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# Astrophysical $S_{E2}$ factor of the $^{12}$C$(\alpha,\gamma)^{16}$O reaction through the $^{12}$C$(^{11}$B$,{}^{7}$Li$)^{16}$O transfer reaction

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**Abstract.** The $^{12}$C$(\alpha,\gamma)^{16}$O reaction plays a key role in the evolution of stars with masses of $M > 0.55\ M_{\odot}$. At the Gamow peak ($E_{\mathrm{c.m.}} = 300$ keV, $T_9 = 0.2$), the cross section of the $^{12}$C$(\alpha,\gamma)^{16}$O reaction is so small (about $10^{-17}$ barn) that the direct measurement in ground laboratory is not feasible with the existing technology. Up to now, the cross sections at lower energies can only be extrapolated from the data at higher energies. However, two subthreshold resonances, locating at $E_x = 7.117$ MeV and $E_x = 6.917$ MeV, make this extrapolation more complicated. In this work the 6.917 MeV subthreshold resonance in the $^{12}$C$(\alpha,\gamma)^{16}$O reaction was investigated via the $^{12}$C$(^{11}$B$,{}^{7}$Li$)^{16}$O reaction. The experiment was performed using the Q3D magnetic spectrograph at HI-13 tandem accelerator. We measured the angular distribution of the $^{12}$C$(^{11}$B$,{}^{7}$Li$)^{16}$O transfer reaction leading to the 6.917 MeV state. Based on DWBA analysis, we derived the square of ANC of the 6.917 MeV level in $^{16}$O to be $(2.45 \pm 0.28) \times 10^{10}$ fm$^{-1}$, with which the reduced-$\alpha$ width can be computed. Finally, we calculated the astrophysical $S_{E2}$ factor of the 6.917 MeV resonance to be $67.6 \pm 7.7$ keV b.

## 1 Introduction

The $^{12}$C$(\alpha,\gamma)^{16}$O reaction is believed to be one of the most crucial reactions in nuclear astrophysics [1, 2]. By competing with the triple-$\alpha$ process, it strongly influences the ratio of the abundances for the main isotopes of carbon and oxygen ($^{12}$C and $^{16}$O) which are the fourth- and third-most abundant nuclei in the visible universe. The C/O ratio at the end of helium burning affects not only the production of all elements heavier than $A = 16$, but also the explosion of supernovae [1]. While the cross section for the triple-$\alpha$ process is experimentally well determined [3, 4], the cross section of the $^{12}$C$(\alpha,\gamma)^{16}$O reaction taking place in helium burning phase ($T_9 = 0.2$) is thought to be the most serious uncertainty in nucleosynthesis [5]. The Gamow peak for the $^{12}$C$(\alpha,\gamma)^{16}$O reaction at $T_9 = 0.2$ centers at $E_{\mathrm{c.m.}} = 300$ keV. Stellar model desires the uncertainty for the $^{12}$C$(\alpha,\gamma)^{16}$O cross section at $E_{\mathrm{c.m.}} = 300$ keV to be better than 10% [6], while the present uncertainty is about 40% [7].

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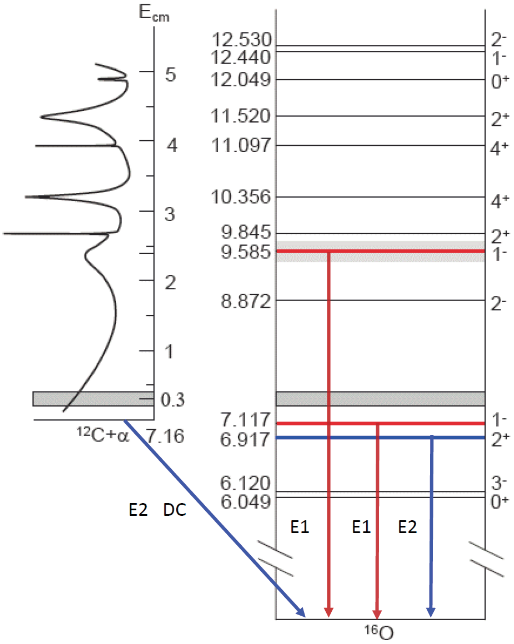

**Figure 1.** Spins and excitation energies of the $^{16}$O levels, and interference modes which are relevant to the $^{12}$C($\alpha, \gamma$)$^{16}$O reaction.

At energies corresponding to the Gamow peak, the $^{12}$C($\alpha, \gamma$)$^{16}$O cross sections are too low (at the order of $10^{-17}$ barn) to be measured directly in the ground laboratory. Therefore all direct measurements so far were done at higher energies above $E_{\text{c.m.}}$ = 890 keV [4]. How to achieve a reliable extrapolation of the cross sections from measured to the Gamow window has been a long-standing problem. Furthermore two subthreshold resonances, 7.117 MeV $1^-$ and 6.917 MeV $2^+$, make this extrapolation more complicated. There are two main capture modes in the $^{12}$C($\alpha, \gamma$)$^{16}$O reaction, as displayed in Fig. 1. One is the $E1$ capture which includes the contributions from the $1^-$ resonance at $E_x$ = 9.585 MeV and the subthreshold $1^-$ resonance at $E_x$ = 7.117 MeV. The other is the $E2$ capture which includes the contributions from the direct capture and the subthreshold $2^+$ resonance at $E_x$ = 6.917 MeV. The states with identical multipolarity interfere with each other. To date considerable experimental methods have been utilized to study these two subthreshold resonances, such as the $\alpha$ + $^{12}$C elastic scattering [8], the $\beta$-delayed $\alpha$ decay of $^{16}$N [9], radiative capture cross sections [10], transfer reactions [11] and Coulomb dissociation [12].

As for transfer reaction method, Brune et al. [11], Belhout et al. [13], Oulebsir et al. [14] and Adhikari et al. [15] investigated the subthreshold resonances in the $^{12}$C($\alpha, \gamma$)$^{16}$O reaction through the $^{12}$C($^6$Li$, d$)$^{16}$O and $^{12}$C($^7$Li$, t$)$^{16}$O reactions, respectively. Additional measurement via independent transfer reactions is desirable. In this work measurement of the $^{12}$C($^{11}$B$,^7$Li)$^{16}$O reaction is performed to derive the reduced $\alpha$-width of the 6.917 MeV $2^+$ subthreshold resonance. The astrophysical $S_{E2}$ factor at the Gamow peak of the $^{12}$C($\alpha, \gamma$)$^{16}$O reaction is then studied.

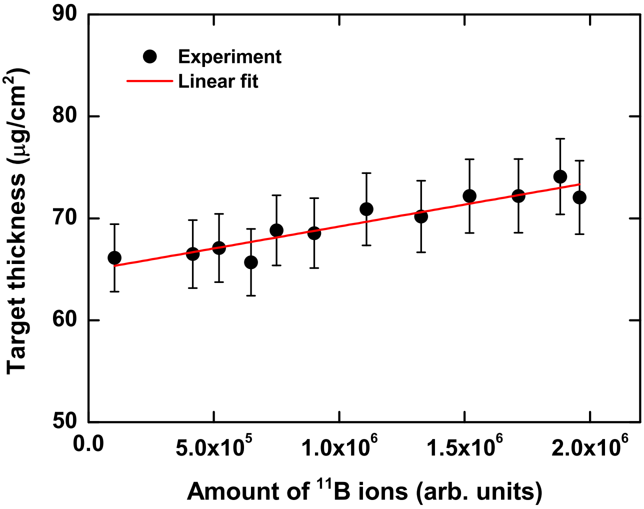

**Figure 2.** Thickness of the $^{12}$C target as a function of the amount of incident $^{11}$B ions.

## 2 Experiment

The experiment was performed at the HI-13 tandem accelerator of the China Institute of Atomic Energy (CIAE) in Beijing. The experimental setup and procedures are similar to those previously reported [16–18]. The $^{11}$B beam with an energy of 50 MeV was delivered and utilized to measure the angular distribution of the $^{12}$C($^{11}$B, $^{7}$Li)$^{16}$O reaction leading to the excited state of $^{16}$O at $E_x$ = 6.917 MeV and the $^{11}$B+$^{12}$C elastic scattering. A self-supporting $^{12}$C target was used in the present experiment. In addition, the $^{7}$Li beam with an energy of 26 MeV and a SiO target were used for the measurement of the $^{7}$Li+$^{16}$O elastic scattering. The reaction products were focused and separated by Q3D magnetic spectrograph. A two-dimensional position sensitive silicon detector (PSSD, 50×50 mm) was fixed at the focal plane of Q3D. The two-dimensional position information from PSSD enabled the products emitted into the acceptable solid angle to be completely recorded, and the energy information was used to remove the impurities with the same magnetic rigidity.

The buildup of $^{12}$C can increase the amount of the $^{12}$C atoms in the target, and influences the determination of the reaction cross sections. To monitor the possible buildup of $^{12}$C, the $^{11}$B elastic scattering on the $^{12}$C target was measured at the start and at the end of the measurement for each angle. In Fig. 2 we show the result of measurement of the $^{12}$C buildup which was clearly observed in the present experiment. Although the amount of $^{12}$C in the target increases by ~ 9% in the whole measurement, it is less than 2% for measurement of the cross sections at single angle. All the measured cross sections are calculated with the corrected target thickness.

As an example, Fig. 3 displays the focal-plane position spectrum of $^{7}$Li at $\theta_{\text{lab}} = 10°$ from the $^{12}$C($^{11}$B, $^{7}$Li)$^{16}$O reaction. One see that the $^{7}$Li events were well separated from others. In Fig. 4 we show the angular distribution of the $^{12}$C($^{11}$B, $^{7}$Li)$^{16}$O reaction leading to the 6.917 MeV $2^+$ state.

## 3 Extraction of the ANC

The finite-range distorted wave Born approximation (DWBA) calculations were performed to derive the asymptotic normalization coefficient (ANC) of the 6.917 MeV $2^+$ subthreshold state in $^{16}$O by

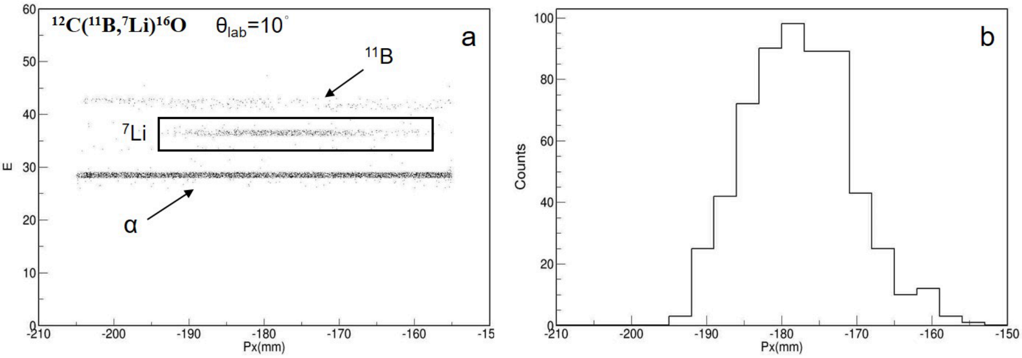

**Figure 3.** Focal-plane position spectrum of $^7$Li at $\theta_{\rm lab} = 10°$ from the $^{12}$C($^{11}$B, $^7$Li)$^{16}$O reaction. (a) Two dimensional spectrum of energy vs. focal-plane position. (b) Spectrum gated by the $^7$Li events in (a).

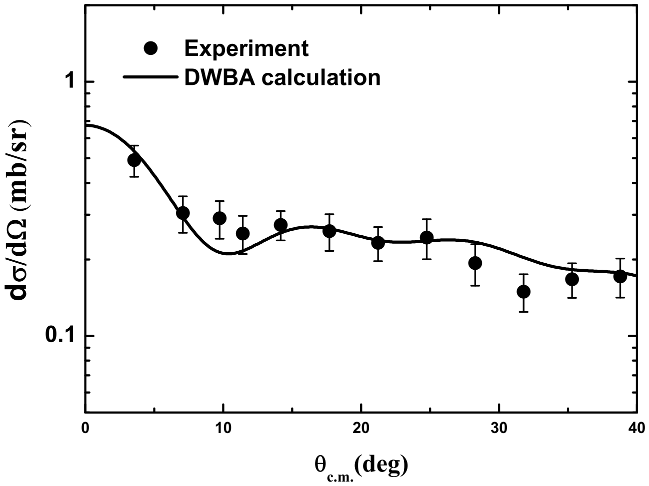

**Figure 4.** Angular distribution of the $^{12}$C($^{11}$B, $^7$Li)$^{16}$O reaction leading to the 6.917 MeV 2$^+$ state of $^{16}$O.

using the FRESCO code [19]. The optical model potential (OMP) parameters for entrance and exit channels of transfer reaction were obtained by fitting the present $^{11}$B + $^{12}$C and $^7$Li + $^{16}$O angular distributions. Full complex remnant term interactions were included in the transfer reaction calculations.

To obtain the ANC of $^{16}$O the spectroscopic amplitudes of $\alpha$-cluster in the ground state of $^{11}$B need to be fixed. The single-particle wave function describing the relative motion between $\alpha$-cluster and $^7$Li core in the $^{11}$B ground state can have two components denoted by quantum numbers $NL_j$ = $3S_0$ and $2D_2$, respectively. The spectroscopic amplitudes of these two components are −0.509 and 0.629, respectively, from a shell model calculation [20], and −0.638 and −0.422, respectively, from the translationally invariant shell model [21]. In the present analysis, both sets of spectroscopic amplitudes were used and the resulting difference was incorporated in the total uncertainty of our result. In addition, the geometry parameters, radius $r_0$ and diffuseness $a$, of the Woods-Saxon potential

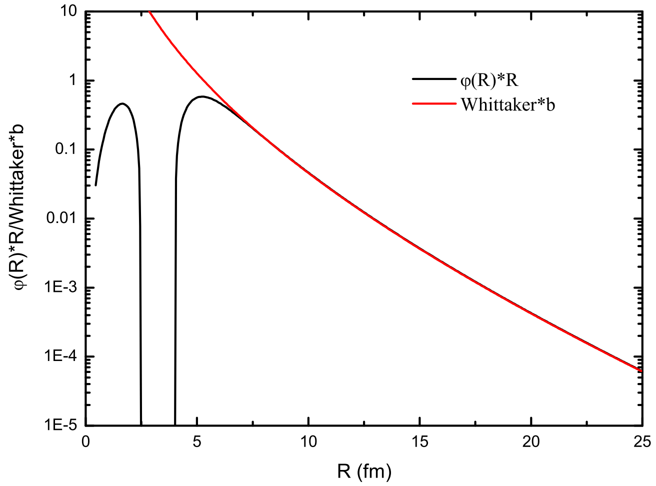

**Figure 5.** Single-particle wave function and Whittaker function of $\alpha$-cluster in the 6.917 MeV $2^+$ state of $^{16}$O.

for $\alpha$-cluster in $^{11}$B were adjusted to reproduce the root-mean-square (RMS) radius ( $\sqrt{\langle r^2 \rangle}$ = 3.204 fm) of the $\alpha$-cluster wave function using the formula given in Ref. [16]. The resulting parameters are $r_0$ = 0.92 fm and $a$ = 0.65 fm.

The geometric parameters of $^{16}$O were extracted to be $r_0$ = 1.16 fm and $a$ = 0.73 fm which presents the best description for the experimental angular distributions in Ref. [14]. In Fig. 4 we display the DWBA angular distribution of the $^{12}$C($^{11}$B, $^7$Li)$^{16}$O reaction, together with the experimental data. The ANC of the 6.917 $2^+$ state in $^{16}$O was the extracted to be (2.45 ± 0.28) $\times 10^{10}$ fm$^{-1}$ by the normalization of DWBA calculation to the experimental angular distribution. The error mainly results from the statistics (10%) and the uncertainty of target thickness (5%).

## 4 Astrophysical $S_{E2}$ factor of the $^{12}$C($\alpha, \gamma$)$^{16}$O reaction

The astrophysical S-factor of the $^{12}$C($\alpha, \gamma$)$^{16}$O reaction via the resonances can be calculated with the R-matrix theory. For the subthreshold resonance, the energy dependence of the $\alpha$-width is expressed as

$$\Gamma_\alpha(E) = 2\gamma_\alpha^2 P_{l_i}(E). \tag{1}$$

Here the reduced $\alpha$-width $\gamma_\alpha^2$ can be given by

$$\gamma_\alpha^2 = \frac{\hbar^2 R_c}{2\mu} S_\alpha \phi(R_c)^2 = \frac{\hbar^2}{2\mu R_c} C^2 W(R_c)^2, \tag{2}$$

where $S_\alpha$ and $C$ represent the spectroscopic factor and ANC, $\phi(R_c)$ and $W(R_c)$ are single-particle wave function and Whittaker function, respectively. $\gamma_\alpha^2$ was extracted to be 16.7 ± 1.9 keV at the channel radius $R_c = 7.0$ fm. This large radius was chosen to reach the Coulomb asymptotic behavior of $\phi(R)$, as demonstrated in Fig. 5 and also suggested in Ref. [14].

The astrophysical $S_{E2}$ factor of the 6.917 $2^+$ resonance at Gamow peak ($E_{\text{c.m.}}$ = 300 keV) was then derived to be 67.6 ± 7.7 keV b. The new value is agreement with those obtained from the $^{12}$C($^6$Li, $d$)$^{16}$O and $^{12}$C($^7$Li, $t$)$^{16}$O reactions given in Refs. [11, 14, 15]. It should be mentioned that the uncertainty from the geometry parameters of $^{16}$O was not included in the present result. The dependence of the present result on the geometry parameters of $^{16}$O will be investigated in the future.

## 5 Summary

In the present work we measured the angular distribution of the $^{12}$C($^{11}$B, $^{7}$Li)$^{16}$O reaction populating the 6.917 MeV $2^+$ subthreshold state in $^{16}$O using the Q3D magnetic spectrograph. The ANC of this state in $^{16}$O was derived based on a DWBA analysis, and then used to calculate the reduced-$\alpha$ width. Finally, we extracted the astrophysical $S_{E2}$ factor of the 6.917 $2^+$ resonance in the $^{12}$C$(\alpha,\gamma)^{16}$O reaction. This work presents an independent examination to the most important data in nuclear astrophysics.

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