Vector and tensor analyzing powers for the ($\vec{d}$, ^{6}Li) reactions on ^{12}C and ^{16}O

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Measurements of the cross section, vector analyzing power, iT_{11}, and all three tensor analyzing powers, T_{20}, T_{21}, and T_{22}, have been made for the ($\vec{d}$, ^{6}Li) reactions on ^{12}C and ^{16}O at bombarding energies of 18 and 22 MeV. The observed large values of the tensor analyzing powers do not agree with distorted-wave Born approximation calculations assuming a one-step alpha-cluster transfer.

Four-nucleon pickup reactions such as (d, ^{6}Li) have been studied extensively with unpolarized beams.[1] However, little is known about the analyzing powers except for measurements of vector analyzing powers in the (d, ^{6}Li) reactions on ^{12}C and ^{16}O at $E_d = 52$ MeV.[2] To our knowledge no measurements of the tensor analyzing powers have been published. We report on recent results of measurements of the cross section, $\sigma(\theta)$, vector analyzing power, iT_{11}, and all three tensor analyzing powers, T_{20}, T_{21}, and T_{22}, for the (d,^{6}Li) reactions on ^{12}C and ^{16}O. Analyzing-power measurements were made for the ground state in ^{8}Be at bombarding energies of 18 and 22 MeV and the ground state and 4.43 MeV 2^+ state in ^{12}C at $E_d = 22$ MeV.

The main purpose of the present experiment was to study the reaction mechanism of the (d, ^{6}Li) utilizing the analyzing power as a probe. One also expects to obtain information on the cluster structure of ^{6}Li nuclei, since the tensor analyzing powers should be sensitive to the relative angular momentum L of the alpha plus deuteron clusters in ^{6}Li, especially to the $L = 2$ (D-state) component. Some of the results to be discussed here have previously been reported in Ref. 3.

The experiment was performed with a polarized deuteron beam from the tandem accelerator using a Lamb-shift source[4] at the University of Tsukuba. The vector and tensor analyzing powers, iT_{11}, T_{20}, T_{21}, and T_{22}, were obtained by measuring the cross sections for incident deuterons with the $m_I = +1$, 0, and -1 magnetic substates, respectively. The polarized ion source provided $\vec{d}$-beams with three particular orientations of the spin alignment axis: normal to the scattering plane, along the incident beam direction, and in the scattering plane at an angle of 54.7° to the beam direction. Target beam currents were 70—100 nA and the typical beam polarization was 80% of the theoretical maximum. Self-supporting natural carbon foils of 30—100 μg/cm^2 were used as ^{12}C targets and the ^{16}O targets consisted of WO_3 and SiO_2 foils of 200—500 μg/cm^2. The emitted particles were momentum analyzed with a magnetic spectrograph (ESP-90) and detected by one or two 5-cm long Si position sensitive detectors placed in the focal plane. The energy resolution was 300—500 keV (FWHM) with a solid angle of 2 msr ($\Delta\theta = 1.5°$). In the case of (d,^{6}Li) on ^{16}O, a ΔE-E counter telescope was used to detect and identify the ^{6}Li particles at backward angles between $\theta_{lab} = 32°$ and 68°. An ionization chamber served as a ΔE counter and a 5-cm long Si position sensitive detector covered by a multislit collimation mask was used as an E detector. The slits were separated by 2 deg and each solid angle was 1 msr. Data were taken at seven angles simultaneously by using this counter telescope. In this setup the energy resolution was $\simeq$500 keV (FWHM).

Angular distributions of $\sigma(\theta)$, iT_{11}, T_{20}, T_{21}, and T_{22}, for the (d, ^{6}Li) reactions on ^{12}C and ^{16}O are shown in Figs. 1 and 2, respectively. The error bars indicated represent statistical errors only. For the ground state transitions, the angular distribution patterns of $\sigma(\theta)$ and all four analyzing powers are quite different for ^{12}C and ^{16}O targets at $E_d = 22$ MeV. All the analyzing powers are out of phase at forward angles. For the ground state transition on ^{12}C, the angular distribution $\sigma(\theta)$ shows a strong forward rise, indicating the typical pattern for transferred angular momentum $L = 0$, which suggests that this reaction proceeds predominantly via a direct alpha transfer mechanism. On the other hand, for the ^{16}O target $\sigma(\theta)$ exhibits a monotonous angular distribution pattern for the ground state transition at a deuteron energy of 22 MeV, which indicates the presence of a more complex reaction mechanism at this incident energy. However, the typical angular distribution pattern for $L = 0$ transfer has been observed at an incident energy of 28 MeV.[5] Both the $\sigma(\theta)$ and iT_{11} for the reaction ^{16}O($\vec{d}$,^{6}Li)^{12}C (g.s.) exhibit angular distribution patterns similar to the inverse reaction ^{12}C($^6\vec{Li}$,d)^{16}O(g.s.).[6]

We compared the data with finite-range distorted-wave Born approximation (DWBA) calculations assuming a one-step alpha-cluster transfer by using the computer code TWOFNR.[7] In the present analyses we tried to reproduce the trends rather than fit the data in detail. A macroscopic cluster model was assumed for ^{6}Li nuclei. It is possible for the deuteron plus alpha cluster within ^{6}Li to be in the $L = 0$ (S-state) and $L = 2$ (D-state) relative orbital angular momentum states. A simple cluster model wave function, in which the intercluster motion is assumed to be in the pure S state, is usually used for calculations of the cross sections. However, to analyze the tensor analyzing

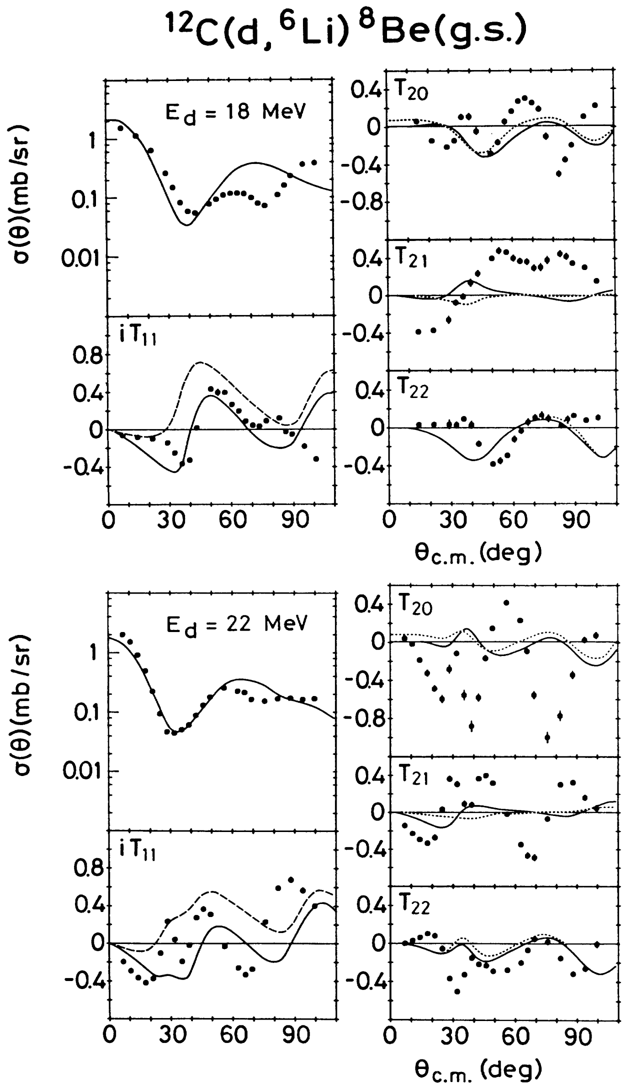

FIG. 1. Cross sections and analyzing powers in ^{12}C($\vec{d}$,^{6}Li)^{8}Be (g.s.) reactions at $E_d = 18$ and 22 MeV. The solid curves are finite-range DWBA calculations which include the D-state component in the relative motion of the deuteron and alpha clusters in ^{6}Li, and the dotted curves for the tensor analyzing powers correspond to a pure S state. The dashed curves in iT_{11} neglect the spin-orbit term in the ^{6}Li optical potential.

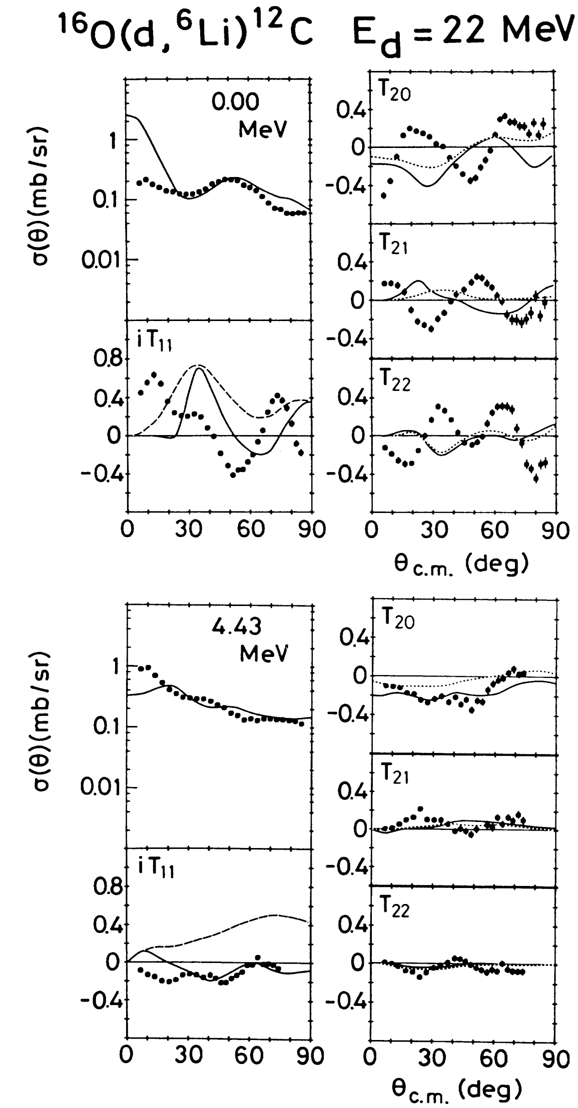

FIG. 2. Cross sections and analyzing powers in the ^{16}O($\vec{d}$,^{6}Li)^{12}C (g.s. and 4.43 MeV) reaction at $E_d = 22$ MeV. The curves are as in Fig. 1.

powers the D-state component must be included. We used the intercluster wave function derived by Nishioka *et al.*,[8] which contains S- and D-state components with amplitudes chosen to reproduce the experimental value of the ^{6}Li Q moment. The radial parts of the intercluster wave function were taken to be the $2S$ and $1D$ states of a Woods-Saxon potential ($r_0 = 1.2$ fm, $a = 0.65$ fm) within the framework of the separation energy method. The effective interaction between the deuteron and the alpha particle was assumed to be of the Woods-Saxon form with $R = 1.9$ fm and $a = 0.65$ fm.[9] The target nucleus was assumed to be a core plus alpha cluster. The alpha cluster state was assumed to be bound in a Woods-Saxon potential with parameters $R = 1.2A^{1/3}$ fm and $a = 0.65$ fm, and the depth of the Woods-Saxon potential was determined to fit the separation energy of the alpha cluster from the target nucleus in question. The deuteron optical model potential parameters were chosen to fit both the observed elastic cross sections and vector analyzing powers on ^{12}C and ^{16}O at $E_d = 22$ MeV. Optical-model parameters for ^{6}Li on ^{8}Be are not available; they were obtained by fitting the shape of $\sigma(\theta)$ in the (d, ^{6}Li) reaction at $E_d = 22$ MeV. The ^{6}Li+^{12}C optical potentials were taken from the work of Vineyard *et al.*,[10] which were obtained from fits to the elastic cross sections. The spin-orbit term of the ^{6}Li optical potential is not known well. We studied the effects of the usual Thomas-form spin-orbit potential.

TABLE I. Optical-potential parameters.

Channel	V_R (MeV)	r_R (fm)	a_R (fm)	W (MeV)	r_I (fm)	a_I (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)	r_c (fm)
$d+{}^{12}C$	97.4	1.0	0.83	9.57[a]	1.55	0.65	4.01	1.2	0.476	1.25
$d+{}^{16}O$	85.8	1.14	0.70	6.22[a]	1.50	0.81	4.4	1.01	0.42	1.3
${}^{6}Li+{}^{8}Be$	140.0	1.2	0.8	22.0[a]	1.9	0.4	4.01	1.2	0.8	1.4
${}^{6}Li+{}^{12}C_{g.s.}$	168.0	1.28	0.79	6.44[b]	2.36	0.62	4.4	1.28	0.79	1.25
${}^{6}Li+{}^{12}C_{4.43}$	174.0	1.24	0.79	4.67[b]	2.38	0.62	4.4	1.24	0.79	1.25

[a]Surface absorption.
[b]Volume absorption.

Results of DWBA calculations are shown in Figs. 1 and 2; the calculated cross sections are normalized to the data. The optical-model parameters used in the calculations are listed in Table I. The shape of the angular distribution $\sigma(\theta)$ was fairly well reproduced by the DWBA calculations in the case of the ${}^{12}C$ target, but not for the ${}^{16}O$ target. It was found that the ${}^{6}Li$ spin-orbit term has a strong effect on the vector analyzing powers, but not on the cross sections and the tensor analyzing powers. The DWBA including the spin-orbit term in the ${}^{6}Li$ optical potential predicts the general trends of iT_{11}, but is not satisfactory in detail. A strong oscillating pattern observed in the iT_{11} for the ground state transition on ${}^{12}C$ at $E_d=22$ MeV at the angular region around 30° was not reproduced by the DWBA calculations. The agreement between the DWBA and the data is very poor for all three tensor analyzing powers but better for $\sigma(\theta)$ and iT_{11}. The DWBA predicted only small values for the tensor analyzing powers. A small admixture of the D-state component for the ${}^{6}Li$ nuclei produced only a small change in the angular distribution of the tensor analyzing powers. We could not obtain values for the tensor analyzing powers as large as observed within the framework of the DWBA calculations assuming a one-step alpha-cluster transfer.

In summary, the vector analyzing power iT_{11} and all three tensor analyzing powers T_{20}, T_{21}, and T_{22}, as well as the cross section $\sigma(\theta)$, were measured in (d, ${}^{6}Li$) reactions on ${}^{12}C$ and ${}^{16}O$ at bombarding energies of 18 and 22 MeV. The data were compared with finite-range DWBA calculations assuming a one-step alpha-cluster transfer. The DWBA predicted the general trends of the vector analyzing power iT_{11}, but, however, failed to reproduce the three tensor analyzing powers, T_{20}, T_{21}, and T_{22}. The DWBA predicted very small values for the tensor analyzing powers compared to the data. The D-state effect for the ${}^{6}Li$ nuclei is small even for the tensor analyzing powers in the (d, ${}^{6}Li$) reaction on ${}^{12}C$ and ${}^{16}O$ at $E_d=22$ MeV. It is possible that some of the failure of the DWBA calculations may be due to the presence of more complex reaction mechanisms such as the inelastic or sequential two-step process. Such a higher order effect can possibly enhance the analyzing power, especially in the angular region of minimum cross sections. The present analyzing power data should be useful for investigating such mechanisms.

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