NN SPIN AMPLITUDES AND PD SCATTERING

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Content

- Motivation
- Spin amplitudes in $NN \rightarrow NN$
- Invariant spin amplitudes in $pd \rightarrow pd$
- Spin-dependent Glauber theory of $pd$ elastic scattering
- Inelastic $dp$-scattering $dp \rightarrow \{pp\}(^1S_0)+n$
- $dd \rightarrow dd$ and inelastic $dd$-scattering with formation of $NN(^1S_0)$ pairs
- Search for $T$-invariance violation in double polarized $pd$ scattering
- Conclusion
For identical spin $\frac{1}{2}$ particles under Lorentz and P-,T- invariance:

spin non-flip \( \phi_1(s, t) = <++|M|++> \)

double spin-flip \( \phi_2(s, t) = <++|M|--> \)

spin non-flip \( \phi_3(s, t) = <+-|M|+-> \)

double spin-flip \( \phi_4(s, t) = <-+|M|--> \)

single spin-flip \( \phi_5(s, t) = <++|M|++-> \).

For non-identical (pn) nucleons one has 6 amplitudes,
T-reversal non-invariance provides two additional amplitudes.

All spin-observables of NN elastic scattering are described in terms of \( \phi_i \)

\[
d\sigma/dt = N[|\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 + 4|\phi_5|^2],
\]

\[
A_N \sim Im[(\phi_1 + \phi_2 + \phi_3 - \phi_4)\phi_5^*]
\]

\[
A_{NN} \sim 2|\phi_5|^2 + Re(\phi_1^*\phi_2 - \phi_3^*\phi_4)
\]

\[\ldots\]
Helicity amplitudes of NN-scattering

Number of linearly independent non-zero spin observables:
single-spin (asymmetries $A_i$, polarizations $P_i$) – 2
double-spin ($A_{ii}$, ...) – 12
triple-spin – 9
four- spin – 2

Complete polarization experiment
for pp-elastic requires 9 independent observables.
PWA GWU is performed for pp-elastic up to 3.8 GeV/c (SAID
R.A. Arndt, I.I. Strakovsky, B.L. Workman PRC 56, 3005 (1997);
PWA for pn- elastic – up 1.2 GeV/c

Concerning SPD NICA, above 3 GeV/c $d\sigma/dt$ and mainly $A_N$ (up to 50 GeV/c) and $A_{NN}, C_{LL}$ (up to 6 GeV/c, 12 GeV/c) are measured. Data on double-spin observables $D_{NN}, K_{NN}$ are rather poore in the region of forward angles.

Parametrizations (fit) of the pp- data:
A systematic analysis of pp elastic scattering from COSY-EDDA, SATURNE, GZS ANL /A. Sibirtsev et al. EPJA 45 (2010) 357/
\omega, \rho, f_2, a_2 Reggeon and Pomeron exchanges for $P = 3 - 50$ GeV/c. Isospin structure and G-parity relations allow to obtain the $\bar{p}p$- and $\bar{p}n$- elastic amplitudes from the $pp$ amplitudes (J.R. Pelaez, 2006):

$$\phi(pp) = -\phi_\omega - \phi_\rho + \phi_{f_2} + \phi_{a_2} + \phi_P$$
$$\phi(\bar{p}p) = \phi_\omega + \phi_\rho + \phi_{f_2} + \phi_{a_2} + \phi_P$$
$$\phi(pn) = -\phi_\omega + \phi_\rho + \phi_{f_2} - \phi_{a_2} + \phi_P$$
$$\phi(\bar{p}n) = \phi_\omega - \phi_\rho + \phi_{f_2} - \phi_{a_2} + \phi_P$$

However, not all available data ($C_{NN}, C_{LL}, C_{SS}, C_{LS}, D_{NN}, D_{SS}, D_{LS}, K_{NN}, \Delta \sigma_T, H_{SNS}$... measured by ANL at 6 GeV/c, and some at 12 GeV/c) were included into the fit.
PN elastic scattering

SAID date base:
R.A. Arndt et al. m PRC 56 (1997) 3005; http://gwdac.phys.gwu.edu
pp up 3.0 GeV/c, pn – up 1.2 GeV
A. Sibirtsev et al, (2010); Only 3-4 GeV/c
Re $f(0^\circ)/\text{Im}(0^\circ)$ ratio.

A problem with antip-$p$ theory: no zero

A. Sibirtsev et al, EPJA (2010)

**Fig. 16.** Ratio of the real-to-imaginary parts of the forward amplitudes for $pp$ (triangles, solid line) and $\bar{p}p$ (squares, dashed line), respectively. The data are taken from the PDG [32].
$\sqrt{s} = 13.4; 18.4; 30.4; 44.7 \text{(GeV)}$;

$\sqrt{s} = 52.8 \text{GeV}$;

$\sqrt{s} = 7 \text{TeV}$;

O.V. Selyugin, PRD 91 (2015)
high-energy general structure model (HEGS) model
Invariant spin amplitudes of pd- elastic scattering

\[ M_{fi} = \phi^+_\mu e^{(\lambda)^*}_\beta e^{(\lambda)}_\alpha T_{\beta\alpha} (\vec{p}, \vec{p}', \vec{\sigma}) \phi_\mu, \]

\[ 2 \times 3 \times 2 \times 3 = 36 \]

P-invariance (18 amplitudes)

\[ T_{\alpha\beta} (-\vec{p}, -\vec{p}', \vec{\sigma}) = T_{\alpha\beta} (\vec{p}, \vec{p}', \vec{\sigma}) \]

T-invariance (lefts 12 amplitudes):

\[ T_{\beta\alpha} (\vec{p}, \vec{p}', \vec{\sigma}) = T_{\alpha\beta} (-\vec{p}, -\vec{p}, -\vec{\sigma}) \]
\begin{align*}
\hat{q} &= (p - p'), \quad \hat{k} = (p + p')/||\hat{n} = [k \times q] - \text{unit vect.} \\
M &= (A_1 + A_2\sigma\hat{n}) + (A_3 + A_4\sigma\hat{n})(S\hat{q})^2 + (A_5 + A_6\sigma\hat{n})(S\hat{n})^2 + A_7(\sigma\hat{k})(S\hat{k}) + \\
&\quad A_8(\sigma\hat{q})[(S\hat{q})(S\hat{n}) + (S\hat{n})(S\hat{q})] + (A_9 + A_{10}\sigma\hat{n})(S\hat{n}) + A_{11}(\sigma\hat{q})(S\hat{q}) + \\
&\quad A_{12}(\sigma\hat{k})[(S\hat{k})(S\hat{n}) + (S\hat{n})(S\hat{k})] \\
&\quad + (T_{13} + T_{14}\sigma\hat{n})[(S\hat{k})(S\hat{q}) + (S\hat{q})(S\hat{k})] + T_{15}(\sigma\hat{q})(S\hat{k}) + T_{16}(\sigma\hat{k})(S\hat{q}) + \\
&\quad T_{17}(\sigma\hat{k})[(S\hat{q})(S\hat{n}) + (S\hat{n})(S\hat{q})] + T_{18}(\sigma\hat{q})[(S\hat{k})(S\hat{n}) + (S\hat{n})(S\hat{k})] \\
A_1 \div A_{12} \text{ T-even P-even:} \\
\text{M. Platonova, V.L. Kukulin, PRC 81 (2010) 014004} \\
\text{\textbf{T}_{13} \div \textbf{T}_{18} : TVPC}
\end{align*}

The polarized elastic differential $pd$ cross section

\begin{align*}
\left( \frac{d\sigma}{d\Omega} \right)_{pol} = \left( \frac{d\sigma}{d\Omega} \right)_0 \left[ 1 + \frac{3}{2} p_i^p p_i^d C_{ij} + \frac{1}{3} P_{ij} A_{ij} + \ldots \right].
\end{align*}

(3)
Spin observables of the pd-pd

\[
A_j^p = \frac{TrM \sigma_j M^+}{TrMM^+}, \\
A_j^d = \frac{TrM \hat{S}_j M^+}{TrMM^+}, \\
A_{ij} = \frac{TrM \hat{P}_{ij} M^+}{TrMM^+}, \\
C_{ij} = \frac{TrM \sigma_i \hat{S}_j M^+}{TrMM^+}, C_{ij,k} = \frac{TrM \sigma_k \hat{P}_{ij} M^+}{TrMM^+}, \ldots
\]

\[
\hat{P}_{ij} = \frac{3}{2} (\hat{S}_i \hat{S}_j + \hat{S}_j \hat{S}_i) - 2 \delta_{ij}
\]
Elastic $pd \rightarrow pd$ transitions

$$
\hat{M}(q, s) = \exp \left( \frac{1}{2} i q \cdot s \right) M_{pp}(q) + \exp \left( - \frac{1}{2} i q \cdot s \right) M_{pn}(q) + \int \frac{i}{2\pi^{3/2}} \exp \left( i q' \cdot s \right) \left[ M_{pp}(q_1) M_{pn}(q_2) + p \leftrightarrow n \right] d^2q'.
$$

On-shell elastic $pN$ scattering amplitude (T-even, P-even)

$$
M_{pN} = A_N + (C_N \sigma_1 + C'_N \sigma_2) \cdot \hat{n} + B_N (\sigma_1 \cdot \hat{k})(\sigma_2 \cdot \hat{k}) + (G_N - H_N)(\sigma_1 \cdot \hat{n})(\sigma_2 \cdot \hat{n}) + (G_N + H_N)(\sigma_1 \cdot \hat{q})(\sigma_2 \cdot \hat{q})
$$

M. Platonova, V. Kukulin, PRC 81 (2010) 014004:
Test calculations: $pd$ elastic scattering at 135 MeV


Data: von B. Przewoski et al. PRC 74 (2006) 064003
The Glauber model and exact Faddeev calculations

The Glauber theory: eikonal approximation, on-shell hN-scattering amplitudes (no off-shell effects), maximal multiplicity is equal to A (no multiple scatterings taken into account in Faddeev calculations)

Why the Glauber model is so successful?

Test calculations: $pd$ elastic scattering at 1 GeV
Vector analyzing powers $A_y^p$ and $A_y^d$ in pd elastic

$$A_y^p = 2 \text{Re}[2(A_1^* + A_3^* + A_5^*)(A_2 + A_4 + A_6) + A_1^* A_2 - A_3^* A_6 - A_4^* A_5 + 2 A_9^* A_{10})]/(3d\sigma/dt)$$

$$A_y^d = 2 \text{Re}[2 A_1^* + A_3^* + 2 A_5^*) A_9 + 2(A_2^* + A_4^* + 2 A_6^*) A_{10} + A_7^* A_{12} + 2 A_8^* A_{11})]/(3d\sigma/dt)$$

At $q\to0$, SS- mechanism:

$$R = A_y^d / A_y^p, R(q = 0) = \frac{2}{3}$$

$$\text{Re}(A_2^* A_{10}) / \text{Re}(A_2^* A_1) = \frac{9}{2}(R - \frac{2}{3})$$

$$A_1 = (S_0 + \sqrt{2}S_2) A_N; A_2 = (S_0^{(0)} + \sqrt{2}S_2^{(1)}) C_N; A_{10} = (S_0^{(0)} + \frac{1}{\sqrt{8}} S_2^{(1)})(G_N - H_N)$$

$$M_N = A_N + (C_N + C_N^t) \bar{\sigma} \bar{n} + (G_N + H_N)(\bar{\sigma} \bar{q})(\bar{\sigma}_N \bar{q}) + (G_N + G_N)(\bar{\sigma} \bar{n})(\bar{\sigma}_N \bar{n})$$
\[ \hat{M} = a + ib\hat{\sigma}_y + ic\hat{S}_y. \]

Here \( \hat{\sigma}_y \) and \( \hat{S}_y \) are operators acting, respectively, on the spins of the proton and deuteron. The proton analyzing power results from an interference between the amplitudes \( a \) and \( b \) whereas that of the deuteron is due to an interference between \( a \) and \( c \). Straightforward calculations yield

\[ A_y^p = 2\text{Im}\{ab^*\}/[|a|^2 + |b|^2 + \frac{2}{3}|c|^2], \]
\[ A_y^d = \frac{4}{3}\text{Im}\{ac^*\}/[|a|^2 + |b|^2 + \frac{2}{3}|c|^2]. \]

\[ b = c \quad \text{at} \quad q \approx 0 \quad \text{then} \quad R = \frac{2}{3} \]
It follows from the results given in Table 1 that, within the refined Glauber model, most of the deviations of \( R \) from 2/3 at \( q = 0 \) are due to the spin-spin term in single scattering; the modifications due to the double scattering are small in comparison and may be estimated from theory with sufficient precision. Using the

**Table 1**

Predicted values of the ratio of deuteron to proton analyzing powers in \( pd \) elastic scattering as \( q \to 0 \). The single (SS) and full (SS + DS) models of Ref. [12] were evaluated using as input a partial wave analysis of the nucleon-nucleon amplitudes [16]. The table shows the small deviations of \( R \) from 2/3.

<table>
<thead>
<tr>
<th>( T_p ) MeV</th>
<th>( 100(R - 2/3) )</th>
<th>SS+DS</th>
</tr>
</thead>
<tbody>
<tr>
<td>135</td>
<td>-1.09</td>
<td>-1.24</td>
</tr>
<tr>
<td>200</td>
<td>-0.82</td>
<td>-0.73</td>
</tr>
<tr>
<td>250</td>
<td>-1.02</td>
<td>-0.81</td>
</tr>
<tr>
<td>450</td>
<td>-2.25</td>
<td>-1.55</td>
</tr>
<tr>
<td>600</td>
<td>-4.28</td>
<td>-3.31</td>
</tr>
<tr>
<td>800</td>
<td>-2.75</td>
<td>-2.00</td>
</tr>
<tr>
<td>1000</td>
<td>-0.36</td>
<td>0.25</td>
</tr>
<tr>
<td>1125</td>
<td>1.84</td>
<td>2.35</td>
</tr>
<tr>
<td>1135</td>
<td>2.04</td>
<td>2.53</td>
</tr>
</tbody>
</table>

\[
R = \frac{A_y^d}{A_y^p}
\]

\[
\delta = R - 2/3 \text{ is sensitive to spin-spin NN terms}
\]

Figure 2: Difference between the predictions of the refined Glauber model \cite{10} without \(R\) and with \(Rf\) the NN spin-spin contribution at 800 MeV expressed as a percentage of their average.
precise measurement of $R$ could provide some information on the $NN$ transverse spin-spin amplitude in the forward direction that is independent of the measurement of the spin dependence of total cross sections and the use of forward dispersion relations [2].

constraint on the spin-spin amplitudes. This may present a severe experimental challenge because, even in the well-controlled IUCF experiment, the overall uncertainty in $(A^p_y, A^d_y)$ was (0.9%, 1.5%) and (2.3%, 2.0%) at 135 MeV and 200 MeV, respectively [8].
Inelastic dp-scattering $dp \rightarrow \{pp\}(^{1}S_{0}) + n$

$pd \rightarrow (pp) + n$, $E_{pp} < 3\text{MeV}$, $1S0$ ANKE
dd- elastic and quasi-elastic scattering

Plan for further calculations

“Inelastic intermediate states in proton-deuteron and deuteron-deuteron elastic collisions at the ISR”

The solid curve is the absolute prediction of the full theory Glauber +IS
SEARCH for T-invariance VIOLATION IN DOUBLE POLARIZED PD -SCATTERING
Why search for Time-invariance Violating P-conserving Effects?

- The T-violating, P-violating (TVPV) effects arise in SM through CP violating phase of CKM matrix and the QCD $\theta -$ term.

  EDM.

- T-violating P-conserving (TVPC) (flavor-conserving) effects (first considered by L. Okun, Yad.Fiz. 1 (1965) 938) do not arise in SM as Fundamental interactions, although can be generated through weak corrections to TVPV interactions

  ★ Observed (in $K^0, B^0, D^0$) CP violation in SM leads to simultaneous violation of T- and P-invariance.

  Therefore, to produce T-odd P-even term one should have one additional P-odd term in the effective interaction: $g \sim M^4 G_F^2 \sin \delta \sim 10^{-10}$


  ★ ...much larger $g$ is not excluded by unknown interaction beyond the SM.

  ★ Experimental limits on TVPC effects are much weaker than for EDM.
Forward elastic $pd$ scattering amplitude (P-even, T-even):

$$e'_\beta \hat{F}_{\alpha\beta}(0)e_\alpha = g_1[e \ e'^*- (\k e)(\k e'^*)] + g_2(\k e)(\k e'^*) +$$

$$ig_3\{\sigma[e \times e'^*] - (\k e)(\k \cdot e'\times e'^*])\} + ig_4(\sigma \k)(\k \cdot e \times e'^*)$$


... and plus T-odd P-even term

$$\cdots + g_5\{(\sigma \cdot [\k \times e])(k \cdot e'\times e'^*]) + (\sigma \cdot [\k \times e'^*])(k \cdot e)\}$$

Generalized Optical theorem:

$$Im\frac{Tr(\hat{\rho}_i\hat{F}'(0))}{Tr\hat{\rho}_i} = \frac{k}{4\pi}\sigma_i$$
T-even P-even

\[ M_N(p, q; \sigma, \sigma_N) = A_N + C_N \sigma \hat{n} + C'_N \sigma_N \hat{n} + B_N(\sigma \hat{k})(\sigma_N \hat{k}) + (G_N + H_N)(\sigma \hat{q})(\sigma_N \hat{q}) + (G_N - H_N)(\sigma \hat{n})(\sigma_N \hat{n}) \]

T-odd P-even

\[ t_{pN} = h_N[(\sigma \cdot k)(\sigma_N \cdot q) + (\sigma_N \cdot k)(\sigma \cdot q) - \frac{2}{3}(\sigma_N \cdot \sigma)(k \cdot q)]/m_p^2 \]

\[ + g_N[\sigma \times \sigma_N] \cdot [q \times k][\tau - \tau_N]z/m_p^2 \]

\[ + g'_N(\sigma - \sigma_N) \cdot i [q \times k][\tau \times \tau_N]z/m_p^2. \]

Null-test signal:

\[ \tilde{g} = \frac{i}{4\pi m_p} \int_0^\infty dq q^2 \left[ S_0^{(0)}(q) - \sqrt{8} S_2^{(1)}(q) - 4 S_0^{(2)}(q) + \sqrt{2} \frac{4}{3} S_2^{(2)}(q) + 9 S_1^{(2)}(q) \right] \left[ -C'_n(q) h_p + C'_p(q)(g_n - h_n) \right] \]
\[ C' \approx i\phi_5 + i q/2m(\phi_1 + \phi_3)/2 \]


\[
\sigma_{tot} = \underbrace{\sigma_0 + \sigma_1 p^p \cdot P^d}_{T-even,P-even} + \sigma_2 (p^p \cdot \hat{k})(P^d \cdot \hat{k}) + \sigma_3 P_{zz} \quad + \quad \underbrace{\tilde{\sigma}_{tvpc} p^p y P^d}_{T-odd,P-even} \quad \underbrace{P_{xz}}_{T-odd,P-even}
\]
Conclusion and outlook

- Measurement of spin observables \((d\sigma/dt, A^p_y, A^d_y, A_{yy}, A_{xx}, C_{i,j})\) of \(pd\)- elastic, \(pd \rightarrow n\{pp\}_s, dd \rightarrow dd, \{pp\}_s + \{nn\}_s\) at SPD NICA is important. Available Regge parameterizations for pp amplitudes at \(P_L = 3 - 50\) GeV/c (A. Sibirtsev et al. 2010; Van Orden; others) can be used for calculation of these observables within the Glauber theory. Comparison between data and theory will provide a clean test for the pp- and pn- elastic amplitudes.

- The ratio \(R = A^d_y/A^p_y\) at small \(q\) being measured with a high accuracy (\(\sim 1\%\)) gives an information about spin-spin transversal NN amplitudes.

- The Regge pp-formalism provides an access to \(\bar{p}N\) elastic, but actually was not tested in double spin observables. The necessary data \(A_{NN}\) can be obtained at SPD NICA \(\rightarrow\) to test the pp-amplitudes, to study “oscillation effects” and to test the dispersion relations for pN-data.

- Search of T-invariance violation in double polarized pd and dd scattering at energies corresponding to the early Universe seems to be very important. The elastic (T-even) pN- amplitudes at SPD NICA energies are necessary to analyse data of the dedicated experiment.
NN-forces are fundamental to nuclear physics on the whole. It is important to study a full set of their components, including such small components as spin-spin forces both at low and high energies... via the NN elastic scattering amplitudes
Thank you for attention!
Fig. 2. Calculated results at 12 GeV/c; (a) $d\sigma/dt$, data are from Ref. 20), (b) $P$, data from Refs. 21) and 22), (c) $C_{nn}$, data from Ref. 22), (d) $C_{LL}$, data from Ref. 23).
- Planned experiments to search for CP violation beyond the SM

- Detecting a non-zero **EDM** of elementary fermion (neutron, atoms, charged particles). The current experimental limit

\[ |d_n| \leq 2.9 \times 10^{-26} \text{e cm} \]

is much less as compared the SM estimation (B.H.J. McKellar et al. PLB 197 (1987) 1.4 \times 10^{-33} \text{e cm} \leq |d_n| \leq 1.6 \times 10^{-31} \text{e cm} 

- Search for CP violation in the **neutrino sector** \((\theta_{13} \neq 0, \text{ then generation of lepton asymmetry and via } B - L \text{ conservation to get the BAU})\).

Thouse are T-violating and Parity violating (TVPV) effects.

**Much less attention was paid to T-violating P-conserving (TVPC) flavor conserving effects.**
Search for T-violation in other processes

- Search for T-violation in decays
  \( \bar{n} \to p e\bar{\nu} \) or triple nuclear fussion
  
  \[ W_{if} \sim X s_{n}[k_n \times k_\nu] + R s_{n}[k_n \times s_e] \]

i) FSI with Coulomb
ii) Not all T-odd correlations are related to the true T-invariance violation

- Total cross section of the \( nA \) interaction from forward \( nA \) scattering amplitude

  \[
  f = \underbrace{A + p_n p_T B(s \cdot I)}_{\text{strong}} + p_n C(s \cdot k) + p_n p_T D(s \cdot [k \times I]) +
  \underbrace{p_T E(k \cdot I)}_{\text{PV}} + p_n p_T F(k \cdot I)(s \cdot [k \times I])
  \]

  T-odd correlations in forward elastic scattering (\( = \)in total cross section):

  - Three-fold \( (s \cdot [k \times I]) - \text{TVPV} \)
  - Five-fold \( (k \cdot I)(s \cdot [k \times I]) - \text{TVPC} \)

  TRANSMISSION experiment!
Time-Reversal Violation in the Kaon and $\bar{B}^0$ Meson Systems

- CP-violation in K- and B-meson physics (under CPT) $\implies$ T-violation
- T violation in the K-system:
  $K^0 \rightarrow \bar{K}^0$ and $\bar{K}^0 \rightarrow K^0$

Difference between probabilities was observed
These channels are connected both by T- and CP- transformation!

- Direct observation of T-violation in
  $\bar{B}^0 \rightarrow B_-$ and $B_- \rightarrow \bar{B}^0$

connected only by T-symmetry transformation
(There are three other independent pairs)
J.P. Lees et al. (BABAR Collaboration) PRL 109 (2012) 211801
The results are consistent with current CP-violating measurements obtained invoking CPT-invariance

We will focus on TVPC flavor conserving effects.
This process is described by the transmission factor $T(n)$:

$$T(n) = \frac{I(n)}{I(0)} = \exp(-\sigma_T \rho d n)$$  \hspace{1cm} (5)

with:
- $I(0)$ - Intensity of the primary beam
- $I(n)$ - Intensity of the beam having passed $n$ times the internal target with density $\rho$ and thickness $d$
- $\sigma_T$ - Total cross-section
- $\rho d$ - The areal target density

For the case of polarized particles $\sigma_T$ has to be replaced by:

$$\sigma_T = \sigma_{y,xz} + \sigma_{Loss} = \sigma_o \left(1 + P_y P_{xz} A_{y,xz}\right) + \sigma_{Loss}$$  \hspace{1cm} (6)

with:
- $\sigma_o$ - Unpolarized total cross-section
- $\sigma_{Loss}$ - Loss cross-section, taking account of beam losses outside of the target
\[
\Delta T_{y,xz} = \frac{T^+ - T^-}{T^+ + T^-} = \frac{\exp(-\chi^+) - \exp(-\chi^-)}{\exp(-\chi^+) + \exp(-\chi^-)}
\]

with: 
\( T^+ \) - Transmission factor for the proton-deuteron spin-configuration 
with \( P_y P_{xz} > 0 \)

\( T^- \) - Transmission factor for the time reversed situation, i.e. 
\( P_y P_{xz} < 0 \)

\( \chi^{+/−} \) - Is the product of the factors \((\sigma T \cdot p d \cdot n)\) with respect to the proton-deuteron spin-alignment

this gives:

\[
\Delta T_{y,xz} = -\tanh(\sigma_o \Delta d n P_y P_{xz} A_{y,xz}) \tag{8}
\]

Is the argument of the \( \tanh \) in equation (8) small, then:

\[
\Delta T_{y,xz} = -\sigma_o \rho d n P_y P_{xz} A_{y,xz} =: S A_{y,xz} \tag{9}
\]
$$Del = \frac{\frac{d\sigma}{dt_{\text{data}}} - \frac{d\sigma}{dt_{\text{theor-exp.}}}}{\frac{d\sigma}{dt_{\text{theor-exp.}}}}$$

P. Gauron, B. Nicolescu, O.V. Selyugin, PLB 397 (1997)
To further development of the HEGS model

\[ s = s / s_0 e^{i\pi/2}; \]
\[ s_0 = 4m_p^2. \]
\[ 9 \leq \sqrt{s} \leq 8000 \text{GeV}; \]
\[ n = 980 \rightarrow 3416; \quad 0.00037 < |t| < 15 \text{GeV}^2; \]
\[ F_1^B(s,t) = h_2 G_{em}(t) \left( \hat{s} \right)^{\Delta_1} e^{\alpha' / (2t \ln(\hat{s})}; \]
\[ F_3^B(s,t) = h_3 G_A(t)^2 \left( \hat{s} \right)^{\Delta_1} e^{\alpha' / 4t \ln(\hat{s})}; \]
\[ F^B(\hat{s},t) = F_2^B(\hat{s},t) \left( 1 + R_1 / \sqrt{\hat{s}} \right) + F_3^B(\hat{s},t) \left( 1 + R_2 / \sqrt{\hat{s}} \right) \]
\[ + F_{\text{odd}}(s,t); \quad \alpha'(t) = (\alpha_1 + k_0 q e^{k_0 t \ln(\hat{s})}) \ln(\hat{s}). \]
\[ F_{\text{odd}}^B(s,t) = h_{\text{odd}} G_A(t)^2 \left( \hat{s} \right)^{\Delta_1} \frac{t}{1 - r^2 \hat{s}} e^{\alpha' / 4t \ln(\hat{s})}; \]
\[ F^{+-}(s,t) = h_{sf} q^3 G_{em}(t)^2 e^{\mu t}; \]

M.Galynskii, E.Kuraev, JETP Letters (2012)
A problem with dispersion relations at 5-8 GeV/c.

anti p - p
\[ M = \frac{1}{2} \left\{ (a + b) + (a - b) \sigma_{1n} \sigma_{2n} + (c + d) \sigma_{1m} \sigma_{2m} + (c - d) \sigma_{1l} \sigma_{2l} + e(\sigma_{1n} + \sigma_{2n}) + f(\sigma_{1n} - \sigma_{2n}) + \right. \\
\left. + \ g(\sigma_{1l} \sigma_{2m} + \sigma_{1m} \sigma_{2l}) + h(\sigma_{1l} \sigma_{2m} - \sigma_{1m} \sigma_{2l}) \right\}, \]

where

\[ l = \frac{k_f + k_i}{|k_f + k_i|}, \quad m = \frac{k_f - k_i}{|k_f - k_i|}, \quad n = \frac{k_i \times k_f}{|k_i \times k_f|} \]

\[ f = h = 0. \]
Available experimental data set on the differential cross sections for the elastic $dp$, $dd$ and $pd$ collisions in CM and Collider systems.

Colliding $d^+d^-$ beams. Beam kinetic energy $T_d$: 2-5.5 GeV/u

Elastic $dd$, $dp$ CM, Col diff. cross sect. $d\sigma/d\Omega_{CM,Col}$, mb/sr

- $T_d_{Lab}=6.244$ GeV
- $T_d_{CM}=1.186$ GeV
- $\theta_{1,3}_{CM}=19.2^\circ$
- $t_{1,3}=-0.65$ (GeV/c)$^2$

- $T_d_{Lab}=1.015$ GeV
- $T_d_{CM}=0.239$ GeV
- $\theta_{1,3}_{CM}=88.36^\circ$
- $t_{1,3}=-1.85$ (GeV/c)$^2$

ISR $dd/s=63$ GeV
- $T_d_{CM}=29.624$ GeV
- $\theta_{1,3}_{CM}=2.164^\circ$
- $t_{1,3}=-1.41$ (GeV/c)$^2$

- $T_d_{Lab}=4.986$ GeV
- $T_d_{Col}=0.988$ GeV
- $\theta_{1,3}_{Col}=95.40^\circ$
- $t_{1,3}=-6.593$ (GeV/c)$^2$

Count rate $R$ at luminosity $L_r = 1 \times 10^{30}$ cm$^{-2}$s$^{-1}$

- $pd = 0.135$ GeV
- $pd = 0.180$ GeV
- $dp = 0.447$ GeV
- $dp = 0.454$ GeV
- $dp = 0.641$ GeV
- $dp = 0.851$ GeV
- $dp = 0.988$ GeV
- $dp = 0.223$ GeV
- $dp = 0.239$ GeV
- $dp = 0.410$ GeV
- $dp = 0.722$ GeV
- $dp = 0.894$ GeV
- $dp = 1.186$ GeV
- $dp = 1.214$ GeV
- $dd = 1.442$ GeV
- $dd = 2.545$ GeV

For $dd/s=53$ GeV

- $dd/s=53$ GeV
- $dd/s=63$ GeV

- $pd/s=53$ GeV
- $pd/s=63$ GeV
What can be done at SPD NICA?

- Measurement of spin observables \( \left( \frac{d\sigma}{dt}, A^p_y, A^d_y, A_{yy}, A_{xx}, C_{i,j} \right) \) of \( pd\)- elastic, \( pd \rightarrow n\{pp\}, dd \rightarrow dd, dd \rightarrow \{pp\} + \{nn\} \).

Available Regge formalism for pp amplitudes at \( P_L = 3 - 50 \) GeV/c (A. Sibirtsev et al. 2010; W. Ford, J.W. Van orden, 2013) can be used for calculation of these observables within the Glauber theory. Comparison between data and theory will be a clean test for the pp- and pn- elastic amplitudes.

- This Regge pp-formalism provides an access to \( \bar{p}N \) elastic, but actually was not tested in double spin observables at i) \( >4 \) GeV/c at ii) forward pp-scattering angles. The necessary data on \( A_{NN}, A_{LL}, ... \) can be obtained at SPD NICA \( \Rightarrow \) test of the pp-amplitudes, dispersion relations for \( pN, \bar{p}N\)-data, study of “oscillation effects”.

- New theoretical model for pN-elastic scattering amplitudes at NICA energies with minimum free parameters will be developed (O.V. Selyugin) interpolating between 3 GeV and 10 TeV.

- Search of T-invariance violation in double polarized pd-, and dA- scattering at energies corresponding to the early Universe was not yet performed. The elastic (T-even) pN- amplitudes at SPD NICA energies are necessary to analyse data of the dedicated experiment.
\[ \sigma_{\text{tot}} = \sigma_0 + \sigma_1 \mathbf{p}^p \cdot \mathbf{P}^d + \sigma_2 (\mathbf{p}^p \cdot \hat{\mathbf{k}})(\mathbf{P}^d \cdot \hat{\mathbf{k}}) + \sigma_3 P_{zz} + \tilde{\sigma}_{\text{tppc}} p^p P^d \]

whith

\[
\sigma_0 = \frac{4\pi}{k} \text{Im} \frac{2g_1 + g_2}{3}, \quad \sigma_1 = -\frac{4\pi}{k} \text{Im} g_3, \\
\sigma_2 = -\frac{4\pi}{k} \text{Im} (g_4 - g_3), \quad \sigma_3 = \frac{4\pi}{k} \text{Im} \frac{g_1 - g_2}{6}.
\]

Yu.N. Uzikov, J. Haidenbauer, PRC 79 (2009) 024617; PRC 87 (2013) 054003,

\[ \tilde{\sigma}_{\text{tppc}} = -\frac{4\pi}{k} c \text{Im} g_5 \]
\[ \frac{1}{2} + 1 \rightarrow \frac{1}{2} + 1 \]

\[(2 + 1)^2 (2\frac{1}{2} + 1)^2 = 36 \text{ transition amplitudes}\]
P-parity $\Rightarrow$ 18 independent amplitudes
T-invariance for $pd \rightarrow pd$ $\Rightarrow$ 12 independent amplitudes

Transition matrix element

\[ M_{fi} = \langle \mu' \lambda' | M | \mu \lambda \rangle \]