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ADVANCED EVOLUTION OF MASSIVE STARS. IV. SECONDARY NUCLEOSYNTHESIS DURING HELIUM BURNING

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ABSTRACT

The thermonuclear processing of ^{14}N during core helium burning in massive stars is examined. A detailed discussion of the relevant reaction rates is given, including the evaluation of recent experimental data, and the presentation of analytic fits for $N_A\langle\sigma v\rangle$. If, as seems likely, the ^{12}C and ^{16}O that we observe was produced under such conditions, then most, if not all, the ^{22}Ne was produced at the same time by the sequence ^{14}N$(\alpha, \gamma)^{18}$F$(\beta^+)^{18}$O$(\alpha, \gamma)^{22}$Ne. For stars in the mass range ($4 \lesssim M/M_\odot \lesssim 8$) it is unlikely that ^{25}Mg, which can be an effective contributor to the Urca process, is greatly enhanced by helium burning.

I. INTRODUCTION

There are several reasons to reconsider the detailed synthesis of nuclei by secondary processes during helium burning [by "secondary" we refer to processes other than $3\alpha \rightarrow {}^{12}$C $+ \gamma$, ^{12}C$(\alpha, \gamma)^{16}$O, and ^{16}O$(\alpha, \gamma)^{20}$Ne]. For example, a fundamental question regarding the fate of stars in the mass range $4 \leqslant M/M_\odot \leqslant 8$ is that of the nuclear Urca processes (Arnett 1971; Paczyński 1972). The nucleus ^{25}Mg is particularly effective in this regard (Tsuruta and Cameron 1970). The solar-system abundance of ^{25}Mg is thought to be about 7.5×10^{-5} by mass; but in Population I matter processed by helium burning this could be enhanced to a maximum of about 3×10^{-2} (by mass) by the reaction sequence

$$^{14}\text{N}(\alpha, \gamma)^{18}\text{F}(\beta^+)^{18}\text{O}(\alpha, \gamma)^{22}\text{Ne}(\alpha, n)^{25}\text{Mg} .$$

These abundances scale with the initial metal abundance of the star. Since the Urca rate is proportional to the abundance of reacting nuclei, this can produce a considerable enhancement of that rate.

Another reason to reconsider helium burning is the following. It appears that ^{12}C and ^{16}O may be produced in hydrostatic helium burning in massive stars, and survive explosive disruption (Arnett 1972*a*, *b*). It has been suggested (Howard, Arnett, and Clayton 1971) that ^{22}Ne is probably synthesized in the same way. By calculating the ^{22}Ne/(^{12}C + ^{16}O) production ratio we can test this hypothesis. Since ^{22}Ne is relatively abundant (in the solar system it is about the twelfth most abundant nucleus by mass), the question gains particular importance.

Further motivation comes from the fact that detailed evolutionary models for helium burning in massive stars, using revised reaction rates, have recently been constructed (Arnett 1972*a*). The use of these models facilitates the exploration of secondary nucleosynthesis during helium burning, and recent experimental information concerning secondary reactions provides added incentive for our study. We shall pay particular attention to the dependence of our results upon uncertainties in the nuclear reaction rates.

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TABLE 1

NUCLEAR REACTIONS CONSIDERED

Reaction	Source	Temperature Range
$^{14}N(\alpha, \gamma)^{18}F(\beta^+)^{18}O$	Couch *et al.* (1972)	$T_9 \geq 0.1$
$^{18}O(\alpha, \gamma)^{22}Ne$	Jaszczak *et al.* (1971); Adams *et al.* (1969)	$T_9 > 1.0$
$^{18}O(\alpha, n)^{21}Ne$	Haas and Bair (1971)	$T_9 > 0.6$
$^{21}Ne(\alpha, n)^{24}Mg$	Haas and Bair (1971); Mak (1971)	$T_9 > 1.0$
$^{22}Ne(\alpha, n)^{25}Mg$	Haas and Bair (1971); Ashery (1969)	$T_9 > 1.0$
$^{21,22}Ne(\alpha, \gamma)^{25,26}Mg$	Our estimate	...

II. REACTION RATES

The reactions to be considered in this study are listed in table 1, along with the sources of experimental information, and the temperature ranges in which the available nuclear data allow an accurate determination of the reaction rate without extrapolation. Only for the $^{14}N(\alpha, \gamma)^{18}F$ reaction have the cross-sections been measured at the energies relevant for helium burning ($0.1 \leq T_9 \leq 0.5$). For all other reactions one must resort to extrapolations of higher-energy data or estimates based on physical intuition. We consider the reactions individually below.

a) $^{14}N(\alpha, \gamma)^{18}F(\beta^+)^{18}O$

The rate for the $^{14}N(\alpha, \gamma)^{18}F$ reaction was taken from the study by Couch *et al.* (1971). Uncertainties in the rate of less than 50 percent are quoted for the temperatures of interest. However, this reaction proceeds so quickly that even larger uncertainties would be insignificant. The resultant ^{18}F will decay by positron emission to ^{18}O with a half-life of approximately 110 minutes. The only reaction which could compete was $^{18}F(\alpha, p)$, but this rate was estimated and found to be several orders of magnitude slower than positron decay, and as a result was not included in the calculations. The timescale for helium burning is much longer than the half-life of ^{18}F; consequently it could be assumed to decay to ^{18}O instantaneously.

b) $^{18}O(\alpha, \gamma)^{22}Ne$; $^{18}O(\alpha, n)^{21}Ne$

The data of Haas and Bair (1971) on the $^{18}O(\alpha, n)$ reaction extends down to approximately 1.0 MeV, which is very close to the neutron threshold (0.854 MeV). Therefore, the extrapolation to threshold should be reliable. However, because of the neutron threshold the (α, γ) rate will control the consumption of ^{18}O at helium-burning temperatures, and uncertainties in the $^{18}O(\alpha, n)$ rate will be of little significance. The data of Jaszczak *et al.* (1971) were used in this analysis in preference to the older data of Adams *et al.* (1969), because of the improved resolution obtained in the former work. Unfortunately, the yield below the neutron threshold is too small to be measured, and direct extrapolation of the (α, γ) data to the important region below threshold is likely to be greatly in error. We have attempted to find a straightforward empirical method with which to make the extrapolation.

It was found that in the temperature range where the (α, γ) and (α, n) rates were well determined by the experimental data $\langle\sigma v\rangle_{\alpha,\gamma} \simeq 10^{-3}\langle\sigma v\rangle_{\alpha,n}$. To interpret this, consider the contribution to the reaction rate from a given resonance

$$\langle\sigma v\rangle_{\alpha(\gamma,n)} \sim \frac{\Gamma_\alpha \Gamma_{(\gamma,n)}}{\Gamma_\alpha + \Gamma_\gamma + \Gamma_n}, \quad (1)$$

where the Γ_i are the partial widths of the state in the compound nucleus. Above the neutron threshold, $\Gamma_n \gg \Gamma_\alpha + \Gamma_\gamma$ and $\langle\sigma v\rangle_{\alpha n} \approx \Gamma_\alpha$, while $\langle\sigma v\rangle_{\alpha\gamma} \approx \Gamma_\alpha\Gamma_\gamma/\Gamma_n$. Therefore, it appears that when averaged over a number of resonances $\Gamma_\gamma/\Gamma_n \simeq 10^{-3}$. Furthermore, the quantity Γ_α can be estimated by using the relation

$$\Gamma_\alpha = \frac{3\hbar^2}{MR^2} P_l \theta_\alpha^2 , \tag{2}$$

where P_l is the penetration factor, l is the orbital angular momentum of the α-particle, R is the nuclear radius, M is the reduced mass of the $^{18}O + \alpha$ system, and θ_α is the ratio of the reduced width to the Wigner limit. The expression used for P_l is $kR/(G_l^2 + F_l^2)$ and $R = 1.4(A_0^{1/3} + A_\alpha^{1/3})$ fermis. If $l = 0$ is assumed, then θ_α^2 is the only adjustable parameter. Using the value obtained for Γ_γ/Γ_n, the average level spacing observed by Haas and Bair (approximately 100 keV), and equations (1) and (2), we have determined that the measured (α, γ) rate can be reproduced by our calculations if, on the average, $\theta_\alpha^2 = 0.05$. The extrapolation to the region below the neutron threshold was then obtained by assuming $\Gamma_\alpha\Gamma_\gamma/(\Gamma_\alpha + \Gamma_\gamma) \simeq \Gamma_\alpha$, where Γ_α is evaluated at 100-keV intervals with $\theta_\alpha^2 = 0.05$. This procedure is not very precise, and we must place a large uncertainty on the extrapolated $^{18}O(\alpha, \gamma)$ rate. We expect that the true rate should lie in the range $0.01\langle\sigma v\rangle_{calc} \leq \langle\sigma v\rangle \leq 10\langle\sigma v\rangle_{calc}$. There is a significant possibility that the $^{18}O(\alpha, \gamma)$ rate may be overestimated, because at the very low temperatures at which ^{18}O is consumed any "average" description of the compound nucleus becomes highly uncertain. This suspicion is reflected in the uncertainties quoted for this rate. There is an upper limit on the rate which is determined by the value of P_0 and the requirement $\theta_\alpha^2 \lesssim 1.0$, but the lower limit is much less certain.

c) $^{21,22}Ne(\alpha, n)^{24,25}Mg$

The cross-section values for these reactions in the range $1.7 < E_\alpha < 5.0$ MeV were obtained from Haas and Bair (1971). These data were chosen over those of Mak (1971) and Ashery (1969) because of the superior resolution obtained by the former authors, but on the whole, there was little difference in the measured cross-sections. The yield curves indicated that for both nuclei the reaction proceeds through a number of fairly broad resonances. By averaging over energy intervals, it was found that the "averaged" cross-sections increased with the α-particle penetrability for $1.7 \leq E_\alpha \leq 2.3$ MeV, and increased somewhat more slowly at higher energies. The rates were found by fitting the lower-energy cross-sections to the expression

$$\sigma(E) = \frac{S(E)}{E} \exp\left[-(E_G/E)^{1/2}\right] , \tag{3}$$

where E_G is the "Gamow energy" (Fowler, Caughlan, and Zimmerman 1967). The cross-section was allowed to go to zero at the $^{22}Ne(\alpha, n)$ threshold (0.567 MeV). The S-factors obtained were $(8.0 \pm 4.0) \times 10^8$ MeV-b for $^{21}Ne(\alpha, n)$ and $(1.0 \pm 0.5) \times 10^9$ MeV-b for $^{22}Ne(\alpha, n)$. We expect the uncertainty in the reaction rates calculated using these data to be a factor of 10 for temperatures $0.1 < T_9 < 0.5$.

d) $^{21,22}Ne(\alpha, \gamma)^{25,26}Mg$

The (α, γ) rates for ^{21}Ne and ^{22}Ne were determined relative to the (α, n) rates by the same procedure used to obtain the $^{18}O(\alpha, \gamma)$ rate. It was assumed that again $\Gamma_\gamma/\Gamma_n \simeq 10^{-3}$. In the region where $\langle\sigma v\rangle_{\alpha,n}$ was directly determined by the experimental data, it was found that $\langle\sigma v\rangle_{\alpha,\gamma} \simeq 10^{-3}\langle\sigma v\rangle_{\alpha,n}$ if the average reduced width was $\theta_\alpha^2 = 0.01$. The expected error in the calculated rate is a factor of 10.

These reactions have previously been studied by Reeves (1966) and by Fowler,

TABLE 2

PARAMETERS USED IN REACTION-RATE EXPRESSION

Reaction	A	B	C	D	E
$^{18}O(\alpha, \gamma)^{22}Ne$.........	1.474(17)	−39.37	− 3.14	3.496(3)	−14.47
$^{18}O(\alpha, n)^{21}Ne$.........	3.272(31)	−62.69	−10.69	2.405(6)	−14.12
$^{21}Ne(\alpha, \gamma)^{25}Mg$.......	6.063(16)	−47.88	− 4.172	3.280(2)	−16.44
$^{21}Ne(\alpha, n)^{24}Mg$.......	1.847(20)	−48.62	− 1.359	9.868(6)	−20.38
$^{22}Ne(\alpha, \gamma)^{26}Mg$.......	7.061(12)	−40.00	− 1.621	2.963(2)	−15.87
$^{22}Ne(\alpha, n)^{25}Mg$.......	7.417(20)	−49.96	− 1.352	1.580(7)	−21.43

Caughlan, and Zimmerman (1972). In all cases the differences between our rates and those calculated by these investigators are much less than the stated uncertainties. The differences are typically factors of 2 or 3.

The analytic expression used for the $^{14}N(\alpha, \gamma)^{18}F$ rate was that given by Couch *et al.* (1972). The other rates were fitted by the expression

$$N_A\langle\sigma v\rangle = AT_9^{-2/3} \exp(B/T_9^{1/3} + CT_9^2) + D \exp(E/T_9), \tag{4}$$

where N_A is Avogadro's number and A, B, C, D, and E are constants obtained by a least-squares fit. This form for the rate is one developed by Fowler *et al.* (1972). The expressions obtained reproduce the reaction rates in the range $0.1 < T_9 < 3.0$. The values obtained for the constants are given in table 2. The numbers in parentheses are the powers of 10 by which the number should be multiplied.

III. RESULTS

We have used the helium-burning models of Arnett (1972*a*) for our study. In particular we have investigated helium cores of mass $M_\alpha = 2, 4, 8, 16, 32,$ and $64\ M_\odot$ which correspond to stars with total mass in the range $7\ M_\odot < M < 125\ M_\odot$. From the numerical models we have obtained the central temperature, central density, and mass fraction of ^{4}He as a function of time. The approximate structural exponent,

$$n \equiv \frac{d \ln \rho/dr}{d \ln T/dr},$$

and the mass of the convective core M_{cc} were also determined. These quantities are given in table 3; see Arnett (1972*a*) for more detail.

TABLE 3

HELIUM-CORE PARAMETERS

$M_\alpha/M_\odot$	$M/M_\odot$	M_{cc}/M_α	n	$\rho_c/10^3$ g cm^{-3}	$T_c/10^9$ ° K
2............	7–10	0.31	1.65	2.37	0.152
4............	~15	0.43	1.85	1.14	0.169
8............	20–24	0.61	2.05	0.698	0.189
16............	34–40	0.76	2.25	0.427	0.196
32............	70–80	0.86	2.45	0.296	0.208
64............	110–125	0.90	2.65	0.220	0.220

NOTE.—M is the total mass of the star, M_α is the core mass, M_{cc} is the mass of the convective part of the core, n is the exponent in the structural (ρ, T) relationship, and ρ_c and T_c are the central density and temperature at the time of helium ignition.

We have assumed that the cores consisted initially of ^{4}He and ^{14}N, that the nuclear reactions involving ^{14}N had no effect on the evolution of the cores during helium burning, and that the convective core was well mixed. The first two approximations should be excellent, but a comment on the degree of mixing is necessary. The characteristic time for mass motion in the convective core is $\tau_{cc} \simeq r_{cc}/v_c$. For example, in the $M_\alpha = 8\ M_\odot$ model the radius of the convective core was $r_{cc} \simeq 2 \times 10^{10}$ cm and the convective velocity $v_c \simeq 5 \times 10^4$ cm s^{-1}, so that $\tau_{cc} \simeq 4 \times 10^5$ sec. The timescale for helium depletion was $\tau_n \simeq 10^{13}$ sec, so that it might be expected that each mass element would be exposed to the high temperatures in the central regions of the convective core many times. In this sense the convective core is well mixed. The evolution of abundances was performed by averaging the quantity $\dot{X}/X$ over the convective core at each time step and then logarithmically integrating over the time interval to obtain ΔX_i. The time steps were chosen such that $\Delta X_i/X_i \leq 0.4$ for $X_i > 10^{-9}$. The radial density variation was obtained by assuming that the helium core was a polytrope of index 3, and the radial dependence of temperature followed from $T \sim \rho^{1/n}$. After each time step the mass fraction of ^{4}He was adjusted to account for the consumption of ^{4}He in this series of reactions.

Table 4 summarizes the results of the calculations. The numbers quoted are the final fractions by mass, assuming an initial abundance $X(^{14}\text{N}) = 0.01$. Besides the "standard" cases which use our best estimates for the rates, we have also performed the calculations with certain rates varied by amounts which we consider to be the extent of their uncertainty. The results depend most strongly on the rates of ^{18}O(α, γ), ^{22}Ne(α, γ), and ^{22}Ne(α, n). A faster value for the ^{18}O(α, γ) rate has essentially no effect. A slower rate decreases the production of ^{25}Mg and ^{26}Mg slightly; however, the production of ^{21}Ne and ^{24}Mg is increased in inverse proportion to the change in the rate. Assuming a faster or slower rate for the reactions on ^{21}Ne and ^{22}Ne increases or decreases the production of the Mg isotopes proportionally. Reactions of ^{4}He with the magnesium isotopes were investigated and found to be unimportant.

TABLE 4

ABUNDANCES BY MASS

$M_\alpha/M_\odot$	Case	^{18}O	^{21}Ne	^{22}Ne	^{24}Mg	^{25}Mg	^{26}Mg
2......	1	0.0	3.40(−10)	1.56(−2)	2.50(−13)	6.21(−5)	5.32(−5)
	2	7.05(−3)	4.72(−5)	7.02(−3)	3.86(−9)	1.00(−5)	9.65(−6)
	3	0.0	3.40(−10)	1.51(−2)	2.50(−13)	6.12(−4)	5.26(−5)
4......	1	0.0	3.67(−9)	1.54(−2)	9.07(−12)	1.74(−4)	9.88(−5)
	2	2.17(−3)	6.83(−4)	1.21(−2)	1.21(−6)	1.66(−4)	5.70(−5)
	3	0.0	3.66(−9)	1.23(−2)	2.69(−11)	3.64(−3)	8.32(−5)
8......	1	0.0	3.34(−8)	1.37(−2)	2.11(−9)	1.92(−3)	2.88(−4)
	2	9.73(−5)	1.72(−3)	1.28(−2)	3.09(−5)	8.57(−4)	1.48(−4)
	3	0.0	3.36(−8)	5.28(−3)	1.95(−9)	1.16(−2)	2.10(−4)
16......	1	0.0	3.54(−7)	1.24(−2)	4.83(−8)	3.31(−3)	4.30(−4)
	2	1.48(−11)	1.12(−3)	1.18(−2)	1.28(−4)	2.67(−3)	3.03(−4)
	3	0.0	3.56(−7)	2.60(−3)	4.59(−8)	1.46(−2)	2.57(−4)
32......	1	0.0	5.64(−7)	7.54(−3)	4.06(−7)	8.58(−3)	7.30(−4)
	2	0.0	8.05(−4)	6.24(−3)	7.94(−4)	8.39(−3)	6.06(−4)
	3	0.0	6.99(−7)	1.49(−4)	2.48(−7)	1.74(−2)	2.96(−4)
64......	1	0.0	4.33(−7)	1.57(−3)	3.07(−6)	1.50(−2)	1.06(−3)
	2	0.0	1.30(−4)	1.09(−3)	1.73(−3)	1.37(−2)	8.97(−4)
	3	0.0	5.31(−7)	5.31(−11)	2.96(−6)	1.75(−2)	3.12(−4)

NOTE.—Case 1 abundances were determined using the best values for all reaction rates. Case 2 calculations were made with the ^{18}O(α, γ) rate reduced by a factor of 100, and case 3 with the ^{22}Ne(α, n) rate increased by a factor of 10.

IV. CONCLUSIONS

a) Nucleosynthesis

Let us denote the abundance by mass of one of the species ^{18}O, $^{21,22}Ne$, or $^{25,26}Mg$ by X_i, and the combined abundance of ^{12}C and ^{16}O by X_{CO}. Following the analysis of Talbot and Arnett (1972; to be referred to as TA) we find that at any given time the abundances of these species in the interstellar gas are related by

$$q_{CO,i}/q_{H,CO} \simeq 2X_i/(X_{CO})^2 , \tag{5}$$

where

$$q_{j,k} = \int_0^\infty \Psi_m Q_{jkm} dm$$

is an element of the dimensionless time-independent matrix, Ψ_m is the initial mass function, and the matrix element Q_{jkm} indicates how much of species j is converted to species k and ejected from a star of mass m. This is a general result relating primary and secondary species, and is relatively insensitive to the details of specific models of galactic evolution (see TA for discussion). Of course it must be recognized that galactic evolutionary theory is not sufficiently well established to make these arguments conclusive, but they are interesting and highly suggestive. In the case we now consider, we find

$$q_{CO,i}/q_{H,CO} \simeq \sum_m (X_i/0.01)_m w_m , \tag{6}$$

where

$$w_m \propto \Psi_m Q_{H,CO,m} \Delta m .$$

Following TA, we take $\Psi_m \propto m^{-1.6}$ in this mass range. By using this and the results of Arnett (1972*a*, *b*), the weighting factors w_m can be estimated for $M_\alpha = 4, 8, 16$, and $32\ M_\odot$ (for example, we obtain values of 0.21, 0.23, 0.27, and 0.28 or so, respectively). The model $M_\alpha = 64\ M_\odot$ ($M \simeq 125\ M_\odot$) was eliminated by the assumption that if Population I stars which are that massive actually exist, they undergo significant mass loss as a consequence of pulsational instability during hydrogen burning (see, for example, Talbot 1971). It would be unwise to place undue reliance on the accuracy of these numerical values of w; for simplicity we take $w = 0.25$ for these four M_α. This simplification will not affect our conclusions. Using table 4 and equation (6), we can now evaluate the left-hand side of equation (5) for each species ($^{21,22}Ne$ and $^{25,26}Mg$) and each of the three assumptions regarding reaction rates. These values can be compared, for each species, with an evaluation of the right-hand side of equation (5) made with solar-system abundances. The results are presented in table 5.

One reasonably firm conclusion can be made: If ^{12}C and ^{16}O are produced by the ejection without further nuclear processing of the outer parts of the old helium-burning convective core in massive stars, then ^{22}Ne can be produced in the same way. For all

TABLE 5

COMPARISON OF OBSERVATION AND PREDICTION

Quantity	^{18}O	^{21}Ne	^{22}Ne	^{25}Mg	^{26}Mg
$2X_i/(X_{CO})^2$	2.18(−1)	3.21(−2)	1.10	6.68(−1)	7.68(−1)
$q_{CO,i}/q_{H,CO}$:					
(1) Standard case	0.0	9.6(−5)	1.2	3.5(−1)	3.9(−2)
(2) $^{18}O(\alpha, \gamma) \times 0.01$	5.7(−2)	4.3(−1)	1.1	3.0(−1)	2.8(−2)
(3) $^{22}Ne(\alpha, n) \times 10$	0.0	1.1(−4)	5.1(−1)	1.2	2.1(−2)

three cases the theoretical quantity entered in the table equals the observed quantity $2X(^{22}\mathrm{Ne})/(X_{\mathrm{CO}})^2$ to within the accuracy of the observations. Drastic revisions in the stellar models or in the other reaction rates could alter this conclusion of course.

If in fact the rate of $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$ is 10 times the value we assume, then production of $^{25}\mathrm{Mg}$ is large enough to suggest a contradiction with the idea that $^{25}\mathrm{Mg}$ comes from explosive carbon burning. From the astrophysical point of view the latter idea seems more likely; a laboratory test by the nuclear experimentalist would resolve the problem. Total cross-section measurements of $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$ for $E_\alpha < 1.7$ MeV would be needed. In none of the three cases was the production of $^{26}\mathrm{Mg}$ very significant. Due to the rapidity of convective motion, $^{18}\mathrm{O}$ and $^{14}\mathrm{N}$ were transported to regions where their destruction rates were high; little $^{14}\mathrm{N}$ or $^{18}\mathrm{O}$ remained. Finally, it should be noted that while the production of $^{25,26}\mathrm{Mg}$ is enhanced by including more massive stars, the estimates above assumed an upper mass limit of $M \simeq 100\ M_\odot$ for matter processed in this way, so that these estimates might tend to overestimate the $^{25,26}\mathrm{Mg}$ abundance.

b) *Urca Rates and* ^{12}C *Ignition*

As may be seen from table 4, the abundance of $^{25}\mathrm{Mg}$ increases with increasing mass. Arnett (1972*a*) has shown that the case $M_\alpha = 2\ M_\odot$ undergoes core helium burning in such a way as to represent the most massive star which could ignite $^{12}\mathrm{C}$ under conditions of high electron degeneracy (i.e., $M \simeq 8\ M_\odot$). In this sense the $^{25}\mathrm{Mg}$ production by this model represents an upper limit to its abundance (for the reaction rates used). Our best estimate, case 1, predicts that the enhancement of $^{25}\mathrm{Mg}$ is modest, only a factor of 2 above the initial value expected for Population I. Uncertainties in the reaction rates do not allow us to rule out a larger enhancement (say a factor of 10) as table 4 shows. However, it is clear that the combination of reaction rates and stellar models used here does not suggest a large enhancement of $^{25}\mathrm{Mg}$ during helium burning.

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