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New study of the astrophysical reaction ^{13}C(α,n)^{16}O via the ^{13}C(^{7}Li,t)^{17}O transfer reaction

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The cross section of the ^{13}C(α,n)^{16}O reaction is a key ingredient for the comprehension of the s-process (slow neutron captures) in stars. This reaction is considered as the main neutron source for the s-process in low-mass Asymptotic Giant Branch (AGB) stars (1-3 solar mass) [1, 2, 3].
At the α-^{13}C energies of astrophysical interest (E_{cm} around 190 keV, corresponding to a temperature of 10^8 K) the contribution of the ^{17}O α-decay subthreshold resonance at 6.356 MeV to the ^{13}C(α,n)^{16}O cross section should be taken into account. The effect of this resonance is controversial after the different analyses of the Kubono et al. measurement [4] of the 6.356 MeV α-spectroscopic factor (S_α) via the transfer reaction ^{13}C(^{6}Li,d)^{17}O .
In order to further investigate the contribution of the 6.356 MeV resonance to the ^{13}C(α,n)^{16}O cross section, we performed a new measurement of its S_α factor via a different α-transfer reaction, namely the ^{13}C(^{7}Li,t)^{17}O reaction. The experiment was performed at the Orsay Tandem by using a ^{7}Li beam of 28 and 34 MeV on a ^{13}C target. The angular distribution for the transfer differential cross section was measured by detecting the tritons at the focal plane of the SPLITPOLE spectrometer. The analysis procedure used in order to extract the yield of the 6.356 MeV level will be described. Preliminary results of the angular distribution will be shown.

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1. Astrophysical motivation

Nearly half of the heavy elements observed in the Universe are produced by a slow sequence of neutron capture reactions, the so-called s-process. For this astrophysical process, two neutron sources are used in all evolution models: the reactions $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$. For AGB stars of 1-3 solar masses at low temperatures, only the $^{13}C(\alpha,n)^{16}O$ reaction is considered as the main neutron source for the s-process [1, 2, 3]. ^{13}C is synthesized, in the He intershell of stars, by the CNO cycle $^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C$. This leads to the formation of the so-called ^{13}C pocket on the top of the intershell region, where the neutrons necessary for the s-process, are produced through the burning reaction $^{13}C(\alpha,n)$. Hence, the predictions of the models describing the s-process nucleosynthesis in these AGB stars depend critically on the neutron flux from the $^{13}C(\alpha,n)^{16}O$ reaction.

As the cross section of the $^{13}C(\alpha,n)^{16}O$ reaction decreases drastically when the α-^{13}C energy decreases, a direct measurement of this reaction at energies of astrophysical interest (i.e $E_{cm}\sim$190 keV) is extremely difficult. Direct measurements have only been performed down to 270 keV [5, 6]. R-matrix extrapolations [7] of the cross section down to the energy of astrophysical interest depend on the contribution of the α-decay subthreshold level of ^{17}O at 6.356 MeV to the cross section at the low energy region. However, the error bars of the direct experimental points at 270 keV are too large to discriminate between extrapolations which use different reduced α-widths for the state of interest.

Kubono et al. [4] then suggested that a way to determine the reduced α-width of the state of interest is via a measurement of its α-spectroscopic factor (S_α) through a transfer reaction. To populate the 6.356 MeV state, they used the $^{13}C(^6Li,d)^{17}O$ reaction induced by a 60 MeV ^6Li beam. They measured the angular distribution of the transfer differential cross section leading to the 6.356 MeV level and determined an S_α value of about 0.011 by using a finite-range Distorted Wave Born Approximation (DWBA) analysis of the data. This leads to a very small contribution of this subthreshold state to the cross section of $^{13}C(\alpha,n)^{16}O$ at energies of astrophysical interest. However, a reanalysis of the same data by Keeley et al. [8] ends up to a drastically different conclusion since they found $S_\alpha \sim 0.4$, forty times higher than Kubono's value, which leads to cross section values consistent with the theoretical calculations [9].

2. The experimental method

In order to reinvestigate the importance of the 6.356 MeV state, we have studied it by means of an other α-transfer reaction, the $^{13}C(^7Li,t)^{17}O$. The use of ^7Li nuclei instead of ^6Li (as in Kubono et al.[4]) to populate the various excited states of ^{17}O has some advantages, despite a smaller α-structure coefficient:

(i) Possible multi-step effects are less marked for the (^7Li,t) reaction than for (^6Li,d) one [10].

(ii) Transfer cross sections to low spin states are enhanced because of the non-zero α angular momentum in ^7Li which leads to a better momentum matching. This was deduced from the study of the transfer reactions $^{12}C(^6Li,d)^{16}O$ [12] and $^{12}C(^7Li,t)^{16}O$ [11] which used a ^{12}C target.

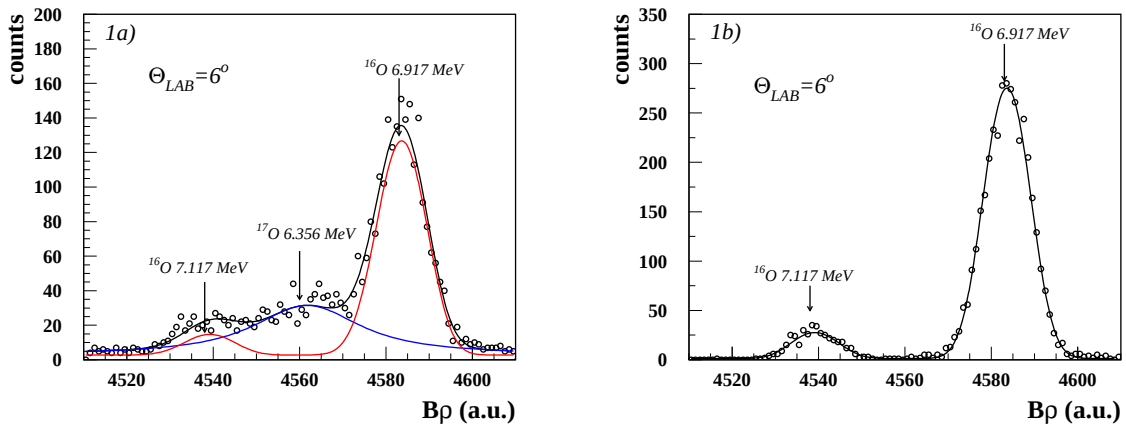

Figure 1: Example of the fitting procedure for the extraction of transfer cross section for the 6.356 MeV level. In Fig. 1a), open circles represent the experimental spectra obtained by using the ^{13}C target. The number of detected tritons is plotted as a fuction of the triton position measured at the focal plane detector. The blue line and the red line in Fig. 1a represent the contribution of the 6.356 MeV level and the contribution of ^{16}O levels evaluated by the fitting procedure, respectively. The black line is the result of the fit (blue line plus red line). In Fig. 1b, open circles represent data obtained by using the ^{12}C target. Only the ^{16}O peaks are visible. Parameters from the fit (black line in Fig. 1b) have been used to constrain the fit in Fig. 1a.

(iii) It is important to populate the same final states in ^{17}O using different transfer reactions. They involve different parameters such as internal spin, angular momenta and optical potentials and they allow to improve the systematic errors estimation introduced in DWBA analysis.

Once the spectroscopic factor S_α of the subthreshold state at 6.356 MeV deduced from the following equation,

$(d\sigma/d\Omega)_{exp}=C^2S_l(d\sigma/d\Omega)_{DWBA}$ (1)

one can determine the α width Γ_α of the state and then calculate the cross section of the $^{13}C(\alpha,n)^{16}O$ reaction through the tail of the subthreshold resonance by using the Breit-Wigner single level formula.

The experiment was performed at the Tandem-Splitpole spectrometer. The transfer reaction $^{13}C(^7Li,t)^{17}O$ was induced on a 0.1 mg/cm^2 self-supporting ^{13}C target irradiated by a ^7Li beam. Two different beam energies were used, 28 MeV and 34 MeV, in order to investigate and possibly confirm the direct mechanism. In the following we will refer just to the measurement at 34 MeV. The reaction products were momentum analyzed by the magnetic spectrometer Splitpole and the tritons were detected at the focal plane by a position-sensitive gas chamber and a ΔE proportional gas-counter. The angular distribution for the transfer differential cross section was measured at angles ranging from 0 to 31 degrees in the laboratory frame, this covers angles up to 43 degrees in the center of mass frame. The ^7Li elastic scattering on ^{13}C was also measured to subsequently calculate the entrance channel optical potentials needed for the transfer DWBA calculation.

3. Preliminary results

The main difficulty of this experiment is the presence of ^{12}C contaminants in the ^{13}C target. This implies the reaction $^{12}C(^{7}Li,t)^{16}O$ and then the presence of tritons coming from the excited stated of ^{16}O (at 6.917 and 7.117 MeV) which are energetically close by the ^{17}O 6.356 MeV state.

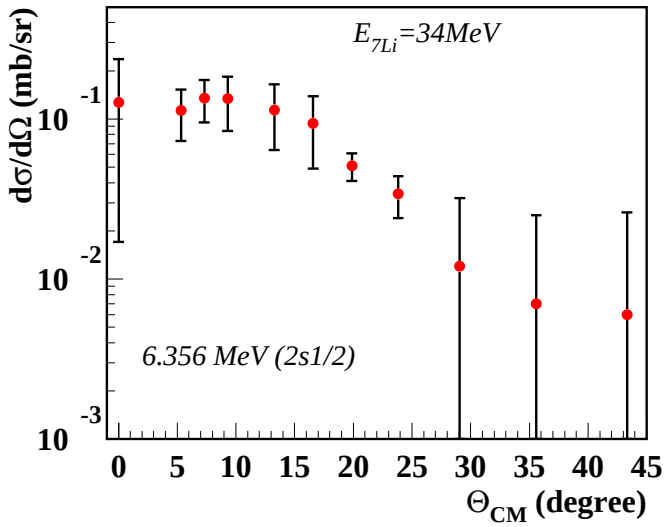

Figure 2: Preliminary results for $^{13}C(^{7}Li,t)^{17}O$ differential cross section for the 6.35 MeV level obtained by fitting procedure in Fig1.

A further difficulty comes from the shift of the ^{17}O peak with respect to energy position of the ^{16}O peaks, which makes the yield extraction at larger angles harder. This last is simply due to a different kinematics because of different involved masses. In order to evaluate the amount of ^{12}C contaminant in the ^{13}C target, a background measurement of the $^{12}C(^{7}Li,t)^{16}O$ reaction was performed by using a ^{12}C target at the same experimental set-up.

An example of the fitting procedure which have been used to extract the 6.356 MeV transfer cross section is shown in Fig. 1a. The blue curve represents the yield for the 6.356 MeV peak at the angle of 6 degree in the laboratory frame of reference. The parameters describing the contaminant peaks coming from the excited levels of ^{16}O (at 6.917 and 7.117 MeV) have been extracted from the measured ^{12}C target spectrum (Fig. 1b) and have been used to constrain the fit of the ^{13}C target spectrum (Fig. 1a).

Preliminary results of the angular distribution of the state of interest (6.356 MeV) are displayed in Fig. 2. A further analysis to better evaluate the 6.356 MeV yield at each angle and the corresponding errors coming from the fitting procedure is under development. A finite-range DWBA calculation of the $^{13}C(^{7}Li,t)^{17}O$ reaction is also in progress in order to calculate the angular distribution of the differential cross sections and to extract the spectroscopic factor.

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