Quark Matter 95: Concluding Remarks

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Abstract: Highlights of Quark Matter 95 are discussed.

1. The View from Mount RHIC

This year marked a major milestone in the field of high energy nuclear collisions. Lead beams were successfully accelerated to 160 AGeV at the CERN/SPS and the first data

![Diagram](image-url)

Figure 1: The charged particle rapidity density in central Au+Au (AGS,RHIC) and Pb+Pb (SPS) in the HIJING model\[6\] compared to pseudo-rapidity, $\eta$, Emulsion data\[2\] on the highest multiplicity event recorded at the SPS to date. Preliminary E866 data on ($\pi^\pm$, $\pi^0$) as well as $dN_{ch}/d\eta$ from E877 at the AGS are also shown\[3, 4\].

on $Pb + Pb$ interactions were presented at this meeting. At the last quark matter meeting

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we saw the first data on $Au + Au$ reactions at BNL/AGS energies (11 AGeV). Now an entirely new domain of energies has become accessible with heavy nuclear beams. Figure 1 summarizes where we are now and where we are going in the next five years.

In the foothills of Mount RHIC, Figure 1 displays the highest multiplicity events measured at both the AGS and SPS. The preliminary pseudo-rapidity distribution, $dN_{ch}/d\eta$, by the EMU01 collab.[2] and from E877[4] and the pion pseudo-rapidity distribution from the E866 multiplicity array[3] are shown. I remind you that the famous JACEE cosmic ray event[4] on $Si + Ag$ at $\sim 5$ ATeV with $dN_{ch}/dy \approx 200$, which was used for over a decade to motivate research in this field, is now overshadowed by $Au + Au$ at the AGS. The calculated curves are based on the HIJING monte carlo model[6] (which combines FRITIOF[7] for soft beam jet fragmentation and PYTHIA[8] for semi-hard mini jet physics) and are similar to results obtained with other models[7, 9, 10, 11, 12] developed in the last few years to calculate multiparticle production in nuclear collisions. We recall that many of the ideas now entombed into subroutines of the above codes were begot by the venerable patriarchs in ref.[13] long before Au was accelerated even in the Bevalac. The charged particle density and the transverse energy systematics reported at this meeting show that spectacular $Pb + Pb$ reactions producing $\sim 1600 ($\pi, p, K$)'s at 160 AGeV are, in fact, close (20%) to expectations based on those models. However, as discussed below, even though the detailed distributions of hadrons and leptons provide more stringent probes of the dynamics, it is satisfying that the global characteristics of high energy nuclear reactions, related to entropy production, are under control. This gives us additional confidence in extrapolations up to the RHIC frontier that will become accessible by 1999. Until then there are certainly many interesting trails to explore in the AGS, SPS foothills.

Before going into further details, I also want to remark on the impressive technical progress made in getting to where we are today. That progress is well illustrated in Fig.

Figure 2: a) A 160 AGeV $Pb + Pb$ reaction recorded by one of the NA49 TPC’s at the CERN/SPS. b) Electronically reconstructed tracks using the 3D information from the TPC.
2, showing a 2D projection of a Pb+Pb event in one of the new NA49 TPC detectors\cite{14}. In the past, such a picture from the streamer chamber would send shivers down the spine of poor graduate students assigned the task of identifying and tracking the hundreds of produced particles. However, the right hand side shows that because the TPC provides three dimensional data, tracking such extremely complex events can be done essentially on-line using the simplest follow-your-nose tracking algorithms. This provides an existence proof for the feasibility of exclusive measurements at RHIC and LHC in spite of the enormous multiplicities $\sim 10^4$. There now exist adaptive tracking algorithms that could milk even multipion correlation functions out of the jumble of such events\cite{15}.

Figure 3 compares the spectrum of pion and protons in $S+S$ at 200 AGeV with the PRELIMINARY $Pb+Pb$ reactions at 160 AGeV\cite{16}. The various data sets from

\begin{align*}
S+S(200 \text{ AGeV}), Pb+Pb(160 \text{ AGeV})(b=0-1 \text{ fm}) \quad \text{HIJING(--) vs. VENUS(--)}
\end{align*}

Figure 3: Comparison of central $S+S$ at 200 AGeV (a,b) from NA35\cite{20} to Preliminary $Pb+Pb$ reactions at 160 AGeV (c,d) from NA49\cite{14}. Expectations based on HIJING\cite{6}, VENUS\cite{10}, and RQMD\cite{11} models are depicted as solid, dashed, and dotted histograms, respectively\cite{16}.

NA35 for $S+S \rightarrow \pi^-$ correspond to different centrality triggers, with the higher one corresponding to a more severe veto trigger cut. We see that the negative pion rapidity
densities are well accounted for by both HIJING[6] and VENUS[10], but the flat valence proton distribution in $S + S$ is only reproduced by VENUS. Recall that VENUS, like RQMD, includes a model of final state interactions in dense matter as well as a color rope effect, called double strings.

The main experimental unknown as yet is the fate of the baryons in the $Pb + Pb$ reaction illustrated in Fig.3d. As discussed by Sorge in this meeting, the RQMD model[11,18] predicts a much higher degree of baryon stopping at midrapidity than VENUS, and HIJING as well as FRITIOF predicts a hole at midrapidity. These very large differences between predicted valence proton spectra, in contrast to the inclusive pion spectra in parts a,c, are due to the very different dynamical assumptions associated with nuclear stopping power. Baryon stopping is limited in the FRITIOF type models like HIJING by the assumption that a diquark propagates as a hard nugget unscathed through a nucleus and fragments into a baryon and mesons only outside the nucleus due to time dilation[17]. In RQMD the large nuclear stopping power is due to the assumption that multiple collisions of diquarks in nuclei can be treated incoherently, neglecting formation time physics. In VENUS, extending the Dual Parton phenomenology[9], the diquarks are allowed to disintegrate and form double strings, which make it possible to shift the valence baryon number further away from the fragmentation regions. The VENUS model parameters are tuned to reproduce available $p + A \rightarrow p + X$ data and comes closest to the expectations for baryon stopping emerging from earlier studies[19]. My bet is that this is where the data will land unless molten lead has a big surprise in store for us.

The final experimental resolution of nuclear stopping power problem must await the next quark matter meeting. This problem is of fundamental interest because it is related to how high the baryon densities may get in such reactions. Are we still in the baryon stopping regime at the SPS, as is the case at the AGS (see S. Margetis[22]), or are reactions at SPS making the transition to the low baryon density regime expected at RHIC? In the first case, the dynamics of shock formation and Landau hydrodynamics may be relevant. In the second case, the Bjorken longitudinal expansion and inside-outside cascade dynamics is more relevant.

2. The Flow of Gold

The discovery of collective sidewards flow in Au+Au at the AGS[24] is a major highlight this year. It shows the persistence of collective flow phenomena all the way up to AGS energies. This phenomena was first discovered[25] at Bevalac energies in 1984 when heavy nuclear beams first became available. It is of fundamental importance because it provides a direct probe of the equation of state at extremely high densities[26].

E877[24] found as shown in Figure 4, that the distribution of the normalized transverse energy dipole moments

$$v_1 \propto \left[ \sum_i E_{\perp i} \cos(\phi_i) \right]^2 + \left( \sum_i E_{\perp i} \sin(\phi_i) \right)^2 \right]^{1/2}$$

in $Au + Au$ is systematically shifted toward finite values for more central collisions. The sum above is over calorimeter modules sensitive to only forward of $y_{cm}$ fragments with
different azimuthal angles $0 \leq \phi_i \leq 2\pi$. This variable provides one of the measures of the collective transverse flow pattern of the system.

The quantitative evaluation of such flow data requires the use of elaborate transport codes. In the lower energy domain,

$$0.05 \leq E_T \leq 0.1 \text{ GeV}$$

$$0.15 \leq E_T \leq 0.2 \text{ GeV}$$

$$0.25 \leq E_T \leq 0.3 \text{ GeV}$$

$$1/N \frac{dN}{v}$$

$$v = 180 \text{ GeV}$$

$$E_T = 200 \text{ GeV}$$

Figure 4: E877 data showing evidence of transverse collective flow in $Au+Au$ reactions at 10 AGeV. Left side corresponds to peripheral collisions and right side to mid-impact parameter collisions.

Figure 5: a) Mean in plane transverse momentum ($y_{cm} > 0$) in $Ar+Pb$ Flow parameter $F = d\langle p_x \rangle/dy|_{y=y_{cm}}$ in $Au+Au$

It took a decade of work by many groups to achieve what is now a truly impressive degree of convergence. This is because sufficiently high precision and detailed triple differential cross sections have only become available with technical developments such as the EOS/TPC and major improvements in the theoretical transport tools were required. Figure 5 shows the results of the most recent analysis of ref. of the mean in-plane transverse collective momentum per nucleon in $Ar + Pb$ and $Au + Au$ reactions from $0.2 - 1.2 \text{ AGeV}$. What is so remarkable about these results is that all the flow data on asymmetric as well as symmetric nuclear collisions are reproduced by a BUU transport model taking a momentum and density dependent optical potential (NMDYI) that is consistent with the Urbana UV14+UVII force. That force is known to provide a good
description of light nuclei and bulk nuclear matter properties and has a compressibility \( K = 210 \text{ MeV} \) consistent with nuclear breathing modes. This is the first time that nuclear collective flow in nuclear collisions can be explained quantitatively in terms of well known nuclear interactions. Actually, the flow data is providing new information on aspects of the nuclear interactions not tested by ordinary nuclear properties near saturation. However, a consistent picture is beginning to emerge that links not only low energy nuclear phenomena to collective flow in low and intermediate energy nuclear collisions, but also to the types of equations of state used in calculating the bounce in supernovae and the structure of neutron stars.

Figure 5 establishes therefore a very important fixed point from which explorations deeper into the high baryon density domain can be based. At Bevalac and now GSI/SIS energies the compressions are modest \( \rho_B < 4\rho_0 \), and it may not be too surprising that conventional nuclear theory works so well. However, at the AGS energies, all estimates indicate that baryon densities up to \( 10\rho_0 \) are generated. In that case, a breakdown of extrapolations of conventional nuclear physics may occur since the baryons and mesons are squeezed on top of each other, possibly melting into a quark plasma. In order to identify any new physics associated with the expected QCD phase transition, of course much more work will be needed both experimentally and theoretically. On the experimental side, it will be necessary to measure detailed triple differential cross sections of identified fragments and especially to study the beam energy dependence of the flow phenomena (H. Stöcker[22]). At present the first generation of cascade models like ARC[23, 36] apparently reproduce the trends seen in Figure 4 (see talk by Y. Pang[22]), but only at the price of introducing assumptions about hard core, classical repulsive scatterings as in earlier models for flow at Bevalac/SIS energies[38].

As shown at the last quark matter[32], flow phenomena at AGS energies are of interest because they are sensitive to possible softening of the equation of state across the hadron to quark-gluon plasma transition. Depending on the nature of the QGP transition at high baryon density, the crossover energy \( E_{lab} = 2 - 10 \text{ AGeV} \). Thus, the current \( Au + Au \) AGS experiments at \( 10 \text{ AGeV} \) may have overshot the transition region! Indeed, a very speculative interpretation[33] of the relatively small flow observed in the E877 experiment in Figure 4 is that this may be already the direct consequence of the soft equation of state in the QCD plasma phase. The most striking prediction is that if this is the case, then the degree of flow should increase with decreasing lab energy below \( 10 \text{ AGeV} \). I feel that this is certainly one of the most exciting directions to pursue experimentally at the AGS in the next several years along with the search for exotic multistrange objects (S. Kumar[22]). Such phenomena if observed would be very difficult to imitate with cascade models. If, on the other hand, the flow is shown to remain independent of energy and continues along the same flat curve as in Fig. 5b, then an abrupt QGP transition at high \( \rho_B \) could be ruled out. In any case, the EOS/TPC used in ref.[28] would be an ideal tool for such further studies at the AGS.
3. Gold is Strange, But $p + S$ is Weirder

An important diagnostic of dense matter formed in nuclear collisions is strangeness. The E802 team (B. Cole, Z. Chen) has mapped out with most precision the systematics of strangeness enhancement at the AGS. In Figure 6, the old together with the new data on $Au + Au$ are shown. Most conspicuous is the apparent saturation effect of the $K/\pi$ ratio as the size of the projectile nucleus increase. Also the very weak power dependence of $K/\pi \sim A^{0.13}_{proj}$ from $A_{proj} = 1$ to 197 is remarkable. These results suggest that strangeness production in $A + A$ smoothly extrapolates from $pp$ to $pA$ to $AA$. There is obviously no threshold effect indicating the onset of any equilibrium source of strangness.

This conclusion is brought into even clearer focus in Figure 7 comparing $\Lambda^0$ production in $p + S$ and $S + S$ reactions at SPS energies. Again HIJING and VENUS calculations are contrasted. Data from NA35 (M. Gazdzicki) and NA36 (E. Judd) are also compared. As in the last quark matter conference, there is a significant discrepancy between the two data sets. The weirdest result is the NA35 $pS$ data that exceeds the NA36 $p + Pb$ data and lies a factor of two above the HIJING results. In ref. [16], it was shown on the other hand that HIJING reproduces well the observed $\Lambda^0$ production in $pp$. There also appears a large difference between VENUS and HIJING results. This is especially remarkable given that minimum biased $pS$ is the most boring extension of $pp$ collisions imaginable! On the average, in $pS$, the projectile nucleon interacts with only two target nucleons. Nothing could be further from the thermodynamic limit, except of course $pp$. How could extrapolations from $pp$ breakdown so quickly in $p + 2p$. The trick invoked in VENUS, as well as in RQMD, is to invoke the color rope idea. Overlapping strings even in $p + A$ from different target nucleons may fuse into one with a higher string tension. Pair production in such enhanced color fields can easily produce hoards of extra strange and even charm quarks.

In Fig 7b, midrapidity $\Lambda$’s are enhanced by another factor of two in $S + S$, at least in
the NA35 data. For heavier targets there is a saturation effect as in Figure 6a. Therefore all the enhancement of strange baryons can be traced back to the rapid increase of strangeness in the non-equilibrium dynamics of $p+p+p$ and $p+p+p+p$. It is therefore simply not relevant, in my opinion, to apply thermal fireball models to explain strangeness enhancement. It has to do instead with interesting new dynamical effects, possibly along the rope ideas, and little to do with the QGP transition. The problem is not to reproduce the ratios of integrated yields, but to explain quantitatively the distributions in the weird $p+A$ systems.

4. The Shine of Gold

While direct $\gamma$'s from light ion reactions continue to elude WA80 (T. Awes[22]), the very dimness of the emitted light delighted Srivastava[22], who claimed that this was the smoke-less gun that proved the QGP transition. NA45 presented new data[42] (P. Wurm[22], I. Tserruya[22]), on the other hand, revealing an excess of dilepton pairs in the mass region $2m_\pi < m < 1.5$ GeV for $S+Au$. A similar effect was reported by the HELIOS collaboration (M. Masera[22]), which also showed an excess in the intermediate mass range $m \sim 1.5 \pm 2.5$ GeV as compared to $p+A$. In $p+A$ the observed pairs light mass pairs were well accounted for by $\eta$ and $\omega$ Dalitz decays. However, extrapolations of those backgrounds to $S+Au$ appears to under-estimate the observed yield by a factor $5 \pm 0.7 \pm 2$. This may indicate new physics or the onset of final state processes such as $\pi\pi \rightarrow e^+e^-$. Another rare probe that showed hints of unusual behavior is the mass spectrum of the $\phi$ meson. Last meeting, Y. Wang reported the first successful measurement of $\phi$ spectra in $Si+Au$ at the AGS. This meeting (see Y. Wang[22]) hints for a tiny few MeV shift were
presented. This is much smaller than the spectacular 100 MeV shifts predicted by Ko and Asakawa\cite{44} as a signature of the chiral restoration transition in the dilepton channel, but their is not much phase space in the KK decay channel. A few MeV shift is consistent with the uncertainty principle only if the system lived $\sim 100$ fm! In any case, it could be an interesting interference or final state effect and we should keep an eye on this problem.

The most well established and hotly debated rare probe since quark matter 1987 is the $J/\psi$ and now $\psi'/\psi$ suppression. The data from NA38 (see S. Ramos\cite{22}) are quite convincing of a true nuclear suppression effect that must involve the formation of a very dense comoving system. The debate focuses on whether there is any evidence for a threshold effect or, as is in the case of the strangeness enhancement, this phenomenon extrapolates smoothly back to $pA$ and $pp$. Last quark matter conference, Gavin\cite{46} presented a strong case that the suppression of hidden charm smoothly extrapolates down from $S + U$ back to $pp$ and can be understood quantitatively if one assumes a comover density $\sim 5\rho_0 \approx 0.8$ fm$^{-3}$ and a dissociation cross section of a few mb. This meeting D. Kharzeev (see these proceedings\cite{22}) challenged those finding with a new estimate based on heavy quark mass limit of QCD arguing that the $J/\psi$ dissociation cross section should be much smaller. However, the burden on theory is then again shifted to explain the suppression in the manifestly non-equilibrium conditions of $p + A$ and light ion induced reactions. It will be interesting to see if there is enhanced suppression in upcoming $Pb + Pb$ measurements beyond that predicted by the comover model\cite{46}.

5. The Charm of Gold

The possibility that at RHIC energies nuclear collisions will become even more charming was emphasized by K. Geiger\cite{47} and R. Vogt\cite{50} at the last meeting. In Figure 8a,

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8.png}
\caption{(a) Comparison of open charm transverse momentum distribution produced in $Au + Au$ at 200 AGeV. Predictions of ref. \cite{12, 48, 49} are shown. (b) The dilepton rapidity spectrum for $M = 2$ GeV is dominated by open charm decay, from ref.\cite{50}.}
\end{figure}

the initial gluon fusion rate into $c\bar{c}$ pairs is compared to three models. The highest
curve is the prediction of the PCM model [47] that predicts a factor of ten enhancement, the Muller-Wang fireball model [48] (MW) that predicts comparable yield from the pre-equilibrium stage after mini-jet formation, and the recent calculation in ref. [49] (see Z. Lin [22], these proceedings) that predicts a factor ten less than initial fusion. The order of magnitude differences between these theoretical predictions is due to different assumptions for the intrinsic charm component and phase space correlations in the plasma. Most of the charm of PCM comes from an enormous intrinsic charm component assumed in the nucleon structure function (GRV), which now appears to be ruled out [49]. The comparable charm in [48] arises from the assumption that the plasma fireball decouples to avoid the Bjorken longitudinal expansion. In [49] both the pre-equilibrium and equilibrium charm production is found to be suppressed even if the ideal $y = \eta$ Bjorken phase space correlations are smeared by the Bjorken cloud. The conclusion is that most of the open charm expected comes from the initial gluon fusion stage.

A similar conclusion was found by Vogt et al [50] shown in Figure 8b. Here the contributions to the observable dilepton spectrum from different sources are shown. Clearly the dilepton spectrum in the $M = 2$ GeV range should be an ideal probe of the initial gluon fusion into charm pairs. As such it is an ideal probe of the nuclear gluon structure function. Thus the dilepton measurements in this mass range will provide essential information on gluon shadowing and anti-shadowing (see talk of K. Eskola [22]) so essential for the mini-jet physics that makes mount RHIC tower in Figure 1 so much higher than the current SPS range. PHENIX will be the detector of choice for this observable.

6. The Color of Gold

T. D. Lee [22] reminded us that the main reason we are in this business of inverse alchemy (transforming Au into a colorful, strange and charming topless-bottomless quark-gluon plasma), is to wreak havoc on the non-perturbative QCD vacuum. The Au beams are the bulldozers with which we hope to sweep away the vacuum condensates over a large space-time volume. The ultra-dense matter formed in their wake, at least at RHIC energies and above, should be most economically described in terms the fundamental quark and gluon degrees of freedom rather the hoards of resonances in the particle data book or the subroutines of event generators. As discussed by K. Eskola [22] and X.N. Wang [22], high energy nuclear collisions provide the unique tool to probe experimentally the structure of the physical vacuum by heating it to at least 10 GeV/fm$^3$ in the form of $\sim 1000$ mini-jets. At present AGS and SPS energies, the energy densities are significantly smaller but perhaps sufficient to penetrate through the intermediate mixed phase. The precise nature of the QCD transition remains unclear. In Figure 9, the state the art [53] from the lattice QCD as discussed by F. Karsch [22] is shown. This is similar to many previous calculations but perhaps closer to the continuum limit, and also the temperature scale is fixed using the nonperturbative beta function and the $\rho$ mass measured on the lattice. It shows that the transition is perhaps continuous but still confined to a rather narrow temperature range. The perturbative Stefan Boltzmann domain may hold approximately already at $T > 2T_c \approx 300$ MeV, which is easily reached at RHIC. Near the mixed phase region, significant deviations from ideal behavior is expected and maybe that is why hadronic
transport models are working so well at present AGS and SPS energies.

T. D. Lee[22] also presented a new theory[54] involving a non-compact formulation of lattice QCD that removes spurious fermion modes while retaining computation advantages of a finite lattice. A complete set of Bloch wavefunctions was proposed in which to expand the wavefunction of the QCD vacuum. The next step requires a clever choice of a trial wavefunction with the goal of computing systematic corrections perturbatively including higher bands.

Figure 9: The energy density and pressure in units of $T^4$ as a function of temperature for $N_f = 2$ QCD on a $12^3 \times 4$ lattice from [53]. The squares and circles are for quark masses $m_q/T = 1/4, 1/10$ respectively.

On the Disordered Chiral Condensate front introduced last meeting by Wilczek[1], we heard several progress reports. Gavin[22] discussed its formation and proposed several observables that may help look for them. In particular there may be a low $p_T$ enhancement above the huge incoherent background. However, Asakawa[22] showed that the so called annealing scenario does not favor DCC formation using a simulation that includes both transverse and longitudinal expansion. The original rapid quench scenario, which seems to allow for the growth of DCC crystals, requires on the other hand a miraculous inverse Baked-Alaska scenario proposed by Bjorken, whereby the hot plasma ejects rapidly its enormous entropy and leaves a cold chunk of disoriented vacuum behind. This is a looong shot, but worth searching for.

A major new development reported at this meeting by Venugopalan[55] was a theory for the gluon and quark structure functions for very heavy nuclei. All parton cascade
models, such as HIJING, VENUS and PCM, must make assumptions on how the structure functions of nuclei may differ from \( A^1 \) times that of nucleons. Shadowing and anti-shadowing effects can significantly modify the initial conditions (see Wang and Eskola\cite{22}). The initial conditions of course control the final observables. For example, Mount \( RHIC \) in Figure 1 could be 2-4 times as high, as in the PCM model\cite{12}. This translates into macroscopic differences in the final transverse energy corresponding to several \( \text{ergs} \) per unit rapidity!! This uncertainty originates from the poorly known early evolution of the mini-jet plasma. By developing a systematic treatment of the origin of the non-abelian Weizsacker-Williams fields around nuclei, it should be possible to compute the early evolution of the color fields more reliably. This method should enable us to estimate the height of Mount \( RHIC \) better in the near future\cite{56}.

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[56] The Fall 1996 program of the Institute for Nuclear Physics in Seattle, WA will concentrate on this topic; contact organizers L. McLerran or me.