PHYSICAL REVIEW C **87**, 025805 (2013)

Updated evidence of the Trojan horse particle invariance for the ^{2}H(d, p)^{3}H reaction

R. G. Pizzone,[1] C. Spitaleri,[1,2] C. A. Bertulani,[3] A. M. Mukhamedzhanov,[4] L. Blokhintsev,[5] M. La Cognata,[1] L. Lamia,[2] A. Rinollo,[1,*] R. Spartá,[1,2] and A. Tumino[1,6]

[1]*Laboratori Nazionali del Sud-INFN, Catania, Italy*

[2]*Dipartimento di Fisica e Astronomia, Università degli studi di Catania, Catania, Italy*

[3]*Texas A&M University Commerce, Commerce, Texas, USA*

[4]*Texas A&M University, College Station, Texas, USA*

[5]*Institute of Nuclear Physics, Moscow State University, Russia*

[6]*Universitá Degli studi di Enna Kore, Enna, Italy*

(Received 13 November 2012; published 26 February 2013)

The Trojan horse nucleus invariance for the binary $d(d, p)t$ reaction was tested by means of an experiment using the quasifree ^{2}H(^{6}Li,pt)^{4}He and ^{2}H(^{3}He,pt)H reactions after ^{6}Li and ^{3}He breakup, respectively. The astrophysical $S(E)$ factor for the $d(d, p)t$ binary process was extracted from the present data in the framework of the plane wave approximation applied to the two different breakup schemes. The obtained results are compared with direct data as well as with previous indirect investigations. The very good agreement confirms the applicability of the plane wave approximation and suggests the independence of the binary indirect cross section on the chosen Trojan horse nucleus also for the present case.

DOI: 10.1103/PhysRevC.87.025805 PACS number(s): 25.60.Pj, 21.10.Pc, 24.50.+g, 25.55.Hp

I. INTRODUCTION

The study of nuclear reactions induced by charged particles at astrophysical energies has many experimental difficulties, mainly connected to the presence of the Coulomb barrier and the electron screening effect. In the last decades strong efforts were devoted to the development and application of indirect methods in nuclear astrophysics. Among the most-used indirect methods, an important role is played by the Trojan horse method (THM) which has been applied to several reactions in the past decade [1–17] at the energies relevant for astrophysics (typically smaller than few hundred keV), which usually are far below the Coulomb barrier; of the order of MeVs. Many tests have been made to fully explore the potential of the method and extend as much as possible its applications: the target-projectile breakup invariance [18], the spectator invariance [19,20], and the possible use of virtual neutron beams [21,22]. Such studies are necessary, because the Trojan horse method has become one of the major tools for the investigation of reactions of astrophysical interest (for recent reviews see [23,24]). In recent works [19,20] the spectator invariance was extensively examined for the ^{6}Li(^{6}Li,$\alpha\alpha$)^{4}He and the ^{6}Li(^{3}He,$\alpha\alpha$)H case as well as the ^{7}Li(d,$\alpha\alpha$)n and ^{7}Li(^{3}He,$\alpha\alpha$)^{2}H reactions, thus comparing results arising from ^{6}Li and ^{3}He and deuteron and ^{3}He breakup, respectively [20]. 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$\to d + p$ breakup energy (5.49 MeV) and that the THM cross section does not depend on the chosen Trojan horse nucleus, at least for the processes mentioned above.

In the present paper the TH-nucleus invariance will be investigated for the ^{2}H(d, p)^{3}H reaction using the most recent data and all available experimental THM data. The $S(E)$ factor measured for the ^{2}H(d, p)^{3}H reaction through ^{3}He breakup in the ^{2}H(^{3}He,pt)H interaction will be compared with the $S(E)$ factor for the same binary reaction obtained through ^{6}Li breakup in the ^{2}H(^{6}Li, pt)^{4}He process. Our aim is to show that in both cases the plane wave impulse approximation (PWIA) is valid and that the use of a different spectator particle does not influence the THM reliability, in a case that confirms what was already observed in Ref. [20] for other reactions of astrophysical interest.

II. METHOD

The THM was successfully applied to study several two-body reactions relevant for astrophysical applications by using appropriate three-body breakup reactions. The method has proven to be particularly suited for acquiring information on charged- as well as neutral-particle-induced reaction cross sections at astrophysical energies, since it allows the particles to overcome, in the case of charged-particle-induced reactions, the Coulomb barrier of the two-body entrance channel. THM allows one to extract the low-energy behavior of a binary reaction by applying the well-known theoretical formalism of the quasifree (QF) process. The basic idea of the THM is to extract the cross section in the low-energy region of a two-body reaction with significant astrophysical impact,

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

from a suitable three-body QF reaction,

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

Referring to Fig. 1, the assumption is that of an interaction between the impinging nucleus and one of the clusters constituting the target (called participant x, a deuteron in the present case), while the residual nucleus does not participate

[*]Present address: Dipartimento della Protezione Civile, Rome, Italy.

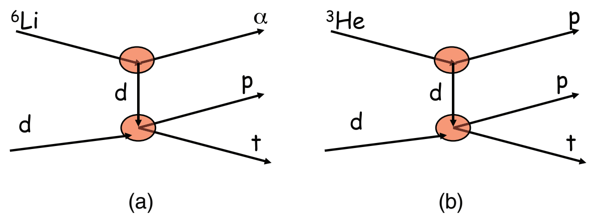

FIG. 1. (Color online) Sketch of the processes discussed in the text. (a) The quasifree reaction involving the ^{6}Li breakup. (b) The ^{3}He breakup.

in the reaction (spectator s, ^{4}He or p in the two different cases). The latter is free from any effect due to the interaction between the incoming nucleus and the participants, reflecting in the exit channel the same momentum distribution, for the intercluster (x-s) motion inside b, it had before the occurrence of the QF breakup.

QF processes are direct mechanisms in which the interaction between an impinging nucleus and the target can cause the target breakup (TBU) or the projectile breakup (PBU). In particular, these processes have three particles in the exit channel, one of which can be thought as a spectator to the binary interaction of interest.

Under appropriate kinematical conditions, the three-body reaction $a(b, cC)s$ is considered as the decay of the Trojan horse b into the clusters x and s followed by the interaction of a with x. If the bombarding energy E_a is chosen high enough to overcome the Coulomb barrier in the entrance channel of the reaction, the effect of the Coulomb barrier and electron screening effects are negligible.

The application of the THM significantly simplifies if the PWIA is valid. In this approach the triple differential cross section in the center of mass of the TH reaction can be written as

$$\frac{d^3\sigma}{dE_c d\Omega_c d\Omega_C} \propto K_F |\Phi(p_{sx})|^2 \sum_{l_l} |L_{l_l}|^2 \left(\frac{d\sigma_{l_l}}{d\Omega}_{\text{c.m.}}\right)^{\text{HOES}}, \tag{3}$$

where

(i) l_l is the orbital angular momentum of particles s and x in the entry channel of the binary subreaction and L_{l_l} is a function of relative momentum and kinetic energy in the entry channel of the binary subreaction as defined in Ref. [25];

(ii) $[(d\sigma_l/d\Omega)_{\text{c.m.}}]^{\text{HOES}}$ is the half-off-energy-shell (HOES) differential cross section for the two-body reaction at the center-of-mass energy $E_{\text{c.m.}}$ given in postcollision prescription by

$$E_{\text{c.m.}} = E_{c\text{-}C} - Q_{2b}, \tag{4}$$

where Q_{2b} is the two-body Q value of the binary process and $E_{c\text{-}C}$ is the relative energy between the outgoing particles;

(iii) K_F is a kinematical factor containing the final-state phase-space factor and is a function of the masses, momenta, and angles of the outgoing particles;

(iv) $\Phi(p_{sx})$ is the Fourier transform of the radial wave function $\chi(r)$ for the x-s intercluster motion, usually described in terms of Hänkel, Eckart, and Hultheń functions depending on the x-s system properties.

The success of the THM relies on the QF kinematics (equivalent to $p_{sx} \sim 0$ for nuclei like ^{3}He or ^{2}H where the dominant wave of the intercluster relative motion is $l = 0$), at which the TH conditions are best fulfilled. The occurrence of the QF mechanism at low energies has been pointed out in a number of papers [1,26–28]. We will see how the application of the conditions on the spectator momentum distribution, as discussed in Ref. [29], allows us to use a quite simple approach. This was already observed in Ref. [30]. It has also been verified that, for spectator momenta around zero, the PWIA gives results similar to those obtained by more complicated approaches, as reported in Ref. [31].

The TH triple differential cross section can be written in a factorized form, as in Eq. (3) in terms of the HOES differential cross section whose energy trend is the relevant information for the THM. Its absolute value can be extracted through normalization by the direct data available at higher energies. Thus, if the PWIA is valid, the HOES differential cross section for the binary subreaction determined from the TH reaction should not depend on the type of the TH nucleus, as was outlined in Refs. [19,20] for the two examined cases. Here the same methodology is applied to the ^{3}He breakup in the ^{2}H(^{3}He,pt)H interaction that will be compared with the same binary reaction obtained through ^{6}Li breakup in the ^{2}H(^{6}Li,pt)^{4}He process. In Fig. 1 the two studied processes are sketched: in Fig. 1(a) the ^{2}H(d, p)^{3}H reaction studied through the ^{2}H(^{6}Li,pt)^{4}He process is shown while in Fig. 1(b) the same reaction is studied through the ^{2}H(^{3}He,pt)H interaction.

III. EXPERIMENT

The study of the quasifree reaction ^{2}H(^{6}Li,pt)^{4}He for the THM application was performed in the Tandem-Dynamitron Laboratorium of the Ruhr Universität Bochum for a preliminary run. The results are presented in Ref. [32]. A second experimental run, on which the present paper is focused, was then performed at the Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Sud Catania (INFN-LNS-Catania). In particular, in this second run, the number of detectors was increased to improve the statistics and also the larger dimensions of the "CAMERA 2000" scattering chamber (2 m diameter) allowed for improved angular resolution. The experimental setup is described in Fig. 2: four position sensitive detectors (PSD) were placed at angles corresponding to the quasifree regions (see Table I for the details). The ^{6}Li beam (intensity 2/5 pnA and energy $E_{\text{Li}} = 14$ MeV) provided by the INFN-LNS-Catania Tandem impinged on a deuterated polyethylene foil ($\approx$170 μg/cm^2 thick). The beam spot on target was around 1 mm while the target was tilted 12 degrees with respect to the beam axis. In front of each PSD a silicon detector (15 μm thick) was placed to allow $\Delta E/E$ particle identification.

IV. DATA ANALYSIS AND RESULTS

The position and energy calibration of the detectors involved were performed by using data from different scatterings

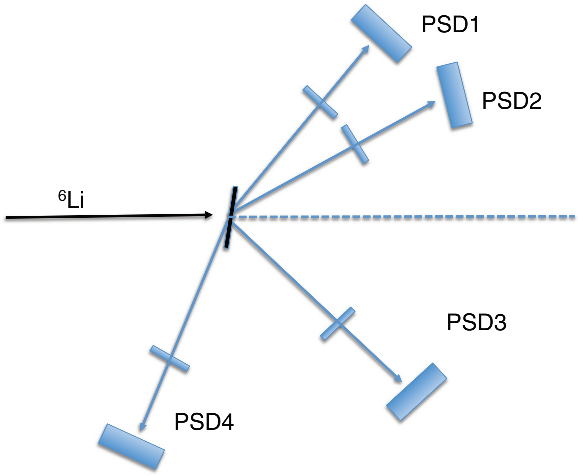

FIG. 2. (Color online) Sketch of experimental setup discussed in the text.

and reactions on different targets induced at a beam energy of 4, 7, and 14 MeV. A standard α source of 5.48 MeV was also used. Since position and energy of the two ejectiles were measured, the complete kinematics of the reaction was determined, allowing us to extract information on the energy, momentum, and angle of the third undetected particle.

After detector calibration, protons and tritons were identified by means of the $\Delta E/E$ technique. Once selecting p and t on the two detectors, the Q value of the three-body reactions was extracted, as reported in Fig. 3. Events below the peak, whose centroid is at about 2.6 MeV (in good agreement with the theoretical prediction, $Q = 2.56$ MeV) are produced by the ^{2}H(^{6}Li,pt)^{4}He reaction and have been selected for further analysis.

As in all standard THM analysis, the next step is to identify and separate the quasifree mechanism from all the other processes occurring in the target, and we refer the reader for further details to Ref. [33].This is usually done by recalling the definition of a QF reaction, i.e., a reaction where the third particle (spectator) retains the same momentum it had in the entrance channel, i.e., within the Trojan horse nucleus (^{3}He in our case). In fact, among all the available observables, the most sensitive to the involved reaction mechanisms is the shape of the momentum distribution $|\varphi(p_{sx})|^2$. According to the prescriptions in Refs. [34–36], the momentum distribution of the third and undetected particle will be examined. This gives a major constraint for the presence of the quasifree mechanism and the possible application of the THM. In order to extract the experimental momentum distribution of the

TABLE I. Experimental details of setup described in the text.

Detector	Angular range (deg.)
PSD_1	42–54
PSD_2	18–28
PSD_3	42–54
PSD_4	105–115

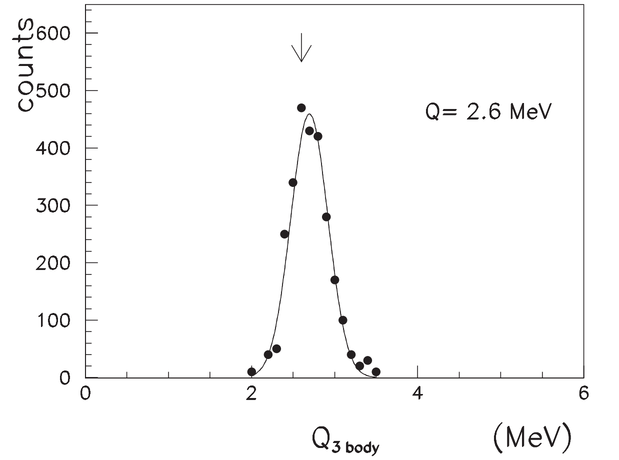

FIG. 3. Q value for the ^{2}H(^{6}Li,pt)^{4}He reaction after kinematical reconstruction. The peak around 2.6 MeV is a clear signature of the good calibration of detectors as well as of the correct identification of the reaction channel. The solid line represents the Gaussian fit to the data.

spectator, $\varphi(p_{sx})^2_{\text{expt}} = \varphi(p_s)^2_{\text{expt}}$, in the system where the Trojan horse particle b is at rest, the energy-sharing method can be applied to each pair of coincidence detectors, selecting narrow energy and angular windows, $\Delta E_{\text{c.m.}}$ and $\Delta\theta_{\text{c.m.}}$. The center-of-mass angle $\theta_{\text{c.m.}}$ is defined according to Ref. [37]. Keeping in mind the factorization of Eq. (3), since $[(d\sigma/d\Omega)_{\text{c.m.}}]^{\text{HOES}}$ is nearly constant in a narrow energy and $\theta_{\text{c.m.}}$ window, one can obtain the shape of the momentum distribution of the undetected proton directly from the coincidence yield divided by the kinematical factor.

The obtained momentum distribution is reported in Fig. 4 where it is compared with the theoretical prediction of the spectator momentum distribution, obtained using the Woods-Saxon potential with the standard geometrical parameters reported in Ref. [36]. An evident distortion of the momentum distribution shows up and its measured full width at half maximum turns out to be around 47 MeV/c which is much

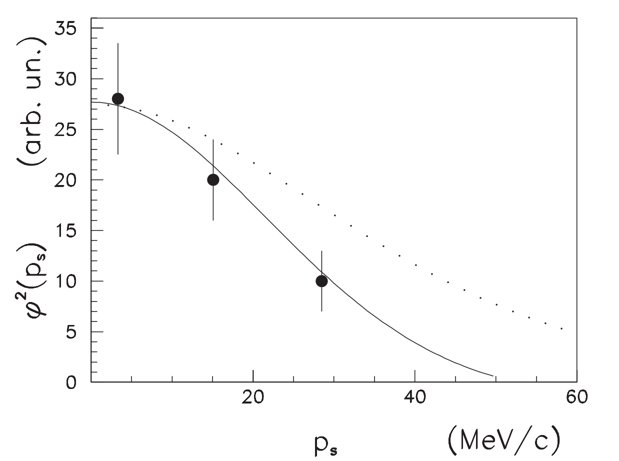

FIG. 4. Momentum distribution for intercluster motion of deuteron inside ^{6}Li for the ^{2}H(^{6}Li,pt)^{4}He case. The fit to the experimental data is reported for comparison. The dotted line represents the theoretical calculation discussed in the text.

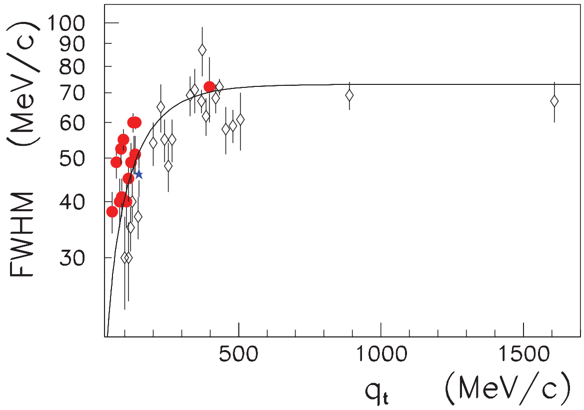

FIG. 5. (Color online) Momentum distribution width for the deuteron inside ^{6}Li as a function of the transferred momentum as reported in Ref. [35]. The present result is marked as a blue star, red dots mark results from Ref. [35], diamonds results from Ref. [34], and the line represents the best fit reported in Ref. [35].

smaller than the expected prediction of 72 MeV/c. This evidence was already observed for ^{6}Li as well as for other isotopes in Refs. [35,36] where the width of the momentum distribution for the spectator inside the Trojan horse nucleus was studied as a function of the transferred momentum from the projectile a to the center of mass of the final system $B = C + c$. This can be written as the Galilean invariant quantity following the approach of Refs. [35,36]. In the present case the value of q_t is about 150 MeV; the present result is then compared with the data from Refs. [35,36] in Fig. 5. A clear agreement is present both with the other experimental data as well as with the curve which represents the best fit to the function reported in Ref. [35].

The next step is to apply the standard procedure of the THM, as discussed in Ref. [23], to extract the energy trend of the $S(E)$ factor. Therefore, Eq. (3) is applied, allowing the extraction of the binary cross section from the measured three-body cross section. The sequential mechanisms and their contributions were treated as in Ref. [32] and the Coulomb penetration factor was calculated following Ref. [32].

The results for the $d(d,p)t$ reaction in terms of the bare nucleus astrophysical $S(E)$ factor are presented in Fig. 6 (blue points) after normalization with direct data (red points, [38,39]). We point out that direct data suffer from the electron screening effect which does not affect the THM results. The data from the present experiment (blue points) are compared with those arising from ^{6}Li breakup in a previous experimental run (black points) and already published in Ref. [32]. An overall agreement is present among both indirect and direct data sets, within the experimental errors.

The two data sets obtained via THM applied to the ^{2}H(^{6}Li,pt)^{4}He reaction were then averaged, after weighting over the errors, and the result is shown in Fig. 7 as a function of the energy (black points). The averaged results are then compared with the THM results for the $d(d,p)t$ reaction from ^{3}He breakup, as reported in Ref. [40] (red triangles). We point out that the errors in the present case are much larger than in the case of ^{3}He breakup. This is mainly due to the presence of the sequential mechanism in ^{7}Li, already

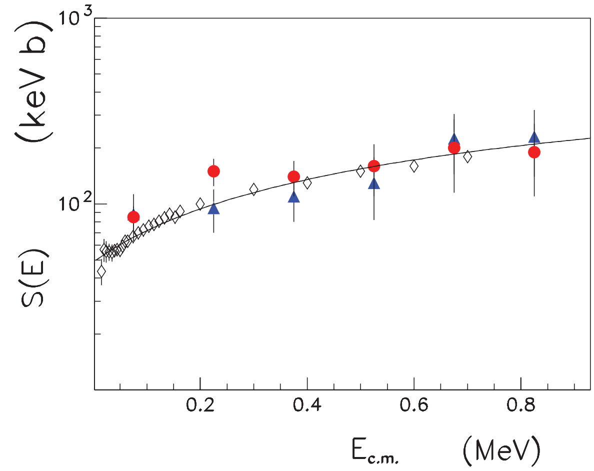

FIG. 6. (Color online) Astrophysical $S(E)$ factor for the $d(d,p)t$ reaction measured via THM after ^{6}Li breakup. The blue points represent the data extracted in the present work, while the red points refer to those reported in Ref. [32]. Both data sets are normalized to the direct data from Refs. [38,39] (diamonds). The polynomial fit to the direct data is given as a dashed line.

discussed in Ref. [32], that decreases the number of the QF events. Also, the normalization errors and errors connected to the penetrability factor are fully included in the error bar shown in the pictures. A polynomial fit was then performed on the averaged data giving $S_0 = 75 \pm 21$ keV b in agreement, within the experimental errors, with previous THM results. The full polynomial parametrization of the $S(E)$ factor as a function of energy (in units of MeV) gives

$$S(E) = 75 + 148.4E + 14.6E^2, \tag{5}$$

expressed in keV b.

Thus we find that, also in the present case, data extracted via the THM applied to ^{6}Li and ^{3}He breakup are comparable among themselves and that the THM shows Trojan horse

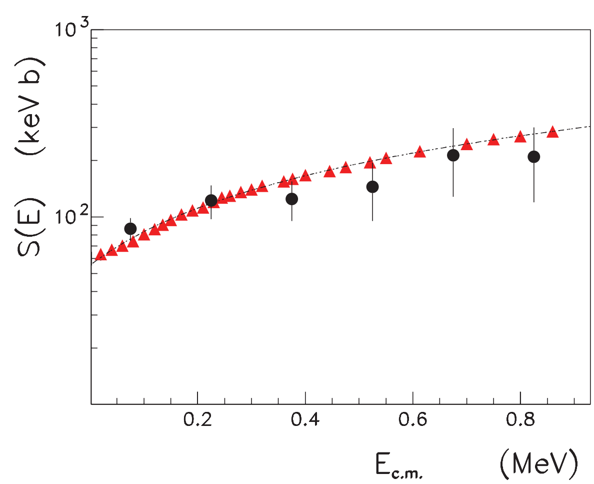

FIG. 7. (Color online) Averaged astrophysical $S(E)$ factor for the $d(d,p)t$ reaction measured via THM after ^{6}Li breakup (black dots) and after ^{3}He breakup(red points), extracted from Ref. [40], clearly showing the Trojan horse particle invariance. The polynomial fit to data from Ref. [40] is reported for comparison as a solid line.

particle invariance also in the case of the $d(d,p)t$ reactions. This confirms in an additional and independent case what was already observed in Ref. [20] for the ^{6}Li(d,α)^{4}He and the ^{7}Li(p,α)^{4}He reactions.

V. CONCLUSIONS

A full investigation of the ^{2}H(^{6}Li,pt)^{4}He reaction is presented in the present paper. The QF contribution is extracted and the THM applied to retrieve information on the astrophysical $S(E)$ factor for the $d(d,p)t$ reaction. A good agreement with the direct data is achieved in the whole energy range. The present result is then compared with data from ^{3}He(d, pt)H reaction to confirm also for the $d(d,p)t$ case the evidence of the TH nucleus invariance at energies above and below the Coulomb barrier. As for the ^{6}Li(d,α)^{4}He and the ^{7}Li(p,α)^{4}He reactions [20], we conclude that the PWIA is valid in all these cases and that the use of a different spectator particle does not influence the THM results also in this further case.

ACKNOWLEDGMENTS

This work was supported in part by the Italian Ministry of the University under Grant No. RBFR082838. A.M. M. acknowledges the support of the US Department of Energy under Grant Nos. DE-FG02-93ER40773, DE-FG52-09NA29467, and DE-SC0004958 (topical collaboration TORUS) and NSF under Grant No. PHY-0852653. C.B. acknowledges the support of the US Department of Energy under Grant Nos. DE-SC0004971 and DE-FG02- 08ER41533.

[1] S. Cherubini *et al.*, Astrophys. J. **457**, 855 (1996).
[2] C. Spitaleri *et al.*, Nucl. Phys. A **719**, 99c (2003).
[3] A. Tumino *et al.*, Phys. Rev. C **67**, 065803 (2003).
[4] C. Spitaleri *et al.*, Phys. Rev. C **69**, 055806 (2004).
[5] A. Tumino *et al.*, Phys. Rev. Lett. **98**, 252502 (2007).
[6] A. Tumino *et al.*, Phys. Rev. C **78**, 064001 (2008).
[7] R. G. Pizzone *et al.*, Astron. Astrophys. **398**, 423 (2003).
[8] R. G. Pizzone *et al.*, Astron. Astrophys. **438**, 779 (2005).
[9] M. La Cognata *et al.*, Phys. Rev. C **76**, 065804 (2007).
[10] M. La Cognata *et al.*, Phys. Rev. C **72**, 065802 (2005).
[11] M. La Cognata *et al.*, Astrophys. J. **739**, L54 (2011).
[12] M. L. Sergi *et al.*, Phys. Rev. C **82**, 032801 (2010).
[13] L. Lamia *et al.*, Nucl. Phys. A **787**, 309C (2007).
[14] L. Lamia *et al.*, J. Phys. G **39**, 015106 (2012).
[15] L. Lamia, M. La Cognata, C. Spitaleri, B. Irgaziev, and R. G. Pizzone, Phys. Rev. C **85**, 025805 (2012).
[16] S. Romano *et al.*, Eur. Phys. J. A **27**, 221 (2006).
[17] Q. Wen *et al.*, Phys. Rev. C **78**, 035805 (2008).
[18] A. Musumarra *et al.*, Phys. Rev. C **64**, 068801 (2001).
[19] A. Tumino *et al.*, Eur. Phys. J. A **27**, 243 (2006).
[20] R. G. Pizzone *et al.*, Phys. Rev. C **83**, 045801 (2011).
[21] A. Tumino *et al.*, Eur. Phys. J. A **25**, 649 (2005).
[22] M. Gulino *et al.*, J. Phys. **37**, 125105 (2010).
[23] C. Spitaleri *et al.*, Phys. At. Nucl. **74**, 1725 (2011).
[24] A. Tumino *et al.*, AIP Conf. Proc. **1488**, 87 (2012).
[25] A. M. Mukhamedzhanov (unpublished).
[26] M. Zadro, D. Miljanić, C. Spitaleri, G. Calvi, M. Lattuada, and F. Riggi, Phys. Rev. C **40**, 181 (1989).
[27] C. Spitaleri *et al.*, Phys. Rev. C **63**, 055801 (2001).
[28] M. Lattuada *et al.*, Astrophys. J. **562**, 1076 (2001).
[29] I. S. Shapiro *et al.*, Nucl. Phys. **61**, 353 (1965).
[30] N. S. Chant and P. Roos, Phys. Rev. C **15**, 57 (1977).
[31] M. La Cognata *et al.*, Phys. Rev. Lett. **101**, 152501 (2008).
[32] A. Rinollo *et al.*, Nucl. Phys. A **758**, 146c (2003).
[33] A. Rinollo, Ph.D. thesis, University of Catania, 2004 (unpublished).
[34] S. Barbarino, M. Lattuada, F. Riggi, C. Spitaleri, and D. Vinciguerra, Phys. Rev. C **21**, 1104 (1980).
[35] R. G. Pizzone *et al.*, Phys. Rev. C **71**, 058801 (2005).
[36] R. G. Pizzone *et al.*, Phys. Rev. C **80**, 025807 (2009).
[37] I. Slaus, Nucl. Phys. A **286**, 67 (1977).
[38] A. Krauss, H. W. Becker, H. P. Trautvetter, C. Rolfs, and K. Brand, Nucl. Phys. A **465**, 150 (1987).
[39] R. E. Brown and N. Jarmie, Phys. Rev. C **41**, 1391 (1990).
[40] A. Tumino *et al.*, Phys. Lett. B **705**, 546 (2011).