Quasifree Knockout of Deuterons in the ^{6}Li(α, αd)^{4}He Reaction at 23.6 MeV

K. Bähr, T. Becker, O. M. Bilaniuk,* and R. Jahr
Max-Planck-Institut für Kernphysik, Heidelberg, Germany
(Received 18 July 1968)

α-d correlations in quasi-elastic scattering of 23.6-MeV α particles on the deuteron cluster of the ^{6}Li target were measured in and off the principal reaction plane. Despite the low c.m. energy of 14.2 MeV, the impulse approximation provides a reasonable description of the quasifree process. Computations were based on the asymptotic α-d S-state wave function and on the cluster-model wave function of ^{6}Li. Insensitivity of the fits to the details of the ^{6}Li cluster-model wave function indicates an extreme surface reaction mechanism. The full width at half-maximum of the spectator momentum distribution was found to be 48 ± 6 MeV/c. By comparing the experimental cross section for the quasifree process at the maximum of the angular correlation ($d^2\sigma/d\Omega_d d\Omega = 68\pm9$ mb/sr^2 at $\theta = 25°$, $\theta_d = 45°$) with the corresponding cross section for the free process, the probability of finding ^{6}Li as an α-d cluster was evaluated.

INTRODUCTION

PRONOUNCED quasifree α-α knockout off a ^{6}Li target has been observed,[1,2] in the principal reaction plane, at energies of 25 and 62 MeV. The corresponding α-d knockout has been studied,[3] also in the principal plane, at 42.5 MeV. In the present experiment, the ^{6}Li(α, αd)^{4}He reaction was investigated at $E_\alpha = 23.6$ MeV, in the principal plane and out of it, in order to test the validity of the ^{6}Li cluster model and to ascertain the applicability of the impulse approximation at the relatively low c.m. energy of 14.2 MeV.

In the present investigation three kinds of data were obtained: (a) energy spectra of deuterons recorded in coincidence with α particles for a fixed pair of angles, (b) d-α angular correlations in the principal scattering plane, and (c) d-α angular correlation off the principal scattering plane. Theoretical fits, based on the impulse-approximation cross section and on cluster-model wave functions, were computed for all three types of data, leading to consistent results regarding the momentum distribution of the spectator α particle in the ^{6}Li target. Furthermore, the measurement of the absolute value of the differential cross section for the quasifree process at the maximum of the angular correlation permitted the determination of the fraction of the ^{6}Li wave function describable in terms of the α-d cluster model.

EXPERIMENTAL PROCEDURE

The 23.6-MeV α beam from the Heidelberg cyclotron was focused, by means of a system of quadrupole lenses, to a 3×3-mm^2 spot on the target. The target consisted of enriched lithium (95.63% ^{6}Li) evaporated onto a thin carbon leaf. Target thickness, determined by flame photometry, was 77.3 μg/cm^2.

Detectors were mounted on movable arms inside a scattering chamber of 50-cm diameter. A conventional semiconductor ΔE-E detector telescope was used for selective counting of deuterons. The position of this telescope remained fixed at $\theta_d = 45°$, $\phi_d = 180°$ throughout the experiment. (The beam direction is chosen as the z axis.) The position of the α-particle counter was varied from $\theta_\alpha = 17°$ to $\theta_\alpha = 60°$ in the principal reaction plane ($\phi_\alpha = 0°$) and from $\phi_\alpha = 0°$ to $\phi_\alpha = 32°$ at $\theta_\alpha = 23°$ out of that plane.

Electronic circuitry comprised the two spectroscopic branches (for deuterons and α particles), the multicoincidence circuits furnishing the gate pulse for the multichannel analyzer, the ΔE-E particle discrimination circuit, and a circuit for registry of accidental coincidence rates. The resulting three-dimensional spectra were recorded in a 128×32 grid of a 4096-channel analyzer.

In Fig. 1 four sample spectra are juxtaposed for comparison. The spectra were obtained by projecting the content of the "Dalitz" curve onto the deuteron energy axis, a procedure which is described elsewhere.[4] All spectra show a pronounced peak structure with less than 5% contribution by the phase space. The kinematic shifts of peaks have facilitated their unambiguous identification. Peaks lying on lines labeled A and B correspond to the sequential decay through the ground state and the first excited state of ^{8}Be, respectively. Peaks on lines D and C correspond to the first and third excited states of a ^{6}Li intermediate nucleus (the ^{6}Li ground state is stable and the formation of the second excited state of ^{6}Li is isospin-forbidden).

At the angle of $\theta_\alpha = 20°$ a broad peak, labeled E, may be noted. This peak was interpreted as quasi-elastic scattering of incoming α particles on the deuteron cluster of the ^{6}Li target. To verify this interpretation and to learn more about the process of the quasifree knockout, further spectra were taken in 2° steps in the range 17°–29° in the principal reaction plane and in larger steps out of that plane. Four of the latter spectra are shown in Fig. 2. The total number of counts in the peak of interest was usually about 1600, so that the corresponding statistical errors were small.

* NSF Science Faculty Fellow on leave from Swarthmore College.
[1] V. V. Balashov and D. V. Memboniya, Nucl. Phys. **A107**, 369 (1968).
[2] M. Jain, M. Epstein, H. D. Holmgren, H. G. Pugh, and P. G. Roos, Bull. Am. Phys. Soc. **12**, 1176 (1967).
[3] J. F. Mollenauer (private communication).
[4] T. Becker, K. Bähr, R. Jahr, and W. Kuhlman, Phys. Letters **24B**, 458 (1967).

DISCUSSION

In the impulse approximation, the differential cross section for quasifree scattering may be written[5]

$$\frac{d^3\sigma}{d\Omega_\alpha d\Omega_d dE_d}=\rho\left(\frac{m_\alpha+m_d}{m_\alpha m_d}\right)^2 v_{\rm rel}^{-1}\left(\frac{d\sigma}{d\Omega}\right)_f P_{\alpha d}P(q), \quad (1)$$

where ρ is the phase-space factor; m_α and m_d are the α-particle and deuteron masses, respectively; $v_{\rm rel}$ is the velocity of the incoming α particle; $(d\sigma/d\Omega)_f$ is the c.m. differential cross section for free α-d scattering; $P_{\alpha d}$ is the probability of finding ^{6}Li as an α-d cluster; and $P(q)$ is the probability that the spectator has a momentum q, given by the square of the absolute value of the Fourier transform of the spatial distribution of the α spectator in the ^{6}Li target. In the present case, all factors preceding $P(q)$ are either constant or practically constant, so that the cross section for the quasifree process is dominated by the q dependence of $P(q)$.

It follows from three-body kinematics that the spectator momentum q is a function of five independent kinematic variables, e.g., $q=q(\theta_d, \phi_d, \theta_\alpha, \phi_\alpha, E_d)$. Since in the present experiment the deuteron angles were held fixed, the $P(q)$ dependence could be determined experimentally by three independent measurements, viz., variation of θ_α, variation of ϕ_α, and recording of the E_d spectrum at a fixed set of angles. All three of these measurements were performed and found to lead to consistent results regarding $P(q)$. Corresponding data are shown in Figs. 3(a)–3(c). Figure 3(a) shows the projected E_d spectrum taken at $\theta_\alpha=23°$, where a maximum of the cross section for the quasifree knockout was expected. Figure 3(b) represents the α-d angular correlation corresponding to the quasifree process, taken in the principal reaction plane. The experimental points are the integrated (over E_d) counts of the quasi-elastic peaks at the angles indicated. Figure 3(c) contains similar data for the measurements out of the principal reaction plane.

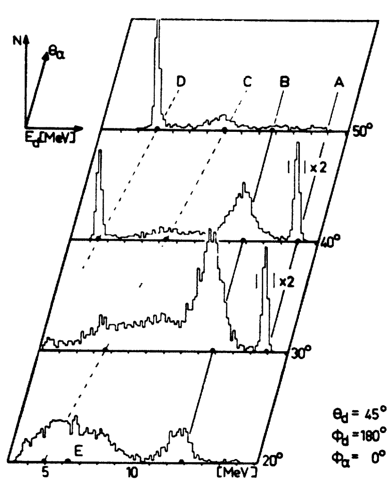

FIG. 1. Sample α-d correlation spectra from the reaction $\alpha+{}^6\text{Li}\to\alpha+\alpha+d$ at $E=23.6$ MeV, taken in the principal reaction plane with $\theta_d=45°$ and θ_α as indicated. Spectra were obtained by projecting the content of the "Dalitz" curve onto the deuteron energy axis.

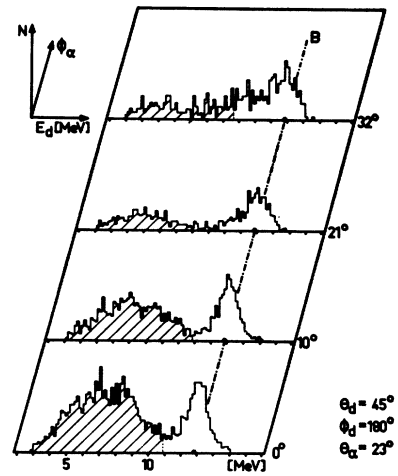

FIG. 2. Four nonplanar angular correlation spectra from the $\alpha+{}^6\text{Li}\to\alpha+\alpha+d$ reaction. While the deuteron telescope remained in the principal plane (defined by the beam direction and the deuteron path), the α-particle counter was moved out of that plane up to $\phi_\alpha=32°$, while holding θ_α at 23°. The shaded areas correspond to quasi-elastic scattering.

Two approaches were used to calculate theoretical fits to these data.

(a) In one, $P(q)$ was assumed to be given by

$$P(q)=(2m_\alpha\epsilon)^{1/2}/\pi^2(2m_\alpha\epsilon+q^2)^2, \quad (2)$$

where $\epsilon=E_B/(1+m_\alpha/m_d)$ is the reduced binding energy of the deuteron in the ^{6}Li nucleus, E_B is the corresponding true binding energy, and m_α and m_d are the masses of the α particle and the deuteron, respectively. This $P(q)$ dependence follows simply by Fourier-transforming the asymptotic α-d S-state wave function $\psi(r)=(\gamma/2\pi)^{1/2}[\exp(-\gamma r)]/r$, where $\gamma^2=2\mu E_B/\hbar^2$ and $\mu=m_\alpha m_d/(m_\alpha+m_d)$. Curves obtained on the basis of this $P(q)$ dependence are labeled "asymptotic."

(b) The E_d spectral shape and the θ_α and ϕ_α angular correlations were also fitted by evaluating $P(q)=|\varphi(q)|^2$, where $\varphi(q)$ is the Fourier transform of

$$\psi_1(r)\propto r^2\exp(-\tfrac{2}{3}\beta r^2) \quad \text{for} \quad r\leq R \quad (3a)$$

and

$$\psi_2(r)\propto[\exp(-\gamma r)]/r \quad \text{for} \quad r\geq R. \quad (3b)$$

Here $\psi_1(r)$ is the cluster-model wave function of ^{6}Li with the deuteron and α particle in a relative S state, taking $\beta=0.329$ fm^{-2} as the width parameter.[6] The $\psi_1(r)$ and $\psi_2(r)$ have been joined smoothly, which led to a value of $R\approx3$ fm. The corresponding curves in

[5] C. Zupančič, *Les réactions nucléaires à trois corps* (Institut de physique nucléaire de Université de Lausanne, Lausanne, Switzerland, 1967), p. 42.

[6] Y. C. Tang, K. Wildermuth, and L. D. Pearlstein, Phys. Rev. **123**, 548 (1961); M. A. K. Lodhi, Nucl. Phys. **A97**, 449 (1967).

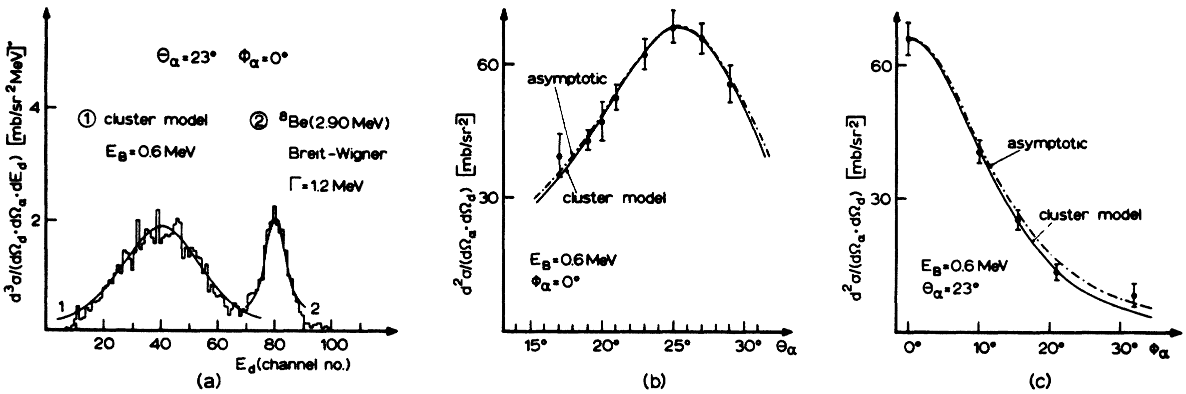

FIG. 3. Theoretical fits to the α-d angular correlation data from the present experiment. (a) Fits of the spectral shapes of the quasi elastic group and the α-α $[E_x(^8\text{Be})=2.9\text{ MeV}]$ final-state interaction. (b) Fits to the planar angular correlation for quasi-elastic α-d scattering using impulse approximation with cluster-model wave function and its asymptotic form. (c) Fits to the nonplanar angular correlations from quasi-elastic α-d scattering.

Fig. 3 are labeled "cluster model." It is seen that the description of the quasifree process is rather insensitive to the finer details of the α-d cluster wave function.

The best fit to the E_d spectrum of Fig. 3(a) resulted by assuming a binding energy of $E_B=0.6$ MeV. Use of the actual binding energy of 1.47 MeV led to a theoretical peak which was 51% too broad. Moreover, the maximum of the experimental quasifree scattering cross section does not lie at the spectator momentum of $q=0$, but at $q=15$ MeV/c, which corresponds to a recoil energy of 30 keV of the spectator particle. This effect is possibly due to the long-range Coulomb interaction between the incoming and the spectator α's.

The full width at half-maximum (FWHM) of the spectator momentum distribution is 48 ± 6 MeV/c. This value is somewhat smaller than that obtained by Jain *et al.*,[1,7] but is in good agreement with the results of an analysis of earlier ^{6}Li(p, pd)^{4}He data.[8]

To obtain the best fit to the angular correlation data of Fig. 3(b), again a value of $E_B=0.6$ MeV had to be used. However, to produce the fit, the calculated curve had to be shifted by 2.5° to backward angles relative to the experimental data. This is probably also due to the nonzero spectator momentum at the maximum of the quasifree scattering cross section.

The same parameters were used to obtain the best fit to the nonplanar angular correlation of Fig. 3(c).

The value of the experimental cross section for the quasifree process at the maximum of the angular correlation is $d^2\sigma/d\Omega_d d\Omega_\alpha=68\pm9$ mb/sr^2.

By evaluating all the factors of the theoretical cross section of Eq. (1), and by using a value of 59 mb/sr for the corresponding free process,[9] the factor $P_{\alpha d}$ indicating the probability of finding ^{6}Li as an α-d cluster was evaluated. At an assumed $E_B=0.6$ MeV, this probability was 3.5% when the cluster-model wave function of Eq. (3) was used and 6.5% when the asymptotic form of the wave function was used. These values are in close agreement with those obtained from the analysis of the ^{6}Li(p, pd)^{4}He reaction.[8] When the actual value of the binding energy $E_B=1.47$ MeV was substituted in the calculations, the corresponding factors were 6.8 and 17.5%, respectively.

The shape of the peak due to the 2.9-MeV level of ^{8}Be, which appears in the spectrum of Fig. 3(a), was fitted using the Breit-Wigner expression. Because of its large width, the experimental peak had to be recast first into the c.m. system, correcting it point by point by the c.m. transformation factor. The best fit resulted by using a width of $\Gamma=1.2\pm0.3$ MeV for this state, which is in good agreement with values obtained in other experiments.[10]

In conclusion, one may say that the impulse approximation is apparently still valid at our comparatively low energies. Furthermore, the cluster model is known to be a good approximation only in the surface region of the nucleus.[11] Thus the fact that the simple cluster-model wave function, or even the asymptotic wave function, respectively, provides good fits to the data indicates an extreme surface reaction mechanism.

ACKNOWLEDGMENTS

The authors are indebted to Professor W. Gentner and Professor U. Schmidt-Rohr for their interest in this work. They are thankful to Professor K. Dietrich, Professor H. Hackenbroich, Dr. W. Ebenhöh, and Dr. Schäfer for stimulating discussions. The assistance of the technical staff of the cyclotron is gratefully acknowledged. One of the authors (O.M.B.) wishes to express his sincere thanks for the hospitality accorded him by the Max Planck Institute for Nuclear Physics, Heidelberg.

[7] M. Jain, M. Epstein, H. D. Holmgren, H. G. Pugh, and P. Roos, Bull. Am. Phys. Soc. **12**, 466 (1967).

[8] D. W. Devins, B. L. Scott, and H. H. Forster, Rev. Mod. Phys. **37**, 396 (1965).

[9] L. S. Senhouse and T. A. Tombrello, Nucl. Phys. **57**, 624 (1964).

[10] T. Lauritsen and F. Ajzenberg-Selove, Nucl. Phys. **78**, 62 (1966); F. Nüsslin, Dissertation, Universität Heidelberg, 1968 (unpublished).

[11] H. Hackenbroich (private communication).