Heavy ion collisions studied with BRAHMS at RHIC

C. E. Jørgensen[a] for the BRAHMS Collaboration

[a]Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

BRAHMS have measured yields of pions, kaons and protons as function of rapidity and transverse momentum in central Au+Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$. These measurements are interpreted using simple theoretical models and a qualitative picture of the collision dynamics is suggested.

1. Introduction

BRAHMS has the unique ability, among the RHIC experiments, to identify hadrons ($\pi^\pm, K^\pm, p$ and $\bar{p}$) over a wide range of rapidity and transverse momentum. This gives the opportunity to study the collision dynamics and draw a comprehensive picture of heavy ion collisions at RHIC energies.

In 2002 the BRAHMS experiment recorded a large sample of central Au+Au events at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$, the maximum RHIC energy. In the following the main results from this data run will be presented and interpreted. Only data from central (0-5%) collisions are shown. A description of the experimental setup and details on the analysis can be found in [1–3].

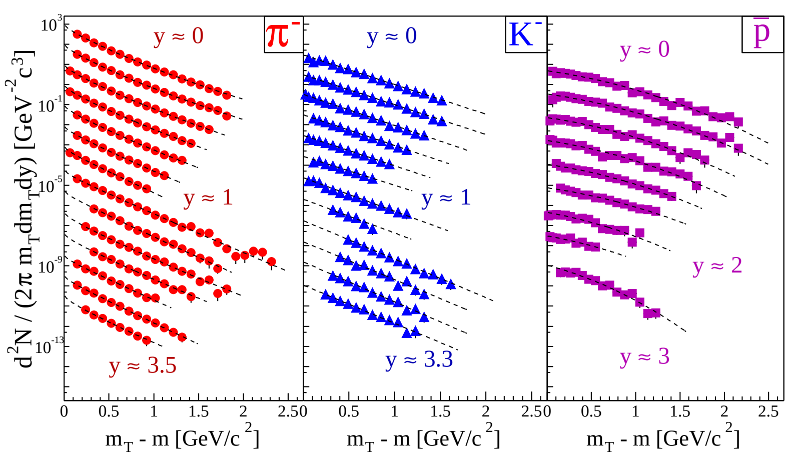

Figure 1. $m_T - m$ spectra for π^-, K^- and $\bar{p}$ for different rapidities. The dashed lines indicate the fits to the data (see text).

2. Kinetic freeze out

Figure 1 shows the inclusive transverse mass spectra of π^-, K^- and $\bar{p}$ at different rapidities. From this plot it is obvious that the shape of the spectra are different for the different particle species – the hardness of the spectra seems to follow the particle mass, which is also reflected in the mean transverse momentum of the particles (see lower panel in figure 2). The exact shape can been modeled by the so called blast wave models (see for example [4]). These models describes the source of particle emission as a thermalized system with a transverse radial collective expansion. At midrapidity preliminary results give a kinetic freeze out temperature of around 130 MeV and a flow velocity around 0.6cAt forward rapidities $y \approx 3$ the blast wave fits gives a lower flow velocity and a slightly higher temperature. A naive interpretation of this observation could be that the lower density at forward rapidity results in less radial flow and an earlier freeze out (at a slightly higher temperature).

3. Chemical freeze out

The particle yields as a function of rapidity can be obtained by fitting the m_T spectra by appropriate functions and then integrating over the full m_T range. Figure 2 shows the rapidity densities for the six particles species. The distribution for the positive and negative pions are almost identical. The protons become more abundant than the anti-protons as one goes to higher rapidities, i.e. as one gets into the fragmentation region where most of the baryons from the initial nuclei are situated. This is also reflected in excess of K^+ over K^- at forward rapidities. Here associated production ($p + p \to p + K^+ + \Lambda$) in the baryon rich environment creates K^+, while K^- are only produced in pairs with K^-.

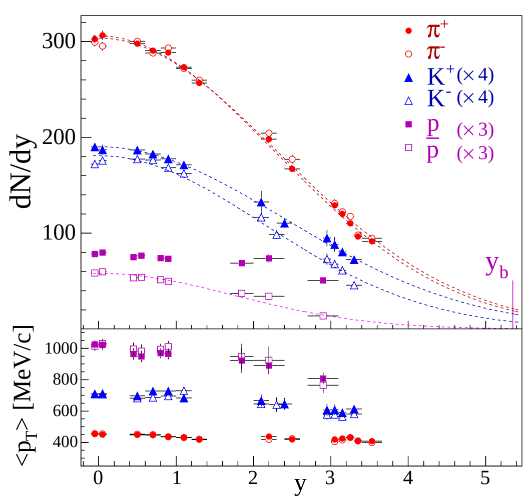

Figure 2: Pion and kaon rapidity densities (upper panel) and mean transverse momentum $\langle p_T \rangle$ (lower panel) as a function of rapidity. y_b is the beam rapidity at RHIC.

The particle abundances can be interpreted in terms of the statistical model (see for example [5]) assuming different sources at different rapidities. The model gives the temperature and the baryon chemical potential of the source at the chemical freeze out. If the temperature of the sources are kept constant ($T \approx 170 MeV$) the change in particle abundances translate into an increase in the baryon chemical potential from $\mu \approx 25 MeV$ at midrapidity to $\mu \approx 130 MeV$ at $y \approx 3$ [6].

4. Nuclear Stopping

How much of the original baryon kinetic energy is converted into particle production and transverse dynamics during the collision? This can be studied by measuring the net-proton rapidity distribution. If the protons are stopped in the collisions one would expect the proton rapidity density to peak around midrapidity, while if the protons only loose a fraction of their initial energy the rapidity distribution would have minimum around midrapidity and peaks closer to the rapidity of the beam.

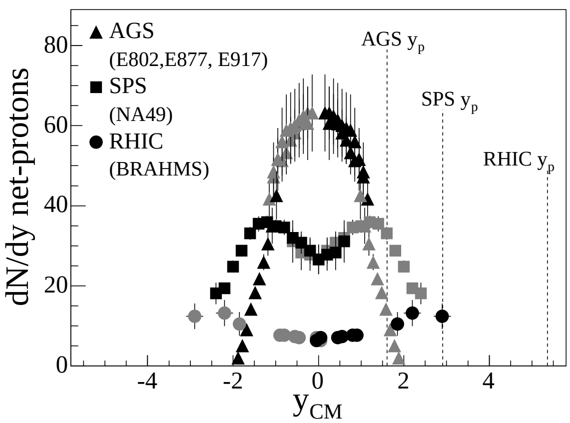

Figure 3. Net-proton rapidity densities for central heavy ion collisions at AGS, SPS and RHIC. The shapes of the distribution show that the collision evolution is very different for the different energies.

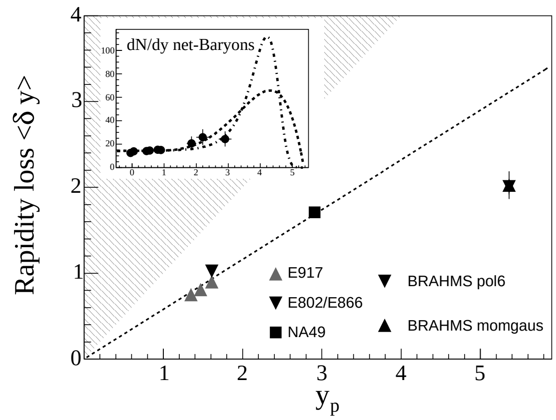

Figure 4. The rapidity scaling of the nuclear stopping δy observed at lower energies is broken at RHIC – in fact the stopping is not much higher than at SPS.

Figure 3 shows the net-proton distributions as function of rapidity for three different beam energies (at AGS, SPS and RHIC). The shape of the distributions are clearly different and shows that the collisions scenario is very different: there is a high degree of nuclear stopping at AGS, while at RHIC the collisions are more *transparent*. The stopping is often quantified as the mean rapidity loss of the baryons δy. From the net-proton distribution the net-baryon distribution has been estimated as described in ref. [2]. The full rapidity range is not covered by BRAHMS, but baryon number conservation strongly limits the behavior of the net-baryon distribution outside the coverage and limits on the nuclear stopping at RHIC can be determined. Figure 4 shows that the rapidity scaling of stopping ($\delta y = 0.58 \times y_{beam}$) observed at lower energies [7] is broken at RHIC. The stopping at RHIC is not much higher than at SPS – it therefore seems that at RHIC we are approaching a regime where the baryons loose approximately two units of rapidity independent of the beam energy. This was predicted by Bjorken in 1983 in his paper on the evolution of ultra relativistic heavy ion collisions: "...the net baryon number of the projectile is found in fragments of comparable momentum (more precisely within 2–3 units of rapidity of the source)." [9]. However, in the Bjorken scenario the midrapidity region should show a plateau-like behavior, with vanishing net-baryon density and flat particle rapidity distributions. Whether this is really fulfilled is subject to discussion. There is still approximately 15 net-baryons per unit rapidity around $y = 0$ and the rapidity distributions of pions and kaons are well described by gaussians.

Bjorken gave a recipe to calculate the initial energy density in the collisions (see ref [9]). This estimate for the energy density in central Au+Au collisions at RHIC gives $\epsilon \approx 5\,\mathrm{GeV/fm^3}$, which is around five times higher than the energy density estimated for quark gluon plasma creation [8].

5. Summary

Figure 5 shows a simple picture of the space time evolution of heavy ion collisions at this energy. The measurements presented here sheds light on the different stages in the collision evolution. The shape of the transverse mass spectra are fitted well by the blast wave model and indicates a thermal freeze-out temperature around 130 MeV and collective radial motion around half the speed of light – the kinetic freeze out happens on a timescale of around $t \approx 10\,\mathrm{fm/c}$ after the initial collisions. The statistical model also reproduces the data well and gives chemical freeze out temperatures and baryon chemical potentials on the border of the phase transition between hadron gas and quark gluon plasma as predicted by QCD lattice calculations ($t \approx 5\,\mathrm{fm/c}$).

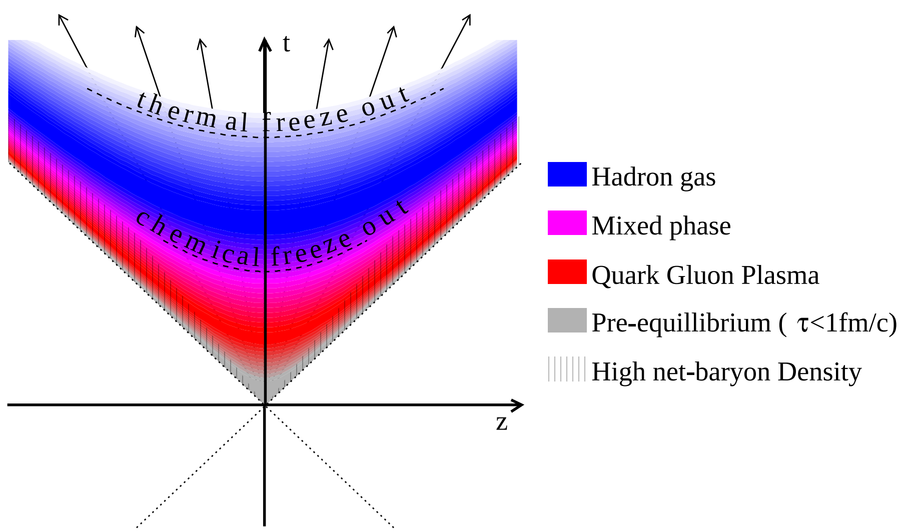

Figure 5. Schematic picture of the time evolution of a central heavy ion collision at RHIC energies.

The net baryon rapidity density shows that the initial baryons, or to be more precise the baryon number, is only shifted two units of rapidity and that the midrapidity region is almost net-baryon free – these conditions are reminiscent of the Bjorken scenario. Using Bjorkens estimate for the energy density in the early stages ($t \approx 1\,\mathrm{fm/c}$) of the collision one gets well above the limit for quark gluon plasma creation predicted by lattice QCD calculations. Recent theoretical work [10] suggests that quantum evolution effects (gluon saturation) sets in during the very early stages of the collision ($t << 1\,\mathrm{fm/c}$) – these effects are the evidence for a new state of matter named the Color Glass Condensate. The BRAHMS measurements related to the early stages of the collisions are presented and discussed in another contribution to this meeting [11].

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