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Three-body dN interaction in the analysis of the $^{12}\mathrm{C}(\vec{d}, d')$ reaction at 270 MeV

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Abstract

We have measured the cross sections and analyzing powers A_y and A_{yy} for the elastic and inelastic scattering of deuterons from the 0^+(g.s.), 2^+(4.44 MeV), 3^-(9.64 MeV), 1^+(12.71 MeV), and 2^-(18.3 MeV) states in ^{12}C at an incident energy of 270 MeV. The data are compared with microscopic distorted-wave impulse approximation calculations where the projectile-nucleon effective interaction is taken from the three-nucleon t-matrix given by rigorous Faddeev calculations presently available at intermediate energies. The agreement between theory and data compares well with that for the (p, p') reactions at comparable incident energies/nucleon.

Keywords: (d, d') reaction; DWIA analysis; Three-nucleon t-matrix

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Light-ion-induced inelastic scattering at bombarding energies above 100 MeV/nucleon is an appealing probe of nuclear structure due to the simple reaction mechanism. In such an energy domain, the reaction proceeds predominantly through a single step, and the distorted-wave impulse approximation (DWIA) gives a reasonable starting point for the theoretical description of data. In the IA for the (p, p') reaction, the effective interaction between a projectile nucleon and a target nucleon is taken to be the free nucleon–nucleon (NN) t-matrix. For the (d, d') reaction, the situation is not as simple as that for the nucleon case because the structure of the deuteron must be considered. Recently Orsay group has developed a DWIA model [1] using the double folding method to calculate the deuteron inelastic scattering at intermediate energies. In previous applications [1,2], the deuteron-nucleus (dA) transition matrix was calculated, first by folding the on-shell NN t-matrix with the deuteron wave function to yield the deuteron-nucleon (dN) t-matrix, then by folding it with the target transition density. In a comparison between model predictions and data, however, it was found that the $d + N$ elastic differential cross sections were overestimated by the first folding, leading to too large dA cross sections by factors of 1.2–2.0 [2].

Present day state-of-the-art three-nucleon $(3N)$ Faddeev calculations have made it possible for the $3N$ scattering processes at intermediate energies to be described with a reliable accuracy using modern NN potentials [3]. Since the dN t-matrix obtained from the rigorous $3N$ Faddeev calculations helps reduce uncertainties involved in the folding dN t-matrix, it is quite conceivable that the Faddeev amplitude, when used as an effective interaction, provides a more precise DWIA description of the (d, d') reaction. Such rigorous $3N$ amplitudes have recently been successfully employed in a PWIA model for interpreting analyzing power data in the $^3\mathrm{He}(\vec{d}, p)^4\mathrm{He}$ reaction [4]. They would also facilitate analyzing deuteron spin-flip data taken in search for isoscalar single- and double-spin-flip excitations [5].

This Letter reports on the differential cross sections and vector and tensor analyzing powers A_y and A_{yy} for low-lying states in ^{12}C excited via the $(\vec{d}, d')$ reaction at $E_d = 270$ MeV. The purpose is twofold: (1) provide accurate $(\vec{d}, d')$ scattering data which are scarce at intermediate energies; and (2) test the $3N$ amplitude given by the Faddeev calculations as the effective interaction in a DWIA model. The ^{12}C target was chosen as it provides both spin-flip $(\Delta S = 1)$ and non-spin-flip $(\Delta S = 0)$ states which are strongly excited via hadron inelastic scattering and whose structure information is available from shell-model calculations. Furthermore since the $\Delta S = 1$ and $\Delta S = 0$ states are excited from the 0^+ ground state through spin-dependent and spin-independent parts of the effective interaction, respectively, we can investigate the interaction in both spin channels separately by using these transitions.

The experiment was performed at RIKEN Accelerator Research Facility (RARF). The vector and tensor polarized deuteron beams of 270 MeV from the $K = 540$ Ring Cyclotron were used to bombard a 31.3-mg/cm^2-thick ^{12}C target. Beam polarization was measured by using the $d + p$ elastic scattering at 270 MeV [6]. Typical polarizations of 60–70% were obtained. The scattered deuterons were analyzed with the QQDQD-type magnetic spectrometer SMART [7]. The angular acceptance of the spectrometer was 100 and 50 mrad in the vertical and horizontal directions, respectively, with a momentum acceptance of 4%. The beam deuteron was stopped by a Faraday cup inside the scattering chamber. The scattering plane was perpendicular to the dispersive plane of the spectrometer due to the beam swinger system [8], and the scattering angle at the target was determined from the position at the focal plane normal to the dispersive plane. The angular resolution was less than 0.2° in FWHM, and the scattering angles were subdivided into 0.5° bins to obtain angular distributions.

Since elastically scattered deuterons produced formidable count rates at forward angles, a movable slit was employed to stop them at the intermediate focusing point of SMART. This allowed us to take data at excitation energies as small as 1 MeV and at angles as small as 2.5°. The position counter consisted of a 64-cm-wide and 16-cm-high multiwire drift chamber (MWDC) having four wire planes in both X and Y directions. Four plastic scintillation counters (5 mm thick) behind the MWDC provided pulse hight and time-of-flight information for particle identification. Fourfold coincidence of these counters generated a trigger for data-acquisition system [9].

Fig. 1 shows typical excitation energy spectra for the $^{12}\mathrm{C}(d, d')$ reaction at $E_d = 270$ MeV at (a) $\Theta_{\mathrm{lab}} = 3°$ and (b) $\Theta_{\mathrm{lab}} = 5°$. The spin-flip 1^+

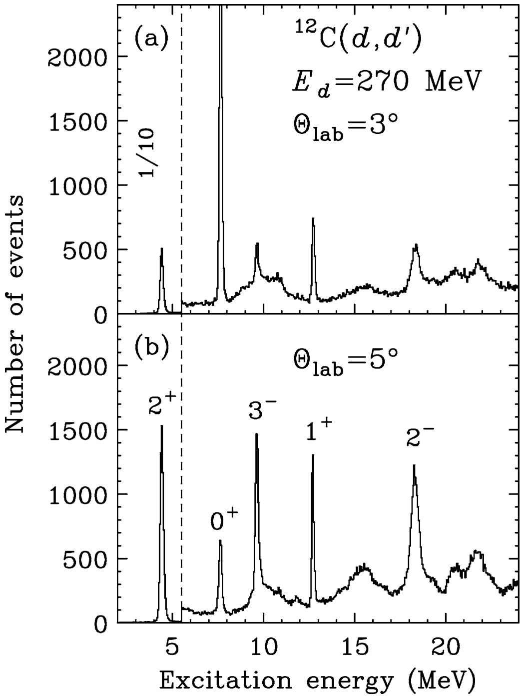

Fig. 1. Typical excitation energy spectra for the $^{12}\mathrm{C}(d,d')$ reaction at $E_d = 270$ MeV at (a) $\Theta_{\mathrm{lab}} = 3°$ and (b) $\Theta_{\mathrm{lab}} = 5°$.

(12.71 MeV) and 2^- (18.3 MeV) states are clearly observed along with the non-spin-flip 2^+ (4.44 MeV), 0^+ (7.65 MeV), and 3^- (9.64 MeV) states. The broad structures at 10.3 and 15.4 MeV are probably due to the resonances tentatively assigned to be 0^+ and 2^+ states, respectively [10]. All the states are isoscalar states due to the isospin selectivity, and isovector states, such as the isovector 1^+ (15.11 MeV) state, are entirely unseen.

The spectra were analyzed by using a peak fitting program SPECFIT [11] to extract yields contained in each peak. The cross sections and analyzing powers A_y and A_{yy} were calculated from the yields, and the continuum background and other overlapping states were subtracted from the data. The experimental cross sections and analyzing powers for the 2^+, 3^-, 1^+, and 2^- states are shown as full circles in Figs. 2(a) and 3(a), respectively. The error bar includes the statistical error and the error from the fitting procedure. The systematic uncertainty in the absolute magnitude of the cross section is estimated to be less than 10% taking account of ambiguities in charge collection, target thickness and solid angle. The systematic uncertainties for A_y and A_{yy} are 2% and 6%, respectively, which come from the normalization of beam polarizations. The excitations of the 1^+, 2^-, 2^+, and 3^- states are dominated by transitions with transferred angular momenta ΔL of 0, 1, 2, and 3, respectively. Cross section data show angular distributions which are characteristic of ΔL. In contrast, analyzing power data depend on ΔL only weakly, while they are characterized by transferred spin values ΔS. For example, A_y monotonically increases for the non-spin-flip 2^+ and 3^- states for an angular range between 3° and 15°, while it decreases in the same range for the spin-flip 1^+ and 2^- states. Such a unique ΔS-dependence of the analyzing powers can be used as a signal of spin transfer for a given state under investigation.

Measured cross sections and analyzing powers of the $^{12}\mathrm{C}(d,d)$ elastic scattering at $E_d = 270$ MeV are shown as full circles in Figs. 2(b) and 3(b), respectively. The optical potential parameters were determined by fitting the data using the code ECIS [12]. The results of the optical model fit are shown as solid lines in Figs. 2(b) and 3(b). The deduced parameters are listed in Table 1. They are consistent with the systematics of parameters at different energies [1,13].

Microscopic DWIA calculations were performed using the formalism described in Ref. [1]. The T-matrix in the dA system is given by

$$\begin{aligned} T_{dA}^{\mathrm{DWIA}} = {} & \left\langle X^{(-)}\chi_{d'}\Phi_{A^*} \middle| t_{dN} e^{i\vec{q}\cdot(\vec{R}'-\vec{R})} \right. \\ & \times \left| X^{(+)}\chi_d \Phi_A \right\rangle, \end{aligned}$$

where the distorted waves in the initial and final channels are denoted by $X^{(+)}(\vec{R})$ and $X^{(-)}(\vec{R})$, the target wave functions by $\Phi_A(\vec{R}')$ and $\Phi_{A^*}(\vec{R}')$, and the deuteron spinors by χ_d and $\chi_{d'}$, respectively. $\vec{q} = \vec{k}_{\mathrm{in}} - \vec{k}_{\mathrm{out}}$ is the momentum transfer, where $\vec{k}_{\mathrm{in}}$ and $\vec{k}_{\mathrm{out}}$ are the incoming and outgoing deuteron momenta, respectively. The on-shell dN t-matrix t_{dN} is used as the projectile-nucleon effective interaction. In the dN c.m. frame this is given by [14]

$$\begin{aligned} t_{dN}(q) = {} & \alpha + \beta S_n + \gamma\sigma_n + \delta S_n\sigma_n + \epsilon S_q\sigma_q \\ & + \zeta S_p\sigma_p + \eta Q_{qq} + \xi Q_{pp} + \kappa Q_{qq}\sigma_n \\ & + \lambda Q_{pp}\sigma_n + \mu Q_{nq}\sigma_q + \nu Q_{np}\sigma_p, \end{aligned}$$

where σ is Pauli spin matrix, S and Q deuteron spin operators, and the coefficients α through ν are complex parameters which depend on the incident energy

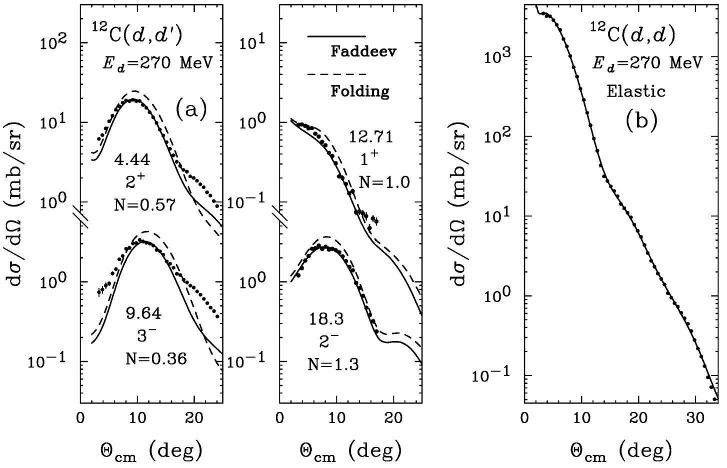

Fig. 2. (a) Measured differential cross sections for the ^{12}C(d, d') reaction at $E_d = 270$ MeV leading to low-lying excited states in ^{12}C are shown as full circles. The solid (dashed) lines are results of the DWIA calculations using the projectile-nucleon effective interaction derived from the Faddeev (folding) calculations. (b) Measured differential cross sections for the elastic scattering of deuterons from ^{12}C at $E_d = 270$ MeV. The solid line shows the result of the optical model calculation using the parameters listed in Table. 1.

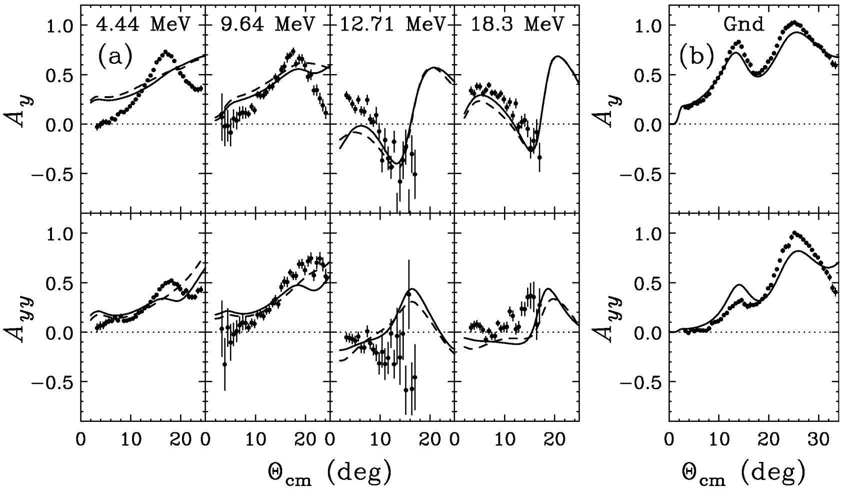

Fig. 3. Same as Fig. 2, but for vector and tensor analyzing powers A_y and A_{yy}.

Table 1
Optical potential parameters obtained from the analysis of the present elastic scattering data of deuterons from ^{12}C at $E_d = 270$ MeV. The potential is given by $U(r) = V_R f(x_R) + \mathrm{i} W_I f(x_I) - [V_{\mathrm{RSO}} \frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r} f(x_{\mathrm{RSO}}) + \mathrm{i} W_{\mathrm{ISO}} \frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r} f(x_{\mathrm{ISO}})] \boldsymbol{L} \cdot \boldsymbol{s} + V_{\mathrm{Coul}}(r_C)$, where $f(x_i) = [1 + \exp(x_i)]^{-1}$ with $x_i = (r - r_i A^{1/3})/a_i$. The Coulomb radius parameter is $r_C = 1.3$ fm

V_R (MeV)	r_R (fm)	a_R (fm)	W_I (MeV)	r_I (fm)	a_I (fm)	V_{RSO} (MeV)	r_{RSO} (fm)	a_{RSO} (fm)	W_{ISO} (MeV)	r_{ISO} (fm)	a_{ISO} (fm)
−19.27	1.41	0.75	−19.64	1.08	0.89	−7.20	0.91	0.71	1.64	0.89	0.71

and q. Unit vectors are given by $\hat{q}$, $\hat{n}//\vec{k}_{\text{in}} \times \vec{k}_{\text{out}}$ and $\hat{p} = \hat{n} \times \hat{q}$. We examined two different dN interactions: (1) the Faddeev interaction given by the $3N$ Faddeev calculations at $E_d = 270$ MeV, in which the total angular momenta of the two nucleon system up to $j = 5$ are taken into account [3]; and (2) the folding interaction obtained by folding the on-shell NN t-matrix at half the incident deuteron energy with a full deuteron wave function [1]. In both calculations the CD-Bonn potential [15] was used for the NN interaction and for the deuteron wave function. A good agreement has been found between the predictions of the Faddeev calculations and the $\vec{d} + p$ elastic scattering data at 270 MeV [16,17]. In contrast, only a fair agreement could be obtained with the folding calculations [18]; for instance, the calculated cross section is about 1.5 times larger than the experimental one at $\Theta_{\text{c.m.}} = 50°$ where the Faddeev result almost coincides with the data. The distorted waves X were generated by using the optical potential parameters in Table 1. The target wave functions Φ were those of Cohen and Kurath [19] and Millener and Kurath [20] for positive and negative parity states, respectively. To account for the effect of core polarization the spectroscopic amplitudes for natural parity states were renormalized to reproduce the observed electric transition probabilities [10]. The single particle wave functions were those of a harmonic oscillator well, with the center of mass motion corrected in q-space following the Ref. [21]. The integral over q in T_{dA}^{DWIA} was carried out over the range of q where t_{dN} is known: $q_{\max} = 3.4$ and $2.5\ \text{fm}^{-1}$ for the Faddeev and folding interactions, respectively. Since the form factors decreased rapidly with q for states examined, the results with the Faddeev interaction did not depend sensitively on the choice of the $q_{\max}$ values.

The calculated cross sections using the Faddeev and folding interactions are respectively shown as solid and dashed lines in Fig. 2(a). The curves are normalized with values indicated in the figure. For natural parity transitions normalization factors of around 0.5 are required, while for unnatural parity transitions the factors are around unity. The theoretical cross sections obtained with the folding interaction overestimate those with the Faddeev interaction by about 30% near the peak for both $\Delta S = 0$ and $\Delta S = 1$ transitions. The difference between the two curves is ascribed to higher order processes within the projectile-nucleon system, such as the multiple scattering, virtual breakup and/or rearrangement, which are included in the Faddeev interaction but not in the folding one. It is to be noted that such an effect of correlation among the interacting three nucleons (cross section reduction near the peak), previously noted on the basis of the comparison of the $d + N$ elastic cross sections with the folding model calculations [2], has been primarily concerned in the $\Delta S = 0$ channel. This is because the $d + N$ elastic amplitude is dominated by the isoscalar spin independent ($\Delta S = 0$) part of the effective interaction, especially at low momentum transfer region where the cross section reaches the maximum. Therefore the present results suggest that there clearly exists a similar effect of correlation, to reduce cross sections, in the $\Delta S = 1$ channel as well. The shapes near the peak in the angular distribution are well reproduced with a harmonic oscillator size parameter $b = 1.76$ fm determined from elastic electron scattering on ^{12}C [22], except for the 3^- state for which a larger value of $b = 1.90$ fm is required. Such a larger value of b for the 3^- state is consistent with the analysis of the (p, p') reaction [23].

Calculated analyzing powers with the Faddeev and folding interactions are shown in Fig. 3(b) as solid and dashed lines, respectively. The Faddeev interaction gives results which differ only in details from those given by the folding interaction. Both calculations reproduce qualitative features of the data. However, neither of them gives a full description of the detailed oscillating patterns of analyzing powers for natural parity states, and of the forward angle behavior of A_y for the 1^+ state where the data show positive values while the calculations exhibit negative values. Such discrepancies may result from processes not treated by the present DWIA, such as those arising from the presence of nuclear medium where the struck nucleon is embedded. The treatment of the deuteron as a single unit during the distortion process may also be responsible for the failure of the calculation.

The normalization factors for the calculated cross sections of around 0.5 required for natural parity states are consistent with those found in (p, p') studies in the 100–200 MeV range [23,24]. The factors, however, are different from the ones in electron scattering, which gives the normalizations close to unity [25]. It is likely that the use of a density-dependent interaction [26] and/or a fully microscopic optical potential [27,28] helps solve the normalization problem. The normalization factor of unity for the $T = 0\ 1^+$ state is consistent with that obtained by Willis et al. [29] at $E_p = 200$ MeV, who used the NN t-matrix in q-space directly as the projectile-nucleon effective interaction, similarly to the present analysis. In other (p, p') analyses for the $T = 0\ 1^+$ state in the same energy range the Love and Franey interaction [30] was employed for the effective interaction. It was found that the calculated cross sections overestimated the data by a factor of 2 at forward angles [23,24, 31]. From the studies, however, the origin of the discrepancy could be identified neither in terms of the nuclear structure nor the effective interaction. Note that inelastic electron scattering is insensitive to the $\Delta S = 1$ isoscalar transitions, and the nuclear structure for the $T = 0\ 1^+$ state at 12.71 MeV is not as well understood as that for the $T = 1\ 1^+$ state at 15.11 MeV. Present analysis with the Faddeev interaction, giving a satisfactory description for the cross section in both magnitude and shape, suggests that there is little reason that the spectroscopic terms of Cohen and Kurath [19] for this 1^+ (12.71 MeV) transition contain errors. In the $^{12}\mathrm{C}(d, d')$ study at $E_d = 400$ MeV, it was pointed out that the DWIA cross sections using the folding interaction for the 1^+ (12.71 MeV) state were larger than the data by factors of 1.5–2.0 at forward angles [1,32]. It is interesting to see if the use of the Faddeev interaction at 400 MeV could reduce the DWIA cross sections so that the calculated cross sections might in fact come close to the experiment.

In summary, we have measured the cross sections and analyzing powers for low-lying states in ^{12}C by the $(\vec{d}, d')$ reaction at $E_d = 270$ MeV. Microscopic DWIA calculations were performed by using the three-nucleon ($3N$) t-matrix given by rigorous Faddeev calculations as the effective interaction. All the characteristic features of the data are reproduced satisfactorily. Normalization factors required for calculated cross sections are consistent with those obtained from comparable analyses of the (p, p') reactions at similar incident energies. Correlations among nucleons in the projectile-nucleon system are found to reduce peak cross sections by about 30% in both $\Delta S = 0$ and $\Delta S = 1$ channels. This work represents the first application of the $3N$ Faddeev amplitude presently available at intermediate energies in a DWIA analysis of the (d, d') reaction as an effective interaction. Such a rigorous $3N$ amplitude will find a wide range of new applications for intermediate energy nuclear spectroscopy.

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