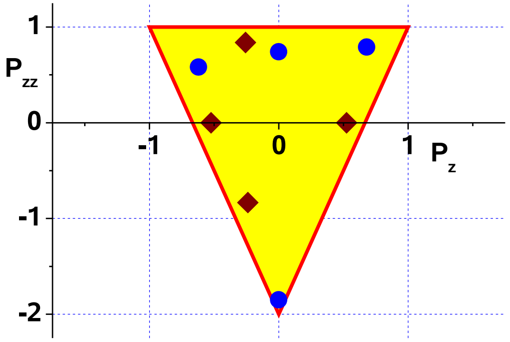
Spin Physics at Nuclotron-M



V.P.Ladygin et al. (on behalf of LHE SPIN group)

SPIN-2007, 3-7 September 2007, Dubna

Content of the talk

- Introduction
- Review of the current status of spin physics at LHE
- Future plans for Nuclotron-M
- Spin physics at NICA
- Conclusions

The results obtained in different experiments are given in the talks of

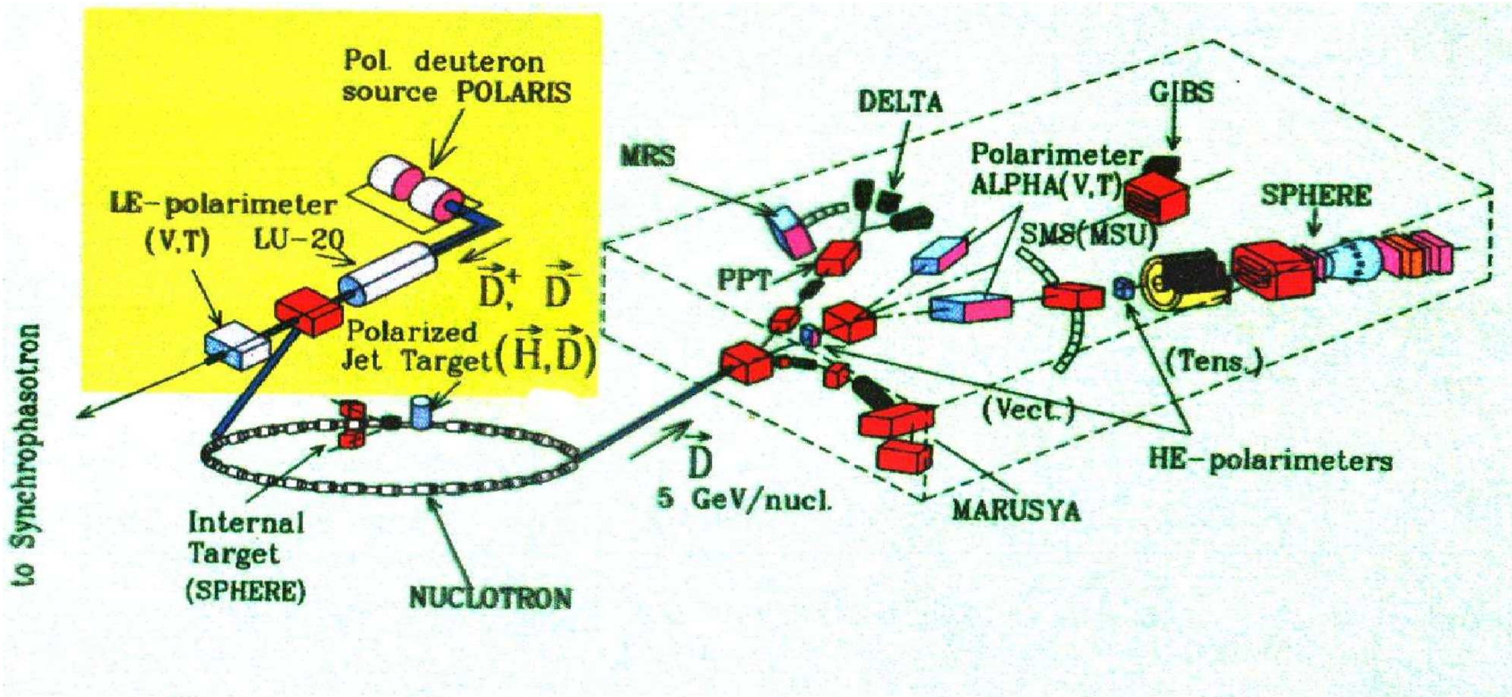
L.S.Azhgirey, V.I.Sharov, N.M.Piskunov, L.N.Strunov, A.A.Morozov, A.K.Kurilkin, P.K.Kurilkin, M.A.Shikhalev, A.S.Kiselev et al.

Motivation to study spin effects in a GeV-range

The main goal of the polarization program at Nuclotron is to investigate the spin effects in the region of transition regime from nucleon-meson degrees of freedom to the fundamental one: quarks and gluons.

- Non-perturbative QCD region
- Importance of the effective degrees of freedom
  ($\mathbf{\Delta\Delta}$, $\mathbf{NN^*}$, $\mathbf{N^*N^*}$ configurations - hidden color)
- Threshold effects in meson-production
- Relativistic effects
- Medium effects for the polarization observables
  (χ-symmetry restoration)

Synchrophasotron-Nuclotron Accelerator Complex



- PIS on 360 kV terminal
- 10 MeV/A LINAC
- Tensor and vector LEPs
- Nuclotron Ring: 6 GeV/A
- ITS polarimeter
- Extraction beam line
- HE polarimeters
- Experimental setups

Deuteron structure

- Such static properties as a binding energy ϵ, quadrupole, $\mathbf{Q_d}$, and magnetic, $\mu_{\mathbf{d}}$, momenta, radius $\mathbf{r_d}$ are very well measured and are reproduced by the nonrelativistic calculations using standard nucleon-nucleon potentials based on one-bosons exchange.

  (Moreover, $\mu_{\mathbf{d}}$ is very sensitive to the relativistic corrections.)

- Nonrelativistic deuteron wave function, obtained by the solving of the Schredinger equation, depends on the relative nucleon momentum $\vec{\mathbf{q}}$ only:

$$\mathbf{\Psi} = \mathbf{\Psi}(\vec{\mathbf{q}})$$

- As the deuteron and its nucleons energies increase, the relativistic effects play more important role at short internucleonic distances, as well as in the dynamics of the interaction.

Relativistic effects

- The principal feature of the relativistic quantum mechanics is the impossibility to separate the relative motion of the constituents and motion of the composite system as a whole. This leads to the dependence of the relativistic wave function not only on the relative momenta of the nucleons $\vec{\mathbf{q}}$ inside the composite system, but also on the total momentum $\vec{\mathbf{p}}$ of this system

$$\boldsymbol{\Psi} = \boldsymbol{\Psi}(\vec{\mathbf{q}}, \vec{\mathbf{p}})$$

- Therefore, relativistic wave function is the function of the relative momentum $\vec{\mathbf{q}}$ in each new reference system.

- However, it is enough to know wave function in the infinite momentum frame, $\vec{\mathbf{p}} \rightarrow \inf$, where the structure of the wave function simplifies. Namely, the dependence on $|\vec{\mathbf{p}}|$ disappears, only the dependence on the direction of the vector $\vec{\mathbf{n}} = \vec{\mathbf{p}}/|\vec{\mathbf{p}}|$

$$\boldsymbol{\Psi} = \boldsymbol{\Psi}(\vec{\mathbf{q}}, \vec{\mathbf{n}})$$

Deuteron wave function on the light cone

Relativistic deuteron wave function on light cone (V.A.Karmanov, J.Carbonell et al.) is defined by 6 invariant functions $\mathbf{f_1, ..., f_6}$ (instead of 2 in the non-relativistic case), each of them depends on 2 scalar variables $\mathbf{k}$ and $z = cos(\widehat{\mathbf{kn}})$:

$$\psi(\mathbf{k},\, \mathbf{n}) \;=\; \frac{1}{\sqrt{2}}\sigma f_1 + \frac{1}{2}\left[\frac{3}{k^2}\mathbf{k}(\mathbf{k}\cdot\sigma) - \sigma\right] f_2 + \frac{1}{2}\left[3\mathbf{n}(\mathbf{n}\cdot\sigma) - \sigma\right] f_3 + \frac{1}{2k}[3\mathbf{k}(\mathbf{n}\cdot\sigma)$$
$$+\; 3\mathbf{n}(\mathbf{k}\cdot\sigma) - 2\sigma(\mathbf{k}\cdot\mathbf{n})]f_4 + \sqrt{\frac{3}{2}}\frac{i}{k}[\mathbf{k}\times\mathbf{n}]f_5 + \frac{\sqrt{3}}{2k}[[\mathbf{k}\times\mathbf{n}]\times\sigma]f_6,$$

$$k \;=\; \sqrt{\frac{m_p^2 + \mathbf{k}_T^2}{4x(1-x)} - m_p^2}, \qquad (\mathbf{n}\cdot\mathbf{k}) = (\frac{1}{2} - x)\cdot\sqrt{\frac{m_p^2 + \mathbf{p}_T^2}{x(1-x)}},$$
$$x \;=\; \frac{E_p + p_{pl}}{E_d + p_d} \qquad (x \approx x_F),$$

where $\mathbf{E_d}$ and $\mathbf{p_d}$ are the energy and momentum of the initial deuteron, respectively, $\mathbf{p_{pl}}$ is the longitudinal momentum of the proton, $\mathbf{m_p}$ and $\mathbf{E_p}$ are the mass and energy of the proton, respectively.

Short internucleonic distances

- When the distances between the nucleons are comparable with the size of the nucleon, the nucleon-nucleon interaction is non-local.
- Fundamental degrees of freedom in the frame of QCD are the quarks and gluons. These degrees begin to play a role at the internucleonic distances comparable with the size of the nucleon.

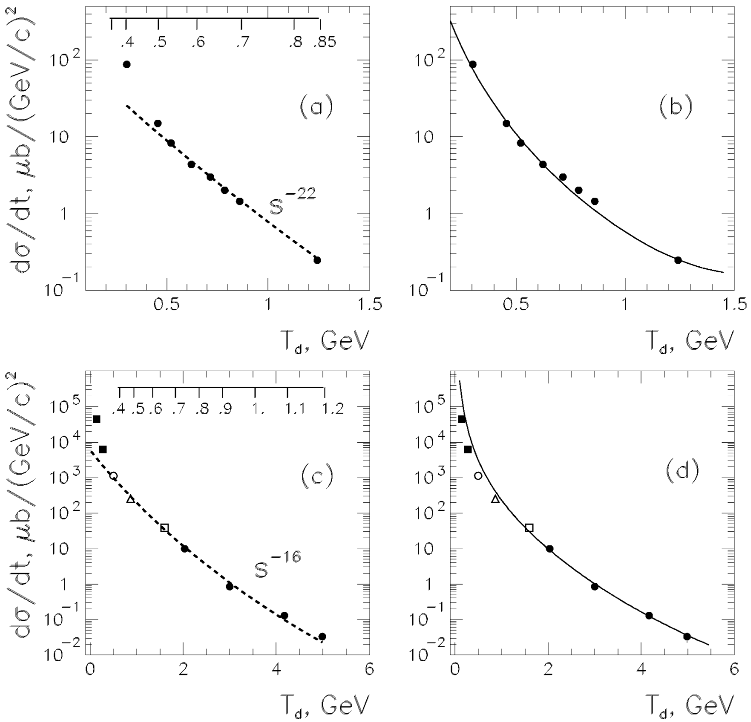
  ($\Delta\Delta$, N^*N, N^*N^*, $6q$ components in the deuteron)
- At high energies **s** and large transverse momenta $\mathbf{p_T}$ the constituent counting rules (CCR) are working. For the binary reactions:

$$\frac{d\sigma}{dt}(AB \to CD) \sim \frac{F(t/s)}{s^{n_{part}-2}}$$

$$n_{part} = n_A + n_B + n_C + n_D$$

(Matveev, Muradian, Tavkhelidzhe, Brodsky, Farrar et al.)

Quark degrees of freedom



Yu.N.Uzikov

- For the reaction $\mathbf{dp \to pd}$

  $$\mathbf{n_A + n_B + n_C + n_D - 2 = 16}$$

- For the reaction $\mathbf{dd \to^3 Hen}$

  $$\mathbf{n_A + n_B + n_C + n_D - 2 = 22}$$

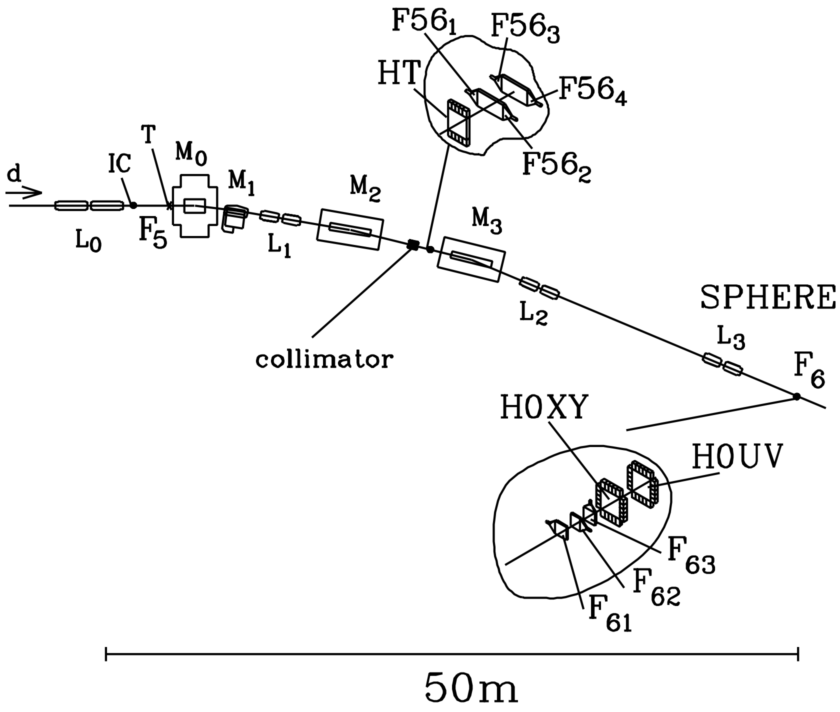
- The regime corresponding to CCR occurs already at T_d ~500 MeV.

Three nucleon forces manifestation

- During last several years a new generation of NN potentials are built (Nijmegen, CD-Bonn, AV-18 etc.). These potentials reproduced the NN scattering data up to 350 MeV with very good accuracy.
- But these potentials cannot reproduce triton binding energy (underbinding is 0.8 MeV for CD-Bonn), deuteron-proton scattering and breakup data.
- Incorporation of the 3 nucleon forces (3NF), when interaction depends on the quantum numbers of the all three nucleons, allows to reproduce triton binding energy and unpolarized deuteron-proton scattering and breakup data.
- However, the 3NF cannot reproduce polarization data intensively accumulated during last decade.

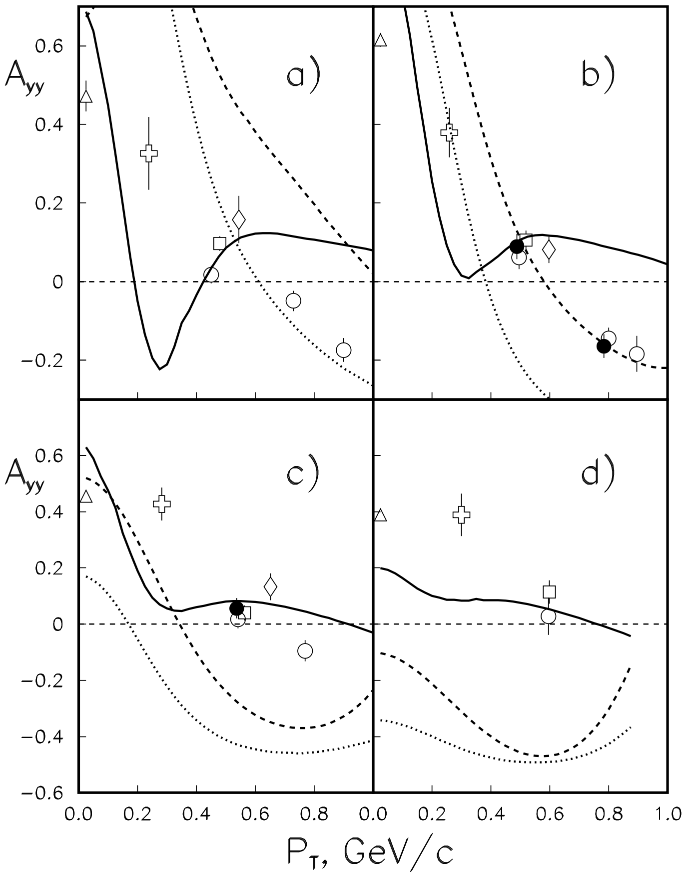
Energy dependence of 3NF spin structure via dp elastic scattering measurements

Experiments on the deuteron breakup at large transverse proton momenta at the SPHERE-setup



- Deuteron beam intensity:
  $I_{\vec{d}} \sim 5 \times 10^8 \div 2 \times 10^9$/spill
- Targets: $\mathbf{H_2}$ – 30 cm; ^{9}**Be** – 16 and 20 cm; ^{12}**C** – 7 and 16 cm.
- Particle identification: **TOF** on the baseline 28 or 34 m.
- Beam polarization:
  $|\mathbf{p_{zz}}| \sim \mathbf{0.7 - 0.8}$ and
  $|\mathbf{p_z}| \sim \mathbf{0.15 - 0.25}$
  Tensor: $\mathrm{dA} \rightarrow \mathrm{pX}$ at $\mathrm{P_p} = \mathbf{2/3} \cdot \mathrm{P_d}$
  Vector: pp- quasielastic scattering at CH_2

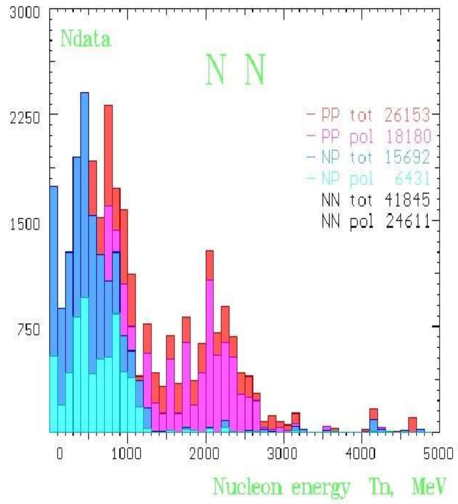
A_{yy} for the reaction $A(d,p)X$ versus p_T



- The strong variation of A_{yy} obtained at the fixed values of $x \sim 0.62, 0.67, 0.72, 0.78$ versus p_T.
- The value of A_{yy} is positive at small p_T and changes the sign at $p_T \sim 600$–650 MeV/c.
- The deviation of the data on the calculations with the use both standard and covariant DWFs is observed.

V.P.Ladygin et al., Phys.Lett. **B629** *(2005) 60*

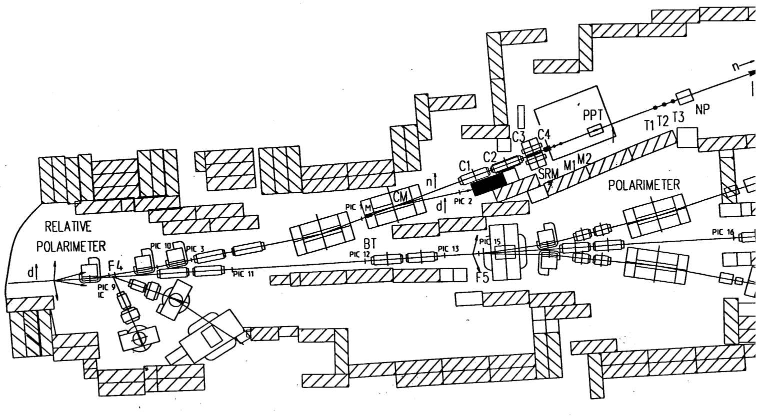
NP versus PP data



Red - are the PP data

Blue - are the NP data (practically absent at $T_n \geq 1.1$ GeV)

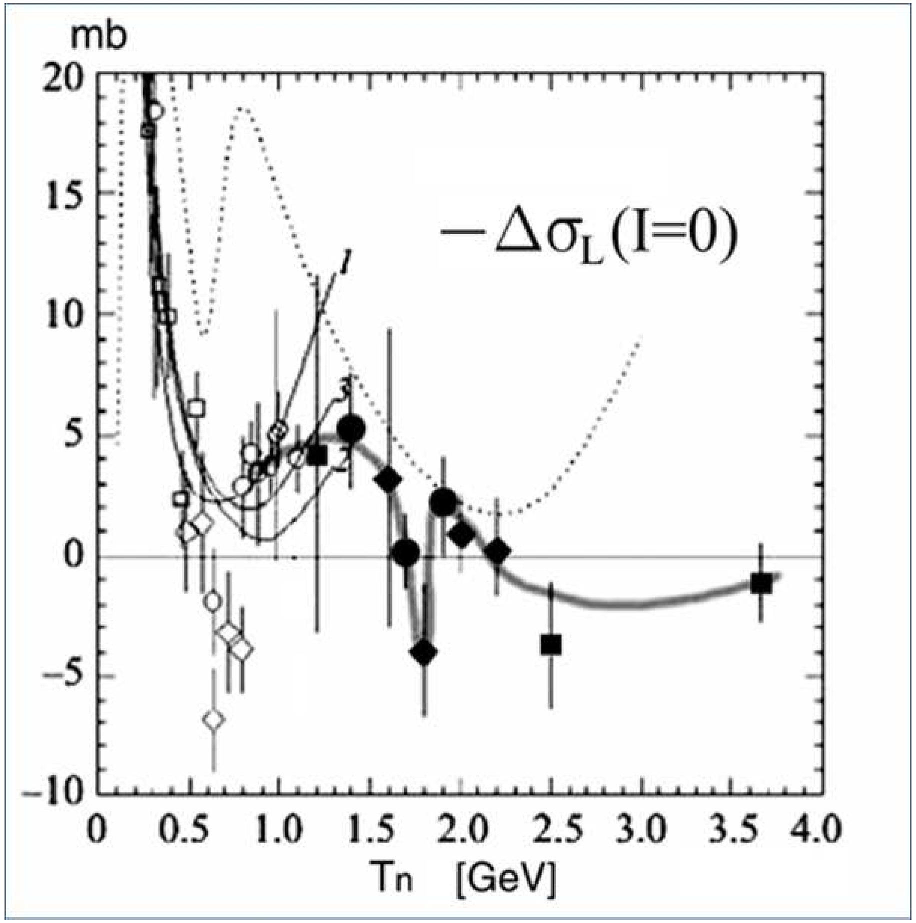
LHE neutron channel



-The unique neutron channel with the energies 0.55-3.7 GeV equipped by the polarized proton, liquid and nuclear targets.

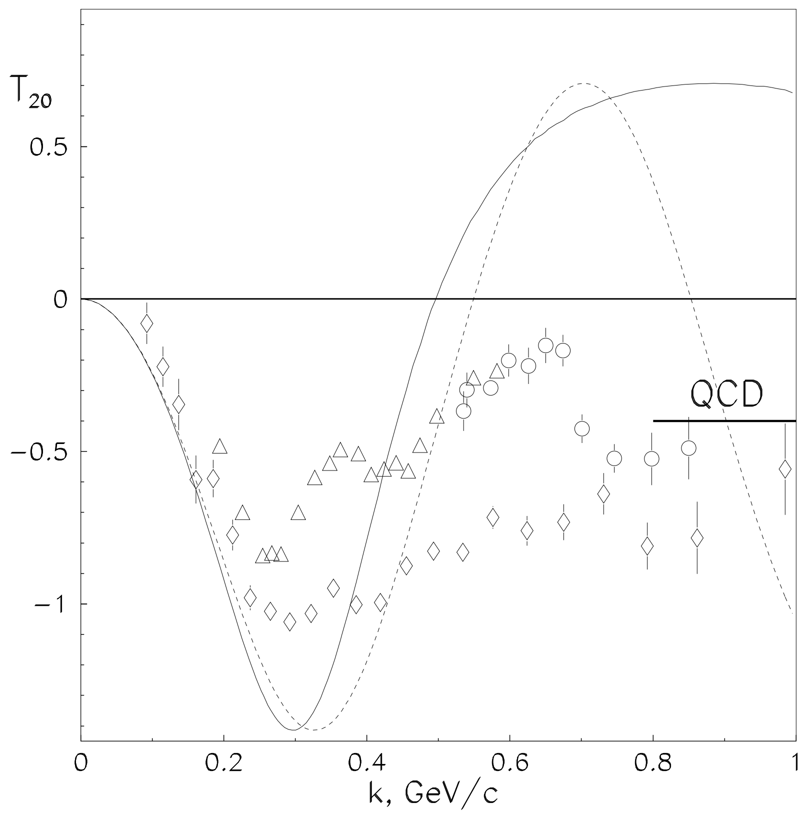
-Neutrons are obtained from deuteron breakup (Δp/p $\sim$3%).

Results on $\Delta\sigma_L$ in np elastic forward scattering



- The measurements of the np and pp elastic scattering allow to extract the amplitudes with $\mathbf{I = 0}$
- The significant variation of $\Delta\sigma_L(\mathbf{I = 0})$ versus energy:
- Structure at $T_n \sim$0.5–1.0 GeV
- Structure at $T_n \sim$1.7 GeV ???

Results on T_{20} in $p(\vec{d}, p)X$ reactions



- The $\mathbf{T_{20}}$ behavior for the reactions $\mathbf{dp \to pd}$ and $\mathbf{dp \to pX}$ cannot be reproduced by the standard DWFs.
- Asymptotic value of $\mathbf{T_{20} \sim -0.4}$ at large internal momenta is in agreement with QCD-motivated model prediction.

  (*A.P.Kobushkin*)
- Relativistic effects, nonnucleonic degrees of freedom, three-nucleon forces manifestation depends on the initial energy.

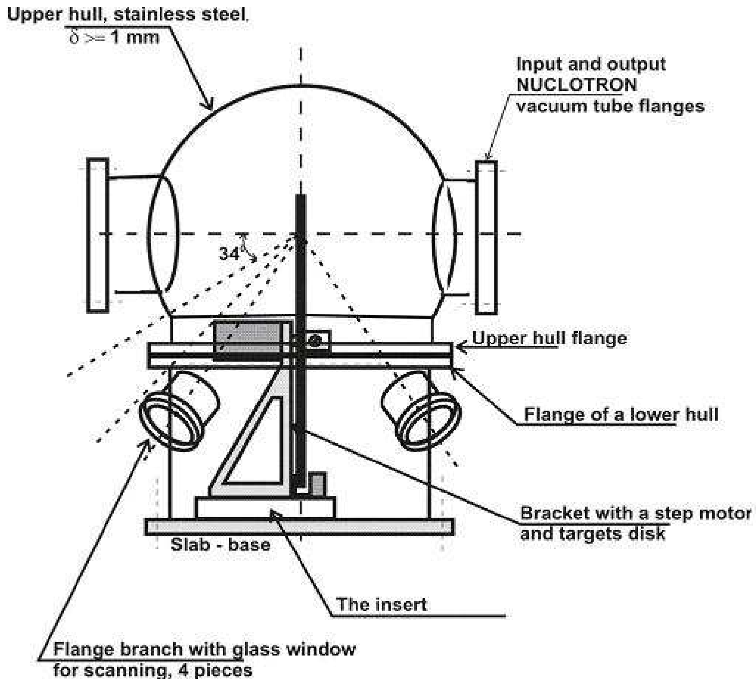
Current LHE SPIN-program

- Spin structure of few-nucleon systems
  LNS, PHe3-CUPID, TPD
- Spin structure of nucleon-nucleon interaction
  $\Delta\sigma$, STRELA, SMS-MSU
- Spin effects in meson production
  DELTA-2
- Development of the polarization techniques
  PPT, ALPOM

Postponed experiments

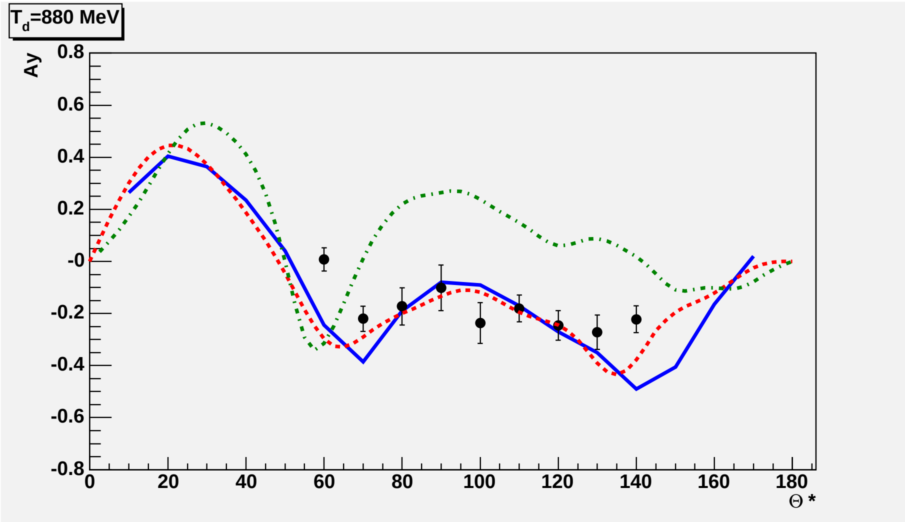
PIKASO, A_{yy}, KAPPA, BES, PP-SINGLET, DP-Φ

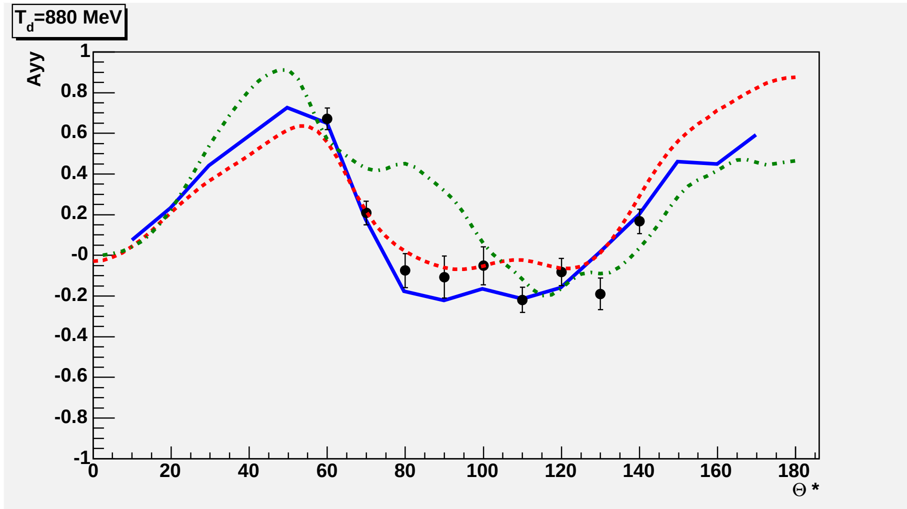
Joint CNS-JINR experiment at Internal Target Station at Nuclotron (LNS-PHe3-projects)



New Internal Target Station is very well suited for the measurements of the **dp**- elastic scattering observables at large angles in the cms.

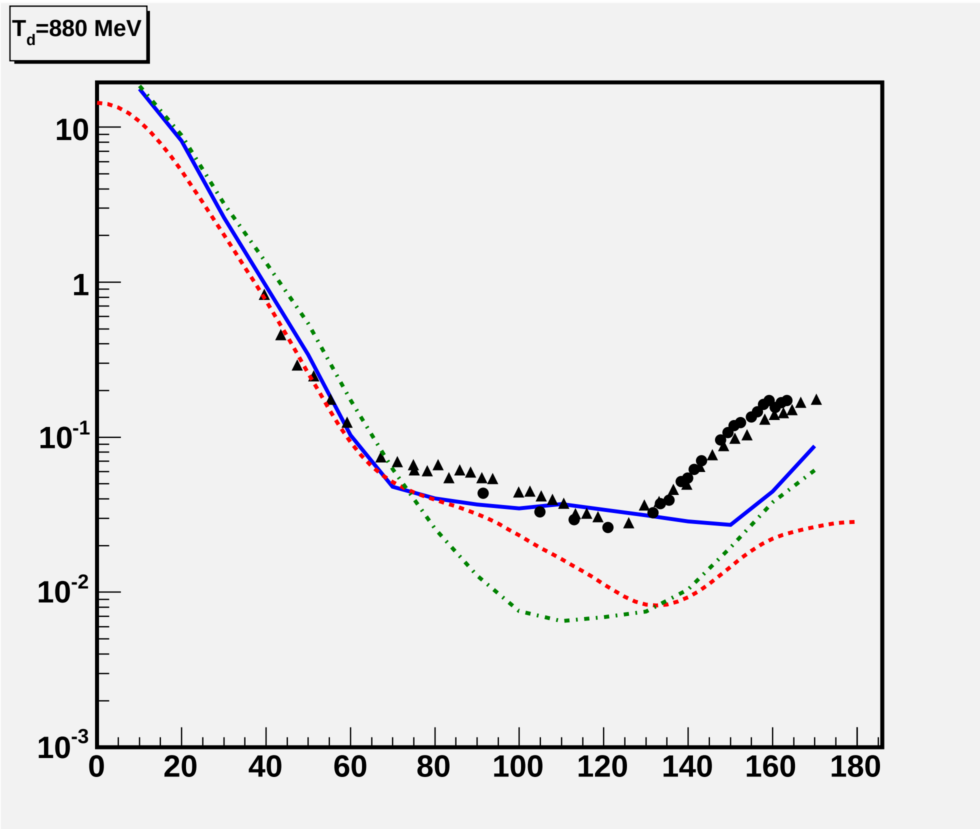
A_y and A_{yy} in dp- elastic scattering at 880 MeV





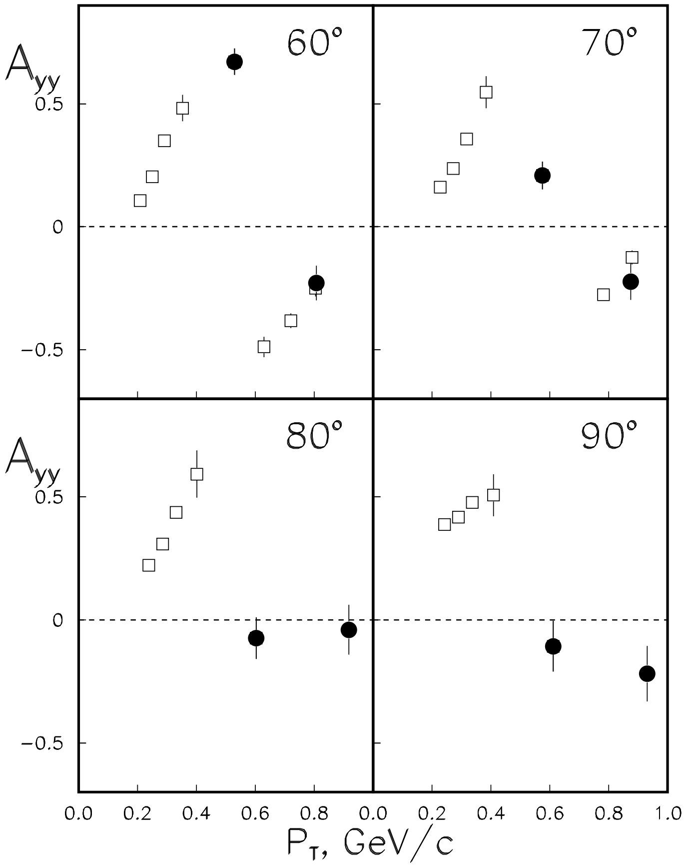
- Solid lines are the multiple scattering model calculations using CD-Bonn DWF
  (N.B.Ladygina, arXiv:0705.3149v1 [nucl-th]);
- Dashed lines are the Faddeev calculations using CD-Bonn DWF
  (H.Witala, private communication);
- Dott-dashed lines are the optical-potential calculations using Dibaryon DWF (M.Shikhalev, to be submitted in Yad.Fiz.)

Cross section in dp- elastic scattering at 880 MeV



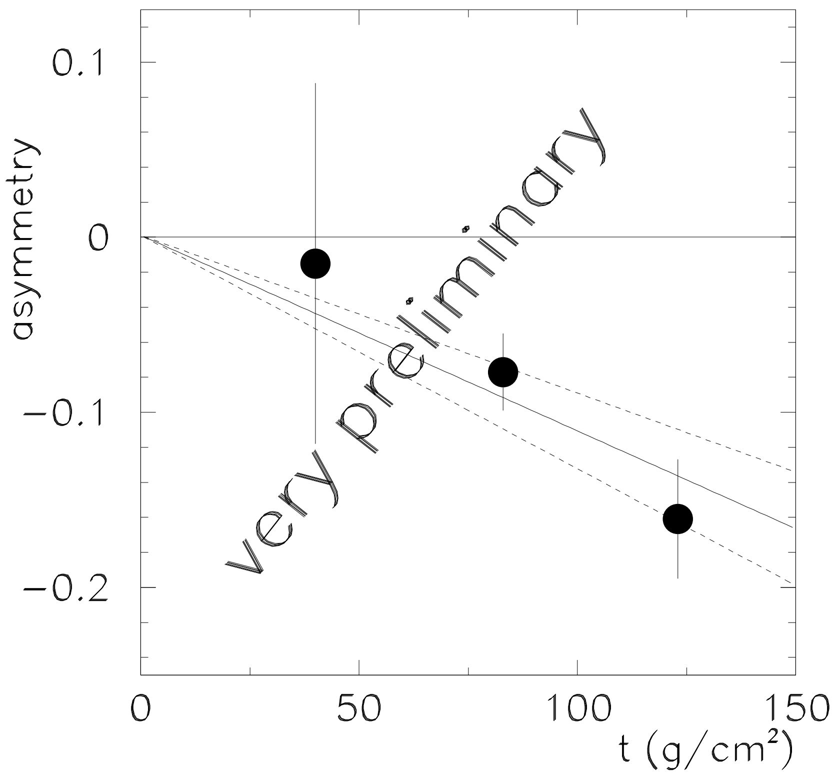
- The results of the multiple scattering model are in agreement with the cross section data in the range **30 – 130°**.
- Faddeev calculations (without usual 3NF) fails to reproduce the data at the angles larger than **90°**
- Double scattering dominates over single scattering at the angles larger than **70°**
- The deviation of the data on the calculations at backward angles are related with the **s – type** of **FM 3NF**.

Energy dependence of A_{yy} in dp- elastic scattering



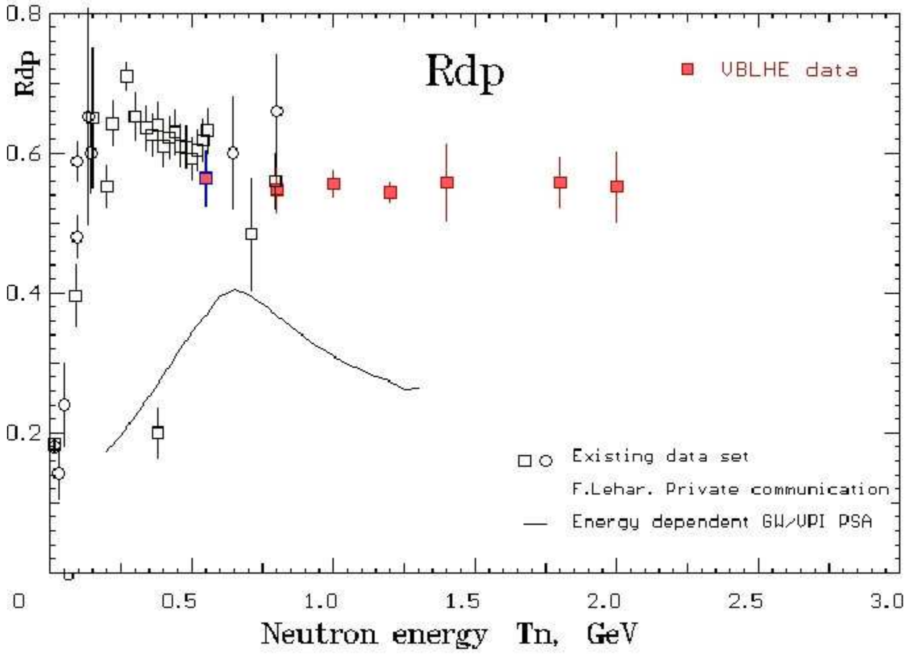
- The strong variation of A_{yy} obtained at the fixed values of the cms angles 60°, 70°, 80° and 90° versus p_T.
- The values of A_{yy} are positive at small p_T and changes the sign at $p_T \sim 600$–650 MeV$/c$ as in the case of deuteron breakup reaction.
- Negative asymptotic of A_{yy} at large p_T?

Tensor polarizability of the deuteron passing through the matter (TPD-project)



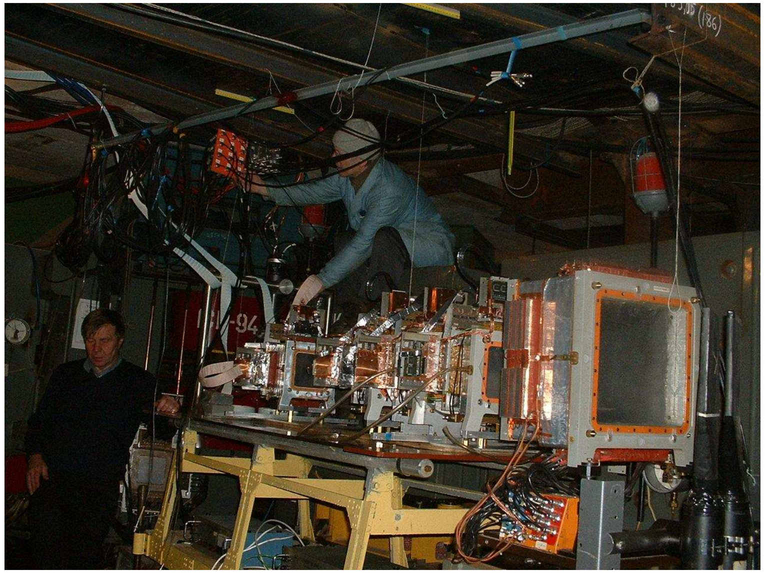
- The strong variation of tensor asymmetry versus the target length is observed for unpolarized deuterons with the momentum **5.5 GeV**.
- The effect of the deuteron spin rotation and oscillations in the matter is predicted by V.Baryshevsky. Another explanation of such effect is the Glauber multiple scattering.
- The experiment is planned for continuation in 2007-2008.

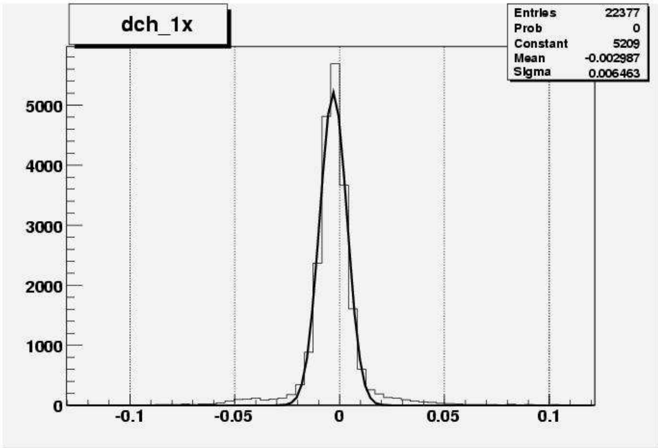
Measurements of the $\sigma(\mathbf{nd} \to \mathbf{pX})/\sigma(\mathbf{np} \to \mathbf{pX})$-ratio ($\Delta\sigma$-project)



- The ratio $\mathbf{R_{dp}}$ is expected to be sensitive to the ratio of spin-dependent to spin-independent parts of **np**-backward elastic scattering amplitude.
- Additional observable to $\Delta\sigma_L$, $\Delta\sigma_T$, $\mathbf{A_{ookk}}$ and $\mathbf{A_{oonn}}$.
- Large values of $\mathbf{R_{dp}}$ at high energies reflect the significance of spin-dependent part of **np**- amplitude.
- Strong deviation from the results of current PWA (even taking into account FSI).

Investigation of charge-exchange process $dp \to pp(^1S_0)n$ at Nuclotron (STRELA-project)

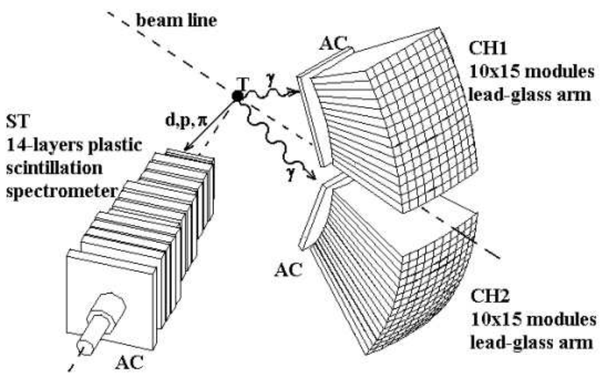




The main goal of the project is the study of charge-exchange **np** interactions by measuring the $dp \to pp(^1S_0)n$ reaction in collinear kinematics. A new setup was built to register two protons at emitted angles less than 3 degree and relative momentum less than 100 MeV/c. As the detected protons have a momentum close to half of incoming deuteron momentum.

Measurement of η-mesons yield in polarized NN collisions (DELTA – 2-project)

Schematic View of DELTA Detector Positions



Main Characteristics of the DELTA - Installation

1. Fiber-optics Multi–ΔE Spectrometer

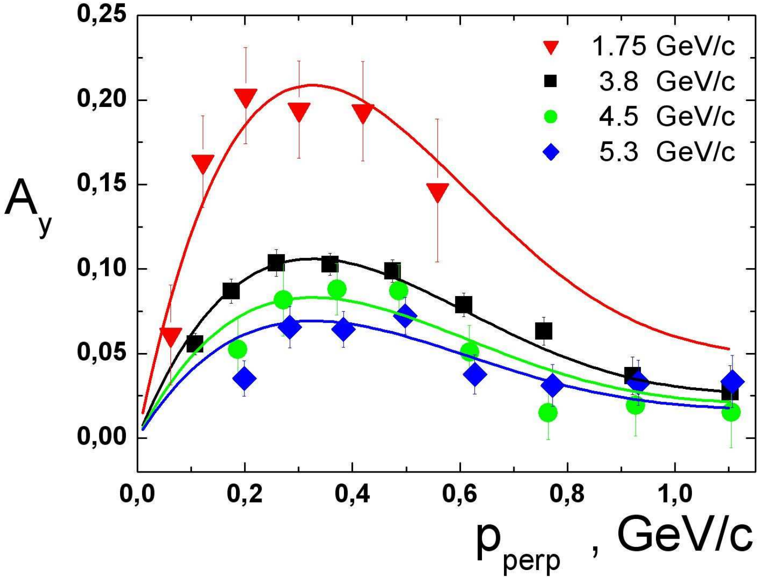
1. Number of plates: 14
2. Plates dimensions: 160 to 270 mm
3. Plates thickness: 20 to 40 mm
4. Structure: 2 polystyrene scintillators glued together plastic fiber optics wires
5. Light yield: $N_{ph.e.} = 21 * \Delta E(\text{MeV}) - 10$
6. Uniformity of the light collection over the area: > 95%
7. Particle energy interval:
   - $\pi^{\pm}$: 30 - 150 MeV
   - K^{+} : 80 - 280 MeV
   - p : 100 - 320 MeV
   - d : 200 - 600 MeV
8. Energy resolution: < 5% (FWHM)

2. Two-arms Pb-Glass Spectrometer

1. Number of modules: 2 arms * 150
2. Material: F8- type glass (45% PbO), light absorption <0.05%/cm
3. Module dimensions: 22(front)x36(end)x400 mm (12r.l.)
4. γEnergy resolution: $\sigma_E = 1.62 * (E(\text{MeV}))^{1/2}$
5. γCoordinate resolution: $\sigma_x = \sigma_y = 3$ mm (at 600 meV)
6. Energy interval:
   - π^0 : 0.03 - 2 GeV
   - η : 0.03 - 5 GeV
7. Effective accepted solid angle: $\Delta\Omega \leq (8 - 12)$ mster (for $/X/ \leq 0.3$)
8. Energy resolution: ≈(5-10) Mev (FWHM)

- Due to strange content in the η-meson the spin correlation $\mathbf{C_{yy}}$ in the $\vec{\mathbf{n}}\vec{\mathbf{p}} \rightarrow \eta\mathbf{X}$ reaction is expected to be sensitive to the polarized $\mathbf{s\bar{s}}$ content of the nucleon.
- The detection of η-mesons will be done by 300-channel lead-glass spectrometer via $\eta \rightarrow \gamma\gamma$ decay.

Measurement of the inclisive $\vec{p}CH_2$ analyzing power at high energies (ALPOM-project)



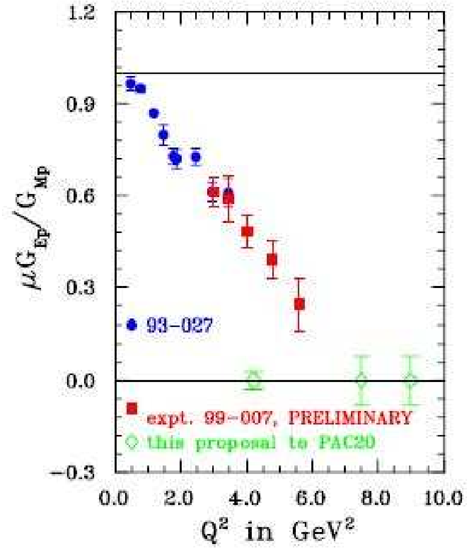
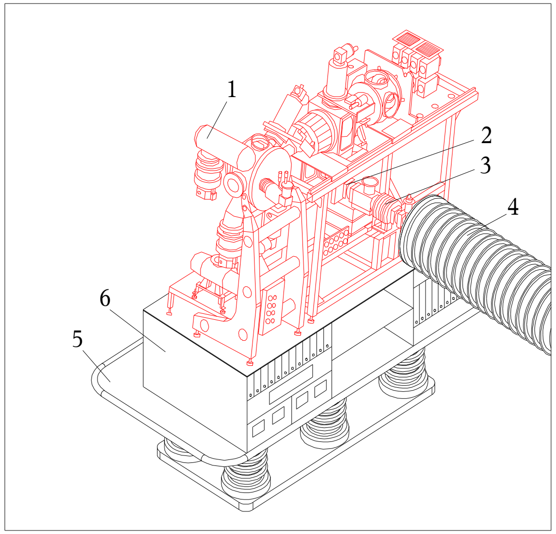


Figure 16: The $\mu_p G_{Ep}/G_{Mp}$ results of experiments 93-027, 99-007 (PRELIMINARY) and proposed 00-111.

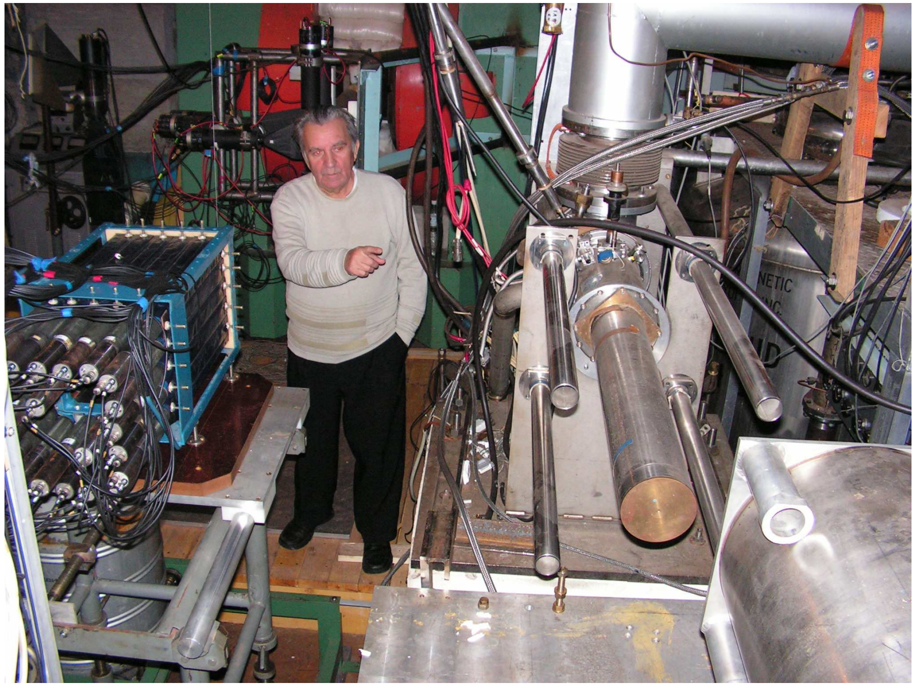
The main goal of the project is to obtain the analyzing power for $pCH_2 \rightarrow pX$ reaction at large momenta for G_{Ep}/G_{Mp} experiment at JLAB. Also these data are necessary to develop the proton focal-plane polarimetry at hadronic facilities.

New Polarized Deuteron Source for LHE



- New source will provide up to 10^{10} ppp and higher values of polarization than POLARIS.
- Part of the IUCF source can be used for the construction.
- 250 k$ and 2 years are required to put into operation new source.
- First operation is planned in 2010 y. (see talk of V.D.Kekelidze at June-2007 PAC-meeting)

Polarized Proton Target Upgrade



- Main purpose of the PPT upgrade is to provide the proton polarization normal to the beam direction.
- The upgrade of PPT is planned for 2007-2009 yy. The cost of upgrade is 50 k$.
- Putting into operation is planned together with new PIS. (see talk of V.D.Kekelidze at June-2007 PAC-meeting)

Strategy of polarization investigations at Nuclotron-M

Short-term: 2007-2009 yy.

- unpolarized: LNS-PHe3, STRELA, $\Delta\sigma$, DELTA-2, TPD
- polarized based on the use of POLARIS:
  (LNS-PHe3 at ITS, STRELA, ALPOM)
- Commision runs with New PIS and PPT:
  ($\Delta\sigma$, DELTA-2, LNS-PHe3, STRELA, ALPOM)

Goals: physics, polarimetry for NICA

During these years:

- New PIS installation and PPT upgrade
- Revision of the scientific polarization program and wide international collaborations around PPT, ITS etc.
- International spin collaboration for NICA

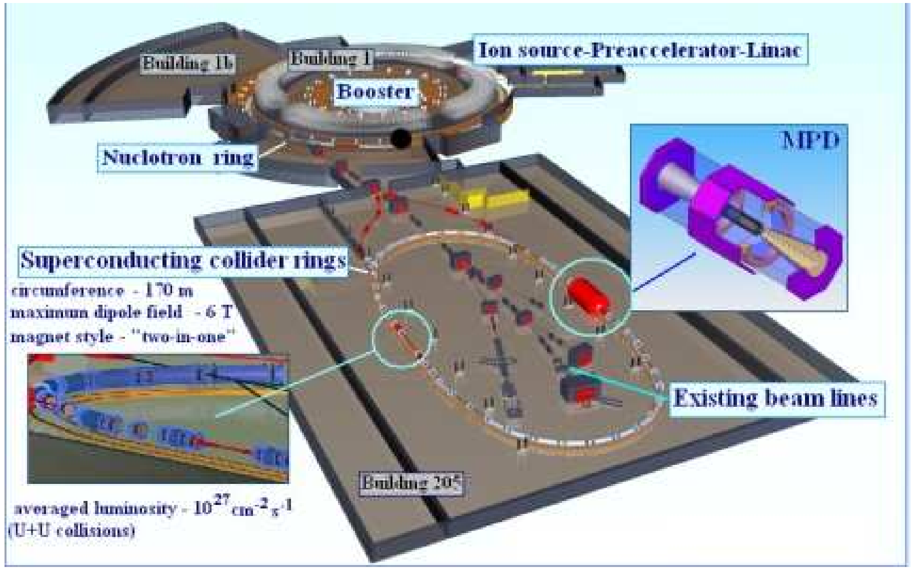
Long term studies at Nuclotron-M

Long term (after 2009 y).

Experiments with NEW PIS and PPT at Nuclotron:

- Spin structure of NN and 3N forces
  (relativity and transition to non-nucleonic degrees of freedom)
- Polarization effects in meson production (spin crisis).
- Medium effects for polarization observables
  (χ-symmetry restoration)
- Development of polarization techniques

Spin-NICA activity

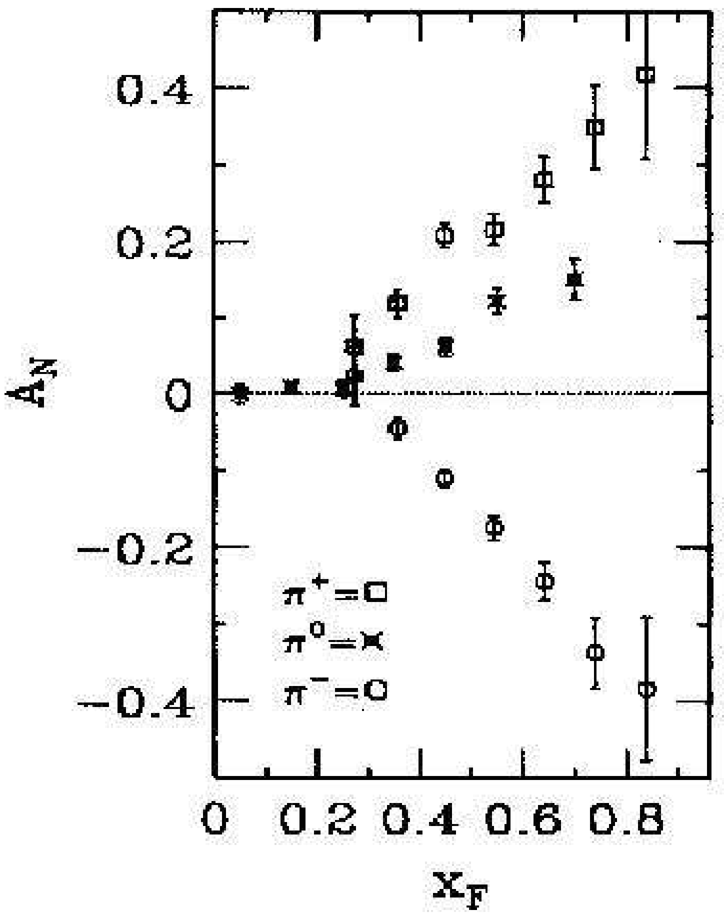


- Spin content of nucleon.
- Nuclear and color transparency in spin observables.
- Polarization effects in hyperon production
- Single and double spin asymmetries in meson production
- Deuteron short-range spin structure (A_{yy} measurements)

New facility is planned to work at $\sqrt{s_{\rm NN}} = 4 \div 9$ GeV

Serious advantage is the polarized deuterons (neutrons).

Spin physics using at NICA with polarized deuterons



- The perturbative regime in SSA for meson production occurs already at T_N =22 GeV.
- Single and double spin asymmetries for charged mesons in polarized neutron-proton collisions can be measured using polarized deuteron. Neutrons are produced from deuteron breakup with the proton spectator identification.
- The same motivation for P_N, A_N and D_{NN} for Λ^0 and Ξ^- production.

Unfortunately, MPD will detect only charged hadrons and will have poor PID at large x_F

Nucleon spin content at NICA with polarized deuterons

See A.V.Efremov et al.

Drell-Yan process: $\mathbf{NN \to e^+e^-X}$ and $\mathbf{pd \to e^+e^-X}$

- Sivers effect in Drell-Yan process (having opposite sign to SIDIS) can be studied in SSA
- Transversity $\mathbf{A_{TT}}$ measurement: $\mathbf{h_1}$
- $\mathbf{A_{LL}}$ measurement: $\mathbf{\Delta\bar{u} - \Delta\bar{d}}$
- Tensor structure of the deuteron in $\vec{\mathbf{p}}\vec{\mathbf{d}}$ Drell-Yan process. Total number of structure functions is 108 (S.Kumano et al.).

These studies are additional to U-70, J-PARC and FAIR

spin programs.

Other spin physics at NICA

- Deuteron short-range spin structure (L.Azhgirey et al.).
- Charmonium production (A.Vasiliev et al.).
- Nuclear and color transparency (S.Shimansky et al.).

Double wide apperture arms spectrometer (like DLS) at the second interaction point at NICA is required!

This spectrometer has to detect and identify both leptons and hadrons.

Conclusions

- The current spin program at Nuclotron-M brings new insight on the spin effects in the region of non-perturbative QCD where the transition from nucleon-meson degrees of freedom to the quark-gluon ones occurs.
- The putting into operation new PIS and upgrade of the existing PPT will significantly increase the potentialities of Nuclotron-M as a spin facility in a GeV range. This development is also the key point for NICA.
- The development of the setup with the possibility to detect both hadrons and leptons at the second interaction point at NICA is necessary to have rich spin physics.