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Light elements burning reaction rates at stellar temperatures as deduced by the Trojan Horse measurements

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Abstract. Experimental nuclear astrophysics aims at determining the reaction rates for astrophysically relevant reactions at their Gamow energies. For charged-particle induced reactions, the access to these energies is usually hindered, in direct measurements, by the presence of the Coulomb barrier between the interacting particles or by electron screening effects, which make hard the determination of the bare-nucleus S(E)-factor of interest for astrophysical codes. The use of the Trojan Horse Method (THM) appears as one of the most suitable tools for investigating nuclear processes of interest for astrophysics. Here, in view of the recent TH measurements, the main destruction channels for deuterium (^{2}H), for the two lithium ^{6,7}Li isotopes, for the ^{9}Be and the one for the two boron ^{10,11}B isotopes will be discussed.

Keywords: nuclear reactions, nucleosynthesis, abundances—stars: abundances, stars: evolution
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INTRODUCTION

The curve of abundances reveals several features, confirming the action of both primordial and stellar nucleosynthesis. Among the deduced abundances, the one relative to the light element lithium, beryllium and boron plays a crucial role for understanding and constraining both cosmological and stellar models. Their role have been in fact highlighted in the seminal B^{2}FH paper [1], in which the lower abundances of lithium, beryllium and boron (LiBeB) have been explained in terms of the *x-processes*, where "x" stands for "unknown". In the framework of stellar nucleosynthesis and models, the combined study of the LiBeB residual abundances in stellar atmospheres gives an unique opportunity for understanding stellar structure and mixing phenomena, because of their different fragility against (p,α) reactions at different stellar depths for which the residual atmospheric abundances reflect the effect of plasma mixing. Being these reactions ignited at temperatures of few 10^6 K, experimental nuclear astrophysics has to use often extrapolation procedures to access the relevant Gamow energy peak, even if they are inevitably affected by several uncertainties such as the currently not-well-understood *electron screening effects* [2]. This effects, due to the electronic (atomic) cloud surrounding the positively charged nucleus, alter the cross-section at low-energies, thus shielding the pure Coulomb repulsion between the charged-interacting nuclei. This considerably inhibits the experimentalist to reach the ultra-low energy region, thus causing an additional problem for experimental nuclear astrophysicists. In addition, its understanding is far to be completely understood since the current available theoretical dynamics models (i.e. adiabatic approximation) largely underestimate the electron screening potential values with respect those measured in terrestrial laboratories (see Fig.1).

In order to by-pass the difficulties connected with both Coulomb barrier penetration and electron screening effects, the Trojan Horse Method (THM) has been largely applied for measuring the bare nucleus S(E)-factor for astrophysically relevant reactions, being its power the access to the bare-nucleus S(E)-factor without any kind of extrapolation. A detailed discussion can be found in the contribution of prof. C. Spitaleri and in [3].

THM allows one to extract the bare-nucleus cross-section of a charged-particle induced reaction a+x→c+C at astrophysical energies free of Coulomb suppression, by properly selecting the quasi-free (QF) contribution of an appropriate reaction a+A→c+C+s, performed at energies well above the Coulomb barrier, where the nucleus A has a dominant x⊕s cluster configuration.The THM study of the astrophysical reaction a+x→c+C does not experience tunneling effects, since the $a+x$ interaction occurs in the pure nuclear field without the influence of the Coulomb barrier. This assures to the experimentalist to be able to measure the corresponding S(E)-factor even at astrophysical energies at which direct measurements can access only via the extrapolation procedures. However, it must be stressed here that the TH S(E)-factor determination requires a normalization procedure to the available direct measurements performed

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Reaction	U_{ad} (eV)	U_{exp} (eV)
^{6}Li(p,α)^{3}He	186	440$\pm$150
^{6}Li(d,α)^{4}He	186	330$\pm$120
H(^{7}Li,α)^{4}He	186	300$\pm$160
^{2}H(^{3}He,p)^{4}He	65	109$\pm$9
^{3}He(^{2}H,p)^{4}He	120	219$\pm$7
H(^{9}Be,α)^{6}Li	240	900$\pm$50
H(^{11}B,α)^{8}Be	340	430$\pm$80

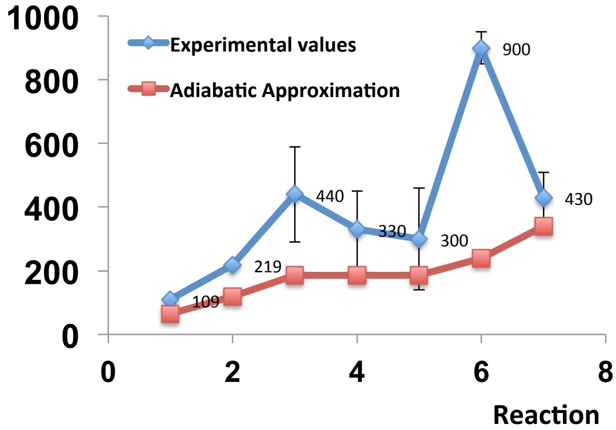

FIGURE 1. The current (unsatisfactory) picture of the electron screening phenomenon: discrepancy between the experimental values (blue symbols) and the theoretical ones (red symbols). The vertical axis reports the electron screening potential U_e in eV. The connecting lines help only the visualization. The experimental values, listed in the table, are reported in the NACRE compilation of [24].

at higher energies (Spitaleri et al. [3]), thus making the TH as a complementary experimental technique for nuclear astrophysics aimed to reach the ultra-low energy region of interest for astrophysical applications. THM has been used in studying several problems, ranging from BBN (see for instance Pizzone et al. [4]), light element burning reactions (Romano et al. [5]; Lamia et al. [6, 7]; Tumino et al. [8, 9, 10]; Pizzone et al. [13, 14, 12, 15]), CNO reactions (La Cognata et al. [16, 17]; Sergi et al. [18], Palmerini et al. [19]), and removing/producing neutron reactions (Gulino et al. [20], La Cognata et al. [21, 22]).
For a complete review of the method, refers to the contribution of prof. C. Spitaleri given in the present volume.

SOME DETAIL ON THM DATA ANALYSIS

As already discussed in the previous section, THM founds its theoretical formulation in the so-called "quasi-free reaction mechanisms", widely used in the past for evaluating nuclear structure with particular regard to the cluster configurations (see for example the detailed discussion reported in [3]). By performing a devoted experiment for studying the three-body reaction a+A→c+C+s, it is possible to connect the three-body cross section (measured in the laboratory) with the one of interest for astrophysics (*extracted* with the support of a dedicated theoretical formalism) through the relation [3]

$$\frac{d^3\sigma}{dE_c C\Omega_c C\Omega_C} \propto KF \cdot \mid \Phi(\vec{p}_s) \mid^2 \cdot \left(\frac{d\sigma}{d\Omega}\right)\Bigg|_{a-x}^{HOES} \tag{1}$$

where KF represents the kinematical factor, $\mid \Phi(\vec{p}_s) \mid^2$ is the square of the momentum distribution for the $x-s$ relative motion inside the TH-nucleus A, and $\frac{d\sigma}{d\Omega}\Big|_{a-x}^{HOES}$ the half-off energy shell cross section. This last quantity represents the "bare-nucleus" cross section of interest for astrophysics, once it has been corrected for the penetrability through the Coulomb barrier and normalized to the available high-energy direct data.
In order to assess the method, it is customary to underline the role of some of the most important sources of uncertainties in a typical THM experiment and/or data analysis:

- **Energy resolution effects.** THM data are expressed in terms of the relative energy between two-out-of three c and C detected particles, being this experimental solution sufficient to reconstruct completely the kinematic for a reaction having three-particles in the exit channel by properly applying energy and momentum conservation rules. Thus, energy resolution effects on the relative E_{cC} energy are measured by means of standard errors propagation theory, taking into account both energy and angular resolution due to the adopted experimental setup. In the case of the ^{11}B+p reaction discussed in [27], this has been evaluated to be $\sim$40 keV;

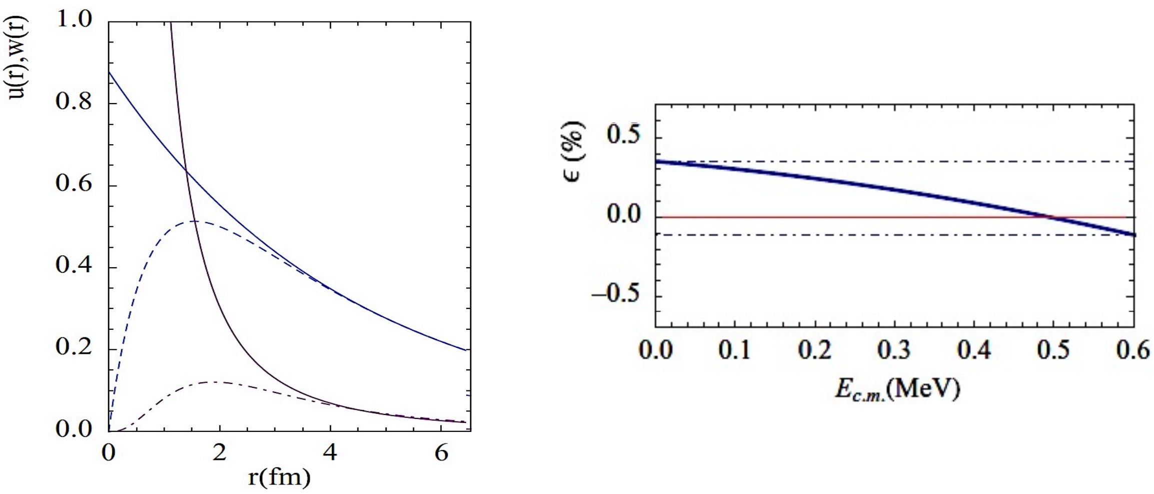

FIGURE 2. **(Left panel).** The exact (dashed) and asymptotic (full line) solution for the s-state ($u(r)$, blue color) and the d-state ($w(r)$, purple color). **(Right panel).** Influence of the d-state component of the deuteron ground-state wave function on a typical THM result, giving a maximum variation of 0.5% for the ^{11}B(p,α)^{8}Be S(E)-factor (see [28] for details).

- **Determination of the experimental momentum distribution.** The measurement of the experimental momentum distribution is one of the most important steps of a typical THM analysis, this reflecting the presence of the quasi-free reaction mechanism. The behaviour of the experimental momentum distribution (for which a detailed discussion can be found in the contribution given in present volume by prof. C. Spitaleri) is then discussed in terms of both Plane Wave Impulse Approximation (PWIA) and Distorted Wave Born Approximation (DWBA). By referring to the ^{11}B+p case, its has been found that the two approach, PW and DWBA, nicely agree within lower momentum of the exiting neutron, being the same result confirmed in a variety of THM experiment discussed in the literature (i.e. [18, 16, 17] ;
- **Introduction of the penetration factor trough the Coulomb barrier.** THM results are naturally bared from Coulomb penetration effects. However, in order to get THM results in absolute units, a normalization procedure is required by using the available direct data. Thus, THM data need to be corrected for analytical function describing the penetration through the Coulomb barrier, as given in several text book (see for example [2]). To such purposes, ones has to fix a cut-off radius in terms of the standard formula r=1.2*($A_1^{1/3}$+$A_2^{1/3}$) fm [2], even if such choice could introduce some uncertainties in the final results. This further source of uncertainty has been investigated in [27], leading to an overall $\sim$14% of uncertainty on the final evaluation of the zero-energy S(E)-factor;
- **Influence of the momentum distribution in THM data.** The role of the momentum distribution and, in particular, of the FWHM of the experimental momentum distribution on THM data has been firstly investigated in the work of [13]. Additionally, in [28] we have investigate the role of the d-state when describing the deuteron ground-state wave function. In particular, both the s and d state wave functions have been calculated by using the exact form and the asymptotic one, their shape being the one shown in the left panel of Fig.2. In order to evaluate the impact on THM data, we have introduced the d state contribution in the THM analysis of [27] and we found a maximum variation of about 0.5% on the absolute value of the S(0) for the ^{11}B+p reaction.

RECENT RESULTS: LIGHT ELEMENTS IN ASTROPHYSICS

The d(d,n)^{3}He and d(d,p)^{3}H reactions. Deuterium is a fragile element easily destroyed in stars due to its relatively low burning temperature (about 10^6 K); the amount survived to the BBN is thus destroyed during the first stages of Pre-Main Sequence (PMS) evolution. Besides the major role played by the ^{2}H(p,γ)^{3}He nuclear reaction, the ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He reactions need to be carefully studied since they are active, too. When the central temperature exceeds 10^6 K, deuterium is burnt; the PMS phase occurs when the star is fully convective, and due to the continuous mixing

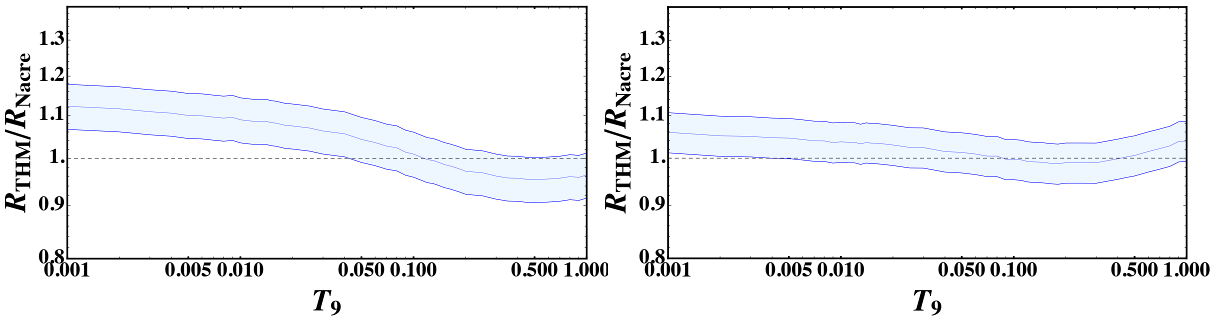

FIGURE 3. The THM to NACRE ratio for the d(d,n)^{3}He (left panel) and the d(d,p)^{3}H (right panel) reaction rates together with the corresponding uncertainties, as discussed in [11].

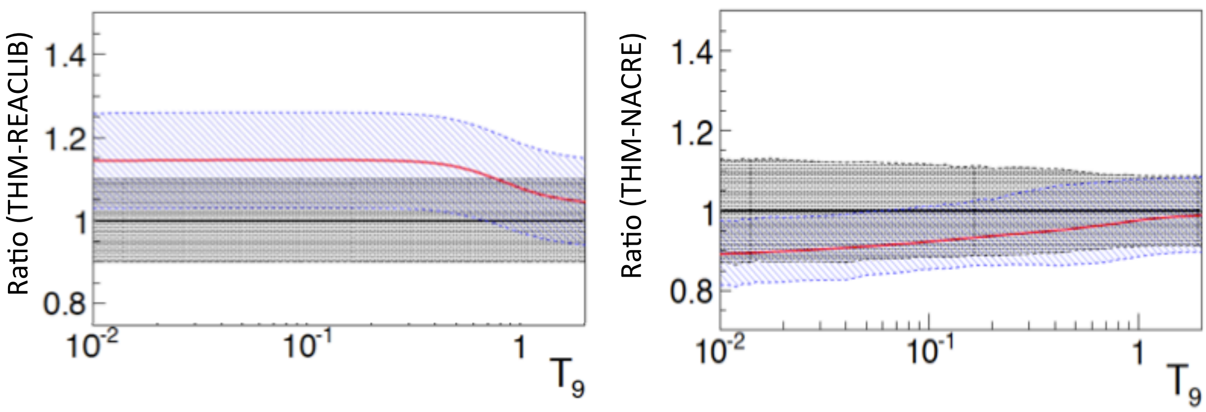

FIGURE 4. The THM to REACLIB ratio for the ^{6}Li(p,α)^{3}He (left panel) and the THM to NACRE ratio ^{7}Li(p,α)^{4}He (right panel) reaction rates together with the corresponding uncertainties, as discussed in [29, 26].

that brings surface matter toward the stellar center, deuterium is efficiently depleted in the whole structure. For these reasons, the two deuterium-depleting reactions have been recently investigated by means of THM and detailed discussed in [11]. In particular, they have been studied after the selection of the QF-contribution of the two reaction channels ^{2}H(^{3}He,p ^{3}H)^{1}H and ^{2}H(^{3}He,n ^{3}He)^{1}H, for which a devoted experiment has been performed at the Nuclear Physics Institute of ASCR in Rez. Fig.3 displays the ratio between the THM reaction rates and those reported in the NACRE compilation [24]. A maximum variation of about $\sim$15% has been found at PMS temperatures and its impact evaluated for different stellar masses using an updated version of the FRANEC evolutionary code [30]. No relevant differences on the stellar properties have been found among models with and without the two additional burning channels, but a maximum variation of about $\sim$15% of the deuterium abundance inside the star, limited to the early stages of PMS evolution.

The ^{6,7}Li(p,α)^{3,4}He reactions. The main burning channels for the lithium isotopes have been measured in [14] and recently by means of the THM, in view of the precise S(E)-factor direct measurements (i.e. total error bars of about 5% on average) at astrophysical energies discussed in [31, 32]. For the ^{6}Li+p reaction, the THM approach leads to S(0)=3.44$\pm$0.39MeV barns and U_e=355$\pm$100 eV [29]. By comparing the THM reaction rate to the one deduced in the REACLIB compilation [25], a variation ranging from $\sim$5% to $\sim$15% is visible as the temperature decreases from 1 to 10^{-2} T_9 (left panel of Fig.4). The astrophysical implications have been evaluated by means of the FRANEC code for pre-main sequence (PMS) models since the surface ^{6}Li is essentially burned in this stellar phase [30]. From such calculations, a clear influence of the temperature at the bottom of the convective envelope on the final amount of lithium has been found, i.e., the higher the metallicity, and/or the lower the stellar mass, the deeper and hotter the base of the convective envelope. For the ^{7}Li case [26], the THM measurement returns S(0)=53$\pm$5 kev b and U_e=425$\pm$60 eV for the bare-nucleus S (E)-factor at zero energy and the electron screening potential, respectively. The reaction rate determination shows that the THM reaction rate deviates from $\sim$5% to $\sim$13% as the temperature decreases from T_9=1 down to $T_9=10^{-2}$ (right panel of Fig.4). Its astrophysical impact has been evaluated in red-giant (RGB) star's framework, leading to large uncertainties on the stellar mixing phenomena with respect the uncertainty (of about 13%) on the THM measurement.

The ^{9}Be(p,α)^{6}Li and the ^{9}Be(p,d)^{8}Be reactions. Beryllium, together with lithium and boron, represents one of the most interesting isotope to be studied. Its residual amount in stellar atmospheres can be used to constrain stellar models and mixing phenomena. For such a reason and in view of the research program of the Catania group "ASFIN (AStroFIsica Nucleare)", a first measurement of the ^{9}Be(p,α)^{6}Li S(E)-factor has been performed in 2006, as discussed in [5], by properly selecting the QF-contribution of the three-body reaction ^{2}H(^{9}Be, α^6Li)n for which a devoted experiment has been performed at INFN-LNS of Catania. This measurement, although affected by a large energy resolution effects, allowed for the first time to detect via the THM the low-lying resonance of interest for astrophysics at $\sim$250 keV, as shown discussed in [5]. Recently, thanks to both experimental and theoretical improvements concerning the method, a second experiment has been performed at CIAE (Beijing, Cina) and the results reported in the work of [33]. By using their bare-nucleus S(E)-factor, the "preliminary" reaction rate has been calculated and compared with the NACRE one. The result shows an increase of the beryllium-burning reaction rate as deduced by the recent THM measurement, calling for a devoted evaluation on astrophysical scenario. The (p,d) destroying channel for beryllium case has been investigated in two different experiments performed at INFN-LNS (Catania) and CIAE (Beijing, Cina). The first part of the experiment has been devoted to the study of the d_0 channel, namely the one leaving the unstable ^{8}Be nucleus in its ground state. The ^{9}Be(p,d)^{8}Be reaction has been studied by means of the THM applied to the quasi-free ^{2}H(^{9}Be, d ^{8}Be)n, with an experimental apparatus similar to the one used in [3] in which a devoted silicon array has been used for detecting alpha particles coming from the ^{8}Be decay. The analysis leads to an unambiguous identification of the ^{2}H(^{9}Be, d ^{8}Be)n reaction channel, by means of the experimental Q-value reconstruction and to the identification of the p-n momentum distribution for the intercluster motion inside deuteron. The detailed analysis is still ongoing together with its astrophysical implications.

The (p,α) and (n,α) ^{10}B destroying channels. The ^{10}B(p,α)^{7}Be reaction is among the most interesting nuclear process in astrophysics, because its difficulty in measuring the corresponding S(E)-factor at Gamow energies and the interest of astrophysical community in the production/destroying processes of the unstable ^{7}Be isotope (see for instance [34]). Indeed, the 8.701 MeV excited level of ^{11}C dominates the S(E)-factor trend at low-energies, being this an *s*-wave resonance in the ^{10}B-p system at 10 keV. However, due to the action of both Coulomb barrier and electron screening effects, the S(10 keV)-factor was only extrapolated from high energy measurement [24]. To by-pass extrapolations, a first THM measurement has been already discussed in [6], where the dominance of the quasi-free reaction mechanism intervening in the ^{2}H(^{10}B, α ^{7}Be)n has been constrained via the study of the experimental momentum distribution. However, due to the very limited energy resolution (of about $\sim$60 keV), a further experiment has been performed with the aim of enhancing the energy resolution and constraining the S(10 keV)-factor. The detailed analysis is reported in [23] and it has been discussed during the conference (see the contribution of S.M.R. Puglia).

In addition, and because of the large interest in the pure-nuclear physics community [35], an indirect study of the ^{10}B(n,α) reaction has been performed firstly in [6], in which we firstly tested again the power of THM in investigating neutron-induced reactions and secondly deduced the corresponding cross section. Due to its importance, we have repeated the same experiment in 2014 in order to improve the previous experimental conditions.

The ^{11}B(p,α_0)^{8}Be reaction. The boron burning reaction ^{11}B(p,α_0)^{8}Be has been investigated by means of the THM application to the quasi-free ^{2}H(^{11}B, $\alpha_0{}^8$Be)n reaction (see [27] for details. A devoted experiment has been performed at LNS of Catania, by using a 27 MeV ^{11}B beam delivered onto a $\sim$150μg thick CD_2 target. The produced α particles were detected by means of standard position sensitive silicon detectors (PSD). No detection was necessary for the exiting neutrons, since their kinematical quantities are determined once the angles and energies of α and ^{8}Be have been measured. The ^{8}Be events have been reconstructed as a "coincidence-event" in a DPSD (Dual PSD) detector, basically designed as two standard PSD detectors mounted one-above-the-other and separated by a $\sim$1 cm of empty space. The selection of the quasi-free mechanism has been performed by studying the experimental momentum distribution for the p-n relative motion inside the deuteron and its distortion from simple PWIA approximation have been evaluated by performing DWBA calculations by means of the FRESCO code. After selection of the QF-contribution, the S(E)-factor was extracted and reported on the left after normalization to the available direct data. The extracted value of S(0)THM = 2.07$\pm$0.41 MeV b is in good agreement with the extrapolated one. It should be noted that the value of S(0) for the ^{11}B(p,α)^{8}Be reaction is dominated by the α_1 contribution, with the α_0 part being $\sim$1% of the total value. The value of the electron screening potential parameter (U_e) THM= 472$\pm$160 eV is in agreement within the experimental errors with the value of Ue = 430$\pm$80 eV reported in the NACRE compilation [24].

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