Coincidence Measurement of the $^{12}C(\alpha,\gamma)^{16}O$ Cross Section at Low Energies

R. M. Kremer,[a] C. A. Barnes, K. H. Chang,[b] H. C. Evans,[c] B. W. Filippone, K. H. Hahn,[d] and L. W. Mitchell[e]

W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

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The $E1$ capture cross section for the reaction $^{12}C(\alpha,\gamma)^{16}O$ to the ^{16}O ground state has been measured for $E_{c.m.}=1.29$–3.00 MeV. A γ-ray–recoil-particle coincidence technique has been used to obtain essentially background-free reaction yields. A three-level R-matrix analysis of the $E1$ S factor leads to an allowed range for S_{E1} at 300 keV of 0.00–0.14 MeV b. A model-dependent R-matrix analysis and a hybrid R-matrix analysis result in values of 0.14 and 0.08 MeV b, respectively, for $S_{E1}(300)$.

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Both the elemental abundance predicted from nucleosynthesis[1,2] and the final evolutionary state of a massive star[2] (neutron star/black hole) depend critically upon the rate of the reaction $^{12}C(\alpha,\gamma)^{16}O$. Although this reaction has been the subject of intense experimental and theoretical effort for the past twenty years, there is still considerable uncertainty in the value of the astrophysical S factor at stellar helium burning energies ($E_{c.m.}\simeq 0.3$ MeV). The S factor removes most of the strong energy dependence of the reaction cross section due to the Coulomb penetrability and is defined as

$$S(E_{c.m.})=E_{c.m.}\sigma(E_{c.m.})e^{(E_G/E_{c.m})^{1/2}}, \qquad (1)$$

where E_G is the Gamow energy $[E_G=(2\pi\alpha Z_1Z_2)^2\mu c^2/2$; μ is the reduced mass of the incident channel and α is the fine-structure constant].

The cross section at $E_{c.m.}\simeq 0.3$ MeV is expected to be dominated by p-wave ($E1$) and d-wave ($E2$) capture to the ($J^\pi=0^+$) ^{16}O ground state. Two states at 6.92 MeV ($J^\pi=2^+$) and 7.12 MeV ($J^\pi=1^-$), which are just bound ($Q=7.16$ MeV), appear to provide the bulk of the capture strength through their finite widths that extend into the continuum.[3,4] Determination of the S factor at stellar energies requires a considerable extrapolation from the experimentally accessible energies of $E_{c.m.}\gtrsim 1.0$ MeV, where the cross section is dominated by a broad $E1$ resonance at $E_{c.m.}=2.4$ MeV.

Two previous measurements of the $E1$ cross section[5] and the total cross section[6] are in substantial disagreement, differing by $\simeq 30\%$ in the vicinity of the $E_{c.m.}=2.4$ MeV resonance and by nearly a factor of 4 at the lowest measured energies ($E_{c.m.}\simeq 1.4$ MeV). Only a part of this discrepancy can be accounted for by the presence of a significant $E2$ cross section that has been suggested by recent experimental[7] and theoretical[8–11] work. Recently, a new experiment has extended the measurements down to $E_{c.m.}\lesssim 1.0$ MeV and has reported results for the $E1$ S factor[12] (S_{E1}) which appear to be in reasonable agreement with the data of Ref. 5.

In all previous experiments, the reaction γ ray alone was detected, and these experiments thus suffered from beam-induced, cosmic-ray, and natural radioactivity backgrounds. Since the cross section, in the energy range where measurements are feasible, varies by more than 3 orders of magnitude from a maximum of $\simeq 50$ nb, significant background reduction is essential, especially where the cross section is very small. In this Letter we report new measurements of the $^{12}C(\alpha,\gamma)^{16}O$ cross section using a novel time-of-flight coincidence technique. This coincidence requirement provides a unique signature of the reaction that is essentially background-free.

Reaction yields were measured by the detection of the reaction γ rays in delayed coincidence with the recoiling ^{16}O ions, which were separated from the ^{12}C beam by a recoil separator. The ^{12}C beam was produced from a Cs sputter source and accelerated by the NSF-Caltech 3-MV tandem Pelletron accelerator. With a ^{12}C beam, the reaction kinematics constrain the recoil ions to a forward cone with a half angle of $\lesssim 1.6°$ for the energies of the present experiment. The recoil-particle–γ-ray coincidence apparatus, shown schematically in Fig. 1, was designed specifically for the reaction $^{12}C(\alpha,\gamma)^{16}O$. Briefly, the apparatus consisted of large NaI(Tl) γ-ray detectors surrounding a windowless ^{2}He gas target, followed by the recoil separator whose key element was an $\mathbf{E}\times\mathbf{B}$ velocity filter. A gas ionization detector and a

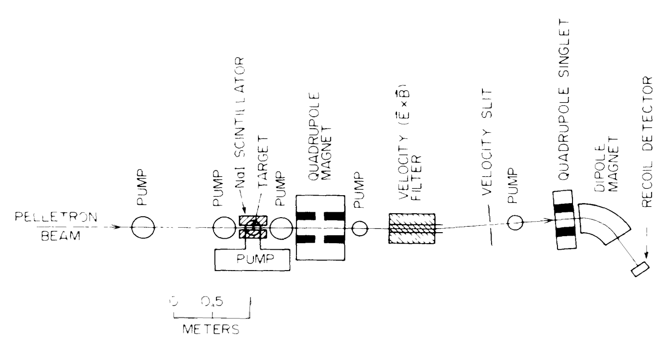

FIG. 1. Schematic diagram of the experimental apparatus.

multiwire proportional chamber were located at the end of the separator for measurement of recoil energy and arrival time. A more detailed description of the recoil separator, γ-ray detection, and heavy-ion detection apparatus can be found in Hahn *et al.*[13]

The reaction yields were extracted from time-of-flight histograms which were constructed with cuts on measured recoil-particle energy, specific energy loss (dE/dx), and γ-ray energy. Examples of these spectra are shown in Fig. 2. The γ-ray cut was above the energy of cascade radiation to excited states in ^{16}O in order to allow extraction of the ground-state cross section.

The absolute cross section depends directly on the measured yields, the number of incident particles, the number of target particles, and the total detection efficiency of the apparatus. The number of incident-beam particles (up to 15 particle μA) was determined from the yield of elastically scattered α particles monitored with a silicon surface-barrier detector at a laboratory angle of 60°. The density of the target was determined from the measured energy loss of ^{1}H, ^{12}C, and ^{16}O ions in the ^{4}He target combined with global fits to ion stopping powers.[14] The target density obtained from this procedure, 3.6 ± 0.2 μg/cm^2, was consistent with that calculated from the measured pressure, target length, and density profile (measured with elastically scattered protons) to $< 10\%$.

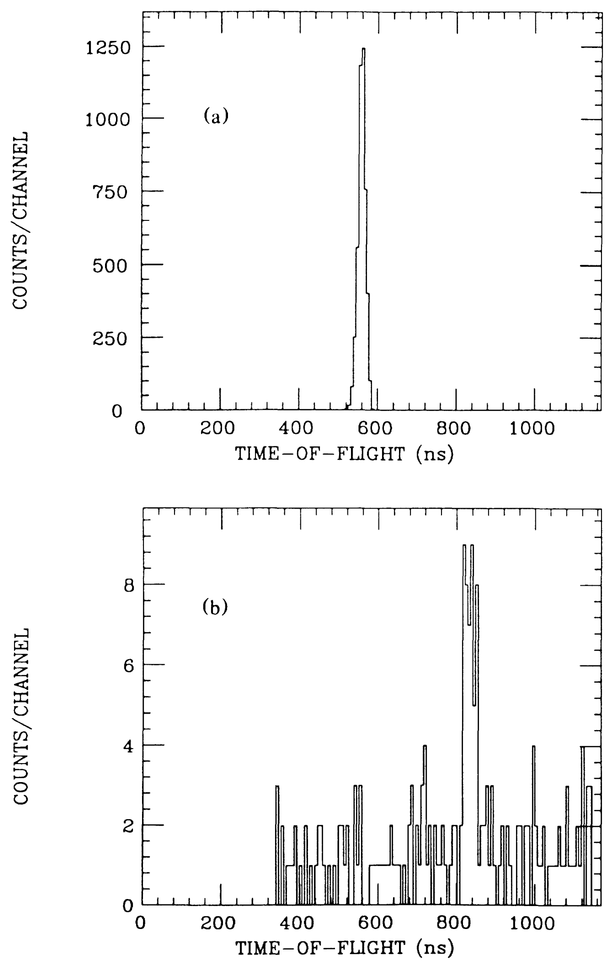

FIG. 2. Time-of-flight spectra for γ ray and recoil ^{16}O coincidence from the reaction $^{12}C(\alpha,\gamma)^{16}O$. (a) $E_{c.m.}=2.68$ MeV, (b) $E_{c.m.}=1.29$ MeV. The absence of counts for time of flight < 330 ns is due to a threshold condition in the electronics.

Determination of the total detection efficiency of the apparatus relied on independent measurements of the γ-ray efficiency and recoil-ion acceptance which were used in a Monte Carlo simulation of the apparatus to determine the total acceptance. The predictions of the simulation were checked with direct measurements at several high-yield points as discussed below. Both the absolute γ-ray efficiency and the efficiency above the γ-ray cut were determined from resonances in the reactions $^{11}B(p,\gamma)^{12}C$ ($E_p=165$ keV) and $^{19}F(p,\alpha\gamma)^{16}O$ ($E_p=340$ keV).

In order to study the acceptance of the recoil separator a large number of calibration measurements were performed. The solid-angle acceptance of the separator was measured by the transmission of α particles from an ^{241}Am source located at the front of the target chamber through the system. The measured solid angle was large enough to accept $> 95\%$ of the ^{16}O recoils for the selected charge states down to $E_{c.m.}=1.0$ MeV. The velocity acceptance was determined in the vicinity of the broad $E_{c.m.}=2.4$ MeV ($J^\pi=1^-$) resonance in the reaction $^{12}C(\alpha,\gamma)^{16}O$ by our varying the beam energy while keeping the parameters of the recoil separator fixed. The full velocity acceptance was defined by the velocity slits to be $\Delta v/v \simeq 2.5\%$. The recoil separator was tuned and the recoil detectors calibrated prior to each run by the transport of an ^{16}O beam with the same momentum as the ^{12}C beam through the entire system.

The Monte Carlo simulation included complete reaction kinematics, γ-ray angular distributions, the effects of incident-beam and recoil-particle energy loss, multiple scattering, finite beam size, and finite target length. Beam-optics transport coefficients were calculated to second order with the code TRANSPORT.[15] Comparisons between the Monte Carlo predictions and measured transport properties were made at several energies where resonances in $^{12}C(\alpha,\gamma)^{16}O$ and $^{16}O(\alpha,\gamma)^{20}Ne$ provided sufficient yield to compare single γ-ray measurements with coincidence yields. These measurements confirmed the prediction of the Monte Carlo simulations that the total transport efficiency was substantially higher for pure $E1$ γ decay than for pure $E2$, because of the smaller velocity dispersion of the recoils for $E1$ decay as the γ-ray angular distribution is peaked at 90°. Over the energy range of the experiment the calculations indicated that the efficiency for $E2$ capture was 50%–65% of the efficiency for $E1$ capture. This reduced efficiency for $E2$

capture allows for extraction of the $E1$ cross section with less sensitivity to the value of the $E2$ cross section as discussed below.

Because the dispersion of the recoil separator depends on the charge of the recoil ion, only one charge state of the recoil ion is transported to the recoil detector at each beam energy. Charge-state fractions (CSF) were measured with an ^{16}O beam passing through the ^{4}He target at all energies where cross-section data were obtained. These equilibrium CSF ranged from 20% to 40% depending on the charge state selected and the energy of the beam. Departures from equilibrium CSF due to production of ^{16}O from the reaction $^{12}C(\alpha,\gamma)^{16}O$ were calculated to be small.

The $E1$ cross sections were determined from the equation

$$\sigma_{E1}=\frac{Y_{\mathrm{TOF}}}{\beta[1+(\epsilon_{E2}/\epsilon_{E1})(\sigma_{E2}/\sigma_{E1})]}, \tag{2}$$

where Y_{TOF} is the peak yield from the time-of-flight spectra, and β is the product of the number of incident particles, the number of target particles per square centimeter, the total $E1$ detection efficiency, the CSF, and the detector live-time fraction. The last factor in the denominator is the product of the ratio of efficiencies and the ratio of cross sections for $E1$ and $E2$ capture. To extract the $E1$ cross section, the ratio of σ_{E2}/σ_{E1} is needed. This ratio has been measured previously[5,12] over most of the energy range of the present experiment, and there exist calculations[8,11] of this quantity which, although they differ by nearly a factor of 4, particularly at low energies, indicate that the $E2$ capture remains $\lesssim 0.5$ of the $E1$ cross section. In fact, if we extract σ_{E1} from our data using the entire range of published values for σ_{E2}/σ_{E1}, the maximum variation in the $E1$ cross section is still only 20%. The extracted $E1$ cross section for capture into the ground state is shown in Fig. 3(a), where σ_{E2}/σ_{E1} from the calculation of Ref. 8 (which uses the $E1$ data from Ref. 5) has been used.

To determine the reaction rate at the temperatures relevant to stellar helium burning, an extrapolation of the cross section to the appropriate energies ($E_{\mathrm{c.m.}}=300$ keV) is necessary. For this extrapolation, we use Eq. (1) to convert the measured cross sections to S factors. Figure 3(b) shows the S factor for $E1$ capture from the present experiment, where a 2σ upper limit at $E_{\mathrm{c.m.}}=10$ MeV from the present experiment has also been included. In order to model the energy dependence of the cross section, a three-level R-matrix analysis[20] has been performed. The three levels correspond to the $E^*=7.12$ MeV bound state, the $E^*=9.5$ MeV unbound state [the broad peak in Fig. 3(a)], and a level at higher excitation energy to account for all higher-lying 1^- states. Three parameters are required to define each level: an α-particle width, a γ-ray width, and an eigenenergy. Two of these parameters can be expressed in terms of the others,[21] and the eigenenergy of the higher-lying state may also be fixed.[21] This leaves six parameters to be determined from the data. Some of these parameters can be constrained by our calculating the $l=1$ phase shift for α-^{12}C elastic scattering and comparing with the measurements. By our simultaneously fitting the parameters of the three-level R-matrix analysis to both the $^{12}C(\alpha,\alpha)^{12}C$ data[16-18] and the $^{12}C(\alpha,\gamma)^{16}O$ data from the present measurement, we obtain an allowed range for the S factor at 300 keV of 0.00–0.14 MeV b. The χ^2 for the fit is actually minimized at a value of 0.01 MeV b, but the χ^2 dependence on $S_{E1}(300)$ is quite flat for the above range. The allowed range was deduced by the observation of a 30% increase in χ^2 from its minimum

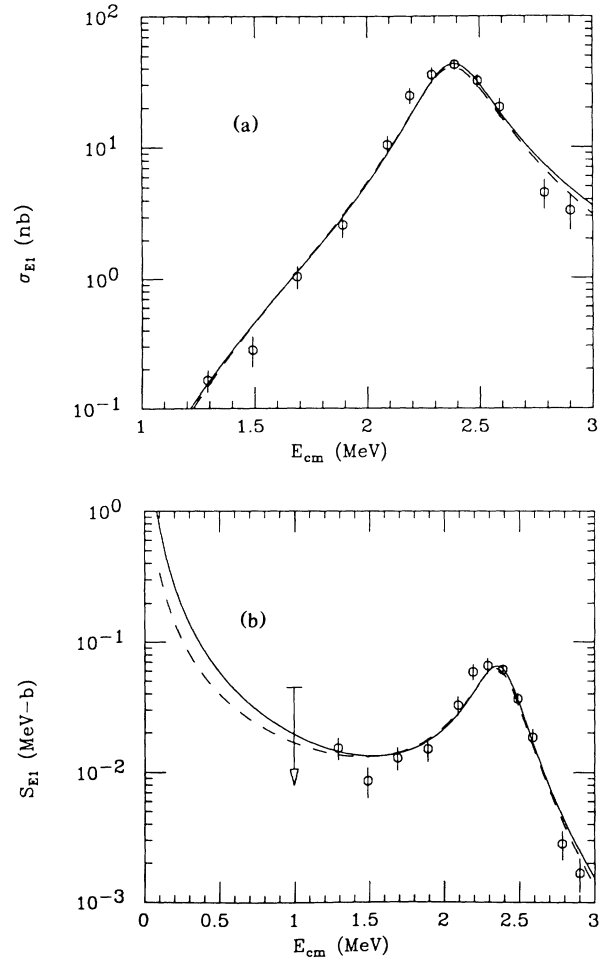

FIG. 3. (a) $E1$ cross section from the present measurement. Error bars correspond to statistical uncertainties only. In addition there is an estimated overall systematic uncertainty of 15%. The solid line is the simultaneous fit to the present data and the elastic-scattering measurements of Refs. 16, 17, and 18 with use of the procedure of Barker (Ref. 19). The dashed line is the fit with use of the hybrid R-matrix analysis. (b) $E1$ S factor deduced from the cross-section measurements of the present experiment. The lines are the same as in (a).

value of 1.3 per data point, where χ^2 is calculated for both the elastic-scattering data[16–18] and the present data. This procedure corresponds to a confidence level of $\simeq 95\%$, based upon the total number of data points. The present result can be compared with two previous determinations of the $E1$ S factor at 300 keV with use of a similar analysis which yielded ranges of 0.02–0.28[5] and 0.02–0.48 MeV b.[12] In all cases the large range in the allowed values results from the correlation of the strength of the bound state with that of the background level. A large value for the high-lying strength and a small value for the bound-state strength and the converse give a reasonable description of the measurements.

Several attempts have been made to characterize the high-energy 1^- strength in order to eliminate this parameter and thus reduce the uncertainty in the extrapolation. In the hybrid R-matrix analysis[22] the 9.5-MeV state and the higher-lying 1^- strength are both described by a single potential. Barker[19] has argued that the contribution to the reaction $^{12}C(\alpha,\gamma)^{16}O$ from higher energies is negligible in the energy range of the measurements (i.e., $\Gamma_\gamma=0$ for this contribution), thereby eliminating this as a free parameter. For comparison, these analyses yield best-fit values (simultaneously fitting both the elastic-scattering and α-capture data of the present experiment) for $S_{E1}(300)$ of 0.08 MeV b for the hybrid calculation[23] and 0.14 MeV b for a three-level R-matrix fit with $\Gamma_\gamma=0$ for the high-lying 1^- strength.[24]

A combined analysis of the various experiments is underway[25] with use of the techniques described above in order to better limit the allowed range in $S_{E1}(300)$. New measurements of the reaction $^{12}C(\alpha,\gamma)^{16}O$ at *higher* energies may also prove useful as a means of experimentally characterizing the high-lying 1^- strength and thus reducing the uncertainty in $S_{E1}(300)$.

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[a]Present address: Western Research Corp., San Diego, CA 92121.

[b]Present address: AT&T Bell Laboratories, Norcross, GA 30071.

[c]Permanent address: Queen's University, Kingston, Ontario, Canada K7L 3N6.

[d]Present address: Department of Physics, Stanford University, Stanford, CA 94305.

[e]Present address: N. Bridge Laboratory of Physics, California Institute of Technology, Pasadena, CA 91125.

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