Eur. Phys. J. A **18**, 515–519 (2003)
DOI 10.1140/epja/i2002-10273-7

THE EUROPEAN PHYSICAL JOURNAL A

Exploring superdense matter at RHIC

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Received: 30 September 2002 /
Published online: 22 October 2003 –

Abstract. I report first results on Au + Au collisions at $\sqrt{s} = 130$ GeV per nucleon pair from all four experiments at the Relativistic Heavy Ion Collider.

PACS. 25.75.Dw Particle and resonance production

1 Introduction

RHIC collides the heaviest possible ions at the highest possible energy to create matter at maximum temperature and density. These collisions should reproduce the conditions that existed in the first microseconds after big bang, where the distances among hadrons were much smaller than the size of the hadrons themselves. Such conditions probably still occur in the universe, at the core of neutron stars. Quantum chromodynamics indicates that under such extreme conditions quarks and gluons are no longer confined into hadrons, but rather exist as a plasma, with constituents free to roam over the entire volume of the hot matter. We seek to reproduce these conditions in the laboratory and study the properties of such matter. I will describe results from the first run of the Relativistic Heavy Ion Collider at Brookhaven National Laboratory. In 2000, gold ions were collided with each other at a center of mass energy of 130 GeV per nucleon pair. The 2001 run of RHIC reached 200 GeV per nucleon pair.

The QCD potential between quarks increases linearly in strength with the distance between quarks and confines them into hadrons. At high density and/or temperature, the color charges of the quarks are screened, decreasing the potential. At sufficiently high temperature/density, the potential at large distance vanishes altogether, and the system should undergo a phase transition to quark gluon plasma. It has been further proposed that the gluon density just after the nuclei collide could be so large that the gluon distribution is saturated.This happens if the wavefunctions of partons overlap sufficiently that the self-coupling gluons fuse. In effect, the gluons become weakly coupled and may be treated as a classical field. This would imply a different initial condition for the quark gluon plasma formation.

In the strongly coupled regime of the quark gluon plasma, QCD cannot be solved perturbatively, and calculations are carried out via simulation on a lattice. Recent progress in computational technology has allowed large-scale lattice simulations at high temperature. Karsch, Laermann and Peikert showed that the energy density of a 3 flavor system experiences a rapid rise when the temperature reaches 170 ± 10 MeV, characteristic of a phase transition [1]. The calculation indicates that experiments must achieve an energy density of 1–3 GeV/fm^3 to enter the quark gluon plasma regime.

Four complementary experiments have been carried out at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory in Upton, NY. Beams start in a Tandem Van de Graaf accelerator, then enter the Booster, Alternating Gradient Synchrotron, and finally RHIC. After filling, RHIC accelerates each beam to 100 GeV per nucleon, and then brings the beams into collision in up to 6 intersection regions around the ring. The design of RHIC is for luminosities of $2 \times 10^{26}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

There are two large and two smaller experiments currently running at RHIC. BRAHMS, one of the small experiments, consists of a pair of movable small-acceptance spectrometers with good particle identification capability. BRAHMS is optimized to sample the particle distributions over a wide range of longitudinal velocity. The other small experiment is PHOBOS, which employs highly granular silicon detectors to count all charged particles and measure the particle spectra at low momentum near the rapidity of the center of mass of the collision. PHOBOS also has hadron identification by time-of-flight. It is optimized to search for large distance phenomena and fluctuations in particle production. PHENIX is a large experiment optimized to measure leptons and photons to probe the early time of the collision via electromagnetically interacting probes. PHENIX has high rate capability and selective triggers to measure rare processes, in both electromagnetic and hadronic observables. STAR is the other large experiment and consists primarily of a large time projection chamber. STAR is optimized to have large acceptance for

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hadrons to study particle production and event-by-event fluctuations.

When two nuclei collide at RHIC, they are highly Lorentz contracted and the initial nucleon-nucleon collisions all take place in less than 1 fm/c. Nucleons undergo multiple collisions that do not factorize well in time, making theoretical description of the low-momentum-transfer processes very challenging; models of the collisions are crucial tools. At $\sqrt{s}$ of 130 or 200 GeV per nucleon pair, the collisions can probe parton distributions near $x = 10^{-2}$. At such short distances, the interactions that take place are necessarily at the partonic, rather than hadronic level. Large Q^2 processes are in the weakly coupled regime and may be calculated by perturbative QCD, with the collision probability given by nuclear structure functions. The large number of individual collisions gives rise to copious secondary particle production and a parton cascade results. Around 10^4 gluons, quarks and antiquarks are produced, and it is these produced partons which are expected to thermalize and form a quark gluon plasma.

The cascade of parton interactions is modeled using a cutoff separating "hard" from "soft" processes, handling the former perturbatively and the latter via string models of particle production (such as the Lund model). Thermalization on the timescale of 1 fm/c is predicted [2]. Of course, the thermalized system expands into the vacuum, cooling and eventually re-hadronizing. Experimentally, the challenge is to deal with many thousands of particles in the final state and identify observables which illuminate the underlying physics. I separate the observables into two classes.

One class of observables reflects the collision dynamics and addresses the extent of equilibration. Measures of collective behavior and the pressure generated in the collision fall into this class, along with hadron spectra and correlations which map the space-time evolution of the hadronic part of the collision. The other class of observables consists of probes of the early, hot phase of the collision. Such probes are particles produced early in the collision, which either do not interact with the hot, dense medium at all (such as thermal radiation) or which interact with the medium differently than with normal nuclear matter. These include fast quarks which lose energy depending on the density of scattering centers in a colored medium, charm quarks and antiquarks created by gluon fusion, the $c\bar{c}$ bound state J/ψ which can be dissolved by screening in a colored medium, and strange quarks formed more easily by a hot medium.

2 Thermodynamics of dense matter

It is important to first ascertain that the initial conditions at RHIC are in fact sufficient for creation of quark gluon plasma. This is generally addressed by measuring the number of produced particles and the energy flow perpendicular to the direction of the beams. At RHIC, over 5000 charged particles are formed in collisions of two gold nuclei at small impact parameter, *i.e.* in central collisions [3]. Compared to p-p collisions at the same $\sqrt{s}$, the number of charged particles produced per interacting nucleon pair is considerably higher. All four experiments find more than 3 charged particles per nucleon pair in central Au + Au, rather than the 2 seen in p-p.

Measurement of the energy flow transverse to the beam allows estimation of the energy density attained in the early phase of the collision, prior to expansion and cooling. PHENIX measured the transverse energy,

$$E_{\mathrm{T}} = \sum_i E_i \sin\theta_i \,,$$

where the sum runs over produced particles at mid-rapidity [4]. For central collisions at $\sqrt{s} = 130$ GeV per nucleon pair, E_{T} per unit rapidity equals 503±2 GeV. This can be used to estimate the energy density assuming longitudinal expansion at the speed of light, using Bjorken's formula

$$\epsilon_{\mathrm{Bj}} = \frac{1}{\pi R^2}\frac{1}{2c\tau_0}(2\frac{\mathrm{d}E_{\mathrm{T}}}{\mathrm{d}y})\,,$$

yielding $\epsilon \geq 4.6$ GeV/fm^3. This is 50% higher than previously observed and is comfortably above the threshold predicted by lattice QCD. The value has a significant uncertainty because the value of the parton formation time τ_0 is not well known. The value given here uses 1 fm/c, which is almost certainly an overestimate.

As many particles are produced in a rather small volume, one may expect that significant pressure is developed in the early stage of the collision. To quantify this experimentally, we need a "barometer" for heavy-ion collisions. Such a barometer is available by measuring collective "elliptic flow" of particles in each collision. The origin of the elliptic flow is the spatial anisotropy of the overlap region of two nuclei (this overlap region only approaches isotropy for the most central collisions). Extensive rescattering of the particles in the evolving system can translate the spatial anisotropy to a momentum space anisotropy as it is easier to emit particles in the thinner direction of the almond-shaped overlap region. The anisotropy is experimentally accessible by Fourier analysis of the azimuthal distribution of particles. One can identify in each event a preferred direction, which is aligned with the reaction plane, or direction of the impact parameter between the two nuclei. The second harmonic Fourier coefficient of the azimuthal distribution of particles with respect to the reaction plane, known as v_2 is used to quantify the collective elliptic flow. STAR showed that v_2 reaches 6% in semi-peripheral collisions of Au + Au [5], and the magnitude of v_2 is quite well reproduced by hydrodynamical models of the collision [6]. The other three experiments have confirmed this high value of v_2.

As hydrodynamics, by definition, treats the medium as fully equilibrated, its applicability to the early stage of the collision while the spatial anisotropy is still large implies early equilibration of the matter at RHIC. It should be noted that RHIC produces the highest-energy heavy-ion collisions so far, and this is the first time that hydrodynamics provides an accurate description of experimental observables.

Eventually the expansion cools the system below the critical temperature and the quark gluon plasma hadronizes. The thermodynamics of the hadron gas is studied via distributions of emitted hadrons in the final state. These reflect the temperature of the system when the hadrons cease to interact: the relative yields are fixed when the inelastic collisions stop (chemical freeze-out), and the spectra are determined later, at the time of kinetic freeze-out. The hydrodynamic flow affects the system during its entire thermal history. Hadrons are identified by time-of-flight (PHENIX, PHOBOS and BRAHMS) or energy loss in gas detectors (STAR and BRAHMS).

To evaluate the chemical freeze-out temperature, hadron yields from all four experiments are used. Braun-Munzinger, Magestro, Redlich and Stachel assumed emission of hadrons from a chemically and thermally equilibrated gas [7]. They fit the ratios of different hadron yields according to a Grand Canonical ensemble and extracted the temperature and baryo-chemical potential for central Au + Au collisions at RHIC. They found a baryo-chemical potential of 51 MeV, corresponding to a nearly, but not quite, *net* baryon-free gas at central rapidity. The observed antibaryon-to-baryon ratios near 1 at mid-rapidity confirm this [8]. The chemical freeze-out temperature of 175 MeV from their fit is surprisingly near that expected for the hadronization phase transition. This implies that the hadrons are created in chemical equilibrium from the plasma, and the expansion is so explosive that the hadrons decouple immediately, undergoing no inelastic collisions. This is in qualitative agreement with prediction of hydrodynamics, though the density at hadronization is predicted to be very large and one would naively expect *some* hadronic interactions to take place once the hadrons are formed.

The hydrodynamic models which reproduce the elliptic flow, v_2, indicate very rapid expansion [6,9], which should give rise to a collective radial expansion in addition to the observed elliptic flow. The radial expansion can be measured with spectra of hadron momenta transverse to the beam. In order to use hadrons of different masses, the spectra are plotted as a function of transverse mass, $m_{\mathrm{T}}^2 = p_{\mathrm{T}}^2 + m_0^2$. PHENIX [10], followed by BRHAMS, showed that the proton spectrum is flatter in m_{T} than the lighter mesons. Such a flattening would be expected if all particles receive a collective velocity boost, resulting in a larger momentum boost for the heavier hadrons. Fitting the observed pion, kaon, proton and antiproton spectra simultaneously, PHENIX found that they could be described by emission from a gas at 140–150 MeV temperature, expanding radially about the beam direction at a mean velocity of approximately half the speed of light. In peripheral collisions, the kinetic freeze-out temperature does not change much, but the radial flow is considerably less.

The large radial flow velocity causes the proton yield to nearly equal that of the pions at transverse momenta larger than approximately 2 GeV/c [10]. Such a "crossing" of the spectra has never been observed before, and impacts the interpretation of high-momentum particle production. It is noteworthy that the hydrodynamical calculations successfully reproduce the hadron spectra, including the cross of the baryon spectra over that of the mesons [6,9].

Another experimental observable sensitive to the expansion of the hadronic source is two-particle correlations. Identical pion pairs and identical kaon pairs, following Bose-Einstein statistics, experience final-state interactions that reflect the particle density and momentum distributions at freezeout. Thus the study of correlation functions of identical bosons is a further tool to understand the expansion dynamics. Both STAR [11] and PHENIX [12] have observed smaller apparent source radii and stronger dependence of the correlation on particle momentum than is expected from the above picture of an expanding hadron gas. It remains one of the mysteries at RHIC that hydrodynamics can explain single-hadron spectra and multi-hadron correlations, but fails to reproduce the observed two-hadron correlations.

3 Hard processes as early stage probes

We have already seen that there is copious production of particles and development of significant pressure early in the collision —these give rise to the observed radial and elliptic flows and indicate that high densities are achieved. There exists, however, a more direct probe of the early density and its effects on gluon transport by the medium. The probe is a high momentum quark or gluon, arising from hard scattering of partons in the initial nucleon collisions. These partons are scattered early, at a rate calculable by perturbative QCD, and traverse the hot, dense medium on their way out of the collision region. As they traverse the colored medium, these scattered partons radiate gluons, and the radiation rate is sensitive to the density of the medium [13,14]. There is a characteristic formation time, which depends on the transverse momentum of the radiated gluon. If the medium is sufficiently dense, the mean free path can be less than the distance the parton travels before the radiation is complete. In this case, the radiation becomes coherent, and the amount of energy radiated can change substantially. Radiation by partonic probes has observable effects as it decreases the production of high-p_{T} particles when the scattered parton fragments into a hadronic jet. The process is referred to as "jet quenching" and can be measured experimentally via the spectrum of leading high-p_{T} particles from jet fragmentation or by azimuthal correlations of the leading particle from each of the two hard-scattering partons.

Both PHENIX and STAR measured the hadron spectrum to large transverse momentum ($p_{\mathrm{T}} \approx 5$ GeV/c). PHENIX alone made three separate measurements of the spectrum of charged hadrons and of identified π^0's [15]. In all channels the observed spectra in peripheral collisions of Au + Au nuclei agree well with the spectrum predicted by folding individual p-p collisions by the number of binary nucleon-nucleon collisions corresponding to the selected centrality range. However, this is not the case in central collisions. The spectral shape is more exponential than the scaled p-p spectrum, and the observed yield is well below that expected by scaling individual p-p collisions by the approximately 900 binary nucleon-nucleon collisions corresponding to the most central 10% of $Au + Au$ collisions. The suppression is by a factor of 3–4 for π^0 and a factor of approximately 2 for charged hadrons.

Comparing the measurements at RHIC to those at lower energy at the SPS makes the observation even more striking. At the SPS, the yield in central $Pb + Pb$ was not only not suppressed, it was actually *enhanced* due to multiple scattering of the incoming partons in the nuclear medium prior to the hard scattering which sends them to large p_T. This initial state scattering, referred to as the "Cronin effect" is well known from p + nucleus collisions and should occur at RHIC as well. If so, the actual suppression of high-p_T hadrons is even larger than that inferred by comparing to scaled p-p collisions! We have investigated the importance of another known nuclear effect upon the parton distributions, namely nuclear shadowing. This occurs at small momentum fraction, x, in large nuclei, due to recombination of nearby partons from the overlapping parton clouds in neighboring nucleons. Moderate to large Q^2 processes at RHIC reach $x \approx 2 \times 10^{-2}$. However, data and calculations show that quark and gluon shadowing have less than 10% effect at these modestly small x values. Thus nuclear shadowing cannot explain the suppression, supporting its interpretation as a first observation of jet quenching.

We can understand the difference in the suppression of charged hadrons and identified neutral pions recalling the momentum boost for protons from the collective radial flow. The near parity of baryon or antibaryon yields and pion yields at 2 GeV/c leads one to expect a smaller suppression factor for all hadrons compared to just pions. This is because the boost applies to particles produced by "soft" processes, rather than those arising from jet fragmentation. These soft particles should not be sensitive to the hard-scattered parton energy loss. It would appear from the existing data that this is so. An important corollary is that the large hydrodynamic boost extends the p_T region where non-perturbative processes contribute substantially to the particle yields. This seems to be the case in $Au + Au$ collisions at RHIC for $p_T \leq 3$ GeV/c.

The data suggest that there is substantial energy loss by partons traversing the dense medium created in central $Au + Au$ collisions. This can be tested and quantified by comparison to model calculations. One such calculation has been made by X.N. Wang and co-workers, taking into account the expected nuclear shadowing and Cronin effects [16]. The data are best described by inclusion of an energy loss of 0.25 GeV/fm. This value seems rather low, and is in fact very close to that expected in cold nuclear matter. However, this is an average value over the lifetime of the medium, which is not at all static. Taking into account the rapid expansion of the medium, the data require an initial energy loss closer to 7 GeV/fm. This is large indeed.

Another probe of the medium is charmed quark production. The primary formation mechanism for charm and anti-charm quark pairs is gluon fusion. Thus the production rate should be sensitive to the gluon number and distribution and may be expected to increase in the presence of hot plasma with many gluons. Furthermore, spectroscopy of the bound $c\bar{c}$ states offers an excellent probe of the color screening capability of the medium.

By observation of single-electron production in $Au + Au$ collisions, PHENIX can measure the rate of open charm (D-meson) production [17]. Unambiguous identification of the few electrons among the many charged particles produced is technically very challenging, but PHENIX accomplishes this by use of a Ring Imaging Čerenkov Counter with photomultiplier tube readout, in concert with a very granular electromagnetic calorimeter. Electrons produce Čerenkov light, and their energy in the calorimeter should match the measured momentum. Comparison to a calculation of hadronic decay sources of electrons along with photon conversions in the detector material of PHENIX provides a measure of the D-meson production cross-section. The background calculation is tuned using measured hadron yields. The result shows that the charm yield matches very well that expected from cross-sections measured in p-p and p-antiproton collisions. Thus, there appears to be no enhancement of charm production, nor energy loss as observed for the light quarks. It may, of course, be that Mother Nature is very sly and the two effects happen to cancel exactly. But this is not extremely likely.

4 Conclusions

First results from RHIC have shown that the final state in central $Au + Au$ collisions consists of more than 5000 charged particles, and the energy density achieved early in the collision is well above the threshold predicted by Lattice QCD for deconfinement. High pressure is developed early in the collision, leading to a very significant collective elliptic flow. The fact that the system "remembers" the initial spatial asymmetry indicates that thermalization must occur rapidly. Chemical freeze-out of the hadrons from this system occurs near 170 MeV, which is also the temperature at which the transition back to hadrons is expected.

Hard processes with large momentum transfer at RHIC are important. They boost the number of produced particles and result in significant production of charmed quarks and scattered light quarks and gluons to probe the medium. A deficit of high-p_T particles from the fragmentation of these scattered partons is observed in central collisions, which may be the first indication of jet quenching. Charmed quarks are not suppressed, which could indicate that their larger mass suppresses collinear gluon radiation.

The second run at RHIC collected significantly more data, allowing measurements to higher transverse momenta, correlations among particles from jets, multi-strange baryon spectra, direct photon measurements and a first look at charmonium spectroscopy. Furthermore, the baseline physics in proton-proton collisions has been measured in the same detectors. Subsequent RHIC runs will provide proton-nucleus data to quantify nuclear effects and will then allow study of the volume and energy dependence of the collision dynamics and probes of the hottest, densest phase.

So, is there quark gluon plasma being made at RHIC? At this point there is not yet an unambiguous answer. However, the evidence for early thermalization, high temperature achieved, and energy loss by fast quarks suggest that there is indeed quark gluon plasma at RHIC. Proton-nucleus reference data is absolutely essential to demonstrate that these are indeed the correct interpretations of the data.

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