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Excitation function of the quasifree contribution in the ^{2}H(^{7}Li,$\alpha\alpha$)n reaction at $E_0 = 28-48$ MeV

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The ^{2}H(^{7}Li, $\alpha\alpha$)n reaction was studied in a kinematically complete experiment at energies between 28 and 48 MeV. Coincidence spectra show the contribution from the quasifree $p + {}^7\mathrm{Li} \rightarrow \alpha + \alpha$ reaction. The excitation function of the quasifree reaction cross section at small neutron momenta was extracted and compared with the behavior of the free reaction cross section.

I. INTRODUCTION

Quasifree (QF) processes at medium energies ($E \geq 100$ MeV) have been used for the study of nuclear cluster structure.[1] At low energies QF contributions to the three-body reaction cross section have been observed too.[2] However, at low energies strong distortion effects heavily influence the interpretation of these processes.

Both the plane-wave (PWIA) and distorted-wave (DWIA) impulse approximations have been used in the analysis of experimental data. While the PWIA can be used mainly for a qualitative understanding of the process, the DWIA approach is used for quantitative analysis.[3] Extensive DWIA calculations have been performed at incident energies around 100 MeV for QF scattering and reactions on different nuclei.[1,4,5] However, no detailed analysis of QF processes at very low energies through the DWIA approach has been reported.

The factorization test can be used to check the validity of these approximations. In the PWIA as well as in the DWIA (without spin-orbit dependent distortion) the three-body reaction cross section is proportional to the cross section of the virtual two-body reaction. While experimental results at medium energies support the validity of this approximation,[1,4,5] low-energy experiments give different, even contradictory, results.[6–9]

The existence of isolated, well-known resonances in the two-body cross section may make the interpretation of low-energy data easier. Along this line several reactions have been studied in recent years in order to verify whether enhancements of the coincidence cross section could be observed and related to resonances in the two-body reaction. The results obtained so far do not allow, at present, a unique interpretation. In the case of ^{6}Li(α,$\alpha\alpha$)^{2}H at 6–13 MeV (Ref. 6) and of ^{6}Li(^{3}He,$p\alpha$)^{4}He between 3.5 and 5.5 MeV,[7] no effect has been observed in the three-body cross section around the expected two-body resonances. On the other hand, the excitation functions of the ^{9}Be(^{3}He,$\alpha\alpha$)^{4}He (Ref. 8) and ^{6}Li(^{6}Li,$\alpha\alpha$)^{4}He (Ref. 9) reactions exhibit strong resonances, but they do not seem to be related to any known ^{8}Be state. However, the resonant behavior of the ^{6}Li(α,$\alpha\alpha$)^{2}H reaction at 42.8 MeV agrees reasonably well with the known cross section of the free α-α scattering.[10,11]

In the present study the ^{2}H(^{7}Li,$\alpha\alpha$)n reaction has been chosen. This could be a good candidate to show possible resonance effects in the QF cross section since (i) the deuteron has simple "cluster" structure and its wave function is well known, (ii) the nucleon separation energy in the deuteron is low, (iii) the high Q value for the reaction allows relatively high momentum transfer to the outgoing particles, and (iv) the cross section for the two-body $p + {}^7\mathrm{Li} \rightarrow \alpha + \alpha$ reaction exhibits two broad resonances at $E_p = 3$ MeV and $E_p \approx 5.7$ MeV, due to the states near 20 and 22.2 MeV in ^{8}Be.[12]

Recently Warner *et al.*[13] studied the same reaction in the energy range $E_d = 3-15$ MeV. The kinematical conditions were chosen to study the sequential decay of the 16.6 and 16.9 MeV states in ^{8}Be. It was concluded that quasifree processes are not dominant at these energies, since the energy spectra could be fitted by using the Breit-Wigner expression for the sequential decay of these two levels. However, the energy dependence of the cross section for forming the levels with the neutron emitted at 0° is in agreement with the assumption that the neutron from ^{2}H is acting as a spectator in this process.

The kinematical conditions chosen in Ref. 13 do not allow small neutron momenta in ^{2}H to be reached in all the spectra. Furthermore, in their PWIA approach the energy spectra were compared with the spectator momentum distributions, without taking into account the influence of the two-body virtual reaction. The same reaction was then reconsidered in the present experiment. Its aim was to explore the behavior of the three-body cross section in kinematical conditions where the minimum momentum of the spectator neutron in ^{2}H is small and the energy range for the $p+{}^7\mathrm{Li}\rightarrow\alpha+\alpha$ quasifree reaction includes the resonances at $E_p=3$ and 5.7 MeV.

II. EXPERIMENTAL PROCEDURE

The measurements were performed by using the SMP Tandem Van de Graaff accelerator at the Laboratorio Nazionale del Sud, Catania. ^{7}Li ion beams ($28<E<48$ MeV) were used to bombard deuterated polyethylene targets (400 μg/cm^2 thick). Coincident particles were detected by silicon surface barrier detectors. Their solid angles were about 1 msr. Detector pulses were processed by standard electronics and an acquisition system was used to store coincident event data on magnetic tape for their offline analysis. Another detector positioned at $\theta=60°$ was used to monitor elastically scattered deuterons.

Absolute cross sections for the ^{2}H(^{7}Li,$\alpha\alpha$)n reaction were obtained by normalization to the elastic scattering cross section. The elastic scattering data were taken from Refs. 14 and 15 for $E_0<36$ MeV and $E_0=42$ MeV, and measured in the present experiment for $36<E_0<48$ MeV at $\theta_d=60°$.

III. EXPERIMENTAL RESULTS AND ANALYSIS

Measurements were done at $E_0=28$, 32, 36, 38, 42, and 44 MeV at symmetrical angles, chosen in such a way that the minimum momentum of the undetected neutron was $p_s\approx 0$ MeV/c. Other measurements were done at 42, 46, and 48 MeV and in all cases the minimum spectator momentum was lower than 20 MeV/c. Figure 1 shows a few coincidence spectra projected onto the E_1 axis. Figure 2 shows spectra obtained at $E_0=48$ MeV. Vertical arrows mark the positions where spectator momenta have the minimum value (QF) as well as the positions where a contribution from the sequential decay process

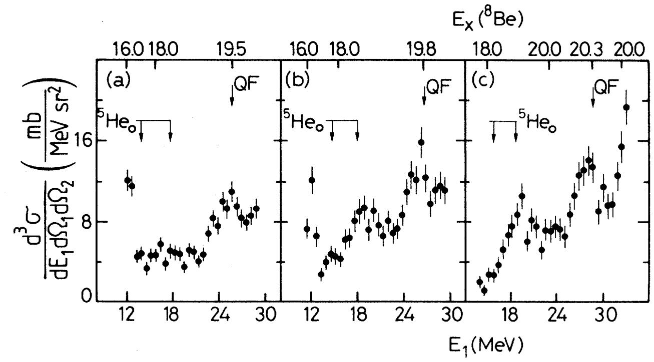

FIG. 1. α-α coincidence spectra from ^{2}H(^{7}Li,$\alpha\alpha$)n reaction projected onto E_1 axis. The upper scale shows the excitation energy in ^{8}Be. The arrows mark positions where the spectator momentum has its minimum value (QF), and positions where the contribution due to the ^{5}He ground-state level is expected. (a) $E_0=36$ MeV, $\theta_1/\theta_2=38.3°/-38.3°$, (b) $E_0=38$ MeV, $\theta_1/\theta_2=37.7°/-37.7°$, (c) $E_0=42$ MeV, $\theta_1/\theta_2=36.7°/-36.7°$.

through the ^{5}He ground state is expected. The upper scale reports the ^{8}Be excitation energy. A peak is present in all spectra at the minimum spectator momentum, while the corresponding excitation energy in ^{8}Be changes from 19.5 to 21.9 MeV. The ^{5}He excitation energy near the QF peaks changes among the reported spectra from 4.2 to 7.5 MeV.

The data were analyzed by the plane-wave impulse approximation. In this approximation the cross section for the $A(a,cd)B$ reaction, where $A=B+b$, is given by

$$\frac{d^3\sigma}{dE_1d\Omega_1d\Omega_2}\sim \mathrm{KF}|\Phi(p_s)|^2\left[\frac{d\sigma}{d\Omega}\right]. \tag{1}$$

KF is a kinematical factor, $(d\sigma/d\Omega)$ is the off-energy-shell cross section for the $b(a,c)d$ virtual reaction. In the PWIA, $\Phi(p_s)$ is the Fourier transform of the relative motion wave function of the clusters b and B in the nucleus A.

In our experimental conditions the kinematics of this reaction are strongly dependent on the angle settings. Because of that the effects of the finite-detector openings and of the beam spot size should be taken into account. Experimental spectra were then compared with the following expression:

$$Y(E_1,\theta_1,\theta_2)=\int_{\Delta E_1}\int_{\Delta\Omega_1}\int_{\Delta\Omega_2}\mathrm{KF}|\Phi(p_s)|^2\left[\frac{d\sigma}{d\Omega}\right]dE_1d\Omega_1d\Omega_2/\Delta E_1\Delta\Omega_1\Delta\Omega_2\,, \tag{2}$$

where $\Delta\Omega_i$ are the detector solid angles and ΔE_1 is the width of the energy channel. Variations of KF over the detector opening angles and energy channel width are small with respect to changes in $(d\sigma/d\Omega)$. Then, in order to factorize expression (2) as Eq. (1), the following approximation was made:

$$Y(E_1,\theta_1,\theta_2)\approx\mathrm{KF}|\Phi(p_s')|^2\int_{\Delta E_1}\int_{\Delta\Omega_1}\int_{\Delta\Omega_2}\left[\frac{d\sigma}{d\Omega}\right]dE_1d\Omega_1d\Omega_2/\Delta E_1\Delta\Omega_1\Delta\Omega_2=\mathrm{KF}|\Phi(p_s')|^2\left[\overline{\frac{d\sigma}{d\Omega}}\right], \tag{3}$$

where $(\overline{d\sigma/d\Omega})$ is the two-body cross section averaged over the energy channel width and the detector solid angles, and p_s' is an effective value of the spectator momentum p_s,

$$p_s'=\int_{\Delta E_1}\int_{\Delta\Omega_1}\int_{\Delta\Omega_2} p_s \mathrm{KF}|\Phi(p_s)|^2\left[\frac{d\sigma}{d\Omega}\right]dE_1 d\Omega_1 d\Omega_2 \Big/ \int_{\Delta E_1}\int_{\Delta\Omega_1}\int_{\Delta\Omega_2} \mathrm{KF}|\Phi(p_s)|^2\left[\frac{d\sigma}{d\Omega}\right]dE_1 d\Omega_1 d\Omega_2 \; . \tag{4}$$

It was found that with this choice of p_s', Eqs. (2) and (3) give the same values within a few percent.

The cross sections $(d\sigma/d\Omega)$ used for the two-body ^{1}H(^{7}Li,α)^{4}He reaction were taken from Ref. 16 at relative energies of the outgoing α particles (final energy prescription). The validity of this prescription was confirmed experimentally[1,5,11] as well as theoretically.[17] The momentum distribution $|\Phi(p_s)|^2$ was calculated by using the Hulthén wave function to describe the n-p motion in ^{2}H, i.e.,

$$u(r)\sim(e^{-\alpha r}-e^{-\beta r})/r \; , \qquad \alpha=0.2317 \text{ fm}^{-1}, \;\; \beta=1.202 \text{ fm}^{-1} \; . \tag{5}$$

Figure 2 shows the experimental results obtained at $E_0=48$ MeV together with PWIA calculations through Eq. (2), normalized to each experimental spectrum. The effective minimum spectator momentum p_s' is always between 8 and 15 MeV/c for all the spectra reported in Figs. 1 and 2. Data taken at $E_0=48$ MeV were selected for a comparison with theoretical predictions from PWIA since the ^{5}He ground state is far from the QF region in these spectra. One can see that agreement between experimental and calculated shape is satisfactory. On the other hand, the shape of the experimental spectra near the QF region cannot be fitted by assuming a Breit-Wigner expression for the contribution of the sequential decay through the states near 20 and 22.2 MeV in ^{8}Be. As an example, for the angles 34.3°/−35.5° [Fig. 2(b)] the experimental results show a peak at $E_1\approx 32$ MeV, while the Breit-Wigner expression gave a valley at this energy.

The ratio of the three-body cross section to the quantity $\mathrm{KF}(\overline{d\sigma/d\Omega})$ gives the so-called experimental momentum distribution

$$|\Phi(p_s')|^2=Y(E_1,\theta_1,\theta_2)/\mathrm{KF}\left[\overline{\frac{d\sigma}{d\Omega}}\right] . \tag{6}$$

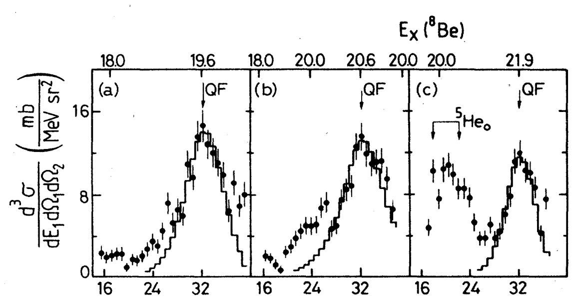

FIG. 2. α-α coincidence spectra measured at $E_0=48$ MeV. Histograms are the prediction for the quasifree contribution calculated by PWIA and separately normalized to each experimental spectrum. (a) $\theta_1/\theta_2=33.5°/-34.5°$, (b) $\theta_1/\theta_2=34.3°/-35.5°$, (c) $\theta_1/\theta_2=35.7°/-36.7°$.

The distributions obtained in this way from the experimental cross section for spectator momenta lower than about 40 MeV/c are shown in Fig. 3. The curve represents the theoretical momentum distribution normalized to the data measured at $\theta_1/\theta_2=34.3°/-35.5°$. It can be seen that experimental momentum distributions extracted from different angle pairs are in agreement, both in shape and magnitude. The agreement in magnitude has to be especially emphasized, because the two-body reaction cross section in Eq. (6) changes by a factor of 2 for different angle pairs.

Using Eq. (3) one can obtain the two-body cross section in the following way:

$$\left[\overline{\frac{d\sigma}{d\Omega}}\right]=Y(E_1,\theta_1,\theta_2)/\mathrm{KF}|\Phi(p_s')|^2 \; . \tag{7}$$

Results on $(\overline{d\sigma/d\Omega})$ obtained in this way for the minimum spectator momenta at all energies and angle pairs are shown in Fig. 4 as a function of the average energy $\overline{E}_p$. E_p is the laboratory proton energy for the ^{7}Li(p,α)^{4}He reaction corresponding to the final state α-α relative energy E_r, i.e.,

$$E_p=(m_p+m_{\mathrm{Li}})(E_r-Q)/m_{\mathrm{Li}} \; ,$$

where Q refers to the two-body reaction. Because of the finite geometry of our experiment, the averaged proton energy, $\overline{E}_p$, was used in Fig. 4. The errors in $\overline{E}_p$ correspond to uncertainties in the detector angle (±0.3°). The solid curve is obtained from the free two-body cross section[16] by averaging over the angle and energy spread in

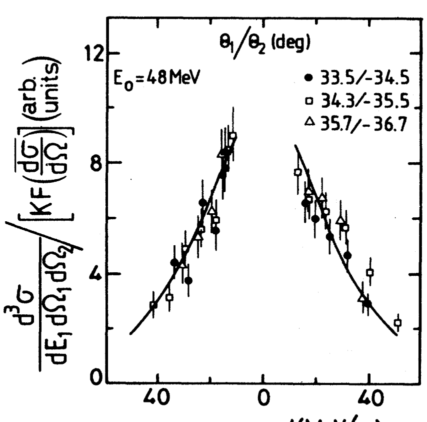

FIG. 3. Experimental momentum distribution of the p-n motion in ^{2}H obtained from the energy spectra for three different angle pairs at $E_0=48$ MeV. The solid line is the theoretical distribution calculated by using Hulthén wave function, normalized to the data for $\theta_1/\theta_2=34.3°/-35.5°$.

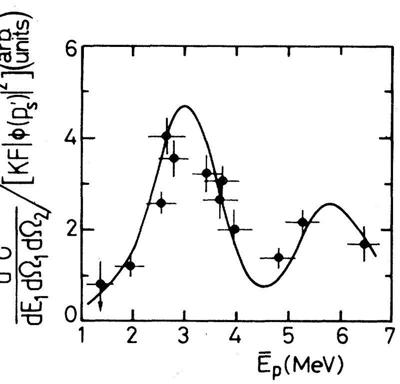

FIG. 4. Excitation function of the quasifree ^{7}Li$(p,\alpha)^4$He reaction contribution extracted from the data at the minimum spectator momentum. The solid line represents the free two-body reaction cross section averaged over the angle and energy spread in the experiment.

the experiment. It is seen that the data obtained from the three-body reaction follow the trend of the two-body reaction cross section.

In the DWIA the cross section is also given by Eq. (1). However, in this case $|\Phi(p_s)|^2$ is the momentum distribution modified by distortion effects. The qualitative agreement of PWIA calculations with experimental results shows that these effects do not change significantly in this energy region.

IV. CONCLUSIONS

The measured coincidence spectra from the ^{2}H(^{7}Li,$\alpha\alpha$)n reaction in the low-energy region, $E_{c.m.}=6.2-10.7$ MeV, show a significant quasifree contribution through the ^{1}H(^{7}Li,α)^{4}He virtual reaction. The shape of the experimental spectra is well described by PWIA calculations, by using the final energy prescription for the QF reaction cross section. The energy dependence of the virtual reaction cross section extracted by the same analysis fairly agrees with the known excitation function of the free ^{7}Li$(p,\alpha)^4$He reaction cross section.

The present results can be compared with those obtained from other experiments at low energy. The quasifree cross sections measured for the ^{6}Li$(\alpha,\alpha\alpha)^2$H (Ref. 6) and ^{6}Li(^{3}He,$p\alpha$)^{4}He (Ref. 7) reactions exhibit a smooth behavior in the energy range where resonances in $\alpha+\alpha$ and ^{3}He$+d$ systems, respectively, are expected. Moreover, the virtual reaction cross sections extracted from ^{9}Be(^{3}He,$\alpha\alpha$)^{4}He (Ref. 8) and ^{6}Li(^{6}Li,$\alpha\alpha$)^{4}He (Ref. 9) reactions are peaked at α-α relative energies not corresponding to any known ^{8}Be resonance. An apparent difference between the ^{2}H(^{7}Li,$\alpha\alpha$)n reaction and these reactions is in the spectator particle. In the first case it is a neutron and in all other cases it is a charged particle. The long-range Coulomb interaction between the charged spectator and the other particles influences the cross section. Consequently, the energy dependence of the cross section could be very different from a simple PWIA prediction. This effect should be more important at low energies, where the relative energy between the spectator and the system of the other two particles is comparable with their Coulomb barrier. The absence of the Coulomb distortion caused by the spectator may be an explanation for the good agreement between the virtual and free reaction cross section in the case of the ^{2}H$+^7$Li reaction. Another reason for the agreement may be also the "simple" structure of the deuteron and its low binding energy.

Obviously, it would be highly desirable to measure other similar quasifree reactions at low energy in order to clear up these points.

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