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NUCLEOSYNTHESIS DURING SILICON BURNING*

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Silicon burning at temperatures in the neighborhood of 4×10^9 °K has been studied with the aid of a quasiequilibrium model which describes the abundance of the nuclei in the interval $28 \leq A \leq 62$. It is found that, for a broad range of temperatures and densities, silicon burning leads to nuclear abundance distributions which match important features of the natural solar-system abundance distributions and that a large nuclear energy release accompanies silicon burning.

It is generally believed that in the evolution of the thermonuclear gas which constitutes the matter of stellar interiors, an epoch is reached in which the matter is primarily in the form of ^{28}Si and, to a lesser extent, of ^{32}S. This phase can be reached after the fusion of ^{16}O at temperatures in the neighborhood of 2×10^9 °K. It follows from general considerations[1,2] based on the unusually large nuclear binding energy of ^{28}Si that little subsequent nuclear activity occurs until the temperature becomes sufficiently high to cause (γ,p) and (γ,α) reactions on ^{28}Si. This breakdown of ^{28}Si by photodisintegration is accepted[1,2] as being the precursor to a reassembly of the nucleon gas into the nuclei which constitute the iron-group natural abundance peak (predominantly isotopes of Fe and Ni). By a sequence of (γ,α) reactions, and to a lesser degree (γ,p) and (γ,n) reactions, ^{28}Si nuclei are decomposed into α particles, protons, and neutrons, which are then captured by other ^{28}Si nuclei leading to ^{32}S and then heavier nuclei. The present paper describes the results of an analysis which clarifies the detailed nature of this process, termed silicon burning, which determines the time scales and energy generation during silicon burning, and which shows how silicon burning accounts for many crucial features of the observed natural solar-system abundances of the nuclei between $A=28$ and $A=57$. A more complete discussion of these results and their astrophysical applications is being prepared for publication elsewhere.

For simplicity in this analysis, it was assumed that the starting point is a gas of pure ^{28}Si and that the gas remains at constant temperature and density as the conversion of ^{28}Si to other nuclei proceeds. The rate of buildup of the nuclei heavier than ^{28}Si is governed by the rate at which α particles are made available through the photodisintegration of ^{28}Si.[1,2] The crucial qualitative feature of this rate is that it is slow compared to the nuclear reaction rates above ^{28}Si. The rate is determined by a photodisintegration chain in the nuclei lighter than ^{28}Si. In the first instance, ^{24}Mg is formed and its density rises to a value limited by equilibrium in the reactions $^{24}\mathrm{Mg}+\alpha \rightleftarrows {}^{28}\mathrm{Si}+\gamma$. By virtue of the high α-particle binding energy in ^{28}Si, the ^{24}Mg number density is small compared to the ^{28}Si density. The further disintegration of ^{28}Si then occurs by way of the photodisintegration of the much less abundant, and also tightly bound, ^{24}Mg.[3] It is the slow ^{24}Mg photodisintegration rate which sets a limit on the effective photodisintegration rate of ^{28}Si and allows the reactions in the heavier nuclei to come into the quasiequilibrium condition discussed below.

As the α particles are liberated by the photodisintegration of ^{28}Si they are initially consumed by the reaction $^{28}\mathrm{Si}(\alpha,\gamma)^{32}\mathrm{S}$, resulting in a buildup of ^{32}S. However, because the ^{32}S undergoes (γ,α) reactions with a shorter lifetime than ^{28}Si, the capture of α particles and the buildup of ^{32}S is halted by the equilibration of the inverse reactions $^{28}\mathrm{Si}+{}^{4}\mathrm{He} \rightleftarrows {}^{32}\mathrm{S}+\gamma$. [If substantial amounts of ^{32}S are admitted to be initially present, the same equilibrium is established by (γ, α) reactions on ^{32}S.] In a similar manner, the reactions involving heavier nuclei subsequently achieve equilibrium, and the heavier nuclei build up to concentrations such that they liberate α particles at virtually the same rate at which they consume α particles; therefore, the α-particle density assumes a quasistatic value. On a much longer time scale the ^{28}Si slowly "melts," thereby injecting more α particles into the bath. The new α particles are consumed in the formation of more heavy nuclei, establishing just the abundance required to maintain a new equilibrium between (α, γ) and (γ, α) reactions. In an analogous manner, quasistatic concentrations of free protons and neutrons are maintained by equilibration of reactions involving nucleons, photons, and α particles. We call this situation nuclear quasiequilibrium, in that the nuclei heavier than ^{28}Si are in equilibrium under the exchange of protons, neutrons, and α particles. It is not a true nuclear equilibrium because the ^{28}Si itself, which is disintegrated comparatively slowly, does not have sufficient time to come into equilibrium with the free concentrations of light particles and because the quasiequilibrium densities change slowly with time.

In the quasiequilibrium, the number densities $n(^AZ)$ of nuclei heavier than ^{28}Si are determined relative to the concentration of ^{28}Si itself by the number densities of free α particles, protons, and neutrons and by the temperature. Accordingly, one has the set of equations

$$n(^AZ) = C(^AZ)n(^{28}\mathrm{Si})n_\alpha^{\delta_\alpha} n_p^{\delta_p} n_n^{\delta_n}, \qquad (1)$$

where each nucleus (^AZ) is thought of as being composed of ^{28}Si plus δ_α α particles plus δ_p protons plus δ_n neutrons. The quantities $C(^AZ)$ depend only upon nuclear binding energies, nuclear partition functions, and the temperature. The α particles and nucleons are themselves in mutual equilibrium via rapid chains of nuclear reactions in heavier nuclei. Thus only two of the densities n_α, n_p, and n_n are independent. At a given temperature, there is a unique solution to Eq. (1) for each value of the amount of residual ^{28}Si if the density and nuclear charge-to-mass ratio are specified.

We have studied the silicon-burning problem by finding $n(^AZ)$, for nuclei in the interval $28 \leq A \leq 62$, for a succession of quasiequilibrium configurations, each with a progressively lower amount of ^{28}Si remaining. The temperature and density were taken to be constant. The time to progress from one configuration to the next is controlled by the effective ^{28}Si photodisintegration rate. These time intervals determine both the rate of nuclear energy generation and the decrease, due to β-decay processes, of the nuclear charge-to-mass ratio, which starts at $\frac{1}{2}$ for the initial ^{28}Si. Electron capture is the principle β-decay process. It was found that, in the most likely silicon-burning circumstances, the conversion is fast enough that β-decay processes can only slightly alter the ratio. In consequence, the equilibrium solutions of the present analysis are characterized by much higher densities of free protons than of free neutrons, and thus by high densities of nuclei on the proton-rich side of the valley of nuclear stability.

Calculations of the evolution of abundances in silicon burning were carried out for temperatures extending from $(3.4 \text{ to } 5.0)\times 10^9\,{}^\circ\mathrm{K}$ and for densities extending from 10^5 to 10^9 g/cm^3. The quasiequilibrium abundance distributions found through this analysis have considerably different properties than the equilibrium solutions which have been studied by other workers[1,4,5] as the source of the iron-group abundance peaks (commonly called the *e* process after Ref. 4). The crucial differences stem from the high ratio of the free-proton to free-neutron number densities and the retention of a substantial fraction of the material in the form of ^{28}Si. The most striking characteristic of the present solutions is the production of ^{56}Ni as the most abundant iron-group nucleus for a wide range of temperatures and densities. However, in the lower range of temperatures (near $3\times 10^9\,{}^\circ\mathrm{K}$) the conversion is slow enough that β-decay processes reduce the ratio n_p/n_n causing ^{54}Fe to replace ^{56}Ni as the most abundant iron-group nucleus. Some aspects of these results have been reported in a study of silicon burning in which the individual reaction rates were integrated numerically.[2,6]

In Fig. 1 we show as an example the quasiequilibrium abundance distribution that obtains when initially pure ^{28}Si has been disintegrated to 35% of its initial value at a temperature of $4.4\times 10^9\,{}^\circ\mathrm{K}$ and a density of 10^8 g/cm^3. (This point is reached after 0.3 sec of ^{28}Si burning.) A recent compilation of the natural solar-sys-

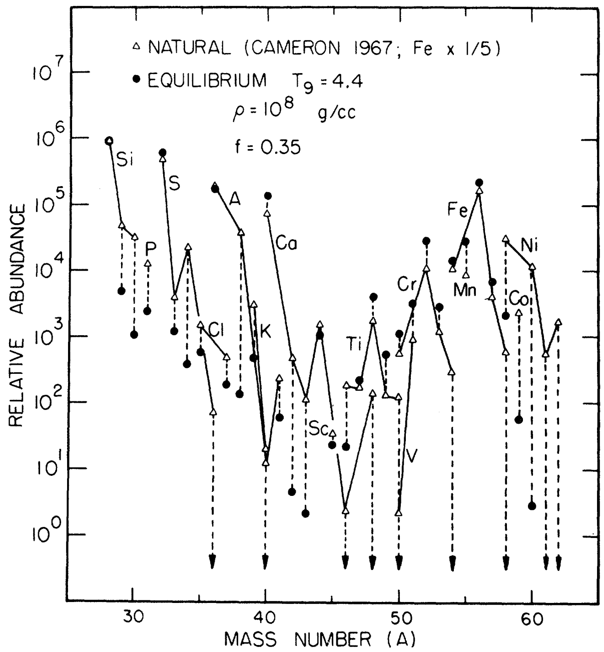

FIG. 1. Comparison between quasiequilibrium abundance reached under typical conditions in ^{28}Si burning and the natural solar-system abundances. (Cameron's value for the Fe abundance has been reduced by a factor of $\frac{1}{5}$, corresponding to a choice of the solar abundance for Fe rather than the meteoritic abundance.) The vertical lines with arrows represent cases where the quasiequilibrium abundances fall off scale.

tem abundances in this mass range is shown for comparison. There is a strong similarity in these abundance patterns for the most abundant nuclei below $A = 58$, namely the $A = 4n$ nuclei and the iron group for $50 \leq A \leq 57$. In this comparison, account is taken of the β-decay processes which occur after silicon burning is completed so that, for example, the natural abundance of ^{56}Fe is attributed to the decay of ^{56}Ni.

The results shown in Fig. 1 are typical of the main features of the abundances achieved in partially burned ^{28}Si over a band of temperatures and densities extending from about 3.8 $\times 10^9$ °K and 10^7 g/cm^3 to 5.0×10^9 °K and somewhat over 10^9 g/cm^3. (Note that at high temperatures, high densities are required to maintain the abundance of ^{56}Ni against dissociation into ^{54}Fe$+2p$). Because of this broad region of agreement with observed abundances and because silicon burning now appears to be a natural epoch in the history of a thermonuclear gas, we surmise that the natural abundance pattern between $A = 28$ and $A = 57$ reflects primarily a superposition of silicon quasiequilibrium burning sequences, followed by ejection of the material from the site of the burning, probably supernovae. If this surmise proves to be correct, the less common nuclei (primarily the neutron-rich isotopes of these elements) must be attributed to a secondary process, most likely the freezing reactions that occur during the expulsion and cooling of this gas, or, alternatively, a subsequent s process.[4,8]

The silicon burning process is strongly exoergic under those conditions of temperature and density which lead to agreement with the observed natural abundances, largely because the dominant product, ^{56}Ni, is tightly bound. Typical energy releases, calculated from the change in total rest mass, are in the neighborhood of 100 keV per nucleon of disintegrated ^{28}Si, which is equivalent to 10^{17} erg/g. The time rate of energy release is governed by the effective rate of the silicon photodisintegration and increases rapidly with increasing temperatures. Over the temperature interval from (3.6 to 5.0)$\times 10^9$ °K, the rate of energy release when the ^{28}Si has been half consumed ranges roughly from 10^{14} to 10^{19} erg/g sec. This power can provide for a short epoch of thermonuclear stability in the core of a presupernova star. The detailed implementation of these results should aid in the understanding of the energy balance in supernova events.

In summary, the distinctive conclusions of the present analysis are the following: (1) The synthesis of the α-particle nuclei above $A = 28$ and of the iron-group nuclei occur simultaneously during silicon burning (specifically, the α process and the e process of Ref. 4 occur simultaneously). (2) The chief quasiequilibrium product in the iron group is generally ^{56}Ni, and its decay after the expulsion of the matter from the star probably accounts for the high natural abundance of ^{56}Fe. (3) Under the most likely conditions, the production of the iron-group nuclei in silicon burning is accompanied by a large release of nuclear energy. (4) The natural abundance of Ni cannot be understood until the secondary processes responsible for the heavy isotopes of Si, S, A, and Ca are understood in detail, but equilibrium explanations for the abundances of ^{58}Ni and ^{60}Ni now appear to be unpromising.

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EVIDENCE FOR THE $I=\frac{1}{2}$ $N^*(1400)$ RESONANCE PRODUCTION IN $\pi^{\pm}p$ INTERACTIONS AT 6 GeV/c*

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Results from a number of high-energy missing-mass spectrometer experiments have indicated the presence of a peak in the strangeness-zero and baryon-number–one system at a mass of about 1.4 GeV.[1] Because its production is peripheral and the width is large (approximately 200 MeV), kinematic interpretations of this peak are possible.[2] However, an extensive pion-nucleon phase-shift analysis suggests that an amplitude, with the same quantum numbers as the nucleon ($I=\frac{1}{2}$ and $J^P=\frac{1}{2}^+$), exhibits resonant properties near this mass region with a large width and inelasticity ($\sigma_{\text{inel}}/\sigma_{\text{total}}\approx\frac{1}{3}$).[3] In order to associate this $N_{1/2}^*(1400)$ deduced from the pion-nucleon phase-shift analysis with the peak observed from production experiments, it is essential to determine its quantum numbers from its decay products. To date, the only relevant bubble-chamber data with adequate statistics have come from a study of the reaction $pp\to pp\pi^+\pi^-$ at 6.6 GeV/c,[4] where a kinematic interpretation of this enhancement is favored. In this Letter, we report our observation of well-defined π^+n and π^-p enhancements centered at 1.42 GeV with a width of the order of 100 MeV, from the reactions $\pi^+p\to\pi^+\pi^+n$ and $\pi^-p\to\pi^0\pi^-p$ at 6 GeV/c. The resonance interpretation of this enhancement is clearly favored in our data. We have determined its isospin to be $\frac{1}{2}$, and we associate it with the $N_{1/2}^*(1400)$ suggested by the phase-shift analysis.

The samples of events for this study come from a 6-GeV/c $\pi^{\pm}p$ experiment in the Brookhaven National Laboratory (BNL) 80-in. liquid-hydrogen bubble chamber. About 30 000 two-prong events in the π^+p exposure and 60 000 two-prong events in the π^-p exposure were analyzed. About one-half of the events were measured by conventional measuring machines and the other half by the BNL flying-spot digitizer. The size of the event samples and cross-section equivalents of the four reactions studied[5] are shown below:

Reaction	Number of events	Events/Cross section equivalent (events/μb)
(1) $\pi^+p\to\pi^+\pi^+n$	1195	1.5
(2) $\pi^+p\to\pi^0\pi^+p$	265	0.3
(3) $\pi^-p\to\pi^+\pi^-n$	5334	4.8
(4) $\pi^-p\to\pi^0\pi^-p$	3376	4.8

In these four reactions, there are two major sources contributing to the background observed in the low $(\pi N)_{I_z=\pm\frac{1}{2}}$ mass region. They are (a) the reflection of strong $\pi\pi$ resonances,[6] which contribute to reactions (2), (3), and (4) but not to (1), and (b) proton dissociation into $(\pi N)_{I_z=+\frac{1}{2}}$ at the nucleon vertex without $N_{1/2}^*$ formation, which contributes to all $(\pi N)_{I_z=+\frac{1}{2}}$ combinations but not to (π^-p) in reaction (4). It should be emphasized that the (π^+n) and (π^-p) mass spectra from reactions (1) and (4), respectively, are the only