Two-body final states in the $d + d$ interaction in the 50–85 MeV incident energy range

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Angular distributions of the ^{2}H(d,d)^{2}H, ^{2}H(d,p)^{3}H, and ^{2}H(d,n)^{3}He reactions at six incident energies in the 50-85 MeV range have been measured. The ^{2}H(d,p)^{3}H reaction data have been analyzed in terms of the plane-wave Born-approximation theory. A smooth cutoff in the partial wave expansion of the reaction matrix has been introduced to allow the suppression of the low angular momentum components. The calculated angular distributions obtained with a constant cutoff angular momentum $l_{co} = 3$ show reasonably good agreement with the experimental data in the whole 50-85 MeV energy range. This is consistent with the peripheral character of the reaction.

[NUCLEAR REACTIONS ^{2}H(d,d), ^{2}H(d,p), ^{2}H(d,n), E=50–85 MeV; measured $d\sigma/d\Omega$; analysis in terms of PWBA with a smooth l cutoff; deduced cutoff angular momenta.]

I. INTRODUCTION

The $d+d$ system provides the simplest case to study the interaction between composite particles. In addition it is an obvious manifestation of the four-body problem in nuclear physics. Recent theoretical developments made by Sawicki[1] and Perne and Sandhas[2] toward the exact treatment of the four-body problem seem to be encouraging. At present, however, such calculations cannot explain the data in all the details. For instance, the calculations of Ref. 2 can reproduce the first maximum of the $d+d\rightarrow p+t$ experimental angular distributions; however, they fail completely to describe the second one. In view of this it may be interesting to pick out certain aspects of the problem which are accessible to a more phenomenological approach by comparing experimental data with predictions of simpler models. Such a treatment of the $d+d$ system has been carried out in a previous paper[3] where the modified simple impulse approximation (MSIA) model[4] was applied to the ^{2}H(d, dp)n reaction measured under the kinematical conditions favoring the quasifree $d-p$ scattering. The MSIA model is characterized by the introduction of a radial cutoff in the wave function of the target deuteron; the interior of the wave function which is presumed not to contribute to single-step processes is thus eliminated. The model gave good fits to the experimental data over a large range of incident energies and the values of the cutoff radius varied consistently with the incident energy. In the framework of the above model, these features indicate the peripheral character of the quasifree process.

In view of the results obtained for the above *three-body* final state, one could naturally ask whether similar features also show up in the *two-body* final state. In the present work we have investigated the two-body final states of the $d+d$ interaction by measuring the angular distribution of the outgoing charged particles at incident energies between 50 and 85 MeV.

For the present ^{2}H(d, p)^{3}H angular distributions a comparison has been made with the results of model calculations in which the reaction is described in the framework of the plane-wave Born approximation (PWBA) theory. The same reaction has been studied at incident energies in the E_d = 8–28 MeV range by several authors[5-9] who introduced different simplifications in their PWBA approach. In this paper the PWBA theory has been modified by the introduction of a cutoff in the relative orbital angular momentum in the exit channel.

II. EXPERIMENT

The measurements were performed with the unanalyzed deuteron beam of the Jülich variable energy isochronous cyclotron (JULIC). The energy resolution and the relative uncertainty in the energy calibration were both about 0.3%. The beam spot was 2–3 mm in diameter in the center of the 200 mm diameter scattering chamber, which had

19 μm thick mylar windows. The target deuterium was contained at $p \simeq 235$ Torr and $T \simeq 30$°C in a 60 mm diameter gas cell with 2.2 μm thick Havar windows. No special measures were taken to stabilize p and T, but their values were read periodically and found to be constant within 4% and 0.3%, respectively, during the 55 h of the experiment. The purity of the $(^2\mathrm{H})_2$ gas was 99.5%.

The charged ejectiles were detected by means of two ΔE-E telescopes placed outside the scattering chamber. The ΔE counters were commercial Si surface barrier detectors, 100–400 μm thick. The E counters were 25 mm long side-entry Ge (Li) detectors developed at this laboratory.[10] The particle identification was achieved using ORTEC 423 particle identifiers. The p, d, t, and ^{3}He spectra were collected simultaneously via eight analog-to-digital converters (ADC's) of an analyzing system operating in the 8×1000 multiplex mode. The logic particle identification signals as well as the corresponding busy signal from the ADC's were counted by scalers for control and evaluation of dead time. A Ge(Li) monitor detector was placed at a fixed angle of $\theta_{\mathrm{lab}} = -30°$.

The two telescopes were mounted on a turntable, ten degrees apart. Each telescope had two diaphragms of 7 mm thick tantalum with cylindrical holes. The rear diaphragm (diam = 2 mm) was placed directly in front of the ΔE detector. The front diaphragm (diam = 4 mm) was situated 100 mm from the rear one. The rear diaphragm-to-target distance was 277 mm for the telescope placed at the lower angle and was 217 mm for the other. The geometrical "G factors"[11] for the yield-to-cross section conversion have been calculated from the formulas given by Silverstein,[11] which were derived neglecting (i) diaphragm thickness and (ii) beam diameter. Both effects could be estimated in our case to be <1% and were neglected.

At the present high ejectile energies the reduction of the detector efficiency due to nuclear reactions in the detector material must be considered. For protons, the reaction loss data from Ref. 12 were used, while those for d, t, and ^{3}He were calculated on the basis of total reaction cross sections σ_R taken from a geometrical cross section parametrization of the experimental σ_R data compiled in Ref. 13. The deuteron correction factors are in good agreement with the results of Ref. 14. The corrections are <7% for p and d, $\leq 5\%$ for t, and $\leq 1\%$ for ^{3}He. Their relative errors are estimated to be 10% for the p data[12] and 20% for the present d, t, and ^{3}He data.

The angular distributions have been measured at incident energies $E_d = 50.0$, 51.5, 60.0, 70.0, 77.5, and 85.0 MeV. They were taken from $\theta_{\mathrm{lab}} = 12.5°$ in 2.5° steps up to $\theta_{\mathrm{lab}} \simeq 45°$. At some angles data were taken by both telescopes for consistency checks. The beam currents were chosen in the 10–500 nA range such as to keep the dead time below 3%.

III. THEORETICAL ANALYSIS

The measured $^2\mathrm{H}(d,p)^3\mathrm{H}$ angular distributions have been analyzed in terms of the PWBA theory. Formalism, wave functions, and perturbing potentials are similar to those given in Ref. 15 for $p+{}^4\mathrm{He}$ reactions. However, instead of introducing a radial cutoff in the radial integrals,[15] the present analysis makes use of an angular momentum expansion of these integrals followed by the introduction of an l cutoff.[16] For clarity the main steps of the theoretical treatment will be presented.

A. Formalism

The differential cross section for the reaction $\alpha \to \beta$ can be written as

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{c.m.}} = \frac{1}{(4\pi)^2}\,\frac{2\mu_\alpha}{\hbar^2}\,\frac{2\mu_\beta}{\hbar^2}\,\frac{k_\beta}{k_\alpha}\,|M|^2\,, \tag{1}$$

with

$$|M|^2 = \sum_i \sum_f |M_{fi}|^2\,. \tag{2}$$

The symbols $\sum_i$ and $\sum_f$ represent averaging over the initial (i) and summing over the final (f) spin states, respectively. The reduced mass, the wave number of the relative motion and the reaction matrix elements are denoted by $\mu, k,$ and M, respectively.

Using the plane-wave Born approximation, the post form of the reaction matrix elements for the $^2\mathrm{H}(d,p)^3\mathrm{H}$ reaction can be written as (cf. Ref. 15)

$$M_{fi}^{\mathrm{post}} = \langle [(1/\sqrt{2})(1-P_{13})\psi_f(1,234)|V_{12}+V_{13}+V_{14}]| \times [\tfrac{1}{2}(1-P_{24})(1-P_{13})\psi_i(12,34)]\rangle\,. \tag{3}$$

The interaction potential between the particles i and j is given by V_{ij} and their exchange operator by P_{ij}. The wave functions $\psi_i(12,34)$ and $\psi_f(1,234)$ describe the initial $d+d$ and the final $p+t$ system, respectively. The two protons are labeled 1 and 3, the two neutrons 2 and 4. The intrinsic ^{3}H wave function contained in $\psi_f(1,234)$ is already antisymmetrized in the two neutrons, but the wave functions still await the complete antisymmetrization by the P_{ij} operators which reduces Eq. (3) to

$$M_{fi}^{\mathrm{post}} = \sqrt{2}\,[\langle\psi_f(1,234)|V_{12}+V_{13}+V_{14}|\psi_i(12,34)\rangle - \langle\psi_f(1,234)|V_{12}+V_{13}+V_{14}|\psi_i(32,14)\rangle]\,, \tag{4}$$

where the two terms are physically interpreted as a direct and an exchange process, respectively. The use of the Serber-type N-N force (see Sec. III B) implies conservation of the channel spin S and therefore reduces $|M|^2$ to an incoherent sum over the contributions for the different S values. In the $^2H(d,p)^3H$ case exclusion of $S=2$ in the $p+{}^3H$ exit channel reduces Eq. (2) to

$$|M|^2=\tfrac{1}{4}|M_{fi}(S=0)|^2+\tfrac{3}{4}|M_{fi}(S=1)|^2 . \tag{5}$$

Since target and projectile are identical bosons $\psi_i(12,34)$ must be symmetric in the $12 \leftrightarrow 34$ exchange. This implies that each term of the symmetrized ψ_i is a product of an $S=1$ ($S=0$) spin function, which is odd (even) in $12 \leftrightarrow 34$, and a space function which is also odd (even) in $12 \leftrightarrow 34$, which means $\theta \leftrightarrow (\pi-\theta)$ in terms of the c.m. angle θ. Substitution of the symmetric ψ_i in Eq. (4) gives

$$M_{fi}(\theta,S)=M_{fi}^{\text{post}}(\theta,S)\pm M_{fi}^{\text{post}}(\pi-\theta,S),$$

$$+\text{for } S=0,\ -\text{for } S=1 . \tag{6}$$

From Eq. (6) it follows that the contributions for $S=0$ and $S=1$ come exclusively from even and odd partial waves, respectively.

B. Physical input

The calculation of the matrix elements $M_{fi}^{\text{post}}(\theta,S)$ is based on the choice of

(i) an N-N perturbing interaction of the Serber type with a Yukawa form factor $U_{ij}(r)$, and

(ii) the spatial parts of the intrinsic wave functions of ^2H and ^3H. The first is a pure S-state Hulthén function, the latter has the form $\exp(-\gamma\sum_{ij}r_{ij}^2)$.

The same choice of interaction and wave functions, both in type and in parameter values, can be found in Refs. 15, 17, except for the value of γ. In the present calculations this is taken to be $\gamma=0.1320$ fm^{-2}, instead of $\gamma=0.1572$ fm^{-2}. The new value was found to give a better fit to the experimental triton charge form factor.[18,19] The matrix elements $M_{fi}^{\text{post}}(S)$ can be written[15,17] as

$$M_{fi}^{\text{post}}(0)=\sum_{m=1}^{4}\gamma_m I_m ,$$
$$M_{fi}^{\text{post}}(1)=\sum_{m=1}^{4}\alpha_m I_m , \tag{7}$$

where[15,17]

$$I_1=\langle 1,234|U_{12}|12,34\rangle ,$$
$$I_2=\langle 1,234|U_{13}|12,34\rangle ,$$
$$I_3=\langle 1,234|U_{13}|32,14\rangle , \tag{8}$$
$$I_4=\langle 1,234|U_{14}|32,14\rangle .$$

The coefficients γ_m and α_m represent the spin and isospin parts of the matrix elements.

From the identity of target and projectile, the following relations hold:

$$I_1(\theta)=I_4(\pi-\theta) ,$$
$$I_2(\theta)=I_3(\pi-\theta) . \tag{9}$$

So the calculation of $d\sigma/d\Omega$ is now reduced to the determination of the overlap integrals I_1 and I_2.

C. Evaluation of overlap integrals

Introducing the coordinate transformation

$$\vec{R}=\tfrac{1}{4}(\vec{r}_1+\vec{r}_2+\vec{r}_3+\vec{r}_4) ,\ \vec{r}=\vec{r}_1-\tfrac{1}{3}(\vec{r}_2+\vec{r}_3+\vec{r}_4) ,$$
$$\vec{\rho}=\tfrac{1}{2}[(\vec{r}_3+\vec{r}_4)-(\vec{r}_1+\vec{r}_2)] ,\ \vec{\xi}=\vec{r}_3-\vec{r}_4 , \tag{10}$$

the overlap integral I_1, for instance, becomes

$$I_1=\left(\frac{3}{2}\right)^3\int\int\int d\vec{\rho}\,d\vec{r}\,d\vec{\xi}\,e^{-i\vec{k}_f\cdot\vec{r}}$$
$$\times\phi_t(\vec{r}_{23},\vec{r}_{34},\vec{r}_{24})U(\vec{r}_{12})\phi_d(\vec{r}_{12})$$
$$\times\phi_d(\vec{r}_{34})e^{i\vec{k}_i\cdot\vec{\rho}} , \tag{11}$$

with $r_{ij}\equiv|\vec{r}_i-\vec{r}_j|$. Functions in r_{ij} can be expressed in the new coordinates. To facilitate the evaluation of Eq. (11), $\phi_d(r_{12})$ and $U(r_{12})$ are approximated by linear combinations of three Gaussians, which are identical to those used in Ref. 15. The resulting expression can be calculated

(i) directly by analytical integration,

(ii) with a radial cutoff[15] in the entrance[15] and/or in the exit channel,

(iii) with a cutoff in its angular momentum expansion; again this cutoff procedure can be applied in the entrance and/or in the exit channel.

Under the assumption of the Serber-type forces, the orbital angular momenta $\vec{l}_{mn}$ of the transfer reaction

$$(b+x)+A\to b+(A+x) ,\quad (b+x)=a,\ (A+x)=B$$

satisfy the relation

$$\vec{l}_{aA}-\vec{l}_{bB}=\vec{l}_{xA}-\vec{l}_{bx} . \tag{12}$$

Application of Eq. (12) to the present description of the $d+d\to p+t$ reaction where pure s states are assumed for the deuteron and triton wave functions leads to

$$\vec{l}_{dd}=\vec{l}_{pt} . \tag{13}$$

From Eq. (13) it is obvious that cutting out certain partial waves in one channel automatically removes the corresponding ones from the other. This implies equivalence of the three l-cutoff procedures mentioned in (iii). It is worth noting that this property is an advantage of the l-cutoff over the radial cutoff where such an equivalence does not exist.

In view of the above remarks, the overlap integrals have been evaluated using an angular momentum expansion. This enables the study of contributions of different partial waves. Furthermore the introduction of a lower l-cutoff[16] can be used to simulate effects neglected in the PWBA theory. At this stage $M_{fi}^{\text{post}}(\theta, S)$ can generally be written as

$$M_{fi}^{\text{post}}(\theta,S)=\sum_{l} f(l)M_{fi}^{\text{post}}(\theta,S,l)\,, \tag{14}$$

where $f(l)$ represents the cutoff function. In this work a "smooth" cutoff has been used, where

$$f(l)=1-\{1+\exp[(l-l_\infty)/\Delta]\}^{-1}\,. \tag{15}$$

IV. RESULTS

The experimental data are shown in Figs. 1, 2, where the error bars indicate statistical errors only. The absolute error, mainly due to the uncertainty in the G factor and in the estimate of efficiency loss due to nuclear reactions in the Ge(Li) detector, was estimated to be 5% for all cross section. From the experimental set up the precision of θ_{lab} was estimated as $\Delta\theta_{\text{lab}}=\pm0.2°$, in agreement with some checks based on the strong θ_{lab} dependence of ejectile energies in elastic scattering of deuterons on deuterons (gas target) and on protons $[(CH_2)_n$ foil$]$.

From the kinematical broadening of the peaks in the particle spectra an effective angular opening of about 1.9° was deduced; its effect on the measured angular distributions was shown to be negligible.

A list of the cross section data is available upon request.

A. Elastic channel

The experimental data for the elastic cross sections are shown in Fig. 1, together with the results from a previous measurement[20] at 51.5 MeV for comparison. The latter agree well with the present data. There are only two other measurements[21,22] known in the 50–85 MeV range. The data of Ref. 21 were taken at 80.9 MeV. The three angular distributions of Ref. 22 were measured in the 25–70 MeV range with a beam energy spread of more than 10 MeV.

The curve presented with the data at 60 MeV is from the calculation of Queen,[23] where the deuteron-deuteron interaction is taken as the scattering of the incident deuteron on the two target nucleons.

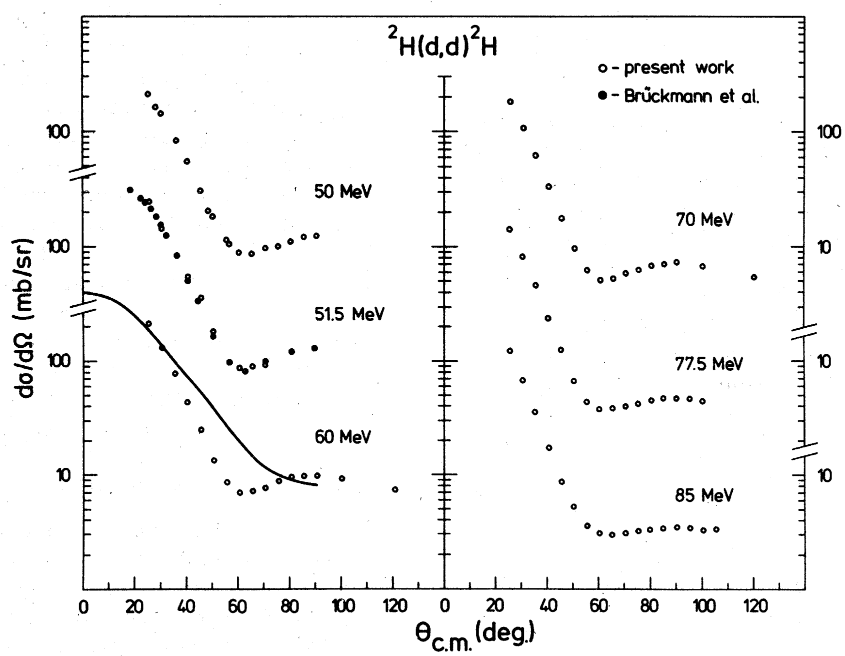

FIG. 1. Angular distributions for the ^{2}H$(d,d)^2$H elastic scattering at six incident energies. The present incomplete distribution at $E_{\text{inc}}=51.5$ MeV has been taken only to provide a comparison with the numerical results from measurements by Brückmann *et al.* (Ref. 20). The error bars are given only when they are significantly larger than the data points. The solid curve is taken from the theory of Queen (Ref. 13) calculated at 64 MeV.

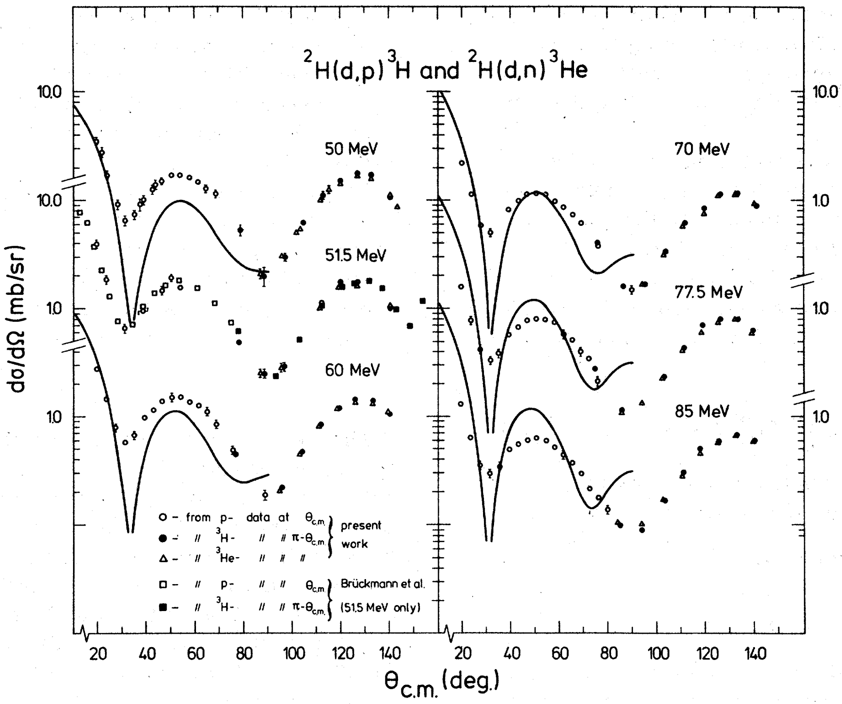

FIG. 2. Angular distributions for the ^{2}H$(d,p)^3$H and ^{2}H$(d,n)^3$He reactions at six incident energies. The open and solid squares at 51.5 MeV represent the measurement of Ref. 20. The solid curves are the PWBA predictions as described in the text.

Although absolute agreement is achieved in the forward region, the model fails to reproduce the minimum at $\theta_{\text{c.m.}} \simeq 50°$.

B. Reaction channel

The experimental angular distributions obtained for the ^{2}H$(d,p)^3$H and the ^{2}H$(d,n)^3$He reactions are shown in Fig. 2. At 51.5 MeV the results of Ref. 20 are in agreement with ours within the error bars. The results of Roy *et al.*[24] measured at 83 MeV are also in agreement within about 10% with the present 85 MeV data. In the whole energy range measured, the ratio of the ^{2}H$(d,p)^3$H to the ^{2}H$(d,n)^3$He cross sections at corresponding c.m. angles is consistent with unity, i.e., with charge symmetry of the nuclear force. The present angular distributions have their minima at practically the same angle $\theta_{\text{c.m.}} = 31.0° \pm 1.0°$, independent of incident energy. This value is rather close to $\theta_{\text{c.m.}}^{\text{min}} = 36.0° \pm 1.0°$ observed by Van Oers and Brockman[9] at 25 MeV.

The PWBA theory with a smooth l cutoff as described in Sec. III has been applied to the ^{2}H$(d,p)^3$H data. The calculated angular distributions obtained with the values $l_\infty = 3$ and $\Delta = 0.1$ constant for the whole 50–85 MeV incident energy range show reasonably good agreement with the experimental data both in magnitude and in shape (see Fig. 2). This finding supports the conclusion obtained earlier by Van Oers and Brockman[9] in an analysis of the ^{2}H$(d,p)^3$H data at 25 MeV. The position of the first minimum is well reproduced by the present calculations. The main disagreement between the experimental and theoretical shapes is observed at $\theta_{\text{c.m.}} \simeq 90°$. The enhancement of the theoretical cross section in this angular region is due to the contribution of even l components which all have a maximum at $\theta_{\text{c.m.}} = 90°$. In the present case the largest of them is that due to $l = 4$. Theoretical cross sections calculated without l cutoff are about two orders of magnitude larger than the experimental values and decrease monotonically with angle, at variance with experiment. Contributions from l values larger than $l = 7$ could be neglected.

V. DISCUSSION

Charged particle angular distributions from all two-body final states in the $d+d$ interaction have been measured at six incident energies in the 50–85 MeV range. The data for the ^{2}H$(d,p)^3$H reaction have been analyzed in terms of a modified plane-wave Born approximation.[16] The analysis shows that, in the framework of this model, the contributions from low partial waves have to be suppressed to account for the experimental data. This was accomplished by an orbital angular momentum expansion of the PWBA amplitude and introducing a cutoff in the low l values. Comparison with the data shows that calculations with $l_{co}=3$ give satisfactory fits in the whole 50–85 MeV incident energy range. A similar model has been proposed by Borbelyi[25] and was successfully applied to several transfer reactions on light nuclei.

Previous ^{2}H$(d, dp)n$ quasifree data[3] were analyzed using the modified simple impulse approximation where a radial cutoff R_{co} was applied to the target deuteron wave function. Here the incident deuteron was treated as a point particle. It may be interesting to connect these R_{co} values to the present l values by introducing a relation $l_{co}=0.5kR_{co}$, where k stands for the wave number in the relative motion. The factor 0.5 stems from the fact that in the expression $l=kR$, R is the distance between the centers of mass of the two deuterons, while R_{co} is related to the internucleon distance in the target deuteron. The R_{co} values of Ref. 3 correspond to l_{co} values between $l_{co}\simeq 3$ ($E_d=50$ MeV) and $l_{co}\simeq 2$ ($E_d=85$ MeV). So the MSIA analysis indicates that the contributions of lower l values ($l \leq 2$) are negligible in the ^{2}H$(d, dp)n$ process.

It is worth noting that in the analysis of the ^{3}He$(p, d)pp$ reaction[16] with the PWBA model including l decomposition, the value $l_{co}=3$ was also needed to fit the shape of the final-state interaction peak and its angular distribution. In addition, Faddeev calculations by Haftel *et al.*[26] on the ^{2}H$(p, pp)n$ reaction showed that the contribution of low angular momenta is small in the quasifree region of the phase space. The same conclusion has also been drawn by Haftel *et al.*[27] in their application of a similar three-body model to the reactions ^{6}Li(^{3}He, ^{3}He t)^{3}He and ^{6}Li(^{3}He, ^{3}He^{3}He)^{3}H.

The necessity to cut off the low orbital angular momenta as has been found for the reaction studied in this work and in those mentioned above[3,16] implies that the contribution to these reactions mainly stems from the outer region where the intrinsic wave functions of target and projectile have a relatively small overlap (off-central collision). At this peripheral condition, however, one expects a lower probability for more than two nucleons to be near to each other so as to interact at short range and possibly to manifest off-shell effects. Therefore the region of the phase space where two-body or quasi two-body processes dominate does not seem appropriate for the study of short-range interactions and/or off-shell effects.

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