EPJ Web of Conferences **17**, 06004 (2011)
DOI: 10.1051/epjconf/20111706004

Spectator invariance test in the study of the ^{6,7}Li fusion reactions via the Trojan Horse Method

R.G. Pizzone[12,a], L. Lamia[13], C. Bertulani[4], A. Mukhamedzhanov[2], C. Spitaleri[13], L. Blokhintsev[5], V. Burjan[6], S. Cherubini[13], Z. Hons[6], G.G. Kiss[1], V. Kroha[6], M.La Cognata[13], C. Li[7], J. Mrazek[6], S. Piskoř[6], S.M.R. Puglia[13], G.G. Rapisarda[13], S. Romano[13], M.L. Sergi[13], and A. Tumino[8]

[1] INFN-LNS, Catania, Italy
[2] Cyclotron Institute, Texas A&M University, College Station, USA
[3] Dipartimento di Fisica e Astronomia, Universitá di Catania,Italy,
[4] Department of Physics and Astronomy, Texas A&M University-Commerce, Commerce, USA
[5] Institute of Nuclear Physics, Moscow State University, Moscow, Russia
[6] Institute of Nuclear Physics of ASCR, Praha-Řež, Czech Rep
[7] Beijing Radiation Center, Beijing, China
[8] Università degli Studi di Enna "Kore", Enna, Italy

Abstract. Fusion reactions play a crucial role for several astrophysical scenarios. At the low energies typical of such environments direct measurements of reaction cross sections are very difficult, and even sometimes impossible. In such cases the use of indirect methods can give a substantial help. The Trojan Horse Method (THM) is based on the quasi-free break-up of a nucleus, which can be described in terms of a cluster structure. In such applications the independence of THM results with different break-up schemes, was tested using the quasi free^{3}He(^{6}Li,$\alpha\alpha$)H and ^{3}He(^{7}Li,$\alpha\alpha$)^{2}H reactions. Results were then compared with the direct behaviours obtained from available data as well as with the cross sections extracted from previous indirect investigations of the same binary reactions using a different nuclide as a Trojan Horse nucleus.

1 Introduction

Fusion reactions induced by charged particles at astrophysical energies have many experimental difficulties, mainly connected to the presence of the Coulomb barrier and the electron screening effect. So several indirect methods have been developed, mainly based on direct reactions mechanisms (e.g. ANC [1]) . Among them, an important role is played by the Trojan Horse Method (THM) which is discussed extensively elsewhere [2–9]. In recent years many tests have been made to deepen the knowledge of the method and to extend its possible applications: the target-projectile break-up invariance [10], the spectator invariance [11, 12] and the possible application to neutron beams [13,14]. Such studies are crucial, as the Trojan Horse method has become one of the major tools for the investigation of reactions of astrophysical interest. In a recent work [11] a test TH nucleus invariance was performed for the ^{7}Li(d,$\alpha\alpha$)n and the ^{7}Li(^{3}He,$\alpha\alpha$)^{2}H reactions, thus comparing results from deuteron and ^{3}He targets. In Ref. [11] the ^{7}Li(p,α)^{4}He two-body cross section was deduced in the Plane wave impuls approximation (PWIA) using only a part of the collected experimental data, and compared with the direct behavior as well as with previous indirect data from the ^{7}Li(d, $\alpha\alpha$)n [15]. Agreement between the sets of data was found below and above the Coulomb barrier. This suggests that ^{3}He is a good "Trojan Horse nucleus", in spite of its quite high ^{3}He→ d + p break-up energy (5.49 MeV) and that the THM cross section does not depend on the chosen Trojan Horse nucleus, at least for the ^{7}Li-p interaction. Here we report on a recent investigation of the ^{6}Li(p,α)^{4}He reaction by means of the quasi free ^{3}He(^{6}Li,$\alpha\alpha$)H. We reconsider also the final results of ^{3}He(^{7}Li,$\alpha\alpha$)^{2}H experiment with all the available collected data.

Our aim is to show that in both cases the PWIA is valid and that the use of a different spectator particle does not influence the THM reliability, at least for the examined cases.

2 Experimental procedure

The Trojan Horse Method (THM) allows one to extract the low energy behavior of an astrophysically relevant binary reaction by applying the well known theoretical formalism of the Quasi-Free (QF) process. The basic idea of the THM [16] is to extract the cross

[a] e-mail: rgpizzone@lns.infn.it

Article available at http://www.epj-conferences.org or http://dx.doi.org/10.1051/epjconf/20111706004

section of an astrophysically relevant two-body reaction

$$a + x \to c + C \tag{1}$$

at low energies from a suitable three-body QF reaction.

$$a + b \to s + c + C. \tag{2}$$

Details of the THM are described elsewhere [3,2]. The independence of the differential cross section extracted from the TH reaction on the TH nucleus is called TH particle invariance of the HOES cross section [12]. It means that the study of a binary reaction of astrophysical interest, $a(x,c)C$, via a QF process with three particles in the exit channel, can proceed whatever the spectator particle is. Hence, instead of studying the binary reaction through the $a(b,cC)s$ reaction, one can study it by means of the $a(b^{'},cC)s^{'}$ reaction.

The present paper reports on the investigation of the ^{6}Li(d,α)^{4}He and ^{7}Li(p,α)^{4}He reactions by means of the THM applied to the ^{6}Li(^{3}He,$\alpha\alpha$)H and the ^{7}Li(^{3}He,$\alpha\alpha$)^{2}H three-body reactions respectively. The experiments were both performed at the Nuclear Physics Institute, Nuclear Reactions Department of the ASCR in Řež (Praha). The full description of the experimental set-up adopted is described in details in [12].

The first step of the analysis is to discriminate the three body reaction of interest from all the others induced by the interaction of the ^{3}He beam with the LiF target. This was achieved via the standard ΔE/E technique together with the investigation on the scatter plot of the detected alpha-particle energies, i.e. the so called kinematical locus for the selected events was studied and it turns out to be in agreement with our simulations. By means of energy conservation rules, the Q-value spectrum for the selected events was reconstructed. The position of a well separated peak is compared with the theoretical Q-value of 16.87 MeV for the ^{6}Li(^{3}He,$\alpha\alpha$)H reaction. The agreement, within the experimental uncertainties, is a signature of our good calibration and a precise selection of the three-body channel. Only these events falling inside the Q-value peak were taken in account in the following analysis.

3 Data Analysis and results

The next step of the THM data analysis is the study of the reaction mechanisms feeding the exit channel. This is a necessary step to disentangle the QF events from those ascribed to other mechanisms producing the same ejectiles in the final state. In particular, for our case, the study of the $E_{\alpha\alpha}$, $E_{\alpha p}$ and $E_{\alpha p}$ relative energies allows one to obtain information on the presence of excited states of ^{8}Be and ^{5}Li respectively. After removing this contribution as discussed in [12] the QF events are selected by studying the spectator particle momentum distribution.

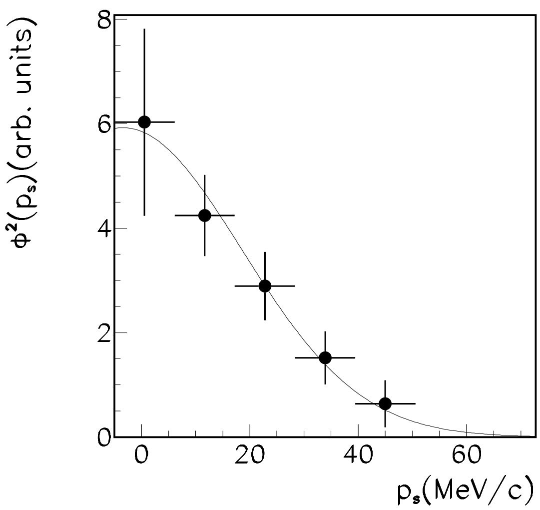

Fig. 1. Momentum distribution for p inside ^{3}He obtained as reported in the text. The FWHM is about 62±6 MeV/c.

The most sensitive variable to the involved reaction mechanisms is the momentum distribution shape $|\varphi(\mathbf{p_s})|^2$. Thus, the tests to discriminate the QF contribution from all the others are based on the study of this quantity. In order to extract the experimental momentum distribution of the spectator, $|\varphi(\mathbf{p_s})|^2_{exp}$, the energy sharing method can be applied to each pair of coincidence detectors, selecting narrow energy and angular windows, ΔE_{cm} and $\Delta\theta_{cm}$. The center-of-mass angle, θ_{cm}, is defined in [17]. The obtained momentum distribution for proton in ^{3}He is shown in Fig. 1. The solid line reported in the figure represents the Fourier transform of the Eckart function with a FWHM about 62±6 MeV/c, thus confirming the presence of the QF mechanism. This result is consistent with what has been observed for the ^{3}He nucleus in [18,19] as regards the correlation between the transferred momentum ($q_t \simeq 250$ MeV/c in the present case) and the width at half maximum of the experimental momentum distribution (see Fig. 2 for clearness). According to the prescription adopted in [20], data in the $|p_s| < 35$ MeV/c range were chosen and used in the further analysis.

The results were compared with recent results [18, 19] on distortion effects in reactions induced by light nuclei. The expected FWHM of the p momentum distribution in ^{3}He is around 64±5 MeV/c. In Figure 2 the good agreement of these results (black dots) is shown thus confirming what was observed for ^{3}He in [18,19] (solid line).

In the standard THM analysis, the half-off-energy-shell two body cross section is derived by dividing the experimental three-body one by the product of the kinematic factor and $|\varphi(\mathbf{p_s})|^2_{exp}$ [2], i.e.:

$$\frac{d^3\sigma}{dE_c d\Omega_c d\Omega_C} \propto KF \left(\frac{d\sigma}{d\Omega_{cm}}\right)^{off} \cdot |\varphi(\mathbf{p_s})|^2_{exp} \tag{3}$$

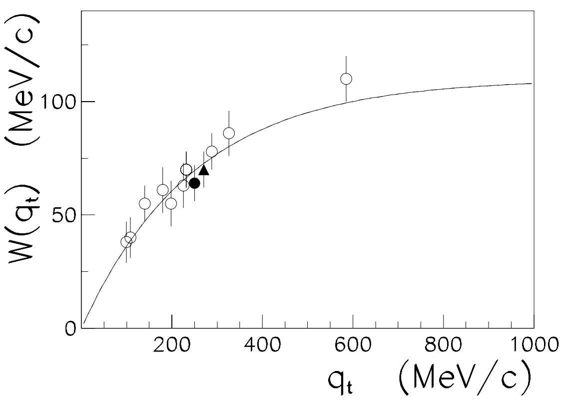

Fig. 2. Full width of the momentum distribution for p inside ^{3}He obtained as reported in the text compared with the behaviour (solid line) and data (open circles) reported in [18,19]. Results from present data are shown as a full circle for the ^{6}Li(^{3}He,$\alpha\alpha$)H and full triangle for the ^{7}Li(^{3}He,$\alpha\alpha$)^{2}H reaction.

where $[(d\sigma/d\Omega)_{cm}]^{off}$ is the half-off-energy-shell differential cross section for the $a(x,c)C$ two body reaction at the center of mass energy E_{cm} and KF contains the final state phase-space factor, function of the masses, momenta and angles of the outgoing particles.

The width of the momentum distribution, $|\varphi(\mathbf{p_s})|^2_{exp}$, was set to the experimentally measured value in order to account for the distortion effects arising at low transferred momenta [18,19].

The first validity check that standard THM prescriptions do recommend is to reproduce both the angular distribution as well as the direct excitation function both below and above the Coulomb barrier. This is done by comparing the distributions measured with direct methods to the one measured by means of THM. The latter should be normalized to the direct data.

In the present case the angular distribution was extracted for $E_{cm} = 2.940$ MeV which was also investigated in direct measurements present in literature [22]. In Figure 3 THM data are compared with direct data extracted from [22] (shown as a solid line) and a nice agreement shows up in the angular range where overlap is present.

The THM cross section obtained according to the standard prescription is then corrected for the penetrability factor (below the Coulomb barrier) which also make it possible the comparison of half-of-shell and on-shell data [21]. The penetrability factor is, as usual, described in terms of the regular and irregular Coulomb functions [2]. In particular, due to the presence of the l=2 resonant state in the entrance ^{6}Li-d channel, a function describing the non-resonant l=0 term as well as one describing the l=2 term were taken into account to get the THM data [12]).

The measured cross section, extracted by the THM, is compared, after normalization, in the $E_{cm} = 0.4-5$ MeV energy range with several data sets present in literature [22–25] (Figure 4). The agreement is very good throughout the whole energy range after normalization of the indirect to direct data. Moreover the resonance at about 3 MeV (corresponding to the 25.2 MeV, 2^+, energy level in ^{8}Be) is clearly reproduced.

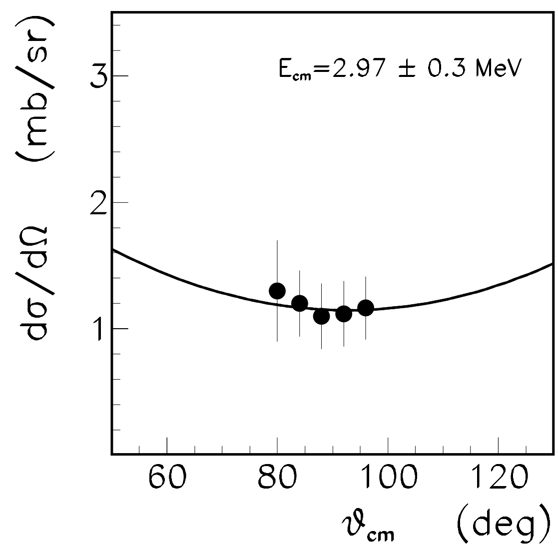

Fig. 3. Angular distribution for the ^{6}Li(d,α)^{4}He reaction extracted by means of THM (full circles). The indirect data are compared with direct ones (solid line) from [22]

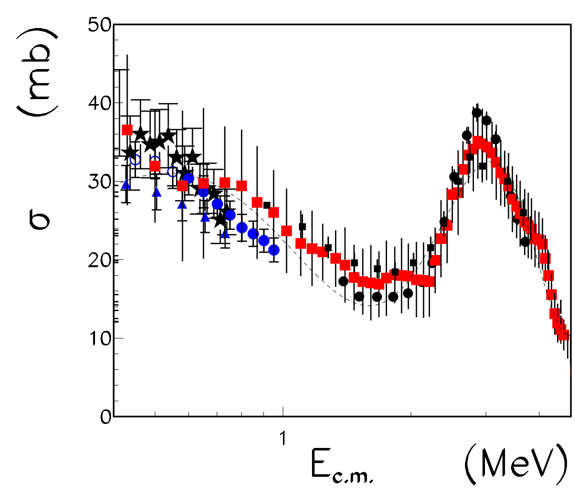

Fig. 4. Excitation function for the ^{6}Li(d,α)^{4}He reaction extracted by means of THM. The indirect data (red squares) are normalized and compared with direct ones from [22] (black dots), [23] (black squares),[24] (blue circles),[25] (triangles). The agreement is clearly evident both below and above the Coulomb barrier.

The investigation of this energy range is not relevant for astrophysical implications for the ^{6}Li depletion [26] but it provides a strong validity test for THM. In fact, the excitation function extracted in an indirect way does indeed reproduce the direct data both below and above the Coulomb barrier. Another interesting aspect of this analysis is the possibility to study the TH nucleus invariance of the QF mechanism [11].

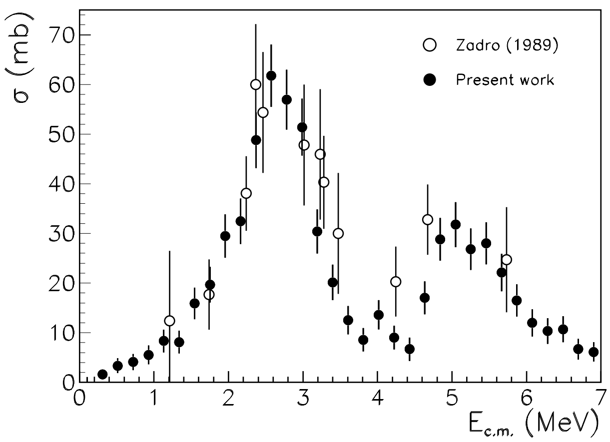

Fig. 5. ^{7}Li(p,α)^{4}He excitation function (full circles) extracted by means of the THM using ^{3}He as Trojan Horse nucleus, compared, after normalization, with data extracted from d break-up (open symbols) in the whole energy range.

If we focus in the $0.4 - 1$ MeV energy range, we can compare data for the ^{6}Li(d,α)^{4}He extracted from the ^{6}Li(^{3}He,$\alpha\alpha$)H reaction (present work) with the ones extracted from ^{6}Li(^{6}Li,$\alpha\alpha$)^{4}He [2,10] (black stars in figure 4). The agreement is very good within the experimental errors and extensively discussed in [12].

The ^{7}Li(p,α)^{4}He reaction was already studied with the same method discussed before for ^{6}Li(d,α)^{4}He. Again a test on the TH nucleus invariance was performed and results from the deuteron and ^{3}He break-up are compared. In Ref. [15] the ^{7}Li(p,α)^{4}He was studied through the deuteron break-up while in [11] ^{3}He break-up was investigated. The same standard analysis already presented in this paper was performed for the ^{7}Li(p,α)^{4}He (as reported in [11]), studied through the ^{3}He break-up via the ^{7}Li(^{3}He,$\alpha\alpha$)^{2}H three-body reaction. Here, results with the total collected events are presented.

In Fig. 5 the data extracted through d break-up from [15] are shown in Figure as empty circles superimposed onto the full dots arising from the present work. We can see that both resonances are reproduced and the agreement within the whole excitation function is very good also in this case. This gives a further validity test of the TH nucleus invariance in a different case and simultaneously above and below the Coulomb barrier. Also at lower energies the behaviour is coherent with data extracted from d break-up as reported in [27].

4 Conclusion

In this paper a full investigation of the ^{6}Li(^{3}He,$\alpha\alpha$)H reaction is presented. The QF contribution is extracted and the THM applied to retrieve information on the TH nucleus invariance of the ^{6}Li(d,α)^{4}He cross section at energies above and below the Coulomb barrier. A good agreement with the direct data is achieved as well as with THM data from ^{6}Li break-up is found in the whole energy range. The TH particle invariance is also validated for the ^{7}Li(p,α)^{4}He cross section extracted by means of ^{3}He break-up in the ^{7}Li(^{3}He,$\alpha\alpha$)^{2}H three-body reaction. Also in this case the agreement with direct data as well as with THM data obtained from the deuteron break-up is evident (see [11]).

We conclude that the PWIA is valid in both cases and that the use of a different spectator particle does not influence the THM result.

References

1. A. Mukhamedzhanov A., et al., Phys. Rev. C **78**, 015804 (2008)
2. C. Spitaleri et al., Phys. Rev. C **63**, 005801 (2001).
3. M. Lattuada et al., Ap. J. **562**, 1076 (2001).
4. A. Tumino et al., Phys. Rev. Lett. **98**, 252502 (2007).
5. C. Spitaleri et al., Phys. Rev. C **69**, 055806 (2004).
6. M. La Cognata et al., Ap.J., **708**, 796 (2010).
7. M. La Cognata et al., Phys. Rev. C **76** , 065804 (2007).
8. L. Lamia et al., Nucl. Phys. A, **A 787** , 309C-314C (2007).
9. M.L. Sergi et al., Phys. Rev. **C 82**, 032801 (2010).
10. A. Musumarra et al., Phys. Rev. C **64**, 068801 (2001).
11. A. Tumino et al., Eur. Phys. J. A **27** Supplement 1, 243 (2006).
12. R.G. Pizzone et al., Phys. Rev. **83** , 045801 (2011)
13. A. Tumino et al., Eur. Phys. J. A **25**, 649 (2005).
14. M. Gulino et al., Jour. of Phys. **37** , 125105 (2010).
15. M. Zadro et al., Phys. Rev. C **40**, 181 (1989).
16. G. Baur, Phys. Lett. B **178**, 35 (1986).
17. I. Slaus, Nucl. Phys. A **286**, 67 (1977).
18. R.G. Pizzone et al., Phys. Rev. C **71**, 058801 (2005).
19. R.G. Pizzone et al., Phys. Rev. C **80**, 025807 (2009).
20. I.S. Shapiro et al., Nucl. Phys. **61**, 353 (1965).
21. A. Mukhamedzhanov et al., Nucl. Phys. A **787**, 321(2007).
22. C.R. McClehanan and R.E. Segel, Phys. Rev. C **11**, 370 (1975).
23. G.S. Mani et al., Proc. Phys. Soc. **85**, 281 (1964).
24. A.J. Elwyn et al., Phys. Rev. C **16**, 1744 (1977).
25. S. Engstler et al., Z. Phys. **342**, 47 (1992).
26. R.G. Pizzone et al., A. A. **438**, 779 (2005).
27. R.G.Pizzone et al., A. A. **398**, 423 (2003).