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HADRONIZATION OF A QUARK-GLUON PLASMA WITH KADANOFF SCALING

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Meson as well as baryon production as a phase transition of a quark-gluon plasma is discussed in the context of a two-dimensional (rapidity, proper time) model with Kadanoff scaling. Features not met in perturbative QCD or in the dual parton model are stressed.

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Much attention has recently been directed to the possibility of forming a quark-gluon plasma, especially in relativistic heavy ion collisions[1]. It is believed that the hadrons emerging due to the subsequent confinement phase transition of this plasma will throw some light to the dynamics of the evolution of the early universe, which, presumably, went through such a phase soon after the big bang[2].

In this work we assume that a quark-gluon plasma is formed due to a high-density hadron collision at $\tau=0$. This evolves with time along the space-time hyperbolas $t^2-x^2=\tau^2$, parametrized as $t=\tau\cosh y$, $x=\tau\sinh y$, where τ is the proper time and y the c.m. rapidity[3]. We assume that at a critical time $\tau_c \sim 0.2$-0.5F hadrons begin to emerge due to a phase transition, until confinement is completed at a time $\tau_h \sim 5$-10F. That is, hadron formation takes place between the hyperbolas τ_c, τ_h in a rapidity region $Y_c=2\ln\tau_h/\tau_c$, required by causality[4].

Once a one-dimensional system of n points, filling a "volume" Y_c, near the critical point obeys Kadanoff scaling at the thermodynamic limit, assumed to be finite, it is described by the generic partition function[5]

$$Z_n(Y_c) = \frac{b}{2\sqrt{\pi}} \frac{n-1}{Y_c^{3/2}} \exp\left[-\frac{b^2}{4}\frac{(n-1)^2}{Y_c}\right] , \qquad (1)$$

that is, interactions are only allowed between nearest neighbours (factorization). This is equivalent to introducing a potential $V(\varphi) = (z-1)\varphi\varphi^* - \frac{1}{4}b^2(\varphi\varphi^*)^2$ in the Landau-Ginzburg model of the phenomenon (z is the fugacity)[6]. The para-

meter b should be determined by the data. Note that, when (1) is identified with a hadron (cluster) multiplicity, Kadanoff scaling is equivalent to KNO scaling. In the following analysis, the form (1) is extrapolated to finite values of n and Y_c.

The thermodynamics of the system is conveniently described by means of a grand partition function

$$Q\,(z\,,Y_c) = \sum_n z^n\, Z_n\,(Y_c), \qquad (2)$$

which generates all measurable quantities. For example, the asymptotic behaviour of the average multiplicity is given by

$$\langle n\rangle = \frac{\sqrt{\pi}}{b}\, Y_c^{\frac{1}{2}} \quad (Y_c \to \infty) \quad . \qquad (3)$$

The configuration (n,y), where n points are distributed within a length Y_c, any of them being fixed at the position y, is described by the density

$$\rho_n\,(y\,,Y_c) = Z_n(Y_c)^{-1} \sum_{k=1} Z_k(\tfrac{1}{2}\,Y_c + y)\; Z_{n-k+1}(\tfrac{1}{2}\,Y_c - y) \qquad (4)$$

Weighting this expression with the probability $P_n\,(Y_c) = Z_n\,(Y_c)/Q\,(1,Y_c)$ and summing over n, we get the fully inclusive factorizable density

$$\rho(y,Y_c) = Q(1,Y_c)^{-1}\; Q(1,\,\tfrac{1}{2}\,Y_c + y)\; Q\,(1,\,\tfrac{1}{2}\,Y_c - y) \quad . \qquad (5)$$

In order to estimate the range of values of the parameter b, required to describe the production of baryon chains in the

near-forward or near-backward regions, we identify the maximum density, $\rho^{max} \simeq 3\sqrt{6}/(\pi e^3)^{\frac{1}{2}}\, b^2$ (independent of Y_c), predicted by (5) near the end points (Fig.1) with the final density, $\Delta n_N/\Delta y$, of the cold nucleon matter. Taking $\Delta n_N/\pi R^2\; \tau_h\; \Delta y = \rho_c \equiv 1/\frac{4}{3}\,\pi r_N^3 \simeq 0.5\ F^{-3}$, where $R = R_o A^{1/3}$ is the radius of the colliding nuclei of mass number A ($R_o \simeq 1.2F$), we find

$$b = (6/\pi e)^{3/4} R_o^{-1}\; A^{-1/3}\; (2\rho_c\;\tau_h)^{-1/2} \equiv b_f. \qquad (6)$$

For example, in Pb-Pb collisions (A = 208) for τ_h = 3-10 F we have $b_f \simeq 0.062$-0.034.

In this range of values of the parameter b, the two sharp maxima of the density (5) are formed almost at $\tau \simeq \tau_c$ and then they move appart. At $\tau = \tau_h$ they are found at a causal distance Y_c (Fig.1). That is, we require a total available rapidity $Y > Y_c$ in order that they materialize.In our numerical example above, with $\tau_c \simeq 0.5$ F, we have $Y_c \simeq 4$-6 units of rapidity. Very low baryon density is predicted by Eq.(5) at the central region, namely $\rho\,(0,Y_c)/\rho^{max} \simeq 2e^{3/2}\; b_f/3\sqrt{6Y_c}$ ($\simeq 0.040$-0.017 in our example).

Notice that the energy-density difference between its forward (quark matter) and its central (normal baryonic matter) values may be thought of as the "latent heat" density of the transition. Thus, measuring the baryonic spectrum probes directly the properties of the quark-gluon plasma phase transition.

Once b is fixed, all quantities relevant to baryon production in the longitudinal region due to q-g plasma formation are predictable, through Eq.(2)[7].For example, the average baryon

multiplicity in Pb-Pb collisions at a laboratory energy E_L = 200 GeV/nucleon is $\langle n_B \rangle \simeq 130$ {assuming $\tau_h = 10F$}. This is close to the IRIS Monte-Carlo estimate, without plasma formation [8]. However, there is an important feature of the present model, which is not shared by either QCD (e.g. diquark hard scattering) or the dual parton model, namely the natural accommodation of unconventional events with unusually high multiplicity (Centauro's) [9]. Such events are predicted to be absent above a certain energy threshold.

Indeed, from Eq.(6) we find that a baryonic chain produced in Pb-Pb collisions, as an example, with a final density much larger than the typical nuclear density, e.g. $\rho_c \simeq 3.5\ F^{-3}$, is described by a b-value $b_f \simeq 0.023 - 0.013$ for $\tau_h \simeq 3\text{-}10$ F (Fig.1). Moreover, baryon number conservation, namely $\langle n_B \rangle < 2A$, in a central collision of two identical nuclei of mass number A, requires $Y_c \lesssim (4/\pi)A^2\, b_f^2$. This means that if the laboratory energy per nucleon of the produced system exceeds

$$E_L^{max} = \frac{1}{2}\, m_N \exp\left[\left(\frac{6}{\pi e}\right)^{3/2} \frac{2}{\pi R_o^2}\, \frac{A^{4/3}}{\rho_c \tau_h}\right], \qquad (7)$$

where m_N is the nucleon mass, a substantial fraction of the initial energy is transferred into a system of mesons created in the central region through the excitation of the vacuum. According to this bound, events with unusually high density produced in Pb-Pb collisions disappear above a total final-state laboratory energy about 1000 TeV (for $\tau_h \simeq 10F$). It is worth-noting that typical Centauro events are not observed above this

range of energies in ultra-high-energy cosmic-ray collisions [9], in qualitative agreement with the above bound.

Turning now to the central region, we assume that mesons are produced in droplets of size $\Delta_c \lesssim 1$, at an average distance $\delta y \gtrsim 1$ [10]. Since Kadanoff scaling (or, equivalently, KNO scaling for droplet multiplicities) is our universal hypothesis, central production of droplets is again described by Eqs.(1)-(5), where now n , y refer to the nth droplet at the position y. However, the parameter b is now expected to take a different range of values. In order to turn (5) into a meson distribution one may further assume that within a droplet the meson density follows that of the original quanta (gluons), i.e. $dn_g/dy \simeq 2A(xG)_{x=0}$ [3], whence the meson distribution is given by

$$\rho_{meson}\,(y, Y_c) \simeq 2A(xG)_{x=0}\, \Delta_c\, \rho(y, Y_c)\,. \qquad (8)$$

To elaborate on the physical content of the distribution (8) we extrapolate it at earlier times, $\tau \leq \tau_h$, and we assume that we start with a single droplet of size $\Delta_c \lesssim 1$ (Fig.1a). Thus, only the first term, n = 2, in the "droplet expansion" (2) of the grand partition function Q is present in (5). As the time passes, for $\tau > \tau_c \exp(\frac{1}{3} b^2)$, corresponding to a droplet size $Y > 2b^2/3$, this splits into two secondary droplets appearing at the positions $y_\pm(Y) = \pm\frac{1}{2}\, Y\, (1 - 2b^2/3Y)^{1/2}$. When confinement is completed, at $\tau = \tau_h$, their distance should be $\delta y = y_+(Y_c) - y_-(Y_c)$ (Fig. 2b), whence we find

$$b = \{\tfrac{3}{2}\, Y_c\, [1 - (\tfrac{\delta y}{Y_c})^2]\}^{1/2} \equiv b_c\,, \qquad (9)$$

independent of the mass number of the colliding nuclei. Within our standard example ($Y_c \simeq 4$-6, determined by causality) with $\delta y = 1$ [10] we find $b \simeq 2.3 - 3 \gg b_f$. It is interesting that there are experimental hints [11] in favour of such secondary maxima in the central meson distribution [7].

To summarize, novel features of hadron production, due to the formation a q-g plasma obeying Kadanoff scaling near the critical point, which lie outside the framework of perturbative QCD or of the dual parton model are:

(i) Development of an unconventional baryonic spectrum, with two pronounced spikes separated by about five units of rapidity and very low baryon density in between.

(ii) Accommodation of events with exceptionally high multiplicities (Centauro's) in the fragmentation region.

(iii) These events are absent above an energy limit, calculable for each type of collision.

(iv) Development of meson clusters, appearing as secondary maxima of the inclusive cross section in the central region.

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REFERENCES

1) L. Van Hove, Proceed. XVII Int. Symposium on Multiparticle Dynamics (Seewinkel, 1986), p.801.

2) E. Witten, Phys. Rev. D30 (1984) 272;
G. Baym, Nucl. Phys. A447 (1985) 463.

3) J.P. Blaizot and A.H. Mueller, Nucl. Phys. B289 (1987) 847.

4) J.D. Bjorken, Phys. Rev. D27 (1983) 140.

5) N.G. Antoniou and S.D.P. Vlassopulos, Phys. Rev. D18 (1978) 4320.

6) N.G. Antoniou, A.I. Karanikas and S.D.P. Vlassopulos, Phys. Rev. D29 (1984) 1470;
P. Carruthers and I. Sarcevic, Phys. Lett. B189 (1987) 442.

7) N.G. Antoniou et al., in preparation.

8) J.P. Pansart, DPHPE 86-06 (1986); Nucl. Phys. A461 (1987) 521.

9) K. Goulianos, Comments Nucl. Part. Phys. 17(1987)195;
A.D. Panagiotou, A. Karabarbounis and A. Petridis, UA/NPPS 8 (1987); and references therein.

10) L. Van Hove, Z. Phys. C27 (1985) 135.

11) P.L. Jain, K. Sengupta and G. Singh, Phys. Rev. Lett. 59 (1987) 2531.

FIGURE CAPTIONS

Fig.1 Density of baryons emerging due to a phase transition of a quark-gluon plasma with Kadanoff scaling {Eq.(5) with $b \sim O(10^{-2})$}. Two sharp spikes appear at $\tau = \tau_c$. When confinement is completed, at $\tau = \tau_h$, they are at a distance $Y_c \simeq 5$.

Fig.2 Same as in Fig.1 for the meson density {Eqs.(8) and (5) with $b \sim O(1)$} :

a. Single droplet of causal spread $Y(\tau) = 2\ln\tau/\tau_c$.

b. Appearance of daughter droplets at a distance $\delta y \simeq 1$.

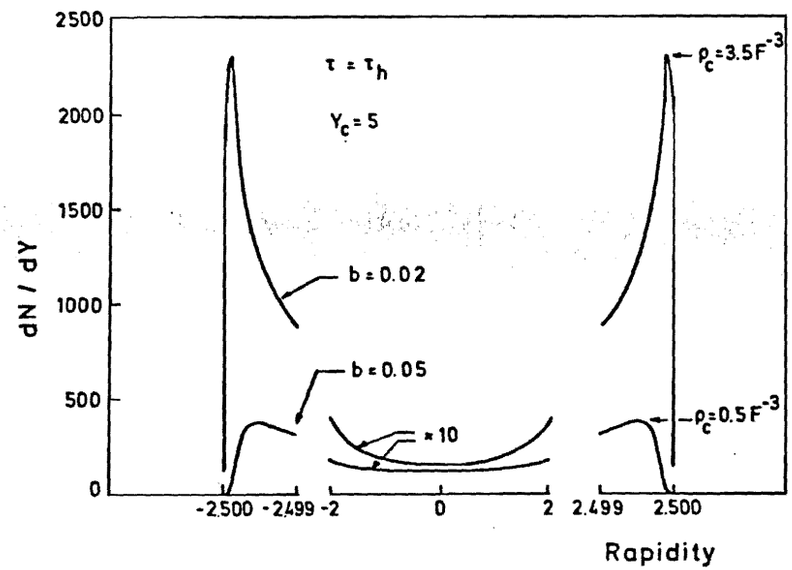

Fig. 1

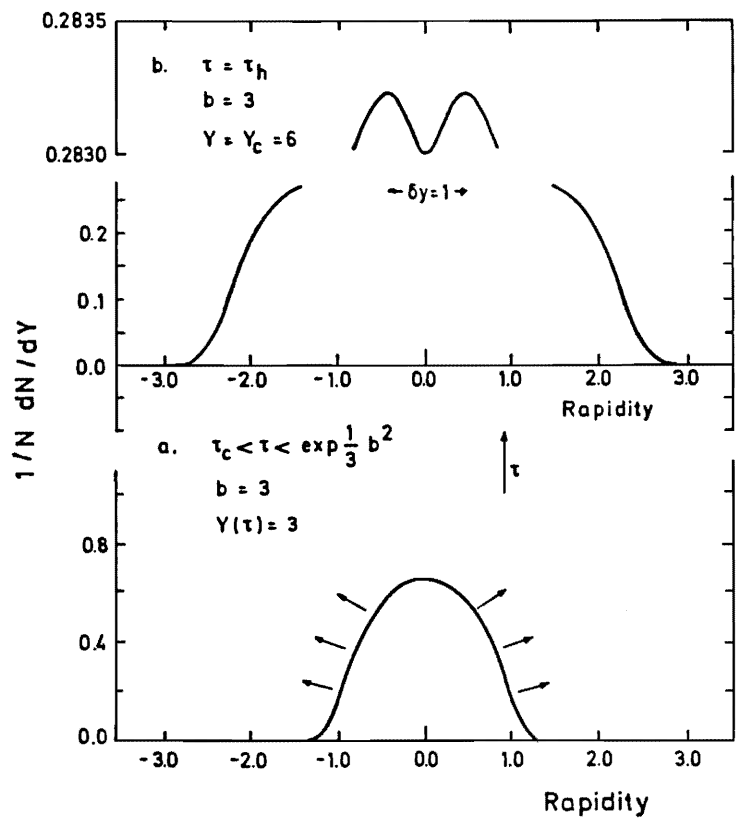
0.2835
0.2830
b. τ = τh
b = 3
Y = Yc = 6
δy = 1
0.2
0.1
0.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
Rapidity
1/N dN/dY
a. τc < τ < exp 1/3 b2
b = 3
Y(τ) = 3
τ
0.8
0.4
0.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
Rapidity

Fig. 2