# PROBES OF THE QUARK-GLUON PLASMA AS IT MIGHT BE PRODUCED IN ULTRA-RELATIVISTIC NUCLEAR COLLISIONS

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ABSTRACT

The energy densities which might be achieved in ultra-relativistic nuclear collisions are discussed. Using these estimates, promising probes of a quark-gluon plasma as it might be produced in such collisions are reviewed. I discuss in detail the emission of photons and di-leptons. The consequences of hydrodynamic expansion and a first order phase transition are explored for the transverse momentum spectrum of hadrons. Fluctuations in the rapidity distribution of hadrons are also discussed as a possible signal for a first order phase transition. The possibility that copious production of strange particles may signal the production of a quark-gluon plasma is also critically assessed.

I shall discuss the possible experimental probes of the quark-gluon plasma as it might be produced in ultra-relativistic nuclear collisions. I shall concentrate on the central region of collisions of large nuclei, $A \geq 200$, for head on collisions at extremely high energies, $E_{CM}/A \geq 50$ Gev/Nucleon. A picture of such a collision is shown in Fig. 1.[1-2]

MATTER FORMING

$t = \gamma_0$
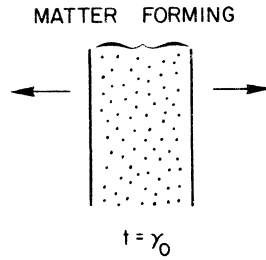
At some time τ_0 after the two nuclei pass through one another, matter begins to form between them. In the inside-outside cascade picture of this collision, this forming matter is assumed to be non-interacting until after the time τ_0.

The rapidity of the particles which constitute newly forming matter is therefore

$$y = \frac{1}{2} \ln \left\{ \frac{1+v}{1-v} \right\} = \frac{1}{2} \ln \left\{ \frac{t+x}{t-x} \right\} \tag{1}$$

where v is a particle velocity, t is the time measured from the initial time of the collision, and x is the longitudinal coordinate measured from the position of the collision. This correlation between momentum and space-time persists after the time τ_0 as a consequence of the hydrodynamic equations, and may be taken to be valid for all times.

The energy density of matter at the formation time τ_0 is [1]

$$\rho = \frac{1}{\pi A^{2/3}} \frac{dN}{dx} \langle m_t \rangle = \frac{1}{\pi A^{2/3}} \frac{dN}{dy} \frac{\langle m_t \rangle}{\tau_0} \tag{2}$$

This result has been used to estimate the energy densities achieved in the ultra-relativistic collisions observed by the JACEE cosmic ray experiment.[3] If $\langle m_t \rangle \sim .4$ Gev and $\tau_0 \sim 1$ Fm/c, the dN/dy distributions observed for intermediate A nuclei extrapolated to heavy nuclei such as uranium predict energy densities of 5-10 Gev/Fm^3. Such energy densities may be sufficient to produce a quark-gluon plasma.[4]

Recent results for hadron-nucleus collisions indicate that the formation time $\tau_0 \sim 1$ Fm/c may be a little large.[5] The dependence of the energy density of Eqn. 2 upon τ_0 is not trivial. By the uncertainty principle,

$$\langle m_t \rangle \geq 1/\tau_0 \tag{3}$$

so that

$$\rho \geq \frac{1}{\pi A^{2/3}} \frac{dN}{dy} \frac{1}{\tau_0^2} \tag{4}$$

Since the energy density of a quark-gluon lasma scales as T^4 where T is the temperature, $T \sim \tau_0^{-1/2}$.

In a nice analysis presented by D. Kisielewska, the possible values of τ_0 are extracted from hadron-nucleus and lepton-nucleus experimental data.[6] The range of values consistent with this data are determined to be $1/5 < \tau_0 < 1$ Fm/c. The preferred values are $1/2 - 1/3$ Fm/c. (It should be noted that in string models of nucleus-nucleus collisions, the formation time depends upon A, and may be considerably smaller for large A nuclei than is the case for hadron-nucleus collisions.)[7] If we consider a range $1/20 < \tau_0 < 1$ Fm/c, the corresponding energy densities and temperatures are $\rho \sim 5 - 5000$ Gev/Fem^3 and $T \sim .2-1$ Gev.

Since the width of the fragmentation region is given by

$$y_{frag} \sim \ln R_{nuc}/\tau_0 \tag{5}$$

experimental measurements of the width of this region may aid in a resolution of τ_0. Such a measurement might be to determine the rapidity distribution of baryons minus anti baryons or $\pi^+ - \pi^-$ mesons. The values of E_{CM}/A required to produce a baryon free central region depend upon τ_0, and for the values of τ_0 above are 15 - 300 Gev/Nucleon. Much more refined analysis of hadron-nucleus collisions, perhaps along the lines suggested by Hwa might clarify this issue.[8] Experiments with $E_{lab} = 10 - 1000$ Gev, for a wide variety of A including hadron-proton and hadron-deuterium would be useful. A wide range of x_f is most useful, but coverage of the central region and nuclear fragmentation regions might also be useful if good cascade models of the hadronic interaction are developed.

Some measure of the degree of thermalization and

the validity of a hydrodynamic treatment have been suggested by Shuryak.[9] In the transverse expansion of the matter produced in nuclear collisions, a transverse flow velocity develops. Particles of all masses flow with the fluid. The more massive particles therefore have their transverse momentum enhanced more relative to lighter particles. A detailed treatment of this problem using the methods developed in Refs 10-11 would be useful.

If there is a first order phase transition in hadronic matter, the transverse momentum distribution of hadrons may be drastically altered. Following Shuryak, the transverse momentum distributions receive a contribution due to transverse hydrodynamic expansion, and a thermal contribution due to the breakup of the system at some temperature T,

$$\langle p_t \rangle = \langle p_t \rangle_{hydro} + \langle p_t \rangle_{thermal} \qquad (6)$$

The hydrodynamic contribution arises from work which is done on constituents of the matter as the matter is driven into the vacuum. This work is produced from the pressure difference of the matter and the vacuum. Consider the work done as a function of the energy density achieved by the matter in a nuclear collision. As the energy density increases, the pressure will increase except when the energy density is in the region of a mixed phase of hadronic matter and quark-gluon plasma. For such energy densities, the pressure remains constant. As the pressure increases, the transverse momentum due to hydrodynamic expansion increases. In the region of the phase transition, the pressure remains constant, as does the transverse momentum of hadrons.

This general feature of the hydrodynamic expansion coupled with a phase transition may be explored by plotting measured transverse momentum vs inferred achieved energy densities.[9,12] Such a plot has been made by the JACEE cosmic ray collaboration, and is shown in Fig. 2.[13]
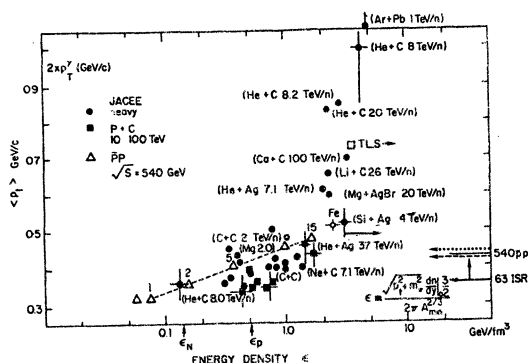
ENERGY DENSITY ε

Although the inferred energy density is somewhat model dependent, the sharp break in the transverse momentum distribution is quite suggestive.

Electromagnetic probes of the nuclear collisions may be characterized by the value of the transverse mass, $M_t = \{p_t^2 + M^2\}^{1/2}$. For di-lepton and photon transverse masses $M \leq R_{nuc}^{-1} \sim 30$ Mev for Uranium, the photons and di-leptons are coherently produced.[14] These particles may be copiously produced in the nuclear fragmentation regions, or may be copiously produced in the central region by fluctuations in the charge distributions of mesons in the central region. Detailed measurements of these distributions in correlation with measurements of the charge distributions, $dN/dy \mid_{charge}$, may probe the electromagnetic plasma oscillation.

For transverse masses 30 Mev $\leq M \leq$ 200 Mev, the effects of coherence begin to subside, and incoherent production processes begin to dominate. In the region 200 $\leq M \leq$ 600 Mev, incoherent processes should dominate. In these low mass regions it might be possible to prove the effects of chiral symmetry restoration.[15] The rate of production of such low transverse mass particles might be very sensitive to the constituent quark masses. The outstanding problem in this low mass region is resolving background processes arising from hadronic decays. A thorough theoretical analysis of backgrounds and a comparison with emissions from a quark-gluon plasma has not yet been carried out.

In the intermediate transverse mass region .6$\leq M \leq$ 1-5 Gev, thermal production may be a dominant process.[16-18] Resonable estimates of the emission rates from a plasma indicate that in this mass range, thermal emission may be comparable to or dominate hard processes such as Drell-Yan emission.[18] These estimates are quite sensitive to the achieved temperature of the quark-gluon plasma, and vary by three orders of magnitude as the achieved temperature varies between 200 Mev and 600 Mev. At the lowest temperatures, the thermal emission rate is comparable to the Drell-Yan rate, and at the highest temperatures is three orders of magnitude larger.

The analysis of the thermal emission process is formally similar to the analysis of Drell-Yan pair production. The emission is characterized by thermal expectation values of electromagnetic current correlation functions. The structure functions for this thermal expectation value may be computed if a sufficiently high temperature plasma is produced. For all temperatures, the emission process satisfies thermal scaling relations. These relations imply that for high transverse mass particles, the rapidity of the particles is the same as the rapidity of the plasma which produced it. The emission process also highly correlates transverse mass and plasma temperature. This correlation is extremely useful, since in the hydrodynamic expansion, the plasma temperature is time dependent. The correlation is

$$M_t \sim \{\frac{2}{v_s^2} + \frac{1}{2}\} T \qquad (7)$$

A first order phase transition which induces discontinous changes as a function of temperature may appear as a sharp change as a function of transverse mass.

The thermal distributions for a very high temperature quark-gluon plasma are functions only of transverse mass,

$$\frac{dN}{dM^2 dy d^2p} \sim M_t^{-2/v_s^2} \qquad (8)$$

where v_s is the sound velocity in the plasma. As a consequence the mass and transverse momentum of di-lepton pairs are correlated, in sharp contrast to the Drell-Yan spectrum.

Finally, the A dependences of the emission rates test space-time pictures of the collision dynamics, and in most models are highly correlated with the overall photon and di-lepton emission rates. These A dependences may be computed independently if the A dependences of the total hadron multiplicity, and of the formation time τ_0 are known.

At large transverse masses 1-5 $\leq M \leq$ 10-20 Gev, there should be corrections to the Drell-Yan emission rates arising from the pre-equilibrium distributions of quarks and gluons. At present a theory of these distributions is lacking, but the development of such a theory is necessary to put the production of a quark-gluon plasma in ultra-relativistic nuclear collisions on a stable foundation.

At transverse masses M $\geq$ 10-20 Gev, the Drell-Yan process should dominate.

The production of strange particles has long been suggested as a signal for the production of a plasma.[19] The ratio of strange to non-strange anti-baryons might retain some trace of an abundance of strange quarks and anti-quarks produced in a plasma. This conclusion is on somewhat shaky ground since in the hydrodynamic expansion of the plasma, the strange quarks and anti-quarks may become diluted. Also, a recent computation due to Redlich suggests that the abundance of strangeness in a hadronic gas may not be so far different from that of a quark-gluon plasma.[20] A proper theoretical assessment of strangeness production probably needs non-perturbative input from lattice Monte-Carlo computations, and a thorough analysis of the effects of hydrodynamic expansion.

Charm particle production may also be important if sufficiently high plasma temperatures are achieved, T $\geq$ 500 Mev. Corrections due to hydrodynamic expansion are probably less important for charmed particles than for strange since the charmed quark hadronic cross section is small, $\sigma < 1$ mb.

A final extremely speculative experimental probe of quark-gluon plasma production may be in multi-particle correlations, and in large scale rapidity fluctuations. Such correlations and fluctuations may arise as the matter participating in a nuclear collisions tries to negotiate a first order transition.[21-24] A variety of scenarios are possible all of which involve the production of large scale density fluctuations over rapidity intervals $\Delta y \geq 1$. In the collisions of heavy nuclei, such a rapidity interval may include several hundred to several thousand particles, and large scale fluctuations should be separable from statistical fluctuations. These density fluctuations may be generated by superheating, supercooling or the spinodal decomposition of the plasma. They might occur in baryon, anti-baryon or meson distributions. There might also be p_t enhancements if the density fluctuations are accompanied by burning or explosive phenomenon. Backgrounds such as jet production may be ruled out by the azimuthal angle distributions.

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