POSSIBLE SIGNATURE FOR AND EARLY HADRONIZATION
MECHANISMS OF QUARK-GLUON PLASMA

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ABSTRACT

We consider the ratio of particle abundances radiated from quark-gluon plasma above mean thermal energy and point out significant differences expected as compared with global particle yields. Two microscopic processes leading to medium to high $E_{\perp}$ abundances are quantitatively considered and the means of determining the plasma baryochemical potential are discussed. Strong anomalies in strange anti-baryon spectra are found, characteristic of the formation of quark-gluon plasma.

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There is evidence from recent relativistic nuclear collision experiments¹⁾ that the reaction proceeds through a stage in which a hot and dense region of nuclear matter has been formed. The key issue, if the quark-gluon plasma state has been excited, will not be easy to ascertain, although this reaction mechanism is viewed as a rather compelling intermediate stage given the current QCD-based hadronic phenomenology.

Our objective in this paper is to explore particle radiation mechanisms operating at the early stages of the plasma life as well as to see if some of the key properties of the plasma state can be measured soon after its formation through observation of particular particle abundances. Two competing channels of particle production may be considered. In the first primordial particle emission mechanism a fast quark from the plasma impinges on the boundary between the plasma perturbative vacuum and the true vacuum. In the associated color string breaking process, at least one quark-antiquark pair is formed. We will refer to this process as a 'microjet', not to be confused with the minijet processes²⁾: the latter are products of single scattering of quarks on quarks, while in our microjet the high transverse momentum is derived from a fluctuation in the kinetic equilibrium in the plasma, i.e from a relatively large number of soft scattering processes. Indeed, we are dealing with a (nearly) thermalised system - as $E_{\perp}$ of a particle increases, the microjet contribution in its spectrum exponentially decreases and ultimately there is the minijet component in the spectrum at very high $E_{\perp}$. Second, in the recombination approach, several constituents of the plasma, clustered into colorless objects, penetrate the surface and hadronize. This latter scenario is also often used in order to model the phase transformation of the plasma to the hadronic gas at the later stages of the plasma life³⁾. However, our recombination approach is, in detail, different in that we do not allow gluon fragmentation. The equilibrium quark abundances in plasma contain the effect of continuous gluon and quark fragmentations and recombinations. Only at phase transition equilibrium is lost and entropy generating microscopic processes such as gluon fragmentation³⁾ become necessary. We expect that the microjet

picture will dominate the spectra at medium to high $E_{\perp} \sim (2-4)m$. It may be worth noting that the mechanisms we are discussing for medium $E_{\perp}$ particle evaporation from plasma have a great degree of similarity with the way a droplet of water freezes - as the surface freezes, icicles form through discharge of internal pressure through the surface, just as our microjets generate medium $E_{\perp}$ particles.

We have previously used the microjet mechanism in order to estimate the cooling rate of early quark-gluon plasma by π -emission⁴⁾ - the resulting high cooling rates were later challenged and this relevance of the microjet mechanism to the plasma evolution was questioned⁵⁾. However, the existence of the microjet particle radiation mechanism is agreed upon, but its quantitative influence on the particle spectra is one of the key questions relating to the understanding of the early evolution of the plasma. We believe that a suitable signature for the microjet particle production mechanism is the medium range of transverse energy particle spectra, constrained further to the central rapidity region and small impact parameter nuclear collisions.

Let us first study the abundance ratio of K^+/π^+ at above mean transverse energy $E_{\perp}$. The quark content of $K^+(u\bar{s})$ and $\pi^+(u\bar{d})$ implies that mainly u-quarks, which are abundantly present in the baryon-rich plasma may be viewed as seeds in the formation of these particles. In the microjet picture the ratio of abundances is simply obtained by considering the likelihood of one of the required quarks impinging on the surface (the other forming in the string breaking):

$$\left. \frac{K^+}{\pi^+} \right|_{\text{Microjet High } E_{\perp}} = \frac{u f_{\bar{s}} + \bar{s} f_u}{u f_{\bar{d}} + \bar{d} f_u} \quad (1)$$

where $f_i = f_{\bar{i}}$ are the branching fractions of the string into the i-th quark: $f_u = f_{\bar{d}} = f_{\bar{q}} = \frac{1}{2}(1-f_s)$; we assume along with others that $f_s = 0.15$. In principle, the particle abundance denoted by u, s, etc. in eq.(1) are also energy dependent; however, taken at the

same energy $E \gg M$ we find that it is possible to consider only the Boltzmann expansion of respective Fermi distributions. Hence, the common Boltzmann factor $e^{-E/T}$ cancels, up to the chemical potential factor $e^{\mu_b/3T}$ for u, d and $e^{-\mu_b/3T}$ for $\bar{u}, \bar{d}$ quarks. The baryochemical potential has no influence on the $s, \bar{s}$ -quark abundance³⁾. We thus find

$$\left. \frac{K^+}{\pi^+} \right|_{\substack{\text{Microjet} \\ \text{High } E_\perp}} = \frac{f_s/f_q e^{\mu_b/3T} + 1}{e^{\mu_b/3T} + e^{-\mu_b/3T}} \begin{cases} \xrightarrow{\mu_b \gg 3T} & \frac{f_s}{f_q} = 0.35 \\ \xrightarrow{\mu_b = 0} & \frac{f_s/f_q + 1}{2} = 0.68 \end{cases} \quad (2)$$

This result is very similar to the one obtained for the total multiplicity ratio K^+/π^+ from entropy based arguments⁶⁾, though the curvature of the result as a function of μ_b is somewhat different (c.f. Fig.1.). We are thus led to expect a slightly increasing K^+/π^+ ratio as a function of transverse energy, always remaining smaller than unity.

We now consider the same particle ratio in the recombination model. The abundance ratio at high $E_\perp$ is controlled by the product of the equilibrium quark spectra, as no additional gluon fragmentation will be allowed as discussed above. We have therefore, during the early stages of plasma lifetime

$$\left. \frac{K^+}{\pi^+} \right|_{\substack{\text{recombin} \\ \text{high } E_\perp}} = \frac{u\bar{s}}{u\bar{d}} = \frac{\bar{s}}{\bar{d}} = e^{\mu_b/3T} \quad (3)$$

which, contrary to the microjet result, eq.(2), is a monotonically growing function of μ_b , always greater than one! This occurs, since at a given transverse energy the $\bar{d}$ -quarks are suppressed as compared to the $\bar{s}$ -quarks by the chemical potential factor. This very surprising result documents the need for extensive data on particle abundance ratios at medium to high $E_\perp$. Should K^+/π^+ be observed to be greater than one, this would constitute a rather persuasive evidence for the dominance of the recombination

mechanism at medium to high $E_{\perp}$. Note that the comparison must be made at the same $E_{\perp}$ not $p_{\perp}$.

In principle, we could embark now on a long list of different particle production ratios for mesons and baryons, particularly emphasizing the strangeness content as a marker. Some of these are a duplication of others, e.g. K^{-}/π^{-} arises from K^{+}/π^{+} by changing $\kappa_b \rightarrow -\kappa_b$ in eqs.(2,3) as required by particle-antiparticle conjugation. Others arise by taking a diquark as the seed for both reaction mechanisms. For example, replacing u by $\bar{s}u$ above in eq.(3) we arrive at the ratio of Ξ^0 to $\bar{\Lambda} + \Xi^0$

$$\left. \frac{\Xi^0}{\bar{\Lambda} + \Xi^0} \right|_{\substack{\text{recomb} \\ \text{high } E}} = \frac{(\bar{s}u)\bar{s}}{(\bar{s}u)\bar{d}} = e^{\kappa_b/3T} \quad (4a)$$

The probability of finding $(\bar{s}u)$ or $(\bar{s}d)$ is nearly equal, thus we can consider the more accessible ratio

$$\left. \frac{\Xi^0 + \Xi^{-}}{\bar{\Lambda} + \Xi^0} \right|_{\substack{\text{recomb} \\ \text{high } E_{\perp}}} = \frac{[(\bar{s}u) + (\bar{s}d)]\bar{s}}{(\bar{s}u)\bar{d}} = 2 e^{\kappa_b/3T} \quad (4b)$$

which again displays (cf. Fig.2) the rather shocking result that the more complex particle (Ξ) is possibly more copiously produced. As has been recently shown⁷⁾, measurement of the abundance of longitudinally polarised 'V' events determine this ratio. If acceptance problems are important an alternative way to estimate the $\Xi/\bar{Y}$ ratio is to study the apparent mean decay path of $\bar{Y}$: if it is 1.5-2 times longer than expected, the $\bar{Y}$ -signal is dominantly a descendant of Ξ decay. While this method is potentially less sensitive than the longitudinal polarisation one⁶⁾, especially at medium $E_{\perp}$ where this ratio seems to be greater than one, it will lead to valid tests of the above prediction.

In the microjet picture we have to consider all diquark combinations penetrating the surface (here q stands for either u or d)

$$\left. \frac{\bar{\Xi}^0 + \bar{\Xi}^-}{\bar{\Lambda} + \bar{\Xi}^0} \right|_{\substack{\text{microjet} \\ \text{high } E_{\perp}}} = \frac{2(\bar{s}s) f_q + 2(\bar{s}q) f_s}{2\bar{s}q f_q} = \frac{\bar{s}}{q} + \frac{f_s}{f_q} = e^{\mu_b/3T} + 0.35. \quad (5)$$

In Fig.2 we show the predictions of eqs.(4,5) and compare them to global abundance ratios (including low $p_{\perp}$), taken from Ref.(6,3). The surprise is that in both early emission processes (microjet, recombination) populating medium to high $E_{\perp}$ portions of the spectra we are led to expect more anticascades than antilambdas (since $\bar{\Xi}^0 \rightarrow \bar{\Lambda} + \pi^0$ we included $\bar{\Xi}^0$ into the 'lambda' abundance). But there is some difference concerning the precise prediction, (cf. eqs.(4,5)) and which is difficult to differentiate unless the value of μ_b is known to some accuracy.

It will be possible to evaluate the required value of the surface baryochemical potential at the early plasma stage once the dominance of one of the mechanisms for early particle emission is established, e.g. by the study of K^+/π^+ ratio, c.f. Fig.1. Perhaps the simplest particle ratio to look at for the purpose of μ_b measurement is the K^+/K^- ratio. We select the K^+/K^- -ratio as characteristic for the chemical potential, as it contains the symmetry between $\bar{s}$ and s quarks as an essential ingredient, while, $u-\bar{u}$ asymmetry is used as the signal. The $s-\bar{s}$ symmetry in early plasma stages is not broken by the strangeness re-equilibration processes discussed recently⁸⁾. In the recombination picture we have

$$\left. \frac{K^+}{K^-} \right|_{\substack{\text{recomb} \\ \text{high } E_{\perp}}} = \frac{u\bar{s}}{\bar{u}s} = e^{2\mu_b/3T} \quad (6)$$

while the microjet leads to

$$\left. \frac{K^+}{K^-} \right|_{\substack{\text{microjet} \\ \text{high } E_{\perp}}} = \frac{\bar{s} f_q + u f_s}{s f_q + \bar{u} f_s} = \frac{1 + e^{\mu_b/3T} f_s/f_q}{1 + e^{-\mu_b/3T} f_s/f_q} \quad (7)$$

Results of eqs(6,7) are shown in Fig.3. The K^+ abundance is greater than the K^- in both approaches; the precise relation between M_B and K^+/K^- -ratios depends on the mechanism. (Note that T can be fixed from the slope of the spectra). At this point it is worthwhile to note that in chemically equilibrated hadronic gas phase the ratio of total abundances of K^+ to K^- is of the same analytical structure⁹⁾ as shown in eq.(7) with the colour string breaking parameter f_s/f_q being replaced by F_Y/F_K , the ratio of hyperon to kaon phase space (its inverse is displayed in Fig.1, Ref.(8)). However, unlike f_s/f_q the phase space ratio F_Y/F_K is strongly temperature dependent, changing from $\sim 1/3$ at $T \sim 200$ MeV to less than $\sim 1/20$ at $T = 120$ MeV. These significant differences in the behaviour of particle ratios as functions of the simultaneously observed particle spectra (temperature) will be essential to the understanding of their origin (i.e. plasma vs hadronic gas). In Fig.3 the K^+/K^- ratio for equilibrated hadronic gas at $T = 140$ MeV is shown. We note that the K^+ dominance over K^- is greatly reduced (factor 6 at $M_B/3T \sim 3$) in the hadronic gas as compared to the microjet mechanism. Thus we are led to expect that the K^+/K^- ratio increases with increasing $E_\perp$ (should QGP be formed).

We have shown that the K^+/π^+ abundance ratio at high $E_\perp$ can distinguish between mechanisms of early particle production in quark-gluon plasma. Once the medium to high $E_\perp$ particle production mechanisms are understood, other particle ratios, e.g. $K^+/K^-|_{\text{high } E_\perp}$ can be used to assess the surface value of the baryochemical potential at early plasma stages. Anticascade to antihyperon abundance ratio at medium to high $E_\perp$ shows a great anomaly, characteristic for the formation of the new quark gluon plasma phase of matter.

ACKNOWLEDGEMENT

We thank M. Jacob for his interest in this project, stimulating comments, and careful reading of the manuscript.

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FIGURE CAPTIONS

- Figure 1 : K^+/π^+ particle abundance ratio as a function of M_b at $T = 180$ MeV : Full lines: medium to high $E_\perp$ estimates based on minijet and recombination models. Dashed: global ratio arising from entropy based arguments (from Ref.5).
- Figure 2 : $\Xi/(\bar{Y}/2)$ particle ratio as a function of $M_b/3T$ for the microjet, recombination pictures of particle radiation at medium to high $E_\perp$. Dashed: global ratio (from Ref.6,3).
- Figure 3 : K^+/K^- ratio at medium to high $E_\perp$ particle ratio as function of $M_b/3T$ for the minijet and recombination descriptions of early particle radiation from plasma. Dashed: global equilibrium hadronic gas result at $T = 140$ MeV.

FIGURE 1

FIGURE 2

FIGURE 3