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Indirect study of (p,α) and (n,α) reactions induced on boron isotopes

L. Lamia(1)(2), C. Spitaleri(1)(2), N. Carlin(3), S. Cherubini(1)(2), M. G. Del Szanto(3), M. Gulino(1)(2), M. La Cognata(1)(2), M. G. Munhoz(3), R. G. Pizzone(1)(2), S. M. R. Puglia(1)(2), G. G. Rapisarda(1)(2), S. Romano(1)(2), M. L. Sergi(1)(2), A. Szanto de Toledo(3), S. Tudisco(1)(2) and A. Tumino(1)(2)(*)

(1) *INFN, Laboratori Nazionali del Sud - Catania, Italy*
(2) *Dipartimento di Metodologie Fisiche e Chimiche, Università di Catania - Catania, Italy*
(3) *Departamento de Fisica Nuclear, Universitade de Sao Paulo - Sao Paulo, Brasil*

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Summary. — Several experiments were performed to investigate both (p,α) and (n,α) reactions induced on boron isotopes, by means of Quasi-Free (QF) reactions induced on deuteron target. The experimental study of the astrophysically relevant $^{11}\mathrm{B}(\mathrm{p},\alpha_0)^8\mathrm{Be}$ reaction was performed by selecting the QF-contribution on the $^2\mathrm{H}(^{11}\mathrm{B},\alpha_0{}^8\mathrm{Be})\mathrm{n}$ reaction. Moreover, due to the large interest of a better understanding of (n,α) reactions both for nuclear and astrophysical developments, a preliminary study of the $^{10}\mathrm{B}(\mathrm{n},\alpha)^7\mathrm{Li}$ through the QF $^2\mathrm{H}(^{10}\mathrm{B},\alpha^7\mathrm{Li})\mathrm{p}$ reaction was also performed. The results concerning the two experiments will be shown and discussed.

PACS `24.50.+g` – Direct reactions.
PACS `25.45.-z` – ^{2}H-induced reactions.
PACS `25.45.Hi` – Transfer reactions.

1. – Introduction

The application of the Quasi-Free (QF) break-up mechanisms in the past was mostly connected to an extensive study of nuclear structure [1-4]. Basically, these mechanisms are direct processes in which the interaction between an impinging nucleus and the target can cause the *break-up* of the target (TBU) or, that is the same, of the projectile (PBU). In particular, the so-called QF are processes having three particles in the exit channel one of which can be thought as "spectator". Sketching for simplicity a TBU process, the picture is that of an interaction between the impinging nucleus and fraction of the

(*) Present address: Università Kore, Enna, Italy.

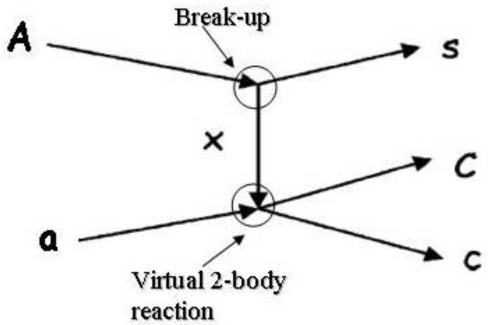

Fig. 1. – Pole diagram describing the quasi-free (QF) mechanism, discussed in the text.

nucleons forming the target (called "participants"), while the other counterpart does not participate to the reaction. The spectator in this picture will be then "free" from any effect due to the interaction between the incoming nucleus and the participants [5].

The analysis of the QF reactions is usually performed in the framework of the Impulse Approximation (IA) [6], for which, by assuming the cluster $A = x \oplus s$ configuration, the QF $A + a \rightarrow c + C + s$ process can be described through the pseudo-Feynman diagram shown in fig. 1, where only the first term of the Feynman series is retained. The upper pole refers to the target nucleus break-up into its constituents, while the lower pole to the virtual two-body reaction $a + x \rightarrow c + C$ leaving s as spectator. This approach allows then to factorize the three-body cross-section as [1, 2]

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}E_c \mathrm{d}\Omega_c \mathrm{d}\Omega_C} \propto KF|\Phi(\vec{p_s})|^2 \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)\Bigg|_{a\text{-}x}, \tag{1}$$

where KF is a kinematical factor containing the final state phase-space factor and it is a function of the masses, momenta and angles of the outgoing particles [1], $\Phi(\vec{p_s})$ is essentially the Fourier transform of the radial wave function for the x-s inter-cluster motion inside A, usually described in terms of Hänkel, Eckart or Hulthén functions depending on the cluster configuration involved in the reaction [3], $(\mathrm{d}\sigma/\mathrm{d}\Omega)_{a\text{-}x}$ is the off-energy-shell a-x cross-section [1, 2]. Further, the $a + x \rightarrow c + C$ reaction is then induced at energy E_{cm}, given in post-collision prescription by $E_{\mathrm{cm}} = E_{cC} - Q_{2\mathrm{body}}$, E_{cC} being the relative energy between the two detected-outgoing particles and $Q_{2\mathrm{body}}$ the Q-value of the two-body process. If the behavior of the momentum distribution is known from independent experiments and the kinematical factor is known, it is possible to *extract* the two-body reaction cross-section from a *measurement* of the three-body coincidence yield by inverting eq. (1).

This approach was successfully used in these years to evaluate the cluster structure properties of several nuclei, such as ^{2}H, ^{3}He, ^{6,7}Li and ^{9}Be [1-4]. In particular, due to its $\mathrm{p} \oplus \mathrm{n}$ cluster structure and a well-known radial wave function for the p-n relative motion ([7] and references therein), deuteron was largely used to investigate QF break-up reactions having neutron or proton as spectator in the exit channel allowing to extend the QF studies to that of proton-induced or neutron-induced reactions. Following, the results concerning $^2\mathrm{H}(^{11}\mathrm{B}, \alpha_0{}^8\mathrm{Be})\mathrm{n}$ and $^2\mathrm{H}(^{10}\mathrm{B}, \alpha^7\mathrm{Li})\mathrm{p}$ reactions will be shown.

2. – Deuteron as source of virtual protons: indirect study of ^{11}B(p, α)^{8}Be reaction

Recently, the QF mechanisms have been applied in the framework of the Trojan Horse Method (THM), an indirect technique mainly aimed to overcome the experimental difficulties typical of direct cross-section measurements for charged particles reactions induced at low energies ($\sim$ keV's). Due to the Coulomb barrier between the interacting nuclei, the study of an astrophysically relevant reaction at stellar energies is hindered by the low values of their cross-section, exponentially decreasing to nano or picobarn. In addition, the electron screening effect [8,9], triggered by the electronic cloud surrounding the interacting ions, prevents one to measure the bare nucleus cross-section, which is necessary for the astrophysical application.

The main idea of the THM is to extract the cross-section for the astrophysical reaction $a + x \to C + c$ through the selection of the QF contribution of a suitable three-body reaction $a + A \to C + c + s$, A being the "TH-nucleus" $A = x \oplus s$. This allows then to by-pass the "extrapolations" procedures, up to 80's believed as the only way to extract ultralow-energies cross-sections [10-13]. 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. Figuratively, this "nuclear Trojan Horse" brings directly the proton into the nuclear field of the incoming a nucleus without the presence of the Coulomb barrier "Troys walls" effects. 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 [14], it is necessary to introduce an appropriate penetration function P_l [15] 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 "bare" and the direct "shield" data represents an independent experimental approach to extract the experimental value for the electron screening potential for the studied reaction.

2·1. *Selection of the quasi-free contribution.* – The ^{2}H(^{11}B, α^{8}Be)n reaction was studied through an experiment performed at the Laboratori Nazionali del Sud in Catania by using a ^{11}B 27 MeV beam impinging on a CD_2 target, in order to extract the astrophysical S-factor for the ^{11}B(p, α)^{8}Be reaction, the latter being defined as

$$S(E) = E\sigma(E)\exp[2\pi\eta], \quad (2)$$

where the term $\exp[2\pi\eta]$ was historically introduced to remove the dominant energy dependence of $\sigma(E)$ due to the barrier penetrability [8]. In particular, due to the ^{8}Be instability against α decay, this reaction has been studied from previous works both evaluating the α_0 contribution, related to those events coming from the ^{8}Be ground-state decay, and the α_1 contribution, related to the 3.03 MeV ^{8}Be decay. As first stage of our approach to its study, we performed a first experiment aimed to the α_0 evaluation, while the second one was recently focused on the α_1 investigation. Up to now only the α_0 contribution was carefully evaluated and here the recent results concerning such

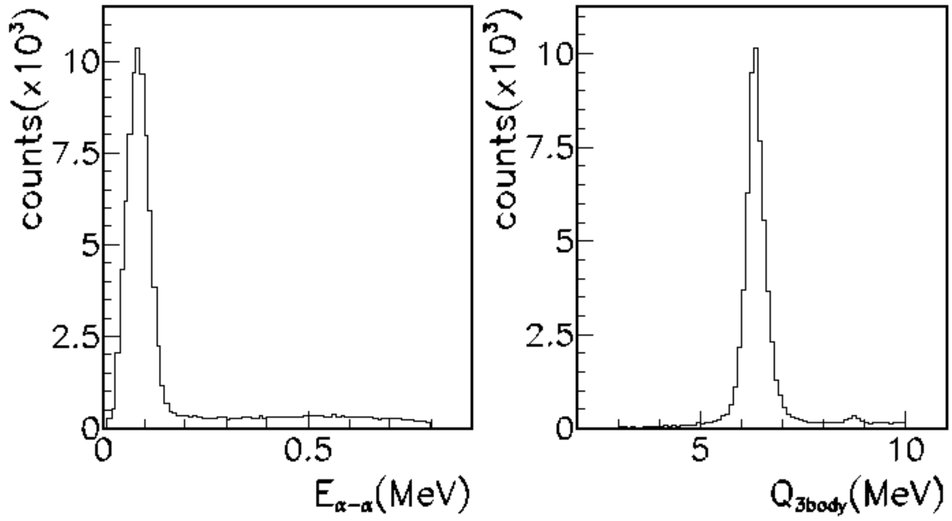

Fig. 2. – Left panel: relative α-α energy between two events in coincidence on the DPSD detectors. The pronounced peak around 90 keV is a signature of their decay for the ^{8}Be ground state. Right panel: experimental Q-value for the ^{2}H(^{11}B, $\alpha_0{}^{8}$Be)n reaction peaked at 6.4 MeV, in agreement with the 6.36 MeV expected from theoretical calculations.

experiment will be shown. The adopted detection set-up was thought in order to detect the α's coming from the ^{8}Be$_{\rm g.s.}$ decay through two-Position Sensitive Silicon Detectors (DPSD) mounted one-above-other, with the purpose of an off-line reconstruction of their relative energy. Other 3 PSDs, placed on opposite side with respect to the beam line, were further used to detect the product α-particles of the three-body reaction of interest, allowing to know their emission angles and energies. Moreover, the angular position of such detection system was chosen in order to cover as much as possible the *QF-angular region*, *i.e.* the angular region where a strong contribution of the events related to low-momentum values of the *undetected* neutron is expected [16]. 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 PSDs. 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 the analysis was the off-line reconstruction of the relative energy for two events hitting in coincidence upper and lower part of the DPSD system: by knowing both angles and energies of those events, their relative energy was reconstructed and shown in fig. 2. The peak around 90 keV's allows a strong experimental selection of ^{8}Be events, for which both angles and energies were reconstructed. By means of momentum and energy conservation rules, the $Q_{\rm 3body}$ for the ^{2}H(^{11}B, $\alpha_0{}^{8}$Be)n was reconstructed (fig. 2 right panel): the good agreement with the theoretical 6.4 MeV value is a signature of the goodness of our calibrations and allows us to progress further in the analysis, with particular regard to the investigation on the reaction mechanisms producing the outgoing α, ^{8}Be, and n particles.

The production of such particles could in fact come from both QF or Sequential Mechanims (SM), *i.e.* possible formation/de-excitation of intermediate compound nucleus states. In order to evaluate the contribution of such "competing" SM, the relative

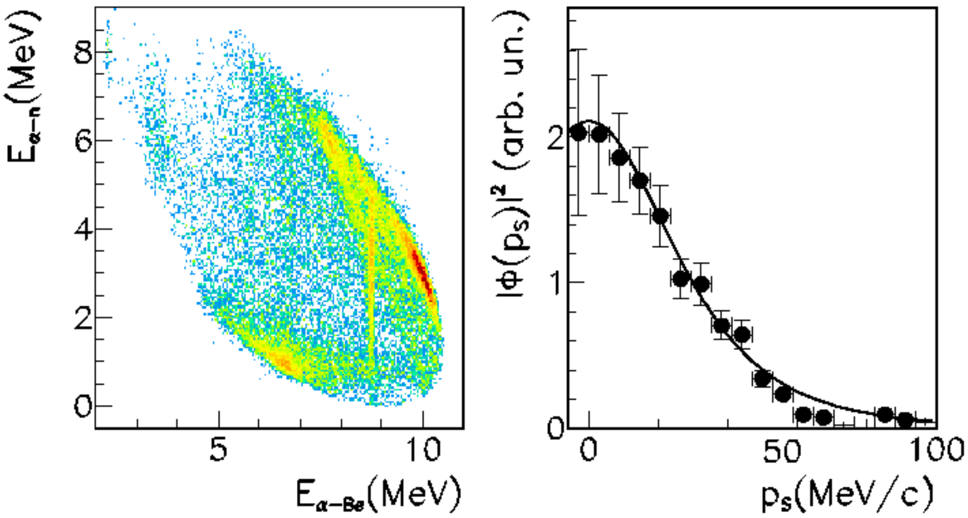

Fig. 3. – Left panel: relative energy two-dimensional plot. On y-axis the relative $E_{\alpha\mathrm{n}}$ energy is shown as the relative $E_{\alpha\mathrm{Be}}$ energy varies. The intense vertical locus belongs to the events coming from the ^{12}C 16.106 MeV excited state, while oblique ones come from ^{9}Be sequential decays. Right panel: experimental momentum distribution (black points) superimposed on the theoretical Hulthén one (full line).

energies between the outgoing particles were then reconstructed. In particular the study of the $E_{\alpha\mathrm{Be}}$, $E_{\alpha\mathrm{n}}$, 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 the analysis of the typical two-dimensional plot (left panel in fig. 3), different states of ^{12}C were recognized; in particular the 16.106 MeV ($J^\pi = 2^+$) one corresponds to a $l = 1$ resonance in the ^{11}B-p system at $E_{\mathrm{cm}} = 148$ keV and then its contribution to the total S-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 (oblique loci in left panel of fig. 3) 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 momenta distribution of the undetected third particle in the exit channel, making of great importance a detailed study of such quantity as a necessary check to progress in our analysis. 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. Indeed, the 0.3 fm de Broglie wavelength associated with the ^{11}B beam has to be compared with the deuteron effective radius of ~ 4.5 fm, fulfilling the present IA approach.

After selecting then a small energy region where the two-body cross-section can be assumed almost constant, the three-body coincidence yield for the neutron momentum p_{n} corrected for the phase-space factor will be proportional to the $\Phi(\vec{p_{\mathrm{n}}})$ momentum distribution, by using relation (1). The experimental result is shown in fig. 3 (right panel), where the coincidence yield for the events in the energy window $E_{\mathrm{cm}} = 0.15 \pm 0.05$ MeV correct for the phase-space factor is reported. The good agreement between

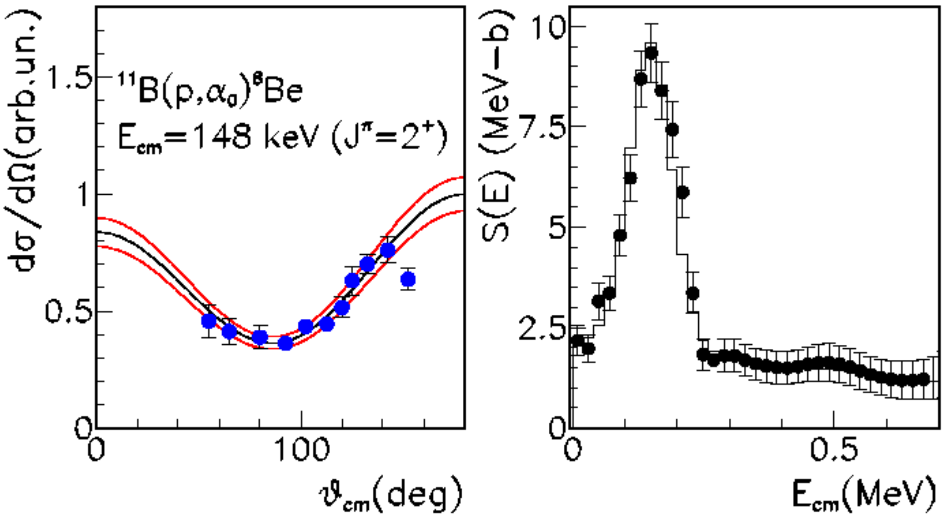

Fig. 4. – Left panel: experimental angular distributions for the 148 keV level in the ^{11}B-p center-of-mass rest frame (points) superimposed on the fit of the available direct data. Right panel: indirect $S(E)$-factor (black points) superimposed on the direct data smeared-out (histogram) for the present resolution of ~ 40 keV.

the experimental data and the theoretical Hulthén function for the p-n motion inside the deuteron represents the experimental evidence that the neutron acted as a "spectator" during the break-up occurred in the ^{2}H(^{11}B, $\alpha_0{}^8$Be) reaction.

2˙2. *Study of the two-body reaction: angular distributions and S-factor.* – In order to select the region where the QF is dominant, coincidence events in the momentum region $|p_{\rm n}| < 30\,{\rm MeV}/c$ were selected for the further analysis. Following the factorization (1), it was possible to extract the two-body ^{11}B(p, α_0)^{8}Be cross-section. First of all, indirect angular distributions were extracted an then compared with the available direct ones [17], where the $\theta_{\rm cm}$ angle was calculated by using the formula in [1, 2]. In particular fig. 4 shows the angular distributions of the 148 keV resonant state, that represent in this case an $l = 1$ resonance in the ^{11}B-p system. These distributions were obtained by fitting the excitation function for different ranges in $\theta_{\rm cm}$; once that the resonant contribution was known for each spectrum, we report each integral as a function of $\theta_{\rm cm}$. The indirect angular distributions (points) were compared with the direct ones (solid line) of [17] and the good agreement represents a fundamental validity test for the indirect exploration of the reaction. The bare-nucleus S-factor was then extracted by means of eq. (2). For the normalization to the available direct data [17], the relative weights between the resonant ($l = 1$) and the non-resonant ($l = 0$) contributions, known from the direct measurements, were taken into account following the same procedure adopted in [18]. The preliminary result for this new-approach is shown in fig. 4 where both data sets, direct and indirect ones, are reported by taking into account the present uncertainties. The errors bars are mainly due to the statistics, while the error for the normalization procedure was evaluated at about 5%. 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 $E_{\rm cm} = 150\,\text{keV}$. A preliminary evaluation on these data leads to the value of $S(0) = 2.2 \pm 0.3$ (MeV b).

3. – Deuteron as source of virtual neutrons: indirect study of $^{10}\text{B}(\text{n},\alpha)^7\text{Li}$ reaction

A further extension of the QF-mechanisms induced on deuterium concerns the study of neutron-induced reactions: in a very intuitive way and referring again to fig. 1, the picture is the same as before but in this case the proton will act as "spectator" while the neutron is the "participant" of the two-body process. A first application of such idea was the study of the $^6\text{Li}(\text{n},\alpha)^3\text{H}$ through the $^2\text{H}(^6\text{Li},{}^3\text{H}\alpha)\text{p}$, confirming the presence of the $E_{\rm cm} = 200\,\text{keV}$ resonance in agreement with the available direct data [19, 20]. In the present work, the preliminary study of the $^2\text{H}(^{10}\text{B},{}^7\text{Li}\alpha)\text{p}$ is reported. An extension of such results is the preliminary investigation of the $^{10}\text{B}(\text{n},\alpha)^7\text{Li}$ which, together with the $^6\text{Li}(\text{n},\alpha)^3\text{H}$, represents one of the most important neutron-induced reactions mainly because of their importance in neutron flux detection or shielding.

The indirect study of the $^{10}\text{B}(\text{n},\alpha)^7\text{Li}$ reaction was achieved through the $^2\text{H}(^{10}\text{B}, \alpha^7\text{Li})\text{n}$ experiment, performed at the Pelletron-Linac laboratory (Departamento de Fisica Nuclear (DFN)) in São Paolo (Brazil) and more details about the experimental set-up can be found in [21]. Shortly, a 27 MeV ^{10}B beam, with intensity of about 1 nA, impinges on $\sim 200\,\mu\text{g}$ thick CD_2 target, placed at 90° with respect the beam line direction. The experimental set-up consisted of a $1000\,\mu\text{m}$ PSD detector and one *telescope* system ΔE-E, having a proportional counter (PC) as ΔE stadium and a further $500\,\mu\text{m}$ thick PSD detector as E stadium. The telescope was placed at the angle $14° \pm 6°$, with the main aim of lithium-detection. The other PSD was placed on the opposite side with respect to the beam direction, covering the laboratory angles $16° \pm 8°$. Such angles were chosen in order to cover the whole QF-angular range, according to the usual experimental approach of the method. Standard electronics was used to filter and shape the signals; the trigger for the acquisition was made by selecting the coincidences between the *telescope* and the other PSD. Angular and energy calibration were performed by using a ^{6}Li beam, impinging on ^{12}C as well as ^{197}Au; moreover a standard 3-peaks α-source was used as additional low-energy calibration point.

3·1. *From the* $^2\text{H}(^{10}\text{B},\alpha^7\text{Li})\text{p}$ *to the* $^{10}\text{B}(\text{n},\alpha)^7\text{Li}$. – By selecting in charge the lithium among the ΔE-E loci, the events corresponding to the $^2\text{H}(^{10}\text{B},\alpha^7\text{Li})\text{p}$ reaction channel were recognized by applying the energy conservation between the detected α and lithium particles and the *reconstructed* energy of the undetected neutron. The experimental Q-value shown in fig. 5 (left panel) strongly confirms the goodness of the adopted calibration as well as the selection of the exit reaction channel. Moreover, the right panel of the same fig. 5 shows the kinematical locus, *i.e.* the energy plot between the two detected outgoing particles. Such locus was then compared with previous simulations, giving a further experimental evidence of the correct reaction channel selection.

A variable that turns out to be more sensitive to the reaction process is the experimental momentum distribution, describing the behavior of the neutron momenta in the exit channel. In order to have the quasi-free mechanism, one of the essential hypotheses is that such distribution should keep in the exit channel the same shape it had before the deuteron break-up, induced by the impinging ^{10}B beam. The experimental result is shown in fig. 6 (left panel), where the coincidence yields for the events within

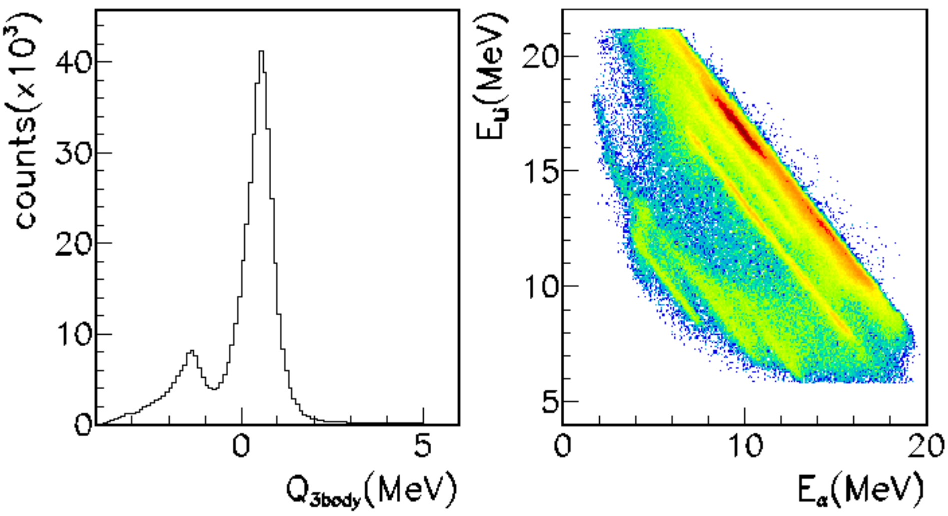

Fig. 5. – Left panel: experimental Q-value spectrum for the ^{2}H(^{10}B, α^{7}Li)p reaction. The peak at 0.56 MeV is in good agreement with the theoretical 0.565 MeV one. Right panel: kinematical locus for the ^{2}H(^{10}B, α^{7}Li)p reaction, with a beam energy of 27 MeV.

$E_{\alpha\mathrm{Li}} = 2.83 \pm 0.05$ MeV corrected for the phase-space factor are reported. The good agreement between the experimental data and the theoretical Hulthén function for the p-n motion inside the deuteron represents further experimental evidence that the proton acted as a "spectator" during the break-up occurred in the ^{2}H(^{10}B, α^{7}Li)p reaction.

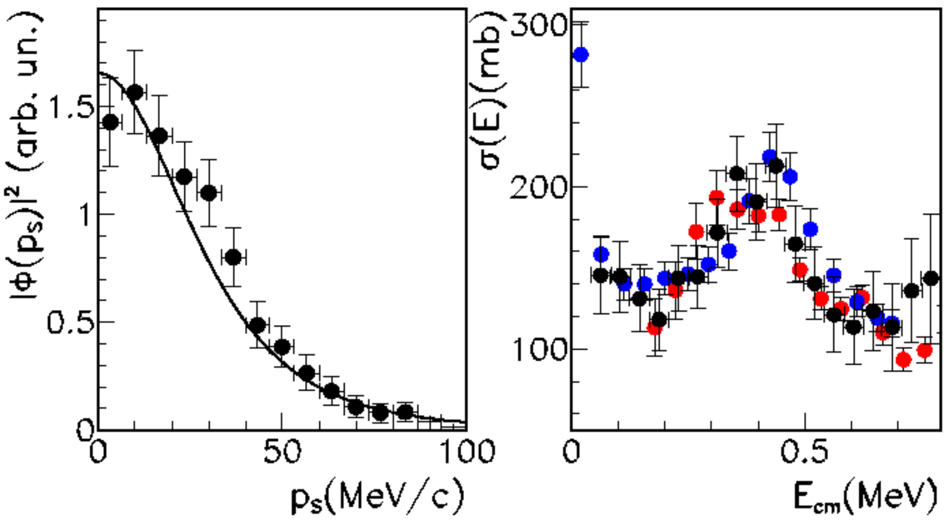

Fig. 6. – Left panel: experimental momentum distribution for the *undetected* proton (black points) superimposed on the theoretical Hulthèn function. The good agreement strongly confirms the presence of a QF-mechanism. Right panel: indirect cross-section for the ^{10}B(n, α)^{7}Li reaction (black points) normalized to the direct data in [22, 23].

By selecting the events within $|p_p| < 10\,\mathrm{MeV}/c$ for wich the QF-kinematical conditions are fulfilled and following the PWIA, the cross-section for the two-body $^{10}\mathrm{B}(\mathrm{n}, \alpha)^7\mathrm{Li}$ reaction was then extracted. The preliminary result showed in right panel of fig. 6 shows up an agreement with the available direct data [22, 23], with a possible contribution of the 11.89 MeV of ^{11}B. We have here in any case to stress that in this first approach, due to the present energy resolution, we cannot distinguish the contribution coming from the α_0 or the α_1 channel and a more detailed analysis is still needed.

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