Indirect ^{7}Li$(p,\alpha)^4$He reaction at astrophysical energies

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Information on the ^{7}Li$(p,\alpha)^4$He reaction cross section at energies relevant for astrophysics has been obtained by means of the indirect Trojan-horse method applied to the three-body ^{2}H$(^7$Li$,\alpha\alpha)n$ reaction. Measurements at ^{7}Li-beam energies of 19, 19.5, 20, and 21 MeV have been carried out. The results are reported in terms of the astrophysical $S(E)$ factor. The value $S(0)$ measured in the present experiment is compared with that extrapolated from a direct measurement. [S0556-2813(99)01510-1]

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I. INTRODUCTION

Understanding energy production in stars and related nucleosynthetic processes requires the knowledge of nuclear reaction cross sections [1] at interaction energies usually far below the Coulomb barrier. These cross sections often range between nano- and picobarns [2] so that, in general, their direct evaluation is severely hindered and in some cases even beyond present technical possibilities. Usually experimental data at higher energies together with theoretical calculations are used in order to extrapolate the astrophysical $S(E)$ factor down to the relevant energy. However, such a procedure might be unreliable if unknown resonances are present in the region of extrapolation or if the electron screening effect (e.g., [3]) is not duly taken into account.

In the last years an increasing number of indirect methods has thus been employed for the investigation of key reactions. For instance, Coulomb dissociation of fast projectiles has been proposed [4] as a method to investigate radiative capture processes (time reversal of photodisintegration). Transfer reactions have been used in order to study various capture processes [5–7].

Among indirect approaches, the so-called Trojan-horse method (THM) [8] seems to be particularly suited for investigation of low-energy charged-particle reactions relevant for nuclear astrophysics. This method has already been used in a recent work of ours [9] in order to obtain information on the low-energy cross section for the ^{6}Li$(d,\alpha)^4$He reaction from the ^{6}Li$(^6$Li$,\alpha\alpha)^4$He one. The extracted astrophysical $S(E)$ factor has been compared with that extrapolated from a direct measurement [10] and showed to be in good agreement.

In the present paper we report on the application of the Trojan-horse method to the ^{2}H$(^7$Li$,\alpha\alpha)n$ as a tool to acquire information on the ^{7}Li$(p,\alpha)^4$He reaction at the astrophysical energy of interest. The ^{7}Li$(p,\alpha)^4$He reaction is of importance in astrophysics, in that it is invariably connected with the so-called Li problem. It is well known that lithium, of which ^{7}Li is the most abundant isotope, is produced during the very early stages of universe evolution together with other light elements such as ^{2}H, ^{3}He, ^{4}He, ^{9}Be [11–13]. Apart from spallation processes still occurring in the interstellar medium, which contribute to the synthesis of ^{7}Li, this latter is mostly destroyed during the evolution of a star to an extent which, among other factors, depends on the rate of the ^{7}Li$(p,\alpha)^4$He reaction. However, the lithium abundance expected on the basis of ^{7}Li$(p,\alpha)^4$He cross-section measurements (e.g., Ref. [10]) does not match that observed in several astrophysical sites. The measurement of such a cross section at energies as low as possible is then necessary to gather more hints about the lithium destruction in astrophysical environments. In this paper we shall stress the importance of the THM as a complementary tool to direct measurements in the study of reactions of astrophysical interest.

II. THE PRINCIPLE OF THE METHOD

Quasifree reactions (QFR) can be easily described by means of the impulse approximation (IA). Let us consider as a typical case a particle a striking a complex system A. The assumptions underlying the IA are then the following [14]: (i) the incident particle never interacts strongly with two constituents of the system at the same time; (ii) the amplitude of the incident wave falling on each constituent is nearly the same as if that constituent were alone; (iii) the binding forces between the constituents of the system are negligible during the decisive phase of the reaction. Under these hypotheses, the incident particle a is considered to interact only with a part b of the target nucleus A (whose wave function is assumed to have a large amplitude for the C-b cluster configuration), while the other part C behaves as spectator to the process $a+b\rightarrow c+d$. In Fig. 1(a) a pseudo-Feynman diagram representing this reaction mechanism is shown. In order to completely determine the kinematic properties of the spectator C, the energy E_c and E_d of the two particles c and d must be measured in coincidence at specified angles, θ_c and θ_d. In the plane-wave impulse approximation (PWIA)

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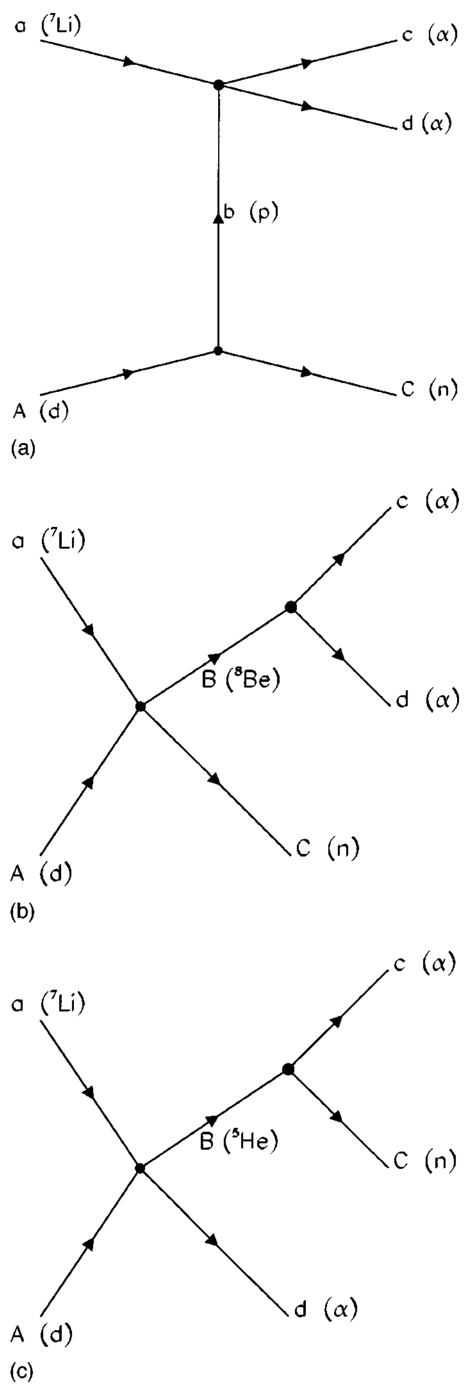

FIG. 1. Different possible reaction mechanisms leading to the same final state represented by pseudo-Feynman diagrams. In (a) a quasifree process is shown while two different sequential decays are shown in (b) and (c). Ion species in brackets refer to the actual situation relevant to the present experiment.

the three-body cross section may be expressed as

$$\frac{d^3\sigma}{dE_c d\Omega_c d\Omega_d} \propto (KF)\,|\Phi(\vec{p}_s)|^2 \left(\frac{d\sigma}{d\Omega}\right), \qquad (1)$$

where KF is a kinematic factor containing the final state phase-space factor, $|\Phi(\vec{p}_s)|^2$ is the momentum distribution of the (spectator) C particle inside the nucleus A and $(d\sigma/d\Omega)$ is the off-energy-shell differential reaction cross section for the a-b two-body subsystem [15]. Assuming that $|\Phi(\vec{p}_s)|^2$ is known and calculating KF, it is then possible to derive $(d\sigma/d\Omega)$ from a measurement of $d^3\sigma/dE_c d\Omega_c d\Omega_d$. An experimental way of testing the basic assumptions underlying the QF model was originally proposed by Treiman and Yang [16] for high-energy single-pion exchange reactions and later extended by Shapiro, Kolybasov, and August [17] to some nonrelativistic cases involving nonzero spin particles [18]. It has been suggested (Refs. [15,19,20]) that the energy behavior of the virtual two-body cross section, which can be extracted from that of the QF processes according to Eq. (1), could be studied and compared with the corresponding two-body one measured in a direct way.

In this framework the Catania-Zagreb collaboration has performed several experiments on quasifree reactions with a neutron as spectator. In particular the excitation functions of reactions $^2\mathrm{H}(^7\mathrm{Li},\alpha\alpha)n$ and $^6\mathrm{Li}(d,^3\mathrm{He}^4\mathrm{He})n$ have been studied in the low-energy region $E_{^7\mathrm{Li}} = 28-48$ MeV [21] and $E_{^6\mathrm{Li}} = 21.6-33.6$ MeV [22], respectively. In both cases the energy dependence of the virtual reaction cross sections fairly agrees with the known excitation functions of the corresponding two-body reactions and also resonances are reproduced, confirming the reliability of the factorization suggested in Eq. (1). These results led us to investigate reactions of astrophysical interest [23] by means of the quasifree mechanism, in the form of the Trojan-horse method (THM).

If the bombarding energy is chosen to overcome the Coulomb barrier in the incident channel of a reaction

$$a + A \rightarrow c + d + C, \qquad (2)$$

the particle b can be brought into the nuclear interaction zone to induce the reaction

$$b + a \rightarrow c + d. \qquad (3)$$

If the Fermi motion of particle b inside A compensates at least in part for the initial projectile velocity v_a the latter reaction is induced at very low (even vanishing) relative energy between a and b, so as to match the relevant astrophysical energy (Ref. [8]). In this way it is possible to extract the two-body cross section as

$$\frac{d\sigma^N}{d\Omega} \propto \frac{d^3\sigma}{dE_c d\Omega_c d\Omega_d}[KF\,|\Phi(\vec{p}_s)|^2]^{-1}. \qquad (4)$$

It has to be emphasized that in the present case the obtained cross section $d\sigma^N/d\Omega$ is the nuclear part, the Coulomb barrier being already overcome in the entrance channel. In the case at hand, since we are investigating relative $^7\mathrm{Li}$-p energies below the corresponding Coulomb barrier, the extracted two-body cross section is, as just mentioned, a ''pure nuclear'' one, the $^7\mathrm{Li}$-p interaction occurring once the proton is already in the nuclear field of the system. So, in order to get the ''usual'' two-body cross section to be compared to the directly measured one, it is necessary to multiply $d\sigma^N/d\Omega$ by the transmission coefficient through the Coulomb barrier, that is

$$\frac{d\sigma}{d\Omega}=\sum_l G_l\frac{d\sigma_l^N}{d\Omega}, \tag{5}$$

where G_l represents the transmission coefficient for the relevant lth partial wave and $d\sigma_l^N/d\Omega$ is its related cross section.

The fact that the PWIA is not able to give results in absolute units [hence, the proportionality sign in Eqs. (1) and (4)], makes it necessary to normalize the extracted two-body cross section to the directly measured one in a suitable energy region. It should be stressed here that in general the same final state of reaction (2) can be reached through reaction mechanisms other than the quasifree breakup (e.g., sequential decays). Diagrams for these processes are shown in Figs. 1(b) and 1(c). In particular, in the energy range investigated in the present measurement, the reaction ^{7}Li$(d,\alpha\alpha)n$ is known to be dominated by a strong sequential decay from the two excited levels in ^{8}Be at $E^*=16.63$ and 16.92 MeV [24]. Such a contribution, therefore, represents an undesired physical background which has to be subtracted in order to get the quasifree part of the investigated cross section. Moreover the formation of ^{5}He has to also be taken into account, even though it is known that the contribution from this channel is very small compared to the ^{8}Be one (Ref. [24]).

III. EXPERIMENTAL SETUP

The SMP Tandem Van de Graaff accelerator of the Laboratori Nazionali del Sud - Catania, provided a ^{7}Li-ion beam at energies 19, 19.5, 20, and 21 MeV and intensities up to 70 nA. The energy spreading of the beam was about 10^{-4} and the spot on target, after collimation, had a diameter of $\sim$1.5 mm. The 2000-mm-diameter *Camera 2000* scattering chamber maintained at a pressure of $\sim 10^{-6}$ mbar was used.

A deuterated polyethylene target was placed at 10° with respect to the beam. During the experiment four different targets had to be used because of deterioration problems; their thicknesses were determined using an Am source. A silicon ΔE-E detector placed at a distance $d=50.5$ cm from the target and at $\theta=18.5°$ with respect to the beam axis was used to detect the elastically scattered particles, thus allowing for a continuous monitoring of the target thickness during the measurement.

Since the Q value (15.121 MeV) for the ^{2}H$(^7$Li$,\alpha\alpha)n$ reaction is much larger than that for other possible reactions occurring with carbon or impurities in the target, and since the α particles coming from the ^{1}H$(^7$Li$,\alpha)^4$He reaction, occurring with hydrogen also present in the target, can be easily separated from those of interest, it was not necessary to identify the reaction products by means of ΔE-E telescopes. Detection of the outgoing α particles has therefore been performed by using six (50×10) mm silicon position sensitive detectors (PSD), three at each side of the beam axis. The resulting detection setup is thus different from that of a previous experiment where ionization chambers were used as ΔE-E telescopes [25].

Calculations of quasifree angles have shown that the two α's are emitted with a relative angle $\theta_{\rm rel}\sim 90°$ almost independently of the beam energy. Detectors have then been centered at fixed angles 44°, 34°, 23°, 45°, 55°, and 65°, respectively, for the PSD1, PSD2, PSD3, PSD4, PSD5, and PSD6; the monitor was fixed at 18°. Detectors PSD1 and PSD4 (from now on we will refer to detectors by numbers simply) were placed at a distance $d=70$ cm so as to compare the data taken from this experiment with those of the previous experiment (Ref. [25]). All other detectors were placed closer to the target in order to increase their solid angles, which then rose from $\sim$1 msr (of detectors 1 and 4) to $\sim$2.5 msr for detectors 2, 3, 5, and 6. Coincidences were carried out between each pair of PSD's placed on opposite side of the beam direction. However, while coincidences between detectors 1 and 4, 2 and 5, and 3 and 6 fulfilled the requirement $\theta_{\rm rel}\sim 90°$, the remaining ones did not. This allowed to cross check the method, since in those cases no quasifree contributions were expected.

The selected angular ranges corresponded to kinematical conditions under which the momentum p_s of the undetected spectator neutron ranges from ~ -80 MeV/c to ~ 80 MeV/c. This assures that the bulk of quasifree contributions falls inside the investigated regions.

The signals coming from the detectors were processed by using standard electronic chains and sent to the acquisition system which allowed the on-line monitoring of the experiment and the storage of data on magnetic tapes for later data analysis.

IV. EXPERIMENTAL PROCEDURE, DATA ANALYSIS, AND RESULTS

At the initial stage of the measurement, grids with 16 equally spaced slits each were placed in front of each PSD in order to operate a calibration in position. A correspondence between position signals from the PSD and angle of particle detection is therefore established. Energy calibration was performed by means of a standard three-peak α source at energies of 5.155, 5.484, and 5.806 MeV. At higher energies the elastic scattering of ^{7}Li on CD_2 and Au targets was employed at beam energies of about 15, 20, and 25 MeV.

From the study of the two-body ^{1}H$(^7$Li$,\alpha)^4$He reaction occurring with hydrogen in the target the angular resolution was found to be of about 0.2° and the energy resolution was checked to be better than 1%.

Although measurements of the α-α coincidences were carried out at incident beam energies 19 and 20 MeV, in what follows we shall refer for clarity only to one of the several events investigated, namely to coincidences between detectors 1 and 4 at ^{7}Li-beam energy of 20 MeV.

In order to reduce the contribution from random coincidences, constraints on the time-to-amplitude converter parameter as well as on the reaction Q-value spectrum have also been operated. In such a way clean projections on one- and two-dimensional spectra have been obtained. As an example, Fig. 2 shows the number of counts versus E_{α_1} at $\theta_{\alpha_1}=45°\pm 0.5°$ and $\theta_{\alpha_2}=45°\pm 0.5°$. In order to check the nature of the two peaks of Fig. 2 projections have been performed on the variables $E_{\alpha_1\alpha_2}$ (relative energy between the

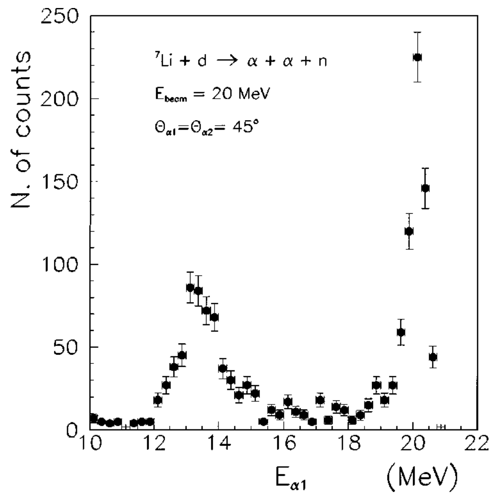

FIG. 2. $\alpha-\alpha$ coincidence spectrum projected on the E_{α_1} axis. Experimental conditions are also given. Similar spectra have been obtained for all the events and angles as reported in the text.

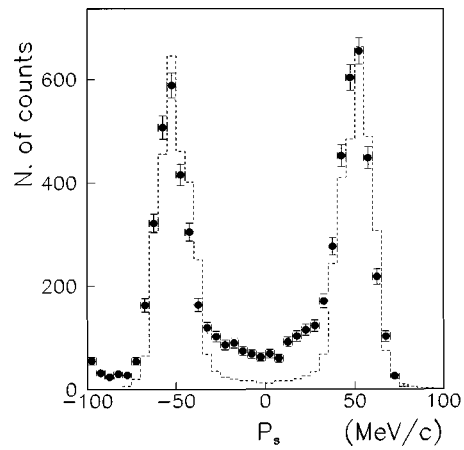

FIG. 3. Spectrum in p_s fitted according to the procedure described in the text. It is clearly seen that the region between ± 40 MeV/c cannot be accounted for by a sequential decay contribution alone.

two outgoing α particles), $E_{\alpha_1 n}$ and $E_{\alpha_2 n}$ (relative energy between the neutron and each of the α particles), so as to investigate possible contributions from formation of ^{8}Be and ^{5}He, respectively.

From such an analysis it is concluded that the reaction ^{2}H(^{7}Li,$\alpha\alpha$)n mainly proceeds through formation of the 16.6 and 16.9 MeV levels of the ^{8}Be* as expected for the energy and angular conditions studied in the present measurement (Ref. [24]). The same procedure described above has been applied to each event, each beam energy, and all possible angle pairs: similar results have been obtained for events where a quasifree contribution is expected. However, in coincidences 2–5 and 3–6 a small contribution due to ^{5}He formation seems to have been observed and could overlap the energy region of interest for the quasifree mechanism (Ref. [24]). Therefore, in order to reduce the chance for a systematic error connected with the subtraction of such a contribution, only data analysis related to coincidences 1–4 is reported in the present paper.

In order to separate quasifree contributions from those due to the sequential decay of ^{8}Be, data from each event and beam energy have been projected on to p_s, momentum of the neutron, with the further condition that the relative angle between any two coincident α's matches the quasifree value at the proper beam energy. A typical projection is shown in Fig. 3. Each of the two peaks is due to both of the unresolved 16.63 and 16.92 MeV levels in ^{8}Be. Such a sequential contribution has been reproduced by means of a Monte Carlo calculation. A Breit-Wigner formula integrated over the accessible phase-space volume has been used and contributions from the two levels were incoherently added with a relative weight determined by a best fit to the experimental spectra. The levels' parameters used were as reported in [26] with a correction for the experimental energy resolution. It has been verified that the relative weights given by this fit are in good agreement with those coming from a fit on the E_{α_1,α_2} spectra.

It is clearly seen that the region between the two peaks, namely that around $p_s=0$, cannot be accounted for with such a fit and this has therefore been interpreted as evidence that the quasifree mechanism actually takes place in the reaction ^{2}H(^{7}Li,$\alpha\alpha$)n. After subtraction of sequential-decay contributions from the experimental spectra, quasifree data have been plotted as a function of E_p, that is the relative ^{7}Li-p energy, defined in the so-called post-collision prescription as

$$E_p = E_{\alpha_1,\alpha_2} - Q, \tag{6}$$

where Q (=17.346 MeV) is the Q value for the two-body ^{7}Li(p,α)^{4}He reaction.

The nuclear differential cross section shown in Fig. 4 was then obtained from Eq. (4), where $|\Phi(\vec{p}_s)|^2$ was calculated using the well-known approximation in terms of a Hulten wave function to describe the n-p motion in ^{2}H, i.e., $U(r) = (e^{-ar}-e^{-br})/r$ with $a=0.2317$ fm^{-1} and $b=1.202$ fm^{-1} (Ref. [21]). A remarkable agreement in the trend of $d\sigma^N/d\Omega$ derived by measuring the three-body cross section at different beam energies has to be stressed. This is shown in Fig. 4

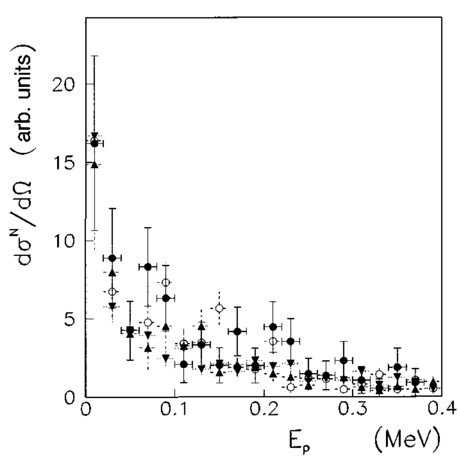

FIG. 4. Nuclear differential cross sections obtained for four different beam energies: 19 (full dots), 19.5 (empty dots), 20 (downward triangles), and 21 MeV (upward triangles).

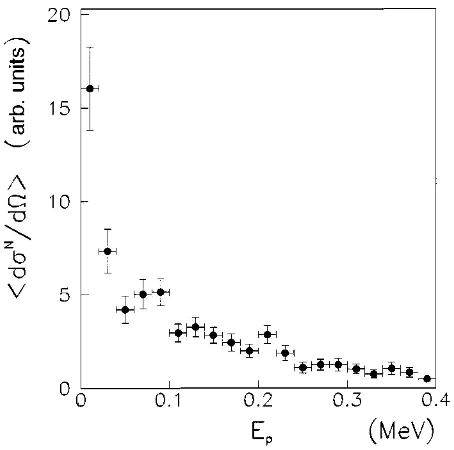

FIG. 5. Nuclear differential cross section averaged over the four data sets of Fig. 4.

where $d\sigma^N/d\Omega$ from data set at 19, 19.5, 20, and 21 MeV have been normalized to each other. Figure 5 shows the $d\sigma^N/d\Omega$ averaged over the four energy data sets.

In order to compare our results with those of a direct measurement it is now necessary to correct the nuclear cross section for the penetration function through the Coulomb barrier. As a first approximation we have assumed that the $l=0$ partial wave represents the main contribution to the reaction process, so that the probability of barrier penetration can be expressed as

$$G_0=\exp\left\{-2KR_c\left[\frac{\arctan(R_c/R_n-1)^{1/2}}{(R_c/R_n-1)^{1/2}}-\frac{R_n}{R_c}\right]\right\} \tag{7}$$

with

$$K=\left[\frac{2\mu}{\hbar^2}(E_c-E)\right]^{1/2}$$

and $R_n=R_{^7\mathrm{Li}}+R_p(=3.21\ \mathrm{fm})$ and R_c are, respectively, the nuclear radius of interaction and the distance of classical turning point (e.g., [27]). Although a more realistic Woods-Saxon potential would give a more accurate calculation of the penetration probability, the above expression is a good enough approximation for the purposes of the present work.

The comparison between the excitation function thus obtained and that of a direct measurement [28] is shown in Fig. 6. Our data (full circles) have been normalized to the direct ones (open circles) in the energy region around $E_{\mathrm{c.m.}}\sim 0.3$ MeV. The good agreement between the two data sets reveals that the assumption for a dominant $l=0$ partial wave is correct within the accuracy of the experimental information available. Moreover, it has to be stressed that a good agreement between the two trends (direct and indirect) is a necessary condition before extracting the astrophysical $S(E)$ factor by means of the THM (applicability test). In a previous work (Ref. [21]), we had already shown that this agreement was indeed obtained above the Coulomb barrier (i.e., without having to correct for the penetration probability). The present result then shows the consistency of the method used even at energies well below the Coulomb barrier.

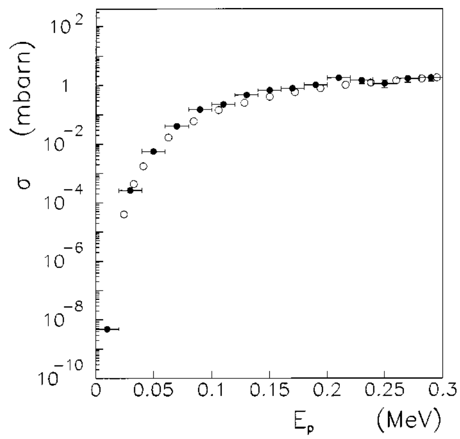

FIG. 6. Excitation function for the ^{1}H$(^7$Li$,\alpha)^4$He reaction. The present result (full dots) is compared to that obtained in Ref. [28] (empty dots).

V. ASTROPHYSICAL FACTOR

Two different procedures have been adopted to derive the astrophysical $S(E)$ factor from our data. The first one employs the usual definition of the $S(E)$ function, namely,

$$S(E)=\exp(2\pi\eta)E\sigma(E). \tag{8}$$

This definition has been applied to our data in the form of $\sigma(E)=\sigma^N(E)G_0$ as shown in Fig. 6 (full circles). The second approach explicitly takes into account the fact that the THM allows for a measurement of the nuclear cross section. According to the formalism given in Ref. [9] it is then possible to express the astrophysical factor as

$$S^N(E)=E\sigma^N(E). \tag{9}$$

This is justified by observing that the penetration function given in Eq. (7) and the usual Gamow factor $\exp(-2\pi\eta)$, introduced in the extrapolation of $S(E)$ from direct data, should cancel out. Indeed, since the Gamow factor represents an approximate expression for the tunneling probability given in Eq. (7), there is a small discrepancy between the trend of the two $S(E)$ factors obtained according to the two different methods, as shown in Fig. 7. It is worth noticing, however, that the astrophysical $S(E)$ factor obtained with the second approach [i.e., what we have indicated as $S^N(E)$] is independent of approximations introduced by any tunneling probability function, which makes an interesting peculiar feature of the THM.

The comparison between the $S(E)$ factor obtained in the present measurement (first approach) and that reported in Ref. [28] (empty circles) is shown in Fig. 8. Again a good agreement is found. In order to determine the value of $S(0)$ our data have been fitted with a second-order polynomial expansion:

$$S(E)=S(0)+S_1E+S_2E^2 \tag{10}$$

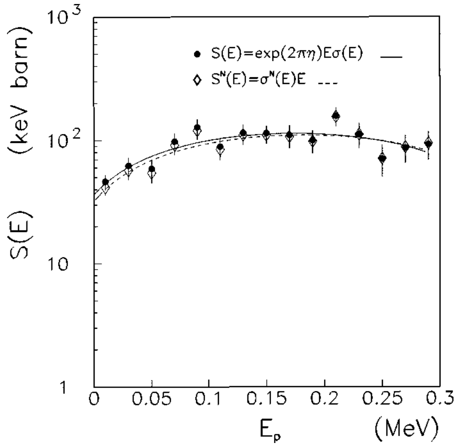

FIG. 7. Astrophysical $S(E)$ factors for the ${}^{1}\mathrm{H}({}^{7}\mathrm{Li},\alpha){}^{4}\mathrm{He}$ reaction calculated according Eq. (8) (full dots) and Eq. (9) (diamonds). Fits to both trends are also reported.

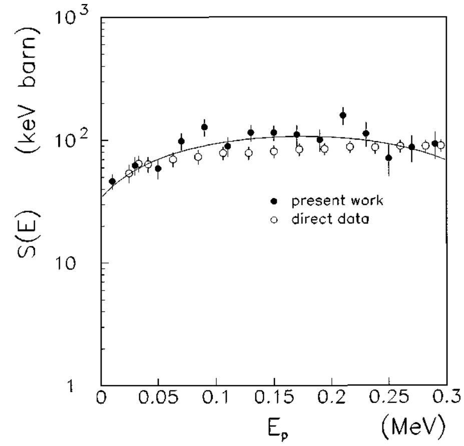

FIG. 8. Astrophysical $S(E)$ factor for the ${}^{1}\mathrm{H}({}^{7}\mathrm{Li},\alpha){}^{4}\mathrm{He}$ reaction as obtained from our data according to Eq. (8) (full dots). Data from Ref. [28] (empty dots) are also shown for comparison.

in the energy region $E_{\mathrm{c.m.}}=0-0.3$ MeV. To determine the influence of the point at 10 keV the same fit has also been performed without this latter point. The results of these fits are summarized in Table I.

Our best estimate of $S(0)=36\pm7$ keV b has to be compared with the extrapolated one [$S(0)=52\pm8$ keV b] of Ref. [28]. It has to be observed, however, that both data sets also suffer from a systematic error of $\sim$20% and $\sim$10%, respectively, arising from the normalization procedure of our data to those of Ref. [28] and of these latter to those of an absolute cross section measurement [29]. It can then be concluded that, within the uncertainties, the trend of the $S(E)$ factor as obtained in the previous work agrees with that given in Ref. [28]. As far as our previous measurement (Ref. [25]) is concerned, where an estimated value of $S(0)=23\pm9$ keV b was obtained, it has to be recalled that former data suffered from a much lower statistics and were affected by a possible systematic error due to energy-loss reconstruction in the gas inside the ionization chambers as well as in their windows.

VI. CONCLUSIONS

The present work shows the possibility of measuring the astrophysical S(E) factor at energies relevant for astrophysical applications by means of the Trojan-horse method. The astrophysical $S(E)$ factor for the ${}^{1}\mathrm{H}({}^{7}\mathrm{Li},\alpha){}^{4}\mathrm{He}$ reaction has been evaluated in two ways, as described in Sec. V. A possible explanation for the small discrepancy observed in the two values of the $S(0)$ factors, namely the one obtained in the present work through Eq. (8) and that extrapolated from direct measurements (Ref. [28]), might be ascribed to the approximate calculation of the penetration probability as given in Eq. (7). Also, the uncertainties deriving from the evaluation of the electron screening correction in the direct data cannot be completely ruled out. It has to be recalled that our result should in fact be independent of such an effect, being our measured cross section the nuclear part only. This seems to be confirmed from the fact that our values of the astrophysical S factors agree quite well within the experimental uncertainties when we consider the two different ways used to calculate the S factor itself. It is also worth noticing that the nuclear cross section varies very slowly with energy and therefore the evaluation of the astrophysical S factor by means of Eq. (9) is not affected by the strong variation of cross section around the Gamow peak encountered in direct measurements. Finally, the THM can also be regarded as an independent tool to estimate the effects of the electron screening by comparing the nuclear cross section with the cross section for bare nuclei (Ref. [3]), usually evaluated from a theoretical point of view.

As far as the influence of the point at 10 keV is considered, the $S(0)$ value obtained by neglecting this point is even lower than the one arrived at considering the full data set. In this respect the value reported in Ref. [28] can be regarded as an upper limit and the results shown in the present work cannot help solving the problem of lithium depletion.

In the light of this new value of $S(0)$ we would like to

TABLE I. Results of a second-order polynomial fit on the $S(E)$ factors, calculated according to the two different approaches described in the text. Values of the fit without the lowest energy point (i.e., at 10 keV) are also given.

	$S(E)=\exp(2\pi\eta)E\sigma(E)$		$S^N(E)=E\sigma^N(E)$	
Coefficients	Full data set	-10 keV point	Full data set	-10 keV point
$S(0)$ (keV b)	36 ± 7	31 ± 14	32 ± 6	26 ± 13
S_1 (b)	897	974	868	957
S_2 (keV^{-1} b)	-2585	-2810	-2393	-2660

make some comments on the Li problem in the astrophysical context, in particular in environments such as dwarf stars and open clusters. It is well known that the abundance of Li in dwarf stars is generally too small (one or two orders of magnitude) with respect to the prediction of evolutionary models. A typical example is the Sun [30]. Lithium abundance deduced from data on the Sun's photosphere is 100 times lower than that found in meteorites. Such an observational evidence had brought to the hypothesis that Li burning in pre-main sequence evolution might proceed at a higher rate than previously supposed.

However, since during this evolutionary phase the temperature of a one solar-mass star is not high enough to justify such a rate, it was also taken into account the possibility that Li be burned also during the main sequence phase at the bottom of the convective zone. From helioseismological data [31] we know that the temperature in such a region ranges from 2.1–2.3$\times 10^{6}$ K and that it has not changed by more than 10% during preceding stages of the Sun's evolution. In view of such a fact our result does not solve the problem, but rather supports even more the idea that a solution has to be found by taking into account factors other than the cross section, such as for instance the opacity of the stellar matter or the treatment of convection.

As far as the Li depletion in open clusters like the Hyades is concerned, it has already been pointed out by [32] that only an exceeding $S(0)$ factor of about 78% with respect to that given in Ref. [28] could match the observations. Our result is clearly far from fulfilling such a requirement.

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