Soft pion emission from fat flux tubes

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The emission of pions from multiquark flux tubes is examined as an explanation of the soft pion puzzle. Although the soft pion spectra from the decay of fat flux tubes can account for some low $p_\perp$ enhancement, the dependence on the number of involved quarks is too weak to provide a plausible explanation of the observed enhancement in the pion spectrum at low transverse momenta.

In the search for signals of a quark-gluon plasma (QGP) in CERN energy ultrarelativistic heavy-ion collisions, one often studies differences in experimental spectra between the nuclear collisions and nucleon-nucleon collisions. In this respect, a striking feature has emerged in the transverse momentum spectrum of pions. An enhancement of soft pions (low $p_\perp$) is observed when comparing $p+A$ and $A+A$ collisions at 200 GeV/c spectra with $p+p$ collisions at the same energy [1–3], accounting for roughly $\frac{1}{4}$ of the observed pions. Such signatures can be suggestive of a QGP, with an enhanced soft pion component resulting from the evaporation of cooled quark-gluon plasma droplets. In considering the origin of the excess of soft pions, it is necessary to examine possible sources of soft pions in the framework of a hadron gas, before resorting to a QGP as an explanation. This soft pion puzzle has been vigorously debated in the recent literature [4–9]. Simple phenomenological solutions of the hydrodynamic equations for the hadron gas were proposed by Atwater *et al.* [4] and Lee and Heinz [5] to account for this enhancement. However, a covariant treatment of the hydrodynamic equations and of the freeze-out surface by Kusnezov and Bertsch [6] demonstrated that the hydrodynamic description results in a convex-shaped spectrum, further enhancing the low $p_\perp$ component. The role of excited hadrons in shaping the transverse spectrum has been investigated. Barz *et al.* [7] used two extreme models of resonance production, one assuming chemical equilibrium and another using a string fragmentation picture, neither of which provided a full description of the additional low $p_\perp$ peaking. Sollfrank *et al.* [7] have also studied the effect using a simple thermodynamic model, indicating that while resonance decays are important, they do not provide a complete picture of the situation. Shuryak has explored the puzzle in terms of a modified pion dispersion relation [8]. Kataja and Ruuskanen [9] have suggested that the pions freeze-out while they are strongly out of chemical equilibrium, with a chemical potential close to the pion mass.

In this Brief Report we investigate the production of pions in the nonequilibrium scenario of fat flux tube decay resulting from nucleus-nucleus collisions at CERN energies, such as O + Au or S + W at 200 GeV/ nucleon. The central region of these collisions can be characterized as a region of high energy density and low baryon density. Further, the Lund model, in the study of quark jets, indicates that string fragmentation combined with spin-isospin statistics provides a good picture of the physical situation. Hence, it is reasonable to consider the physical mechanism or particle production via string production and fragmentation. However, if the central region is of sufficiently high string density, one might expect that individual strings will coalesce, and a distribution of fat or multiquark flux tubes will dynamically evolve in time. Eventually, these fat flux tubes will also freeze-out, generating the final transverse spectrum of pions. Since these multiquark flux tubes decay with a softer transverse pion spectrum than single-quark strings, we consider the role of the fat tubes in shaping the low $p_\perp$ spectrum.

The transverse momentum distributions for single strings can be extracted phenomenologically from the pp data, which has the characteristic form

$$\frac{dN}{p\perp dp\perp} \sim e^{-\alpha' R p_\perp} . \tag{1}$$

Here α' is a slope parameter which can be extracted from the experimental spectrum, and R is the radius of the flux tube. The primary interaction in these pp collisions is quark-quark, in which only a single quark from each nucleon participates in the collision. The radius of the string, or single-quark flux tube, could be taken from the inelastic cross section. From the 40 mb nucleon-nucleon inelastic cross section, one can extract the quark-quark cross section, which results in a naive quark radius of $R \sim 0.37$ fm. Although this value is not crucial to our arguments, since we extract the slope $\alpha = \alpha' R$ directly from the data, it is more relevant to modeling the coalescence of tubes.

Using the string picture introduced by Johnson and Thorn [10], we can relate the radius of the flux tube to the chromo-electric charge at the ends of the string. Applying Gauss' law on one end of the flux tube, and assuming a uniform flux tube radius, we have

$$g_e = \pi R^2 \mathcal{E} . \tag{2}$$

g_e is the color-electric charge, and $\mathcal{E}$ is the chromo-electric field. g_e is related to α_{qcd} through the relation $g_e^2=16\pi\alpha_{qcd}/3$. For a uniform field, the energy density per unit length of the flux tube is [10,11]

$$\kappa(R)=(\tfrac{1}{2}\mathcal{E}^2+B)\pi R^2 , \tag{3}$$

where B is the bag constant. Following Johnson and Thorn, the radius of the tube will equilibrate in such a way as to minimize the energy with respect to the radius. The result is that

$$\kappa=g_e\mathcal{E} . \tag{4}$$

Combining (2)–(4), we can solve for g_e in terms of the radius R and bag constant B:

$$R=\left[\frac{g_e}{\pi\sqrt{2B}}\right]^{1/2}\sim g_e^{1/2} . \tag{5}$$

Since the quarks on the ends of the flux tube are randomly produced, the charge associated with the multiquark configuration can be obtained with a random walk through color space, keeping in mind that the next configuration is a color singlet [12]. The result is that after n steps through color space, or, equivalently, if you have n quarks at the end of the tube, the mean square of the charge is

$$\langle g_e^2(n)\rangle=n\langle g_e^2(1)\rangle . \tag{6}$$

The overall constant is not important, since we extract the slope from the experimental spectra. As a result, combining (1), (5), and (6), we obtain the transverse spectra generated by an ensemble of fat flux tubes as

$$\frac{dN}{p_\perp dp_\perp}=\sum_n A_n e^{-\alpha n^{1/4}p_\perp} , \tag{7}$$

where the sum extends over all multiquark flux tubes at the time of freeze-out, and the coefficients A_n are to be determined either experimentally or by simple models. The crucial aspect of (7) is that there is an extremely weak dependence on the number of quarks at the ends of the fat flux tube, making it an unlikely solution of the low $p_\perp$ puzzle.

In principle, the coefficients A_n can have a dependence on the radius of the decaying flux tube. However by fitting the coefficients to the data, this dependence is unimportant. It is a simple exercise to fit the parameters A_n and α to $p+p$ data (Ref. [2], Fig. 10) and the Helios data for S + W collisions at 200 Gev $/c$. For $p+p$ collisions, a good fit is obtained with $A_n=0$, $n>1$, and a slope of $\alpha=5.64$. For the S+W, we can assume different final distributions of flux tubes which contribute to the transverse spectrum of pions. Taking $n=1$, we find $A_1=0.45$, which underestimates the number of pions, as indicated in Fig. 1. For $n=2$, the optimal fit is for $A_1=0.41$ and $A_2=0.07$. This undercounts the number of pions by roughly the same amount. The two cases, shown in Fig. 1, indicate the very small contribution to the soft pion spectrum due to fatter tubes. If one allows

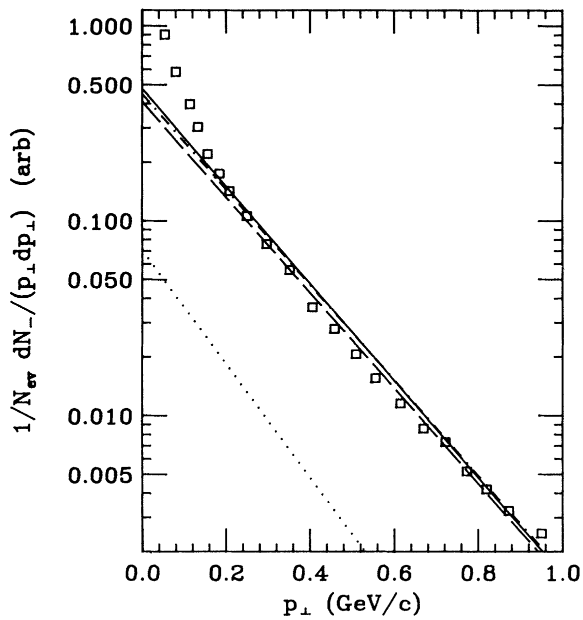

FIG. 1. Experimental transverse momentum spectrum for π^- from S+W at 200 GeV/nucleon compared to flux tube approach. The dot-dashed line corresponds to a single flux tube with $n=1$ and $A_1=0.45$. The solid line is the $n=2$ case. The single-quark contribution (dashes) has an amplitude of $A_1=0.41$ and the two-quark contribution (dots) has an amplitude of $A_2=0.07$. The slope $\alpha=5.64$ is extracted from the $p+p$ collisions at the same energy. Data are from the Helios Collaboration [3].

for larger n's, the optimal fits one finds are unphysical, since the spectrum favors a very fat tube, a very small tube, and no intermediate sizes. Further, one can easily produce simple string formation models, based on the overlap of nucleons, folding in the nuclear density distribution, and the Lorentz contraction. In these models, it is always the case that $A_n>A_{n+1}$ for all n. In general, large flux tubes are suppressed with respect to small flux tubes due to simple statistics. It should also be remarked that changes in the functional dependence of the distribution on $Rp_\perp$ in Eq. (1) do not improve the situation. If we consider $(Rp_\perp)^2$ in the exponent, the distribution will have zero slope at $p_\perp=0$ for any size flux tube, which will reduce the agreement with the data. By choosing $R^2p_\perp$ in the exponent, the improvement in the agreement with the data improves only a negligible amount.

In conclusion, we find that the contribution of fat flux tubes to the enhancement of the low $p\perp$ pion spectrum is quite small. This is a result of the weak dependence of the transverse spectrum on the number of quarks at the end of the flux tube in Eq. (7). If additional hadronic phase explanations were excluded, one might be led to other possibilities, such as supercooled glueballs, pions with a very high chemical potential, cold plasma droplets, or effects due to chiral-symmetry restoration.

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