Distorted-wave analysis of proton scattering from ^{6}Li near the α-d breakup threshold

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(Received 7 July 1992)

The ^{6}Li(p,p') continuum data at $E_p=65$ MeV were reanalyzed in the framework of the distorted-wave impulse approximation and the distorted-wave Born approximation. This provides an analysis consistent with the ^{6}Li(α,α') work at $E_\alpha=50$ MeV and reconfirms an earlier observation that the ^{6}Li target breakup data, studied at low relative fragment energies, indicate a change in the reaction mechanism below a critical transfer of momentum. This is possibly due to the recombination of the breakup fragments, an effect which should be seriously considered in the analysis of all the breakup reaction data measured at low relative fragment energies.

PACS number(s): 25.40.Ep, 25.55.Ci

Recently, the continuum spectra near the α-d breakup threshold were studied through the ^{6}Li(p,p') and ^{6}Li(α,α') reactions at $E_p=65$ and 80 MeV [1] and $E_\alpha=50$ MeV [2]. In these experiments, by choosing a fixed continuum region near the α-d breakup threshold, it was possible to investigate the ^{6}Li target breakup reaction at low relative fragment energies. From a comparison of the proton and alpha-particle induced data, it was suggested [2] that possibly a change in the reaction mechanism occurs under the condition of low relative energies of the breakup fragments when the transfer of momentum from the projectile falls below a critical value. This could be due to a strong final-state interaction leading to recombination of fragments which effectively changes the three-body final state to a two-body one at low relative fragment energies.

The ^{6}Li(α,α') continuum data at $E_\alpha=50$ MeV were initially analyzed [2] in the framework of a plane-wave impulse approximation (PWIA) and also, to include the effects of the final-state interaction (FSI), in terms of a distorted-wave impulse approximation (DWIA) assuming a quasifree (QF) reaction mechanism leading to a three-body final state. The impulse approximation calculations were found to be inadequate at the forward angles where the calculated cross sections showed a steep rise in contrast to the experimental data. The DWIA code used in the analysis included most of the FSI except recombination. As a first attempt to understand the effect of recombination in the ^{6}Li(α,α') reaction, a simple phenomenological distorted-wave Born approximation (DWBA) calculation was carried out taking a virtual state (1^+, 1.475 MeV) excitation at the α-d breakup threshold. It was found that although the DWBA calculations for a two-body final state failed to account for the angular distribution, they produced a reduction of the cross section at the forward angles. In order to arrive at any definite conclusion about the reaction mechanism it is essential that both the (α,α') and the (p,p') continuum data be analyzed identically in a consistent manner. Only a PWIA analysis has so far been carried out for the (p,p') continuum data [1]. In this work we report the results of a DWIA and DWBA analysis of the ^{6}Li(p,p') continuum data at $E_p=65$ MeV.

The DWIA calculations were carried out using the THREEDEE code of Chant. In this calculation, the three-body target breakup cross section for the reaction $a+A\rightarrow a+b+B$ ($A=B+b$) takes a factorized form [3]

$$\frac{d^3\sigma}{d\Omega_a d\Omega_b dE_a}=\mathrm{SF}\left|\sum_\lambda T^{L\lambda}\right|^2\frac{d\sigma}{d\Omega}\bigg|_{a-b}. \tag{1}$$

Here $T^{L\lambda}$ is the so-called distorted momentum distribution given by

$$T^{L\lambda}=\frac{1}{(2L+1)^{1/2}}\int \chi_a^{(-)*}(\mathbf{r})\chi_b^{(-)*}(\mathbf{r}) \times\Phi_{nLj}(\mathbf{r})\chi_0^{(+)}\left[\frac{B}{A}\mathbf{r}\right]d\mathbf{r}, \tag{2}$$

where χ's are the incoming and outgoing distorted waves and $\Phi_{nLj}(r)$ the bound state wave function in the ground state of the nucleus. In the plane-wave limit, $T^{L\lambda}$ is simply the Fourier transform of the cluster wave function. $(d\sigma/d\Omega)|_{a-b}$ is properly a half-off-the-energy-shell two-body cross section for the interaction of the particle a and b and SF is the spectroscopic factor corresponding to the $B+b$ structure of target A. To obtain the inclusive cross section, the integration is carried out over the solid angle of the unobserved particle b, i.e.,

$$\frac{d^2\sigma}{d\Omega_a dE_a}=\int\frac{d^3\sigma}{d\Omega_a d\Omega_b dE_a}d\Omega_b. \tag{3}$$

The continuum spectra near the α-d breakup threshold

TABLE I. Optical potential parameters.

Reaction	System	V^a	r_0	a_0	W_D	r_W	a_W	r_c	Ref.
^{6}Li$(p,p'\alpha)^2$H	$p+^6$Li	37.8	1.14	0.79	4.48	1.32	0.580	1.2	[4]
	$p+^2$H	92.1	1.05	0.50	7.67	1.02	0.511	1.3	[5]
^{6}Li$(p,p'd)^4$He	$p+^6$Li	37.8	1.14	0.79	4.48	1.32	0.480	1.2	[4]
	$p+^4$He	45.7	1.10	0.35	8.88	2.23	0.10	1.1	[6]

[a]In the distorted-wave impulse approximation calculation for the $A(a,a'b)B$, the well depth V for $p+^6$Li was multiplied by B/A to crudely exclude the interaction between the incoming p and the knocked-out particle.

in the (p,p') reaction may originate from the QF scattering of the incident proton with the bound alpha or deuteron cluster in ^{6}Li. In the (p,p') work [1] it was noted that the magnitude of the cross section for the $d+p$ elastic scattering is about $\frac{1}{4}$ of that for the $\alpha+p$ scattering and therefore in the measured continuum data the contribution from the ^{6}Li$(p,p'\alpha)^2$H reaction is by far the dominating one compared to the ^{6}Li$(p,p'd)^4$He reaction. Moreover, in the QF scattering formalism, the contribution to the continuum (in the fixed region of interest) from ^{6}Li$(p,p'd)^4$He reaction diminishes rapidly with increase of scattering angles because of kinematics [2].

For the ^{6}Li$(p,p'\alpha)^2$H reaction at $E_p=65$ MeV, the distorted waves were generated for the $p+^6$Li at the entrance channel and $p'+^2$H at the exit channel using available optical potential parameters from Refs. [4] and [5], respectively (Table I). For the ^{6}Li$(p,p'd)^4$He reaction in the $p+^4$He exit channel we used the optical potential parameter of Ref. [6] (Table I). The bound state wave function was taken to be the same as used in the (α,α') work [2] for a consistent analysis. Since, in an inclusive measurement, only one of the particles is detected, the wave function of the unobserved particle cannot be complex and should be calculated in a purely real potential. For the $\alpha+^2$H exit channel the optical potential parameters are not available. Here we used only the Coulomb potential, as it was done in the (α,α') work. The half-off-the-energy-shell two-body p-α cross sections were replaced by the nearby on-shell data [7] at appropriate energies and center-of-mass angles following the final-energy prescription (FEP) of the code THREEDEE. The spectroscopic factor was obtained by normalizing the DWIA calculation with the experimental data.

The DWIA calculations produce a fairly good fit to the data for laboratory angles greater than 23° (Fig. 1). The extracted SF ($\sim$1.0) is also in good agreement with the theoretical prediction of 0.93 [6]. The uncertainty of the optical potential parameters contributes $\sim$15% in the value of the SF. For laboratory angles less than 23°, the DWIA calculations overpredict the experimental cross sections and an inclusion of the ^{6}Li$(p,p'd)^4$He reaction channel only adds to this discrepancy by increasing the forward angle calculated cross sections by $\sim$20%. A similar phenomenon was observed in the DWIA analysis of the (α,α') continuum data [2] which led to the conjecture of a two-body final state instead of a three-body one below a critical transfer of momentum.

For the DWBA calculations of the ^{6}Li(p,p') continuum data with a two-body final state we employed a microscopic folding model [8] to avoid the uncertainties of the optical potential parameters. Moreover, such analyses using realistic nucleon-nucleon interaction and microscopic transition densities are more fundamental than the phenomenological collective model. Petrovich *et al.* have already shown [9] that the microscopic folding model produces good fit to the low energy ^{6}Li(p,p') data.

The solid curve in Fig. 2 is the result of the microscopic calculation using the computer code DWUCK4 of Kunz [10]. To construct the real part of the $p+^6$Li interaction potential a single folding model was used in which

$$V_{p+^6\mathrm{Li}}(r_p)=\int \rho_{^6\mathrm{Li}}(r)V_{pN}(|\mathbf{r}_p-\mathbf{r}|)r^2dr\ . \tag{4}$$

For V_{pN} we took the M3Y interaction with a single nucleon exchange term [11]. The ground state density $\rho_{^6\mathrm{Li}}(r)$ was constructed from the electron scattering data [12]. Here we assumed the same density distributions for the neutron and the proton. The imaginary potential parameters of Table I were used for the imaginary part of the $p+^6$Li interaction potential.

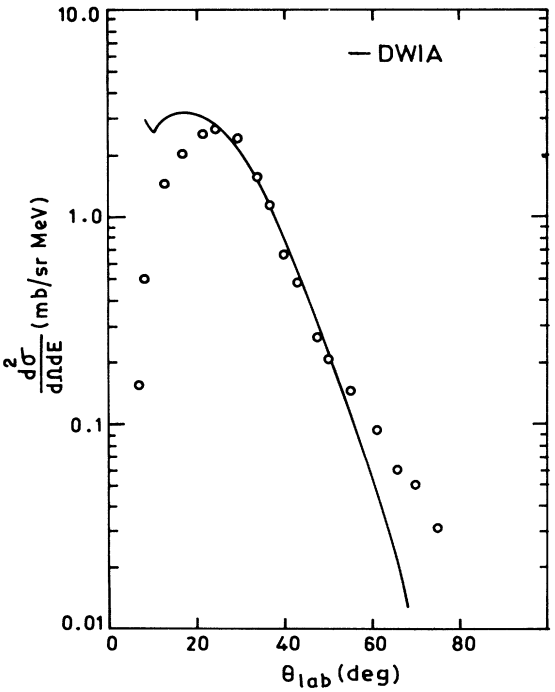

FIG. 1. ^{6}Li(p,p') reaction data at $E_p=65$ MeV ($E_x=1.48$–3.5 MeV) and the DWIA calculation with a three-body final state.

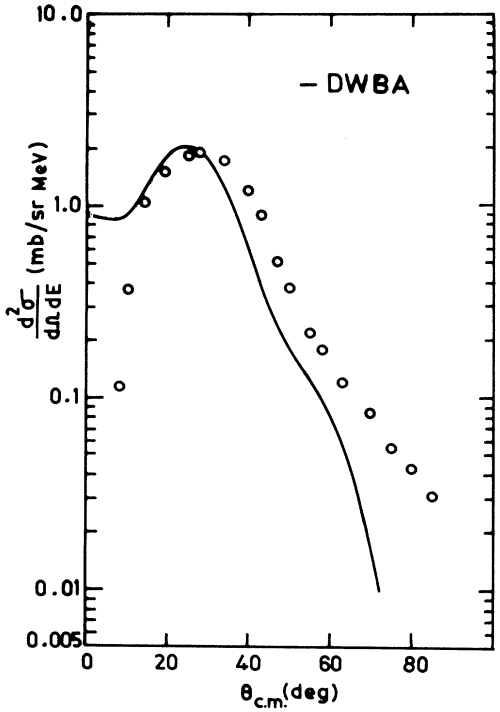

FIG. 2. ^{6}Li(p,p') reaction data at $E_p=65$ MeV ($E_x=1.48-3.5$ MeV) and the microscopic DWBA calculation with a two-body final state.

For inelastic scattering the real part of the radial form factor for the lth multipole may be written as [13]

$$F_l(r_p)=\int \rho_{\rm tr}(r)V_l(r,r_p)r^2dr \ , \tag{5}$$

where $V_l(r,r_p)$ is related to the p-N effective interaction by

$$V_{pN}(\mathbf{r},\mathbf{r}_p)=\sum_{l,m} V_l(r,r_p)Y^*_{lm}(\hat{r}_p)Y_{lm}(\hat{r}) \ . \tag{6}$$

Following the (α,α') work [2], the virtual excitation to the 1^+ state was taken as a $l=2$ transition and $\rho_{\rm tr}(r)$, the transition density from the ground state $|1^+\rangle$ to the virtual excited state $|1^+\rangle$ at 1.475 MeV, was taken as

$$\rho_{\rm tr}=\left\langle 1^+ \left|\left| \sum_j Y_2(\hat{r}_j) \right|\right| 1^+ \right\rangle \ , \tag{7}$$

the sum over j in Eq. (7) running over either protons or neutrons. Since the transition density for the above-mentioned ritual excitation is not known, we assumed it to be proportional to the $1^+(0.0\ \text{MeV}) \rightarrow 3^+(2.185\ \text{MeV})$ transition density which also corresponds to a $l=2$ transition. We took the proton transition charge density $\rho^p_{\rm tr}(r)$ for ^{6}Li (3^+, 2.185 MeV) from electron scattering data of Bergstrom *et al.* [14]. The shape of the neutron transition density $\rho^n_{\rm tr}(r)$ was taken to be the same as that of proton, $\rho^p_{\rm tr}(r)$, an assumption consistent with the work of Hansen *et al.* [15]. The transition density $\rho_{\rm tr}(r)=\rho^p_{\rm tr}(r)+\rho^n_{\rm tr}(r)$ thus defined was used to calculate the form factor. We then multiplied this form factor by an arbitrary constant 1.5 to normalize the calculated cross section with the (p,p') data. Any change in this proportionality constant just raises and lowers the calculated curve without changing its shape.

For the imaginary part of the radial form factor, the collective model imaginary form factor $\beta_I R_W dW/dr$ was used where $R_W=r_W A^{1/3}$. The imaginary parameters were the same as used in our DWIA calculation (Table I). The value $\beta_I=0.19$ was taken from the collective model calculation employed in the (α,α') work [2]. Any change of this β_I value produced a minor change in the shape of the DWBA curve at the large angle region without changing the magnitude of the cross section significantly.

The microscopic DWBA calculations gave the general trend of the data without actually reproducing the exact numbers at larger angles, while for $\theta_{\rm c.m.} \lesssim 28°$ (i.e., $\theta_{\rm lab} \lesssim 24°$), the trend, including the exact numbers, was reproduced quite well except for the two extreme forward angle data.

A comparative study of the ^{6}Li(p,p') and ^{6}Li(α,α') continuum data near the α-d breakup threshold studied at $E_p=65$ and 80 MeV and $E_\alpha=50$ MeV and their analyses point to the following conclusions. A lowering of the cross section at forward angles was exhibited in both the reactions. The angle, henceforth called the critical angle, below which the cross section starts falling shifts backwards or forwards depending on the projectile energy (Figs. 4 and 6 of Ref. [1]), the nature of the projectile used (Fig. 6 of Ref. [2]), and the excitation energy zone of the continuum spectra under investigation (Fig. 4 of Ref. [1]). Interestingly, in all the above data these critical angles correspond to roughly the same magnitude of momentum transfer from the projectile. Thus this effect appears to be controlled by the kinematics of the reaction and therefore can be utilized for further experimental investigation with different projectiles (viz., ^{3}He, d, etc.) of different incident energies. The relative success of the DWBA calculations with a two-body final state in comparison to the DWIA calculations with a three-body final state in the forward angles also suggests that recombination due to FSI is possibly a dominant reaction mechanism in quasifree breakup when the relative energy between the fragments is low and the transfer of momentum from the projectile falls below a critical value. If this recombination effect is not properly accounted for in the analysis of the quasifree target—or projectile—breakup reaction data taken at low relative fragment energies any physical quantity extracted from it might lead to wrong conclusions. We tried to address the problem through a virtual state excitation of target nucleus only as a first step to understand the effect of recombination. However, in order to properly understand the (p,p') and (α,α') continuum data in the entire angular region a complete self-consistent theory is necessary. Perhaps a CDCC (coupled discretized continuum channels) type of calculation [16] taking into account the couplings between the different regions of the continuum and the excited states of ^{6}Li would lead to a better understanding of the experimental data. But such a calculation is really beyond the scope of this work.

The authors gratefully acknowledge helpful discussions with Professor S. K. Ghosh, SINP, Calcutta.

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