Few-Body Syst (2013) 54:869–875
DOI 10.1007/s00601-013-0690-5

A. Tumino · C. Spitaleri · C. Bertulani
A. M. Mukhamedzhanov

Nuclear Astrophysics from View Point of Few-Body Problems

Received: 8 October 2012 / Accepted: 1 February 2013 / Published online: 27 February 2013

Abstract Few-body systems provide very useful tools to solve different problems for nuclear astrophysics. This is the case of indirect techniques, developed to overcome some of the limits of direct measurements at astrophysical energies. Here the Coulomb dissociation, the asymptotic normalization coefficient and the Trojan Horse method are discussed.

1 Introduction

Over the past 40 years nuclear physicists have been trying to measure the rates of the most relevant reactions for astrophysics, but there is still considerable uncertainty about their values. The main problem is the difficulty to measure the rates at the thermal energies relevant to stellar interiors. Although these temperatures are high, on the order of hundred million degrees, the corresponding reaction rates are extremely small making it difficult for them to be measured directly in the laboratory. Indeed, the cross sections $\sigma(E)$ at the relevant low energies E are extremely small due to the Coulomb barrier for charged particle reactions and in many cases unstable nuclei are involved in the reactions of astrophysical interest. As a consequence, direct experiments are very demanding and special experimental techniques have to be developed. Often one relies on an extrapolation of higher energy data to the relevant low energy range. This is accomplished by introducing the astrophysical factor $S(E) = \sigma(E)E\exp(2\pi\eta)$ that shows a weak dependence on energy for non-resonant reactions. The Sommerfeld parameter $\eta = Z_1Z_2e^2/(\hbar v)$ depends on the relative velocity v between the charged particles 1 and 2 in the initial state of the reaction. The extrapolation into unknown territory can be dangerous because of missed resonances, bound state tails etc. An additional problem is the electron screening effect for some direct

Plenary talk at the 20th International IUPAP Conference on Few-Body Problems in Physics, Fukuoka, Japan, 20–25 August 2012.

A. Tumino (✉) · C. Spitaleri
Laboratori Nazionali del Sud, INFN, Catania, Italy
E-mail: tumino@lns.infn.it

A. Tumino
Università degli Studi di Enna "KORE", Enna, Italy

C. Spitaleri
Dipartimento di Fisica e Astronomia, Università di Catania, Catania, Italy

C. Bertulani
Texas A&M University-Commerce, Commerce, TX, USA

A. M. Mukhamedzhanov
Cyclotron Institute, Texas A&M University, College Station, TX, USA

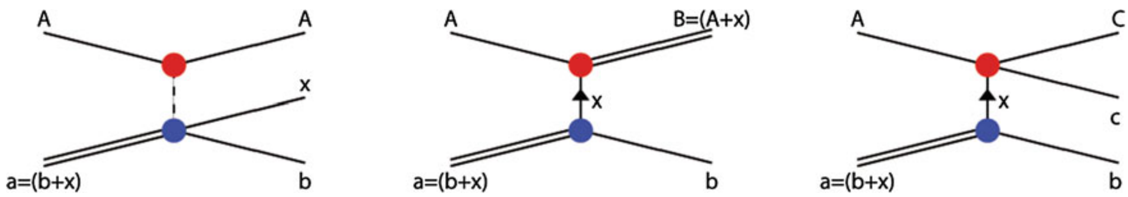

Fig. 1 Pole diagrams of the indirect methods: Coulomb dissociation (*left*), ANC method (*center*), and Trojan Horse Method (*right*)

measurements in the laboratory [20]. At extremely low energies, the measured cross sections are enhanced as compared to the cross sections for bare nuclei and correction have to be applied to the data. Unfortunately, this effect is not fully understood theoretically and independent experimental information is required. Thus, a number of indirect methods [1,2,11,20,21] have been introduced as alternative approaches for determining the bare nucleus S(E) factors of astrophysical interest. They make use of direct reaction mechanisms, such as transfer processes (stripping and pick-up) and quasi-free reactions (knock-out reactions). In this paper, general characteristics in the description of three closely related and successful indirect methods (Coulomb dissociation, asymptotic normalization coefficients, Trojan Horse method) are discussed. The first two methods mainly refer to radiative capture reactions $b(x,\gamma)a$ and are complementary approaches to extract their absolute astrophysical S factors as a function of the energy (CD) or at zero energy (ANC). The Trojan Horse method (THM) is applied to charged particle reactions either resonant or non resonant where no photons are involved and allows to extract the energy-dependence of their S(E) factors. All indirect approaches share some common features. The astrophysically relevant two-body reaction at low energies is replaced by a high-energy reaction usually with a three-body final state. In all cases a virtual particle (photon γ or nucleus x) is transferred between the two subsystems in the reaction. This is clearly seen from the diagrams in Fig. 1. The virtuality means that the transferred particle does not obey the usual dispersion relation of a free particle. For the ANC, x can be transferred into a bound state of nucleus B, thus feeding a two body final state instead of a three-body one (see Fig. 1 (center)).

The relation of the cross sections is found with the help of nuclear reaction theory. Approximations are essential to factorize the cross sections of the "surrogate" reactions into a contribution that can be calculated from theory and a quantity that more or less gives directly the cross section of the two-body reaction. This factorization is related to the appearence of two vertexes in the diagrams of Fig. 1. The approximations exploit the fact that the reaction mechanisms are dominated by peripheral processes where only the asymptotic part of the wave functions is relevant. This also leads to a selection of specific kinematical conditions in the indirect experiments.

2 Coulomb Dissociation Method

The Coulomb dissociation method [1,2], determines the absolute astrophysical S(E) factor of a radiative capture reaction $b(x,\gamma)a$ by studying the reversing $a(\gamma,x)b$ photodisintregration process. Instead of using real photons in the breakup reaction, the Coulomb field of a heavy target nucleus A is used as a source of virtual photons and the dissociation reaction $A(a,bc)A$ is measured experimentally. For large impact parameters (i.e. small scattering angles) in the projectile-target scattering, the nuclear contribution to the interaction potential can be neglected.

Then, the measured CD cross section assumes the simple form

$$\frac{d^2\sigma}{dE d\Omega_{aA}} = \frac{1}{E_\gamma}\sum_\lambda \sigma_{E\lambda}(a+\gamma\rightarrow b+x)\frac{dn_{E\lambda}}{d\Omega_{Aa}} \quad (1)$$

with virtual photon numbers $\frac{dn_{E\lambda}}{d\Omega_{Aa}}$ that can be calculated in quantal or semiclassical approximations. From the indirect experiment it is possible to extract the photo dissociation cross section $\sigma_{E\lambda}(a+\gamma\rightarrow b+x)$ and to convert it to the radiative capture cross section

$$\sigma_{E\lambda}(b+x\rightarrow a+\gamma) = \frac{2(2J_a+1)}{(2J_b+1)(2J_x+1)}\frac{k_\gamma^2}{k_{bx}^2}\sigma_{E\lambda}(a+\gamma\rightarrow b+x) \quad (2)$$

using the theorem of detailed balance. Since the factor k_γ^2/k_{bx}^2 is generally much smaller than one, the photodissociation process has a much larger cross section as compared to the radiative capture reaction. In addition, in a CD experiment the number of events is enhanced by large factors due to the huge virtual photon flux and to the possibility to use thicker targets. The expression (1) corresponds to a first-order approximation in time-dependent perturbation theory. It is only valid if higher-order contributions, i.e., multi-photon exchange with a post-acceleration of the fragments in the final state, and nuclear contributions to the breakup are neglected. These effects can be minimized by selecting appropriate kinematical conditions. In addition, large impact parameters, namely small fragment detection angles should be considered to make the nuclear contribution to the break-up negligible. Otherwise quantal calculations (DWBA/Eikonal) and optical potentials are needed. Moreover, one has to take properly into account that different multipolarities can contribute with different weights in the dissociation processes and radiative capture processes. This produces effects on angular distributions and on the slope of the extracted S factor [3–7]. This is the reason why a number of prescriptions should be followed in the analysis of a CD experiment:

- reconstruction of the three body reaction channel in complete kinematics: b and x fragments must be identified and detected in coincidence, measuring their energies and emission angles;
- detection of fragments at small angles (large impact parameters): this corresponds to bx relative angles of few degrees at most;
- selection of elastic break up events: they contribute as a straight line in a $\mathrm{E}_b - \mathrm{E}_x$ plot;
- reconstruction event by event of the E_{bx} relative energy by applying the so called magnifying glass effect: it consists in the selection of the kinematical regions where a large variation in the $\mathrm{E}_b(\mathrm{E}_x)$ variable corresponds to a small variation in E_{bx}. This provides an improvement of energy resolution in the E_{bx} variable such that $\Delta(\mathrm{E}_{bx})/\Delta(\mathrm{E}_b)$ is about 5 %. To reach this number, the relative angle between the fragments must be measured with good resolution;
- extraction of the angular distributions for different bins of E_{bx}: by fitting angular distributions with Eq. (1), $\sigma_{E\lambda}(a+\gamma \to b+x)$ can be extracted;
- theorem of detailed balance to get back to the relevant $\sigma_{E\lambda}(b+x \to a+\gamma)$.

3 ANC

The ANC technique [11] is based on the observation that direct proton-capture reactions of astrophysical interest involve systems where the binding energy of a captured charged particle is low. Hence at stellar energies, the capture proceeds through the tail of the nuclear overlap function. The shape of the overlap function in this tail region is determined by the Coulomb interaction, so the amplitude of the overlap function alone dictates the rate of the capture reaction. The ANC, C, for $A+p \leftrightarrow B$ specifies the amplitude of the tail of the overlap function for the system. Astrophysical S factors for peripheral direct radiative capture reactions can be determined through measurements of ANC's using traditional nuclear reactions such as peripheral nucleon transfer [11,12]. The ANC can also be used to determine the external part of Γ_γ for resonance capture [11]. Thus the ANC is connected to both the resonant and nonresonant capture amplitudes, and it can be used to determine astrophysical S factors when the capture occurs through a subthreshold resonance state [11].

It is easy to get the connection between ANCs and a direct proton capture rate at low energies. At stellar energies, the proton energy is small compared to the Coulomb barrier so the capture cross section is small. The cross section for the direct capture reaction $A+p \to B+\gamma$ can be written as

$$\sigma = \lambda \left| < I_{Ap}^B(\mathbf{r}) \mid \hat{O}(\mathbf{r}) \mid \psi_i^{(+)}(\mathbf{r}) > \right|^2, \tag{3}$$

where $\hat{O}$ is the electromagnetic transition operator, $\psi_i^{(+)}$ is the scattering wave in the incident channel, λ contains kinematical factors and I_{Ap}^B is the overlap function for $B \to A+p$. If the dominant contribution to the matrix element comes from outside the nuclear radius, the overlap function may be replaced by

$$I_{Ap}^B(r) \approx C\,\frac{W_{-\eta,l+1/2}(2\kappa r)}{r}, \tag{4}$$

where C, the ANC, defines the amplitude of the tail of the radial overlap function I_{Ap}^B, W is the Whittaker function, η and l are the Coulomb parameter and orbital angular momentum for the bound state $B = A+p$, and κ is the bound state wave number. If resonance parameters are known either from measurements or calculations and ANCs are known, the resonant and nonresonant components can be used together in an R-matrix calculation to obtain capture cross sections. As mentioned, peripheral transfer reactions provide an excellent way to determine ANCs. Consider the proton transfer reaction $(p = x)\, a + A \to b + B$, where $a = b + x,\; B = A + x$. Both the nucleus A in the initial state and the nucleus B in the final state are bound states of the transferred nucleus x. In this approach, the cross section factorizes as [11]:

$$\frac{d\sigma}{d\Omega_{Bb}} = \left|C^{a}_{bx}\right|^2 \left|C^{B}_{Ax}\right|^2 \frac{d\tilde{\sigma}}{d\Omega_{Bb}} \tag{5}$$

with a reduced DWBA cross section that has to be calculated with carefully adusted optical potentials. If one ANC is known, e.g. C^{B}_{Ax}, the second one C^{a}_{bx} can be extracted from the indirect experiment and it is just the one needed in Eq. 3 to determine the capture reaction cross section. In order to reduce the dependence of the result on the potential (or nuclear phase shift) in the scattering state of the $b + x$ system, only the S factor close to zero energy is considered. This procedure is justified for reactions where the nuclei b and x are only weakly bound in the ground state of a. In general, the relation between the ANC and the S factor is not unique. For stronger bound systems, the final-state interaction can lead to sizable changes in the zero-energy S factor. For a practical purposes, here some prescriptions to extract the ANCs from a transfer reaction:

- the reaction must be peripheral: this criterion can be checked with a DWBA code by changing the radius and diffuseness parameters for the binding of the transferred particle to the core and determining the cross section. In a peripheral transfer, the DWBA cross section will be nearly constant over a broad range of parameters, otherwise it will change by large factors.
- Once a reaction has been verified as being peripheral, the next step is to obtain accurate absolute differential cross sections.
- The final step for extracting ANCs requires good optical model parameters for the DWBA calculation. For stable beams and targets, the optical model parameters can be obtained from measurements of elastic scattering in the entrance channel. Exit channel parameters can similarly be obtained from elastic scattering measurements using beams and targets of isotopes of the outgoing system.

4 Trojan Horse Method

The THM [20–22] determines the cross section of the binary $A + x \to c + C$ process at astrophysical energies by measuring the two-body to three-body ($2 \to 3$) process, $A + a \to b + c + C$, in the quasifree (QF) kinematics regime, where the "Trojan Horse" particle, a has a strong $(b\,x)$ cluster structure. The $a + A$ interaction takes place at energies above the Coulomb barrier, such that nucleus a undergoes breakup leaving particle x already in the nuclear field of A, while b remains spectator to the binary reaction. 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

$$E_{q.f.} = E_{Aa} - B_{x-s} \tag{6}$$

where E_{Aa} represents the beam energy in the center-of-mass system and B_{x-s} is the binding energy for the $x - s$ system. Then, a cutoff in the momentum distribution, which is related to the Fermi motion of s inside the Trojan Horse a, fixes the range of energies around the "quasi-free two-body energy" accessible in the astrophysical relevant reaction. In the impulse approximation either in plane wave or in distorted wave (this does not change the energy dependence of the two-body cross section but only its absolute magnitude), the three body-cross cross section can be factorized as:

$$\frac{d^3\sigma}{dE_c d\Omega_c d\Omega_C} \propto [KF\; |\varphi_a(\mathbf{p}_{sx})|^2] \left(\frac{d\sigma}{d\Omega_{c.m.}}\right)^{\text{HOES}} \tag{7}$$

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 [28]; $\varphi_a(\mathbf{p}_{sx})$ is proportional to the Fourier transform of the radial wave function $\chi(\mathbf{r})$ for the $x - s$ inter-cluster relative motion; $(d\sigma/d\Omega_{c.m.})^{\text{HOES}}$ is the half-off-energy-shell (HOES) differential cross section for the binary reaction at the center of mass energy $\text{E}_{c.m.} = \text{E}_{cC} - \text{Q}_{2b}$. 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.

The HOES nature of the binary cross section is a consequence of the virtual nature of the transferred particle x. This means that its energy and momentum are not connected by the usual on-shell equation $E_x = k_x^2/(2\,m_x)$. 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. Data analysis follows a number of steps that can be listed as:

- identification of the three body reaction. This is usually done by means of the standard ΔE-E technique;
- selection of the quasi free mechanism. Often other competitive processes can contribute in the phase space region of interest [25,27,33]. The selection is done in several ways, mostly by looking at the shape of the experimental momentum distribution for the b particle. If QF condition is fulfilled, this shape should resemble the theoretical one that in PWIA is given by the Fourier transform of the radial wave function describing the relative motion between x and b;
- extraction of the binary cross section $\sigma_b(E)$ from the measured TH cross section in arbitrary units. At sub-Coulomb energies the penetrability factor has to be introduced;
- normalization of $\sigma_b(E)$ to $\sigma_s(E)$ (from direct data) in a region where screening is still negligible;
- validity test comparing direct and indirect data in terms of both excitation functions, including resonances, and angular distributions.

After these validations, THM data can be considered reliable where direct data are not available.

5 Recent Applications

CD, ANC and THM have been successfully applied to several reactions connected with fundamental astrophysical problems (see references [3–10] for CD, [12–19] for ANC, [22–37,40–42] for THM). A list of the most

Table 1 Reactions studied via indirect methods

Indirect reactions	Direct reactions	Indirect method	References
[1] ^{208}Pb(^{8}B, ^{7}Bep)^{208}Pb	^{1}H(^{7}Be, γ)^{8}B	CD	[3–7]
[2] ^{208}Pb(^{14}O, ^{13}Np)^{208}Pb	^{1}H(^{13}N, γ)^{14}O	CD	[8]
[3] ^{208}Pb(^{6}Li, αd)^{208}Pb	^{2}H(α, γ)^{6}Li	CD	[9]
[4] ^{208}Pb(^{15}C, ^{14}Cn)^{208}Pb	n(^{14}C, γ)^{15}C	CD	[10]
[5] ^{10}B(^{14}N)(^{7}Be, ^{8}B)^{9}Be(^{13}C)	^{1}H(^{7}Be, γ)^{8}B	ANC	[13]
[6] ^{16}O(^{3}He, d)^{17}F	^{1}H(^{16}O, γ)^{17}F	ANC	[14]
[6] ^{14}N(^{3}He, d)^{15}O	^{1}H(^{14}N, γ)^{15}O	ANC	[16]
[7] ^{12}C(d, p)^{13}C	n(^{12}C, γ)^{13}C	ANC	[15]
[8] ^{13}C(^{6}Li, d)^{17}O	^{4}He(^{13}C, n)^{16}O	ANC	[17]
[9] ^{14}N(^{13}N, ^{14}O)^{13}C	^{1}H(^{13}N, γ)^{14}O	ANC	[8]
[10] ^{12}N(^{3}He, d)^{13}O	^{1}H(^{12}N, γ)^{13}O	ANC	[18]
[11] ^{15}N(^{3}He, d)^{16}O	^{1}H(^{15}N, γ)^{16}O	ANC	[19]
[12] ^{2}H(^{7}Li, $\alpha\alpha$)n	^{1}H(^{7}Li, α)^{4}He	THM	[22]
[13] ^{3}He(^{7}Li, $\alpha\alpha$)d	^{2}H(^{7}Li, α)^{4}He	THM	[23]
[14] ^{2}H(^{6}Li, α^{3}He)n	^{1}H(^{6}Li, α)^{3}He	THM	[24]
[15] ^{6}Li(^{6}Li, $\alpha\alpha$)^{4}He	^{2}H(^{6}Li, α)^{4}He	THM	[25]
[16] ^{2}H(^{9}Be, α^{6}Li)n	^{1}H(^{9}Be, α)^{6}Li	THM	[26]
[17] ^{2}H(^{10}B, α^{7}Be)n	^{1}H(^{10}B, α)^{7}Be	THM	[27]
[18] ^{2}H(^{11}B, $\alpha_0{}^{8}$Be)n	^{1}H(^{11}B, α)^{8}Be	THM	[28,29]
[19] ^{2}H(^{15}N, α^{12}C)n	^{1}H(^{15}N, α)^{12}C	THM	[30]
[20] ^{2}H(^{18}O, α^{15}N)n	^{1}H(^{18}O, α)^{15}N	THM	[31]
[21] ^{2}H(^{17}O, α^{14}N)n	^{1}H(^{17}O, α)^{14}N	THM	[32]
[22] ^{6}Li(^{3}He, p^{4}He)^{4}He	^{2}H(^{3}He, p)^{4}He	THM	[33]
[23] ^{2}H(^{6}Li, p^{3}H)^{4}He	^{2}H(d, p)^{3}H	THM	[34]
[24] ^{6}Li(^{12}C, α^{12}C)^{2}H	^{4}He(^{12}C, ^{12}C)^{4}He	THM	[35]
[25] ^{2}H(^{6}Li, t^{4}He)^{1}H	n(^{6}Li, t)^{4}He	THM	[36,37]
[26] ^{2}H(p, pp)n	^{1}H(p, p)^{1}H	THM	[38,39]
[27] ^{2}H(^{3}He, p(n)^{3}H(^{3}He))p	^{2}H(^{2}H, p(n))^{3}H(^{3}He)	THM	[40,41]
[28] ^{2}H(^{19}F, α^{16}O)n	^{1}H(^{19}F, α)^{16}O	THM	[42]

relevant reactions studied so far is reported in Table 1. Some of the reactions have been studied with different methods and results are consistent, as in the case pf the $p(^7Be,\gamma)^8B$ reaction. The existing disagreement with the direct results in the ultra-low energy region is still under debate. There might be a contribution due to the electron screening in the direct experiment yet to be considered. We refer to the Bibliography (and references therein) for a deeper analysis of the relevant features of each experimental study.

Acknowledgments This work was supported in part by the US Department of Energy under Grant DE-FG02-93ER40773 and DE-FG52-06NA26207, No. de-sc0004958 (topical collaboration TORUS) and NSF under Grant No. PHY-0852653.

References

1. Baur, G., Bertulani, C., Rebel, H.: Coulomb dissociation as a source of information on radiative capture processes of astrophysical interest. Nuc. Phys. A **458**, 186 (1986)
2. Baur, G., Rebel, H.: Coulomb breakup of nuclei—applications to astrophysics. Annu. Rev. Nucl. Part. Sci. **46**, 321 (1996)
3. Motobayashi, T. et al.: Coulomb dissociation of ^{8}B and the $^7(p,\gamma)^8B$ reaction at low energies. Phys. Rev. Lett. **73**, 2680 (1994)
4. Davids, B. et al.: $S_{17}(0)$ determined from the Coulomb Breakup of 83 MeV/Nucleon ^{8}B. Phys. Rev. Lett. **86**, 2750 (2001)
5. Schuemann, F. et al.: Coulomb dissociation of ^{8}B and the low-energy cross section of the $^7Be(p,\gamma)^8B$ solar fusion reaction. Phys. Rev. Lett. **90**, 232501 (2003)
6. Esbensen, H. et al.: Reconciling Coulomb dissociation and radiative capture measurements. Phys. Rev. Lett. **94**, 42502 (2005)
7. Gai, M. et al.: Critical assessment of the claim of a significant difference between the results of measurements of the Coulomb dissociation of ^{8}B and the $^7Be(p,\gamma)^8B$ direct capture reaction. Phys. Rev C **74**, 025810 (2006)
8. Motobayashi, T. et al.: Determination of the astrophysical $^{13}N(p,\gamma)^{14}O$ cross section through the Coulomb dissociation method. PLB **264**, 259 (1991)
9. Hammache, F. et al.: High-energy breakup of ^{6}Li as a tool to study the Big Bang nucleosynthesis reaction $^2H(\alpha,\gamma)^6Li$. Phys. Rev. C **82**, 065803 (2010)
10. Esbensen, H. et al.: Coulomb dissociation of ^{15}C and radiative neutron capture on ^{14}C. Phys. Rev. C **80**, 024608 (2009)
11. Mukhamedzhanov, A.M., Tribble, R.E.: Connection between asymptotic normalization coefficients, subthreshold bound states and resonances. Phys. Rev. C **59**, 3418 (1999)
12. Mukhamedzhanov, A.M. et al.: Asymptotic normalization coefficient for $^{10}B \rightarrow ^9 Be + p$. Phys. Rev. C **56**, 1302 (1997)
13. Azhari, A. et al.: Asymptotic normalization coefficient for $^7Be(p,\gamma)^8B$. Phys. Rev. C **63**, 055803 (2001)
14. Gagliardi, C.A. et al.: Tests of transfer reaction determinations of astrophysical S factors. Phys. Rev. C **59**, 1149 (1999)
15. Imai, N. et al.: Test of the ANC method via (d,p) reaction. Nucl. Phys. A **688**, 281 (2001)
16. Bertone, F.P. et al.: $^{14}N(^3He,d)^{15}O$ as a probe of direct capture in the $^{14}N(p,\gamma)^{15}O$ reaction. Phys. Rev. C **66**, 055804 (2002)
17. Kubono, S. et al.: Determination of the Subthreshold State Contribution in $^{13}C(\alpha,n^{16}O$, the main neutron-source reaction for the s process. Phys. Rev. Lett. **90**, 062501 (2003)
18. Skorodumov, S. et al.: Lowest excited states of ^{13}O. Phys. Rev. C **75**, 024607 (2007)
19. Mukhamedzhanov, A.M. et al.: Asymptotic normalization coefficient and important astrophysical process $^{15}N(p,\gamma)^{16}0$. J. Phys. Conf. Ser. **202**, 012017 (2010)
20. Spitaleri, C. et al.: The Trojan Horse Method in nuclear astrophysics. Phys. Atomic Nuclei **74**(12), 1725 (2011)
21. Tumino, A., et al.: New advances in the Trojan Horse method as an indirect approach to nuclear astrophysics. Few-Body Syst. (2012). doi:10.1007/s00601-012-0407-1
22. Spitaleri, C. et al.: Indirect ^{7}Li(p,α)^{4}He reaction at astrophysical energies. Phys. Rev. C **60**, 055802 (1999)
23. Tumino, A., et al.: Validity test of the Trojan Horse Method applied to the ^{7}Li + p $\rightarrow \alpha + \alpha$ reaction via the ^{3}He break-up. *Eur. Phys. J. A.* (2006). doi:10.11140/epja/i2006-08-038-1
24. Tumino, A. et al.: Validity test of the "Trojan Horse" method applied to the ^{6}Li(p,α)^{3}He reaction. Phys. Rev. C **67**, 065803 (2003)
25. Spitaleri, C. et al.: "Trojan Horse" method applied to ^{2}H(^{6}Li, α)^{4}He at astrophysical energies. Phys. Rev. C **63**, 005801 (2001)
26. Wen, Q. et al.: Trojan Horse method applied to ^{9}Be(p, α)^{6}Li at astrophysical energies. Phys. Rev. C **78**, 035805 (2008)
27. Lamia, L. et al.: Indirect study of (p, α) and (n, α) reactions induced on boron isotopes. Il Nuovo Cimento **31**, 423 (2009)
28. Spitaleri, C. et al.: The ^{11}B(p, α_0)^{8}Be reaction at sub-Coulomb energies via the Trojan Horse method. Phys. Rev.C **69**, 055806 (2004)
29. Lamia, L. et al.: New measurement of the ^{11}B(p,α_0)^{8}Be bare-nucleus S(E) factor via the Trojan Horse method. J. Phys. G **39**, 015106 (2012)
30. La Cognata, M. et al.: Astrophysical S(E) factor of the ^{15}N(p, α)^{12}C reaction at sub-Coulomb energies via the Trojan horse method. Phys. Rev.C **76**, 065804 (2007)
31. La Cognata, M. et al.: A novel approach to measure the cross section of the ^{18}O(p, α)^{15}N resonant reaction in the 0-200 keV energy range. Astrophys. J. Lett. **708**, 796 (2010)
32. Sergi, M.L. et al.: Indirect measurement of ^{17}O(p, α)^{14}N cross section at ultra-low energies. Phys. Rev. C **82**, 032801(R) (2010)
33. La Cognata, M. et al.: Bare-nucleus astrophysical factor of the ^{3}He(d,p)^{4}He reaction via the "Trojan Horse" method. Phys. Rev. C **72**, 065802 (2005)

34. Rinollo, A. et al.: Measurement of cross section and astrophysical factor of the ^{2}H(d,p)^{3}H reaction using the Trojan Horse Method. Nucl. Phys. A **758**, 146 (2005)
35. Spitaleri, C. et al.: The $\alpha -^{12}$ C scattering studied via the Trojan Horse method. Eur. Phys. J. A **7**, 181 (2000)
36. Tumino, A. et al.: Quasi-free $^{6}Li(n,\alpha)^{3}H$ reaction at low energy from ^{2}H break-up. Eur. Phys. J. A **25**, 649 (2005)
37. Gulino, M. et al.: Study of the ^{6}Li(n, α)^{3}H reaction via the ^{2}H quasi-free break-up. J.Phys. G Nucl. Part. Phys. **37**, 125105 (2010)
38. Tumino, A., et al.: Suppression of the Coulomb interaction in the off-energy-shell p-p scattering from $p + d \rightarrow p + p + n$ reaction. Phys. Rev. Lett. **98**, 252502 (2007)
39. Tumino, A. et al.: Off-energy-shell p-p scattering at sub-Coulomb energies via the Trojan Horse method. Phys. Rev. C **68**, 064001 (2008)
40. Tumino, A., et al.: Low-energy d+d fusion reactions via the Trojan Horse Method. Phys. Letters B **700**, 111 (2011) and Erratum to "Low-energy d+d fusion reactions via the Trojan Horse Method". Phys. Lett. B 700(2), 111 (2011). Tumino, A., et al., Phys. Lett. B. **705**(5), 546 (2011)
41. Tumino, A. et al.: Indirect study of the $^{2}H(d,p)^{3}H$ and $^{2}H(d,n)^{3}He$ reactions at astrophysical energies via the Trojan Horse Method. Few Body Syst. **323**(1–4), 50 (2011)
42. La Cognata, M. et al.: The Fluorine destruction in stars: first experimental study of the ^{19}F(p, α_0)^{16}O reaction at astrophysical energies. Astrophys. J. Lett. **739**, L54 (2012)