burning, but outside the zone of Be^9 burning, the permitted solar-wind torque falls for $q=2$ in a narrow range, $(3.8-4.2)\times10^{30}$ dyn cm; for $q=1$ the range is greater, $(5.3-7.9)\times10^{30}$ dyn cm.

The right side of Eq. (1) represents the rate of loss of angular momentum from the rapidly rotating core. Alternatively this loss rate can be directly calculated from the diffusion equation assuming viscous forces, mainly ion transport in origin. The right side of Eq. (1) has the dependence on time derived from this diffusion equation, assuming a discontinuity in angular velocity at the core as initial condition. For simplicity the variation with time of the size of the discontinuity is neglected. Also it is assumed that the requirement of a finite initial angular-velocity gradient (stability) is met by waiting for a time $\Delta t \geqslant 10^8$ yr for a reasonable slope to develop. The solution to the diffusion equation yields the core angular velocity Ω_c as a function of angular momentum flux from the core [i.e., right side of Eq. (1)].

Under the assumption $\Delta t = 10^8$ yr, the computed value for Ω_c is only a lower bound. For $q=1$ and 2, a wide range of core radii, and initial angular velocities Ω^* falling in the range $2\Omega_0 < \Omega^* < 5\Omega_0$ it is found that this *lower bound* for Ω_c falls in the range $4.3\Omega_0 < \Omega_c < 15\Omega_0$.

The solar oblateness is compatible with a core angular velocity of $\Omega_c \sim 20\Omega_0$. For a core radius $r_c = 0.56 r_0$, kinematic viscosity $\nu_c = 15.6$ cm^2/sec, density $\rho_c = 0.65$ gm/cm^3; and $\Delta t = 10^8$ yr, the above calculation with a core angular velocity $\Omega_c = 19\Omega_0 = 5.5\times10^{-5}$ sec^{-1} yields a viscous loss of angular momentum from the core at the rate 3.5×10^{30} dyn cm.[1]

The above value, 3.5×10^{30} dyn cm, an *upper bound*, is to be compared with the solar-wind torque 4×10^{30} dyn cm required for the correct lithium depletion (with $q=2$) and the "observed" torque of $\sim5\times10^{30}$ dyn cm. The close agreement suggests that a rapidly rotating core is the principle source of angular momentum for the solar wind. If so, the initial surface angular velocity on the main sequence must have been low, not much greater than the present value.

*Work supported at the Institute for Advanced Study by the U. S. Air Force Office of Scientific Research, Office of Aerospace Research, under Grant No. 70-1866 and at Princeton University under grants from the Office of Naval Research of the U. S. Navy and by the National Science Foundation.

[1]R. H. Dicke, Nature 202, 432 (1964).
[2]R. H. Dicke and H. M. Goldenberg, Phys. Rev. Lett. 18, 313 (1967).
[3]R. Kraft, Astrophys. J. 150, 551 (1967).
[4]P. Goldreich and G. Schubert, Astrophys. J. 150, 571 (1967).
[5]P. Goldreich and G. Schubert, Astrophys. J. 154, 1005 (1968).
[6]P. S. Conti, Astrophys. J. 152, 657 (1968).
[7]I. J. Danziger, Astrophys. Lett. 3, 115 (1969).
[8]G. Wallerstein and P. S. Conti, Annu. Rev. Astron. Astrophys. 7, 99 (1969), for references.
[9]A. Clark, J. H. Thomas, and P. A. Clark, Science 164, 290 (1969).
[10]A. J. Hundhauser, Rev. Geophys. 8, 729 (1970), for references.

Astrophysical Importance of the Reaction $C^{12} + O^{16}$ †

Stanford E. Woosley, W. David Arnett,*‡ and Donald D. Clayton
Rice University, Houston, Texas 77001
(Received 3 May 1971)

The nuclear reactions between C^{12} and O^{16} are shown to be vitally important during explosive oxygen burning because they regulate the number of α particles produced per Si^{28} nucleus. Since it appears that explosive oxygen burning produces the observed abundances of the nuclei between Si^{28} and Ca^{42}, the value of the $C^{12}+O^{16}$ total reaction cross section will help determine the nature of the explosions that have produced the elements.

We have found that nuclear reactions between C^{12} and O^{16} have a subtle but important effect upon oxygen burning in exploding stars. Otherwise, as has been suspected, the reaction $C^{12}+O^{16}$ is relatively unimportant because the Coulomb barrier is too great to allow the reaction to occur during carbon burning (when $C^{12}+C^{12}$ is the dominant reaction) and because C^{12} is scarce during later evolution. During the explosive burning of oxygen, however, a supply of C^{12} nuclei is produced in the gas by (γ, α) reactions on O^{16}. The C^{12} thus produced is quickly destroyed either by reactions with itself or by reactions with the much more abundant O^{16} nuclei; moreover, the final abundances produced by the thermonuclear combustion of the oxygen can be greatly influenced by the relative importance of these two modes of destruction of the C^{12}. This rather surprising discovery suggests that careful laboratory measurements of the total reaction cross section for $C^{12}+O^{16}$ are as important as those of $C^{12}+C^{12}$ and $O^{16}+O^{16}$.

If the oxygen burns only by reacting with itself, as in the case of burning in stars in hydrostatic equilibrium, the effective net result is $O^{16}+O^{16} \to Si^{28}+He^4$. This reaction does not produce enough α particles per Si^{28} nucleus to convert the initial Mg^{24} and the Si^{28} into the natural yield of S^{32}, Ar^{36}, and Ca^{40}, as measured by the observed distribution of natural abundances. However, Truran and Arnett[1] were able to find convincing evidence that the nuclei between $28 < A < 42$ have been produced in the explosive ejection of oxygen from stars. This result was possible because the higher temperature of the explosive burning consumes O^{16} at a comparable rate by photodisintegration, which results in more α particles liberated per oxygen burned. Our detailed studies of the reaction network show that if the C^{12} created by the reaction $O^{16}(\gamma,\alpha)C^{12}$ is destroyed by reacting with itself, the net effect is

$$2O^{16} \to 2C^{12}+2\alpha,$$

$$2C^{12} \to Ne^{20}+\alpha,$$

$$Ne^{20}+\gamma \to O^{16}+\alpha.$$

The sum of these reactions is $2O^{16} \to O^{16}+4\alpha$, just as if O^{16} were being disintegrated into 4 α particles at half the rate of $O^{16}(\gamma,\alpha)C^{12}$. Exclusive burning of oxygen by this cycle alone produces too many α particles per Si^{28} nucleus, and Truran and Arnett found that an initial explosive temperature near $T_9 = 3.6$ ($T_9 \equiv T/10^9$ deg) and initial density near $\rho = 5\times 10^5$ gm cm^{-3} gave the proper relative rates of these two modes of O^{16} burning to produce the observed solar abundances. The key thing is that these modes of O^{16} destruction have different temperature and density dependences.

Our further studies have also shown that a sizable fraction of the C^{12} created by O^{16} photodisintegration will react with O^{16}. The branching ratios $C^{12}+O^{16} \to Mg^{24}+\alpha$, $Al^{27}+p$, $Si^{27}+n$ are unimportant because in each case the primary products have been shown by us to interact in such a way as to produce only Si^{28}. Thus the effective reaction is $C^{12}+O^{16} \to Si^{28}+\gamma$ at a rate determined by the *total* reaction cross section for $C^{12}+O^{16}$. If the C^{12} produced were consumed exclusively by reactions with O^{16}, the net effect would be

$$2O^{16}+\gamma \to O^{16}+C^{12}+\alpha \to Si^{28}+\alpha,$$

which is the same α yield per Si^{28} produced as if O^{16} reacted only with itself. That is, the result of a significant $C^{12}+O^{16}$ rate is to produce a more α deficient abundance distribution.

Stars of differing mass and state of evolution will explode oxygen at differing peak temperatures and densities. It will require a major research program to establish this correlation in the dynamic evolution of stars. The fact that only a restricted class of stars will be likely to explode oxygen under conditions giving the proper relative rates for the three basic oxygen-consuming cycles to account for the α richness of the abundances observed in nature should help identify the class of stars that have produced the elements.

We find that the C^{12} concentration established during the explosive oxygen burning is governed by three dominant terms:

$$dC^{12}/dt = -(C^{12})^2\langle\sigma v\rangle_{12,12} - C^{12}O^{16}\langle\sigma v\rangle_{12,16} + O^{16}\lambda_{\gamma,\alpha}{}^{16}, \tag{1}$$

where $\langle\sigma v\rangle$ is the thermally averaged product of cross section times velocity for the total reaction cross sections, $\lambda_{\gamma,\alpha}{}^{16}$ is the thermally averaged $O^{16}(\gamma,\alpha)C^{12}$ rate per O^{16} nucleus, and number densities are expressed by chemical symbols. The C^{12} concentration assumes a steady-state value characterized by $dC^{12}/dt \approx 0$; therefore

$$C^{12} \approx -\frac{O^{16}}{2}\frac{\langle\sigma v\rangle_{12,16}}{\langle\sigma v\rangle_{12,12}} + \left[\left(\frac{O^{16}}{2}\right)^2\left(\frac{\langle\sigma v\rangle_{12,16}}{\langle\sigma v\rangle_{12,12}}\right)^2 + \frac{O^{16}\lambda_{\gamma\alpha}}{\langle\sigma v\rangle_{12,12}}\right]^{1/2}. \tag{2}$$

Inspection of this result shows that at constant temperature the ratio C^{12}/O^{16} is a decreasing function of the O^{16} density. This decreasing ratio increasingly favors $C^{12}+O^{16}$ over $C^{12}+C^{12}$ as the mode of destruction of C^{12}. From nuclear reciprocity, $\lambda_{\gamma,\alpha}{}^{16}$ is proportional to $\langle\sigma v\rangle_{\alpha,12}$ for the reaction $C^{12}(\alpha,\gamma)O^{16}$. Thus the concentration C^{12} depends upon the concentration O^{16}, the temperature, and the ratios of thermally averaged cross sections

$$\frac{\langle\sigma v\rangle_{12,16}}{\langle\sigma v\rangle_{12,12}} \text{ and } \frac{\langle\sigma v\rangle_{\alpha,12}}{\langle\sigma v\rangle_{12,12}}.$$

The relative rates of C^{12} on C^{12} and on O^{16} lead (for each O^{16} photodisintegration) to the relative sequences

$$\frac{C^{12}+C^{12}}{C^{12}+O^{16}}=\frac{\frac{1}{2}(C^{12})^2\langle\sigma v\rangle_{12,12}}{C^{12}O^{16}\langle\sigma v\rangle_{12,16}} =\frac{2O^{16}\to O^{16}+4\alpha}{2O^{16}\to Si^{28}+\alpha}, \qquad (3)$$

and it is the competition between these two sequences which determines the α richness of the nucleosynthesis results.

We have used recent measurements of the cross sections for the reactions $O^{16}(C^{12},\alpha)Mg^{24}$ and $O^{16}(C^{12},p)Al^{27}$ by Patterson, Nagorcka, Symons, and Zuk[2] in a center-of-mass energy range between 4.5 and 8.5 MeV to make a quantitative estimate of the importance of these reactions. Measurements of the total cross section for the reaction $C^{12}+O^{16}$ have also been made by Kuehner and Almqvist[3] for a somewhat higher range of center-of-mass energies (6.5 MeV $<E$ <15.5 MeV). In the region of overlap these two sets of measurements are in good agreement. Combining the results of these two groups we find that in the energy range 4.54 to 11.3 MeV the total cross section for the reaction $C^{12}+O^{16}$ is represented to within a factor of 2 by

$$\sigma=(S/E)e^{-124.31/E}, \qquad (4)$$

where $S=\tilde{S}e^{-gE}$, with $\tilde{S}=1.5\times10^{22}$ MeV b, $g=0.98$ MeV^{-1}, and E is the center-of-mass energy in MeV. The upper bound on the energy range of our fit corresponds roughly to the maximum center-of-mass energy of importance at explosive oxygen burning temperatures.

The effective stellar energy range $E_0\pm\Delta$ for this interaction is[4]

$$E_0=3.06T_9{}^{2/3}\text{ MeV},\quad \Delta=1.19T_9{}^{5/6}\text{ MeV}. \qquad (5)$$

Thus our fit to the cross section is valid to within a factor of 2 or better for temperatures as high as $T_9=3.9$. If the fit given by (7) is valid in the as yet unmeasured interval from 3.4 to 4.54 MeV, then our fit is valid for temperatures as low as $T_9=3.0$. This represents the lowest temperature at which we feel this reaction will be important. The corresponding thermally averaged cross section times velocity in this temperature range ($3.9>T_9>3.0$) is

$$\langle\sigma v\rangle_{12,16}=T_9{}^{-2/3}\exp[19.8-106.6(1+0.086T_9)^{1/3}] \text{ cm}^3\text{ sec}^{-1} \qquad (6)$$

which agrees to within about a factor of 3 with the theoretical calculation of Fowler and Hoyle.[5] For the temperatures of explosive oxygen burning, this expression is slightly preferable to one recently proposed by Hansen and Zaidins[6] to fit the low-energy data of Patterson *et al.*[2] because their fit overestimates the cross-section data around 10 MeV. Here we have used g simply as a numerical fitting parameter: Our high value for g is required to obtain the flattening of σ above 10 MeV. The Hansen-Zaidins value for g may be a better measure of the effective interaction radius. Our calculations show that this reaction is important; for example, at a temperature $T_9=3.6$, a density $\rho=5\times10^5$ gm cm^{-3}, and an O^{16} mass fraction of 0.54 approximately 60% of the C^{12} formed by the photodisintegration of O^{16} is consumed by reactions with O^{16} nuclei.

We wish to repeat several points of interest to an experimenter hoping to make the appropriate knowledge more secure: (1) The most important center-of-mass energies are relatively high for nuclear astrophysics, say $3.5<E$ (MeV) <11.3; (2) the *total reaction cross section* is the quantity needed because the distribution among possible exit channels makes little difference; and (3) the heavy ion total reaction cross sections $C^{12}+C^{12}$, for which $E_0=2.42T_9{}^{2/3}$ MeV and $\Delta=1.05T_9{}^{5/6}$ MeV, and $O^{16}+O^{16}$, for which $E_0=3.90T_9{}^{2/3}$ MeV and $\Delta=1.34T_9{}^{5/6}$ MeV, are equally important at explosive oxygen-burning temperatures, as indicated by our discussion.

A full account of the details of explosive oxygen burning is in preparation by us.

†Work supported by the National Science Foundation Grants No. GP-18335 and No. GP-23459.

*Present address: Departments of Astronomy and Physics, University of Texas, Austin, Texas 78712.

‡Alfred P. Sloan Foundation Fellow.

[1] J. W. Truran and W. D. Arnett, Astrophys. J. 160, 181 (1970).

[2] J. R. Patterson, B. N. Nagorcka, G. D. Symons, and W. M. Zuk, Nucl. Phys. A165, 545 (1971).

[3] J. A. Kuehner and E. Almqvist, Phys. Rev. 134, B1229 (1964).

[4]D. D. Clayton, *Principles of Stellar Evolution and Nucleosynthesis* (McGraw-Hill, New York 1968), Chap. 4.

[5]W. A. Fowler and F. Hoyle, Astrophys. J. Suppl. 9, 201 (1964).

[6]C. J. Hansen and C. S. Zaidins, to be published.

$\pi^- p$ Elastic Scattering Near 180° Between 600 and 1280 MeV/c*

D. G. Crabb, R. Keller, J. R. O'Fallon, and T. J. Richards
Physics Department, Saint Louis University, St. Louis, Missouri 63103

and

R. J. Ott, J. Trischuk, and J. Va'vra
Physics Department, McGill University, Montreal, Canada

and

L. S. Schroeder
Institute for Atomic Research and Department of Physics, Iowa State University, Ames, Iowa 50010
(Received 17 May 1971)

The differential cross sections for $\pi^- p$ elastic scattering over the angular range 155° to 177° in the center of mass have been measured at 33 incident-pion momenta in the range 600 to 1280 MeV/c. Angular distributions are presented. The extrapolated differential cross sections at 180° show considerable structure, in particular a dip near 1150 MeV/c. In general the near-180° cross sections do not agree with existing phase shift solutions above 1000 MeV/c

An experiment to measure the $\pi^- p$ elastic differential cross section near 180° in the momentum range 600 to 1280 MeV/c has been performed at the Bevatron at the Lawrence Radiation Laboratory. These measurements were made to provide a systematic set of data, with good statistical accuracy, in a momentum region where a number of resonances exist and where phase-shift analyses[1] are particularly useful in establishing the parameters of these resonances. The structure of the backward elastic-scattering cross section is particularly sensitive to the presence of resonant states. Data in this momentum region have come from a number of experiments,[2-7] but in general almost no measurements existed for center-of-mass angles greater than 165° previous to recently published data from a Saclay group.[8] These data are not reproduced by the existing phase-shift solutions.

The experimental layout is shown in Fig. 1 and consists of a double-arm spectrometer which measures the angle-angle correlations between the scattered particles with the appropriate time-of-flight requirements for elastic scattering. The incident pion beam was produced by an internal copper target, momentum analyzed, and focused onto a liquid hydrogen target. The hydrogen target was 21 cm long and 5 cm in diameter. The momentum spread of the beam, $\Delta p/p$, was ±1.5% and the mean momentum was known to better than $\pm\frac{1}{2}$%. The beam counters $S_1S_2S_3$ defined a beam spot at the hydrogen target of ±1 cm full width at half-maximum (FWHM) with a beam divergence of ±15 mrad. A Cherenkov counter was moved into the beam between runs to measure the lepton contamination.

The scattered particles were detected in three scintillation counter arrays A, B, and C. The A array detected the backward-scattered pion and consisted of eight closely packed counters each 25.4 cm wide. The A counters defined the scattering angle, the whole array covering the range 155° to 177° in the center-of-mass system. The forward-scattered proton was bent by the dipole magnet M and detected in the B and C arrays. The proton scattering angle was defined by the fourteen-element B-counter array. Each B counter had a corresponding C counter which was over matched and formed a two-counter telescope to define the forward particles accepted by the system. The G and Δ counters were trigger elements, G defining the vertical acceptance of the system. The horizontal acceptance was defined by the width of each A element.

The counter coincidences necessary to define an event were as follows: (i) A beam particle,