JOINT INSTITUTE FOR NUCLEAR RESEARCH

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EXECUTIVE SUMMARY
Conceptual and technical design of the Spin Physics Detector (SPD) at the NICA collider

Since the famous ”spin crisis” that began in 1987, the problem of the nucleon spin structure remains one of the most intriguing puzzles in the contemporary high-energy physics. The central component of this problem, attracting for many years enormous both theoretical and experimental efforts, is the problem how the spin of the nucleon is built up from spins and orbital momenta of its constituents. The searches brought up a concept of the spin-dependent parton distribution functions of the nucleon, at the beginning only two were proposed: f_1 for unpolarized and g_1 for polarized nucleons. Now we know that there must be of about 50 different parton distribution functions for a complete description of the nucleon structure. While today a part of the polarized distributions can be considered as sufficiently well known, there is a number of PDFs that either are absolutely unknown, or poorly known, especially the spin dependent ones.

The composite nature of the nucleon spin structure has been studied for a long time by means of deep inelastic scattering (DIS) of leptons and production of Drell-Yan (DY) [1, 2] lepton pairs. In a regime of a large momentum transfer Q the scattering occurs in a collinear configuration between the incident lepton and a single parton in the nucleon (the so called Bjorken regime). A factorization theorem exists [3–6] that allows us to express the inclusive DIS and DY cross sections as a convolution of two contributions: one that corresponds to the hard process occurring at a short distance between the probe and the parton; and another one that accounts for the coherent long-distance interactions between the struck parton and the target, and is described in terms of parton distributions.

At leading order (leading twist, LO) the Bjorken variable x can be interpreted as the fraction of the longitudinal momentum of the parent (fast-moving) nucleon carried by the active parton, and one may distinguish three kinds of parton distributions functions (PDF). Two of them are well-known structure functions measured in DIS and other processes: $f_1^a(x)$ (a is a parton flavor, often suppressed) is the density of unpolarized partons with longitudinal momentum fraction x in an unpolarized nucleon, and $g_1(x)$ giving the net helicity of partons in a longitudinally polarized nucleon. The third one, the transversity $h_1(x)$, describing the density of partons with polarization parallel to that of a transversely polarized nucleon minus the density of partons with antiparallel polarization, is chiral-odd and requires a quark helicity flip in the scattering that cannot be achieved in the hard subprocess. Other parts of the cross section have to be explored for that. They are either chiral-odd fragmentation functions (FF) (e.g. Collins fragmentation function $H_1^{\perp}(x)$ in semi inclusive DIS (SIDIS)) or yet another transversity, that of the second polarized incident hadron in the DY.

However, in addition to the information on the longitudinal behaviour in momentum space along the direction in which the nucleon is moving, drawing a complete three-dimensional picture of the nucleon also requires knowledge of the transverse motion of the partons [7, 8]. A full account of the orbital motion, which is also an important issue to understand the spin structure of the nucleon, can be given in terms of transverse-momentum dependent parton distribution functions (TMDs). There are eight leading-twist TMDs: $f_1(x,p_T)$, $f_1^{\perp}(x,p_T)$, $g_{1L}(x,p_T)$, $g_{1T}(x,p_T)$, $h_1(x,p_T)$, $h_{1L}^{\perp}(x,p_T)$, $h_{1T}^{\perp}(x,p_T)$ and $h_1^{\perp}(x,p_T)$ [9].

Two of them, the Boer-Mulders and Sivers functions, $h_1^{\perp}(x,p_T)$ and $h_{1T}^{\perp}(x,p_T)$ [9–11], are T-odd, i.e. they change sign under naive time reversal, which is defined as usual time reversal, but without interchange of initial and final states. The other six leading-twist TMDs are T-even.

In order to be sensitive to intrinsic transverse parton momenta, it is necessary to measure the transverse momenta of the produced hadrons in the final state, e.g., in processes like semi-inclusive lepton-nucleon DIS (SIDIS), hadron production in e^+e^- annihilation [7] or the transverse momentum of the lepton pair in the Drell-Yan processes in hadron-hadron collisions. Here, factorization has been proven at leading twist [12–15] allowing to get information about TMDs as well as on fragmentation functions (FFs) describing the hadronization process of the hit quark into the detected hadrons.

By measuring the angular distribution of produced hadrons in SIDIS or lepton pairs in DY, it is possible to obtain information about all the eight leading-twist TMDs in combinations with the two leading-twist FFs.

According to the factorization theorem, each of the leading-twist structure functions can be conceived as a convolution between one TMD and one FF in SIDIS or two TMDs (for the quark and antiquark) in the DY. Since the structure functions enter the cross section with a defined angular coefficient, they can be accessed by looking at specific azimuthal asymmetries. This has become now a powerful tool for studying the three-dimensional structure of the nucleon and many more data are expected to come in the future. The remarkable experimental progress was motivated and accompanied by numerous theoretical and phenomenological studies.

During the past decades, dilepton production in high-energy hadron-hadron collisions played an important role in order to pin down parton distributions (PDFs) of hadrons. While the focus was on PDFs of the nucleon, also information on the partonic structure of the pion was obtained through Drell-Yan measurements. Experimentally, the Drell-Yan process is quite challenging because of the relatively low counting rates. On the other hand, from the theoretical point of view it is the cleanest hard hadron-hadron scattering process. The fact that there is no need to detect hadrons in the final state simplifies the proof of factorization in comparison to hadron-hadron collisions with hadronic final states. This important point is one of the main reasons for the continued interest in the Drell-Yan reaction in hadron-hadron collisions.

Currently, not less than six programs for future Drell-Yan measurements are pursued. These plans comprise dilepton production in nucleon-nucleon collisions (at RHIC [16], J-PARC (KEK) [17, 18], IHEP (Protvino) [19], and at the JINR (Dubna) [20, 21], in antiproton nucleon collisions (at FAIR (GSI) [22], as well as in pion nucleon collisions (at COMPASS (CERN) [23]. Past measurements exclusively considered measurements of the unpolarized cross section, but all future programs are also aiming at polarization measurements. Including polarization of the incoming hadrons opens up a variety of new opportunities for studying the strong interaction in both the perturbative and the non-perturbative regime.

The objective of the proposed experiment is also the study of the gluon structure of the nucleon. It is of fundamental importance as it is needed to understand the nucleon internal structure as a whole. The unpolarized gluon content of the proton is well-known while our knowledge of polarized parton distributions (including TMDs) is limited.

There are two main hard processes for the production of direct photons: gluon Compton scattering, $gq(\bar{q}) \to \gamma q(\bar{q})$, which dominates and gives access to the gluon distributions in the nucleon, and quark-antiquark annihilation, $q\bar{q} \to \gamma g$. The contribution of the latter process to the total cross section presumably does not exceed 20%. A few fixed-target and collider experiments performed unpolarized measurements of the prompt-photon production differential cross section [24]. A certain tension between data of the fixed-target results, the collider ones and the theoretical expectations takes place. New precise measurements could clarify the issue.

Measurement of single transverse spin asymmetry in prompt-photon production at high p_T in polarized p-p and d-d collisions could provide information about the gluon Sivers function, which is the mostly unknown function at the moment [25]. In general, the investigation of processes with prompt photons, as well as charmonium production is a proven way to enhance the available rather scarce experimental information on the gluon content of the hadrons.

The opportunity to have high luminosity collisions of polarized protons and deuterons at the NICA collider allows for studies of a great variety of spin and polarization dependent effects in the hadron-hadron collisions:

– Drell-Yan (DY) pair production and prompt-photon processes with longitudinally and transversely polarized p and d beams. Extraction of unknown (poor known) parton distribution functions

(PDFs) from J/ψ production processes and spin effects in baryon, meson and photon production;

– different effects in various exclusive reactions;

– diffractive processes;

– cross sections, helicity amplitudes and double spin asymmetries (Krisch effect) in elastic reactions;

– spectroscopy of quarkonia.

The principal aim of this proposal is to elaborate a design concept for a detector (Spin Physics Detector, SPD) capable to exploit the broad spin physics potential of the NICA collider. The physics program, requirements for the detector and the design ideas are based on the submitted in 2014 Letter of Intent [21] that was endorsed by the JINR Pphysics Advisory Committee (PAC) for Particle Physics .

Figure 1: Layout of the NICA collider with SPD at the south collision point.

The SPD facility is foreseen to be allocated in the south beam interaction point of the NICA collider. as shown in Figure 1.

The requirements for the detector are listed below:

– close to 4 geometry for secondary particles;

– high-precision ($\sim 50\mu m$) and fast vertex detector;

– high-precision ($\sim 100\mu m$) and fast tracking system;

– precision momentum measurement of secondary particles;

– good particle identification capabilities ($e^{\pm}, \pi^{\pm}, K^{\pm}, \mu^{\pm}, p^{\pm}$ etc.);

– 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^{-2}s^{-1};

– modularity and easy access to the detector elements in view of reconfiguration and further upgrade of the facility.

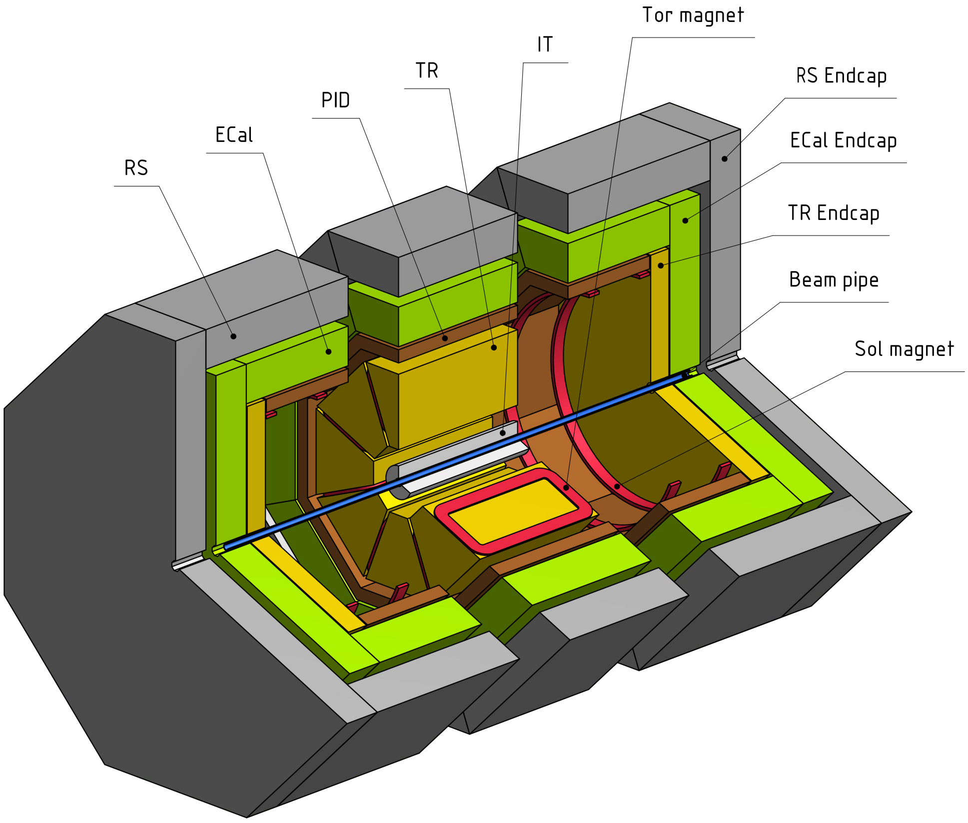

Figure 2: General view of the SPD facility

The aim is to have yet simple but universal detector that could be relatively easily reconfigured and/or upgraded. An idea about the composition and design of the SPD set-up is presented in Figure 2.

The detector consists of three modules: two end-caps and a barrel section. Each part has an individual magnet system: the endcaps - solenoidal coils, the barrel - toroidal magnetic system. The main detector systems as shown in the Figure 2, are as follows: Range System (for muon identification), Electromagnetic Calorimeter, PID/Time-of-Flight system, Main Tracker and Vertex Detector. The proposed three-module design gives a possibility for upgrade and modification of each of the main detector subsystems and for performing measurements in different detector configurations.

Preliminary MC simulations have been carried out in order to evaluate the capabilities of such a system to perform the foreseen measurements. The results are encouraging.

The current project includes as a component design and construction of a SPD test zone at one of the extracted beams of the Nuclotron for testing of the detector prototypes in beams of various particle species and of different momenta in the energy range of interest.

Host institute of the project is the Laboratory of High-Energy Physics of the Joint Institute for Nuclear Research. The main part of the human resources engaged with the project comes from there (74 researchers, 24.4 FTE). The Laboratory of Nuclear Problems is the other laboratory of the JINR that participates in the project with substantial number of researchers (30 researchers, 11.3 FTE). Altogether the JINR engagement in the project now evaluates to 37.7 full-time-equivalent (FTE) researchers.

Fourteen institutes from the JINR Member States and other countries have expressed by now their interest for participation in the project and indicate that they could allocate resources and manpower for the project.

We propose a three-year project for delivering of a technical design of the start-up configuration of the SPD facility based on the necessary simulation work, prototypes construction and test measurements.

The time-line is seen as follows:

- submission of a JINR project for design of the SPD facility for the PAC meeting in January 2019;
- setting up of the SPD collaboration and election of its management bodies (2019);
- signing of MoU (2019);
- preparation of Conceptual Design Report and submission to the PAC by the end of 2019;
- preparation of Technical Design Report for the start-up configuration of the facility, including prototyping and test measurements (2020 - 2021);

We hope to be able to start construction of the start-up configuration of the detector in 2022 and perform first measurements somewhere in 2025.

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