Hadron Physics at the Charm and Bottom Thresholds and Other Novel QCD Physics Topics at the NICA Accelerator Facility

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The NICA collider project at the Joint Institute for Nuclear Research in Dubna will have the capability of colliding protons, polarized deuterons, and nuclei at an effective nucleon-nucleon centerof mass energy in the range $\sqrt{s_{NN}} = 4$ to 11 GeV. I briefly survey a number of novel hadron physics processes which can be investigated at the NICA collider. The topics include the formation of exotic heavy quark resonances near the charm and bottom thresholds, intrinsic strangeness, charm, and bottom phenomena, hidden-color degrees of freedom in nuclei, color transparency, single-spin asymmetries, the RHIC baryon anomaly, and non-universal antishadowing.

I. INTRODUCTION

The NICA collider project at the Joint Institute for Nuclear Research in Dubna [1, 2] will have the capability of colliding nucleons, polarized deuterons, and nuclei at an effective nucleon-nucleon center-of mass energy in the range $\sqrt{s_{NN}} = 4$ to 11 GeV.

In tis brief report, I will discuss a number of novel hadron physics topics which can be investigated at the NICA collider. The topics include the formation of exotic heavy quark resonances near the charm and bottom thresholds, intrinsic strangeness, charm, and bottom phenomena, hidden-color degrees of freedom in nuclei, color transparency, single-spin asymmetries, the RHIC baryon anomaly, and non-universal antishadowing.

II. THE ULTRA-LOW ENERGY DOMAIN USING VARIABLE-ANGLE COLLISIONS

If the interaction region at NICA is designed so that A and B can collide at a variable finite center of mass angle $0 < \theta < \pi$, then the effective CM energy squared $s = (p_A + p_B)^2 = M_A^2 + M_B^2 + 2E_A E_B(1 - \beta_A \beta_B \cos \theta)$ will span from very low energies to beyond the bottom flavor threshold. (Here $\beta_i = |\vec{p_i}|/E_i$ are the colliding beam velocities.) For example, if the beams are arranged to collide while moving in the same direction $(\theta \to 0)$, one could study collisions close to zero relative velocity at the NICA, a novel nonrelativistic regime for studying nuclear and Coulombic interactions. Bjorken has called this comoving configuration the "Fool's Intersecting Storage Ring" (FISR) [3]. The direction of the beam polarization could also be also modified from longitudinal to transverse if the colliding beams are perpendicular.

III. CHARM AND BOTTOM PHYSICS AT THRESHOLD

The threshold for hidden-charm production in pp channels such as $pp \rightarrow ppJ/\psi$ is $\sqrt{s} = 5$ GeV. The corresponding threshold for hidden-bottom production in $pp \rightarrow pp\Upsilon$ is $\sqrt{s} = 7$ GeV. Thus an array of interesting hidden and open heavy quark reactions is accessible at the NICA collider. One can also access open-charm reactions such as $pp \rightarrow \Lambda_c(cud)D(\bar{c}u)p$, the production of double-charm baryons $\Lambda(ccu)$, $\Lambda(ccd)$ single and double charmonium, charmstrangeness channels and, in principle, even open-bottom channels such as $pp \rightarrow \Lambda_b(bud)B(\bar{b}u)p$. One can also study strange or charm dijets and measure the asymmetries analogous to the $t\bar{t}$ asymmetries observed at the Tevatron [4, 5]. Such processes are sensitive to the correct choice of QCD renormalization scale [6], as well as the lensing effects due to the final-state interactions of the heavy quarks with the beam and target spectator quarks [7].

The rates for heavy quark production processes near threshold in proton collisions is enhanced by the existence of intrinsic charm and intrinsic bottom Fock states within the proton wavefunction; i.e., five quark $|uudQ\bar{Q}\rangle$ configurations in the proton's light-front wavefunction where the heavy quarks are multi-connected to the proton's valence quarks via two or more gluons. As discussed in more detail in the next section, the intrinsic contributions [8] correspond to $gg \rightarrow Q\bar{Q} \rightarrow gg$ gluon-gluon scattering insertions in the proton self energy. They scale as $1/M_Q^2$ due to the non-Abelian couplings of QCD [9, 10] and are maximal at equal rapidity; i.e. $x_i \propto \sqrt{m_i^2 + k_{\perp i}^2}$. Thus the heavy quarks carry most of the light-front momentum x_i of the proton. This allows the energy of the beam hadrons to be efficiently transferred to the production of heavy quark charm and bottom states [11, 12]. In addition, the gluonic interactions between heavy quarks of opposite color provide a strong attractive potential analogous to the Sommerfeld-Schwinger-Sakharov (SSS) Coulomb threshold enhancement in QED [13] For example, the cross section for $e^+e^- \rightarrow \mu^+\mu^-$ is enhanced by a power of $\frac{1}{\beta}$ canceling the phase space factor at small relative velocity β because of the SSS Coulombic interactions. In fact the rate just above the muon pair threshold matches the production of the infinite series of nS-state Bohr bound states of "true muonium" just below threshold [14, 15].

Hadrons interact very strongly when their relative velocity β is small, and the time for their interactions is maximal. This phenomenon has been observed at the thresholds for baryon-pair production in $e^+e^- \rightarrow p\bar{p}$, and $e^+e^- \rightarrow \Lambda\bar{\Lambda}$ reactions [16]. The baryon pair cross sections remain finite at $\beta \rightarrow 0$, even though the phase space vanishes. One also observes enhancements at $\beta_{p\bar{p}} = 0$ in the decay $J/\psi \rightarrow p\bar{p}\gamma$ [17].

The enhancement of hadronic interactions at threshold implies that new types of charm-based resonances can be formed and studied at NICA. This includes the production of possible J/ψ - nucleon resonances at threshold in reactions such as $pp \rightarrow p[J/\psi p]$, $pd \rightarrow pp[J/\psi n]$, and "nuclear bound quarkonium" $pA \rightarrow pp[J/\psi A - 1]$ [18]. These heavy-quark bound states are expected in QCD from QCD gluonic interactions at small relative velocity. For example, nuclear-bound quarkonium $[J/\psi A]$ can be formed due to the attractive two-gluon exchange QCD van der Waals potential. [18–21] Furthermore, if hadrons share the same valence (or even intrinsic sea quarks), resonances can be formed due to attractive QCD covalent interactions in analogy to covalent molecular forces. In each case, the strength of the hadronic interactions can overcome the phase-space suppression at zero relative velocity.

Another example of enhanced dynamics near the heavy-quark thresholds is the remarkably large 4 : 1 transversetransverse spin correlation A_{NN} observed in large-angle elastic proton-proton scattering [22] at $\sqrt{s} \simeq 3$ GeV and $\sqrt{s} \simeq 5$ GeV. These center-of-mass energies correspond to the strange and charm thresholds relevant to the twobaryon system. In fact, the observed strong spin correlations are consistent with the formation in the *s*-channel of J = L = S = 1 uudssuud and uudccuud "octoquark" resonances near the heavy-quark pair production thresholds. [23]. It thus would be very interesting to study th collisions of polarized proton beams at the NICA. Guy de Teramond and I used unitarity to estimate that the charm production cross section $\sigma(pp \to c\bar{c}X) \sim 1$ mb at the charm threshold.

IV. INTRINSIC STRANGE AND CHARM DISTRIBUTIONS AT LARGE x

As shown by Chang and Peng [24], the HERMES electroproduction data [25] for the strange quark distribution $s(x, Q^2)$ in the proton exhibits two components, a contribution at small $x_{Bj} < 0.1$ – consistent with $g \rightarrow s\bar{s}$ gluon splitting, as incorporated into DGLAP evolution – and an approximately flat component at 0.1 < x < 0.4 which is consistent with a five-quark Fock state $|uud\bar{s}s\rangle$ intrinsic to the proton eigenstate. The intrinsic strange quarks arise from diagrams which are multi-connected to the valence quarks; they are thus *intrinsic* to the structure of the proton itself.

In fact, the broad intrinsic strangeness contribution at large x is also consistent with the EMC [26] measurement of the charm structure function $c(x, Q^2)$ at large x as well as the BPHS model [8] for intrinsic charm. The charm structure function measured by EMC at x = 0.42 and $Q^2 = 75 \ GeV^2$ is 30 times larger that the extrinsic contribution from gluon splitting. The probabilities for Intrinsic strangeness and charm scale as M_s^2/M_c^2 , the scaling, as predicted by the operator product expansion [9, 10] for non-Abelian theory. The probability of intrinsic bottom is thus smaller than the intrinsic charm probability in the proton by a factor $m_c^2/m_b^2 \sim 1/10$.

The anomalously large $pp \to c\gamma X$ rate observed by D0 [27] at the Tevatron could be due to intrinsic charm in the subprocess $gc \to \gamma c$ at $x_c > 0.1$ [28]. This anomaly can be checked at NICA.

The intrinsic Fock states in the proton's eigensolution are a rigorous prediction of QCD. For example, the existence of QED intrinsic muons in the positronium Fock state wavefunction $|e^+e^-\mu^+\mu^-\rangle$ reflects the light-by-light muonloop insertion into the positronium self-energy. There is no "tunneling" suppression. A bound-state wavefunction is an off-shell amplitude describing arbitrarily off-shell configurations. In the case of the Front Form [29], the frameindependent light-front wavefunction (LFWF) $\psi_n(x_i, \vec{k}_{\perp i})$ describes a hadron at fixed light-front time $\tau = t + z/c$ as as a function of its *n* constituents' invariant mass squared $\mathcal{M}^2 = \sum_i^n \frac{k_{\perp i}^2 + m_i^2}{x_i}$. As discussed in ref. [12], the cross section for charm production $\gamma p \to J/\psi p$ at the charm threshold measured in

As discussed in ref. [12], the cross section for charm production $\gamma p \rightarrow J/\psi p$ at the charm threshold measured in photoproduction at CESR [30] is considerably larger than extrapolations based on phase space suppression. This is expected from the intrinsic heavy quark configurations of the proton. The production of heavy quark states at threshold requires that the valence quarks of the proton efficiently transfer their four-momentum to the heavy quark production process. This is possible since the five-quark intrinsic charm Fock state $|uudc\bar{c}\rangle$ in the proton has maximum probability at minimum off-shellness; i.e., when all of the quarks have the same rapidity.

Intrinsic charm can also be investigated at NICA by measuring the x_F distribution of processes such as $\frac{d\sigma}{dx_F}(pp \rightarrow t)$

 $\Lambda_c X$). The Λ_c is created from the coalescence and combined momenta of the comoving quarks in the proton's fivequark Fock state $|uudc\bar{c}\rangle$. Indeed the Λ_c [31, 32] and the $\Lambda_b >$ [33] was first discovered in pp collisions at large x_F using the split field magnet at the ISR. Diffractive open charm production such as $pp \to \Lambda_c pX$ has also been observed [34–37]

One can also study single- and double-quarkonium production [38] $pp \rightarrow J/\psi X$ and $pp \rightarrow J/\psi J/\psi X$ at high x_F at NICA. The double charmonium channels were first observed in pA and πA collisions at $x_F^{total} > 0.5$ in the NA3 fixed target experiment at CERN, evidently reflecting the existence of Fock states such as $|uudc\bar{c}c\bar{c}\rangle$ The SELEX experiment at Fermilab [39] has observed doubly-charmed baryons $|ccu\rangle$ and $|ccd\rangle$; the anomalously large isospin spitting of the doubly-charmed baryons reported by the SELEX has not been explained. [40]

Gardner and I [42] have also shown that the existence of intrinsic charm in the higher Fock states B meson can affect the rare decays of the B meson, particularly the decay channels where "penguin" diagrams are important.

The intrinsic heavy quark distributions can be quark/antiquark asymmetric [41]; e.g. $s(x) \neq \bar{s}(x)$ as well as have novel spin properties since the five-quark Fock state $|uuds\bar{s}\rangle$ is dual to off-shell hadronic excitations such as $|K^+(u\bar{s})\Lambda(sud)\rangle$. For a recent review of intrinsic heavy quark phenomenology, see ref. [43]

V. OTHER NOVEL PHYSICS TOPICS AT NICA

1. The anomalous nuclear dependence of high- x_F quarkonium production

One of the outstanding QCD puzzles is the nuclear dependence of $\frac{d\sigma}{dx_F}(pA \rightarrow J/\psi X)$. The observed Adependence breaks QCD factorization since it is not a function of the gluon momentum, and it behaves as $A^{\alpha(X_F)} \simeq 2/3$ at high x_F . This phenomenon could reflect the special color-octet/color-octet composition of the $|uud_{8C}c\bar{c}\rangle$ intrinsic charm Fock state; because of its large color dipole moment the intrinsic charm fluctuation of incoming proton at high x_F will then interact to produce the J/ψ at the front surface, yielding the $A^{2/3}$ dependence [44, 45]. It will be very interesting to investigate such nuclear effects at NICA. The quarkonium polarization and other physics issues are reviewed in ref. [46]

2. The Sivers effect: breakdown of pQCD leading-twist factorization The Sivers pseudo-*T*-odd correlation of the target hadron's spin with the virtual photon to jet plane arises in deep inelastic lepton scattering from rescattering of the struck quark; i.e., a final-state lensing effect [47]. The Sivers effect satisfies Bjorken scaling and is leading twist, but it does not have the normal factorization properties of pQCD. In fact one predicts an opposite single-spin asymmetry in Drell Yan reactions from initial state interactions [48, 49]. One can study such lensing effects at NICA in polarized deuteron or polarized proton beam Drell Yan reactions such as $d^{\uparrow}A \rightarrow \mu^{+}\mu^{-}X$.

The source of the large single-spin asymmetries at large x_F in $p^{\uparrow}A \to \pi X$ is not understood [50, 51]. This provides another an important NICA physics opportunity which can be studied in polarized deuteron reactions such as $d^{\uparrow}A \to \pi X$, etc.

- 3. The Double Boer-Mulders Effect: the breakdown of pQCD leading-twist factorization As shown by Boer, Hwang, and myself [52], the Initial-state interactions of both the quark and antiquark in unpolarized Drell-Yan reactions $pp \to \mu^+\mu^- X$ generates an anomalous $\cos 2\phi \sin^2 \theta$ distribution of the lepton pair and the breakdown of the Lam-Tung relation of pQCD at leading twist. This was first observed in $\pi^- A \to \mu^+ \mu^- X$ by NA10 [53]. This type of lensing phenomena can be investigated in detail at NICA.
- 4. Higher-Twist Effects in the Drell-Yan Reaction At high x_F the Drell-Yan reaction can utilize multiparton correlations of the beam hadron. For example, the Chicago-Princeton fixed target experiment [54] observed a dramatic change of the muon angular distribution $1+\lambda \cos^2 \theta$ from $\lambda = +1$ to $\lambda = -1$ at high x_F in $\pi^- p \to \mu^+ \mu^-$. This effect can be ascribed to the higher twist subprocess $(d\bar{u}) + u \to d\gamma^* \to d\mu^+ \mu^-$ where both valence quarks of the pion contribute their momentum to the hard reaction at large x_F [55]. This interesting phenomenon can be investigated at NICA.
- 5. Scaling of hard inclusive reactions An important test of pQCD is the scaling behavior of inclusive cross sections [56, 57]

$$\frac{d\sigma}{d^3p_C/E_C}(AB\to CX) = \frac{F(\theta_{CM},x_T)}{p_T^n}$$

at fixed $x_T = \frac{2p_T}{\sqrt{s}}$ and fixed θ_{CM} . The conformal parton model predicts n = 4 simply from dimensional analysis. This become $n \sim 5$ for direct photon reactions $pp \to \gamma X$ due to evolution and running coupling. This is verified by experiment. However, the predicted pQCD power law $n \simeq 5.5$ fails to describe any experiment. For example, the Chicago Princeton experiment [58] as well as ISR measurements found that $\frac{d\sigma}{d^3 p_C/E_C}(pp \to pX)$ scales with n > 11 far from the leading twist pQCD prediction $n \sim 5.5$. This breakdown of pQCD could be explained by the fact that one can also create hadrons directly from a hard subprocess such has $uu \to p\bar{d}$ in addition to the standard jet fragmentation $q \to qp$ [59]

The breakdown of leading twist scaling is particular interesting to study at NICA in nuclear collisions such as $AA \rightarrow pX$, since the directly-produced proton is formed as a small color singlet and is thus color transparent [60]. This phenomenon can explain the "baryon anomaly" observed in high centrality heavy ion collisions at RHIC. [61]

One can also study reactions such as $pA \rightarrow \text{JetJetJet}X$ to check color transparency and measure aspects of the proton's three-quark light-front wavefunction [62–64].

6. Exclusive Reactions pQCD Counting rules predict the leading fall-off of hard exclusive reactions $\frac{d\sigma}{dt}(AB \rightarrow CD) = \frac{F(s/t)}{t^{n-2}}$ where *n* counts the minimum number of initial and final-state partons, according to the twist of the hadrons [65, 66]. This scaling is also predicted by AdS/QCD [67, 68]. These reactions are also quark helicity-conserving [69] and "color transparent." Color transparency predicts no absorption of the hard scattering hadrons in the nucleus; i.e. the cross section scales as the number of nucleons [60] Experiments at BNL have in fact found evidence [70] for increasing color transparency in quasielastic pp scattering with p_T below the charm threshold.

The angular distribution of virtually all hard hadron-hadron exclusive reactions at fixed t/s appears to be consistent with quark interchange (e.g. u quark exchange in $K^+p \to K^+p$) rather than gluon exchange [71]. These experimental facts and phenomena could be evidence for the "sublimation" of gluons into an effective color-confining potential below gluon virtuality $Q^2 \sim 1 \ GeV^2$, as suggested by the successful phenomenology of AdS/QCD [72].

As shown by Landshoff [73], an anomalous odderon contribution due to triple-gluon exchange with three equal momentum transfers t/9 can give a contribution $\frac{d\sigma}{dt}(pp \rightarrow pp) \propto s^0/t^8$, but this contribution has never been observed, perhaps again because of gluon sublimation.

Many such tests of QCD in hard exclusive reactions, including $pn \to pn$, $pp \to \Lambda Kp$, $pd \to pd$, and $pd \to npp$ with each hadron detected at fixed CM angle, can be performed at NICA. It will also be interesting to check the polarization dependence of exclusive reactions, such as single-spin asymmetries.

- 7. Hidden-color of nuclear wavefunctions. The deuteron six-quark $|uudddu\rangle$ Fock state has five different color-singlet configurations. The hidden color [74] Fock states, which cannot be identified with the np configuration are activated when the six quarks have small transverse separation. Hard exclusive reactions involving the deuteron such $pd \rightarrow pd$ are thus particularly interesting since they probe the hidden-color Fock states of the deuteron six-quark Fock state. In addition to the usual pn configuration, there are four other color-singlet combinations of six color-triplet quarks in the deuteron's QCD eigensolution. Hidden-color QCD phenomena can thus be investigated at NICA in many different high Q^2 elastic and transition deuteron reactions.
- 8. Non-universal antishadowing. There is evidence that the nuclear dependence of structure functions measured in charged-current deep inelastic neutrino-nucleus scattering is different than in deep inelastic lepton-nucleus scattering [75]. This could occur, for example, if antishadowing is flavor-specific, since antishadowing is driven by diffractive contributions which involve Reggeon exchange [76] Experiments at NICA can investigate flavor-tagged Drell-Yan reactions to see whether shadowing and antishadowing are quark specific [77].
- 9. Odderon phenomenology. The existence of Odderon exchange, the C = three-gluon exchange analog of the Pomeron, is predicted to exist in QCD, but it has never been observed [78–82]. The interference of two-gluon and three-gluon exchange will lead to charm meson D^{\pm} asymmetries in $pp \rightarrow D^+D^-pp$ reactions [83], a phenomenon which may be testable at the NICA.

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