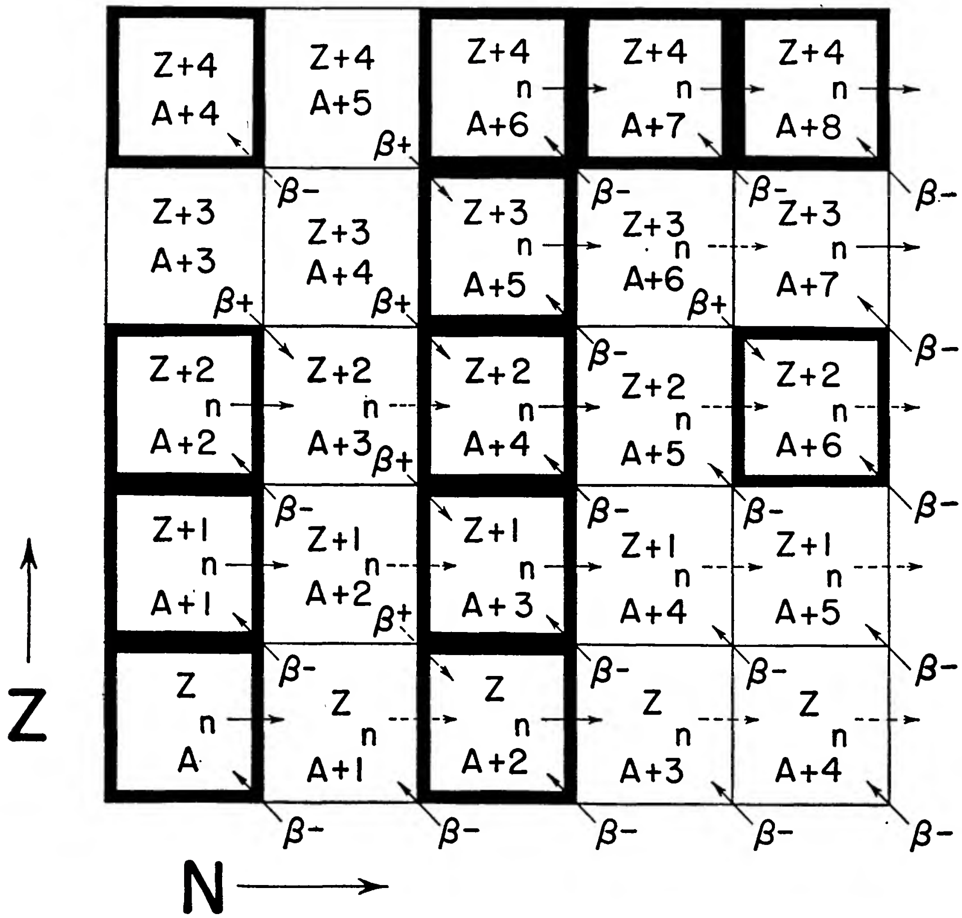

FIG. 8.—A typical section of the nuclide chart.

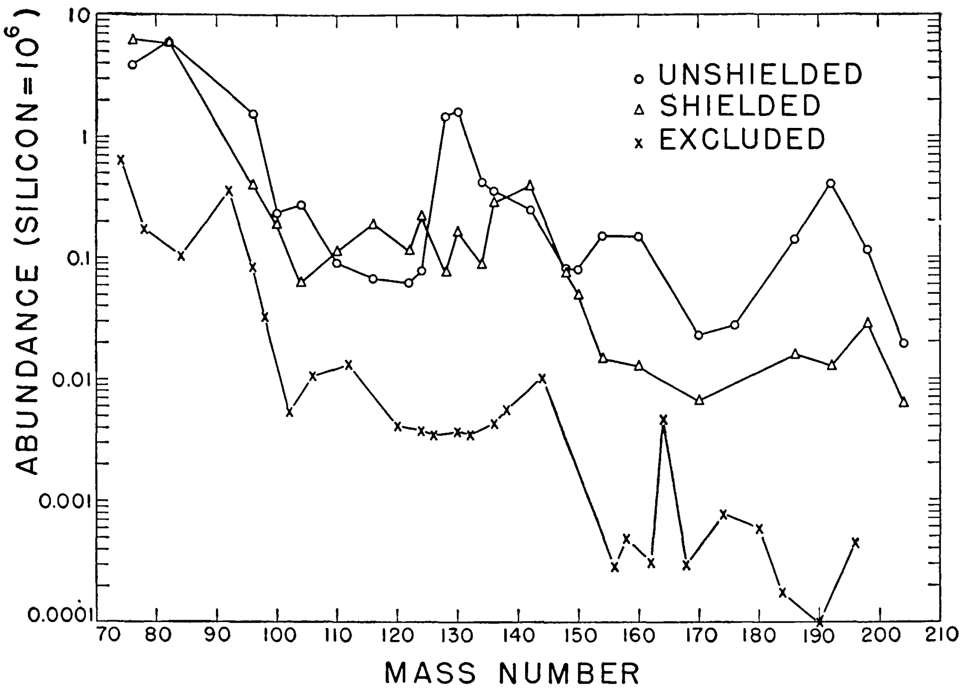

FIG. 9.—The cosmic abundances of the three classes of even-even isobars according to Suess and Urey.

The abundances of the excluded isobars are less than those of the shielded ones by a roughly constant factor, as would be expected if the excluded isobars are formed from the products of neutron capture on a slow time scale. Above mass number 150 there are 4 high and 6 low abundances of excluded isobars. The high group can be formed by photonuclear reactions on both fast and slow time scales, but the low group can only be formed on the fast time scale. No such fluctuations are apparent below mass number 150, and it is likely that these isobars are formed mainly by proton capture.

SUMMARY

The methods suggested for the formation of various kinds of nuclei in stellar interiors are summarized in Table I. Many of the suggested mechanisms are slow time scale processes, and their products may be emitted into space by any of the three forms of ejection mentioned in the introduction. A few mechanisms involve a fast time scale; their products would be ejected only in supernova explosions. A great deal of astrophysical research will

TABLE I

Mechanisms of Nucleogenesis

Elements	Method of Formation
D, Li, Be, B	Not formed in stellar interiors. Possibly made by nuclear reactions in stellar atmospheres
He, C, N, O, F, Ne	Hydrogen and helium thermonuclear reactions in orderly evolution of stellar interiors
Ne to Ca	1. Heavy-ion thermonuclear reactions in orderly evolution of stellar interiors 2. Neutron capture on slow time scale 3. Hydrogen and helium thermonuclear reactions in supernova explosions
Fe peak	Statistical equilibrium in pre-supernovae and in supernovae
Heavy elements:	
(*a*) Unshielded	Neutron capture on fast time scale in Type I supernovae
(*b*) Shielded	Neutron capture on slow time scale in orderly evolution of stellar interiors
(*c*) Excluded	1. Proton capture and photonuclear reactions in Type II supernovae 2. Photonuclear reactions on slow time scale in orderly evolution of stellar interiors
(*d*) Trans-bismuth	Neutron capture on fast time scale in Type I supernovae

be required to determine the relative importance of different sources in contributing to the element abundances in the interstellar medium, not only at the present time but also much earlier in the history of the Galaxy when the material of the solar system was formed. The elements deuterium, lithium, beryllium, and boron are not formed in stellar interiors, but it is possible that they may be made by nuclear reactions in stellar atmospheres after the acceleration of charged particles in changing magnetic fields.[27]

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