Separation of Flip and Non-Flip parts of \( np \rightarrow pn \) Charge Exchange at energies \( T_n = 0.5 - 2.0 \text{GeV} \)

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Abstract

The new Delta-Sigma experimental data on the ratio \( R_{dp} \) allowed separating the Flip and Non-Flip parts of the differential cross section of \( np \rightarrow pn \) charge exchange process at the zero angle by the Dean formula. The PSA solutions for the \( np \rightarrow np \) elastic scattering are transformed to the \( np \rightarrow pn \) charge exchange representation using unitary transition, and good agreement is obtain.

1 Introduction

The Delta-Sigma experiment research program [1] intends to obtain a complete \( np \) data set at the zero angle: the measurements of total cross section differences \( \Delta \sigma_L(np) \) and \( \Delta \sigma_T(np) \) for the longitudinal (L) or transverse (T) beam and target polarizations and spin-correlation parameters \( A_{00kk}(np) \) and \( A_{00nn}(np) \) [2] as well as unpolarized measurements of values \( \sigma_{tot}(np) \), \( d\sigma/dt(np \rightarrow pn) \) and \( R_{dp} \). The main task of these studies is to determine the \( Re \) and \( Im \) parts of \( np \) amplitudes over the energy region 1.2–3.7 GeV. The energy dependence of \( \Delta \sigma_L(np) \) [2] shows an anomalous decrease to zero above 1.2 GeV and the structure in \( -\Delta \sigma_L(I = 0) \) around 1.8 GeV [3] predicted in [4, 5]. For the exhaustive analysis of this structure it is necessary to build the Argand diagrams for the \( Re \) and \( Im \) parts of each of the three \( NN \) forward scattering amplitudes. To reduce the sign ambiguities the Delta-Sigma collaboration measured the ratio \( R_{dp} = d\sigma/dt(nd) / d\sigma/dt(np) \) for the charge exchange quasi-elastic and elastic processes at 0° using the \( D_2 \) and \( H_2 \) targets. The knowledge of \( R_{dp} \) could provide additional constraint and will allow one of some sign uncertainties to be eliminated for the direct reconstruction of the \( Re \) parts of the scattering amplitudes.

The \( R_{dp} \) value at zero angle defines the ratio \( r^{nfl/\text{fl}} \) of the Non-Flip to Flip contributions in the \( np \rightarrow pn \) charge exchange process. This possibility is based on the deuteron properties that the deuteron is the amplitude filter at small momentum transfer in the \( nd \rightarrow p(nn) \) reaction, and the Non-Flip part vanishes due to the Pauli principle for two slow neutrons. Therefore, the quasi-elastic \( nd \) differential cross section is the Flip yield of the \( np \rightarrow pn \) charge exchange process. It is expressed by the Dean formula [6, 7, 8].

The \( np \) elastic reaction can be represented by two approaches: either as the charge exchange \( np \rightarrow pn \) reaction to the \( \theta \) angle (\( \theta = \theta_{CM} \)) or as the neutron elastic scattering \( np \rightarrow np \) in the inverted direction to the \( (\pi - \theta) \) angle. Though both representations have equivalent differential cross sections, their Flip or Non-Flip parts are absolutely different [9, 10]. The main cause for this distinction will be shown in section 3. To compare the energy dependencies of experimental \( R_{dp} \) or estimated \( r^{nfl/\text{fl}} \) with the PSA solutions of \( np \) elastic scattering, we should use the true charge exchange amplitudes, which requires the unitary transition from the \( np \rightarrow np(\pi - \theta) \) to the \( np \rightarrow pn(\theta) \) elastic representation.

2 Theoretical approach for \( R_{dp} \) and \( r^{nfl/\text{fl}} \)

The observable \( R_{dp} \) is the ratio of the quasi-elastic \( nd \rightarrow p(nn) \) differential cross section to the free \( np \rightarrow pn \) charge exchange one (also named as CEX)

\[
R_{dp} = \frac{d\sigma/dt_{nd\rightarrow p(nn)}}{d\sigma/dt_{CEX}}.
\]

Following the theory in [6, 7, 8], where the duration of \( nd \) collision is much smaller than the characteristic motion period of deuteron nucleons, the \( nd \rightarrow p(nn) \) quasi-elastic reaction can be expressed within the
framework of impulse approximation by the Dean formula

\[
\frac{d\sigma}{dt_{\text{nd} \rightarrow p(nn)}} = (1 - F(t)) \frac{d\sigma_{\text{Non-Flip}}}{dt_{\text{CEX}}} + \left(1 - \frac{1}{3}F(t)\right) \frac{d\sigma_{\text{Flip}}}{dt_{\text{CEX}}}. \tag{2}
\]

Here \(F(t)\) is the deuteron form-factor which equals one for the forward direction, and when the scattering angle \(\theta\) approaches zero, the first term on the right-hand of (2) vanishes

\[
\frac{d\sigma}{dt_{\text{nd} \rightarrow p(nn)}} (0) = \frac{2}{3} \frac{d\sigma_{\text{Flip}}}{dt_{\text{CEX}} (0)}. \tag{3}
\]

Note that this simplification is not possible if we take the elastic backward reaction \(np \rightarrow np\) instead of the charge exchange forward one, because if the difference of masses \(M_n\) and \(M_p\) is neglecting, the four-momentum transfer \(t\) will be defined as \(-4P_C^2\) and the form-factor \(F(t)\) will not equal to one. The similar replacement could be justified if both \(np\)-elastic scattering representations \((np \rightarrow np\) backward or \(np \rightarrow pn\) forward) are absolutely identical together with their Flip and Non-Flip parts. However, this hypothesis is not valid, as will be shown in the next section (see also [9, 10]). Moreover according to the source [7] the formula (2) is defined using the representation of the charge exchange process as a “generalization of the result found originally for \(K^+d \rightarrow K^0pp\) by Lee [11]”. The author of this work told also that: “For the non-charge-exchange reaction, however, no such simple result follows”.

For \(R_{dp}(0)\) and \(r_{CEX}^{n\tilde{n}/\tilde{f}}(0)\) we have

\[
R_{dp}(0) = \frac{2}{3} \frac{d\sigma_{\text{Flip}}}{dt_{\text{CEX}} (0)} = \frac{2}{3} \frac{1}{1 + r_{CEX}^{n\tilde{n}/\tilde{f}} (0)}; \quad r_{CEX}^{n\tilde{n}/\tilde{f}} (0) = \frac{1}{3} R_{dp}(0) - 1. \tag{4}
\]

Thus, the deuteron as an amplitude filter can be used in the measurement of \(R_{dp}\) for defining the Flip and Non-Flip parts of the \(np \rightarrow pn\) process, i.e. for observing spin effects in the \(np\) interaction even without the beam and target polarizations.

### 3 Transition from the \(np \rightarrow np (\pi - \theta)\) to the \(np \rightarrow pn (\theta)\) reaction

Within the framework of isotopic invariance the nucleon-nucleon scattering matrix is

\[
M(k', k) = M_0(k', k) \frac{1 - \hat{\tau}_1 \hat{\tau}_2}{4} + M_1(k', k) \frac{3 + \hat{\tau}_1 \hat{\tau}_2}{4}. \tag{5}
\]

Here \(\hat{\tau}_1\) and \(\hat{\tau}_2\) are the isotopic Pauli operators of nucleons, \(k\) and \(k'\) are the unit vectors of the initial and final relative momenta and the matrices \(M_0\) and \(M_1\) describe the \(NN\) scattering for the isotopic spin \(T = 0\) and \(T = 1\) respectively. For the \(np \rightarrow np\) and \(np \rightarrow pn\) elastic reactions at the same angle \(\theta\) it can be written

\[
< np|M|np >= \frac{1}{2} (M_1 + M_0) \quad < np|M|pn >= \frac{1}{2} (M_1 - M_0) \tag{6}
\]

With the Pauli spin operators \(\hat{\sigma}_1\) and \(\hat{\sigma}_2\) the scattering matrix \(M(k', k)\) can be expressed in the Goldberger-Watson amplitude representation [12, 13]

\[
M_T(k', k) = a_T + b_T(\hat{\sigma}_1 n)(\hat{\sigma}_2 n) + c_T(\hat{\sigma}_1 n + \hat{\sigma}_2 n) + d_T(\hat{\sigma}_1 m)(\hat{\sigma}_2 m) + f_T(\hat{\sigma}_1 l)(\hat{\sigma}_2 l). \tag{7}
\]

Here \((a, b, c, e, f)\) are the complex functions of the interacting particle energy and the variable \((k \cdot k') = \cos \theta\), the index \(T\) equals the value of the isotopic spin, and the basic vectors are defined as \(n = \frac{k - k'}{|k - k'|}\), \(m = \frac{k + k'}{|k + k'|}\). The Goldberger-Watson formalism is very suitable for the separation of elastic scattering into the Flip and Non-Flip parts because the amplitude \(a_T\) does not have operator term and it is Non-Flip by definition

\[
\frac{d\sigma_{\text{Non-Flip}}}{dt} = |a|^2 \quad \text{and} \quad \frac{d\sigma_{\text{Flip}}}{dt} = |a|^2 + |b|^2 + |c|^2 + |e|^2 + |f|^2. \tag{8}
\]
The Wolfenstein formalism\(^1\) [14, 15, 16] allows dividing the matrix \(M(k', k)\) into the spin-singlet and spin-triplet parts using the spin projection operators \(\hat{S} = \frac{1}{2}(1 - \hat{\sigma}_1\hat{\sigma}_2)\) and \(\hat{T} = \frac{1}{2}(3 + \hat{\sigma}_1\hat{\sigma}_2)\)

\[
M_T(k', k) = B_T \hat{S} + \left[ C_T(\hat{\sigma}_1 n + \hat{\sigma}_2 n) + \frac{1}{2} G_T(\hat{\sigma}_1 m)(\hat{\sigma}_2 m) + (\hat{\sigma}_1 l)(\hat{\sigma}_2 l) + \frac{1}{2} H_T(\hat{\sigma}_1 m)(\hat{\sigma}_2 m) - (\hat{\sigma}_1 l)(\hat{\sigma}_2 l) \right] \hat{T}.
\]  

(9)

\(B_T\) is the spin-singlet amplitude and the others are the spin-triplet amplitudes. Both matrix representations (7) and (9) are related by the linear transitions

\[
\begin{align*}
a_T &= \frac{1}{4}(B_T + G_T + N_T), & b_T &= \frac{1}{4}(3N_T - B_T - G_T), & c_T &= C_T \\
e_T &= \frac{1}{4}(G_T + 2HT - B_T - N_T), & f_T &= \frac{1}{4}(G_T - 2HT - B_T - N_T).
\end{align*}
\]

(10)

Let us to quote the works [15, 16]: “The requirement of antisymmetry of the final wave function \(M(k', k)\). \(\chi_S \cdot \chi_T\) (\(\chi_S\) and \(\chi_T\) are the spin and isotopic functions of the initial state) relative to the total permutation, including the permutation of the vector \((k' - k')\), permutation of the spin and isotopic variables does not change the signs of the amplitudes \(B_1(\theta), C_1(\theta), H_1(\theta), G_0(\theta)\) and \(N_0(\theta)\) after the turn \(\theta \rightarrow (\pi - \theta)\), but the amplitudes \(B_0(\theta), C_0(\theta), H_0(\theta), G_1(\theta)\) and \(N_1(\theta)\) become inverse”. It is accepted as the symmetry properties of these amplitudes (Table 1)

| \(T = 0\) | \(T = 1\) |
|---|---|
| \(B_0(\theta) = -B_0(\pi - \theta)\) | \(B_1(\theta) = +B_1(\pi - \theta)\) |
| \(C_0(\theta) = -C_0(\pi - \theta)\) | \(C_1(\theta) = +C_1(\pi - \theta)\) |
| \(H_0(\theta) = -H_0(\pi - \theta)\) | \(H_1(\theta) = +H_1(\pi - \theta)\) |
| \(G_0(\theta) = +G_0(\pi - \theta)\) | \(G_1(\theta) = -G_1(\pi - \theta)\) |
| \(N_0(\theta) = +N_0(\pi - \theta)\) | \(N_1(\theta) = -N_1(\pi - \theta)\) |

This rule (Table 1) and the symbolical addition \(M_1^{CEX} = M_1, M_0^{CEX} = -M_0\) allow the new \(np \rightarrow pn (\theta)\) charge exchange\(^2\) forward (Goldberger–Watson) amplitudes to be obtain from (10) via the old \(np \rightarrow np (\pi - \theta)\) elastic backward (Wolfenstein) amplitudes

\[
\begin{align*}
a_T^{CEX} &= \frac{1}{4}(B_T - G_T - N_T) \\
b_T^{CEX} &= \frac{1}{4}(G_T - B_T - 3N_T) \\
c_T^{CEX} &= C_T \\
e_T^{CEX} &= \frac{1}{4}(N_T + 2HT - B_T - G_T) \\
f_T^{CEX} &= \frac{1}{4}(N_T - 2HT - B_T - G_T).
\end{align*}
\]

(11)

As can be seen in (10) and (11) the Non-Flip amplitudes \(a_T(\pi - \theta)\) and \(a_T^{CEX}(\theta)\) are different from each other due to the yield of spin-triplet amplitudes \(G_T\) and \(N_T\). For all other Flip terms (except the \(c_T^{CEX}\) and \(c_T\)) the yields of \(G_T\) and \(N_T\) are also inverted. It is not difficult to define the direct amplitude transition from the \(np\) elastic backward to the charge exchange forward. The amplitudes \(c_T^{CEX}\) and \(c_T\) are equal, and for others we have

\[
\begin{pmatrix}
a_T^{CEX}(\theta) \\
b_T^{CEX}(\theta) \\
c_T^{CEX}(\theta) \\
f_T^{CEX}(\theta)
\end{pmatrix} = A \cdot \begin{pmatrix}
a_T(\pi - \theta) \\
b_T(\pi - \theta) \\
e_T(\pi - \theta) \\
f_T(\pi - \theta)
\end{pmatrix}, \quad \text{where} \quad A = \begin{pmatrix}
\frac{1}{2} & -\frac{1}{2} & -\frac{1}{2} & \frac{1}{2} \\
-\frac{1}{2} & -\frac{1}{2} & +\frac{1}{2} & +\frac{1}{2} \\
\frac{1}{2} & +\frac{1}{2} & +\frac{1}{2} & -\frac{1}{2} \\
-\frac{1}{2} & +\frac{1}{2} & -\frac{1}{2} & +\frac{1}{2}
\end{pmatrix}.
\]

(12)

\(^1\)The vector \(m\) in [14] defined as \(m = (k' - k)/(k - k')\). Therefore the Wolfenstein \((n, m, l)\) basic is left-hand in comparison with the Goldberger-Watson definition: \(m = -m_g\). However the signs of amplitudes will not change by the means of bilinear form of operator \((\hat{\sigma}_1 m)(\hat{\sigma}_2 m)\). Hereinafter we shall use the right-hand \((n, m, l)\) basis only.

\(^2\)Now each of the charge exchange full amplitudes \(Amp_1^{CEX}\) is the half-sum of the new defined pure isotopic amplitudes \(Amp_1^{CEX}\) and \(Amp_0^{CEX}\): \(Amp_1^{CEX} = 1/2[Amp_1^{CEX} + Amp_0^{CEX}]\).
The inverse transition from the $np \rightarrow pn$ forward reaction to the $np \rightarrow np$ backward one will be equivalent because the matrix $A$ is symmetric and unitary: $A = A^{-1} \Rightarrow |A| = 1$. The unitary transition (12) and definition (8) give the equivalence of the differential cross sections of both $np$ elastic representations even if their Non-Flip or Flip parts are different

$$\frac{d\sigma}{dt} np \rightarrow np (\pi - \theta) = \frac{d\sigma}{dt} np \rightarrow pn (\theta).$$

(13)

According to the properties of the $NN$ amplitudes, when the scattering angle $\theta$ approaches zero, the additional simplification arises $b(\pi) = f(\pi)$, $b_{CEX}^\pi(0) = e_{CEX}^\pi(0)$ and $c(\pi) = e_{CEX}^{\pi}(0) = 0$. In this case our formulas will coincide with the expressions from [9, 10]

$$a_{CEX}^\pi(0) = -\frac{1}{2}(a(\pi) + 2b(\pi) + e(\pi))$$
$$b_{CEX}^\pi(0) = -\frac{1}{2}(a(\pi) - e(\pi))$$
$$c_{CEX}^\pi(0) = -\frac{1}{2}(a(\pi) - 2b(\pi) + e(\pi)).$$

(14)

Here all amplitudes are half-sums of pure isotopic ones. We can see again the essential distinction of the Non-Flip amplitudes $a_{CEX}^\pi(0)$ and $a(\pi)$. It is very interesting that the formalism of $NN$ elastic scattering was created more than 50 years ago but this issue was revealed only in 2005 year. The elegant method of papers [9, 10] uses the Hermitian operator of spin permutation $\hat{P} = \frac{1}{2}(1 + \hat{\sigma}_1 \hat{\sigma}_2)$ and relates both scattering matrices

$$M_{CEX}^\pi(k', k) = -\hat{P} \cdot M_{np-np}^\pi(-k', k).$$

(15)

Dividing the matrices into the spin-singlet $SS$ and spin-triplet $ST$ parts and using the simplest arithmetics $\hat{P} \hat{S} = -\hat{S}$ and $\hat{P} \hat{T} = +\hat{T}$, we can easily define

$$M_{np-np}^\pi(-k', k) = SS + ST \quad M_{CEX}^\pi(k', k) = SS - ST.$$  

(16)

The inversion of $ST$ amplitudes$^3$ is the main cause for the difference of these two $np$ elastic representations and for the discrepancy between their spin structures.

4 Experimental results and comparison with PSA solution

According to the research program, the Delta-Sigma collaboration has successfully fulfilled the measurements of the ratio $R_{dp}(0)$ in four data-taking runs in 2002–2007. Using the liquid D$_2$/H$_2$ targets as well as the solid CD$_2$/CH$_2$/C complimentary targets we obtained the 8 points at energies $T_n = 0.5–2.0$ GeV (see Tab. 2 and Fig. 1). Our preliminary results of $R_{dp}(0)$ measurements were published in [3, 17, 18]. In addition, Delta-Sigma group have determined in 2007 a new data point at $T_{kin} = 0.55$ GeV to check the consistency with other world experimental data at low energies. We presented all our points in [20, 19] and the full description of the data processing and the resulting values at energies $T_n = 0.5$, 0.8, 1.0, 1.2, 1.4, 1.8 and 2.0 GeV was given in [21] and will be published in [22]. The point at 1.7 GeV is also measured for the first time by the Delta-Sigma collaboration, but we have some doubts on its quality. It is related with the estimation of number of nuclear in the H$_2$ target, and the $R_{dp}(0)$ value at 1.7 GeV have a preliminary status for the present. All results of the ratio $R_{dp}(0)$ are very close to 0.56 and their errors are $\approx 5\%$. Using (4) we calculated the values of the ratio $r_{CEX}^{np/\hat{R}}(0)$ between the Non-Flip and Flip parts of the $np \rightarrow pn$ charge exchange process (see Table 2, Fig. 2). Our data are in a good agreement with the LAMPF [23, 24] results (see 3 points below 1 GeV) and coincide exactly with the JINR [25] point at 1.0 GeV. Other world values of $R_{dp}(0)$ were taken from [26].

For comparison of our and other world data on $R_{dp}(0)$ and $r_{CEX}^{np/\hat{R}}(0)$ with the Phase Shift Analysis (PSA) we took from the SAID data base the solutions FA91 [27], VZ40 [28] and SP07 [29] for the $np \rightarrow np(\pi)$ elastic reaction and transformed them to the $np \rightarrow pm(0)$ charge exchange representation using the unitary transition (12). These energy dependencies were calculated using (4) and (8). As can

$^3$The symmetry properties of the Wolfenstein amplitudes (Table 1) can be defined directly from (16): the amplitude $B (\in SS)$ is transformed without change of sign; $G$ and $N (\in ST)$ are inverted; the $C$ and $H$ (belonging also to the $ST$ part) are inverted twice if we take into account that after the turn $k' \rightarrow k'$ the right-hand basic vectors change too: $n \rightarrow -n$, $m \rightarrow l$ and $l \rightarrow m$. 

4
be seen, the experimental $R_{dp}(0)$ and estimated $r^{nfl/fl}_{CEX}(0)$ data are very similar to the PSA solutions, and practically coincide with the FA91 one. Without the proper unitary transformation this agreement disappears (the PSA curve in Fig. 8 in [18]).

Table 2: $R_{dp}(0)$ and $r^{nfl/fl}_{CEX}(0)$ results and their total errors $\varepsilon_{tot}$

| $T_n$, GeV | 0.55 | 0.8 | 1.0 | 1.2 | 1.4 | 1.7 | 1.8 | 2.0 |
|------------|------|-----|-----|-----|-----|-----|-----|-----|
| $R_{dp}$   |      |     |     |     |     |     |     |     |
|            | 0.589| 0.554| 0.553| 0.551| 0.576| 0.565| 0.568| 0.564|
| $\varepsilon_{tot}$ | 0.046| 0.023| 0.026| 0.022| 0.038| 0.038| 0.033| 0.045|
| $r^{nfl/fl}_{CEX}$ | 0.133| 0.204| 0.206| 0.209| 0.158| 0.179| 0.174| 0.183|
| $\varepsilon_{tot}$ | 0.088| 0.051| 0.057| 0.048| 0.077| 0.080| 0.068| 0.094|

Figure 1: Energy dependence of the ratio $R_{dp}(0)$ between the yields of the $nd \rightarrow p \,(nn)$ quasi elastic and $np \rightarrow pn$ elastic charge exchange reactions. The PSA solutions VZ40, FA91 and SP07 were taken from the SAID data base as amplitudes for the $np$ backward reaction, transformed to the charge exchange by the unitary transition (12), and the $R_{dp}(0)$ curves are calculated using (4).

Figure 2: Energy dependence of the ratio $r^{nfl/fl}_{CEX(0)}$ between the Non-Flip and Flip parts of the $np \rightarrow pn$ charge exchange elastic process. Our and others world points were obtained directly from the $R_{dp}(0)$ data using (4). The PSA solutions are transformed by (12). The Binz points from [30, 31] are the results of the DRSA analysis for the $np$ elastic backward reaction and they were recalculated again using (12).

5 Conclusion

- The final [22] and preliminary (at 1.7 GeV) experimental results of defining 8 points of the ratio $R_{dp}$ at the zero angle at energies $T_n = 0.5–2.0$ GeV are presented (see Table 2, Fig. 1). The existing world experimental data at lower energy agree with our points.
- With formula (4), the values of $r^{nfl/fl}_{CEX(0)}$ are calculated for the charge exchange process $np \rightarrow pn \,(0)$ (see Table 2, Fig. 2). The Non-Flip part is not zero and equals $\approx 17\%$ of the differential cross section.
- The unitary transition from the $np \rightarrow np$ elastic backward reaction to the charge exchange $np \rightarrow pn$ forward process is considered and the PSA curves of $R_{dp}(0)$ and $r^{nfl/fl}_{CEX(0)}$ calculated by this approach describe the experimental points well (see Fig. 1 and Fig. 2).
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