Strong Color Field Baryonic Remnants in Nucleus-Nucleus Collisions at 200A GeV.

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The effects of strong color electric fields (SCF) on the baryon production at RHIC are studied in the framework of HIJING/BB (v2.0) model. The particle species dependence of nuclear modification factors (NMF) are analyzed for Au+Au collisions at 200A GeV. A doubling of the string tension leading to a modification of the strangeness suppression according to Schwinger mechanism is shown to provide an alternate explanation to coalescence models for the interpretation of the observed baryon and meson production at moderate \( p_T \) and results in a predicted enhancement in the (multi)strange (anti)hyperon production.

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I. INTRODUCTION

While the phase transition from hadronic degree of freedom to partonic degrees of freedom (quarks and gluons) in ultra-relativistic nuclear collisions is a central focus of recent experiments at the Relativistic Heavy Ion Collider (RHIC), data on baryon and hyperon production has revealed interesting and unexpected features at RHIC that may be of novel dynamical origin instead.

In a previous paper \cite{7} we studied the possible role of topological baryon junctions \cite{8} in nucleus-nucleus collisions. We have shown in the framework of HIJING/B\( \overline{\text{B}} \) (v2.0) model. The particle species dependence of nuclear modification factor (NMF) between total charged \( \pi^0 \) and neutral pions \( (\pi^0) \) at moderate transverse momenta \( (2 < p_T < 5 \text{ GeV}/c) \).

In the case of quark-gluon plasma (QGP) creation it is expected that the color electric fields, SCF) including baryon junctions \cite{8} and loops \cite{10} that may arise in nuclear reactions. Our emphasis here will be on the novel baryon observables measured at RHIC. In nucleus-nucleus collisions the color charge excitations may be considerably greater than in nucleon-nucleon collisions due to the almost simultaneous interaction of several participating nucleons in a row \cite{11,12}. Molecular dynamics models \cite{15–17} have been used to study the effects of color ropes as an effective description of the non-perturbative, soft gluonic part of QCD \cite{18–20}. Strangeness enhancement \cite{21–29}, strong baryon transport \cite{30}, and increase of intrinsic \( k_T \) \cite{19} are all expected consequences of SCF. This can be modeled in microscopic models as an increase of the effective string tension that controls the \( qq \) pair creation rates and strangeness suppression factors \cite{11}.

For a uniform chromoelectric flux tube with field \( E \) the probability to create a pair of quarks with mass \( m \), effective charge \( e \), and transverse momentum \( p_T \) per unit time per unit volume is given by \cite{31}:

\[
P(p_T)\, d^2p_T = -\frac{|eE|}{4\pi^3} \ln \left\{ 1 - e^{-\frac{|eE|}{P_0(p_T)}} \right\} \, d^2p_T
\]

(1)

The integrated probability \( (P_m) \) reproduces the classical Schwinger results \cite{32}, derived in spinor quantum electrodynamics (QED) for \( e^+e^- \) production rate, when the leading term in Eq. 2 is taken into account, i. e.:

\[
P_m = \frac{(eE)^2}{4\pi^3} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp \left( -\frac{\pi m^2 n}{|eE|} \right)
\]

(2)

In general in microscopic string models the heavier flavors (and di-quark) are suppressed according to Schwinger formula \cite{32}:

\[
\gamma_Q = P(Q\bar{Q}) = \frac{P(\bar{q}q)}{P(qq)} = \exp \left( -\frac{\pi (m_Q^2 - m_\bar{Q}^2)}{\kappa} \right)
\]

(3)

where \( \kappa = |eE| \) is the string tension; \( m_Q \) is the effective quark mass; \( Q=s \) for strange quark; \( Q=qq \) for a di-quark), and \( q=u,d \) are the light nonstrange quarks.

In the case of quark-gluon plasma (QGP) creation it is necessary to modify the dynamics of particle vacuum production at short time scales, and the abundance of newly
produced particle may deviate considerably from the values obtained for the constant field [33]. Two possible processes may lead to an increase of strangeness production within the framework of Schwinger mechanism are: i) increasing the field strength by a modified string tension \(\kappa\) [11,19,25,26,34], or ii) dropping the quark masses due to chiral symmetry restoration [35,34,36,37]. A specific chiral symmetry restoration could be induced by a rapid deceleration of the colliding nuclei [38].

Present estimates [39] of the \textit{current quark masses} range from: \(m_u=1.5-5\) MeV; \(m_d=3-9\) MeV; \(m_s=80-190\) MeV. For di-quark we consider \(m_{qq}=450\) MeV [40]. Taking for constituent quark masses of light non-strange quark \(M_{u,d}=230\) MeV, strange quark \(M_s=350\) MeV [41], and di-quark mass \(M_{qq}=550 \pm 50\) MeV as in Ref. [40], it is obvious that the masses of (di)quark and strange quark will be substantially reduced at the chiral phase transition. If the QGP is a chirally restored phase of strongly interacting matter, in this picture the production of strange hadrons will be enhanced [37]. In this case a possible decrease of the strange quark mass would lead to a similar enhancement of the suppression factors, obtained (in microscopic models) by an increase of string tension [18,19,34,33,36]. Moreover, if we consider that Schwinger tunneling could explain the thermal character of hadron spectra and that, due to SCF effects the string tension value \(\kappa\) fluctuates we can define an apparent temperature \(T = \sqrt{<\kappa>}/2\pi\) [42].

**II. OUTLINE OF THE HIJING/BB V2.0 MODEL**

Our analysis are performed in the framework of HIJING/BB v2.0 model [7] that is based on HIJING/BB v1.10 [43]. Multiple hard and soft interactions proceed as in HIJING v1.37 [44]. In HIJING/BB v2.0 we introduced [7] the possible topology with two junctions [47], and a new algorithm where \(J\bar{J}\) loops are modeled by an enhancing di-quark \(pT\) kick characterized by a gaussian width of \(\sigma_{qq}' = f \cdot \sigma_{qq} = 1.08\) GeV/c, with \(\sigma_{qq}=0.360\) GeV/c (consistent with PYTHIA [45] default value), i.e. \(f=3\), which we fit to best reproduce the observed \(pT\) spectrum of the baryons.

Following the equations above, we take into account SCF in our model by an \textit{in medium effective string tension} \(\kappa > \kappa_0\), which lead to new values for the suppression factors, as well as the new effective intrinsic transverse momentum \(k_T\) [18–20]. This includes: i) the ratio of production rates of di-quark to quark pairs (di-quark suppression factor), \(\gamma_{qq} = \frac{P(qq\bar{q}\bar{q})}{P(q\bar{q})}\), ii) the ratio of production rates of strange to nonstrange quark pairs (strangeness suppression factor), \(\gamma_s = \frac{P(ss)\bar{s}\bar{s}}{P(q\bar{q})}\), iii) the extra suppression associated with a diquark containing a strange quark compared to the normal suppression of strange quark \(\gamma_s\), \(\gamma_{us} = \frac{P(u\bar{s}\bar{s})\bar{u}\bar{d}}{P(u\bar{d}\bar{d})}\), iv) the suppression of spin 1 diquarks relative to spin 0 ones (apart from the factor of 3 enhancement of the former based on counting the spin states), \(\gamma_{10}\), and v) the (anti)quark \(\sigma''_q = \sqrt{\kappa/\kappa_0} \cdot \sigma_q\) and (anti)di-quark \(\sigma''_{qq} = \sqrt{\kappa/\kappa_0} \cdot f \cdot \sigma_{qq}\) gaussian width. These parameters correspond to \(\gamma_{qq} = \text{PARJ}(1),\ \gamma_s = \text{PARJ}(2),\ \gamma_{us} = \text{PARJ}(3),\ \gamma_{10} = \text{PARJ}(4),\) and \(\sigma_{qq} = \text{PARJ}(21)\) of the JETSET7.3 subroutines [45]. Our calculations are based on the assumption that the effective enhanced string tension \(\kappa\), in both basic ropes \((q^n - \bar{q}^n)\) and junction ropes \((q^n - q^m - q^n)\) are the same. For elementary \(n\) strings and junctions this ansatz is supported by baryon studies [46]. A different approach to baryon production without baryon junctions has been proposed in [25] where SCF from string fusion process can lead to \((qq)\bar{s} - (\bar{q}ar{q})\bar{s}\) with about double the string tension. Both types of SCF configurations may arise but predict different rapidity dependence of the valence baryons. We consider in this version 2.0 of HIJING BB only baryon junction rope loops.

There is a debate in the study of qqq system on the shape of \(\Delta\)-like geometry and \(Y\)-like geometry [47], [48], and on the stability of these configurations for the color electric fields [49]. In both topologies we expect a higher string tension than in an ordinary \(q\bar{q}\) string \((\kappa_Y = \sqrt{3\kappa_0}\) and \(\kappa_2 = (3/2)\kappa_0)\). It was shown [49] that the total string tension has neither the \(Y\) nor the \(\Delta\)-like value, but lies rather in-between the two pictures. However, the \(Y\) configuration appears to be a better representation of the baryons. If two of these quarks stay close together, they behave as a di-quark [48]. In a dual superconductor models of color confinement for the \(Y\)-geometry the flux tubes converge first toward the centre of the triangle and there is also another component which run in opposite direction. They attract each other and this lower the energy of \(Y\)-configuration [47].

Phenomenological applications are currently based on Regge trajectory which gives the appropriate relationship between the mass M of the hadrons and its spin \(J_s\): \(J_s = \alpha + \alpha_s M^2\), where \(\alpha \approx 0.5\) is the Regge intercept; \(\alpha_s\) is the Regge slope. The value of the Regge slope for baryons is \(\alpha_s \approx 1 \text{ GeV}^{-2}\) [43] that yields a string tension \((\kappa_Y = \sqrt{3}\kappa_0)\) and \(\kappa_2 = (3/2)\kappa_0)\). It was shown that the total string tension has neither the \(Y\) nor the \(\Delta\)-like value, but lies rather in-between the two pictures. However, the \(Y\) configuration appears to be a better representation of the baryons. If two of these quarks stay close together, they behave as a di-quark [48]. In a dual superconductor models of color confinement for the \(Y\)-geometry the flux tubes converge first toward the centre of the triangle and there is also another component which run in opposite direction. They attract each other and this lower the energy of \(Y\)-configuration [47].
GeV/c. The results obtained with this set of parameters are labeled here w/SCF, i.e. with strong color field, or by $\kappa^2 = 2$ GeV/fm. We note, that the increase of “intrinsic $k_T$” (the gaussian width $\sigma''_{q\bar{q}}$), is strongly supported by recent experimental values reported by PHENIX [52], which show an increase from p+p ($k_T=1.08 \pm 0.05$ GeV/c) to d+Au collisions ($k_T=1.36 \pm 0.07 \pm 0.12$ GeV/c) at $\sqrt{s_{NN}}=200$ GeV.

III. NUCLEAR MODIFICATION FACTORS

Here we will concentrate our analysis on species dependence of the nuclear modification factors (NMF) $R_{AA}$ and $R_{cp}$ in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV. $R_{AA}$ is the ratio of the heavy-ion yield to the pp cross section normalized by the number of binary collisions, while $R_{cp}$ is the ratio of scaled central to peripheral particle yield and are defined as in Ref. [7]. For p+p interactions we have used in our calculations, the set of optimized parameters from PYTHIA [45] or HIJING [44].

Figure 1 shows the predicted NMF $R_{AA}$ for the sum of hadrons for two centralities. The results are compared to the data obtained by the PHENIX collaboration [53]. The data at both centralities could not be described by assuming only a broadening of the intrinsic $k_T$ from its standard value (dotted histograms) to $\sigma''_{q\bar{q}}=1.08$ GeV/c (i.e $f=3$, dashed histograms). The introduction of SCF has an effect on the predicted nuclear modification factors of the total inclusive hadrons and results in a better agreement with data (solid histograms). The data indicate at most a small variation with centrality of the factor “f” consistent with the broadening originating at the parton level.

In order to better quantify possible effects of strong color field on particle production we investigate species dependence of NMFs $R_{AA}(p_T)$ for central collisions (Fig. 2a-d), where higher sensitivity to SCF is expected. Because of their dominance, the production of pions is only moderately modified when we consider an increase of the string tension value, since the total energy is conserved. Taking into account SCF effects (solid histograms) results in changes at moderate $p_T$ of less than $\approx 20\%$ for the pion yield (Fig. 2a). The scaling behaviour in $R_{AA}(p_T)$ of the pions is different from those of the sum of protons and anti-protons (Fig. 2c). The pions yield in central events is strongly suppressed compared to binary collisions scaling ($R_{AA}(p_T)=1$).

The hadron production in HIJING/Bb v2.0 is mainly from the fragmentation of energetic partons. Thus, the observed suppression of pions in central collisions may be a signature of the energy loss of partons during their propagation through the hot and dense matter (possibly QGP) created in the collisions, i.e jet quenching. On the contrary, strange particles are highly sensitive to the presence of SCF. Kaons (Fig. 2b) and lambda (Fig. 2d), show an increase by a factor of two and ten, respectively. Such an increase results in a predicted enhancement of the lambda yield relative to scaled binary collisions as opposed to the strong suppression predicted (and observed) for pions. These results are consistent with the PHENIX data [54] and preliminary STAR [55,56] collaborations. Only statistical error bars are shown.
order to study the sensitivity to string tension values we also present the results corresponding to an intermediate value of the string tension i.e. $\kappa_i = 1.5$ GeV/fm (dotted histograms). The discrepancy seen at low $p_T < 1.2$ GeV/c (solid histograms) comes from a sizeable contribution from radial flow, not included in our model. The low $p_T$ region at RHIC seems to be better described within hydrodynamical approach [14].

The predicted particle dependence is due to the interplay between nuclear effects such as jet quenching and shadowing and fluctuations of the chromoelectric field in the early phase of the reaction. Insight into the source of the particle dependence is obtained from Fig. 3 and Fig. 4. The comparison of the NMF $R_{cp}(p_T)$ for protons and pions (Fig. 3a) as well as for kaons (Fig. 3c) presents a behavior similar to $R_{AA}(p_T)$, i.e. shows a meson/baryon anomaly that is well described and was interpreted in [7] as due to a possible exotic gluonic mechanism (JJ loops).

In Ref. [9] it is suggested that the behavior of $R_{cp}(p_T)$ may be interpreted as due to the competition between recombination and parton fragmentation. The results obtained for $R_{cp}(p_T)$ for the strange (Fig. 3b) and multi-strange particles (Fig. 3d) show a small suppression relative to binary scaling, consistent with the experimental results for $\Lambda$ [2,57], and preliminary data for $\Xi$ [55].

In contrast, the equivalent predictions of $R_{AA}(p_T)$ for protons and (multi)strange particles (Fig. 4) show a predicted strong enhancement of NMF due to SCF effects dependent on the mass and strangeness content of the produced particles.

![Image](https://via.placeholder.com/150)

**FIG. 4.** (Color online) HIJING/BB v2.0 predictions with SCF (right) and without SCF (left) for species dependence of $R_{AA}(p_T)$ in central (0-5%) Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV. The preliminary STAR data are from [55,56]. Only statistical error bars are shown.

In particular, the model predicts a dramatic enhancement in the multi-strange (anti-)hyperon production at moderate $p_T$, up to a factor of roughly 2 (relative to binary scaling) for $\Xi$s and up to a factor of more than 10 for $\Omega$s (Fig. 4b). The striking difference between $R_{AA}$ and $R_{cp}$ could be explained in our model as a consequence of SCF which manifest in both central and peripheral collisions. This shows that there is a clear difference between using peripheral Au+Au yields (as in $R_{cp}$), or p+p yields (as in $R_{AA}$) as base-line for comparison with binary collisions scaling ($R_{AA}=R_{cp}=1$).

**IV. SUMMARY AND CONCLUSIONS**

In summary, we studied the influence of possible strong longitudinal color fields in particle production in heavy-ion collisions. We modeled SCF effects within HIJING/BB v2.0, by varying the effective string tension that controls the $q\bar{q}$ and $qq\bar{q}\bar{q}$ pair creation rates and strangeness suppression factors. We show that junction-(anti)junction loops and a higher string tension $\kappa = 2\kappa_0$ ($\kappa_0 \approx 1$ GeV/fm), could be important dynamical mechanisms in the solution of the observed baryon/meson anomaly. Our approach has the advantage of correlating many observables in the same dynamical model including pions, kaon, and baryons productions and of predicting species dependence of the nuclear modification factors $R_{AA}(p_T)$ and $R_{cp}(p_T)$, and the transverse momenta over a large $p_T$ range. A greater sensitivity to SCF effects is predicted for the nuclear modification factors of (multi)strange hyperons. In particular, the measurement of $\Omega$ and $\bar{\Omega}$ yields would provide an important test of the consistency of SCF and baryon junction mechanisms at RHIC.
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