Antihyperon Enhancement through Baryon Junction Loops

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Midrapidity antihyperon ($\bar{Y}$) production in nuclear collisions is studied using a new hadronic string mechanism. This mechanism of baryon junction-antijunction ($J\bar{J}$) loops is an extension of the baryon junction exchange mechanism recently proposed to explain valence baryon number transport. These loops are shown to enhance the $\bar{\Lambda}$, $\bar{\Xi}$, and $\bar{\Omega}$ as well as lead to long range rapidity correlations. Comparisons are made with recent observations of Pb + Pb $\rightarrow Y\bar{Y}X$ at the CERN Super Proton Synchrotron (SPS), and predictions are made for upcoming experiments.

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Striking nonlinear nuclear enhancements of multistrange hyperons and antihyperons have been recently reported for central Pb + Pb collisions at incident momentum of $158A$ GeV/c [1–3] at the CERN Super Proton Synchrotron (SPS). For example, the midrapidity density of $\Xi^-(ssd)$ is claimed [3] to be enhanced by an order of magnitude relative to the linear $A^{1.0} \sim 200$ extrapolation from pp data. These large enhancements are of particular interest since they have been proposed as one of the signatures of the formation of the quark-gluon plasma in nuclear collisions [4–6]. The pattern of hyperon and antihyperon production is also interesting since it provides a detailed probe of the transport of baryon number over many units of rapidity away from the leading valence quarks. This tests (especially with the Ω) topological pictures of the baryon, where the conserved baryon number is carried by the gluons (junction) instead of the valence quarks.

The nuclear A dependence of baryon stopping, the transfer of baryon number into the central rapidity region, and the associated hyperon production are not correctly described by multiparticle production models such as HIJING [7], FRITIOF [8], and the DPM [9] which are based on the diquark-quark string picture for excited baryons. These models underestimate the midrapidity Λ yield by a factor of 6 (see Ref. [10]) and the Ω^- yield by a factor of 10^3 (see Fig. 2 below).

Recently, diquark breakup mechanisms have been proposed [11–15] to explain the valence baryon number transport in nuclear collisions. These mechanisms can also account for part of the leading "valence" hyperon enhancements, but are unable to explain the observed $\bar{\Lambda}$, $\bar{\Xi}$, and $\bar{\Omega}$ enhancements. In this Letter, we extend the valence baryon junction (diquark breaking) mechanism [13,16] and propose a new mechanism for antihyperon production. Like the valence baryon junction mechanism, this junction-antijunction loop ($J\bar{J}$) mechanism is also derived from the topological gluon structure of the baryon and originates in the context of Regge phenomenology.

The baryon junction, $J(x)$, naturally arises when writing the QCD gauge invariant operator for a baryon, being the vertex which links the three color flux (Wilson) lines flowing from the valence quarks [16]. Gauge invariant combinations of junctions, antijunctions, quarks, and antiquarks lead to the prediction of many new states [16], e.g., a quarkless hybrid glueball ($J\bar{J} = M_0^J$) and hybrid exotic mesons [($qJ\bar{J}\bar{q} = M_2^J$) and ($qqJ\bar{J}\bar{q}\bar{q} = M_4^J$)]. In the context of Regge phenomenology, the exchange of M_0^J trajectory was proposed to explain the difference in multiplicities between the inelastic cross sections of $p + \bar{p}$ and $p + p$ scattering. However, since the experimental results were not conclusive (due to the low energies involved) and since the M_i^J states have not been observed spectroscopically (although a few candidates exist [17]), the junction concept lay dormant until recently.

A new test of the junction picture of the baryons was proposed in [13] based on an analysis of the valence ($p - \bar{p}$) rapidity distributions in high energy reactions. This baryon junction exchange mechanism was implemented in the HIJING/B event generator in [14]. It was shown to provide not only a very effective mechanism for the transport of the *valence* baryon number over large rapidity intervals in nuclear collisions, as observed in [18], but it also was shown to naturally enhance the valence hyperon ($Y - \bar{Y}$) production. Most strikingly, in e$^-$ + p collisions at HERA [19] this gluonic mechanism is able to explain [20] a preliminary measured baryon asymmetry which has been observed approximately eight units of rapidity away from the proton's fragmentation region. However, in spite of this success, the valence junction mechanism has been unable to explain the observed antihyperon enhancement.

The M_0^J or $J\bar{J}$ trajectory corresponds in operator form to the exchange of a closed three-string configuration (three-sheet topology) written below,

$$M_0^J = \epsilon^{j_1 j_2 j_3}\epsilon_{k_1 k_2 k_3}\left[P\exp\left(ig\int_{x_{\bar{J}}}^{x_J} dx^\mu A_\mu\right)\right]_{j_1}^{k_1} \times \left[P\exp\left(ig\int_{x_{\bar{J}}}^{x_J} dx^\mu A_\mu\right)\right]_{j_2}^{k_2} \times \left[P\exp\left(ig\int_{x_{\bar{J}}}^{x_J} dx^\mu A_\mu\right)\right]_{j_3}^{k_3}. \quad (1)$$

When in a highly excited state, this $J\bar{J}$ three-string configuration fragments into a baryon and an antibaryon with approximately 3 times the rapidity density of mesons of e^+e^- between the baryon pair. The fragmentation of the three independent strings naturally enhances the transverse momentum as well as the strangeness content of the baryon and the antibaryon. In particular, the fragmentation of $J\bar{J}$ into Ω^- and $\bar{\Omega}^+$ is possible. In addition, novel long range rapidity correlations are predicted by this mechanism, as shown below.

The generalized optical theorem and Regge theory [21] provide the calculus to compute the differential inclusive cross section of baryons resulting from the $J\bar{J}$ exchange. The Regge diagram shown in Fig. 1a represents the extra contribution to the single inclusive valence baryon distribution due to the junction exchange [13,21] and gives

$$E_B \frac{d^3\sigma}{d^3\mathbf{p}_B} \to C_B e^{-[\alpha_0^J(0)-1]y_B}, \qquad (2)$$

where C_B is an unknown function of the transverse momentum of the valence baryon and the couplings of the M_0^J Regge state to the Pomeron and the baryons. Another diagram (same as Fig. 1a, but where the P and the M_0^J are interchanged) gives rise to the contribution of $\exp\{[\alpha_0^J(0) - 1]y_B\}$ for the target region. The contribution to the double differential inclusive cross section for the inclusive production of a baryon and an antibaryon in NN collisions due to $J\bar{J}$ exchange (shown diagrammatically in Fig. 1b) is

$$E_B E_{\bar{B}} \frac{d^6\sigma}{d^3\mathbf{p}_B d^3\mathbf{p}_{\bar{B}}} \to C_{B\bar{B}} e^{[\alpha_0^J(0)-1]|y_B - y_{\bar{B}}|}, \qquad (3)$$

where $C_{B\bar{B}}$ is an unknown function of the transverse momentum and the $M_0^J + P + B$ couplings. We include these processes in the string model by introducing di-

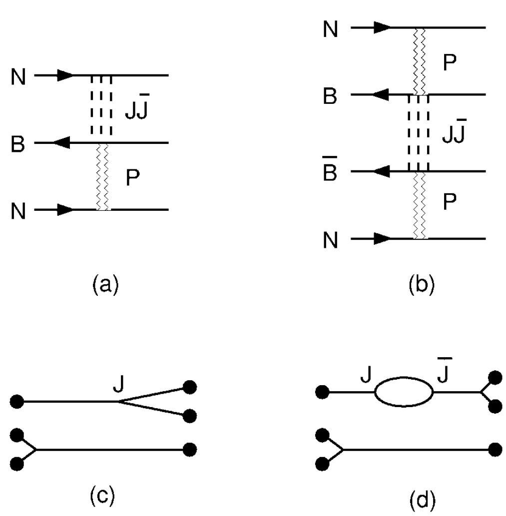

FIG. 1. The Regge diagrams for the single baryon junction exchange and $J\bar{J}$ loops are shown in (a) and (b), respectively. The string model implementation of each Regge diagram is shown in (c) and (d).

quark breaking (Fig. 1c) and $J\bar{J}$ loop (Fig. 1d) string configurations.

From Eq. (3), the predicted rapidity correlation length $[1 - \alpha_0^J(0)]^{-1}$ depends on the value of the intercept $\alpha_0^J(0)$. As in [13,14], we assume $\alpha_0^J(0) \simeq 1/2$. Our choice is based upon arguments and estimates from a multiperipheral model approximation [16,22] and is consistent with the multiplicity and energy dependence of $\Delta\sigma = \sigma_{p\bar{p}} - \sigma_{pp}$ [23]. This value $\alpha_0^J(0)$ can now again be tested through the rapidity correlations. To test for this M_J^0 component $[\alpha_0^J(0) \simeq 1/2]$ requires the measurement of rapidity correlations on a scale $|y_B - y_{\bar{B}}| \sim 2$. Shorter range rapidity correlations are modeled [24] and are observed in e^+e^- data [25]. In contrast, novel, infinite range rapidity correlations have been suggested based on Decameron corrections to the Pomeron [11]. Thus, it is especially important to look for rapidity correlations in high energy $p + p \to B + \bar{B} + X$, especially at RHIC where very high statistics multiparticle data will soon be available.

Replacing the M_0^J Reggeon in Fig. 3b (below) with the Pomeron or other Reggeon states gives the remaining contributions to the double inclusive differential cross section. Replacing the M_0^J with the Pomeron leads to a uniform rapidity distribution which corresponds to the uncorrelated product of two single inclusive differential cross sections [21]. [The short range $\Delta y \sim 1$ dynamical (Schwinger) correlations in string models lie outside the Regge kinematic region]. Replacing the M_0^J with other Reggeons such as the ω provides a contribution which is similar to Eq. (3) but with a different coupling and with $\alpha_R(0)$ instead of $\alpha_0^J(0)$. The contributions from these other Reggeons may be small since the contribution from the M_0^J seems to dominate the contribution from the ω in pp and $p\bar{p}$ scattering at lower energies (see [16,23], and references therein). In addition, in the string picture, the contribution of the ω is modeled as single string between the baryon and the antibaryon which leads to *lower* multiplicities and does *not* provide a strangeness enhancement.

We modified HIJING/B [14] to include the above $J\bar{J}$ loops and the new version, called HIJING/$B\bar{B}$, is available at [26]. By fitting $\bar{p}$ and $\bar{\Lambda}$ data from $p + p$ [27] and $p + S$ [28,29] interactions at 400 GeV/c and 200 GeV/c incident momentum, respectively, the cross section for $J\bar{J}$ exchange is found to be $\sigma_{B\bar{B}} = 6$ mb. We took the threshold cutoff mass of Fig. 1d configurations to be $m_c = 6$ GeV. This large minimum cutoff is necessary in order to provide sufficient kinematical phase space for fragmentation of the strings and for $B\bar{B}$ production. In addition, the applicability of the Regge analysis also requires a high mass between all of the external lines in Fig. 1b. At SPS energies ($\sqrt{s} \sim 20$ GeV), this kinematic constraint severely limits the number of $J\bar{J}$ configurations allowed, reducing its effective cross section to $\sim$3 mb. The $\vec{p}_T$ of the baryons from the $J\bar{J}$ loops are obtained by adding the $\vec{p}_T$ of the three sea quarks along with an additional soft p_T kick. The soft p_T kick is taken from a

Gaussian distribution whose width $\sigma = 0.6$ GeV$/c$ is fit to $p + S$ data [28] at 200 GeV$/c$. At collider energies, hard PQCD processes are modeled as kinks in strings as in HIJING [7].

In multiple collisions, a (color 6) diquark broken through a junction exchange in a previous collision has a finite probability to reform (color $\bar{3}$) in a subsequent collision. However, in the present implementation, we assume that a junction loop cannot be destroyed once it is excited in a collision. The *pA* data are consistent with these assumptions. We emphasize that the present version of HIJING$/B\bar{B}$ does not include final state interactions, since the point of this study is to emphasize the large contribution of this initial state production mechanism to the final yields of the antihyperons.

In Fig. 2, we show the computed net hyperon yields $(Y + \bar{Y})$ from the HIJING, HIJING$/B$, and HIJING$/B\bar{B}$ event generators for p + Pb, S + S, and Pb + Pb at $p_{\rm lab} = 160A$ GeV$/c$. HIJING (open triangle) is seen to underpredict the hyperons in Pb + Pb reactions. HIJING$/B$ results (open squares) show that the valence junction exchange significantly enhances the multiple strange baryon yields. The anomalously large WA97 Ω yield (solid triangle) in Pb + Pb, however, is not explained. The $J\bar{J}$ mechanism in HIJING$/B\bar{B}$ enhances the net $(Y + \bar{Y})$ yield only modestly. However, Fig. 3 shows the large effect of the $J\bar{J}$ loops on the ratio of the yields of the antihyperons to the hyperons, $\eta = N_{\bar{Y}}/N_Y$. In HIJING, this ratio is close to 1 for $S = -2, -3$ baryons because they are mostly formed via diquark-antidiquark fragmentation of single strings. In HIJING$/B$, the splitting of the string in Fig. 1c into three smaller mass strings strongly reduces the phase space for antihyperon production and leads to a very small ratio of $\eta = N_{\bar{Y}}/N_Y$ shown in Fig. 3. HIJING$/B\bar{B}$ solves this problem by providing a natural channel that enhances antihyperon production, as seen with the $\bar{\Xi}/\Xi$ and the $\bar{\Omega}/\Omega$ ratios. The disagreement with the measured $\bar{\Lambda}/\Lambda$ ratio may be due to our neglect of the final state rescatterings $\bar{Y} + h \rightarrow X$, which reduce the $\bar{\Lambda}$ yields more strongly than the $\bar{\Xi}$ and $\bar{\Omega}$ yields.

Returning to the striking enhancement of the Ω in Fig. 2, we note that the diamonds show that even a very modest enhancement of $\kappa = 1.4$ GeV/fm compared with $\kappa = 1.0$ GeV/fm is enough to enhance the Ω by another factor of 10. The ropes [30] represent strings with increased energy density, κ, which enhance the Schwinger tunneling probability [31,32] for $s\bar{s}$ and $(ss)(\bar{s}\bar{s})$ production. The Ω is thus exponentially sensitive to uncertainties in the multiparticle phenomenology. We note that there are more complex multibaryon loop diagrams of junction-antijunction vertices and also certain final state interactions [33] that can further enhance $\Omega\bar{\Omega}$ production. We do not pursue such possibilities here, but leave them for a future paper, since our main point is to show that $J\bar{J}$ loops are natural and provide a *qualitative* explanation of the observed moderate antihyperon/hyperon ratios in Fig. 3.

Finally, we predict in Fig. 4 the initial distribution of antibaryons for Au + Au collisions at $\sqrt{s} = 200A$ GeV for $b \leq 3$ fm. At these energies, the yields of the antibaryons are only sensitive to the relative string fragmentation probability of producing diquarks to quarks, $P_{qq/q}$, and not to the small cross section for the production of $J\bar{J}$ loops. Here, $P_{qq/q} = 0.1$ is chosen to fit $p\bar{p}$ data [34] at Tevatron energies. It is important to note that near SPS energies a significantly smaller value of $P_{qq/q} = 0.02$ is

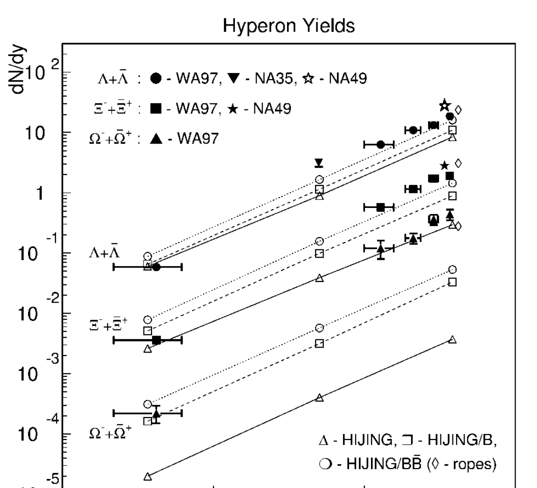

FIG. 2. Hyperon yields from HIJING, HIJING$/B$, and HIJING$/B\bar{B}$ for p + Pb, S + S, and Pb + Pb at incident momentum $p_{\rm lab} = 160A$ GeV$/c$ are shown along with data from the NA35 [28], the NA49 [2,3], and the WA97 [1] collaborations.

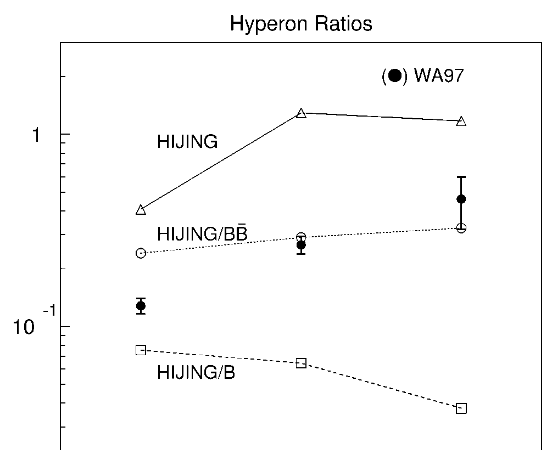

FIG. 3. The ratios of the yields of antihyperons to hyperons are shown for HIJING, HIJING$/B$, and HIJING$/B\bar{B}$ for p + Pb, S + S, and Pb + Pb at incident momentum $p_{\rm lab} = 160A$ GeV$/c$ along with data from the WA97 [1] collaboration.

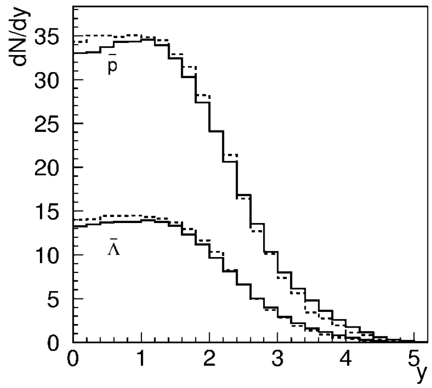

FIG. 4. Predictions for the initial $\bar{p}$ and $\bar{\Lambda}$ rapidity distributions are given for HIJING (solid lines) and for HIJING/$B\bar{B}$ (dashed lines) for Au + Au collisions at $E_{\rm cm} = 200A$ GeV at $b \leq 3$ fm.

needed to fit the pp data [27]. This energy dependence of the diquark suppression factor may be due to kinematic constraints at lower energies. While the $J\bar{J}$ loops do not significantly affect the absolute yields, they are important in producing rapidity correlations between baryons and antibaryons, such as the $\Delta^{++}(uuu)$ and $\bar{\Omega}^{+}(\bar{s}\bar{s}\bar{s})$, which are absent in present $qq\ \bar{q}\bar{q}$ fragmentation schemes.

In summary, we showed that modifications in the multiparticle production dynamics which are consistent with pp and pA physics can yield significant (anti)hyperon production as well as baryon stopping power in AA collisions. The large WA97 antihyperon-hyperon yields reveal the necessity of including baryon pair production mechanisms, the $J\bar{J}$ loops in this approach, along with the baryon stopping mechanisms. However, we note that additional mechanisms (multijunction loops and/or final state interactions) are needed since the absolute yields of especially the $\Omega^{-}(sss)$ are underestimated while the $\bar{\Lambda}/\Lambda$ ratio is overestimated. Upcoming measurements at RHIC on baryon number transport and $B\bar{B}$ correlations will be important to clarify the role of the $J\bar{J}$ exchange mechanism in hyperon and antihyperon production.

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