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THE RATE OF THE $^{14}N(\alpha, \gamma)^{18}F$ REACTION*

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ABSTRACT

New experimental and theoretical results are presented on the $^{14}N(\alpha, \gamma)^{18}F$ reaction. A new resonance has been found at $E_\alpha = 0.56$ MeV with $(2J + 1)\Gamma_\alpha\Gamma_\gamma/\Gamma = 2.8 \pm 0.5 \times 10^{-4}$ eV (lab). From a theoretical calculation of the cross-section for direct radiative capture, and an extrapolation of the tails of the measured resonances to $E_\alpha = 0.0$, a value $S \approx 0.7$ MeV-barns is estimated for the nonresonant S-factor. The reaction rate is calculated, and the significance of this rate is discussed. It is found that in most stars α-capture by ^{14}N takes place after the initiation of helium burning by the $3\alpha \rightarrow {}^{12}C$ reaction.

I. INTRODUCTION

Estimates of the $^{14}N(\alpha, \gamma)^{18}F$ reaction rate given by Reeves (1966) and by Fowler, Caughlan, and Zimmerman (1967) have been used almost exclusively in the literature. An experimental investigation by Parker (1968) showed that the reaction rate had been greatly overestimated, but the data still allowed a considerable uncertainty in the rate. A recent experimental and theoretical study by the authors (Couch *et al.* 1971) has removed much of this uncertainty. In the remainder of this introduction we describe briefly the stellar circumstances in which the $^{14}N(\alpha, \gamma)^{18}F$ reaction may play an important role. All investigations referred to in this introduction have used a value for the $^{14}N(\alpha, \gamma)^{18}F$ rate consistent with that given by Reeves or by Fowler *et al.*, except for the work of Howard, Arnett, and Clayton (1971), which is consistent with the experimental data of Parker. In the second section we present the new data available on this reaction, and recalculate the reaction rate. The final section contains a discussion of the consequences of this new calculation for the $^{14}N(\alpha, \gamma)^{18}F$ reaction rate under astrophysical circumstances.

A result of the burning of hydrogen by the CNO cycle, provided this process attains equilibrium, is the conversion of nearly all CNO nuclei to ^{14}N. Consequently, there is expected to be a significant concentration of ^{14}N in the hydrogen-depleted region of most stars. The ^{14}N burns predominantly by the $^{14}N(\alpha, \gamma)^{18}F$ reaction; thus the rate of this reaction can, in certain circumstances, be quite important for further evolution of the star, and for nucleosynthesis of the elements.

It is particularly important to know the rate of the $^{14}N(\alpha, \gamma)^{18}F$ reaction relative to that of the $3\alpha \rightarrow {}^{12}C$ reaction, Iben (1967*a*) has studied the evolution of Population I stars of 2.25, 3, 5, 9, and 15 $M_\odot$ through the onset of helium burning. Assuming that the 3α process was much slower than α-capture by ^{14}N, Iben found that for the 9 $M_\odot$ and 15 $M_\odot$ stars the onset of $^{14}N(\alpha, \gamma)^{18}F(\beta^+\nu)^{18}O$ reactions produced a distinct rise in luminosity. In the lower-mass stars the ignition of ^{14}N occurred along the red-giant branch, and in the case of the 3 $M_\odot$ star the conversion of ^{14}N to ^{18}O caused the star to descend along the red-giant branch until the ^{14}N was exhausted, after which it again began to ascend. For stars with $M \leq 2.25\ M_\odot$ electron degeneracy became significant before the initiation of helium-burning reactions. A result of the onset of degeneracy is that these lower-mass stars will rise a considerable distance above the base of the red-

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giant branch before helium burning begins. This stage of evolution is terminated by the helium flash, which can be caused by the rapid burning of helium by the 3α process at temperatures $T_9 \approx 0.09$. If the rate of α-capture by ^{14}N is large at temperatures lower than $T_9 \approx 0.09$, the $^{14}N(\alpha, \gamma)^{18}F(\beta^+\nu)^{18}O$ reactions can generate enough energy to either remove the degeneracy or raise the temperature enough to allow the 3α process to cause the flash. Iben (1967*b*) concludes that the luminosity at the red-giant tip could vary by several magnitudes depending on whether or not the flash is triggered by the $^{14}N(\alpha, \gamma)^{18}F$ reaction, and that the energy produced in α-capture by ^{14}N places the critical mass above which flashing does not occur at approximately 2.25 $M_\odot$. The question of a nitrogen-induced flash has also been considered by Reeves (1966) and by Eggleton (1968). Asano and Sugimoto (1968), assuming a model in which the helium flash is triggered by the $^{14}N(\alpha, \gamma)^{18}F$ reaction, have determined theoretical luminosities of horizontal-branch stars in the helium-burning phase for different abundances of helium and metals, and concluded that the results indicate a primordial helium abundance. Also, Reeves (1966) has suggested that sufficient energy may be generated in α-capture by nitrogen to induce helium burning in some stars with $M = 0.4\ M_\odot$ which otherwise could not reach temperatures great enough to initiate the $3\alpha \rightarrow {}^{12}C$ reaction.

The rate of the $^{14}N(\alpha, \gamma)^{18}F$ reaction has important consequences for nucleosynthesis. The ^{18}F nucleus decays by positron emission to ^{18}O with a half-life of 109.8 minutes. The ^{18}O thus produced is an abundant source of neutrons in subsequent nuclear processing. If the $^{14}N(\alpha, \gamma)^{18}F$ reaction takes place at high enough temperatures, it is possible that reactions with ^{18}F will occur more rapidly than the decay to ^{18}O. Molnar (1971) has investigated the nucleosynthesis which occurs in the model of the helium flash given by Edwards (1969). In this model, in which a Population II red giant with $M = M_\odot$ is considered, temperatures in excess of 10^9 ° K are reached during the flash. By assuming that all ^{14}N has been converted to ^{18}O prior to the helium flash, Molnar has shown that the production of neutrons, mainly by $^{18}O(\alpha, n)^{21}Ne(\alpha, n)^{24}Mg$, is sufficient to produce the *r*-process nuclei.

Howard *et al.* (1971) have investigated explosive nucleosynthesis in hydrogen-depleted helium zones ($X_N \approx 0.015$) which surround a more evolved core. The explosive heating and expansion of the helium zone is the result of an event taking place in the core. They found that only a few percent of the helium is consumed by the $3\alpha \rightarrow {}^{12}C$ reaction, and that most of the other elements produced (mainly ^{15}N, ^{18}O, ^{19}F, and ^{21}Ne) are the result of reactions with ^{14}N—the (α, γ) channel being the most important.

II. THE REACTION RATE

Table 1 lists the states of ^{18}F above the α-particle threshold which can be expected to contribute to the reaction rate. The most relevant previously existing data on $^{14}N(\alpha, \gamma)^{18}F$ are due to Parker (1968), and consist of total cross-section measurements for the four resonances at $E_\alpha = 1.140$, 1.395, 1.532, and 1.619 MeV, and an upper limit on the yield below 1.0 MeV. This limit did not rule out a possible contribution to the reaction rate by one or more of the four states at laboratory α-particle energies of 0.310, 0.417, 0.559, and 0.698 MeV. Of these levels, the one at 0.559 MeV is the most likely to contribute to the reaction rate. Alpha capture by the state at 0.310 MeV is greatly inhibited by the large angular momentum ($l = 4$) required to form it. In addition, this state has isospin $T = 1$, and thus can be formed only through a $T = 0$ admixture in the state, or $T = 1$ admixture in ^{14}N or ^4He. The state at 0.698 MeV also has $T = 1$ and is expected to be similarly inhibited. The level at $E_\alpha = 0.417$ MeV is assigned $J^\pi = 0^+$ and thus cannot be populated in $\alpha + {}^{14}N$. There is also a state of ^{18}F at 4.402 MeV just below threshold, but it is expected to be too far below the most effective α-particle energy (for $T_9 > 0.05$) to be relevant.

The experimental investigation of the $^{14}N(\alpha, \gamma)^{18}F$ reaction by the authors (Couch *et al.* 1971) was restricted to the regions $E_\alpha < 1.2$ MeV. The data obtained indicated a

TABLE 1

RESONANCE STRENGTHS FOR $^{14}N(\alpha, \gamma)^{18}F$

			$(2J+1)\Gamma_\alpha\Gamma_\gamma/\Gamma$ eV (lab)	
E_α (MeV)	E_x (MeV)	J^π; T	Present Experiment	Parker
0.310.......	4.656	4^+; 1	$<2\times10^{-5}$	...
0.417.......	4.739	0^+; 1	Forbidden by selection rules	...
0.559.......	4.849	1; 0	$2.8\pm0.5\times10^{-4}$	...
0.698.......	4.957	2^+; 1	$<0.5\times10^{-4}$	...
1.140.......	5.301	$1^+, 2, 3, 4^+$; 0	0.108 ± 0.015	0.084 ± 0.004
1.395.......	5.501	...	...	0.027 ± 0.003
1.532.......	5.607	$(1^-; 0)$	...	$4.80\ \pm0.40$
1.619.......	5.674	$(1^-; 0)$	...	$1.35\ \pm0.15$

resonance at approximately 0.56 MeV, corresponding to the 4.849-MeV level in ^{18}F, and no measurable contribution from any other state in ^{18}F below $E_\alpha = 1.0$ MeV.

The resonance strengths, $(2J + 1)\Gamma_\alpha\Gamma_\gamma/\Gamma$, of the 0.56- and 1.140-MeV states are presented in Table 1, along with an upper limit on the strength of any resonance below 0.5 MeV. The strengths measured by Parker (1968) are also included. The value which we obtained for the 1.140-MeV resonance is in agreement with that obtained by Parker.

Parker also obtained an upper limit on the nonresonant S-factor by assuming that the cross-section below 1.0 MeV is determined by the Coulomb barrier, and thus obeys the relation (Fowler *et al.* 1967)

$$\sigma_{\text{nonres}} = \frac{S}{E} \exp\left[-0.989 Z_0 Z_1 A^{1/2}/E^{1/2}\right], \tag{1}$$

where Z is the charge, E is the α-particle energy in MeV in the center-of-mass system, and A is the reduced mass in atomic mass units. Using his limit on the yield below 1.0 MeV, Parker obtained $S \leq 1.5 \times 10^3$ MeV-barns. By using the same reasoning, the limit which we obtained for the S-factor is at least an order of magnitude lower. However, parametrizing the cross-section by equation (1) is valid only if the reaction is dominated by nonresonant direct radiative capture, or if the reaction proceeds through many low-energy resonances whose strength is proportional to the Coulomb barrier penetrability. Neither case is applicable for the $^{14}N(\alpha, \gamma)^{18}F$ reaction.

A theoretical estimate of the contribution of direct capture processes to the low-energy yield has been made by Tombrello (1971). The result of this calculation is an upper limit for the direct-capture cross-section, which yields the value $S \approx 0.1$ MeV-barns. The tails of the resonances also contribute to the S-factor, but only the 0.56-MeV resonance is significant; and, estimating its width to be 1 eV, the contribution to S is ≈ 0.6 MeV-barns. The sum of these two terms has been used in the calculation of the reaction rate. The estimates for the S-factor given by Reeves (1966) and by Fowler *et al.* (1967) were $S \approx 10^7$ MeV-barns.

Although the level in ^{18}F at 4.656 MeV ($E_\alpha = 0.310$) has $T = 1$, it cannot be completely ignored since α-particle capture can still take place through isospin impurities which may be present. The experimental upper limit on the strength of this resonance is many orders of magnitude too large to rule out a contribution to the reaction rate. However, at low α-particle energies $\Gamma_\alpha \ll \Gamma_\gamma$ and $\Gamma_\alpha\Gamma_\gamma/\Gamma \approx \Gamma_\alpha$, and an estimate can be made of its strength. The alpha width is given by 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 angular momentum of the α-particle, R is the nuclear radius, M is the reduced mass, and θ_α is the ratio of the reduced width to the Wigner limit. The 4.656-MeV level has $J^\pi = 4^+$; thus it can only be formed by $l = 4$ capture on ^{14}N. The reduced width can only be estimated, but, taking into account the $T = 1$ nature of the state, a value $\theta_\alpha^2 = 10^{-3}$ was chosen as a conservative upper limit. If this value is used for θ_α^2, the estimate of the strength of a state at $E_\alpha = 0.310$ MeV is 2.5×10^{-14} eV.

The reaction rate $N_A\langle\sigma v\rangle$ has been calculated in the range $0.01 \leq T_9 \leq 1.0$ by using the equations of Fowler *et al.* (1967). The term $\langle\sigma v\rangle$ is the averaged velocity cross-section product, and N_A is Avogadro's number. The results are presented in Table 2, where the contributions from the nonresonant cross-section, the resonances at 0.310 and 0.559 MeV, and the higher resonances are listed separately, along with the sum of all the terms. The nonresonant term is dominant for $T_9 \leq 0.05$. The rate in this temperature range is not well known because the width of the 4.849-MeV state in ^{18}F could only be estimated and the state just below the $^{14}N + \alpha$ threshold has been ignored. In the range $0.05 < T_9 < 0.09$ the resonance at $E_\alpha = 0.310$ MeV controls the rate (for the estimate of the strength given above), and the rate in this temperature range should be considered as an upper limit. For $T_9 > 0.1$ the reaction rate is determined by the measured resonances with an uncertainty of about 20 percent.

In analytic form, the reaction rate is

$$N_A\langle\sigma v\rangle = \frac{9.05 \times 10^9}{T_9^{2/3}} \exp\left[\frac{-36.031}{T_9^{1/3}} - \left(\frac{T_9}{0.863}\right)^2\right](1.0 + 1.16 \times 10^{-2} T_9^{1/3})$$
$$+ \frac{2.373 \times 10^{-10}}{T_9^{3/2}} \exp\left(\frac{-2.798}{T_9}\right) + \frac{2.028}{T_9^{3/2}} \exp\left(\frac{-5.054}{T_9}\right)$$
$$+ 1.415 \times 10^4 \exp\left(\frac{-12.138}{T_9}\right). \tag{3}$$

TABLE 2

REACTION RATE, $N_A\langle\sigma v\rangle$, FOR THE $^{14}N(\alpha,\gamma)^{18}F$ REACTION

T_9	Nonresonant	Resonance $E_\alpha=0.310$	Resonance $E_\alpha=0.559$	Higher Resonances	Sum*
0.01......	4.55×10^{-62}	...	...	...	4.55×10^{-62}
0.02......	2.77×10^{-47}	1.48×10^{-68}	...	...	2.77×10^{-47}
0.03......	4.10×10^{-40}	1.44×10^{-48}	2.67×10^{-71}	...	4.10×10^{-40}
0.04......	1.36×10^{-35}	1.25×10^{-38}	3.39×10^{-53}	...	1.36×10^{-35}
0.05......	2.23×10^{-32}	1.06×10^{-32}	2.29×10^{-42}	...	3.29×10^{-32}
0.06......	6.31×10^{-30}	9.05×10^{-29}	3.61×10^{-35}	...	9.68×10^{-29}
0.07......	5.71×10^{-28}	5.62×10^{-26}	4.82×10^{-30}	6.96×10^{-72}	5.67×10^{-26}
0.08......	2.34×10^{-26}	6.80×10^{-24}	3.28×10^{-26}	1.80×10^{-62}	6.85×10^{-24}
0.09......	5.41×10^{-25}	2.77×10^{-22}	3.07×10^{-23}	3.78×10^{-55}	3.09×10^{-22}
0.10......	8.07×10^{-24}	5.30×10^{-21}	7.20×10^{-21}	2.72×10^{-49}	1.25×10^{-20}
0.20......	4.41×10^{-17}	2.23×10^{-15}	2.40×10^{-10}	6.21×10^{-23}	2.40×10^{-10}
0.30......	7.60×10^{-14}	1.29×10^{-13}	5.96×10^{-7}	3.79×10^{-14}	5.96×10^{-7}
0.40......	7.84×10^{-12}	8.60×10^{-13}	2.61×10^{-5}	9.37×10^{-10}	2.61×10^{-5}
0.50......	2.00×10^{-10}	2.49×10^{-12}	2.34×10^{-4}	4.05×10^{-7}	2.34×10^{-4}
0.60......	2.22×10^{-9}	4.82×10^{-12}	9.59×10^{-4}	2.32×10^{-5}	9.82×10^{-4}
0.70......	1.43×10^{-8}	7.44×10^{-12}	2.53×10^{-3}	4.17×10^{-4}	2.95×10^{-3}
0.80......	6.26×10^{-8}	1.00×10^{-11}	5.11×10^{-3}	3.64×10^{-3}	8.76×10^{-3}
0.90......	2.05×10^{-7}	1.24×10^{-11}	8.65×10^{-3}	1.97×10^{-2}	2.83×10^{-2}
1.00......	5.38×10^{-7}	1.45×10^{-11}	1.29×10^{-2}	7.57×10^{-2}	8.87×10^{-2}

* Above $T_9 = 0.09$ the rate is well determined by the experimental data. For $0.05 < T_9 < 0.09$, the quoted values of $N_A\langle\sigma v\rangle$ should be considered upper limits. Below $T_9 = 0.05$ the rate is determined by the S-factor, which is less accurately known because the width of the 4.849-MeV state could only be estimated, and the state just below threshold was ignored.

The T_9^2 term is included in the first exponential (the nonresonant term) to suppress its contribution in the temperature range in which the reaction rate is accurately determined by the measured resonances. The second and third terms give the contribution from resonances at $E_\alpha = 0.310$ and 0.559 MeV, respectively. The contribution of the higher resonances is contained in the final term.

III. DISCUSSION

The importance of knowing the rate of the $^{14}N(\alpha, \gamma)^{18}F$ reaction relative to the rate of the $3\alpha \rightarrow {}^{12}C$ reaction has been discussed in the first section of this paper. We consider first the possibility that the $^{14}N(\alpha, \gamma)^{18}F$ reaction is a significant source of energy prior to the helium flash. The energy generated per unit time by a reaction which liberates energy Q involving n nuclei having a mean life for reaction τ, is

$$\frac{dE}{dt} = \frac{nQ}{\tau} . \tag{4}$$

The ratio of the energy generated by the 3α process to the energy generated by the $^{14}N(\alpha, \gamma)^{18}F(\beta^+\nu)^{18}O$ reactions is then

$$\frac{E(3\alpha)}{E(\alpha, \gamma)} = \frac{Q(3\alpha)}{Q(\alpha, \gamma)} \frac{\tau_N(\alpha)}{\tau_{3\alpha}(\alpha)} , \tag{5}$$

where $\tau_{3\alpha}(\alpha)$ is the mean life of an α-particle to the $3\alpha \rightarrow {}^{12}C$ reaction and $\tau_N(\alpha)$ is the mean life of an α-particle to capture by ^{14}N. The Q-value for the 3α process is 7.27 MeV, and the Q-value for $^{14}N(\alpha, \gamma)^{18}F(\beta^+\nu)^{18}O$ is 6.07 MeV. The value of $\tau_N(\alpha)$ can be determined using the $N_A\langle\sigma v\rangle$ values of Table 2 and the relation (Fowler *et al.* 1967)

$$\tau_N(\alpha) = \frac{A_N}{\tau X_N N_A{}^\alpha\sigma v\rangle} \tag{6}$$

where A_N and X_N are the atomic weight and mass fraction of ^{14}N, ρ is the density in g cm^{-3}, and τ is in seconds. The mean life of a ^4He nucleus to the 3α process is given by

$$\tau_{3\alpha}(\alpha) = \frac{1.51 \times 10^9}{(\rho X_\alpha)^2} T_9^3 \exp{(4.410/T_9)} . \tag{7}$$

This equation is from Fowler *et al.* (1967) except that we have used the results of more recent measurements of the energy difference between the 7.65-MeV excited state of ^{12}C and three α-particles (Austin, Trentelman, and Kashy 1971; McCaslin, Mann, and Kavanagh 1971). Härm and Schwarzschild (1966) have studied the evolution of low-mass stars of Population II through the helium flash. They found that for a star with $M = M_\odot$ and $Z = 0.001$, the helium flash occurs at a temperature $T_9 \approx 0.09$ and a central core density $\rho \approx 10^6$ g cm^{-3}. We have calculated the ratio $E(3\alpha)/E(\alpha, \gamma)$ for $\rho = 10^6$, but to maximize the effect of the $^{14}N(\alpha, \gamma)^{18}F$ reaction we have taken $X_N = 0.01$. The logarithm of this ratio is plotted in Figure 1 for temperatures $0.05 \leq T_9 \leq 0.3$. Above $T_9 = 0.3$ the ^{14}N is rapidly consumed and is no longer a significant source of energy. At temperatures in the region $T_9 \approx 0.09$ the energy produced by the 3α process is considerably greater than that produced by $^{14}N(\alpha, \gamma)^{18}F(\beta^+\nu)^{18}O$. At lower temperatures ($T_9 \leq 0.06$) energy generation by α-capture on ^{14}N is dominant due to the greater temperature dependence of the 3α reaction, but the net energy produced is too small to be significant. If both sources are included, the energy generated at $T_9 = 0.06$ is approximately 10^{-10} times the energy generation at $T_9 = 0.09$. This argument depends on the value chosen for the density because $\tau_{3\alpha}(\alpha)$ varies as ρ^{-2} whereas $\tau_N(\alpha)$ varies only as ρ^{-1}. However, the core density at the time of the helium flash does not depend strongly on the stellar mass; thus we conclude that the $^{14}N(\alpha, \gamma)^{18}F$ reaction is of little consequence in the evolution of the low-mass stars along the red-giant branch.

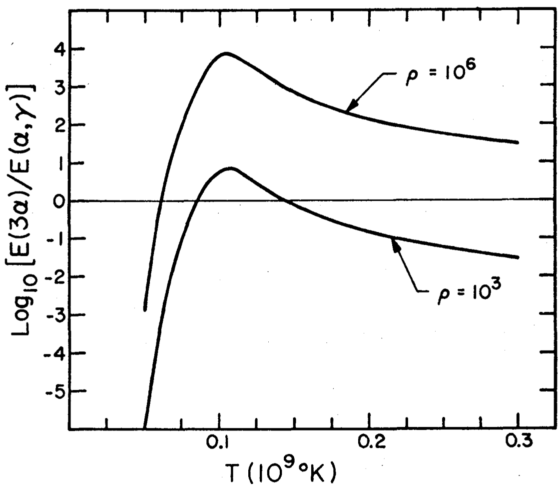

FIG. 1.—Plot of the temperature dependence of the ratio of the energy generated by the 3α process to that generated by $^{14}N(\alpha, \gamma)^{18}F\ (\beta^+\nu)^{18}O$ for mass fractions $X_\alpha = 0.99$ and $X_N = 0.01$ at densities of 10^3 and 10^6 g cm^{-3}. The mass fractions are assumed to remain constant.

In higher-mass stars the initiation of helium-burning reactions occurs at much lower densities. Iben (1966) has studied the evolution of a 15 $M_\odot$ star through the onset of helium burning. In this star the $3\alpha \rightarrow {}^{12}C$ reaction becomes important at $T_9 \approx 0.11$ and $\rho \approx 10^3$ g cm^{-3}. In Figure 1 we have also plotted the logarithm of $E(3\alpha)/E(\alpha, \gamma)$ for this density. At $T_9 = 0.11$ the 3α process is still the dominant energy source, and it seems unlikely that nitrogen burning will have an appreciable effect.

The present value for the reaction rate also makes invalid the assumption by Molnar (1971) that all ^{14}N present in the red-giant phase is consumed prior to the helium flash. The mean life of ^{14}N to α-capture is

$$\tau_\alpha(\mathrm{N}) = \frac{A_\alpha}{\rho X_\alpha N_A \langle\sigma v\rangle} . \tag{8}$$

The quantity log $[\rho X_\alpha \tau_\alpha(\mathrm{N})]$, where $\tau_\alpha(\mathrm{N})$ is in years, is plotted in Figure 2. Using the model of Härm and Schwarzschild (1966) we expect a central core density of approximately 10^6 g cm^{-3} and a temperature $T_9 \approx 0.09$ at the time of the helium flash. From equation (8) we obtain $\tau_\alpha(\mathrm{N}) = 4 \times 10^8$ years at $T_9 = 0.09$. Since $\tau_\alpha(\mathrm{N})$ is much larger to lower temperatures and since the time during which the core remains at these elevated temperatures is small compared with 4×10^8 years, very little of the ^{14}N is converted to ^{18}O by the $^{14}N(\alpha, \gamma)^{18}F(\beta^+\nu)^{18}O$ reactions prior to the helium flash. Consequently, ^{18}O cannot act as a source of r-process neutrons in the manner described by Molnar.

Howard *et al.* (1971) have investigated the nucleosynthesis which takes place in helium zones ($X_N \approx 0.015$) whose temperature is rapidly increased and then allowed to expand adiabatically. The study was restricted to peak temperatures less than 10^9 ° K. We find that in the range $0.1 \leq T_9 \leq 0.8$ the reaction rate is much greater, due to the 0.56-MeV resonance, than assumed by Howard *et al.*, but the two rates are nearly equal for $T_9 \geq 0.9$. Howard *et al.* have pointed out that the most important factor in determining the final abundances is the amount of ^{14}N consumed. However, in testing the dependence of the abundances on the $^{14}N(\alpha, \gamma)^{18}F$ rate, they discovered that variations in this rate could be compensated for, almost exactly, by varying the adiabat in order to burn the same amount of ^{14}N. Thus it is not immediately obvious what effect the increased $^{14}N(\alpha, \gamma)^{18}F$ rate will have on the nucleosynthesis; however, at the temperatures

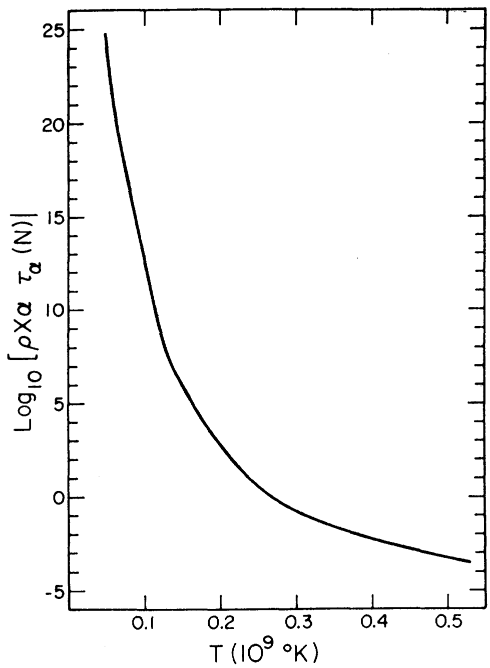

FIG. 2.—Temperature dependence of $\rho X_\alpha \tau_\alpha(\mathrm{N})$, where $\tau_\alpha(\mathrm{N})$ is the mean life in years of ^{14}N to α-capture.

of interest here, the reaction rate is well determined by the experimental measurements, and it should place restrictions on the circumstances in which nucleosynthesis occurs in helium zones.

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