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New application of the quasi-free reaction mechanism to study neutron induced reactions at low energy

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Abstract. The quasi-free break-up of deuteron was used to study the neutron induced $^{6}Li + n$ reaction via the $^{2}H(^{6}Li, \alpha^{3}H)p$.cross section of the $^{6}Li + n \rightarrow^{3} H + \alpha + p$ reaction corresponding to the excited level at 7.454 MeV of ^{7}Li, with the same resolution of the direct measurement. Two experimental runs were performed at Laboratori Nazionali del Sud (LNS) in Catania.channel of interest in the three body reaction. In the second experiment the "magnifying glass" effect is used to improve the resolution in the $^{6}Li - n$ relative energy in the region where the resonance is present.agreement demonstrating the possibility to use deuteron as a virtual neutron beam.

Key words. Stars: neutrons – indirect methods

1. Introduction

Quasi-free (QF) reactions have been extensively studied in the past in order to investigate the cluster structure of light nuclei (Milijanic et al. 1973; Kasagi et al. 1975; Lattuada et al. 1986). The selection of QF events in a three body reaction, $A + a \rightarrow B + b + s$, where a has a strong $x \bigoplus s$ cluster structure and s acts as a spectator, allows to get information about the two body reaction $A + x \rightarrow B + b$. Many theoretical approaches, based on the Impulse Approximation (Chew et al. 1950; Chant & Roos 1977), describe this kind of processes using a pseudo-Feynman diagram. A pole of the diagram represents the break-up of the nucleus a in x and s, while the other one describes the virtual two body reaction $A + x \rightarrow B + b$. In Plane Wave Impulse Approximation (PWIA) the three body cross section is factorized into two terms representing these two poles of the Feynmann diagram:

$$\frac{d^{3}\sigma}{dE_{b}d\Omega_{b}d\Omega_{B}} \propto KF|\Phi(p_{s})|^{2}\left(\frac{d\sigma}{d\Omega}\right) \tag{1}$$

where $(d\sigma/d\Omega)$ is the off-energy shell differential cross section for the two body reaction, KF

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is a kinematical factor depending on masses energy and angles of the outgoing particles and $|\Phi(p_s)|^2$ is the Fourier transform of the radial wave function for the $p-n$ inter-cluster motion inside the deuteron (Chew et al. 1950; Chant & Roos 1977). According to the post-collision prescription, the center of mass energy for the virtual reaction is defined as $E_{cm} = E_{Bb} - q_{2b}$, where E_{Bb} is the relative energy of the two outgoing particles and q_{2b} is the q-value for the $A + x \rightarrow B + b$ on-shell reaction. Measuring the three body cross section it is then possible to extract the two-body cross section dividing by the factor $KF|\Phi(p_s)|^2$, calculated using a Monte Carlo simulation (see Eq. 1).

The QF mechanism was successfully used in the framework of the Trojan Horse Method to measure two body reactions induced by charged particles in the energy region of astrophysical interest, without Coulomb suppression and screening effects (Spitaleri et al. 1999, 2004; Lattuada et al. 2001). In the present work an original application of the QF reaction mechanism to study two body reactions induced by neutrons is presented. The idea is to select from $A + d$ reactions the interactions leaving the proton as spectator, using in this way a deuteron as a virtual source of neutron. In particular the study of the ${}^6Li(n,\alpha)^3H$ reaction via the 3 body reaction ${}^2H({}^6Li,\alpha^3H)p$ is presented in this work.

The directly measured cross section for the ${}^6Li + n$ reaction shows a resonance at energy $E({}^6Li - n) = 210\ keV$ with a FWHM of $100\ keV$ corresponding to the excited level at $7.454\ MeV$ of ${}^7Li$. The aim of this study is to reproduce the resonance with a resolution comparable with the direct measurements.

2. The experiment

Two measurements of the ${}^2H({}^6Li,\alpha^3H)p$ reaction were performed at LNS in Catania. The first one, described in (Tumino et al. 2005), has shown a good agreement with the results of the direct measurement even if the poor resolution of the indirect data did not allow to reproduce the resonance width.

The second experiment was optimized in order to reproduce the resonance in the two body cross section with a resolution comparable with the direct measurements.

For this reason, the experimental set-up was chosen such that a "magnifying glass" effect (Baur 1986) can be exploited to obtain a better resolution in the measure of ${}^6Li - n$ relative energy .

In a three body reaction, if the angles of two outgoing particles are fixed in a "in plane" geometry, the events related to the reaction of interest describe a well defined curve in the correlation spectra of the detected energies. The allowed energy combinations map the variation of any two of the three particles relative energy and of the momentum of the spectator. Under proper kinematical conditions, it is possible to translate a slow variation in the relative energy into a large variation in the energy of the two outgoing particles, obtaining the so called "magnifying glass" effect. This effect enables detailed studies of the variation of the cross section with the relative energy.

Detailed kinematical calculations have then been performed in order to define the experimental set-up useful to exploit the "magnifying glass" effect. The best kinematical conditions were found using a beam energy of $17\ MeV$ and selecting α and ${}^3H$ particles falling respectively in the angular ranges ($22° - 26°$) and ($36° - 40°$). Indeed, under these conditions, the calculated kinematical loci present a region where the ${}^3H - \alpha$ relative energy is almost constant while the energy of the two outgoing particles have a range of $4 - 5\ MeV$. As an example, in Fig. 1 it is reported the correlation between the relative energy $E({}^3H - \alpha)$ and the energy of ${}^3H$ and α, calculated using a beam energy of $17\ MeV$, $\theta_{{}^3H} = 36°$ and $\theta_\alpha = 25°$. The full dots in Fig. 1 indicate the region where the momentum of the undetected proton ranges from about $-40\ MeV/c$ up to $40\ MeV/c$ thus assuring that the phase region where a QF contribution to the break-up process of interest is favored falls inside the investigated region.

Following these calculations, the second experiment was performed using a ${}^6Li$ beam of $17 MeV$ delivered by the SMP Tandem Van de Graaf at LNS, impinging on a CD_2 tar-

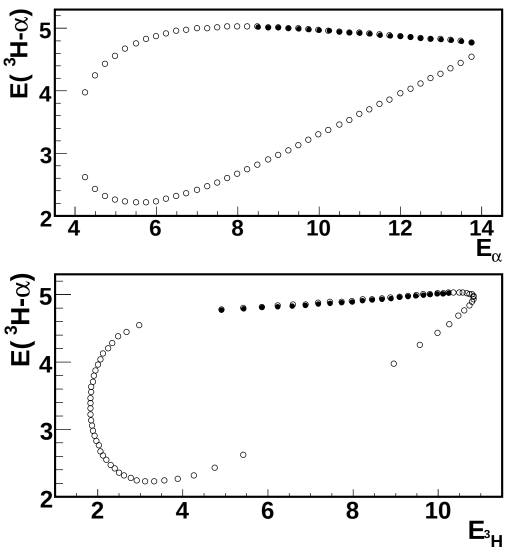

Fig. 1. Correlation between the relative energy $E(^3H-\alpha)$ and the energy of ^3H and α particles detected with outgoing angles $\theta_{^3H} = 36°$ and $\theta_\alpha = 25°$. The full dots represent the regions where the momentum of the undetected proton ranges from about $-40\ MeV/c$ up to $40\ MeV/c$.

get of 100 $\mu g/cm^2$. The beam was focused on the target using a collimator of 1 *mm* diameter. The outgoing particles were detected in coincidence using two Position Sensitive Silicon Detectors (PSD). The two detectors were placed on opposite sides with respect to the beam axis and covered the laboratory angles $22° - 26°$ and $36° - 40°$ (for α and ^3H particles respectively) in a "in plane" geometry. As it is possible to discriminate α and ^3H particles by kinematics, no ΔE detectors were used in order to avoid the angular and energy straggling of the detected particles and consequently to improve the energy resolution. Moreover, taking advantage of the large dimension of the scattering chamber, 2000 *mm* in diameter, the detectors were fixed at a distance of 780 *mm* from the target to improve the angular resolution.

Using this experimental set-up it is possible to achieve a resolution of 30 *keV* in $^6Li - n$ relative energy taking into account the angular and energy spread of the beam on the target and of the detected particles on the target and on the dead layer of the detector.

3. Data analysis and experimental results

The PSDs used in the experiment were calibrated in position and energy using the elastic scattering measured at different beam energies for the reactions ^6Li+Au and ^6Li+C. The spot and energy spread of the beam on the target, the detected particle energy loss on the target and on the dead layer of the detectors were also taken into account.

The identification of the $\alpha +^3 H + p$ channel of interest was done by selecting the correspondent kinematical locus on the correlation spectra of the energies measured by the two PSDs. In Fig. 2 the correlation between the measured energies is reported. A kinematical calculation (full dots) has been superimposed on the experimental data in order to select the three body channel of interest, $^6Li + d \rightarrow \alpha +^3 H + p$. In the figure the locus of the $^6Li + d \rightarrow \alpha +^3 He + n$ reaction is also visible. For the events falling in the region of interest the q-value is reconstructed (under the hypothesis of a proton as third particle) and it is centered at $2.58 \pm 0.05\ MeV$ to be compared with the theoretical value of $2.56\ MeV$.

Sequential processes through the ground state of ^5Li or excited states of ^4He or ^7Li can also in principle feed this channel but no evidence for these was found.

It is possible to investigate the mechanisms involved in the reaction and to identify the QF coincidence events by examining the shape of the experimental momentum distribution of the proton inside the deuteron. This distribution is described by the Hulthén function. If we select a narrow relative energy region where the two body cross section can be considered as constant and we calculate the KF term using a Monte Carlo simulation, it is possible to reconstruct the experimental momentum distribution for the spectator p using Eq. (1). In Fig. 3 the experimental momentum distribution of the proton is shown. The line represents the theoretical Hulthén function and it is in good agreement with the experimental data.

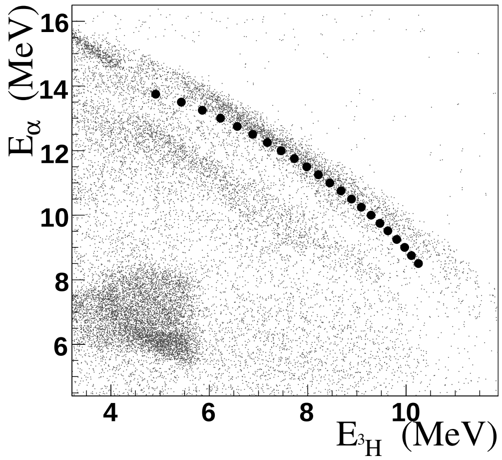

Fig. 2. Correlation spectra of the energies detected by the two PSD detectors. A kinematical calculation of the reaction of interest is superimposed on the data (full dots).

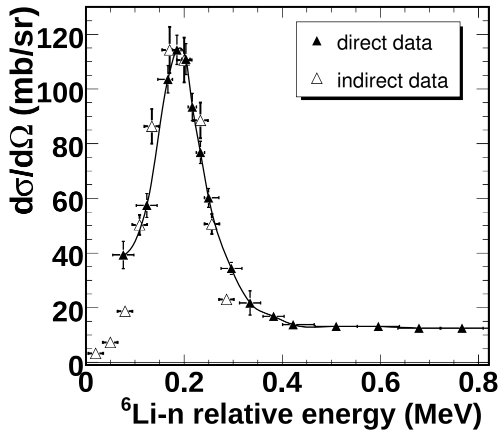

Fig. 4. Good sharp Two body cross section (open triangles) obtained in this work compared with the directly measured one (full triangles) integrated over the center of mass angular region $\theta_{cm} = 60° - 90°$. The line just guides the eye.

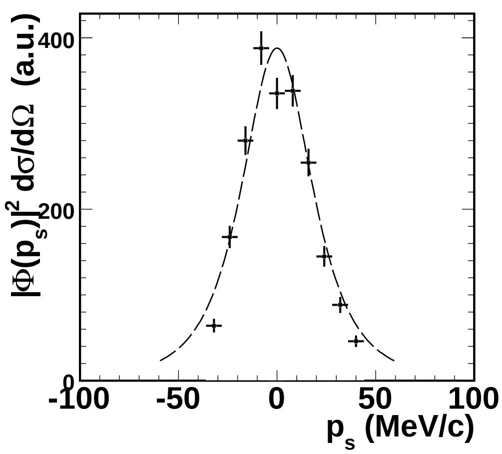

Fig. 3. Reconstructed momentum distribution of the undetected proton inside the cluster nucleus, deuteron. The dashed line represents the theoretical Hulthén function.

The two body cross section is extracted by dividing the three body coincidence yield with $|p_s| < 40\ MeV/c$ by the term $KF|\Phi(p_s)|^2$ (see Eq. 1) calculated using a Monte Carlo simulation. In Fig. 4, the extracted two body cross section is compared with the experimental direct data integrated over the same center of mass angular region, $\theta_{cm} = 60° - 90°$ (Overly et al. 1974). The indirect data are normalized to the top of the resonance, around $E(^6Li - n) = 200\ keV$. The two sets of data show a good agreement not only in the peak energy value but also in the width of the resonance peak. Moreover the comparison to the direct data was performed without the need to smear them out at a larger energy bin. To compare the resolution achieved in the two different indirect measurements, previous data are reported together with the present ones in Fig. 5, both integrated over the same center of mass angular region, $\theta_{cm} = 60° - 70°$. The strong improvement achieved using the "magnifying glass" effect is evident.

4. Conclusions

The $^6Li + d$ reaction was studied at LNS to get information about the $^6Li + n$ processes by using the break-up of ^2H. The experiment was optimized in order to reproduce the central value and the width of the resonance at 7.454 MeV of ^7Li that was already measured in direct experiments. To improve the resolution in the $^6Li - n$ relative energy, it is necessary to exploit the "magnifying glass" effect and to use an experimental set-up so to achieve a very good angular and energy resolution in the outgoing particles detection that

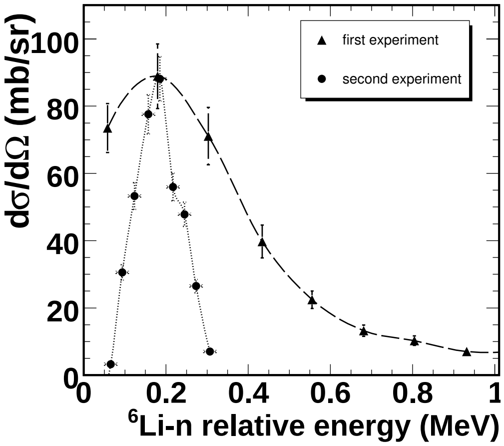

Fig. 5. Remember to keep Indirect two body cross section measured in the two experimental runs integrated in the same center of mass angular region $\theta_{cm} = 60° - 70°$. The line guides the eye.

results in a $^3H - \alpha$ relative energy resolution of about 30 keV. For this reason the detectors were placed at a distance from the target much larger than the usual one in this kind of experiments. Moreover no ΔE detector was used to avoid angular and energy straggling of the detected particles, as the particle identification was done by kinematics.

A careful analysis was performed taking into account the beam spot and the beam energy spread on the target, the energy loss of the detected particle in the target and in the dead layers of the detectors. The comparison of the $^6Li(n,\alpha)^3H$ cross section obtained in this work and the directly measured data in the same two-body center of mass angular region shows a very good agreement and demonstrates that it is possible to reach a good resolution in the measure of neutron induced two body cross section by using an indirect method. This result represents an important test in view of further applications to measure key reaction cross sections for nuclear astrophysics at low energy using deuterons as a source of neutrons.

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