The Little Bang! Results from RHIC

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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. The energy density achieved is well above the threshold predicted by Lattice QCD for quark deconfinement. Large pressure is developed early in the collision, leading to collective asymmetric flow of the particle transverse to the beam energy and explosive expansion of the hot system. The hadron yields indicate presence of an equilibrated hadron gas in which the chemistry is fixed at a temperature near 170 MeV, which is also the temperature at which the quark gluon plasma to hadron phase transition is expected. A deficit of high transverse momentum particles is observed in central Au+Au collisions, compared to expected yields from independent nucleon-nucleon collisions or expectations from peripheral Au+Au collisions. This is likely the first indication of jet quenching by energy loss of hard scattered partons traversing the dense medium created in the collision.

I Introduction

The goal of experiments at RHIC is to collide 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 are thought to still occur in the current universe, at the core of neutron stars. Quantum chromodynamics postulates that under such extreme conditions the 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. It is of extreme interest to reproduce these conditions in the laboratory and study the properties of such matter. I will describe what is known about this kind of matter 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.

Quantum Chromodynamics (QCD), the theory of the strong interaction, yields a potential which increases linearly in strength with the distance between quarks. This strong attractive force is responsible for the confinement of quarks into baryons (3-quark bound states) and mesons (bound states of a quark and antiquark). In matter which is very dense or hot, or both, the color charges of the quarks become screened and the potential decreases. At sufficiently high temperature and/or density, the potential at large distance vanishes altogether, leading to the deconfinement of quarks.

In analogy to phase diagrams for everyday materials, one may sketch a phase diagram of hadronic matter. At low temperatures, below 8 MeV, and near normal nuclear matter density, one finds hadrons consisting primarily of nucleons bound into nuclei. As the temperature or density increases, the nucleons melt into a gas of hadrons - the initial nucleons along with pions, the main carriers of the inter-nucleon attractive force. If the temperature exceeds 150-200 MeV, or the density exceeds 5 times normal nuclear matter density, then the confinement of quarks and gluons into hadrons should vanish, and a phase transition to quark-gluon plasma take place. QCD predicts an additional phase transition, at low temperature but very high density. In the super-dense phase, the quarks and gluons behave as a color superconductor. This new phase is under intense theoretical investigation, but difficult to reach in the laboratory. It may, however, exist deep in the core of quark stars.

In order to identify the conditions required to create and study quark gluon plasma, we must reply upon theory. Unfortunately, in the strongly coupled regime of a quark-gluon plasma, QCD cannot be solved perturbatively, and calculations must be carried out by simulation on a lattice. Recent progress in computational technology has allowed large-scale lattice simulations of QCD at high temperature. Karsch, Laermann and Peikert showed that the energy density of a 3 flavor system shows a very rapid rise when the temperature reaches 170 ± 10 MeV. Exactly such a rise is characteristic of a phase transition. The calculation thus indicates that experiments must achieve an energy density of 1-3 GeV/fm^3 to enter the quark gluon plasma regime.

II Heavy ion collisions at RHIC

The experiments I will describe have been carried out at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory in Upton, NY. RHIC is actually a suite of accelerators, with beams starting in a Tandem Van de Graaf accelerator. When the beam reaches a few MeV per nucleon it is sent to the Booster, and then to the Alternating Gradient Synchrotron, with stripping of electrons from the beam atoms between each accelerator. Au beams reach more than 11 GeV per nucleon in the AGS, while lighter beams can be accelerated to somewhat higher energies. The AGS then sends beam pulses into the two rings of RHIC; upon entering RHIC the beam is fully stripped. 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 2×10^{26} cm^{-2} sec^{-1}.

Currently, four intersection regions are instrumented with a suite of complementary experiments built by international collaborations. There are two large and two smaller experiments. 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 is a "table-top" experiment (if you have a large table). PHOBOS 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, also in the hadronic sector. STAR is the other large experiment and consists primarily of a large time projection chamber. STAR is optimized to have large acceptance for 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. Because of the contraction, it is not possible to order the collisions in time, however, many of the collisions occur among nucleons already disturbed by an encounter with another nucleon. This makes theoretical description of the low momentum transfer processes very challenging, and the interactions are customarily studied with the aid of models, rather than directly calculated using QCD. At $\sqrt{s}$ of 130 or 200 GeV/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. Parton cascades can be modeled with the aid of 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). Parton cascade calculations predict thermalization on the timescale of 1 fm/c. Of course, the thermalized system then expands into the vacuum, cooling and passing through the phase transition back into hadrons.

III Initial conditions and dynamics of the collisions

Experimentally, the challenge at RHIC is to deal with many thousands of particles in the final state and identify and measure observables which illuminate the underlying physics. I separate the observables into two classes. One class of observables allows study of the collision dynamics and addresses to what extent the particles equilibrate. Measures of collective behavior and the pressure generated in the collision fall into this class. Hadron yields and spectra tell about the evolution of the system and properties later in the collision and thus also shed light upon the collision dynamics.

The other class of observables consists of probes of the early, hot phase of the collision. Such probes are particles which are created early in the collision and 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. Thermal radiation can be measured via direct photon emission or virtual photons decaying to oppositely charged lepton pairs; both of these interact only electromagnetically so are unaffected by strong interactions with the dense medium formed in the collision. Of course, there can be thermal radiation from a hot hadron gas as well, and this must be controlled if one is to detect the quark gluon plasma radiation. Probes of the dense medium itself 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. Strange quark production also tells about the early medium, as they which can be formed more easily in a hot medium if the temperature is near the strange quark mass.

Before studying medium effects on the probes, however, it is important to 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. 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. The increase can be ascribed to multiple successive collisions suffered by the nucleons in the overlap region between the two nuclei. As all of the produced particles come into existence in a volume roughly that of two nuclei, the density reached is much larger than normal nuclear matter density.

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,

$$E_T = \sum_i E_i sin\theta_i$$

where the sum runs over produced particles at mid-rapidity. For central collisions at $\sqrt{s} = 130$ GeV/nucleon pair, E_T per unit rapidity = 503 ± 2 GeV. This can be used to estimate the energy density assuming longitudinal expansion at the speed of light, using Bjorken's formula

$$\epsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{2c\tau_0}(2\frac{dE_T}{dy})$$

yielding $\epsilon \geq 4.6\text{GeV/fm}^3$. This is 50% higher than previously observed and is well 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.

First PHENIX, then PHOBOS studied the collision centrality dependence of the number of charged particles produced. Charged particle production increases, of course, as the impact parameter decreases and more nucleons are involved in the collision. However, the absolute number of particles is larger than that predicted by HIJING, an event generator incorporating parton cascading and energy loss of partons as they traverse the dense medium. The centrality dependence is stronger than expected from a model of gluon "saturation", or recombination when the gluon density becomes very large. Both of these comparisons are used to control model parameters; the disagreement is not large enough to rule out the basic physics assumptions they incorporate. It is quite common to decompose the particle yields into a component which scales with the number of nucleons participating in the collision and a component scaling with the number of binary nucleon-nucleon collisions. Though it is tempting to identify the collision scaling part of the yield with hard, or large Q^2 processes, such a two-component model is not quantitatively correct. Nevertheless, high momentum transfer processes are indeed important at RHIC energy.

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, and the magnitude of v_2 is quite well reproduced by hydrodynamical models of the collision. 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.

IV Thermodynamic properties

The thermal history of collisions at RHIC can be studied by two kinds of measurements. Both the quark gluon plasma phase and the hot hadron gas formed after cooling back through the phase transition can emit real and virtual photons. In the first case, the photons are emitted by quark-antiquark annihilations and quark-gluon Compton scattering. In a hadron gas, thermal radiation arises from hadronic collisions and annihilations. Furthermore, a large photon and lepton background comes from hadronic decays. Nevertheless, the photons can be measured, and interpreted as long as the hadron yields and momentum distributions are also measured to allow high precision subtraction of the hadronic backgrounds.

Later in the collision, as the hadron gas further expands and cools, its thermodynamic properties can be measured by studying the 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, when elastic collisions cease (kinetic freeze-out). The hydrodynamic flow - known to exist from measurement of elliptic flow - affects the system during its entire thermal history. Thus measurement of hadron spectra yields dynamical information as well as a snapshot of the system at kinetic freeze-out. 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. They fit the ratios of different hadron yields according to a Grand Canonical ensemble and extracted the temperature and baryo-chemical potential best matching the observed data in 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 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 a chemically equilibrated plasma, and that the expansion is so explosive that the hadrons decouple immediately and undergo 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.

Actual baryon yields have been reported by PHENIX and BRAHMS, and though the *net* baryon density is quite low, the actual number of protons and antiprotons at midrapidity is substantial. The rapidity density of protons is 28 in central Au+Au at $\sqrt{s} = 130$ GeV/nucleon pair, while it is 20 for antiprotons. The number of net baryons ($p-\overline{p}$) per participant nucleon is approximately 0.05, whereas it was 0.18 in lower energy collisions at the SPS, where the initial baryons from the interacting nuclei were more successfully transported to the center of mass rapidity. Of course, this required less change in the longitudinal velocity for the lower energy collisions. All experiments find that the antibaryon to baryon ratios approach one at RHIC; this is also the case for anticascades to cascades, as measured by STAR.

Strangeness production was predicted to be a possible signature of quark gluon plasma production, though the interpretation is complicated by the possibility of producing strange and anti-strange hadrons in a hot hadron gas. PHENIX has measured the K/π ratio in Au+Au collisions, and finds that both K^+/π^+ and K^-/π^- increase with collision centrality from a peripheral collision value of $\approx 10\%$ as seen also by UA5 in proton-antiproton collisions at similar $\sqrt{s}$. Both positive and negative ratios increase together with centrality to $\approx 15\%$, whereas they differ in central Pb+Pb collisions at $\sqrt{s} = 17$ GeV/A. At the lower energy, only K^+/π^+ increases with collision centrality; the difference between positive and negative kaons can be understood from the larger net baryon density in heavy ion collisions at lower energy.

The hydrodynamic models which reproduce the elliptic flow, v_2, indicate a very explosive expansion of the collision system. Such an explosion should give rise to a collective radial expansion in addition to the observed elliptic flow. The radial expansion can be measured by the spectrum 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, $m_T^2 = p_T^2 + m_0^2$. PHENIX and STAR, followed by BRHAMS, have shown that the proton spectrum is flatter in m_T than the lighter mesons. Such a flattening would be expected if all particles receive a common 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 the data can be described by emission from a gas at 140-150 MeV temperature, expanding radially about the beam direction with 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. 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 crossing of the baryon spectra over that of the mesons.

V Probes of the hottest, densest phase

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, with a radiation rate sensitive to the density of the medium. There is a characteristic formation time for the bremsstrahlung gluons, which depends on the transverse momentum of the radiated gluon. Thus, 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 increase substantially. Large energy 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 ($p_T \approx 5$ GeV/c). PHENIX alone made three separate measurements of the spectrum of charged hadrons and of identified π^0's. 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 that 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 yield of high momentum particles is suppressed 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.

It is important to understand the difference in the observed suppression between charged hadrons and identified neutral pions. This turns out not to be surprising, if we recall the effect of the momentum boost on protons from the substantial radial collective flow developed in the collision. 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 coworkers, taking into account the expected nuclear shadowing and Cronin effects. 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. 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 Cherenkov Counter with photomultiplier tube readout, in concert with a very granular electromagnetic calorimeter. Electrons produce Cherenkov light and energy which is measured in the calorimeter. Requiring Cherenkov light and that the measured energy matches the measured particle momentum yields a clean identification of electrons. 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 "excess" electron production. The background calculation is performed using the measured hadron yields as input, and the difference yields the D meson production cross section. The result shows that the charm yield matches very well that expected from cross sections measured in p-p and proton-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.

VI 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. Large 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.

The second run at RHIC collected significantly more data, allowing measurements to higher transverse momenta, correlations among particle from jets, multi-strange baryon spectra and a first look at charmonium spectroscopy. The baseline physics in proton-proton collisions has been measured in the very 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.