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EXPLOSIVE NUCLEOSYNTHESIS IN HELIUM ZONES

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ABSTRACT

We study by numerical integration the network of nuclear reactions that are expected to occur when the helium zones of a star are instantaneously heated and allowed to expand adiabatically. The dependence of the results on nuclear cross-sections, on the peak temperature, and on the time scale of the hydrodynamic expansion are discussed. Of particular interest is the result that the nucleus ^{14}N, constituting about 2 percent by mass following the earlier operation of the CNO cycle, is substantially converted into ^{15}O, ^{18}F, ^{19}Ne, and ^{21}Ne in ratios close to the solar abundances of ^{15}N, ^{18}O, ^{19}F, and ^{21}Ne. It is very likely that these nuclei are synthesized in such zones. The nucleus ^{22}Ne, on the other hand, is apparently not produced in the explosion in sufficient amounts relative to ^{21}Ne, which indicates that ^{22}Ne is probably synthesized in hydrostatic helium burning and survives the ejection.

I. INTRODUCTION

A great deal of success has been achieved in reproducing the abundance distribution of nuclei observed in the solar system by calculating the nucleosynthesis that occurs when nuclear fuels are overheated and quickly expanded. Such thermal histories are chosen to simulate the behavior of noncentral stellar zones when strong pressure waves (or shocks) propagate outward from a dynamic stellar core. The nuclear reactions may burn furiously but briefly. Such nucleosynthesis calculations have come to be called "explosive nucleosynthesis," and their quantitative success in the range of atomic weights $20 \leq A \leq 62$ has recently been summarized by Arnett and Clayton (1970), who also give detailed references to the papers that have established the fruitfulness of this procedure. The success is sufficiently compelling that we presently must believe that the elements have largely been synthesized in exploding objects, probably massive stars.

In this paper we consider the nuclear fate of helium zones surrounding the more evolved core. These zones should in fact be called hydrogen-exhausted zones, because nothing of great interest occurs in a pure-helium zone, which has insufficient time to fuse significant amounts of helium. Nonetheless, we continue the practice of using the terminology "helium zone" to refer to zones whose major constituent is helium produced in an earlier epoch of hydrostatic hydrogen burning. We shall show that the nucleus ^{14}N, constituting about 2 percent by mass following the earlier operation of the CNO cycle, is converted substantially in overheated helium zones into ^{15}O, ^{18}F, ^{19}Ne, ^{21}Ne, and ^{22}Na in relative amounts similar to the solar abundances of ^{15}N, ^{18}O, ^{19}F, and ^{21}Ne; however, the yield of ^{22}Na seems likely to be inadequate for the abundance of ^{22}Ne. We will discuss the nuclear features upon which this transmutation depends and the likelihood that such zones are the natural sources of those nuclei.

II. METHOD OF CALCULATION

A computer code was employed to follow the abundance changes due to nuclear interactions within a helium zone whose temperature was suddenly increased and then allowed to expand adiabatically (a good approximation) on the hydrodynamic time scale used by Arnett (1969). A differential equation for the rate of change of the number density of each nuclear species in the network is written which involves the participating reaction rates. The set of differential equations is then solved by a method of backward

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differencing at each time as described by Arnett and Truran (1969). The original network evolved forty-six nuclei linked by 150 reactions. However, an abbreviated network (see Fig. 1) which included only seventeen nuclei was found to produce nearly the same results (within 10 percent) for the important products. The reactions whose rates were included in the abbreviated code are listed in Table 1. Experimental reaction rates from Fowler; Caughlan, and Zimmerman (1970) are used when available, and estimated rates were taken from Wagoner (1969). Beta-decay rates were included from the ground state of the radioactive nuclei, but they play no significant role during the nuclear burning. The rates for reactions which have no designation in Table 1 are taken from Fowler *et al.* (1970).

III. INITIAL COMPOSITION

The elements synthesized in the helium zone during the explosion are produced from the seed nuclei present in the initial composition of the star but modified by any pre-explosion burning. The pre-explosion burning consists of the hydrogen burning that produced the helium zone plus any hydrostatic helium burning that may have had time to occur in these zones before the explosive pressure wave arrives. For definiteness, we assume the initial composition of the star to have been solar,[1] choosing the abundances of Cameron (1968), and we assume that the hydrogen was exhausted by the CNO cycle. The results of exhausting hydrogen at the temperatures $T = 20$, 40, and 60×10^6 ° K

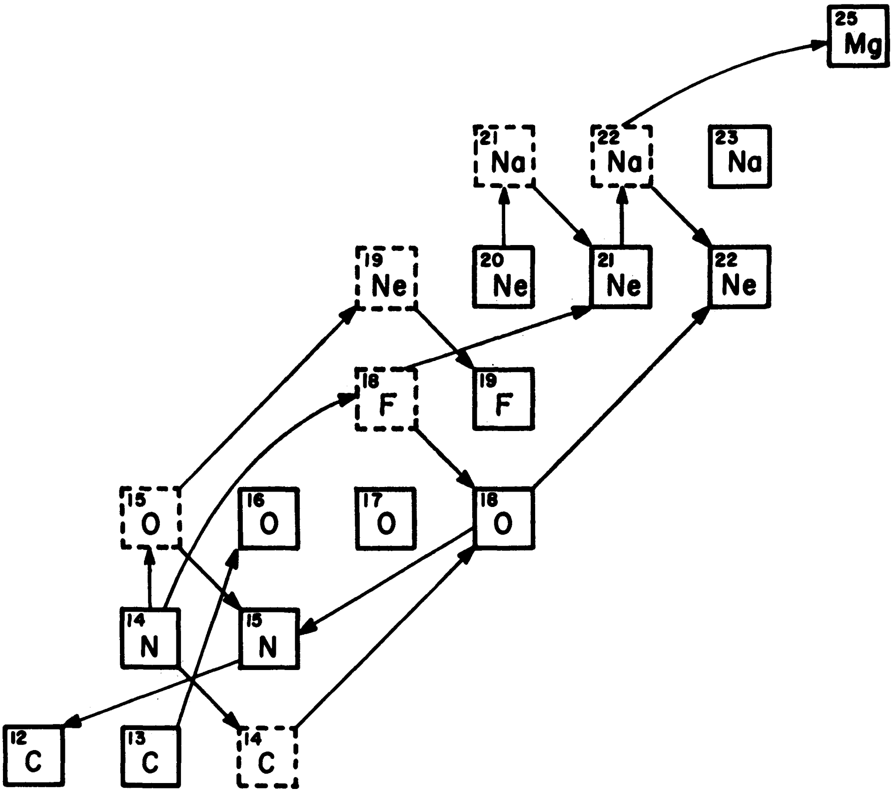

FIG. 1.—The important nuclei participating in the burning, along with key reaction links. *Solid squares,* stable nuclei; *dashed squares,* radioactive nuclei. These nuclei (except ^{17}O and ^{23}Na) comprise the abbreviated network. Arrows represent important reaction links which will be discussed in the paper.

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[1] *Footnote added in proof.*—We find the final abundances to be almost exactly linear in the initial CNO concentration, even though some small nonlinearities exist in the reaction network.

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TABLE 1

NETWORK REACTIONS

$3\ ^4He \rightarrow ^{12}C$
$^{12}C(\alpha,\gamma)^{16}O$
$^{12}C(\alpha,n)^{15}O$
$^{13}C(p,\gamma)^{14}N$
$^{13}C(\alpha,n)^{16}O$
$^{14}C(p,\gamma)^{15}N$
$^{14}C(p,n)^{14}N$
$^{14}C(\alpha,\gamma)^{18}O$
$^{14}N(p,\gamma)^{15}O$
$^{14}N(\alpha,\gamma)^{18}F$
$^{15}N(p,\gamma)^{16}O$
$^{15}N(p,n)^{15}O$
$^{15}N(p,\alpha)^{12}C$
$^{16}O(\alpha,\gamma)^{20}Ne$
$^{18}O(p,\alpha)^{15}N$
$^{18}O(\alpha,\gamma)^{22}Ne$
$^{18}O(\alpha,n)^{21}Ne$
$^{19}F(p,\gamma)^{20}Ne$
$^{19}F(p,n)^{19}Ne$
$^{19}F(p,\alpha)^{16}O$
$^{19}F(\alpha,p)^{22}Ne$
$^{20}Ne(p,\gamma)^{21}Na$
$^{22}Ne(\alpha,n)^{25}Mg$

$^{12}C(n,\gamma)^{13}C$†
$^{13}C(n,\gamma)^{14}C$†
$^{14}N(n,\gamma^{15}N$†
$^{15}N(\alpha,n)^{18}F$†
$^{15}N(\alpha,\gamma)^{19}F$†
$^{18}F(p,\alpha)^{15}O$‡
$^{15}O(\alpha,\gamma)^{19}Ne$†
$^{16}O(\alpha,n)^{19}Ne$†
$^{18}O(p,n)^{18}F$†
$^{18}O(p,\gamma)^{19}F$†
$^{18}F(p,\gamma)^{19}Ne$†
$^{18}F(\alpha,p)^{21}Ne$†
$^{18}F(\alpha,n)^{21}Na$†
$^{19}Ne(\alpha,p)^{22}Na$†
$^{20}Ne(n,\gamma)^{21}Ne$†
$^{21}Ne(n,\gamma)^{22}Ne$†
$^{21}Ne(p,n)^{21}Na$†
$^{21}Ne(p,\gamma)^{22}Na$†
$^{22}Ne(p,n)^{22}Na$†
$^{22}Na(\alpha,p)^{25}Mg$†

† These rates were taken from Wagoner (1969).

‡ The nonresonant cross-section factor $S(E)$ for this reaction was taken to be equal to that of $^{19}F(p,\alpha)^{16}O$.

are listed in Table 2. The classic result of CNO burning is evident: those nuclei are converted almost entirely into ^{14}N, which then serves as the primary seed nucleus for helium reactions. For $T_6 \geq 40$ the ^{16}O is reduced to its equilibrium value by the hydrogen exhaustion; in any case it is sufficiently consumed that it plays no significant role. The only other initial nucleus of any significance is ^{13}C, which quickly liberates neutrons by the $^{13}C(\alpha, n)^{16}O$ reaction when the hydrogen-exhausted zone is heated by the pressure wave. The net effect is changed to a quick burst of protons, however, because the neutrons are almost entirely absorbed by the $^{14}N(n, p)^{14}C$ reaction. At the highest of the three temperatures a small fraction ($\lesssim 10^{-3}$) of the helium is the result of the Ne-Na cycle, and at all three temperatures the initial ^{21}Ne and ^{22}Ne are almost completely consumed by the hydrogen exhaustion.

TABLE 2

MASS FRACTIONS FOLLOWING CNO BURNING

Nucleus	$T_6=20$	$T_6=40$	$T_6=60$
^{12}C	7.9(−5)	2.5(−4)	4.2(−4)
^{13}C	2.5(−5)	7.8(−5)	1.3(−4)
^{14}N	1.4(−2)	1.5(−2)	1.5(−2)
^{15}N	5.7(−7)	4.9(−7)	4.3(−7)
^{16}O	1.5(−3)	2.0(−4)	1.0(−4)
^{17}O	4.3(−5)	2.0(−8)	1.3(−8)
^{18}O	<(−10)	<(−10)	<(−10)
^{19}F	<(−10)	<(−10)	<(−10)
^{20}Ne	1.3(−3)	1.3(−3)	1.3(−3)
^{21}Ne	7.4(−8)	7.9(−8)	7.8(−8)
^{22}Ne	7.8(−8)	8.2(−8)	8.5(−8)
^{23}Na	1.3(−4)	1.2(−6)	7.8(−7)

We present the results of Table 2 because they were obtained with high numerical accuracy with the aid of the latest evaluation by Fowler's group of the values of the cross-sections involved; however, it turns out that this high accuracy is not needed for the explosive helium shells. The final nuclear abundances produced in those zones that destroy most of the original ^{14}N are very nearly equal to the abundances that would have resulted from seed nuclei of pure ^{14}N. For definiteness we have used as the initial composition the results of hydrogen exhaustion at $T_6 = 60$, as might befit a hydrogen-burning shell in a massive star. Our basic set of results to follow were calculated on the assumption that no nuclear reactions occur between the time of hydrogen exhaustion and the arrival of the pressure wave from the core that initiates the helium reactions. Clearly this assumption cannot be true for all helium zones. A massive evolved star will in general have a helium-burning shell that separates the unignited helium from the helium-exhausted carbon core. The helium-burning shells tend to be thin, however, and the bulk of the helium mass lies in unignited regions, so we believe this assumption is warranted for a first investigation of the phenomenon. A somewhat tricky problem exists *vis-à-vis* the ^{14}N, however, which will be partially converted in hydrostatic helium shells to ^{22}Ne while helium burning occurs. It may be that there exist zones in which this has happened before the explosion and in which the ^{22}Ne survives the explosion. That such zones could be an important source of ^{22}Ne is suggested by our results, which show inadequate explosive synthesis at $A = 22$.

IV. BASIC NUMERICAL RESULTS

Our basic survey consists of following the helium-initiated reaction network when the composition following the CNO cycle is heated to temperatures in the range $5.0 \lesssim T_8 \lesssim 8.0$ and expanded on the two adiabats, $\rho = hT_9{}^3$:

$$a)\ \rho = 10^5 T_9{}^3 \text{ g cm}^{-3}\,, \qquad b)\ \rho = 10^3 T_9{}^3 \text{ g cm}^{-3}\,,$$

which will for convenience be hereafter called adiabat *a* and adiabat *b*. The values for the expansion parameter have been chosen on the assumption (which is presently difficult to justify but which leads to an interesting range of results) that the peak temperatures of interest are less than 10^9 ° K with maximum densities at that temperature of $\rho = 10^5$ g cm^{-3} (on the lower adiabat) and $\rho = 10^3$ g cm^{-3} (on the higher adiabat). These choices lead to expansions that burn negligible amounts of the initial helium but display an interesting range of alteration of the initial ^{14}N, which can be thought of as "seed" for the other nuclei produced.

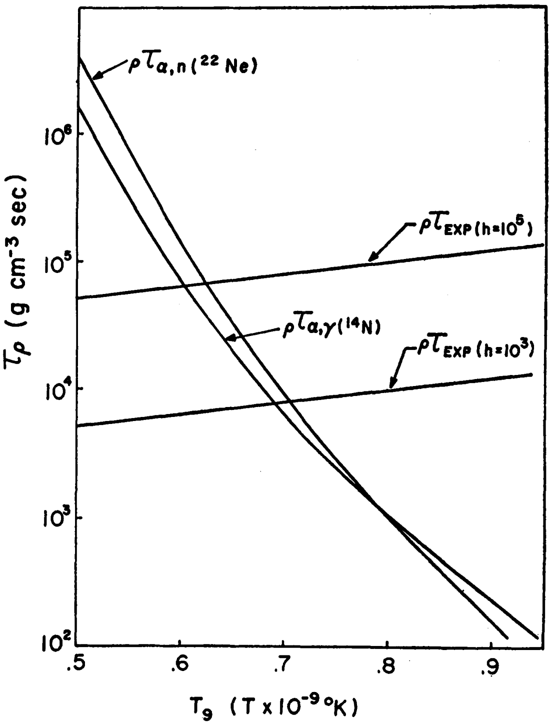
Table 3 gives the final yields in mass fractions of the explosive nuclear burning for various initial temperatures ($5 \lesssim T_8 \lesssim 8$) expanded along our two adiabatic tracks. The column headings show the initial burning temperature $(T_8)_0$ and the adiabat *a* or *b* of the expansion. The power of 10 multiplying the final mass fraction is enclosed in parentheses.

An important criterion in determining the products of explosive burning in the helium zone is the amount of initial ^{14}N that is consumed during the burning. Figure 2 compares the expansion time scale of our two adiabats with the lifetime of ^{14}N against α-particle capture as a function of temperature. For explosions having the property that $\tau_{\alpha,\gamma}$ $(^{14}N) \gtrsim \tau_{\rm exp}$ (little of the ^{14}N is consumed), the nuclei ^{14}N, ^{15}O, ^{18}F, and ^{21}Ne are produced in approximately the solar-system abundance ratios of ^{14}N, ^{15}N, ^{18}O, and ^{21}Ne, whereas under the circumstances for which $\tau_{\alpha,\gamma}(^{14}N) \lesssim \tau_{\rm exp}$ the yields of ^{15}O, ^{18}F, ^{19}Ne, and ^{21}Ne are produced in approximately the abundance ratios of ^{15}N, ^{18}O, ^{19}F, and ^{21}Ne. In what follows we will discuss several of the key features of the burning for various initial temperatures that lead to interesting results.

TABLE 3

FINAL MASS FRACTIONS FOR VARIOUS $(T_8)_0$, (h)

NUCLEUS	$(T_8)_0=8.0$		$(T_8)_0=7.0$		$(T_8)_0=6.5$		$(T_8)_0=6.0$		$(T_8)_0=5.0$	
	a	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*
^{4}He.........	9.6(−1)	9.7(−1)	9.7(−1)	9.8(−1)	9.7(−1)	9.8(−1)	9.8(−1)	9.8(−1)	9.8(−1)	9.8(−1)
^{12}C.........	6.9(−3)	7.2(−4)	3.0(−3)	4.8(−4)	3.1(−3)	4.4(−4)	1.1(−3)	4.3(−4)	5.5(−4)	4.5(−4)
^{13}C.........	1.4(−8)	7.1(−10)	6.4(−9)	1.9(−8)	5.0(−8)	2.0(−8)	6.1(−8)	5.0(−9)	1.7(−8)	9.3(−7)
^{14}N.........	1.2(−9)	2.4(−3)	1.8(−3)	1.2(−2)	6.9(−3)	1.4(−2)	1.3(−2)	1.5(−2)	1.5(−2)	1.5(−2)
^{15}N.........	<(−10)	9.3(−5)	5.7(−5)	2.1(−4)	3.3(−4)	8.4(−5)	1.6(−4)	5.8(−5)	2.9(−5)	2.8(−5)
^{16}O.........	1.5(−3)	1.1(−3)	9.3(−4)	3.3(−4)	5.9(−4)	2.8(−4)	2.8(−4)	2.7(−4)	2.6(−4)	2.6(−4)
^{17}O.........	<(−10)	2.5(−7)	2.1(−8)	8.9(−7)	5.8(−8)	7.0(−7)	1.2(−7)	1.5(−7)	1.3(−8)	1.2(−8)
^{18}O.........	8.9(−10)	1.2(−3)	1.1(−3)	2.5(−3)	3.2(−3)	1.2(−3)	1.9(−3)	2.7(−4)	8.1(−5)	8.0(−6)
^{19}F..........	6.2(−6)	8.1(−4)	1.7(−3)	7.5(−5)	9.7(−4)	1.7(−5)	6.8(−5)	3.6(−6)	8.1(−7)	6.6(−8)
^{20}Ne........	1.5(−3)	9.9(−4)	7.5(−4)	1.1(−3)	8.2(−4)	1.2(−3)	1.2(−3)	1.2(−3)	1.3(−3)	1.3(−3)
^{21}Ne........	1.2(−3)	3.6(−3)	3.2(−3)	9.6(−4)	2.9(−3)	2.1(−4)	5.2(−4)	5.1(−5)	2.7(−5)	2.5(−5)
^{22}Ne........	8.4(−3)	9.8(−3)	1.2(−2)	3.3(−4)	4.2(−3)	6.5(−5)	1.7(−4)	9.9(−6)	3.9(−6)	1.5(−6)
^{23}Na........	4.7(−5)	2.6(−4)	2.8(−4)	2.4(−5)	7.0(−5)	4.1(−5)	2.3(−5)	7.5(−7)	7.8(−7)	7.8(−7)
^{24}Mg........	4.9(−3)	2.3(−3)	2.0(−3)	7.0(−4)	9.0(−4)	6.8(−4)	6.8(−4)	6.8(−4)	6.8(−4)	6.8(−4)
^{25}Mg........	8.0(−3)	7.9(−4)	7.3(−4)	9.4(−5)	1.8(−4)	8.2(−5)	9.0(−5)	7.9(−5)	7.9(−5)	7.9(−5)
^{26}Mg........	3.4(−3)	1.6(−4)	1.5(−4)	8.7(−5)	9.1(−5)	8.7(−5)	8.7(−5)	8.7(−5)	8.7(−5)	8.7(−5)



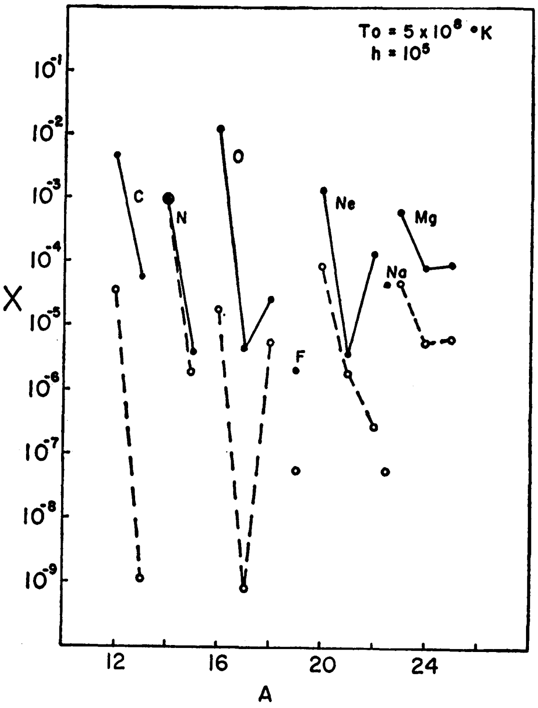


FIG. 2.—The expansion time scales ($\tau_{\text{exp}} = 446/\sqrt{\rho}$) of our two adiabats, the lifetime of ^{14}N against destruction by ^{14}N(α,γ)^{18}F, and the lifetime of ^{22}Ne against destruction by ^{22}Ne(α,n)^{25}Mg, as a function of temperature in billions of degrees Kelvin.

FIG. 3.—The final yields by mass fraction when the helium zone is heated to the initial temperature $T_0 = 5 \times 10^{8}$° K and then allowed to expand along the approximate adiabat $\rho = 10^5 T_9{}^3$. Solar-system abundances are represented by black dots connected by solid lines, whereas calculated abundances are represented by open circles connected by dashed lines. The yields are normalized to the solar-system mass fraction of ^{14}N. With this normalization the yields of ^{15}N, ^{18}O, and ^{21}Ne are also close to their solar values.

a) $(T_8)_0 = 5.0$

On the lower adiabat [$\tau_{\alpha,\gamma}(^{14}\text{N}) \gg \tau_{\text{exp}}$] only 1 percent of the initial ^{14}N is processed during the burning. Figure 3 shows the final yields from such an expansion. Protons are quickly liberated during the burning by the two reactions

$$^{13}\text{C}(\alpha, n)^{16}\text{O} \quad \text{and} \quad ^{14}\text{N}(n, p)^{14}\text{C}$$

until the initial source of ^{13}C is consumed. Most of the ^{15}N (~90 percent) owes its yield to the nuclear reaction ^{14}N(p, γ)^{15}O. The ^{15}N created during the explosive event by the reaction ^{15}O(n, p)^{15}N is rapidly destroyed by a (p, α) reaction. Likewise, ^{18}O owes its abundance also to the presence of ^{14}N, but through two different nuclear processes, namely,

$$^{14}\text{N}(\alpha, \gamma)^{18}\text{F} \quad (\sim 85 \text{ percent}) \quad \text{and} \quad ^{14}\text{N}(n, p)^{14}\text{C}(\alpha, \gamma)^{18}\text{O} \quad (\sim 15 \text{ percent}) .$$

Some ^{18}O created during the explosive event is also destroyed by a (p, α) reaction.

The yield of ^{21}Ne results from the following two reactions on the ^{20}Ne initially present in the zone:

$$^{20}\text{Ne}(p, \gamma)^{21}\text{Na} \quad (\sim 46 \text{ percent}) \quad \text{and} \quad ^{20}\text{Ne}(p, \gamma)^{21}\text{Na}(n, p)^{21}\text{Ne} \quad (\sim 54 \text{ percent}) .$$

As we expand the helium zone along adiabat *b*, even less of the ^{14}N is consumed, and only the yields of ^{14}N, ^{15}N, and ^{21}Ne are within their solar-system ratios. The inadequate production of mass $A = 18$ nuclei under such circumstances, due to the reaction $^{14}N(\alpha, \gamma)^{18}F$ being inhibited at lower density, may provide us with a lower limit to the temperature-density conditions at which the processing of the helium zones appears to have occurred in nature.

b) $(T_8)_0 = 6.0$

During the expansion along adiabat *a*, we have $\tau_{\alpha,\gamma}(^{14}N) \approx \tau_{exp}$, and approximately 14 percent of the initial ^{14}N is processed into ^{15}O, ^{18}F, ^{19}Ne, and ^{21}Ne in ratios close to the solar-system abundances of ^{15}N, ^{18}O, ^{19}F, and ^{21}Ne. Figure 4 shows the final yield from such an expansion. The yields of the nuclei ^{15}N, ^{18}O, ^{19}F, ^{21}Ne, ^{22}Ne, and ^{23}Na are increased by an order of magnitude over the previous lower-temperature calculation due to increased consumption of ^{14}N and α-particles. The yield of ^{19}F (made as ^{19}Ne) is produced by the increase of the rate of the reaction $^{15}O(\alpha, \gamma)^{19}Ne$, and the yield of ^{22}Ne is produced in approximately equal parts by the reaction series

$$^{14}N(n, p)^{14}C(\alpha, \gamma)^{18}O(\alpha, \gamma)^{22}Ne \quad \text{and} \quad ^{14}N(\alpha, \gamma)^{18}F(\alpha, p)^{21}Ne(p, \gamma)^{22}Na\,,$$

the latter series of reactions accounting for the yield of ^{21}Ne. The yield of ^{21}Ne at this and higher temperatures results from nuclear reactions on the initial ^{14}N rather than on the ^{20}Ne.

During the expansion on adiabat *b*, we have $\tau_{\alpha,\gamma}(^{14}N) > \tau_{exp}$ and only a little over 2 percent of the ^{14}N is processed into heavier nuclei. As a consequence, the yields of the product nuclei are down by as much as an order of magnitude from yields produced from expansion along adiabat *a*. However, this calculation gives us some very interesting results. If we normalize the yield of the burning to a solar-system abundance of ^{14}N, then the nuclei ^{15}N, ^{18}O, and ^{21}Ne are produced almost exactly within their solar-system amounts and the abundance of ^{19}F is deficient by an order of magnitude. The nuclei ^{13}C, ^{17}O, and ^{23}Na are not produced in any significant amount, and ^{22}Ne is an order of

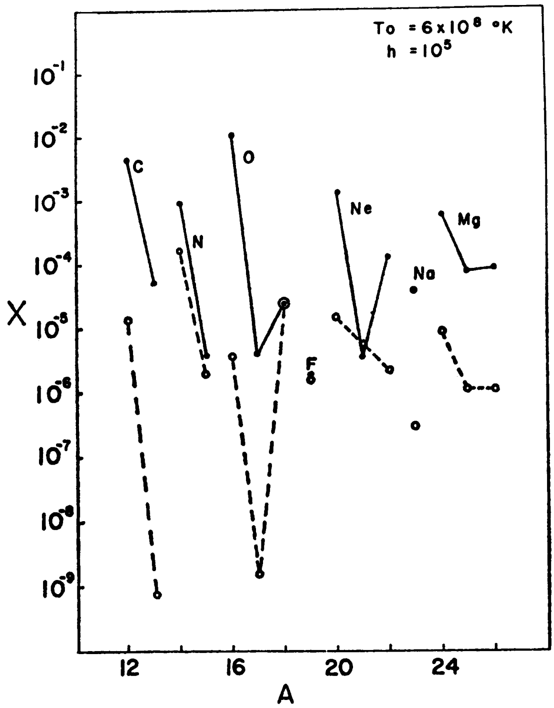


FIG. 4.—Final yields by mass fraction for the expansion $(T_8)_0 = 6.0$ and $h = 10^5$. The yields are normalized to the solar mass fraction of ^{18}O

magnitude less abundant than ^{21}Ne (whereas in nature ^{22}Ne is 35 times more abundant than ^{21}Ne). The ^{22}Ne is primarily (~83 percent) produced as itself because of a scarcity of protons from the reaction $^{18}F(\alpha, p)^{21}Ne$ during the later expansion phase, which would inhibit the $^{21}Ne(p, \gamma)^{22}Na$ reaction along this adiabat. Otherwise, the nuclear reactions proceed basically in the same way as they did in the expansion along adiabat *a*.

c) $(T_8)_0 = 7.0$

When the burning proceeds along adiabat *a*, we have $\tau_\alpha(^{14}N) \ll \tau_{exp}$. The associated increase of α-particle capture on ^{14}N proceeds toward a buildup at mass $A = 22$ via the series of reactions

$$^{14}N(\alpha, \gamma)^{18}F(\alpha, p)^{21}Ne(p, \gamma)^{22}Na\ .$$

If the yield is normalized to the solar-system abundance of ^{21}Ne, only the yield of ^{19}F is within its solar-system value, and the yields of ^{15}N, ^{18}O, and ^{22}Ne are underabundant by at least an order of magnitude. The buildup toward mass $A = 22$ is not sufficient to establish the mass ratio of $A = 22$ to $A = 21$ observed in nature. Some of the ^{21}Ne (~20 percent) is produced as ^{21}Na via the reaction $^{20}Ne(p, \gamma)^{21}Na$, with a small contribution from the initial ^{16}O present:

$$^{16}O(\alpha, \gamma)^{20}Ne(p, \gamma)^{21}Na\ .$$

Figures 5 and 6 show the important currents, J_{ij}, as a function of time during the expansion from an initial temperature of $(T_8)_0 = 7.0$ along adiabat *a*, where we define the current as

$$J_{ij} = Y_i Y_j N_A \rho \langle \sigma v \rangle_{ij}\ \sec^{-1}\ ,$$

where the symbols have their usual meanings. As mentioned previously, the initial burst of free protons in the gas is due to the presence of ^{13}C. However, once the initial ^{13}C is consumed, the mass fraction of free protons in the gas is dependent upon the amount of ^{14}N consumed via the following series of reactions:

$$^{14}N(\alpha, \gamma)^{18}F(\alpha, p)^{21}Ne\ .$$

Thus, when the temperature and density are low enough that little ^{14}N is consumed, reducing the initial ^{13}C abundances restricts the free-proton mass fraction and hence the yields of the products. However, when a significant amount (> 10 percent) of the ^{14}N is consumed, the initial ^{13}C abundance has no effect in determining the final yield.

When we calculate the burning along adiabat *b*, we find a dramatic change in the results. Doing the burning at a lower density restricts α-capture on ^{14}N enough that only 20 percent of the initial ^{14}N is consumed during the expansion. The resulting yields are very similar to the yields produced when the helium zone is expanded on adiabat *a* from an initial $(T_8)_0 = 6.0$, for which it also happens that 14 percent of the ^{14}N is consumed.

d) $(T_8)_0 = 8.0$

On adiabat *b* we have at this temperature $\tau_\alpha(^{14}N) < \tau_{exp}$. If the yields are to produce a solar-system abundance of ^{21}Ne, only the abundance of ^{19}F is close to its solar-system value; the abundances of ^{15}N, ^{18}O, and ^{22}Ne are all more than an order of magnitude low. The yields are similar (within a factor of 2 for abundances of key nuclei) to the yields produced along adiabat *a* with $(T_8)_0 = 7.0$ because the amount of ^{14}N consumed (~90 percent) is approximately the same in both expansions. As the initial temperature is increased from $T = 7 \times 10^8$ ° K to $T = 8 \times 10^8$ ° K, the cross-section for $^{21}Ne(p, \gamma)^{22}Na$ (source of ^{22}Na) remains almost constant whereas the rate of the major destructive reaction of $^{22}Na[^{22}Na(\alpha, p)^{25}Mg]$ increases by an order of magnitude. Thus, increasing the initial temperature beyond $(T_8)_0 = 7.0$ enhances the Mg isotopes in-

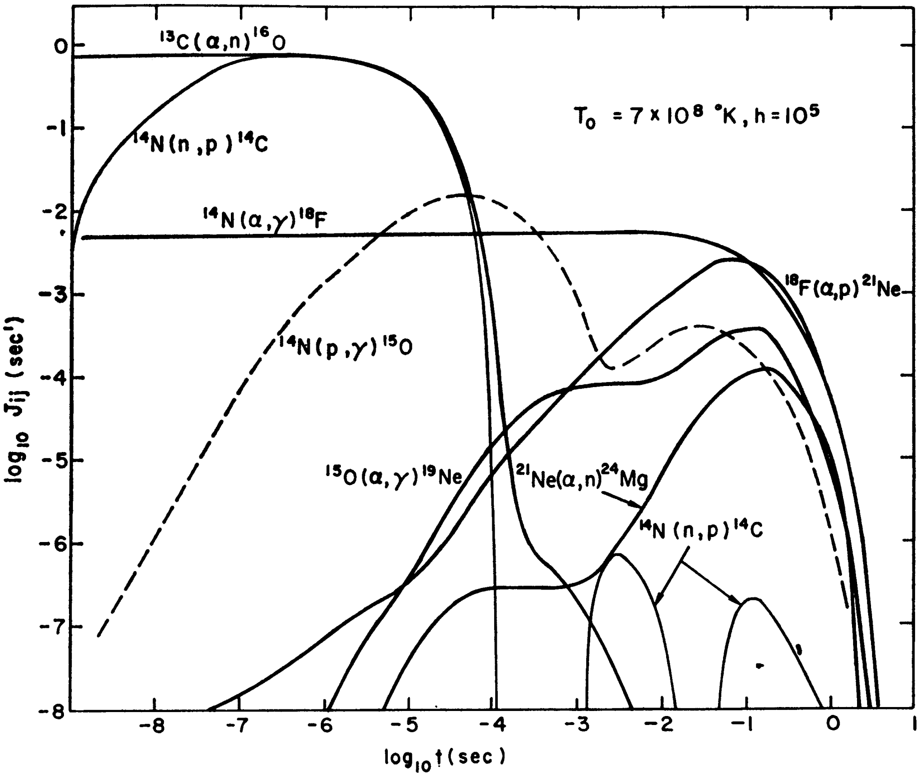


FIG 5

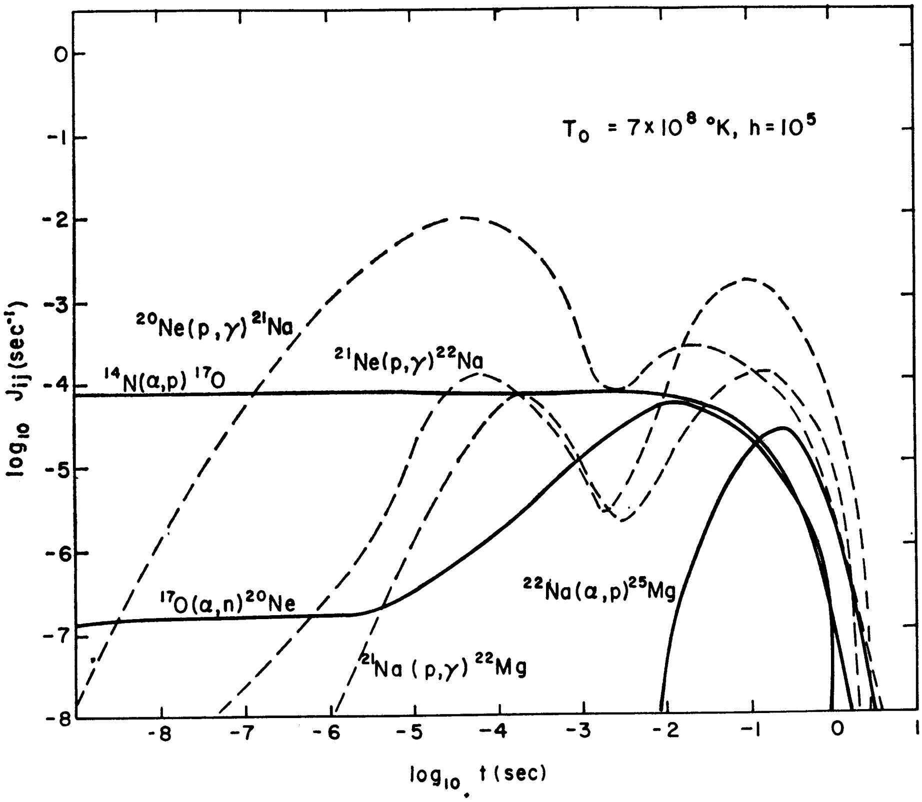


FIG 6

FIGS. 5 and 6.—Selected reaction rates $J_{ij} = Y_iY_jN_A\rho\langle\sigma v\rangle_{ij}$ as a function of time during the expansion $(T_8)_0 = 7.0$ and $h = 10^5$. *Heavy solid curves*, rates of α-reactions; *heavy dashed curves*, rates of proton reactions; *fine solid curve*, rate of the $^{14}N(n,p)^{14}C$ reaction. Note especially that protons liberated by $^{14}N(n,p)^{14}C$ are due to three different neutron sources: $^{13}C(\alpha,n)^{16}O$, then $^{17}O(\alpha,n)^{20}Ne$, then $^{22}Ne(\alpha,n)^{25}Mg$. Note also that the concentrations of ^{17}O and ^{18}O reach values such that the rate of their destruction approximately equals the rates of the reactions forming them. The reaction $^{18}F(\alpha,p)^{21}Ne$ is the major source of protons after the initial ^{13}C is exhausted.

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stead of ^{22}Na. It therefore appears to be difficult to eject the proper mass ratio of $A = 22$ to $A = 21$ observed in nature from such an explosive helium zone without overproducing ^{25}Mg.

In the expansion along adiabat *a* from $(T_8)_0 = 8.0$, we have $\tau_\alpha(^{14}\mathrm{N}) \ll \tau_{\mathrm{exp}}$ so that all of the initial ^{14}N is consumed. The yield of ^{25}Mg is greater than along adiabat *b* by an order of magnitude with no significant yield of ^{18}O and ^{19}F. The yield of ^{22}Ne remains approximately the same, so that if we were to use such a zone to account for the natural abundance of ^{22}Ne, we would also have to ascribe the thermonuclear origin of ^{25}Mg to such a zone, as well as overproducing the solar-system abundance of ^{21}Ne by a factor of 4. Since from previous nucleosynthesis results we believe the thermonuclear origin of all the Mg isotopes to be explosive carbon burning, we suggest that the production of ^{25}Mg sets a limit on the temperature and density at which *most* helium zones will be explosively processed.

V. PRODUCTION OF ^{22}Ne

We have shown that the production of ^{22}Na plus some ^{22}Ne from ^{14}N during explosive ejection of helium shells is inadequate to account for the natural abundance of ^{22}Ne. It seems more likely that ^{22}Ne has resulted from its production from ^{14}N during *hydrostatic* helium burning in stars, in which case the ^{22}Ne must "survive" the explosive ejection (if we assume for the discussion that all fresh products of nucleosynthesis are ejected from the same explosive objects). This possibility is made plausible by the fact that with recent estimates of the nuclear cross-sections the ^{14}N is converted to ^{22}Ne during helium burning; for example, at $T_8 = 2.0$ about 90 percent of the ^{14}N has been converted to ^{22}Ne when about half of the helium has been fused in ^{12}C and ^{16}O. The conversion happens by the sequence $^{14}\mathrm{N}(\alpha, \gamma)^{18}\mathrm{F}(\beta^+\nu)^{18}\mathrm{O}(\alpha, \gamma)^{22}\mathrm{Ne}$ because in hydrostatic burning, unlike the explosive ejection we have been discussing, there is ample time for the positron decay of ^{18}F. The conversion proceeds from ^{18}O to ^{22}Ne because, in spite of the higher Coulomb barrier, the ^{18}O lifetime is less than that of ^{14}N; for example, the rates we have used give $\tau_\alpha(^{14}\mathrm{N})/\tau_\alpha(^{18}\mathrm{O}) \approx 60$ at $T_8 = 2.0$. The flow stops at ^{22}Ne in hydrostatic burning because of the high Coulomb barrier.

The ^{22}Ne could in principle survive from two types of stellar zones: partially burned helium (the helium-burning shell of the presupernova) or totally burned helium (the inert carbon-oxygen shell of the presupernova). The relative likelihood of these shells can be determined only from stellar models; as an example of the first type Paczyński (1970) finds that, at the time of carbon ignition in his 15 $M_\odot$ stellar model, about 0.5 $M_\odot$ of the star consists of zones of partially processed helium. If the ^{22}Ne in such zones is to survive a core-generated explosion, the lifetime of ^{22}Ne against α-particles must be longer than the hydrodynamic time scale of the zone. These time scales were compared in Figure 2, and we note that the peak temperature must not exceed $T_8 = 8.0$ if ^{22}Ne is to survive. Within the context of our earlier results it is of interest to note that any ^{22}Ne initially present in those zones that explosively synthesize ^{15}O, ^{18}F, ^{19}Ne, and ^{21}Ne in good agreement with the solar abundances of ^{15}N, ^{18}O, ^{19}F, and ^{21}Ne—namely, those zones having $\tau_\alpha(^{14}\mathrm{N}) \approx \tau_{\mathrm{exp}}$—will survive the explosion. In such cases the yield of ^{22}Ne relative to the combined yield of the other group of nuclei will be approximately $f/(1 - f)$, where f is the fraction of the ^{14}N burned hydrostatically before the explosion.

It may be more likely that the ^{22}Ne survives the ejection of some of the carbon-oxygen shells that are not sufficiently heated to burn substantial amounts of ^{12}C on the hydrodynamic time scale ($T_9 < 2$). The ^{22}Ne can survive considerably higher peak temperatures in this case because there exist no free α-particles or protons to destroy the ^{22}Ne unless they are liberated by the $^{12}\mathrm{C} + {}^{12}\mathrm{C}$ reaction.

In either case, we must be prepared to admit that the zones from which ^{22}Ne survives must also be significant contributors to the ^{12}C abundance. In helium burning at $T_8 = 2.0$, for example, we calculate that a substantial amount of ^{12}C ($X_{12} \approx 0.3$) has been formed by the time the ^{14}N has been converted to ^{22}Ne ($X_{22} \approx 10^{-2}$), producing a ratio $X_{12}/X_{22} \approx 30$. The solar ratio by mass is $(X_{12}/X_{22})_{\odot} = 36$, so significant production of ^{12}C seems to be associated with ^{22}Ne survival. Although the survival-theory origin of ^{22}Ne seems plausible, rather exact stellar models will be required for its evaluation. The circumstances of helium burning and the value of the $^{12}C(\alpha, \gamma)^{16}O$ cross-section enter crucially.

VI. DISCUSSION OF IMPORTANT REACTION RATES

The reactions which play a significant role in determining the yields in our calculation of explosive helium burning are listed in Table 4 along with designation as to whether the corresponding reaction rate is experimental or estimated.

To examine the effect of the magnitude of these rates upon our results, we increased and decreased the nonresonant cross-section factor $S(E)$, for each of the reactions listed in Table 4, by a factor of 100 or 10, depending upon whether the rate was estimated or experimental, and repeated the series of calculations discussed earlier. We then repeated the set of calculations, changing only one reaction rate at a time.

We find that the final abundances depend more on the amount of ^{14}N burned during the expansion than upon the other particulars characterizing the adiabat. Increasing $S(E)$ for the $^{14}N(\alpha, \gamma)^{18}F$ reaction by a factor of 10 obviously causes more ^{14}N to burn, resulting in increased yields, and conversely for a reduction of the cross-section. If, however, we compare adiabats that for each choice of the ^{14}N cross-section result in the same consumption of ^{14}N, we find that the final abundances are nearly the same (differences less than a factor of 2) for those zones in which a substantial amount (>1 percent), but not all, of the ^{14}N is consumed.

We repeated the calculations, with the nonresonant cross-section factor $S(E)$ for the reaction $^{18}F(\alpha, p)^{21}Ne$ increased and decreased by a factor of 100. When a substantial (>10 percent) amount of the ^{14}N is burned, an increase in the cross-section decreases the final yield of ^{18}O by almost two orders of magnitude and increases the final yields of ^{15}N, ^{19}F, ^{21}Ne, and ^{22}Ne by factors of 2 or 3. Even when little of the initial ^{14}N is processed, the yield of ^{18}O is decreased by a factor of 2–4. If the cross-section factor were as much as a factor of 100 larger than that estimated by Wagoner, it would appear difficult to account for the production of a solar-system abundance of ^{18}O in the processing of a helium zone that burned a substantial amount of its initial ^{14}N. When less than 10 percent of the initial ^{14}N is consumed, reducing the cross-section factor by 100 has almost no effect upon the final results. However, if the cross-section factor were as much as a factor of 100 smaller than that estimated by Wagoner, it would appear difficult to produce the solar-system abundances of ^{15}N, ^{19}F, and ^{21}Ne in explosive helium zones that exhausted most of their ^{14}N since most of the mass would remain at atomic weight $A = 18$.

The rate of the reaction $^{15}O(\alpha, \gamma)^{19}Ne$ can have a significant effect upon the yields of ^{15}N and ^{19}F when at least 1 percent of the initial ^{14}N is consumed in the explosive burning. When the nonresonant cross-section factor is increased by a factor of 100, essentially

TABLE 4

IMPORTANT REACTIONS

Reaction	Source of Rate
$^{14}N(p,\gamma)^{15}O$	Experimental
$^{14}N(\alpha,\gamma)^{18}F$	Experimental
$^{20}Ne(p,\gamma)^{21}Na$	Experimental
$^{15}O(\alpha,\gamma)^{19}Ne$	Estimated
$^{18}O(\alpha,\gamma)^{22}Ne$	Experimental
$^{18}F(\alpha,p)^{21}Ne$	Estimated
$^{21}Ne(p,\gamma)^{22}Na$	Estimated
$^{22}Na(\alpha,p)^{25}Mg$	Estimated

all of the mass at $A = 15$ is converted to mass at $A = 19$ in the final yields. For example, when the helium zone is shock-heated to the initial temperature $T_8 = 6$ and allowed to expand along adiabat *a*, the yield of ^{15}N is reduced by a factor of 20 and the yield of ^{19}F is enhanced by a factor of 3. Thus conditions that previously gave good agreement of the yields of ^{15}O, ^{18}F, ^{19}Ne, and ^{21}Ne to the solar-system values of ^{15}N, ^{18}O, ^{19}F, and ^{21}Ne now well underproduce the solar-system abundance of ^{15}N and slightly overproduce the abundance of ^{19}F (keeping the normalization to produce the mass fraction of ^{18}O observed in nature). Nuclear burning from an initial temperature $T_8 = 7$ along adiabat *b* with the same increased cross-section factor reduces the yield of ^{15}N by two orders of magnitude while again enhancing the yield of ^{19}F by a factor of 3. Reducing the nonresonant cross-section factor by a factor of 100 has the maximum effect of enhancing the yield of ^{15}N by one-third and decreasing the yield of ^{19}F by a factor of 2 and would therefore pose few problems for the picture of nucleosynthesis presented here.

Increases and decreases by a factor of 10 of the experimentally determined cross-section factor for the reaction $^{18}O(\alpha, \gamma)^{22}Ne$ made little difference in the final yields of ^{18}O and ^{22}Ne, because ^{18}O is more effectively destroyed during the explosive nuclear processing by a (p, α) reaction and little ^{22}Ne is produced from the ^{18}O nucleus.

Increases and decreases by a factor of 100 in the estimated cross-section factor for the reaction $^{21}Ne(p, \gamma)^{22}Na$ made no significant changes in the results. The yields of ^{21}Ne and ^{22}Ne are decreased and enhanced, respectively, by a factor of 2 or 3 in some calculations when the rate is increased by a factor of 100, but this is still insufficient to establish the yields of mass $A = 22$ and mass $A = 21$ in the ratio observed in nature. For example, even in the case of the most extreme enhancement of ^{22}Ne (made as ^{22}Na) ($T_8 = 7.0$, $h = 10^5$) the calculated ratio of the yield of ^{22}Ne to that of ^{21}Ne is approximately 10, whereas the solar-system ratio is $X_{22}/X_{21} = 35$. It appears that even increasing the rate of the reaction $^{21}Ne(p, \gamma)^{22}Na$ by a factor of 100 will not help the problem of understanding the thermonuclear origin of ^{22}Ne. Decreasing the reaction rate by a factor of 100 had almost no effect upon the results.

When we increased and decreased the experimentally determined cross-section factors by a factor of 10 for the proton-capture reactions $^{14}N(p, \gamma)^{15}O$ and $^{20}Ne(p, \gamma)^{21}Na$, it had virtually no effect upon the final results.

Increases and decreases by a factor of 100 of the estimated cross-section factor for the reaction $^{22}Na(\alpha, p)^{25}Mg$ had no effect on the results except for the expansion from the initial temperature $(T_8)_0 = 7.0$ along adiabat *a* when the yield of ^{22}Ne was reduced by an order of magnitude by the increase of rate. Decreasing the reaction rate by a factor of 100 had no effect upon the results.

The most important nuclear reaction rates in determining the final products ejected from explosively burned helium zones are the rates for the reactions $^{14}N(\alpha, \gamma)^{18}F$, $^{18}F(\alpha, p)^{21}Ne$, and $^{15}O(\alpha, \gamma)^{19}Ne$. The yields of ^{15}O, ^{18}F, ^{19}Ne, and ^{21}Ne are dependent upon the order of magnitude chosen for these nonresonant cross-section factors. Experimentally determined rates, except for ^{14}N, were found to have little effect upon the character of our final results when varied by an order of magnitude. Although many of the numerical values for the reaction rates used in our calculations will undoubtedly change, we believe in the basic correctness of the ideas discussed in this paper.

VII. CONCLUSIONS

We should first mention that the yields of ^{13}C and ^{17}O are noticeably deficient in all of our calculations. The reason that these nuclei are not produced in sufficient amounts in relation to the yields of ^{15}N and ^{18}O to account for their abundances as observed in nature is as follows. The major constituent of the helium zone, apart from α-particles, is the nucleus ^{14}N; and it is the interaction of this nucleus with the free α-particles and protons in the gas that constitutes the initial reactions in the subsequent nuclear burning. Since mass $A = 13$ and mass $A = 17$ are bypassed by such a sequence, their final yields from such an evolution are very low. Any ^{13}C initially present in the helium zone is quickly destroyed during the explosive burning.

A natural place to look for the thermonuclear origin of ^{13}C and ^{17}O is a hydrogen-rich zone with solar compositions of ^{12}C and ^{16}O that has undergone the same type of explosive nuclear processing as the helium zone. If the temperature is low enough during the burning to inhibit the *second* proton capture on the ^{12}C, ^{14}N, and ^{16}O initially present in the gas, the yields of ^{13}N, ^{15}O, and ^{17}F can correspond to the solar-system values of ^{13}C, ^{15}N, and ^{17}O. For example, the calculation of the explosive nuclear processing of material of a solar-system composition will yield such a result if $T_0 = 1.4 \times 10^8$ ° K and $h = 10^5$. However, Paczyński (1970) has recently calculated evolutionary sequences (of 10 and 15 $M_\odot$) up to the ignition of carbon in their cores. At this time their extended hydrogen-rich envelopes have a characteristic density of only 10^{-7} to 10^{-8} g cm^{-3}. At such low densities the particle flux is too small during the expansion for significant capture to occur unless we allow the peak particle temperature to reach suspiciously high values. The problem is quite complicated and involves the time scales of the post-shock thermalization, so we prefer to make no further quantitative statements on this problem until we have completed our study of it. Nonetheless, the general idea of forming all or part of the ^{13}C and ^{17}O abundances in overheated hydrogen shells remains an enticing possibility.

We believe that the nuclei ^{15}N, ^{18}O, ^{19}F, and ^{21}Ne observed in nature are created primarily as ^{15}O, ^{18}F, ^{19}Ne, and ^{21}Ne in the explosive nuclear processing of helium zone raised to an initial high temperature by shock wave from a thermonuclear detonation in the stellar core and then allowed to expand on a hydrodynamic time scale. We believe that the nuclei ^{14}N and ^{22}Ne owe their origin to creation under hydrostatic stellar evolutionary conditions and to survival of the final explosive nuclear processing.

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