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Indirect Measurements for (p,α) Reactions Involving Boron Isotopes

L. Lamia*,†, C. Spitaleri*,†, S. Romano*,†, N. Carlin**, S. Cherubini*,†, V. Crucillà*,†, M.G. Del Szanto**, M. Gulino*,†, M. La Cognata*,†, R. Liguori Neto**, M.M. De Moura**, M.G. Munhoz**, R.G. Pizzone*,†, S.M.R. Puglia*,†, M.L. Sergi*,†, F.A. Souza**, A.A.P. Suaide**, E. Szanto**, A. Szanto de Toledo**, S. Tudisco*,† and A. Tumino*,†

*Laboratori Nazionali del Sud, Catania, Italy
†Dipartimento di Metodologie Fisiche e Chimiche per l'Ingegneria, Università di Catania, Catania, Italy
**Departamento de Fisica Nuclear, Universitade de São Paulo, São Paulo, Brasil

Abstract. Light elements lithium, beryllium and boron (LiBeB) were used in the last years as "possible probe" for a deeper understanding of some extra-mixing phenomena occurring in young Main-Sequence stars. They are mainly destroyed by (p,α) reactions and cross section measurements for such channels are then needed. The Trojan Horse Method (THM) allows one to extract the astrophysical S(E)-factor without the experience of tunneling through the Coulomb barrier. In this work a résumé of the recent results about the ^{11}B(p,α_0)^{8}Be and ^{10}B(p,α)^{7}Be reactions is shown.

Keywords: Nuclear Astrophycsics; Indirect Methods
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1. INTRODUCTION

Stellar structure and mixing mechanisms for low-mass Main-Sequence stars have been better understood in the last years thanks to the amount of work regarding the "depletion problem" of light elements lithium, beryllium and boron (LiBeB) [1]. Different authors ([1] and references therein) suggest that the study of LiBeB abundances in young F and G stars can give useful informations about different mixing processes presently not well known. In particular for such stars, the Standard Stellar Model does not take into account the possibility of "communication" between the convective zone and the nuclear destruction zone where the burning of such elements occurs mainly via (p,α) reactions induced at temperatures of about T_6 ~10. This means that the residual LiBeB abundances in such stars would have to reflect the abundances of the original interstellar gas [2]. In contrast, the observational evidence suggests that for F main sequence young stars there is a depletion of lithium and beryllium as the observations on Hyades, Praesepe (~600 My) and on other young clusters reveal, while there is not evidence of this depletion in F pre-main sequence stars according to the observations on Pleiades cluster (~70 My) [3]. The evidence of a Li-dip connected with a less pronounced Be-dip and the constancy of boron abundance as the stellar temperature varies together with the Li-Be and Be-B correlation are interpreted as a signature of non-standard mixing mechanisms acting inside these stars: in particular, *slow-mixing mechanisms* induced

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by stellar rotation seem to give the largest contribution for the description of the current observational status [4, 5].

Moreover these processes (and mixing mechanisms in general) transport the surface material into the regions where LiBeB are mainly destroyed via (p,α) reactions induced at a Gamow energy E_G of few keV's and then precise cross-section measurements focused in the astrophysically-relevant energy window are needed. Since both Coulomb barrier and electron screening effects make it difficult to directly determine the cross-section for charged-particle induced reactions in the energy domain relevant for astrophysics, the Trojan Horse Method (THM) provide an alternative way. It allows to extract the cross section for a charged-particle induced two body reaction by selecting the quasi-free (QF) contribution to a suitable three body reaction. Due to its theoretical apparatus the method allows to extract the information down to the astrophysical energies, overcoming the problem connected with both Coulomb barrier penetration and electron screening effects.

The present work reports on the recent investigations of the $^{11}B(p,\alpha)^{8}Be$ and $^{10}B(p,\alpha)^{7}Be$ reactions through the THM applied to the $^{2}H(^{11}B,\alpha^{8}Be)n$ and $^{2}H(^{10}B,\alpha^{7}Be)n$ three-body processes respectively. Both (p,α) reaction were then studied by using the deuteron (^{2}H) as "Trojan-Horse" nucleus: figuratively, this "nuclear Trojan Horse" brings directly the proton into the nuclear field of the boron isotopes inducing the (p,α) reactions on $^{11,10}B$ without those feel the presence of the Coulomb barrier "Troy's walls" effects.

2. THEORY OF THE THM

The main idea of the THM [6, 7] is to extract the cross section for the astrophysical reaction a+x→C+c through the selection of the QF contribution of a suitable three-body reaction a+A→C+c+s, being A the cluster structure A=x⊕s. A very intuitive theoretical description of such mechanisms can be given by using the *impulse approximation (IA)* [8]. In particular, in the framework of the Plane Wave Impulse Approximation (PWIA), the three-body cross section can be factorized into three different terms [9] by the relation:

$$\frac{d^3\sigma}{dE_c d\Omega_c d\Omega_C} \propto (KF) \mid \Phi(\overrightarrow{p_n}) \mid^2 \left(\frac{d\sigma}{d\Omega}\right)_{cm} \tag{1}$$

The term $\left(\frac{d\sigma}{d\Omega}\right)_{cm}$ is the differential two-body cross section induced at energy E_{cm} given in post-collision prescription by $E_{cm}=E_{ax}=E_{Cc}-Q_{2body}$. The variable E_{Cc} is the relative energy between the outgoing particles and Q_{2body} is the Q-value of the virtual two body reaction. If the energy of the incoming nucleus is chosen high enough to overcome the Coulomb barrier in the entrance channel of the three-body reaction, the decay of the "TH nucleus" *A* in its constituents *a* and *x* occurs in the nuclear field and both Coulomb barrier penetration and electron screening effects are negligible. Moreover, the effect of the binding energy of the cluster structure compensates for the energy of the incoming projectile, inducing the 2-body reaction even at energy relevant for astrophysics. Since the two-body interaction occurs without the effects of penetration through the Coulomb barrier, it is necessary to introduce an appropriate penetration function P_l in order to take into account these effects affecting the direct data below the Coulomb barrier. After the normalization to the direct data, the astrophysical S(E)-factor is extracted following the usual definition; however it is necessary to keep in mind that the TH S-factor is "bared" from the electron screening effects present in the direct data. The comparison between the indirect "bared" and the direct "shielded" data represents an independent experimental approach to extract the experimental value for the electron screening potential for the studied reaction (more details on the method can be found in [7, 11]).

3. THE $^{11}B(p,\alpha_0)^8Be$ REACTION STUDIED THROUGH THE THM

3.1. The Experiment and the Selection of the Three-Body Channel

The ^{2}H(^{11}B,α^8Be)n experiment was performed at the Laboratori Nazionali del Sud in Catania and as a first stage of our investigation only the ^{2}H(^{11}B,$\alpha_0{}^8$Be)n channel was investigated [12]. The SMP Tandem Van de Graaf accelerator provided a 27 MeV ^{11}B beam with a spot size on target of about 1.5 mm and intensities up to 2-3 nA. Deuterated polyethylene targets (CD_2) of about 170 μg/cm^2 were placed at 90° with respect to the beam direction. The detection set up consisted of a Dual Position Sensitive Detector (DPSD), made of two 50x10 mm^2 silicon detectors mounted one above the other and separated by 1 mm, and three 50x10 mm^2 standard Position Sensitive Detectors (PSD1, PSD2 and PSD3).
Due to its instability against α-decay, the ground state of ^{8}Be was selected by reconstructing the relative energies between two-alpha particles hitting in coincidence the upper and lower part of the DPSD. The trigger for the event acquisition was given by the triple coincidences between the upper and lower part of the DPSD and one of the three PSD's. This allowed for the kinematic identification of ^{8}Be in the DPSD and its coincident detection with an α particle.
After the calibration of the involved detectors, the first step of a typical "TH analysis" is to discriminate the channel of the three-body reaction of interest from the ones induced, in this case, by the interaction of ^{11}B on CD_2. Under the hypothesis that the third *undetected particle* had mass number 1, all the variables of interest were further calculated. In particular, by means of the energy conservation law, the Q-value spectrum for the selected events was also reconstructed and reported in Fig. 1. The presence of a well separated peak around 6.4 MeV must be compared with the theoretical Q-value of 6.36 MeV for the ^{2}H(^{11}B,$\alpha_0{}^8$Be)n reaction. The agreement, within the experimental uncertainties, is a signature of our good calibration and a precise selection of the three-body channel.

3.2. Selection of the Quasi Free Mechanism

As we mentioned above, the basic idea of the method is to extract the two-body cross section of interest for astrophysics by selecting properly the Quasi-Free (QF)

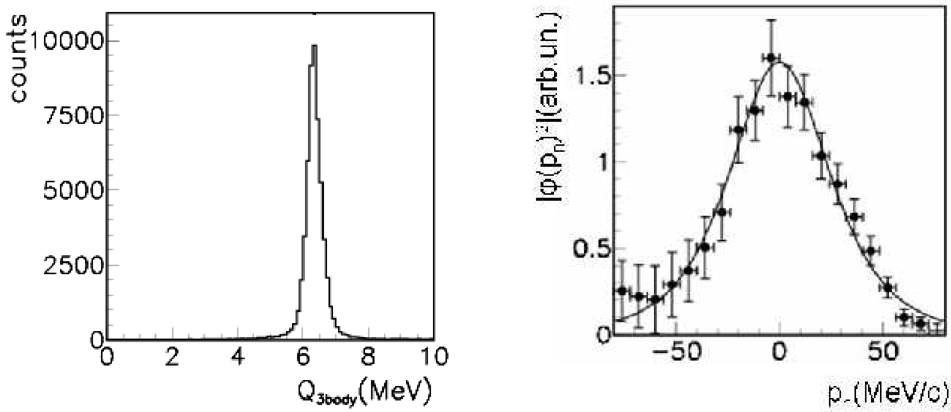

FIGURE 1. Experimental Q-value (left panel) and momentum distribution (right panel) for the ^{2}H(^{11}B,α^{8}Be)n reaction.

contribution on the three-body data: only after this strict selection we can move from the ^{2}H(^{11}B,α^{8}Be)n reaction to the astrophysically relevant ^{11}B(p,α_0)^{8}Be one. However, since in the THM approach one works with a three-body channel, it is expected that the same particles of interest (α, ^{8}Be, n) could come from the so called Sequential Mechanism (SM), possible formations/de-excitation of intermediate compound nucleus state. In order to evaluate the contribution of such "competing" mechanisms, the relative energies between the outgoing particles were then reconstructed. In particular the study of the $E_{\alpha Be}$, $E_{\alpha n}$ and E_{Ben} relative energies allows to obtain information on the presence of excited states of ^{12}C, ^{5}He and ^{9}Be respectively. From such analysis different states of ^{12}C were recognized; in particular the 16.106 MeV (J^{π}=2^{+}) one corresponds to a l=1 resonance in the ^{11}B-p system at E_{cm}=150 keV and then its contribution to the total S(E)-factor must be carefully evaluated. Moreover, different contribution come from the 1.68 MeV, 2.43 MeV and 3.30 MeV levels of ^{9}Be right in the energy region of interest for astrophysics. These events represent a "noise" for the THM and a careful determination of their contribution on the total yield is necessary. After this study, we can proceed with the further steps of the analysis and, in particular, with the selection of the events coming from the QF-mechanism.

The QF-mechanism is connected with the behavior of the undetected third particle in the exit channel. A necessary check is performed by studying the experimental momentum distribution of the neutron in the exit channel. In the "quasi-free" hypothesis, the neutron should maintain in the exit channel the same impulse distribution for the p-n relative motion inside the deuteron that it had before interaction with the impinging particle. Selecting then a small energy region where the two-body cross section can be assumed almost constant, the three-body coincidence yield (Eq.1) correct for the phase-space factor will be proportional to the momentum distribution. The experimental result is shown in Fig.1, where the coincidence yield for the events in the energy window E_{cm}=0.15±0.05 MeV correct for the phase-space factor is reported. The good agreement between the experimental data and the theoretical Hulthèn function for the p-n motion inside the deuteron represents a further experimental evidence that the neutron acted as a "spectator" during the break-up occurred in the ^{2}H(^{11}B,α^{8}Be)n reaction.

4. THE $^{10}B(p,\alpha)^{8}Be$ REACTION STUDIED THROUGH THE THM

4.1. The Experiment and the Selection of the Three-Body Channel

The ^{2}H(^{10}B,α^{7}Be)n experiment was performed at the Pelletron-Linac laboratory (Departamento de Fisica Nuclear (DFN)) in São Paolo (Brazil) and more details about can be found in [13]. The Tandem Van de Graaf accelerator provided a 27 MeV ^{10}B beam with a spot size on target of about 2 mm and intensities up 1 nA. A deuterated polyethylene target (CD_2) of about 192 μg/cm^2 was placed at 90° with respect to the beam axis direction. The detection setup consisted of a 1000 μm PSD detector (PSD1) and a "telescope" system, having a proportional counter (PC) as ΔE and an E-detector made of a standard 500 μm PSD detector (PSD2). In order to evaluate the contribution of the ^{2}H(^{10}B,α^{7}Be)n reaction, a selection of the ^{7}Be particles was made by using the standard ΔE-E technique while no identification was used for α particles on PSD2. After particle identification and under the assumption of mass number 1 for the undetected third particle, the Q-value was calculated. The selected events correspond to the experimental Q-value spectrum (Fig.2) centered at about $Q_{exp}\sim$-1 MeV, according to the expected theoretical value (Q_{theor}=-1.08 MeV). Events within this peak were then selected as belonging to the ^{2}H(^{10}B,α^{7}Be)n and used for the further analysis.

4.2. Selection of the Quasi Free Mechanism

As before, the presence of the QF-mechanism has to be evaluated also. A necessary check is performed by studying the experimental momentum distribution of the neutron in the exit channel. A small energy region where the two-body cross section can be assumed almost constant was then selected and the three-body coincidence yield (Eq.1) correct for the phase-space factor. This quantity will be proportional to the momentum distribution. The experimental result is shown in Fig.2, where the coincidence yield for the events in the energy window $E_{\alpha Be}$=1.15±0.05 MeV corrected for the phase-space factor is reported. The good agreement between the experimental data an the theoretical Hulthèn function for the p-n motion inside the deuteron represents a further experimental evidence that the neutron acted as a "spectator" during the break-up occurred in the ^{2}H(^{10}B,α^{7}Be)n reaction. After these experimental evidence and the further check shown in [12], we can conclude that the QF-mechanism is present in the energy region relevant for the astrophysics.

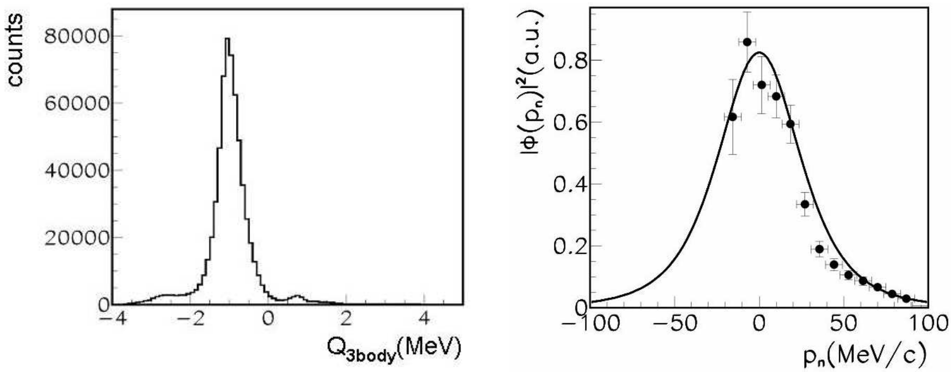

FIGURE 2. Experimental Q-value (left panel) and momentum distribution (right panel) for the $^{2}H(^{11}B,\alpha^{8}Be)n$ reaction.

5. RESULTS AND DISCUSSION

5.1. S(E)-Factor for the $^{11}B(p,\alpha_0)^{8}Be$ and the $^{10}B(p,\alpha)^{7}Be$ Reaction

After the selection of the QF-mechanism on the three-body $^{2}H(^{11}B,\alpha_0{}^{8}Be)n$ channel and using the PWIA approach (Eq.1), it was possible to extract the nuclear part of the two body $^{11}B(p,\alpha)^{8}Be$ cross section in the energy range $0<E_{cm}<1000$ keV. In particular events corresponding to $|p_n|<40$ MeV/c condition were selected, being the kinematical region where the QF-mechanism is dominant. Moreover, due to the different energy resolution of the involved detectors, in this recent analysis only data coming from the pair DPSD-PSD2 were further selected, showing an energy resolution of about 40 keV. The bare-nucleus S(E)-factor was then extracted following the usual definition [10]. For the normalization to the available direct data [14] the relative weights between the resonant (l=1) and the non-resonant (l=0) contributions, known from the direct measurements, were taken into account. The preliminary result for this new-approach is shown on the left side of Fig.3 where both data set, direct and indirect ones, are reported with the same energy resolution ($\sim$20 keV). The reaction mainly proceeds through the formation of the 16.106 MeV ($J^{\pi}=2^{+}$) level of ^{12}C, representing a l=1 resonance in the ^{11}B-p channel; a good agreement is clearly evident in the whole energy range and, in particular, around the resonant state at about E_{cm}=150 keV. A preliminary evaluation on these data gives a value of S(0)=1.98$\pm$0.31 (MeV b).

Following the same steps of the previous case, it was possible to extract the S(E)-factor for the $^{10}B(p,\alpha)^{7}Be$ reaction. The preliminary experimental data (points) are shown in the right panel of Fig.3. The histogram reproduces above $E_{cm}\sim$30 keV the behavior of direct data smeared out at the same energy resolution (about 45 keV) while, below this value, the same histogram reports the extrapolation of the bare-nucleus S(E)-factor [15]. The increase of the S(E)-factor down to 300 keV is mainly due to the contribution of

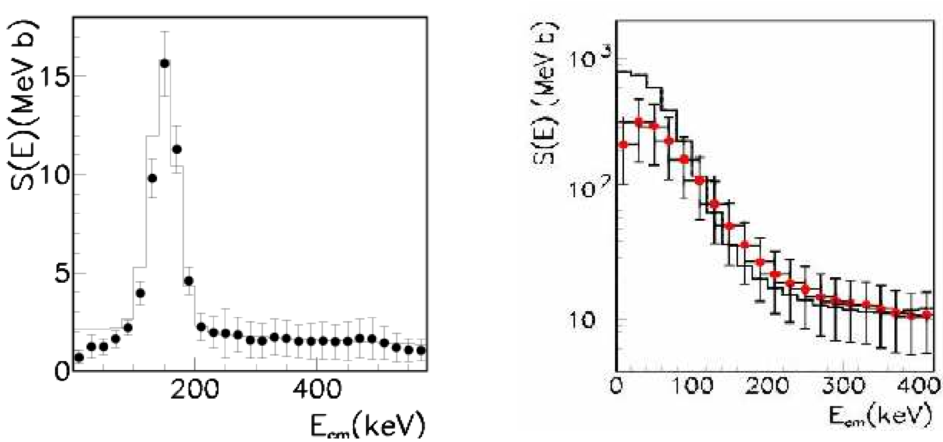

FIGURE 3. Astrophysical S(E)-factor for the $^{11}B(p,\alpha_0)^8Be$ (left panel) and the $^{10}B(p,\alpha)^7Be$ (right panel) reaction. The indirect TH-data are reported as points while the available direct data as histogram.

the 8.701 MeV level of ^{11}C (J^{π}=5/2$^+$), that represents a l=0 resonant state in the ^{10}B-p channel. The FWHM obtained for the resonance was about 110 keV, while independent measurements of such level report a value of about 16 keV ([15] and ref. ther.). Due to the poor resolution, it is not possible to extract any information about the value of the astrophysical S(0)-factor or about the electron screening potential. However, this first approach to the study of the present reaction confirms the power of the THM to reach the ultra-low energy values. This is an important feature of the method, since its application allows to study the resonant contribution even in the energy region, usually reached through the extrapolations, where both Coulomb penetration and electron screening effects are dominant.

In conclusion, the main channels for the boron destruction in the energy range relevant for astrophysics have been studied by means of the Trojan Horse Method. The (p,α) reactions involving boron isotopes show a clear contribution of resonant levels. These are well reproduced by the present indirect investigation, confirming that the Trojan Horse is a powerful "tool" for the investigation of reactions relevant for astrophysics. However, both set of data are still under investigation and, in particular, the analysis of new experimental data available from two different experiments recently performed at LNS of Catania is presently being undertaken.

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