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Origin of the Elements in Stars

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Experimental (*1, 1a*) and observational (*2–6*) evidence has continued to accumulate in recent years in support of the theory (*7–10*) that the elements have been and are still being synthesized in stars. Since the appearance of a new and remarkable analysis by Suess and Urey (*11*) of the abundances of the elements, we have found it possible to explain, in a general way, the abundances of practically all the isotopes of the elements from hydrogen through uranium by synthesis in stars and supernovae. In this article we wish to outline in a qualitative fashion the essentially separate mechanisms which are required in stellar synthesis (*12*).

Thermal Conversion of Pure Hydrogen through Helium to Iron

As long as extremely high temperatures in excess of 5×10^9 degrees Kelvin are not under consideration, the general tendency of nuclear reactions inside stars is to increase the average binding energy per nucleon. For a given temperature and density and for a given time scale of operation of the nuclear processes, the increase of binding that takes place is usually limited by Coulomb effects, but, subject to this limitation, the binding becomes as large as possible. That is to say, energy is degraded as fast as is consistent with Coulomb barrier effects, mitigated in some cases by resonance penetration. Since barrier effects become less severe as the temperature increases, it follows that the binding energies increase with temperature. This will become clear from the following examples.

At temperatures from about 10^7 to 5×10^7 degrees in main-sequence stars, hydrogen is transformed to helium, $4H^1 \rightarrow He^4$, with an average binding energy of 7.07 million electron volts (Mev) per nucleon. We emphasize that the proton-proton sequence of reactions makes possible the production of helium starting only with hydrogen. The recent discovery of the free neutrino as reported by Cowan *et al.* (*1a*) leads to increased confidence in the existence of the primary proton-proton interaction which proceeds through prompt electron-neutrino emission. At temperatures from 10^8 to 2×10^8 degrees in red giant stars, He^4 is transformed principally to C^{12}, O^{16}, and Ne^{20} with an average binding energy of 7.98 Mev per nucleon. The important roles of the ground state of Be^8 and of the second excited state of C^{12} in expediting the primary process of helium fusion, $3He^4 \rightarrow C^{12}$, have recently been clarified (*1*), and it is now clear that the long-standing difficulties in element synthesis at mass 5 and mass 8 are bypassed in this process. At temperatures of the order 10^9 degrees, Mg^{24}, Si^{28}, S^{32}, A^{36}, and Ca^{40} are formed from the carbon, oxygen, and neon, the average binding thus rising to 8.55 Mev per nucleon, while, at temperatures from 2×10^9 to 5×10^9 degrees, Fe^{56} and neighboring nuclei are synthesized, yielding an average binding energy of 8.79 Mev per nucleon. No higher binding than this exists, so that further heating of material will not synthesize in quantity elements of appreciably greater atomic weight than Fe^{56}.

The situation, then, is that a thermal "cooking" of pure hydrogen yields principally He^4 and the α-particle nuclei with $A = 4n$, $Z = 2n$, $n = 3, 4, 5, 6, 7, 8, 9$, and 10 (C^{12} to Ca^{40}), together with nuclei centered around Fe^{56}. These are the most abundant nuclei. Moreover, the relative abundances that have been calculated for these nuclei, and particularly for the 20-odd isotopes of titanium, vanadium, chromium, manganese, iron, cobalt, and nickel, show good agreement with observed abundances. The original equilibrium calculations by Hoyle (*7*) have been considerably improved by taking into account the low-lying excited states of the iron-group nuclei and of the radioactive nuclei which ultimately decay to them, and by statistically weighting each state according to its observed spin or that expected on nuclear shell theory. Typical results for the equilibrium abundances of the chromium isotopes at 3.8×10^9 degrees are indicated in Table 1.

We regard results similar to those presented in Table 1 as giving strong support to the view that the elements under consideration were synthesized inside stars and that they became subsequently distributed in space, either by slow emission from late-type giants or by catastrophic explosion, as for instance in supernovae.

Thermal Reactions of Hydrogen and Helium with Light Elements

More complicated effects arise when the thermal cooking is considered, not of completely pure hydrogen, but of hydrogen adulterated with a small proportion of the elements mentioned in the previous paragraphs. When a second-generation star condenses, the hydrogen out of which it forms will in general have been adulterated by other elements—for example, C^{12}, O^{16}, Ne^{20}, and Fe^{56}—that are synthesized by, and ejected from, previously existing stars. Mixing of core and envelope material in the giant stage of a star may also lead to the same situation.

The presence of the light elements leads to the conversion of hydrogen to helium through the catalytic carbon-nitrogen-oxygen and neon-sodium cycles. In these cycles, the isotopes C^{13}, N^{14}, N^{15}, O^{17}, Ne^{21}, Ne^{22}, and Na^{23} are produced. Eventually O^{18} and F^{19} are pro-

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duced in helium reactions, so that all the isotopes of the elements from carbon to sodium are accounted for.

Stellar Surface Reactions

Only deuterium and the isotopes of lithium, beryllium, and boron among the light elements cannot be produced in stellar interiors. They are disintegrated rather than synthesized by interaction with hydrogen and helium at energies that correspond to temperatures in stellar interiors. The possibility that they are produced by high-energy protons and alpha particles in hot spots on stellar surfaces has been previously discussed (*9*). There is now some evidence for such particles from observations in radio astronomy. The frequency-time curve of type-III bursts in radio noise from the sun (*4*) indicates propagation of the agent of noise excitation through the solar corona at velocities from 3×10^9 to 10×10^9 centimeters per second. If such velocities are attributed to protons, the energies of these particles are 5 to 50 Mev. It is to be expected that, in the magnetic stars, acceleration to even higher energies and on a greater scale will take place. At such energies, neutrons, alpha particles, and lithium, beryllium, and boron nuclei will be produced by spallation processes. The neutrons will diffuse from the hot spots into quiescent regions and will there be primarily captured by hydrogen to form deuterium, with the emission of 2.23-Mev radiation (which may eventually prove to be detectable). The deuterium, in turn, when accelerated, may lead to production of anomalous abundances of the heavy elements through stripping reactions (d,p and d,n) and subsequent neutron capture. Anomalous abundances are seen (*9*) in magnetic stars that, unlike the sun, have shallow convective zones in their outer envelope. The acceleration of the particles is probably due to time-varying magnetic fields in the hot spots. Those particles that escape from the stellar surface may be further accelerated to cosmic-ray energies in interstellar magnetic fields.

Neutrons

During the $H \rightarrow He^4$ stage of second-generation stars, Ne^{20} is processed by the reactions $Ne^{20}(p,\gamma)Na^{21}$, $Na^{21}(\beta^+)Ne^{21}$. During the latter stage of the phase, $He^4 \rightarrow C^{12}$, O^{16}, Ne^{20}, free neutrons are generated by $Ne^{21}(\alpha,n)Mg^{24}$. The free neutrons are partly added to the light elements with $A = 4n$, producing the remaining isotopes of these elements, and are partly added to Fe^{56} and allied nuclei. Because the Fe^{56} is present in only very low abundance, the number of neutrons thus made available per Fe^{56} nucleus is approximately 10 to 200, which is sufficient to build the iron into the heaviest elements. Most important of all is the fact that neutrons are produced in a medium primarily composed of He^4, which does not capture neutrons. If He^5 were stable, its production by neutron capture in He^4 would consume all available neutrons and heavy-element synthesis would not be possible. In theories of primordial synthesis, the break in the neutron-capture chain at He^4 has been an insuperable stumbling block. In contrast, it is the saving factor in stellar neutron synthesis. We emphasize that there are no Coulomb electric barrier effects in synthesis of the heavy elements by a succession of neutron captures. Each capture or addition increases the atomic weight approximately by one unit.

Table 1. Equilibrium abundances of the chromium isotopes at a temperature of 3.8×10^9 degrees.

Isotope	Binding energy per nucleon (Mev)	Log abundance relative to Cr^{52}	
		Calculated	Observed
Cr^{50}	8.706	− 1.89	− 1.27
Cr^{52}	8.776	0.00	0.00
Cr^{53}	8.760	− 0.85	− 0.94
Cr^{54}	8.778	− 1.78	− 1.50

We have distinguished two conditions under which the neutron capture can take place, a slow (*s*) process and a rapid (*r*) process. Suess and Urey (*11*) and Coryell (*13*) have already pointed out that the peaks in the abundance curves at stable nuclei with filled neutron shells ($A = 90, N = 50$; $A = 139, N = 82$; $A = 208$, $N = 126$) strongly indicate the operation of the *s*-process in element synthesis and that the nearby peaks at $A = 82$, 130, and 194, shifted by $\delta A \sim 8$ to 14, similarly require the operation of the *r*-process. The *s*-process we associate with giant stars that evolve in approximately 10^5 years. We regard the observed presence (*2*) of technetium in the atmospheres of the giant S-type stars as a demonstration that the building of very heavy elements by neutron addition actually takes place in stars. The *r*-process we associate with the explosion of supernovae, the time scale being as small as 10 to 100 seconds. We regard the observed 55-day decay of the light curves of type I supernovae as giving strong support to this view, for an explanation of this decay seems to demand (*5*) the building of Cf^{254} in a process of very rapid neutron addition. The 55-day spontaneous fission decay of Cf^{254} is the source of energy dominating the light emission of the supernovae after maximum. The production (*6*) of Cf^{254} in the thermonuclear test at Bikini in November 1952 demonstrates that rapid neutron capture can surmount spontaneous radioactivity. In spite of the extreme provincialism implied, we have been able to find no other nucleus with the unique property of Cf^{254}—a 55-day half-life decay by spontaneous fission in which some 200 million electron volts of energy is released with little or no competition by low-energy alpha-particle decay.

Certain isotopes of the heavy elements can be built only by the *r*-process, while other isotopes can be built only by the *s*-process. The two processes differ in this respect because they allow very different times for the occurrence of the beta disintegrations that occur along the chain of nuclei built by the neutron addition. The *s*-process involves neutron captures in the stable elements or those with life times greater than 10^3 years. Most beta-active nuclei produced in the process have time to decay before additional capture occurs. On the other hand, the *r*-process involves neutron captures and beta decays with approximately equal reaction times (0.1 to 1.0 seconds) in isobars with neutron excess of approximately 5 to 10, relative to that for the stable species.

Finally, a third set of heavy-element isotopes cannot be built by either the rapid or slow capture of neutrons. Consider, for example, the eight isotopes of the element tellurium (which turns out to be aptly named if we persist in the belief that terrestrial abundances are representative samples of the cosmic products of the many mechanisms of synthesis in stars). The light isotopes ${}_{52}Te_{70}{}^{122}$ and ${}_{52}Te_{71}{}^{123}$ and ${}_{52}Te_{72}{}^{124}$ can be produced only in the *s*-process. In the *r*-process, the ultimate beta decays of the neutron-rich isobars at 122 to 124 produced by rapid neutron addition terminate at stable ${}_{50}Sn_{72}{}^{122}$, ${}_{51}Sb_{72}{}^{123}$, and ${}_{50}Sn_{74}{}^{124}$, which are on the neutron side of the mass valley. On the other hand, the heaviest isotope Te^{130} can be produced only in the *r*-process, where it is the stable product of the decay of neutron-rich isobars of mass 130. In the *s*-process, radioactive Te^{129} with a half-life of 70 minutes has time to decay to I^{129} (half-life 2×10^7 years), and, after another neutron capture, the resultant I^{130} decays in 12.6 hours to Xe^{130}, which is thus produced in the *s*-chain instead of Te^{130}. The isotopes Te^{125}, Te^{126}, and Te^{128} can be produced in either the *s*- or *r*-process, although Te^{128} is produced in the slow capture of neutrons only in a weak side link of the chain resulting from the fact that I^{128} decays 5 percent of the time by positron emission or electron capture. The rarest and lightest isotope, Te^{120}, cannot be built in either process, and we discuss in a subsequent paragraph the infrequent proton capture processes in which such rare proton-rich isotopes can be produced. Tellurium-120 is about 1 percent as abundant and Te^{122}, Te^{123}, and Te^{124} are about 10 percent as abundant as Te^{128}, and Te^{130}, and thus we assign Te^{126}, which has an abundance comparable to Te^{128}, and Te^{130}, to the *r*-process. Tellurium-125 is an intermediate case, but it follows the trend of the *r*-process, and to this we thus assign its production. In this manner we have been able, in general, to assign all the nuclear species with few exceptions to production by one or the other of the neutron processes or to the rare proton-capture process; in a few cases both neutron processes contribute to the abundance.

These considerations are perhaps made clearer by Fig. 1, which has been produced after the manner of Suess and Urey (*11*) and which shows their abundance data in the region from atomic weight 120 to 150. In this figure, nuclear species produced in the same process are connected by shaded curves, and the general trend of the production by the three processes becomes clear. The magic number peaks noted by Suess and Urey (*11*) and by Coryell (*13*) stand out clearly in both the odd-*A* and even-*A* nuclei.

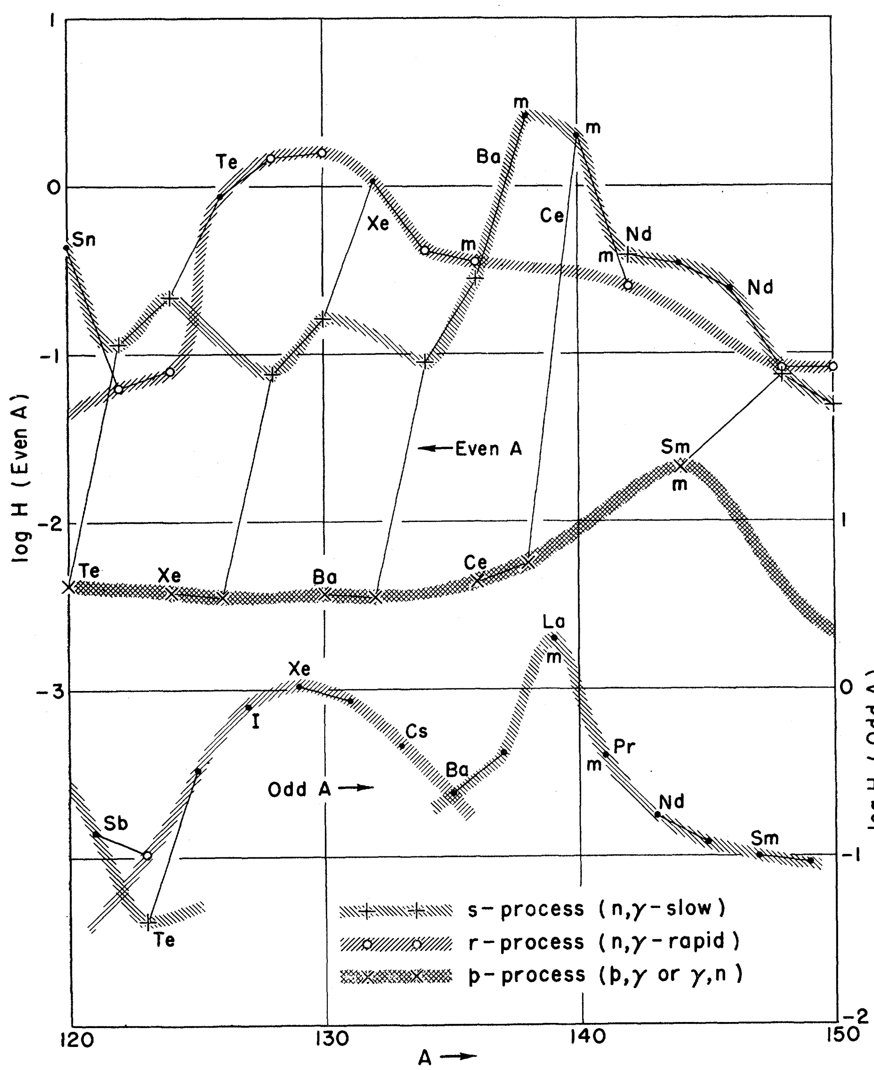

Fig. 1. Logarithm of abundance H (silicon = 6.00, hydrogen = 10.60) from $A = 120$ to 150 according to Suess and Urey (*11*). Odd mass numbers are shown in the bottom curve (read right ordinate). Even mass numbers are shown in the top curves (read left ordinate). Isotopes of a given element are connected by light lines (not to be confused with cross-hatched modes of element synthesis). Nuclei are distinguished by their method of synthesis as follows: +, produced only in neutron capture at a slow rate (*s*-process); ○, produced only in neutron capture at a rapid rate (*r*-process); ●, produced in both processes but predominant mode of production assigned as discussed in text; ×, produced only in proton capture or photoneutron processes (*p*-process). The paths of the three processes are then indicated by the crosshatching indicated in the figure. The stable nuclei with the magic number of closed shell neutrons, $N = 82$, are indicated by *m*. The abundance peak near $A = 139$ follows from the low neutron-capture cross section of the magic stable nuclei in the *s*-process. The abundance peak near $A = 129$ follows from the low neutron-capture cross section and slow beta decay in the *r*-process for the magic neutron-rich isobars (for example, $A = 129$, $N = 82$, $Z = 47$) which eventually decay by beta emission to the stable nuclei in this region. These arguments are based on the fact that in "steady-streaming" the abundance of a given nucleus will be inversely proportional to the rate at which it is transmuted by neutron capture or beta decay. The alternation in abundances exhibited by the sequence Te^{122}, Te^{124}; Xe^{128}, Xe^{130}; and Ba^{134}, Ba^{136} is to be expected in the *s*-process because of the difficulty in adding further neutrons after two have already been captured. In general there is only one isobar at odd mass numbers. However, Te^{123} and Sb^{123} differentiate the *r*- and *s*-processes in an odd *A*-curve. Tellurium-123 is probably unstable but with a very long lifetime.

Capture of Protons and Photodisintegrations

Just as adulteration of the hydrogen of a star by elements up to Fe^{56} is to be expected, so adulteration of the hydrogen by the heavier elements that are built in the *r*- and *s*-processes is to be expected. Such adulteration leads to an interesting additional effect when hydrogen remains unconsumed in the outer regions of a supernova, as it probably does in the case of type I supernovae. In a former paper (*5*), reasons were given for the generation of temperatures of approximately 2.5×10^9 degrees in this hydrogen. At such temperatures (p,γ) reactions occur in a time of the order of 10 seconds, even on the heaviest nuclei (*p*-process). It seems that the proton-rich isotopes of the heavy elements were built in this fashion. These isotopes are characterized by the important property that they cannot be built directly by either the *r*- or *s*-process and that their abundances bear an approximately constant ratio of 10^{-2} to that of those neighboring isotopes that are built by *r*- and *s*-processes. The low value of this ratio, together with its approximate constancy from atomic weight of approximately 70 up to approximately 200, is satisfactorily explained by a process in which a few protons are added at high temperatures to the products of *r*- and *s*-processes. The number of protons that can be added is independent of atomic weight when the energy is large enough that barrier effects are not important at the higher values of atomic weight. This is because proton instability sets in at the same proton excess (approximately 10) relative to the stable nuclei independently of atomic weight. The proton-rich isotopes may also be explained by (γ,n) and (γ,p) reactions at high temperature, operating on the products of the *r*- and *s*-processes.

General Conclusions

The trends of the three processes can be mapped throughout the heavy-element region, and there is reason to believe that the abundance curves will be amenable to quantitative treatment in terms of beta decay rates and of the cross-sections for the neutron- and proton-capture processes. In the past, this has not been possible, for it was not realized that the abundance curve represented a superposition of contributions from several processes. The magic number peaks in the *s*-process and their shifted counterparts in the *r*-process are not as pronounced in the over-all abundance curve as they are in the contributing curves. It is already clear that both the slow and rapid neutron-capture processes operated under conditions of "steady streaming." For instance, in the case of the *s*-process, it appears that the products obtained by multiplying the abundances built through the *s*-process by the appropriate (n,γ) cross sections of the stable nuclei are remarkably constant from isotope to isotope, as would be expected on the basis of steady streaming. There is one notable discrepancy, in the case of the element lead. Neutron-capture processes should terminate in a cycling among the lead isotopes at the onset of alpha activity. If steady streaming has occurred, there should be a consequent building up of the abundance of lead, and we find that the abundance as given by Suess and Urey (*11*) is too low, by a factor of approximately 10 to 10^2, to be consistent with this.

A consideration of the building of the transuranic elements by the *r*-process has enabled us to estimate the numbers of progenitors of U^{235} and of U^{238}. Uranium-235 results from the alpha decay which follows the beta decay of the neutron-rich nuclei produced with $A = 235$, 239, 243, 247, 251, and 255. Beyond $A = 259$, the ultimate decay is probably by spontaneous fission rather than by alpha emission. Uranium-235 results from production at $A = 238$, 242, 246, and 250. Thus U^{235} has six odd A progenitors while U^{238} has four even A progenitors. Odd-even pairing energy effects become progressively less important throughout the heavy stable nuclei, and we would expect neutron-capture cross sections to be very nearly equal for odd-A and even-A elements in the heaviest nuclei. This must indeed be the case in the rapid neutron-capture peak near $A = 194$ (similar to the peak at $A = 130$ in Fig. 1), where the abundances of odd A-even A are nearly equal—for example, $Pt^{195}/Pt^{194} = 1.03$. Thus, it appears that the production ratio U^{235}/U^{238} was probably about 1.5 and, in any case, was unlikely to be less than unity. If we suppose that the elements of which the earth is composed were not all built at one moment of time but were built at a uniform rate, starting at the time of origin of the galaxy and extending almost up to the formation of the solar system some 5×10^9 years ago, then, using the ratio of the uranium isotopes found at present in the earth, the age of the galaxy can be calculated. For the case of a production ratio of U^{235}/U^{238} equal to unity, the age is 7.5×10^9 years, while a still greater age is obtained if a production ratio of 1.5 is used for U^{235} relative to U^{238}. The argument for this high value can be restated as follows. At the time of the formation of the solar system, we can calculate that the ratio $U^{238}/^{235} = 3.5$ On the basis of production, either in a single event or continuously, an additional time interval is required to reach the time at which $U^{238}/U^{235} \approx 1$.

Finally, it may be remarked that, since the production of the heavy elements $(A > 60)$ is a by-product of ordinary thermal cooking that depends on the adulteration of the hydrogen out of which a star forms, it is to be expected that these elements will be synthesized in abundances that are very low compared with the ordinary products of thermal cooking (for example, O^{16}, Si^{28}, and Fe^{56}). This is precisely the case.

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Nomenclature of Enzymes of Fatty-Acid Metabolism

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Spectacular developments during the last few years have led to the isolation in a soluble form of a number of enzymes of fatty-acid metabolism in several independently working laboratories. This circumstance resulted in the denoting of enzymes that catalyze similar reactions by different names, either according to the substrate attacked or according to the favored equilibrium of the particular reaction. This could lead to confusion among those not working in the field.

The second International Conference on Biochemical Problems of Lipids, attended by representatives of 20 nations and held between 27 and 30 July 1955 at the University of Ghent, Belgium, under the presidency of R. Ruyssen, gave an opportunity to iron out these difficulties. A special meeting to discuss problems of nomenclature was convened at the conference. A memorandum by Priscilla Hele and G. Popják, London, was presented and formed the basis of the discussions. There was unanimous agreement, and the conclusions reached are presented here.

Suggested Principles

Before we considered individual enzymes, an agreement was reached concerning the broad principles that should govern the nomenclature.

It is recommended that enzymes be called by a systematic name that should