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Experimental measurement of the ^{12}C+^{16}O fusion cross sections at astrophysical energies

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Abstract. The total cross sections of the ^{12}C+^{16}O fusion have been experimentally determined at low energies to investigate the role of this reaction during late stellar evolution burning phases. A high-intensity oxygen beam was produced by the 5MV pelletron accelerator at the University of Notre Dame impinging on a thick ultra-pure graphite target. Protons and γ-rays were measured simultaneously in the center-of-mass energy range from 3.64 to 5.01 MeV, using strip silicon and HPGe detectors. Statistical model calculations were employed to interpret the experimental results. A new broad resonance-like structure is observed for the ^{12}C+^{16}O reaction, and a decreasing trend of its S-factor towards low energies is found.

1 Introduction

The ^{12}C+^{16}O reaction is widely considered to play a critical role in early stellar evolution, in explosive carbon burning and explosive and hydrostatic oxygen burning[1, 2]. The ^{12}C+^{16}O reaction is relatively unimportant due to its high Coulomb barrier when ^{12}C+^{12}C is still the dominant reaction. It becomes more and more important when temperature and density of stars increase during oxygen burning stage, and the ^{16}O$(\gamma, \alpha)^{12}$C reaction is a supply of ^{12}C nuclei. The produced ^{12}C will be consumed either by reacting with itself or with ^{16}O, and the final abundances of remain elements after oxygen burning can be greatly affected by them. Type Ia supernovae are interpreted as the consequence of explosive carbon burning ignited near the core of white dwarf stars. The importance of ^{12}C+^{12}C used to be emphasized as ignition process, however, ^{12}C+^{16}O reaction may also plays a significant role. Recent studies showed that the ^{12}C+^{16}O rate is expected to have an unusually large effect on the calcium and sulfur yields in type Ia supernovae. The higher ^{12}C+^{16}O rate suppresses the alpha-particle abundance, which in turn decreases the Ca/S mass ratio in supernovae remnants [3].

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The corresponding stellar thermal energy range of the $^{12}C+^{16}O$ fusion spans from 3.0 MeV to 7.2 MeV, where the major competing exit modes are the $^{24}Mg+\alpha$ (Q=6.772 MeV) and $^{27}Al+p$ (Q=5.170 MeV) channels. The contribution of $^{27}Si+n$ (Q=-0.424 MeV) channel is only a small percentage of the total due to low Q-value. The cross section of the fusion is governed by possibilities of penetrating through the Coulomb Barrier, and it thus rapidly drops when the reaction energy decreases under the barrier. This results to extremely low cross section values near and within its astrophysical interested energies, therefore, the direct experimental measurement at stellar energies is always difficult. The $^{12}C+^{16}O$ fusion has been widely studied at stellar energies, by measuring either γ rays[4, 5] or charged particles[6]. *Christensen*[5] *et al.* extended studied energies down to $E_{c.m.}$=3.9 MeV, and *Čujec*[4] *et al.* extrapolated the total cross section down to $E_{c.m.}$=3.0 and 3.5 MeV. It is generally accepted that the compound nucleus mechanism dominates the reaction cross section at low bombarding energies. The selective population of ^{24}Mg, ^{27}Al and ^{27}Si excited states can be explained by the compound nucleus mechanism. Hauser-Feshbach (HF) statistical-model calculations have been performed to explain the branching ratio of different channels and the relative population possibilities of excited states. Nuclear level density is critical input for HF theory, thus essential for determining the total cross section.

2 Measurement procedure

This work measured simultaneously both charged particles (mainly protons) and γ-rays emitted by the $^{12}C+^{16}O$ fusion, using silicon and HPGe detectors. $^{16}O^{5+}$, $^{16}O^{3+}$ ions produced by the Santa Ana 5MeV accelerator were applied to bombard a thick pure graphite target. The Santa Ana accelerator is a new electrostatic Pelletron accelerator at the Nuclear Science Laboratory (NSL) at the University of Notre Dame. This accelerator provides voltage up to 5 MV and high intensity (∼10s particle μA) heavy ion beams. The target is highly oriented pyrolytic graphite (HOPG) with dimension of 20mm×20mm×1mm, which has a layered structure and is made of many graphene layers.

The schematic of experimental setup can be found in the reference [7].The silicon-detector array consists of six YY1-type 16-strip silicon detectors and one S2-type silicon detector, covering angles from 102° to 146° and 151° to 170°. HPGe detector was applied to measure γ-rays. The absolute efficiencies for typical γ-rays are 1.74% for 844 keV, 1.65% for 1014 keV and 1.46% for 1368 keV. The data was collected by ASIC (Application Specific Integrated Circuit) data acquisition system at NSL. During the measurement, $^{16}O^{3+}$ beams of energies from 8.5 MeV to 11.7 MeV in step of 100 or 200 keV, equivalent to 3.64 MeV$\leqslant E_{c.m.} \leqslant$5.01 MeV, were applied to bombard the target. $^{16}O^{5+}$ beams were used at 15.0 and 16.0 MeV for testing purpose. A measurement was also taken at E_{beam}= 7.0 MeV ($E_{c.m.}$=3.0 MeV) to study beam induced background.

3 Results and conclusion

Based on the measurement introduced above, the partial cross sections for various exit channels in the $^{12}C+^{16}O$ fusion were obtained from the thick-target yields for γ transitions associated with the different decay channels, protons, proton and γ coincident events, individually. An advantage of current measurement is that coincidence between protons and γ rays can be performed. This is the first time the coincidence method applied to $^{12}C+^{16}O$ measurement. To provide total cross sections from experimental data, the ratios of α, p and n and typical γ rays partial cross sections were provided by statistical calculations performed with the code SAPPHIRE [8]. Therefore, two sets of total cross sections and thus S(E) factors were accomplished from p and γ singles and p-γ coincidence datas, being displayed in figure 1, which shows the S(E) factor of the $^{12}C+^{16}O$ fusion reaction as a function of center-of-mass energy, comparing with other results[4–6]. The two data sets show good agreement with each other within the experimental uncertainties. An R-matrix fit using the code AZURE2 [9, 10] was also obtained and could be found in the reference [7]. The fit is based on the analysis of the different proton channels, normalized to the total S(E) factors. A decreasing trend of its S-factor towards low energies is predicted. However, present data do not evidently support the hindrance effect model [12] due to huge uncertainties.

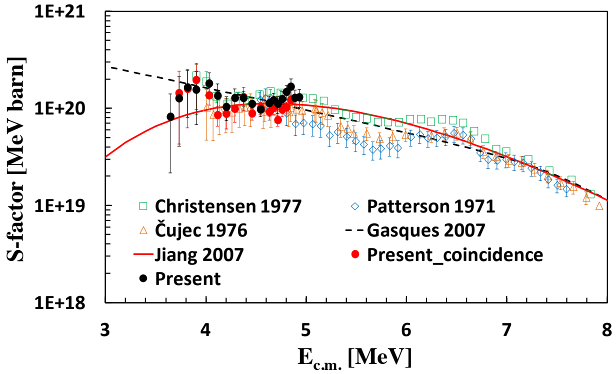

Figure 1. The S(E) factors of $^{12}C+^{16}O$ fusion are shown, including the present work (solid symbols) and previous data (open symbols) [4–6]. Reference [6] does not include the *n* channel. The Sao Paulo potential calculation (dashed line) [11] and hindrance model fit (solid line) [12] are also displayed.

In conclusion, the total cross sections for the $^{12}C+^{16}O$ fusion are determined by this work, and evidences for the existence of wide resonance-like structures from $E_{c.m.}$=3.9 MeV to 4.0 MeV in the $^{12}C+^{16}O$ fusion are observed. The decreasing trend of S-factor towards low energies could not be conclusive due to the huge uncertainties in the lower energy range.

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