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Nuclear reactions involving light elements & BBN

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Abstract. Light elements play a key role in different scenario in astrophysics, ranging from primordial nucleosynthesis up to stellar nucleosynthesis and cosmic ray nucleosynthesis. The nuclear reaction cross section measurements of interest in primordial and stellar nucleosynthesis have been investigated in terrestrial laboratories via devoted experiments. However, because of the difficulties in reaching the Gamow energy windows of interest for such processes through direct approaches, the indirect Trojan Horse Method (THM) have been used in the last '30 years for shedding light on some unsolved questions. After an introductory discussion about the role of the light elements, the discussion will be focused on the application of THM to two different case studies.

1 Introduction

The cosmic abundances of the light element lithium, beryllium and boron (LiBeB) play an important role in the understanding of at least three different topics in astrophysics, such as primordial nucleosynthesis, stellar nucleosynthesis and cosmic rays induced nucleosyntheis, as firstly highlighted in the seminal B^2FH paper [1]. In case of stellar physics, the simultaneous determination of LiBeB abundances offer the unique opportunity of studying stellar structure and mixing phenomena. Indeed, because of their different fragility against (p,α) reactions at different stellar depths, their residual atmospheric abundances reflect the effect of plasma mixing phenomena [2]. Taking into account that in a stellar environments thermonuclear fusion reactions depleting LiBeB can be triggered at the relatively low temperatures of few 10^6 K, devoted cross section measurements need to be performed in order to cover the corresponding Gamow windows centered at energies of some tens of keV, being these values order of magnitude lower than the Coulomb barrier for proton-induced thermonuclear reactions of about some MeV. Thus, the tunneling effect through the Coulomb barrier reduces cross section values to the regime of nano or picobarn (depending on the nuclei involved), making direct cross-section measurements very challenging. Thus, extrapolations are often invoked, even if they could be affected by additional sources of uncertainties such as those related to the contribution of the tail of subthreshold resonances and/or those related to *electron screening effect* [3], for which a complete understanding is far from being reached. Indeed, the current available theoretical models (i.e. adiabatic approximation [4]) largely underestimate the electron screening potential values with respect those measured in terrestrial laboratories, as one can see from an inspection of Tab.1.

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Reaction	$U_{theor.}$ (eV)	$U_{exp.}$ (eV)
^{2}H(d,p)^{3}H	14	13.4±0.6
^{6}Li(p,α)^{3}He	186	440±150
^{6}Li(d,α)^{4}He	186	330±120
H(^{7}Li,α)^{4}He	186	300±160
^{2}H(^{3}He,p)^{4}He	65	109±9
^{3}He(^{2}H,p)^{4}He	120	219±7
H(^{9}Be,α)^{6}Li	240	900±50
H(^{11}B,α)^{8}Be	340	430±80
H(^{17}O,α)^{14}N	594	1356±1037

Table 1. The adiabatic values for electron screening potential U_e (second column) to be compared with the experimental ones (third column).

2 Indirect approaches for experimental nuclear astrophysics: the Trojan Horse Method

To overcome the difficulties discussed above, indirect approaches have been largely adopted in the field of experimental nuclear astrophysics over the last ~30 years [5–8]. Among them, the Trojan Horse Method (THM) has been largely applied to 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. By means of a THM approach, the experimenter can deduce the bare-nucleus cross-section of a charged-particle induced reaction a+x→c+C at astrophysical energies free of Coulomb suppression and electron screening effects, by performing the experimental study of an appropriate 2→3 body reaction a+A→c+C+s and, among the possible reaction mechanims feeding the output channel $c + C + s$, selecting only the quasi-free (QF) one. It must be noticed that [8]:

- the 2→3 experiment is performed at energies well above the Coulomb barrier;
- nucleus A has a dominant x⊕s cluster configuration;
- nucleus A is selected according also to its relatively low binding energy and its well known momentum distribution for the x-s intercluster motion.

By invoking the simplest Plane Wave Impulse Approximation (PWIA), the link between the cross section of the a(x,c)C reaction and the 2→3 one is given by

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

being KF a kinematic 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 [9, 10]. 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. The method has been largely applied in the past for studying astrophysically relevant reactions involving both stable (i.e. [11–14]) and unstable beams (i.e. [15, 16]) in which also neutrons are involved. An in-depth discussion about the method as well as its recent applications can be found in [8].

2.1 Cross section measurements via THM: the case of the ^{11}B(p,α_0)^{8}Be reaction

The ^{11}B(p,α)^{8}Be represents the main destruction channel for the most abundant boron isotope in stars. Beside its role in astrophysics, the interest on studying the ^{11}B(p,α)^{8}Be reaction has increased in the last years because of its role as a possible aneutronic fusion reaction of interest for energy generation and plasma physics studies [17–19]. In addition to ^{11}B, natural boron accounts also for a ~20% of ^{10}B. Thus, devoted experiments were also performed to measure the corresponding burning (p,α) cross section via THM [11] as well as to study its nuclear structure [20]. In the two different ^{11}B(p,α)^{8}Be THM investigastions [7, 21], a 27 MeV ^{11}B beam provided by the Tandem accelerator of INFN-LNS (Catania, Italy) was delivered onto a ~200μg/cm^2 CD_2 target manufactured by the local target laboratory. In order to study the astrophysically relevant ^{11}B(p,α)^{8}Be reaction, the quasi-free component of the 2→3 ^{2}H(^{11}B,α^8Be)n reaction was investigated. By following the momentum-energy prescription necessary for the application of the method (see [22] for instance), two-out-of-three of the exit particles have been detected, namely alpha's and ^{8}Be nuclei, and the corresponding energies and emission angles determined. The kinematic quantities for the *undetected* neutron were reconstructed by invoking energy and momentum conservation laws [8]. Because of its decay, ^{8}Be events have been "reconstructed" as coincidence on proper position sensitive silicon detectors [7, 21]. Such as solution allowed us to investigate only the α_0 channel (i.e. the one for which a ^{8}Be in its ground state is produced). After the selection of the three body exit channel by using the standard THM approach (reconstruction of the experimental Q-value spectrum, reconstruction of the experimental kinematical locus, investigation of relative energy spectra to investigate the population of the intermediate ^{12}C nucleus), an in-depth data analysis was carried out to select the QF reaction mechanism. Indeed, in the proposed ^2H+^{11}B experiment, deuteron has been used as TH-nucleus because of its obvious p-n structure, its binding energy of ~2.2 MeV and its well-known momentum distribution usually described in terms of the Hulthén wave function in momentum space [10]. Further, we were interested in the QF events for which neutron acted as *spectator* of the virtual ^{11}B(p,α)^{8}Be reaction. Detailed studies were then performed in order to deduce the experimental momentum distribution of the deuteron and to compare it with both plane-wave and distorted-wave theoretical description (see [21] for details). By only considering events belonging to a strict condition on neutron momentum values ($-30<p_n<30$ MeV/c), the bare-nucleus THM cross section was extracted and then, after a proper normalization with the direct data of [23], the zero-energy S(E)-factor derived leading to the value of S(0)=2.07±0.41 MeV b. Further, by comparing THM result with the low-energies data of Becker et al. [23], the experimental value of 472±160 eV was deduced for the electron screening potential to be compared with the adiabatic one of 340 eV thus confirming the discrepancies between experimental and theoretical values [21].

2.2 BBN cross section measurements via THM: the case of the ^{7}Be(n,α)^{7}Be reaction

Big Bang Nucleosynthesis (BBN) is one of the three-pillars for the Big Bang cosmological model, together with Hubble expansion and the existence of the relic cosmic microwave background (CMB) radiation. BBN predicts observables quantities of the primordial abundances for the light elements ^{2}H, ^{3,4}He and ^{7}Li by simply using the baryon-to-photon ratio η as a free parameter, once neutron lifetime and neutrino families have been fixed (see for details [24] and references therein). Although the *observed* abundances for ^{2}H, ^{3,4}He nicely agree with those *predicted* by BBN, a disagrement of a factor ~2.5-3 exists if one considers the ^{7}Li abundances. This evidence triggered the so-called "cosmological lithium problem"

for which possible solutions were (and still are!) explored in different fields such as astronomical observations, nucleosynthesis in old-stars, particle physics (also beyond the standard model) and nuclear physics [24].
From a pure nuclear physics point of view, several efforts were made in the years for measuring both the production and destruction reaction channels affecting the ^{7}Li nucleosynthesis. Recently, nuclear physics community focused its interest on the role played by the neutron induced reactions on the unstable ^{7}Be nucleus which enters in the final budget of ^{7}Li abundance because of its electronic capture ^{7}Be(e$^-$,ν_e)^{7}Li [24]. Further, the neutron-induced reactions on ^{7}Be have been investigated in the recent papers of [25] and [26], showing for the first time the application of THM to neutron induced reactions involving radioactive isotopes. In the first experiment of [25], the ^{7}Be(n,α)^{4}He of interest for BBN was studied via the devoted THM experiment ^{2}H(^{7}Be,$\alpha\alpha$)p experiment performed at the EXOTIC facility [27] of Laboratori Nazionali di Legnaro (INFN-LNL) using a 20.4 MeV ^{7}Be beam impinging on a CD_2 target with a thickness of 400 μg/cm^2. Deuteron was used again as TH-nucleus but here, with respect the ^{11}B(p,α) investigation discussed above, neutron acted as *participant* while the proton has been thought as *spectator*. Detection setup was thought to detect energies and emission angles of the outgoing alpha particles while the kinematic of the proton was reconstructed by means of energy and momentum conservation laws. As improvement of the experiment, the study we performed in [26] allowed us also to investigate the ^{7}Be(n,p_0)^{7}Li and ^{7}Be(n,p_1)^{7}Li reaction channels, being the ones mostly influencing the final abundance of lithium-7 at BBN energies. In this case, the experiment was performed at the CRIB facility of University of Tokyo [28] via a ~22 MeV ^{7}Be beam impinging on a 64μg/cm^2 CD_2 target. Both experiments followed the standard procedure of firstly selecting the events belonging only to the QF-component (via the study of the experimental momentum distribution, for instance) and secondly by deriving the reaction rates at BBN energies once THM-cross sections were normalized to the available direct data [29–32]. Thus, the THM reaction rates were used as input for devoted BBN abundances calculations by means of the PRIMAT code [33], resulting in a reduction of the primordial ^{7}Li abundance by about one-tenth with respect to previous evaluations. Although still incomplete, these results can be accounted as part of the solution to the cosmological lithium problem [26].

3 Conclusions

THM is a complementary tool in experimental nuclear astrophysics for studying nuclear reactions of interest for astrophysics triggered with stable or unstable isotopes involving either charged-particles and neutrons as well. In this brief contribution, two case studies were summarized to highlight the main advantages of using THM, the main steps of a typical THM analysis and the impact in astrophysics. The author is in debt with all for sharing their interest for these fascinating research topics. The author thanks the organizers of the ISNA23 Symposium for the high-quality of the proposed program and the fruiful discussions triggered in a friendly atmosphere. The author acknowledge the PIA.CE.RI. 2020/2022 program of University of Catania.

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