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Measurement of single and double spin-flip probabilities in inelastic deuteron scattering on ^{12}C at 270 MeV

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Abstract

The deuteron single and double spin-flip probabilities, S_1 and S_2, have been measured for the $^{12}\mathrm{C}(\vec{d};\vec{d}')$ reaction at $E_d = 270$ MeV for an excitation energy range between 4 and 24 MeV and a scattering angular range between $\Theta_{\mathrm{lab}} = 2.5°$ and 7.5°. The extracted S_1 exhibits characteristic values depending on the structure of the excited state. The S_2 is close to zero over the measured excitation energy range. The SFP angular distribution data for the 2^+ (4.44 MeV) and 1^+ (12.71 MeV) states are well described by the microscopic DWIA calculations.

Studies of polarization phenomena in nucleon induced inelastic scattering at intermediate energies (100–1000 MeV) have been one of the active fields of research in nuclear physics. Not only giving an insight into the reaction mechanisms, the measurement of spin-flip probability (SFP), S_{nn} in particular, provided useful information on the spin-flip modes of nuclear excitation [1]. At the intermediate energy region the spin transitions are dominated by the isovector ones due to the overwhelmingly large vector–isovector component of the effective interaction. Therefore, except for a few isolated states [2], there is still limited knowledge on the isoscalar spin excitations by the nucleon induced reactions as well as by other conventional probes.

The polarization transfer measurement in inelastic deuteron scattering should be one of the essential probes of the isoscalar spin excitations. Since deuterons have an isospin quantum number of $T = 0$, the reaction is selective of isoscalar transitions. The spin $S = 1$ nature of the deuteron allows spin transfer to the target. The measurement of deuteron SFP should provide a means to disentangle between spin and non-spin excitations, and one may expect that a similar polarization technique used to extract information on the spin-dependent structure from nucleon scattering may also be exploited for deuteron case.

The deuteron single and double SFPs, defined as fractions of deuteron undergoing spin-flip by one and

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two units along an axis normal to the reaction plane, are expressed in terms of polarization observables by the relations:

$$S_1 = \frac{1}{9}\left(4 - P^{y'y'} - A_{yy} - 2K_{yy}^{y'y'}\right), \quad (1)$$

$$S_2 = \frac{1}{18}\left(4 + 2P^{y'y'} + 2A_{yy} - 9K_y^{y'} + K_{yy}^{y'y'}\right). \quad (2)$$

The quantities A, P and K refer to the analyzing power, polarizing power and polarization transfer coefficient, one (two) indices stand for the vector (tensor) polarization, and lower (upper) ones the incident (outgoing) beam. The determination of S_1 and S_2 thus requires vector and tensor polarized beams and vector and tensor polarimeters. The SFPs, however, represent the projectile spin-flip and do not necessarily indicate the target spin-flip [3]. One thus needs to rely on a certain reaction model to interpret the SFP data in terms of the effective interaction and the target structure.

The earliest measurement of S_1 utilized the $(d, d'\gamma)$ method for states in ^{12}C [4]. The correlation measurements of the scattered deuterons and the emitted γ-rays could yield S_1 for states with known γ decay branch to the 0^+ ground state. A direct measurement of S_1 was made using a tensor polarimeter [5] at $E_d = 400$ MeV [6]. The limited coverage of the experimental setup, however, confined the measurement to be done only for the 1^+ (12.71 MeV) state in ^{12}C at 4°. Using a vector polarimeter [7] the $(\vec{d}, \vec{d}')$ measurements were performed on a wide range of nuclei [8–10]. The vector quantity $S_d^y = \frac{4}{3} + \frac{2}{3}A_{yy} - 2K_y^{y'}$ was used as the signal for the isoscalar spin states. This quantity, however, is an approximate one, which coincides with S_1 only when $A_{yy} = P^{y'y'}$ and $S_2 = 0$. In further pursuing a systematic study of the isoscalar spin-flip transitions it is therefore important to develop an experimental technique to measure S_1 over an extended range of the excitation energy. Furthermore, it is fascinating to see if the intriguing existence of $\Delta S = 2$ states, such as the proposed double GT state [11,12], could be revealed through S_2 as the probe.

In this Letter we report on a measurement of the deuteron single and double SPFs using a focal plane deuteron polarimeter specifically designed to measure both vector and tensor polarization components of deuterons. The ^{12}C target was chosen as it provides a typical isoscalar spin-flip 1^+ state at 12.71 MeV along with non-spin-flip collective states, therefore affording a study of ΔS-dependent features of the deuteron SFPs.

The experiment was performed at RIKEN accelerator research facility (RARF). The polarized deuteron beam from the Ring Cyclotron with an energy of 270 MeV and an average current of 10 nA was led onto a ^{12}C target with a thickness of 87.2 mg/cm^2. The vector and tensor polarizations with maximum values of $(p_y, p_{yy}) = (0, 0), (0, -2), (2/3, 0)$ and $(-1/3, 1)$ were used, the magnitudes were measured using the $d + p$ elastic scattering at 270 MeV [13] to be 60–70% of the ideal values. Scattered deuterons were detected using the SMART spectrometer [14] consisting of quadrupoles (Q) and horizontally bending dipoles (D) in the QQDQD configuration. It was instrumented with a multiwire drift chamber (MWDC) backed by two plastic scintillation detectors for track reconstruction and triggering. It had a solid angle of 5.0 msr and a momentum acceptance of 4%. The polarizations of outgoing deuterons were measured in a deuteron polarimeter DPOL installed in the focal plane. Data were acquired at a spectrometer setting of 5°.

Measurements of both vector and tensor components of the outgoing deuterons are crucial in extracting S_1 and S_2. This was realized by utilizing, as the analyzer reactions, the $\vec{d}$ + C elastic scattering and the ^{1}H$(\vec{d}, 2p)$ charge exchange reaction, which show large angular asymmetries depending, respectively, on the vector and tensor components. The deuterons from the primary scattering were incident on the analyzer target consisting of a 2.5-cm thick CH_2 block bracketed by the trigger counters. A counter hodoscope consisting of two layers of plastic scintillation counter array HOD and CM ($\sim 2 \times 2$ m^2) was located 4 m behind the analyzer target. It was used to detect deuterons from the $\vec{d}$ + C elastic scattering and pairs of protons produced through the ^{1}H$(\vec{d}, 2p)$ reaction with small relative momenta. An iron absorber between HOD and CM was used to discriminate between deuterons and protons. In off-line analysis the analyzer reactions were separated from other parasitic ones, such as the $\vec{d} + p$ and ^{12}C$(\vec{d}, 2p)$ reactions, using cuts on missing-mass spectra. The calibration of DPOL was done in the energy range between 230 and 270 MeV [15].

The analysis of the polarimeter has been proceeded in the same way as that in the calibration analysis. The cross section for spin-1 deuterons is given by

$$\sigma(\theta,\phi) = \sigma_0(\theta)\big[1 + it_{11}T_{11}(\theta)\cos(\phi) + t_{20}T_{20}(\theta) + 2t_{21}T_{21}(\theta)\cos(\phi) + 2t_{22}T_{22}(\theta)\cos(2\phi)\big], \quad (3)$$

where σ_0 is the cross section for the unpolarized deuterons, T_{kq} the analyzing powers, t_{kq} the polarization components of the deuterons, θ and ϕ the polar and azimuthal scattering angles. For each angular and excitation energy bin in the primary scattering, σ_0 and T_{kq} were calculated by interpolating the calibration results with respect to the incident deuteron energy. Possible differences in beam geometry between the calibration and this experiment could result in different detection efficiencies, which is implicit in σ_0. Corrections for the geometrical effects were made by using a Monte Carlo simulation [16]. The polarization components t_{kq} were extracted through a χ^2 minimization procedure using the measured angular distributions of the analyzer reactions. After a small correction for spin precession inside the spectrometer ($\sim 9.8°$), the polarization observables were deduced by using the relation given in Ref. [17].

Since the polarization transfer coefficients were extracted using differences of cross sections in the secondary scattering obtained with different polarization modes, they were unaffected by the uncertainties in σ_0. On the other hand, the polarizing powers $P^{y'}$ and $P^{y'y'}$ were extracted from double scattering cross sections obtained with an unpolarized beam. The systematic uncertainties in $P^{y'}$ and $P^{y'y'}$ are estimated from measurements of elastically scattered deuterons to be less than 0.12 and 0.20, respectively. The uncertainty for $P^{y'y'}$ contributed less than 0.02 to the uncertainties in S_1 and S_2.

Fig. 1(a) shows the double differential cross sections as a function of the ^{12}C excitation energy. The well known isoscalar 1^+ (12.71 MeV) state is clearly excited along with the other natural parity 2^+ (4.44 MeV), 0^+ (7.65 MeV) and 3^- (9.64 MeV) states. Isovector states such as the 1^+ state at 15.11 MeV are absent due to the isospin selection rule. Fig. 1(b) shows the cross section multiplied by S_1. The error bars represent the statistical and systematic errors added in quadrature. We see that the 1^+ $\Delta S = 1$ transition is strongly enhanced, while for the other $\Delta S = 0$ natural parity transitions the strengths are suppressed. This ΔS dependence of S_1 indicates that the measurement of S_1 in the $(\vec{d}, \vec{d}')$ reaction shows promise of becoming a useful tool in search for the isoscalar spin strength in heavier nuclei. The state at 18.3 MeV has been assigned as $(J^\pi, T) = (2^-, 0)$ from the S_{nn} measurement in $(\vec{p}, \vec{p}')$ [18]. The present result, which exhibits a large S_1 strength for this state, shows consistency with its identification as an isoscalar spin-flip transition. Fig. 1(c) plots the cross section multiplied by S_2. The values are consistent with zero over the measured excitation energy region, and no clear indication of the $\Delta S = 2$ states has been obtained from the present measurement.

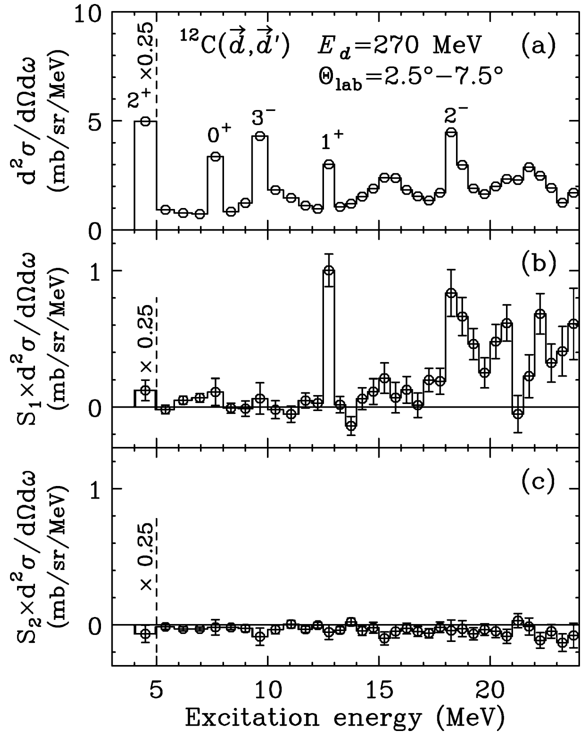

Fig. 1. Excitation energy spectra for the $^{12}\mathrm{C}(d, d')$ reaction at $E_d = 270$ MeV integrated over $\Theta_L = 2.5°$–$7.5°$. (a) An excitation energy spectrum. (b) The spectrum multiplied by S_1. (c) The spectrum multiplied by S_2.

Fig. 2(a) and (b) show the angular distributions of the SPFs for the 2^+ and 1^+ states, respectively. The S_1 values for the 2^+ state are close to zero, while those for the 1^+ state are large at small scattering angles. The S_2 data points are consistent with zero for both transitions. The results of the microscopic DWIA calculations are shown as solid lines in Fig. 2.

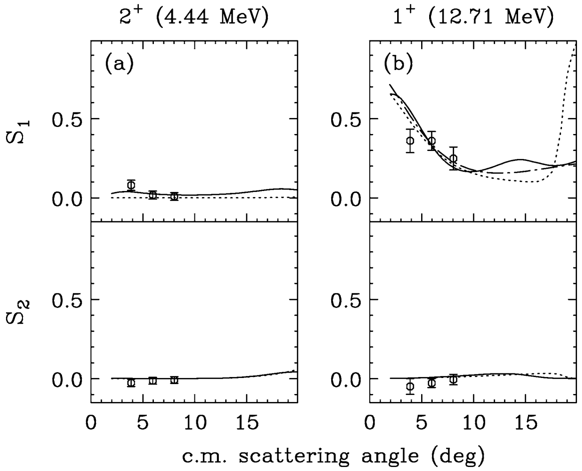

Fig. 2. The angular distributions of S_1 and S_2 for (a) the 2^+ (4.44 MeV) state and (b) the 1^+ (12.71 MeV) state. The solid (dashed) line is the DWIA (PWIA) calculations. The dot-dashed line for S_1 for the 1^+ state is an estimate using the IA amplitudes for $LSJ = (0\,1\,1)$.

Details of the calculation formalism can be found in Ref. [19]. The one-body transition densities were obtained using the $1p$ shell wave functions of Cohen and Kurath [20]. The optical potential was determined by fitting the elastic scattering data. The projectile–nucleon effective interaction was taken to be the on-shell deuteron–nucleon t-matrix given by [21]

$$
\begin{aligned}
&t_{dN}(q) \\
&\quad = \alpha + \beta S_n + \gamma \sigma_n + \delta S_n \sigma_n \\
&\qquad + \epsilon S_q \sigma_q + \zeta S_p \sigma_p + \eta Q_{qq} + \xi Q_{pp} \\
&\qquad + \kappa Q_{qq} \sigma_n + \lambda Q_{pp} \sigma_n + \mu Q_{nq} \sigma_q + \nu Q_{np} \sigma_p .
\end{aligned} \tag{4}
$$

The amplitudes α through ν were determined from the three-nucleon Faddeev calculations [22]. The PWIA results obtained by turning off the optical potential are also shown as dashed lines in Fig. 2.

As shown in Fig. 2 the overall features of the experimental angular distributions of S_1 for the 2^+ and 1^+ states are reasonably described by the present calculations. Small but finite DWIA values of S_1 for the 2^+ state is due to the spin–orbit distortion in the optical potential. The dot-dashed line of S_1 for the 1^+ state represents an IA prediction for transferred orbital, spin and total angular momenta of $LSJ = (0\,1\,1)$ calculated by the relation [21]:

$$
\begin{aligned}
S_1 = {}& \left(2|\epsilon|^2 + 2|\zeta|^2 + 2|\mu|^2 + 2|\nu|^2\right) \\
& \times \left(3|\gamma|^2 + 2|\delta|^2 + 2|\epsilon|^2 + 2|\zeta|^2 + |\kappa|^2 + |\lambda|^2 \right. \\
& \left. - |\kappa + \lambda|^2/3 + |\mu|^2 + |\nu|^2\right)^{-1}.
\end{aligned} \tag{5}
$$

The close agreement between the DWIA and this simple IA estimate below 10° indicates that S_1 for the 1^+ state in this angular region is relatively insensitive to distortion effects as well as to details of the transition density, instead it is mainly determined by the relative strengths of various parts of the IA amplitudes. This characteristic behavior of S_1 at forward angles is similar to that reported for S_{nn} in (p, p') [23]. The calculated S_2 values for both 2^+ and 1^+ states are consistent with zero below 10°. Since the effective interaction used in the present calculations adequately takes into account correlation effects among the projectile–nucleon system, the calculated results suggest that any possible non-zero values for S_2 at forward angles would have to be explained by reaction mechanisms which are not included in the present calculation, such as two-step processes involving spin-flip of two target nucleons, and tensor terms in the optical potential.

In summary, we have succeeded in measuring the single and double spin-flip probabilities through direct observation of polarization transfer in inelastic deuteron scattering on ^{12}C at $E_d = 270$ MeV. The focal plane polarimeter, which utilized the $\vec{d}$ + C elastic scattering and the ^{1}H$(\vec{d}, 2p)$ charge exchange reaction, allowed all the polarization components of the scattered deuterons to be measured simultaneously over a wide excitation energy range (4 and 24 MeV). The S_1 value is large for the spin-flip 1^+ (12.71 MeV) state, while it is close to zero for other non-spin-flip states, such as the first 2^+ (4.44 MeV) state. The S_2 values are consistent with zero for all the measured excitation energy range. The overall trends of the SFP angular distributions for the 1^+ and 2^+ states are well described by the microscopic DWIA calculations. The demonstrated feasibility of measuring the deuteron SFPs as well as the capability of the DWIA theory to reproduce the data will add a new and an alternative probe of nuclear structure. Further experiments are planed in search for the $\Delta S = 1$ and 2 transitions in higher excitation energy region in ^{12}C and in other nuclei.

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