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# Trojan Horse Method: recent results in nuclear astrophysics

C Spitaleri<sup>1,2</sup>, L Lamia<sup>1,2</sup>, M Gimenez Del Santo<sup>3</sup>, V Burjan<sup>4</sup>, N Carlin<sup>3</sup>, Chengbo Li<sup>5</sup>, S Cherubini<sup>1,2</sup>, V Crucilla<sup>2</sup>, M Gulino<sup>1,2</sup>, Z Hons<sup>4</sup>, V Kroha<sup>4</sup>, B Irgaziev<sup>6</sup>, M La Cognata<sup>2</sup>, J Mrazek<sup>4</sup>, M Mukhamedzhanov<sup>8</sup>, M G Munhoz<sup>3</sup>, S Palmerini<sup>2</sup>, R G Pizzone<sup>2</sup>. M R Puglia<sup>2</sup>, G G Rapisarda<sup>1,2</sup>, S Romano<sup>1,2</sup>, L Sergi<sup>2</sup>, Shu-Hua Zhou<sup>7</sup>, E Somorjai<sup>9</sup>, F A Souza<sup>3</sup>, G Tabacaru<sup>8</sup>, A Szanto de Toledo<sup>3</sup>, A Tumino<sup>2,10</sup>, Qungang Wen<sup>11</sup>, Y Wakabayashi <sup>12</sup> and H Yamaguchi<sup>12</sup> <sup>1</sup> Dipartimento di Fisica e Astronomia, Università di Catania, Catania, Italy <sup>2</sup> INFN, Laboratori Nazionali del Sud, Catania, Italy <sup>3</sup>Departamento de Fisica Nuclear, Universitade de Sao Paulo, Sao Paulo, Brasil <sup>4</sup>Nuclear Physics Institute of ASCR, Rez, Czech Republic  $^5\mathrm{Beijing}$  Radiation Center, 100875 Beijing, China <sup>6</sup>GIK Institute of Engineering Sciences and Technology, Topi, Districti Swabi, K.P. Pakistan <sup>7</sup>China Institute of Atomic Energy, Beijing, China <sup>8</sup>Cyclotron Institute, Texas A&M University, College Station, TX 77843, USA <sup>9</sup>Institute for Nuclear Research (ATOMKI), Debrecen, Hungary <sup>10</sup>University of Enna, Unikore, Enna, Italy <sup>11</sup>,china  $^{12}\mathrm{CNS}\text{-}\mathrm{University}$  of Tokio, Japan E-mail: spitaleri@lns.infn.it

Abstract. The accurate knowledge of thermonuclear reaction rates is important in understanding the energy generation, the neutrinos luminosity and the synthesis of elements in stars. The physical conditions under which the majority of astrophysical reactions proceed in stellar environments make it difficult or impossible to measure them under the same conditions in the laboratory. That is why different indirect techniques are being used along with direct measurements. The Trojan Horse Method (THM) is introduced as an independent technique to obtain the bare nucleus astrophysical S(E)-factor. As examples the results of recent the application of THM to the  ${}^{2}H({}^{11}B, \alpha_{0}{}^{8}Be)n$  and  ${}^{2}H({}^{10}B, \alpha_{0}{}^{7}Be)n$  reactions are presented.

# 1. Introduction

Big efforts have been devoted in the last years to the study of light elements abundances, being their importance related to cosmology as well as to stellar structure and evolution. In fact hints on the primordial Big Bang Nucleosynthesis (BBN) can be achieved from Li primordial abundance [1]. Moreover these studies can be a precious tool for testing and understanding the inner stellar structure, especially for what regards the mixing processes in stellar envelopes [2].

In this framework, the different nuclear processes producing or destroying lithium (Li), beryllium (Be) and boron (B) must be studied in details and an accurate knowledge of the

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involved nuclear cross sections are necessary. In particular we will focus our attention on one of the main destruction channels for these elements in stellar environments, the  $(p, \alpha)$  reactions.

For this reason bare nucleus cross section measurements of the p-capture reaction at the Gamow energy  $(E_G)$  should be known with an accuracy better than 10% [3] because of their crucial role in understanding the first phases of the Universe history and the subsequent stellar evolution.

The effective cross section for stellar plasma  $\sigma_{pl}(E)$ , is connected to the bare nucleus cross section  $\sigma_b(E)$  and to the stellar electron screening enhancement factor  $f_{pl}$  by the relation

$$\sigma_{pl}(E) = \sigma_b(E) f_{pl}(E) = \sigma_b(E) \cdot exp(\pi \eta U_{pl}/E)$$
(1)

where  $U_{pl}$  is the plasma potential energy and  $\eta$  the Sommerfeld parameter. If  $\sigma_b(E)$  is measured at the ultralow energies  $E_G$  and  $f_{pl}$  is estimated within the framework of the Debye-Hückel theory, it is possible estimate from equ.(1) the  $\sigma_{pl}(E)$ .

In the neutron-induced reactions, the lack of a Coulomb barrier and the typical  $\sigma_b(E) \sim 1/E^{1/2}$  energy dependence led to a precise knowledge of  $\sigma_b(E_G)$  for many cases. Whereas the Coulomb barrier of height  $E_C$  in charged-particle induced reactions  $E_C$  causes an exponential decrease of the cross section at  $E < E_C$ ,  $\sigma_b(E) \sim exp(-2\pi\eta)$ , leading to a low-energy limit of direct  $\sigma_b(E)$  measurements, which is typically much larger than  $E_G$ . Owing to the strong Coulomb suppression, the behavior of the cross section at  $E_G$  is usually extrapolated from the higher energies by using the definition of the smoother astrophysical factor S(E):

$$S_b(E) = E\sigma_b(E)exp(2\pi\eta) \tag{2}$$

where  $exp(2\pi\eta)$  is the inverse of the Gamow factor, which removes the dominant energy dependence of  $\sigma(E)$  due to the barrier penetrability.

Although the  $S_b(E)$ -factor allows for an easier extrapolation, large uncertainties to  $\sigma_b(E_G)$  may be introduced due to for instance the presence of unexpected resonances. In order to avoid the extrapolation procedure, a number of experimental solutions were proposed in direct measurements for enhancing the signal-to-noise ratio at  $E_G$ .

In recent years the availability of hight-current low-energy accelerators, such as that at the underground Laboratori Nazionali del Gran Sasso (e.g.[4]), together improved target and detection techniques have allowed us to perform  $\sigma_b(E)$  measurements in some cases down to  $E_G$ or at least close to  $E_G$ .

Then in principle no  $\sigma_b(E)$  extrapolation would be needed anymore for these reactions. However, the laboratory measurements at ultra low-energies suffer the presence of electron screening effects [5, 6], which exponentially enhances the measured cross section  $\sigma_s(E)$  values [or equivalently the corresponding  $S_s(E)$  astrophysical factor] with respect the case of bare nuclei. This is usually described in terms of an *enhancement* factor defined as [3]

$$f_{lab}(E) = \sigma_s(E) / \sigma_b(E) = exp(\pi \eta U_e / E)$$
(3)

In this equation  $U_e$  is the electron screening potential measured in the laboratory which is different from the  $U_{pl}$  in the stellar environment. Clearly, a precise knowledge of  $U_e$  is needed for calculating  $\sigma_b(E)$  from the experimental  $\sigma_s(E)$  values by using Eq.(3). In turn, the understanding of  $U_e$  may help to better understand  $U_{pl}$ , needed to calculate  $\sigma_{pl}$ .

Then, even in those cases for which direct cross section measurements are possible in the Gamow energy range, the bare nucleus cross section  $\sigma_b(E)$  is extrapolated by high-energies direct measurements, negligibly affected by electron screening effects.

Thus, alternative methods for determining bare nucleus cross sections of astrophysical interest are needed. In this contest a number of indirect methods, e.g. the Coulomb dissociation [7],

the ANC (asymptotic normalization coefficient) method [8, 9, 10], and the Trojan-horse method (THM) were developed [11, 12, 13, 14, 15, 17, 16]. The THM is a powerful tool which selects the quasi-free (QF) contribution of an appropriate three-body reaction performed at energies well above the Coulomb barrier to extract a charged particle two-body cross section at astrophysical energies free from Coulomb suppression. The THM has already been applied several times to reactions connected with fundamental astrophysical problems and here its application for studying the astrophysically relevant  ${}^{11}B(p,\alpha_o){}^8Be$  and  ${}^{11}B(p,\alpha_o){}^8Be$  reactions will be discussed.

### 2. The Trojan Horse method



Figure 1. Feynman diagram representing the quasi-free B(A, CD)S reaction.

The basic idea underlying indirect methods is the use of nuclear reaction theory to link the cross section of a reaction of astrophysical importance to the one of a different process, easier to study with present-day facilities. Indirect techniques have been developed over the past several decades to determine reaction rates that cannot be measured in the laboratory. An example is the application of the detailed balance principle to the time-reversed reaction. In the case of  $(\alpha, p)$  reactions this approach allows one to deal with larger cross sections, thanks to the smaller Coulomb barrier for proton-induced reactions than for  $\alpha$ -induced ones. However, only the cross section for ground state to ground state transition of the time reversed  $(p, \alpha)$  reaction can be obtained, setting a lower limit to the total cross section.

This is a feature in common with several indirect approaches: since a different process is measured with respect to the one of astrophysical interest, different physical features could be displayed that have to be carefully inspected not to incur into systematic errors.

The THM aims at obtaining the cross section of the binary process  $x + B \rightarrow C + D$  at astrophysical energies by measuring the Trojan Horse (TH) reaction (the two-body to threebody process ( $2 \rightarrow 3$  particles))  $A+B \rightarrow C + D+S$  in quasi-free (QF) kinematics regime ([17, 18, 19, 20] and references therein), where the "Trojan Horse" particle, A = (Sx), which has a dominant cluster structure, is accelerated at energies above the Coulomb barrier.

After penetrating the barrier, the TH nucleus A undergoes breakup leaving particle x (participant) to interact with target B while particle S (spectator) flies away. From the measured cross section of TH reaction, the energy dependence of the binary sub-process is determined [11, 27].

The reaction used in the THM can proceed through different reaction mechanisms. The reaction mechanisms shown schematically in Fig. 1 gives the dominant contribution to the cross section in a restricted region of the three-body phase space when the relative momentum of the fragment S and x is zero (the QF kinematical condition) or small compared to the

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bound state (Sx) wave number [11]. The THM has been extensively discussed in the literature [21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 36, 37, 38, 40, 41]. This method, as the Asymptotic normalization coefficient (ANC) and Coulomb dissociation (CD) methods, has a common underlying connection to nuclear reaction theory.

Since the transferred particle x in the TH reaction is virtual, its energy and momentum are not related by the on mass shell equation, thus

$$E_{xA} \neq \frac{p_{xA}^2}{2\mu_{xA}} \tag{4}$$

being the initial channel A + B, where A = (Sx), rather than the simple x + A. To increase the TH triple differential cross section, the relative kinetic energy  $E_{AB}$  in the initial channel of the TH reaction should be higher than the Coulomb barrier between particles A and B. Then, the probability to find nucleus A near B, which is given by the modulus square of the scattering wave function, is not suppressed by the Coulomb barrier, leading to a finite probability that B can be in proximity of x.

Thus, there is no additional Coulomb barrier between B and the constituent particle x of the TH nucleus B.

Moreover the THM cross section turns out to be insensitive to the electron screening effect and allows one to determine the energy dependence of the binary cross section in the region of astrophysical interest with no need of extrapolation. THM makes it possible also to retrieve independent information on the electron screening potential  $U_e$  when direct ultra-low energy measurements are available [11].

Despite being based on a relatively simple idea, the method involves a non trivial theoretical description (see [11] and references therein) and requires the careful selections of experimental conditions to guarantee that the correct reactions and the appropriate reaction mechanism are selected.

The absolute value of  $S(E_{xB})$  can be found by normalization of TH data to available direct measurements at higher energies. A recent application of the THM has addressed the possibility of studying neutron induced reactions at low energies on radioactive nuclei using deuteron as source of "virtual" neutrons n, being the n-induced reactions only affected by centrifugal barrier. This idea has been successful tested with stable beams in [21, 22, 23]. Thus, the THM is currently an alternative technique for measuring cross sections for reactions related to the s, r processes in nuclear astrophysics (or nuclear structure). Furthermore the cost of production of virtual neutron targets is negligible. Indeed "virtual neutron" targets are easy to prepare from deuterated polyethylene material in any chemical laboratory. In addition, the THM cannot be applied to radiative capture reactions (p, $\gamma$ ), (n, $\gamma$ ), ( $\alpha$ , $\gamma$ ).

The first attempt to deliver the TH reaction theory has been done by [16], where they introduced the surface approximation. Although the idea of the surface approximation is quite attractive, its practical realization required the surface integral formalism, recently applied to deuteron stripping reactions populating bound states and resonances [10]. The developed theory of the deuteron stripping was based on DWBA and post Continuum Discretized Coupled Channel (CDCC) formalism, the surface integral formulation of the reaction theory, and of the R-matrix method. This theory can be directly applied for analysis of the TH reactions, in which the TH nucleus is a deuteron, even if it can be also extended to other TH nuclei (see for instance [11]).

The absence of the absolute measurements allows us to consider the theory of the TH reactions in the plane wave impulse approximation (PWIA), which often predicts reasonable well the energy dependence of the three-body cross sections and it is much simpler then the DWBA and CDCC approaches.

The description of the quasi-free reaction (QFR) is very simple in the Impulse Approximation (IA) and can be represented by the Feynman diagram in Fig. 1.

In the IA, the three body reaction cross section is proportional to the cross section of the binary reaction [39] and, by using the PWIA approximation the three body reaction can be factorized into two terms corresponding to the vertices of figure 1 and is given by:

$$\frac{d^3\sigma}{d\Omega_C d\Omega_D dE_C} \propto (KF) \cdot |\phi(p_{x-S})|^2 \cdot \left[\frac{d\sigma}{d\Omega}\right]^{HOES}$$
(5)

where:

(i)  $\left[\frac{d\sigma}{d\Omega}\right]^{HOES}$  is the half-off-energy-shell differential cross section for the binary B(x,C)D reaction at the center of mass energy  $E_{cm}$  given in post-collision prescription (*PCP*) by the relation:

$$E_{cm} = E_{CD} - Q_{2b} \tag{6}$$

where  $Q_{2b}$  is the Q-value of the binary  $x + B \rightarrow C + D$  reaction and  $E_{CD}$  is the C - D relative energy;

- (ii) KF is a kinematical factor containing the final state phase space factor and is a function of the masses, momenta, and angles of the outgoing particles (see [27] and ref. ther.);
- (iii)  $|\phi(p_{x-S})|^2$  is the Fourier transform of the radial wave function for the (x-S) inter-cluster motion usually described in terms of Hankel, Eckart, and Hulthen functions depending on the x-S system properties.

The applicability of the pole approximation is limited to small momenta  $p_{x-S}$ . Namely, the region where the pole diagram is expected to be predominant in the reaction mechanism was suggested to be [42]

$$0 \le p_{x-S} \le k_{x-S} \tag{7}$$

with

$$k_{x-S} = \sqrt{2\mu_{x-S}B_{x-S}} \tag{8}$$

where  $\mu_{x-S}$  is the reduced mass and  $B_{x-S}$  is the binding energy of the system x-S, respectively.

If the experimental momentum distribution  $|\phi(k_{x-S})|^2$  is measured, one can, in principle, extract the HOES cross-section by measuring the three body reaction and by calculation of (KF). Following the *PWIA* the two body cross section is derived by dividing the measured three-body cross section by product of the kinematic factor and the experimental momentum distribution  $(KF)|\phi(k_{x-S})_{exp}|^2$ :

$$\left[\frac{d\sigma}{d\Omega}\right]^{HOES} \propto \frac{\frac{d\sigma^3}{d\Omega_C d\Omega_D dE_C}}{(KF)|\phi(k_{x-S})_{exp}|^2} \tag{9}$$

#### 2.1. Incident energy prescriptions.

For the applicability of the IA, the incident energy  $E_{A-B}$  of the projectile must be much larger than the binding energy  $B_{x-S}$  [39] in such a way the bombarding energy  $E_{A-B}$  overcomes the Coulomb barrier  $(E_{A-B})^{C.B.}$  in the entry channel as well

$$E_{A-B} > (E_{A-B})^{C.B.}$$
 (10)

The QF kinematical conditions must be chosen in such a way that the  $E_{x-B}$  relative energy can span the astrophysical region of interest below the Coulomb barrier  $(E_{x-B})^{C.B.}$  [16]

$$E_{x-B} < (E_{x-B})^{C.B}.$$
 (11)



**Figure 2.** The experimental Q-value spectrum for the TH reaction  ${}^{2}\text{H}({}^{10}\text{B}, \alpha_{0}{}^{7}\text{Be})$ n studied at INFN-LNS by using a boron beam energy of 27 MeV [12].

The commonly used THM approach differs from original idea by Baur [16], for which the initial velocity of the projectile B is compensated for by the Fermi motion of particle x. In this framework, a momentum of the order of hundreds of MeV/c could be needed. However, in the case of a Trojan Horse nucleus with a predominant l = 0 inter-cluster motion, these momenta populate the tail of the momentum distribution for particle x, making the separation from eventual background reaction mechanisms very critical.

Moreover the tail of the calculated momentum distribution changes depending on the theoretical approach applied, therefore a very sophisticated treatment might be required in order to get the relevant binary reaction cross section.

In order to overcome these problems, we have introduced a different approach based on the idea that the initial projectile velocity is compensated for by the binding energy of particle x inside A necessary to compensate for the high impinging momenta (equation (6)).

$$E_{cm} = E_{xB} - B_{x-S} \tag{12}$$

with  $E_{x-B}$  projectile energy in the two-body center of mass system.

Thus the relative energy of the fragments in the initial channel x + B of the binary reaction can be very low and even negative. In the THM approach we fix the beam energy and vary the relative momentum x-S within few tens of MeV/c; in this case the kinematics of the experiment slightly deviates from the QF condition, but one can easily cover the whole astrophysical energy region of interest.

#### 3. Data analysis

As already mentioned, the main feature of the THM is the extraction of the astrophysical S(E)-factor at low-energies via the selection of the QF mechanism to extract the two-body cross section of interest.

Thus, particular attention is devoted to the data analysis procedure. In more detail, several steps are involved in the data analysis before the extraction of the two-body cross section of astrophysical relevance, namely:



Figure 3. The experimental kinematical locus (black points) superimposed onto the simulated one (red points) for the TH reaction  ${}^{2}\text{H}({}^{10}\text{B}, \alpha_{0}{}^{7}\text{Be})$  [12].

- (i) identification of the three-body reaction channel of interest  $A + B \rightarrow C + D + S$  (Fig.2 and Fig.3);
- (ii) identification of the events belonging to the quasi-free (QF) reaction mechanism;
- (iii) subtraction of spurious events arising from mechanisms other than the QF breakup as, for instance, sequential decay (SD);
- (iv) selection of the QF reaction mechanism and related tests ;
- (v) extraction of the THM two-body cross section, from the measured three-body one, in arbitrary units via Eq. (9);
- (vi) correction of the THM two-body cross section via the Coulomb barrier penetration factor;
- (vii) normalization high-energy direct data to obtain the bare nucleus cross section  $\sigma_b(E_{CM})$ , in absolute units;
- (viii) validity tests;
- (ix) extraction of astrophysical factor  $S_b(E)$  in absolute units;
- (x) determination of screening potential.

#### 3.1. Extraction of two-body cross section from the measured three-body reaction

In the analysis, the HOES two body cross section is derived by dividing the selected three-body coincidence yield (Y) by the result of a Monte Carlo calculation for the product between the kinematical factor and the experimental momentum distribution

$$\left[\frac{d\sigma}{d\Omega}\right]^{HOES} \propto \left[\frac{Y}{(KF) \mid \phi(p_{xS}) \mid^2}\right]$$
(13)

where  $|\phi(p_{xS})|^2$  is referred to the spectator momentum range values corresponding to those given by Eq. (1). We stress that this relation is a limit of the pole approximation applicability.



**Figure 4.** The TH <sup>10</sup>B(p, $\alpha_0$ )<sup>7</sup>Be S<sub>b</sub><sup>THM</sup>(E) factor at infinite resolution [12], together with its allowed upper and lower limits, compared with the low-energy direct data of [10]. At energies lower than 30 keV direct data are described in terms of the enhanced S<sub>b</sub><sup>THM</sup>(E) factor [12]. The measured S<sub>b</sub>(10keV)=3127±583 (MeV b) agrees with the one extrapolated in [43].

This cross section needs to be normalized to the binary reaction one in order to obtain the absolute value in an energy range  $\Delta(E_{CM})$  of the excitation function above the Coulomb barrier. In fact, above the Coulomb barrier, must be

$$\left[\frac{d\sigma}{d\Omega}\right]^{HOES} \propto \left[\frac{d\sigma}{d\Omega}\right]^{OES} \tag{14}$$

where the angular range  $\theta(\mathbf{E}_{CM})$  is constant in both the relations. In the THM application the reaction  $\mathbf{x} + \mathbf{B} \to \mathbf{C} + \mathbf{D}$  is induced inside the short-range nuclear field, thus the Coulomb penetration factor

$$P_l(k_{xB}r_{xB}) = \frac{k_{xB}r_{xB}}{F_l^2(k_{xB}r_{xB}) + G_l^2(k_{xB}r_{xB})}$$
(15)

has to be introduced in order to compare the THM cross section with the direct data from literature in the energy region below the Coulomb barrier. In Eq.(15),  $F_l$  and  $G_l$  are the regular and irregular Coulomb wave functions,  $k_{xB}$  and  $r_{xB}$  the x-B relative wave number and interaction radius, respectively. Thus, the THM cross section will be given by

$$\left[\frac{d\sigma}{d\Omega}\right]^{THM} \propto \left[\frac{Y_l}{(KF)\phi^2(p_{xS})}\right] \left[P_l(k_{xB}r_{xB})\right] \tag{16}$$

being this the quantity to be compared with the OES cross section for both normalization purposes and validity test.

#### 4. Astrophysical S-factor

The THM provides an independent measurement of the bare nucleus cross section  $\sigma_b(E)$  (or equivalently of the corresponding bare nucleus astrophysical factor,  $S_b(E)$ ). Thus, it is possible to measure the electron screening potential [3] by comparing  $S_b(E)$  with the directly measured one with shielded nuclei. Once the two-body cross section has been extracted , the THM astrophysical S(E)-factor can be obtained according to:

$$[S_b(E)]^{THM} = E[\sigma_b(E)]^{THM} exp(2\pi\eta)$$
(17)



**Figure 5.** The TH <sup>11</sup>B(p, $\alpha_0$ )<sup>8</sup>Be S(E)-factor (black points) compared with the one reported in NACRE ([43] and references therein), including the THM experimental resolution effects (black line). See [35] for a complete discussion.

where  $\sigma_b(\mathbf{E})^{THM}$  is the THM bare nucleus cross section obtained by Eq. (18). Thus, the energy dependence of  $[\mathbf{S}_b(\mathbf{E})]^{THM}$  should show the same trend of the directly measured one. Clearly, this procedure does not allow us to extract the absolute value of the astrophysical S-factor. However, the absolute scale for  $\mathbf{S}_b(\mathbf{E})^{THM}$  can be obtained by normalizing the THM data to the direct  $\mathbf{S}(\mathbf{E})^{OES}$  ones in a range of energies  $\Delta \mathbf{E}^*$  where the electron screening effects are negligible, as

$$N_{abs.value} = \frac{[S(\Delta E^*)]^{OES}}{[S_b(\Delta E^*)]^{THM}}$$
(18)

In the ultra low-energy range,  $S_b(E)^{THM}$  differs from the  $S(E)^{OES}$  one because of the enhancing electron screening effects on direct data. Thus, THM could also provide an independent measurement of electron screening potential by simply fitting the direct data with an analytical form in which  $\sigma_b(E)$  of Eq. (2) is replaced by  $\sigma_b(E)^{THM}$ .

#### 5. Results

The first run of the  ${}^{10}\text{B}(\text{p},\alpha_0)^7\text{Be}$  experiment was performed at the Pelletron-Linac laboratory (Departamento de Fisica Nuclear (DFN) in Sao Paulo (Brazil) [31]. The Tandem Van De Graaf accelerator provided a 27 MeV  ${}^{10}\text{B}$  beam with a spot size on target of about 2 mm and intensities 1 npa. The second run was performed at the Laboratori Nazionali del Sud in Catania using the SMP Tandem Van the Graaff accelerator to produce a  ${}^{10}\text{B}$  beam with an energy of 24.5 MeV [12]. The beam was accurately collimated in order to have a spot diameter of about 1.5 mm. In both cases, a  $\sim 200 \mu \text{g/cm}^2$  thick deuterated polyethylene target were used. The detection set up consisted of Position Sensitive Silicon Detectors, placed on both sides of the beam direction, and of an ionization chamber (IC) for <sup>7</sup>Be identification. The obtained THM S(E)-factor is displayed in Fig.4 (solid blue line), compared with the direct measurements given in [43]. At energies lower than about 30 keV, direct data have been described in terms of the standard factor  $f_{enh}$  given in Eq.3 (see [12] for details).

The  ${}^{11}B(p,\alpha_0)^8Be$  experiment was performed at the Laboratori Nazionali del Sud in Catania using the SMP Tandem Van the Graaff accelerator to produce a  ${}^{11}B$  beam with an energy of 27

MeV [27, 35, 36]. The beam was accurately collimated in order to have a spot diameter of about 1.5 mm. In this cases an about 150  $\mu$ g/cm<sup>2</sup> deuterated polyethylene target were used. The detection set up consisted of Position Sensitive Detectors and Dual Position Sensitive Detectors (DPSD) placed on both sides of the beam direction. In particular the DPSD's made up of two PSD mounted one above the other with a 1 mm empty space, are specially suitable for the identification of the two  $\alpha$  particles coming from <sup>8</sup>Be decay.

The <sup>11</sup>B(p, $\alpha_0$ )<sup>8</sup>Be THM S(E)-factor is displayed in Fig.5 (black points), compared with the fit of direct data given in [43] smeared out for the THM experimental resolution of ~45 keV, as discussed in [35].

# 6. Conclusions

THM represents an useful tool for experimental nuclear astrophysics, avoiding the extrapolation procedures for extracting low-energy S(E)-factor values for astrophysical purposes. Important results have already been obtained also for pure nuclear physics (i.e. resonant reactions treatment), while new extensions of the method to further cases of interest (e.g., reactions involving neutrons and/or reactions with Radioactive Ion Beams), are currently underway.

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