MEASUREMENTS OF ENERGY BEHAVIOURS OF SPIN-DEPENDENT np - OBSERVABLES OVER 1.2 - 3.7 GEV REGION

Dubna "Delta-Sigma" Experiment

V.I. Sharov[1,a], N.G. Anischenko[1], V.G. Antonenko[2], S.A. Averichev[1], L.S. Azhgirey[3], V.D. Bartenev[1], N.A. Bazhanov[3], A.A. Belyaev[5], N.A. Blinov[1], N.S. Borisov[3], S.B. Borzakov[6], Yu.T. Borzunov[1], Yu.P. Bushuev[1], L.P. Chernenko[6], E.V. Chernykh[1], V.F. Chumakov[1], S.A. Dolgii[1], A.N. Fedorov[3], V.V. Fimushkin[1], M. Finger[3,7], M. Finger, Jr.[3], L.B. Golovanov[1], G.M. Gurevich[8], D.K. Guriev[11], A. Janata[3], A.D. Kirillov[1], V.G. Kolomiets[3], E.V. Komogorov[1], A.D. Kovalenko[1], A.I. Kovalev[4], V.A. Krasnov[1], P. Krstonoshich[3], E.S. Kuzmin[3], N.A. Kuzmin[11], V.P. Ladygin[1], A.B. Lazarev[3], F. Lehar[9], A. de Lesquen[9], M.Yu. Liburg[1], A.N. Livanov[1], A.A. Lukhanin[5], P.K. Maniakov[1], V.N. Matafonov[3,†], E.A. Matyushevsky[1], V.D. Moroz[1,†], A.A. Morozov[1], A.B. Neganov[3], G.P. Nikolaevsky[1], A.A. Nomofilov[1], Tz. Panteleev[6,10], Yu.K. Pilipenko[1], I.L. Pisarev[3], Yu.A. Plis[3], Yu.P. Polunin[2], A.N. Prokofiev[4], V.Yu. Prytkov[1], P.A. Rukoyatkin[1], V.A. Schedrov[4], O.N. Schevelev[3], S.N. Shilov[3], R.A. Shindin[1], M. Slunečka[3,7], V. Slunečková[3], A.Yu. Starikov[1], G.D. Stoletov[3,†], L.N. Strunov[1], A.L. Svetov[1], Yu.A. Usov[3], T. Vasiliev[1], V.I. Volkov[1], E.I. Vorobiev[1], I.P. Yudin[11], I.V. Zaitsev[1], A.A. Zhdanov[4], V.N. Zhmyrov[3]

[1)] Joint Institute for Nuclear Research, Veksler and Baldin Laboratory of High Energies, 141980 Dubna, Russia

[2)] Russian Scientific Center "Kurchatov Institute", 123182 Moscow, Russia

[3)] Joint Institute for Nuclear Research, Dzhelepov Laboratory of Nuclear Problems, 141980 Dubna, Russia

[4)] St.Petersburg Nuclear Physics Institute, High Energy Physics Division, 188350 Gatchina, Russia

[5)] Kharkov Institute of Physics and Technology, 310108 Kharkov, Ukraine

[6)] Joint Institute for Nuclear Research, Frank Laboratory of Neutron Physics, 141980 Dubna, Russia

[7)] Charles University, Faculty of Mathematics and Physics, V Holešovičkách 2, 180 00 Praha 8, Czech Republic

[8)] Institute for Nuclear Research, Russian Academy of Sciences, 117312 Moscow, Russia

[9)] DAPNIA, CEA/Saclay, 91191 Gif-sur-Yvette Cedex, France

[10)] Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Tsarigradsko shaussee boulevard 72, 1784 Sofia, Bulgaria

[11)] Joint Institute for Nuclear Research, Laboratory of Particle Physics, 141980 Dubna, Russia

[a] *e-mail: sharov@sunhe.jinr.ru*

† *Deceased*

Abstract
New accurate data on the neutron-proton spin-dependent total cross section difference $\Delta\sigma_L(np)$ at the neutron beam kinetic energies 1.4, 1.7, 1.9 and 2.0 GeV are presented. A number of physical and methodical results on investigation of an elastic $np \to pn$ charge exchange process over a few GeV region are also presented. Measurements were carried out at the Synchrophasotron and Nuclotron of the Veksler and Baldin Laboratory of High Energies of the Joint Institute for Nuclear Research.
Keywords: relativistic polarized neutron beam, polarized proton target, total cross section difference, spin correlation parameters, charge exchange process.

1. Introduction

The investigations were performed under the program of the first priority JINR project "Delta-Sigma" Experiment. (For more detailed information see *http://www.jinr.ru/PAC_2003_nov/PAC – PP/*). Full name of the project is "Determination of spin-dependent elastic np forward scattering amplitudes over 1.2 3.7 GeV region: measurements of $\Delta\sigma_{L,T}(np)$ and $A_{00kk}(np)$ and $A_{00nn}(np)$ - total np cross sections differences and spin-correlation parameters from $np \to pn$ scattering".

The aim of the project is to extend investigations of NN interaction over the new high energy region (1.2 - 3.7 GeV) of free polarized neutron beams, *provided only by the JINR VBLHE accelerators at present.* The main task of these studies is to determine the imaginary and real parts of spin dependent forward scattering np amplitudes over this energy region for the first time. For this purpose a sufficient data set of np spin dependent observables has to be obtained for the direct reconstruction of scattering amplitudes at several energies.

THE "DELTA-SIGMA" EXPERIMENT RESEARCH PROGRAM.

Using longitudinally (L) and transverse (T) *polarized neutron beams* and the Dubna movable *polarized proton target* (PPT) to measure the energy dependences of following quantities:

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

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

c) using *the high intensity unpolarized neutron beam* and the *liquid hydrogen or deuterium targets*, to measure at the same energies as for item a) the ratio $R_{dp} = d\sigma/d\Omega(nd)/d\sigma/d\Omega(np)$ for elastic charge exchange process $np \to pn$ at 0° with statistical errors of $\sim 5\,\%$.

The observables $\Delta\sigma_L$ and $\Delta\sigma_T$ as well as $\sigma_{0\mathrm{tot}}$ are obtained in transmission measurements. They are linearly related to the imaginary parts of forward scattering NN invariant amplitudes via optical theorems and allow to extract their imaginary parts.

The $A_{00kk}(np)$ and $A_{00nn}(np)$ values will be obtained by a registration of yields of protons from elastic charge exchange process $np \to pn$ at 0°. They are bilineary related to real parts of amplitudes which can be extracted from measured data.

The ratio R_{dp} of differential cross sections on deuterium and hydrogen targets gives one additional relation between NN-amplitudes and a set of such data allows to avoid one uncertainty of the real parts determination.

The data set of energy dependences of 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 contribute to extend NN phase shift analysis (PSA) to high energies and to check the predictions of dynamical models.

THE ACCELERATORS AND TOOLS.

1. The Synchrophasotron and Nuclotron of the JINR VBLHE.
2. Relativistic (1-5 GEV)

a) *polarized neutron beams* with L or T orientation of polarization, reversion of polarization direction cycle by cycle and average polarization value of ~ 0.53;
b) *high intensity* $(2-3)\cdot 10^{10}$ *d/cycle unpolarized deuteron beam.*

3. Large *polarized proton target (PPT)* with volume of $140 cm^3$ and polarization value of 0.7-0.8.
4. Cryogenic *liquid hydrogen* H_2 *and deuterium* D_2 *targets* 30 cm long.
5. Experimental set-up "DELTA-SIGMA" with

a) monitor and transmission neutron detectors;
b) magnetic spectrometer with multiwire proportional chambers (MPC);
c) detectors for target surrounding (DTS);
d) time-of-flight (TOF) system and
e) data acquisition system.

In the following sections a determination of the NN spin-dependent observables and some results of investigations under the "Delta-Sigma experiment" program will be done. The last accurate data [1, 2] on the neutron-proton spin-dependent total cross section difference $\Delta\sigma_{\rm L}(np)$ at the neutron beam kinetic energies 1.4, 1.7, 1.9 and 2.0 GeV will be presented. A number of physical and methodical results on investigation of the elastic $np \to pn$ charge exchange process over the energy region under discussion will be also presented.

2. The $\Delta\sigma_{L,T}(np)$ observables

In this contribution, we use NN formalism and the notations for elastic nucleon-nucleon scattering observables from [3].

The general expression for the total cross section of a polarized nucleon beam trasmitted through a polarized proton target, with arbitrary directions of beam and target polarizations is

$$\sigma_{\rm tot} = \sigma_{\rm 0tot} + \sigma_{\rm 1tot}(\mathbf{P}_{\rm B}, \mathbf{P}_{\rm T}) + \sigma_{\rm 2tot}(\mathbf{P}_{\rm B}, \mathbf{k})(\mathbf{P}_{\rm T}, \mathbf{k}), (1)$$

where $\mathbf{P_B}$ and $\mathbf{P_T}$ are the beam and target polarizations, and $\mathbf{k}$ is a unit vector in the direction of the beam momentum. The term $\sigma_{\rm 0tot}$ is the total cross section for unpolarized particles, $\sigma_{\rm 1tot}$ and $\sigma_{\rm 2tot}$ are the spin-dependent contributions. They are related to the measurable observables $\Delta\sigma_{\rm T}$ and $\Delta\sigma_{\rm L}$ by:

$$-\Delta\sigma_{\rm T} = 2\sigma_{\rm 1tot}, (()2)$$

$$-\Delta\sigma_{\rm L} = 2(\sigma_{\rm 1tot} + \sigma_{\rm 2tot}), (()3)$$

Values of $\sigma_{\rm 0tot}$, $\Delta\sigma_{\rm T}$ and $\Delta\sigma_{\rm L}$ are connected with the imaginary parts of three invariant forward scattering amplitudes $a+b$, c and d via three optical theorems

$$\sigma_{\rm 0tot} = (2\pi/K)\ {\rm Im}\ [a(0)+b(0)], (()4)$$

$$-\Delta\sigma_T = (4\pi/K)\ {\rm Im}\ [c(0)+d(0)], (()5)$$

$$-\Delta\sigma_L = (4\pi/K)\ {\rm Im}\ [c(0)-d(0)], (()6)$$

where K is the c.m. momentum of the incident nucleon. Relations (5) and (6) allow one to extract the imaginary parts of the spin-dependent invariant amplitudes $c(0)$ and $d(0)$ at an angle of 0° from the measured values of $\Delta\sigma_L$ and $\Delta\sigma_T$.

Using the measured values of $\Delta\sigma_{L,T}(np)$ and the existing $\Delta\sigma_{L,T}(pp)$ data at the same energy, one can deduce $\Delta\sigma_{L,T}(I=0)$ as

$$\Delta\sigma_{L,T}(I=0) = 2\Delta\sigma_{L,T}(np) - \Delta\sigma_{L,T}(pp).(()7)$$

3. Results of the $\Delta\sigma_L(np)$ measurements

A large amount of results for np elastic scattering and transmission experiments at energies up to 1.1 GeV was accumulated by the end of the 80-th. (See for example review [4].) The possibility to extend measurements of the np spin-dependent observables to higher energies exists now at the JINR VBLHE accelerators only.

The measurements of energy dependences of the np total cross sections differences $\Delta\sigma_L(np)$ and $\Delta\sigma_T(np)$ for parallel and antiparallel particle spins oriented longitudinally or transverse were proposed [5, 6] at the beginning of the 90-th and started [7-10] in Dubna. To implement the proposed $\Delta\sigma_{L,T}(np)$ experimental program, a large Argonne-Saclay polarized proton target (PPT) was reconstructed in Dubna [11-13], and a new polarized neutron beam line with suitable parameters [14, 15] was constructed and tested. A set of necessary neutron detectors with corresponding electronics, and up-to-date data acquisition system and other needed equipment were also prepared, tuned and tested. Two successful data taking runs were carried out in 1995 and 1997. The energy dependence of $\Delta\sigma_L(np)$ was measured at 1.19, 1.59, 1.79, 2.2, 2.49, and 3.66 GeV [7-10].

This contribution presents new results for the spin-dependent np total cross section difference $\Delta\sigma_L(np)$ obtained in 2001 with longitudinally polarized both the quasi-monochromatic polarized neutron beam and the PPT. The values of $\Delta\sigma_L(np)$ were measured at neutron beam kinetic energies of 1.4, 1.7, 1.9 and 2.0 GeV. The measured $-\Delta\sigma_L(np)$ values are presented in [1, 2] and shown in Fig. 1. Statistical and systematic errors are taken into account. Total errors are the quadratic sums of experimental and systematic uncertainties. The results of our earlier measurements [7-10] together with the existing $\Delta\sigma_L(np)$ data [4], obtained with free polarized neutrons at lower energies, are also shown in Fig. 1. One can see that the new results smoothly connect with the lower energy data and confirm a fast decrease to zero within a 1.2-2.0 GeV energy region, observed previously [7-10].

The solid curves show the last energy-dependent GW/VPI PSA fits [16, 17] (FA95, SP99 and SP03 solutions) of this observable over the interval from 0.1 to 1.3 GeV. Above 1.1 GeV (Saturne II), the np database is insufficient and a high energy part of the $\Delta\sigma_L(np)$ PSA predictions still disagrees with the measured data.

Below 2.0 GeV, a usual meson exchange theory of NN scattering [18] gives the $\Delta\sigma_L(np)$ energy dependence as shown by the dotted curve in Fig. 1. It can be seen that this model provides a qualitative description only.

More detailed and accurate $-\Delta\sigma_{\rm L}(np)$ measurements around 1.8 GeV and obtaining of new $-\Delta\sigma_{\rm T}(np)$ data using coming high intensity ($\geq 2\cdot 10^{10}$ d/cycle) relativistic polarized deuteron beam from the JINR VBLHE Nuclotron are planned.

4. Measurements of the $A_{00kk}(np)$ and $A_{00nn}(np)$ observables from $np \to pn$ process

An expression for the differential cross sections for scattering of polarized nucleon beam with energy E on the polarized target nucleons with the scattered particle detection at an angle of θ is [3, 4]

$$[d\sigma/d\Omega]_{pol}(E,\theta) = d\sigma/d\Omega(E,\theta)\cdot[1 + A_{00n0}(E,\theta)\cdot P_{B^n} + A_{000n}(E,\theta)\cdot P_{T^n} + A_{00nn}(E,\theta)\cdot P_{B^n}\cdot P_{T^n} + A_{00ss}(E,\theta)\cdot P_{B^s}\cdot P_{T^s} + A_{00kk}(E,\theta)\cdot P_{B^k}\cdot P_{T^k} + A_{00sk}(E,\theta)(P_{B^s}\cdot P_{T^k} + P_{B^k}\cdot P_{T^s})], \quad (()8)$$

where $d\sigma/d\Omega$ is the cross section for unpolarized nucleons.

If the scattered particles are detected at 0° then analyzing powers $A_{00n0}(E,0) = A_{000n}(E,0) = 0$ and parameters $A_{00sk}(E,0) = 0$ and $A_{00ss}(E,0) = A_{00nn}(E,0)$. Thus, only two different non-vanishing spin-dependent quantities $A_{00nn}(E,0)$ and $A_{00kk}(E,0)$ remain in Eq.(8).

Due to symmetries of amplitudes, which hold separately for isospins $I=0$ and $I=1$, the same relations are valid at $\theta_{c.m.} = \pi$. Moreover the amplitude $e(0) = e(\pi) = 0$ for any isospin. The measured np observables at $\theta_{c.m.} = \pi$ are connected with the invariant amplitudes as follows

$$d\sigma/d\Omega = \frac{1}{2}[|a|^2 + |b|^2 + |c|^2 + |d|^2], (()9)$$

$$d\sigma/d\Omega\cdot A_{00nn} = \frac{1}{2}[|a|^2 - |b|^2 - |c|^2 + |d|^2], (()10)$$

$$d\sigma/d\Omega\cdot A_{00kk} = Re\, a^*\cdot d + Re\, b^*\cdot c, (()11)$$

where all experimental quantities and amplitudes are at $\theta_{c.m.} = \pi$. These equations can be transformed to

$$d\sigma/d\Omega(1 + A_{00kk}) = A + (Re\, b + Re\, c)^2, (()12)$$

$$d\sigma/d\Omega(1 - A_{00kk} - 2\cdot A_{00nn}) = B + (Re\, b - Re\, c)^2, (()13)$$

$$d\sigma/d\Omega(1 - A_{00kk} + 2 \cdot A_{00nn}) = C + (Re\, b + Re\, c - 2 \cdot Re\, d)^2, (()14)$$

where terms A, B, C contain the imaginary parts of amplitudes only. The real parts of the amplitudes b, c, and d can be determined from Eq.s (12)-(14) using known imaginary ones. A knowledge of $I = 1$ system is assumed in order to use the amplitude symmetries for the transformation of $I = 0$ amplitudes from $\theta = 0$ to $\theta = \pi$ and vice versa [19].

Measurements of the $A_{00kk}(np)$ and $A_{00nn}(np)$ observables were examined for example in [19, 20]. Obtaining of data set on energy dependences of $A_{00kk}(np)$ and $A_{00nn}(np)$ spin observables over the JINR VBLHE accelerators energy region were discussed [1, 2, 7-10] and planned under the program of "Delta-Sigma" experiment. The $A_{00kk}(np)$ and $A_{00nn}(np)$ values will be determined from the asymmetry measurements of yields of $np \to pn$ charge exchange process at 0° (i.e. elastic scattering at $\theta = \pi$) for parallel and antiparallel orientations of polarizations of the L and T polarized neutron beam and PPT.

Energy dependence of the ratio

$$R_{dp} = d\sigma/d\Omega(nd)/d\sigma/d\Omega(np)(()15)$$

for the elastic charge exchange process $np \to pn$ at 0° in Lab. (or elastic $np \to np$ backward scatteting in c.m.s) will be measured with high intensity unpolarised neutron beam from Nuclotron using the magnetic spectrometer and liquid hydrogen and deuterium targets. R_{dp} is connected with helicity NN amplitudes by (see for example [20])

$$R_{dp} = \frac{2}{3} \cdot \frac{1}{(1 + R')}, (()16)$$

$$R' = \frac{|\Phi_4 - \Phi_2|^2}{2 \cdot |\Phi_1|^2 + |\Phi_4 + \Phi_2|^2}, (()17)$$

where Φ_i are the helicity NN amplitudes and R' is the ratio of "spin non-flip" to "spin flip" contributions to the cross sections of $np \to pn$ process. For $R' = 0$ we have

$$d\sigma/d\Omega(nd) = 2/3 d\sigma/d\Omega(np).(()15)$$

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

The first measurement of the ratio R_{dp} was carried out [21] at the Dubna synchrocyclotron at neutron energy of 380 MeV.

5. Magnetic spectrometer for investigation of elastic $np \to pn$ charge exchange process

In the last few years the measurements of spin-correlation parameters $A_{00kk}(np)$ and $A_{00nn}(np)$ from $np \to np$ elastic charge exchange at $0°(Lab.)$ were prepared in frame of the "Delts-Sigma experiment" project. These spin-correlation np observables can be measured simultaneously (and independently) with the transmission measurements of $\Delta\sigma_{L,T}(np)$.

The method of scattered particle detection is used to measure the yield of charge exchanged protons and differential cross section for $np \rightarrow pn$ process at $0°$. A magnetic spectrometer for detection of protons from $np \rightarrow np$ elastic charge exchange at $0°(Lab.)$ was installed and tested at the polarized neutron beam line (see Fig. 2).

The spectrometer consist of analyzing dipole SP-94, two sets of multiwire proportional chambers before and after SP-94 for momentum analyzis of detected secondaries, time-of flight system $(S1, TOF1, 2)$ for particle identification, liquid H_2 or D_2 targets, surrounded by a device for detecting of recoils and gammas, and trigger counters A, $S1, ST$.

Investigations of the charge exchange $np \rightarrow pn$ process at $0°$ were performed during a number of last metodical and physical runs using a high intensity unpolarized neutron beam from the JINR VBLHE Nuclotron. Some characteristics of the spectrometer and studied process and a number of physical results, obtained in these runs, are shown in Fig.s 3-10.

The momentum spectra of charged secondaries, detected by spectrometer using H_2 and D_2 liquid targets, at the neutron beam energies of 1.0 and 1.2 GeV are shown in Fig.s 3 and 4. The momentum resolution of spectrometer, measured using primary monochromatic deuteron beam, was estimated as $\Delta P/P = 1.65\%$.

An information from the detectors for target surrounding DTS allows to suppress the contributions from other (inelastic) np-reaction channels. The upper histograms in Fig.s 5 and 6 present spectra of charged secondaries as function of angle of deflection in analyzing magnet obtained without using the information from the DTS. The middle and bottom histograms in Fig.s 5 and 6 show the same as the upper ones but when the signal from the DTS is in anticoincidence or in coincidence with the spectrometer trigger, respectively.

The detected particle identification, using both the magnetic analyzis and time-of-flight spectra is demonstrated by Fig. 7. An angular acceptance of spectrometer in polar θ and asimuthal φ angular planes is shown in Fig. 8.

Two examples of angular dependences of differential cross sections of the $np \rightarrow pn$ process near $0°$, obtained with H_2 andD_2 targets at $T_n = 1.0$ GeV, are presented in Fig. 9 and an estimation of the ratio R_{dp} at neutron energy of 1.0 GeV is shown in Fig. 10.

A sufficient statistics to determine the differential cross sections for $np \rightarrow pn$ process at $0°$ were accumulated over 1-2 GeV energy region, using liquid H_2 and D_2 targets. Our preliminary results on the momentum spectra of elastic charge exchange protons and $d\sigma/d\Omega(np)$ at 1.0, 1.2 GeV are in good agreement with the existing data [22, 23]. The accumulated data treatment and analyzis are in progress.

6. Conclusion

1. New $-\Delta\sigma_{\rm L}(np)$ results complete in the main the measurement of the $-\Delta\sigma_{\rm L}(np)$ energy dependence at the Dubna Synchrophasotron energy region.

2. Measured $-\Delta\sigma_{\rm L}(np)$ values are in accordance with the existing np results at low energies, obtained with free neutron beams. The rapid decrease of $-\Delta\sigma_{\rm L}(np)$ values above 1.1 GeV was observed in the first data taking runs and is confirmed in the latest run and a minimum or a shoulder around 1.8 GeV is observed.

3. The necessity of more detailed and accurate $-\Delta\sigma_{\rm L}(np)$ measurements around 1.8

GeV and new $-\Delta\sigma_T(np)$ data in the kinetic energy region above 1.1 GeV is emphasized.

4. A number of physical and methodical results on investigation of the elastic $np \rightarrow pn$ charge exchange process over a few GeV region are also presented. The possibilities for $A_{00kk}(np)$, $A_{00nn}(np)$ and R_{dp} measurements, using prepared magnetic spectrometer, were demonstrated.

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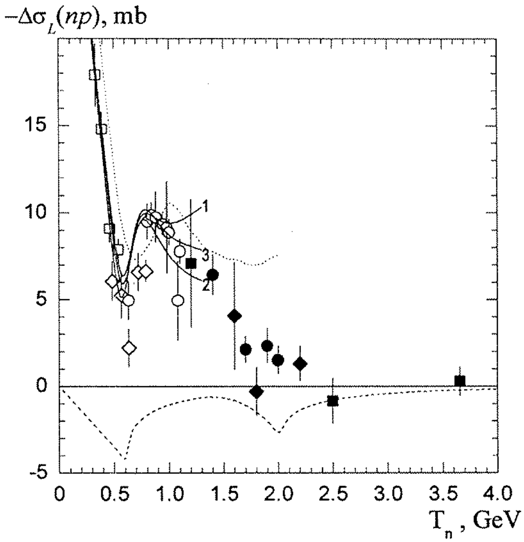

Fig. 1. Energy dependence of the $-\Delta\sigma_L(np)$. Black circles – the last JINR results [1, 2], black squares – JINR [7, 8], black rhombes – JINR [9, 10], open squares – PSI, open rhombes – LAMPF and open circles – Saturne II (see [4]), solid curves – ED GW/VPI PSA [16, 17](1-FA95 solution, 2-SP99 solution and 3-SP03 solution), dotted curve – meson-exchange model [18], dashed curve – contribution from nonperturbative QCD interaction induced by instantons [7, 8, 10]

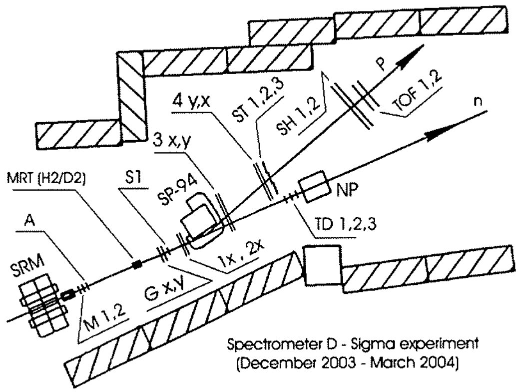

Fig. 2. Magnetic spectrometer for detection of protons from $np \to np$ elastic charge exchange at $0°(Lab.)$. SP-94 – analyzing dipole, Gx,y, 1x, 2x, 3x,y, 4x,y – two sets of multiwire proportional chambers, MPT,H_2/D_2 – polarized proton target or liquid H_2 or D_2 targets, $S1$, $TOF1,2$ and A, $S1$, ST – time-of flight and trigger counters

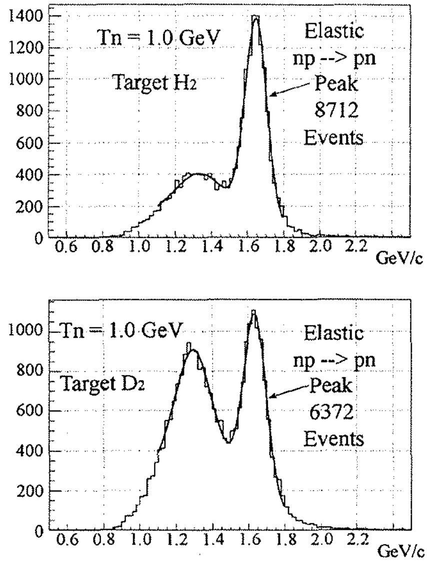

Fig. 3. The momentum spectra of charged secondaries, detected by spectrometer using H_2 and D_2 liquid targets, at the neutron beam energy of 1.0 GeV

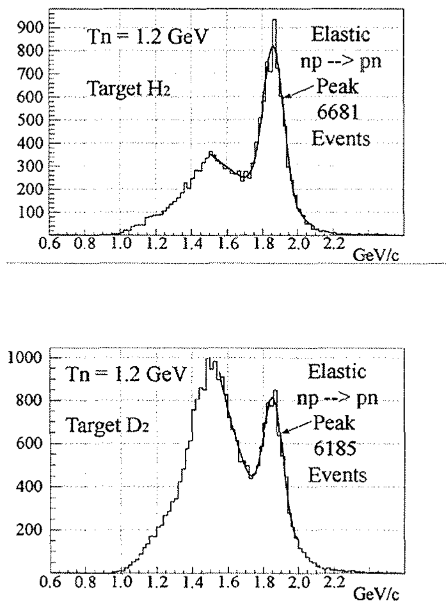

Fig. 4. The same as in Fig. 3 but at the neutron beam energies of 1.2 GeV

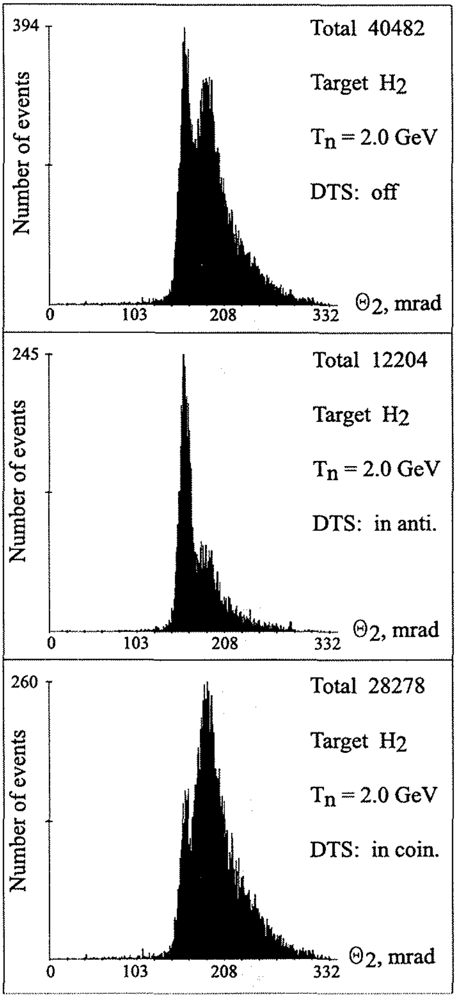

Fig. 5. The "on-line" histograms as function of angle of deflection in analyzing magnet of charged secondaries, detected by spectrometer using H_2 liquid target, at the neutron beam energy of 2.0 GeV. Information from the detectors for target surrounding DTS allows to suppress the contributions from other (inelastic) *np*-reaction channels. The upper histogram shows the spectrum of charged secondaries obtained without using the information from the DTS. The middle and bottom histograms show the spectra when the signal from the DTS is in anticoincidence and in coincidence with the spectrometer trigger, respectively

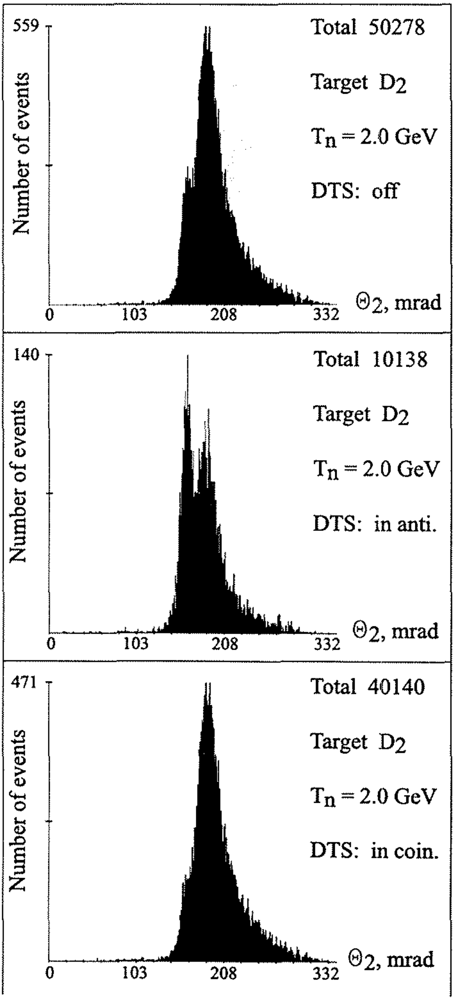

Fig. 6. The same as in Fig. 5 but with D_2 liquid target

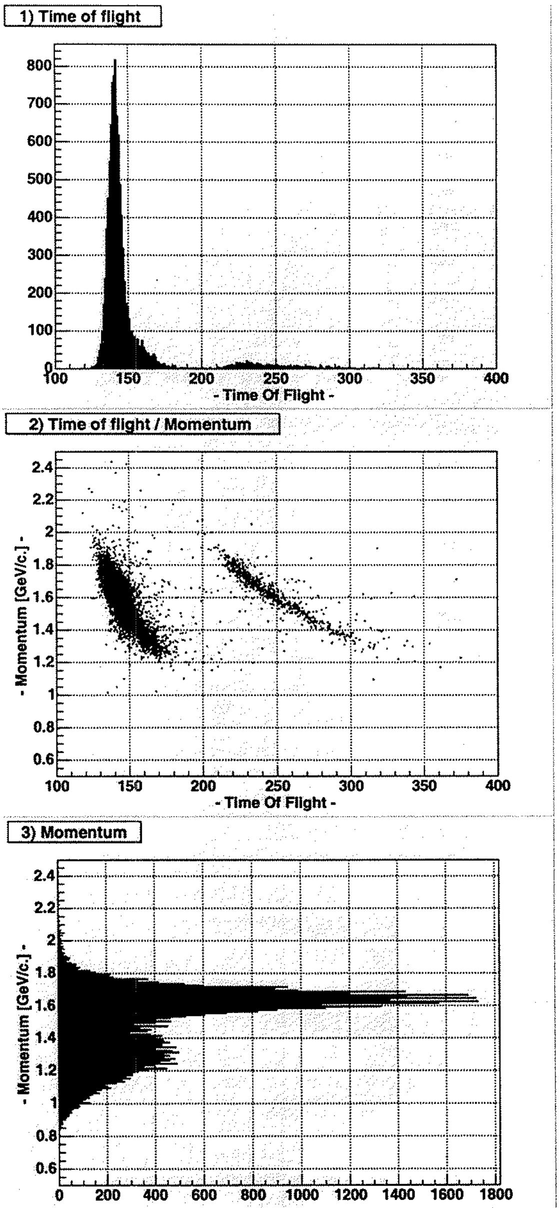

Fig. 7. The detected particle identification, using both the magnetic analyzis and time-of-flight spectra

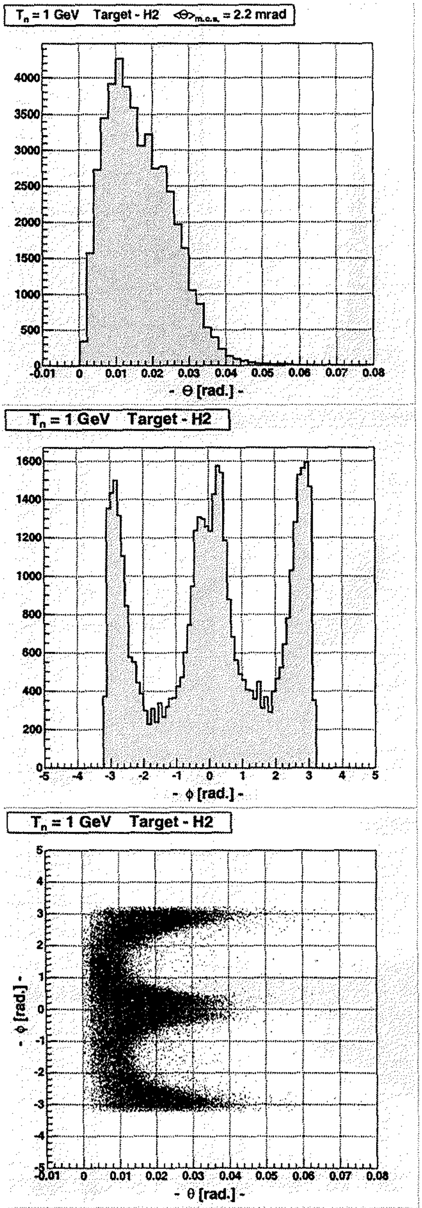

Fig. 8. Angular acceptance of spectrometer in the polar θ and asimuthal φ angular planes

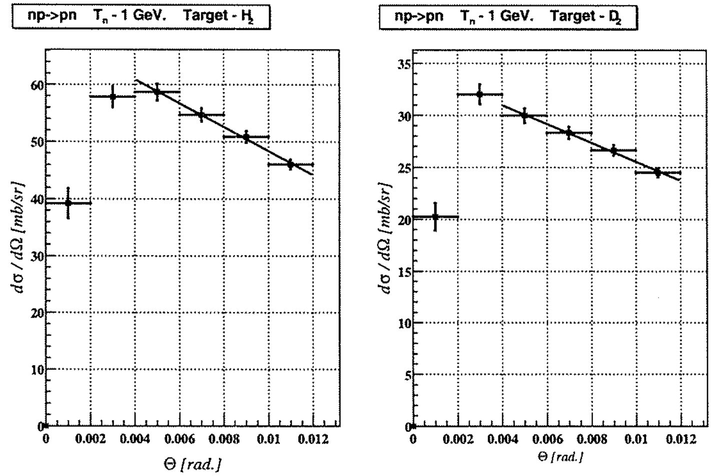

Fig. 9. Angular dependences of differential cross sections of the $np \to pn$ process near 0°, obtained with H_2 and D_2 targets at $T_n = 1.0$ GeV

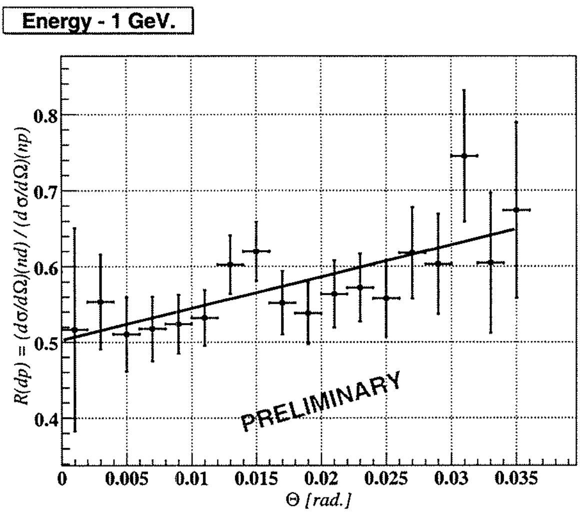

Fig. 10. An estimation of the ratio R_{dp} at neutron energy of 1.0 GeV

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