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Direct Production of 56Fe In Silicon Quasi-Equilibria and the Problem of 58Ni

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DIRECT PRODUCTION OF ^{56}Fe IN SILICON QUASI-EQUILIBRIA AND THE PROBLEM OF ^{58}Ni

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ABSTRACT

We consider two questions of importance to the science of nucleosynthesis: (1) Can ^{56}Fe, rather than ^{56}Ni, have been synthesized in its observed ratio to ^{28}Si within a silicon-burning quasi-equilibrium? (2) What accounts for the large abundance of ^{58}Ni? The answer to the first question is in the negative, because a large overabundance of other neutron-rich nuclei, especially ^{54}Fe or ^{52}Cr, appears in the quasi-equilibrium distributions which yield the observed abundance ratio for ^{56}Fe/^{28}Si. The large ^{58}Ni abundance seems to imply one of the following: (1) the iron peak is synthesized in an *e*-process dominated by ^{56}Ni, in which case the lighter α-particle nuclei are probably synthesized in a cooler mass zone of the same object; (2) the iron peak represents a superposition of at least two considerably different types of equilibrium processes, one accounting for ^{56}Ni and the other accounting for ^{54}Fe and ^{58}Ni; or (3) ^{58}Ni is due to the *p*-process. Determination of the proper means of production of ^{58}Ni is one of the most important problems associated with nucleosynthesis today.

In their paper on the *e*-process, Fowler and Hoyle (1964) showed that the isotopes of iron could be synthesized in their observed ratios in a complete nuclear equilibrium near $T_9 = 3.8$ in a gas having a proton-to-neutron ratio near $\langle Z \rangle / \langle A - Z \rangle = 0.87$. They observed that the proton-rich nuclei ^{50}Cr and ^{58}Ni were noticeably absent in such circumstances, and they conjectured that some special component rich in those two nuclei would be required to account for their presence.

Bodansky, Clayton, and Fowler (1968*a*, *b*) raised quite a different possibility by showing that the partial equilibrium which is naturally established during silicon burning in a gas having $\langle Z \rangle / \langle A - Z \rangle \approx 1$ reproduces not only the isotopes of iron but all of the most abundant nuclei in the range $28 \leq A \leq 57$ (see, e.g., their Fig. 3 of 1968*b*). In addition to the iron peak, their results rather nicely account for the abundances of ^{50}Cr, ^{52}Cr, and ^{53}Cr, along with the α-particle nuclei, ^{44}Ca, and three isotopes of Ti. So impressive is the overall fit that Bodansky *et al.* suggested the hypothesis that such quasi-equilibria were probably the major sources of nucleosynthesis in this mass range. This supposition has assumed added importance with the demonstration by Clayton, Colgate, and Fishman (1969) that, if the hypothesis of Bodansky *et al.* is correct and if nucleosynthesis occurs in supernovae, then young supernovae will have an identifiable and measurable spectrum of nuclear γ-ray lines. These lines are expected to be emitted following the decay of ^{56}Ni (and other less abundant radioactive species) to ^{56}Fe (and other daughters). These lines would not be expected, on the other hand, if the Fowler-Hoyle *e*-process is the correct alternative, because the important radioactive species are not prominent when ^{56}Fe is produced directly. Bodansky *et al.* found that partially burned silicon in general does not produce ^{58}Ni and ^{58}Fe in the observed quantities; however, a relatively modest subsequent *s*-process (Clayton *et al.* 1961) can produce ^{58}Fe from ^{56}Fe and ^{57}Fe. The difficulty for each theory lies in the problem of ^{58}Ni, for its considerable abundance cannot be produced by neutron irradiation of any seed nucleus. Indeed, the position of ^{58}Ni in the chart of nuclides warrants a *p*-designation (Clayton 1968), although its source may not be the same *p*-process (Burbidge *et al.* 1957; Ito 1961) that is responsible for the heavier proton-rich nuclei.

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The silicon quasi-equilibrium produces an iron peak dominated by ^{56}Ni, because $\langle Z\rangle/\langle A - Z\rangle \approx 1$. In this paper we consider whether a silicon quasi-equilibrium, with $\langle Z\rangle/\langle A - Z\rangle < 1$ for some unspecified reason, can also reproduce the main abundance features in the range $28 \leq A \leq 57$ accompanied by direct production of ^{56}Fe near its observed abundance relative to ^{28}Si, and whether the same circumstances may not also account for the large abundance of ^{58}Ni. Both conjectures fail, and in examining the sources of failure we shall place this problem in clearer perspective. Then we shall show that ^{58}Ni can be produced in an *e*-process dominated by ^{56}Ni.

I. FITTING ^{28}Si, ^{56}Fe, AND ^{58}Ni

The basic calculation is simple. It is possible to demand that the quasi-equilibrium with ^{28}Si contain any desired ratios for ^{56}Fe/^{28}Si and ^{58}Ni/^{56}Fe. In the notation of Bodansky *et al.* (1968*a*, *b*),

$$\frac{n(^{56}\mathrm{Fe})}{n(^{28}\mathrm{Si})} = C(^{56}\mathrm{Fe},T)n_\alpha{}^6 n_n{}^4 \qquad (1)$$

and

$$\frac{n(^{58}\mathrm{Ni})}{n(^{56}\mathrm{Fe})} = \frac{C(^{58}\mathrm{Ni},T)}{C(^{56}\mathrm{Fe},T)}\frac{n_\alpha}{n_n{}^2} = \frac{C(^{58}\mathrm{Ni},T)C_\alpha(T)}{C(^{56}\mathrm{Fe},T)}n_p{}^2 , \qquad (2)$$

where the coefficients $C(^AZ,T)$ are given in their Table 1. The equilibrium $n_\alpha = C_\alpha(T)n_n{}^2n_p{}^2$ which is employed in equation (2) causes the values of n_α, n_p, and n_n to be determined by specification of the two abundance ratios displayed in equations (1) and (2). From those light-particle densities the abundance of every species can be calculated. In particular, we may take the choices $n(^{56}\mathrm{Fe})/n(^{28}\mathrm{Si}) = 0.18$ and $n(^{58}\mathrm{Ni})/n(^{56}\mathrm{Fe}) = 0.19$, which correspond to Fe $= 1.8 \times 10^5$ on the scale Si $= 10^6$, and take the remaining abundances directly from Cameron (1967). The associated abundance distribution calculated for the temperature $T_9 = 4.4$ is shown in Figure 1. The same calculation at other values of the temperature gives results so similar to this one that they need not be shown. The major difficulties with this abundance distribution are the abundance ratio $n(^{54}\mathrm{Fe})/n(^{56}\mathrm{Fe})$, which is greater than 1, and the high abundance of ^{52}Cr. The first difficulty, which is hopelessly severe, implies that an upper limit on the presence of this component in the solar abundances can be obtained by limiting it to a mass fraction consistent with the production of our entire supply of ^{54}Fe. This upper limit is so small that one can conclude that this distribution has made a negligible contribution to every abundance except ^{54}Fe and ^{52}Cr. There is thus little reason to consider it at all.

A simple demonstration of the impossibility of getting a proper yield of ^{58}Ni in a quasi-equilibrium distribution having substantial concentrations of the medium α-particle nuclei as well can be obtained from the ratio of ^{58}Ni to ^{54}Fe:

$$\frac{n(^{58}\mathrm{Ni})}{n(^{54}\mathrm{Fe})} = \frac{C(^{58}\mathrm{Ni},T)}{C(^{54}\mathrm{Fe},T)}n_\alpha , \qquad (3)$$

which has a value of 3 for the choice Fe $= 1.8 \times 10^5$ and a value of 0.6 if the higher meteoritic abundance of Fe is used. The difficulty is that obtaining a ratio in this range requires such a large value for n_α that one must have $n(^{40}\mathrm{Ca})/n(^{28}\mathrm{Si}) \gg 1$. For example, at $T_9 = 4.4$, the limit $n(^{58}\mathrm{Ni})/n(^{54}\mathrm{Fe}) > 1$ yields $\log n_\alpha > 28.27$, in which case $n(^{40}\mathrm{Ca})/(^{28}\mathrm{Si}) > 50$. Such a steeply rising slope for the α-particle abundances is quite unlike the falling slope obtained in a silicon quasi-equilibrium having a large component of unburned silicon. In fact, such a demand clearly requires that the ^{28}Si be almost completely consumed. If we stipulate, in addition, that the neutron density n_n have a value consistent with the ^{56}Fe/^{54}Fe isotope ratio,

$$
\begin{aligned}
n_n^2 &= \frac{4\omega(^{54}\mathrm{Fe})}{\omega(^{56}\mathrm{Fe})}\left(\tfrac{54}{56}\right)^{3/2}\left(\frac{2\pi M_u kT}{h^2}\right)^3 \exp\left[-\frac{B_n(^{56}\mathrm{Fe})+B_n(^{55}\mathrm{Fe})}{kT}\right]\frac{n(^{56}\mathrm{Fe})}{n(^{54}\mathrm{Fe})} \\
&= \frac{C(^{54}\mathrm{Fe},T)}{C(^{56}\mathrm{Fe},T)}\,\frac{n(^{56}\mathrm{Fe})}{n(^{54}\mathrm{Fe})}\,,
\end{aligned}
\tag{4}
$$

we then see easily from equation (1) that a value of n_α large enough to satisfy the ^{5}Ni/^{54}Fe abundance ratio in equation (3) necessarily requires $n(^{56}\mathrm{Fe})/(^{28}\mathrm{Si}) \gg 1$. For example, at $T_9 = 4.4$ the limit $\log n_\alpha > 28.27$ yields $\log n(^{56}\mathrm{Fe})/n(^{28}\mathrm{Si}) > 8.68$ for those values of n_n obtained from equation (4). Such a situation is more suggestive of *complete*

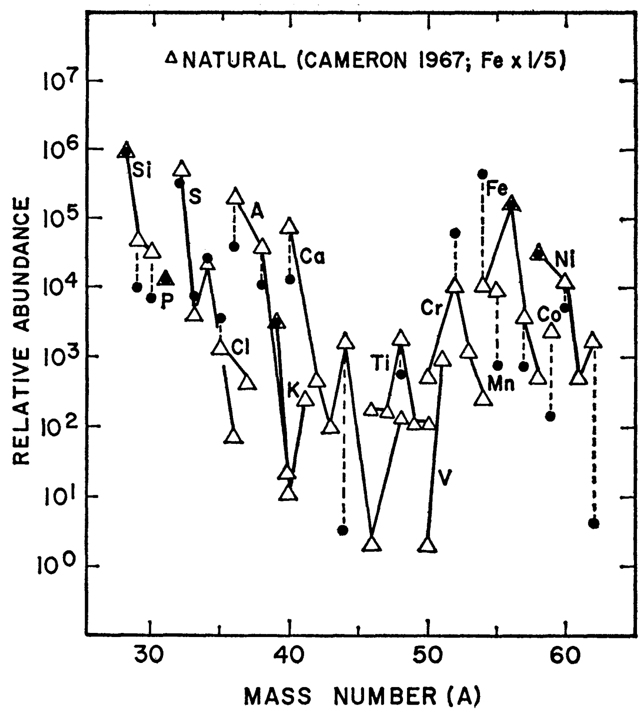

FIG. 1.—Quasi-equilibrium abundances at $T_9 = 4.4$ and $\rho = 10^8$ g cm^{-3} for a composition that produces the solar abundance ratios for ^{28}Si, ^{56}Fe, and ^{58}Ni. *Triangles*, solar abundances; *dots*, abundances in quasi-equilibrium with ^{28}Si. Calculated abundances not shown are all very small. The huge overabundances of ^{54}Fe disqualify this distribution. Different choices for T and ρ do not substantially alter this conclusion.

nuclear equilibrium (*e*-process) than of incomplete silicon burning. In neither of these processes, however, is it possible to obtain $\log n_\alpha > 28.3$ at $T_9 = 4.4$. That is, although n_α increases as ^{28}Si disappears, complete nuclear equilibrium limits the value of n_α to values too small to satisfy equation (3).

Assigning to Fe its meteoritic abundance (an increase by a factor of 5) does not improve the overall fit of the quasi-equilibrium abundances when ^{56}Fe is produced directly. The ratio in equation (1) is *increased* by a factor of 5, whereas the ratio in equation (2) is *decreased* by a factor of 5; clearly, n_p decreases and n_n increases. The calculated abundance distribution at $T_9 = 4.4$ is shown in Figure 2. The results at other temperatures are similar. The change has reduced $n(^{54}\mathrm{Fe})/(^{56}\mathrm{Fe})$ to a value only slightly less than unity, but the overabundance of ^{52}Cr is now even more severe. Once again we can conclude that this component in the solar abundances is negligible. In general we conclude that the direct production of ^{56}Fe and ^{58}Ni in a silicon-burning quasi-equilibrium cannot have occurred in substantial amounts.

II. FITTING ^{28}Si, ^{54}Fe, AND ^{56}Fe

Suppose we relax the constraint requiring that $n(^{58}\mathrm{Ni})/n(^{56}\mathrm{Fe})$ assume its observed value and replace it instead with a constraint requiring that $n(^{56}\mathrm{Fe})/(^{54}\mathrm{Fe})$ assume its observed value of 15.7. We may still retain any desired value for the ratio $n(^{56}\mathrm{Fe})/n(^{28}\mathrm{Si})$. The combination of equations (1) and (4) then fixes the abundances of every nucleus. Inasmuch as the new constraint increases the neutron density by a factor consistent with the large increase of the $n(^{56}\mathrm{Fe})/n(^{54}\mathrm{Fe})$ ratio, this quasi-equilibrium distribution must be characterized by a smaller proton-to-neutron ratio $\langle Z\rangle/\langle A - Z\rangle$. The

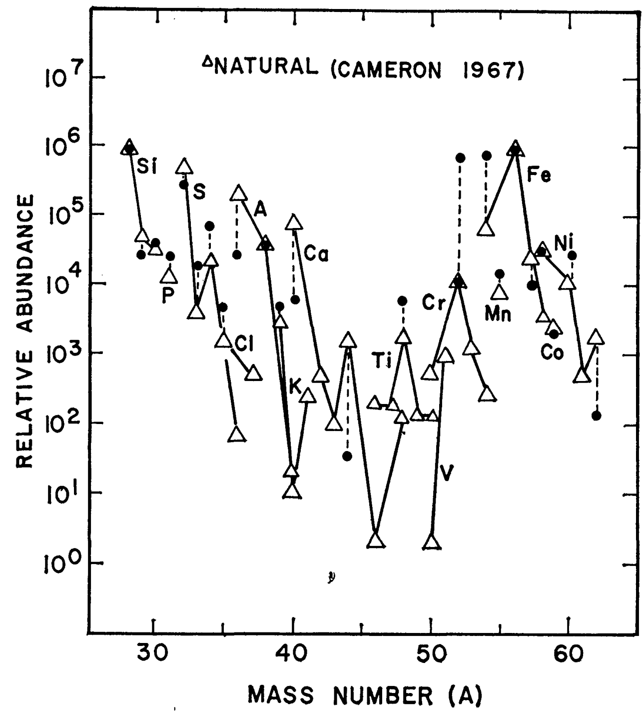

FIG. 2.—The solar abundance of iron increased by a factor of 5 over the value used for Fig. 1; but fitting the revised abundance ratios for ^{28}Si, ^{56}Fe, and ^{58}Ni still shows disqualifying overabundances of ^{52}Cr and ^{54}Fe.

results of one such calculation are shown in Figure 3, which was computed for the same temperature ($T_9 = 4.4$) and the same ^{56}Fe/^{28}Si ratio as in Figure 1. As expected, ^{58}Ni is essentially absent, but the isotopes of Fe and Mn fit well. To ascertain whether this distribution may be naturally prominent, we must examine the remainder of the distribution for overabundances that limit this component. Such overabundances are not hard to find. The worst case is ^{52}Cr, which is now more abundant than ^{56}Fe. This unrealistic ratio reflects a small α-particle density, which is also discernible in the extremely rapid decrease among the α-particle nuclei ^{28}Si, ^{32}S, ^{36}A, and ^{40}Ca. Another great overabundance occurs in the neutron-rich isotopes of Si and S. The two-neutron separation energy required to reduce ^{34}S to ^{32}S is essentially equal to that required to reduce ^{56}Fe to ^{54}Fe, so a value of n_n large enough to reproduce the ratio $n(^{56}\mathrm{Fe})/n(^{54}\mathrm{Fe})$ greatly overestimates the ratio $n(^{34}\mathrm{S})/n(^{32}\mathrm{S})$. For these reasons, we can once again conclude that distributions similar to this one are of little natural significance. Changes of temperature have little effect. The overabundance of the heavy isotopes of Si and S can be eliminated by reducing the ^{28}Si/^{56}Fe ratio by an order of magnitude, but the overabundance at ^{52}Cr persists until considerably greater reductions in n^{28}(Si)/n(^{56}Fe) have been made. Again, we have found that we are driven toward thermal equilibrium (e-process) to achieve a satisfactory distribution in which ^{56}Fe is produced directly. That eventuality would be disappointing for γ-ray astronomy (Clayton *et al.* 1969), for it is only those silicon-burning quasi-equilibria that produce ^{56}Ni rather than ^{56}Fe which are rich in the prominent radioactive species responsible for the γ-ray lines. If ^{56}Fe had been synthesized in a complete e-process, the outstanding success of the silicon quasi-equilibrium would have to be regarded as fortuitous.

The resolution of this problem may be the most important task presently confronting nuclear astrophysics, for the two alternatives will demand quite different models of

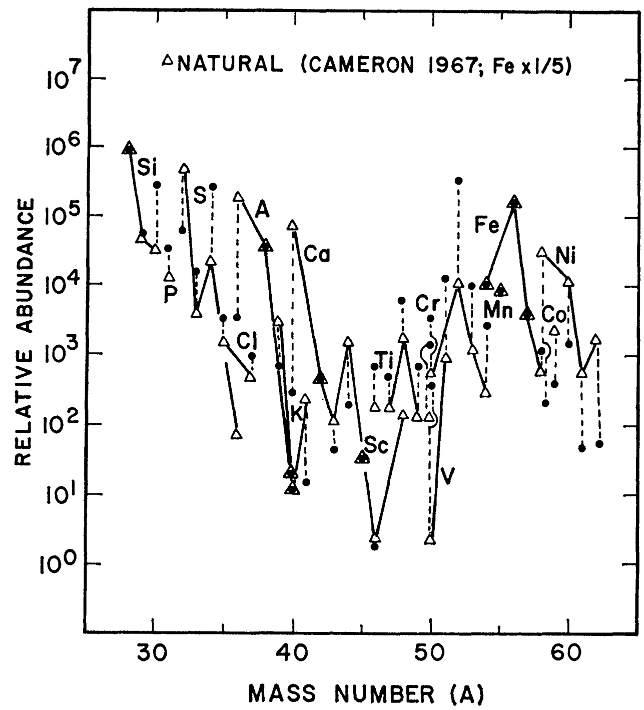

FIG. 3.—Quasi-equilibrium abundances at $T_9 = 4.4$ and $\rho = 10^8$ g cm^{-3} for a composition that produces the solar-abundance ratios for ^{28}Si, ^{54}Fe, and ^{56}Fe. The huge overabundance of ^{52}Cr disqualifies this distribution. Different choices for T, ρ, and the Fe abundance do not alter this conclusion.

the site of nucleosynthesis. We have here a most remarkable situation—one in which the abundances of the isotopes of Fe (and ^{55}Mn) can be successfully reproduced by two very different equilibrium processes, one which correlates the abundances of ^{56}Fe and ^{57}Fe with the nuclear properties of ^{56}Ni and ^{57}Ni, and another which correlates the abundances of ^{56}Fe and ^{57}Fe with their own nuclear properties.

Neither model accounts for the high abundance of ^{58}Ni, which has always been assumed to be a participant in the correct equilibrium process because it is bypassed in the secondary neutron processes. We can present a particularly clear display of this dilemma. Abundances of isotopes of the same element in any bath in which equilibrium is maintained between (n,γ) and (γ,n) reactions are related by the free-neutron density n_n. The corresponding relations can be reduced to the following numerical equations:

$$\frac{n(^{56}\text{Fe})}{n(^{57}\text{Fe})} = 0.128 \times 10^{13\ 16/T_9}\left[\frac{n(^{54}\text{Fe})}{n(^{56}\text{Fe})}\right]^{1/2} \qquad (5a)$$

$$\frac{n(^{57}\mathrm{Fe})}{n(^{58}\mathrm{Fe})} = 8.97 \times 10^{1.05/T_9}\left[\frac{n(^{54}\mathrm{Fe})}{n(^{56}\mathrm{Fe})}\right]^{1/2} ; \tag{5b}$$

$$\frac{n(^{58}\mathrm{Ni})}{n(^{60}\mathrm{Ni})} = 1.23 \times 10^{0.56/T_9}\,\frac{n(^{54}\mathrm{Fe})}{n(^{56}\mathrm{Fe})} . \tag{5c}$$

These ratios are plotted against the ratio $n(^{54}\mathrm{Fe})/n(^{56}\mathrm{Fe})$ in Figure 4 for three different values of the temperature. The temperature dependence is quite weak except in equation (5a). The points corresponding to the natural solar isotope ratios are also shown. Although it is possible to find near fits for the isotopes of Fe, the natural ratio $n(^{58}\mathrm{Ni})/n(^{60}\mathrm{Ni})$ falls far from its lines, which are almost completely temperature insensitive. The difference is in the direction of excess natural ^{58}Ni. Weak *s*-processing of equilibrium distributions can account for some ^{60}Ni but no ^{58}Ni, so any subsequent *s*-process only makes the problem worse. The predicament is so impossible that we wish to emphasize it and to add that a natural clue is probably lurking in the large ^{58}Ni abundance. A natural source of this nucleus will have many implications for the isotope ratios of other elements and for the site of nucleosynthesis. We turn now to possible solutions of this problem.

III. FITTING ^{54}Fe, ^{56}Ni, AND ^{58}Ni

The most likely solution appears to us to lie in yet another alternative for fixing key equilibrium ratios. The ^{58}Ni can be produced in the equilibrium bath if ^{56}Ni rather than ^{58}Ni is the source of the natural ^{56}Fe. In that case we may constrain the solution to produce ^{54}Fe, ^{56}Ni, and ^{58}Ni in the desired ratios by choosing the free-nucleon densities such that

$$\begin{aligned} n_n^2 &= \frac{4\omega(^{56}\mathrm{Ni})}{\omega(^{58}\mathrm{Ni})}\left(\tfrac{56}{58}\right)^{3/2}\left(\frac{2\pi M_u kT}{h^2}\right)^3 \exp\left[-\frac{B_n(^{58}\mathrm{Ni})+B_n(^{57}\mathrm{Ni})}{kT}\right]\frac{n(^{58}\mathrm{Ni})}{n(^{56}\mathrm{Ni})} \\ &= \frac{C(^{56}\mathrm{Ni},T)}{C(^{58}\mathrm{Ni},T)}\,\frac{n(^{58}\mathrm{Ni})}{n(^{56}\mathrm{Ni})} \end{aligned} \tag{6}$$

and

$$n_p^2 = \frac{C(^{54}\mathrm{Fe},T)}{C(^{56}Ni,T)}\,\frac{n(^{56}\mathrm{Ni})}{n(^{54}\mathrm{Fe})} . \tag{7}$$

Simultaneous satisfaction of equations (6) and (7) determines the value of n_α, which of course also satisfies equation (3). These free densities once again determine all heavy-abundance ratios. In Figure 5 we show the abundance distribution corresponding to the choices $\log n_\alpha = 21.77$ and $\log n_n = 28.65$ at $T_9 = 4.4$. It can be seen that this solution provides an interesting approach to fitting the abundances in the iron peak. It corresponds to a nearly complete equilibrium, so the abundances below Cr are very small and are not shown.

The value of $\langle Z\rangle/\langle A - Z\rangle$ corresponding to Figure 5 is slightly density dependent, having the value $\langle Z\rangle/\langle A - Z\rangle = 0.9825$ if $\rho = 10^8$ g cm^{-3}. It is also possible to satisfy these three abundances for other values of the temperature if $\langle Z\rangle/\langle A - Z\rangle$ and ρ have a proper relationship to each other. For example, Table 1 shows how the proper values of $\langle Z\rangle/\langle A - Z\rangle$ and the ^{28}Si mass fraction f_{Si} depend upon temperature at the density $\rho = 10^8$. The smallness of the silicon mass fraction indicates that the conditions are *similar* to an *e*-process in which ^{56}Ni is the major nucleus. These *f*-values are in fact *smaller* than their values in nuclear equilibrium at the same temperature, so attainment of such distributions would, in fine detail, be coupled to a rapid dynamic history.

The value of $\langle Z\rangle/\langle A - Z\rangle$ yielding the desired ratios exceeds unity at very high temperature because of the very large free-proton density, which increases the total $\langle Z\rangle/\langle A - Z\rangle$ to a value significantly larger than the one corresponding to the heavy-element distribution alone. The material contributing to nucleosynthesis must be expanded and cooled, so the value $\langle Z\rangle/\langle A - Z\rangle \approx 0.98$ is probably near the one that will produce the desired results. Careful dynamic calculations of the "nuclear freezing" will clarify the fine details of this point, but we have not attempted such elaborate calculations for the purposes of this paper. We note only that the magnitude of the neutron excess, here

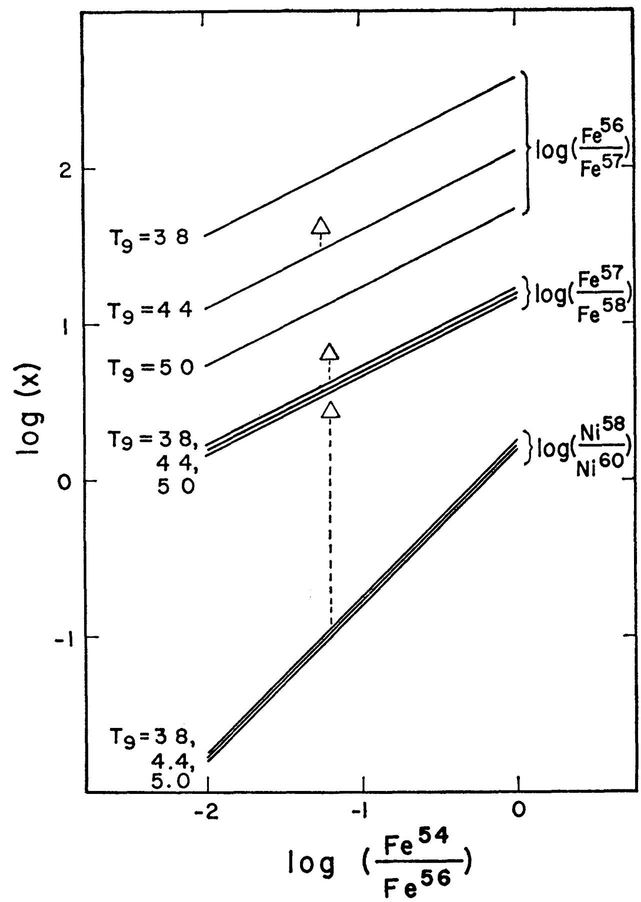

FIG. 4.—The way in which isotope ratios for Fe and Ni depend upon the ratio $n(^{54}\text{Fe})/n(^{56}\text{Fe})$ under conditions characterized by equilibrium with the free-neutron gas. Solar ratios indicated by points connected with dashed lines to the relevant set of lines. Only the ratio $n(^{56}\text{Fe})/n(^{57}\text{Fe})$ shows considerable temperature sensitivity. Inasmuch as simultaneous satisfaction of these ratios is impossible, one must consider the question of which ratios participate in the equilibrium process and which do not.

of the order of 1 percent, will greatly influence the ^{58}Ni abundance in solutions of this type. Thus if ^{58}Ni is to be due to such processes, we may anticipate some exacting constraints on the history of the synthesizing event, in which case the "problem of ^{58}Ni" will be a blessing in disguise.

It should also be noted that ^{55}Mn, ^{57}Fe, and ^{59}Co are also well represented in Figure 5 by the parents ^{55}Co, ^{57}Ni, and ^{59}Cu. From this point of view the nuclei ^{58}Fe, ^{60}Ni, ^{61}Ni, and ^{62}Ni will most likely be relegated to the subsequent small *s*-process irradiations in later generations of stars, and calculations checking the feasibility of this procedure are under way. The isotopes of Cr are underabundant in this particular figure, but there always exist other possibilities for making up the underabundances, whereas eliminating overabundances, such as those that plague Figures 1 and 2, seems impossible. In short, we regard solutions of this type as being good candidates for the synthesis of the iron peak. Satisfactory solutions involving the higher meteoritic Fe abundance are not out of the question, although we have found with that choice a tendency to overproduce ^{55}Mn by factors of 5–10 if its natural abundance is not also increased. It is in fact an interesting feature of this type of solution that it depends on the relative abundances of Mn, Fe, and Ni, whereas other equilibrium processes do not seem to have much relation to Ni abundances. We do not feel that an elaborate discussion of these many details is required for the point of this paper, however.

The outstanding success of Bodansky *et al.* in reproducing the abundant nuclei throughout the range $28 \leq A \leq 57$ is not necessarily relegated to a fortuitous coincidence if this alternative C is correct, for it seems quite natural also that two somewhat different mass fractions of a dynamically exploding star are involved. The hotter mass

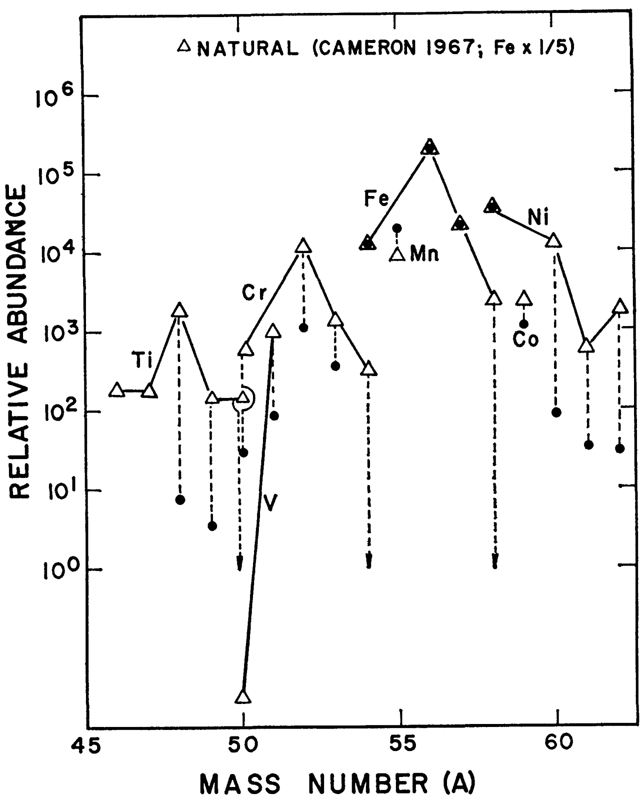

FIG. 5.—Quasi-equilibrium abundances at $T_9 = 4.4$ and $\rho = 10^8$ g cm^{-3} for a composition that produces the solar-abundance ratios for ^{54}Fe, ^{56}Ni, and ^{58}Ni. The nuclei ^{55}Mn, ^{57}Fe, and ^{59}Co may also be accounted for by such distributions. Atomic weights less than 52 are not substantially synthesized in such distributions, because these conditions are near an e-process dominated by ^{56}Ni.

TABLE 1

COMPOSITION PARAMETERS AT $\rho = 10^8$ g cm^{-3}

T_9	$\langle Z\rangle/\langle A-Z\rangle$	f_{Si}	log n_p
4 4....	0 9825	8 4×10^{-10}	28 650
5 0.... .	0.9927	3 2×10^{-9}	29 574
5.6........	1.0518	7.3×10^{-9}	30 308

fraction may carry silicon burning to completion, whereas the cooler fraction may have time only to establish the quasi-equilibrium up to the abundance minimum near $A = 44$. The relative constancy of the abundance ratios observed in stars in this mass range may reflect only the near constancy of the ratio of these two mass fractions, much in the manner recently discussed by Arnett (1969). The exciting new prospects for γ-ray astronomy discussed by Clayton *et al.* (1969) then remain intact.

IV. OTHER POSSIBILITIES

Other possibilities seem to exist if different nuclei within the iron peak can be attributed to different equilibria. The only plausible possibility was suggested to us by R. A. Wolf (personal communication). The silicon quasi-equilibria with $\langle Z\rangle/\langle A - Z\rangle \approx 1$ may upon freezing contain only the α-particle nuclei in substantial numbers and thereby contribute to the iron peak only as ^{56}Ni. To this component may be added an *e*-process accounting for ^{54}Fe and ^{58}Ni, and perhaps others, but adding little at $A = 56$. Such *e*-processes are possible, as shown for example by Clifford and Tayler (1965), when $\langle Z\rangle/\langle A - Z\rangle$ is sufficiently less than unity that ^{56}Ni is not prominent, yet is not small enough for ^{56}Fe to have taken over—roughly $0.90 < \langle Z\rangle/\langle A - Z\rangle < 0.98$. How nature will provide for two such widely different circumstances is not clear, but the possibility should not be regarded as overly implausible. We have not surveyed this type of possibility for this paper, partly because the nonequilibrium freezing reactions must apparently be included to ascertain whether the details of the iron peak can be assembled in this way.

Finally, we must recognize that ^{58}Ni may not participate in the process responsible for the iron peak. The only feasible possibility that we have imagined is production in a secondary *p*-process in the events (essentially unknown) responsible for the heavier *p*-nuclei. The addition of two protons to ^{56}Fe could in principle do the trick inasmuch as the abundance ratio of ^{56}Fe/^{58}Ni could be as large as 30 if the meteoritic abundances correctly represent the solar abundances. Only an unambiguously correct *p*-process theory can provide a definitive answer to this possibility.

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