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THEORETICAL ISSUES IN THE SEARCH FOR THE QUARK GLUON PLASMA

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Abstract: Issues connected with independent string fragmentation, initial conditions, and hadronic transport in light ion reactions at AGS and SPS are discussed.

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Theoretical Issues in the Search for the Quark Gluon Plasma

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The experimental program on ultrarelativistic nuclear collisions started in 1986 at the AGS at BNL and the SPS at CERN to search for a new phase of nuclear matter called the quark gluon plasma. A comprehensive survey of this field can be found in the Quark Matter '88 proceedings[1] and the contributions of R. Stock and S. Nagamiya in these proceedings. I therefore limit this talk to a few remarks connected with possible interpretations of the new data.

Although only light ion beams have been available up to now, a number of interesting phenomena were discovered to depend strongly on on the atomic number of the colliding nuclei. The NA38 collaboration found a factor of two suppression of J/Ψ in central $O + U$ at 200 AGeV. The E802 collaboration found a factor of four enhancement K^+/π^+ in central Si+Au collisions at 15 AGeV, and NA35 found indications for a factor of two enhancement of Λ production at 200 AGeV. Interferometry analysis of NA35 indicated that the pion decoupling volume may be an order of magnitude larger than the nuclear interaction volume. These and other data that deviated considerably from *linear* extrapolations of p+p data have provoked a lively debate on whether these phenomena are related to quark gluon plasma formation or to new transport phenomena in dense hadronic matter.

In my opinion hadronic transport phenomena provide a more compelling explanation at this time. The primary reason is that the present data extrapolate smoothly from data on p+A, where similar though less dramatic phenomena are also found. In other words, no obvious threshold effects (as a function of multiplicity or transverse energy) were found yet that would signal the onset of plasma formation. The second main point that I amplify further below is that there is a good reason why plasma formation is not yet observed- namely, that the initial energy densities in the present light ion reactions are probably below the deconfinement threshold during most of the dynamical evolution of the reaction.

With regard to the first point, I note that the increase of the average transverse momentum of J/ψ's produced in $O + U$ as a function of transverse energy can be understood quantitatively by extrapolating the observed increase found in p+A relative to p+p (see S. Gavin p.447c [1]). Furthermore, the overall suppression can also be understood if new $\psi + meson \rightarrow D\bar{D} + X$ dissociation processes in the dense comoving mesonic medium are taken into account[2]. Other phenomena such as the enhanced Λ and K^0 production and an extra low $p_\perp$ component relative to that found in p+p are nearly identical to that seen in p+A reactions (see e.g. J.

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Harris, p.133c [1]). The large decoupling volume observed via pion interferometry can be understood when the nuclear geometry is folded together with effects due to long lived resonances (see S. Padula, p.489c [1] and [3]). The high $p_\perp$ enhancement of K^+/π^+ has been explained in terms of associated $\pi + N \to K + \Lambda$ final state processes[4]. The point is that initial and final state hadronic processes lead to interesting new phenomena whether or not there is a plasma state produced. Indeed, learning about the physics of dense hadronic matter is itself an important goal of heavy ion research. The new physics associated with the onset of plasma formation at sufficiently high multiplicities or transverse energies can only be identified if additional nonlinear behavior (beyond that expected from hadronic transport theory alone) is observed above some critical multiplicity or transverse energy. Up to now the observed nonlinearities can be understood without the additional plasma contribution.

Nevertheless, the new data are very valuable because they provide the foundation for extrapolations to even heavier ion collisions and to even higher energies. Because the expected multiplicity and transverse energy systematics have been confirmed by the data, we now have a much greater degree of confidence in such extrapolations. Also the data constrain heretofore unknown elements in hadronic transport models such as the effective $\psi + meson \to D\bar{D} + X$ dissociation cross sections mentioned above. Finally, direct evidence for final state interactions in light ion interactions is an essential prerequisite if local equilibration is to be realized in collisions of heavier nuclei.

Fortunately in the past several years, the theoretical progress on developing transport theories has kept up with the very rapid advances in experiment. There exists several detailed transport codes that have been tested extensively on the new data. The most powerful and successful models are those which treat high energy hadronic interactions in terms of the production and decay of multiple string like excitations[5]-[9]. Strings are formed whenever colored partons separate on account of color confinement. In hadronic or nuclear collisions, multiple soft gluon exchange between the interacting partons naturally leads to the separation of a large number of colored partons. The essential simplifying assumption in all these models is that the resulting color field configuration can be approximated by many independent string like color flux tubes. This picture is analogous to the creation of a system of quantized magnetic vortices in type II superconductors.

In its simplest form, as embodied by the LUND Fritiof model[5], each interacting nucleon is excited into a quark-diquark string configuration specified by its light cone momenta $E^\pm = E \pm p_z$, its invariant mass, $M^2 = E^+E^-$, and its cm rapidity, $Y = \frac{1}{2}\ln E^+/E^-$. The excitation law is assumed to be of diffractive type with a probability dM/M subject to kinematic constraints. Typically, in a pp collision at a given $\sqrt{s}$, the average string masses are $M \sim \sqrt{s}/2$. Strings are assumed to decay via $q\bar{q}$ pair production,and the distribution of final hadrons produced from a quark-diquark string is parametrized from data on deep inelastic $\ell + p$. Typically, this leads to rapidity density of secondary $dN/dy \approx 2$ for y near Y at $\sqrt{s} = 20$

GeV. Since the hadrons emerge with a typical transverse mass, $m_\perp \sim 0.5$ GeV, the transverse energy generated by a typical string per unit rapidity is $m_\perp dN/dy \sim 1$ GeV.

The total number of string excitations follows simply from Glauber geometry. For central A+Au collisions, a total of $N_T \approx 11A^{2/3} - A$ target nucleons participate in the interactions with the $N_P = A$ incident projectile nucleons. Therefore, $N_s \approx 11A^{2/3}$ strings are formed. For the $A = 16$ and 32 beams available up to now, $N_s \approx 70$ and 110 respectively. We can therefore immediately estimate the rapidity density and transverse energy per unit rapidity as

$$dN/dy(A + Au) \approx 20A^{2/3}$$

$$dE_\perp/dy(A + Au) \approx 10A^{2/3} \text{ GeV} \ .$$

These simple estimates and the more detailed Monte Carlo calculations account well for the new data[1].

There are however several important theoretical issues in connection with the above string model phenomenology. First, how can the strings fragment *independently* when the Glauber geometry indicates that the initial string density must be very high $\rho_s = N_s/(\pi R_A^2) \approx 2.5$ fm^{-2}? Second, how can *hadronic* transport theory be applied to decay products of those strings when some estimates for the initial energy densities range up to 4 GeV/Fm^3[10]? At such densities many hadrons must be piled up on top of each other, and a hadron gas description is not expected to work. After all QCD predicts that matter should transform into quark gluon plasma at those densities.

The first issue is an open problem. A possible explanation could be that the structure of the produced strings is rather different than one would guess naively based on the MIT Bag model. In that model, transverse area A_T of a color flux tube is fixed by the balance of the internal color electric field pressure $\frac{1}{2}E^2$ by the external pressure, B, exerted by the nonperturbative vacuum. The string tension is then given by $\kappa = 2BA_T$. The critical string density beyond which strings must overlap is thus $\rho_c = 1/A_T = 2B/\kappa$. In the MIT phenomenology, $B \approx 0.06$ GeV/Fm^3 and the resulting critical density would be extremely low $\rho_c \sim 0.1$ fm^{-2}. MIT strings are in fact fat tubes with a radius $R_s \approx 1.6$ fm!! However, the true value of the nonperturbative energy density is $B \sim 0.5$ GeV/Fm^3, as obtained via QCD sum rules and charmonium spectroscopy and is much larger than the MIT value as emphasized especially by Shuryak[11]. Using this value of B instead leads to $\rho_c \sim 1$ fm^{-2}. Recall that Glauber geometry gave $\rho_s \sim 2.5$ fm^{-2} for the string density produced in $A + Au$ collisions. Independent string fragmentation can only be expected to work when $\rho_s \lesssim \rho_c$. With the QCD sum rule B, this is at least marginally satisfied. However, there is another point in connection with string interactions that should be noted. Another model for the structure of strings is the Nielsen-Olson Abelian Higgs model[13] fashioned after the analogy of confinement to superconductivity. In that model, a string is a vortex consisting of a cylindrical hole of a radius ξ in which the Higgs field vanishes and a hole of radius λ, called the London penetration length, in which the electric flux is nonvanishing. In Type I superconductors, characterized by $\xi > \lambda$, vortices have attractive interactions, while in type II superconductors with $\xi < \lambda$ have repulsive interactions. There is an amazing theorem that for $\xi = \lambda$ vortices simply do not interact[14]. In phenomenological fits it was in fact found that $\xi \approx \lambda$ for parameters consistent with charmonium spectra with this model[15]. Furthermore, the rms radius of the vortex energy density in that model is much smaller than 1 fm[16]. This model could thus provide a possible explanation for why independent string fragmentation works because not only would ρ_c be high, but also the string interactions would be very weak!

Turning next to the second major issue raised above, I want to emphasize that in light ion reactions at present (intermediate) energies, $\lesssim$ 200 AGeV, the maximum energy density reached is probably much smaller than that estimated applying the Bjorken scaling formula[12]. For a central $A + Au$ collisions at a laboratory energy $E \approx 2\gamma_c^2 m_N$ in the midrapidity frame, two Lorentz contracted nuclei with thickness, $2R_A/\gamma_c$ and $2R_{Au}/\gamma_c$, pass through each other in a time interval, $\Delta\tau = (R_A + R_{Au})/\gamma_c$. For $O + Au$ and $Au + Au$ at $E = 200$ AGeV, $\Delta\tau \approx 1.0$ and 1.4 fm/c respectively with a comparable spread in the longitudinal coordinate. The Bjorken estimate of the energy density assumes, on the other hand, a common origin for the decay of all N_s strings. That assumption together with the neglect of transverse expansion gives an upper bound on the energy density at early times. That bound is obtained by taking a fixed transverse area πR_A^2 and a common formation proper time,$\tau_0 \approx 1$ fm/c. A group particles with a rapidity difference, dy, have a longitudinal separation $dz = \tau_0 dy$ and thus occupy a volume $\pi R_A^2 \tau_0 dy$. Since those particles have a transverse energy, $dE_\perp$, the initial energy density is simply

$$\epsilon_0 \approx (\tau_0 \pi R_A^2)^{-1} dE_\perp/dy \approx 2 \text{ GeV/Fm}^3 \ . \tag{1}$$

Note that ϵ_0 is essentially independent of A if a heavy target $A = 197$ is used in this approximation.

In order to calculate the energy and baryon densities reached during nuclear collisions free from the above unrealistic assumptions, it is necessary to understand space-time development of hadronization[17, 18]. String models possess a simple interpretation in phase space because momentum space and coordinate space are linearly related through an effective string tension κ via the classical string equations

$$dE^\pm/dz^\pm = \mp\kappa \quad , \quad dE^\pm/dz^\mp = 0 \ , \tag{2}$$

where $z^\pm = t \pm z$ are light cone coordinates.

With (2) we can translate string fragmentation into coordinate space. Consider the fragmentation of an excited baryon string with a diquark at one end with a large E^+ and negligible E^- and a quark with large E^- and negligible E^+ at the other. As the end points recede from each other along the light cones, they lose $E^\pm$ on account of (2) and turn around at at light cone coordinates $(z^+, z^-) = (L^+, 0)$ and $(0, L^-)$, where

$$L^\pm = E^\pm/\kappa$$

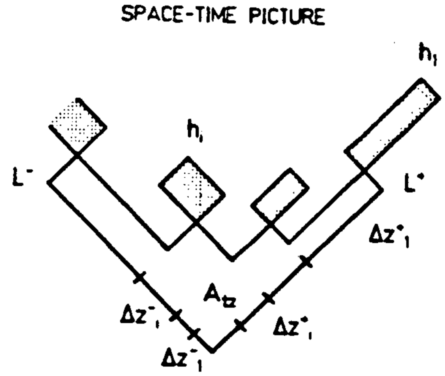

Figure 1: Fragmentation of a string via $q\bar{q}$ pair production followed by hadron formation in space-time.

are the space-time lenght scales bounding the string fragmentation region. Suppose that the pairs $q_i\bar{q}_i$ are produced at light cone coordinates (z_i^+, z_i^-). Given the $E_i^\pm$ of the final hadrons, (2) constrains the production coordinates to be at

$$z_i^+ = L^+ - \sum_{j=1}^{i} E_j^+/\kappa \ , \ \ z_i^- = \sum_{j=1}^{i} E_i^-/\kappa \ . \tag{3}$$

Conversely, given the production coordinates, the transverse mass and rapidity of the i^{th} rank hadron are given by

$$E_i^\pm = \kappa\Delta z_i^\pm \ , \ \ m_{\perp i}^2 = \kappa^2 \Delta z_i^+ \Delta z_i^- \ , \ \ y_i = \tfrac{1}{2}\log(\Delta z_i^+/\Delta z_i^-) \ , \tag{4}$$

where $\Delta z_i^+ = z_i^+ - z_{i+1}^+$ and $\Delta z_i^- = z_{i+1}^- - z_i^-$ as illustrated in fig.1

Fig. (1) reveals the inherent ambiguity in the definition of the formation point of a composite hadron. The production coordinates of the $q\bar{q}$ pairs is fixed by (3), and thus the constituents of hadron h_i intersect for the first time at

$$(z_i^+, z_i^-)_Y = \sum_{n=1}^{i} (\Delta z_i^+, \Delta z_i^-) \ .$$

This is called the "yo-yo" point beyond which the constituents execute regular oscillations. However, at least one of the constituents of that hadron was born at

$$(z_i^+, z_i^-)_C = (z_i^+, z_i^-)_Y - \Delta z_i^+ \ .$$

We define this as the constituent point for hadrons with $E^+ \geq E^-$. If h_i carries a large $E_i^+ = \kappa\Delta z_i^+$, there is obviously be a large difference between the yo-yo and constituent points. It is not at all clear which, if either, of these points we should take as the effective formation point of h_i [17, 18].

The ambiguity in defining the formation length of a composite particle of course leads to a theoretical uncertainty about the values of the energy density achieved

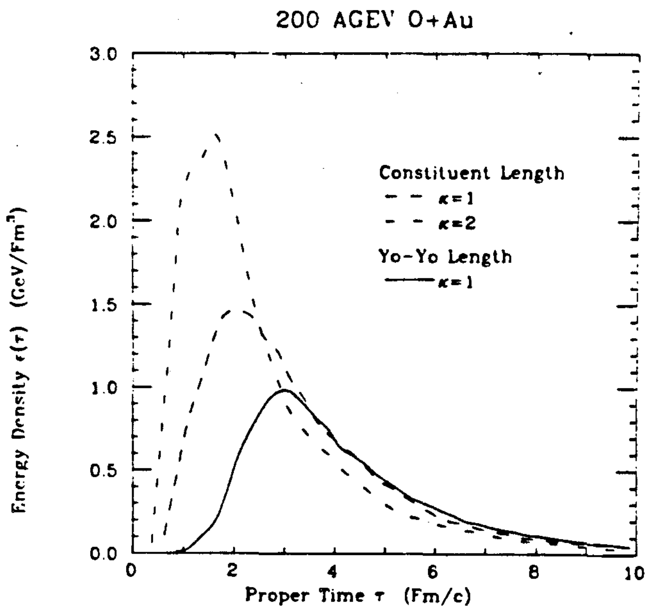

Figure 2: Sensitivity of the evolution of the central energy density to different assumptions about the formation length of secondary hadrons.

in nuclear collisions. Fig.2 shows the results obtained using ATTILA[7] for several different possibilities. For O+Au at 200 AGeV the high density phase lasts only for about 2 fm/c and the maximum energy densities achieved are only on the order of 1 GeV/Fm^3 with $\kappa = 1$. However, if the effective string tension were 2, then roughly twice as high energy densities can be reached. This calculation includes the finite nuclear geometries, the finite smearing of string origins, and the effects of free transverse expansion, all of which significantly reduce the maximum energy density by a factor of 2-3 below the value the ideal Bjorken formula would give. Only at much higher energies (RHIC) is that formula applicable (modulo novel mini-jet effects).

What Fig.2 demonstrates that it is possible and indeed likely that the energy densities in present experiments may fall considerably below the deconfinement scale $4B \sin 2$ GeV/Fm^3. Furthermore, for these light ions transverse expansion rapidly takes over and the energy density falls much more quickly than ideal longitudinal expansion give. This may then explain why a purely hadronic transport theory is sufficient to explain many features of the present data. Note that much higher energy densities were reported in ref.[10] using a variant of the DPM model[6]. In that case the high energy densities ~ 4 GeV/Fm^3 are due however to the large number of very small mass $q\bar{q}$ pairs produced in that model, which are assumed to have zero formation time. However, more realistic estimates[18, 19, 9] point to much smaller initial ϵ_0.

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