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^{3}He Breakup Reactions by Deuterons

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Differential cross sections for the $^2H(^3He, dd)^1H$ reaction at $E_{^3He}=120$ MeV and $^3He(d, dd)^1H$ at $E_d=60$ MeV have been measured. The Plane Wave Impulse Approximation (PWIA) calculations were done and compared with the experimental data. The shapes of the energy spectra and the correlation functions were qualitatively reproduced by the PWIA calculation. However the PWIA calculation overestimated the absolute cross section comparing with the experimental data. The ratio of the experimental data to the calculations becomes small rapidly with decreasing angle.

KEY WORD: Helium-3/ Breakup Reaction/ Angular Correlation/

1. INTRODUCTION

In recent years, theoretical treatments for the few body system consisting of more than four nucleons have been developed extensively.[1] So soon, the mechanism of the breakup reaction of the system will be explained by microscopic theories, but at present stage it is not established yet. Thus the tightly bound particle such as ^{4}He is approximated as one particle at a few tens MeV region, and three nucleon-like calculations can be applied to the three body breakup reaction such as $d+{}^4He \rightarrow p+n+{}^4He$[2]. It is well known that the quasifree scattering (QFS) process is an important mechanism in the breakup reaction of such particle system. However its not confirmed for the three body system consisting of the loosely bound particle such as deuteron and ^{3}He. To study the ^{3}He breakup reactions by deuterons is interesting at this point. Slaus et al. studied the $^2H(^3He, dd)^1H$ reaction and the $^3He(d, dd)^1H$ reaction at $E_{c.m.}=13.5$ MeV and 21 MeV[3] and concluded the QFS description (PWIA) did not explain the reaction mechanism. In our previous study for the ^{3}He (d, dd)^{1}H reaction at $E_{c.m.}=36$ MeV[4] whose measurements were kinematically restricted in the region including the zero energy point of the unobserved proton, the $d+{}^3He$ system could be treated as the $d+d+p$ system. And the QFS process was observed as an important mechanism and also observed that the multiple scattering

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calculation with the double scattering term improved the insufficiency of the PWIA calculation. Thus the aim of present study is to confirm these descriptions via d+^{3}He system by measuring in other kinematical conditions. Measurements were done for both the ^{3}He induced reaction and the deuteron induced reaction. Also the correlation functions of the breakup cross sections were investigated.

2. EXPERIMENTAL PROCEDURE

(1) The ^{2}H(^{3}He, dd)^{1}H reaction

The ^{3}He beam of 120 MeV from the AVF cyclotron at Research Center for Nuclear Physics (RCNP) of Osaka University bombarded a deuterium gas target. Deuterium gas was filled in a 16 cm diameter chamber with 10 μm thick Havar windows and pressured at absolutely 3 atm. For defining the target volume, a double-slit system was used. In this system, the laboratory angular spread was less than 0.4°. Counter telescopes denoted by A, B, C and D were consisted of a 200 μm or 300 μm thick Si ΔE counter and a 25.4 mm thick NaI(Tl) E or a 3 mm thick Si E counter. Counters A and B were set on one side of the beam and counters C and D were set on the other side of the beam. Two deuterons were detected coincidently by counters A and D or B and C at laboratory angles (θ_1, θ_2)=(15.0°, 66.7°), (17.5° ,65.2°), (20.0°, 63.4°), (22.5°, 61.4°), (25.0°, 59.3°), (30.0°, 54.8°), (35.0°, 50.1°), (40.0°, 45.2°), (42.5°, 42.8°) and (47.5°, 37.7°), with ϕ_1=0° and ϕ_2=180°, respec-

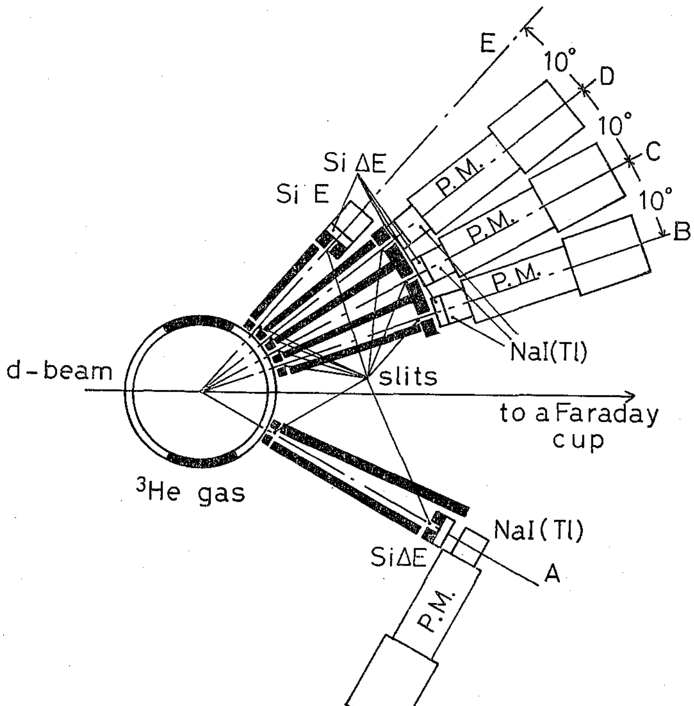

Fig. 1. The experimental set up for the $^3He(d, dd)^1H$ reaction at E_d=60 MeV.

tively. Overall energy resolution was about 1 MeV.

ΔE, E and timing signals were sent to the coincidence circuits and accumulated through the raw data processor and PDP 11/40 system on magnetic tapes. Data reductions were made by the FACOM M-180 II AD computer of the Institute for Chemical Research of Kyoto University and the MELCOM-700 computer of Kyoto University of Education.

(2) The ^{3}He(d, dd)^{1}H reaction

The deuteron beam of 60 MeV from the AVF cyclotron at RCNP bombarded a ^{3}He gas target. The experimental setup is shown in fig. 1. The gas cell was same as the one in exp. (1) and ^{3}He gas was filled at the absolute pressure of 3 atm. In the double-slit system, the laboratory angular spread was about 0.5°. Five counter telescopes denoted by A, B, C, D and E which were similar to the ones in exp. (1) were used. The thickness of the counters were 100 μm or 200 μm for a Si ΔE counter, 25.4 mm for a NaI(Tl) E and 5 mm for a Si E counter, respectively. The counter A was set on one side of the beam and counters B, C, D and E were set on the other side of the beam. Two deuterons were detected coincidently by counters A and B, A and C, A and D or A and E at angular region of $25° \leqq \theta_1 \leqq 48.5°$ and $22.5° \leqq \theta_2 \leqq 58.5°$ with $\phi_1 = 0°$ and $\phi_2 = 180°$. Overall energy resolution was about 1 MeV.

The data acquisition and reduction system was same in exp. (1).

3. RESULTS AND DISCUSSIONS

(1) The ^{2}H(^{3}He, dd)^{1}H reaction

Coincidence energy spectra of deuterons for the ^{2}H(^{3}He, dd)^{1}H reaction were obtained. A typical map at angles ($\theta_1 = 35.0°$, $\theta_2 = 50.1°$) was shown in fig. 2. Concentration of yields was seen in the figure. Measured angular set kinematically corresponds to the projectile breakup QFS region including the zero energy point of the unobserved proton in the beam system. As the projectile mass is larger than the target mass, a three body breakup locus is kinematically restricted into a very small region on a correlation map. In this kinematical condition, small angular deviations change the locus drastically. Because the finite angular resolution in the experiment, coincidence yields spread into the localized area. At other angular sets similar correlation maps were obtained. Experimental cross sections were summed over the area and listed in table 1.

The PWIA calculations were done. The formula for the projectile breakup reaction are described as follows,

$$\frac{d\sigma}{d\Omega_1 d\Omega_2 dE_1} = \frac{k_i (E_{cm})^2 E_3 E_p k_1 k_2^2 |\Phi|^2}{k_f p E_t E_T (k_2 E_3 + E_2 (k_2 - p\cos\theta_2 + k_1 \cos\theta_{12}))} \left(\frac{d\sigma}{d\Omega}\right)^{dd}_{cm},$$

where the momenta of the projectile, the scattered deuteron 1 and 2 in the laboratory system are $\boldsymbol{p}$, $\boldsymbol{k}_1$ and $\boldsymbol{k}_2$. E_i shows a total energy of a particle i. E_t means the energy of the transferred particle from the projectile. $\boldsymbol{k}_i$ and $\boldsymbol{k}_f$ are the relative memomenta of the projectile and the transferred particle in the two body initial state, and

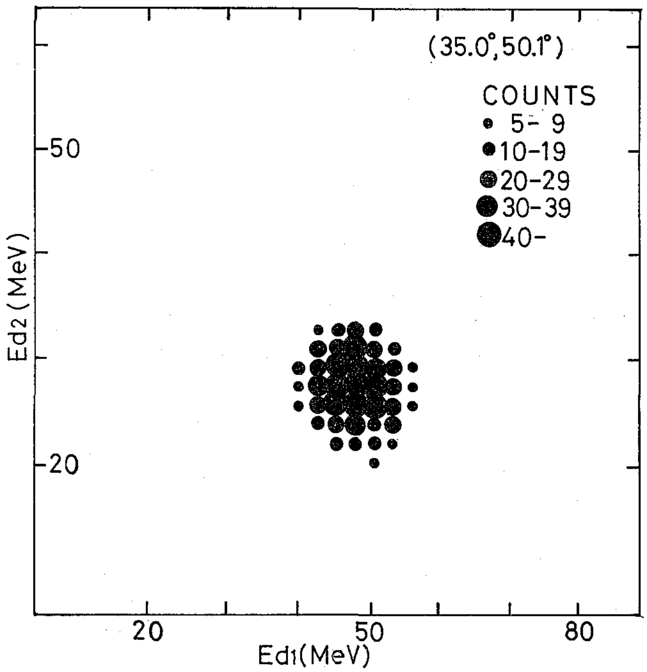

Fig. 2. The correlation map for the $^2H(^3He, dd)^1H$ reaction at $E_{^3He}=120$ MeV at angles (35.0°, 50.1°).

Table I. Summed cross sections in the $^2H(^3He, dd)^1H$ reaction

(θ_1, θ_2)	$d\sigma$ (exp.) (mb/sr^2)	$d\sigma$ (PWIA) (mb/sr^2)	N
(15.0°, 66.7°)	44.82±1.82	2440	0.018
(17.5°, 65.2°)	41.30±1.87	1548	0.027
(20.0°, 63.4°)	58.87±2.28	934.5	0.063
(22.5°, 61.4°)	49.65±1.90	626.7	0.079
(25.0°, 59.3°)	47.89±1.63	428.0	0.11
(25.0°, 59.3°)*	45.09±1.64	402.6	0.11
(30.0°, 54.8°)	52.81±1.64	443.4	0.12
(30.0°, 54.8°)*	50.57±1.77	408.6	0.12
(35.0°, 50.1°)*	80.32±2.19	432.7	0.19
(40.0°, 45.2°)*	101.93±2.53	573.4	0.18
(42.5°, 42.8°)*	108.64±2.57	470.7	0.23
(47.5°, 37.7°)*	97.56±2.43	463.5	0.21

No mark shows the experiment in the B-C system and * shows the one in the A-D system.

deuteron 1 and 2 in the final state, respectively. The used dd elastic scattering cross section data are shown in other paper[4]. $|\Phi|^2$ is the momentum distribution of deuteron in ^{3}He[3]. For each experimental angular set, the calculations were done for all of the possible kinematical loci considering the angular acceptance of each counter and summed. Moreover the reduced cross sections were summed over the locus. The ratios N of the summed cross section by the experiment to the one by the

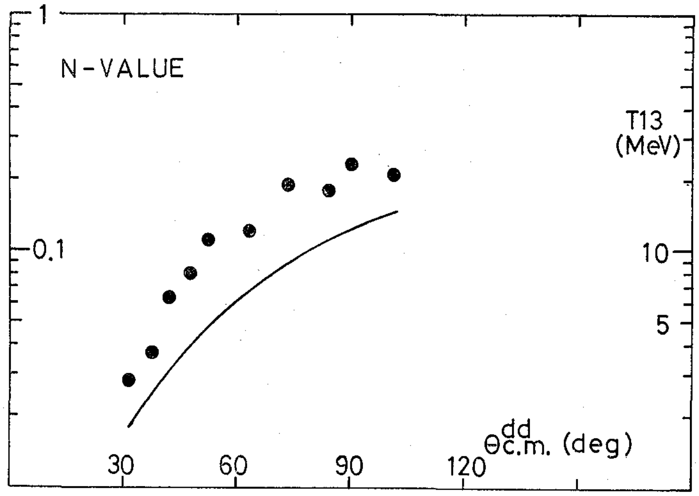

Fig. 3. The angular dependence of the ratio N of the experimental cross section to the calculated cross section by PWIA. The solid curve shows the relative energy between one of the scattered deuterons and the unobserved proton (T_{13}).

calculation were also listed in table 1. The ratios N were plotted versus the deuteron angle in the two deuterons center of mass system in fig. 3. The solid curve in the figure shows the relative energy between one of the scattered deuterons and the unobserved proton (T_{13}). As seen in the figure, the ratio N becomes small rapidly when the angle decreases and correspondingly T_{13} becomes small. Similar results were seen in other few body breakup reactions such as ^{2}H(p, p′)[5], ^{3}He(p, p′)[5], ^{4}He(p, p′)[5], ^{2}H(d, dp)n[6], ^{3}He(d, dd)^{1}H[4] and ^{2}H(^{4}He, ^{4}Hep)n[7]. If the PWIA was a good description, N should be constantly 1. Thus the existence of such angular dependence of N suggests that the unobserved proton cannot behave as a spectator in this reaction mechanism even in the kinematical QFS region. According to the multiple scattering calculation[4] for the ^{3}He(d, dd)^{1}H reaction, the dp interaction succeeds to the first dd interaction and this effect reduces the cross section. When the relative energy T_{13} becomes small, the dp interaction becomes effective. Thus the ratio of the experimental cross section to the PWIA one which includes only the first interaction decreases in the small angular region where T_{13} becomes small. This feature explains the present experimental results well. The maximum value of the ratio N is about 0.25. This value is very small. In the present experiment, the total energy in the center of mass system ($E_{c.m.}$) corresponds to 48 MeV. In the previous data for the ^{3}He(d, dd)^{1}H and ^{2}H(^{3}He, dd)^{1}H reactions corresponding to $E_{c.m.}=13.4$ MeV, 21 MeV and 36 MeV, the maximum values of the ratio N are about 0.1, 0.14 and 0.3, respectively. So the energy dependence of N is not so clear compared with the three nucleon system.

(2) The ^{3}He(d, dd)^{1}H reaction

Coincidence energy spectra of deuterons for the ^{3}He(d, dd)^{1}H reaction were obtained. Yields were seen along the three body kinematical line. Data are pro-

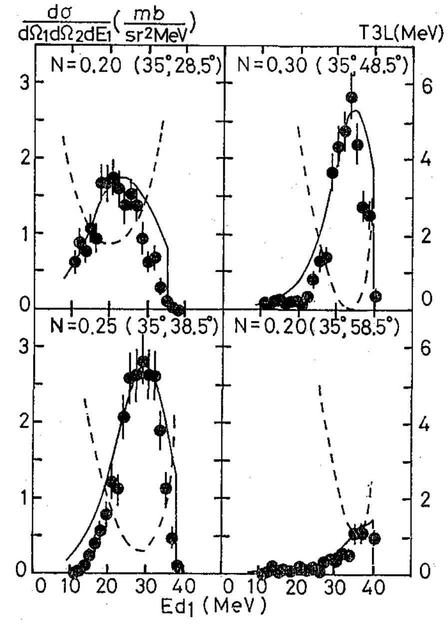

Fig. 4. Projected deuteron energy spectra for the $^3He(d, dd)^1H$ reaction at $E_d=60$ MeV. Measured angular sets are written in each figure, with $\phi_1=0°$ and $\phi_2=180°$, respectively. Dashed curves show the laboratory energy of the unobserved proton (T_{3L}). Solid curves show the PWIA calculations multiplied by N written in the figure.

jected on the one of the deuteron energy axis. Examples of the projected spectra are shown in fig. 4. Experimental angular sets are written in the figure. The dashed curves in the figure show the laboratory energy of the unobserved proton T_{3L}. Broad bumps whose peak positions correspond to the minima of T_{3L} are seen in all figures. They correspond to the QFS bumps. The PWIA calculations were done and compared with the data. Solid curves in the figure show the results of the PWIA calculations which are multiplied by N. The shapes of the bumps are qualitatively reproduced by this calculation. However for the width of the bump, the one by the calculation is wider than the experimental one. The PWIA calculation overestimated the absolute cross section comparing with the experimental data. The ratios N of the experimental data to the calculations are written in the figure. Peak cross sections of the bumps are plotted versus the deuteron angle θ_2 for each fixed angle θ_1 in the fig. 5. We call these as correlation functions. As seen in the figure, correlation functions have bumps. The dashed curve corresponds to the energy T_{3L}. Grossly the maximum position of the bump is near the minimum energy position of T_{3L}. However, in detail we see, at the region of $\theta_1 \leqq 30°$, bump peaks deviate toward the smaller angle of θ_2. At θ_1 is near 45°, bump peaks become consistent with the minimum point of θ_2. Solid curves in the figure show the results of the PWIA calculations multiplied by 0.25. The PWIA calculation reproduces the bump shape qualitatively except at $\theta_1 \leqq 30°$. Then it is suggested that near the kinematical QFS region, the PWIA calculation reproduces the experimental results and at the

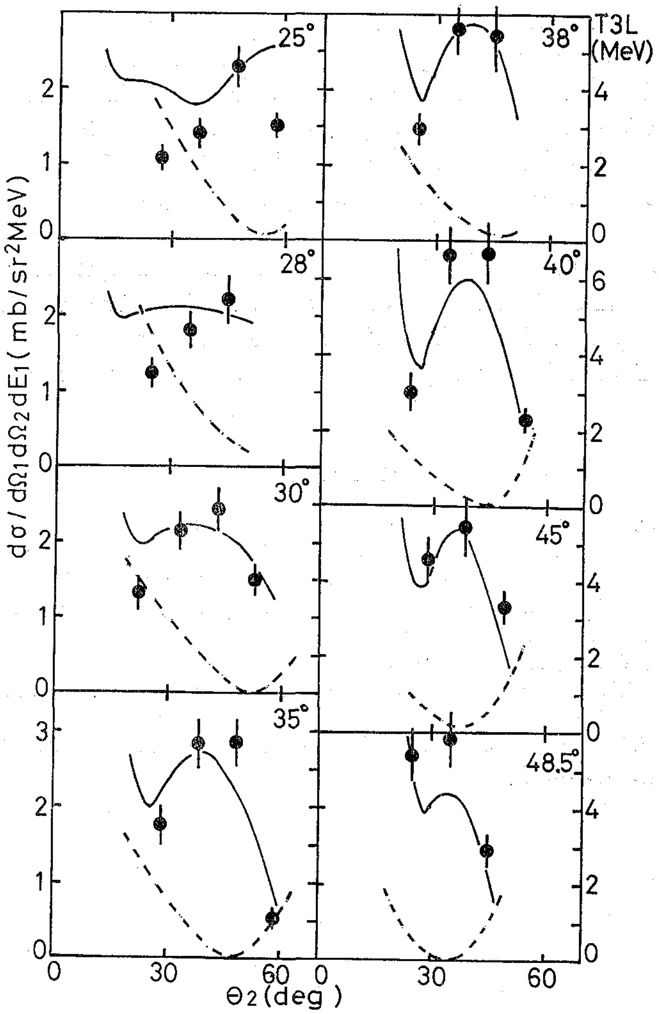

Fig. 5. Correlation functions of the differential cross sections for the $^3He\,(d,\,dd)^1H$ reaction. Experimental angles θ_1 are written in each figure and θ_2 are presented by abscissas. Dashed curves show the laboratory energies of the unobserved protons (T_{3L}). Solid curves show the PWIA calculations multiplied by 0.25.

region deviated from the kinematical QFS region, It fails to do.

4. SUMMARY

The QFS process is an important mechanism in the ^{3}He breakup reactions by deuterons. The QFS bumps whose peak positions correspond to the minimum energy points of the unobserved protons were seen in all deuteron energy spectra. The PWIA calculation reproduces the shapes of the energy spectra and the correlation functions near the kinematical QFS region qualitatively. However as for the absolute cross section and the angular dependence, experimental results cannot be reproduced by such a simple mechanism even in the kinematical QFS region. The relation between the angular dependence of the ratio N and the relative energy T_{13} suggests the interaction of the unobserved proton with one of the scattered deuterons becomes effective and the proton cannot behave as a spectator in this reaction mechanism. Multiple scattering correction including the double scattering term will improve the absolute cross section and the angular dependence. According to this, three body model seems to be successful despite the loosely bound constituents in the kinematical QFS region.

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