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The NICA-SPD project: a new tool to investigate the hadron structure

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SPD is an international Collaboration gathering around the Spin Physics Detector at the Nuclotron-based Ion Collider FAcility (NICA), presently under construction at the Joint Institute for Nuclear Research, in Dubna. The project is briefly presented with special focus to the opportunities opened by the collision of high luminosity polarized proton and deuteron beams with total energy up to $\sqrt{s}$=27 GeV. Examples of the foreseen research program are highlighted, in connection with the spin structure of light nuclei, the proton gluon content and the spin dependence of the nucleon-nucleon interaction. The unicity of NICA-SPD makes the future results complementary to the studies that have been or will be performed at other polarized hadron machines in different energy domains.

Keywords: Hadron collider; gluons; protons; deuterons.

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1. Introduction

A new project devoted to hadron physics is under construction at the Joint Institute for Nuclear Research in Dubna, Russia. The Nuclotron Based Ion Collider fAcility (NICA) will accelerate the beams injected from the superconducting synchrotron Nuclotron, that is working since the years 1990's. The Nuclotron has undergone an important upgrade including the construction of a booster, a pre-injector and different ion sources. In particular, a polarized source received from the University of Indiana at Bloomington (USA) has been rebuilt [1]. It is especially important for the polarized proton and deuteron program. NICA will accelerate light ions as protons, deuterons and heavy ions up to gold [2]. The beams will collide in two interaction points, where the $\sim 4\pi$ detectors will be installed: the multipurpose detector (MPD), devoted to heavy ion collisions and focused to the study of states of nuclear matter in extreme conditions of pressure, and the Spin Physics Detector (SPD) dedicated to the physics with polarized beams, that will study the structure and the properties of light hadrons and their composition in terms of quarks and gluons.

The kinematical region accessible at NICA covers the transition region from non perturbative to perturbative QCD. The symmetries of the strong interaction, the properties of the QCD vacuum, basic properties of particles as mass and spin will be studied through different processes. The kinematical range, the choice of the probes (proton and deuterons), the power of polarization observables, together with the performances expected from a modern $\sim 4\pi$ detector, are expected to bring important breakthroughs. For protons, the available energy range will be up to $\sqrt{s} = 27$ GeV with a peak luminosity that can reach 10^{32} cm^{-2}s^{-1}. The comparison with other polarized proton world facilities is illustrated in Fig. 1. The contribution to the world effort in understanding the dynamics created by the strong interaction is characterized by the variety of polarization observables that are accessible with proton and deuteron beams that can be polarized along and transversal to the beam direction.

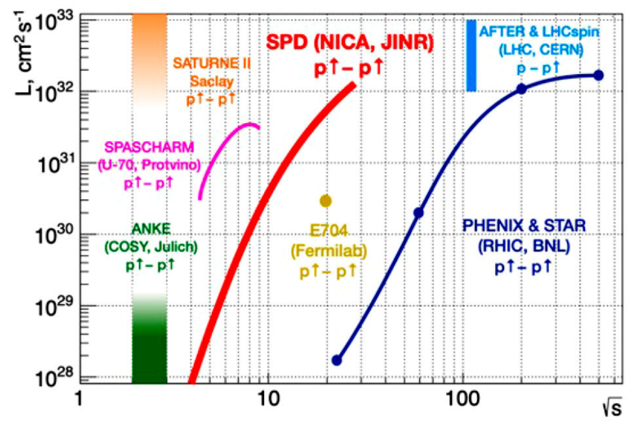

FIGURE 1. Expected luminosity at NICA-SPD, compared with other hadron machines, as a function of the total energy.

The purpose of this contribution is to describe the main properties of the SPD detector and the physics goals of the SPD collaboration.

2. The detector

SPD is conceived as a compact detector built with the technology developed for the large instruments as ALICE@LHC or PANDA@FAIR. It will have a cylindrical symmetry around the collider beam axis, set at the collision point, with longitudinal dimensions $\simeq 8$ m and transverse dimension of 6.5 m. The detector will be embedded in a solenoidal magnetic field of 1 T. The detection of charged and neutral particles, as well as photons, produced in the collisions of (un)polarized proton and deuteron beams requires:

- particle identification system, consisting in a time of flight (scintillators or Multigap Resistive Plate Chambers) to provide pion, kaon and proton separation up to 1.5 GeV. The required resolution in time is 60-70 ps. An aerogel detector may be added for higher particle momenta.

- tracking system: a vertex detector (silicon tracker) and a straw tracker will contribute to the track reconstruction, momentum and energy loss measurements. It should have a spatial resolution of 150 μm, as low as possible material budget, and operate in the 1T magnetic field.

- electromagnetic calorimeter: layers of Pb and scintillator must ensure the detection of prompt photons and photons from particle decays, as well as the identification of electrons. For this aim a low energy threshold of 50 MeV is necessary, and an energy resolution of $5\%/\sqrt{E}$.

- a range system for the detection of muons, optimized for the $J/\psi \to \mu^+\mu^-$ decay.

To the detector itself should be added a system to control locally the polarization of the beams (charged pions will be detected in beam-beam counters). Zero degree calorimeters will be used as a luminosity monitor and for ensuring the separation between neutrons and gammas. In order to avoid possible bias, a triggerless data acquisition system is developed. The expected collision rate is 4 MHz. A schematic view of the detector is shown in Fig. 2. More details can be found in Ref. [3].

3. Hadrons at SPD

A complete and systematic study of nucleon-nucleon (deuteron) elastic and inelastic collisions is mandatory for a better understanding of the strong interaction, driving the dynamics of the quarks and gluons, the components of hadrons. At low energies effective theories describe effectively the experimental observations, in terms of mesonic degrees of freedom. This domain of research has been explored in the past by different experiments, with different probes leaving observations not yet explained. Polarization phenomena bring essential information about the structure of the particles and allow to disentangle different reaction mechanisms. Single and double polarization observables in NN interactions are very powerful in constraining models and reconstruct the reaction amplitudes. At large scattering angles, structures were observed in the analyzing power of pp elastic scattering from a few GeV [4] up to few hundred GeV [5, 6]. These structures are still unexplained, although different models, based on Glauber description or Regge formalism may give a partial explanation of the data.

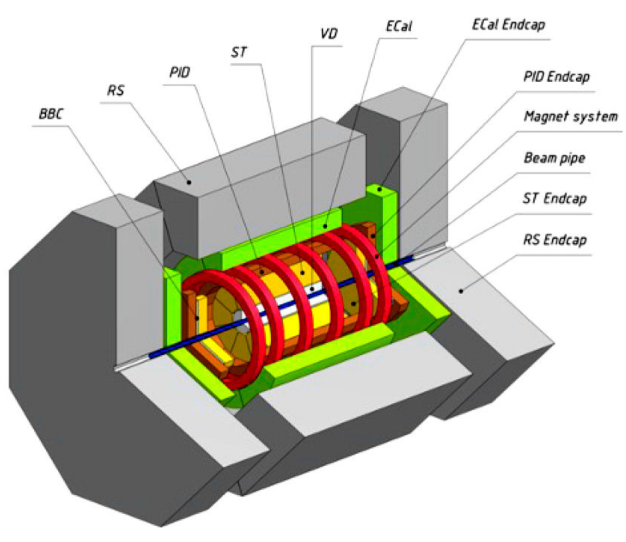

FIGURE 2. Schematic view of the SPD detector. BBC: beam-beam counter, RS range(muon) system, PID: particle identification system, VD: vertex detector, ECal: electromagnetic calorimeter.

The peripheral region of the nucleon can be studied using diffractive pp-scattering. Several oscillations in the differential cross section were found in experiments at Protvino, Fermilab, LHC and attributed to the effect of the meson cloud, *i.e.*, to the components located at larger distances, whereas the three quarks are assumed to be concentrated in a region of few tenths of $fermi$.

Inelastic pp reactions include meson production. Light mesons will be copiously produced and detected in SPD. Scalar, vector, strange meson production have brought deeper understanding of the pp interaction and dynamics. In the threshold region (expected to be quite wide) model independent predictions that apply to all vector mesons, have been done in Ref. [7], as for example, strong isotopic effects where the vector meson $(J/\psi, \phi..)$ production would be larger in np compared to pp reactions. The vector meson would be transversally polarized (even in reactions with unpolarized particles), with equal polarization in nn and np collisions. The kinematical range available at SPD allows precise measurements of the excitation function for J/ψ production. Data exist in this region mostly for nucleon-nuclei production. The extraction of the J/ψ cross section requires the understanding of how charm quarks are created, how they interact with the nuclear medium, and how they hadronize. The properties of polarized and unpolarized observables in open charm production as $N + N \to \Lambda_c + \bar{D} + N$ were investigated in Ref. [8] and Refs. therein. The cross section is not negligible, reaching tens of μb in the SPD region. Charm quarks, not pre-existent in the nucleon, are formed in a very compact region $r_c \ll 1/m_c \simeq m_c$, therefore selecting very small distances among partons. In particular, in deuteron collisions, all six valence quarks must contribute coherently, selecting the hidden color part of the deuteron wave function [9].

The short distance dynamics will be investigated with different processes. Short range correlations can be studied in the reaction $pd \to ppn$, where one nucleon has small transverse momentum while the other two are emitted back to back carrying most of the momentum. It has been suggested that nucleons interact in small size configuration inducing small cross section. This *color transparency* phenomenon can be difficult to observe, due to the evolution of the parton wave function in nuclear matter. In this respect, deuterons are ideal probes allowing also to compare the dynamics for pn and pp pairs at hight transverse momenta p_T [10].

Diquarks, and multiquarks correlations can be observed in different processes and may have different origin: fluctuations of nuclear matter from compact multinucleon states, multiparton re-scattering processes or formation of exotic multiquark resonances. Di-quarks can be observed in large p_T hadron emission, producing an increase of the two particle correlation function outside the back-to-back scattering region. Cumulative production, *i.e.*, the production of particles with energies beyond the kinematic limit for free nucleon collisions, is a preferred region to select compact multi-quark clusters.

More experiments have been suggested: test of scaling laws of QCD, through the momentum slope of the differential cross section for different processes; precise tests of fundamental symmetries as parity violation in high energy pp asymmetry; measurement of the cross section of antiproton production of interest for astroparticle physics and Dark Matter searches... these and others suggestions are compiled in Ref. [11].

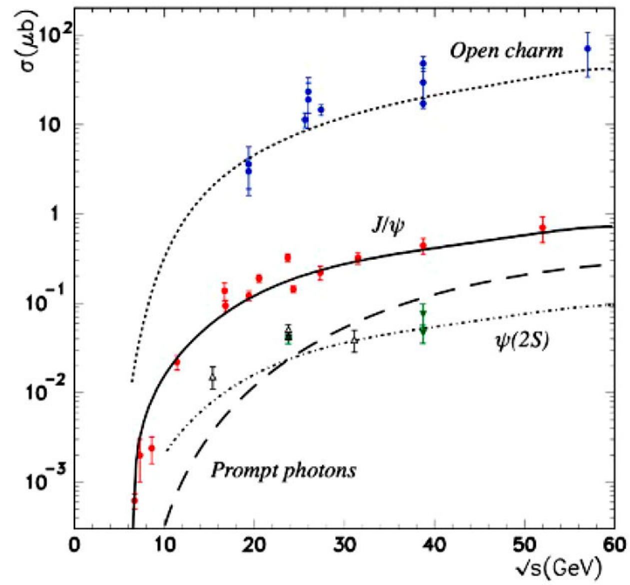

FIGURE 3. Cross section for open charm (dotted line), J/ψ (solid line), $\psi(2S)$ (dash-dotted line) and prompt photon (long dashed line) production processes.

4. Quarks and gluons at SPD

One of the main questions of hadron physics is how the mass and the spin of the proton are built. The Higgs mechanism explains the mass of the quarks, however the mass of the three valence quarks contributes for a few percent to the mass of the proton. The spin of the proton is 1/2, however the spin carried by the quarks has been measured to be $\sim 1/4$. It is assumed that most of the mass of the proton is dynamically created by the interactions among the gluons and the sea quarks. Most of the experimental effort is now focussed on the spin carried by the gluons or created by the angular momentum of the partons. SPD will contribute essentially to this issue by measuring polarized and unpolarized observables related to gluon density and to specific parton distribution functions as transverse momentum dependent distributions TMD PDF [12]. Again the deuteron will bring a unique information as a non-zero deuteron transversity can only originate from non-nucleonic components: as it requires two units of helicity flip it can not be generated by spin 1/2 particles as proton and neutron.

Three processes will be investigated to access the polarized and unpolarized properties of the gluon content in the nucleon: open charm production, J/ψ production, and prompt photons. The cross section for these processes is illustrated in Fig. 3. The study of these three channels is complementary. The largest cross section is for open charm production. The detection is quite challenging, as the D-meson is reconstructed from its decay channels, the charged D^+ (the neutral D^0) decays to $\pi^+K^-\pi^+$ (D^0 to $K^-\pi^+$). A precise vertex detection will allow to determine the secondary vertex of the D decay, displaced by 100 μm from the interaction point. The reaction $J/\psi \rightarrow \mu^+\mu^-$ gives a narrow signal over a background, with a relatively large cross section and branching ratio 6%. A large fraction of J/ψ is also produced in the decay of heavier resonances, making the analysis more complicated. In general, the results from these reactions are model dependent, and have to be interpreted through a modelization of the charm quark production and of the fragmentation function.

Prompt photons are produced at the level of hard parton scattering and re-interact weakly, carrying the information of the $gluon\text{-}quark$ or $quark\text{-}antiquark$ interaction. However, they need to be disentangled from a large background, particularly at low transverse momenta where photons from secondary mesons largely contribute.

The kinematical region covered by SPD, the large x region, has been covered till now mostly with lepton probes. The parametrizations of the gluon density vary essentially in the different models fitted on the data. The data on charmed mesons not far from threshold will be very effective to constrain the gluon density, the strong coupling constant and even the charm mass.

More details can be found in Ref. [13].

5. Conclusions

The SPD (Spin Physics Detector) at the JINR-NICA collider is a new multipurpose 4π facility detecting the reactions induced by polarized high-luminosity proton and deuteron beams at $\sqrt{s}$ up to 27 GeV. SPD will bring new precise data with systematic studies of elastic and inelastic pp and dd scattering, production of charmonia, open charm and prompt photons.

SPD will join the world effort in understanding the properties of QCD dynamics and the structure of light hadrons, by contributing to the study of the internal dynamics of gluons and quarks in protons and deuterons at large x, bringing precise information on the gluon helicity, on the transverse momentum distributions of gluons and unpolarized gluon parton distribution functions. The large x kinematical region will be systematically investigated collecting new data with hadronic probes. Due to the unicity of its polarized deuteron beams, SPD can bring totally new information on the gluon transversity in deuteron.

A programme for the study of nucleon-nucleon interaction and deuteron structure at short distances is proposed when the first beams will be available. Note that SPD will be a unique facility to study polarized deuteron collisions. Let us mention, in this respect, that polarized deuteron beams are already available in Dubna, accelerated at the Nuclotron facility up to a momentum of 13 GeV/c. Polarized proton and neutron beams can be obtained by deuteron break-up. A strong tradition for experiments using polarized beams and targets exists in Dubna [14]. An important breakthrough for increasing the performances of polarized beams, as the suggestion of controlling the beam polarization in a spin transparency mode, are under development [15].

Today, the NICA-SPD collaboration gathers about 300 researchers in 33 laboratories from 14 countries. The collaboration is consolidating and undergoes a review process from an international expert committee in view of a final endorsement by JINR as early as 2022.

Let us stress that NICA-SPD is open for new ideas and collaborators.

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