Investigation of Adiabatic Approximation of Deuteron-Breakup Effect on $(d, p)$ Reactions

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The defect of adiabatic approximation for $(d, p)$ reactions is investigated in the $d+^{58}\text{Ni}$ system at $E_d=80\text{ MeV}$. It is shown that the breakup wave functions play an important role in the $T$-matrix elements of $(d, p)$ reactions and the approximation gives an insufficient description of these wave functions.

The deuteron-breakup process is known to give a large effect on deuteron induced reactions. The adiabatic (AD) approximation has been used to take account of this effect. It can reproduce elastic and inelastic scattering data especially at high incident energies such as $E_d=80\text{ MeV}$. Most of experimental data on pickup and stripping reactions are better reproduced by this model than by conventional DWBA.

On the other hand, theoretical examinations of the AD approximation have been done by comparing calculations based on the AD approximation with non-adiabatic (NA) calculations in which an exact three-body Hamiltonian is solved by the coupled-discretized-continuum-channels (CDCC) method. These examinations have mainly been done at lower incident energies $E_d \approx 20\text{ MeV}$; it can be said that the AD approximation is good for elastic scattering but poor for $(d, p)$ reactions. No examination, however, has been done in a higher incident energy region where the AD approximation is believed to become good.

In the present paper, we examine the case of the $d+^{58}\text{Ni}$ system at $E_d=80\text{ MeV}$ and show that the defect of the AD approximation for $(d, p)$ reactions is due to the fact that the approximation is poor for the deuteron-breakup-channel wave functions although rather good for the elastic-channel wave function.

For this purpose, the method of Ref. 13) is used in which the model space is spanned by the deuteron-ground state $(d_0)$ and the deuteron-breakup state $(d^*)$ with the momentum $k \approx k_{\text{max}}$ and the angular momentum $l \approx l_{\text{max}}$ and the $k$-continuum is discretized into $k$-bins with an equal width $\Delta k$. The values

$$k_{\text{max}}=1.0\text{ fm}^{-1}, \quad l=0, 2 \quad \text{and} \quad \Delta k=1/8\text{ fm}^{-1}$$

are used which have been shown to be adequate for the convergence of the $S$-matrix calculated within the model. The model spaces in Refs. 2) and 8)–11) seem to be inadequate with respect to Eqs. (1).

We adopt coupled channel Born approximation (CCBA) in which the coupling between the deuteron channels $(d_0$ and $d^*)$ is treated in the CDCC framework and the coupling of the proton channel $(p)$ in first order perturbation theory. In this approximation, $T$-matrix elements of $(d, p)$ reactions are given by

$$T_{pd} = \langle \chi_{d} \varphi_d | V_{pd} | \Psi_{d} \rangle$$

and
where the p-n relative and center-of-mass coordinates are denoted by $p$ and $R$, $\chi_0$ is the distorted wave of the outgoing proton in a phenomenological potential $V_{pn}$ and $V_{pn}$ is the p-n interaction. The wave function of a transferred neutron $\phi_n$ is given by the usual depth-adjusted-separation-energy method. The functions $\phi_0$ and the $\phi_i$ ($i = 1 \sim N$) represent the deuteron ground state and the discretized p-n breakup states, respectively. The corresponding p-n center-of-mass wave functions are denoted by $\chi_0^{P}$ and $\chi_i^{P}$ ($i = 1 \sim N$).

We adopt the zero-range approximation:

$$V_{pn}(p)\phi_i(p) = D\delta(p)$$

with $D = \int V_{pn}(p)\phi_i(p)dp$ for $\phi_i$ in s-state ($i = 0$), and $V_{pn}(p)\phi_i(p) = 0$ for $\phi_i$ in d-state ($i = 2$).

The d-state breakup channels contribute to $T_{pd}$ through the coupling to the elastic and s-state breakup channels.

The difference between the NA and AD calculations of $T_{pd}$ lies in the fact that NA uses $\Psi_{F}^{T}$ which is an eigenfunction of a three-body Hamiltonian $H_{3}$, while AD uses $\Psi_{F}^{T}$ which is an eigenfunction of the adiabatic Hamiltonian in which the p-n internal Hamiltonian of $H$ is replaced by the ground-state energy $E_0$ of the deuteron.

The NA and AD results of elastic and transfer cross sections are shown in Figs. 1 and 2. In spite of the general expectation that the AD approximation is good at high energies, its error in the $(d, p)$ cross section is evident still at this energy. In comparison, it is a much better approximation for the elastic cross section.

To investigate the origin of this defect of the AD approximation for the $(d, p)$ reaction, we decompose the $T_{pd}$ as follows:

$$T_{pd} = T_{pd}(d \rightarrow p) + T_{pd}(d^* \rightarrow p),$$

where $d$ and $d^*$ denote the d-state and d* states, respectively. The d-state breakup channels contribute to $T_{pd}$ through the coupling to the elastic and s-state breakup channels.

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\[ T_{pd}(d_0 \rightarrow p) = \langle \phi_0 | V_{pd} | \phi_2(0) \rangle, \]
\[ T_{pd}(d^* \rightarrow p) = \langle \phi_0 | V_{pd} | \sum \phi_2(0) \rangle. \]

The processes (a) and (b) are distinguished by the final step \( d_0 \rightarrow p \) and \( d^* \rightarrow p \), respectively. It is clearly shown in Fig. 4 that the agreement between the AD and the NA result is satisfactory for the cross section calculated from \( T_{pd}(d_0 \rightarrow p) \), but is poor for that from \( T_{pd}(d^* \rightarrow p) \). This is reasonable from the fact that the breakup component in \( \psi_d^{(p)} \) differs from that in \( \psi_d^{(a)} \) in contrast to the good agreement in the elastic component, as evident in Fig. 5. This difference in the breakup component is important for \((d, p)\) reactions, because the multi-step process \([d_0 \rightarrow d^*] \rightarrow p\) makes a significant contribution to \((d, p)\) reactions as shown in Fig. 4.
In Fig. 2 we also show the \((d, p)\) cross section obtained by the conventional DWBA calculation in which the distorting potential of the \(d\)-channel is adjusted to reproduce the elastic cross section of the NA calculation in Fig. 1. The DWBA calculation does not agree with the NA calculation, but excellently reproduces the NA cross section from the \(d_0 \rightarrow [d^* \rightarrow d_0] \rightarrow p\) process shown in Fig. 4. From this result it can be said that the conventional DWBA can describe the process \(d_0 \rightarrow [d^* \rightarrow d_0] \rightarrow p\), but does not include the effect of the process \([d_0 \rightarrow d^*] \rightarrow p\) on the \((d, p)\) cross section. On the other hand, the AD approximation includes this effect though not accurately, and so the AD approximation can give a better description of the \((d, p)\) reaction than conventional DWBA, as shown in Fig. 2.

Finally, we remark on the effect of the \(d\)-state \((l=2)\) breakup on \((d, p)\) reactions. In our zero-range CCBA calculation, the effect was relatively small at \(E_d \approx 80\,\text{MeV}\). The same analysis for \(E_d = 21.6\,\text{MeV}\), however, has shown that the effect is as sizable as the difference between NA and AD calculations including the \(s\)-state breakup only. This is in accordance with the finding in Ref. 10) on \(^{40}\text{Ca}(d, p)^{41}\text{Ca}(0f)\) at \(E_d = 21.6\,\text{MeV}\). Thus, the effect of the \(d\)-state breakup on \((d, p)\) reactions is important at low incident energies, though relatively unimportant at high energies, within the limit of the approximation. This point will be discussed in detail in a forthcoming paper.

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