STELLAR RATES FOR THE $^{28}\text{Si}(\alpha, \gamma)^{32}\text{S}$ AND $^{16}\text{O}(\alpha, \gamma)^{20}\text{Ne}$ REACTIONS*

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ABSTRACT

The stellar interaction rate for the $^{28}\text{Si}(\alpha, \gamma)^{32}\text{S}$ reaction has been calculated from new cross-sections for this reaction for temperatures from $(0.3-5) \times 10^9$ ° K. The astrophysical implications of new data for the $^{16}\text{O}(\alpha, \gamma)^{20}\text{Ne}$ reaction at low energy are also discussed.

I. THE $^{28}\text{Si}(\alpha, \gamma)^{32}\text{S}$ REACTION

Bodansky, Clayton, and Fowler (1968), among others, have stressed the importance of the astrophysical rates for particle-capture reactions in the nuclear mass region $24 < A < 56$ in silicon burning, particularly during the “freeze-out” stage. These rates are also essential to studies of explosive nucleosynthesis processes, which have been discussed by Arnett (1969), Truran and Arnett (1969), Truran, Cameron, and Gilbert (1966), Truran, Arnett, and Cameron (1967), Wagoner (1969), and others. The present paper describes the results of an experimental study of the reaction $^{28}\text{Si}(\alpha, \gamma)^{32}\text{S}$, a continuation of the program begun at this laboratory some years ago (Lyons, Toevs, and Sargood 1969; Lyons *et al.* 1970).

The $^{28}\text{Si}(\alpha, \gamma)^{32}\text{S}$ reaction yield was measured for incident α -particle energies between 1400 and 2750 keV, and resonance strengths were determined for six resonances, of which five have not been reported previously; the resonance energies and strengths are listed in Table 1. These six resonances dominate the stellar interaction rate for temperatures up to 4×10^9 ° K, and are responsible for about 46 percent of the yield at 5×10^9 ° K. No evidence was found for reaction yield below 1700 keV, and upper limits were determined for the strength of undetected resonances that might exist at low energy; these upper limits also appear in Table 1. An analysis of these limits (Toevs 1970) showed that no undetected, low-energy resonance could contribute significantly to the astrophysical rate for temperatures above 2×10^9 ° K. The experimental details of this investigation will be published elsewhere (Toevs 1971).

For the calculation of the astrophysical rates, the new data were supplemented with results at higher energy obtained by Smulders (1964) and Langevin, Laurent, and Verotte (1965). The resonance strengths of Smulders include only the contributions from γ -transitions to the ground state and first excited state of ^{32}S . These values have therefore been normalized at 2618 keV to the value obtained in the present investigation; an uncertainty of 50 percent was assumed for the renormalized data. Approximate values for the strengths of resonances studied by Langevin *et al.* were deduced from the yield curve appearing in that paper. An uncertainty of a factor of 2 was estimated for those data. The large uncertainty assigned to Langevin’s data does not carry over to the interaction rates since the contribution of his data to the total rate is only 11 percent at 5×10^9 ° K, and is less at lower temperatures.

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TABLE 1
RESONANCE ENERGIES AND STRENGTHS
FOR $^{28}\text{Si}(\alpha,\gamma)^{32}\text{S}$

Resonance Energy (keV)*	^{28}S Excitation (MeV)	$(2J+1)\Gamma_\alpha\Gamma_\gamma/\Gamma$ (eV)*
1776±5.....	8.50	0.025±0.007
1995±5.....	8.69	0.020±0.006
2187±7.....	8.86	0.041±0.014
2370±4.....	9.02	0.093±0.023
2415±5.....	9.06	0.134±0.034
2618±4.....	9.24	0.61 ±0.15
(2581).....	9.207	<0.015
1400-1700.....	...	<0.0008
<1400.....	...	<0.0001

* Measured in laboratory units.

The interaction rate for this reaction was calculated from the equation given by Clayton (1968, p. 357),

$$\langle\sigma v\rangle_{\alpha,\gamma}=\left[\frac{2\pi\hbar^2}{\mu kT}\right]^{3/2}\sum_r\left(\frac{\omega\Gamma_\alpha\Gamma_\gamma}{\hbar\Gamma}\right)_r\exp\left(-\frac{E_r}{kT}\right).$$

Values for $N_A\langle\sigma v\rangle$ at several temperatures are listed in Table 2, where N_A is Avogadro's number. The units used throughout this paper for $N_A\langle\sigma v\rangle$ are reactions $\text{s}^{-1}\text{ g}^{-1}\text{ cm}^3$. The nonresonant yield was assumed to be negligible throughout the astrophysically important energy region.

It should be remarked that interaction rates calculated from experimentally determined cross-sections can include only the contribution from the ground state of the target nucleus (^{28}Si). Since, at $T=5\times10^9\text{ }^\circ\text{K}$, approximately 7 percent of the ^{28}Si nuclei will be found in the first excited state, alpha capture on this state could be of some importance.

Two- and four-parameter fits to the interaction rates as a function of temperature are provided to facilitate astrophysical calculations. The formula, $N_A\langle\sigma v\rangle=9.36\times10^2\exp(-18.8/T_9)$ fits the rates calculated from the experimental data within 30 per-

TABLE 2
THE STELLAR INTERACTION RATE FOR $^{28}\text{Si}(\alpha,\gamma)^{32}\text{S}$ *

Temperature ($10^9\text{ }^\circ\text{K}$)	$N_A\langle\sigma v\rangle(\text{s}^{-1}\text{ g}^{-1}\text{ cm}^3)$	Temperature ($10^9\text{ }^\circ\text{K}$)	$N_A\langle\sigma v\rangle(\text{s}^{-1}\text{ g}^{-1}\text{ cm}^3)$
0.3.....	2.43×10^{-23}	1.5.....	2.64×10^{-3}
0.4.....	5.32×10^{-17}	2.0.....	5.68×10^{-2}
0.5.....	3.16×10^{-13}	2.5.....	4.12×10^{-1}
0.6.....	9.93×10^{-11}	3.0.....	1.63
0.7.....	5.87×10^{-9}	3.5.....	4.44
0.8.....	1.23×10^{-7}	4.0.....	9.46
0.9.....	1.30×10^{-6}	4.5.....	17.0
1.0.....	8.59×10^{-6}	5.0.....	27.1

* Due to uncertainties in the experimental data, standard deviations of 35-45 percent should be assigned to the interaction rate.

cent for $T_9 = 1-5$, but is too low by a factor of 7.4 at $T_9 = 0.5$. The form $N_A \langle \sigma v \rangle = 2.73 \times 10^2 \exp(-17.1/T_9) + 2.81 \times 10^3 \exp(-24.9/T_9)$ fits the data within 8 percent over the range $T_9 = 0.5-5$. The experimental uncertainty in the data, however, is much greater than 8 percent; and the possible existence of resonances at low energy, below our limit of detectability, casts some doubt on the validity of these expressions below $T_9 \sim 1$.

II. THE ¹⁶O(α,γ)²⁰Ne REACTION

Asano and Sugimoto (1968) have described a model in which the helium flash, which precedes stable helium burning, is initiated by energy released in alpha capture on ¹⁴N, the major nuclear remnant of CNO burning. Although recent data on low-energy resonances in ¹⁴N(α,γ)¹⁸F (Parker 1968; Couch *et al.* 1971) may eliminate this possibility, Fowler (1969) has suggested that an undetected resonance at low energy in ¹⁶O(α,γ)²⁰Ne might provide the energy required for the Asano-Sugimoto model. In addition, the ¹⁶O(α,γ)²⁰Ne reaction rate is important in predicting nuclear abundances at the end of helium burning.

The ¹⁶O(α,γ)²⁰Ne reaction was therefore reinvestigated for incident alpha energies between 850 and 2490 keV. No new resonances were found, and the values given by Van der Leun, Sheppard, and Smulders (1965) for the strengths of the three lowest known resonances were verified within the experimental uncertainty. Special efforts were made to establish upper limits for the reaction yield at low α-particle energy; these results are listed along with the measured resonance strengths in Table 3.

Although the existence of an undetected resonance at low energy in the ¹⁶O(α,γ)²⁰Ne reaction was *a priori* unlikely, the present results eliminate the possibility that alpha capture on ¹⁶O could provide the energy required for the Asano-Sugimoto model of the helium flash.

On the basis of our results and of estimates for nonresonant direct radiative capture by Tombrello (1971) it is found that

$$\begin{aligned} N_A \langle \sigma v \rangle = & 5.36 \times 10^9 (1 + 1.05 \times 10^{-2} T_9^{1/3}) T_9^{-2/3} \exp[-39.76(T_9^{-1} + 0.064)^{1/3}] \\ & + 40.9 T_9^{-3/2} \exp(-10.36 T_9^{-1}) + 391 T_9^{-3/2} \exp(-12.24 T_9^{-1}) \\ & + 882 T_9^{-3/2} \exp(-23.11 T_9^{-1}) . \end{aligned}$$

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TABLE 3
RESONANCE STRENGTHS FOR ¹⁶O(α,γ)²⁰Ne

RESONANCE ENERGY (keV)*	(2J+1) Γ _α Γ _γ /Γ (MeV)*		(2J+1) Γ _α Γ _{γ₁} /Γ (MeV)*
	This Experiment	Van der Leun <i>et al.</i>	This Experiment
2490.....	41 ± 12	33 ± 15	...
1319.....	18.2 ± 3.6	12 ± 3	...
1116.....	1.9 ± 0.38	1.4 ± 0.4	...
<1000.....	≤ 0.044	...	≤ 0.031
<850.....	≤ 0.036	...	≤ 0.024

* The resonance energies and strengths are given in laboratory units.

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