The transverse momentum spectrum in ultrarelativistic heavy ion collisions is not statistical

H.W. Barz \(^{a,b}\), G. Bertsch \(^a\), D. Kusnezov \(^a\) and H. Schulz \(^{a,b}\)

\(^a\) NSCL, Michigan State University, East Lansing, MI 48824, USA
\(^b\) Zentralinstitut für Kernforschung, Rossendorf, 0-8051 Dresden, Germany

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We examine the role of decays of excited hadrons in shaping the transverse momentum spectrum of pions in ultrarelativistic heavy ion collisions. No reasonable statistical model can reproduce the experimentally observed peak in the spectrum at low transverse momentum.

A striking difference has been observed in the pion spectrum produced by nuclear collisions as compared to nucleon–nucleon collisions at ultrarelativistic energy, namely an enhancement of low-transverse momentum pions in nuclear collisions \([1,2]\). This puzzling phenomenon is vigorously debated in the literature \([3–9]\). Atwater et al. \([5]\) and Lee and Heinz \([6]\) interpreted the additional peaking in the \(\pi\) spectrum as a collective flow effect. However, Kusnezov and Bertsch \([7]\) pointed out that a covariant treatment of the freezeout surface gives a convex shaped spectrum and cannot account for the experimentally found behaviour at low \(p_\perp\). Shuryak has explored the change of the \(\pi\) dispersion relation in the medium in connection with the cool component of the \(\pi\) spectrum \([4]\). Kataja and Ruuskanen \([8]\) fit the spectrum by assuming that the \(\pi\)'s are strongly out of chemical equilibrium. Brown et al. \([9]\) pointed out that at temperatures of the order \(\sim 150–200\) MeV the excited states of the hadrons have to be taken into account, because the \(\pi\) originating from the decay of the excited baryon states may increase the total \(\pi\) yield at low \(p_\perp\) values and in this way may explain the observed peak structure.

In this note we wish to examine this idea in more detail. Parenthetically, we mention that in low energy nuclear collisions decays of excited nuclei lower the visible temperatures of products in the final state \([10]\). We consider here an initial state that is some statistical mixture of light quark mesons and baryons. We limit the mesons to the \(q\bar{q}\) states with zero orbital momentum, i.e. the \(\pi, \rho, \omega, \) and \(\eta\) mesons \(^*1\).

Two extreme statistical models can be imagined. In the first model, the hadronic abundances are calculated by assuming chemical equilibrium. Then the meson abundances are determined by a single parameter, the temperature. One additional parameter, the baryon abundance, specifies the model completely.

In the second model, we assume that the mesons have the statistical weights associated with their spin and isospin degeneracies. That is, the mesons are forced in the ratio \(\pi: \rho: \omega: \eta \sim 3: 9: 3: 1\). This model is suggested by string-breaking pictures in which a quark and antiquark are formed independently in the final meson. Phenomenological modelling of quark jets, such as done in the Lund model, have statistical weights close to these values.

In both cases we assume that the initial momentum distribution is a superposition of thermal distributions uniformly spread in rapidity along the beam axis. The thermal distribution function is

\[
dN = V d^3p \frac{1}{\exp(p^2u_{\perp}/T) + 1},
\]

\(^*1\) A similar model including additionally the decay of K* and Σ* particles was recently considered by Sollfrank et al. \([11]\).
where \( \pm \) applies to fermions or bosons, respectively, \( p^\mu \) is the four momentum, \( u_\mu \) is the four-velocity, \( V \) is the volume and \( T \) the temperature. When this is boosted uniformly in rapidity along the longitudinal axis, the transverse momentum distribution becomes

\[
\frac{dN}{dy d^2p_\perp} = A \int dy \frac{m_\perp \cosh \eta}{\exp(m_\perp \cosh \eta/T) \pm 1},
\]

(2)

where \( A \) is a normalization constant. If pions are created via the decay of the \( \rho \), \( \omega \), \( \eta \) mesons or the \( \Delta \) decay, then their distribution function is obtained by folding the distribution (2) with a \( \delta \)-shaped distribution function \( \delta(p^\mu u_\mu - e_\pi^* ) \), where \( e_\pi^* = \sqrt{m_\pi^2 + p_\pi^*} \) is the energy of the emitted \( \pi \) in the rest frame of the decaying particle. The resulting distribution function is of the form

\[
\frac{dN_\pi}{dy d^2p_\perp} = \frac{1}{4\pi p_\perp^*} \times \int dy' d^2p_\perp' \frac{dN}{dy' d^2p_\perp'} \delta\left(\frac{p'^\mu u_\mu - e_\pi^*}{m_\pi} \right),
\]

(3)

where the primed quantities refer to the particle emitting the pions.

Our results are shown in figs. 1 and 2. The temperature of \( T = 185 \text{ MeV} \) has been chosen to fit the slope of the experimental spectrum. In fig. 1 we show the result assuming that the decaying hadrons are initially in chemical equilibrium. The baryon abundance is chosen as one baryon for every five final state pions. This is the approximate ratio of the participant nucleons, calculated by a geometric overlap, to the observed final state \( \pi \)'s in collisions of \( O + Au \) or \( S + S \). One sees that for low momenta all hadrons under consideration give approximately the same contribution to the total \( \pi \) yield. The \( \eta \) mesons give an insignificant contribution in the \( \pi^- \) yield, but would be somewhat more important in the \( \pi^0 \) spectrum, because they decay preferentially to \( \pi^0 \) channels. However, all the \( \pi \)'s originating from the hadronic decays do not produce a peaking of the spectrum at low momenta. The shape of the \( \Delta \) spectrum is flat at low momentum, so it does not seem possible that any admixture of baryons could explain the data. For momenta \( p_\perp > 0.2 \text{ GeV/c} \) most of the secondary \( \pi \)'s come from \( \rho \) meson decay. Their yield is almost comparable with that of the primordial pions.

In fig. 2 we show the corresponding results under the assumption that the primordial hadrons have abundances given by the \( (2J+1)(2J+1) \) statistical weights. This spectrum is practically indistinguisha-
ble from the result of the equilibrium model. The experimental spectrum is again well reproduced at high transverse momentum. In this model, more π's come from decays of ρ mesons than from any other single source. The η meson has a negligible contribution to the overall π⁻ spectrum. However, since 32% of the η's decay through the 3π⁰ channel, the contribution of the η in the π⁰ spectrum would exceed that of the primordial π's. Again, the baryon component is incapable of significantly altering the shape of the spectrum.

Although we have considered a longitudinally boost-invariant scenario, this actually provides for more low pₓ peaking than sources of limited rapidity range. By shifting η to (η−y) in eq. (2) and multiplying the resulting integrand by the longitudinal rapidity distribution exp [−(η−η₀)^2/2σ^2], we can obtain non-invariant modifications to eq. (3). The resulting distributions are typically found to enhance the transverse spectrum at pₓ ≈ m', where m' is the mass of the decaying resonance. By neglecting the finite longitudinal distribution, the enhancement is smoothed out, further peaking the π spectrum at pₓ ≈ 0. A similar but weak effect is caused by the finite width of the resonances.

In summary, despite the fact that for transverse momenta pₓ > mₓ, the data are described quite satisfactorily, we found that neither a chemical equilibrium model nor a statistical string fragmentation model of the initial hadronic abundances can explain the experimentally observed peaking at low momenta. This gives credence to more radical suggestions, such as the influence of chiral symmetry restoring effects at high temperature, the formation of cold plasma droplets, or the initial formation of the hadronic gas with a high positive π chemical potential. Perhaps experiments directed toward the measuring the relative abundance of the different hadrons can be informative.

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References