Measurements of the ratio R_{dp} of the quasi-elastic nd →pnn to the elastic np → pn charge-exchange process yields at 0º 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 $R_{dp} = d\sigma/d\Omega(nd) / d\sigma/d\Omega(np)$ 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.

Participants of this study

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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 $np \to pn$ at 0^o 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 $R_{dp} = [d\sigma/d\Omega(nd \to pnn)] / [d\sigma/d\Omega(np \to pn)]$ for elastic charge exchange process $np \to pn$ at 0^o 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.**

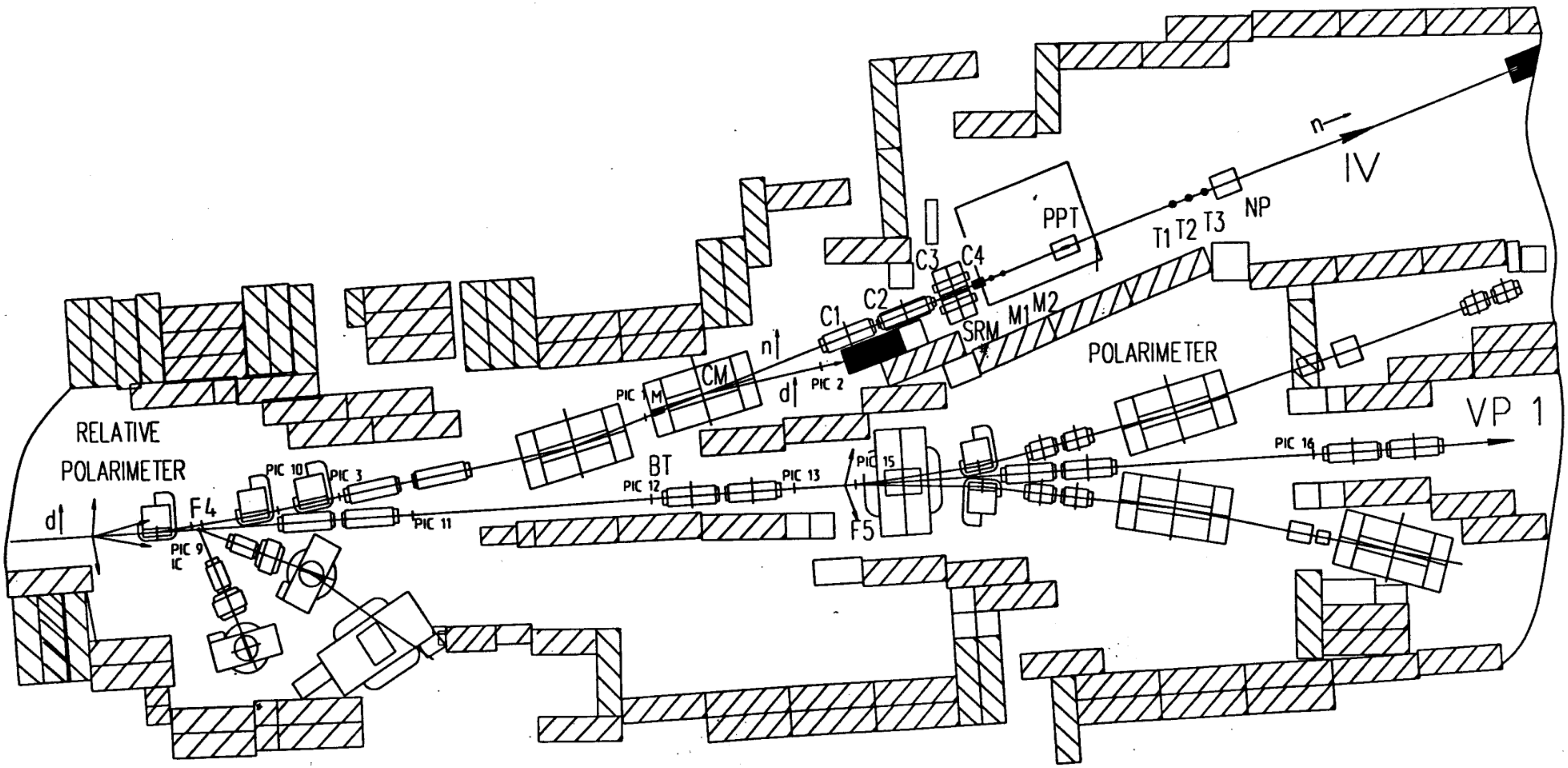
  Relativistic 1 – 5 GeV
  - **polarized neutron beams with average polarization value of 0.53,**
    orientation of polarization L or T and
    reversion of polarization direction from cycle to cycle;
  - **unpolarized neutron beam with high intensity**
    ($4x10^6$ n/cycle at T_n = 2 GeV).

- **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**

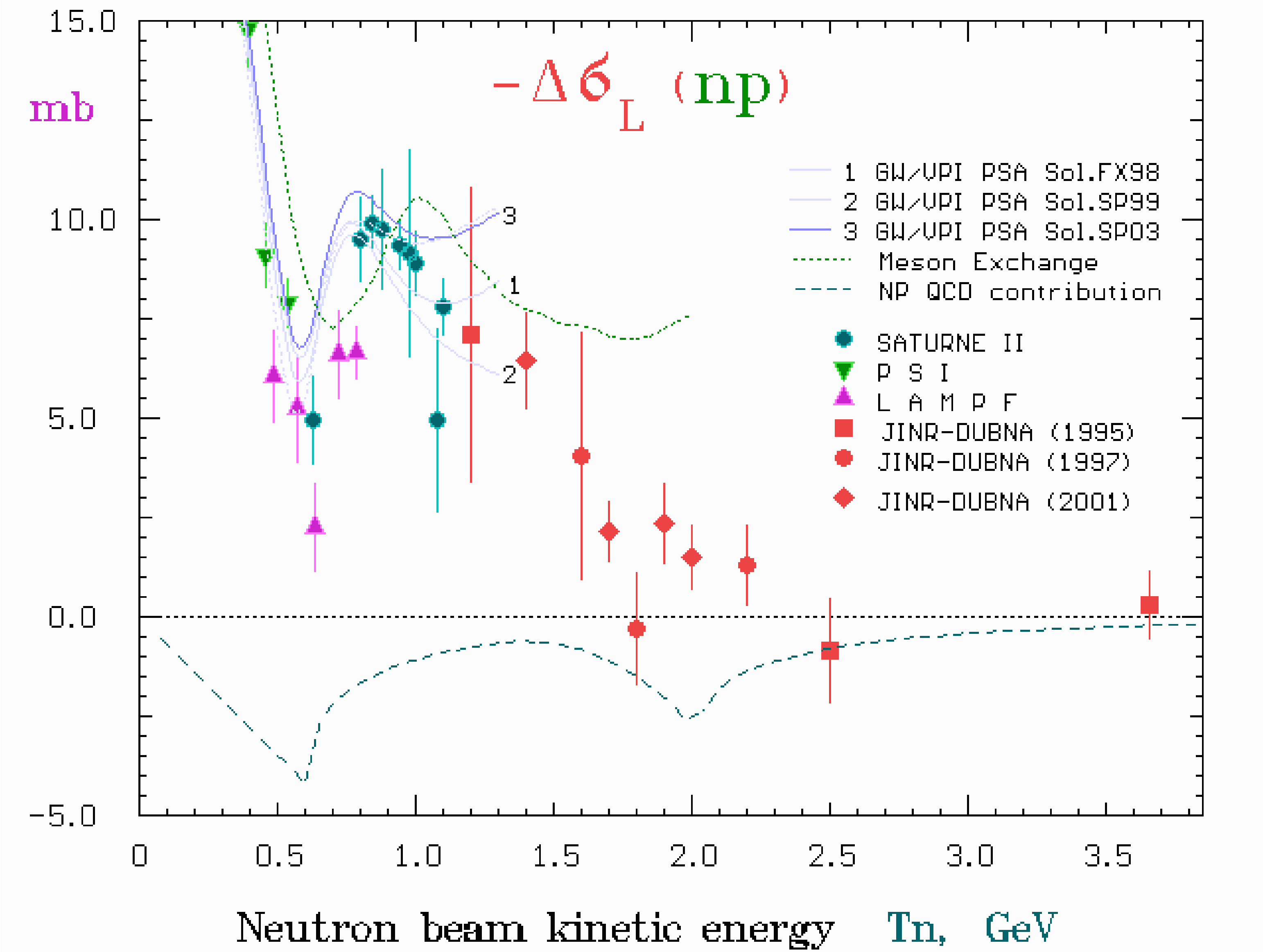
Measurements of the $-\Delta\sigma_L$ (np) energy dependence were in the main completed using L-polarized neutron beam at the Synchrophasotron facility and the Dubna L-polarized proton target .

Results were published in:

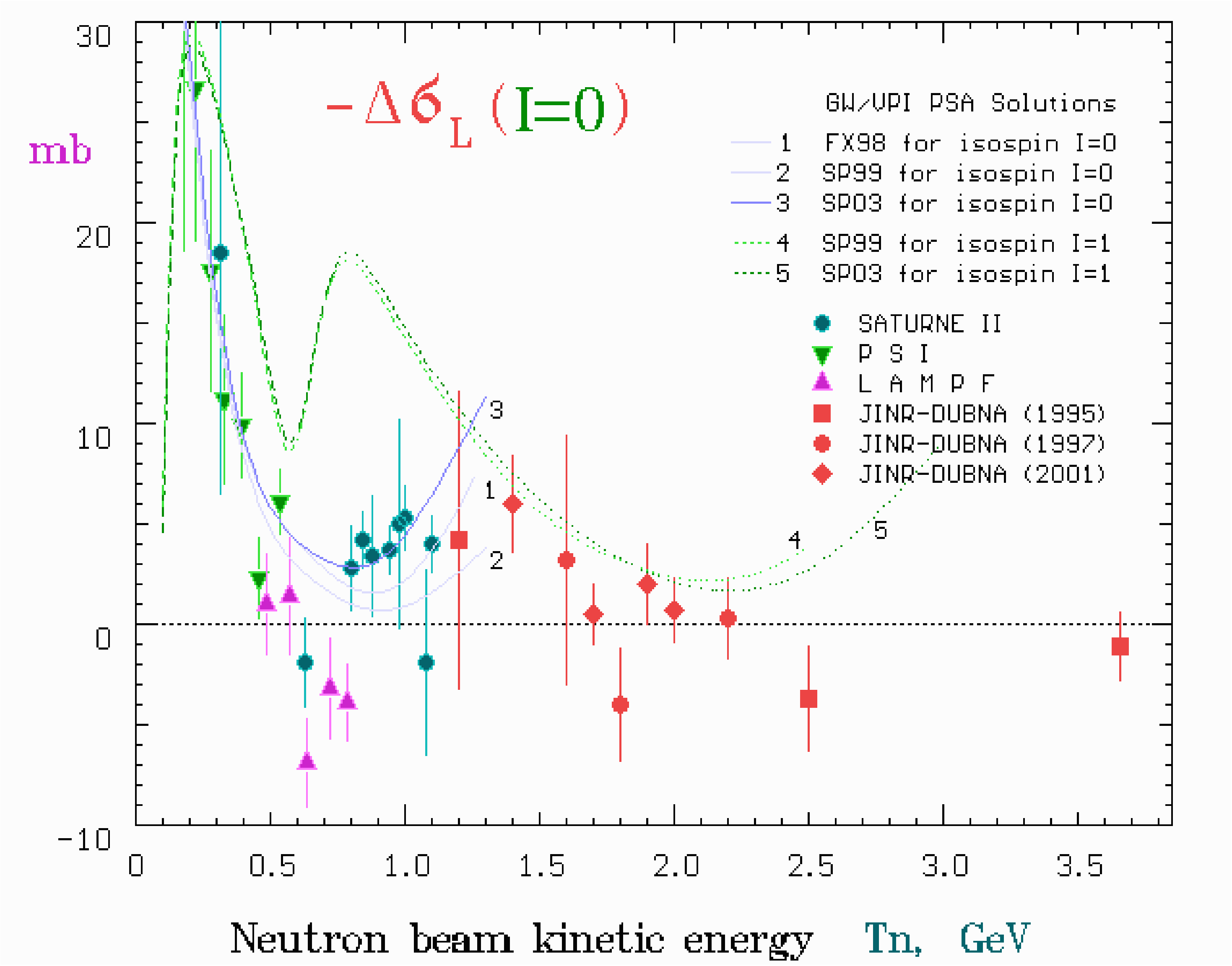
References on $-\Delta\sigma_L$ (np) results

1. B.P.Adiasevich, V.G.Antonenko, S.A.Averichev, L.S.Azhgirey et al.
   Zeitschrift fur Physik C71 (1996) 65.
2. V.I.Sharov, S.A.Zaporozhets, B.P.Adiasevich, V.G.Antonenko et al.
   JINR Rapid Communications 3[77]-96 (1996) 13.
3. V.I.Sharov, S.A.Zaporozhets, B.P.Adiasevich, N.G.Anischenko et al.
   JINR Rapid Communications 4[96]-99 (1999) 5.
4. V.I.Sharov, S.A.Zaporozhets, B.P.Adiasevich, N.G.Anischenko et al.
   European Physical Journal C13 (2000) 255.
5. V.I.Sharov, N.G.Anischenko, V.G.Antonenko, S.A.Averichev et al.
   European Physical Journal C37 (2004) 79-90.
6. V.I.Sharov, N.G.Anischenko, V.G.Antonenko, S.A.Averichev et al.
   Yadernaya Fizika v.68, №11 (2005) 1858-1873.
   Physics of Atomic Nuclei v.68, №11 (2005) 1796-1811.

Energy Dependence of the $-\Delta\sigma_L$ (np) Observable Obtained with Free Neutron Polarized Beams

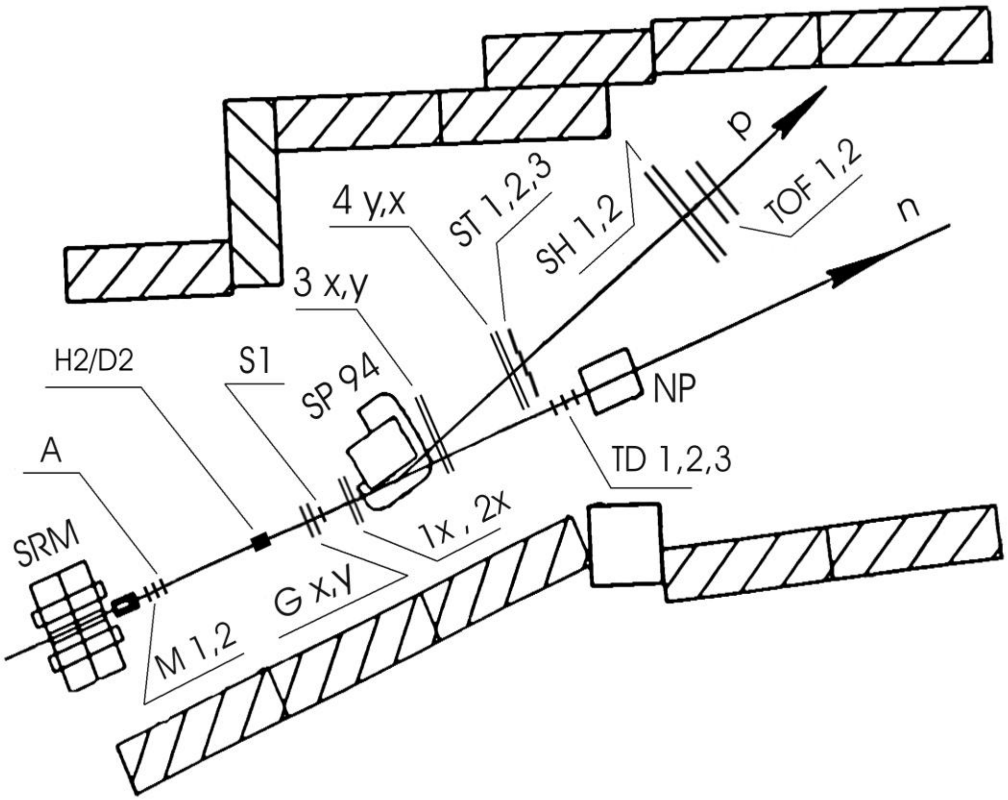


Energy Dependence of the $-\Delta\sigma_L$ (I=0)



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.



Spectrometer of the “Delta-Sigma” set-up

- 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 analyzis 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.

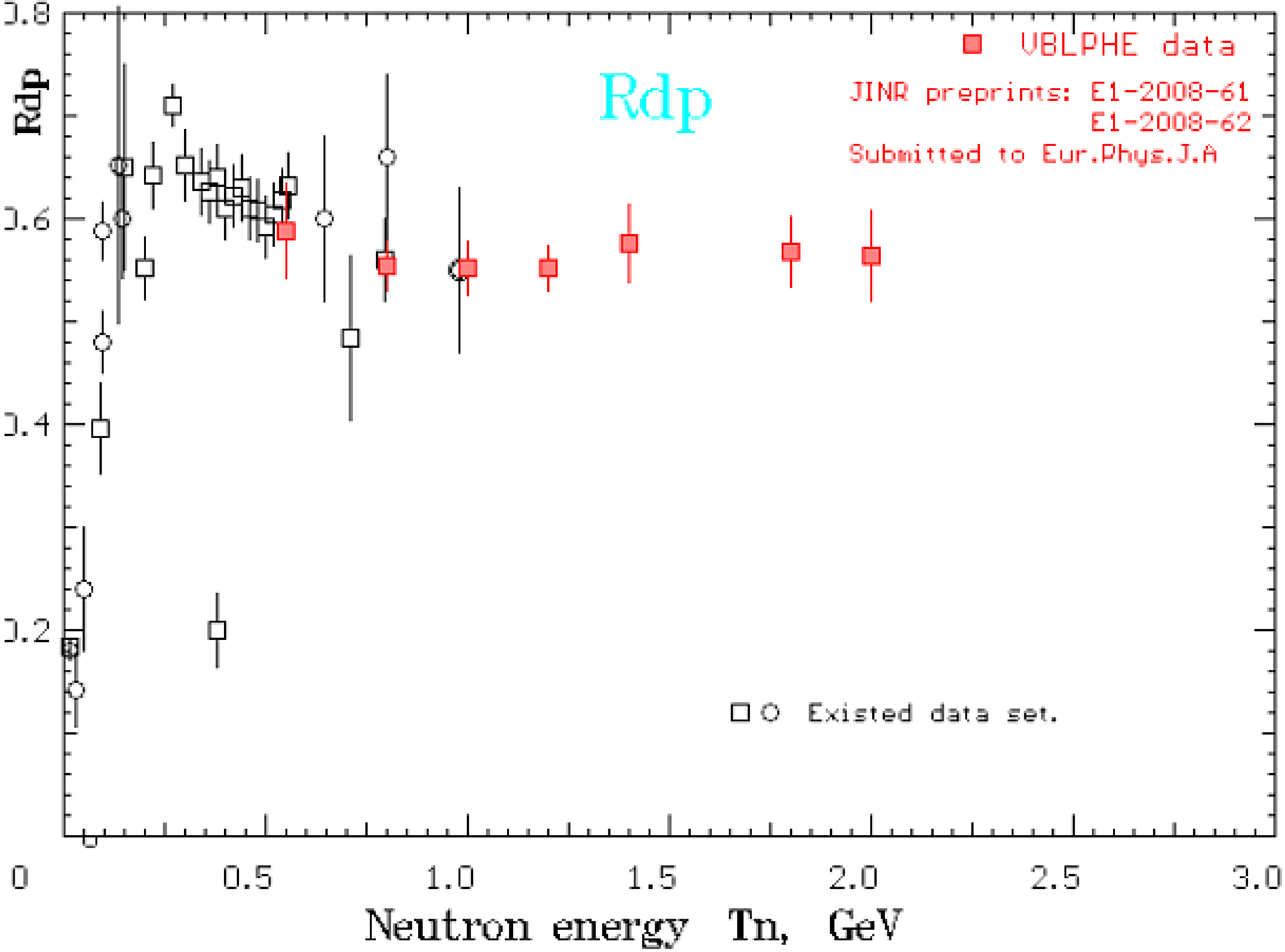
Estimations for data at Tn = 1.4 GeV.

Sources of systematic error	Absolute values of the Rdp error
1. Total PC efficiency	**0.0027**
2. Trigger PC efficiency	**0.0026**
3. Efficiency of the DTS	**0.0179**
4. Efficiency of TOF	**0.0034**
5. Error in shift determination of the H2 and D2 elastic peak center positions	**0.0177**
6. Number of H/D nuclei in the targets	**0.0014**
Total:	**0.0257**

Values of $R_{dp} = d\sigma/d\Omega\,(nd) / d\sigma/d\Omega\,(np)$.

Total errors are the quadratic sums of statistical and systematic uncertainties.

NN	Tn, GeV	Pn, GeV/c	R_{dp}	Errors Stat.	Syst.	Total
1	0.550	1.1559	**0.589**	0.024	0.039	**0.046**
2	0.800	1.4640	**0.554**	0.017	0.016	**0.023**
3	1.000	1.6968	**0.553**	0.011	0.023	**0.026**
4	1.200	1.9222	**0.551**	0.011	0.019	**0.022**
5	1.400	2.1426	**0.576**	0.028	0.026	**0.038**
6	1.800	2.5734	**0.568**	0.016	0.029	**0.033**
7	2.000	2.7854	**0.564**	0.014	0.042	**0.045**



Rdp
Rdp
VBLPHE data
JINR preprints: E1-2008-61
E1-2008-62
Submitted to Eur.Phys.J.A
Existed data set.
0.8
0.6
0.4
0.2
0
0.5
1.0
1.5
2.0
2.5
3.0
Neutron energy Tn, GeV

Nucleon-Nucleon Formalism

Throughout the project and results publications we used the NN formalism and notations for elastic nucleon-nucleon scattering observables from Bystricky J., Lehar F., Winternitz P. J. Phys. (Paris). 1978. v.39. p. 1.
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

$$M(\mathbf{k}', \mathbf{k}) = \tfrac{1}{2}\,[(a+b)+(a-b)(\boldsymbol{\sigma}_1,\mathbf{n})(\sigma_2,n)+(c+d)(\boldsymbol{\sigma}_1,\mathbf{m})(\boldsymbol{\sigma}_2,\mathbf{m})+(c-d)(\boldsymbol{\sigma}_1,\mathbf{l})(\boldsymbol{\sigma}_2,\mathbf{l})+e(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2,\mathbf{n})], \quad (1)$$

where $\boldsymbol{\sigma}_1$ and $\boldsymbol{\sigma}_2$ 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 θ.

In the forward direction at θ=0, total angular momentum conservation implies that e=0 and a-b=c+d. Similarly at 180° one obtains e=0 and a-b=c-d.

The center of mass basis vectors are given by

$$\mathbf{l} = (\mathbf{k}'+\mathbf{k})/(|\mathbf{k}'+\mathbf{k}|), \quad \mathbf{m} = (\mathbf{k}'-\mathbf{k})/(|\mathbf{k}'-\mathbf{k}|), \quad \mathbf{n} = (\mathbf{k}'\times\mathbf{k})/(|\mathbf{k}'\times\mathbf{k}|). \quad (2)$$

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

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

where τ_1 and τ_2 are isosinglet and isotriplet scattering matrices. Ignoring electromagnetic interaction, one can write

$$M(pp\rightarrow pp) = M(nn\rightarrow nn) = M_1, \qquad (4a)$$

$$M(np\rightarrow np) = M(pn\rightarrow pn) = \tfrac{1}{2} (M_1+M_0), \qquad (4b)$$

$$M(np\rightarrow pn) = M(pn\rightarrow np) = \tfrac{1}{2} (M_1-M_0). \qquad (4c)$$

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

$$d\sigma/d\Omega\, X_{pqik} = \tfrac{1}{4} Tr\, (\sigma_{1p}\, \sigma_{2q}\, M\, \sigma_{1i}\, \sigma_{2k}\, M^+), \qquad (5)$$

where

$$d\sigma/d\Omega = I_{0000} = \tfrac{1}{4} Tr\, (M\, M^+), \qquad (6)$$

is the unpolarized differential cross section.

Experimental observable

$$R_{dp} = d\sigma/d\Omega(nd\to pnn) \,/\, d\sigma/d\Omega(np\to pn) \qquad (7)$$

is the ratio of a quasi-elastic nd charge-exchange process yield to the free elastic np one. In frame of impulse approximation following by

L.I. Lapidus, J. Exp. Theor. Phys. 32, 1957, 1437,

N.W. Dean, Phys. Rev. D 5, 1972, 1661; 2832,

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

$$d\sigma/d\Omega(nd) = (2/3)\cdot d\sigma/d\Omega^{SD}(np), \qquad (8)$$

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

This gives

$$R_{dp} = (2/3)\cdot d\sigma/d\Omega^{SD}(np) \,/\, d\sigma/d\Omega(np). \qquad (9)$$

Using the invariant NN amplitudes formalism

J. Bystricky, F. Lehar, P. Winternitz , J. Phys. (Paris). 1978. v.39. p. 1,

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

(F.Lehar. Private communication)

$$R_{dp}(0,\pi) = (2/3)\cdot [0.25\cdot |a - b|^2 + 0.5\cdot (|c|^2 + |d|^2)] \,/\, 0.5\cdot (|a|^2 + |b|^2 + |c|^2 + |d|^2). \qquad (10)$$

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→np and pp→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

R.A.Arndt, C.H.Oh, I.I.Strakovsky, R.L.Workman, and F.Dohrmann,

"Nucleon-nucleon elastic scattering analysis to 2.5 GeV",

Phys. Rev. C 56, 3005 (1997) [nucl-th/9706003].

SP00

R.A.Arndt, I.I.Strakovsky, and R.L.Workman,

"Nucleon-nucleon elastic scattering to 3 GeV",

Phys. Rev. C 62, 034005 (2000) [nucl-th/0004039].

SP07

R.A.Arndt, W.J.Briscoe, I.I.Strakovsky, and R.L.Workman,

"Updated analysis of NN elastic scattering to 3 GeV",

Phys. Rev. C 76, 025209 (2007); arXiv:0706.2195 [nucl-th].

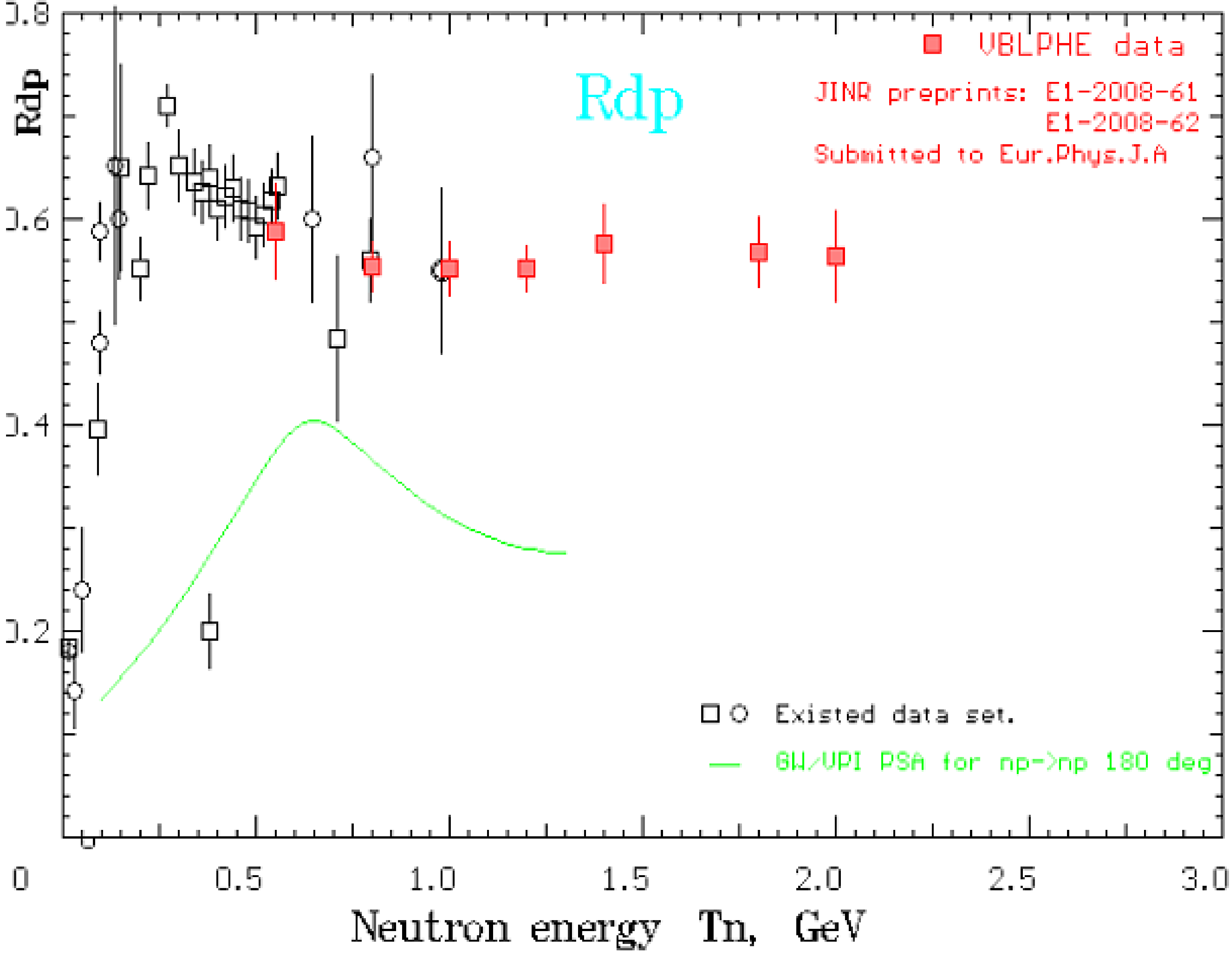
The amplitudes np→np are the mixture of pure isospin I=1 and I=0 states amplitudes according Eq. (4b)

Amp (np) = ½ (Amp (I=1 (pp)) + Amp (I=0)) **(11)**

and Amp (I=0) = 2 Amp (np) - Amp (I=1(pp)). **(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→np scattering at $\theta_{CM} = \pi$ one can obtained by Eq. (10) using either Amp (np) set or ½ (Amp (I=1) + Amp (I=0)) one.


Rdp
Rdp
VBLPHE data
JINR preprints: E1-2008-61
E1-2008-62
Submitted to Eur.Phys.J.A
Existed data set.
GW/VPI PSA for np->np 180 deg
0.8
0.6
0.4
0.2
0
0.5
1.0
1.5
2.0
2.5
3.0
Neutron energy Tn, GeV

To obtain the R_{dp} values for the elastic np→pn charge exchange at $\theta_{CM} = 0$ one needs to perform the k'→- k' and n→p transformations of the Amp (I=1) and Amp (I=0) sets according to Table 1.
(J. Bystricky, F. Lehar, P. Winternitz , J. Phys. (Paris). 1978. v.39. p. 1)

Table 1. Symmetry properties of the NN invariant amplitudes.

I=0 amplitudes	I=1 amplitudes
$a_o(\theta) = + a_o(\pi - \theta)$	$a_1(\theta) = - a_1(\pi - \theta)$
$b_o(\theta) = + c_o(\pi - \theta)$	$b_1(\theta) = - c_1(\pi - \theta)$
$c_o(\theta) = + b_o(\pi - \theta)$	$c_1(\theta) = - b_1(\pi - \theta)$
$d_o(\theta) = - d_o(\pi - \theta)$	$d_1(\theta) = + d_1(\pi - \theta)$
$e_o(\theta) = - e_o(\pi - \theta)$	$e_1(\theta) = + e_1(\pi - \theta)$

The scattering matrix simplifies at the forward $\theta_{CM} = 0$ and backward $\theta_{CM} = \pi$ angles.

The amplitudes at these angles satisfy

$$a(0) - b(0) = c(0) + d(0), \qquad e(0) = 0,$$

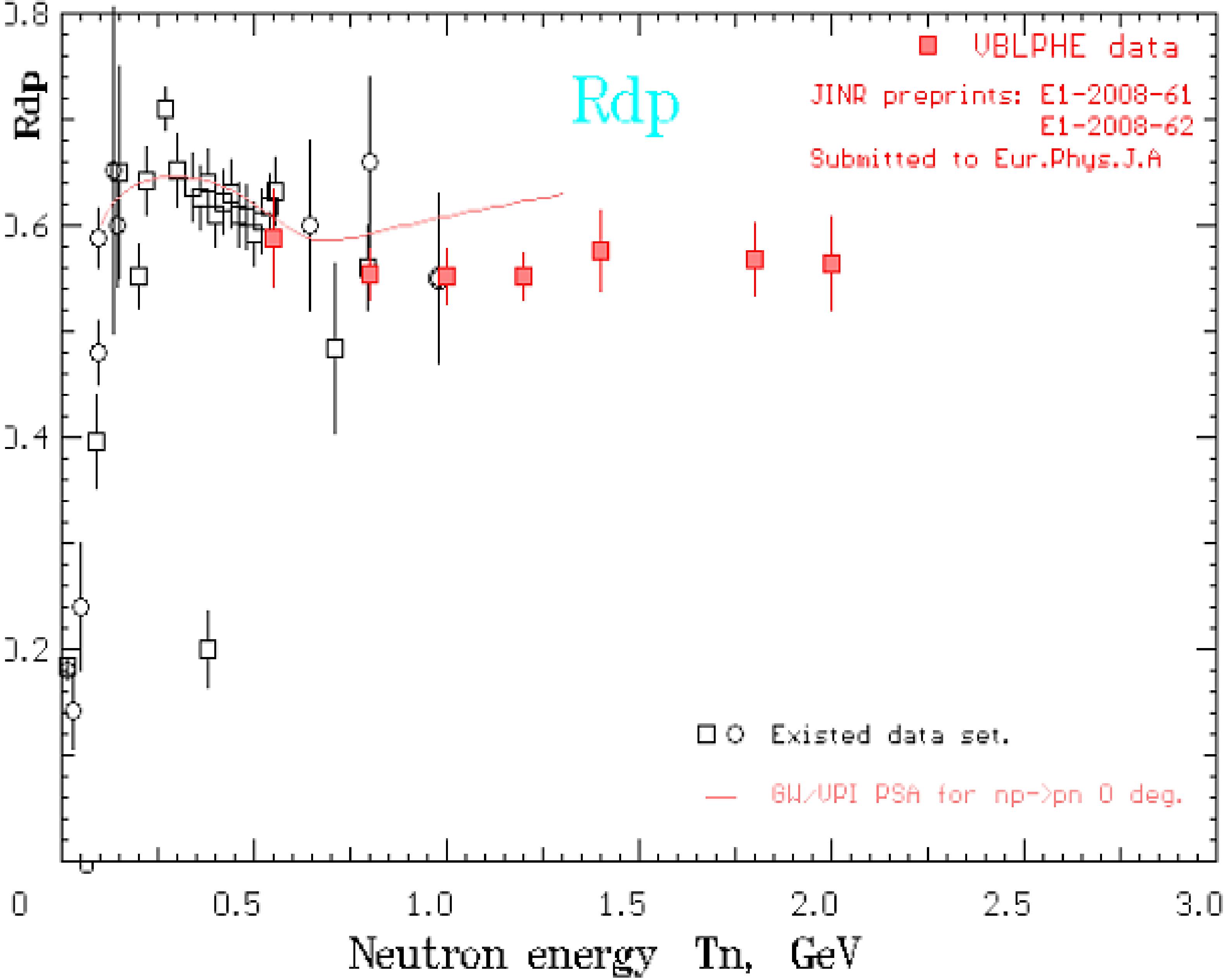
$$a(\pi) - b(\pi) = c(\pi) - d(\pi), \qquad e(\pi) = 0.$$

The $np \to np$ elastic scattering and $np \to pn$ charge exchange differential cross sections are given by

$$d\sigma/d\Omega = \tfrac{1}{2} (|a|^2 + |b|^2 + |c|^2 + |d|^2 + |e|^2)$$

and equal each other.

The R_{dp} values for the elastic $np \to pn$ charge exchange at $\theta_{CM} = 0$ one can obtained by Eq. (10) using ½ (Amp (I=1) - Amp (I=0)) set of the transformed NN amplitudes.



Rdp
Rdp
VBLPHE data
JINR preprints: E1-2008-61
E1-2008-62
Submitted to Eur.Phys.J.A
Existed data set.
GW/VPI PSA for np->pn 0 deg.
0.8
0.6
0.4
0.2
0
0.5
1.0
1.5
2.0
2.5
3.0
Neutron energy Tn, GeV

Conclusions

1. New results at $\theta_{CM} = 0$ for $R_{dp} = d\sigma/d\Omega(nd) / d\sigma/d\Omega(np)$ – the ratio of a quasi-elastic $nd \rightarrow pnn$ charge exchange yield to the free elastic $np \rightarrow pn$ 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 $np \rightarrow np$ and $pp \rightarrow pp$ scattering at $\theta_{CM} = \pi$ were performed.

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

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

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

6. It is shown that the Eq. (10) gives one additional relation between spin-dependent 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.