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

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The radiative capture reaction ^{12}C(α,γ)^{16}O plays a key role in stellar nucleosynthesis and evolution. However the cross section of this reaction at stellar energies remains highly uncertain despite various experimental studies. The extrapolation down to stellar energy ($E_{cm}\sim$300 keV) of the measured cross sections at higher energies is made difficult by the overlap of various contributions of which some are badly known such as that of the 2^+ (E_x=6.92 MeV) and 1^- (E_x=7.12 MeV) sub-threshold states of ^{16}O. Indeed, the α-reduced widths and so the α-spectroscopic-factors of these two sub-threshold states are spread over too-large a range of values. Accordingly, a new determination of these quantities through ^{12}C(^{7}Li,t)^{16}O transfer reaction measurements at two incident energies and a detailed DWBA analysis of the data was performed recently at Orsay. 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. The R-matrix calculations of the ^{12}C(α,γ)^{16}O cross section using our obtained α-reduced widths for the two sub-threshold resonances are presented and discussed.

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1. Introduction

The radiative capture reaction ^{12}C(α,γ)^{16}O plays an important role in helium burning in massive stars and their subsequent evolution [1]. However, the low-energy cross section of this reaction remains highly uncertain despite the various experiments performed this last four decades. At the Gamow peak of 300 keV where this reaction occurs during the He burning stage, the expected cross section is about 10^{-8} nbarn, hence impossible to measure direcly. Direct measurements were performed down to 900 keV in center-of-mass system and then extrapolated to the energy of interest. Unfortunately the extrapolation is made difficult by the presence of several contributions, the most important ones being the E1 and the E2 transitions to the ground state via the low energy tail of the 1^- broad resonant state at 9.58 MeV of ^{16}O and the high energy tails of the 2^+ and 1^- sub-threshold resonant states at 6.92 and 7.1 MeV of ^{16}O respectively. The tails of all these states can interfere and enhance the cross section at 300 keV. However, the contribution of the two sub-threshold states is badly known because their measured alpha spectroscopic factors S_α and so their corresponding reduced alpha width are spread over a large range of values [2]. So, in view of the importance of ^{12}C(α,γ)^{16}O reaction and the large uncertainties surrounding the S_α and the γ_α^2 of the two sub-threshold states, we perfomed a new measurement of these quantities via the transfer reaction ^{12}C(^{7}Li,t)^{16}O [3].

2. Experiment description

The experiment was performed using a $^7Li^{3+}$ beam provided by the Orsay TANDEM. A self-supporting ^{12}C target, with a thickness of 80 $\pm$ 4 μg/cm^2 was used. The absolute amount of ^{12}C was deduced from an α-energy loss measurement. The reaction products were analyzed with an Enge Split-pole magnetic spectrometer and detected at the focal plane by a 50 cm long position-sensitive gas chamber and a ΔE proportional gas-counter. The particle identification was made unambiguously using ΔE versus position measurements.

The tritons were detected at angles ranging from 0 to 31° corresponding to angles up to 43° in the center of mass frame. The beam and ^{12}C amount were continuously monitored with a telescope of silicon detectors mounted inside the scattering chamber at θ_{lab}=35^o.

A typical excitation energy spectrum of ^{16}O measured at 11.5° is given in Figure 1.

The strong population of the α-cluster states, the 6.92 and 10.35 MeV states indicates that the data are consistent with a direct α-transfer mechanism. One can notice, also, the weak population of the non-natural parity state 2^-, the 8.87 MeV state of ^{16}O which can not be populated by direct transfer mechanism. It is probablly populated by the compound nucleus mechanism. This will be used to evaluate the contribution of the compound nucleus mechanism in this transfer reaction [3].

3. Results

3.1 DWBA analysis and results

The experimental ^{12}C(^{7}Li,t)^{16}O differential cross sections of the 6.05, 6.13, 6.92, 7.12, 8.87, 9.58, 9.85 and 10.35 were measured at the two incident energies of 28 and 34 MeV [3]. In Fig.2a

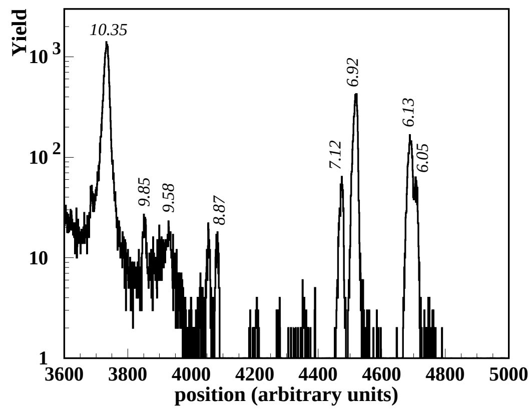

Figure 1: Triton spectrum obtained at 11.5° [3] with the 34 MeV ^{7}Li beam on ^{12}C target in the excitation energy region from 6 to 11 MeV . The excitation energy (MeV) of ^{16}O levels are indicated.

and Fig.2b are displayed the differential cross sections of 6.13, 6.92, 7.12 and 8.87 states respectively. The accuracy assigned to our measured cross sections includes the uncertainties on the peak yield, the number of target atoms, the solid angle and the integrated charge except for the zero degree run (no charge measurement) where the number of counts in the silicon monitor detector placed at 35^{o} was used.

Calculations with finite-range DWBA (FRDWBA) method, using the FRESCO code [4] , were performed. For the ^{7}Li channel, we used the optical potential parameters of Schumacher et al. [6] who performed ^{7}Li elastic scattering measurements on ^{12}C at the energy of 34 MeV. Concerning the triton channel, the optical model potentials used were taken from Garrett et al. [5]. The optical potential parameters finally selected are those giving the best fit for all the studied transitions in the (^{7}Li,t) reaction.

For the α wave function in ^{16}O, an α+^{12}C Wood-Saxon potential was used. A range of radius (3.5 fm $\leq$ R $\leq$ 4.5 fm) and diffuseness (0.53 fm $\leq$ a $\leq$ 0.93 fm) was selected by using the maximum likelihood function (set at 3σ level) on the angular distributions of all measured levels except the non-natural parity 8.87 MeV state and the 9.85 MeV state which displays a quasi-flat distribution [3]. Within this radius and diffuseness range, the boundary values R=4.5 fm and a=0.73 fm provide the best fit for the angular distributions of all the studied states at both incident energies (fig.2) except the 8.87 and the 9.85 MeV states. Details in the DWBA analysis procedure is given in [3]. The calculated FRDWBA angular distributions normalized to the data are shown in Figure 2 together with the Hauser-Feshbach (HF) calculations and the incoherent sum of HF and FRDWBA calculations.

Except for the 8.87 MeV state, the good agreement between the DWBA calculations and the measured differential cross sections of the different populated states of ^{16}O at the two bombarding energies of 28 MeV and 34 MeV respectively, gives strong evidence of the direct nature of the (^{7}Li,t) reaction populating these levels and confidence in our DWBA analysis. However, as one can see in Figure 2, a disagreement at angles smaller than 10° is observed for the 7.12 MeV state and for both incident energies. This discrepancy is not understood and it was also observed in

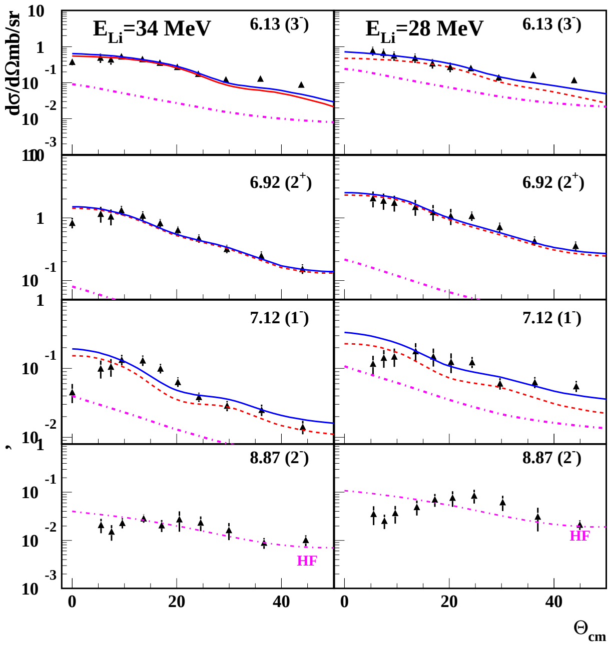

Figure 2: Experimental differential cross sections of the $^{12}C(^{7}Li,t)^{16}O$ reaction obtained at 34 MeV (left column) and 28 MeV (right column) for the 6.13, 6.92, 7.12 and 8.87MeV states [3], compared with FRDWBA calculations (dashed red curve) normalized to the data, Hauser-Feshbach (HF) calculations (dashed-dotted pink line) and the sum HF+FRDWBA (blue solid line).

$^{12}C(^{7}Li,t)^{16}O$ experiment of Becchetti et al. [7] at 34 MeV. To try to understand if the decrease of the cross section at angles smaller than 10° is due to a multi-step effect mechanism, coupled channel calculations are needed and they are in progress.

From a χ^2 minimization of the DWBA differential cross sections to the measured ones, S_α mean values 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 The uncertainty on the extracted α spectroscopic factors for the states of interest was evaluated from the dispersion of the deduced S_α values at the two incident energies and using different sets of optical potentials in the entrance [6] and exit channels [5] and different α-^{12}C well geometry parameters selected above.

Once the S_α of the states of interest are determined, one can then deduce their α-reduced widths using the expression, $\gamma_\alpha^2 = \frac{\hbar^2 R}{2\mu} S_\alpha |\varphi(R)|^2$ [8] where μ is the reduced mass and φ(R) is the radial part of the α-^{12}C wave function. The latter is calculated at the radius R=6.5 fm where it reaches its asymptotic behavior. α-reduced widths γ_α^2 of about 26.7±10.3 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 asymptotic normalisation constants (ANC) [9] were also deduced and the obtained values $\tilde{C}^2$=(2.07±0.80)10^{10} fm^{-1} and $\tilde{C}^2$=(4.00±1.38)10^{28} fm^{-1} for the 6.92 and 7.12 MeV states respectively were found in good agreement with those obtained by Brune et al. [10] who deduced the ANC's and the α-widths of the states of interest via a sub-coulomb ANC measurement.

3.2 R-matrix calculations and results

The deduced α-reduced widths were included in an R-matrix calculation of the E1 and E2 astrophysical S-factor of $^{12}C(\alpha,\gamma)^{16}O$ reaction using P. Descouvemont code. In the R-matrix calculations, both the $^{12}C(\alpha,\gamma)^{16}O$ astrophysical S-factors obtained by direct measurements at higher energies and the phase shifts data from elastic scattering $^{12}C(\alpha,\alpha)$ measurements were fitted and the two components were fitted separately. For the E2 component, four 2^+ states were considered in the calculation; the 6.92 MeV state for which we determined the γ^2_α, the 9.85 MeV, the 11.52 MeV and a background equivalent state which takes into account the tails of other higher-lying 2^+ states. In the R-matrix fitting procedure, the resonance parameters of all states except the background state are kept fixed [3]. From the best fits displayed in figure 3, we deduced an E2 S-factor at 300 keV of 50$\pm$19 keV-b.

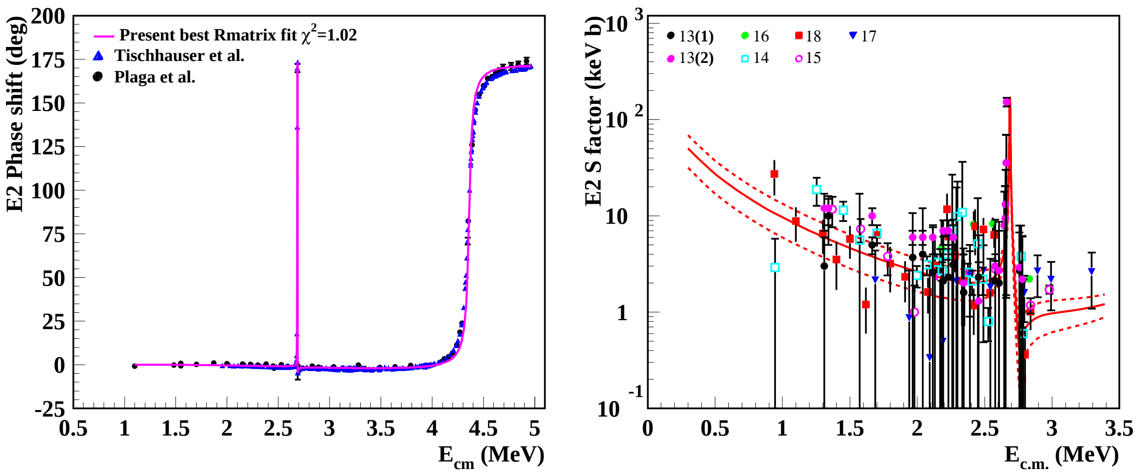

Figure 3: left: Phase shifts for $^{12}C(\alpha,\alpha)^{12}C$ elastic diffusion reaction with *R*-matrix calculations of the E2 component [3]. Data points are from [11] (black points) and [12] (blue triangles). The solid line correspond to our best R-matrix fit with χ^2=1.02. right:Astrophysical *S*-factor for the $^{12}C(\alpha,\gamma)^{16}O$ reaction with *R*-matrix calculations of the E2 component [3]. Experimental data are from [13, 14, 15, 16, 17, 18]. The solid line is our best R-matrix fit using our deduced γ^2_α for the 6.92 MeV state and the dashed lines when using our upper and lower values for γ^2_α.

The same fitting procedure was applied for the E1 component and the 1^- states considered are the 7.12 MeV state, the broad resonant state at 9.58 MeV and a background equivalent state which takes into account the tails of other higher-lying 1^- states and the direct component. The only free parameters are those of the 1^- background equivalent state. From the best fits shown in Figure 4, an E1 S-factor at 300 keV of 100$\pm$28 keV-b was deduced.

To validate furthermore our R-matrix fits and results, especially for the E1 component, we performed a p-wave calculation of the β-delayed α-spectrum of ^{16}N. For the calculation, we used equation 3 of ref [20] and our R-matrix parameters while we considered the β-feeding amplitudes, $A_{\lambda l}$ (see equation 3 of ref. [20]), as free parameters. Our calculation describes well, as one can see in Figure 5, the measured data of Tang et al. [20] and this gives strong confidence in our R-matrix calculations. The disagreement between the calculation and the data in the energy region between

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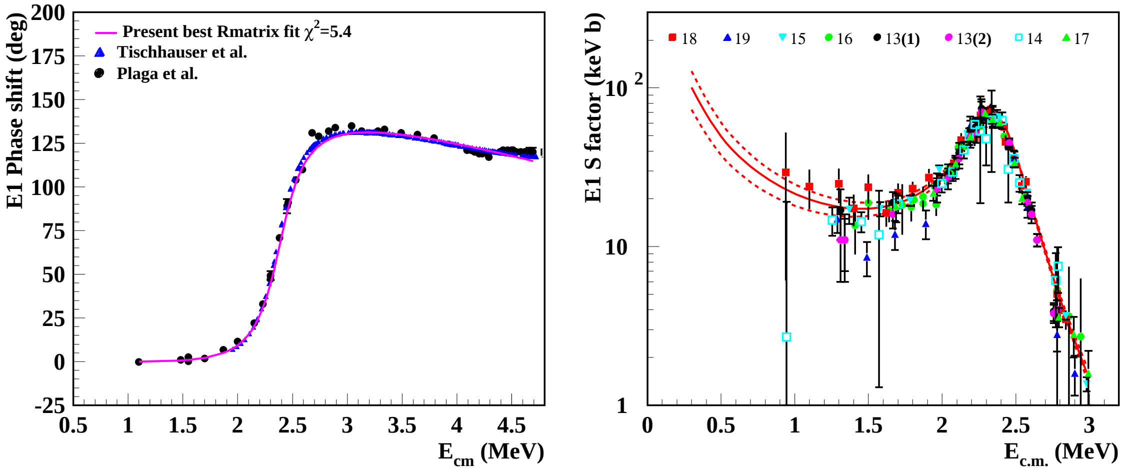

Figure 4: Left:Phase shifts for ^{12}C(α,α)^{12}C elastic diffusion reaction with *R*-matrix calculations of the E1 component [3]. Data points are from [11] (black points) and [12] (blue triangles). The solid line correspond to our best R-matrix fit with χ^2=5.4. Right:Astrophysical *S*-factor for the ^{12}C(α,γ)^{16}O reaction with *R*-matrix calculations of the E1 component [3]. Experimental data are from [13, 14, 15, 16, 17, 18, 19]. The solid line is our best R-matrix fit using our deduced γ_α^2 for the 7.12 MeV state and the dashed lines when using our upper and lower values for γ_α^2

1.3 and 1.5 MeV is due to the f-wave contribution which was not considered in the calculation as it is not contributing to the E1 component we are interested in.

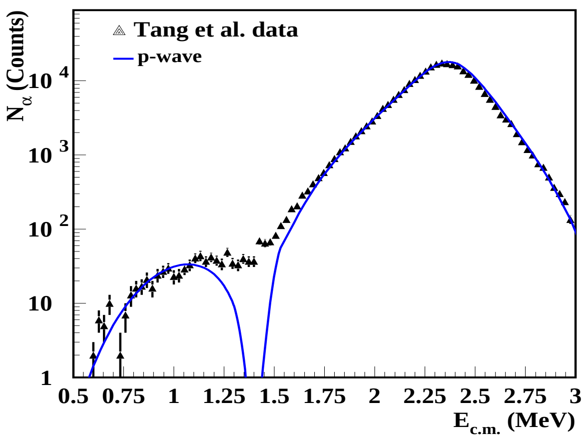

Figure 5: R-matrix calculation [3] (see text) of the β-delayed α-spectrum of ^{16}N together with data obtained in [20]. Only the p-wave was considered in the calculation.

The values obtained for the E1 and E2 S-factors at 300 keV are given in table 1 together with the results of some previous works.

Our deduced values for the E1 and E2 S-factors are in excellent agreement with those of Brune et al. [10] and in good agreement with those of Kunz et al. [14] within the error bars. Concerning

Experiment	S_{E1}(0.3 MeV) (keV-barn)	S_{E2}(0.3 MeV) (keV-barn)	S_{total}(0.3 MeV) (keV-barn)
This work [3]	100±28	50±19	175^{+63}_{-62}
Brune [10]	101±17	44^{+19}_{-23}	170^{+52}_{-55}
Kunz [14]	76±20	85±30	186^{+66}_{-65}
NACRE [21]	79±21	120±60	224^{+97}_{-96}

Table 1: Comparison of the astrophysical S-factor at 300 keV obtained in various experiments including this work for the E1 and E2 component as well as the total.

NACRE recommended values, our E1 S-factor is in agreement with NACRE result within the error bars while for the E2 component, our central value is two times smaller than NACRE recommended value and our error bar is much smaller.

If we consider for the cascade transition, the value of 25±16 keV-b obtained by Matei et al. [22], we obtain a total S-factor of 175±16 keV-b which is in good agreement with Brune's et al result (see table 1) and some previous works [3]. Note that in our work as well as in Brune's et al one, the γ_α^2 of the two sub-threshold states were fixed in the R-matrix calculation at the measured values contrary to all other works.

4. Conclusion

From the analysis of the transfer reaction $^{12}C(^7Li,t)^{16}O$ measurement recently performed at two incident energies, we determined the α-spectroscopic factors S_α and the reduced α-widths γ_α^2 of the two sub-threshold 2^+ (E_x=6.92 MeV) and 1^- (E_x=7.12 MeV) states of ^{16}O. The uncertainties on the S_α and γ_α^2 of the 6.92 and 7.12 MeV states of interest are now well and carefully determined thanks to the detailed finite range DWBA analysis of the measured data. The obtained γ_α^2 for the 2^+ and 1^- sub-threshold resonances were introduced in R-matrix calculations in order to determine the E2 and E1 S-factor at the energy of 300 keV. The result for the E1 S-factor at 300 keV confirms the values obtained in various direct and indirect measurements as well NACRE compilation [3] while for the E2 component, the central value of our result is found to be nearly two times smaller than NACRE recommended value. Our results are in excellent agreement with Brune's et al. [10] ones and in both works, the γ_α^2 or the ANC's of the two sub-threshold states were fixed in the R-matrix calculation at the measured values leading to a bigger constraint in the fitting procedure. However to have a more precise determination of the total S-factor at 300 keV, more precise cascade transitions measurements as well as more precise E2 direct data at higher energies are needed.

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