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Recent measurements of the ^{12}C + ^{12}C fusion cross section near the Gamow energy by γ-ray spectroscopy

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Recently, the fusion cross sections of the reactions ^{12}C(^{12}C,α)^{20}Ne and ^{12}C(^{12}C,p)^{23}Na have been measured by γ-ray spectroscopy at energies as low as 2.10 MeV in the center of mass [10]. These measurements employed targets of ultra-low hydrogen contamination to suppress background which had hindered previous studies of the reactions. In this report the results are discussed relative to several parametrizations of the ^{12}C + ^{12}C cross section devised for the purpose of extrapolation of the reaction rate.

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1. Introduction

The fusion reactions ^{12}C(^{12}C,α)^{20}Ne (Q = 4.62 MeV) and ^{12}C(^{12}C,p)^{23}Na (Q = 2.24 MeV) are among the set of reactions referred to as carbon burning in stellar environments. The rates of these reactions are critical not only to the nucleosynthesis and subsequent abundances of ^{20}Ne and ^{23}Na, but also to the basic evolution of a star, e.g., whether a star proceeds to the heavy-ion burning branches following hydrogen and helium burning and whether a white dwarf evolves into a type Ia supernova. Thus, the cross section of these reactions must be known with high accuracy down to the Gamow energy E_G = 1.5 ± 0.3 MeV which corresponds to a temperature of 5×10^8 K [1].

Extensive experimental work on the ^{12}C + ^{12}C reactions has provided data over a wide energy range, down to a minimum energy of 2.25 MeV in the center-of-mass using charged-particle or γ-ray spectroscopy [2, 3, 4, 5, 6, 7, 8, 9]. Inspection of the data reveals several notable inconsistencies, however. Throughout the energy range investigated all experiments show qualitatively similar resonance structure, but disagree significantly (up to 100 keV) as regards the energies at which these structures are found [8]. Additionally, and possibly of greater significance to the extrapolation of the cross section into the Gamow window, there is considerable uncertainty in the general trend of the cross section at the lowest energies, below 3.0 MeV.

2. Experimental setup and measurement

The fusion cross section of ^{12}C + ^{12}C at 2.25 MeV is of nano-barn order of magnitude, thus the primary experimental challenge is to measure a sufficient number of reactions for a meaningful statistical analysis. This difficulty is compounded by the presence of ^{1}H and ^{2}H contamination in the C targets which produce intense background in both the charged-particle and γ-ray spectra. This is particularly problematic in γ-ray spectroscopy where the transitions from the first excited states of ^{20}Ne and ^{23}Na (E_γ = 1634 and 440 keV, respectively) are completely swamped by the Compton plateaus of the E_γ = 2.36 MeV line from ^{1}H(^{12}C,γ)^{13}N and the E_γ = 3.09 MeV line from ^{2}H(^{12}C,pγ)^{13}C (cf. e.g. fig. 1 of Kettner et al. [5] and fig. 6 of Barrón-Palos et al. [9]). Thus, experimental progress to lower energies requires targets of ultralow hydrogen contamination.

The beam delivery and experimental process are described elsewhere [10]. Briefly, the 4 MV Dynamitron tandem provided the ^{12}C beam at up to 40 particle μA at low incident energies. The beam is characterized by high purity (better than one part in 10^{11} for O and other light ions [11]), high energy resolution (2 keV [12]), and an energy calibration known to better than 3 keV. The beam was tightly collimated onto the target and secondary electrons were suppressed, such that beam current could be integrated using the electrically insulated target mount as a Faraday cup, with an estimated error of 3%. A Ge γ detector was placed at 0° to the beam axis in close geometry (detector front face to target distance = 2 cm). A shield of 15 cm Pb was placed around the detector and target chamber and a cosmic ray veto was performed using a plastic scintillator (thickness = 4 cm) placed above the setup. The shielding and cosmic ray veto combined to reduce γ-ray background by a factor of 800 near E_γ = 1600 keV.

The target was a graphite foil (1.0 mm thick, 20 x 20 mm^2 in area) of natural isotopic composition obtained from Goodfellow with a quoted purity of 99.8%. In the absence of external target cooling, the intense ^{12}C beam heated the graphite target to an estimated temperature of 700 °C. By observing the aforementioned γ-rays produced by interaction of the beam with contaminants, we found that the level of contamination in the target was reduced to a negligible level within about 20 minutes of exposure to the beam. Furthermore, no re-contamination of the target was observed while the target remained under vacuum, thus allowing for subsequent indirect water cooling of the target.

3. Results and Conclusions

At present several semi-empirical extrapolations of the ^{12}C + ^{12}C cross section at energies below the Coulomb barrier (E $\lesssim$ 6.7 MeV) are available. In the simplest approximation the gross behavior of the sub-Coulomb cross sections is assumed to behave according to the barrier penetrability calculated from the one-dimensional radial square-well nuclear potential. This extrapolation invites the definition of the so called modified astrophysical S factor, $\tilde{S}$(E), as the remaining energy dependence of the cross section when barrier penetrability has been stripped away [2],

$$\sigma(E) = \frac{\tilde{S}(E)}{E}\exp(-2\pi\eta - 0.46E) \tag{3.1}$$

where η is the Sommerfeld parameter and E is in units of MeV. The extrapolation proceeds by fitting this functional form, with a constant value for $\tilde{S}$(E), to experimental data. The ^{12}C + ^{12}C reaction rate of the compilation of Caughlan and Fowler [14] employs this extrapolation with $\tilde{S}$(E) = 3.0 × 10^{16} MeV b, based on a fit of the data available at that time.

An alternate extrapolation was used in the earlier compilation of Fowler, Caughlan and Zimmerman [15]. In this extrapolation an analytical function (eq. 3.2) is derived which reproduces the behavior of optical model calculations of the cross section with good accuracy. This analytic model is then fit to the available experimental data and used to extrapolate the reaction rate to lower energies.

$$\sigma(E) = S(0)\frac{\exp(-2\pi\eta)}{E}\frac{\exp(-\alpha E)}{\exp(-\gamma E^m) + b\exp(\beta E)} \tag{3.2}$$

The parameters of the best fit of [15] are; S(0) = 8.83 × 10^{16} MeV b, α = .772 MeV^{-1}, β = .697 MeV^{-1}, γ = 5.01 × 10^{-5} MeV^{-m}, b = 5.56 × 10^{-3} and m = 6.

Finally, it has recently been suggested by Jiang et al. [16] that sub-barrier fusion hindrance may have a significant effect on the fusion cross section within the Gamow window. Jiang et al. construct a parametrization of the cross section predicated upon boundary conditions of its logarithmic derivative with the form,

$$\sigma = \sigma_s\frac{E_s}{E}\exp\left\{A_0(E-E_s) - B_0\frac{1}{E_s^{n-1}(n-1)}\left[\left(\frac{E_s}{E}\right)^{n-1} - 1\right]\right\} \tag{3.3}$$

where the fit to experimental data fixes the parameters; n = 1.5, E_s = 3.68 MeV, A_0 = -1.32 MeV^{-1}, B_0 = 52.93 MeV$^{1/2}$ and σ_s = 2.3×10^{-2} mb.

The extraction of the fusion cross section from the experimental data has been discussed elsewhere [10]. The resulting $\tilde{S}$(E) factor, along with selected previous data and the parametrizations of Caughlan et al., Fowler et al. and Jiang et al. are presented in fig. 1. Qualitatively, the $\tilde{S}$(E) factor shows many narrow resonances (occurring roughly every 400 keV) superimposed upon a relatively flat background. Notable among the resonances observed is a stark, narrow structure at 2.14 MeV, which may increase the reaction rate by up to a factor of five with respect to that of the non-resonant background [10]. The average value of the $\tilde{S}(E)$ factor is 1.4×10^{16} MeV b over the energy range of the present study, corresponding to a cross section on the order of picobarns. The fusion hindrance parametrization of Jiang et al. offers the best agreement with experimental data at energies greater than 2.5 MeV. However, at the lowest energies ($E \leq 2.5$ MeV) the data are too uncertain to confirm the presence of sub-barrier fusion hindrance. It has been calculated that sub-barrier fusion hindrance of the $^{12}C + ^{12}C$ reaction, should it exist, will have significant effects on stellar processes [17]. Thus measurements of the $^{12}C + ^{12}C$ cross section with reduced uncertainty below 2.5 MeV is a high priority, which is currently being addressed by complementary charged-particle measurements.

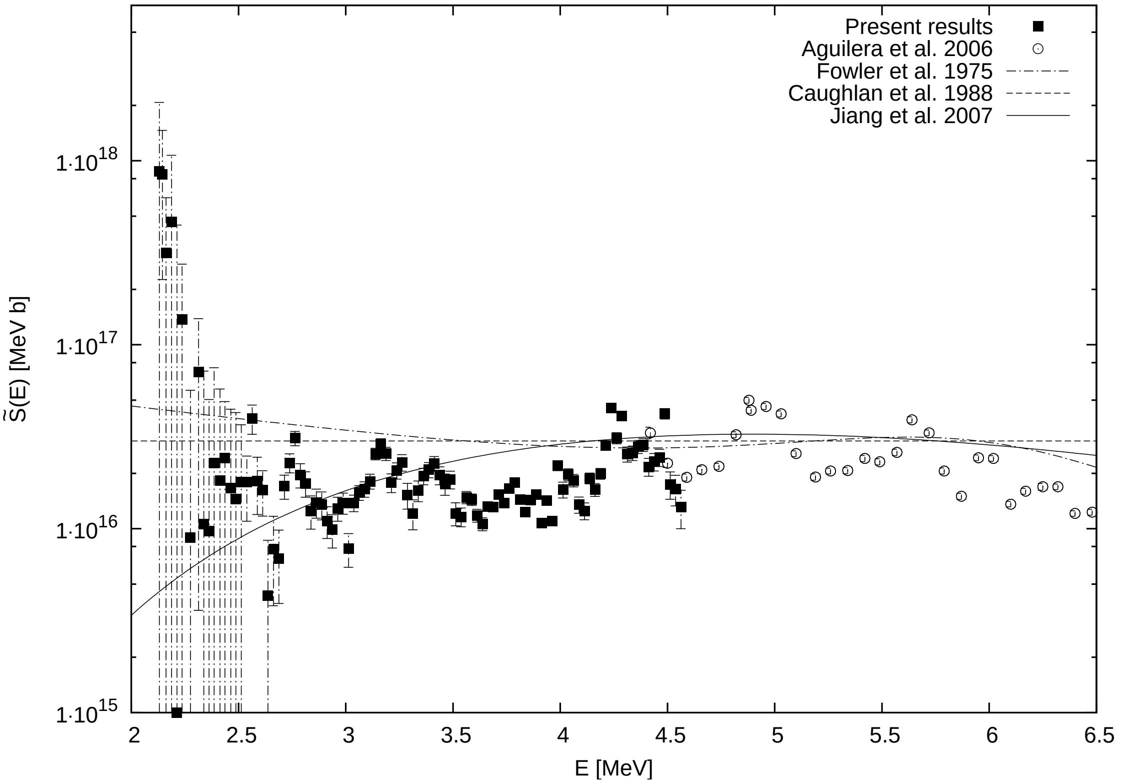

Figure 1: The modified $\tilde{S}(E)$-factor from the present work (solid squares) and the data of Aguilera et al. [8] (open circles). The extrapolations of Fowler et al. [15] (dot-dashed line), Caughlan et al. [14] (dashed line) and Jiang et al. [16] (solid line) are plotted for comparison. Among the extrapolations, the fusion barrier hindrance expectation of Jiang et al. shows the best agreement to the experimental data over a wide energy range.

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