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Clusterization of light nuclei and the Trojan Horse Method

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Abstract. The THM is a unique indirect technique to measure astrophysical rearrangement reactions down to astrophysical relevant energies, where direct experiments are unfeasible. This is done by measuring a suitable three body process in quasi free kinematics. The basic principles are recalled and some applications presented.

1. Introduction

A critical issue in nuclear astrophysics is the Coulomb barrier that makes the study of all nucleosynthesis processes at the relevant energies extremely challenging. The Coulomb repulsion between like charges is indeed responsible for the exponential decrease of the cross section $\sigma(E)$ at those energies. Thus, its behaviour at low energies is quite often extrapolated from higher energies (usually E>100 keV) by means of the astrophysical S(E)-factor

$$S(E) = E\sigma(E)\exp(2\pi\eta), \tag{1}$$

with η the Coulomb parameter of the colliding nuclei, and $\exp(2\pi\eta)$ the inverse of the Gamow factor that removes the Coulomb dependence of $\sigma(E)$. However, extrapolation can be source of additional uncertainties for $\sigma(E)$ due, for instance, to the presence of unexpected resonances.

Another critical issue in the laboratory measurement of nucleosynthesis processes is represented by the electron screening effect that leads to an increased cross section for screened nuclei, $\sigma_s(E)$, compared to the cross section for bare nuclei $\sigma_b(E)$ [1, 2]. Therefore, the so called screening factor, defined as

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

where U_e is the so-called "electron screening potential"' [1, 2], has to be taken into account to determine the bare nucleus cross section. Indeed, this is the key parameter to determine a reaction rate and the only way to get it measured is via indirect methods ([3, 4] and references therein). They make use of direct reaction mechanisms, such as transfer processes (stripping and pick-up) and quasi-free reactions (knock-out reactions).

In particular, the Trojan Horse Method (THM) ([5, 6, 3] and references therein) has been successfully applied many times in the last two decades to reactions connected with fundamental astrophysical problems. Here we present some of the basic ideas of the THM.

2. Characteristics of the Trojan Horse Method

The THM applies to an appropriate three-body reaction $A + a \to c + C + s$ performed in quasi free (QF) kinematics at energies well above the Coulomb barrier to extract the cross section of a charged particle two-body process $A + x \to c + C$ in the Gamow energy window. This is done making use of the theory for direct reactions, assuming that the nucleus a is described in terms of the $x \oplus s$ cluster structure, e.g. its wave function is required to have a large amplitude for a $x \oplus s$ cluster configuration. In most of the applications performed so far, where a = deuteron, x = proton, s = neutron [7, 8, 9, 10, 11], this is an obvious assumption. The high energy in the $A+a$ entrance channel ensures that the two body interaction takes place inside the nuclear field, without experiencing either Coulomb suppression or electron screening effects. The $A+a$ relative motion is compensated for by the $x - s$ binding energy, determining the so called "quasi-free two-body energy" given by

$$E_{QF} = \frac{m_x}{m_x + m_A} E_A - B_{x-s}. \tag{3}$$

where E_A represents the beam energy, m_x and m_A are the masses of x and A particles respectively, and B_{x-s} is the binding energy for the $x - s$ system. This can be retained as a prescription to determine the best value of the beam energy to populate the relevant E_{QF}. A cutoff in the momentum distribution reflecting the Fermi motion of s inside the Trojan-horse a, defines the range of energies around E_{QF} accessible in the astrophysical relevant reaction. In the Plane Wave Approximation, the three body-cross cross section can be factorized as:

$$\frac{d^3\sigma}{dE_c d\Omega_c d\Omega_C} \propto [KF \, |\varphi_a(\mathbf{p}_{sx})|^2] \left(\frac{d\sigma}{d\Omega_{c.m.}}\right)^{\mathrm{HOES}} \tag{4}$$

where KF is a kinematical factor containing the final state phase-space factor. It is a function of the masses, momenta and angles of the outgoing particles [7]; $\varphi_a(\mathbf{p}_{sx})$ is proportional to the Fourier transform of the radial wave function $\chi(\mathbf{r})$ for the $x - s$ inter-cluster relative motion; $(d\sigma/d\Omega_{c.m.})^{\mathrm{HOES}}$ is the half-off-energy-shell (HOES) differential cross section for the binary reaction at the center of mass energy $E_{c.m.}$ given in post-collision prescription by

$$E_{c.m.} = E_{cC} - Q_{2b} \,. \tag{5}$$

Here, Q_{2b} is the Q-value of the binary reaction and E_{cC} is the relative energy of the outgoing particles c and C. Using the PWA does not change the energy dependence of the two-body cross section but only its absolute magnitude.

In a typical THM experiment the decay products (c and C) of the virtual two-body reaction of interest are detected and identified by means of telescopes (silicon detector or ionization chamber as ΔE step and position sensitive detector as E step) placed at the so called quasi free angles. After the selection of the reaction channel, the most critic point is to disentangle the quasi free mechanism from other reaction mechanisms feeding the same particles in the final state, e.g. sequential decay and direct break-up. An observable which turns out to be very sensitive to the reaction mechanism is the shape of the experimental momentum distribution of the spectator. In order to reconstruct the experimental p_s distribution, the energy sharing method [12] is applied for each pair of coincidence QF angles, selecting c-C relative energy windows of 50 to 100 keV. The extracted experimental momentum distribution is then compared with the theoretical one and further data analysis is limited to the data lying in the region where the agreement between the two distributions exists (usually within few tens of MeV/c).

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Therefore, it is possible to derive the HOES $((d\sigma/d\Omega_{cm})^{\mathrm{HOES}}$ from the three-body coincidence yield by simply inverting eq.5. In a final step, the HOES cross section has to be related to the relevant on-energy-shell (OES) cross section by applying the corresponding corrections. In a heuristic approach this consists essentially in replacing the Coulomb suppression in the HOES cross section, by means of the penetrability factor:

$$P_l(k_{Ax}R) = \frac{1}{G_l^2(k_{Ax}R) + F_l^2(k_{Ax}R)} \tag{6}$$

with F_l and G_l regular and irregular Coulomb wave functions. It was demonstrated that there is no Coulomb barrier in the two-body amplitude extracted from the TH reaction [13, 10, 14] and this is due to the virtuality of particle x. This seems to be the only consequence of off-energy-shell effects as suggested by the agreement between HOES and OES cross-sections for the ^{6}Li(n,α)^{3}H reaction [15].
This procedure does not allow us to extract the absolute value of the two-body cross section. However this is not a real problem since the absolute magnitude can be derived from a scaling to the direct data available at higher energies.
For resonant the two-body reactions, $(d\sigma/d\Omega_{c.m.})^{\mathrm{HOES}}$ has to be worked out to determine the corresponding on-energy-shell (OES) S(E) factor. The corresponding theoretical formalism has been recently developed in a very rigorous way [16] leading to the so called modified R-matrix approach that accounts for HOES effects due to the virtual nature of particle x. By fitting the experimental THM cross section, the reduced width amplitude γ for entrance and exit channels, energy levels and energy shifts can be deduced and used to determine the astrophysical S(E) factor, since these parameters are the same in both direct and THM data. In this way, an exact parameterization of the astrophysical S(E) factor can be obtained overcoming the extrapolation. If the resonance parameters of a single level in the relevant energy region are known, they can be fixed in the fitting procedure to obtain directly the astrophysical S(E) factor in absolute units. Several test studies have been performed in the past years to validate the THM [17], such as the invariance of the two-body reaction amplitude with changing the Trojan Horse nucleus hiding the participant cluster x [18, 19, 20], or the use of momentum distributions from Distorted Wave Born Approximation instead of the simple PWA shape, providing same results within experimental errors [21, 22]. The THM has been applied to many reactions of astrophysical interest connected to fundamental problems in different scenarios, from BBN nucleosynthesis [8, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33] to AGB and more explosive sites [34, 21, 35, 22, 36]. In the last years, reactions involving heavier systems, such as ^{12}C and ^{16}O have been investigated [37, 38].

3. The ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He reactions via the Trojan Horse Method

The Trojan Horse Method was applied for the first time to the ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He reactions by measuring the ^{2}H(^{3}He,p^{3}H)^{1}H and ^{2}H(^{3}He,n^{3}He)^{1}H processes in quasi free kinematics [28, 29, 31]. The ^{3}He+d experiment was performed at 17 and 18 MeV, corresponding to a d-d energy range from 1.5 MeV down to 2 keV. This range overlaps with the relevant region for Standard Big Bang Nucleosynthesis as well as with the thermal energies of future fusion reactors and deuterium burning in the Pre Main Sequence phase of stellar evolution. This is the first pioneering experiment in quasi free regime where the charged spectator is detected. Both the energy dependence and the absolute value of the bare nucleus S(E) factors have been extracted for the first time. They are shown in Figs. 1 and 2 for the for the ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He reactions respectively. THM data are reported as black symbols (full squares and full circles for the 17 and 18 MeV run respectively), with uncertainties accounting for statistical and normalization errors. TH data for the p+^{3}H run at 17 MeV experience a larger scatter with respect to those at 18 MeV, due to the lower statistics in that experiment. Nonetheless, a fair agreement between them is apparent. Direct data from the different sources are shown as colored symbols, as reported in the legend. Their overall trend experience a large scatter, with deviations of more than 15%, in particular for the ^{3}He+n channel, where a new direct study of the cross section over a larger energy region would be desirable. In contrast, the THM S(E) factors exhibit a much smoother behavior, with deviations from the direct data at ultra-low energies, because of the screening, and in the SBBN region.

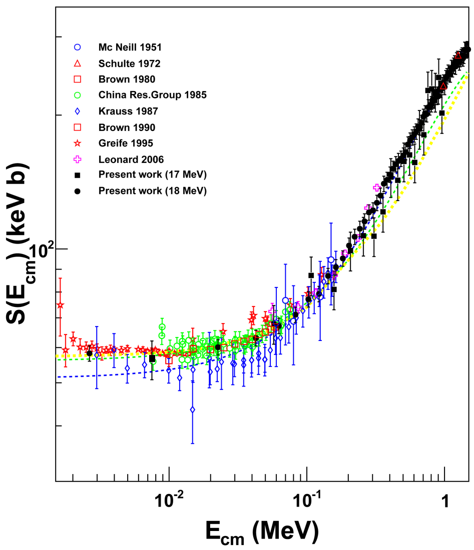

Figure 1. S(E) factor for the ^{2}H(d,p)^{3}H reaction: black solid squares and circles are THM data (17 and 18 MeV respectively); colored symbols represent direct data as described in the legend.

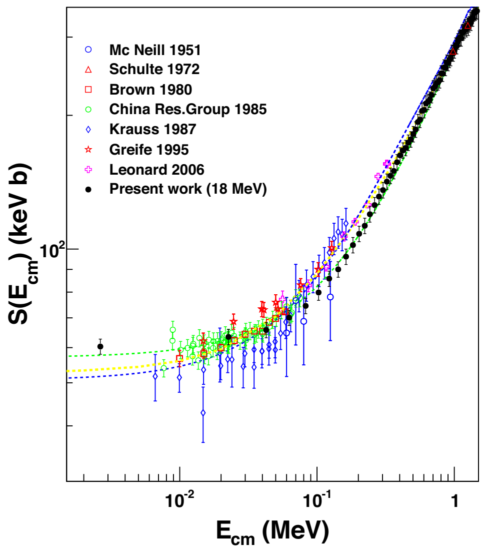

Figure 2. S(E) factor for the ^{2}H(d,n)^{3}He reaction: black solid circles are THM data (18 MeV run only for this channel); colored symbols represent direct data as described in the legend.

The THM S(0) values are of 57.7±1.8 MeVb for ^{3}H+p and 60.1±1.9 MeVb for ^{3}He+n. None of the existing fitting curves is able to provide the correct slope of the new data in the full range, thus calling for a revision of the theoretical description. This has consequences in the calculation of the reaction rates with a maximum increase of 20% at the temperatures of the Pre Main Sequence phase and of future fusion reactors.

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