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The ^{9}Be(p,α)^{6}Li reaction in the context of light element problem in astrophysics

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Abstract. In the last twenty years particular interest was devoted to the study of light element lithium, beryllium and boron abundances. These elements can be seen as possible diagnostics between different scenarios in primordial or stellar nucleosynthesis. LiBeB are mainly destroyed via (p,α) reactions in both astrophysical environments and therefore precise measurements of their burning cross-sections are needed. In this brief paper a recent study of the ^{9}Be(p,α)^{6}Li via the Trojan Horse Method in the astrophysical energy range 0<E_{CM}<1 MeV is presented. Preliminary results are discussed and a comparison with direct data is shown.

In recent years the abundances of light elements lithium, beryllium and boron (LiBeB) have been increasingly used as diagnostics between different scenario for primordial or stellar nucleosynthesis. As reported in Boyd and Kajino (1989), beryllium primordial abundances can provide a powerful test to discriminate between homogeneous and inhomogeneous primordial nucleosynthesis. Moreover, as reported in Stephens et al. (1997), the study of beryllium abundances in young stars, together with lithium and boron, can provide a strong test for understanding stellar structure and discriminate between possible non-standard mixing processes in stellar interiors. In both stellar and primordial environments, however, LiBeB are mainly destroyed by proton-capture reactions via the (p,α) channel with a Gamow energy E_G ranging from ~10 keV (for stellar nucleosynthesis) to ~100 keV (for primordial nucleosynthesis). These energies are low if compared with the Coulomb barrier E_C, usually of the order of MeV's. Thus the reactions take place via tunnel effect with an exponential decrease of the cross section to nano or pico barn values. The behavior of the direct cross sections are usually extrapolated at astrophysical energies from that at higher energies by using the definition of the astrophysical factor

$$S(E) = E\sigma(E)exp(2\pi\eta) \quad (1)$$

Send offprint requests to: C. Spitaleri (where η is the Sommerfeld parameter) which varies smoothly with energy. To overcome the uncertainties due to the extrapolation at low energies (e.g. unexpected sub-threshold resonances or electron-screening effects (Rolfs 1988)) in recent years many indirect methods have been developed in order to extract the S(E)-factor. In particular the THM (Baur 1986; Spitaleri et al. 1999, 2004)) is a powerful tool which selects, under appropriate kinematical conditions, the quasi-free (QF) contribution of a suitable three-body reaction performed at energies well above the Coulomb barrier. The method allows to extract a charged particle two-body cross section at astrophysical energies, free of Coulomb suppression.

1. THM in experimental nuclear astrophysics

The aim of the present work was to extract the information about the ^{9}Be(p,α)^{6}Li reaction after selecting the QF contribution of ^{2}H(^{9}Be,^{6}Liα)n reaction. The beryllium is the projectile while the deuteron was used like "trojan horse target nucleus", having a p⊕n structure. By using the Impulse Approximation hypothesis the proton acts like participant while the neutron is the spectator to the virtual two-body reaction. If the beam energy is chosen high enough to overcome the Coulomb barrier in the entrance channel of the three-body reaction, both Coulomb barrier and electron screening effects are negligible in the two-body THM data. The astrophysical two-body reaction will be then induced at very low energy

$$E_{CM} = E_{Li-\alpha} - B_{p-n} \pm E_{p-n} \qquad (2)$$

where $E_{Li-\alpha}$ represents the beam energy in the center of mass of the two-body ^{6}Li-α system, B_{p-n} is the binding energy of the deuteron (p-n system) and E_{p-n} describes the intercluster motion of proton and neutron inside the deuteron. In the PWIA (Plane Wave Impulse Approximation) approach, the three-body reaction cross section is factorized as

$$\frac{d^3\sigma}{dE_{cm}d\Omega_{Li}d\Omega_{\alpha}} \propto KF \cdot |G(\boldsymbol{P}_s)|^2 \cdot \frac{d\sigma^N}{d\Omega} \qquad (3)$$

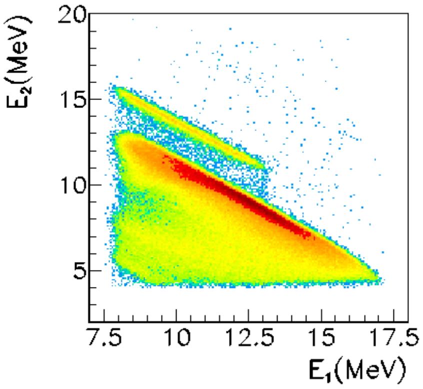

Fig. 1. Experimental kinematical locus for the three-body reaction ^{2}H(^{9}Be,^{6}Liα)n. The locus was obtained by selecting the lithium and alpha particles by usual ΔE-E procedure.

where KF is a kinematical factor, $|G(\boldsymbol{P}_s)|^2$ is the momentum distribution of the neutron inside the deuteron and $d\sigma^N/d\Omega$ is the nuclear differential cross section for the astrophysical two-body interaction ^{9}Be(p,α)^{6}Li. We stress that the extracted two-body cross-section is not affected by the penetrability through the Coulomb barrier. The correction for the penetration factor must be introduced and then, after normalization to direct data, it is possible to compare the THM set with the direct ones. More details about the theoretical description of the method can be found in Spitaleri et al. (1999, 2004) and references therein.

2. Data analysis: from the three-body to the two-body cross section

The experiment was performed at the LNS in Catania, by using a 22 MeV ^{9}Be beam on a CD_2 target. The detection of α and ^{6}Li particles was performed by using two standard ΔE-E telescopes with a PSD as E detector. These detectors were placed at opposite sides with respect to the beam direction in order to cover the whole QF-angular range. The first step in a THM analysis is to select the correct channel for the three-body reaction. After the energy and position calibration of the two PSD's in telescopes, Li and α particles were selected

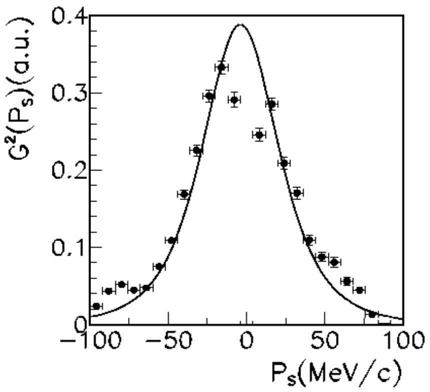

Fig. 2. Comparison between experimental (points) and theoretical Hulthen function (solid line) for the neutron momentum distribution. Error bars are due to the statistical error.

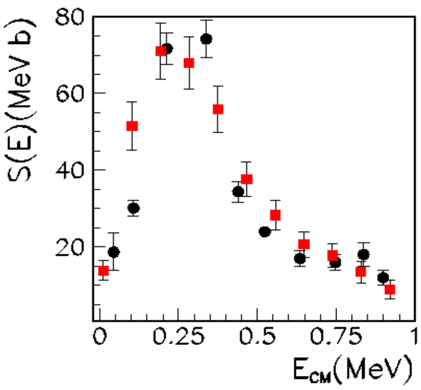

Fig. 3. Extracted astrophysical factor for ^{9}Be(p,α)^{6}Li (red points) compared with the direct one (black points, Sierk & Tombrello (1973)), both averaged out with the same bin of 90keV.

with the standard ΔE-E technique. With the assumption of mass number 1 for the *undetected* third particle, the kinematical locus of events (E_{Li}.vs.E_α) was reconstructed (Fig.1) in very good agreement with the simulation.

In order to investigate the presence of the QF mechanism on the three-body coincidence yield, a study of the momentum distribution $|G(\boldsymbol{P}_s)|^2$ of the neutron inside the deuteron was made and the result is showed in Fig.2. The good agreement between the experimental data and the theoretical Hulten wave function make us confident that in the chosen kinematical region its possible to select the QF contribution for the three-body reaction ^{2}H(^{9}Be,^{6}Liα)n and that no other mechanism are significant.

By selecting the condition $|P_s|$<25 MeV/c, the behavior of the S(E)-factor for the reaction studied here is showed in Fig.3. The resonance at E_{CM}=250keV, corresponding to the 6.87 MeV state of ^{10}B, is well reproduced with respect to the experimental errors. The result showed in this paper represents a further validity test of the THM in the energy windows of interest for astrophysics, i.e. well below the Coulomb barrier.

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