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Determination of alpha spectroscopic factors for unbound ^{17}O states

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Abstract. It has been recently suggested that hydrogen ingestion into the helium shell of massive stars could lead to high ^{13}C and ^{15}N excesses when the blast of a core collapse supernova (ccSN) passes through its helium shell. This prediction questions the origin of extremely high ^{13}C and ^{15}N abundances observed in rare presolar SiC grains which is usually attributed to classical novae. In this context the ^{13}N(α,p)^{16}O reaction plays an important role since it is in competition with ^{13}N β^+-decay to ^{13}C. As a first step to the determination of the ^{13}N(α,p)^{16}O reaction rate, we present a study aiming at the determination of alpha spectroscopic factors of ^{17}O states which are the analog ones to those in ^{17}F, the compound nucleus of the ^{13}N(α,p)^{16}O reaction.

1 Introduction

Primitive meteorites hold several types of dust grains that condensed in stellar winds or ejecta of stellar explosions. These grains carry isotopic anomalies which are used as a signature of the stellar environment in which they formed. As such, extreme excesses of ^{13}C and ^{15}N in rare presolar SiC grains have been considered as a diagnostic of an origin in classical novae [1], however an origin in ccSNe has also been recently proposed [2]. In the context of ccSNe, explosive He shell burning can reproduce the high ^{13}C and ^{15}N abundances if H was ingested into the He shell and not fully destroyed before the explosion [3]. The supernova shock will then produce an isotopic pattern similar to the hot-CNO cycle signature obtained in classical novae. It has been shown that a variation of a factor of five for the ^{13}N(α,p)^{16}O reaction rate induces several orders of magnitude uncertainty in the production of ^{13}N which β^+-decays to ^{13}C.

Currently the ^{13}N(α,p)^{16}O reaction rate is calculated using a statistical model or the time reverse reaction and these determinations have large uncertainties. The goal of this work is to put the ^{13}N(α,p)^{16}O reaction rate on a firmer basis. Given that the alpha emission threshold (S_α = 5.819 MeV) is much higher than the proton emission threshold (S_p = 0.600 MeV) in the compound nucleus ^{17}F, the resonance strength of individual resonances is directly proportional to their alpha

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widths. We report on the analysis of ^{13}C(^{7}Li,t)^{17}O data populating the analog states of the states of interest in ^{17}F. After a DWBA analysis of the measured differential cross sections, alpha spectroscopic factors are extracted and alpha widths are deduced.

2 Data reduction

An analysis of existing data from the alpha-transfer ^{13}C(^{7}Li,t)^{17}O experiment performed at the Tandem-ALTO facility in Orsay, France, was undertaken. All the experimental details can be found in Ref. [4] which focused on the study of the sub-threshold state at 6.356 MeV in ^{17}O relevant for the ^{13}C(α,n)^{16}O reaction and its role in the main *s*-process. Tritons from the ^{13}C(^{7}Li,t)^{17}O reaction were momentum analyzed by an Enge Split-Pole magnetic spectrometer, and detected and identified at the focal plane. Figure 1 shows the triton focal-plane position spectrum obtained in the case of a spectrometer angle of 7° covering ^{17}O excitation energies between 6.2 and 7.4 MeV. Calibration of the focal-plane position detector at the same magnetic field using the natural carbon target and known ^{16}O levels populated through the ^{12}C(^{7}Li,t)^{16}O reaction was used to identify the ^{17}O states. The best least-square fit of the triton spectrum for states above the α+^{13}C threshold (S_α = 6.359 MeV) is also represented in Fig. 1 together with the individual contribution of each ^{17}O state. While narrow states were described by a skewed Gaussian function needed to account for the low energy tail of each triton peak, a Voigt function was used for the broad ^{17}O state at 7.202 MeV (Γ = 280 (30) keV [5]). Since most of the levels have a natural width much smaller than the experimental width, a common width was taken for each Gaussian function describing ^{17}O states in the fitting procedure. A width of $\approx$ 60 keV (FWHM) is obtained which reflects the experimental resolution. The previous procedure has been repeated for each of the eleven spectrometer angles where the measurement was performed.

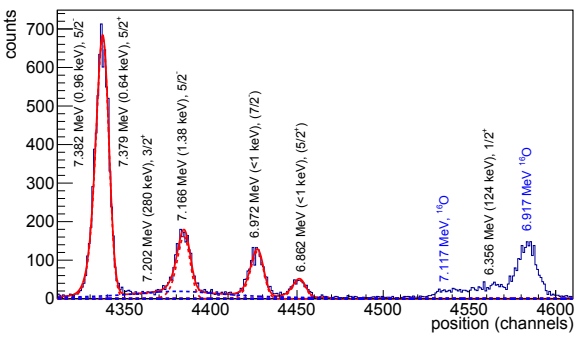

Figure 1. (Color online) Tritons magnetic rigidity spectrum at spectrometer angle of 7°. Excitation energies in ^{17}O between 6.2 and 7.4 MeV are covered and the best fit of the spectrum is represented for states above the α+^{13}C threshold. Note the presence of an experimentally unresolved doublet including ^{17}O states at 7.379 and 7.382 MeV. Note also the presence of two ^{16}O contamination states away from the region of interest.

3 Angular distributions and DWBA analysis

The differential cross sections corresponding to ^{17}O states were obtained by normalizing the number of tritons determined at each detection angle to the target thickness, solid angle and accumulated charge. As an example, the differential cross section of the 7.382 MeV (5/2$^-$) state is displayed in Fig. 2. Finite-range DWBA calculations were performed with the FRESCO code [6]. Several combinations of entrance and exit optical potentials have been tried as inputs of the DWBA calculations together with two values of the number of radial nodes N of the α-wave function in ^{17}O (see Fig. 2). The most sensitive parameter is the number of radial nodes and N = 2 was selected for the 7.382 MeV state. For this state the different combinations of optical potential give similar angular distribution shapes even

if the spread on the normalization factor accounts for ±20%. The best compromise for describing all differential cross sections at the same time is with potential III from Schumacher et al. [7] for the entrance channel and with potential I f7/2 from Garrett et al. [8] for the exit channel, in line with the study of the sub-threshold 6.356 MeV state [4].

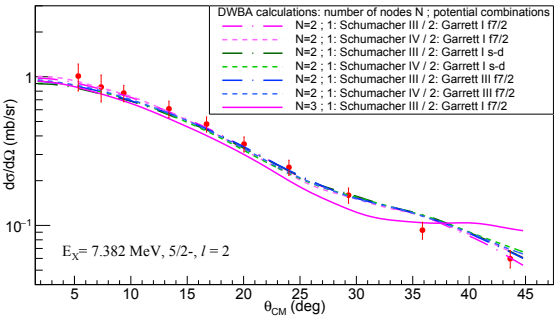

Figure 2. (Color online) Experimental cross section of the ^{17}O state at 7.382 MeV populated with the ^{13}C(^{7}Li,t)^{17}O reaction. Finite-range DWBA calculations are represented for different sets of entrance and exit optical potentials. The effect of the number of radial nodes of the α-wave function in ^{17}O is also explored.

Assuming that the overlap between the ^{7}Li and α+t systems is equal to one (see discussion in Ref. [4]), the normalization factor between the experimental and DWBA differential cross sections is the ^{17}O alpha spectroscopic factor (C^2S_α). The procedure to extract C^2S_α for unbound ^{17}O states follows the prescription from Ref. [9]. For low transferred angular momentum ($\ell < 2$) such as for the ^{17}O state at 7.202 MeV, the alpha spectroscopic factor is determined at several binding energies and extrapolated at the actual α-separation energy (BE = -844 keV) as shown in Fig. 3. For higher transferred angular momentum, C^2S_α is determined for an hypothetical ^{17}O state bound by 100 keV since the α-cluster is quasi-bound due to the large centrifugal barrier. Alpha spectroscopic factor of 0.40 is obtained in the case of the 7.202 MeV broad state. Concerning the experimentally unresolved doublet including ^{17}O states at 7.379 and 7.382 MeV, alpha spectroscopic factors are 0.28 and 0.42, respectively, assuming all the strength is on one or the other state.

The alpha spectroscopic factor can be used to derive the corresponding partial width in case of unbound states using the following formula [10]: $\Gamma_\alpha = 2P_l(r,E)\frac{\hbar^2}{2\mu}C^2S_\alpha\,|\phi(r)|^2$, where $P_l(r,E)$ is the penetrability for transferred angular momentum ℓ, and $|\phi(r)|$ is the radial part of the α+^{13}C wave function. This formula should be evaluated at the interaction radius r where the α+^{13}C wave function reaches an asymptotic behavior. This radius was determined by comparing the alpha reduced width γ_α^2 with the corresponding Whittaker function (see Fig. 4) and a value of r = 6.5 fm is obtained. This procedure was done for all states and a similar radius was obtained. Alpha widths obtained for the 7.202 MeV and 7.379 MeV states are 6.5×10^{-2} and 7.8×10^{-3} keV, respectively. This is in very good agreement (within a factor of two) with alpha widths of 0.07 and 0.01 keV, respectively, reported in the literature [5].

4 Conclusions

Data from the ^{13}C(^{7}Li,t)^{17}O reaction were analysed with the goal to determine the alpha spectroscopic factors of ^{17}O states relevant for the study of the ^{13}N(α,p)^{16}O reaction. Details of the analysis in the case of the ^{17}O states at 7.202 MeV and 7.382 MeV are given. Results for other ^{17}O states will be presented in a forthcoming paper together with a new ^{13}N(α,p)^{16}O reaction rate and its astrophysical implication.

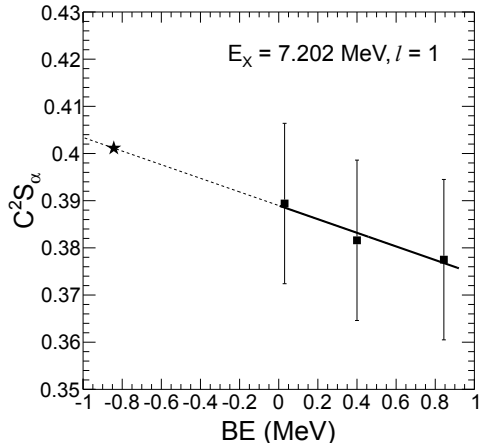

Figure 3. Determination of the α-spectroscopic factor for low transferred angular momentum (here the ^{17}O state at 7.202 MeV). DWBA calculations at several binding energies are performed, and the spectroscopic factors are extrapolated to the actual α-separation energy (filled star).

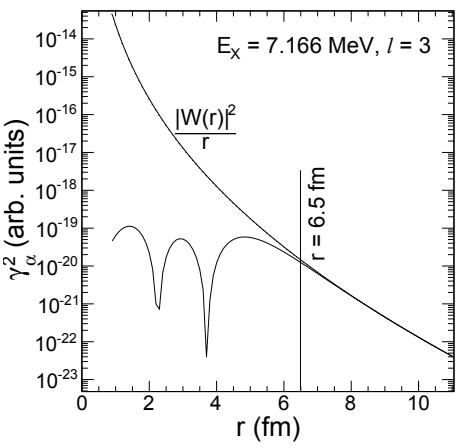

Figure 4. Alpha reduced width (γ_α^2) as a function of the interaction radius for the 7.166 MeV state in ^{17}O. The asymptotic behavior of γ_α^2 is given by ($|W(r)|^2/r$) where $W(r)$ represents the Whittaker function. The interaction radius is defined when both functions have the same radius dependance.

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