RELATIVISTIC HEAVY-ION COLLISIONS: RECENT RESULTS FROM RHIC

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High energy collisions of heavy nuclei at the Relativistic Heavy-Ion Collider permit the study of nuclear matter at extreme densities and temperatures. Selected experimental highlights from the early RHIC program are presented. Measurements of the total multiplicity in heavy-ion collisions show a surprising similarity to measurements in e^+e^- collisions after nuclear geometry is taken into account. RHIC has sufficient center-of-mass energy to use large transverse momentum particles and jets as a probe of the nuclear medium. Signatures of "jet quenching" due to radiative gluon energy loss of fast partons in a dense medium are observed for the first time at RHIC. In order to account for this energy loss, initial energy densities of 30-100 times normal nuclear matter density are required.

1. Introduction

Quantum Chromodynamics, the theory of the strong interaction, is predicted to have a rich phase diagram. At normal nuclear densities and at low temperature, quarks are confined in color-neutral mesons and baryons. At very high baryon densities and low temperatures, i.e. conditions that may be found in the interior of neutron stars, exotic states such as strange quark matter or color superconductors might be found. These high density, low temperature states are of astrophysical importance but are inaccessible in the laboratory.

At low baryon densities and high temperatures, QCD may have a phase transition to a quasi-deconfined state of quarks and gluons. This state is known as the Quark-Gluon plasma. Lattice QCD calculations predict that this phase transition occurs when the system reaches 150-170 MeV.[1]

RHIC was built to collide nuclei at ultra-relativistic energies. Such collisions may create an extended system with sufficient energy density and temperature for Quark-Gluon plasma formation. Nuclear collisions at lower energies (BNL/AGS and CERN/SPS) have shown novel collective phenomena associated with highly excited nuclear matter. Experimental results from Pb+Pb collisions at the SPS have shown that quark and gluon degrees of freedom are important during the early stages of the collision.[2] At SPS energies, however, the system probably spends insufficient time in the "Quark-Gluon Matter" phase to equilibrate. Hence these measurements do not allow for the investigation of the bulk properties of hot and dense QCD.

At RHIC, the system may live in a pre-hadronic phase for several fm/c, thereby raising the possibility that it can equilibrate in the Quark-Gluon plasma phase before hadronizing and disintegrating. I will review recent experimental results from RHIC, focusing on what they tell us about the existence of the Quark-Gluon plasma and the properties of such a state.

2. The Accelerator and the Experiments

The Relativistic Heavy-Ion Collider began taking data in the summer of 2000. The first collisions were of Gold nuclei at $\sqrt{s} = 56$ GeV, followed by the first scientific run with Au nuclei at $\sqrt{s} = 130$ GeV. The year 2001 saw full energy Au+Au collisions at $\sqrt{s} = 200$ GeV and the first proton-proton collisions at the same energy. The proton-proton program at RHIC is unique in that it is the first collider where protons can be longitudinally and transversely polarized in order to study the spin structure of the proton. The 2002-2003 RHIC run was devoted to understanding cold nuclear matter effects on particle production using d+Au collisions.

In a central (small impact parameter) Au+Au collision at RHIC, over 4000 charged particles are created.[3] No single experiment is able to fully measure and identify each of these particles on a event-by-event basis. Instead each of the four experimental collaborations focuses on a different subset of the possible measurements.

PHOBOS [4] is a table-top sized collection of silicon multiplicity detectors that specializes in counting the total multiplicity of particles produced over 4π on an event-by-event basis. A mid-rapidity spectrometer gives momentum information in a limited region of phase-space.

BRAHMS [5] uses two magnetic spectrometers to measure identified particle inclusive distributions over the largest possible rapidity range. In particular, the forward spectrometer of BRAHMS can be used to understand baryon stopping in these collisions.

STAR [6] is a large acceptance magnetic spectrometer that uses a large cylindrical Time-Projection Chamber to track particles over full azimuth for the near mid-rapidity region ($|\eta| < 1.5$). Particles are identified using topological decay or via smaller acceptance particle identification detectors (time-of-flight and Ring-Imaging Čerenkov).

PHENIX [7] focuses on rarer leptonic obervables as well as hadronic measurements over a moderately large kinematical range. Leptonic observables are identified at mid-rapidity using Ring-Imaging Čerenkovs and Electromagnetic Calorimeters, and muons are identified at forward rapidity using muon spectrometers.

The diversity of experimental approaches shows that the understanding of hot and dense nuclear matter requires a variety of different measurements, with no single measurement able to capture the complete picture.

3. Total Particle Multiplicities

In an ideal Quark-Gluon plasma, the effective degrees of freedom are quarks and gluons. Assuming a massless Stefan-Boltzmann ideal gas, the energy density ϵ of a system is given by,

$$\epsilon_{SB} = \frac{\pi^2}{30}(N_{bosons} + \frac{7}{8}N_{fermions})T^4. \tag{1}$$

In an idealized Quark-Gluon plasma with massless quarks, there are 3 (flavor) $\times$ 2 (spin) $\times$ 3 (color) $\times$ 2 (quark-antiquark) = 36 fermionic quark states and 8 (color) $\times$ 2 (spin) = 16 bosonic gluon states. In a pion gas there are only 3 bosonic degrees-of-freedom (a resonance gas will have more). Hence, an early prediction is that the Quark-Gluon plasma should have a much higher energy (entropy) density than a corresponding hadronic system at the same temperature. If the system evolves adiabatically, the initial partonic entropy is transfered to pionic entropy and Quark-Gluon plasma formation was predicted to enhance total particle production relative a non-QGP reference (i.e. proton-proton collisions).

The PHOBOS collaboration has measured the total multiplicity produced in Au+Au collisions at RHIC and compared these data to e^+e^- and $\bar{p}+p$ reference data. When making such a comparison, nuclear geometry must be taken into account. There are two natural scaling expectations for particle production in nucleus-nucleus collisions:

N_{part} total number of participating projectile and target nucleons; and

N_{binary} total number of inelastic nucleon-nucleon collisions.

The quantities are estimated by the RHIC collaborations using measured data and Glauber calculations.[8]

Figure 1 shows the charged multiplicity as a function of pseudo-rapidity in Au+Au, e^+e^- and $\bar{p}+p$ collision at similar $\sqrt{s}$.[9] In e^+e^- the rapidity density is measured along the thrust axis. In Au+Au collisions, the rapidity density is divided by the number of participating nucleon-nucleon pairs. A remarkable similarity is observed between e^+e^- and Au+Au (except perhaps at large pseudo-rapidity where the participating baryons may have some effect). The pseudo-rapidity density is lower for $\bar{p}+p$ compared to the other systems at the same center-of-mass energy.

Integrating these distributions, one obtains the total multiplicity. This is shown for the three systems as a function of $\sqrt{s}$ in Fig. 2. Above $\sqrt{s} \approx 20$ GeV, e^+e^- is very similar to Au+Au, while the total multiplicity produced in $\bar{p}+p$ is consistently lower. The discrepancy between e^+e^- and $\bar{p}+p$ has already been understood as a consequence of the "leading particle effect".[10] The total multiplicity is proportional to the energy available for particle production, so the energy carried by the spectator fragments must be subtracted to calculate $\sqrt{s}_{\rm eff}$ on and event-by-event basis. After accounting for the leading particle effect, there is a universal behavior in the the total multiplicity versus $\sqrt{s}_{\rm eff}$ in Au+Au, e^+e^- and $\bar{p}+p$ collisions.

If the total multiplicity is indeed proportional to the entropy, these results would indicate that in central Au+Au collisions there is no excess entropy pro-

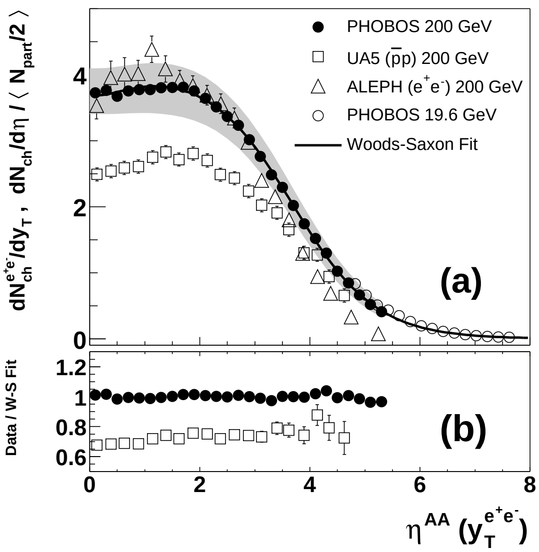

Figure 1. The charged particle pseudo-rapidity density as a function of η in central Au+Au, hadronic e^+e^-, and $\bar{p}$+p collisions.[9] For the Au+Au collisions, the pseudo-rapidity density is divided by the number of participating nucleon pairs. In e^+e^- the rapidity density along the thrust axis is plotted. The bottom panel shows the ratio of the data to the Woods-Saxon fit.

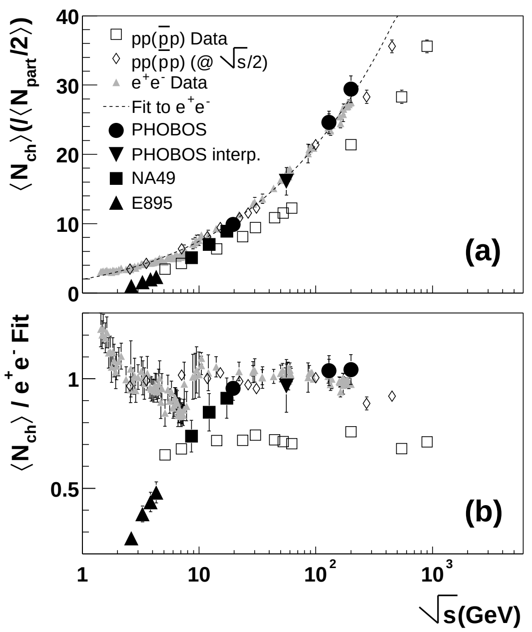

Figure 2. Top: Total charged multiplicity per participant pair in central Au+Au, e^+e^- and p+p($\bar{p}$) collisions as a function of the center-of-mass energy.[9] The p+$p(\bar{p})$ is shown at both the beam center-of-mass energy (open squares) and at $\sqrt{s}/2 \approx \sqrt{s}_{\rm eff}$ (open diamonds). Bottom: Ratio of data to the e^+e^- fit.

duction per participating nucleon-nucleon pair compared to simpler systems. This places severe constraints on the dynamical evolution of the system, in particular on whether the system is able to reach an ideal Quark-Gluon plasma at some point during its evolution. Other observables from RHIC point to a large amount of particle interactions and collective behavior that develops after the initial nucleus-nucleus collision.[11] Apparently, the total multiplicity produced in these collisions is unaffected by the complex dynamical evolution of the system.

4. "High" p_T Physics and "Jet Quenching"

RHIC is the first heavy-ion research facility that has sufficient center-of-mass energy to produce high E_T jets and other hard probes in numbers sufficient for detection. Jets, in particular, are thought to be a sensitive probe of the color-charge density of the medium through which the fast parton travels. A colored object passing through a colored medium may interact coherently with the colored fields.[12] This is the QCD analogue of the Landau-Pomeranchuk-Migdal effect observed in QED. This coherent interaction leads to much greater energy losses than would be expected from stochastic Bethe-Bloch type processes. As a result of the coherence there may be a non-linear dependence of the total energy loss on the path length of nuclear matter traversed. For the color-charge densities predicted in central RHIC collisions, effective energy losses of order 10 GeV/fm are possible.

Quantitative measurements of parton energy loss would allow extraction of the color-charge density of the system at the earliest, hot and dense phase. These densities can then be compared to theoretical estimates of the densities expected in the case of Quark-Gluon plasma formation. The observation of parton energy does not indicate either deconfinement or thermalization and is thus not directly related to Quark-Gluon plasma formation. Instead, parton energy loss is a powerful probe for ensuring that the necessary gluon densities for Quark-Gluon plasma formation are achieved in these collisions, and may be combined with other measurements to map out the time evolution of the system and phase diagram of nuclear matter.

Several experimental observables have been used at RHIC to study the propagation of fast partons in dense nuclear matter and look for signatures of parton energy loss. These observables include inclusive particle production at high p_T, two-particle correlations at high p_T, and the correlations between high p_T particle production and the impact parameter direction. Because of the large multiplicities in a central Au+Au collision at RHIC, full jet reconstruction is difficult if not impossible. Even if full jet reconstruction was possible, parton energy loss would redistribute the observed jet energy into lower momentum gluons and would thus not affect the total rate of jet production (i.e. energy loss is mostly an in-medium modification of the fragmentation function).

Measurement of inclusive particle production at moderate to high p_T (2-15 GeV/c) have been made by all four RHIC experiments. Inclusive high p_T particle production is sensitive to the leading particles produced in jet fragmentation. A softening of the in-medium fragmentation function (i.e. parton energy loss) will tend to reduce the number of produced high p_T particles. As mentioned in the previous section, particle production in nuclear collisions has two scaling expectations, N_{part} and N_{binary}. Since hard processes have very short associated time scales, each nucleon-nucleon collision occurs incoherently and the production of hard partons should scale with N_{binary}. Thus to measure the nuclear matter effects on high p_T particle production the nuclear modification factor R_{AA} is constructed,

$$R_{AA} = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta} \ , \qquad (2)$$

where T_{AA}=$\langle N_{binary}\rangle/\sigma^{NN}_{inel}$ from a Glauber calculation accounts for the nuclear collision geometry. In the absence of nuclear matter effects, R_{AA} should approach unity at moderate p_T (2−3 GeV/c).

Moderate to high p_T particle production in proton-nucleus collisions was studied extensively using fixed target experiments at Fermilab. It was found that there is an "anomalous nuclear enhancement" above p_T=2−3 GeV/c (also called the "Cronin effect").[13] This corresponds to $R_{pA} > 1$. This behavior has been understood qualitatively in terms of multiple soft parton interactions in addition to the hard parton scattering that leads to the production of high p_T particles. The recent deuteron-gold run at RHIC investigated whether the expected Cronin enhancement is still observed at the much larger RHIC center-of-mass energy, or whether other effects such as saturation of gluon parton distribution functions at low Bjorken-x would tend to suppress particle production at moderate to high p_T.

Figure 3 shows PHENIX results on the nuclear modification factor plotted as function of p_T for d+Au and Au+Au collisions.[14] The top panel shows R_{dA} (R_{AA}) for charged hadrons, and the bottom panel shows a comparison of R_{dA} for charged hadrons and π^0. For both charged hadrons and neutral pions, there is an enhancement above unity at high p_T in d+Au collisions. This is consistent with earlier Fermilab observations. Comparing the charged hadrons to the neutral pions, the nuclear enhancement is larger for charged hadrons. A similar effect was observed at Fermilab, with heavier particles (kaons and protons) showing larger high p_T enhancements in proton-nucleus collisions. This flavor dependence of the Cronin effect is not understood theoretically.

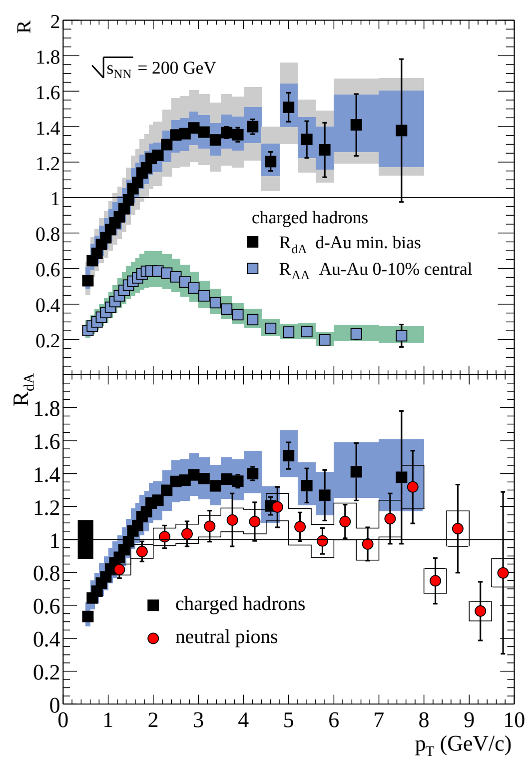

Figure 3. Nuclear modification factor as a function of p_T for charged hadrons and neutral pions as measured by the PHENIX collaboration.[14] The top panel compares d+Au and central Au+Au charged hadron measurements, while the bottom panel compares charged hadrons and neutral pions in d+Au collision.

The top panel compares the nuclear modification factor for d+Au and central Au+Au collisions. While the d+Au collisions show an enhancement, the Au+Au collisions show a dramatic deficit at high p_T compared to the binary collision scaled proton-proton reference. This suppression of high transverse momentum particle yields in central collisions of heavy nuclei was observed for the first time at RHIC.[15] Since this suppression is observed in central Au+Au collisions but not in d+Au collisions, it must be due to the interaction of partons or their fragmentation products with the matter produced in the collisions.

Both STAR and PHENIX have investigated the flavor dependence of the high p_T particle suppression.[16,17] Figure 4 shows the nuclear modification factor for Λ, K_s^0, charged kaons, and charged hadrons. In this case, the nuclear modification factor is the ratio of central (small impact parameter) and peripheral (large impact parameter) Au+Au collisions, with the number of binary collisions for each impact parameter calculated from the Glauber model. Here the baryons (PHENIX observes a similar effect for protons) show a rather different behavior compared to the lighter mesons. The Λ nuclear modification factor approaches unity at moderate p_T (2-4 GeV/c) but seems to have similar suppression as the kaons and charged hadrons at larger p_T.

Several scenarios have been proposed to describe this rather different behavior for baryons and mesons. In a quark coalescence picture, the moderate p_T baryons have a substantial contribution from processes where three quarks recombine to form a baryon. At larger p_T both the baryons and mesons are products of parton fragmentation. Another possibility is that the strong radial pressure gradients produced in a central RHIC collision accelerate soft baryons to moderate p_T ("radial flow"). This process is well established at lower transverse momentum, but the quantitative estimates of the contribution from this process vary. Finally, it has been noted that the anomalous nuclear enhancement observed in proton-nucleus collisions is larger for baryons compared to mesons. The same effect is being seen in nucleus-nucleus collisions and therefore may have the same hitherto unexplained origin. To disentangle the various scenarios for moderate p_T particle production in nucleus-nucleus collisions at RHIC, more experimental measurements are needed. These include

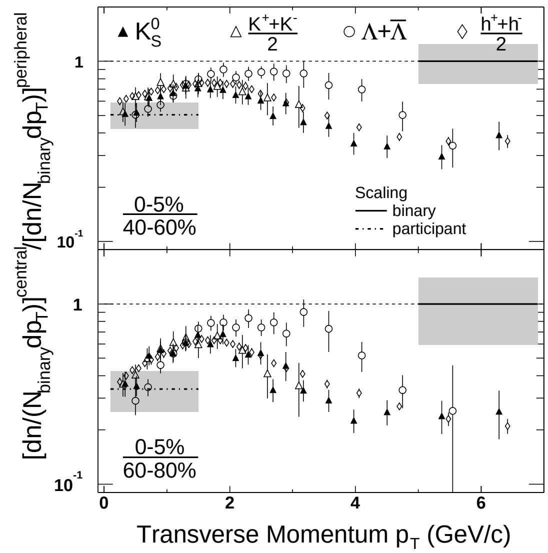

Figure 4. Nuclear modification factor for charged K, neutral K, and Λ as measured by the STAR collaboration.[17] The nuclear modification factor here is the ratio of central (0-5%) and peripheral (40-60% [top] 60-80 % [bottom]) Au+Au collisions.

a comparison of R_{AA} for heavy mesons and baryons to see if the lack of baryon suppression at moderate p_T is due to particle mass or quark content. Measurements of baryon and meson spectra in the d+Au collisions are also needed as the Fermilab measurements cannot be extrapolated to RHIC energies without a a theoretical model. The first such measurements show that the baryon excess at moderate p_T in central Au+Au collisions is not fully realized in d+Au collisions.[18]

The observed suppression of high p_T particle production is consistent with the predictions of jet quenching, but without direct evidence for jet production in nucleus-nucleus collisions it is difficult to draw any firm conclusions. Jets have been observed in e^+e^-, p+p, and proton-nucleus collisions, but had not been observed in previous experiments with nucleus-nucleus collisions due to insufficient center-of-mass energy. While full jet reconstruction is impossible in a central nucleus-nucleus collisions at RHIC energies, both STAR and PHENIX have presented evidence for jet production using two-particle correlations.[19,20]

Jets are characterized by a collimated spray of particles. In a typical jet finding algorithm, particle clusters are identified and the energy is summed to obtain the total jet (parton) energy. In rare cases, a parton fragments such that a single particle carries a large fraction of the energy. These are atypical jets, although they contribute a majority of the high p_T particles observed in a proton-proton collision. In other words, triggering on a leading particle selects a highly biased sample of jets. It is this highly biased jet sample that the RHIC experiments are able to study.

Figure 5 shows the relative azimuthal separation between moderate ($p_T > 2$ GeV/c) and high ($4 < p_T < 6$ GeV/c) transverse momentum charge hadrons in proton-proton, d+Au, and central Au+Au collisions.[21] The p+p measurements show the azimuthal correlations expected from jet production, i.e. a narrow correlation at small relative azimuth and a wider correlation at $\Delta\phi = \pi$ due to back-to-back dijet events. The relative azimuthal distribution looks quite similar to measurements made by UA1.[22] In d+Au collisions, a similar correlation structure is observed indicating the presence of jets and dijets.

The small relative azimuth correlations in central Au+Au collisions are nearly identical to those observed in p+p and Au+Au collisions. This is the first direct evidence of jet production in nucleus-nucleus collisions. Further tests, including the observation of charge-ordering between the trigger and next-to-leading charged hadron,[20] further support the hypothesis of jet production in nucleus-nucleus collisions.

The back-to-back correlations due to dijets, however, are absent in the most central nucleus-nucleus collisions. The back-to-back hadron pairs, however, are observed in peripheral Au+Au collisions.[20] Apparently, when a dijet pair is formed in a central Au+Au collision at RHIC it is highly unlikely that the fragmentation products of both jets escape. This is important additional evidence for the observation of jet quenching at RHIC.

Theoretical attempts to describe both the suppression of high p_T particle production and the absence of correlated back-to-back dihadron pairs require the existence of highly dense medium.[23,24] Early in the evolution of the system, the density must reach 30-100 times normal nuclear matter density ($\approx$ 5-15 GeV/fm^3). It is difficult to conceive of such a system in terms of hadrons, as the spacing between individual hadrons would be much smaller than the size of the hadrons. The existence of such

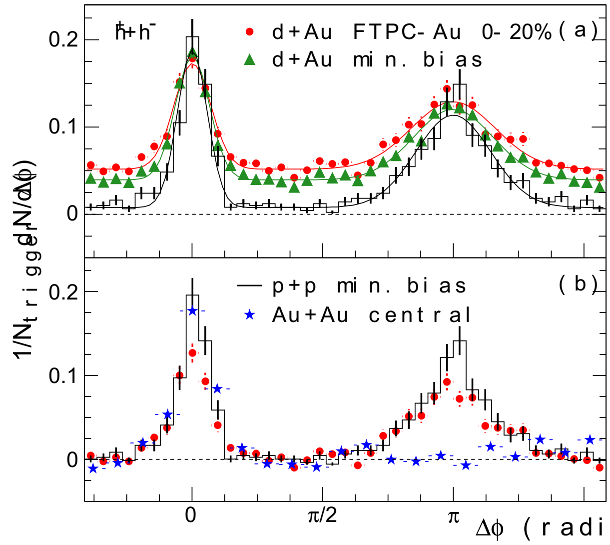

Figure 5. Per trigger particle relative azimuthal distributions in p+p, d+Au and Au+Au collisions measured by the STAR collaboration.[21] The top panel compares p+p and d+Au collisions, while the bottom panel compares p+p, d+Au and central Au+Au collisions with appropriate background subtraction applied to each distribution. The azimuthal distributions for both minimum bias and small impact parameter (FTPC-Au 0-20%) d+Au collisions are shown. The trigger hadron has $4 < p_T < 6$ GeV/c, and the associated hadrons have $p_T > 2$ GeV/c. The correlations from within the same jet are at $\Delta\phi \approx 0$, while the dijet-like correlated pairs have $\Delta\phi \approx \pi$.

a dense system in itself, however, is not proof of a Quark-Gluon plasma. In order to properly be called a Quark-Gluon plasma, the system must reach thermal equilibrium in a high density phase, and show thermodynamic parameters consistent with a collection of deconfined, weakly-interacting quarks and gluons.

5. Conclusions and Outlook

This talk focused on only two of the many interesting results to come from RHIC so far. Studies of particle production in Au+Au collisions at RHIC show a surprising universality in the total multiplicity compared to simpler systems (e^+e^- and p+p) once nuclear geometry is taken into account. This similarity suggests that the number of particles produced in any high energy collision is governed only by the total energy available for particle production. In the case of heavy-ion collisions, particles (or partons) interact many times leading to strong dynamical correlations and collective motion. These interactions, however, do not seem to affect the total particle production.

The other novel observation from RHIC is the first observation of a strong nuclear suppression of high p_T particle production in central Au+Au collisions. The data show a factor of ≈ 5 suppression of single inclusive high p_T yields in central Au+Au collisions compared to the binary collision scaling expectation. In addition, there is an absence of back-to-back high p_T hadron pairs. To explain these observations, very high initial energy densities are required.

Whether or not these energy densities lead to the production of a thermalized Quark-Gluon plasma is an open question requiring other experimental signatures and theoretical investigations. The early experimental results have established that the system produced in Au+Au collisions at RHIC spends some time at densities above the predicted energy density for the phase transition and that there are early interactions among the particles. Whether these interactions can lead to an equilibrated system in the Quark-Gluon plasma phase is uncertain. Hydrodynamical models that assume early equilibration and a QGP equation of state have been quite successful in describing much of the RHIC data,[25] but the success of these models does not constitute proof of equilibration or allow unambiguous determination of the equation of state.

In addition, the current data are unable to constrain the temperature of the system during its early hottest phase, or to even answer when, in the evolution of the system, temperature becomes a well defined quantity. In order to constrain the temperature, leptonic obervables may be used. The dissociation of J/Ψ is thought to be highly temperature dependent and future high luminosity RHIC runs will measure J/Ψ yields with sufficient precision to constrain the temperature. There is also hope that photon or virtual photon (dilepton) radiation directly from the early hottest phase can be measured. By correlating measurements sensitive to the temperature, energy density, and pressure, it may be possible to map out the equation of state of hot nuclear matter and make quantitative measurements of the bulk thermodynamic properties of QCD. Future experimental programs at RHIC the LHC will accomplish this goal.

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References

1. For a recent review see F. Karsch and E. Laermann, hep-lat/0305025.
2. U. Heinz and M. Jacob, nucl-th/0002042.
3. I.G. Bearden *et al.*, *Phys. Rev. Lett.* **88**, 202301 (2002).
4. B.B. Back *et al.*, *Nucl. Instrum. Meth.* A **499**, 603 (2003).
5. M. Adamczyk *et al.*, *Nucl. Instrum. Meth.* A **499**, 437 (2003).
6. K.H. Ackermann *et al.*, *Nucl. Instrum. Meth.* A **499**, 624 (2003).
7. K. Adcox *et al.*, *Nucl. Instrum. Meth.* A **499**, 469 (2003).
8. B.B. Back *et al.*, *Phys. Rev.* C **65**, 031901(R) (2002); K. Adcox *et al.*, *Phys. Rev. Lett.* **86**, 3500 (2001); I.G. Bearden *et al.*, *Phys. Lett.* B **523**, 227 (2001); C. Adler *et al.*, *Phys. Rev. Lett.* **89**, 202301 (2002).
9. B.B. Back *et al.*, nucl-ex/0301017.
10. M. Basile *et al.*, *Phys. Lett.* B **92**, 367 (1980); M. Basile *et al.*, *Phys. Lett.* B **95**, 311 (1980).
11. C. Adler *et al.*, *Phys. Rev. Lett.* **87**, 182301 (2001); K. Adcox *et al.*, nucl-ex/0307010.
12. R. Baier, D. Schiff, and B.G. Zakharov, *Annu. Rev. Nucl. Part. Sci.* **50**, 37 (2000).
13. D. Antreasyan *et al.*, *Phys. Rev.* D **19**, 764 (1979).
14. S.S. Adler *et al.*, *Phys. Rev. Lett.* **91**, 072303 (2003).
15. K. Adcox *et al.*,*Phys. Rev. Lett.* **88**, 022301 (2002); C. Adler *et al.*, *Phys. Rev. Lett.* **89**, 202301 (2002).
16. S.S. Adler *et al.*, *Phys. Rev. Lett.* **91**, 172301 (2003).
17. J. Adams *et al.*, nucl-ex/0306007.
18. J. Adams *et al.*, nucl-ex/0309012.
19. M. Chiu *et al.*, *Nucl. Phys.* A **715**, 761c (2003).
20. C. Adler *et al.*, *Phys. Rev. Lett.* **90**, 082302 (2003).
21. J. Adams *et al.*, *Phys. Rev. Lett.* **91**, 072304 (2003).
22. G. Arnison *et al.*, *Phys. Lett.* B **118**, 173 (1982).
23. T. Hirano and Y. Nara, *Phys. Rev. Lett.* **91**, 082301 (2003).
24. X.N. Wang, nucl-th/0305010.
25. For a review see nucl-th/0305084.

DISCUSSION

Enrico Predazzi (University of Torino): Coming to the question you raised about the analogies between multiplicities in e^+e^-, in p+p and in nucleus+nucleus collisions. As you mentioned, this is related to the leading particle effect, and we have proven long ago that this effect is a consequence of unitarity, or if you prefer of diffraction. So there is no surprise that the two results are similar, even so they come from so widely different initial states. The dynamics of Au+Au is washed away, and whatever remains is just basically diffraction. But we can talk later if you prefer.

David Hardtke: You know there is a great industry of applying saturation models to RHIC multiplicities, and saturation models are one way of enforcing unitarity. So this might not be a surprise, but based on initial predictions of massive entropy production it is a bit of a surprise to me. We need some theorists to sit down and figure out why there is this universality in particle production.

David Christian (Fermilab): One of the early indications from AGS and SPS was real enhanced strangeness production. Can you comment on measurements of strangeness production in the various experiments?

David Hardtke: The current understanding of strangeness production is the following. The idea was that if you have a Quark-Gluon plasma you lower the energy threshold for strange quark production to the same as that for light quarks and you produce much strangeness. At the end we came to the conclusion that in fact strangeness is not enhanced in heavy-ion collisions. It is actually suppressed in p+p collisions, because there are a lot of statistical models of particle production. So people applied canonical and grand canonical formulations to particle production, and what they found is that the p+p collisions are described well by a canonical ensemble, whereas A+A collisions are described well by a grand canonical ensemble. So when you go from a canonical ensemble to a grand canonical ensemble you tend to increase the production of rare stuff like strangeness. So basically what you see in p+p collisions is a canonical suppression of strangeness, and we think that in A+A collisions you just go into the true vacuum value of strangeness production. So it's no longer such a good direct signature of Quark-Gluon plasma, based on recent theoretical work.

Tord Ekdoef (Uppsala University): It appears to me as if, unlike a few years ago, you don't have a predicted evidence or signal of Quark-Gluon plasma. Is this correct?

David Hardtke: There are many predicted signals, but whenever we measure one some theorist comes a long and says: "Aha, but it is not a predicted signal!" The problem is that it is very difficult to distinguish between very high density hadronic matter and very high density quark and gluon matter. From the theoretical standpoint they basically look the same. So signatures such as J/ψ production, jet quenching etc. are all just sensitive to the very high density of quarks and gluons, but you don't know if they are combined in hadrons or free quarks and gluons. So there is no specific signature that can tell us which one we have, but the hope is that by correlating different signatures that are sensitive to energy, temperature, etc.. you can put enough constraints to finally eliminate the purely hadronic model. Most people believe that we have a Quark-Gluon plasma, but there is not a single definitive experiment that can prove it.