Measurements of the ratio $R_{dp}$ of the quasi-elastic $\text{nd} \rightarrow \text{pnn}$ to the elastic $\text{np} \rightarrow \text{pn}$ charge-exchange process yields at 0° over 0.55 - 2.0 GeV neutron beam energy

Measurements were carried out at the Nuclotron of the Veksler and Baldin Laboratory of High Energies of the Joint Institute for Nuclear Research (JINR) at the neutron beam kinetic energies 0.55, 0.8, 1.0, 1.2, 1.4, 1.8 and 2.0 GeV.

The obtained $R_{dp} = \frac{d\sigma/d\Omega(\text{nd})}{d\sigma/d\Omega(\text{np})}$ values remain nearly constant with energy.

The new data are compared with existing ones, measured at energies below 1 GeV, and with calculations using the invariant amplitude sets for the solutions of the GW/VPI phase-shift analyses.

The investigations are being carried out under the program of the first priority JINR project "Delta-Sigma" experiment.
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The main task of the "Delta-Sigma" Experiment is determination for the first time the imaginary and real parts of spin-dependent forward scattering NN amplitudes over 1.2 – 3.7 GeV energy region.

To reach this aim, a sufficient data set on energy dependencies of np spin-dependent observables have to be obtained for direct and simple reconstruction of these amplitudes.
The Delta-Sigma experiment research program

1. Using longitudinally (L) and transverse (T) polarized neutron beams and polarized proton target to measure the energy dependencies of

a) the total cross section differences $\Delta \sigma_L(np)$ and $\Delta \sigma_T(np)$ for parallel and antiparallel directions of beam and target polarizations, with energy steps of 100–200 MeV and expected statistical errors of 1 mb.

The observables $\Delta \sigma_L(np)$ and $\Delta \sigma_T(np)$ are linearly related to the imaginary parts of the two spin-dependent forward scattering invariant amplitudes $c$ and $d$ via optical theorems and allow to extract these imaginary parts.

b) the spin-correlation parameters $A_{00kk}(np)$ and $A_{00nn}(np)$ with expected statistical errors of $0.02 – 0.05$ (simultaneously with and independently of the $\Delta \sigma_{L,T}(np)$ measurements).

The $A_{00kk}(np)$ and $A_{00nn}(np)$ values will be obtained from a registration of yields of elastic charge exchange process $np \rightarrow pn$ at $0^\circ$ angle. They are related to the real parts of the amplitudes mentioned above and data to be obtained will be used to extract these real parts.
The Delta-Sigma experiment research program

2. Using high intensity unpolarised neutron beam and liquid hydrogen and deuterium targets to measure

c) the ratio \( R_{dp} = \frac{[d\sigma/d\Omega(nd\rightarrow pnn)]}{[d\sigma/d\Omega(np\rightarrow pn)]} \) for elastic charge exchange process \( np\rightarrow pn \) at \( 0^\circ \) angle on deuterium and hydrogen targets with 5% statistical errors at the same energies as for i. 1.

Experimental observable \( R_{dp} \) is the ratio of a quasi-elastic \( nd \) scattering differential cross section to the free \( np \) elastic scattering one.

The values of \( R_{dp} \) can give one additional relation between spin-dependent \( NN \)-amplitudes and a set of such data allows to avoid one uncertainty of extraction of amplitudes real parts.

The data set on energy behaviors of spin-dependent observables \( \Delta\sigma_{L,T}(np), A_{00kk}(np), A_{00nn}(np) \) and \( R_{dp} \) will be obtained for the first time over the energy range of neutron beam of 1.2–3.7 GeV.

Besides the direct amplitude reconstruction, this data set will be used to extend the \( NN \) phase shift analysis to higher energies and to verify the dynamical model predictions.
Accelerators and tools

- The Synchrophasotron and Nuclotron VBLHE, JINR.

  Relativistic $1-5$ GeV polarized neutron beams with average polarization value of 0.53, orientation of polarization $L$ or $T$ and reversion of polarization direction from cycle to cycle; unpolarized neutron beam with high intensity ($4 \times 10^6$ n/cycle at $T_n = 2$ GeV).

- Large ($140$ cm$^3$) polarized proton target with polarization value of $0.7-0.8$.

- Cryogenic hydrogen $H_2$ and deuterium $D_2$ targets ($L = 30$ cm).

- “Delta-Sigma” set-up with:
  - monitor and transmission neutron detectors;
  - magnetic spectrometer with proportional chambers;
  - detectors for target surrounding;
  - time-of-flight system;
  - adequate data acquisition system.
DELTA-SIGMA Setup at the Polarized Neutron Beams of the JINR VBLHE

VP 1 – beam line of polarized deuterons; 1V – beam line of polarized neutrons; BT – beryllium neutron production target; IC – ionization chamber; PIC 1-3, 9-16 – multiwire proportional/ionization chambers; CM – sweeping magnet; C1-C4 – set of neutron beam collimators; SRM – neutron spin rotating magnet; PPT – polarized proton target; NP – neutron profilometer
Measurements of the $-\Delta\sigma_L (np)$ energy dependence were in the main completed using L-polarized neutron beam at the Synchrophasotron facility and the Dubna L-polarized proton target.

Results were published in:

**References on $-\Delta\sigma_L (np)$ results**

Energy Dependence of the $\Delta\sigma_L (\text{np})$ Observable Obtained with Free Neutron Polarized Beams
Energy Dependence of the $-\Delta \sigma_L (I=0)$
Measurements of the $\Delta \sigma_{L,T} (np)$ and $A_{00kk}(np)$ and $A_{00nn}(np)$ energy dependences using $L$ and $T$ orientations of beam and target polarizations will be possible in the near future when the new high intensity source of polarized deuterons (CIPIOS) will be put in operation at the Nuclotron and when the $T$ mode of target polarization will be ready.

During the last period, in frame of the project experimental program, the studies of elastic $np \rightarrow pn$ charge exchange process were carried out using high intensity unpolarized neutron beams and cryogenic $H_2$ and $D_2$ targets ($l=34$ cm). The results of these measurements will be presented below.
The magnetic spectrometer consist of the analyzing dipole SP94, two sets of multiwire proportional chambers PCs: Gx, Gy, 1x, 2x before and PCs: 3x, 3y, 4x, 4y after SP94 for momentum analysis of detected secondaries;
• Time-of-flight system S1, TOF1,2 for particle identification;
• Liquid H$_2$ / D$_2$ or solid CH2 / CD2 targets inserted in the neutron beam line instead of the PPT and surrounded by a device DTS for detecting charged recoils and gammas;
• Trigger counters A, S1, ST1,2,3.
Systematical errors.

Estimations for data at $T_n = 1.4$ GeV.

<table>
<thead>
<tr>
<th>Sources of systematic error</th>
<th>Absolute values of the Rdp error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Total PC efficiency</td>
<td>0.0027</td>
</tr>
<tr>
<td>2. Trigger PC efficiency</td>
<td>0.0026</td>
</tr>
<tr>
<td>3. Efficiency of the DTS</td>
<td>0.0179</td>
</tr>
<tr>
<td>4. Efficiency of TOF</td>
<td>0.0034</td>
</tr>
<tr>
<td>5. Error in shift determination of the H2 and D2 elastic peak center positions</td>
<td>0.0177</td>
</tr>
<tr>
<td>6. Number of H/D nuclei in the targets</td>
<td>0.0014</td>
</tr>
</tbody>
</table>

**Total:**                                                                                     **0.0257**
Values of \( R_{dp} = \frac{d\sigma}{d\Omega} (nd) / \frac{d\sigma}{d\Omega} (np) \).
Total errors are the quadratic sums of statistical and systematic uncertainties.

<table>
<thead>
<tr>
<th>NN</th>
<th>( T_n ), GeV</th>
<th>( P_n ), GeV/c</th>
<th>( R_{dp} )</th>
<th>Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Stat.</td>
<td>Syst.</td>
</tr>
<tr>
<td>1</td>
<td>0.550</td>
<td>1.1559</td>
<td>0.589</td>
<td>0.024</td>
</tr>
<tr>
<td>2</td>
<td>0.800</td>
<td>1.4640</td>
<td>0.554</td>
<td>0.017</td>
</tr>
<tr>
<td>3</td>
<td>1.000</td>
<td>1.6968</td>
<td>0.553</td>
<td>0.011</td>
</tr>
<tr>
<td>4</td>
<td>1.200</td>
<td>1.9222</td>
<td>0.551</td>
<td>0.011</td>
</tr>
<tr>
<td>5</td>
<td>1.400</td>
<td>2.1426</td>
<td>0.576</td>
<td>0.028</td>
</tr>
<tr>
<td>6</td>
<td>1.800</td>
<td>2.5734</td>
<td>0.568</td>
<td>0.016</td>
</tr>
<tr>
<td>7</td>
<td>2.000</td>
<td>2.7854</td>
<td>0.564</td>
<td>0.014</td>
</tr>
</tbody>
</table>

Assuming parity conservation, time-reversal invariance, the Pauli principle, and isospin invariance, the nucleon-nucleon scattering matrix can be written in term of only five invariant amplitudes

\[ M(k', k) = \frac{1}{2} \left[ (a+b) + (a-b)(\sigma_1,n)(\sigma_2,n) + (c+d)(\sigma_1,m)(\sigma_2,m) + (c-d)(\sigma_1,l)(\sigma_2,l) + e(\sigma_1+\sigma_2,n) \right], \]  

(1)

where \( \sigma_1 \) and \( \sigma_2 \) are the Pauli 2x2 matrices acting on the first and second nucleon wave functions, and \( k \) and \( k' \) are unit vectors in the direction of the incident and scattered particles, respectively. The invariant amplitudes \( a, b, c, d \) and \( e \) are complex functions of two variables, e.g., the center of mass (c.m.) energy \( k \) and scattering angle \( \theta \).

In the forward direction at \( \theta=0 \), total angular momentum conservation implies that \( e=0 \) and \( a-b=c+d \). Similarly at \( 180^\circ \) one obtains \( e=0 \) and \( a-b=c-d \).

The center of mass basis vectors are given by

\[ l = \frac{(k'+k)}{|k'+k|}, \quad m = \frac{(k'-k)}{|k'-k|}, \quad n = \frac{(k'\times k)}{|k'\times k|}. \]  

(2)
For the $pp$, $nn$, and $np$ interactions, the scattering matrix can be written in terms of two matrices $M_0$ and $M_1$ having the same form as Eq. (1)

$$M(k',k) = \frac{1}{4} M_0 \left[ 1-(\tau_1, \tau_2) \right] + \frac{1}{4} M_1 \left[ 3+(\tau_1, \tau_2) \right],$$

where $\tau_1$ and $\tau_2$ are isosinglet and isotriplet scattering matrices. Ignoring electromagnetic interaction, one can write

$$M(pp\rightarrow pp) = M(nn\rightarrow nn) = M_1,$$

$$M(np\rightarrow np) = M(pn\rightarrow pn) = \frac{1}{2} (M_1+M_0),$$

$$M(np\rightarrow pn) = M(pn\rightarrow np) = \frac{1}{2} (M_1-M_0).$$

This formalism uses a four-subscript notation $X_{srbt}$ for experimental quantities. Subscripts $s$, $r$, $b$, and $t$ refer to the polarization components of the scattered, recoil, beam, and target particles, respectively.

For any c.m. observable $X_{pqik}$, the following expression holds

$$\frac{d\sigma}{d\Omega} X_{pqik} = \frac{1}{4} \text{Tr} \left( \sigma_{1p} \sigma_{2q} M \sigma_{1i} \sigma_{2k} M^+ \right),$$

where

$$\frac{d\sigma}{d\Omega} = I_{0000} = \frac{1}{4} \text{Tr} \left( M M^+ \right),$$

is the unpolarized differential cross section.
Experimental observable

\[ R_{dp} = \frac{d\sigma/d\Omega(nd\rightarrow pnn)}{d\sigma/d\Omega(np\rightarrow pn)} \]  

(7)

is the ratio of a quasi-elastic \( nd \) charge-exchange process yield to the free elastic \( np \) one.


the differential cross section \( d\sigma/d\Omega(nd\rightarrow pnn) \) at \( t\rightarrow 0 \) can be expressed

\[ d\sigma/d\Omega(nd) = \frac{2}{3} \cdot d\sigma/d\Omega^{SD}(np), \]  

(8)

where \( d\sigma/d\Omega^{SD}(np) \) is the “spin-dependent” part of the \( np \rightarrow np \) differential cross section.

This gives

\[ R_{dp} = \frac{2}{3} \cdot \frac{d\sigma/d\Omega^{SD}(np)}{d\sigma/d\Omega(np)}. \]  

(9)

Using the invariant NN amplitudes formalism


the \( R_{dp}(0,\pi) \) can be expressed via invariant NN amplitudes as

(F.Lehar. Private communication)

\[ R_{dp}(0,\pi) = \frac{2}{3} \cdot \left[ 0.25 \cdot |a - b|^2 + 0.5 \cdot (|c|^2 + |d|^2) \right] / 0.5 \cdot (|a|^2 + |b|^2 + |c|^2 + |d|^2). \]  

(10)

The values of \( R_{dp} \) can give one additional relation between spin-dependent NN-amplitudes and a set of such data allows to avoid one uncertainty of extraction of amplitudes real parts.
Estimations of the $R_{dp}$ values were performed by formula (10) using the invariant amplitudes data sets for the elastic $np\rightarrow np$ and $pp\rightarrow pp$ scattering at $\theta_{CM} = \pi$.

The amplitudes data sets were received from I.I. Strakovsky for the GW/VPI phase-shift analysis (PSA) solutions: SM97


SP00


SP07

The amplitudes $np \rightarrow np$ are the mixture of pure isospin $I=1$ and $I=0$ states amplitudes according Eq. (4b)

$$Amp\ (np) = \frac{1}{2} (Amp\ (I=1\ (pp)) + Amp\ (I=0))$$  \hspace{1cm} (11)$$

and $$Amp\ (I=0) = 2\ Amp\ (np) - Amp\ (I=1(pp)).$$  \hspace{1cm} (12)$$

Using existed $Amp\ (np)$ and $Amp\ (I=1\ (pp))$ sets one can obtained the $Amp\ (I=0)$ set by Eq. (12).

The $R_{dp}$ values for the elastic $np \rightarrow np$ scattering at $\theta_{CM} = \pi$ one can obtained by Eq. (10) using either $Amp\ (np)$ set or $\frac{1}{2} (Amp\ (I=1) + Amp\ (I=0))$ one.
Rdp

Neutron energy $T_n$, GeV

- VBLPHE data
- Existing data set
- $GW$/UPI PSA for np$\rightarrow$np 180 deg

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To obtain the $R_{dp}$ values for the elastic $np \rightarrow pn$ charge exchange at $\theta_{CM} = 0$ one needs to perform the $k' \rightarrow -k'$ and $n \rightarrow p$ transformations of the $\text{Amp (I=1)}$ and $\text{Amp (I=0)}$ sets according to Table 1.


Table 1. Symmetry properties of the NN invariant amplitudes.

<table>
<thead>
<tr>
<th>$I=0$ amplitudes</th>
<th>$I=1$ amplitudes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0(\theta) = + a_0(\pi - \theta)$</td>
<td>$a_1(\theta) = - a_1(\pi - \theta)$</td>
</tr>
<tr>
<td>$b_0(\theta) = + c_0(\pi - \theta)$</td>
<td>$b_1(\theta) = - c_1(\pi - \theta)$</td>
</tr>
<tr>
<td>$c_0(\theta) = + b_0(\pi - \theta)$</td>
<td>$c_1(\theta) = - b_1(\pi - \theta)$</td>
</tr>
<tr>
<td>$d_0(\theta) = - d_0(\pi - \theta)$</td>
<td>$d_1(\theta) = + d_1(\pi - \theta)$</td>
</tr>
<tr>
<td>$e_0(\theta) = - e_0(\pi - \theta)$</td>
<td>$e_1(\theta) = + e_1(\pi - \theta)$</td>
</tr>
</tbody>
</table>
The scattering matrix simplifies at the forward $\theta_{CM} = 0$ and backward $\theta_{CM} = \pi$ angles.

The amplitudes at these angles satisfy
\[
\begin{align*}
    a(0) - b(0) &= c(0) + d(0), \\
    e(0) &= 0, \\
    a(\pi) - b(\pi) &= c(\pi) - d(\pi), \\
    e(\pi) &= 0.
\end{align*}
\]

The $np \rightarrow np$ elastic scattering and $np \rightarrow pn$ charge exchange differential cross sections are given by
\[
d\sigma/d\Omega = \frac{1}{2} (|a|^2 + |b|^2 + |c|^2 + |d|^2 + |e|^2)
\]
and equal each other.

The $R_{dp}$ values for the elastic $np \rightarrow pn$ charge exchange at $\theta_{CM} = 0$ one can obtained by Eq. (10) using $\frac{1}{2} (\text{Amp (I=1)} - \text{Amp (I=0)})$ set of the transformed $NN$ amplitudes.
Conclusions

1. New results at $\theta_{\text{CM}} = 0$ for $R_{dp} = \frac{d\sigma/d\Omega(\text{nd})}{d\sigma/d\Omega(\text{np})}$ – the ratio of a quasi-elastic $\text{nd} \to \text{pnn}$ charge exchange yield to the free elastic $\text{np} \to \text{pn}$ one at 0.55, 0.8, 1.0, 1.2, 1.4, 1.8 and 2.0 GeV are presented.

2. Estimations of the $R_{dp}$ values by formula (10) using the invariant amplitudes data sets for the elastic $\text{np} \to \text{np}$ and $\text{pp} \to \text{pp}$ scattering at $\theta_{\text{CM}} = \pi$ were performed.

3. Calculated $R_{dp}$ values with the set of invariant amplitudes data for the elastic $\text{np} \to \text{np}$ scattering at $\theta_{\text{CM}} = \pi$ disagree with experimental data.

4. Calculated $R_{dp}$ values with the set of invariant amplitudes data for the elastic $\text{np} \to \text{pn}$ charge exchange at $\theta_{\text{CM}} = 0$ agree with experimental data.

5. It is confirmed that the $\text{nd} \to \text{pnn}$ process yield caused by the spin-dependent part of the elastic $\text{np} \to \text{pn}$ charge exchange process at $\theta_{\text{CM}} = 0$.

6. It is shown that the Eq. (10) gives one additional relation between spin-dependent $\text{NN}$-amplitudes and obtained experimental $R_{dp}$ results can be used to avoid one uncertainty of extraction of amplitudes real parts.

7. The $R_{dp}$ measurements at the energies above 2 GeV are planned to continue.