FERMILAB–Conf–87/210-T
October, 1987

Fermilab

A Review of the Quark-Gluon Plasma with an Eye to Recent Results

Larry McLerran
Fermi National Laboratory
P.O. Box 500, Batavia, Illinois, 60510

Abstract

I review the physics and proposed signals for the detection of a quark-gluon plasma. I will try to emphasize those results which appear most relevant for the recent results from heavy ion experiments in progress at CERN SPS and at BNL AGS.

Since the subject of quark-gluon plasma and its possible formation and detection in heavy ion collisions has been much discussed in the literature, the review I present here will be brief. There is not space sufficient here except to only briefly enumerate the basic results. In this talk, I shall first discuss the physics of the confinement-deconfinement phase transition. I will then discuss some possible consequences of the quark-gluon plasma for astrophysics. I then turn to a discussion of ultra-relativistic nuclear collisions. I finally enumerate various signals. In particular, I discuss the melting of the J/Ψ, Hanberry-Brown-Twiss interferometry, strangeness, and strange matter formation.

The properties of matter at extremely low, and very high energy densities are very easy to understand. At low temperatures and baryon number densities, there should be a dilute gas of nucleons and pions. The gas should be to a very good approximation ideal, since the nuclear forces are short range. At very high energy densities, we expect an unconfined gas of quarks and gluons. Again, the gas is approximately ideal since at short distances, asymptotic freedom requires that interactions become weak.[1].

The essential difference between these high and low density gasses is that the number of degrees of freedom has changed dramatically between one phase and the other. Recall that for a black body distribution of non-interacting particles, the energy density is

$$\epsilon \propto N_{dof} T^4 \tag{1}$$

where N_{dof} is the number of particle degrees of freedom. Therefore, if we were to plot $\epsilon(T)/T^4$ as a function of T in the limit of zero quark mass so that pions are massless at low temperature, then we might expect that at low T a result proportional to the number of meson degrees of freedom $N_{dof} \sim 3$, and at high temperatures $N_{dof} \sim 50$.

The large number of degrees of freedom for a quark-gluon plasma arises in part because in the limit of a large number of colors $N_{dof} \sim N_c^2$ In the limit of large N_c, the energy density itself is an order parameter for the confinement-deconfinement phase transition. If the energy density of the confined phase is finite, then at the deconfinement transition the energy density diverges at some fixed value of the temperature. This situation is reminiscent of the Hagedorn limiting temperature, and is now understood as an approximation valid at large N_c.[2-3]

The confinement-deconfinement transition is therefore a transition in the number of degrees of freedom. When light fermions are present, there is no requirement that this transition be a phase transition. It could in principle be a slow or a fast, continuous change in the number of degrees of freedom. Also, there need be no direct connection with the restoration of chiral symmetry, a symmetry that requires the quarks have small masses at large temperatures.

Recent Monte-Carlo data has shown that there is a chiral symmetry restoration phase transition of first order for small quark masses. [4] From past experience with finite fermion mass calculations, it is expected that the number of degrees of freedom change rapidly here, and in this sense, the transition is also the confinement-deconfinement transition.[5] Numerical estimates for the magnitude of this transition temperature give $T_c \sim 150 Mev$[4], a low temperature, quite close to that predicted by Hagedorn.[2]

There are of course possible consequences of the existence of a quark- gluon plasma for astrophysics. In the cores of neutron stars the energy density may become $\epsilon \sim 10\epsilon_{NM}$ where ϵ_{NM} is the energy density of nuclear matter. In such a circumstance, it is quite possible that there exist quark cores.[6] If as suggested by Witten,[6], that the stablest state of matter is chirally symmetric strange quark matter, then entire stars may be made. This strange matter could be injected into the cosmic rays, and could in principle explain the Centauro cosmic ray anomalies.[7]

Another interesting possibility is that during the chiral symmetry transition, large scale density fluctuations form associated with the existence of a mixed phase of chirally symmetric plasma, and chiral symmetry broken hadronic matter.[8] Because the quark mass is effectively small in the chirally symmetric phase, the baryon number tends to become concentrated in the plasma. Naive estimates indicate that the baryon number density might be as much as two orders of magnitude greater than that in the hadronic gas.

Such large scale density fluctuations, once formed may be sufficiently large scale that they might not diffuse away until very late times. A detailed calculation,[8] shows that the protons might not diffuse until temperatures as low as $T \sim 1Mev$, although by this time the neutrons have diffused away. The diffusion time for neutrons is shorter since at low temperatures the diffusion involves Coulomb scattering. Such an inhomogeneity in the proton density affects the calculations of nucleosynthesis. Detailed computations show that the abundances of H, H^2, He^3, He^4 agree with observation for a range of baryonic matter density, which includes that sufficient to close the universe. Recall that conventional nucleosynthesis calculations agree only if the baryonic matter density is 1-2 orders of magnitude less than closure, requiring dark non-baryonic matter to close the universe. The quark matter scenario does not work, however, for the abundance of Li^7, and overproduces relative to observation by 1-2 orders of magnitude.

It may be possible to make and study a quark-gluon plasma in a laboratory environment in the ultra-relativistic collisions of hadrons, particularly nuclei. In the collisions of nuclei of large baryon number A for energies per nucleon $E/A > 30 - 100Gev$. At such energies, one expects to form a central region where the multiplicity density dN/dy is a slowly varying function of y. The energy density can be estimated from

$$\epsilon = < p_t > \frac{dN}{dz} \frac{1}{\pi R^2} \tag{2}$$

For free streaming particles,

$$y = \frac{1}{2} ln \left(\frac{E + p_z}{E - p_z} \right) = \frac{1}{2} ln \left(\frac{1 + v_z}{1 - v_z} \right) = \frac{1}{2} ln \left(\frac{t + z}{t - z} \right) \tag{3}$$

The density at $z = y = 0$ is therefore[9]

$$\epsilon = < p_t > \frac{1}{t\pi R^2}\frac{dN}{dy} \tag{4}$$

The value of $< p_t >$ is the value taken at the first time t when we believe that the particles have been formed. The values of $< p_t >$ and t to use are somewhat controversial, but a conservative estimate is to use the observed $< p_t >$ and for the earliest time $t = 1Fm/c$ Using the JACEE cosmic ray data[10], or the CERN data on multiplicities[11], we find that energy densities of several Gev/Fm^3 are easily obtained in ultrarelativistic collisions.

The formula presented above is of course not directly applicable to AGS or CERN experiments. Here the energy is so small that the nuclei are probably not fully transparent, and the rapidity density is a fairly rapidly varying function of y. There is also a projectile target size asymmetry, so that the value of R in this equation is uncertain. Since the nuclei in the center of mass frame are not Lorentz contracted to a distance scale lee than 2 Fm, a value of t less than this is not warranted. Estimates which naively use the above equation are simply wrong at CERN and AGS energies. To properly analyze the energy deposition at such energies requires a detailed simulation, which has not been done. Nevertheless, a variety of estimates indicate that energy densities achieved at CERN energies is probably in excess of $\epsilon > .5\ Gev/Fm^3$, and may be significantly larger.

The current experiments at CERN may allow for some more precise determination of the energy densities which might be achievable in high energy heavy ion collisions at asymptotically high energy and for very large A. To sort this out from the data, one must have models to compare the data with. The data which is now available is primarily for E_t and dN/dy distributions. In principle the correlation between these variables can determine whether there is thermalization. For thermal models the p_t is enhanced due to rescattering. This is a small effect for pions, but is a larger effect for nucleons. In Table 1, I give a list of various models which attempt to describe nuclear collisions and the distinguishing features which may allow their resolution.

Models of Nuclear Collisions

Model	Thermalization?	p_t Enhancement?
DPM, Hi-Jet	no	no
Lund, Rope model	no	some
Nuclear Cascade	some	yes
QGP	yes	yes

In Table 2, various experimental probes of the quark-gluon plasma are presented.

Probes of the Quark-Gluon Plasma

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

I shall here discuss only a few of these probes. These probes have been discussed in great detail in many places, see for example the review by myself and K. Kajantie for a full exposition.[12] In this talk, I shall discuss only a few issues which appear to be relevant as a result of recent experimental results. These issues are Hanberry-Brown-Twiss pion interferometry, the possible melting of the J/Ψ, strangeness production, and the experimental possibility that one might be able to make stable strange quark matter, if it exists, in nuclear collisions.

Hanberry-Brown-Twiss pion interferometry involves the coincidence measurement of pions, and studies the correlation as a function of relative momentum. This method is used in astrophysics with photons to measure the sizes of stars. To see that there is a non-trivial correlation, note that if two identical particles with relative momenta k travel to two coincidence detectors, there are two possible paths, and these paths interfere. The interference is a function of kR, where R is the size of the source.

In a relativistic heavy ion collision, these interference experiments allow for the determination of the transverse size, and the time scale at which the matter produced in the collision decouples. By decoupling size and time scale, we mean the scale at which the pions in the matter distribution in their future light cone can be expected to never scatter. Typically, we expect that if a thermal distribution of matter forms which hydrodynamically expands, then the time scale and distance scale may be of order 5-25 fm. Such scales demand momentum resolution down to scales of the order of 10-50 Mev, and the experiments are indeed non-trivial.

The streamer chamber experiment at CERN, NA35, has recently presented data which claim that in the target fragmentation region, the transverse decoupling scale is 4 Fm for $1 \leq y \leq 2$, and 8 Fm for $2 \leq y \leq 3$.[13] The decoupling time is 4 Fm and 7 Fm. These large numbers would seem to indicate that the plasma existed for relatively long times and to relatively long distance scales. The larger scale for larger rapidities is expected since the multiplicity is higher at the larger rapidity values. It is amusing to note that the decoupling energy density in the fragmentation region, corresponding to the small rapidity values is .2 Gev/Fm^3, which is roughly the energy density of nuclear matter, and for the central rapidity values is .05 Gev/Fm^3 which is the energy density of an ideal pion gas at a temperature of $T = 150 Mev$. If these values stand the test of time, long times and large sizes before the matter decouples are achieved.

Quark-antiquark annihilation produces di-lepton pairs in the plasma. These di-lepton pairs are penetrating in the plasma, and in principle provide a probe of the plasma at very early stages of its development. This probe is probably most interesting in the di-lepton mass and transverse momentum range of 1-10 Gev. I shall not review this subject here, as it has been extensively discussed in the literature. Instead, I shall here discuss the recently measured melting of the J/Ψ in the NA38 experiment.[14].

The basic idea of resonance melting and mass shifts was first presented and discussed in the context of ρ and ω mesons by Pisarski and by Chin and Siemans.[15-16] The basic idea is that in a high temperature quark-gluon plasma, quark resonances become unbound, and dissolve. Those resonances which survive and decay within the plasma have their masses distorted by the presence of the media.

For light mass resonances, unfortunately detailed computations show that resonances from the hadronic gas, low temperature phase of systems produced in nuclear collisions dominate over those from the plasma.[17] These resonances are therefore not much affected by the existence or non-existence of a quark-gluon plasma at early stages of the collision.

In a nice paper, Matsui and Satz show that the J/Ψ resonance is not much produced in the hadronic gas phase due to its large mass, and its melting in the plasma phase might therefore provide a distinctive signal for plasma formation. This relatively clean probe is however a bit obscured for a variety of reasons.[18]

The issue of what temperatures must be achieved in the plasma before the J/Ψ melts is not yet known, and if the temperature is extremely high before it melts, then the J/Ψ might again be produced in the plasma. Also, a charm quark pair produced in the collision form primarily D mesons. If these D mesons do not diffuse far before being stopped by the media, then the recombination of D's into J/Ψ's might enhance the resonances at low temperatures when the matter recombines.[19] There are also other hadronic effects which might induce a melting of the J/Ψ. For example collisions in the hadronic gas might cause melting, although estimates of hadronic collision cross sections suggest that this effect is small. Nevertheless, a direct measurement of hadronic collision melting in the fragmentation region for nuclear production would be useful. Yet another potential effect which complicates the analysis is the A dependence of J/Ψ production, and its dependence on hadronic multiplicity.

In spite of all of the objections and complications mentioned in the previous paragraph, the melting of the J/Ψ provides a crisp experimental probe of the collision which at worst can tell us that at least some effects of final state interactions are important in heavy ion collisions, and at best provides a signal for the existence of a quark-gluon plasma. Although the theoretical verdict is not yet in, there now exist some tantalizing experimental results.[14]. In the NA38 experiment, J/Ψ production in nuclear and hadron nuclear collisions is measured as a function of associated hadronic E_T. In central nuclear collisions corresponding to large E_T there is a suppression of J/Ψ production relative to that observed in pA. The suppression is measured by comparing the production cross section for the resonance to the continuum paris at approximately the same mass values. (This measure of the suppression might in fact correspond to an enhancement of the continuum, and a direct measure of the cross sections is needed to get this answered) This suppression appears to be larger than that expected from A dependent effects in the production cross section. As expected from model computations, the melting is most pronounced at low p_T.[20]

Strangeness has been widely suggested as a possible signal for the production of a quark-gluon plasma.[21,22] 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 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.[23,24] 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.[24-27] The result is typically $K/\pi \sim .3$. This number is a little larger than is typical of $\bar{p}p$ 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.[28]

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.[23,29] These estimates are done for net baryon number zero plasma, and 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 $\bar{p}p$ interactions, and again by the arguments of Rafelski and Muller, perhaps the only way to dynamically achieve this is by production of the plasma.[28] This ratio is therefore interesting for dynamical reasons.

At AGS energies, a detailed computation of strangeness production has recently been done in a realistic hydrodynamic model.[30] The conclusions are that although there is a baryon rich region produced in the collisions, the production of strangeness is not much different for a hadron gas than for a plasma if the hadron gas is in equilibrium. It appears necessary to have a plasma to achieve the degree of equilibrium required to get the large abundance of strangeness which they predict, and in this sense the strangeness production provides an interesting probe of the dynamics.

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.

In the 802 experiment at BNL-AGS, the production of kaons has recently been measured.[31] An enhancement of the K/π ratio of order one has been observed.

I conclude with some very speculative remarks on the possibility of production of stable or metastable strange quark matter, if it exists, in heavy ion collisions. Stable strange quark matter was first proposed by Witten as the possible true ground state of nuclear matter.[6]. Such matter would form large baryon number droplets, and might be present in the cosmic ray spectrum. In fact the observed Centauro cosmic ray events,[7] has all the properties which would be allowed if either strange quark matter was stable and in the cosmic ray spectrum, or if it was metastable and produced in high energy nuclear interactions at the top of the atmosphere.

There has been recent theoretical work from the Frankfurt group which suggest that if such matter exists, then there is some reasonable possibility that it might be produced with reasonable probability in heavy ion collisions. This argument uses the fact that in a strangelet, the typical per nucleon binding energy may be quite large, perhaps 50-100 Mev. These large binding energies might favor the production of a strangelet in the hot baryon rich matter distribution of the nuclear fragmentation region. As a glob of baryon rich matter cools, it may emit K^+ mesons preferentially, and the emission may be sufficiently low energy compared to the strangelet binding energy that the droplet might survive cooling.

If stable or metastable strange quark matter exists, its consequences would be truly revolutionary. It would without a doubt provide a dramatic signal for a quark-gluon plasma. It is however difficult to assess the probability that this occurs, or that if it does that such matter is produced in heavy ion collisions. It is however simple to look for. A strangelet has a distinctive signal: a small charge to mass ratio. In addition, it should have a nuclear cross section and be more penetrating than a nucleus, since the binding energy is larger. Strangelets are most likely unstable below a certain minimum baryon number, and therefore decay into a large number of baryons when this minimum is reached. Weak decays might therefore produce an inflight decay of a strangelet into a large number of secondary baryons.

References

[1] J. C. Collins and M. Perry,*Phys. Rev. Lett.* **34**, 1353 (1975).

[2] R. Hagedorn, *Proc. of Quark Matter 84*, p 53, Edited by K. Kajantie, Springer-Verlag (1985).

[3] C. Thorn, *Phys. Lett.* **99B**, 458 (1981).

[4] R. Gupta, G. Guralnik, G. Kilkup, A. Patel and S. Sharp, *Phys. Rev. Lett.* **57**, 262 (1986); M. Fukugita, S. Ohta, Y. Oyanaga and A. Ukawa, *Phys. Rev. Lett.* **58**, 2515, (1987); E. Kovacs, D. Sinclair, and J. Kogut, *Phys. Rev. Lett.* **58**, 751, (1987); R. Gavai, J. Potvin, and J. Saniclevici, Brookhaven Lab. Preprint Print-87-0742, (1987).

[5] For a review see e. g. L. D. Mclerran, *Reviews of Modern Physics* **58**, 102 (1986).

[6] B. Freedman and L. McLerran, *Phys. Rev.* **D17**, 1109 (1978)
item E. Witten, *Phys. Rev.* **D30**, 272 (1984)

[7] C. M. G. Lattes et. al. *Phys. Rept.* **65**, 151 (1980); A. Borisov et. al. *Phys. Lett.* **B190**, 226 (1987); J. Bjorken and L. McLerran, *Phys. Rev.* **D20**, 1253 (1979); S. A. Chin and A. Kerman, *Phys. Rev. Lett* **43**, 1292 (1979).

[8] S. Bonometto, P. Marchetti, and S. Matarrese, *Phys. Lett.* **157B**, 216 (1985). J. Applegate and C. Hogan, *Phys. Rev.* **D35**, 1151 (1987); G. Fuller, G. Mathews, and C. Alcock, Lawrence Livermore Lab. Preprint UCRL-97316 (1987).

[9] J. Bjorken, *Phys. Rev.*D27, 140 (1983).

[10] Y. Takashi and S. Date, *Nuc. Phys.* **A461**, 263 (1987).

[11] Procedings of Quark Matter 87, Nordkirchen W. Germany, Aug. 24-28 (1987)

[12] K. Kajantie and L. McLerran, to appear in Annual Reviews of Particle and Nuclear Physics.

[13] H. Pugh, talk presented at this meeting.

[14] NA38 Collaboration, Procedings of Quark Matter 87, Nordkirchen W. Germany, Aug. 24-28 (1987).

[15] R. Pisarski, *Phys. Lett.* **110B**, 1551 (1982) A. I. Bochkarov and M. E. Shaposhnikov, *Nuc. Phys.* **B268**, 220 (1986).

[16] P. Siemans and S. A. Chin, *Phys. Rev. Lett.* **55**, 1266 (1986).

[17] K. Kajantie, M. Kataja, L. McLerran and P. V. Ruuskanen, *Phys. Rev.* **D34**, 811 (1986).

[18] T. Matsui and H. Satz, *Phys. Lett.* **178B**, 416 (1986).

[19] B. Svetitsky, Weizmann Institute Preprint, WIS-87/75/Oct-PH (1987)

[20] F. Karsch and R. Petronzio, *Phys. Lett.* **193B**, 105 (1987).

[21] T. Biro, H. Barz, B. Lukacs and J. Zimanyi, *Nuc. Phys.* **A386**, 617, (1982).

[22] B. Muller and J. Rafelski, *Phys. Rev. Lett.* **48**, 1066 (1982).

[23] K. Redlich, *Z. Phys.* **C27**, 633 (1985).

[24] N. Glendenning and J. Rafelski, *Phys. Rev.* **C31**, 823 (1985).

[25] J. Kapusta and A. Mekjian, *Phys. Rev.* **D33**, 1304 (1986).

[26] T. Matsui, L. McLerran, and B. Svetitsky, *Phys. Rev.* **D34**, 783 (1986); *Phys. Rev.* **D34**, 2047 (1986).

[27] K. Kajantie, M. Kataja and P. V. Ruuskanen, *Phys. Lett.* **179B**, 153 (1986).

[28] J. Rafelski and B. Muller, *GSI Preprint GSI-86-7* (1986).

[29] L. McLerran, *Proceedings of Quark-Matter 86*, Asilomar, Ca. (1986).

[30] K. S. Lee, M. Rhoades Brown, and U. Heinz, Brookhaven National Lab. Preprint BNL-40293

[31] Y. Miyake, Procedings of Quark Matter 87, Nordkirchen W. Germany, Aug. 24-28 (1987).

[32] C. Greiner, P. Koch, and H. Stock, *Phys. Rev. Lett.* **58**, 1825 (1987)