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CERN-TH.4204/85

POSSIBLE MANIFESTATION OF QUARK-GLUON PLASMA
IN ULTRA-RELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS

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A B S T R A C T

The written version of this lecture concentrates mainly on recent developments concerning possible detection of quark-gluon plasma formation and covers them at greater length than the oral presentation. The topics covered are:

- early energy and entropy densities, fluctuations, transverse flow,
- dilepton emission by high temperature plasma,
- thermalization, plasma formation versus string and chain models.

Invited Lecture
Second International Conference on Nucleus-Nucleus Collisions
Visby, Sweden
10-14 June 1984
To be published in Nuclear Physics A

CERN-TH.4204/85

June 1985

In the next section we discuss estimates of early energy and entropy densities derived from the cosmic ray data of the JACEE Collaboration, we comment on fluctuations and we make a few remarks on recent work concerning transverse collective flow. Section 3 reviews important recent predictions on dilepton emission by a high temperature plasma. The concluding section contains remarks on thermalization and on the differentiation between plasma formation and non-thermal models.

2. EARLY ENERGY AND ENTROPY DENSITIES, FLUCTUATIONS, TRANSVERSE FLOW

In the Quark Matter '84 Conference, much attention was given to a plot presented by the JACEE cosmic ray collaboration³; it was commented upon in McLerran's opening lecture and in Satz's closing lecture¹. It concerns cosmic ray nucleus-nucleus collisions at energies above 1000 GeV per nucleon (c.m. energy $\sqrt{s} \gtrsim 45$ GeV per nucleon pair) and plots the estimated transverse momentum $\bar{p}_T$ of pions (deduced from measured photons) versus the quantity

$$\tilde{\epsilon} = (3/4\pi)(\bar{p}_T^2 + m_\pi^2)^{1/2} (dn/d\eta)_0 A_{\min}^{-2/3} \quad (1)$$

$A_{\min}$ is the mass number of the lighter colliding nucleus and $(dn/d\eta)_0$ is the distribution of charged particles in pseudorapidity η in the central region (i.e., at η values midway between the rapidities y of projectile and target). The quantity (1) provides a crude estimate⁴ (in fact an underestimate⁵ due to work done during the longitudinal expansion) for the energy density at a proper time $\tau \sim 1-2$ fm/c after the beginning of the collision. The interest of the JACEE plot presented in 1984 was that it suggested a rather sudden increase of $\bar{p}_T$ for $\tilde{\epsilon} \gtrsim 2$ GeV/fm². While the apparent suddenness of this increase was largely due to the use of a logarithmic scale for $\tilde{\epsilon}$, an interesting structure seemed to remain when $\bar{p}_T$ was plotted versus

$$\tilde{\sigma} = (dn/d\eta)_0 A_{\min}^{-2/3} \quad (2)$$

which up to a constant factor provides a crude estimate of the entropy density at $\tau \sim 1-2$ fm/c (in fact an overestimate because some entropy can be produced at later times).

The JACEE results have changed considerably since 1984, both by corrections to previous data and by inclusion of additional events, and no interesting structure emerges in the data presented by O. Miyamura at the present meeting. For reasons explained several years ago⁶, plots of this sort are of interest to

1. INTRODUCTION

Quantum chromodynamics (QCD) predicts that hadronic matter should be in a quark-gluon plasma (QGP) state, also called quark matter state, when its energy density and/or its baryon number density are sufficiently high, and it is reasonable to expect that small, short-lived droplets of QGP could form in nuclear collisions at sufficiently high energy. These general predictions have been discussed at numerous conferences in recent years, their basis and outlook have not significantly changed, so that there is no need to spell them out once more in the written version of this lecture. Excellent surveys are found in the Proceedings of the Quark-Matter '84 Conference¹, especially the summary lecture by H. Satz. Here we shall concentrate on some recent developments.

While QCD lattice calculations continue to give conflicting indications on the nature (1st or 2nd order, or smooth) of the transition between QGP and "hadron gas" (matter composed of well-separated colourless hadrons)², they all agree that at small baryon density (small chemical potential μ) the transition is marked by a large latent heat, i.e., a large surplus of energy density ϵ and entropy density σ in the plasma. Few predictions are available on the other properties of low μ hadronic matter near transition, and on all properties of higher μ matter near transition. On the other hand, far above transition, i.e., at high temperature T and/or μ , QCD predicts that strong interactions become weaker (asymptotic freedom), the QGP should therefore behave as an approximately ideal gas of quarks and gluons, perturbative effects of the interactions can be calculated and non-perturbative plasmon effects can be estimated.

search for phase transitions. However, it is better to plot $\bar{p}_T$ versus $\tilde{\sigma}$ than versus $\tilde{\epsilon}$. The reason is simply that $\bar{p}_T$ tends to slowly increase with $\tilde{\sigma}$ and one is interested in fine structure of this increase (see Section 4). Such fine structures are necessarily less pronounced in a $\bar{p}_T$ - $\tilde{\epsilon}$ plot because $\tilde{\epsilon} \propto \bar{p}_T \tilde{\sigma}$ by (1) and (2), so that using $\tilde{\epsilon}$ as abscissa stretches out the structures in the variation of $\bar{p}_T$ and makes them less visible. The same remark applies when the search for QGP formation is carried out on an event-by-event basis⁷. The large entropy contents of a plasma droplet is expected to manifest itself after hadronization in a high multiplicity, i.e., large $d\sigma/d\eta$ or $\tilde{\sigma}$, whereas the high energy contents can produce in addition higher $\bar{p}_T$ values. It is in terms of $\tilde{\sigma}$ and $\bar{p}_T$ that the two effects are best separated.

We have extracted the $\tilde{\sigma}$ values from the JACEE plot presented at this meeting. They extend from ~ 2 to ~ 20 and there seems to be little correlation between $\tilde{\sigma}$ and the widely scattered values of $\bar{p}_T$ (due to this scatter, such absence of correlation of course induces a trivial correlation between $\bar{p}_T$ and $\tilde{\epsilon}$). As we shall explain at the end of Section 3, the corresponding early entropy densities are likely to be $\lesssim 20 \text{ fm}^{-3}$, probably too low to be compatible with plasma formation.

Another feature of the JACEE results is the presence of strong fluctuations in the pseudorapidity distribution $dn/d\eta$ of single events. This in itself cannot be considered as an indication of phase transition. Any mechanism producing particles from a rather small and fluctuating number of primary sources (clusters, or strings, or dual chains, see Section 4) also gives rise to large fluctuations, as was illustrated by B. Andersson with the Lund model at the conference. What should be done, however, is to look for correlations of the $dn/d\eta$ fluctuations with other signals predicted to be characteristic of QGP formation (direct photons and dileptons, strange particles, $\bar{p}_T$ larger than normal)⁷. These other signals should occur in the same rapidity intervals as the high entropy concentration revealed by abnormally large $dn/d\eta$ or dn/dy (y = rapidity, remember that $\eta \approx y$ holds only for pions).

Many theorists have recently tried to model the space-time evolution of a glob of hot hadronic matter initially formed in an ultra-relativistic nuclear collision, applying hydrodynamics beyond the traditional treatment of the longitudinal expansion and tackling the essential but difficult problem of transfer of energy to collective transverse motion (see, e.g., Baym's review⁸). Even within the limited framework of hydrodynamical models (which exclude fluctuations), differing conclusions can be reached. In some model calculations

with a first order transition, the cooling due to the longitudinal expansion causes an inward transverse flow^{9,10}. But also without phase transition the situation is unclear. In fact, we know practically nothing about the initial longitudinal motion present in the hot hadronic matter when it is first created, i.e., before hydrodynamic expansion starts (the popular assumption that it is given by the rapidity distribution observed for the final particles emerging from nucleon-nucleon collisions is convenient but totally unjustified). If that initial longitudinal motion is not too large, energy can easily be transferred to transverse motion. If it is large there is bound to be less transfer due to rapid cooling.

Remembering the Bevalac experience, we do not expect that much progress will be made on these problems by theory alone, even for normal processes without plasma formation. Fortunately, guidance will soon become available with the SPS ion programme. By multiparticle measurements of rapidity y and transverse momentum vector $\vec{p}_T$ for various sizes of nuclei (the azimuthal correlations in $\vec{p}_T$ are also of interest), one will learn about the energy-momentum flow patterns characteristic of normal processes, an obvious prerequisite if one is to identify abnormal phenomena and try to link them to QGP formation.

Regarding the space-time evolution of hot hadronic matter after QGP formation, one must also take into account the possibility of sudden release of the plasma latent heat at hadronization^{11,12,7}, which could induce large fluctuations especially in dn/dy and p_T , of a type not predictable by hydrodynamical models. As far as we can see, the most likely process of this sort is the surface deflagration phenomenon studied in Refs. 11 and 7^{*)}. It should also be realized that in the rapid expansion of a plasma column, the formation of QCD flux tubes as the transition is approached is likely to affect the expansion and generate fluctuations even before hadronization. In particular, one should expect that the plasma column in longitudinal expansion would often break up into smaller plasma droplets, each having its own rapidity but less internal expansion. This is again a type of phenomenon excluded by assumption in hydrodynamical calculations.

*) Contrary to claims in Refs. 10 and 12, the velocity of the deflagration front in the "burning" plasma is not predicted to be very small. We found it to be $\sim c/6$ for most of the deflagration modes resulting from our equation of state, much larger than the value $c/50$ quoted by Friman¹⁰ with reference to Gyulassy et al.¹². In addition we found⁷ quite large values for the energy flux liberated by the deflagration and carried out by the outflow of hadron gas, resulting in an increase of $\vec{p}_T$ beyond its thermal value.

3. DILEPTON EMISSION BY HIGH TEMPERATURE PLASMA

In this section we discuss dilepton emission as one of the possible signals for detecting QGP formation, in the light of important new work by McLerran and Toimela¹³ and by Hwa and Kajantie¹⁴. As these authors have shown, if plasma is formed with an initial temperature T_i very large compared to the transition temperature T_c (the condition quoted in Ref. 14 implies $T_i \gg 5T_c \sim 1$ GeV), the dilepton spectrum emitted by the plasma is predicted in first approximation to depend on the mass M and the transverse momentum p_T of the dilepton through the single combination $M_T = (M^2 + p_T^2)^{1/2}$, the so-called transverse mass. In addition, for $T_c \ll M_T/5 \ll T_i$, the M_T -spectrum is found to be approximately power-like and independent of T_i . References 13 and 14 also discuss the dileptons emitted by other mechanisms (decays of charmed or heavier quarks, Drell-Yan mechanism due to annihilation of quarks and antiquarks initially present in the colliding nuclei).

It is at present impossible to say whether plasmas with $T_i \gg 1$ GeV have any chance to be created in nuclear collisions. The corresponding initial energy densities are truly enormous, $\epsilon \gtrsim 10^4$ GeV/fm³, a factor 10^3 - 10^4 larger than the largest ϵ values estimated for JACEE events. It is conceivable that they could occur with very small cross-section in colliding nuclear beam experiments at centre-of-mass energy 100-200 GeV per nucleon pair (the RHIC project proposed by Brookhaven is in this class). The interesting events would have extremely large central multiplicity $dn/d\eta \gtrsim 10^5$, instead of the 100-200 reached in JACEE events. The predictions on dileptons would then provide very important tests for plasma formation and plasma properties.

Our aim here is to discuss the main physical basis for the predictions of Refs. 13 and 14. As in these papers, we limit ourselves to plasmas of zero chemical potential (central region) and we neglect transverse expansion. The dilepton distribution has then the simple structure

$$dN/dM^2 dp_T^2 dy = \int d^4x dN_{p\ell}[T(x)]/dM^2 dp_T^2 d[y-y(x)] \quad (3)$$

where the integral extends over the space-time volume of the plasma, $T(x)$ and $y(x)$ are the temperature and rapidity of the plasma at space-time point x and $dN_{p\ell}(T)/dM^2 dp_T^2 dy$ is the dilepton emission rate per unit volume and unit time of a plasma of temperature T taken to be at rest ($p_T=y=0$ for the plasma). Extending slightly a method of Shuryak¹⁵ we rewrite (3) as

$$dN/dM^2 dp_T^2 dy = \int_{T_c}^{T_i} dT dy' \Phi(T, y') dN_{p\ell}(T)/dM^2 dp_T^2 d(y-y') \quad (4)$$

$$\Phi(T, y') = \int d^4x \delta[T(x)-T] \delta[y(x)-y'] \quad (5)$$

Φ depends only on the space-time development of the plasma. In the central region its dependence on y' should be very weak. Its T dependence is in T^{-7} for the adiabatic longitudinal expansion of an ideal quark-gluon gas, and this should be a reasonable approximation as long as $T \gg T_c$.

One may wonder how the behaviour $\Phi \propto T^{-7}$ is to be reconciled with the dimension $[\text{length}]^4/[T] = [T]^{-5}$ of Φ (we use units where Boltzmann constant $= \hbar = c = 1$). This comes about as follows. The longitudinal expansion is assumed to conserve entropy, and the entropy density is $\propto T^3$. Consider the three-dimensional manifold defined by $T(x) = T$, $|y(x)-y| < \delta y$ with y in the central region. Its increasing longitudinal length $L(T)$ and constant transverse area S obey $SL(T) T^3 = \text{dimensionless constant } \Sigma$, in fact the entropy carried by the manifold. Leaving out a velocity factor ($2\delta y$ for $\delta y \ll 1$) one obtains $\Phi \propto SLdL/dT \propto \Sigma^2 S^{-1} T^{-7}$, which has indeed dimension $[T]^{-5}$. In Eq. (7) below, Σ and S appear in the combination $dN/dM^2 dp_T^2 dy \propto \Sigma^2 S^{-1} M_T^{-6}$, again with the correct dimension. The detailed calculations of Ref. 14 confirm these considerations.

As to $dN_{p\lambda}(T)/dM^2 dp_T^2 dy$, it is also very simple in the ideal gas approximation. It is found to depend only on y , T and the transverse mass $M_T = (M^2 + p_T^2)^{1/2}$. Being dimensionless it therefore depends only on y and M_T/T . The latter dependence is cut off by a Boltzmann factor $\exp(-M_T/T)$ when $M_T \gtrsim T$, and these various properties should hold approximately for an actual QGP when $T \gg T_c$. Hence, for $M_T \gg T_c$, the temperature range contributing to the integral in Eq. (4) is limited to $T \gtrsim M_T$ by the Boltzmann cut-off and further to $T \sim M_T$ by the rapid drop of $\Phi(T)$, so that

$$dN/dM^2 dp_T^2 dy \approx \int dy' \left[\int_{M_T}^{T_1} \Phi(T, y') dT \right] dN_{p\lambda}(M_T)/dM^2 dp_T^2 d(y-y') \quad (6)$$

$dN_{p\lambda}(M_T)/dM^2 dp_T^2 dy$ is close to the ideal gas approximation discussed above and therefore independent of M^2 and p_T^2 . As to be integral over Φ , using $\Phi \propto T^{-7}$ one sees that for $T_1 \gg M_T$ it is independent of T_1 and $\propto M_T^{-6}$, which gives

$$dN/dM^2 dp_T^2 dy \propto M_T^{-6} \quad (7)$$

the missing coefficient being independent of M and p_T . Equation (7) reproduces the characteristic M_T -power behaviour obtained in Refs. 13 and 14. It should

not occur for dileptons resulting from the decay of heavy quarks, nor for Drell-Yan emission, and should therefore be helpful for separating the non-plasma background.

The above reasoning can also be applied to direct emission of photons by the plasma in the range $T_c \ll p_T/5 \ll T_1$ for the p_T of the photon^{13,14}. The resulting spectrum is $dN/dp_T^2 dy \propto p_T^{-4}$. In this case, however, the background separation should be more difficult (no variable equivalent to M is available).

Hwa and Kajantie¹⁴ also give explicit formulae for the absolute emission rates of dileptons and direct photons by hot plasmas and find them large enough for detection if such plasmas are formed. These rate calculations require more assumptions than the above proportionality relations, because they relate the size of $\Phi(T)$ to the observed central multiplicity $(dn/dy)_0$ or $(dn/d\eta)_0$. This amounts to calculating the factor between the quantity $\tilde{\sigma}$ defined in Eq. (2) and the early entropy density σ on the basis of an explicit model for the entropy contents of the hadronic system as it goes through the transition from plasma to hadron gas and then freezes out to free-streaming pions⁸. Using Hwa and Kajantie's model which neglects all form of entropy production, namely their Eq. (11), we find

$$\sigma \sim 1.2 \tilde{\sigma}/\tau \text{ fm}^{-3} \quad (8)$$

where τ is, in fm/c, the time at which the hot hadronic system is first formed. If we take $\tau \sim 1$ fm/c and $\tilde{\sigma} \sim 20$, the highest $\tilde{\sigma}$ value deduced from the JACEE data, we obtain $\sigma \sim 24 \text{ fm}^{-3}$, comparable to the estimate of 25 fm^{-3} which we quoted some time ago for the minimum entropy density of the plasma [Eq. (8) of Ref. 7]. We should stress, however, that (8) is an overestimate of the early entropy density, because it neglects entropy production which can occur by dissipation, deflagration and freeze-out. According to Baym⁸, freeze-out alone may increase the entropy by a factor of order 2.

4. THERMALIZATION, PLASMA FORMATION VERSUS NON-THERMAL MODELS

Questions are often raised concerning thermalization at early times, in the first fm/c of the collisions. Is it likely to occur in individual collisions? If no, can one still apply thermodynamics as done for example for the plasma formation problem? Our answers are "probably no" to the first question, "yes" to the second, and we have presented our general arguments in Section 2 of Ref. 11. On the first question, recent calculations by Baym using a simple approximation to a Boltzmann equation find that collisions between partons

produce thermalization after a time $\gtrsim 5\theta$, where θ is a relaxation time which could be quite short, perhaps ~ 0.5 fm/c [see Eq. (9) and Fig. 1 of the 2nd Ref. 16]. Regarding the second question, we repeat the main point¹¹ in relation to the processes discussed in the present paper. In contrast with the usual applications of thermodynamics to single macroscopic systems, for the very small systems produced in high energy collisions the physics can only be extracted from the statistical analysis of many events with common collective characteristics. One analyzes ensembles of collisions and performs measurements on subsystems of the total system formed (for the present paper, the relevant subsystems are the hadronic matter in the central rapidity region as far as Section 2 is concerned, that hadronic matter plus a dilepton in the same region for Section 3; the precise delimitation of the central rapidity region involves some freedom which is immaterial at high energy). Each ensemble of collisions can be defined by specifying small intervals for the values of various "collective variables" of the subsystem (examples of such collective variables are dn/dy , or better the charged particle multiplicity in a given rapidity interval $\Delta y \sim 1$, the average p_T or the total transverse energy in Δy , the presence of one dilepton in Δy and its mass and p_T value, etc.). For sufficiently high multiplicity, these ensembles should be highly randomized as soon as many degrees of freedom are excited, which can occur in the first 1-2 fm/c of the collision (time being defined in the appropriate co-moving frame, e.g., the frame where the above interval Δy is centered only = 0). They can then be approximated by thermalized ensembles with the same values of the collective variables. In other words, it is to these ensembles and not to single collisions that thermodynamics can be applied at early times [for example, the entropy density σ in Eq. (8) at $\tau \sim 1$ fm/c refers to such an ensemble, for which $\tilde{\sigma}$ defined in Eq. (2) is one of the collective variables], and it is in this sense that we answer our second question above by yes, even at early times.

At later times ($\tau \gg 1$ fm/c) thermalization can occur even for individual collisions, but only for those properties which involve many degrees of freedom, e.g., the properties of gluons and light quarks. For rare degrees of freedom like heavy quarks or dileptons, thermodynamics again applies only to the ensembles mentioned above. This can be illustrated with the dilepton emission problem of Section 3. In the notation there used, dileptons of transverse mass $M_T \ll T_i$ are produced when the plasma has cooled down to temperatures $T \sim M_T \ll T_i$. By then, the plasma may have lived long enough to be thermalized in individual events, with thermal distributions for gluons and light quarks in a single event. Per event, however, at most one or very few dileptons are emitted and a distribution like Eq. (7) has only meaning for an

ensemble of events. Of course, the use of ensembles is needed for microscopic systems even if they are in a single quantum state (because of the statistical interpretation of the quantum-mechanical wave function), but thermodynamics is in general not applicable. What happens in our case is that the ensemble of subsystems mentioned above has a density matrix which can be approximated by a thermal one, and that after a relaxation time (presumably several fm/c) even single subsystems have thermal properties for those constituents which are present in large number (gluons and light quarks in the plasma as discussed above). Usually, the event-by-event fluctuations observed in collisions are simply due to quantum mechanics (statistical interpretation of the wave function) and therefore originate very early ($\lesssim 1$ fm/c). In case of plasma formation, as explained in Ref. 7 and at the end of Section 2, strong fluctuations are also expected later on, at the time of the phase transition (break up of plasma column in droplets, hadronization by deflagration).

Notwithstanding all previous considerations, it is also quite possible that thermalized hadronic matter is never produced in high energy nuclear collisions, even for very large values of dn/dy , in which case no quark-gluon plasma could be formed in such collisions despite the fact that quarks and gluons undoubtedly play a major rôle in the particle production process. The by-now standard models for low- p_T ultra-relativistic hadron-hadron collisions, like the Lund string model¹⁷ or the dual parton multi-chain model¹⁸, are being generalized to nucleus-nucleus collisions^{19,20}. These models are far from uniquely determined on theoretical grounds (they deal with non-perturbative QCD), and it will probably not be very difficult to adjust them to fit most of the future experimental findings on ultra-relativistic nuclear collisions. As these developments proceed, it will be necessary to sharpen the tests for QGP formation and the differences with the predictions of the non-thermal models. The difficulty here lies in the qualitative character of both thermal and non-thermal models, none of which are good enough to make hard quantitative predictions.

What are then the qualitative features of QGP which differentiate it from the standard non-thermal models of low- p_T collisions? One is the property of the plasma that a large fraction (about half) of its energy contents is in the form of a disordered gluon gas, whereas in the string and chain models the colour fields are in highly coherent states which contain much energy but no or very few gluons (these models neglect the numerous possible modes of excitation of QCD flux tubes, e.g., their transverse and longitudinal vibrations). Unfortunately, this difference is only theoretical, and the hadronization mechanisms can probably be arranged to give the same consequences for the produced hadrons. For example, the efficient production of strange quarks by

gluons in the plasma²¹ could probably be matched in string and chain models by adjusting their assumptions.

A more hopeful differentiation is likely to come from the fact that in case of QGP formation hadronic matter must undergo a strong phase transition, strong in the sense that a large latent heat must be released at essentially constant temperature and pressure. For such collisions and rapidity intervals that have early entropy and energy densities in the transition region, there is then the thermodynamic relation $\epsilon + p = T\sigma$ with p and T essentially constant while ϵ and σ cover a wide interval (we consider the central region supposed to have net baryon density zero). We also know that p is small compared to ϵ . Estimating σ and ϵ by the quantities $\tilde{\sigma}$ and $\tilde{\epsilon} = \bar{p}_T \tilde{\sigma}$ of Section 2, we then obtain an almost linear relation between them, with $\bar{p}_T$ almost constant because $p \ll \epsilon$. The behaviour below and above transition must be different. This is the fine structure of the $\bar{p}_T$ versus $\tilde{\sigma}$ dependence referred to in Section 2, and we do not see how non-thermal models could produce it naturally^{*)}. Similarly, the strong fluctuations we have discussed earlier (break up of plasma column in droplets, hadronization by deflagration) would probably be hard to reproduce in non-thermal models.

Finally, the question of dilepton production will have to be reconsidered in this context if the non-thermal models are extended to include additional dilepton creation beyond the standard Drell-Yan mechanism, for example along the lines proposed long ago by Bjorken and Weisberg for hadron-hadron collisions²³.

^{*)} Note that an increase of $\bar{p}_T$ with $\tilde{\sigma}$ without fine structure is easily obtained in string models, as shown by the recent "colour rope" extension of the Lund model to nuclei^{20,22} (it results from the assumption that a colour flux tube has a constant radius independent of the flux it carries, see Sections 2 and 3 of Ref. 22).

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