The SPD project
at the Laboratory of High Energy Physics, Joint Institute for Nuclear Research, Dubna

Polarization data has often been the graveyard for fashionable theories. If theorists had their way they might well ban such measurements altogether out of self-protection.

J.D. Bjorken, 1987

Roumen Tsenov (LHEP), for the SPD project team
Main targets of the NICA project:
- **study of hot and dense baryonic matter**
- **investigation of nucleon spin structure, polarization phenomena**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ring circumference, m</strong></td>
<td>503.04</td>
</tr>
<tr>
<td><strong>heavy ions</strong></td>
<td></td>
</tr>
<tr>
<td>energy range for $Au^{79+}$: $\sqrt{S_{NN}}, GeV$</td>
<td>4 - 11</td>
</tr>
<tr>
<td>r.m.s. $\Delta p/p$, $10^{-3}$</td>
<td>1.6</td>
</tr>
<tr>
<td>Luminosity for $Au^{79+}$, $cm^{-2} s^{-1}$</td>
<td>$1 \times 10^{27}$</td>
</tr>
<tr>
<td><strong>polarized particles</strong></td>
<td></td>
</tr>
<tr>
<td>max. $\sqrt{S}$ for polarized $p$, Gev</td>
<td>27</td>
</tr>
<tr>
<td>Luminosity for $p$, $cm^{-2} s^{-1}$</td>
<td>$1 \times 10^{32}$</td>
</tr>
</tbody>
</table>
mini “Big Bang” in the laboratory

<table>
<thead>
<tr>
<th>Time</th>
<th>Big Bang</th>
<th>p &amp; n formation</th>
<th>low mass nuclei formation</th>
<th>neutral atoms formation</th>
<th>star formation</th>
<th>dispersion of massive elements</th>
<th>Today</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>&gt;10^12 K</td>
<td>10^12 K</td>
<td>10^9 K</td>
<td>4000 K</td>
<td>20 - 3 K</td>
<td>&lt; 20 K</td>
<td>3 K</td>
</tr>
<tr>
<td>time</td>
<td>10^-7 s</td>
<td>10^-4 s</td>
<td>3 min</td>
<td>400 k yr</td>
<td>10^9 yr</td>
<td>&gt; 10^9 yr</td>
<td>13.5 10^9 yr</td>
</tr>
</tbody>
</table>

Au + Au
Nuclear collisions and the QGP expansion

Development in time, $1 \text{ fm} / c = 3.3 \times 10^{-24} \text{ sec}$

- lumpy initial energy density
- collision overlap zone
- quantum fluctuations
- QGP phase quark and gluon degrees of freedom
- hadronization
- kinetic freeze-out
- distributions and correlations of produced particles

$\tau \sim 0 \text{ fm/c}$  $\tau \sim 1 \text{ fm/c}$  $\tau \sim 10 \text{ fm/c}$  $\tau \sim 10^{15} \text{ fm/c}$
QCD phase diagram

The Phases of QCD

- Early Universe
- Future LHC Experiments
- Quark-Gluon Plasma
- RHIC Energy Scan
- NICA
- Critical Point
- Hadron Gas
- Color Superconductor
- Future FAIR Experiments
- 1st order phase transition
- Vacuum
- Neutron Stars
- Nuclear Matter
- Hadrons
- Lattice QCD
- Quarks and Gluons
- RHIC-BES
- NICA
- Nuclotron-M
- Proto-Neutron stars
- Compact Stars
- Color Superconductor
- Net baryon density $n/n_0 = 0.16 \text{ fm}^{-3}$
Physics at NICA

Quark-gluon matter at NICA:

- **Highest net baryon density**
- **Energy range covers onset of deconfinement**
- **Complementary to the RHIC/BES, FAIR and CERN experimental programs**

- **Bulk properties, EOS** - particle yields & spectra, ratios, femtoscopy, flow
- **In-Medium modification of hadron properties**
- **Deconfinement (chiral), phase transition at high \( \rho_B \)** - enhanced strangeness production
- **QCD Critical Point** - event-by-event fluctuations & correlations
- **Strangeness in nuclear matter** - hypernuclei
Present and future heavy ion experiments

NICA/MPD will provide most precise results exploring the whole phase space in the most interesting energy range.
**Nuclotron (45 Tm)**

*Injection bunch ~ $2 \times 10^9$ ions, acceleration up to 1 - 4.5 GeV/u*

**Booster (25 Tm)**

*Storage of $(2 \div 4) \times 10^9$ ions, acceleration up to 600 MeV/u*

**Stripping (80%)** $^{197}\text{Au}^{31+} \Rightarrow ^{197}\text{Au}^{79+}$

**Linac HILac**

**Linac LU-20**

**Fixed Target Area**

**Two SC collider rings**

*~ 2 x 22 injection cycles, 22 bunches per ring*

**IP-1**

**IP-2**

**KRION**

**Ion sources**

**Small text:**

*11 Oct. 2018*
The NICA complex

existing facilities

NUCLOTRON
0.6-4.5 GeV/u

KRION-6T+ HILac (3MeV/u)

PS & LU-20
(5MeV/u)

Booster
(600 MeV/u)

to be constructed

MPD hall for fixed target experiments

BM@N

SPD

MPD hall

Collider

MPD
Polarized beams

Bunch crossing each 80 ns; crossing rate 12.5 MHz.

- 503 m,
- 2,
- 0.35 m,
- $\sim 1 \cdot 10^{12}$,
- 22,
- 0.5 m,
- 0.027,
- 0.067,
- 0.15 (normalized at 12.5 GeV)
Physics tasks

- Nucleon spin structure studies
  - Drell-Yan pair production;
  - Direct photons;
  - Nucleon PDFs by J/ψ production;
- Spin-dependent effects in elastic pp, pd and dd scattering;
- Spin effects in exclusive hadron production;
- Spin effects in production of hadrons with high $p_T$;
- etc....
Spin dependent PDFs

Transversity Momentum Distributions: TMD \((x, k_T)\) probe the transverse parton momentum dependence.

Generalized Parton Distributions: GPD \((x, b_T)\): probe the transverse parton distance dependence.
3 PDFs are needed to describe nucleon structure in collinear approximation.

8 PDFs are needed if we want to take into account intrinsic transverse momentum \( k_T \) of quarks.
1. Transversity: \( A_{UT}^{\sin(\phi+\phi_S)} \), represents the number distribution of transversely polarized quarks in a transversely polarized nucleon;

2. Sivers: \( A_{UT}^{\sin(\phi-\phi_S)} \), represents the distribution over the transverse momentum of non-polarized quarks in a transversely polarized nucleon;

3. Pretzelosity: \( A_{UT}^{\sin(3\phi-\phi_S)} \), represents the distribution over the transverse momentum of transversely polarized quarks in a transversely polarized nucleon;

4. Boer-Mulders: \( A_{UU}^{\cos(2\phi_h)} \), represents the distribution over the transverse momentum of transversely polarized quarks in a non-polarized nucleon;

5. Worm-Gears: \( A_{UL}^{\cos(2\phi_h)} \), represents the distribution over the transverse momentum of longitudinally polarized quarks in a longitudinally polarized nucleon.
Drell-Yan pairs

\[ \sigma_{tot} \sim 9 \text{ nb} \]

Dimuon spectrum from NA51 (\( \sqrt{s} = 29.1 \text{ GeV} \))

\[ \frac{dN}{dM_{\mu^+\mu^-}} \text{ Events/0.1 GeV/c}^2 \]
Asymmetries in DY pair production

\( Q^2 = 4 \text{ GeV}^2 \)  \hspace{2cm}  \( Q^2 = 15 \text{ GeV}^2 \)

\[ A_{UT} \sin(\phi - \phi_s) \frac{q_T}{M_N} \]

\[ A_{UT} \sin(\phi + \phi_s) \frac{q_T}{M_N} \]

Sivers

J.C.Collins et al., PRD73
(2006)014021

Boer-Mulders

s = 400 GeV^2
The gluon Compton scattering gives access to the gluon content of proton:

Transverse beam polarization: access to the Sivers function for gluons

\[
\sigma^\uparrow - \sigma^\downarrow = \sum_i \int_{x_{\text{min}}}^1 dx_a \int d^2k_Ta d^2k_Tb \frac{x_a x_b}{x_a - (p_T/\sqrt{s}) e^y} [q_i(x_a, k_{Ta}) \Delta_N G(x_b, k_{Tb})] \\
\times \frac{d\hat{\sigma}}{dt} (q_i G \rightarrow q_i \gamma) + G(x_a, k_{Ta}) \Delta_N q_i(x_b, k_{Tb}) \frac{d\hat{\sigma}}{dt} (Gq_i \rightarrow q_i \gamma)
\]

Longitudinal beam polarization: access to gluon polarization $\Delta g/g$

\[
A_{LL} \approx \frac{\Delta g(x_1)}{g(x_1)} \cdot \left[ \frac{\sum_q e_q^2 [\Delta q(x_2) + \Delta \bar{q}(x_2)]}{\sum_q e_q^2 [q(x_2) + \bar{q}(x_2)]} \right] + (1 \leftrightarrow 2)
\]
Expected asymmetries


Charmonia production

Gluon fusion

Charmonia production is sensitive to gluon distributions of colliding hadrons.

Quark annihilation

NRQCD

CEM

NRQCD cross section at NLO

MRST2002

11 Oct. 2018
Asymmetries in high $p_T$ hadron production

- Diquark properties;
- Confinement laws;
- Nature of the huge spin effects;
- Deuteron spin structure;
- Properties of the bare $N\Lambda$- and $NK$-interactions;
- Nature and properties of the cold super dense baryonic matter (CsDBM) ($pA$ and $AA$);
- Dilepton production puzzle in $np$-interaction.
On spin crisis

TMDs

SPIN PHYSICS WITH HIGH $P_T$

DIRECT PHOTONS ($\Delta G$)
SIDIS WITH $\pi^0$ ($L_g$ $L_q$ PDFs)
EXCLUSIVE DY ($\Delta G$)
DY (PDFs)
SIDIS $J/\psi$ (PDFs)
EXCLUSIVE $J/\psi$ (PDFs)
EXCLUSIVE $\pi^0$ (PDFs)
EXCLUSIVE $\rho$, $\omega$ (PDFs)
SIDIS $\pi^+$, $\pi^-$
ELASTIC, QUASIELASTIC
Minimum biased events

PYTHIA 6, $\sqrt{s_{pp}} = 26$ GeV; 4 MHz event rate

- Average charged particles' multiplicity $\sim 14$
- Average neutral particles' multiplicity $\sim 23$

from A. Guskov

11 Oct. 2018
Requirements for the SPD

- close to $4\pi$ geometrical acceptance;
- high-precision (~50 µm) and fast vertex detector;
- high-precision (~100 µm) and fast tracker,
- good particle ID capabilities;
- efficient muon range system,
- good electromagnetic calorimeter,
- low material budget over the track paths,
- trigger and DAQ system able to cope with event rates at luminosity of $10^{32}$ (cm.s)$^{-1}$,
- modularity and easy access to the detector elements, that makes possible further reconfiguration and upgrade of the facility.

11 Oct. 2018
Dimensions
Hybrid magnetic system

\( \frac{1}{2} \) model symmetry

\[ B^{(z)}(x, y, 0) = 0. \]

\[
J_T = 40 \frac{A}{mm^2},
\]

\[
J_{(1,2)}^{B/F} = n80 \frac{A}{mm^2},
\]

\[ S = 200 \times 20 \text{mm}^2, \]

\[ I_T = J_T \cdot S = 160 \text{kA}, \]

\[ I_{(1,2)}^{B/F} = J_{(1,2)}^{B/F} \cdot S = n320 \text{kA}. \]

\[
\Omega = \begin{cases} 
0 \leq r \leq 3000 \\
0 \leq z \leq 3000 
\end{cases}
\]

\[ B_{max} = 1.0 \text{T} \]

\[ B_{min} = 0 \text{T} \]

\[ Z = 1600 \text{mm} \]

\[ Z = 2800 \text{mm} \]

1. NbTi/Cu 33/33/33%  
2. stainless steel tube  
3. insulation epoxy layer, 0.3 mm  
4. copper shield  
5. multilayer thermal shield  
6. outer cover, 1mm stainless steel
**Vertex detector / Inner tracker**

**Silicon Vertex Detector**
- Silicon vertex detector around the beam pipe;
- Several layers of double sided silicon strips or MAPS;
- Optimized number of layers w.r.t. material budget;
- Goal: few tens of $\mu$m resolution for the vertex reconstruction → detection of particles with open charm and rejection of ($\pi$) decay muons.

**From A. Zinchenko, MPD ITS with MAPS → open charm registration**
Central tracker: straw tubes

- Minimum material on the particle tracks ($X_0 \sim 0.1$);
- Time ($\sim 100$ ns) and spatial resolution ($\sim 100$ μm);
- Expected particle rates (DAQ rates) $\sim$ MHz;
- Technology developed also in JINR, production workshops available.
ECal

- Photon energy range 0.1 - 10 GeV;
- Due to space limitations the total length of the ECAL module should be less than 50 cm;
- Required energy resolution $< 10.0\% / \sqrt{E}$ (GeV) and energy threshold below 100 MeV.
- The version of ECAL modules developed at JINR for the COMPASS-II experiment at CERN could be a good candidate ("shashlik" design);
- Crystal variant is being considered, too.

Avalanche multichannel photodetectors

Surface mount type Custom made
It should provide good (>95%) muon identification for momenta above 1 GeV.

Combination of responses from the ECal and RS could give additional lever for rejecting of pions and protons in a wide energy range.

The RS also provides additional coordinate measurement.

Our design will follow closely the design of the PANDA experiment range system (at FAIR, GSI) being developed now at the DLNP of JINR.
The SPD DAQ may be developed *a la* FPGA-based DAQ of the COMPASS experiment;

- Event rate ~3.0 MHz (at $L=10^{32}$ cm$^{-2}$s$^{-1}$, $\sqrt{s}=27$ GeV);

- Rough preliminary estimation of the total data flux from the detectors (Si tracker + straw tracker + RPC + ECal + range system): 10-20 GBytes/s (no detailed simulation results available yet);

- Triggered or trigger-less DAQ: to be decided.
Project status and roadmap
Start of the SPD project

• **Letter of Intent** presented at the JINR PAC in summer 2014, where:
  • the physics program of the experiment was developed;
  • requirements to NICA polarized beams were formulated;
  • desired detector characteristics and sketch of the facility were given;
• A few presentation at international conferences about the physics potential and program of the SPD were given;
• Several workshops on spin physics at NICA were organized:
  • NICA-SPIN-2013, Дубна, 17-19.03.2013
  • SPIN-Praha-2013, 7-13.07.2013
  • NICA-SPIN-2014, Praha, 11-16.02.2014
  • SPIN-Praha-2015, 26-31.07.2015
  • DSPIN2013, DSPIN2015, DSPIN2017

In 2017 a new stage of the project started:
**From LoI to CDR (Conceptual Design Report)**
Status

- Simplified detector sketch and simulations of basic physics processes (Oct. 2017- end of 2018) **ONGOING**;
- Development of a simplified design of the detector and costing **ONGOING**;
- Negotiations for an international collaboration and sharing of responsibilities for the design and construction of the facility **ONGOING**:
  - INFN section of Turin and University of Turin;
  - Charles University, Prague;
  - Technical University, Prague
  - Tomsk State University;
  - Tomsk Polytechnic University;
  - Institute of Applied Physics of the Belarus Academy of Sciences;
  - Gomel State Technical University, Belarus;
  - Institute for High Energy Physics, Protvino;
  - Institute of Nuclear Physics of the Moscow State University;
  - Institute for Nuclear Research, Troitsk;
  - Lebedev Physics Institute, Moscow;
  - Institute for Theoretical and Experimental Physics, Moscow;
  - St. Petersburg Nuclear Physics Institute, Gatchina;
  - St. Peterspurg State University;
  - St. Petersburg Polytechnic University
  - ...

Protocols for joint research within the SPD project signed.

Bilateral agreements on NICA exist.
Roadmap

- Writing up of a formal JINR project for the SPD design \((i.e. \text{ for preparation of the Conceptual and Technical Design Reports})\) and submission of the project to the PAC for Particle Physics:
  - status report presented at the PAC meeting in Jan. 2018;
  - submission of the application to the PAC in Nov. 2018 for their meeting in Jan. 2019;

- Setting up of the collaboration and election of its management bodies (2019);

- Signing of an MoU based on \(\text{“Regulations for the organization of experiments conducted by international collaborations using the capabilities of the JINR basic facilities”}\) \(\text{http://www.jinr.ru/wp-content/uploads/JINR_Docs/Regulation_for_the_organization_of_experiments_eng.doc}\) (2019).
Roadmap (cont’d)

- Preparation of the Conceptual Design Report (2019);
- Preparation of the Technical Design Report, including prototyping – first stage (2020 – 2022), second stage (2023);
- Construction of the detector (2022-2025);
- First measurements – 2025…
Roadmap

- JINR project for the SPD design (Jan. 2019);
- Setting up of the collaboration, MoU (2019);
- Preparation of the Conceptual Design Report (2019);
- Preparation of the Technical Design Report (including prototyping)
  - first stage (2020 – 2022)
  - second stage (2023);
- Construction of the detector (2022-2025);
- First measurements – 2025…
You are welcome to join the SPD/NICA project!

Web site: spd.jinr.ru.
Contact person: Roumen Tsenov (tsenov@jinr.ru)
SPD/NICA will provide a unique opportunity not available at other facilities to study all of the PDFs in one experiment and obtain comprehensive information on the nucleon spin structure at high statistical level with minimal systematic uncertainties.