Trojan Horse Method and the application to fusion reactors

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Abstract. Owing the presence of the Coulomb barrier at astrophysically relevant kinetic energies, it is very difficult, or sometimes impossible to measure astrophysical reaction rates in laboratory. This is why different indirect techniques are being used along with direct measurements. The THM is unique indirect technique allowing one measure astrophysical rearrangement reactions down to astrophysical relevant energies. The basic principle and a review of the main application of the Trojan Horse Method are presented. The applications aiming at the extraction of the bare S_b(E) astrophysical factor and electron screening potentials U_e for several two body processes are discussed and hints are given for fusion reactor applications.

Keywords: indirect methods, cross section measurements, nuclear astrophysics
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INTRODUCTION

Nuclear fusion reactions, that take place in the hot interiors of remote and long-vanished stars over billions of years, are the origin in the universe of nearly all the chemical elements and their isotopes [BBFH, Fowler 1984, 10]. The detailed understanding of the origin of the chemical elements and their isotopes has combined astrophysics and nuclear physics, and forms what is called nuclear astrophysics. In turn, nuclear reactions are the heart of nuclear astrophysics: they influence sensitively the nucleosynthesis of the elements in the earliest stages of the universe and in all the objects formed thereafter, and control the associated energy generation (by processes called nuclear fusion or nuclear burning), neutrino luminosity, and evolution of stars. A good knowledge of the rates of these fusion reactions is essential for understanding this broad picture [13]. Moreover only understanding how the electron screening goes in the laboratory will provide knowledge for astrophysical application as well as fusion reactor physics.

LIMIT OF THE TWO-BODY MEASUREMENTS

In a stellar plasma the constituent nuclei are usually in thermal equilibrium at some local temperature T. Occasionally they collide with other nuclei, whereby two different nuclei can emerge from collision A+x$\rightarrow$ c+C. The cross section σ(E) of nuclear fusion reaction A(x,c)C is of course governed by the laws of quantum mechanics where, in most cases, the Coulomb and centrifugal barriers arising from nuclear charges and angular momenta in the entrance channel of the reaction strongly inhibit the penetration of one nucleus into another. This barrier penetration leads a steep energy dependence of the cross section. It is the challenge to the experimentalist to make precise σ(E) measurements over a wide range of energies, as our fragmented knowledge of nuclear physics prevents us from predicting σ(E) on purely theoretical grounds. For these reasons bare nucleus cross section measurements $\sigma_{pl}(E)$(for stellar plasma) of the (p,α) reaction at the Gamow energy (E_G) should be known with an accuracy better than 10% [10, 11] because of their crucial role in understanding the first phases of the Universe history and the subsequent stellar evolution. Unfortunately the presence of Coulomb barrier, in the reactions with charge particles, is a limit, often insuperable, to perform measurements of the cross sections at ultralow energies. Indeed the Coulomb barrier of height E_C in charged-particle induced reactions E_C cause an exponential decrease of the cross section $\sigma_b(E)$ 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):

$$S_b(E) = E\sigma_b(E)exp(2\pi\eta) \tag{1}$$

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, or high energy tails of sub-threshold 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 Laboratories together with 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 [2]. Then in principle no $\sigma_b(E)$ extrapolation would be needed anymore for these reactions. However, the measurements in laboratory at ultralow energies suffer from the complication due to the effects of electron screening [1, 13]. This leads to an exponential increase of the laboratory measured cross section $\sigma_s(E)$ [or equivalently of the astrophysical factor $S_s(E)$] with decreasing energy relative to the case of bare nuclei. This can be described by an enhancement factor defined by the relation

$$f_{lab}(E) = \sigma_s(E)/\sigma_b(E) = exp(\pi\eta U_e/E) \tag{2}$$

In this equation U_e is the electron screening potential in the laboratory which is different from the U_{pl} present in the stellar environment. Clearly, a good understanding of U_e is needed in order to calculate σ_b from the experimental data σ_s using equation (2). The effective cross section $\sigma_{pl}(E)$ in the stellar plasma, is connected to the bare nucleus cross section $\sigma_b(E)$ and to the the stellar electron screening enhancement factor f_{pl} by the relation

$$\sigma_{pl}(E) = \sigma_b(E)f_{pl}(E) = \sigma_b(E)\cdot exp(\pi\eta U_{pl}/E) \tag{3}$$

with U_{pl} is the plasma potential energy, η the Sommerfeld parameter.
If $\sigma_b(E)$ is measured at the ultralow energies E_G and U_{pl} is estimated within the framework of the Debye-Hückel theory, it is possible estimate from eq.(3) the effective

cross section $\sigma_{pl}(E)$ in the stellar plasma. In turn, the understanding of U_e may help to better understand U_{pl}, needed to calculate σ_{pl}.
Then, although it is possible to measure cross sections in the Gamow energy range, the bare nucleus cross section σ_b is extracted by extrapolating the direct data behavior at higher energies where negligible electron screening contribution is expected. In order to decrease uncertainties in the case of charged particle induced reactions a rather striking conclusion could be achieved: to avoid extrapolations, experimental techniques were improved. After improving measurements (at very low energies), electron screening effects were discovered. Finally to extract from direct (shielded) measurements the bare astrophysical S_b(E)-factor, extrapolation were performed at higher energy. In any case the extrapolation procedure is necessary and in consequence we find again the uncertainties problem in direct measurements.

THE TROJAN HORSE METHOD

Thus, alternative methods for determining bare nucleus cross sections of astrophysical interest are needed. In this context a number of indirect methods, e.g. the Coulomb dissociation (CD) [Baur 1994, Baur 1996], the Asymptotic Normalization Coefficient method (ANC)[Tang et al. 2003, Azhari et al. 2001, Mukhamedzhanov et al 2001, Mukhamedzhanov et al 1997, Mukhamedzhanov et al 1999] and the Trojan-horse method (THM) were developed (Table I). The THM has already been applied several times to reactions connected with fundamental astrophysical problems [8, Pizzone et al. 2005] . Some of them make use of direct reaction mechanisms, such as transfer processes (stripping and pick-up) and quasi-free reactions (knock-out reactions).
In particular, 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 In the framework of the extrapolation problems linked to the presence of electron screening effects a number of experimental measurements were carried out in order to measure the bare nucleus cross section in reactions of astrophysical interest (Table I).

The idea of the THM [Baur 1986] is to extract the cross section of an astrophysically relevant two-body reaction

$$A + x \rightarrow c + C \tag{4}$$

at low energies from a suitable chosen three-body quasifree reaction

$$A + a \rightarrow c + C + S \tag{5}$$

This is done with the help of direct theory assuming that the nucleus a has a strong $x \ominus S$ cluster structure. In many applications [Spitaleri et al. 2001, Spitaleri et al. 2004, Lattuada et al. 2001], this assumption is trivially fulfilled e.g. a = deuteron, x = proton, S= neutron. This three-body reaction can be described by a Pseudo-Feynmam diagram, where only the first term of the Feynman series is retained The upper pole describes the virtual break-up of the target nucleus a into the clusters x and S; S is then considered to be spectator to the $A + x \rightarrow c + C$ reaction which takes place in the lower pole.

This description, is called Impulse Approximation (IA) [Chew 1950]. In Plane Wave Impulse Approximation (PWIA) the cross section of the three body reaction can be factorized into two terms corresponding to the two poles and it is given by [Neudatchin 1965, Jacob 1966]:

$$\frac{d^3\sigma}{dE_c d\Omega_c d\Omega_C} \propto KF \left(\frac{d\sigma}{d\Omega_{cm}}\right)^{off} \cdot |\Phi(\vec{p}_s)|^2 \quad (6)$$

where:

- $[(d\sigma/d\Omega)_{cm}]^{off}$ is the off-energy-shell differential cross section for the two body A(x,c)C reaction at the center of mass energy E_{cm} given in post collision prescription by:

$$E_{cm} = E_{c-C} - Q_{2b} \quad (7)$$

  where Q_{2b} is the two body Q-value of the $A + x \rightarrow c + C$ reaction and E_{c-C} is the relative energy between the outgoing particles c and C;
- 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:

$$KF = \frac{\mu_{Aa} m_c}{(2\pi)^5 \hbar^7} \frac{p_C p_c^3}{p_{Aa}} \left[\left(\frac{\vec{p}_{Bx}}{\mu_{Bx}} - \frac{\vec{p}_{Cc}}{m_c}\right) \cdot \frac{\vec{p}_c}{p_c}\right]^{-1} \quad (8)$$

- $\Phi(\vec{p}_s)$ is the Fourier transform of the radial wave function $\chi(\vec{r})$ for the x-S inter-cluster motion, usually described in terms of Hänkel, Eckart and Hultheń functions depending on the x-S system properties.

In the experimental works [Table 2] the validity conditions of the IA appear to be fulfilled. We stress that one cannot extract the absolute value of the two-body cross section. However, the absolute value can be extracted through normalization to the direct data available at energies above and/or below the Coulomb barrier. Thanks to this, since we select the region of low momentum p_s for the spectator ($p_s \leq 40$ MeV/c) the PWIA approach can be used for further analysis of the experimental results. If $|\Phi(\vec{p}_s)|^2$ is known and KF is calculated, it is possible to derive $[(d\sigma/d\Omega)_{cm}]^{exp}$ from a measurement of $d^3\sigma/dE_c d\Omega_c d\Omega_C$ by using Eq. 6.

$$\left(\frac{d\sigma}{d\Omega}\right) \propto \left[\frac{d^3\sigma}{dE_c d\Omega_c d\Omega_C}\right] \cdot [KF|\Phi(\vec{p}_s)|^2]^{-1} \quad (9)$$

The application of the quasi-free mechanism to the study of reactions at astrophysical energies, was an extension of previous researches on the quasi-free mechanism at very low energies[Spitaleri 1990] In particular it is an extension, of the indirect excitation function measurements for the two body cross section of the $^7Li(p,\alpha)\alpha$ and $^6Li(p,\alpha)^3He$ reactions [Zadro et al. 1989, Calvi et al. 1990] obtained at low energies. This phenomenological approach was supported from the theory of the THM proposed by Baur ([Baur 1986]), whose basic idea is to extract an $A + x \rightarrow C + c$ two-body reaction cross section, at ultralow energies from a suitable $A + a \rightarrow C + c + s$ quasi-free three-body reaction. Under appropriate kinematical conditions, the threee-body reaction

is considered as the decay of the "Trojan Horse" a into the cluster x and s and the interaction of A with x inside the nuclear field , whereby the nucleus s can be considered as a spectator to the reaction.The Table I shows the "Trojan Horse" nuclei used in recent experiments.
If the bombarding energy E_A is chosen high enough to overcome the Coulomb barrier in the entrance channel of the three-body reaction, both Coulomb barrier and electron screening effects are negligible. In the original paper by [Baur 1986] it was proposed that the initial velocity of the projectile A is compensated for by the Fermi-motion of particle x. In this framework, a momentum of the order of hundreds MeV/c, could be needed. However, in the case of a nuclei with a predominant l=0 inter-cluster motion, such momenta populate the tail of the momentum distribution for particle x, making very critical the separation from eventual background reaction mechanisms, like sequential decays feeding the same exit channel. Moreover, as already mentioned, the tail of the calculated momentum distribution entering Eq. 6 changes depending on the theoretical approach applied, thus a very sophisticated treatment might be required in order to get the relevant two-body cross-section.
We stress that in our have approach the initial projectile velocity is compensated for by the binding energy of particle x inside a. Thus the two-body reaction can be induced at very low (even vanishing) $A-x$ relative energy . Moreover the role of the cutoff in the momentum distribution consists in fixing the accessible astrophysical energy region, as given by:

$$E_{qf} = E_{Ax} - B_{xs} \tag{10}$$

where E_{Ax} is the beam energy in the center-of-mass of the two-body A-x system, B_{xs} represents the binding energy for the x-b system and M_{xs} describes their inter-cluster motion within the chosen cutoff in momentum. In this way it is possible to extract the two-body cross section from Eq.(9) after inserting the appropriate penetration function G_l in order to account for the penetrability effects affecting the direct data below the Coulomb barrier [Cherubini et al 1996, Spitaleri et al. 1999]. The complete formula is given by:

$$\left(\frac{d\sigma}{d\Omega}\right) \propto \left[\frac{d^3\sigma}{dE_c d\Omega_c d\Omega_C}\right] \cdot [KF|\Phi(\vec{p}_s)|^2]^{-1} \cdot G_l \tag{11}$$

As shown above, since in the experimental works the IA validity conditions are fulfilled, the PWIA was applied for the extractions of the two-body cross-section. In this approximation the differential two-body cross-section of Eq.9 is expressed by:

$$\left(\frac{d\sigma}{d\Omega}\right) = \sum_l C_l P_l \left(\frac{d\sigma_l}{d\Omega}\right) \tag{12}$$

As already mentioned, the THM data are not affected by electron screening effects. Therefore, once the behavior of the absolute bare $S_b(E)$ factor from the two-body cross-section is extracted, a model-independent estimate of the screening potential U_e can be obtained from comparison with the direct screened S(E)-factor.
Then, after normalization of the indirect data, the comparison between the two data sets can be performed down to the low energy region.

TABLE 1. Nuclei with cluster structure which can have been used as Trojan Horse nuclei and their principal properties

	TH -nucleus	binding energy MeV	Clusters	Intercluster motion
1	d	2.225	$p-n$	l=0
2	t	6.257	$n-d$	l=0
3	^{3}He	5.494	$p-d$	l=0
4	^{6}Li	1.475	α - d	l=0
6	^{7}Li	2.468	α - t	l=1
7	^{7}Be	1.587	α- ^{3}He	l=1
8	^{9}Be	2.467	α- ^{5}He	l=0

CONCLUSIONS

An experimental program has already been undertaken to study p-capture reactions on $^{6,7}Li$, main responsible for their destruction [Pizzone et al. 2005, 8]. The extracted S(E) factors as well as electron screening potentials, extracted as stated above are shown in table III. Recently, $^3He(d,p)^4He$ and $^{11}B(p,\alpha)^8Be$ were also investigated by selecting the quasi-free contribution to the $^3He(^6Li,\alpha p)^4He$ and $^{11}B(^2H,\alpha^8Be)n$ three-body processes. Their importance is indeed strongly related to the cosmology as well as to stellar structure and evolution. The bare nucleus S(E)-factor for the $^3He(d,p)^4He$ and $^{11}B(p,\alpha)^8Be$ are reported in table 3 as well.

The present paper presents the basic features of the THM and a review of recent applications to several reactions of importance in astrophysics.In particular these results show the possibility of extracting the bare nucleus two-body cross section via THM.However, a lot remains to do in the future to achieve reliable information for many key reactions and processes. New theoretical developments are strongly needed especially for the study of electron screening effects in fusion reactions in order to meet progress in the application field (fusion reactors). This information and the evaluation of fusion reaction cross sections will help to determine the basic properties of future reactors as well as plasma confinement devices.

TABLE 2. Two-body reactions studied via Trojan Horse Method

	Direct reaction	Indirect reaction	E_{inc} (MeV)	Q (MeV)	q_t (MeV/c)	TH_{nucl}	ref
[1]	$^{7}Li(p,\alpha)^{4}He$	$^{7}Li(d,\alpha\ \alpha)n$	19,22	15.122	391	$d = (p \obar n)$	[Lattuada et al. 2001]
[2]	$^{6}Li(d,\alpha\ )^{4}He$	$^{6}Li(^{6}Li,\alpha\ \alpha)^{4}He$	5	22.372	136	$^{6}Li = (\alpha \odot d)$	[Spitaleri et al. 2001]
[2]	$^{6}Li(d,\alpha\ )^{4}He$	$^{6}Li(^{6}Li,\alpha\ \alpha)^{4}He$	5	22.372	136	$^{6}Li = (\alpha \odot d)$	[Spitaleri et al. 2001]
[3]	$^{6}Li(p,\alpha)^{3}He$	$^{6}Li(d,\alpha\ ^{3}He)n$	14, 25	1.795	263	$d = (p \oplus n)$	[14]
[4]	$^{11}B(p\ ,\alpha)^{8}Be$	$^{11}B(d\ ,^{8}Be\ \alpha)n$	27	6.36	370	$d = (p \obar n)$	[Spitaleri et al. 2004]
[5]	$^{10}B(p,\alpha)^{7}Be$	$^{10}B(d,^{7}Be\ \alpha)n$	27	-1.079	360	$d = (p \oplus n)$	[7]
[6]	$^{9}Be(p,\alpha)^{6}Li$	$^{9}Be(d,^{6}Li\ \alpha)n$	22	-0.099	360	$d = (p \obar n)$	[12]
[7]	$^{2}H(^{3}He,p)^{4}He$	$^{6}Li(^{3}He,p\ \alpha)^{4}He$	5, 6	16.88	83-95	$^{3}He = (p \obar n)$	[4]
[8]	$^{2}H(d,p)^{3}H$	$^{2}H(^{6}Li,t\ p)^{4}He$	14	2.59	112	$^{6}Li = (\alpha \odot d)$	[9]
[9]	$^{12}C(\alpha,\alpha)^{12}C$	$^{12}C(^{6}Li,\alpha\ ^{12}C)^{2}H$	20	1.47	130	$^{6}Li = (\alpha \odot d)$	[Spitaleri et al. 2000]
[10]	$^{15}N(p,\alpha)^{12}C$	$^{15}N(p,\alpha^{12}C)n$	60	2.74	645	$d = (p \obar n)$	[5]
[11]	$^{18}O(p,\alpha)^{15}N$	$^{18}O(p,\alpha^{15}N)n$	54	1.76	668	$d = (p \oplus n)$	[6]

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TABLE 3. Two-body reactions results in recent experiments as regards the astrophysical S(E)factor and the electron screening potential

	Reaction	$U_e^{Adiab.}$ (eV)	U_e^{Dir} (eV)	U_e^{THM} (eV)	$S(0)^{Dir}$ (MeVb)	$S(0)^{THM}$ (MeVb)
[1]	^{7}Li + p $\rightarrow \alpha + \alpha$	186	300±160	330± 40	0.059	0.055±0.003
[2]	^{6}Li + d $\rightarrow \alpha + \alpha$	186	330±120	340±50	17.4	16.9±0.5
[3]	^{6}Li + p $\rightarrow ^3He + \alpha$	186	440±150	450±100	2.86	3.0±0.3
[4]	$^{11}B + p \rightarrow ^8Be + \alpha$	304	430±80		2.1	
[6]	d + $^3He \rightarrow p + \alpha$	115	219±7	180±40	6.51	6.08±1.42

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