Deuteron transfer and p-^{8}Be optical model parameters in the ^{6}Li(^{3}He,$\vec{p}$)^{8}Be reaction*

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In the ^{6}Li(^{3}He,p)^{8}Be (0^+,2^+) reaction, the experimental results of the differential cross section and the polarization are fairly well described by a cluster point of view in which, instead of two-nucleon transfer, a deuteron transfer is a dominant process. The optical-model parameters for p-^{8}Be are also investigated.

[NUCLEAR REACTIONS Mechanism of n-p transfer from cross sections and polarizations. Optical model parameters.]

I. INTRODUCTION

The polarization of protons from the reaction ^{6}Li(^{3}He,$\vec{p}$) to the ground and first excited states of ^{8}Be has been measured recently for the first time[1] at 14 MeV incident energy. Angular distributions of the differential cross sections have also been measured. The usual two-nucleon-transfer prescription was not successful in accounting for the experimental data. On the other hand, an approach within the distorted-wave theory consisting of the transfer of a deuteron had a good measure of success in the ^{3}He(^{3}He,$\vec{p}$)^{5}Li reaction.[2]

In the present reaction several points have to be considered. Firstly, ^{8}Be is a particle unstable nucleus; both the 0^+ and 2^+ excited states decay into 2α. The extensive shell-model calculations with a realistic interaction by Hauge and Maripuu[3] show a large discrepancy for the low-lying energy levels of ^{8}Be. Hence the use of the spectroscopic factors obtained from the shell model in a distorted-wave Born approximation (DWBA) calculation is rather questionable for such levels. The cluster representation[4] indicates that ^{8}Be has a molecule-like structure made of two α particles which move about each other. We also observe that the polarization data for the ground state are oscillatory, as are those for the ^{2}H(^{3}He,$\vec{p}$)^{4}He[5] reaction, and this basic process may take place in the case of the ^{6}Li target, the transfer being made to the deuteron cluster. Secondly, due to the instability of ^{8}Be, there are no elastic-scattering data available to determine the optical-model parameters of the $p+^8$Be channel, in particular, the real central potential depth V. One may use parameters found from p-^{9}Be elastic-scattering analysis.[6] We, however, lay stress on p-^{4}He scattering because of the strongly deformed α-cluster nature of ^{8}Be. Thirdly, the target nucleus ^{6}Li is also known to possess the α-d cluster structure.[7] Although the ^{3}H-^{3}He cluster structure[8] may also be present, the α-d structure is dominant[9] and therefore it is the one considered in the present work. Finally, there have been speculations as to the d-p structure of ^{3}He.

A complicated formalism has been developed by Edwards and coworkers and applied to several reactions.[10,11] Their analysis, however, was made only for the angular distribution of the cross section and spin-dependent interactions were ignored, which may have substantial effects on polarization. We, instead, use a spin-dependent DWBA code[12] treating the deuteron as a charged mass-2 particle. This model has been used previously in calculating (d,^{6}Li),[13] (^{3}He,^{6}Li),[14] and (^{6}Li,^{3}H)[15] angular distributions from various nuclei. For the reasons mentioned above the ^{6}Li(^{3}He,p)^{8}Be reaction is likely to be dominated by the cluster structure. Throughout the analysis, a consistent treatment and the same optical-model parameters are desirable to obtain meaningful information.

II. GROUND-STATE REACTION ANALYSIS

The spin and parity of ^{6}Li is 1^+ and that of the residual nucleus is 0^+ so that the total angular momentum J and the orbital angular momentum transferred are $J=1$ and $L=0$ or 2. From the independent particle model point of view, ^{6}Li has picked up two p nucleons to form ^{8}Be. From the cluster point of view the transferred deuteron is in a relative s state and the cluster must have two energy quanta associated with its center of mass motion. This means that a $2s$ or $1d$ center of mass motion is relevant in our analysis.

The Q value of the reaction is 16.787 MeV so that the outgoing proton has an energy of about 28 MeV. As was mentioned in Sec. I, the optical-model parameters for the exit channel are uncertain. As a first step we start with the values for 31-MeV proton scattering from ^{4}He,[16] whereas the parameters for the entrance channel are taken from Ref. 17.

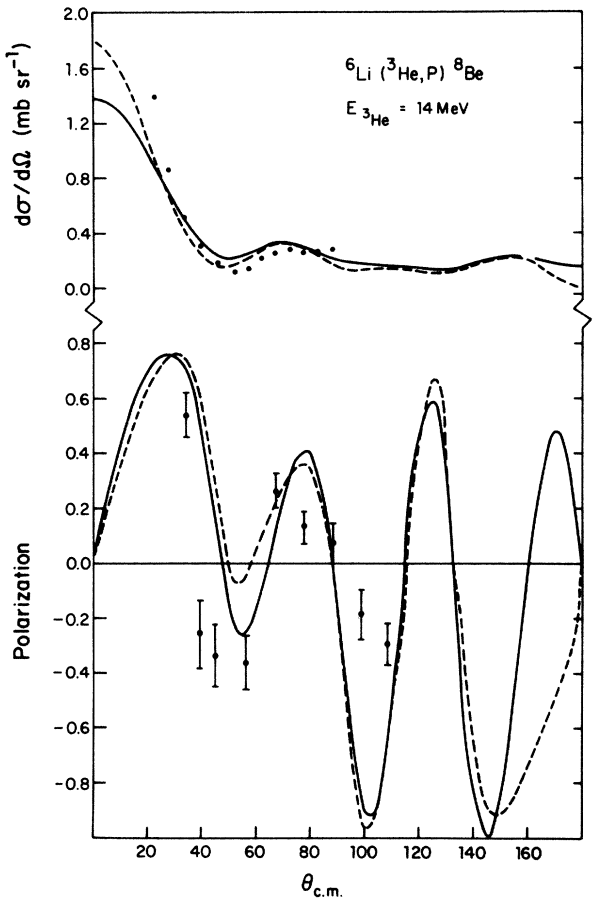

FIG. 1. Differential cross section and polarization for the reaction leading to the ground state of ^{8}Be. $a = 0.35$ and 0.25 fm are indicated, respectively, by a solid and a dashed line for $(JL) = (10)$.

The $(JL) = (12)$ component gives an acceptable pattern for the cross section, especially the first minimum and the second maximum at around 55 and 80° (c.m.), respectively, although the magnitude is almost ten times smaller than the measured cross section, and the polarization is positive and monotonically increasing up to 110°, quite unlike the experimental results shown in Fig. 1 (see Fig. 3). When the central potential depth V is increased the $(JL) = (12)$ component has no longer a peak at 0° but has a broad peak around 55° for the cross section, which resembles then the excited state pattern. However, the $(JL) = (10)$ component becomes similar to the ground-state experimental results. The central potential depth required to obtain reasonable fits for both the differential cross section and the polarization is about twice the usual p-nucleus depth. The results are shown in Fig. 1, and Table I gives the optical-model parameters used in this analysis. To test the effect of the "surface thickness" of the Woods-Saxon potential, the diffuseness parameter a has been varied from 0.23 to 0.50 fm and the result for $a = 0.25$ fm is also shown in Fig. 1 for comparison. As can be seen from Fig. 1, the diffuseness parameter has a pronounced effect on the cross section at forward angles. The validity of the parameters of p-^{8}Be is further tested in the first excited state transition as described in the next section.

III. FIRST EXCITED STATE REACTION ANALYSIS

The energy of the 2^+ state of ^{8}Be is 2.90 MeV, having a width of about 1.5 MeV. As was mentioned in the previous section, the $(JL) = (12)$ component showed some resemblance in shape to the experimental cross section of the first excited state. Hence, the $(JL) = (12)$ and (22) components were calculated (and of course they satisfy the angular momentum conservation). The results are shown in Fig. 2. Note that the same optical-model parameters as those in Table I are used. It appears from Fig. 2 that the $(JL) = (22)$ component is more appropriate than the $(JL) = (12)$ component. Considering that there may be competing processes for the the two-nucleon transfer, which seems more likely in the excited state than in the ground state, the gross features are reasonably well reproduced. This, in turn, indicates that the deuteron cluster transfer is also a dominant process for this transition.

TABLE I. Optical-model parameters.

Channel	V (MeV)	r (fm)	a (fm)	W (MeV)	r_W (fm)	a_W (fm)	W_D (MeV)	r_{WD} (fm)	a_{WD} (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)	r_c (fm)
^{3}He-^{6}Li [a]	140.0	1.20	0.70	30.0	2.11	0.54	0	...	...	6.0	1.20	0.70	1.30
p-^{8}Be [b]	110.0	1.45	0.35	0	...	...	3.15	1.43	0.1	4.26	1.13	0.35	1.38
p-^{8}Be [c]	50.0	1.26	0.578	0	...	...	12	1.33	0.323	0	...	...	1.13

[a] Reference 17.
[b] Present work.
[c] Reference 11. Figure 3 was obtained with this set.

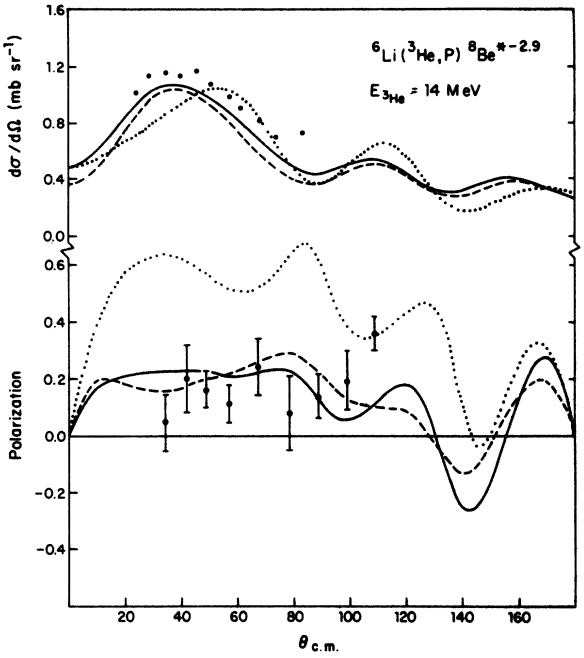

FIG. 2. Differential cross section and polarization for the reaction leading to the first excited state of ^{8}Be. $(JL)=(22)$ with $a=0.35$ fm is indicated by a solid line, the same (JL) but with $a=0.25$ fm by a dashed line, and $(JL)=(12)$ with $a=0.35$ fm by a dotted line.

IV. DISCUSSION

There are two major points that must be considered: (i) Why are the $(JL)=(10)$ or (22) components selectively preferred for the 0^+ and 2^+ states, respectively? The components such as $(JL)=(10)$ or (32) are also allowed for the 2^+ state. (ii) Why is the real central potential depth so large?

The selectivity of the (JL) component may be understood in the light of the previously mentioned α-d cluster structure on ^{6}Li, where the relative α-d motion is a $2s$.[18] The spin of a transferred deuteron has to be aligned antiparallel to the deuteron of the ^{6}Li. This means that the center of mass motion of the transferred deuteron cluster is a $2s$ for the 0^+ state of ^{8}Be. Hence, $(JL)=(10)$ is the only component that should govern the ground-state reaction. For the first excited state, since the sum of the spins is zero, the transferred J must be 2 to reach the 2^+ state of ^{8}Be, thus leading to the $(JL)=(22)$ component. This is equivalent to say that the transferred deuteron cluster has a $1d$ center of mass motion. The $(JL)=(22)$ component also arises from other angular momentum couplings. For instance, the two deuteron spins can couple to $2\hbar$ or to $1\hbar$ requiring, respectively, the $(JL)=(22)$ and (32) components to reach the 2^+ state. These couplings seem to be unlikely because the ^{8}Be decays into two spinless tightly bound α particles. One may still consider a spin-flip or even more sophisticated interaction, but we suspect that these contributions are small and they are beyond the scope of the present work.

Regarding the large potential depth, the Woods-Saxon potential is fairly flat inside the nucleus and the diffuseness parameter a determines the shape for a given interaction radius. The analysis of α-α scattering[19] shows that the distance between the center of the α particles comes as close as 2 fm, indicating a considerable overlap of the surface region. Therefore, when two Woods-Saxon potentials of the α particles are approximated by a single potential, it is plausible that the real central potential depth becomes as deep as twice that of the p-α system. It takes of the order of 10^{-22}–10^{-21} sec for a 30-MeV outgoing proton to pass through the ^{8}Be. Since the lifetime of ^{8}Be is of the order of 10^{-16} sec, a proton may well see the ^{8}Be as described. We have shown in Sec. II that the calculated cross section is sensitive to a. Hence a more realistic shape of the potential might produce still a better agreement with the measure-

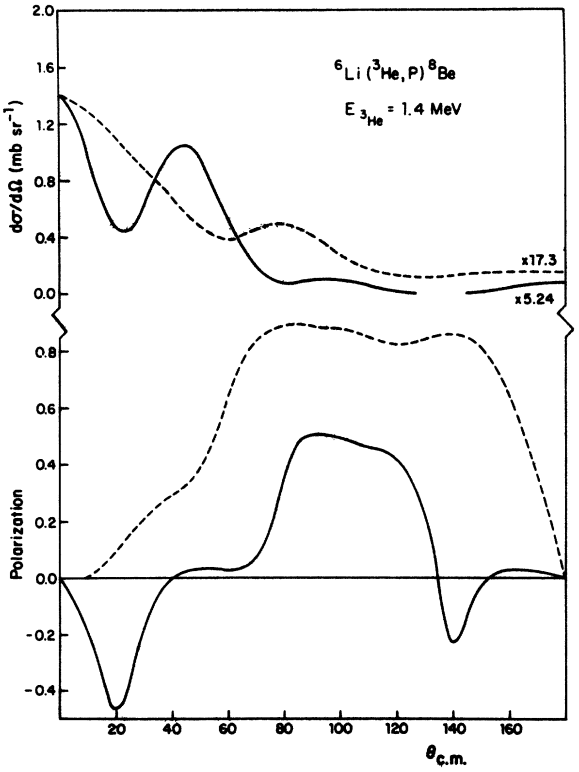

FIG. 3. Differential cross section and polarization patterns obtained with a standard optical-model potential for the $p+^8$Be channel. The curves are normalized to the value at 0° of Fig. 1. $(JL)=(12)$ is indicated by a dashed line and (10) by a solid line.

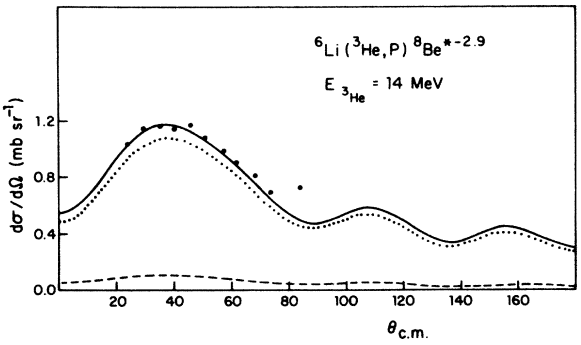

FIG. 4. Differential cross section obtained by a deuteron and two-nucleon-transfer processes for the first excited state of ^{8}Be. The deuteron transfer channel is indicated by a dotted line, the two-nucleon-transfer channel by a dashed line, and the total by a solid line.

ments. It has been known[20,21] that there exists a discrete ambiguity of potentials with substantially different depths which fit the elastic-scattering data equally well.

Concerning the other parameters, calculations were performed using the same values as in Ref. 12 in which the central and the surface absorption potential depth (W_D) are 50.0 and 12.0 MeV, respectively, for the p-^{8}Be channel. It is again found that a $1d$ component gives the cross section similar to the experimental result although the magnitude is not produced correctly, but fails to fit the polarization data as is demonstrated in Fig. 3. To check this point further W_D is varied between 3.0 and 25.0 MeV and keeping $W_D = 12.0$ MeV; the volume absorption potential depth is also increased up to 25.0 MeV. None of these sets of parameters is found to reproduce the measurements. The addition of nonzero spin-orbit values and nonlocality corrections does not yield agreement either.[1]

Finally we would like to discuss briefly the contribution of the two-nucleon-transfer channel for the 2^+ state of ^{8}Be. We consider the $(JSL) = (221)$ component only and assume that the two transferred nucleons are on the pure-shell-model $(p_{3/2}p_{1/2})$ orbits. We again use the same optical-model parameters of Table I. The polarization obtained from this component is very similar to that of the $(JL) = (22)$ component of the deuteron channel, and the result for the cross section is shown in Fig. 4 together with the total of the two channels. It is quite interesting that the total gives a remarkable fit.

V. CONCLUDING REMARKS

On the basis of a deuteron transfer, the calculated proton angular distribution of the differential cross section and of the polarization for the (^{3}He, $\vec{p}$) reaction leading to the ground and the first excited states of ^{8}Be are in fairly good agreement with the experimental results. The optical-model parameters for p-^{8}Be have been studied. Selectivity of the transferred angular momentum is found; that is, the spins 0^+ and 2^+ of the ^{8}Be as a 2α nucleus determine to a large extent the orbital angular momentum of the transferred deuteron cluster.

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