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Jet quenching and the $\bar{p}\gtrsim\pi^-$ anomaly in heavy ion collisions at relativistic energies

Ivan Vitev[1] and Miklos Gyulassy[1,2]
[1]*Department of Physics, Columbia University, 538 West 120th Street, New York, New York 10027*
[2]*Collegium Budapest, Szentharomsag u.2, H-1014 Budapest, Hungary*
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PHENIX data on Au+Au at $\sqrt{s}=130A$ GeV suggest that $\bar{p}$ yields may exceed π^- at high $p_T > 2$ GeV/c. We propose that jet quenching in central collisions suppresses the hard PQCD component of the spectra in central $A+A$ reactions, thereby exposing a novel component of baryon dynamics that we attribute to (gluonic) bayron junctions. We predict that the observed $\bar{p}\gtrsim\pi^-$ and the $p>\pi^+$ anomaly at $p_T\sim 2$ GeV/c is limited to a finite p_T window that decreases with increasing impact parameter.

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Recent data on Au+Au reactions at $\sqrt{s}=130A$ GeV from the Relativistic Heavy Ion Collider (RHIC) have revealed a number of new phenomena at moderate high $p_T \sim 2-6$ GeV/c. The high p_T spectra of π^0 in central collisions were found by PHENIX [1] to be suppressed by a factor $\sim 3-4$ relative to perturbative QCD (PQCD) predictions scaled by the Glauber binary collision density $[T_{AA}(\mathbf{b})]$. Also in noncentral collisions, STAR [2] found that the linearly increasing azimuthal asymmetry moment, $v_2(p_T)$, saturates at ~ 0.15 for $p_T > 2$ GeV/c in contrast to predictions based on ideal hydrodynamics [3]. From Ref. [4] these features were interpreted as evidence for jet quenching in a dense gluon plasma with rapidity density $dN^g/dy \sim 1000$. The initial proper gluon density may thus have reached far into the deconfined QCD phase with $\rho_g(\tau \sim 0.2$ fm/$c) > 10/\mathrm{fm}^3$. Jet quenching at RHIC, if confirmed by further measurements, opens the door to a new class of diagnostic tools that probe AA dynamics and the transient quark-gluon plasma created in such collisions.

One of the unexpected results reported by PHENIX and STAR is that in contrast to the strong π^0 quenching at $p_T > 2$ GeV/c, the summed negatively charged $(\pi^- + K^- + \bar{p})$ and the corresponding positively charged hadron spectra were found to be quenched by only a factor ~ 2 [1,5]. Even more surprisingly, the identified particle spectra analysis at PHENIX [6] suggests that $R_B(p_T) = \bar{p}/\pi^- \gtrsim 1$ at $p_T > 2$ GeV/c. Thus, baryon and antibaryon production may in fact dominate the moderate high p_T hadron flavor yields, a phenomenon never before observed.

These and other data point to novel baryon transport dynamics playing role in nucleus-nucleus (AA) reactions. An important indicator of this are STAR [7] data that revealed a high valence proton rapidity density (~ 10), five units from the fragmentation regions, and a $\bar{p}/p \simeq 0.65$ at midrapidity. An attractive dynamical model that explains copious midrapidity baryon and antibaryon production is based on the existence of topological gluon field configurations (baryon junctions) [8–10]. Junctions predict long-range baryon number transport in rapidity as well as hyperon enhancement (including Ω^-) [9] and considerable p_T enhancement [8,10] relative to conventional diquark-quark string fragmentation [11]. In this Rapid Communication we propose that the baryon/meson anomaly is due to the interplay between the jet quenched [4,11,12] hard component (dN_h) and the phenomenological soft to moderate p_T component (dN_s) of $\bar{p}$ and π^-. The observed baryon junction component is assumed to exist in nucleon-nucleon (NN) and well as AA reactions, but in NN [8,9] it has a smaller amplitude, and its contribution to the high p_T baryon spectrum is "obscured" by unquenched minijet fragmentation into pions.

In this Rapid Communication we extend the study of $K^\pm/\pi^\pm$ [13] and $p/\bar{p}$ [14] ratios to compute the expected differential baryon flavor ratio, $R_B(p_T) \equiv \bar{p}/\pi^-$. We also generalize the two component soft+hard dynamical model of [4] to include the novel baryon junction component. We predict that the enhancement of the $\bar{p}/\pi^-$ ratio reported by PHENIX is actually limited to a finite moderate p_T range 2–6 GeV/c. Beyond this range, the hadron ratios are expected to converge back to the quenched PQCD base. In Au+Au, our proposed mechanism can be further tested via a predicted systematic decrease of $\bar{p}/\pi^-$ with increasing impact parameter, i.e., decreasing nucleon participant number.

The standard PQCD approach expresses the differential hadron cross section in $NN\to hX$ as a convolution of the measured structure functions $f_{\alpha/N}(x_\alpha, Q_\alpha^2)$ for the interacting partons $(\alpha = a,b)$, with the fragmentation function $D_{h/c}(z,Q_c^2)$ for the leading scattered parton c into a hadron of flavor h and the elementary parton-parton cross sections $d\sigma^{(ab\to cd)}/d\hat{t}$. Folding over an intrinsic partons (Gaussian) $f(\mathbf{k}_T)$ distribution:

$$E_h \frac{d\sigma^{NN}}{d^3p} = K \sum_{abcd} \int dz_c dx_a dx_b \int d^2\mathbf{k}_{Ta} d^2\mathbf{k}_{Tb} f(\mathbf{k}_{Ta}) f(\mathbf{k}_{Tb}) \times f_{a/p}(x_a, Q_a^2) f_{b/p}(x_b, Q_b^2) D_{h/c}(z_c, Q_c^2) \times \frac{\hat{s}}{\pi z_c^2} \frac{d\sigma^{(ab\to cd)}}{d\hat{t}} \delta(\hat{s}+\hat{u}+\hat{t}), \tag{1}$$

where x_a, x_b are the initial momentum fractions carried by the interacting partons, $z_c = p_h/p_c$ is the momentum fraction carried by the observed hadron. For NN we use phenomenological smearing $\langle \mathbf{k}_T^2 \rangle = 1.8$ GeV$^2/c^2$. Comparison between the PQCD calculation (1) and the charged hadron multiplicities measured by the ISR (pp) and UA1 ($\bar{p}p$) ex-

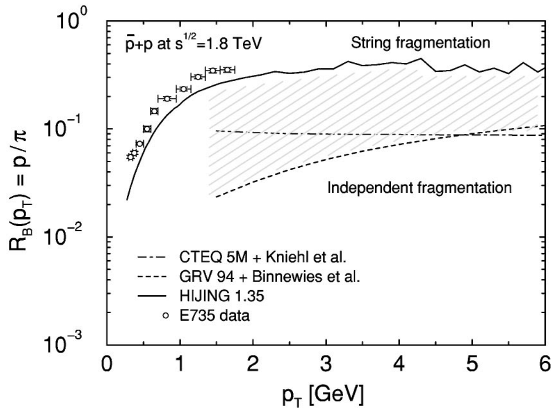

FIG. 1. The ratio $R_B \approx (p+\bar{p})/(\pi^+ + \pi^-)$ is shown for $p\bar{p}$ at $\sqrt{s}=1.8$ TeV as a function of p_T. Low p_T FNAL E735 data [18] are shown for comparison. String fragmentation of minijets via HIJING1.35 [11] is also shown.

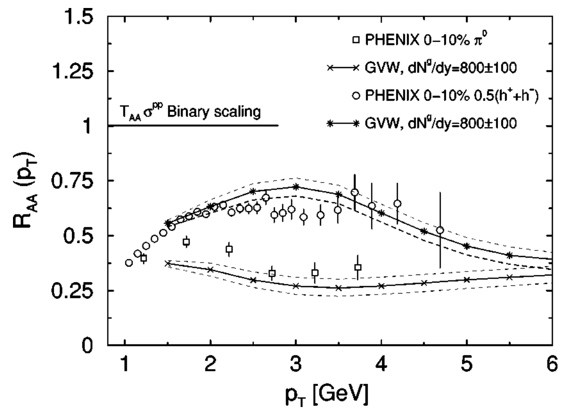

FIG. 2. The ratio of charged hadron and π^0 multiplicities to the binary collision scaled $\bar{p}p$ result is shown from [1]. The curves utilize the GLV quenched hard spectrum and the modified soft component Eq. (3).

periments [15] at $\sqrt{s}=53$ GeV and 200,900 GeV, respectively are in good agreement [10] for various structure and fragmentation function parametrizations [16,17].

Figure 1 compares $R_B(p_T)$ from the conventional independent and string fragmentation PQCD phenomenologies to available E735 [18] data from $\sqrt{s}=1.8$ TeV $\bar{p}p$ collisions. While the pion dominated charged particle inclusive data are fit well by Eq. (1) with different fragmentation models [10], there is a large difference between the predicted $\bar{p}/\pi^-$ ratios in the shown p_T range. Comparing results from two different parametrizations of fragmentation functions [17] and the HIJING1.35 string fragmentation event generator [11] reveals a rather large theoretical uncertainty ~ 3 on R_B at high p_T. Nevertheless, the prediction that $R_B \lesssim 0.5$ at high p_T is robust and intuitively reasonable given that both quark and gluon jets prefer to fragment into lighter mesons than baryons. We conclude that a systematic study of the p_T dependence of the baryon/meson ratios at RHIC should include the ~ 3 uncertainty of the baryon fragmentation schemes shown by an error band in Fig. 1, but the PQCD predictions for $\bar{p}/\pi^-$ is that it stays below 0.5 for $p_T > 2$ GeV/c.

We generalize next the (soft+hard) two component model in Ref. [4] and test it against the observed charged particle quenching pattern [1,2].

In AA collisions the semihard PQCD component is reduced due to the non-Abelian energy loss of hard partons before fragmentation as in [4]. In the calculations below, we use radiative spectrum dI/dx (corresponding to fractional energy loss $\Delta E/E$) computed in the Gyulassy-Lèvai-Vitev (GLV) formalism [12]. The numerical techniques developed in [12] allow us to extend the jet quenching computation to partonic energies as low as ~ 5 GeV that are relevant for the p_T range addressed in this paper. Jet production and propagation through the medium is treated as in [4] including the realistic Woods-Saxon nuclear geometry. We also include 1+1D Bjorken and 1+3D Bjorken+transverse expansion of the interaction region. In [19] the *azimuthally averaged* energy loss was found both analytically and numerically to have little sensitivity to transverse flow

$$\langle \Delta E_{3D} \rangle_\phi \approx \langle \Delta E_{1D} \rangle_\phi . \tag{2}$$

In the computation of the PQCD component we take into account nuclear shadowing as in [11] and Cronin effect as in Ref. [20]. In addition, we take into account multigluon fluctuations of the energy loss via the opacity renormalization approach as discussed in [21]. Fluctuations in the GLV approach effectively reduce the opacity $\chi \propto dN^g/dy$ by a factor ~ 0.5. The fitted initial gluon density quoted in Fig. 2 below takes that reduced energy loss effect into account.

We parametrize the soft phenomenological component of moderate p_T hadrons as follows:

$$\frac{dN_s(\mathbf{b})}{dy\,d^2\mathbf{p}_T} = \sum_{\alpha=\pi,K,p,\ldots} \frac{dn^\alpha}{dy}(\mathbf{b}) \frac{e^{-p_T/T^\alpha(\mathbf{b})}}{2\pi (T^\alpha(\mathbf{b}))^2}. \tag{3}$$

As in string models the soft component is assumed to scale with the number of participants (N_{part}). In Eq. (3) we also account for the possibly different mean inverse slopes T^α for baryons and mesons. In the junction picture [8], the large $T^{\bar{p}}$ may arise from the predicted [9] smaller junction trajectory slope $\alpha'_J \approx \alpha'_R/3$. This implies that the *effective* string tension is three times higher than $1/(2\pi\alpha'_R) \approx 1$ GeV/fm leading in the massless limit to $\langle p_T^2 \rangle_J \simeq 3 \langle p_T^2 \rangle_R$. In terms of the string model the factor three enhancement of the mean square p_T is due to the random walk in p_T arising from the decay of the three strings attached to the junction. Naively, we would thus expect $T^{\bar{p}} \simeq \sqrt{3} T^{\pi^-}$. In a detailed Monte Carlo study [22] using HIJING/B$\bar{\text{B}}$ [9] this relation was indeed found to hold in the $1 \leqslant p_T \leqslant 2$ GeV/c range with $T^\pi \approx 220$ MeV and $T^{\bar{p}} \approx 370$ MeV$\sim \sqrt{3} T^\pi$ with junctions included and $T^{\bar{p}} \sim 270$ MeV without. At higher p_T the PQCD minijets cause the apparent pion slope to increase systematically with p_T, while at lower p_T the resonances cause T^π to be smaller. In going to peripheral collisions a small decrease in the mean inverse slopes $\Delta T^{\pi^-} = -10$ MeV and $\Delta T^{\bar{p}} = -50$ MeV for approximate consistency with $\bar{p}p$ data [18] is introduced.

The general hydrodynamic solution [23] including transverse flow is of course much more complex at low p_T than our simplified parametrization (3). However, at large p_T all hadronic inverse transverse slopes tend to a Doppler shifted value $[T_{eff} = T_f \exp(\eta_r)$, in terms of the transverse flow rapidity η_r at a freeze-out isotherm $T_f]$. As we show below, boosted thermal sources including relativistic transverse flow does not predict an antibaryon anomaly in the $p_T \sim 2$ GeV/c range [10].

The baryon transport mechanism suggested in [9] predicts that the valance baryon number per unit rapidity has the form

$$\frac{dN^B}{dy} \simeq \frac{dN^p}{dy} - \frac{dN^{\bar{p}}}{dy} = \beta Z \frac{\cosh(1-\alpha_B(0))y}{\sinh(1-\alpha_B(0))Y_{\max}}, \qquad (4)$$

where $\alpha_B(0) \simeq 1/2$ is the baryon junction exchange intercept. For Au+Au reactions at $\sqrt{s} = 130A$ GeV Eq. (4) predicts $dN^B/dy \simeq 10$ which is in good agreement with RHIC data [7].

Our phenomenological soft string and baryon junction components depends on two parameters—the total charged particle rapidity density and the mean inverse slope for pions. We take $dN^{ch}/dy \simeq 650$ for the top 6% central events from experiment [25] and $T^{\pi^-} \simeq 220$ MeV. It has been argued that the soft string and baryon junction dynamics is manifested in nucleon-nucleon collisions [8,9]. Therefore the existing pp data [18,26] provide us with reference integrated particle ratios and predictions (e.g., $\bar{p}/\pi^- \simeq 0.06$) for the case of AA reactions. These predictions are found to be consistent with the measurements at RHIC within 30%. Deviations of those p_T integrated ratios from the $\bar{p}p$ case are expected (e.g., strangeness enhancement) but they cannot account for the factor of ~ 5 anomalous enhancement of the p_T differential baryon/meson ratio reported by PHENIX [6].

The full hadronic spectrum is a sum of soft and hard components

$$\frac{dN(\mathbf{b})}{dy d^2\mathbf{p}_T} = \frac{dN_s(\mathbf{b})}{dy d^2\mathbf{p}_T} + \frac{dN_h(\mathbf{b})}{dy d^2\mathbf{p}_T}, \qquad (5)$$

with a hard component computed from the cross section in nucleon-nucleon collisions modified by the medium induced energy loss [4,12,13] and the Glauber profile density at a given impact parameter. To avoid over counting, we smoothly turn on the power law PQCD component at $p_T \sim 2$ GeV/c [4].

We first compute the ratio $R_{AA}(p_T)$ of the hadron multiplicity in Au+Au at $\sqrt{s} = 130A$ GeV normalized to the corresponding multiplicity in $\bar{p}p$ reactions scaled by the number of binary collisions. Such scaling is relevant for the comparison of the moderate to high p_T parts of the hadronic spectra and in absence of nuclear effects is expected to be unity. Figure 2 shows R_{AA} in the 10% central collisions for neutral pions and inclusive charged hadrons. We note that including only nuclear shadowing and Cronin effect gives a ratio consistent with unity within 10% for $p_T \geqslant 2$ GeV/c and inconsistent with data if jet quenching is not taken into account [27]. The fitted parton energy loss is specified by initial gluon rapidity density $dN^g/dy = 800 \pm 100$ and this density is close to predictions based on saturation models [28]. This high gluon density takes into account the reduction of the effect of induced radiative energy loss due to multigluon fluctuations as discussed in detail in Ref. [21].

In relativistic heavy ion collisions early thermalization of the soft background partons is expected. This allows the estimate of the Debye screening μ (which is a natural infrared cutoff in medium) from thermal PQCD. The screening scale then enters the partonic cross section and the transport coefficient used in energy loss calculations [12]. Larger variations of the initial density of the medium have also been studied [10] but they give a less satisfactory description of the PHENIX data [1].

At $p_T \geqslant 2-3$ GeV/c pions are perturbative and exhibit an almost constant suppression as predicted by the GLV formalism [12,13]. In contrast at moderate high p_T the nonperturbative baryon junction component is unaffected. Thus in central collisions baryon excess at intermediate transverse momenta is expected relative to NN. This results in a smaller degree of suppression of inclusive charged hadrons which is p_T dependent. At larger transverse momenta baryon production is expected to be dominated again by PQCD (as in Fig. 1). Therefore baryons are expected to show comparable suppression to pions at high $p_T \gtrsim 5$ GeV/c. From Fig. 2 we conclude that such physical picture is compatible with the data and can be easily tested with future data in the $p_T > 5$ GeV/c range.

In our discussion of the p_T dependence of $\bar{p}/\pi^-$ ratio at RHIC we first turn to a simple description based on boosted thermal sources

$$dN \sim m_T K_1\left(\frac{m_T \cosh \eta_r}{T_f}\right) I_0\left(\frac{p_T \sinh \eta_r}{T_f}\right), \qquad (6)$$

where $\tanh \eta_r = v_\perp$. A computation of $R_B(p_T)$ with $T_f = 160$ MeV and $v_\perp = 0.6$ is included in Fig. 3. It predicts $\bar{p}/\pi^- \leqslant 1$ in the intermediate p_T window and grows monotonically with p_T to $R_B = 2$ which is a general feature of hydrodynamic calculations. We note however, that variations of hydrodynamic initial density profiles, equation of state, and freeze-out criteria as well as dissipative effects may also play a role in the $\bar{p}/\pi^-$ anomaly, since $R_B < 1$ may also occur in hydrodynamics with late chemical freeze-out [3] as well as in the hybrid hydro+UrQMD model due to dissipative effects [24].

As a further test of our model we consider next the expected centrality dependence of R_B. The $\bar{p}/\pi^-$ ratio computed for three different centralities in the soft+hard model Eq. (5) is also shown in Fig. 3. In central collisions the interplay between the anomalous baryon component of $\bar{p}$ and the quenched PQCD component of π^- leads to maximum of R_B near $p_T \sim 3-4$ GeV/c. At large $p_T \geqslant 5-6$ GeV/c we predict a gradual decrease of R_B *below unity* consistent with the the PQCD baseline calculations (see Fig. 1). In Fig. 3 we have included through error bands the factor of ~ 3 uncertainty in the fragmentation functions into $\bar{p}$ at high p_T. The

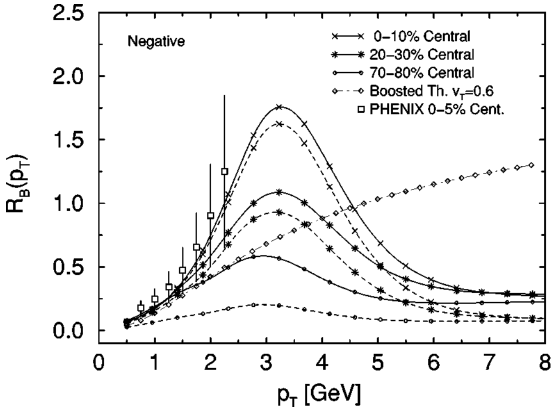

FIG. 3. The centrality dependence of $R_B(p_T)$ is predicted for three different centralities. Solid (dashed) lines correspond to A^1 ($A^{4/3}$) scaling of the junction component. The ratio of $\bar{p}$ and π^- fits to PHENIX data on central reactions is shown for comparison. A boosted thermal source (dashed line) is also shown.

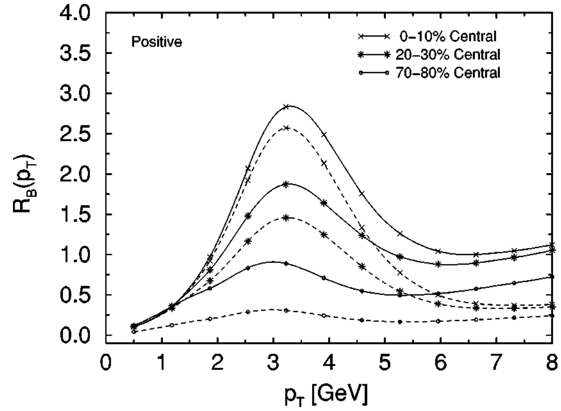

FIG. 4. The centrality and p_T dependence of the p/π^+ ratio is predicted for the same centrality classes as in Fig. 3. The solid (dashed) lines compare the difference between N_{part} ($N_{part}^{4/3}$) scaling of the junction component and $3(1)\times$ the quenched fragmentation component as in Fig. 3.

solid and dashed curves reflect the difference between the N_{part} and $N_{part}^{4/3}$ scaling of the junction component

In peripheral reactions the size of the interaction region as well as the initial density of the medium decrease leading to reduction of energy loss. The absence of quenching reduces the observability of the anomalous component and the $\bar{p}/\pi^-$ ratio may stay below unity for all p_T. The case of peripheral reactions is hence similar to $\bar{p}p$ collisions. The experimentally testable prediction of the model (5) is therefore that the maximum of the $R_B = \bar{p}/\pi^-$ ratio decreases with increasing impact parameter, decreasing participant number, or equivalently decreasing dN^{ch}/dy.

We found that the interplay between jet quenching at RHIC computed as in [4] using the GVW, GLV formalisms [4,12] and a postulated novel baryon junction component could account for the $p_T > 2$ GeV/c $\bar{p}/\pi^- \gtrsim 1$ puzzle suggested by the data. We propose that in central collisions jet quenching exposes this new baryon junction component [8,9]. This was shown in Fig. 2 to provide a natural explanation for the smaller effective quenching of moderate p_T charged particles than π^0. Figure 3 shows that R_B could reach values well above unity in a finite moderate p_T domain but is predicted to decrease to well below unity at $p_T > 5$ GeV/c in contrast to thermal or hydrodynamic models. Whereas the maximum baryon excess, $R_{B\max}$, depends on unknown details of the baryon junction component the shape of $R_B(p_T)$ and its specified centrality and transverse momentum dependence are largely a consequence of the jet quenching phenomenon similar to the saturation of $v_2(p_T)$ reported by STAR [2].

Since from p_T integrated hadron yields $\bar{p}/p \simeq 0.65$ [1,2], the predicted p_T dependence of baryon enhancement and subsequent reduction at high p_T may in fact be more readily observable in the p/π^+ ratio.

We find that the p/π^+ ratio is typically $\sim$50% larger than $\bar{p}/\pi^-$ as a function of p_T at moderate transverse momenta. Comparison between Figs. 3 and 4 shows that for $p_T \geqslant 6$ GeV/c the baryon/meson ratio for positive hadrons predicted here is $\sim 2-3$ times bigger than the corresponding ratio for negative hadrons. This is due to the valance quark dominance in the PQCD fragmentation into baryons versus antibaryons at high p_T (see also Refs. [10,14]). In contrast, hydrodynamic models with flavor independent freeze-out would predict an asymptotic ratio ~ 2.

In summary, a novel test of the baryon junction hypothesis [8,9] for baryon number production and transport in ultrarelativistic nuclear collisions has been proposed through the predicted anomalous dependence of high p_T $\bar{p}/\pi^-$ and p/π^+ ratios and their centrality dependence. The existing PHENIX data [6] strongly motivate the extra effort needed to measure (anti)baryon spectra into the $p_T \gtrsim 5$ GeV/c range as a complement to the (anti)baryon number rapidity transport measurements by STAR [7] and soon by BRAHMS [29].

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