# BRAHMS (EXPERIMENT) AT RHIC (COLLIDER)*

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*(Received February 1, 1999)*

The RHIC facility of Brookhaven National Laboratory will provide the physicists community with a powerful new tool. For more than five years, it will be the only place in the word for experimental studies of strongly interacting matter in a completely new regime. This accelerator will collide different ions from protons to heavy nuclei at c.m. energies up to 500 GeV for protons and 200 GeV per nucleon pairs for Au nuclei. Theory of strongly interacting matter reveals that at very high temperatures there will be a transition from hadronic matter to a plasma of deconfined quarks and gluons. Such phenomenon is also expected at high baryon density even at zero temperature. It is of special interest to investigate different regions of the phase diagram for expected formation of the quark-gluon plasma. Regardless of whether the quark-gluon state of matter will be convincingly discovered or not, it is important to understand the basic phenomena open for investigation in the RHIC energy domain. The BRAHMS experiment has been designed to gather information on momentum spectra and yields for various emitted hadrons as a function of transverse momenta and rapidity. Early phase of the BRAHMS research concerns several subjects which are crucial for understanding phenomena that occur in heavy ion collisions within this unexplored energy domain. Among them are: *(i)* reaction dynamics, *(ii)* mini-jet production, *(iii)* $\Phi$ meson production as quark–gluon plasma creation signature. The BRAHMS experiment will make a unique contribution to research of strongly interacting matter.

PACS numbers: 21.65.+f, 24.85.+p, 29.20.Mr

* Presented at the XXXIII Zakopane School of Physics, Zakopane, Poland, September 1–9, 1998.

## 1. Introduction

The study of ultrarelativistic nucleus–nucleus collisions is a new and rapidly evolving field. First experiments started in 1986 with light ions ($A \approx 30$) almost simultaneously in Brookhaven with the AGS ($E_{\rm beam} \approx 15$ GeV/nucleon) and at CERN with the SPS ($E_{\rm beam} = 200$ GeV/nucleon). Heavy ions ($A \approx 200$) are available in the AGS since 1992 and in the SPS since 1994. In these experiments collisions occur with a fixed target in the laboratory frame. Two new colliders are planned for acceleration of heavy ions to ultrarelativistic energies. The Large Hadron Collider (LHC) is constructed at CERN and is planed to begin operation in 2006. At this facility, the c.m. energy of colliding Pb nuclei will be 5.4 TeV per nucleon pair. The RHIC facility is under construction at BNL. It will provide nuclear physicists community with a powerful new tool for advancing study of strongly interacting matter in a completely new regime. This accelerator will collide different ions from protons to heavy nuclei at c.m. energies up to 500 GeV for protons and 200 GeV per nucleon pairs for Au nuclei. Experiments will begin in the fall of 1999.

The aim of high energy heavy ion physics is to study strongly interacting matter at extreme energy densities. Strongly interacting matter is described at the fundamental level through the interaction of quarks which exchange of gluons. This non-abelian gauge theory, called quantum chromodynamics (QCD), reveals a number of remarkable features. Most important for our discussion is that at very high temperatures, there will be a transition from hadronic matter to a plasma of deconfined quarks and gluons. It is expected that such transition exhibits a discontinuity, *i.e.* a phase transition. Numerical simulations of the lattice gauge theory have established the transition temperature to be in the range of $150 \pm 10$ MeV.

According to the standard cosmological model, temperature of the cosmic background radiation exceeded 200 MeV up to the $10\,\mu s$ after the Big Bang. The early universe was hence filled with the quark–gluon plasma, rather than hadrons. It is important to mention that according to some models a transition to the quark gluon phase is also expected at high enough baryon densities even at zero temperature. Estimated range of such critical densities is $4\rho_0 < \rho < 10\rho_0$, where $\rho_0$ is the ground state density of nuclear matter.

One of the most important goals of the heavy ion physics is to explore different regions of the phase diagram of nuclear matter and to investigate properties of nuclear matter at various temperatures and presures. It is of special interest of ultrarelativistic heavy ion physics to investigate the phase diagram regions for expected formation of the quark–gluon plasma. Extrapolation from present results indicates that the RHIC facility will rich all relevant conditions for expected quark–gluon plasma formation.

Each of the four experiments (BRAHMS, PHENIX, PHOBOS, STAR) [1] being constructed for RHIC will make a unique contribution to the search for and the investigation of the quark–gluon plasma. Detailed description of RHIC experiments are available elsewhere [1] and a brief comparison of these experiments is given in [2]. In the next Section, we will focus on the Broad RAnge Hadron Spectrometer (BRAHMS) experiment [3] which has been designed to gather basic information in heavy ion reactions on momentum spectra and yields for various emitted hadrons as a function of transverse momenta, $p_{\mathrm{t}}$, and rapidity, $y$.

## 2. Experimental set up

The BRAHMS experimental set up (see Fig. 1) is designed to measure inclusive and semi-inclusive charged hadrons ($\pi^{\pm}, K^{\pm}$ and $\mu^{\pm}$) over a wide range of pseudorapidity ($0 \leq \eta \leq 4$) and transverse momentum ($0.2 \leq p_{\mathrm{t}} \leq 3$) GeV/$c$ for all available beams and energies [3]. In addition, centrality of collisions is measured by a global multiplicity detector, and beam-beam counters provide the experiment with vertex determination. Extensive covering of the $y$ versus $p_{\mathrm{t}}$ space for charged particle measurements is a unique feature of the BRAHMS experiment. Design of the spectrometer comes from tracking criteria and the actual choice has been confirmed through extensive simulations.

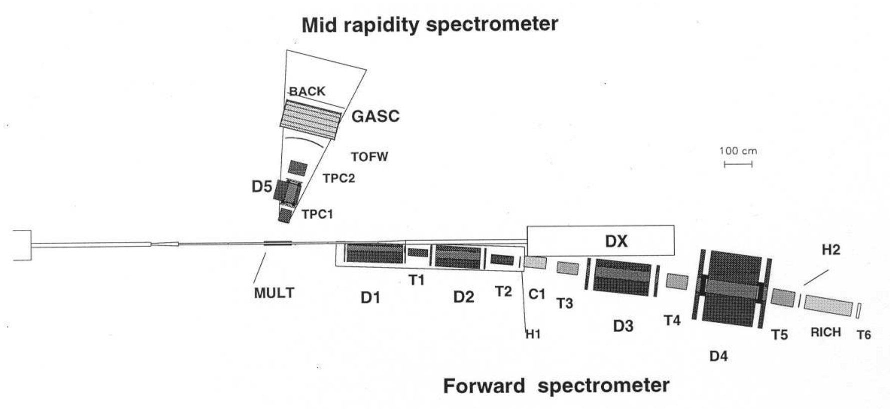


Fig. 1. BRAHMS experimental set up [3].

The BRAHMS has two movable magnetic spectrometers for charged particle measurements. The Forward Spectrometer (FS) will contain four magnets (D1–D4), for sweeping and analysing of primary particles emerging from the reaction vertex. The most forward setting (2.1°) is limited by the beam pipe and the FS can be moved up to 30° position. In order to bend 25 GeV/$c$ particles, the D1 magnet will supply a field up to 1.2 T. The FS will be operated in two different modes: *(i)* the high-momentum mode, *(ii)* the low-momentum mode. The high momentum forward going particles are swept by two dipoles (D1, D2) towards the back region of the spectrometer where they are tracked in several detectors. The particle momenta are obtained by the trajectory determinations and the confirmation that they have passed though another two dipoles (D3, D4). Each of tracking elements T1 and T2 will consist of a Time Projection Chamber (TPC), which provide a good three dimensional track identification and rejection of the background. Requirements for T1 are the most severe since it has to deal with estimated particle densities up to the order of 0.2 cm$^{-2}$. The tracking detectors T3–T5 will be conventional Multiplane Wire Drift Chambers (MWDC). The position of tracks are determined locally with accuracy better than 0.3 mm and their direction to better than 0.5 mrad.

The lower momentum part of the particle identification for the FS is based on two time-of-flight hodoscopes, H1 and H2. Each scintilator staff (H1 $\approx$ 40 and H2 $\approx$ 20 staves, respectively) will be instrumented with a fast photomultiplier at both ends, giving a time resolution of $\sigma < 75$ ps.

High momentum particles will be identified behind T2 using a conventional segmented Čerenkov tank (C1) and behind H2 using a ring-imaging Čerenkov detector (RICH) with $C_4F_{10}$ as a radiator gas.

The Mid Rapidity Spectrometer (MRS) is designed to cover an angular region from 30° up to 90° and to measure and identify particles in the range of momentum $0.2 < p < 5$ GeV/$c$. The MRS has a single dipole magnet D5 and covers of 8 msr solid angle. Since many particles detected behind the magnet arise from decays and secondaries, it is necessary to have tracking in front of the magnet. One of two Time Projection Chambers (TPC1) will be served for this purpose and a second (TPC2) will be placed behind the magnet. The time-of-flight detection will be done with an array of plastic scintilators (TOFW). High momentum particles will be identified using a pressurized gas Čerenkov threshold detector.

The acceptance of both spectrometers is displayed in Fig. 2.

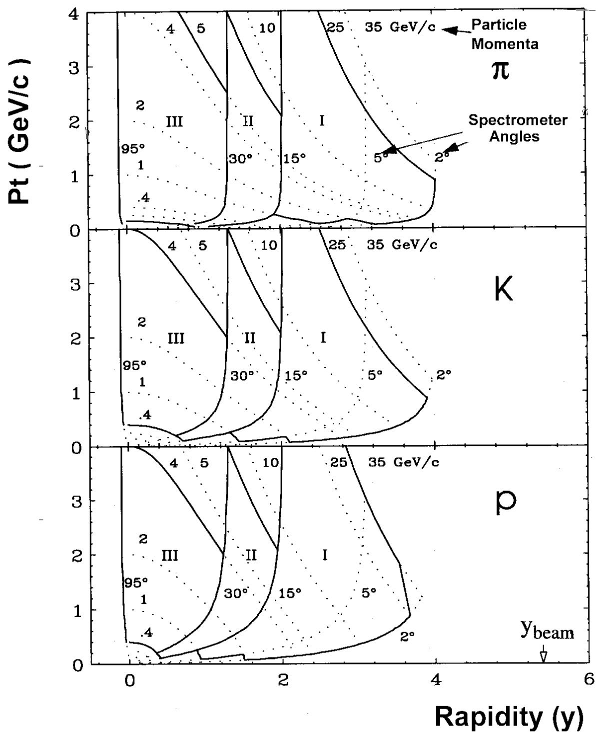


Fig. 2. Acceptance of the BRAHMS experiments. Region I is measured with the full forward arm, Region II with the D1-D2 part alone, and Region III with the MRS [3].

## 3. Physics overview

It has been stated in Sec. 1 that the quark–gluon plasma may be created in high energy nucleus–nucleus collisions under a broad range of conditions. A high net baryon density $(p - \overline{p} + n - \overline{n})$ and low temperature regime can be studied if the stopping of projectile results in high baryon density. This regime is now being studied in the heavy ion fixed target experiments at the AGS (BNL) and at the SPS (CERN). Creation of the baryon poor, high temperature plasma, requires of the collision energies far above the stopping regime. In this situation, the colliding nuclei pass through each other and the baryon rich regions will be close to the rapidity of the original nuclei. After nuclei passed through each other, a strong color field might be created in a space between them. It is anticipated that this color field is a result of the quark–gluon plasma creation with about an equal number of baryons and anti-baryons. The RHIC facility allows studies of both regimes. Namely, the baryon poor quark–gluon plasma will be investigated in the midrapidity region and the baryon rich plasma will be studied in the fragmentation regions of rapidity.

Regardless of whether the quark–gluon state of matter will be convincingly discovered or not, it is important to understand the basic conditions existing in the RHIC energy collisions in terms of energy and baryon densities, thermodynamics and hydrodynamics properties, hadronization *etc.*

Early phase of the BRAHMS research concerns three subjects which are crucial for understanding the phenomena that occur in heavy ion collisions at this unexplored energy domain (up to 200 GeV per nucleon pair).

- A first question concerns reaction dynamics and is related to such topics as stopping, chemical equilibrium and thermalization. The most basic information comes from the momentum spectra and yields of various emitted particles as a function of the transverse momentum, $p_{\mathrm{t}}$ and rapidity, $y$. The rapidity dependence of the spectral shapes reveal the reaction dynamics and the degree of thermalization attained. On the other hand, the particle yields as a function of $y$ are important indicators of densities obtained in the collisions and of the entropy production.

  The importance of these measurements can be justified investigating the model calculations of the net baryon density as a function of rapidity (see Fig. 3) [4]. The FRITIOF 1.7 model [5] predicts a flat, baryon poor region in midrapidity for central collisions at the RHIC energies. The peaks at $y = \pm 3.8$ are shifted by 1.6 units from the beam rapidity of $\pm 5.4$. The VENUS 4.02 code [6] applied for the same system gives dramatically different results from the FRITIOF, showing no baryon free region and smaller peaks at $y = \pm 2.6$. The higher stopping inherent in VENUS spreads the colliding baryons over the whole rapidity domain. Another result from the RQMD transport model [7], which also incorporates a string breaking scheme is in a better agreement with the VENUS results.

  Our discussion has shown the importance of the rapidity dependence of the baryon yield measurements. Equally strong arguments can be made for meson $p_{\mathrm{t}}$ distribution measurements over a wide range of rapidity. Furthermore, it is important to study these distributions as a function of mass of the colliding nuclei and the violence of collision. All these informations are critically sought to set constrains on the theoretical models and for understanding the basic physical conditions of the quark–gluon plasma creation.

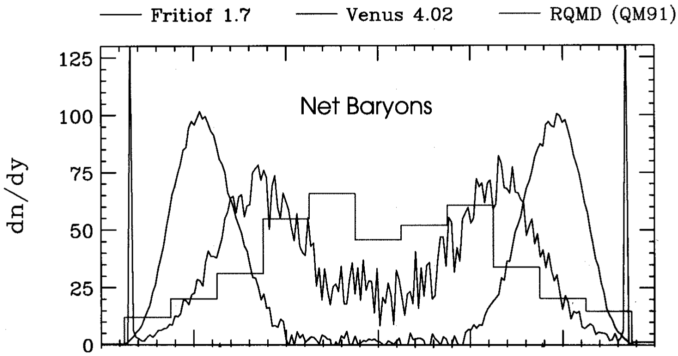


Fig. 3. Calculated rapidity density distributions for central Au+Au reactions [4]. Different models (see text) are indicated by the line-type.

- A second aim of the BRAHMS measurements is related to "mini-jet" particle productions. The mini-jet particles are produced in hard scatterings with $p_t \geq 2$ GeV/$c$ and are a probe of dense matter. The inclusive mini-jet distributions can be used to learn about such nuclear effects as jet quenching and gluon shadowing [8,9]. The HIJING model [8] combines the FRITIOF approach to the soft processes [5] and the PYTHIA [10] treatment of the perturbative QCD for hard processes with elements of the Dual Parton Model [11]. There are also alternative calculations, namely the Parton Cascade Model [12] with a cluster hadronization scheme [13]. Both of these models properly reproduce the data from $p+p$ and $p+\overline{p}$ reactions at RHIC energies [13,14]. Fig. 4 presents the calculated ratio of the invariant cross section at the midrapidity versus the transverse momentum for the Au +Au and $p+p$ collisions at the same beam energy per nucleon pair [15]. The model dependence of this ratio is striking and a great need for the experimental results is evident.

- Signatures of the quark–gluon plasma phase transition will be sought by all RHIC experiments. One of the potential signatures of quark–gluon plasma formation involves the measurement of $\Phi(1020)$ meson production in ultrarelativistic heavy ion collisions [16]. The chiral symmetry restoration might cause some modifications of the $\Phi$ mass width, since the low $p_t$ $\Phi$'s will decay inside the hadronic fireball. A study of the $p_t$ dependence of such effect, might constitute a signature of the quark–gluon plasma formation. The MRS, which has reasonable solid angle and good hadron identification, will be used to study $\Phi$ meson production dynamics via its decay to $K^+, K^-$.

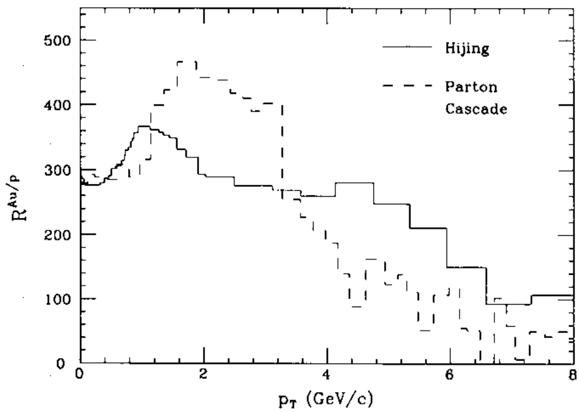


Fig. 4. The ratio of the calculated invariant cross section from central Au+Au to that of $p+p$ as a function of the transverse momentum [15]. The HIJING calculation are taken from Ref. [8] and the Parton Cascade Model calculation from Ref. [12].

## 4. Summary

For more than five years, the RHIC facility will be the only place in the word for experimental study of strongly interacting matter in a completely new regime. Different conditions, and therefore different physics, are expected to exist over the range of rapidities available there. The BRAHMS experiment with its wide range of rapidity and good charged hadron identification makes it a unique in investigation of strongly interacting matter.

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