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The Trojan Horse Method as a tool for investigating astrophysically relevant fusion reactions

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Abstract

The Trojan Horse Method (THM) has been largely adopted for investigating astrophysically relevant charged-particle induced reactions at Gamow energies. Indeed, THM allows one to by pass extrapolation procedures, thus overcoming this source of uncertainty. Here, the recent THM results and their impact in astrophysics are going to be discussed.

1 Introduction

Among the deduced cosmic elemental abundances, the ones relative to the light element lithium, beryllium and boron (LiBeB) play a crucial role for understanding and constraining cosmology or stellar physics, as firstly highlighted in the B^2FH paper [1]. In the framework of stellar nucleosynthesis and models, the combined study of LiBeB gives an unique opportunity for understanding stellar structure and mixing phenomena, because of their different fragility against (p,α) reactions at different stellar depths [2]. Being

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Table 1: Some of the available values for electron screening potential U_e, for both theoretical and experimental determinations. The third column gives the ratio between experimental and theoretical values to highlight the strong discrepancy still present.

Reaction	$U_{theor.}$ (eV)	$U_{exp.}$ (eV)	Ratio	Reference
^{2}H(d,p)^{3}H	14	13.2±4.3	∼ 0.95	[6]
^{6}Li(p,α)^{3}He	186	440±150	∼2.36	[4]
^{6}Li(d,α)^{4}He	186	330±120	∼1.77	[4]
^{1}H(^{7}Li,α)^{4}He	186	300±160	∼1.74	[4]
^{2}H(^{3}He,p)^{4}He	65	109±9	∼1.68	[8]
^{3}He(^{2}H,p)^{4}He	120	219±7	∼1.82	[8]
^{1}H(^{9}Be,α)^{6}Li	240	900±50	∼3.75	[9]
^{1}H(^{11}B,α)^{8}Be	340	430±80	∼1.26	[10]
^{1}H(^{17}O,α)^{14}N	594	1356±1037	∼2.28	[7]

these reactions ignited at temperatures of few 10^6 K, experimental nuclear astrophysics has to use often extrapolation procedures to access the corresponding Gamow energy peak. Extrapolations are in turn inevitably affected by several uncertainties such as the currently not-well-understood *electron screening effects* [3]. These effects have been largely studied in the past, as in [4], or more recently in [5], even if they appear 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, as clearly visible from the values given in Table 1.

To overcome such difficulties related to both the very low signal-to-noise ratio (as due to Coloumb penetrability in the entrance channel) and the electron screening phenomenon, 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 capability of accessing to the bare-nucleus S(E)-factor measurement without any kind of extrapolation [11–13]. 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. Usually, deuteron has been used in THM application because its obvious p-n structure mainly occurring in *s*-wave, even if a small component of *d*-wave could influence THM data (see [14] for instance).

The main advantage of the method is the possibility of accessing the a(x,c)C two-body reaction cross section measurement by performing a devoted experiment aimed at studying the quasi-free three-body reaction a+A→c+C+s. By using the Plane Wave Impulse Approximation (PWIA), the link between the cross sections of the two processes is given by

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

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. A complete review of the experimental approach to THM can be found in [15, 16] and references therein.

2 Astrophysical impact

In last years, THM helped in understanding several unresolved issues in astrophysics, as in the case of the stellar physics case discussed in [17]. In the last work of [18], the impact of the THM measurements for the (p,α) cross sections involving ^{9}Be and ^{10}B has been evaluated. In particular, the ^{9}Be(p,α)^{6}Li THM measurement has been firstly investigated in [19] while an improved measurement is given in [20]. The latter one has been used to firstly extract the bare-nucleus S_b(E)-factor and then for calculating the corresponding reaction rate, by means of standard formulas (see [18] for details). The THM S_b(E)-factor measurements are shown in the left panel of Fig.1, where the experimental points are shown as black-circles with their errors. The full line represents the corresponding fit leading to a value of S(0)=21.8±0.8 (MeV b) while the dashed line gives its enhancing due to an electron screening potential of U_e=676±86 eV [20]. The fit of the THM S(E)-factor has been then used in [18] for calculating the corresponding reaction rate through the standard formula

$$N_A < \sigma v >= \left(\frac{8}{\pi\mu}\right)^{\frac{1}{2}} \frac{N_A}{kT_9^{\frac{3}{2}}} \int_0^\infty S_b(E) e^{-2\pi\eta - \frac{E}{kT}} dE \quad (\mathrm{cm^3\,mol^{-1}\,s^{-1}}) \qquad (2)$$

where the temperature T_9 is expressed in units of 10^9 K and center of mass energy E in MeV. In Eq. 2 the bare-nucleus S(E)-factor, S_b(E), is the one

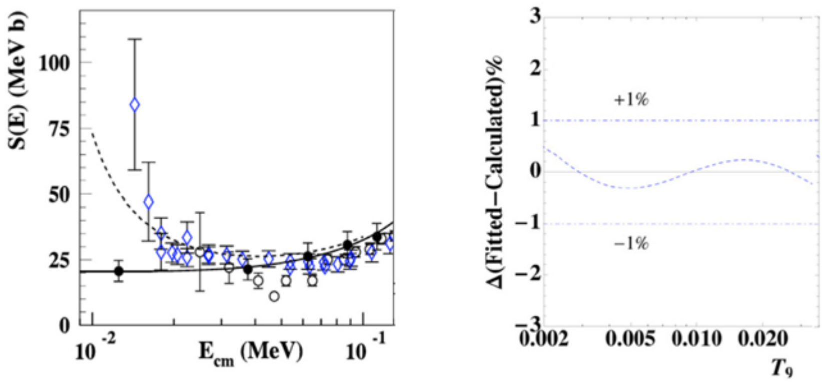

Figure 1: Left panel: The ^{9}Be(p,α)^{6}Li S(E)-factor as given by the THM measurements [20] (black points) compared with the direct measurements available in the NACRE compilation [21]. The full line represents the bare-nucleus THM S(E)-factor while the dashed one refers to its enhancing with the extracted U_e=676±86 eV [20]. Right panel: Discrepancy between the calculated and the parametrized THM reaction rate, as given in [18].

measured by THM. The THM reaction rate has been then parametrized in terms of the temperature T_9 as given in [18]. The differences between the THM calculation of the reaction rate and its parametrization is significantly lower than 1%, as shown in the right panel of Fig.1. However, the comparison between the THM reaction rate and the one proposed in the widely used NACRE compilation [21] leads to a ∼20% of discrepancy, thus calling for an evaluation of the impact of the THM reaction rate in astrophysical environments.

Besides the role played by deuteron, lithium-7 and lithium-6 abundances already investigated in [25–28], the THM ^{9}Be(p,α)^{6}Li S(E)-factor measurements have been then used in [18] for evaluating the fate of ^{9}Be in pre-main sequence (PMS) stars by means of the PROSECCO stellar code derived from the well tested FRANEC one [22, 23]. The calculations have been performed in a wide stellar mass range, starting from 0.08 $M_\odot$ up to 0.7 $M_\odot$ for different stellar ages and metallicity. The data show a remarkable difference in the depletion result of beryllium at different stellar masses, being this the combined effect of both stellar structure and metallicity of the adopted models. As matter of example, models of solar metallicity with masses of about $0.08 \leq M/M_\odot \leq 0.5$ with effective temperatures 2600-3600 K show a maximum difference of the ^{9}Be logarithmic abundance of more than 1 dex when using the THM ^{9}Be(p,α)^{6}Li reaction rate instead of the NACRE one [18].

Once again, THM has been proved to be an useful tool for nuclear astrophysics allowing us to access, without any extrapolation, the Gamow energy region at which astrophysically relevant reactions take place. Further studies are still under investigations, either for induced reactions with stable beam or unstable beams [29].

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