At $\rho = 10^5$ g/cm^3 where the (α, γ) reaction rates are much greater than (γ, α) ones, the emitted α-particles are absorbed instantaneously by ^{12}C, ^{16}O or ^{20}Ne but they are hardly used for the formation of nuclei heavier than ^{28}Si. The result is not different from the case (II).

Our calculations, however, show that the abundances in question can be reproduced by taking the density $\rho \simeq 10^2$ g/cm^3, where the (γ, α) reaction rates are comparable to (α, γ) ones. At this temperature the reaction time for ^{20}Ne (γ, α) ^{16}O is $10^{-2} \sim 1$ sec, while $10^3 \sim 10^7$ sec for the other (γ, α) reactions, and to explain the observed abundances it is necessary for such temperature to continue for a rather short time $1 \sim 10^2$ sec with a rapid heating-up and a subsequent cooling. Such stellar conditions could be realized in the supernovae explosions, as the time scale of implosion preceding the explosions is estimated to be of the order of 10^{-1} sec [4] and such high temperature will continue for $1 \sim 10^2$ sec.

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3. THE PRODUCTION OF ELEMENTS IN SUPER-NOVAE

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The following assumptions concerning super-novae will be employed in the present paper:

(i) The internal temperature is very high, exceeding 10^9 °K;

(ii) a frequency rate of ~ 1 per galaxy per 10^2 years;

(iii) the mass distributed in space $\sim 1\ \odot$ per super-nova.

Taking $\sim 8 \times 10^9$ years for the age of the Galaxy gives a total of $\sim 8 \times 10^7$ super-novae over the whole history of the Galaxy, and $\sim 8 \times 10^7\ \odot$ for the total mass distributed by them into space. Thus the fraction of the mass of the Galaxy that has experienced 'cooking' inside super-novae is of order 0·5 %.

So long as temperatures in excess of 5×10^9 °K are not under consideration the general tendency of nuclear reactions inside stars is to increase the average binding energy per nucleon. This will become clear from the following examples:

At temperatures from about 10^7 to 5×10^7 °K in main-sequence stars hydrogen is transformed to helium, with an average binding energy of 7·07 MeV per nucleon. At temperatures from 10^8 to 2×10^8 °K in giants and super-giants, ^{4}He is transformed principally to ^{12}C, ^{16}O, and ^{20}Ne with an average binding energy of 7·98 MeV per nucleon. At temperatures of the order 10^9 °K, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}A, and ^{40}Ca 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 °K, ^{56}Fe and neighbouring nuclei are synthesized, yielding in average binding energy of 8·79 MeV per nucleon.

The first suggestion of the present paper is that the origin of the very high temperature elements (temperatures above 10^9 °K) is to be associated with super-novae. It is an immediate encouragement to this point of view that the proportion of the mass of the Galaxy that has been processed in this way would appear to amount to a moderate fraction of a per cent, exactly as is required by observation. Moreover the *relative* abundances that have been calculated for these nuclei, and particularly for the score or so of isotopes of titanium, vanadium, manganese, iron, cobalt, and nickel also show good agreement with observation. Typical results are indicated by the following table

Nucleus	Binding energy per nucleon (MeV)	Log abundance relative to ^{52}Cr	
		Calculated	Observed
^{50}Cr	8·706	−1·89	−1·27
^{52}Cr	8·776	0·00	0·00
^{53}Cr	8·760	−0·85	−0·94
^{54}Cr	8·778	−1·78	−1·50

It is of interest to turn to by-product reactions involving neutrons, with particular reference to Baade's discovery of the exponential decline of the light-curves of super-novae of type I. The energy output responsible for this exponential decline has widely been attributed to the radio-active decay of an unstable nucleus, and will be so regarded here. Relevant information is given in tabular form below:

	Half-life of exponential decay	Energy/or mass requirement
Super-nova	55 ± 1 day	$\sim 10^{47}$ ergs
^{7}Be	53	$\sim 10^{33}$ grams
^{89}Sr	54	$\sim 10^{31}$ grams
^{254}Cf	56·2 ± 0·7	$\sim 10^{29}$ grams

Of the nuclei with half lives near that of the super-novae, only ^{254}Cf seems to commend itself (^{7}Be would have to be present in enormous abundance and there seems to be no plausible manner of genesis; ^{89}Sr would be expected to be accompanied by comparable quantities of other β-unstable nuclei of different half-lives).

The origin of ^{254}Cf can be understood on the basis that among the reactions that accompany the outburst of a super-nova there is a powerful source of neutrons, and that the neutrons are added to lower elements (e.g. Fe), thereby building very heavy, neutron-rich, nuclei. Such a process is known to have taken place in the terrestrial explosion at Bikini [1].

Moreover, the relative abundances of the heavy elements produced in this way can be determined by quantitative calculation [2]. The results turn out to be in excellent agreement with observation. Even the absolute abundances are also given correctly, as will be seen from the following argument.

According to the above table the production of ^{254}Cf must be $\sim 10^{29}$ g/super-novae. The production of other heavy elements has the same general order. Thus the total amount of a particular heavy element produced by 8×10^{7} super-novae (the number over the life-time of the Galaxy) amounts to $\sim 8 \times 10^{36}$ g, which is a fraction $\sim 3 \times 10^{-8}$ of the total mass of the Galaxy. Remembering that this estimate is in terms of mass, we see that in terms of number the abundance of a very heavy element should be $\sim 10^{-10}$ of the abundance of hydrogen, a result in order of magnitude accord with observation.

An interesting outcome of the quantitative calculations for this process is that the original production ratio of ^{235}U to ^{238}U can be estimated to have a value close to 1·6. The present day terrestrial ratio is approximately 1/138. A simple calculation shows that if terrestrial uranium was produced in just one super-nova, then the event must have occurred nearly 7×10^{9} years ago. An equally interesting calculation can be performed on a somewhat different basis. Thus we might assume that, instead of being produced by just one super-nova, terrestrial uranium had the general average composition for the whole Galaxy *at the time the solar system was formed*. If further we take 5×10^{9} years for the time that has elapsed since the formation of the solar condensation, and if uranium were produced at a uniform rate from the time of origin of the Galaxy, then the age of the Galaxy itself must be close to 9×10^{9} years.

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4. NEUTRON PROCESSES IN GIANT STARS

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A red giant star is believed to be one in which the central regions have been exhausted of hydrogen. When helium reactions commence in such a star there are two potential sources of neutrons.

1. The ^{13}C hypothesis. When helium reactions start forming ^{12}C in a degenerate helium core, the core must expand and rather a lot of energy is liberated. It is possible that the resulting short-lived extensive convection zone will mix some hydrogen from the envelope with ^{12}C produced in the core to form ^{13}C by the reactions ^{12}C (p,γ) ^{13}N $(\beta^{+}\nu)$ ^{13}C. This can later be consumed by ^{13}C (α, n) ^{16}O reaction [1], producing neutrons which are slowed to thermal equilibrium and then captured by surrounding nuclei. Very little production of heavy elements occurs unless the mixing ratio of protons to ^{12}C is of the order of 0·1 by number [2].

2. The ^{21}Ne hypothesis. In the red giant star the temperature of the hydrogen shell source is probably high enough to produce a considerable amount of ^{21}Ne by the reactions ^{20}Ne (p, γ) ^{21}Na $(\beta^{+}\nu)$ ^{21}Ne [3]. It is not known how much ^{21}Ne will be destroyed by the ^{21}Ne (p, γ) ^{22}Na $(\beta^{+}\nu)$ ^{22}Ne reactions. The surviving ^{21}Ne later produces neutrons by the ^{21}Ne (α, n) ^{24}Mg reaction.

Whatever the source of neutrons, the resulting process may be called neutron capture on a slow time-scale (Burbidge *et al.* have abbreviated this to *s*-process [4]). The early neutrons are captured predominantly by the nuclei of the iron abundance peak. Continuing neutron capture (interspersed with beta-decays) then drives some of the nuclei toward the heavy element region. The heavy element abundances become about three orders of magnitude larger than those originally present in the star [2]. Heavy element synthesis terminates at lead and bismuth because further neutron capture leads to short-lived nuclei which decay by alpha-particle emission. Only a small amount of neutron-evolved material need be mixed into stellar surface layers to produce the characteristic over-abundances of S and Ba II stars.

A brief summary was also given of the speaker's recent work on super-nova explosions: A very massive star is considered in an advanced stage of evolution. It is postulated that there is a degenerate core composed of the nuclei in the iron equilibrium peak at a temperature not much in excess of 2×10^{9} °K. This is surrounded by successive layers of intermediate elements, carbon, helium, and hydrogen. The intermediate layer also contains heavy elements made by neutron capture on a slow time-scale through a series of reactions accompanying carbon consumption (not described above).

As the mass of the central core increases, the central density becomes very large, and the Fermi level of the electrons becomes several MeV. The iron nuclei capture some of the electrons and are driven away from the valley of beta-stability. At a density of about 10^{11} g/cm^{3} the electron capture products become unstable to neutron emission. The core then collapses and most of it is converted to neutrons.

The outer layers also implode, but very little nuclear activity takes place in the hydrogen and helium layers. The carbon layer is mostly converted to oxygen and magnesium-region nuclei. The remainder of the material is converted to nuclei of the silicon-calcium region. The heavy elements mostly survive intact, but some of them suffer photo-disintegration, forming 'by-passed' heavy nuclei. The energy released by these transformations explodes the envelope away from the core.