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Report on the Parallel Session on High Energy Nuclear Interactions

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Abstract

The possibility that high energy nuclear collisions may give some new insight into the dynamics of QCD is discussed. Recent experimental data on the EMC is discussed in the perspective of various theoretical models for the effect. The prospects of making and observing a quark-gluon plasma in ultra-relativistic nuclear collisions is reviewed. The status of experimental programs at CERN and at BNL is assessed.

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1 Introduction

Perhaps the most interesting aspect of high energy nuclear interactions is that it may allow for tests of unique features of QCD. These features reflect non-perturbative phenomenon such as confinement and chiral symmetry breaking. In this talk I shall first give an overview of current theoretical understanding of these non-perturbative phenomenon. The EMC effect gives a measure of these effects when particle number densities are of the order of those in nuclei, $\rho \sim 0.15\ \mathrm{Fm}^{-3}$. This density is less then the typical density scale set for QCD, $\rho \sim \Lambda_{QCD}^3 \sim 1\ \mathrm{Fm}^{-3}$.

To study matter at densities of the order of and larger than those typical of QCD, we must study either the collisions of ultra-relativistic nuclei, or very high multiplicity fluctuations in hadron-hadron collisions. We shall see that simple arguments suggest that densities far in excess of those typical of ordinary nuclei may be achieved under such extreme conditions. I will briefly discuss a few suggested experimental probes of high density matter as it might be produced in such collisions.

There is now a major experimental effort under way at CERN and BNL to make and study ultra-relativistic nuclear collisions, as well as an effort at FNAL to study the extreme environment provided in high multiplicity fluctuations in $\bar{p}p$ collisions at the Tevatron. I shall briefly outline these programs, describing who is involved in these experiments, what they will attempt to measure, and when various experiments will be running.

An exciting subject which I shall not review in this talk is small-x physics. This problem has been studied in detail by the Leningrad groups of Gribov-Levin-Ryskhin and by Frankfurt and Strickman.[1,2] There were no representatives of these groups to present results at this meeting, and with my incomplete knowledge of the field, I do not feel competent to review it.

2 The Properties of High Energy Density Hadronic Matter

In this section I shall discuss the properties of hadronic matter at high energy density. The word high implies a scale for the measurement of the energy density. Such a scale may be provided by a variety of estimates, all of which agree on the order of magnitude of a typical density scale for hadronic matter. The first is the energy density of nuclear matter. With m the proton mass, R_A the nuclear radius, and A the nuclear baryon number, the density of nuclear matter is

$$\rho_A \sim \frac{Am}{\frac{4}{3}\pi R_A^3} \sim .14\ Gev/Fm^3 \tag{1}$$

We can also use Eq. 1 to estimate the energy density inside a proton. If we use a proton radius of .8 Fm, Eq. 1 gives

$$\rho_p \sim .5\ Gev/Fm^3 \tag{2}$$

There is a good deal of uncertainty in this estimate of ρ_p. We might have instead used the MIT bag radius, or a proton hard core radius, corresponding to an order of magnitude uncertainty in Eq. 2. Finally, another estimate comes from dimensional grounds using the value of the QCD Λ parameter, suitably defined as Λ_{ms} or Λ_{mom}, as the dimensional scale factor. Using the Λ parameter, we find

$$\rho_{QCD} \sim \Lambda^4 \sim .2\ Gev/Fm^3 \tag{3}$$

Again there is an order of magnitude uncertainty both due to the lack of precise experimental knowledge of Λ, and differences induced by using alternative sensible definitions of Λ.

In all of the above energy density estimates, the typical scale was in the range of several hundreds of Mev/Fm^3 to several Gev/Fm^3. At energy densities low compared to this scale, we presumable have a low density gas of the ordinary constituents of hadronic matter, that is, mesons and nucleons. At densities very high compared to this scale, we expect an asymptotically free gas of quarks and gluons.[3] At intermediate energy densities, we expect that the properties of matter will interpolate between these dramatically different phases of matter. There may or may not be true phase changes at some intermediate densities.

To understand how such a transition might come about, consider the example of QCD in the limit of a large number of colors, N_C.[4] Recall that extensive quantities such as the energy density, ϵ, or entropy density, σ, measure the number of degrees of freedom of a system. The dimensionless quantities ϵ/T^4 or σ/T^3 should be of the order of the number of degrees of freedom. For hadronic matter, the number of degrees of freedom relevant at low density are the number of low mass hadrons. Since matter is confined at low density, the number of such degrees of freedom is $N_{dof} \sim 1$ in terms of the number of colors. At high energy density, the relevant number of degrees of freedom are those of unconfined quarks and gluons. The gluons dominate and give $N_{dof} \sim N_C^2$. Therefore in the large N limit, the number of degrees of freedom change by an infinite amount.

Assuming that the transition occurs at finite temperature in the large N_C limit, as is verified

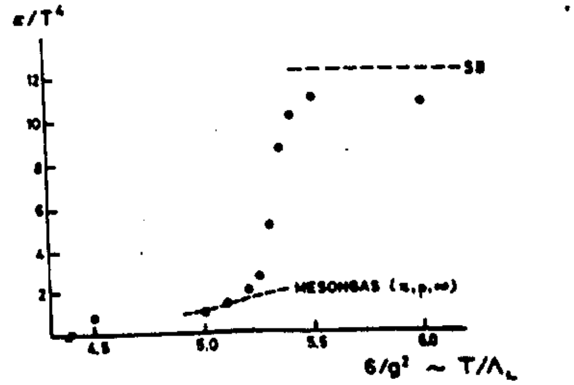

Figure 1: Energy density scaled by T^4 as a function of T

by Monte-Carlo simulation, this result can be interpreted in two ways.[5] From the vantage point of a high density world of gluons, the asymptotic energy density is finite, but at low energy density at some finite temperature the energy density goes to zero. The energy density itself is therefore an order parameter for a phase transition, and there is a limiting lowest temperature. Viewed from the low density hadronic world, there is some limiting temperature where the energy density and entropy density become infinite. Here there is a Hagedorn limiting temperature.[6]

For $N_C = 3$, the above statements are only approximate. The number of degrees of freedom of low mass mesons is

$$N_{dof} \sim N_F^2 \sim 4 \tag{4}$$

where we have taken the number of low mass quarks to be $N_F \sim 2$ for the up and down quarks. The number of degrees of freedom of a quark-gluon plasma is on the other hand

$$N_{dof} \sim 40 \tag{5}$$

The number of degrees of freedom might change in a narrow temperature range, or there might be a true phase transition where the degrees of freedom change by an order of magnitude, if our speculations concerning the large N_C limit are applicable.

Results of a Monte-Carlo simulation of the energy density are shown in Fig. 1.[7-12] These results are typical of the qualitative results arising from lattice Monte-Carlo simulation. The precise values of the energy density are difficult to estimate as is the scale for the temperature. The figure does make clear the essential point, on which all Monte-Carlo simulations agree, that the number of degrees of freedom of hadronic matter changes by an order of magnitude in a narrowly defined range of temperature. There is apparently a first order phase transition for SU(3) Yang-Mills theory in the absence of fermions, and a rapid transition which may or may not be a first order transition for SU(3) Yang-Mills theory with two or three flavors of massless quarks.

For Yang-Mills theory in the absence of dynamical quarks, there is a local order parameter which probes the confinement or deconfinement of a system. This order parameter measures the exponential of the free energy difference between the thermal system with and without the presence of a single static test quark inserted as a probe,

$$< L > = e^{-\beta F_q} \tag{6}$$

As originally proposed by Polyakov[13] and Susskind,[14] and developed in Monte-Carlo studies,[8,9] the Polyakov loop is a Wilson loop at the position of the quark which evolves only in time and is closed by virtue of the thermal boundary conditions which make the system have a finite extent in Euclidian time. The two phases of the theory are the confined and unconfined phases where

$$e^{-\beta F_q} \sim \; finite\; if\; confined, \;\; or\; 0\; if\; deconfined \tag{7}$$

This quantity is an order parameter for a confinement-deconfinement in theories without fermions or in the large N_C limit in theories with fermions (in the fundamental representation of the gauge group). If there are fermions in the fundamental representation, in the 'confined phase' dynamical fermions may form a bound state with a heavy test quark, so the free energy is finite in what would be the confined phase.[15] Since it is already finite in the deconfined phase, the free energy of a static test quark does not provide an order parameter.

Although $< L >$ is not an order parameter, Monte-Carlo simulations with dynamical fermions show that $< L >$ changes very rapidly in a narrow range of temperatures. This is illustrated in Fig 2,[7] which is typical of lattice computations. For SU(3) lattice gauge theory without dynamical quarks, when $< L >$ is a true order parameter, there is a noticeable discontinuous change. It is

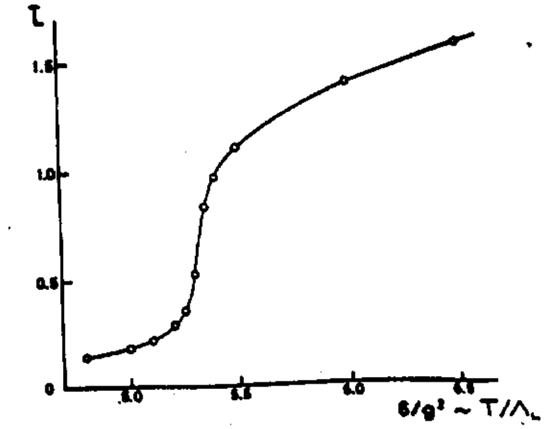

Figure 2: Exponential of free energy of isolated static quark as a function of T

not entirely clear whether there is a discontinuous change corresponding to a true phase change for the theory with fermions.

In the limit of large dynamical quark mass the quarks are no longer important at any finite temperature and decouple. In this limit the confinement-deconfinement phase transitions is a well defined concept with an order parameter which measures a phase change. At zero quark masses there is another phase transition which may be carefully defined, that is, the chiral symmetry restoration phase transition. Chiral symmetry is a continuous global symmetry of the QCD lagrangian in the limit of zero quark mass. Its realization would require that all non-zero mass baryons have partners of degenerate mass and opposite parity. Since this is far from true for the spectrum of baryons observed in nature, chiral symmetry must be broken. Breaking the continuous global symmetry generates a massless Goldstone boson, which we identify with the light mass pion. As a consequence of the breaking of chiral symmetry, the quarks acquire dynamical masses, which may be seen by computing $< \overline{\Psi}\Psi >$. For the chiral symmetric phase, $< \overline{\Psi}\Psi > = 0$, and is non-zero in the broken phase.

For not unreasonable values of the quark masses, $< \overline{\Psi}\Psi >$ is plotted in Fig. 3. There appears to be a rapid change in $< \overline{\Psi}\Psi >$ at about the same place where the order parameter $< L >$ changes rapidly. We conclude therefore that chiral symmetry is approximately restored at the same temperature where quarks stop being approximately confined. The word approximately is important here since absolute confinement or abso-

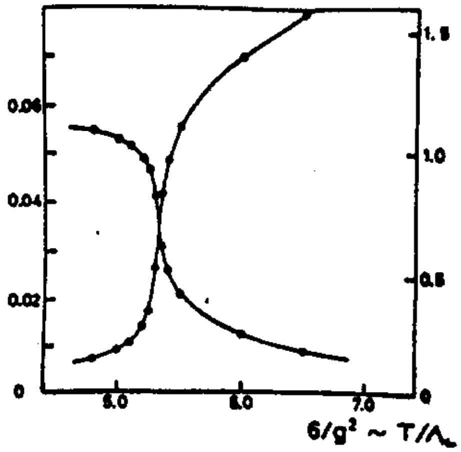

Figure 3: $\overline{\Psi}\Psi$ and free energy of isolated quark as function of T

lute chiral symmetry is impossible for finite mass dynamical quarks.

We can now conjecture on the phase diagram in the temperature mass plane. It is important to realize that we may physically vary the temperature, but not the masses of quarks. Theoretically in a Monte-Carlo simulation, these masses may be changed, but they cannot be changed in nature. It is also important to realize that the mass-temperature diagram represents an oversimplification to the case of equal mass quarks. With different mass quarks, the diagram has more variables and is more complicated.

To plot this diagram, we first discuss the limiting case $m = \infty$. Here there should be a first order confinement-deconfinement phase transition along the T axis. Since a discontinuous change will not be removed by a large but finite quark mass, this first order phase change must be a line of transitions in the m-T plane as shown in Fig. 4. Along the $m = 0$ axis there is a chiral symmetry restoration transition. By the arguments of Pisarski and Wilczek,[16] this transition is first order, and therefore must generate a line of transitions which extends into the m-T plane.

Of course, we do not know what happens with these two lines of transitions, whether they join or never meet, or pass through one another etc. There may be no true phase transition at the values of masses which are physically relevant, or there may be one or two which are the continuation of the chiral transition from zero mass and

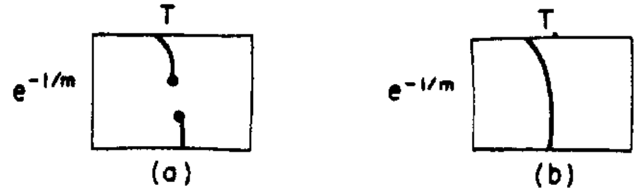

Figure 4: Phase diagrams in the T-m plane for a world where chiral and confinement phase transitions are (a) separate and (b) identified

the confinement-deconfinement transition from infinite mass. The weight of the evidence from Monte-Carlo numerical simulation suggests a very large transition in the properties of matter in a very narrow temperature range, and not much more than that can be said at present. There are a variety of conflicting claims as to whether or not there is a true first order transition at physically relevant masses.[17-22]

There have been serious attempts to obtain reliable quantitative measures of the properties of matter from Monte-Carlo simulation.[23,24] The only truly reliable numbers have been extracted for the unphysical case of $N_F = 0$, that is, no dynamical fermions. It has been shown that the critical temperature of the confinement-deconfinement transition is

$$T_C \;=\; 220 \;\pm\; 50\; Mev \qquad (8)$$

by fitting the potential computed in these theories and comparing it with the potential which fits charmonium. This corresponds to an energy density of $1 - 2\ Gev/Fm^3$ required to make a quark-gluon plasma. These results now appear to be valid for the continuum limit, and seem to be fairly good.

The numerical situation for QCD with $N_F = 2 - 3$ is not nearly so good. The qualitative results have been summarized above, but it is premature to draw any firm conclusions about numbers.

3 The EMC Effect or Physics for $\rho \;\leq\; \Lambda^4_{QCD}$

The density of nuclear matter is $\rho \sim 150\ Mev/Fm^3$, a density which is not so small compared to the scale of densities appropriate for QCD. An outstanding question is whether the high energy density environment provided by nuclei can in anyway allow for an understanding of novel features of QCD. For example, is it possible to measure the effects of quarks in nuclear matter, as different from their presence in ordinary nucleons.

Certainly at some level it must be true that the structure functions of quarks in nucleons, $q_N(x)$ and those of nuclei, $q_A(x)$ must be different. The presence of a nuclear environment certainly allows the quarks to propagate over a larger distance scale than is true for nucleons. This may occur through multi-nucleon interactions where in some sense the quark degrees of freedom propagate through the medium of multi-nucleon forces, or it may happen because quark degrees of freedom may propagate more freely because the nucleon bag swells due to the presence of the nuclear medium. In any case, the shift in the spatial correlation length is correlated with fluctuations in the momentum space distributions because of the uncertainty principle. On quite general grounds, it is possible to show that such an increased freedom for quarks results in a degradation of the momentum of the quarks, that is, the structure functions in nuclei are softer than is the case for nucleons. (For very fast quarks, however, Fermi motion will promote some quarks to the region of $x > 1$. There are not many quarks with such large momentum, and this effect is fairly small, and difficult to measure. We are measuring the momentum distributions of quarks in terms of the energy per nucleon.)

The difficulty of using ordinary nuclei to measure the properties of high density matter are of course that the matter density is not so large, and more important, the variation in density between nuclei is quite small. Because of this small range of density variation in a range of densities probably significantly lower than is needed to study novel features of the phase diagram of QCD, it is difficult to assess the possibilities of producing such new phases of matter in high energy nuclear collisions from data on the EMC effect.

There has been much discussion of the EMC effect at this meeting [25–30]. Some claims have been made in lunchtime conversations that the effect has disappeared. In Fig. 5 the data prior to May 1986 for the ratio of structure functions of iron to deuterium is plotted. In Fig. 6, the corresponding new data from this year are plotted, taken from Ref. 31. The data in this figure are from Refs. 25-27 as given in Ref. 31. The EMC data has been

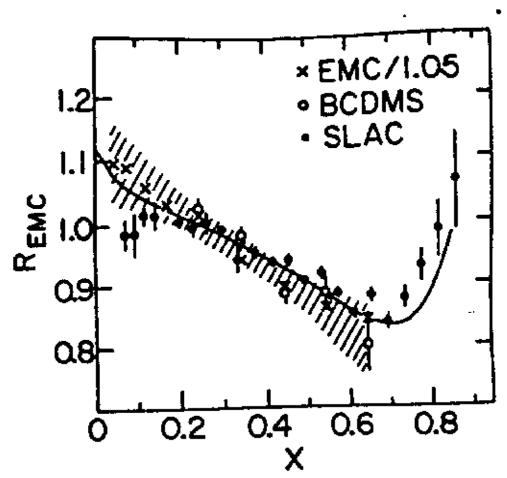

Figure 5: A compilation of data on the EMC effect prior to May 1986.

rescaled by 1.05, and the shaded band represents the EMC group's estimate of the systematic uncertainty. It is clear that the old data and the new data are consistent with one another, if the rescaling by a factor of 1.05 is done to the old EMC data[25]. This rescaling is consistent with quoted systematic uncertainties. Not shown on Fig. 6, is new data, from Ref. 32 where the ratio of $d\sigma/dx$ for Fe and deuterium have been measured with neutrinos, which is also of about the same size as would be inferred from muon measurements.

The controversy over the EMC effect arises not so much from new experimental data, which confirm the effect, but more from theorists enthusiasm based on estimates using the old EMC measurements not rescaled by 1.05. Theoretical speculations have included just about all possibilities from the most radical, that quarks are fully deconfined in nuclei, to the most conservative, where the effect is explained by conventional nuclear physics interactions within the nuclear matter. The size of the predicted effect is of course directly correlated with the radicalness of the theoretical description. The two most popular descriptions of the EMC effect have been explanations based on conventional nuclear physics,[33–35] and the description based on a variable scale parameter for QCD whose magnitude depends upon the density of the media in which it is measured.[36]

Very general arguments suggest that the conventional nuclear physics description, based on models of incoherent nucleons and mesons, must

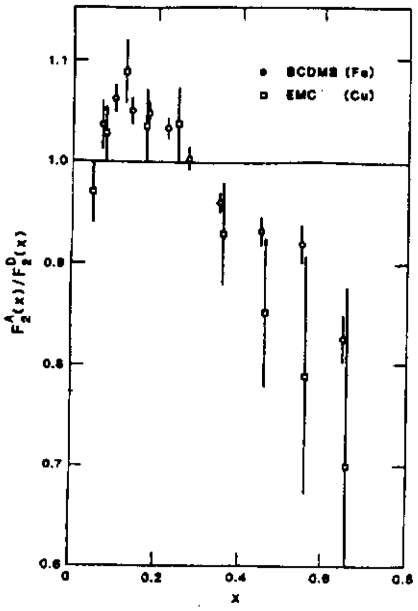

Figure 6: A compilation of new data on the EMC effect.

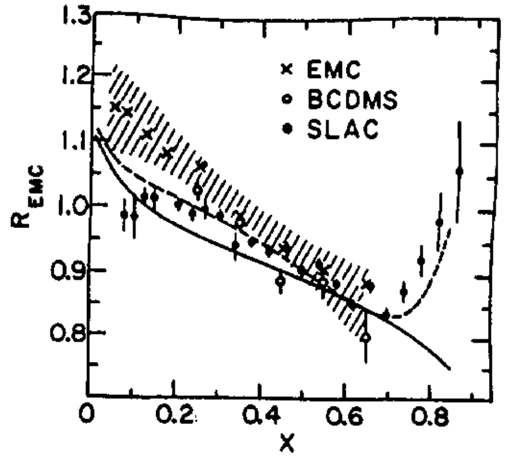

Figure 7: Comparison of nuclear physics model (upper dashed line) with Q^2 rescaling model (lower solid line).

break down at some density scale. Also, at any density, the scale of QCD must change due to the presence of nuclear matter. The real issue is which description adequately and economically describes the data at nuclear matter energy densities. At this range of densities, there is nothing which a priori forces one description to be right or another wrong, although the most exciting possibility would be that one could not describe the effect using conventional nuclear physics.

A comparison of between the Q^2 rescaling model[36] and a nuclear physics computation[34] are shown in Fig. 7. In this figure, the Q^2 rescaling model is evaluated for Q^2 values typical of the EMC experiment.The EMC data is the old data not rescaled down by a factor of 1.05

This comparison shows that the nuclear physics model may do a little better fitting the EMC data than does the Q^2 rescaling model. However, when Q^2 values appropriate for the SLAC data are used in this model, it seems to fit the data fairly well. I think the conservative conclusion based on this type of comparison is that a suitably tailored Q^2 rescaling model or nuclear physics model may be designed to fit the data. The data therefore do not yet warrant radically new phenomenon for their explanation, and a conventional nuclear physics model seems adequate.

Perhaps a better a good way of resolving the difference between the Q^2 rescaling model, and nuclear physics models may be provided by measuring anti-quark distributions in nuclei. The nuclear physics models typically have larger contributions from anti-quarks, arising from an enhanced meson contribution, relative to the rescaling model, where anti-quark distributions are not much enhanced by simply rescaling the distributions. In Fig. 8, a comparison of these two models is shown. The upper curve is a nuclear physics calculation and the lower comes from a rescaling model. The data points with the large error bars are from Ref. 28. The small error bars represent what might be gotten from the experiment FNAL-772.[37] With the results from FNAL-772, these two different models might be clearly resolved.

In conclusion, it seems there is indeed an EMC effect, although no compelling case has been made that it might not be explained as a conventional nuclear physics effect. Perhaps measurements of anti-quark distributions may improve the situation.

4 How to Make a Plasma

The collisions of ultra-relativistic nuclei and fluctuations in $\bar{p}p$ collisions provide the possibility of producing a quark-gluon plasma in a controlled experimental environment.[38,39] Such a collision is shown in Fig. 9 where two nuclei of transverse ra-

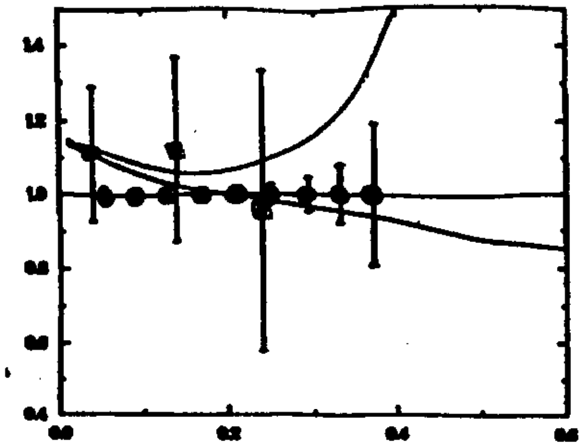

Figure 8: Anti-quark distributions in nuclei. Plotted is the ratio of anti-quark distributions in Fe to D as a function of Feynman x

dius R collide in the center of mass frame. The longitudinal size of the nuclei is Lorentz contracted.

There is a scale implicit in the Lorentz contraction. Once the nuclei have a large enough Lorentz gamma factor so that they would be contracted to a size less than some typical hadronic length scale, possibly a fermi, the Lorentz contraction of virtual quanta with energy corresponding to this length scale stops. Below the beam energy appropriate for this gamma factor, the nuclei Lorentz contract. This energy is

$$E^0_{CM} = m\gamma = \frac{mR}{l_0} = 7 - 70\ Gev \qquad (9)$$

for uranium nuclei and the hadronic distance scale $l_0 \sim .1 - 1\ Fm$. Here and in the rest of this paper, we shall quote the center of mass energy in Gev per nucleon in each nucleus.

We expect qualitative differences in the scattering above E^0_{CM}. Another equivalent estimate of E^0_{CM} is given by estimating the energy at which the fragmentation regions of the two nuclei separate. At energies greater than E^0_{CM} there will be a central region between the two colliding nuclei, which will have small net baryon number density.

An important fact to remember about the matter formed in the collision of two ultra-relativistic nuclei is that it is born expanding in the longitudinal direction. This is because particles are formed with a more or less uniform density in rapidity. Since these particles follow a trajectory which has its origin approximately at $x = t = 0$, and there is

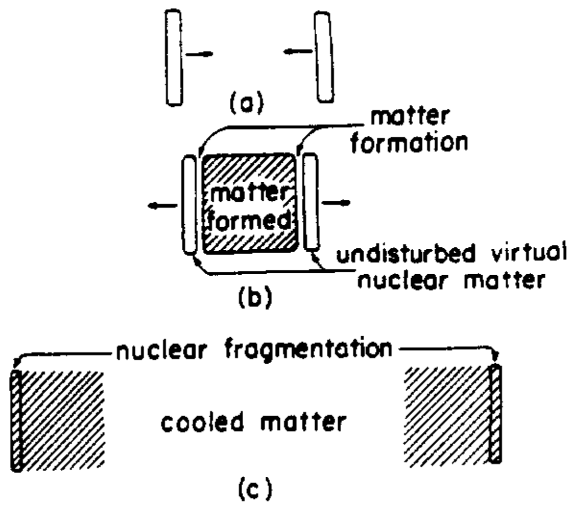

Figure 9: AA collision in the center of mass frame

a large dispersion in particle velocities, there will be a large longitudinal velocity gradient built into the initial matter distribution. There should be no transverse expansion in the initial condition since we expect a random orientation in the transverse momentum of produced particles. It can be shown that if the distribution of produced particles is uniform in rapidity, the expansion is initially a 1+1 dimensional similarity expansion, and the density of particles decreases like $1/t$.

The initial energy density may be estimated on dimensional grounds. The initial energy density should be proportional to the initial rapidity density per unit transverse area. The energy per particle should be of the order of the typical transverse momentum per particle. The longitudinal distance scale and p_T are correlated at early time by the uncertainty principle, since initially the matter appears in a quantum mechanical state, $p_T \sim 1/l_o$. We therefore have

$$\epsilon_i \sim \frac{dN}{dy} \frac{1}{\pi R^2} p_T^2|_{t=t_i} \qquad (10)$$

The initial time t_i will be chosen as the earliest time we believe that the matter may be described as approximately expanding as a perfect fluid.

If the matter expands approximately as a perfect fluid, then ϵ_i may be bounded by parameters which are experimentally measured at late times after the matter decouples, that is, after the pions present in the late state of evolution of the matter have stopped scattering from one another, and are experimentally observed. We first use that the rapidity density in perfect fluid hydrodynamic expansion is proportional to the entropy and because entropy is conserved, one can prove that dN/dy is also conserved, at least in the central region.[40] Since the system cools as it expands, p_T is a monotonically decreasing function of time. (Some of the transverse momentum is recovered by transverse flow, but p_T nevertheless monotonically decreases.) We find therefore that

$$\epsilon_i \; > \; p_t^2 \, \frac{1}{\pi R^2} \, \frac{dN}{dy} \tag{11}$$

In this equation, all quantities are experimentally observable.

Eq. 11 may be used in combination with experimental data from the JACEE collaboration cosmic ray experiment to estimate ϵ_i.[41] For average $\overline{p}p$ collisions at $E_{CM} \sim 100 \; Gev$, $\epsilon_i \sim .6 \; Gev/Fm^3$. If we take the average multiplicity for head-on collisions to be $2A^{1/3}$ as is consistent with the JACEE results and conservatively estimate p_T as the value appropriate for $\overline{p}p$ collisions, we find $\epsilon_i \sim 10 \; Gev/Fm^3$.

To emphasize how difficult it is to make these cosmic ray measurements, I have shown in Fig. 10, a photo of the emulsion in a C Pb interaction at total energy of about 10^3 Gev. This is the most energetic interaction found in the JACEE experiment to date. If the reproduction appears to you to be only a black splot, you are not mistaken. The analysis of events with so many tracks in such a small emulsion chamber as can be put on a balloon is difficult.

The initial energy density might be much larger than this for a variety of reasons. In fluctuations in $\overline{p}p$ collisions, the multiplicity may be much larger. In nuclear collisions, the initial p_T may be much larger than is typical of the final state. This initial p_T may be determined by kinetic theory arguments, and might be in the range of $.4 - 2 \; Gev$,[42,43] corresponding to uncertainty in the energy density of at least an order of magnitude. The initial transverse momentum, and correspondingly, the initial time, may even depend upon the nuclear baryon number A.[44-46] I think the best estimates of the achievable energy densities in central collisions of large nuclei is $2 - 200 \; Gev/Fm^3$. This corresponds to an initial temperature in the range of $T_i \sim 200 - 700 \; Mev$.

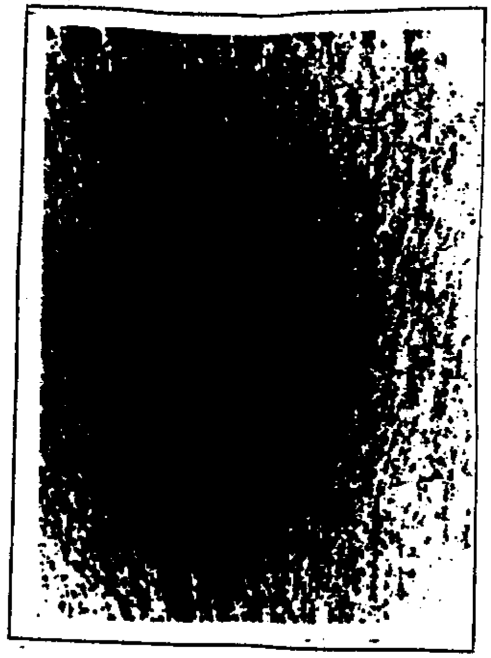

Figure 10: Emulsion photo of the most energetic cosmic ray interaction yet recorded in the JACEE experiment

Such a large uncertainty in the parameters which describe matter formed in ultra-relativistic nuclear collisions is unfortunately typical of the field, a field where there has been little experimental data. While the range of achieved energy densities seems sufficient to form a quark-gluon plasma, there is much reason for caution.

To make a convincing case that there is sufficient time for the formation and evolution of a quark-gluon plasma as an approximate perfect fluid, the expansion rate of the system should be compared to a typical particle collision time. When the collision time is much less than the expansion time, the system should expand approximately adiabatically as a perfect fluid. Since entropy is conserved, the initial and final times for expansion in d dimensions are related by

$$\left(\frac{t_f}{t_i}\right)^d \; = \; \frac{N^i_{dof}}{N^f_{dof}} \, \frac{T_i^3}{T_f^3} \; \sim \; 10 - 10^4 \tag{12}$$

where σ is the entropy density and N_{dof} are the number of particle degrees of freedom. At early time, the expansion is 1 dimensional, and later times becomes three dimensional. We estimate therefore that $t_f/t_i \sim 10 - 10^3$. Detailed hydrodynamic computations show that the final decoupling time is probably somewhere in the range of

$t_f \sim 20 - 50\ Fm/c$.[47,48]

Large nuclei are clearly the more favored system for producing and studying a quark-gluon plasma. This follows simply from the facts that the average energy density achieved is larger, and that the system is physically larger in transverse extent. We require $\lambda_{scat} << R_{nuc}$ in order for a perfect fluid hydrodynamic treatment to be sensible. Estimates of λ_{scat} give $.1 - 1\ Fm$.[42,43]

Experimental data exists which throws some light on the size of systems necessary for fluid dynamic effects to become important. At Bevalac energies, the flow of hadronic matter was studied in nuclear collisions.[49,50] In collisions of nuclei of small impact parameter, single particle collisions occur at large transverse momentum. The nuclei do not collectively flow in a given transverse direction unless there are subsequent rescatterings among the constituents of the nuclei. If these subsequent rescatterings do not occur, the transverse momentum of each particle is randomly oriented. To get collective flow, one needs rescattering, and this should be enhanced in collisions at small impact parameter, and collisions of large A nuclei.

In Fig. 11, the flow angle is plotted for various measures of the impact parameter (large impact parameters at the top and small at the bottom of the figure) for various nuclei (small on the left and large on the right). Little evidence of flow is shown for nuclei as large as calcium, and collective effects begin to become important for nuclei of the size of niobium.

5 Probes of the Quark-Gluon Plasma

In Table 1, various experimental probes of the quark-gluon plasma are presented.

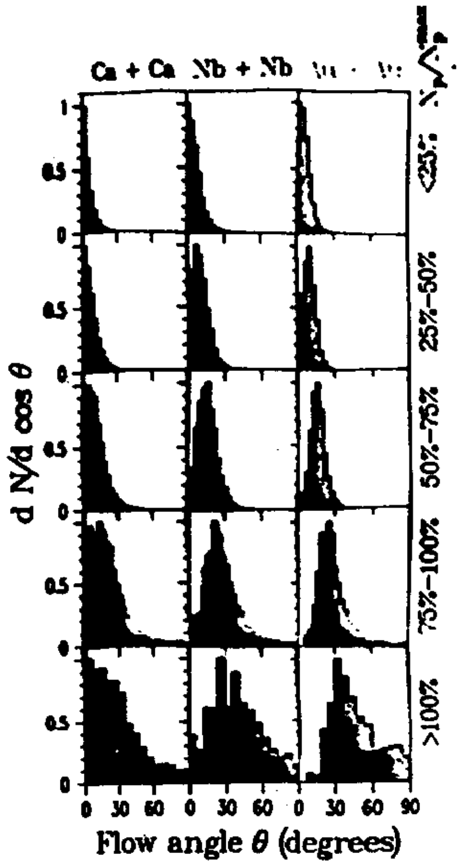

Figure 11: Flow distributions as measured by Gustafsson et. al.

Probes of the Quark-Gluon Plasma

Probe	Physics
Photons and Dileptons	T_i, T_{PT}, Plasma expansion, impact parameter meter, resonance melting
p_t distributions	Equation of state, Evidence of fluid flow
Strangeness	Dynamics of Expansion
Pion Correlations	Size and Lifetime of plasma
Jets	Scattering cross section of quarks or gluons with plasma and hadronic matter

We shall discuss in detail these probes in this section. The bottom line on all of these probes is that they all will involve correlations between several variables. For example, just the requirement of head-on, small impact parameter collisions requires a cut either on total multiplicity or nuclear

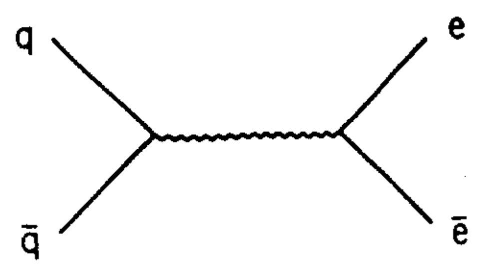

Figure 12: Quark anti-quark annihilation into a di-lepton pair

fragmentation. Because of this often times complicated analysis of correlated variables, it is difficult to argue that any one of the probes will yield an unambiguous signal for a plasma. Nevertheless, in several cases such as photon and di-lepton probes, with a little luck it may be possible to construct a convincing case that a plasma has been formed, and to measure some of its properties.

5.1 Photons and Dileptons

In Fig. 12, quark-antiquark annihilation to produce di-lepton pairs is shown. If we sum over all possible quark-gluon interactions in the initial and final state, then the overall rate for production of di-leptons and photons per unit time and volume is proportional to[51]

$$\frac{dN}{dt\,d^3x\,d^4q} \sim Im \int d^4x \, < J^\mu(x) J^\nu(0) > \, e^{iqx} \tag{13}$$

This assumes emission from a plasma at a fixed temperature T. The brackets $<>$ denote a thermal expectation value. The current $J^\mu(x)$ has a real, Minkowski time argument.

There are of course a variety of non-thermal sources for di-leptons and photons. There are backgrounds for photons from π^o decays, which in the low q region obscure the signal. There may also be backgrounds for the di-leptons arising from decays of charmed particles. For large q, hard scattering processes from the initially unthermalized beams of quarks and gluons presumably dominate. As the momentum is softened, the contributions arise from an ever more thermalized system which eventually may come from a plasma, provided backgrounds from soft hadronic decays do not become too large of a background. In this intermediate range of q, there are several thermal regions which contribute. At the higher q values, there is presumably a contribution from a quark-gluon plasma, at lower q a mixed phase of plasma and hadronic gas, and at the lowest q values larger than that for which background becomes important, there is a contribution from a hadronic gas.

To compute these distributions of photons and di-leptons, a knowledge of the space-time history of the evolution of the quark-gluon plasma is required.[52-55] Detailed estimates of the space-time evolution of matter produced in head-on collisions of nuclei at large A have now been carried out,[56-60] and the di-lepton distributions have been computed in detail. There has as yet been no attempt to treat non-zero impact parameter collisions. Techniques have also been developed to study the fragmentation region.[61-63] No attempt has been made to treat the pre-equilibrium region, although the cascade computation of Boal may be useful for this.[64] A treatment of the late stages in the evolution of the matter are best treated by cascade simulation of pion interactions, and again could easily be used to compute di-lepton and photon distributions.[65]

The general results of these analysis are the following:

1) For photons and di-leptons emitted from the plasma, the rapidity density of the electromagnetically produced particles is correlated with the rapidity density squared of hadrons. This has been shown to be a general feature of models where the electromagnetically produced particles are produced by final state interactions of hadrons.[66] A plot of this correlation computed in a 1+1 dimensional hydrodynamic model is shown in Fig. 13.[59]

2) Pion rapidity fluctuations are correlated with fluctuations in the di-lepton and photon production rate, at the same rapidity, for thermal emission. This correlation is much different from the case for Drell-Yan pair production where there is no such correlation.

3) The rate of thermal production may be as high as 10^2 times background for not unreasonable values of the temperature. The plasma contribution is most sensitive to the values of the initial temperature when the system becomes thermalized. In Figs. 14a-14b, these thermal distributions are compared to backgrounds from Drell-Yan, and

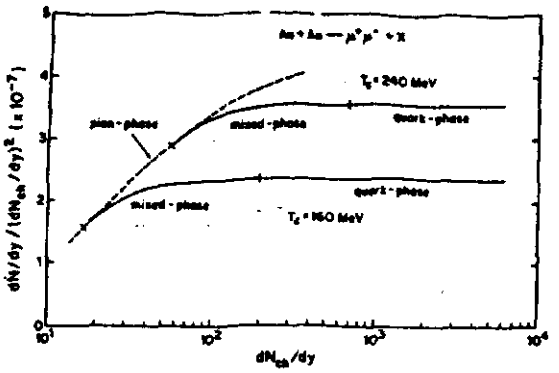

Figure 13: dN/dy of hadrons scaled by $(dN/dy)^2$ of hadrons for head on AA collisions as a function of dN/dy of hadrons

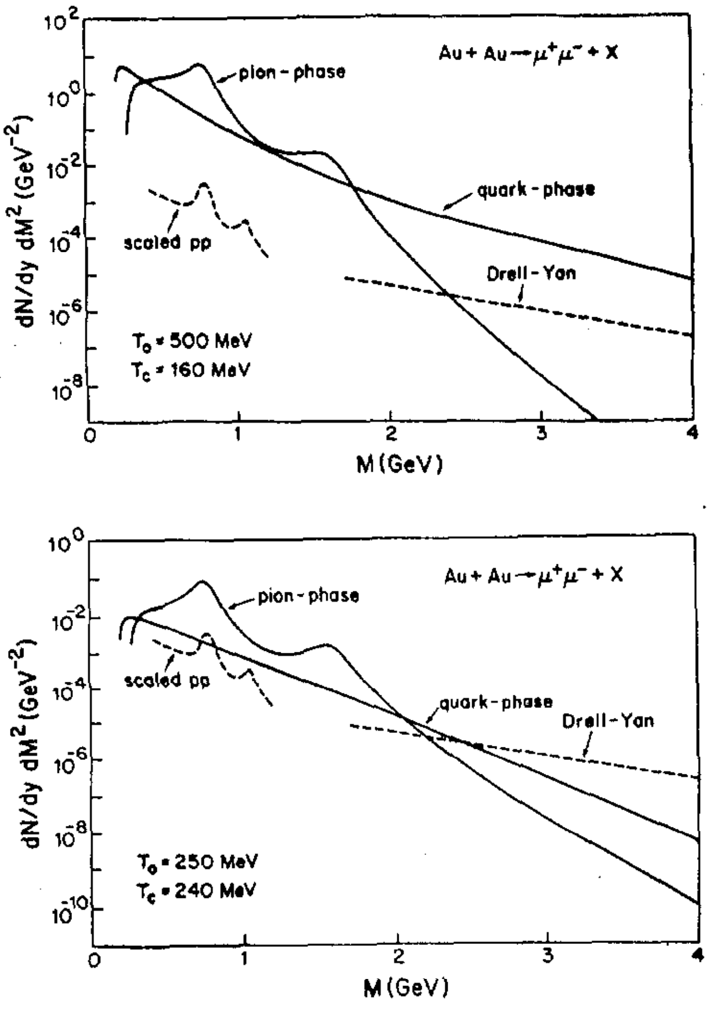

Figure 14: Di-leptons in ultra-relativistic nuclear collisions as a function of mass of di-lepton pair, (a) for an initial temperature of 500 Mev and (b) for 250 Mev.

a generous estimate of backgrounds from resonances and other low p_T phenomenon. For an initial temperature of 500 Mev, the thermal signal is always 10^2 times background for masses of 2-4 Gev, as shown in Fig. 14a. For initial temperature of 240 Mev, the di-lepton spectrum is shown in Fig. 14b. Here the plasma contribution is of the same order as the Drell-Yan contribution for masses of 2-4 Gev.

4) The shape of the thermal di-lepton distribution is fairly sensitive to T_i, the largest value of the temperature for which there is a thermal distribution. The effects of a pre-equilibrium distribution of quarks and gluons has not yet been included so this conclusion is a little soft.

5) For a quark-gluon plasma at high temperature, the distribution of di-leptons is a function only of the transverse mass, $M_t = \{M^2 + p_T^2\}^{1/2}$ There should be a strong correlation between M and p_T, a correlation not present in the Drell-Yan distribution for intermediate mass pairs.

6) The distribution of di-leptons in no simple way reflects the transition temperature. This is a consequence of doing a proper 3+1 dimensional hydrodynamic computation. In 1+1 dimensional computations, the transition temperature controls the distribution in the region of $M \sim 1 - 2$ *Gev*. The shape does of course weakly reflect the transition temperature, but there seems no obvious or convincing way to extract it.

7) The proposed melting of low mass resonances such as the ρ and ω, characteristic of 1+1 dimensional hydrodynamic simulations, [67–69] is not verified in 3+1 dimensional computations. In 1+1 dimensions, the ρ and ω disappear as a resonance in the mass spectrum at large p_T since di-leptons at large p_T are emitted from a high temperature plasma. A high temperature plasma has no ρ or ω resonance. This effect disappears in the 3+1 dimensional computations because transverse expansion makes a large amount of rapidly expanding hadron gas. This transversely expanding hadron gas dominates the spectrum for masses of $M \sim 1$ *Gev* and large p_T. The melting phenomenon is presumably still effective for large mass resonances such as the J/ψ.[70]

Some evidence for what may be thermal dileptons has been proposed in the ISR experiment R807/808[71]. They have attempted to correlate the ratio of single electrons to pions with total charged

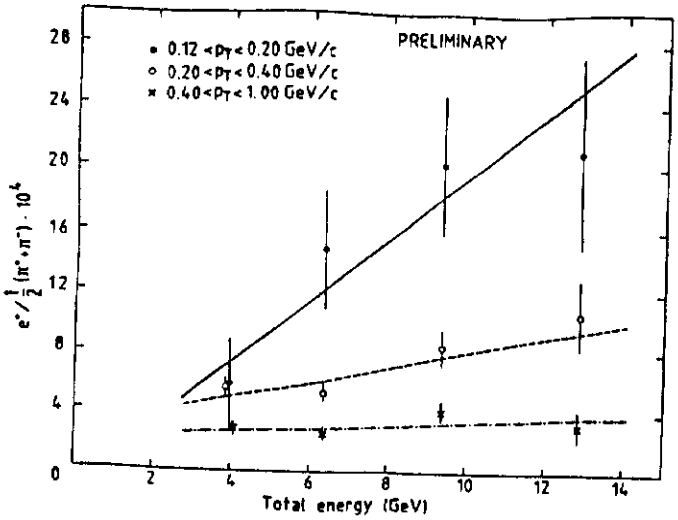

Figure 15: The correlation between e/π in experiment R807/808.

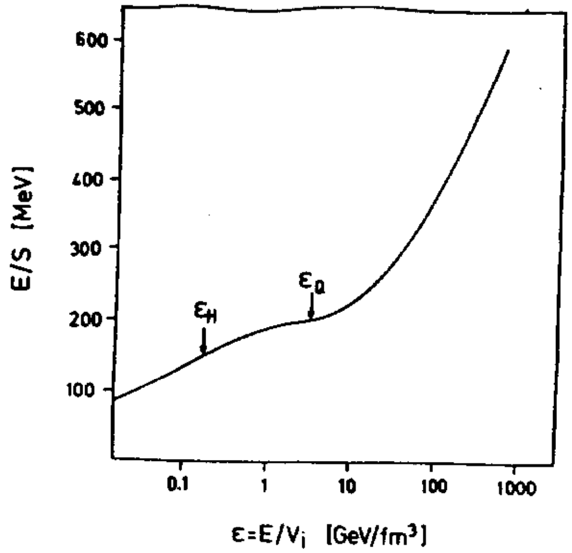

Figure 16: E/S vs ϵ in the MIT bag model

particle multiplicity. In Fig. 15, this correlation is plotted. This ratio should go like dn/dy of charged particles for a thermal source. The data seem to point in this direction, but to have a reliable indicator, it would be useful to have many of the other variables mentioned above measured.

5.2 The Correlation of p_T and $\frac{dN}{dy}$

The correlation between p_T and dN/dy reflects properties of the equation of state of matter.[72,73] This is easily seen from the example of a spherically expanding gas. We assume that at some initial time, there is a spherically symmetric drop of hadronic matter of uniform density matter at rest. We then allow the system to hydrodynamically expand. We assume we know the volume of the initial system, V_o. We measure the total energy of all particles and the total multiplicity of particles in the final state. Since the system is slowly expanding at late times, the entropy of particles in the final state is known assuming the particles were produced thermally from a weakly interacting gas. Since energy and entropy are conserved in the expansion of a perfect fluid, the energy and entropy of the final state is that of the initial state. We can therefore experimentally measure the correlation between say p_T, which is proportional to E/S, and the energy density.[74,75] We can compare this to a theoretically predicted correlation determined by knowing the equation of state.

A plot of E/S verse ϵ is shown in Fig. 16 for a bag model equation of state. The generic features of this curve are straightforward to understand. At low temperature, in the pion gas phase, and high temperatures, in the plasma phase, $E/S \sim T$. The energy density in these two phases goes as $\epsilon \sim N_{dof}T^4$. Since the number of degrees of freedom changes at the transition, there is a gap between these two curves. The gap is filled by the region where the plasma cools into a pion gas. This happens at a fixed T, and almost fixed E/S, for varying ϵ.

There are several problems when this is applied to the more realistic expansion scenarios appropriate for central collisions of heavy nuclei. First p_T is not conserved since longitudinal expansion causes the transverse momentum of individual particles to be converted into un-observed collective flow in the longitudinal direction. A correlation between p_T and say multiplicity is therefore weaker than is the case for spherical expansion. It also depends more on the detailed numerical simulation of the hydrodynamic equations. Also, the initial conditions for the matter are not so well known. The final state de-coupling and perhaps a phase change may produce some entropy. Fortunately these problems do not appear to generate much dispersion in the numerical results for such a correlation.[55] Finally, a severe limitation of present hydrodynamic simulations is that they are limited to the central region of impact parameter zero collisions. If we only have a multiplicity trigger to measure the degree to which collisions occurred at zero impact parameter, then the low

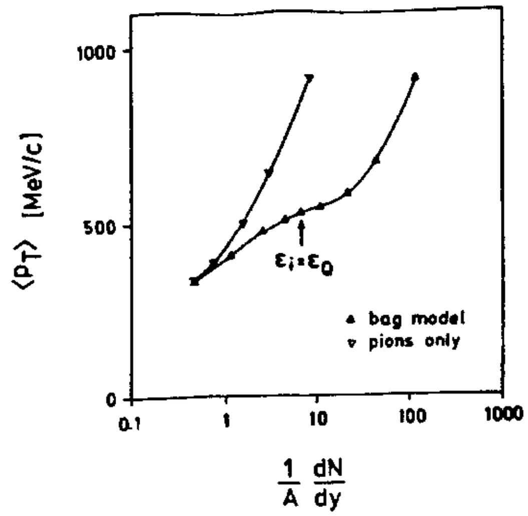

Figure 17: p_T vs multiplicity in head on heavy ion collisions for an ideal gas equation of state (upper curve) and a bag model (lower curve)

multiplicity events will always be dominated by large impact parameter, and their contributions have not been computed. The present computations may therefore only provide information on head-on collisions and their fluctuations. Since the number of particles is already large, the fractional fluctuations in the multiplicity for such head-on collisions is small.

There is also the potential problem of backgrounds from conventional processes such as mini-jets obscuring the p_T enhancement from a quark-gluon plasma.[76] At energies typical of the SPS collider, production of mini-jets is presumably responsible for the high multiplicity events. In nuclear collisions at energies less than or equal to those proposed at RHIC, mini-jets are not expected to be a large background since the beam energy is low. Moreover, mini-jets should thermalize in the high multiplicity environment typical of central collisions of large nuclei, thus changing the initial conditions by making the matter initially a little hotter, but yielding a correlation between p_T and dN/dy which may be computed by hydrodynamics.

In Fig. 17, the results of a hydrodynamic computation of p_T vs dN/dy is shown for an equation of state typical of the bag model and a pion gas equation of state. The difference between these curves is large suggesting that an experimental probe of this correlation can resolve various equations of state. A general feature is that the softer

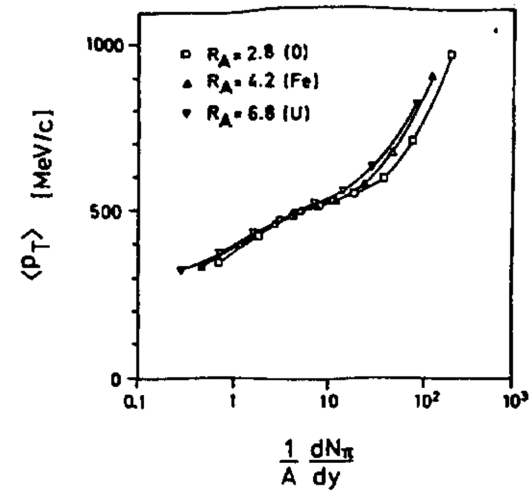

Figure 18: p_T vs dN/dy scaled by 1/A for a variety of A

is the equation of state, the softer is the p_T. A quark-gluon plasma produces lower p_T particles at fixed multiplicity than does a pion gas.

In Fig. 18, the same correlation is shown for head-on collisions of various nuclei. The curves approximately scale as a function of $1/A \; dN/dy$. The factor of $1/A^{2/3} \; dN/dy$ arises because the result must be proportional to the multiplicity per unit area. An additional suppression by a factor of $A^{1/3}$ arises due to the softening effects of longitudinal expansion.

As has been argued by Shuryak,[72] heavy particles should show the effect of collective transverse expansion more strongly than do light particles. This is shown in Fig. 19 where p_T is computed for pions, kaons and nucleons as a function of multiplicity. The physical origin of this effect is that in fluid expansion, there is a collective fluid velocity. Heavier particles have larger masses and therefore $p = mv\gamma$ is correspondingly larger.

In Fig. 20, the p_T distributions of pions, kaons and nucleons are shown. The distribution of nucleons clearly shows the effects of collective flow with the local maximum in dN/d^2p_T at $p_T \sim 1 \; Gev$.

In Fig. 21, an attempt is made to fit the experimentally observed correlation between p_T and transverse energy per unit rapidity as seen in the JACEE collaboration.[41] The JACEE data rises too rapidly to be explained by a quark-gluon plasma. The data does seem to be fit by a pion gas model (dashed line), but the temperatures where the system would be required to be in an ideal pion

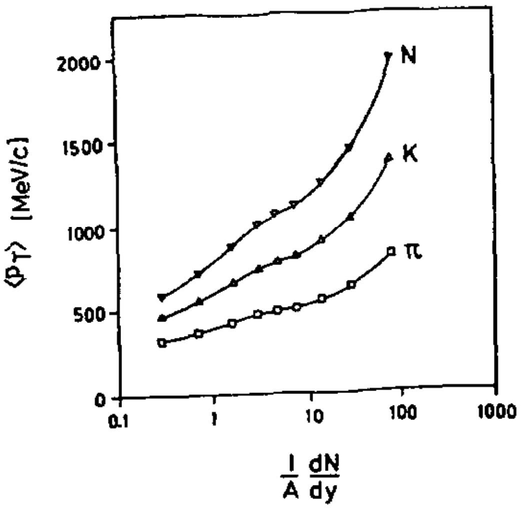

Figure 19: Average p_T vs dN/dy for a variety of particles

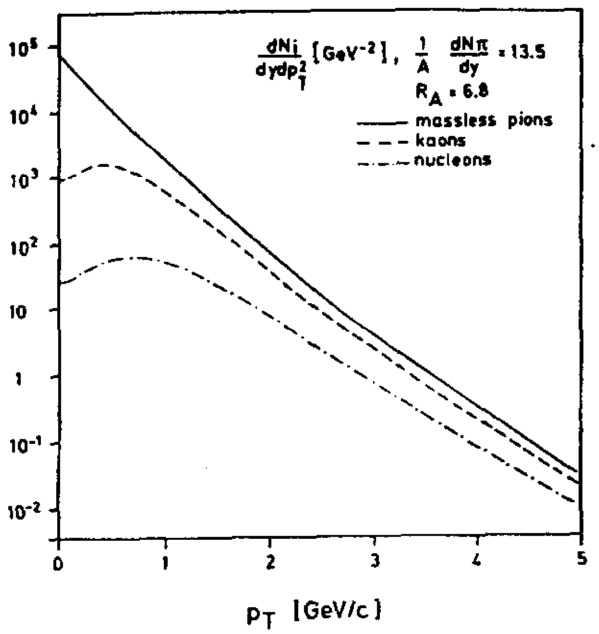

Figure 20: p_T distributions for a variety of particles

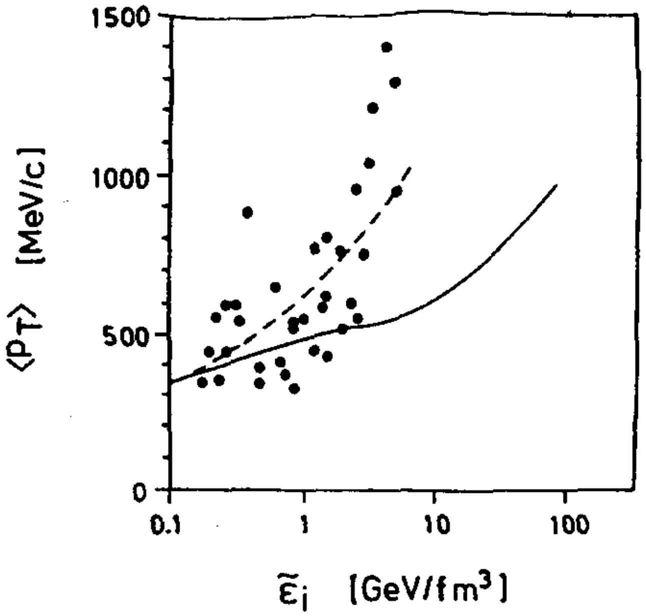

Figure 21: An attempt to fit the JACEE cosmic ray data with a bag model and ideal gas equation of state. The upper curve is the ideal gas

gas are quite large, and we consider this explanation unlikely. Either there is some non-thermal source of high p_T particles in the JACEE data, something is wrong with the space-time picture of the collisions,[74] or something is wrong with the data analysis.

There has been some recent data from p-Pb collisions which indicate that there may be an enhancement in the E_T distribution. [77] In Fig. 22, the E_T distribution of p-Pb collisions is compared to that of pp collisions, and a Glauber theory based multiple scattering model, the Hi-Jet Monte-Carlo.[78] and by Ranft et. al.[79] The theoretical computations do not give nearly the spread in E_T which is experimentally observed. The implications of this E_T enhancement for nucleus-nucleus collisions is not yet known, except that if this enhancement appears in nuclear collisions, the energy densities achieved may be higher than would be expected from conservative estimates.

5.3 Strange Particle Production

Strangeness has been widely suggested as a possible signal for the production of a quark-gluon plasma.[80,81] The argument for large strangeness in its most naive form follows from the observation that there are equal numbers of up, down and strange quarks in the plasma. One might naively

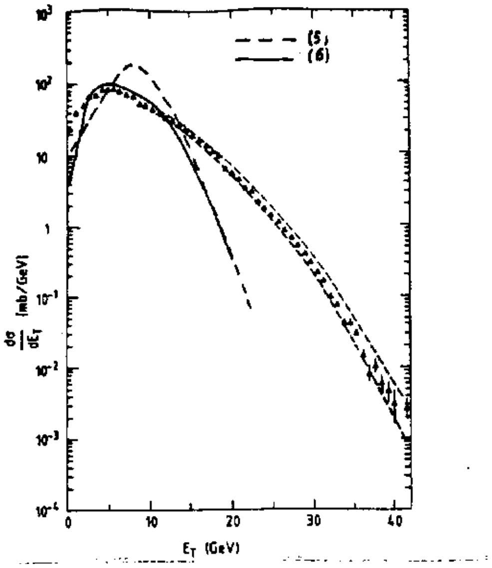

Figure 22: The E_T distribution for p-Pb collisions measured in the HELIOS experiment compared to the predictions of Hi-Jet and Ranft et. al.

expect that there would be roughly equal numbers of kaons and pions produced, and that the ratio of strange to non-strange baryons would be proportional to their statistical weight, $N_S/N_{NS} \sim 2/3$.

For the case of mesons, the above argument may be easily seen to be false.[82,83] In the expansion of the quark-gluon plasma, and later the hadron gas, entropy is conserved, and the pions are a result of this entropy. A better measure of the strangeness of a plasma is therefore the K/S ratio, where S is the entropy. This may be computed and shown to be smaller in a plasma than in a hadron gas for all temperatures larger than 100 Mev. The K/π ratio is therefore not a direct signal for a plasma. Further, the K/π ratio may be computed in a variety of hydrodynamic scenarios.[83-86] The result is typically $K/\pi \sim .3$. This number is a little larger than is typical of $\overline{p}p$ interactions. As has been suggested by Rafelski and Muller, perhaps only if a plasma is formed will the dynamics allow for such a large K/π ratio, and therefore is a signal of interesting dynamics, or perhaps even the production of a plasma.[87]

Strange baryons and anti-baryons may also provide a signal. Direct computations of the ratio of the ratios of strange to non-strange baryons in a plasma to that in a hadronic gas shows however that a hadronic gas is (if at all) only a little less strange than a plasma.[82,88] These estimates are done for net baryon number zero plasma, and

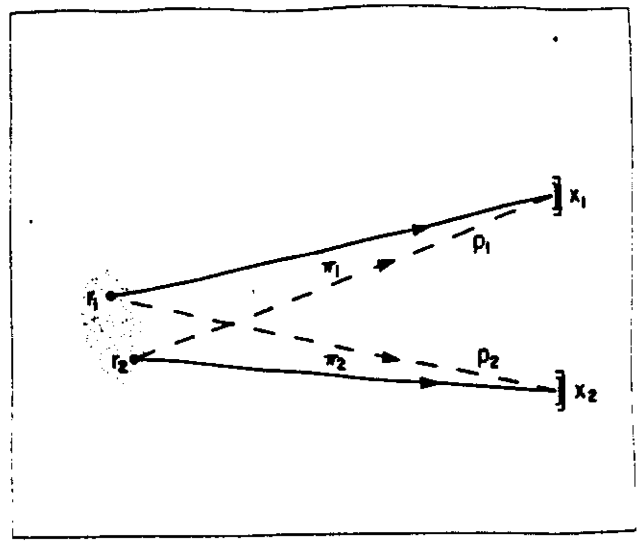

Figure 23: The paths which two particles may take to coincidence detectors

an enhancement may exist for the plasma in the baryon number rich region. At RHIC and SPS energies, the baryon number density is effectively small at all rapidities, and this should be a good approximation. Again, although this ratio of ratios indicates a lack of a signal for equilibrium quark-gluon plasmas, the ratio of non-strange to strange baryons is large, .3-2, in either scenario for $100 Mev < T < 300 Mev$. This number is far larger than is typical of $\overline{p}p$ interactions, and again by the arguments of Rafelski and Muller, perhaps the only way to dynamically achieve this is by production of the plasma.[87] This ratio is therefore interesting for dynamical reasons.

I conclude therefore that a large strangeness signal is not a direct signal for production of a quark-gluon plasma. It is almost certainly a signal for interesting dynamics, and it may be true that the only reasonable dynamical scenarios where large strangeness may be produced involve the formation of a quark-gluon plasma.

5.4 Hanberry-Brown-Twiss

The Hanberry-Brown-Twiss effect arises from the interference of the matter waves of identical particles as they are measured in coincidence experiments. In Fig. 23, the two possible paths of particles from emission to two coincidence detectors are shown. If the amplitudes for this process are summed and squared, even for incoherent emission amplitudes, the result depends on the distance of separation of the emission regions. For relative particle momentum $k \leq R$, the detection probability is modified from its incoherent form.

The measurement of identical particles closely correlated in momentum therefore allows the possibility of measuring properties of the space-time evolution of matter produced in heavy ion collisions.[89–93] One can in principle measure the size and shape of the matter at the temperature when decoupling occurs, and perhaps verify the existence of an inside-outside cascade description.

The theoretical predictions of the Hanberry-Brown-Twiss correlation are complicated by a variety of factors. The interference may be obscured by final state hadronic interactions which are difficult to compute. The space-time profile of decoupling is not yet so well known, and depends on details of the hydrodynamic simulations as well as the details of decoupling. Assuming that decoupling occurs at late times and large transverse sizes, t, $r_T \leq R$, the correlation occurs only for very small relative momentum, and is very difficult to measure.

5.5 Jets

The rescattering of jets after production in a quark-gluon plasma in principle provides a probe of the plasma and hadronic matter as the jet plows through the evolving system.[94–96] The jets will scatter from the constituents of the plasma as well as the constituents of hadronic matter which forms later. The degree of scattering is a measure of the quark-matter or gluon-matter cross section.

This scattering can dramatically change quantities such as the jet acoplanarity, and can produce phenomenon such as single jets. Theoretical predictions of jet acoplanarity for a variety of jet p_T for an $A = 100$ nucleus are shown in Fig. 24. The dashed curve represents the theoretical prediction in the absence of a hadronic matter distribution. The solid line includes rescattering. For jets of mass 10 Gev, the difference is striking, and the rescattering removes the planar nature of the jets. Even at jet mass of 20 Gev, the difference is still significant, and the jets are remarkably planar. In fact at these masses, the jets are probably largely extinguished.

The experimental measurement of this acoplanarity is very difficult. Particles with low rapidi-

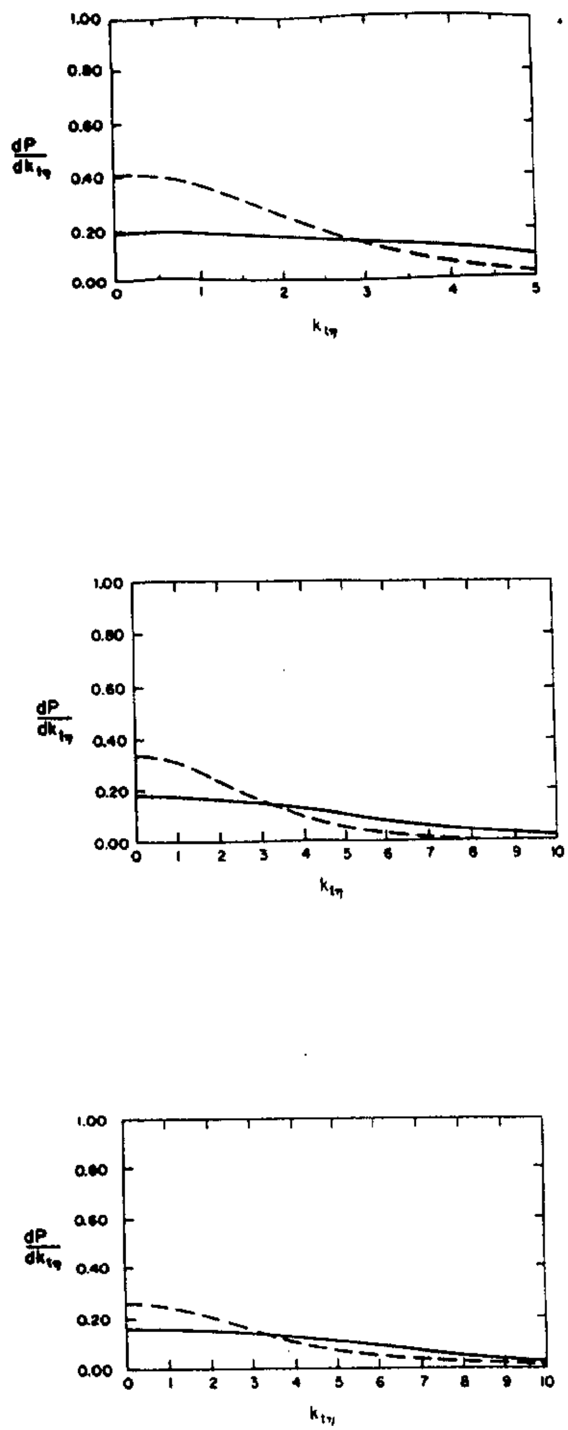

Figure 24: Acoplanarity distributions for jets in head on A=100 collisions (a) Q=10 Gev, (b) Q=20 Gev (c) Q=40 Gev

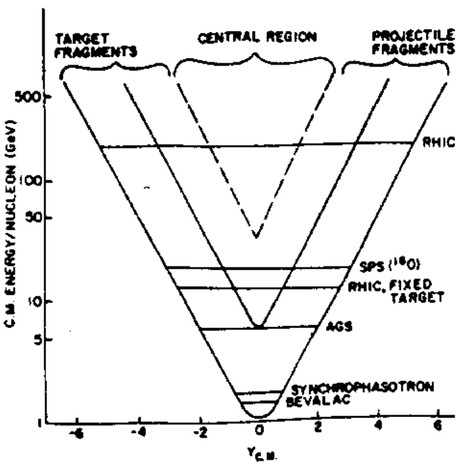

Figure 25: Center of mass energy per nucleon vs center of mass rapidity for various heavy ion accelerators

ties along the jet axis, $y < 2$, must be somehow removed from the sample of particles contributing to the acoplanarity distribution. These low p_T particles arise from conventional low p_T processes, and have little in common with the high p_T particles associated with the jet.

6 Who, What and When

There are a variety of proposed and existing relativistic heavy ion machines where experiments of one sort or another might be done. In Fig. 18, the rapidity gap produced in such machines is plotted against allowed center of mass energy.[97] (On this plot, the proposed ITEP machine is not included. This machine falls a little above the synchophasetron.) The AGS, RHIC and the SPS are the only machines where a reasonably large rapidity gap may be accessed. The RHIC is the only machine which may achieve truly asymptotic energies where a central region opens up.

In addition to beam energy, an important factor for these machines is the A of nuclei which will be accelerated. The AGS in the near future, and the SPS for the foreseeable future will accelerate light ions. In view of the Bevalac data on flow angles, this may be a dangerous thing to do. The collisions at the SPS and the AGS can involve light nuclei on heavy targets, but this considerably complicates any theoretical analysis. Perhaps some hint of the formation of a quark-gluon plasma may be extracted from such collisions, or if there is much good luck, a compelling case. A more important concern is however to see what can and cannot be measured in the dirty experimental environment provided by ultra-relativistic nuclear collisions.

In Table 2, the number of experiments and number of

People and Experiments

	AGS	SPS	TOTAL
Experiments	12	5	17
Physicists	159	208	367
University	93	115	208
Lab	66	93	159
High Energy	23	109	132
Nuclear	136	99	235
US	99	71	170
Non-US	60	140	200

experimentalists involved is shown for the experimental programs at the SPS and the AGS.[98] There are 5 major experiments which will analyze heavy ion collisions at the SPS and 12 experiments at the AGS. About 159 physicists are involved in the AGS program, and 208 at the SPS. The nuclear experimentalists outnumber the high energy by 235 to 132, but there is nevertheless a large commitment from both communities.

Not shown in Fig 25, or listed in Table 2 is the experimental work done at FNAL. The experiment C0 is a dedicated quark-gluon plasma experiment at the Tevatron, involving 27 people.[98] There will also be a small effort with CDF and perhaps D0 to look at high multiplicity, soft processes. These experiments are to be done at very high energy, and of course only with $\bar{p}p$ collisions. The emphasis will be on high multiplicity fluctuations in these collisions, where almost nothing is known about collective effects, or the degree of applicability of a hydrodynamical description.

Ultra-relativistic nuclear physics begins at the AGS and SPS with light ions in the fall of 1986. By 1989, the AGS with a booster should be able to accelerate heavy ions, such as gold. The RHIC project at BNL has R and D money as of 1986.

The largest experiments at the AGS are E802, E810 and E814. [99] E802 will measure inclusive cross sections with full particle identification over a complete kinematic range, with global event trigger. E810 will measure global properties of events. E814 will measure fragmentation with global event triggers.

At the SPS, the major experiments are NA38, NA35, NA36, WA80 and NA34.[100] NA38 is a muon pair experiment. NA35 has a 4π calorimeter and a 2π streamer chamber. NA36 involves a TPC and 2π calorimeter. NA34 has a 4π calorimeter, an external spectrometer, and will measure photons and muon pairs.

At FNAL, C0 will measure multiplicity in the central region, inclusive cross sections and has particle identification over a wide kinematic range.

7 Acknowledments

I gratefully acknowledge the rapid tutorials I received on the EMC effect, a subject the subtleties of which I am largely ignorant, before and after this meeting by E. Berger, R. Jaffe, C. Llewellyn Smith and D. Roberts.

8 Questions

Morris Pripstein (LBL): In your discussion of the EMC effect, you showed that the effect still exists, but then you posed the question 'Is the effect of interest?' Could you be more explicit in your answer?

McLerran: Interest is of course a personal issue. I would be interested if the EMC effect showed an effect which is beyond the ability of conventional nuclear physics to describe. It appears that the data is describable by conventional nuclear physics. This might not be the case after a careful measurement of anti-quark distributions as a function of A, and then I would be interested.

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