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Three-body effects in the ^{7}Li $(d,\alpha\alpha n)$ reaction

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Measurements of the differential cross sections for the ^{7}Li$(d,\alpha\alpha n)$ reaction have been performed at deuteron incident energy $E(d)=6.8$ MeV. The kinematical configurations were chosen so as to optimize the population of the ^{5}He** $\frac{3}{2}^{+}$ state with 16.76 MeV excitation energy. The parameters of this resonance are deduced from the experimental data; deviations from the standard values indicate the relevance of three-body effects and/or rescattering. Some phenomenological considerations give a qualitative explanation of the results obtained. In particular, as far as the width is concerned, we observe a broadening with respect to the standard value, which may be related to the presence of a shadow pole.

I. INTRODUCTION

The modification of the resonance parameters in a two-body channel in presence of a third particle is a basic problem in few body reactions. In the framework of the Resonating Group Method[1] one can describe the ground state of the ^{7}Li to a large extent as a binary configuration, i.e., a bound state of two clusters, α and ^{3}H. Since α-^{3}H is the lowest threshold and the quantum numbers of the lowest ^{7}Li states fit into such a decomposition, this configuration is preferred.[2] In addition, ^{5}He-d fragmentation would allow, in s state, together with $\frac{1}{2}^{-}$, and $\frac{3}{2}^{-}$, also a $\frac{5}{2}^{-}$ state in the ^{7}Li spectrum, but the $\frac{5}{2}^{-}$ state is empirically at ~ 6.7 MeV, above a $\frac{7}{2}^{-}$ state.[3] We conclude that this fragmentation contributes only weakly to the ^{7}Li$_{(\mathrm{g.s.})}$. The ^{6}Li-n configuration is also possible, but if such components are admixed into α-^{3}H wave functions, the higher threshold leads only to minor effects in the binding energy.[4]

In general, a reaction like $d+{}^{7}$Li should be described in terms of ^{9}Be* intermediate states followed by decay processes in various channels. In particular there may be reaction mechanisms in which ^{9}Be* decays in $n+{}^{8}$Be in a first step and subsequently ^{8}Be decays in two α particles; alternatively an α particle is emitted first with a ^{5}He**, the latter decaying in turn into $\alpha+n$. In addition, one can conceive a direct three-body breakup of ^{9}Be*, followed by an $\alpha-n$ final state interaction (FSI) associated to a ^{5}He** excited state (16.76 MeV excitation energy).

In our case, if the ^{7}Li$_{(\mathrm{g.s.})}$ is supposed to be described by a two cluster wave function, $\alpha+{}^{3}$H, one can imagine a reaction mechanism where one of the emitted α particles behaves like a spectator. This process is depicted schematically in Fig. 1: the α-particle constituent of ^{7}Li is supposed to be emitted when the ^{7}Li target is dissociated by the deuteron beam.

One can specialize the kinematical configurations to constrain the excitation to that of the virtual ^{5}He**. We will study in particular the ^{5}He** ($J^{\pi}=\frac{3}{2}^{+}$) propagation in the subreaction

$$d+{}^{3}\mathrm{H}\rightarrow\alpha+n \tag{1}$$

with the relative energy E_{d-t} close to zero. When this state is populated in the reaction

$$d+{}^{7}\mathrm{Li}\rightarrow\alpha+\alpha+n\ , \tag{2}$$

one can expect distortion effects from the primary α particle, especially because a small energy shift can make the ^{5}He** state closed or open against decay into $d+{}^{3}$H channel. In addition, if its narrow width is increased in reaction (2), it can extend any way well below the $d+{}^{3}$H threshold. The fact that ^{5}He** is long lived ($\Gamma\simeq 76$ keV)^{3} makes it possible to describe the ^{5}He**$+\alpha$ as a binary channel. Schematically, one can then expect the propagator of the resonance to be modified because of its interaction with the additional α particles; thereby energy and momentum are transferred to the "spectator". In an optical model approximation it is natural to obtain a shift of the resonance energy and a modification of its width.

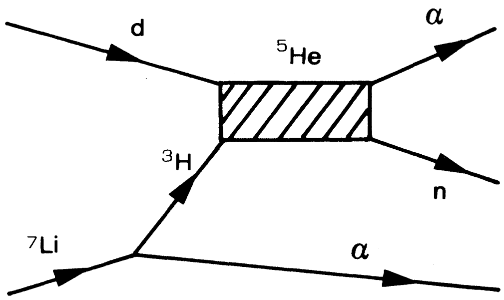

FIG. 1. Two step process with the formation of an intermediate ^{5}He state.

The dependence of the resonant energies and widths on the energy of the beam used in reactions which populate states of light nuclei has been known for a long time. However, a systematic discrepancy exists between the values[3] of the excitation energy and the width deduced from two-body scattering and the ones obtained in experiments where the resonance is formed as an intermediate state in three or four-body reaction, where the "spectator" particle may have a relevant influence. This is particularly true if the resonance is long lived like the $\frac{3}{2}^+$ state of ^{5}He**. In this context we observed the coincident α particles from reaction (2) at $E(d)=6.8$ MeV.

The study of the ^{5}He** resonance is related to the fact that it is rather close to the $d+{}^3$H threshold which makes it necessary to treat it from a theoretical point of view in a coupled channel framework. This opens the possibility of investigating the consequences of the presence of a shadow pole recently proposed in Refs. 5 and 6; in order to have a better understanding of this very peculiar feature of the ^{5}He** resonance, it seems very important to study in the three-body reaction the modification of the resonance parameters in presence of a third particle.

II. THE EXPERIMENT

The experiment was carried out using a 6.8 MeV deuteron beam (typically 100 nA) of the 7 MV CN Van de Graaf of the Laboratori Nazionali di Legnaro. The beam entered the scattering chamber, passing through a collimating system and was stopped in a Faraday cup, after bombarding the target. The target made of LiF, with a composition of 99.9% of ^{7}Li, was obtained by evaporation onto a 30 μg/cm^2 carbon backing. Its thickness was about 80 μg/cm^2.

In order to measure in a kinematically complete way, coincidence spectra of the two α particles are obtained by two solid state detectors (300 μm thick) placed at ϑ_1 and ϑ_2 on the opposite side with respect to the beam. We measured the energy of the two α particles and the time of flight difference by means of a standard fast-slow electronic chain. Spurious coincidences were thus suppressed (the time window, selected off line, was 6 ns). The energy of each event was corrected for the loss in the target. The true events were projected onto the kinematical curve in the E_1-E_2 plane by standard techniques.[7] In such a way one easily takes into account the effects coming from the finite geometry and energy resolution of the detectors.

Two kinematical configurations of the reaction (2) ($\vartheta_1=35°$, $\vartheta_2=75°$ and $\vartheta_1=40°$, $\vartheta_2=68°$) have been chosen in order to allow the production of the ^{5}He in the $\frac{3}{2}^+$ state at 16.76 MeV excitation energy. This means that we are interested specifically in the region where the relative energy is $E_{\alpha\text{-}n}=17.65$ MeV.

Our kinematical configuration not only avoids the competing process presented in Fig. 2, but the possibility that both α particles resonate simultaneously with the neutron, producing thereby interferences by overlap of resonances. We remark, in addition, that the production of ^{5}He ground state and first excited state is kinematically excluded.

The results for the two different kinematical configurations are presented in Figs. 3 and 4. The two peaks, which are rather sharp and well separated, correspond to the production of ^{5}He** as can be seen from Figs. 3 and 4, where the relative energies are also plotted. The smaller peak in both figures reflects the $\frac{3}{2}^+$ ^{5}He state when the first emitted α-particle (cf. Fig. 1) is detected at ϑ_1 and the higher peak reflects the same state when the first emitted α particle is detected at ϑ_2. The former can be pictured qualitatively as an α knockout and the latter as the ^{3}H pickup. An astonishing feature of the spectra is the weakness of background reaction mechanisms; this seems to confirm the heuristic discussion given in the Introduction and supports the idea of making a fit of these peaks in order to deduce the resonance width and position according to the interpretation of the reaction depicted in Fig. 1.

The quantitative dominance of a specific mechanism is rather exceptional in few body reactions at low energies[8] and may be interpreted as due to the α-^{3}H nature of the ^{7}Li to very high accuracy and to the narrow width of the ^{5}He** which makes it a very special resonance within light nuclear systems. The reaction (2) therefore gives a unique opportunity to investigate this narrow resonance in a three particle channel. We would like to emphasize

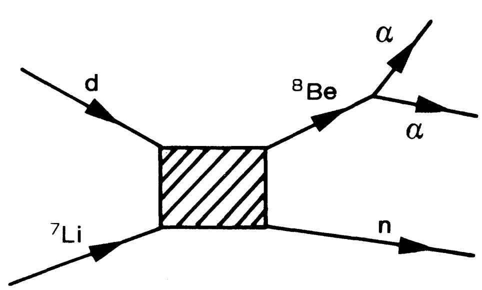

FIG. 2. Two step process with the formation of an intermediate ^{8}Be state.

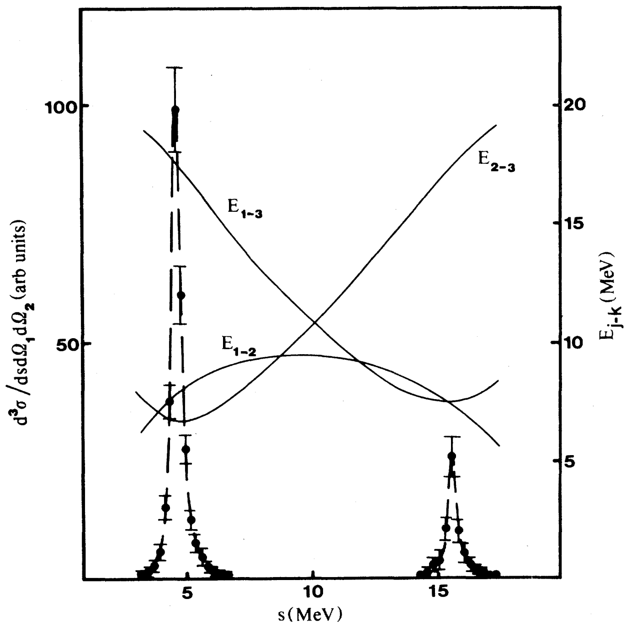

FIG. 3. Cross section versus arclength s at $\vartheta_1=40°$, $\vartheta_2=68°$. The curves E_{1-3}, E_{2-3}, and E_{1-2} refer to the relative energy of the α-n and α-α systems, respectively. The results of the fitting procedure are shown as dashed line.

that the resonance energy can be slightly shifted even below the d-^{3}H threshold; in this case the d-^{3}H decay of ^{5}He** is suppressed and thereby the width of the resonance can be modified.

As a further remark we notice an interesting angular distribution to ^{5}He**; indeed the highest peak in both configurations corresponds to a resonance produced around 70° in the c.m. system and the lower peak refers to an angle around 120°. A rough analysis suggests that the resonance formation occurs mainly in D wave and may be an indication that the highly excited broad levels of ^{9}Be at 21.4 and 22.4 MeV excitation energy have positive parity.

III. DISCUSSION AND CONCLUSIONS

In order to obtain quantitative information about the ^{5}He** resonance parameters, as formed in reaction (2), we transformed our data to the Recoil Center System (RCS).[7] This transformation was performed via the appropriate Jacobian and a fit was then performed in order to determine the resonance parameters (see Fig. 5). The results obtained are summarized in Table I.

Table I provides a circumstantial evidence that, in presence of an α particle, the ^{5}He** resonance is shifted below the d-^{3}H threshold. The width is typically 0.5 MeV, very different from the standard value obtained in two-body experiment and well above the experimental uncertainties. To evaluate the uncertainty in the relative energy $E_{\alpha n}$, one has to take into account that $E_{\alpha n}$ depends solely on the laboratory energy and angle of the α particle not involved in the resonance.[9] The global uncertainty is of the order of 100 keV, therefore we are confident to have observed a physical broadening of the resonance.

Whereas from a microscopic point of view the modification of the ^{5}He** parameters can be calculated in principle in a Faddeev-Yakubowski[10] framework, but the calculations are not immediately feasible, we would like to point out that, on general ground, the collision broadening can be understood in terms of an imaginary part of the α-^{5}He** optical potential. Additional broadening could arise from the "stimulated emission" of an α particle decaying from ^{5}He** in presence of another α particle (this follows the boson approximation for the α particles if they are in the same spatial state). Another contribution to broadening the resonance is expected

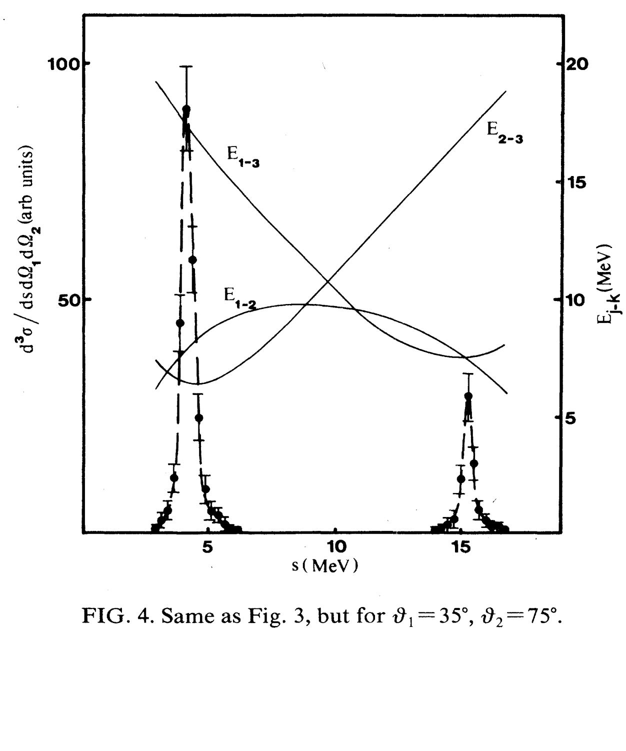

FIG. 4. Same as Fig. 3, but for $\vartheta_1=35°$, $\vartheta_2=75°$.

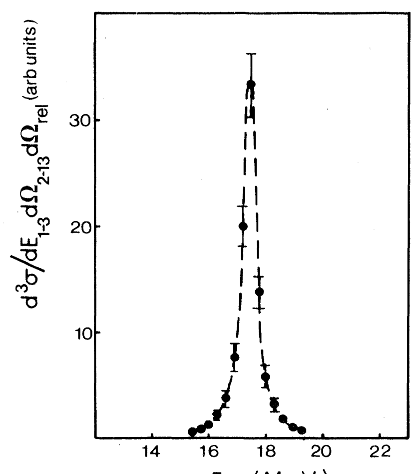

FIG. 5. RCS count distribution vs E_{1-3} referring to α-n system when the first emitted α particle is detected at $\vartheta_2=68°$. Dashed line is the result of the fitting procedure.

TABLE I. Parameters of the $^5He^{**}$ resonance as obtained by the fitting procedure.

ϑ_1 (deg)	ϑ_2 (deg)	s (MeV)	$\vartheta^{c.m.}_{^5He^{**}}$ (deg)	E^* (MeV)	Γ (MeV)
40	68	6.3	73	16.5	0.5
40	68	17.2	116	16.5	0.5
35	75	4	66	16.5	0.6
35	75	15	125	16.4	0.5

from the nuclear motion of the constituent ^3H inside the ^7Li.

As already mentioned in the Introduction, a last exciting possibility is connected to the recently proposed idea that the standard resonance is accompanied by a shadow pole.[5,6] In such a case one may conceive to observe the presence of the shadow pole in a three-body reaction because of the less constraining kinematical conditions in respect to the two-body, namely of the possibility of off-shell effects.

As a natural consequence the effect of the shadow pole could lead to a superimposition of two closeby peaks and therefore, taking into account finite energy resolution, to an effective broadening of the observed peak.

To have an indication of detailed effects related to the modification of the widths one has to improve drastically energy and angular resolution. In addition to experiment detecting the three outgoing particles for this reaction or for the reaction

$$^3\mathrm{He}+{}^6\mathrm{Li}\rightarrow\alpha+\alpha+p \ ,$$

which is a better candidate from an experimental point of view, but studies the mirror ^5Li state, may lead to additional information on the effects of the shadow pole.

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