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The α-^{12}C scattering studied via the Trojan-Horse method

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Abstract. The Trojan-horse method has been suggested as a means to study a two-body reaction at astrophysical energies via a three-body breakup reaction. In order to test this method the ^{6}Li(^{12}C,α ^{12}C)^{2}H reaction was studied in a kinematically complete experiment at an incident energy of 18 MeV. Coincidence spectra show the presence of the quasi-free α-^{12}C scattering process. The excitation function of the three-body reaction is calculated in the plane wave impulse approximation assuming quasi-free scattering and is compared with the experimental data. Also, the excitation function of the virtual α-^{12}C elastic scattering is extracted from the three-body reaction cross section at low deuteron momenta and compared with the behaviour of the free scattering cross section.

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1 Introduction

It is well known that the ^{12}C(α,γ)^{16}O reaction, which takes place in stars during their helium burning phase, plays a key role in astrophysics both for the nucleosynthesis of heavier elements and for the final evolution of massive stars [1,2]. Thus, a large number of measurements has been devoted to the determination of the cross section at energies as close as possible to the relevant Gamow energy ($E_0 \sim 300$ keV) [3,4] (and references therein). Due to the extreme difficulties encountered in direct measurements at sub-Coulomb energies, indirect methods such as α-transfer reactions, Coulomb dissociation, and β-delayed α-emission from ^{16}N [5–13] have been exploited in order to derive the relevant information for the calculation of the ^{12}C(α,γ)^{16}O cross section at astrophysical energies.

A different indirect approach based on the quasi-free reaction mechanism has been suggested for the study of reactions of astrophysical interest [14]. The method, referred to as the "Trojan-Horse Method" (THM), relates the cross section for a two-body reaction

$$t(p,a)b$$

in the quasi-free approximation to the cross section of an appropriate three-body reaction,

$$A(p,ab)s.$$

Here the target $A = (t + s)$ is considered as composed by the clusters t and s, where t interacts with the projectile p and s is assumed to behave as a spectator to the process $t(p,a)b$ (Fig. 1). If the bombarding energy is chosen higher than the Coulomb barrier in the entrance channel of the three-body reaction, particle t can be brought into the nuclear well (interaction region), thus inducing the two-body reaction of interest. Appropriate conditions (i.e., beam energy and detection angles) can be selected so that the Fermi motion, i.e. the momentum distribution, of t inside A compensates, at least partly, for the initial projectile velocity. The interaction $p + t$ can then take place at low relative energies to match the relevant astrophysical energy region. In this way it is possible to eliminate the problem of direct measurements connected with the suppression of the cross section at low energies due to the

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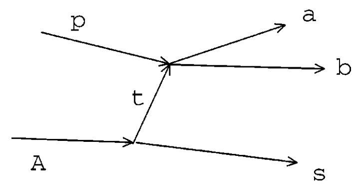

Fig. 1. Pseudo-Feynman diagram of a quasi-free scattering

Coulomb barrier in the two-body reaction. Additionally, due to the high bombarding energy, the deduced cross section is not influenced by the effects of electron screening, which are presently a source of uncertainty in direct measurements at ultra-low energies.

The THM makes assumptions on the reaction mechanism which are discussed in more detail below. In order to use it to obtain information of astrophysical interest, it is important to verify experimentally that kinematical conditions can be specified where these assumptions are justified. Once the conditions under which the method can be applied have been established, it can be used at energies where direct measurements are very difficult or impossible. This program has already been pursued in other cases. For example, measurements of the astrophysical $S(E)$-factor for the ^{2}H(^{6}Li,α)^{4}He and ^{1}H(^{7}Li,α)^{4}He reactions were performed by studying the ^{6}Li(^{6}Li,$\alpha\alpha$)^{4}He [15,16] and ^{2}H(^{7}Li,$\alpha\alpha$)n [17,18] reactions, respectively; the results were found to be in good agreement with those derived from direct measurements [19,20].

As a first step to the application of the THM for the ^{12}C(α,γ)^{16}O reaction, we report in this paper on measurements of the quasi-free ^{6}Li(^{12}C,α ^{12}C)^{2}H scattering. The ^{6}Li nucleus has been chosen as the trojan horse because the ground state is $l = 0$, which makes the application of the method simpler. The Fourier transform of the ground state wave function is well known and peaks at zero momentum which determines the quasi-free scattering angles. A nucleus with a $l = 1$ ground state wave function like ^{7}Li has a much broader momentum distribution and seems to be less suitable for the THM.

We investigate in detail the range of spectator momenta where the assumptions of a quasi-free breakup mechanism is justified. We employ two steps in the evaluation of the experimental data: first, the experiment is described by means of a Montecarlo simulation assuming the quasi-free mechanism for the three-body breakup reaction. This allows to determine the conditions where the quasi-free mechanism actually dominates. We then extract the two-body excitation function and compare it with the results of direct α-^{12}C elastic scattering measurements in the energy range $E_{\rm cm} = 2.5 - 3.5$ MeV.

2 Theoretical formalism

The cross section of the three-body reaction is described by the expression [21] (in standard notation)

$$\frac{\mathrm{d}^3\sigma}{\mathrm{dE}^{\rm f}_{\alpha\mathrm{C}}\mathrm{d}\Omega_{\alpha\mathrm{C}}\mathrm{d}\Omega_{\mathrm{Od}}} = \frac{2\pi}{\hbar}\frac{\mu_{\rm LiC}}{\mathrm{p}^{\rm i}_{\rm LiC}}\frac{\mu_{\alpha\mathrm{C}}\mathrm{p}^{\rm f}_{\alpha\mathrm{C}}}{(2\pi\hbar)^3}\frac{\mu_{\rm Od}\mathrm{p}^{\rm f}_{\rm Od}}{(2\pi\hbar)^3}\left|\mathrm{T_{fi}}(\boldsymbol{p}^{\rm f}_{\alpha\mathrm{C}},\boldsymbol{p}^{\rm f}_{\rm Od},\boldsymbol{p}^{\rm i}_{\rm LiC})\right|^2. \quad (1)$$

It depends on the initial LiC relative momentum $\boldsymbol{p}^i_{\rm LiC}$ and the final αC and Od relative momenta $\boldsymbol{p}^f_{\alpha\rm C}$ and $\boldsymbol{p}^f_{\rm Od}$, respectively, where O indicates the combined αC system. The exact T-matrix element has the form

$$\mathrm{T_{fi}} = \langle \Psi^{(-)}_{\rm Od}(\boldsymbol{p}^{\rm f}_{\alpha\rm C},\boldsymbol{p}^{\rm f}_{\rm Od})|\mathrm{V}_{\alpha\rm C} + \mathrm{V_{dC}}|\phi_{\rm LiC}(\boldsymbol{p}^{\rm i}_{\rm LiC})\chi_{\rm Li}\chi_{\rm C}\rangle \quad (2)$$

with the ^{6}Li and ^{12}C ground-state wave functions $\chi_{\rm Li}$ and $\chi_{\rm C}$, respectively, and $\phi_{\rm LiC}$ the plane wave in the initial channel. In the plane wave Born approximation (PWBA) the full scattering wave function $\Psi^{(-)}_{\rm Od}$ in the final channel is replaced by a product of the full two-body scattering wave function $\Psi^{(-)}_{\alpha C}(\boldsymbol{p}^f_{\alpha C})$ and the corresponding plane wave $\exp(-\boldsymbol{p}^f_{Od})\cdot\boldsymbol{r}_{Od}$, which is justified for high enough momenta well above the Coulomb barrier.

The hypotheses underlying the THM imply that the incident particle interacts with only one cluster at a time in the target nucleus, leaving the other one unperturbed [22]. Since the ^{6}Li nucleus can be considered as being strongly clustered into α+d (e.g. [23]), an off-line selection can be made of those events corresponding to an α-^{12}C interaction only, with the deuteron behaving as a spectator. Under this kinematical condition we neglect the contribution from the dC interaction in the T-matrix element. In this impulse approximation of the PWBA version of the T-matrix of (2) can be evaluated in a straightforward way [24]. The cross section of the ^{6}Li(^{12}C,α ^{12}C)^{2}H scattering can be factorized into a term describing the α-d momentum structure of ^{6}Li and a term describing the α-^{12}C interaction. Since the momentum distribution of the deuteron in ^{6}Li is known [25], the study of the three-body reaction can be used to infer information on the α-^{12}C scattering interaction. Thus, the three-body cross section can be expressed as

$$\frac{\mathrm{d}^3\sigma}{\mathrm{dE}^{\rm f}_{\alpha\mathrm{C}}\mathrm{d}\Omega_{\alpha\mathrm{C}}\mathrm{d}\Omega_{\mathrm{Od}}} = \mathrm{KF}\,|\chi_{\rm Li}(\boldsymbol{p}_{\rm d})|^2\,\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_{\alpha\rm C}}, \quad (3)$$

where

a) KF= $\frac{8\pi^3\hbar^3}{\mu_{\alpha\rm C}}\frac{\mu_{\rm LiC}}{\mathrm{p}^{\rm i}_{\rm LiC}}\mathrm{p}^{\rm f}_{\alpha\rm C}\mu_{\rm Od}\mathrm{p}^{\rm f}_{\rm Od}$ is a kinematic factor, which can be calculated from the experimental conditions;

b) $|\chi_{\rm Li}(\boldsymbol{p}_{\rm d})|^2$ is the deuteron momentum distribution in ^{6}Li, which depends only on the internal wave function and is in principle independent of the experimental conditions; because of the impulse approximation, the momentum of the (spectator) deuteron in its final state is considered to be the same as its initial momentum in ^{6}Li;

c) $\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_{\alpha\rm C}}$ is the two-body differential scattering cross section for the α-^{12}C sub-system which is assumed to be on-shell in the quasi-free approximation.

The assumptions of the THM in general, and those of the plane wave impulse approximation (PWIA) with the quasi-free approximation of (3) in particular, are discussed in a forthcoming paper within the framework of general scattering theory [26]. In particular, the relation of the above approximations to a PWBA calculation with the surface approximation [14] has been investigated, where the 3-body cross section is of the same structure as in (3).

However, the argument in the momentum distribution (actually the Fourier transform of the internal wave function multiplied by the interaction) is not exactly the deuteron momentum $\boldsymbol{p}_d$ but shifted by a small amount. In the PWBA the last factor is not directly the on-shell 2-body cross section, but a more complicated expression containing the 2-body cross section but also incorporating the fact that the 2-body process does not take place on-shell, since the α-particle is initially bound in ^{6}Li.

It is also of interest how Coulomb effects enter in the various approaches. In (3) and in the PWBA they are taken into account in the 2-body cross section but neglected in the incident and exit channels of the 3-body reaction. As long as the energies are high enough, as in the present application, this is of small relevance. But it will become important in applications of the THM at small relative energies for astrophysical purposes. Then it may be neccessary to resort to the formulations containing Coulomb distortion effects, as in [14,26]. In view of all these considerations it is important to test the applicability of (3) under actual experimental conditions as done in this work.

In order to determine completely the kinematic properties of the final state, the total kinetic energy of the two outgoing particles must be measured in coincidence at specific angles, θ_α and $\theta_{\rm C}$. Since the deuteron momentum distribution inside ^{6}Li is peaked around zero (the α-d relative motion is in an $l = 0$ state) [25,27,28], the angles should be chosen to correspond to $p_{\rm d} = 0$. These pairs of *quasi-free angles* then correspond to the kinematic conditions where the quasi-free process, if present, should be dominant.

The angle of emission for the ^{12}C particle in the $\alpha-^{12}$C center-of-mass system can be calculated according to the relation [24]

$$\theta_{\rm cm} = \arccos\frac{(\mathbf{v}_{\rm p}-\mathbf{v}_{\rm t})\cdot(\mathbf{v}_{\rm C}-\mathbf{v}_\alpha)}{|\mathbf{v}_{\rm p}-\mathbf{v}_{\rm t}|\;\;|\mathbf{v}_{\rm C}-\mathbf{v}_\alpha|}, \tag{4}$$

where the vectors $\mathbf{v}_{\rm p}, \mathbf{v}_{\rm t}, \mathbf{v}_{\rm C}$ and $\mathbf{v}_\alpha$ are the velocities of the projectile, the transferred α-particle, and the two outgoing ^{12}C and α particles, respectively. These quantities can be calculated from their corresponding momenta in the lab-system, where - because of the quasi-free assumption - the momentum of the transferred particle is equal and opposite to that of the spectator particle [24]. Since $|\chi_{\rm Li}(\boldsymbol{p}_{\rm d})|^2$ is known and KF can be calculated, the two-body cross section can be extracted from the measured three-body cross section using (3).

3 Equipment and setup

The first experiment on the ^{6}Li(^{12}C,α ^{12}C)^{2}H reaction was performed at the 4 MV Dynamitron Tandem Laboratorium in Bochum (Germany). Additional data were taken at the SMP Tandem Van de Graaff accelerator of the Laboratori Nazionali del Sud (LNS), Catania [29]. A 145 μg/cm^2 thick LiF target (enriched in ^{6}Li to 95%) was evaporated on a thin carbon backing. It was bombarded with a 18 MeV ^{12}C beam, with a spot size on target of about 1 mm diameter.

The reaction products were detected in coincidence by means of two ΔE-E telescopes, each one consisting of an ionization chamber (IC) and a position sensitive silicon detector (PSD). Due to the different specific energy losses of α's and carbon ions, an appropriate choice of the gas and its pressure was made for each IC (in the following referred to as ΔE_α and $\Delta E_{\rm C}$ for α and ^{12}C detection, respectively), in order to optimize the detector's response to the given particle. Continuous flows of isobutane at a pressure of 90 mbar and of an argon-methane mixture (90% argon - 10% methane) at 40 mbar were used for ΔE_α and $\Delta E_{\rm C}$, respectively. Each IC was 5 cm long and had a 0.9 μm thick mylar foil as entrance and exit windows. The PSD's (1000 μm thick) were placed behind their corresponding IC's and were centered at $\theta_\alpha = 22.5^{\rm o}$ and $\theta_{\rm C} = 12.5^{\rm o}$ on opposite sides of the beam direction, at respective distances of 18.7 cm and 33.2 cm from the target. The in-plane angular ranges covered by the telescopes were $\Delta\theta_\alpha = 14.9^{\rm o}$ and $\Delta\theta_{\rm C} = 8.6^{\rm o}$, with solid angles of $\Delta\Omega_\alpha = 12.6$ msr and $\Delta\Omega_{\rm C} = 2.2$ msr. The overall energy thresholds of these telescopes were around 4 and 5 MeV for α and ^{12}C, respectively, mainly due to the thickness of the gas and windows.

The position of the detectors was chosen in order to cover a range of $E_{\rm C}$ values near the known 4^+ resonance where experimental data of elastic α-^{12}C scattering are available. With a smaller angle between the ejectiles lower α-^{12}C relative energies could be reached at the same projectile energy assuming a quasi-free process with zero momentum of the deuteron.

Standard electronic was used for both position and energy signals which were then converted by means of Silena 4418/V peak sensing ADC's and collected by the LNS acquisition system. The delay between the PSD timing signals was also recorded after time-to-amplitude conversion and used in the off-line analysis to select the physical coincidences from the random ones. Data were then stored on tape in an event-by-event mode.

Preliminary runs for the position calibration of the PSD's were performed using regularly spaced slits placed in front of each detector. The angular resolution was found to be about 0.1^o for both detectors. The energy calibration of the PSD's was obtained using an α-source and the elastic scattering peaks of ^{12}C on a thin Au target, at different beam energies. Calibration of the ΔE detectors was performed by comparison of data collected with and without gas in the chambers. The total kinetic energy of the detected particles was reconstructed off-line taking into account the energy loss in the target as well as in the win-

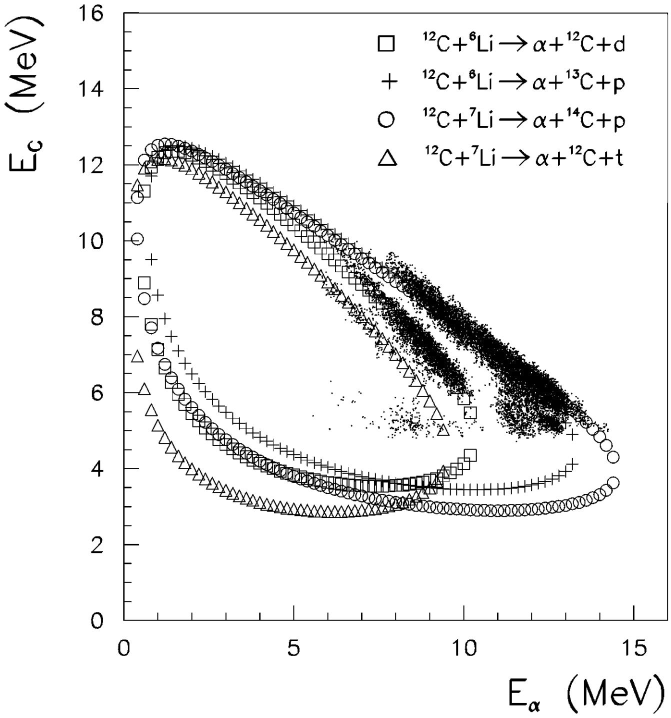

Fig. 2. Kinematic loci for reactions with a three-body final state. Square symbols indicate the reaction of interest

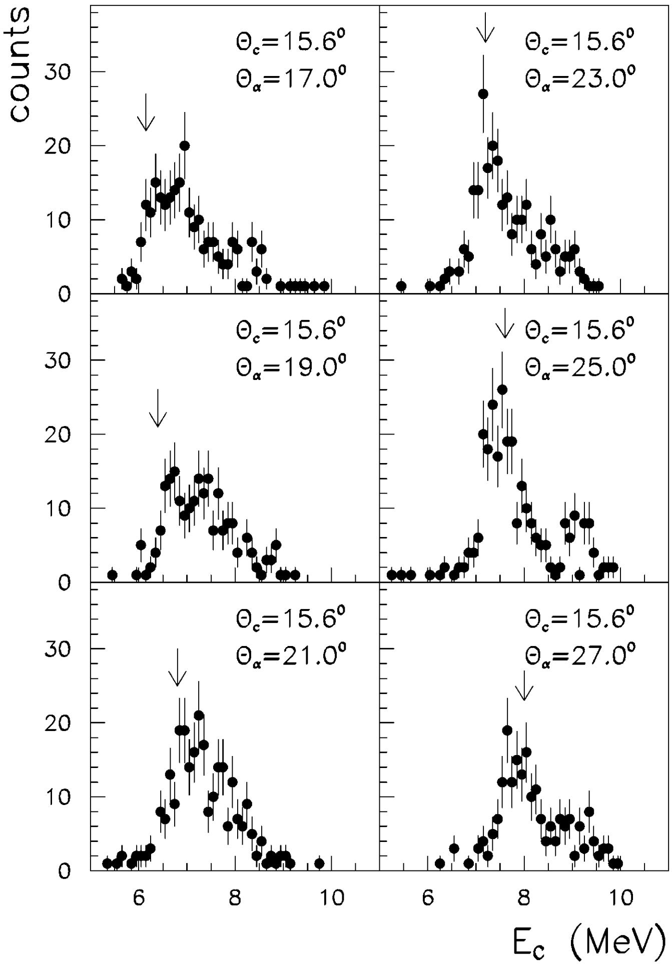

Fig. 3. Coincidence spectra projected on the E_C-axis for a fixed $\theta_C = 15.6^o$ and different θ_α. The data are obtained within the angular ranges of $\pm 1^o$. The condition corresponding to deuteron momentum P_d=0 has been marked with an arrow on the E_C-axis

dows of the IC's. The overall energy resolution was found to be about 2% FWHM for both the 5.48 MeV α-source peak and the elastic scattering peak of ^{12}C on ^{19}F.

4 Data analysis and results

After identification of the He and C ions in the ΔE-E matrices, the locus of the events in the E_α-E_C plane due to the ^{6}Li(^{12}C,α ^{12}C)^{2}H reaction was defined by the corresponding three-body kinematics. Other three-body reactions occurring in the target were identified in the same way. As shown in Fig. 2 the kinematic loci for different reactions do not overlap with the one of interest (square symbols). A graphical cut was then used to select the events corresponding to the reaction ^{6}Li(^{12}C,α ^{12}C)^{2}H.

Figure 3 shows coincidence spectra projected on the E_C axis for a fixed θ_C and for different θ_α angles selected within the angular range of the setup (Sect. 3). The condition of nearly zero deuteron momentum has been marked with an arrow on the E_C-axis. From the sequence of these spectra it can be observed that the coincidence yield attains a maximum when the deuteron momentum approaches zero value. This feature is expected for a quasi-free reaction.

In the spectra of Fig. 4 the coincidence yield is shown as a function of the α-^{12}C relative energy $E_{\rm cm}$, for different ranges of the deuteron momentum p_d. It should be pointed out that, due to the well-known lens effect (e.g. [13]), the relative energy resolution is much better than the experimental resolution of the individually measured kinetic energies E_α and E_C. A 50 keV-bin size was therefore chosen for the presentation of the spectra. A peak at $E_{\rm cm}$ = 3.1 MeV is most prominent for p_d < 10 MeV/c and decreases significantly for higher values of the spectator momentum. This peak has been identified with the $J^\pi = 4^+$ state at E_x=10.35 MeV in ^{16}O [30]. The difference in resonance energy between the measured value and that reported [30] is less than 1%. The experimental evidence of a strong correlation between the magnitude of the observed peak and the value of the deuteron momentum supports strongly the dominance of the quasi-free mechanism at zero deuteron momentum. In fact, as seen in (3), the 3-body cross section is proportional to the momentum distribution of the deuteron in ^{6}Li. For an s-state this is peaked at p_d=0 and it has a width of about 70 MeV/c (see below). The fact, that the 4^+-peak in Fig. 4 decreases over deuteron momenta of this magnitude, in itself is a strong experimental indication of the quasi-free mechanism.

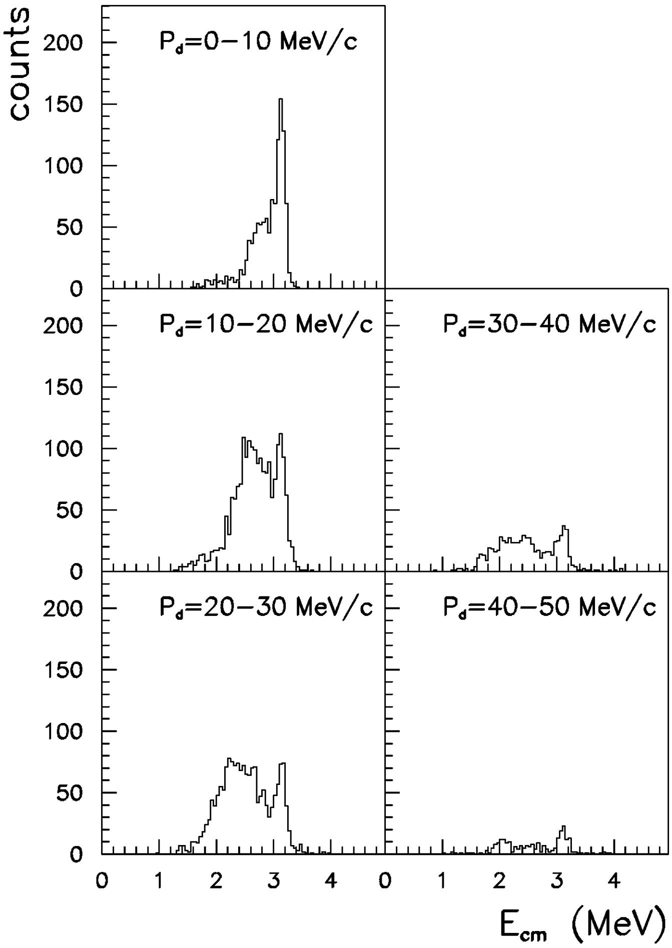

Fig. 4. Coincidence yield as a function of the relative $E_{\alpha C} = E_{cm}$ energy for various ranges of the deuteron (i.e. spectator) momentum

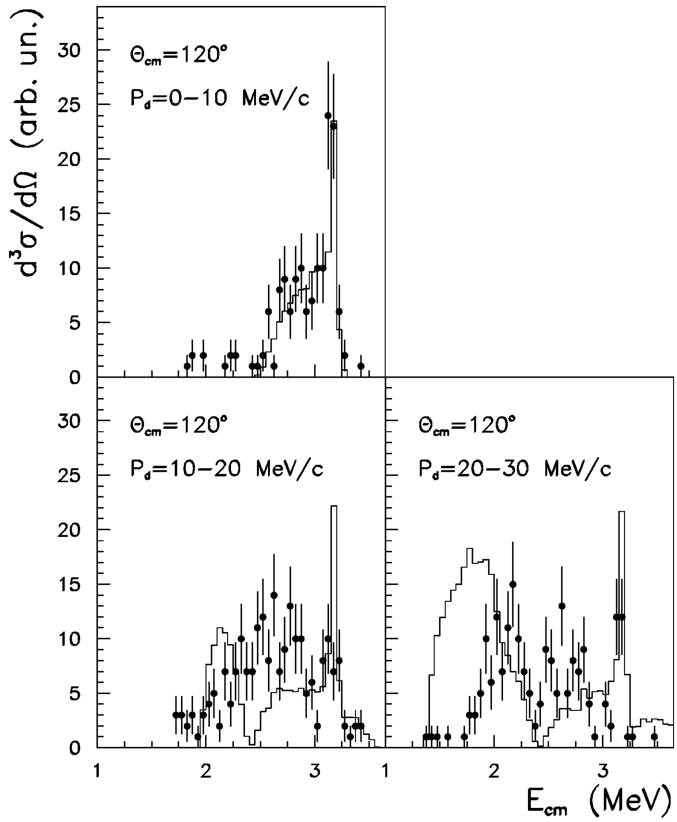

Fig. 5. Simulated three-body cross section (histogram) using (3) and detector efficiencies (see text) compared to the data for the given experimental conditions

The results shown in Fig. 4 can be further evaluated in two ways. A first one is to use experimental α-^{12}C scattering data and calculate the three-body cross section using (3). Since detection efficiency has to be taken into account, this can be achieved in a Montecarlo simulation of the experiment. This analysis is performed in the next section and should show under what conditions the quasi-free assumption is applicable. Secondly, from those spectra which are found to follow the quasi-free assumption we extract directly the two-body cross section and compare it to direct measurements (Sect. 6).

Finally, the center-of-mass angular range covered by our experimental data is $\theta_{cm} = 100^o - 150^o$. Since the direct data of Kettner et al. [31] span a region between $\theta_{cm} = 30^o$ and 120^o, a comparison was possible only for $\theta_{cm} \simeq 120^o$. Further analysis was therefore performed for all those events with $\theta_{cm} = 120^o \pm 2.5^o$.

5 Montecarlo simulation

The experiment has been simulated by means of a Montecarlo calculation under the assumption that the mechanism giving rise to the reaction is purely quasi-free, so that the three-body cross section can be calculated according to (3). The momentum distribution has been obtained from the Fourier transform of the ^{6}Li ground-state wave function, assuming for the α-d interaction a Woods-Saxon potential adjusted so as to reproduce the ^{6}Li binding energy ($B = 1.475$ MeV). A fit to the Fourier transform using the product of a Lorentzian and a Gaussian function gives a FWHM of 73 MeV/c, consistent with observations (e.g. [32]).

The two-body cross section entering (3) was calculated from energy-dependent phase shifts for partial waves $l = 0 \to 6$. These phase shifts were taken from a multilevel R-matrix parameterization of elastic α-^{12}C scattering derived from a phase-shift analysis given in [33]. Finally, the geometrical efficiency of the experimental setup as well as the detection thresholds of the two telescopes have been taken into account. A calculation of the error in the $E_{\alpha C}$ variable has also been carried out, leading to an average value of about 70 keV.

Figure 5 shows both the calculated three-body cross section (histogram) and the experimental data (points) with various conditions on the deuteron momentum and for $\theta_{cm} = 120^o \pm 2.5^o$. The normalization factor between the theoretical calculation and the experimental data has been obtained through a χ^2-minimization procedure for the case with $p_d \leq 10$ MeV/c. The comparison shows an excellent agreement at low spectator momenta (i.e. $p_{\mathrm{d}} \leq 10$ MeV/c). The results demonstrate that the quasi-free mechanism is present and the approximations used to describe the cross section are plausible and give results in agreement with the experimental data. However, a substantial disagreement remains for higher p_{d} values (Fig. 5). The reasons for these discrepancies could be twofold: firstly, mechanisms other than the quasi-free breakup (e.g. sequential processes via intermediate resonance states of the ^{6}Li target) could be present. Secondly, off-shell effects can be important, and they are expected to become more important the more the quasi-free condition is violated, i.e. the for a high momentum transfer to the deuteron. As discussed above, (3) was derived in PWBA and under the assumptions $V_{\mathrm{dC}} = 0$. These assumptions are increasingly violated at larger $|\boldsymbol{p}_d|$. Thus the discrepancies seen in Fig. 5 point to the need for a better description including distortion effects for larger $\mathrm{p_d}$ values.

6 The two-body cross section

According to the results of the simulation (Fig. 5), only events with $\mathrm{p_d} \leq 10$ MeV/c were taken into account for the extraction of the two-body cross section. In order to divide the three-body cross section by the momentum distribution and the kinematic factor, these latter quantities have been calculated as a function of the relative $\mathrm{E}_{\alpha\mathrm{C}}$ energy. Geometrical detection efficiency has also been taken into account. The original statistical errors of the primary data have been preserved throughout the whole procedure. The resulting two-body excitation function is shown in Fig. 6. Shown are also the direct data [31], after having been rebinned in 50 keV steps so as to simulate an energy resolution similar to that obtained in the present measurement. Good agreement is noted between the two data sets, thus confirming the validity of the hypotheses used in the derivation of the two-body cross section.

7 Summary

The study of the ^{6}Li(^{12}C,$\alpha\,^{12}$C)^{2}H reaction at 18 MeV beam energy has shown the dominance of a quasi-free mechanism around the region of spectator momentum close to zero. The mechanism proceeds through a virtual scattering of the incident ^{12}C off the α-cluster in ^{6}Li. The data can be well described by PWBA calculations and the comparison with the directly measured excitation function is good. Under the present kinematical conditions the relative energy covered was between 2.5 and 3.5 MeV, i.e. far away from the astrophysical region. However, if the quasi-free mechanism still dominates at a lower beam energy, e.g. about 10 MeV, one can match the appropriate conditions to study the same reaction at α-^{12}C relative energies close to zero, with the purpose of extracting information on the astrophysically relevant process of radiative α-capture by ^{12}C. Further work in this direction is in progress.

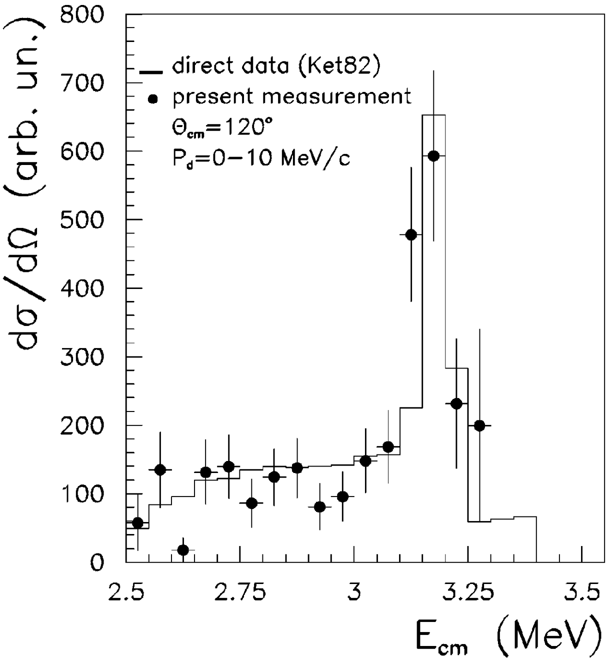

Fig. 6. Comparison between direct (solid curve) and indirect excitation function for the two-body scattering α+^{12}C at $\theta_{\mathrm{cm}} = 120^{o}$ and $E_{\mathrm{cm}} = 2.5 - 3.5$ MeV

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