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Condensation effects in the pion spectrum at RHIC

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1. Bose–Einstein condensation (BEC) and multiparticle interference

BEC occurs because the density of bosons in excited states at given temperature $T = \beta^{-1}$ is bounded above by

$$\rho_e^{\max}(T) \;=\; \rho_e(T, z\!=\!1) \quad , \tag{1}$$

where

$$\rho_e(T, z) \;=\; \int_0^\infty dE\; g(E)\, f_{T,z}(E) \quad , \tag{2}$$

$$f_{T,z}(E) \;=\; \Big[z^{-1} \exp(\beta E) - 1 \Big]^{-1} \quad . \tag{3}$$

Here, the fugacity z (≤ 1) is related to the chemical potential by $z \equiv \exp \beta(\mu - E_0)$. The zero for the single particle energy E has been chosen at the value of the lowest energy level E_0, in the thermodynamic limit; $g(E)$ is the corresponding density of states. If the density ρ exceeds $\rho_e^{\max}(T)$, the ground state accepts the additional particles, and

$$\rho_0 \;=\; \rho - \rho_e \;=\; \frac{1}{V}\, \frac{z}{1-z}$$

becomes appreciable ($z = N_0/(N_0 + 1) \sim 1 - 1/N_0 \sim 1$). BEC is a momentum space effect.

Alternatively, for fixed ρ, BEC occurs for $T < T_c$, where T_c is the solution of $\rho = \rho_e^{\max}(T_c)$. The solid line in Fig. 1 shows T_c as a function of ρ, for ideal relativistic pions of one charge state in a large interaction volume. In this case condensation occurs when $\mu = m_\pi \equiv E_0$.

To orient Fig. 1 with respect to heavy ion collisions, consider first a rough estimate of pion densities at freeze–out. For the AGS, assume 300 like–sign pions per central event in Au+Au collisions [1], and a source radius of around 7 fm (from RQMD simulations [2]). For freeze-out at $T \sim m_\pi = 140$ MeV, the pion density is too small to lead to pion condensation (see circle in Fig. 1). The case for a possible effect in the AGS–regime is further obscured because of the high central baryon density, due to stopping [3], and a low Δ threshold. The nucleons act as "particle reservoir" throughout the collision process, and prevent a pion chemical potential from building up.

For RHIC–energies, estimates from the FRITIOF event generator (Au+Au) suggest that ~ 4000 pions per isospin state will be produced (assume isospin symmetry). If the source size were to scale linearly with the particle multiplicity, as has been suggested in the literature [4], then there is little probability for ρ to exceed $\rho_e^{\max}$ at freeze–out. However, recent measurements [5] and comparison to simulations [2] show that heavy ion collisions deviate quite drastically from a simple scaling law; present calculations indicate a 10–20 fm source radius. For $R = 10$ fm, and if the freeze–out temperature is independent of the incident energy, the square in Fig. 1 then represents the situation at RHIC: freeze–out occurs within the condensed phase. For $R = 20$ fm, the volume increases by a factor of 10, and one is back to AGS freeze–out densities.

Thus, RHIC may provide an environment in which Bose-Einstein condensation is possible. In the extreme case, the mean pion momentum depends only on the freeze–out radius, and is proportional to h/R. All pions are emitted coherently, and the momentum distribution of the pions is strongly peaked at low momenta.

Of course, the (dynamical) situation is somewhat more complicated [6]–[9]. In the initial stages of the re–hadronized phase the total pion number is large, but they will reside in resonances. Any excess pion density will probably be removed by inelastic processes, since the average collisional c.m. energy $\sqrt{s}$ (or "temperature") is high ($\pi\pi \rightarrow \rho$, $\rho\rho \rightarrow \pi\pi$, $\pi\pi \rightarrow K\bar{K}$, etc.). Thus, the pion chemical potential will be close to zero. Later on, as $\sqrt{s}$ drops below the inelastic thresholds, the pion gas possibly has a chance to build up significant chemical potentials. In fact, for an adiabatic expansion, $\mu \rightarrow m_\pi$, but a more rapid evolution would lead to partial thermalization with $\mu \lesssim 130$ MeV.

The pion spectra will thus be affected. The dotted line in Fig. 2 shows a pion momentum distribution

$$\frac{dN}{dp} \;=\; A\, 4\pi\, p^2 \left[\exp\{\beta(\sqrt{p^2 - m_\pi^2} \;-\; m_\pi)\} - 1\right]^{-1} \tag{4}$$

for $\mu = 0$, and $T = 150$ MeV.[1] This curve describes a typical Au+Au RHIC event as generated by FRITIOF rather well. For large $\mu \geq 100$ MeV, the momentum spectrum is significantly shifted toward lower momenta: the dashed curve in Fig. 2 assumes the extreme case of single pion condensation, $\mu \rightarrow m_\pi$. Fig. 3 shows the dependence of the mean transverse momentum on the chemical potential.

Near freeze–out, an additional effect, sometimes known as the "pion laser effect," will influence pion distributions. As suggested by Pratt [13], if pion densities come close to, or exceed, $\rho_e^{\max}$ at any stage during the hadronic evolution, multiparticle

[1] In this non–degenerate limit ($z \ll 1$), f is practically a Boltzmann distribution.

interference plays a role in particle emission. The average particle separation is close to the thermal wavelength, and n–body symmetrization becomes important. Various observables are affected, for example:

- the multiplicity of pions increases dramatically;
- pion emission is coherent with a very low $<p_T>$ that depends strongly on the source size;
- the two pion correlation function approaches 1 at the intercept, characteristic of a coherent state;
- large isospin fluctuations may develop (e.g. unusual π^0/π^+ ratios);

The overall result of this "laser" effect on the spectrum spectrum is comparable to doubling the low momentum component of the dashed curve in Fig. 2 (see solid curve), though this factor depends on dynamical details. Of course, other mechanisms may well contribute to low momentum pions, for example, resonance decays [10],[11], and in–medium dispersion relations [12]. The former mechanism is probably absent in the baryon–free central region expected at RHIC, but the latter will require detailed modeling to disentangle it from condensation and near–condensation effects. Regardless, a sizeable low p enhancement over the Boltzmann distribution may be expected at RHIC.[2]

[2]Charged pions will have an additional Coulomb repulsion effect, which might lead to a reversal of the condensation effect by broadening the momentum distribution, but this effect is rather small compared to the overall mean momentum reduction.

2. Detection of low momentum pions in STAR

There are two ways of measuring these:

- (a) search for very low momentum π^0, by detecting the photons (with energies around 70 MeV) emitted from their decay;
- (b) search for very low momentum charged π's with a very high resolution tracking device.

Method (a) is suited for a high resolution electromagnetic calorimeter, as suggested by the PHENIX collaboration; (b) is an ideal measurement for the SVT detector in STAR. Fig. 4a shows an event without BEC, generated in a 3^o cone around central rapidity for a central Au+Au collision at RHIC; Fig. 4b shows a "pion-laser" event (*i.e.*, with $\langle p_\perp \rangle = 60$ MeV/c) in the same phase space region.

A distinction between these events could be made on an event-by-event basis, but if the statistics in a single event is too small, an inclusive spectrum of the invariant pion cross section would also reveal the effect. In a sample of events a Bose-Einstein condensation would manifest itself in an unusually high low $p_\perp$ enhancement. Because there are several different explanations suggested for the existing low $p_\perp$ effect, a measurement of a inclusive cross section spectrum might not be unambiguous, though.

The SVT with its superior position resolution and its standalone tracking capability might allow one to detect the effect by identifying the particle and determining its momentum on an event by event basis in a central Au+Au collision at RHIC. Fig. 5 shows the momentum resolution for low momentum particles measured using the SVT alone.

The major caveat in doing such a high precision measurement with the SVT is the strong dependence of its performance on the $\langle p_\perp \rangle$ of the pions: In a momentum window from 40 to 60 MeV/c, no pions will reach the TPC, while no multiple hits from one track are recorded in the SVT. If the pion emission has an even lower mean momentum, the SVT tracking has to detect multiple hits emerging from the same helix. Tests of the specific software capabilities are underway.

A second source for concern is the high decay probability of the low momentum pions within the SVT. Table 1 shows the fraction of pions that do this, as a function of the $\langle p_\perp \rangle$ of the condensate.

A third restriction is imposed by the RHIC beampipe. Assuming the present design (1mm thickness Be-pipe) all pions with momentum less than 20 MeV/c do not pass through the beampipe. In principle, a distinction between a low–$\langle p_\perp \rangle$ event and a "normal" event could be made because only electrons and muons would be detected in the SVT in big numbers – the pions range out in the beampipe and their subsequent decays populate electron and muon channels.

$\langle p_\perp \rangle$	% of pions decaying in the SVT
40 MeV/c	40.9%
50 MeV/c	25.9%
60 MeV/c	15.9%
70 MeV/c	8.9%
80 MeV/c	3.9%
90 MeV/c	1.9%
100 MeV/c	0.9%

Table 1. Decay Probability

A summary of the caveats outlined above leads to the following picture:

- For a pion momentum of 20 MeV/c and less all pions range out in the beam pipe. A detection of the electron and muon decay particles could be tried in the SVT although the particle identification with subsequent momentum measurement is very vague.

- For a pion momentum between 20 MeV/c and 40 MeV/c the pions would penetrate the SVT layers partially. One is therefore left with a pion identification with considerable electron and muon background.

- Between 40 MeV/c and 80 MeV/c the pions penetrate the SVT and do not exhibit a long enough track in the TPC to be identifiable by the TPC alone. The helix curvature although makes the SVT measurement unambiguous.

- Above 80 MeV/c the integrated tracking system of TPC and SVT allows particle identification and momentum determination up to 600 MeV/c for pions.

By reviewing the general assumption of a RHIC source that is at least 7 fm and at most 40 fm in size, one concludes that a wide range of pion densities and average pion momenta is possible. It seems that for an event with true BEC one would have to deal with a partial penetration of the SVT. This would require identification by detection of charged pion decay products. Most of the electrons and muons emerging from the pion decay are low in energy so that their helix is not trackable in the TPC. Studies of the decay reconstruction are underway.

In any case, the detection of a big particle flux in the SVT with simultaneous detection of low particle density in the TPC will ensure proper selection of unusual events. This criterion could even be integrated into the STAR trigger concept. Only with a low momentum, high flux, high resolution tracking device, such as the SVT, a potential discovery of BE condensation into charged particles is possible.

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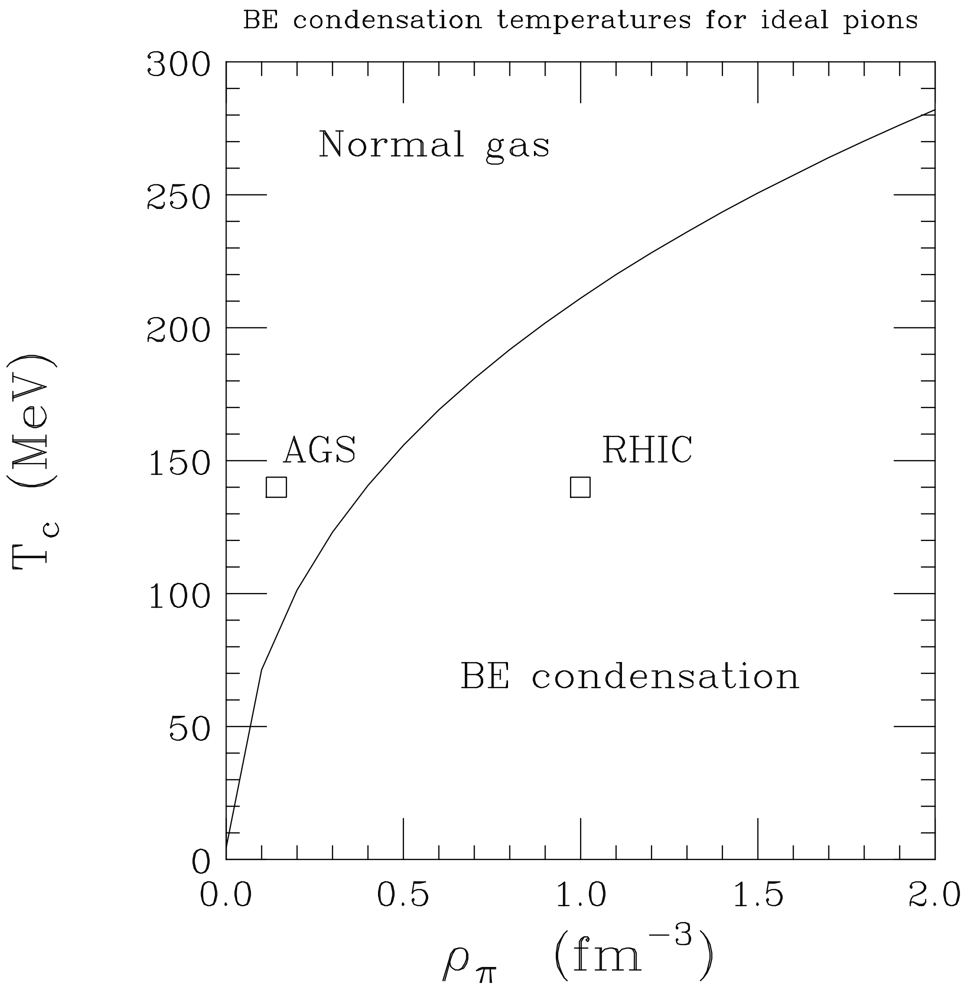

Fig. 1. *Critical temperature for ideal pion BEC as a function of density*

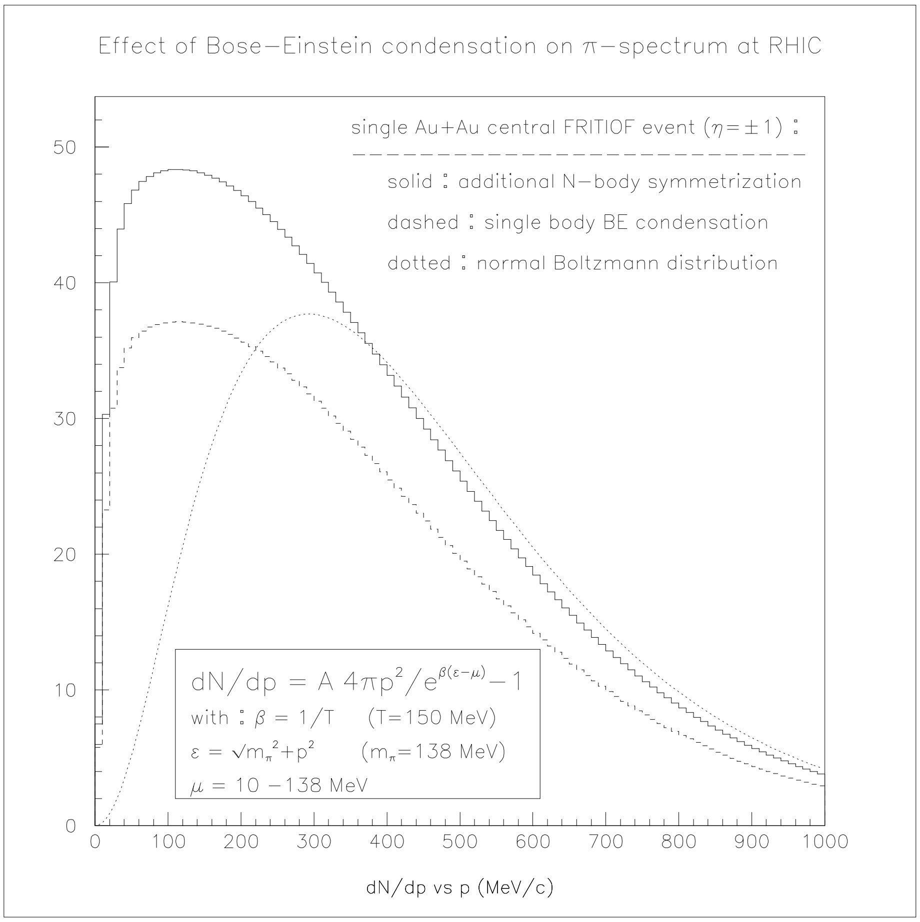

Fig. 2. *Effect of single body condensation and multibody symmetrization on the pion momentum spectrum*

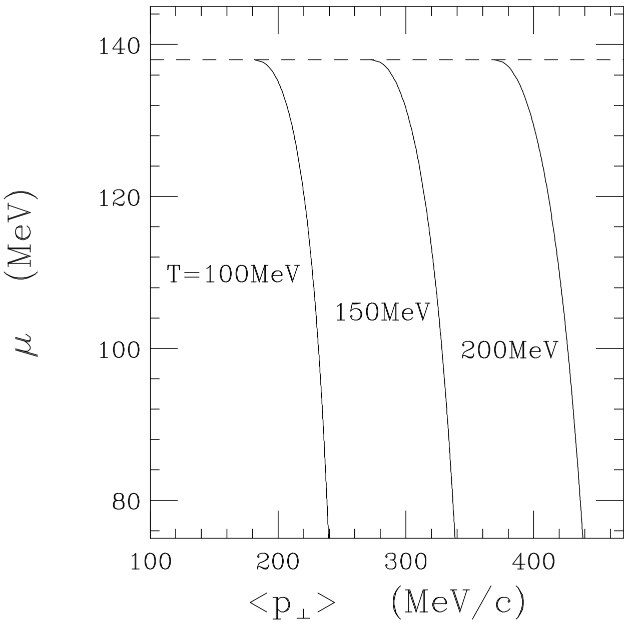

Fig. 3. *Chemical potential versus mean transverse momentum for ideal pions at three different temperatures*

Fig. 4. *(a) Normal Au+Au event, (b) Event with BEC*

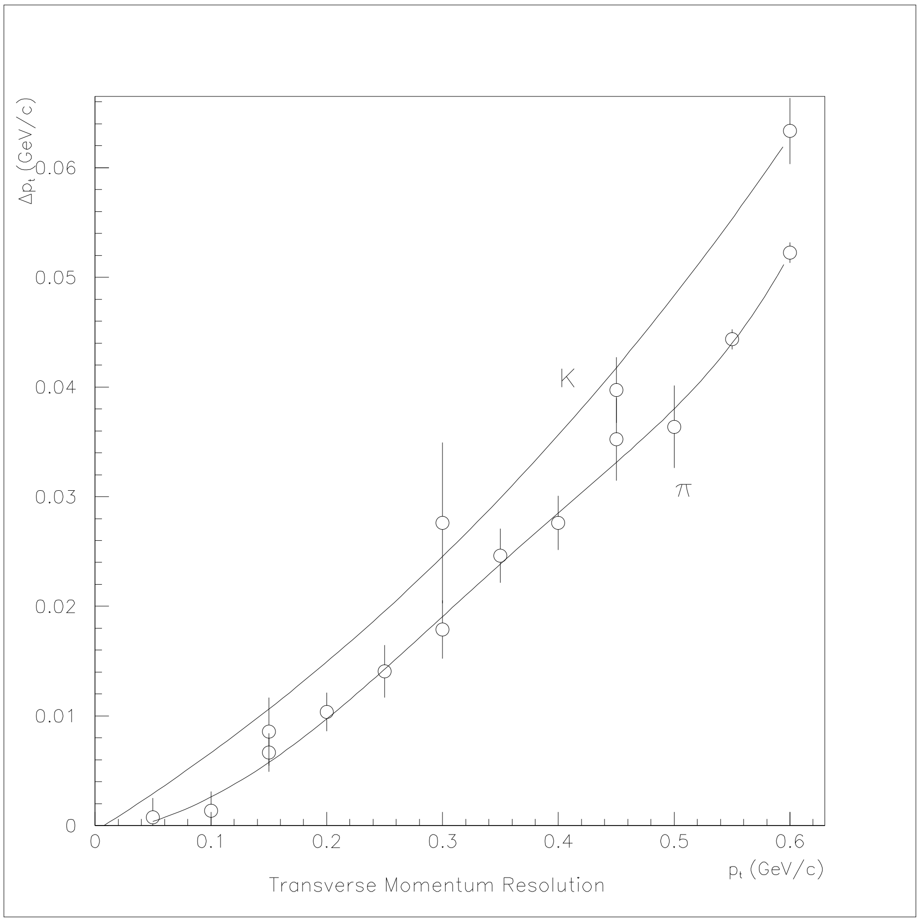

Fig. 5. *The momentum resolution of fitted pion and kaon tracks from thirteen events with MCS determined by the* $\bar{\chi}^2$ *of selected momentum bins from .05 to .7 GeV/c.*