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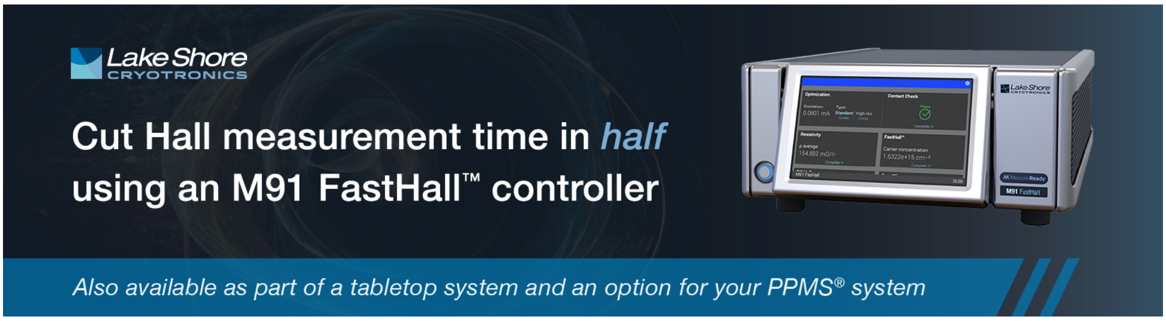

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Selected Topics of the Physical Programme for the First Stage of the NICA SPD

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Abstract. The NICA collider project at the Joint Institute for Nuclear Researches in Dubna will have a capability to study hadronic processes caused by collisions of polarized and unpolarized proton and deuteron beams with usage of the Spin Physics Detector. Several possible studies at the first stage of this project corresponding to an effective nucleon-nucleon center-of-mass energy in the range of $\sqrt{s_{NN}} = 3-10$ GeV are briefly reviewed.

INTRODUCTION

The Nuclotron-based Ion Collider fAcility (NICA) project is developing in the Joint Institute for Nuclear Researches in Dubna to start experiments with colliding heavy ions and also to study hadron spin physics in collision of polarized beams of the protons and deuterons. Processes of double polarized pp-, dd- and pd- collisions at the effective nucleon-nucleon center-of-mass energy up to $\sqrt{s_{NN}} = 27$ GeV will be studied using the Spin Physics Detector (SPD) [1]. The main task of the NICA SPD project is to determine gluon contribution into the spin of the proton and deuteron on the basis of measurement of the cross sections of processes with hidden and open charm production and production of the direct photons [2]. For this aim will be necessary the maximum luminosity and, respectively, the highest collision energy accesible at the NICA SPD $\sqrt{s_{NN}} = 10-27$ GeV. The first stage of the NICA SPD project will start at lower energies $\sqrt{s_{NN}} = 3.5-10$ GeV and, correspondingly, at lower luminosity $\sim (10^{28} \div 10^{29})\text{cm}^{-2}\text{c}^{-1}$. Possible experiments at the first stage of the NICA SPD were suggested in Refs. [3, 4]. Some of these suggestions are briefly discussed here.

TEST OF QCD BASIS IN THE TRANSITION REGION

At low energies, below the GeV region, and low transferred momenta the strong interaction between hadrons is described in terms of meson exchanges in accordance with the chiral effective field theory, which is based on spontaneously broken chiral symmetry of the QCD Lagrangian. At much higher energies and high transferred 4-momenta, perturbative Quantum Chromodynamics (pQCD) characterizes the strong force in terms of quark and gluons carrying color charge, and obeying to parton distribution functions (PDF) of hadrons and nuclei. Although these two pictures are well determined in their respective energy scales, the transition between them is not well identified. The NICA SPD project [1] at its first stage with lower energies is very suitable to search and study the transition region from hadron to quark-gluon degrees of freedom in theoretical analyses of collisions of free protons or/and deuterons. Such QCD predictions like color transparency, dimensional scaling, multiquark configurations can be considered as indications for transition region and as its properties.

pN scattering into forward hemisphere and pd scattering

Elastic nucleon-nucleon (NN) scattering is one of the basic processes in nuclear physics that contains information about the dynamics of the NN interaction. In this case, spin observables contain independent information that cannot be extracted from unpolarized NN scattering. The most complete data on the spin amplitudes of NN scattering are available for pp-scattering at the laboratory energies up to 3 GeV and pn-scattering – up to 1.2 GeV [5]. At higher energies, the available data are substantially incomplete for the pp and very sparse for the pn system. To extract from the experimental data all independent spin amplitudes (5 for pp or nn and 6 for pn, provided T- and

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P-invariance is met) at a fixed energy, it is necessary to perform a complete polarization experiment, including the measurement of at least 10 spin observables. On the other hand, an effective test of the parametrizations of spin pN amplitudes available in the literature is the application of the spin-dependent Glauber theory for elastic *pd* scattering into the forward hemisphere and comparison of the results of the corresponding calculations with experimental data. Examples of such calculations at SPD energies are given in [6]. Additional testing can be performed using the quasi-elastic scattering of $pd \to \{pp\}_s n$, where $\{pp\}_s$ is a pp-pair in a $^1S_0$ state of relative motion, as well as with elastic *dd*-scattering ([3], section 2). Note that the knowledge of the T-even, P-even helicity amplitudes of *pp*- and *pn*-scattering is fundamentally necessary, for example, in the problem of finding a violation of T-invariance, in a doubly polarized *pd*-scattering [7, 8] (see below the last section).

Double-spin correlations in elastic pN-scattering at large angles and multiquark resonances.

An unexpectedly large double spin correlation A_{NN} was observed in elastic *pp* scattering at large angles ($\theta_{cm} = 90°$) at energies $\sqrt{s_{NN}} = 3$ GeV and $\sqrt{s_{NN}} = 5$ GeV [9]. These energies correspond to the thresholds for the production of strangeness and charm in a *pp* collision. The observed strong correlations (the ratio of cross sections 4 : 1 for parallel and antiparallel spins of transversal polarized colliding protons) are compatible with the assumption of the formation of octoquark resonances in the s-channel $uuds\bar{s}uud$ and $uudc\bar{c}uud$, respectively, with quantum numbers $J = L = S = 1$, where L is the orbital momentum, S is the spin and J is the total angular momentum of the resonance [10]. Based on this assumption, the authors of [10] qualitatively explained the unusual behavior of color transparency (see the next subsection) in reactions of type A(p,2p)B and oscillations in the differential cross section of the elastic *pp*-scattering $d\sigma/dt$ in the region of the manifestation of the quark counting rules. However, the last two effects have another explanation in the nuclear filter model [11]. Short-range NN dynamics in elastic *pp* and *pn*-scattering can be quite different [12]. In the *pn* scattering occurs an additional channel with the isospin $T = 0$, which is absent in the *pp*-scattering. In this regard, it is very important to investigate the elastic *pn* scattering with double polarization in the same energy range $\sqrt{s_{NN}} = 3 - 5$ GeV, which can be done on the NICA SPD using double polarized *dd* and *pd* collisions.

Color transparency

The color transparency (CT) as a QCD phenomenon was predicted in Refs. [13] and [14]. The CT means that in hadron induced semi-exclusive reaction $h + A \to h + p + (A-1)$ with large momentum transfer ($Q^2 = -t >> 1\mathrm{GeV}^2$) in the elastic *hp* scattering subprocess, the nucleus A becomes transparent for incoming and outcoming hadrons. The CT is a consequence of the reduced transverse size ($b \sim 1/Q$) of the quark configurations participating in the hard process and their color neutrality. The latest review on CT in Ref. [15] shows the presence of convincing data on the manifestation of color transparency in the processes with mesons. For nucleons the situation is not so clear and this may be connected with larger number of quarks in a baryon than in a meson. The data on CT in the reaction A(p,2p), demonstrating the presence of an effect at certain values of Q^2, show its unexpected decrease with a further increase in Q^2. There are attempts in the literature to explain these data – the excitation of octoquark states at the hidden charm threshold in elastic *pp* scattering [10] and the mechanism of the nuclear filter [16, 17], which are not generally accepted. New data recently obtained in Jlab on the reaction ^{12}C(e,e′p) at large values of the square of the transferred to the proton 4-momentum $Q^2 = 8 - 14\mathrm{GeV}^2$ [18] show that there is no color transparency in this process contrary to the predictions of the theoretical model. This result, along with the previously obtained unusual behavior of color transparency in the reaction of the proton knock out by protons $A(p,2p)B$ is currently being actively discussed in the literature [19, 20, 21, 22].

Authors of Ref. [19] assuming specific three-layer structure on the nucleon argue that in the quasi-elastic processes $e + A \to e' + N + (A-1)$ the quasi-Feynman mechanism could be dominating in a wide range of Q^2. In this scenario, a virtual photon is absorbed by a single quark, which carries a large fraction of the momentum of the nucleon and this is not a democratic chain approximation [23], which requires a squeezed configuration of the nucleon and provides a CCR behaviour of the differential cross section. Therefore, CT should reveal itself in these processes at extremely large Q^2 as the consequence of the presence of the Sudakov form factors, which squeeze a nucleon. Concerning the interpretation of the Jlab data [18], it is mentioned in Ref. [19] that there are uncertainties in parameters of present theoretical estimation of the CT effect. In Ref. [20] was concluded that for nucleons the onset of the CT regime should be expected at higher values of Q^2 than previously expected, namely, at $Q^2 > 14$ GeV^2 for protons and at $Q^2 > 22$ GeV^2 for neutrons. This interval is available on NICA SPD at $\sqrt{s_{pN}} = 5.4 - 6.7$ GeV for the c.m.s. scattering angle $\theta_{c.m.} = 90^\circ$ in the pN system. On the other hand, for mesons the CT regime is expected at much lower transferred momenta $Q^2 \sim 4$ GeV^2 [20]. The authors of Ref. [21] propose to perform new measurements in order to clarify the possibility that CT really indicates the dominance of processes at short distances, and in Ref. [22] it is proposed to investigate the non-covered yet u-channel region of color transparency in experiments with electron beams.

Further development of the model of the deuteron breakup reaction $pd \to pnp$ [24] taking into account the effect of proton-neutron scattering both in the usual (generalized) eikonal approximation and with taking into account the mechanism of CT was recently performed in the work [25] at kinematics accesible for the NICA SPD. For the first time, estimates of the sensitivity of the tensor analyzing power A_{zz} of this reaction to the contribution of the CT effects are given. It is shown that when the c.m.s. pp-scattering angle decreases from 90° to 50°, providing an increase in the pp scattering cross section, the CT effect remains clearly visible in the reaction cross-section and in the tensor analyzing power, and the counting rate becomes high enough to measure these observables at the NICA SPD.

Constituent counting rules in reactions with the lightest nuclei

Properties of the lightest nuclei at short distances between nucleons $r_{NN} < 0.5$ fm, or at relative momenta $q > \hbar/r_{NN} \sim 0.4$ GeV/c, are of fundamental importance for nuclear physics. As noted above, one of the important issues is related to the search for the onset of the transition from the meson-baryon picture to the quark-gluon picture when describing the structure of the nucleus. A clear signal of transition to the quark region is related to the constituent counting rules (CCR): at high energies and large momentum transfers, the differential cross section of the binary reaction takes the form $d\sigma/dt \sim s^{-(n-2)} f(t/s)$, where n is the total minimal number of the point participants (quarks, leptons, photons) involved in the reaction, s and t are Mandelstam variables. This behavior, obtained within the framework of the self-similarity hypothesis [26] and the perturbative QCD [27], is also predicted in the AdS/QCD [28] approach. Under the CCR conditions, the helicity of quarks must be preserved in reactions [29] and the color transparency behaviour has to be pronounced (see the previous subsection). It is important to note that CCR are manifested not only in reactions with free hadrons, but also with the lightest nuclei – in the reaction of photodesintegration of the deuteron $\gamma d \to pn$ at photon energy $E_\gamma = 1 - 5.5$ GeV, as well as for the ^3He nucleus in reactions $^3He(\gamma, pp)n$, $\gamma\, ^3He \to dp$. Unexpected is the manifestation of CCR in the reactions of $dd \to\ ^3Hp$, $dd \to\ ^3Hen$ with the cross section dependence of s^{-22} and in $pd \to pd$ (s^{-16}) at surprisingly low energies of the order of ~ 0.5 GeV (see [30] and references therein). It has been shown recently the CCR behavior of the reaction cross section $pd \to pd$ at energies $\sim$ 1GeV. On the other hand, the reaction $pp \to d\pi^+$ does not follow the CCR under almost the same kinematic conditions at which the reaction $\gamma d \to pn$ demonstrates a clear CCR behavior [31]. A systematic study of the CCR regime in reactions with the lightest nuclei has not been carried out. The NICA SPD will provide a good opportunity to study these issues using polarized and unpolarized beams in collisions of dd and dp (see [3], section 8).

As noted in Ref. [21], it is important to perform new measurements of the differential cross section of the elastic pp scattering in the region of large angles in order to check the CCR behavior and observed oscillations. The same should be done for the pn scattering, about the CCR properties of which is much less known than for the pp channel. The differential cross-section decreases rapidly with increasing energy $\sim s^{-n}$ for a large number of active constituents n. However, to find the onset of the CCR region, one can start to go from the region of not very high values of $|t|$, where the corresponding cross sections are sufficiently large and can be measured [32], to higher $|t|$.

EXOTIC LIGHTEST NUCLEI

Hypernuclei

In the two-neutron system there is a virtual level in the $^1S_0$ state, but not a bound state. According to Ref. [33], experimental data on the possible existence of the bound tetra-neutron state are rather controversial. Recently a resonant state was observed in a system of four neutrons with energies of $2.37 \pm 0.38(stat.) \pm 0.30(sys.)$ MeV and a width of $\Gamma = 1.75 \pm 0.22(stat.) \pm 0.30(sys.)$ MeV in the reaction of $^8He(p, p^4He)$ [34]. A system of four identical nucleons is a subject to the blocking action of the Pauli principle. Therefore, the observation of the $4n$-resonance gives good reason to hope for the existence of a quasi-bound state in the system $^4_{\Lambda\Lambda}n = (n, n, \Lambda, \Lambda)$. In the tetrabaryon system $T =^4_{\Lambda\Lambda} n = (n, n, \Lambda, \Lambda)$ with double strangeness $S = -2$ the action of the Pauli principle is excluded in two pairs of baryons (n, Λ) and it is interesting for this reason to investigate the stability of this system. In theory, there are significant uncertainties in the available models of interaction potentials ΛN and $\Lambda\Lambda$ [35], [36] and a necessity to take into account three- and four-body forces, which have not yet been taken into account in the calculations. Therefore, it remains to be hoped that the answer to the question of the existence of a bound tetrabaryon with double strangeness can be obtained from the experiment.

The idea of such an experiment is proposed in [37] and it consists in studying the reaction $d + d \to K^+ + K^+ + T$, in which the bound state $T =^4_{\Lambda\Lambda} n$, if it exists, can be registered by the spectrum of the missing mass of the system K^+K^+. According to [37], this is an extremely clean process available for study on NICA SPD. Provided that the luminosity will reach the value $10^{29}\mathrm{cm}^{-2}c^{-1}$, the number of events will be approximately 600 per year, which is enough to register the state of interest.

The channel with the formation of two K^+ mesons is a kind of probe for studying other exotic hypernuclei and exotic hadrons. In particular, proton-proton collisions leading to the reaction $p + p \to K^+ + K^+ + \Lambda + \Lambda$ provide a clean and direct way to search for a dibaryon $\Lambda\Lambda$ in the spectrum of the missing mass K^+K^+. The reaction $p + d \to K^+ + K^+ + n + \Lambda + \Lambda$ makes it possible to search for a bound state in the system $n + \Lambda + \Lambda$. The final states in the process $d + d \to K^+ + K^+ n + n + \Lambda + \Lambda$ give access to the spectrum of invariant masses nK^+ and thus make it possible to search for the light pentaquark $\Theta^+(1540)$ [38].

Dibaryon resonances

The search for dibaryon resonances has a long history, a recent review on this topic is given in the work [39]. Currently, one of the most likely candidates for the role of a zero-strangeness dibaryon resonance is an excited state of the *pn* system with a mass of 2380 MeV, isospin $T = 0$, spin and parity $J^P = 3^+$. This state manifests itself as the resonance, $d^*(2380)$, in the total cross section of the reaction $pn \to d\pi^0\pi^0$ at the corresponding mass with the width of $\Gamma = 70$ MeV [40]. From the point of view of theoretical models, this is is either the $\Delta N\pi$ system [41] or the (quasi)bound $\Delta(1232)\Delta(1232)$ state with a large admixture of a component with a hidden color $C\bar{C}$ [42]. There are also experimental indications to the presence of isovector dibaryon resonances from the reactions of $pp \to d\pi^+$ [39] and $pp \to \{pp\}_s\pi^0$ [43, 44] at the kinetic energy of protons in a laboratory system of 0.5-2 GeV. However, information about these resonances is far from complete and it is possible to supplement it on the NICA SPD. The search for isoscalar dibaryon resonances can be performed in deuteron collisions $dd \to dX$, investigating the spectrum of the missing mass of a final deuteron. To search for isovector dibaryon resonances, one can use the reaction $dp \to \{pp\}_s + X + p(0^\circ)$ with the registration of a pair of protons $\{pp\}_s$ at small relative energy $E_{pp} = 0 - 3$MeV, as in [43, 44], and a forward proton in the direction of the initial proton beam. In view of the $\Delta\Delta + C\bar{C}$ structure of the $d^*(2380$ resonance, investigation of the reaction $dp \to pd\pi\pi$ in the region of the $d^*(2380)$ resonance could shed light on the $|\Delta\Delta>$ and hidden color components $|C\bar{C}>$ of the deuteron wave function.

TEST OF DISCRETE SYMMETRIES

Using polarized deuteron and proton beams, which will be available at NICA, one can perform a precision tests of the fundamental discrete symmetries of the P- parity and time-invariance violation. Under CPT symmetry the T-invariance violation is equivalent to CP-violation. The spin-dependent total *pd* cross section can be written as [45]

$$\begin{aligned}\sigma_{\text{tot}} = \sigma_0 + \sigma_{\text{TT}} \left[\left(\mathbf{P}^{\text{d}} \cdot \mathbf{P}^{\text{p}} \right) - \left(\mathbf{P}^{\text{d}} \cdot \mathbf{k} \right) \left(\mathbf{P}^{\text{p}} \cdot \mathbf{k} \right) \right] + \sigma_{\text{LL}} \left(\mathbf{P}^{\text{d}} \cdot \mathbf{k} \right) \left(\mathbf{P}^{\text{p}} \cdot \mathbf{k} \right) + \sigma_{\text{T}} T_{mn} k_m k_n + \sigma_{\text{PV}}^{\text{p}} \left(\mathbf{P}^{\text{p}} \cdot \mathbf{k} \right) \\ + \sigma_{\text{PV}}^{\text{d}} \left(\mathbf{P}^{\text{d}} \cdot \mathbf{k} \right) + \sigma_{\text{PV}}^{\text{T}} \left(\mathbf{P}^{\text{p}} \cdot \mathbf{k} \right) T_{mn} k_m k_n + \sigma_{\text{TVPV}} \left(\mathbf{k} \cdot \left[\mathbf{P}^{\text{d}} \times \mathbf{P}^{\text{p}} \right] \right) + \sigma_{\text{TVPC}} k_m T_{mn} \varepsilon_{nlr} P_l^{\text{p}} k_r \,.\end{aligned} \tag{1}$$

Here $\mathbf{P}^{\text{d}}$ and $\mathbf{P}^{\text{p}}$ are the vector polarizations of deuteron and proton, T_{mn} is the tensor polarization of the deuteron and $\mathbf{k}$ is the unit vector along the collision axis. We chose the latter for the z-axis, the y-axis is orthogonal to the ring plane, so that $T_{mn}k_mk_n = T_{zz}$, and

$$k_m T_{mn} \varepsilon_{nlr} P_l^{\text{p}} k_r = T_{xz} P_y^{\text{p}} - T_{yz} P_x^{\text{p}} \,. \tag{2}$$

In Eq. (1), the cross sections σ_0, σ_{TT}, σ_{LL}, and σ_{T} correspond to ordinary P-invariance and T-invariance conserving interactions, $\sigma_{\text{PV}}^{\text{p}}$, $\sigma_{\text{PV}}^{\text{d}}$, and $\sigma_{\text{PV}}^{\text{T}}$ are signals of the P-violation, and σ_{TVPV} denotes the T- and P-violating one (see Ref. [46]).

The last term, $\sigma_{\rm TVPC}$, is the null-test signal for the time invariance violating parity conserving (TVPC) interaction [47, 48, 49]. This term can not be imitated by initial and final state interactions and would vanish unless the manifest T-violating interaction is at work. Such interaction, proposed in Ref. [50] to explain the violation of CP invariance in kaon physics, preserving flavor, goes beyond the Standard Model and remains a possible cause of the observed baryon asymmetry of the Universe, for which the CM predictions diverge from the data by many orders of magnitude. Earlier, in an experiment on the transmission of polarized neutrons through a target of tensor-polarized holmium nuclei, an estimate of T-odd asymmetry was obtained at the level of 10^{-5} [51]. Another experiment with a doubly polarized *pd* interaction is being prepared on COSY [52], and it is supposed to improve the upper bound estimate for T-odd asymmetry to the level of $\sim 10^{-6}$. If experiments with a fixed dense external target on a nuclotron are appropriate to search for a violation of P-invariance at the NICA installation, then an internal gas target of polarized protons will be needed to search for a null test signal of a violation of T-invariance. In the usual formulation of an experiment with static spins, a serious problem is the separation of a false signal that occurs in the presence of a non-zero vector polarization of the deuteron P_y^d. The magnitude of this polarization must be suppressed to the level of $P_y^d \sim 10^{-6}$ in order for the T-asymmetry to be measured at the level of 10^{-6} [53], that is a very difficult technical task. Using the new method based on precessing polarization in the storage ring in combination with Fourier analysis allows one to solve this problem. Furthermore, this methods allows one to separate the TVPC signal from the TVPV one and other PV-signals [45] that is hardly possible without additional assumptions about relative strength of the TVPV and TVPC signals within the usual method with stationary spins.

CONCLUSION

According to the Standard Model of fundamental interactions, the QCD Lagrangian contains all properties of hadrons and of strong interaction between them which in future will be directly derived from theory. However so far our understanding from the QCD even basic processes, like nucleon-nucleon elastic scattering in the region of few GeV is very limited. A similar situation mit single spin asymmetries in pp- and pA-collisions and other spin observables. Systematic detailed study of collisions of polarized proton and deuteron beams at the NICA SPD at energies $\sqrt{s_{NN}} = 3-10$ GeV will provide more insight into QCD physics of these processes and also allows one to test fundamental discrete symmetries.

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