PROCEEDINGS OF SCIENCE

Study of ^{12}C(α,γ)^{16}O reaction via the transfer reaction ^{12}C(^{7}Li,t)^{16}O

N. Oulebsir[*ab], **F. Hammache**[a], **P. Roussel**[a], **M.G. Pellegriti**[a†], **L.Audouin**[a], **D. Beaumel**[a], **A. Bouda**[b], **P. Descouvemont**[c], **S. Fortier**[a], **L.Gaudefroy**[d‡], **J. Kiener**[e], **A. Lefebvre-Schuhl**[e], **V. Tatischeff**[e]
[a]*Institut de Physique Nucléaire d'Orsay, UMR8608, IN2P3-CNRS, Université Paris sud 11, 91406 Orsay, France*
[b]*Université Abderrahmane Mira, 06000 Béjaïa ALGERIE*
[c]*Physique theorique et Mathematique, ULB CP229, B-1050 Brussels, Belgium*
[d]*GANIL,CEA/DSM-CNRS/IN2P3,Bd Henri Becquerel,BP 55027,F-14076 Caen Cedex 5, France*
[e] *CSNSM, UMR 8609, CNRS/IN2P3 and Université Paris Sud 11, F-91405 Orsay, France*
E-mail: `oulebsir@ipno.in2p3.fr`, `hammache@ipno.in2p3.fr`

The ^{12}C(α,γ)^{16}O reaction plays an important role in helium burning in massive stars and their evolution. However, despite many experimental studies, the low-energy cross section of ^{12}C(α,γ)^{16}O remains highly uncertain. The extrapolation of the measured cross sections to stellar energies (E=300 keV) is made difficult by the presence of the two sub-threshold states at 6.92 (2^+) and 7.12 (1^-) MeV of ^{16}O. In order to further investigate the contribution of these two-subthreshold resonances to the ^{12}C(α,γ)^{16}O cross section, we performed a new determination of the α-reduced widths of the 6.92 and 7.12 MeV of ^{16}O via a measurement of the transfer reaction ^{12}C(^{7}Li,t)^{16}O at two incident energies, 34 and 28 MeV. The measured and calculated differential cross sections are presented as well as the obtained spectroscopic factors and the α-reduced widths for the 2^+ and 1^- sub-threshold states and their effect on the R-matrix calculations of ^{12}C(α,γ)^{16}O.

11th Symposium on Nuclei in the Cosmos
19-23 July 2010
Heidelberg, Germany.

---

[*] Speaker.

[†] Present address: Dipartimento di Fisica e Astronomia, Universitá di Catania and Laboratori Nazionali del Sud - INFN, Catania, Italy

[‡] Present address: CEA, DAM, DIF, F-91297 Arpajon, France

PoS(NIC XI)129

1. Introduction

The most uncertain reaction rate which plays an important role in helium burning in massive stars is ^{12}C$(\alpha,\gamma)^{16}$O reaction rate. This reaction follows the production of ^{12}C by triple alpha-process and the ratio of the yields of these two reactions is crucial in determining the mass fraction of carbon relative to oxygen in stars like red giants at the end of helium burning phase [1] . The ^{12}C to ^{16}O abundance ratio has important consequences for the nucleosynthesis of elements heavier than carbon which are almost exclusively produced in this kind of stars [2]. It governs also the subsequent stellar evolution of the massive stars and their final fate (black hole, neutron star)[2, 3]. The rate of the triple alpha process is well determined (10-15% uncertainty), but it is not the case of ^{12}C$(\alpha,\gamma)^{16}$O reaction which has an uncertainty of about 41% despite the various experiments which studied it these last four decades.

The cross section of ^{12}C$(\alpha,\gamma)^{16}$O reaction, which occurs at the temperature around 0.2 GK corresponding to the Gamow peak of 300 keV, is expected to be 10^{-8} nbarn. This extremely low cross section excludes any direct measurement at this energy with the existing techniques. Even though direct measurements have been performed down to 0.9 MeV (CM) [4], the R-matrix extrapolation of the data to stellar energy is complicated by the vicinity of the two sub-threshold resonances at 7.12 (1^-) and 6.92 (2^+) MeV states of ^{16}O which through their high energy tails can enhance the alpha-capture cross section in the energy region of interest. Unfortunately, the contribution of these two sub-threshold states to ^{12}C$(\alpha,\gamma)^{16}$O cross section at 300 keV is badly known since their α-reduced width and so their α-spectroscopic-factors are spread over a large range of values [5]. Moreover, in the R-matrix calculation, one has to take also into account the contribution of the non-resonant direct capture and all possible interference effects between the different resonances [6].

In view of the importance of ^{12}C$(\alpha,\gamma)^{16}$O reaction, it appeared highly desirable to perform a new precise determination of the spectroscopic factors and the α-reduced widths of the 2^+ and 1^- sub-threshold states through a ^{12}C(^{7}Li,t)^{16}O transfer reaction measurement at two incident energies.

2. Experimental setup

The experiment was performed at the Orsay Alto facility using a ^{7}Li^{3+} beam provided by the high energy resolution tandem accelerator $\frac{\Delta E}{E} \approx 2\times10^{-4}$. An 80 μg/cm^2-thick self-supported natural ^{12}C target was used. The reaction products were analysed with a split-pole magnetic spectrometer and detected at the focal plane by a 50 cm long delayed-line gas counter for position measurements and a ΔE proportional gas-chamber. The particle identification was performed by a Δ E versus position measurements. The tritons were detected at angles ranging from 0 to 31° in the laboratory, corresponding to angles up to 44 ° in the center of mass. The beam and ^{12}C amount were monitored continuously by using a ΔE-E silicon telescope mounted inside the scattering chamber at Θ_{lab}=35 °.

3. Results and discussions

The experimental ^{12}C(^{7}Li, t)^{16}O differential cross section measured for the 6.05, 6.13, 6.92, 7.12 MeV populated states of ^{16}O at the two incident energies of 28 MeV and 34 MeV are displayed in figures 1.a and 1.b respectively. The error bars assigned to the measurements include the uncertainties on the peak yield, the number of target atoms, the solid angle and the integrated charge.

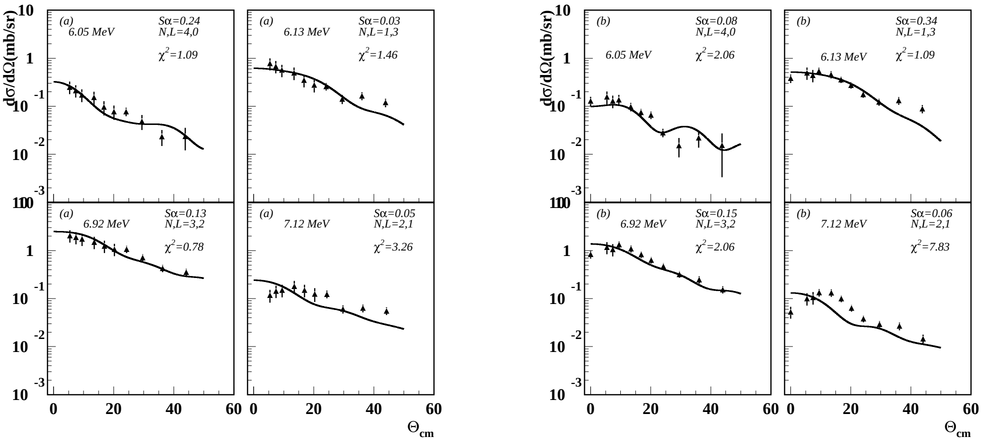

Figure 1: Experimental differential cross section of ^{12}C(^{7}Li, t)^{16}O reaction obtained at 28MeV (fig1.a and 34 MeV (fig1.b), compared with finite range DWBA calculations.

We performed finite-range DWBA calculations, using Fresco code [7] in order to extract from the normalisation of the calculated triton angular distributions to the measured ones, the α spectroscopic factors S_α corresponding to each populated state. Many combinations of entrance and exit optical potentials parameters were investigated. Concerning the ^{7}Li channel, for all the measurements at 34 MeV and at 28 MeV, several ^{7}Li optical potentials given by Schumacher [8] were tested. For the exit triton channel, optical potential parameters from Garrett et al [9] were selected. We also investigated the dependence of our calculation to the ^{12}C-α interaction potential. Finally, the selected optical and interaction parameters are those giving the best fit, using the maximum likelihood function set at 3σ level, for all the studied states (6.05, 6.13, 6.92, 7.12 MeV) at both incident energies (see fig.1.). A good agreement between the DWBA calculations and the measured differential cross sections of the different excited states of ^{16}O at the two bombarding energies of 28 MeV and 34 MeV respectively, can be observed in figure 1 and this gives strong evidence of the direct nature of (^{7}Li,t) transfer reaction.

An S_α mean value of 0.15±0.05 and 0.07±0.03 are deduced for the states of interest at 6.92 MeV and 7.12 MeV of ^{16}O respectively and both are in good agreement with those obtained by Becchetti et al. [10] while only the value obtained for the 7.12 MeV state is in good agreement with the one obtained in Belhout et al. [5] work. The uncertainty on the extracted α spectroscopic factors were evaluated from the dispersion of the deduced S_α values at the two incident energies, using the different sets of optical potentials in the entrance and exit channels and different α-^{12}C interaction parameters selected as described above.

Note that a more detailed paper [11], that includes more information about the reaction mechanism, Hauser Feshbach calculations, error analysis and comparison with all previous transfer reaction works is in preparation.

The α-reduced width of the two states of interest were determined by using the expression,

$\gamma_\alpha^2 = \frac{\hbar^2 R}{2\mu} S_\alpha |\varphi(R)|^2$ [10] where μ is the reduced mass and φ(R) is the radial part of the α-^{12}C wave function calculated at the radius R=6.5 fm. This radius was chosen in order to reach the coulomb asymptotic behavior of the radial part of the α-^{12}C wave function. The α-reduced width γ_α^2 of about 26.70±10.30 keV and 7.8±2.7 keV for the 6.92 MeV and 7.12 states respectively were < obtained at the radius of 6.5 fm.

The present values of γ_α^2 have been included in R-matrix fits of both ^{12}C(α,γ)^{16}O S-factors obtained by direct measurements at high energies and the ^{12}C(α,α) measured phase shifts, using R-matrix code of Descouvemont and Baye [13]

The E1 and E2 contributions were fitted separately. The best fits were determined through a χ^2 minimization. The l=2 Rmatrix fitting was performed using a four 2^+ levels including a background state, the phase shifts from [12] and the astrophysical S-factors data from [4, 14, 15, 16, 17, 18] (see Figure 2, left) . The four levels consist of the sub-threshold state at Ex=6.92 MeV, the states at Ex=9.85 MeV and Ex=11.52 MeV and a higher 2^+ background wich represent the tails of other higher-lying 2^+ states. For the E1 component, the l=1 Rmatrix fitting was performed using a three 1^- levels including a background state, the phase shifts from [12] and the astrophysical S-factors data from [14, 16, 18, 19] (see Figure 2, right). The three levels consist of the subthreshold state at Ex=7.12 MeV, the state at Ex=9.585 MeV and a higher 1^- background state which illustrate the tails of other higher-lying 1^- states.

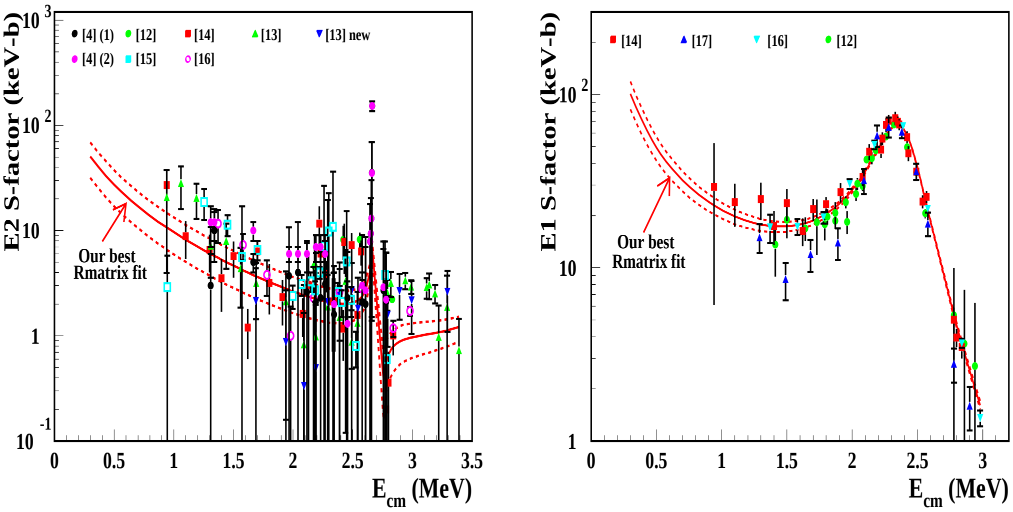

Figure 2: Left: Astrophysical *S*-factor for the ^{12}C(α,γ)^{16} reaction with *R*-matrix calculations of the E2 component. Right: Astrophysical *S*-factor for the ^{12}C(α,γ)^{16} reaction with *R*-matrix calculations of the E1 component. The solid curves correspond to fits when using our recommended γ_α^2 values, and the dashed curves to the lower and upper limits (see text).

An E2-Sfactor of about 50±19 keV-b and an E1-Sfactor of about 100±28 keV-b were obtained at the energy of interest E_{cm}~300 keV with the best fits shown in Figure 2 left and right, respectively. The solid curves are obtained when using our deduced γ_α^2 for the 6.92 and 7.12 MeV states respectiveley and the dashed curves were obtained when using the upper and lower values of our extracted γ_α^2 for the two states of interest.

Our value for the E1 component S_{E1}=100±28 keV-b is in excellent agreement with the results obtained in various direct and indirect measurements [5, 6, 15, 17, 18, 20] while our E2 component S_{E2}=52±19 keV-b is in good agreement within the error bars with the values obtained in [6, 12, 16, 17, 18] .

If we take for the cascade S-factor the value 25^{+16}_{-15} keV-b from [21], we obtain a total S-factor, S(300 keV)=177±63 keV-b. This value is in good agreement with 170±50 keV-b deduced from comparison of solar system abundances of all intermediate mass isotopes $16\leq$ A ≤ 32 with those predicted by calculations [2] of nuclosynthesis in massive stars from 12 to 40 $M_{\odot}$.

4. Conclusion

We determined the reduced α-widths of the sub-threshold 2^{+} and 1^{-} states of ^{16}O from the DWBA analysis of the transfer reaction $^{12}C(^{7}Li,t)^{16}O$ performed at two incident energies. The obtained result for the 2^{+} and 1^{-} sub-threshold resonances were introduced in the R-matrix fitting of radiative capture and elastic-scattering data to determine the low-energy extrapolations of E2 and E1 S-factor. The results confirm the values obtained in various direct and indirect measurements [6, 5, 12, 15, 16, 17, 18, 20]

References

[1] W.A. Fowler et al, Ann. Rev. Astron. and Astrophysics 5, 525 (1967); 13, 69 (1975)

[2] T.A. Weaver and S.E. Woosley, Phys. Reports 227, 65-96 (1993)

[3] M. Hashimoto, Prog. Theor. Phys. 94, 663- 736 (1996)

[4] M. Assunçao et al., Phys Rev C 73, 055801 1-19 (2006) and cited references in

[5] A. Belhout and al., Nucl. Phys. A 793, 178-211 (2007) and cited references in

[6] C. R. Brune et al. Phys. Rev. Lett 83, (1999) 4025

[7] I. J. Thompson, Comput. Phys. Commun 7, 167-212 (1988)

[8] P. Scumacher and al., Nucl. Phys. A 212, 573 -599 (1973)

[9] J.D. Garrett and al., Nucl. Phys. A 212, 600-612 (1973)

[10] F. D. Becchetti and al., Nucl. Phys. A 305, 293-312 (1978)

[11] N. Oulebsir, F. Hammache et al. paper in preparation

[12] P. Tischauser et al., Phys Rev C 79, 055803 (2009)

[13] P. Descouvemont and D. Baye, private communication

[14] P. Dyer et al., Nucl. Phys. A 233, 495 (1974)

[15] G. Rotters et al., Eur. Phys. J A6, 451 (1999)

[16] A. Redder et al, Nucl. Phys. A 462, 385 (1987)

[17] R. Kunz et al., Phys Rev Lett 86, 3244 (2001)

[18] J. M. Ouellet et al. Phys. Rev. C 54, 1982 (1996)

[19] Kremer et al., Phys Rev Lett 60, 1475 (1988)

[20] X. D. Tang et al., Phys Rev Lett 81, 045809 (2010)

[21] C. Matei et al., Phys Rev Lett 97, 242503 (2006)