Title
QUARK MATTER '87: CONCLUDING REMARKS

Author
Gyulassy, M.

Publication Date
1988-03-01

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Presented at the Quark Matter '87 Conference,
Nordkirchen, West Germany, August 24–28, 1987

Quark Matter '87: Concluding Remarks

M. Gyulassy

March 1988

NUCLEAR SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-24768

Quark Matter '87: Concluding Remarks

M. Gyulassy

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

March 1988

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

LBL-24768

Quark Matter '87: Concluding Remarks*

M. Gyulassy
Nuclear Science Division
Lawrence Berkeley Laboratory

Abstract

This year marked the beginning of the experimental program at BNL and CERN to probe the properties of ultra dense hadronic matter and to search for the quark-gluon plasma phase of matter. Possible implications of the preliminary findings are discussed. Problems needing further theoretical and experimental study are pointed out.

1 Introduction

After nearly a decade of planning and preparing[1,2], light ions beams , O^{16} and S^{32}, were successfully accelerated for the first time to 15 AGeV (GeV per projectile nucleon) at the AGS at BNL and to 60 and 200 AGeV at the SPS at CERN in 1986. Several major experimental collaborations were ready with extensive calorimeter and multiplicity arrays, a streamer chamber, hadron and dimuon spectrometers, and a variety of emulsion and plastic detectors. Their long range goal is to produce and diagnose ultra dense hadronic matter and to search for its transition into the quark gluon plasma phase predicted by QCD. Amazingly, most of the experiments worked and the first detailed data on a wide range of observables were recorded. To celebrate the birth of experimental heavy ion physics at ultrarelativistic energies and to look for the first hints of the production of ultra dense matter, over three hundred nuclear and particle physicists from around the world met in Nordkirchen, Germany in August 1987 for the sixth international conference on ultra-relativistic nuclear collisions: Quark Matter '87. Before this year, only a handful of spectacular cosmic ray emulsion events[3] whet the appetites of both theorists and experimentalists. At this meeting such a large volume of new data was presented at a high baud rate that it will take quite some time to digest even a fraction of the findings.

Given the preliminary status of the data, it is especially important to refrain from drawing strong conclusions at this time. Nuclear collisions are obviously very complex involving hundreds of produced particles with many elements of the reaction mechanisms not fully understood. In addition, the experimental devices are complex and the multiparticle acceptances and systematic errors will take some time understand. Only after a careful systematic study of many observables as a function of projectile and target A and of beam energy can we expect a clear picture to emerge. It would be equally foolish to state that we did or we did not see the quark gluon plasma at this time.

What we did see at Quark Matter '87 were impressive measurements[4]-[9] of transverse energy and multiplicity distributions over many decades of cross section. Emulsion studies[10,11] revealed the shape and energy dependence pseudorapidity distributions. We saw how the entire target nucleus explodes in the wake of the 3.2 TeV O projectile[7]. The first $\pi^-\pi^-$ interferometry analysis[12] found possible indications of unusually large transverse radii and proper times as well as anomalous degrees of coherence. We saw evidence for possible small deviations of transverse momentum distributions of pions[5] and photons[7] in comparisons between $O + A$ and $p + p$. We were also presented with two observations that suggest that ultra dense hadronic matter may have been produced even in such light ion reactions. The most provocative observation, reported by NA38[13], was that J/ψ production seems to be suppressed by $\sim 30\%$ in high E_T events. The second provocative result was E802's observation[8] that the K^+/π^+ ratio seems to be enhanced by a factor ~ 2 in a certain kinematical domains relative to pp reactions.

While the correct interpretation of the above observations remains to be worked out, we survey in this report some of the possible implications along with unresolved theoretical and experimental issues. In section 2, we discuss basic "bread and butter" topics associated with (a) initial conditions (b) extrapolations from pp to AB (c) space-time geometry (d) transverse flow and (e) nuclear stopping power. In section 3, we discuss the "provocative" results on (a) J/ψ suppression and (b) K^+ distillation. In section 4, we highlight some of the important theoretical issues discussed at the meeting. A few closing remarks are presented in section 5.

2 Basics

2.1 Initial Conditions

The first question that we need to address is what were the likely initial conditions in these light ion reactions. What initial energy densities may have been reached? How close did we get to the plasma threshold?

In two ideal cases, we can estimate the initial energy density using[2]

$$\epsilon_0 \gtrsim \begin{cases} (E_{lab}/m_N)\epsilon_{n.m.} & \text{Landau stopping domain} \\ dE_\perp/dy(\tau_0 \pi R^2)^{-1} & \text{Bjorken scaling domain} \end{cases} \tag{1}$$

where $\epsilon_{n.m} = 0.15\text{GeV/Fm}^3$ is normal nuclear density and R is the radius of the lighter ion. The Landau estimate follows from application of the Rankine-Hugoniot shock equations. They are relevant only if the nuclear stopping power is large enough to convert the ordered beam energy into random thermal energy in the center of mass. If we define the nuclear stopping power, $\Delta y_B(A)$, as the mean rapidity shift of the leading baryon in pA collisions, then the Landau shock estimates apply only at "low" energies where the rapidity gap, $\Delta Y = \ln(E_{lab} + p_{lab})/m$, is sufficiently small, i.e. for nuclear collisions $A_P + A_T$,

$$\Delta Y < \Delta y_B(A_P) + \Delta y_B(A_T) \approx 2 + \alpha^{-1}(R_P/\lambda + R_T/\lambda - 2) \ , \tag{2}$$

where[14] $\alpha \approx 3 \pm 1$ is the empirical stopping parameter from $pA \to pX$ studies, and $\lambda \approx 2$ fm is the inelastic mean free path. For higher energies, the baryons in the two nuclei cannot stop each other in a single fireball and a large fraction of the energy will be tied up in longitudinal motion. For $O+Pb$ the stopping domain could extend up to $\Delta Y \sim 4$ ($E_{lab} \sim 30$ AGeV) in small impact parameter (central) collisions. This lower energy stopping domain is of interest primarily because in addition to high energy densities, nuclear matter may also be compressed to very high baryon densities, $\rho \sim (2-4)\gamma_{cm}\rho_0 \sim 10\rho_0$.

At much higher energies, on the other hand, a central region is expected to form involving very high energy densities but low baryon densities. A clean central region requires a rapidity gap that exceed the width, $\Delta y_F(A_P) + \Delta y_F(A_T)$ of the fragmentation regions. Recalling the classic estimate in [15]

$$\Delta y_F(A) \approx \ln(2R_A/\tau_0) \ . \tag{3}$$

where $\tau_0 \sim 0.5 - 1$ fm/c is the formation proper time, a clean central region for $O + Pb$ would emerge only when the rapidity gap exceeded 6 units, i.e., $E_{lab} > 200$ AGeV.

The above familiar estimates underscore that the current energies 15-200 AGeV are intermediate in the sense that they probably lie above the simple Landau shock domain and below the simple Bjorken scaling domain. Thus the use of either formula is at best qualitative. Nevertheless, blind application of the Landau estimate at the AGS would imply that central $O+Pb$ may achieve $\epsilon_0 \sim 2\text{GeV/Fm}^3$ at 15 AGeV. Applying the Bjorken estimate to 200 AGeV on the other hand, including the newly measured[4,5,7] maximum value of $dE_\perp/dy$:

$$(dE_\perp/dy)^{max}_{O+Pb} \approx 60 \pm 10\text{GeV}$$

and using $\tau_0 \approx 1$ fm/c leads also to $\epsilon_0 \sim 2\text{GeV/Fm}^3$. While in both cases "interesting" energy densities may have been reached, both are likely to be overestimates since we ignored the finite thickness of the shock front in the Landau estimate and the finite nuclear thickness at intermediate energies in the Bjorken estimate. Furthermore, in both cases, the rapid longitudinal expansion cools the system to moderate energy densities, $\lesssim 1\text{GeV/Fm}^3$, after a very short time ~ 1 fm/c. We should also not forget that O^{16} is essentially all surface so that densities fall off rapidly in the transverse direction. Therefore, a conservative estimate of the energy densities explored in the present experiments is $\epsilon_0 \approx 1$ GeV/Fm^3, i.e., on the order of seven times the energy density in ordinary nuclei.

It is important to contrast these estimates to those expected with heavy ion beams and or much higher energies. With Pb+Pb in the stopping domain, we also expect[16] shocked matter at $\epsilon_0 \sim 2$ AGeV but in that case lasting several fm/c. At RHIC, on the other hand, we expect[2] 10 GeV/Fm^3 in central Pb+Pb. The study the low baryon density quark-gluon plasma phase will thus have to await RHIC. With light ions at the AGS and SPS we may get only a fleeting glimpse into the plasma phase assuming[2] that the threshold of the pure plasma phase stays around a few GeV/Fm^3 (see [17] for a complete review of present lattice QCD results).

2.2 Extrapolations from p+p to A+B

Of course, the detectors see only the final asymptotic fragments from the reactions. Consider, for example, the final charged multiplicity that has been measured by WA80[7] to exceed 400 and the negative pion rapidity density[5] measured to exceed ~ 40 in central $O+Au$ at 200 AGeV. Are these numbers larger or smaller than expected, do they scale with target A and energy as expected, are the shapes of the distributions understood? To answer these questions we need to know first what linear extrapolations from pp phenomenology would give. Fortunately, at the previous Quark Matter meeting[2] the foundations for such comparisons were laid in the extension of phenomenological models of multiparticle production such as LUND[20] and the Dual Parton Model[22] to nuclear collisions. Since that time, variety of event generators have become available to allow almost on-line model comparisons with data.

Reduced to its simplest essence, these models can be classified as "wounded nucleon string" models, where the number of interactions are calculated via classical Glauber (Eikonal) geometry and interactions are assumed to lead to excitations of the nucleons into string-like configurations[18]. Each nucleon emerges as an excited quark-diquark string, characterized by its light cone momenta $E^\pm = E \pm p_z$. The invariant mass $M = (E^+E^-)^{\frac{1}{2}}$ is distributed roughly as dM/M up to a maximum $M_{max} \sim \sqrt{s}$. Because of time dilation, the strings fragment into hadrons only on a long time scale. Thus, in these models string excitation and fragmentation are treated as two independent processes. The fragmentation scheme is adjusted to fit the properties of pp data. Basically this constrains the fragmentation scheme so that a string with a given $E^{\pm}$ fragments into hadrons distributed with limited $p_{\perp} \sim 0.4$ GeV/c over a finite rapidity interval

$$y_{min} = \ln m/E^{-} \lesssim y \lesssim y_{max} = \ln E^{+}/m \ .$$

Details of course vary between different models. However, the basic expectation in these models is that while pp collisions involve the formation and fragmentation of two strings, central ($b < \pi(R_B - R_A)^2$) $A + B$ involve a total number of wounded nucleon strings given by

$$W_{AB}(0) \approx A + B(1 - (1 - (A/B)^{2/3})^{3/2}) \text{ for } A < B \ . \quad (4)$$

The above estimate neglects diffuse nuclear surfaces but is adequate to display the expected scaling of multiplicities and transverse energies for central collisions as a function of A and B. For a heavy target, Au ($B = 197$), this simple geometrical formula can be approximated to $\sim 10\%$ by

$$W_{A+Au}(0) \approx 11A^{2/3} \quad (5)$$

for all A from p to Au. In particular the ratio of multiplicities and transverse energies for $S^{32} + Au$ to $O^{16} + Au$ is expected to be $2^{2/3} \approx 1.6$ in accord with preliminary NA34 and WA80 data[19,7]. For $O + B$ the observed scaling[7] of the multiplicity, transverse energy, and central rapidity density for B=63,108,197 follows (4) to better than 20%. Thus, the gross features of the data are well understood and provide us with added confidence in the theoretical extrapolations to heavier ion collisions.

To study the detailed rapidity dependence of the observables, exact kinematics and trigger conditions must be taken into account. The current Monte-Carlo exclusive event generators are ideal for such analyses. The great advantage of this type of approach is that (1) energy momentum and quantum numbers are conserved exactly, (2) the physical hadronic resonance spectrum together with known decay branching processes are included, (3) the parameters and prescription are tuned to provide a good representation of pp data, (4) because exclusive events are generated it is possible to incorporate the effects complex multiparticle acceptances of the various experiments, and (5) these models can form the input to future transport models incorporating final state cascading of hadrons. These advantages are well known and indispensable already in $e^{+}e^{-}$ and hadron phenomenology. Thus these wounded nucleon string Monte Carlo models provide the best baseline to which the new data can be compared, especially at present intermediate energies. The hope is that new physics can be identified from systematic deviations of data from such baselines.

However, it is important to keep in mind that there is no model independent extrapolation from pp physics to AB physics and that present data on pp are not sufficient to constrain all aspects of exclusive multiparticle production in these models even at the pp level. Thus there exists an intrinsic theoretical uncertainty in the baseline calculations that is difficult to estimate. In particular, in successful models of AB collisions, the average string mass after several collisions is significantly higher than in pp collisions. If we tried to enforce a strict wounded nucleon model by limiting the mass of all strings to be the same as in pp reactions, then the results[24,28] would underestimate the multiplicities and E_T in $O + Au$ by $\sim 50\%$. A similar analysis[8] at the AGS came to the same conclusion. Thus the results are sensitive to untested assumptions on how the string mass increases with multiple collisions. In the LUND Fritiof model[20,21], for example, the mass of projectile strings increases from ~ 6 GeV in the first interaction to ~ 12 GeV after five interactions (see Fig.5 ref.[24]).

The freedom to vary the multiple excitation mechanism of strings represents one of the main sources of theoretical uncertainty in assessing the significance of deviations of data from such baseline calculations at this time.

The only practical way to estimate the magnitude of the above uncertainty is to compare results of many models encompassing large variety of plausible assumptions and range of parameters. Fortunately, there already exist many independent codes[21,23,24,25,26,27,28] to facilitate such comparisons, and more will undoubtedly be developed.

So how do detailed baseline calculations compare with the new data? First the long ramp shape of the the multiplicity and E_T distributions is well reproduced by all models since that shape is controlled totally by nuclear geometry[24]. However, the point at which the cross section begins to drop rapidly is systematically underestimated[4,7,24] by 10-20% in those experiments that include the target fragmentation region. The origin of this discrepancy was clearly shown in [4,7] by comparing dE_T/dy and dN_{ch}/dy with LUND[20,21] and DPM[26] calculations. These comparisons showed that at 200 AGeV the ratio of the data to calculations increases with decreasing rapidity in the rapidity range 0-3 and increases with target mass. While the total integrated discrepancy is small $\lesssim 20\%$, and thus well within model uncertainties, the discrepancy in the rapidity region $y \lesssim 1$ is large and significant. The tell-tale sign of this is the A dependence of the rapidity distribution measured in [7]. WA80 parametrized that dependence as

$$dN_{ch}/d\eta \propto A_T^{\alpha(\eta)}$$

and found for $O + A$ at both 60 and 200 AGeV that

$$\alpha(\eta) \approx 0.2(4 - \eta) \text{ for } 0 \lesssim \eta \lesssim 4 \ . \tag{6}$$

In contrast the wounded nucleon string model[18] the maximum A_T dependence at $\eta = 0$ is $\alpha = 2/3$ since the number of wounded target nucleons goes as $W_T \approx \frac{3}{2} A_T^{2/3} A_P^{1/3}$.

This discrepancy may be an amplified version of the one familiar from $p+A$ studies[27] and is presumably related to cascading of low rapidity secondaries in the target nuclei. Recalling (3), we expect cascading in just that rapidity region $y \lesssim \Delta y_F(A_T)$ where the excess A_T dependence is observed. At present none of the models applied to the analysis of AB data incorporates that cascading. These data may be providing evidence for the importance of cascading at least in the target fragmentation region. This is good news since our goal is not to see A times pp physics, but nonlinear deviation associated with an approach to equilibrium. Secondary cascading is just what we are looking for. The important problem will be to deduce the degree of cascading from a quantitative analysis of both A_P and A_T dependences. That step necessitates the extension of the current models into full hadronic cascade ones incorporating the inside-outside aspect of the space-time dynamics. For steps in that direction see [27].

There is one caveat to the above tentative conclusion though that needs to be checked out further. Emulsion measurements[10] of the pseudorapidity distributions and multiplicity distributions were reported to be well reproduced by the LUND Fritiof model. Is this due to systematic errors in electronic experiments or to the use of different parameters or versions of LUND? It would be very useful to compare the same version of LUND and DPM with the pseudorapidity systematics reported by the KLM emulsion collaboration[11]. In addition we emphasize the necessity of advertising the version and parameters used in any model comparison[24]. For example, the well documented JETSET6.3 string fragmentation code[29] has 120 option flags and parameters in common/ludat1/ that are available for tuning. Any changes of the default parameters must be carefully pointed out to avoid the proliferation of irreproducible results.

2.3 Space-Time Geometry

The extension of present models to incorporate secondary cascading requires an understanding of the space-time geometry of nuclear collisions. Pion interferometry provides a phenomenological tool to help map out that geometry (see [30] for an in depth recent review). The first measurements for $O + Au$ at 200 AGeV by NA35[12] found unexpected values and rapidity dependences of the transverse radius $R_\perp$ and of the chaoticity parameter λ.

	$1 < y < 2$	$2 < y < 3$	$3 < y < 4.5$
$R_\perp$ (fm)	4.3 ± 0.6	8.1 ± 1.6	4.3 ± 1.2
λ	0.34 ± 0.09	0.77 ± 0.19	0.55 ± 0.20

Note in particular that the transverse radius in the mid rapidity region is twice as large as the transverse dimensions of the O beam. These results were obtained by fitting the measured $\pi^-\pi^-$ correlation function with a model correlation function

$$C(k_1, k_2) = 1 + \lambda \exp\{-(q_0^2 \Delta\tau^2 + q_\perp^2 R_\perp^2 + q_z^2 R_z^2)\} \ , \ , \tag{7}$$

corresponding to a gaussian source. For the acceptance of the streamer chamber $q_0 \approx \vec{v}_K \cdot \vec{q}$ is generally smaller than $\vec{q} = \vec{k}_1 - \vec{k}_2$, and it was reported thus the time parameter could not be determined within the statistics of the experiment. Note however that great care must be given to the interpretation of geometrical parameters deduced with a given parametrization. This is especially true if one includes the strong effects that correlations between coordinate and momentum space can induce[31]. An alternate set of geometrical parameters were also decuced from the data by fitting the correlation function with one corresponding to *fixed* proper time inside-outside cascade source (see [31]). In that case, the longitudinal radius parameter, R_z, is replaced by the freezout proper time, τ_f. While the fitted vales of R_z and τ_f turned out to be nearly identical, the physical interpretation of those parameters is very different.

In high energy hadronic processes where such phase space correlations are expected due to longitudinal boost invariance[15] pion interferometry is always dynamical model dependent. Geometry and dynamics are necessarily intermingled. What pion interferometry offers in this case is a further consistency test of such models. An example of such a test is in ref.[33] where pion correlations are computed for a model assuming evaporation of plasma globs followed by pion rescattering in an ideal longitudinal boost invariant setting. That model goes well beyond the simple analytical formula in [31] by incorporating very large time fluctuations about a mean proper time hyperbola, but they still could not account for the large transverse radius found in the midrapidity interval nor the low values of the chaoticity parameter. The source of the discrepancy remains a puzzle at this time. Perhaps it is due to the neglect finite energy nonscaling effects, long lived hadronic resonances, finite experimental acceptance effects, or possibly to interesting new physics. Clearly much work remains to clarify the space-time geometry of nuclear collisions at these energies.

2.4 Transverse Flow

One of the well known proposed probes of quark-gluon plasma formation is the correlation between average transverse momentum, $\langle p_\perp \rangle$ and dN/dy. In the ideal case[44] $\langle p_\perp \rangle$ should increase initially with dN/dy and then level off while the initial energy density is in the mixed phase and the speed of sound vanishes. Eventually beyond a critical dN/dy, corresponding to the threshold of the pure plasma phase, the speed of sound approaches $1/\sqrt{3}$, and $\langle p_\perp \rangle$ is expected to rise again.

Unfortunately, this ideal picture has been complicated as a result of detailed 3+1 D hydrodynamical calculations[35]. While the general dependence of $\langle p_\perp \rangle$ on dN/dy holds qualitatively, those calculations have uncovered the peculiar scaling law

$$\langle p_\perp \rangle \approx F(\frac{1}{A}\frac{dN}{dy}) \ . \tag{8}$$

It is the competition between more rapid decoupling in smaller A and the greater influence of longitudinal expansion in larger A that leads to the above scaling. The function $F(x)$ does reflect the properties of the QCD equation of state, but the problem is that x may be constrained physically to lie in a narrow range.

The initial hope[44] was that the scaling variable is $x = A^{-2/3} dN/dy$. In that case even the conservative wounded nucleon model would lead to a significant variation of $x \propto A^{1/3}$ as a function of A. However, if (8) is correct, then x is approximately independent of A and we have to hope for a major breakdown of the wounded nucleon picture. We note that numerical estimates indicate that to map out the important features of $F(x)$, we must be able to vary x over a large range $1 \lesssim x \lesssim 10$. Thus if (10) holds, this observable is not likely to be as sensitive to the phase transition parameters as originally hoped.

What has been actually observed[5,7] is consistent with the above discussion in that the $\langle p_\perp \rangle$ of pions and photons is remarkably insensitive to the total multiplicity event by event. Of course in biased high E_T triggers, higher $\langle p_\perp \rangle$ were found[5], but in less biased (veto) triggers, $\langle p_\perp \rangle$ differed by at most 10% from those measured in $p+p$. Looking at the detailed π^- distribution, NA35 found that the ratio of $p + Au$ to $O + Au$ at 200 AGeV was in fact consistent with unity, although there may be a slight excess of those distributions relative to pp at small $p_\perp \lesssim 0.2$ GeV/c.

We note that because of the their low mass, pions are expected to be rather poor messengers of collective transverse flow[35] or even higher initial transverse momentum at the quark level[24]. It is possible that as in pp collisions, the observed pions come predominantly from decay of heavy resonances. String models[20,21,24] lead to $\sim$ 70% pions arising from ρ, ω, η decays. A larger p_T of a heavy resonance translates into a small additional transverse velocity boost to the pion on top of an already large decay momentum. The main lesson is that it is much better to look at K, p, Λ, etc. in the search for unusual transverse momenta. At this stage we can only say that the present data are consistent on this point with the string extrapolation models from pp.

2.5 Nuclear Stopping Power

Another basic aspect of the reaction mechanism is the degree to which the baryon number is stopped in the cm. That information is essential for estimating the initial baryon densities.

At this time QCD lattice calculations cannot be done for finite baryon densities. The nature of the hadronic to plasma transition may be very different at high baryon densities and thus is of fundamental interest in its own right.

As discussed in section 2.1, recent $p + A \rightarrow p$ experiments[14] have indicated that the maximum rapidity shift a baryon can suffer in the heaviest nuclei is about 2-2.5 units. Does that stopping power increase or decrease in nuclear collisions? Unfortunately, none of the present experiments at CERN can identify protons at high rapidity. Only indirectly is the stopping power tested in the E_T and veto calorimeter data. These data are roughly consistent with LUND expectations[7,5], and thus to that extent the stopping power is as expected. Thus it is likely that the baryon rapidity density does not peak in the center of mass at 60 or 200 AGeV. However, there is evidence that the probability of very large energy loss (low E_{veto}, high E_T) is systematically underestimated by LUND. In addition, very preliminary data on Λ production from NA35[5] seems to indicate that Λ's may be strongly concentrated at cm rapidities. Thus, the present indirect data on nuclear stopping is not conclusive.

The only direct measurements of protons is at low rapidity[5,7]. However, in that rapidity range a suprizing result was found. Even for the heaviest nuclei, essentially the entire target nucleus disintegrated in the wake of the O^{16} beam. Thus, there appear to be no spectator nucleons in high energy nuclear collisions. On the other hand, Glauber geometry would lead in a central $O + Au$ reaction to only $\sim$ 60 wounded target baryons out of the total 197. However, the data indicate that the remaining $\sim$ 140 spectator nucleons suffer violent interactions as well. The spectators were distributed in fact similar to the particpants at Bevalac energies $\sim$ 1 AGeV[7].

Once observed, *a posteriori* we should have expected this all along. Recalling (3), each wounded target nucleon leads to some moderate rapidity, $\Delta y_F(A_T)$, secondaries being produced within the target volume. Some of those secondaries should be able to cascade and deposit energy into the spectator matter. It would require only a very modest 100 MeV per wounded nucleon to obliterate the target. An important test of future cascade calculations will be the quantitative explanation of the degree of spectator excitation.

One of the unfortunate by products of the above effect is that the distribution of the interesting wounded nucleons is buried beneath the spectator rubble. To make progress on this problem, an equivalent of the E802[8] experiment at the AGS will be required with full particle identification in the $2 < y < 6$ domain. Until that time the debate between the pro and con fireball model makers cannot be settled.

3 Puzzles

3.1 J/Psi Suppression

One of the most novel ideas since QM86[2] was the suggestion[36] that J/ψ production should be suppressed if a quark-gluon plasma is formed. The idea is that in a plasma the $c\bar{c}$ potential is Debye screened and above a critical temperature, $T_\psi \sim (1-2)T_c$ the bound state that used to be a ψ melts into the $c\bar{c}$ continuum. The $c\bar{c}$ pair that was produced early in a semi-hard (gluon fusion) process ends up in open charm D and $\bar{D}$ states.

The dimuon experiment NA38[13] in fact reported that they observed an apparent suppression of ψ production in $O + U$ at 200 AGeV when comparing peripheral (low E_T) to central (high E_T) events. What they measure is the invariant mass distribution of opposite sign $N^{+-} = \mu^+\mu^-$ pairs and like sign pairs $N^{\pm\pm} = \mu^\pm\mu^\pm$. The like sign pairs come predominantly from π and K decay in a gap before a hadron absorber. The true dilepton signal is estimated from

$$S = N^{+-} - 2(N^{++}N^{--})^{1/2} \ . \tag{9}$$

The signal is then fit to a smooth continuum plus a Breit-Wigner ψ part, $S = N_c + N_\psi$. Integrating over the ψ mass range, NA38 found that

$$N_\psi/N_c = \begin{cases} 9.3 \pm 0.6 & \text{for } E_T < 28 \text{ GeV} \\ 5.9 \pm 0.4 & \text{for } E_T > 50 \text{ GeV} \end{cases} \ . \tag{10}$$

This 30% reduction of ψ production caused the most controversy at Quark Matter '87.

There are naturally several caveats that need further consideration. First, there is the problem of proving that the background subtraction scheme (9) correctly removes the quadratic E_T^2 dependent decay background. This will require additional detailed Monte-Carlo simulations. Second, on the theoretical side more studies are needed on competing sources of suppression involving hadronic final state interaction.

To see qualitatively how such hadronic processes could lead to such effects, we note the following estimate[37] for the survival probability, $P(p_\perp)$, of a ψ traversing dense *hadronic* matter of density, $\rho_H(x,t)$:

$$P(p_\perp) = \exp\left(-\int_{t_0}^{\infty} dt \langle\sigma_d v\rangle \rho_H(z=0, \vec{x}_\perp + \vec{v}_\perp(t - t_\psi), t)\right) \ . \tag{11}$$

The exponent is just the average number of inelastic *disassociation* collisions (e.g. $\psi + h \to D + \bar{D} + X$) the ψ could suffer in the expanding hadronic matter around it. It is assumed that a $c\bar{c}$ pair is produced in a hard process at at $z = 0$ and $\vec{x}_\perp$ at time t_ψ. However, since it must take some finite proper time, τ_d, for the $c\bar{c}$ to dress itself to the point that it can interact as a ψ, Lorentz dilation implies that the first disassociation processes are delayed for high $p_\perp$ ψ's according to

$$t_0 \sim \gamma_\perp \tau_d \ .$$

For approximately longitudinal boost invariant boundary conditions,

$$\rho_H \approx \frac{\rho_0 \tau_0}{t} \theta(R_\perp - t) \ . \tag{12}$$

The theta function in (12) marks the end of 1 dimensional expansion and the beginning of rapid 3 dimensional expansion beyond which the system rapidly freezes out[37]. Given the above simple estimates, we get

$$P(p_\perp) \approx \left(\frac{\gamma_\perp \tau_d}{R}\right)^{\langle\sigma_d v\rangle \rho_0 \tau_0} \ . \tag{13}$$

Note that, $P = 1$ for $p_\perp > \gamma_\perp \tau_d \geq R_\perp$ in this simple model.

As a rough estimate, we take $\langle\sigma_d v\rangle \sim 1 - 2$ mb consistent with measured $\psi + N$ disassociation rates and not unreasonable in a dense resonance gas where exothermic processes such as

$$\psi + \omega \to D + \bar{D} + 150 \text{ MeV} \ ,$$

$$\psi + \rho \to \eta_c + \pi + 750 \text{ MeV} \ ,$$

can operate.

For low $p_\perp$ ψ in $O+A$ collisions, we take $\gamma_\perp \tau_d \sim 1$ fm, $R_\perp \approx 3$ fm, and

$$\rho_0 \tau_0 \approx \frac{1}{\pi R^2} \frac{dN}{dy} \quad . \tag{14}$$

Taking the *resonance* rapidity density to be about half the final pion density[5] we expect $dN/dy \sim 50$ in central collisions The exponent is then $\sim 0.15 - 0.3$, while the expression in brackets is also $\sim 0.15 - 0.3$. Consequently, $P(0) \sim 0.7$ is not an unreasonable survival probability in this reaction.

Clearly the above estimate is too crude for quantitative analysis, but it does show the potential importance hadronic disassociation processes. Unfortunately, the result depends sensitively on unmeasured $\psi\omega, \psi\rho$, etc., disassociation cross sections in dense media where perhaps even multi-hadronic reactions (eg. $\psi + \pi + \omega \rightarrow D + \bar{D} + X$) could be important. Much more thought needs to be given to this area since the burden of proof for ψ suppression as a signature of plasma formation is that no combination of ordinary hadronic processes can lead to the same effect. We note that the above estimate also leads to qualitatively the same $p_\perp$ dependence as in the plasma scenario[38] since that only depends on Lorentz dilation effects.

It may turn out that ψ suppression is a generic signature that ultra-dense matter was formed but not necessarily specific to the quark-gluon plasma phase nor to equilibrated systems. In any case, quantitative studies of this phenomena will provide an important test of competing dynamical models and thus deserves careful attention.

3.2 K+/pi+ Enhancement

The second provocative result was that reported by E802[8] on kaon production in $Si + Au$ at 10 AGeV. In the angular range $14 - 28$ degrees they observed in central triggered events that

$$K^+/\pi^+ = 20 \pm 5\% \quad , K^-/\pi^- = 5 \pm 5\% \quad . \tag{15}$$

The corresponding ratios in $p+p$ collisions are $5 - 10\%$ and $3 - 5\%$ resp. Thus, there appears to be a significant nuclear effect in the K^+/π^+ ratio.

Theoretically, just such an effect is expected if very high baryon density matter is formed. This has been called the K^+ distillation effect[39]. This effect is closely related to associated Λ production. At the hadronic level, the reaction $p+p \rightarrow p+\Lambda+K^+$ has a lower threshold than $p+p \rightarrow p+p+K^+ + K^-$. Thus energetics favors associated production over pair production in high baryon density matter. At the quark level, high baryon density implies that the number of u, d quarks greatly exceeds the number of $\bar{u}, \bar{d}$ quarks. Thus when a $\bar{s}$ tries to leave the plasma, it has no problem finding a u quark to emerge as a K^+. On the other hand, a s quark has a hard time finding a $\bar{u}$ but the high abundance of u, d quarks makes it possible for s to emerge in the three body (u, d, s) process as a Λ. The result in both scenarios is thus qualitatively the same, more K^+ and more Λ.

Quantitatively, the precise value of the $K^\pm/\pi^\pm$ ratios does depend on whether the dynamical path entered the plasma phase or not. But the details of that dynamical path are too uncertain at this stage to make quantitative statements. What is encouraging is that if this observation is confirmed, then it gives further confidence in the stopping power estimates (2) and suggests that very high baryon densities may indeed be achieved at the AGS energies. It will be important in future experiments to measure the Λ distributions to gain additional handles on this K^+ distillation effect.

4 Theory

The major new result since QM86[2] was that the first order nature of the transition between hadronic and quark matter was recovered in lattice QCD simulations of SU(3) including dynamical fermions[17,40,41]. This phase transition is thought to be driven by the restoration of chiral symmetry and was only seen when the chiral limit of vanishing quark mass could be approached numerically. In fact critical temperatures were reported[41] to be significantly less than in the case of pure SU(3).

Present results indicate, however, that the plasma is far from ideal. The results in [17] indicate that while the energy density of the quarks rapidly approaches the Stefan-Boltzmann value ($7\pi^2 N_c N_f T^4/60$) the gluon energy density seems to overshoot the Stephan-Boltzmann limit by over a factor of two. This together with deviations of the $p = 1/3\epsilon$ law observed in other studies[42] indicate that the degrees of freedom between $(1-2)T_c$ are not just those of an ideal plasma of quarks and gluons. Indeed there have been arguments[43] that while at short wavelengths, the ideal plasma picture could hold, at larger wavelengths, $\lambda \lesssim 1/gT$, color singlet hadronic like modes could still be important. Studies of hadronic screening lengths[41,42] on lattices found that those lengths did not very much across the transition although correlation lengths in the π and σ channels coalesced on account of restoration of chiral symmetry.

At this meeting there were numerous discussions on the relevance of screening lengths to real time excitations. One interesting new result[41] was the first measurements of the baryon susceptibility, $\chi = d\rho_B/d\mu$. If the carriers of the baryon number had mass much less than T, then $\chi \sim N_f T^2$. On the other hand, if those carriers were baryons of mass close to a nucleon, as screening results would suggest, then χ would be small and suppressed by a factor $e^{-m/T}$. The new calculations indicated that χ is in fact close to the ideal case. Thus, the elementary excitations in the plasma phase that carry baryon number are relatively light quarks and antiquarks. This casts doubt some doubt that small screening lengths necessarily imply large masses of real quasiparticles in the system.

There remains of course the problem of relating results on small lattices to the continuum limit. While a plausible perturbative scaling region ($6/g^2 > 6.2$) has been found[17] for pure SU(3), the present lattices ($8^3 \times 4$) are probably to small to be in the scaling regime. It has been recently noted[48] that finite size corrections could reduce significantly the $O(g^3)$ plasmon contribution to the pressure on present day lattices. Thus, echoing the past[2], calculations on bigger lattices are essential to uncover what QCD really predicts about the plasma phase of hadronic matter.

Shuryak[44] again emphasized that the most fundamental object in QCD is the Vacuum! It is presumably filled with complex fluctuations of gluon and quark fields involving $q\bar{q}$ condensates, instanton liquids, color monopole condensates[45], ... , responsible for confinement and the breaking of chiral symmetry. What Euclidean lattices measure are consequences of changes of the vacuum structure in equilibrium. However, heavy ions collisions act as brief Bunsen burner depositing several GeV/Fm^3 for a few fm/c into the vaccum. To understand plasma formation and evolution, we have to know how the vacuum in the small reaction volume reacts as well. Hopefully those condensates evaporate on a time scale fast compared to the total time the Bunsen burner is applied. But how fast does the vacuum respond? To answer that one must develop a transport theory of the vacuum as well as of the quasiparticles supplied by color neutralization processes. For that an effective Lagrangian, L_{eff} including the condensate degrees of freedom as well as effective quark and gluon couplings to them must be formulated. It is not clear at this time how to even formulate this problem, but it may be important in more realistic calculations of signatures. Ideally, calculations with the yet undeveloped real time numerical lattice techniques could help guide the construction of L_{eff}.

Finally, we note the current controversy over the damping of color plasmon modes. In Ref.[46] a self-consistent QCD linear response theory was developed to study the response of the plasma to an external color perturbation. They found that the longitudinal and transverse plasmon modes, with $\omega^2 = g^2T^2N_c/9+O(k^2)$ are damped in the long wavelength limit with damping rate, $\gamma(k \to 0) = N_c g^2 T/24\pi$. The same result was obtained in three different gauges. However, in Ref.[47] it was found that in the covariant background field gauge, the color dielectric function had the poles at the same real plasmon frequency but with the damping constant of the wrong sign. Even worse the numerical value of γ depended on the gauge fixing parameter. Which result is right? Perhaps it is the question that is wrong. This problem is associated with long wavelength ($k \to 0$) color fields. But we know that perturbation theory breaks down on distance scales $d_M \sim 1/g^2T$ associated with color magnetic screening. So what sense does it make to consider perturbative modes on a scale large than d_M? Presumably short wavelength plasmons (gluons) behave well in all approaches and something nonperturbative happens on large distance scales.

The resolution of the above problem is important in the formulation of QCD transport theory. Proceeding in the canonical Wigner function method, Elze[48] showed how to derive QCD transport equations from the QCD Lagrangian that look similar to Abelian plasma equations. However, several approximations have to be made to reduce the equations to tractable form. The most basic of those is the existence of slowly varying color fields in the plasma. If such fields are not damped as usual by pair production and particle hole excitations, but are unstable to exponential growth, then the whole transport approach would break down and we would be left with no equations to follow the nonequilibrium evolution of quark gluon plasma. It may be that only an effective transport theory involving different quasiparticles and interactions at different scales (along the lines of [43]) can circumvent the above difficulties. On the other hand, in very heavy ion reactions, the very complexity of even heavier ion reactions may help lead to simplifications. As emphasized by Feinberg[49], local equilibration may result from strong multiparticle interactions. In that case, simple hydrodynamics $\partial_\mu T^{\mu\nu} = 0$, may provide a better dynamical framework than current two body kinetic arguments would indicate.

5 Summary

In this report we have considered a number of possible implications of the preliminary AGS and SPS data on light ion reactions and emphasized many open problems needing future study. The pioneering experiments have provided a first close look into the complexities of nuclear collisions and have teased us with a number of puzzles. The newly developed "wounded nucleon string" Monte Carlo event generators have provided the baseline to judge which aspects of the data are mere convolutions of known *pp* physics and which provide important clues on nonlinear phenomena. Analysis of preliminary data have revealed encouraging evidence for secondary cascading in the target fragmentation region. Further development of event generators including final state cascading is thus urgently needed for more quantitative analysis.

We have seen that many of the proposed signatures of quark gluon plasma are not as forge proof as originally hoped. The "smoking gun"[2] still needs to be found. The candidates for forgeries exploit present uncertainties in the dynamical paths followed in such reactions and the competition of hadronic processes. For example, the correlation between the transverse momentum and rapidity density may not be so sensitive to the equation of state if the scaling variable is indeed $A^{-1}dN/dy$ [35]. We emphasized that pions (in contrast to heavier hadrons) are poor messengers of collective flow because they are mostly secondary decay products of resonances. The most provocative findings were the J/ψ suppression and kaon enhancement. It may turn out though, that both are interesting *generic* signatures for ultra-dense matter formation. In that case, further studies are needed to isolate which properties of ultra-dense matter those observables are sensitive to. Finding which correlations among the possible observables best constrains the dynamical scenarios and provides the best probe of ultra dense matter remains the foremost challenge phenomenologically. While any one or two of the observables can perhaps be fit by several competing models, a simulatanous fit to the $p_\perp$ and y distributions of pions, kaons, protons, lambdas, J/ψ, etc. as a function of global multiplicity or E_T is likely to weed out most models. The burden of proof will be to show that only a scheme involving quark plasma formation can account for all the peculiarities in the data.

On the experimental side, the greatest need is for experiments capable of distinguishing pion, kaons, protons, lambdas, etc. over the full kinematic range. Transverse energy and multiplicity distributions provide valuable constraints but necessarily convolute the distributions of the zoo of final hadronic states. An extension of the E802[8] system to SPS energies would be very useful for the CERN heavy ion program, especially if the very attractive *Pb* injector proposal[50] is approved.

On the theory side, we need much better understanding of the real time response of the plasma not far above the critical temperature. What are the relevant quasiparticles and interactions? Lattice calculations may help guide us, but convergence is likely to be slow. Could it be that asking QCD lattice calculations to reveal the varied and novel properties of ultra dense matter is like asking QED to predict high temperature superconductivity?

Now that experiments with heavy ions are a reality, experiments can finally take the lead to uncover subtle phenomena that Nature has so far kept secret in the cores of neutron stars and in the first moments after the Big Bang.

* It is a pleasure to thank the organizers, R. Santo, H. Satz, H. Specht, and R. Stock for arranging an especially exciting and stimulating conference on this frontier topic in physics. It is also a pleasure to acknowledge the distinguished East Block delegation, led by E. Feinberg and E. Shuryak, who were able (thanks to glasnost) to attend and contribute significantly to the lively discussions for the first time in this series of meetings. This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

References

[1] Proc. First Intn. Conf. on Ultra-Relativistic Nucleus-Nucleus Collisions, ed. L.S. Schroeder, LBL-8957, UC-34C, CONF-7905107 (1979).

[2] Proc. Fifth Intn. Conf. on Ultra-Relativistic Nucleus-Nucleus Collisions, eds. L.S.

Schroeder, M. Gyulassy, Nucl. Phys. A461 (1987) 1c.

[3] T.H. Burnett, et al. Phys. ReV. Lett. 50 (1983) 2062; 57 (1986) 3249; W.V. Jones et al., Ann. Rev. Nucl. Part. Sci. 37 (1987) 71.

[4] Helios Collab. (NA34), T. Akesson et al., CERN-EP/87-170, 87-176.

[5] NA35 Collab, A. Bamberger et al., Phys. Lett. B184 (1987) 271; GSI-88-07,08,09 (1988).

[6] NA36 Collab., P.D.Barnes, et al. CERN-EP/87-209.

[7] WA80 Collab., R. Albrecht et. al., Phys. Lett. B199 (1988) 297; GSI-87-81,82 preprints.

[8] E802 Collab., T. Abbott et al, Phys. Lett. B197 (1987) 285; BNL-40536 preprint 1987.

[9] E814 Collab., B. Bassalleck, et al., SUNY preprint 1988.

[10] EMU1 Collab., M. I. Adamovich et al., LUND LU-IP-8706; LBL-24506.

[11] KLM Collab., R. Holynski, et al., HEA-SS-87-04 preprint.

[12] T. Humanic, NA35 collab., LBL-24646 (1987).

[13] NA38 Collab., L. Kluberg et. al., to be published.

[14] W. Busza, A. Goldhaber, Phys.Lett. D27 (1984) 235; S. Date, et al, Phys. Rev. D32 (1985) 619; K. Abe, et al. Phys. Lett. B200 (1988) 266.

[15] R. Annishetty, P. Koehler, L. McLerran, Phys. Rev. D22 (1980) 2793.

[16] M. Gyulassy, Nucl. Phys. A400 (1983) 31c, Nucl. Phys. A418 (1983) 59c.

[17] M. Fukugita, Kyoto preprint RIFP-703 (1987).

[18] S. J. Brodsky et al. Phys. Rev. Lett. 39 (1979) 1120; S. J. Brodsky, Proc. 1st Workshop on Ultra Relativistic Nuclear Collisions, LBL Report 8957 (1979), UC-34C, CONF-7905107; SLAC-PUB-2395 (1979).

[19] R. Stock, CERN Courier Dec. 1987, p.14.

[20] B. Andersson et. al., Phys. Rep. 97 (1983) 31; T. Sjöstrand, Comp. Phys. Com. 39 (1986) 347; 43 (1987) 367.

[21] B. Andersson et. al., Nucl. Phys. B281 (1987) 289; G. Gustafson, LUND LU-TP-87-17 (1987); B. Nilsson-Almquist and E. Stenlund, Comp. Phys. Com. 43 (1987) 387.

[22] A. Capella, et. al., Z. Phys. C3 (1980) 68; C10 (1981) 249; C33 (1987) 541

[23] J. Ranft et al., Z. Phys. C27 (1985) 569; Phys. Lett. B188 (1987) 379.

[24] M. Gyulassy, CERN-TH.4794/87, Proc. 8^{th} Balaton Conf. Nuc. Phys. (1987); CERN-TH.4795/88 in preparation.

[25] K. Werner, BNL-40369 (1987)

[26] J.P. Pansart, Saclay DPhPE 86-06 (1986); Nucl. Phys. A461 (1987) 521c.

[27] Y. Iga, R. Hamatsu, S. Yamazaki, H. Sumiyoshi, Matsusho-Gauken Junior College Preprint MGJC-HE-87-1 (1987); Prog. Theor. Phys. in press.

[28] S. Frankel, W. Frati, UPR-0339T (1987) preprint.

[29] CERN Pool programs W5035, T. Sjöstrand, LU-TP-85-10, LU-TP-86-22 (1986).

[30] W. A. Zajc, NEVIS preprint R-1384 (1987).

[31] K. Kolehmainen, M. Gyulassy, Phys. Lett. B180 (1986) 203.

[32] S. Gavin, M. Gyulassy, S. Padula, LBL-24674 (1988).

[33] G. Bertsch, M. Gong, M. Tohyama, Phys. Rev. C in press.

[34] E. V. Shuryak, O. Zhirov, Phys. Lett. 89B (1980) 253; L. van Hove, Phys. Lett. 118B (1982) 138.

[35] M. Kataja, et al., Phys. ReV. D34 (1986) 2755.

[36] T. Matsui, H. Satz, Phys. Lett. B178 (1986) 416.

[37] S. Gavin, M. Gyulassy, A. Jackson, LBL preprint

[38] F. Karsch, R. Petronzio, Phys. Lett. B193 (1987) 105.

[39] C. Greiner, Z. Phys. in press.

[40] M. Fukugita, et al., Phys. Rev. Lett. 58 (1987) 2515; J. Kogut et al., Nucl. Phys. B250 (1987) 625

[41] S. Gottlieb, et al., Phys. Rev. Lett. 59 (1987) 1513; 1881 ; 2247. Phys. Rev. Lett.

[42] H. Satz, et. al., Bielefeld preprint 1987.

[43] T. A. DeGrand, C. DeTar, Phys. Rev. D34 (1986) 2469.

[44] E. Shuryak, Z. Phys. in press.

[45] J. Polonyi, Nucl. Phys. A461 (1987) 279c.

[46] U. Heinz, et al., Phys. Lett. B183 (1987) 96; Ann. Phys. 176 (1987) 218; Z. Phys. in press.

[47] T. H. Hansson, I. Zahed, Phys. Rev. Lett. 58 (1987) 2397; Nucl. Phys. B292 (1987) 725.

[48] H. T. Elze, et al., Nucl. Phys. B276 (1986) 706; Helsinki preprint HU-TFT-87-39.

[49] E.L. Feinberg, Phys. Rep. 5 (1972) 237.

[50] G. W. London, N. A. McCubbin, R. Stock, CERN/SPSC-87-52 (1987).

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720