JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN, Vol. 44, No. 5, MAY, 1978

The ^{9}Be(d, t)^{8}Be and ^{9}Be(d, α)^{7}Li Reaction in the Energy Range from 12.17 MeV to 14.43 MeV

Seiji TANAKA

Institute for Chemical Research, Kyoto University, Kyoto

(Received May 16, 1977; revised manuscript received November 16, 1977)

(d, t) and (d, α) reactions on ^{9}Be were observed simultaneously. Angular distributions of tritons and alpha particles were measured at $E_d=12.35$ MeV and at 14.06 MeV. Excitation functions were obtained from 12.17 MeV to 14.43 MeV at 85° for tritons and at 35° for alpha particles.

DWBA fit to the (d, t_0) angular distribution gave good results and the spectroscopic factor 0.29 was obtained at both deuteron energies. (d, α) reaction is considered to occur mainly passing through the compound nucleus formation. In both reactions, the cluster structure of ^{9}Be seems to play an important role.

§1. Introduction

The (d, t) reaction has been investigated as a tool to see the one nucleon or one hole state of the nucleus. The ^{9}Be(d, t)^{8}Be reaction was studied by Fitz *et al.*[1] at $E_d=11.8$ MeV and by Darden *et al.*[2] at $E_d=15$ MeV. DWBA fits to the triton angular distributions give different values of the spectroscopic factor for one neutron pick-up from ^{9}Be leading to the ground state of ^{8}Be. Fitz *et al.* give the value of 0.51 and Darden *et al.* the value of 0.38. Both values are smaller than that given by Cohen and Kurath[3] from the theoretical calculation based on the intermediate coupling shell model. It is peculiar that the spectroscopic factor is different when the incident energy is different, if the direct reaction is assumed. Then, this difference leads to the questions. That is, at first, the direct reaction mechanism does not explain the (d, t) reaction on ^{9}Be and second, the ^{9}Be has a structure quite different from that described by the shell model and lastly, although it is not easy to think, the spectroscopic factor changes its value with the incident deuteron energy.

The (d, α) reaction seems to occur via two-nucleon pick-up process. However, the trials to treat the (d, α) reaction as a tool to study the two-nucleon pairing in the nucleus have not been successful in the case of ^{9}Be until now. Yanabu *et al.*[4] studied the ^{9}Be(d, α)^{7}Li reaction at $E_d=14.5$ MeV. The inverse reaction, ^{7}Li(α, d)^{9}Be, was studied by Merchez *et al.*[5] at $E_\alpha=30$ MeV. Both reactions showed nearly 90° symmetric angular distributions of product particles. Angular distributions rise not only at forward angles but also at backward angles. The PWBA or DWBA fit to the ^{7}Li(α, d)^{9}Be reaction assuming two nucleon transfer process failed to explain the experimental distribution, and also the heavy particle stripping theory failed to explain the backward rise. It seems most probable that alpha particles from the ^{9}Be(d, α)^{7}Li reaction are decay products from the intermediate state. Therefore, the structure of the intermediate state is to be taken into account. When one assumes the intermediate state to be a compound nucleus, the mode of excitation of ^{11}B should be examined. The excitation energy of ^{11}B in the case of the above mentioned reactions, lies in the giant resonance region of ^{11}B. The giant resonance of ^{11}B was observed in the ^{11}B(γ, n) and ^{11}B(γ, p) reaction.[6–8] Recently, alpha particle emission was observed from the excited states in the giant resonance region of ^{12}C.[9–11] It is expected that alpha decay occurs from the excited ^{11}B state in the giant resonance region through the ^{9}Be(d, α)^{7}Li reaction. However, the alpha decay of the excited ^{11}B has been studied scarecely until now.

In the present experiment, the excitation functions for (d, t) and (d, α) reactions on ^{9}Be and angular distributions of tritons and alpha particles were measured simultaneously. By this simultaneous detection, one can study the structure of ^{9}Be on one hand, and that of

^{11}B on the other hand. Moreover, the reaction mechanism of (d, t) and (d, α) are considered more clearly, when both reactions are compared.

§2. Experimental Procedure

A deuteron beam from the 105 cm cyclotron of Kyoto University[12] bombarded ^{9}Be. The beam was transported to a scattering chamber after its energy width was defined less than 0.2% by a magnetic analyzer. A self-supporting ^{9}Be foil was prepared from metalic Be by an evaporation chamber in our laboratory.[13] The thickness of the foil was measured by dE/dx method[14,15] and was determined to be 109 ± 13 μg/cm^2. The beam spot on the target was 2 mm × 2 mm and average beam current was 20 nA. The beam current was integrated by a current integrator. A counter telescope consisting of a 50 μm SSD of transmission type followed by a 1000 μm SSD was used for triton detection, and a 200 μm SSD (in the forward angular range) and a 50 μm SSD (in the backward) were used for alpha particle detection. The ΔE signals and E signals from the counter telescope and E signals from the alpha counter were fed into three ADC's, and analyzed by the $64^{ch} \times 128^{ch}$ and 512^{ch} mode. They were stored on-line in a minicomputer (YHP 2100 A) through an ADC controller[16] and dumped onto paper tape. Triton spectra were obtained from two-dimensional data by off-line analysis. The solid angles subtended were approximately 5×10^{-4} sr.

A monitor counter of a 2000 μm SSD was set at 30° with respect to the beam direction, and elastic deuterons were monitored with a 400-channel PHA.

§3. Results

Figure 1(a) shows the energy spectrum of tritons produced from the ^{9}Be(d, t)^{8}Be reaction leaving ^{8}Be nucleus in its ground (0^+) and first excited (2^+, 2.94 MeV) state, which are denoted by t_0 and t_1, respectively. Angular distributions of t_0 and t_1 were obtained at 12.35 MeV and at 14.06 MeV, and are given in Fig. 2. To derive the cross sections for (d, t_1) from the broad t_1 peak, the energy spectrum was fitted with a one-level formula. Then the background was subtracted. The t_0 and t_1 angular distributions show diffraction pattern. The shapes of the angular distributions are almost independent of incident energies. Excitation functions were measured in the energy range from 12.17 MeV to 14.43 MeV at the laboratory angle of 85°, where the angular dependence of the cross section is relatively weak. As shown in Fig. 4, excitation functions for (d, t_0) and (d, t_1) are monotonous.

Figure 1(b) shows the energy spectrum of alpha particles produced from the ^{9}Be(d, α)^{7}Li reaction leaving ^{7}Li nucleus in its ground

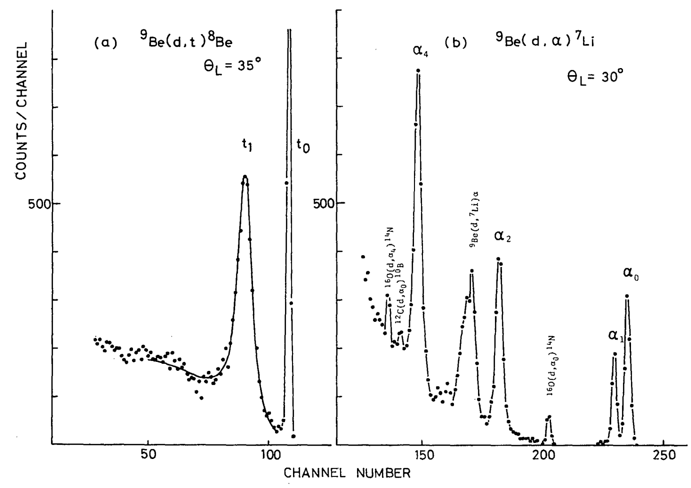

Fig. 1. Energy spectra of tritons (a) and alpha particles (b) from the ^{9}Be+d reaction at E_d=12.35 MeV. The detection angle was 35° for tritons and 30° for alpha particles. The symbol t_1 denotes tritons leaving ^{8}Be in its first excited state and so forth. The solid line in the triton spectrum shows the best fit with a one-level formula.

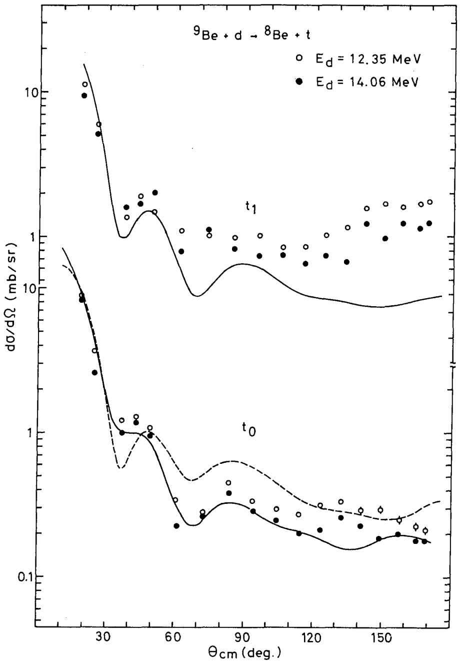

Fig. 2. Cross sections for the ^{9}Be(d, t)^{8}Be reaction at energies of 12.35 MeV and 14.06 MeV, leaving ^{8}Be nucleus in its ground state (denoted by t_0) and the first excited state (denoted by t_1). The curves show DWBA calculations at $E_d = 14.06$ MeV, which were made with the neutron binding energy of $E_b = -1.67$ MeV (shown by the solid line) or -6.50 MeV (by the broken line) for (d, t_0), and with $E_b = -4.61$ MeV (shown by the solid line) for (d, t_1).

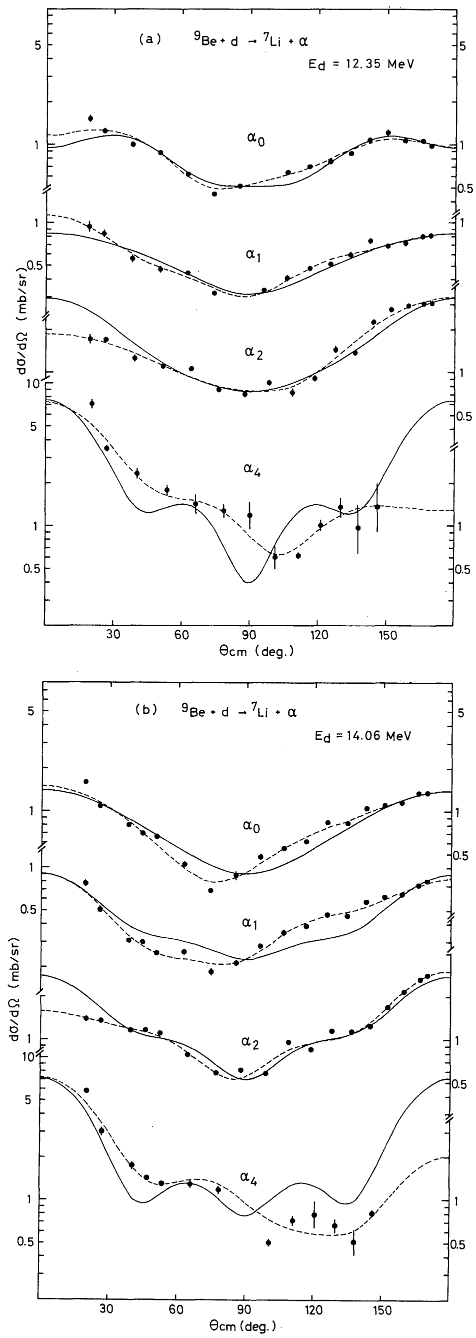

Fig. 3. Cross sections for the ^{9}Be(d, α)^{7}Li reaction at (a) $E_d = 12.35$ MeV and at (b) 14.06 MeV, leaving ^{7}Li in its ground ($3/2^-$), first ($1/2^-$, 0.478 MeV), second ($7/2^-$, 4.633 MeV) and fourth ($5/2^-$, 7.467 MeV) state. The solid lines are the Legendre polynomial fits with even L terms, and the broken lines with even L plus odd L terms.

($3/2^-$), first ($1/2^-$, 0.478 MeV), second ($7/2^-$, 4.633 MeV) and fourth ($5/2^-$, 7.467 MeV) state, which are denoted by α_0, α_1, α_2 and α_4, respectively. A peak corresponding to the third excited state was not observed clearly. Angular distributions of α_0, α_1, α_2 and α_4 were obtained at 12.35 MeV and at 14.06 MeV, and are shown in Fig. 3(a) and (b). The shapes of the α_0, α_1 and α_2 distributions are similar to each other, and are almost symmetric about 90°. The shape of the α_4 distribution is not 90° symmetric and is different from those of α_0, α_1 and α_2. All angular distributions are weakly dependent on incident energies. Excitation functions for (d, α) were measured at the laboratory angle of 35°. The energy range was from 12.17 MeV to 14.43 MeV. As shown in Fig. 4, the excitation functions of α_0, α_1 and α_2 decrease slowly, while the α_4 function decreases rapidly.

Differential cross sections were integrated over the angular range measured, which is from 15° to 130° for (d, α) and from 15° to 165° for the remaining reactions. The integrated cross sections for (d, t) are com-

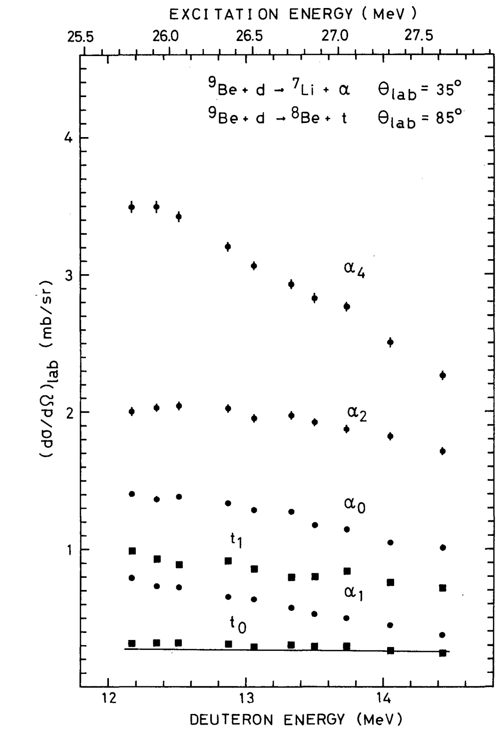

Fig. 4. Excitation functions for the ^{9}Be(d, t)^{8}Be and ^{9}Be(d, α)^{7}Li reaction in the energy range from 12.17 MeV to 14.43 MeV. The detection angles were 85° and 35° respectively. The solid line shows the prediction of the DWBA theory.

parable to those for (d, α) (Table I).

§4. Analyses

In this section, DWBA analysis of the (d, t) reaction, and DWBA and compound nucleus process analyses of the (d, α) reaction are described. The DWBA analysis was performed with the program DWUCK,[17] which is based on the zero range approximation. Optical potential parameters used for the incident channel were obtained from the optical model analysis of elastic scattering data. It is to be

Table I. Integrated cross sections (mb).

Reaction	Incident energy	
	12.35 MeV	14.06 MeV
(d, t_0)	8.65 ± 0.26	6.74 ± 0.28
(d, t_1)	18.92 ± 0.62	16.03 ± 0.34
(d, α_0)	9.37 ± 0.28	8.03 ± 0.24
(d, α_1)	6.00 ± 0.25	4.40 ± 0.19
(d, α_2)	14.71 ± 0.59	12.08 ± 0.36
(d, α_4)	18.2 ± 1.1	13.40 ± 0.66

noticed that these parameters also give good fit to the inelastic scattering angular distribution, if the coupled-channels theory is applied.[18] The parameter set is given in Table II.

4.1 Analysis of the (d, t) reaction

One nucleon pick-up process was assumed in the DWBA calculation of the (d, t) cross section. The form factor for a picked-up neutron was obtained by the separation energy method. This method provides the wave function which gives correct binding energy of a neutron in ^{9}Be to be -1.67 MeV and -4.61 MeV in the (d, t_0) and (d, t_1) calculation. Optical potential parameters for the outgoing channel are not available from experiments, so that the values obtained from the data[19] for the elastic scattering of 18 MeV ^{3}He by ^{9}Be were employed. They are given in Table II. The error due to the use of these parameters to the case of ^{9}Be(d, t)^{8}Be reaction seems to be relatively small in the case of the (d, t_0) reaction, because the rms radius of the triton is nearly equal to the rms radius of ^{3}He, and because the residual nucleus ^{8}Be(g'nd) is almost stable ($\Gamma \sim 7$ eV) and the nuclear shape of ^{8}Be(g'nd) is similar to that of ^{9}Be(g'nd). However, in the case of the (d, t_1) reaction, the error would be significant, because the

Table II. Values of optical potential parameters used in the DWBA analysis.

		V (MeV)	W_V (MeV)	W_S (MeV)	L_{LS} (MeV)	R (fm)	R_W (fm)	R_S (fm)	R_C (fm)	a (fm)	a_W (fm)	a_S (fm)
^{9}Be-d	(a)	77.42	24.20	1.36	5.5	0.882	1.098	1.428	1.25	1.014	0.649	1.161
	(b)	87.64	22.56	2.23	5.5	0.882	1.098	1.428	1.25	1.016	0.692	1.090
^{8}Be-t		153.77		12.33	5.25	1.161		1.464	1.40	0.691		0.719
^{7}Li-α	(c)	275.2	8.16			1.21	1.81		1.30	0.645	0.645	
	(d)	151.2	10.30			1.73	1.73		1.30	0.55	0.55	

(a) for $E_d = 12.35$ MeV, (b) for $E_d = 14.06$ MeV, (c) for α_0 channel, (d) for α_4 channel. W_V is for a Woods-Saxon volume absorption. W_S is for a surface derivative absorption. Note: $R = R_V = R_{LS}$ and $a = a_V = a_{LS}$.

similarity between ^{8}Be*(1st) and ^{9}Be(g'nd) is not assured. The comparison between the calculated angular distributions and experimental data are shown in Fig. 2. The fit to the t_0 distribution is satisfactory. In Fig. 2, the theoretical curve was normalized to the experimental data at 38°, and the spectroscopic factor of 0.29 was obtained. In the case of the (d, t_1) reaction, the fit to the data is only qualitative. Therefore, definite determination of the spectroscopic factor is not possible in this case. If the least-squares fitting procedure is applied, the resultant value is 0.36.

The applicability of the DWBA theory to the (d, t_0) reaction is reinforced by the success of reproducing excitation function for this reaction. The comparison between calculated values and experimental data is shown in Fig. 4. In the calculation, the values of optical potential parameters were not changed with incident energies. In spite of this simplification, the fit is fairly good.

4.2 *Analysis of the* (*d*, α) *reaction*

In the first stage, angular distributions were calculated with the DWBA theory. Because the DWBA theory is successful in qualitative description of angular distributions for the (d, α) reaction on some light nuclei,[20,21] the DWBA fit would allow us to check up the reaction mechanism. In the calculation, microscopic two-nucleon form factor was used. Namely, an incident deuteron, which was assumed to be a point particle, picks up two $1p_{3/2}$ nucleons which couple to $L=0$ and $S=1$. In order to calculate microscopic form factor with the program DWUCK, a small change was made,[22–24] that is to say, the value of 0.27 fm^{-1} was used for the size parameter κ in stead of 0.23 fm^{-1}. As the outgoing energies of α_0 and α_4 at $E_d=14.06$ MeV are 29.27 MeV and 17.54 MeV respectively, different sets of potential parameters should be used for each outgoing channel. Two sets of optical potential parameters are available. One set was obtained from the experiment[25] on the elastic scattering of 29.4 MeV alpha particles by ^{7}Li, and was used in the calculation of α_0, α_1 and α_2 distributions. The other[26] was obtained at $E_\alpha=18.5$ MeV, and was used in the calculation of the α_4 distribution. These sets of parameters are given in Table II.

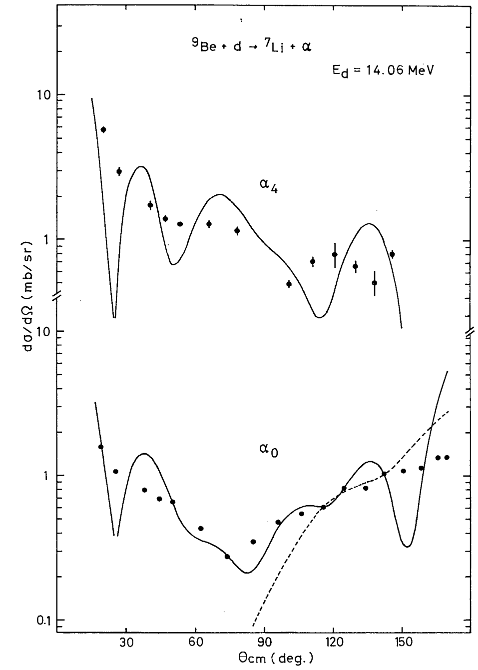

Fig. 5. Comparison of the values calculated by the DWBA theory with experimental data on the ^{9}Be(d, α)^{7}Li reaction at $E_d=14.06$ MeV, leaving ^{7}Li in its ground ($3/2^-$) and fourth ($5/2^-$, 7.467 MeV) state. The solid lines show the values calculated by assuming two-nucleon pick-up process. The broken line shows those calculated by assuming heavy particle stripping process.

The comparison between calculated and experimental angular distributions for (d, α_0) and (d, α_4) are shown in Fig. 5. The calculated distributions show sharp diffraction patterns, contrary to the experimental ones. The slow rise of the α_0 distribution at backward angles was not reproduced by the two-nucleon pick-up process. Then, calculations by assuming heavy particle stripping process were also carried out. Calculated curve increases more rapidly than the experimental distribution.

In the second stage, Legendre polynomial expansion method was applied to the analysis of the angular distributions. According to the formula of Blatt and Biedenharn,[27] the angular distribution of the compound process reaction is expressed by the following equation,

$$\frac{d\sigma_{c'c}}{d\Omega_{c'}}=\frac{1}{(2I_a+1)(2I_A+1)}\frac{1}{k_c^2}\times\sum_{LII'}B_L(c'I', cI)P_L(\cos\theta), \qquad (1)$$

where I_a and I_A denote the spin of the incident particle and the target nucleus, and I and I' denote the channel spin of the incident and outgoing channel. Kinematical factors and dynamical properties of the compound nucleus are included in $B_L(c'I', cI)$. When the summation with respect to I and I' is made, the equation (1) reduces to

$$\frac{d\sigma}{d\Omega}=\sum_L A_L P_L. \qquad (2)$$

If fitting angular distributions with this equation, polynomials up to 6 were included, because the maximum angular momentum introduced by the incident deuteron is at most 3. The values calculated with even L terms are shown by the solid lines in Fig. 3(a) and (b), and the values calculated with even plus odd L terms by the broken lines. The absolute values of coefficient A_L are plotted in Fig. 6. As shown in this figure, $L=0$ and 2 terms are predominant in the (d, α_0), (d, α_1) and (d, α_2) reaction. In the case of the (d, α_4) reaction, terms other than those of $L=0$ and 2 are important. The value of $|A_L|$ decreases with the increase of L.

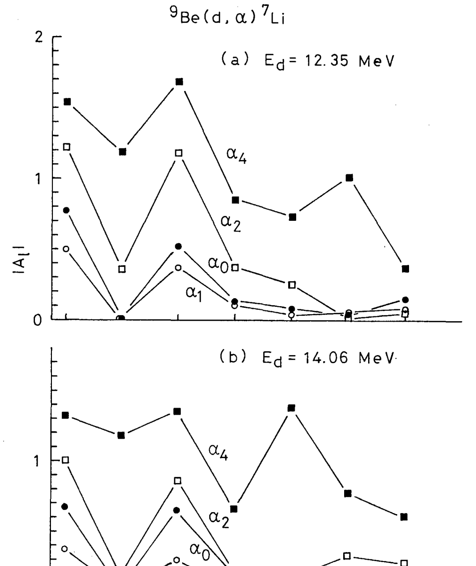

Fig. 6. Absolute values of $|A_L|$, the coefficient of the Legendre polynomial expansion of the angular distribution for the ^{9}Be(d, α)^{7}Li reaction at (a) 12.35 MeV and at (b) 14.06 MeV.

§5. Discussions and Conclusion

5.1 The ^{9}Be(d, t)^{8}Be reaction

The fact that the angular distribution data and excitation function data for ^{9}Be(d, t_0)^{8}Be were reproduced well by the DWBA calculations, indicates that this reaction occurs mainly via the direct one nucleon pick-up process. The spectroscopic factor for the picked-up neutron in ^{9}Be was given by the comparison of the DWBA calculation with experimental data. The same value 0.29 was obtained both at 12.35 MeV and at 14.06 MeV. From this result, it is indicated that the spectroscopic factor takes the same value in the energy range from 12.17 MeV to 14.43 MeV, because the excitation function measured in this energy range is monotonous. As for the magnitude of the S factor, the present result is smaller than the values, 0.38 or 0.51, reported in references.[1,2] The reason for the disagreement in these results is considered as follows. One reason should be the error in the absolute cross section. In this case, however, the errors in the absolute cross sections are less than 20%, so that the disagreement lies beyond the experimental errors. Another is related to the difference in parameters used in the DWBA analysis. The optical potential parameters employed in the present calculation are those which give good fits to both elastic and inelastic scattering data,[18] but the parameters in the references do not necessarily satisfy these conditions. Therefore, the difference in the choice of parameter set gives rise to the scatter in the S factor.

The present result, 0.29, for the S factor is different from 0.58 which was given by Cohen and Kurath[3] from the theoretical calculation based on the intermediate coupling shell model. The reason for the difference is considered as follows. In the present DWBA calculation, the binding energy of the picked-up neutron was assumed to be -1.67 MeV which corresponds to the separation energy of a neutron from ^{9}Be. If the intermediate coupling shell model is assumed, which describes ^{9}Be as ^{4}He plus five nucleons, the binding energy is -6.50 MeV as indicated in ref. 30. The curve calculated with this value is shown by the broken line in Fig. 2. The S factor obtained is 0.57 and is close to that given by Cohen and Kurath,[3] but the fit to the experimental data is not good. It is clear that, in order to explain the angular distribution, the binding energy of a neutron should be taken as -1.67 MeV, rather than -6.50 MeV. That means an incident deuteron mainly picks up a loosely-bound neutron in ^{9}Be. The DWBA fit to the t_1 angular distribution is only qualitative, so that the estimation of the S factor from the (d, t_1) reaction is not conclusive, but the value of the S factor, 0.36, is smaller than 0.67 by Cohen and Kurath. The fact that the S factors, 0.29 and 0.36, are both smaller than the values predicted from the ^{4}He plus five-nucleon picture of ^{9}Be suggests the inadequacy of such a picture in explaining the S factor for the ^{9}Be(d, t)^{8}Be reaction.

5.2 *The $^9Be(d, \alpha)^7Li$ reaction*

The direct two-nucleon pick-up process and the heavy particle stripping process were applied to the analysis of the (d, α) reaction. As a result, it became clear that the reaction mechanism is not so simple as described by such processes. Therefore, we must examine the possibility of other reaction mechanism. The similarity of the shape of the angular distributions for (d, α_0), (d, α_1) and (d, α_2) suggests that the reaction process is similar to each other. As for the structure of ^{7}Li, it is well known[28,29] that the ground, first and second state are described as members of a $K=1/2^-$ rotational band. Namely, they have the same internal configuration. However, the fourth excited state of ^{7}Li does not belong to the ground band. Therefore, the similarity of the α_0, α_1 and α_2 distributions and the difference found for α_4 seem to reflect the structure of the residual states. The excitation functions are monotonous in the present experiment, and the excitation energy of the compound system is as large as about 27 MeV, so that many levels can contribute to this reaction, if compound process is assumed. In such a case, one can expect the $(2I+1)$ rule[31,32] holds among cross sections leading to different residual states, irrespective of the structure of the residual states. In the present case, integrated cross sections for (d, α_0), (d, α_1), (d, α_2) and (d, α_4) approximately obey the $(2I+1)$ proportionality. This fact favours the compound nucleus process. Next, the Legendre polynomial expansion of the angular distribution indicates that significant contributions to the cross section are from low-L terms. The $L=0$ and 2 terms are most important for the (d, α_0), (d, α_1) and (d, α_2) reaction. This fact also favours the compound nucleus process. According to the compound nucleus reaction theory,[33] if l and l' represent possible two angular momenta of the incident or outgoing channel, $l+l'+L$ must be even, and (l, l', L) must form a possible triangle and $L \leqq 2l_{max}$. Therefore, the $l=1$ partial wave is most important. That means the spin and parity of the compound system passed through by these reactions are $1/2^+$, $3/2^+$, $5/2^+$ and $7/2^+$ (since the ground state of ^{9}Be is $J^\pi=3/2^-$). Namely, positive parity states are predominantly excited. In the case of (d, α_4), odd terms have comparable magnitude to even terms. As odd terms stem from interference between the waves with even angular momenta and the waves with odd angular momenta, negative parity states of the compound system are also passed through by the (d, α_4) reaction.

In the incident energy range observed, compound nucleus ^{11}B has excitation energy in accord with the giant resonance, which was observed in the ^{11}B(γ, n) and ^{11}B(γ, p) reaction.[6–8] The quantum numbers of the ^{11}B states excited by the photo-reaction are $T=1/2$ and $T=3/2$, and $J^\pi=1/2^+$, $3/2^+$ and $5/2^+$, if E1 transition is assumed. In the (d, α) reaction, only the $T=1/2$ state can be excited because of the isospin conservation. Thus, the $T=1/2$ portion of the electric dipole states observed in the photo-reaction is possibly expected to correspond to the compound states passed through by (d, α_0), (d, α_1) and (d, α_2) reactions and therefore these dipole states should have large alpha decay width.

5.3 *Conclusion*

The ^{9}Be(d, t)^{8}Be reaction is considered to occur via the process of the pick-up of a loosely-bound neutron in ^{9}Be. The S factors, 0.29 for (d, t_0) and 0.36 for (d, t_1), are smaller than those predicted from the intermediate coupling shell model. The (d, α) reaction occurs possibly via the compound nucleus formation and the alpha decay from the compound nucleus.

Acknowledgements

The author wishes to thank Professor T. Yanabu, Dr. K. Fukunaga, Dr. S. Kakigi, Dr. N. Fujiwara and Mr. T. Ohsawa for their cooperation in performing this experiment, and for many valuable suggestions and discussions. He wishes to thank Professor H. Takekoshi for his support of this work. He also thanks Professor P. D. Kunz for his valuable suggestions in the use of the code DWUCK, and Dr. T. Wada for the use of the code SEARCH. Finally, he thanks the crew of the cyclotron of Kyoto University for their patient hospitality during the experiment.

Numerical calculations were carried out with a FACOM 230–75 computer at the Computer Center of Kyoto University and a FACOM 230–48 at the Institute for Chemical Research of Kyoto University.

References

1) W. Fitz, R. Jahr and R. Santo: Nuclear Phys. **A101** (1967) 449.
2) S. E. Darden, G. Murillo and S. Sen: Nuclear Phys. **A266** (1976) 29.
3) S. Cohen and D. Kurath: Nuclear Phys. **A101** (1967) 1.
4) T. Yanabu, S. Yamashita, S. Kakigi, D. C. Nguyen, K. Takimoto, Y. Yamada and K. Ogino: J. Phys. Soc. Japan **19** (1964) 1818.
5) F. Merchez, J. Arvieux, T. Honda and S. Morita: Nuclear Phys. **A183** (1972) 417.
6) Yu. I. Sorokin, V. G. Shevchenko and B. A. Yur'ev: Sov. J. Nucl. Phys. **9** (1969) 149.
7) R. J. Hughes and E. G. Muirhead: Nuclear Phys. **A215** (1973) 147.
8) U. Kneissl, K. H. Leister, H. O. Heidel and A. Weller: Nuclear Phys. **A264** (1976) 30.
9) L. Marquez, J. P. Laugier, R. Ballini, C. Lemeille, N. Saunier and J. Rey: Nuclear Phys. **A97** (1967) 321.
10) T. Ohsawa: private communication.
11) H. F. Glavish, S. S. Hanna, R. Avida, R. N. Boyd, C. C. Chang and E. Diener: Phys. Rev. Letters **28** (1972) 766.
12) Y. Uemura, K. Fukunaga, S. Kakigi, T. Yanabu. N. Fujiwara, T. Ohsawa, H. Fujita, T. Miyanaga and D. C. Nguyen: Bull. Inst. Chem. Res., Kyoto Univ. **52** (1974) 87.
13) Y. Uemura, S. Kakigi, N. Fujiwara, S. Matsuki, H. Nakamura, T. H. Kim, K. Ogino, N. Imanishi, T. Kayama and S. Kuriyama: Bull. Inst. Chem. Res., Kyoto Univ. **47** (1969) 114.
14) T. Whaling: *Handbuch der Physik* (Springer-Verlag, Berlin, Goettingen and Heidelberg, 1958) Vol. 34, p. 193.
15) C. F. Williamson, J. P. Noujot and J. Picard: Repport CEA-R 3042, Saclay.
16) T. Miyanaga, T. Ohsawa, S. Tanaka, N. Fujiwara, S. Kakigi, K. Fukunaga and T. Yanabu: Bull. Inst. Chem. Res., Kyoto Univ. **52** (1976) 1.
17) P. D. Kunz: COO–535–606 and COO–535–613 (University of Colorado, 1969).
18) S. Tanaka, K. Fukunaga, S. Kakigi, T. Ohsawa, N. Fujiwara and T. Yanabu: in preparation.
19) J. Y. Park, J. L. Duggan, P. D. Miller, M. M. Duncan and R. L. Dangle: Nuclear Phys. **A134** (1969) 277.
20) R. Klabes, F. Baldeweg, V. Bredel, H. Guratzsch, G. Stiller and S. Tesch: Nuclear Phys. **A152** (1970) 232.
21) R. Roy, J. Birchall, B. Frois, U. Von Moellendorff, C. R. Lamontagne and R. J. Slobodrian: Nuclear Phys. **A245** (1975) 87.
22) B. F. Bayman and A. Kallio: Phys. Rev. **156** (1967) 1121.
23) N. K. Glendenning: Atomic Data and Nuclear Data Tables **16** (1975) 2.
24) P. D. Kunz: private communication.
25) S. Matsuki, S. Yamashita, K. Fukunaga, D. C. Nguyen, N. Fujiwara and T. Yanabu: J. Phys. Soc. Japan **26** (1969) 1344.
26) H. G. Bingham, K. W. Kemper and N. R. Fletcher: Nuclear Phys. **A175** (1971) 374.
27) J. M. Blatt and L. C. Biedenharn: Rev. mod. Phys. **24** (1952) 249.
28) F. El-Batanoni and A. A. Kresnin: Nuclear Phys. **89** (1966) 577.
29) C. M. Chesterfield and B. M. Spicer: Nuclear Phys. **41** (1963) 675.
30) S. Cohen and D. Kurath: Nuclear Phys. **73** (1965) 1.
31) N. Macdonald: Nuclear Phys. **33** (1962) 110.
32) T. Komatsuzaki: J. Phys. Soc. Japan **39** (1975) 1152.
33) H. Feshbach: *Nuclear Spectroscopy* (Academic Press, New York and London, 1960) Part B, p. 625.