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THE PROBLEM OF PHASE TRANSITION AND THE HEAVY ION COLLISIONS AT VERY HIGH ENERGIES

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ABSTRACT

This paper presents a review of our current understanding of deconfined phases of strongly interacting matter at high energy densities - quark matter, or the quark-gluon plasma, likely to be produced in ultra-relativistic heavy ion collisions. Properties of the deconfined quark matter and speculations concerning the ways in which this phase transition can be explored in laboratory are discussed. Some suggestions have been put forward for the future experiments.

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1 Introduction

The advent of accelerators producing heavy ion beams of very high energies are expected to lead us to new frontiers of physics. Modern theoretical notions allow the formation of rather large (on the hadron scale) space domain filled with a quark-gluon plasma (QGP). Accordingly, a phase transition to a plasma of deconfined quarks and gluons can occur [1] provided the energy density approaches some critical value. Little is, however, known to-date about the properties of nuclear matter at densities other than the common equilibrium density $\rho = 0.15 \text{ fm}^{-3}$ or at finite temperatures. Experimental information on the unexplored domain is being sought by analysing high energy collisions of the heavy ions. An impressive experimental programme has been pursued [2] to explore the possibility of detecting quark-gluon plasma in the laboratory, but without any success. The problem of investigating the phase transition between a hadron and a quark-gluon matter has become, therefore, one of the most challenging task of theoretical and experimental efforts in high energy physics for the coming years.

In this paper a review of the problem of phase transition has been given with reference to the phenomenological models and the relevant experimental results. Since heavy ion physics is becoming an important field of research, suggestions have been put forward regarding the future experimental efforts and techniques, to the benefit of those who may opt to carry out experimental research in this field.

2 The Situation

The idea of a phase transition from hadronic to quark matter is as old [3] as the quark structure of hadrons. Since then, a great variety of more or less phenomenological approaches to the two-phase nature of strongly interacting matter have been pursued [4]. The advent of quantum chromodynamics (QCD) gave rise to the hopes that both the two-phase character and the transition might be obtained from one basic theory. The exciting developments of the past years seem to indicate that this hope is justified [5-7]. QCD, the most fundamental theory of strong interactions so far developed, specifies the basic interaction of coloured quarks and gluons confined by the spontaneous symmetry breaking of the physical vacuum, together with the colour field coupled to them. The quarks and gluons in the physical vacuum act there as if they were nearly free and massless. QCD suggests that colour confinement prevails under normal conditions; but at sufficiently high density and/or temperature deconfinement should occur, leading to a new phase of matter, the quark-gluon plasma. The resulting plasma of quarks and gluons presents us with a state of matter physically different from anything we have so far explored in the laboratory. Our universe in the first 10^{-5} seconds after the big bang probably consisted of such a plasma, in equilibrium with photons and leptons. After this brief pregenesis interlude was the void created and hadrons appeared. Phenomenological estimates of various kinds suggest that the conditions for such a transition can be attained in very energetic heavy ion collisions. it is the prospect of stimulating such a process in the laboratory, of creating quark matter and watching it freeze into hadrons, that makes relativistic heavy ion collisions a subject of such fundamental interest.

To investigate phase transition in the heavy ion collisions, one needs to find answers to the following basic theoretical questions:

(a) What are th energy density ε and the baryon number n_b attainable in the relativistic heavy ion collisions?

(b) What are the temperature and chemical potential for QGP formation in heavy ion collisions?

(c) What are the stages of expansion and cooling of QGP?

(d) Which are the experimental signals of QGP formation?

(e) How can the phase transition from QGP phase to a confined (hadron) phase be realized?

Since little is known about heavy ion (AA) collisions at 100 GeV/nucleon or above, answers to most of these questions are found by extrapolating the ideas developed for the description of hadron-hadron and hadron-nucleus interactions [8]. Starting with Landau hydrodynamical [9] and the thermodynamic model [10], various theoretical models have later been used for extrapolation purposes. The quark-parton model [11-13], the quark model [14], the additive quark model, [15-17], the constituent quark model [18], the dual parton model [19-27], and finally Fritiof model [28] are the examples to quote that look at the dynamics of quark matter. According to these models multiparticle production in high energy hadron-nucleus collisions provide information on the structure of hadrons and on the interactions and hadronization of their constituents. There are enormous publications [29] trying to answer the above questions based on these models, but all answers are not convincing.

On the experimental side a large amount of work has been done at CERN and through emulsion collaborations using 200 GeV/nucleon 0^{16} and S^{32} beams [30-31]. The first aim of these experiments has been to survey the general properties of relativistic heavy ion collisions, and to compare data with model calculations. Any deviation could signal the onset of new physics. The second aim has been to explore specific probes of QGP, once the general features of the reaction dynamics are understood. In the experiments performed so far, however, no evidence for the quark deconfinement has been found.

In view of the foregoing discussion it becomes evident that QGP phase transition is still an unsolved problem, requiring further efforts, theoretically as well as in the laboratory, applying suitable experimental techniques.

3 Parameters of Quark-Gluon Plasma

As to the first question, the present-day answer is very optimistic and it is reflected in the title of this section. A crude estimate of the energy density, above which the state of a quark-gluon plasma is realized, is the value 1 GeV/fm^3. Let us now discuss how such an energy density can be stored in the central AA- collisions (the central collisions are triggered by high multiplicities of secondaries and are taken as those with an impact parameter less than the range of the interaction, i.e. $b < 1$).

The simplest picture (Fig.1) of a collision of two heavy nuclei is that of their complete overlapping and stopping in the centre of mass system [32,33]. All energy of two centrally colliding nuclei $2AE_N^{cm} = 2m_N a\gamma$ (γ is the Lorentz factor of a projectile nucleus in the

centre of mass system) discharges in the Lorentz contracted volume of one nucleus V_a/γ. Then the energy density and the density of baryonic number are given by the expressions:

$$\varepsilon = 2Am_N\gamma/(Va/\gamma) = 2n_0 m_N\gamma^2 \quad (1)$$

$$n_b = 2A/(Va/\gamma) = 2n_0\gamma \quad (2)$$

where $n_0 = A/v_a = 0.17 fm^{-3}$ is a normal nuclear density and, as known,

$$\gamma = \left(1 + \frac{\mathcal{P}}{2m_N}\right)^{1/2} \quad (3)$$

where $\mathcal{P}$ is the projectile kinetic energy per nucleon in the laboratory frame. Let us now quote some values of ε and n_b, as a function of $\mathcal{P}$, for heavy nuclei such as uranium:

$$\varepsilon = 1GeV/fm^3, \quad n_b = 3.5n_0, \quad \mathcal{P} = 4GeV$$

$$\varepsilon = 2GeV/fm^3, \quad n_b = 5n_0, \quad \mathcal{P} = 9.9GeV$$

It is seen that the critical energy density 1 GeV/fm^3 is attainable at comparatively low laboratory energies and that ε rapidly increases when $\mathcal{P}$ increases (at $\mathcal{P} \gg m_N$, we have approximately $\varepsilon = n_0\mathcal{P}$). However, at high initial energies such an effective mechanism gives rise to serious doubts. It follows from the analysis of data on pp and pA-high energy collisions that the expected picture of AA-collisions is quite different – even in the central collision the nuclei pass through each other.

In Ref. [14] a new original mechanism of quark-gluon plasma formation in AA-collisions, with energy of a few tens of GeV per nucleon in the centre of mass system, has been proposed. The results obtained in Ref.[14] are based on the experimental data on pp-high energy collisions and some quite plausible conjectures. Following Ref.[14], we focus on the fragmentation region of a target nucleus using the laboratory frame for convenient discussion. A projectile nucleus stimulates hadron production. The spectra of which are extracted from the pp-scattering data, supposing that the AA-collision is equivalent to a nucleon-nucleon collision times mass number A. The dominant parts of produced particles have the large momenta at high energies and they are formed outside a target nucleus. However, secondaries rather slow in the laboratory frame behave in a quite different way. it is possible to formulate some kinematical constraints [14] for the momenta of secondaries ensuring their formation inside a target-nucleus. These particles get stuck up in a target nucleus depositing their energy and momentum. The second important point securing a growth of ε and n_b is a compression by k_0 times of a target nucleus (in its new rest frame) after passage of projectile-nucleus through it (Fig.2).

Knowing the total energy E and momentum $\vec{\phi}$ which is deposited inside a target nucleus, we can compute its new mass $M = (E^2 - \phi^2)^{1/2}$ and hence the energy density $\varepsilon = M/(V_a/k_0)$ and the baryonic numbers density $n_b = n_0 k_0$. The calculations made in Ref. [15] show that in the energy interval $E_{cm} = 30 - 70$ GeV/nucleon the quantities ε and k_0 re slowly varying (this fact follows from the approximate scaling of the spectra of secondary hadrons in the fragmentation region) and take the values:

$$\varepsilon = 2GeV/fm^3, k_0 = 3.5$$

A system formed as a result of heating and compression of a target-nucleus moves in the laboratory frame with the Lorentz-factor $\gamma = 2$. The numerical value $\varepsilon = 2GeV/fm^3$ confirms that the nucleus is converted to a quark-gluon plasma.

4 Properties of Quark-Gluon Plasma

The foregoing discussion argues quite seriously the possibility of quark-gluon plasma formation in AA-collisions at energies which are quite realistic for the experimental facilities of the closest future. Let us now try to describe the properties of quark-gluon plasma with initial parameters

$$\varepsilon = 2GeV/fm^3, \; n_b = 3.5n_0 \tag{4}$$

Crude estimates of the quark-gluon plasma lifetime show that it is quite enough to reach a thermodynamical equilibrium in a system (constituents have time to undergo a large number of mutual collisions). so our description of quark-gluon plasma is the following. We introduce a yet unknown temperature and chemical potentials of quark-gluon plasma, and then compute the energy density and the density of baryonic number in the formalism of a canonical ensemble. Equating the quantities of Eq.(4) with the functions of T and u obtained in such a way we have the equations to determine T and u of an initial state.

Following the bag model, we take into account the confinement effect by introducing the phenomenological quantity into the energy density of quark-gluon plasma [32, 33, 32, 35]. The contribution of the perturbatively calculated interactions of the quarks and gluons to the thermodynamical quantities comes to a few percent in the required region of T and u, so we neglect it to simplify calculations. Then we have for the energy density

$$\varepsilon = \frac{8\pi^2}{15}T^4 + \sum_{i=u,d,s} \varepsilon_i + B \tag{5}$$

where

$$\varepsilon_i = \frac{q}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\exp[(\sqrt{p^2+m_i^2} - u_i)/T] + 1} + (u_i \to -u_i)\;, \tag{6}$$

$$p = momentum\;,$$

and $q = 2N_c = 6$. The first term of Eq.(5) corresponds to the gluon contribution. The quantities m_i and u_i are the masses and chemical potentials of u. d and s quarks (the contributions of heavier quarks are considered to be negligible here. Let us note that in Eq.(5) and Eq.(6) as usual we take into account all colour states of quarks and gluons ignoring the requirement of colourlessness of the allowed states of the whole system. (We discuss this point later.)

In what follows we neglect the masses of u and d quarks in comparison with the maximum values of T, u. Then for $m_q = 0$ the quantity ε_q is calculated exactly from Eq.(6) as

$$\varepsilon_1 = \frac{7\pi^2}{20}T^4 + \frac{3}{2}T^2u_q^2 + \frac{3}{4\pi^2}u_q^4 \tag{7}$$

As the strangeness of the system under consideration is equal to zero it is necessary to fix $u_s = 0$ and take, in accordance with the estimations of Ref. [36], $m_s = 280$ MeV.

Let us introduce the densities of quark and antiquark numbers of each kind as:

$$n_i(\bar{i}) = \frac{3}{\pi^2}\int_0^\infty \frac{p^2 dp}{\exp[(\sqrt{p^2+m_i^2} \mp u_i)/T] + 1} \tag{8}$$

The difference between quark and antiquark number of each kind $\Delta n_i = n_i - \bar{n}_i$ is the conserved quantity (we ignore, of course, weak interactions). From Eq.(8) we find for μ and d quarks.

$$\Delta n_q \equiv n_q - n_{\bar{q}} = u_q T^2 + u_q^3/\pi^2 \tag{9}$$

The baryonic number density of a system is then defined by

$$n_b = \frac{1}{3}(\Delta n_u + \Delta n_d) \tag{10}$$

where the strange quarks do not contribute as we take $\Delta n_s = 0$.

In the collision of uranium nuclei ($Z = 92$, $A = 238$) we have for the initial state of quark-gluon plasma ($k_0 = 3.5$)

$$n_b = k_0 n_0,\; n_0 = 0.17/fm^{-3} \tag{11}$$

$$n_q - n_{\bar{q}} = 3.6 \times 0.5/fm^3 \tag{12}$$

where 0.5/fm^3 is the quark density of the usual $T = 0$ nuclear matter. Equating ε of Eq.(5) with the initial value 2 GeV/fm^3 and Δn_u, Δn_d of Eq.(9) with the initial values of Eq.(11) and Eq.(12), respectively, we obtain three equations to determine three unknown quantities T, m_u and u_d. The solution of these equations, by taking $B = 250$ MeV/fm^3 in Eq.(5), is the following

$$T = 165MeV; u_u = 202MeV; u_d = 228MeV \tag{13}$$

Using Eq.(8) we can now find the number of the quark-antiquark pairs in a plasma (i.e. the number n_i^*). For $\bar{u}$ and $\bar{d}$ quarks we obtain (for $\bar{u}_q > T$)

$$n_{\bar{q}}(T \cdot u_{\bar{q}}) = \frac{3}{\pi^2}\int_0^\infty \frac{p^2 dp}{\exp[(p + u_q)|T] + 1} \simeq \frac{6T^3}{\pi^2}\exp(-\frac{u_{\bar{q}}}{T}) \tag{14}$$

In the initial state, of Eq.(13) we have

$$n_{\bar{u}} \simeq 0.11 fm^{-3};\; n_{\bar{d}} \simeq 0.09 fm^{-3} \tag{15}$$

It is seen from Eq.(14) that the availability of a large number of quarks of any kinds (large Δn_q and consequently, large u_q) leads to a statistical suppression of $q\bar{q}$ pairs of the same kind. So the presence of u and d nucleon quarks makes a generation of $u\bar{u}$ and $d\bar{d}$ pairs difficult, but does not prevent a production of $s\bar{s}$ pairs (for $m_s > T$)

$$n_s(T) = n_{\bar{s}}(T) = \frac{3}{\pi^2}\int_0^\infty \int_0^\infty \frac{p^2 dp}{\exp[\sqrt{p^2 + m_s^2}/T] + 1} \simeq \frac{3T^3}{\pi^2}(\frac{m_s}{T})^2 k_0(\frac{m_s}{T}) \tag{16}$$

For $T = 165$ MeV we have

$$n_s = n_{\bar{s}} \simeq 0.21 fm^{-3} \tag{17}$$

We can see from Eq.(15) and Eq.(17) that the number of strange pairs exceeds the number of light quark pairs (in spite of the large mass of strange quark m_s).

5 Colling of Quark-Gluon Plasma

In principle, the stage of quark-gluon plasma expansion has to be described by the equations of relativistic hydrodynamics. However, this task is very complicated (remember, for example, that the quark-gluon system as an ellipsoid form in its own rest frame). So we consider the expansion process in a simplified way. Namely, let us consider that global thermodynamical equilibrium is reached at every stage of the expansion process. Then the state of a quark-gluon system in every new volume can easily be obtained from the conditions of total energy conservation and charge conservation (it means that ε and Δn_q decrease by the same factor in expansion). It is interesting to note that the total entropy of a system is then slightly increasing.

It is mentioned above that the expansion of quark-gluon plasma occurs up to a certain critical value of energy density 1 GeV/fm^3. Afterwards all quarks recombine to form hadrons again. For the value of $B = 250$ MeV/fm^3, the value $\varepsilon_{cr} = 1GeV/fm^3$ corresponds just to the equilibrium value of energy density of a quark-gluon bag $\varepsilon_{cr} = 4B$. At this critical density the pressure $P = \frac{1}{3}(\varepsilon - B)$ of quarks and gluons inside a bag is just balanced by the external vacuum pressure B. The quark-gluon system ceases its expansion and begins to dissociate into final hadrons. Such a picture of a phase transition [34], of course, is not completely pertinent (see section VII) but probably it is quite reasonable to estimate the values of T and n_b in the phase transition region. As we have the critical values $\varepsilon = 1$ GeV/fm^3, $\Delta n_u = 0.41$ fm^3 and $\Delta n_d = 0.48$ fm^3 we can find, in analogy to Eq.(13), Eq.(15) and Eq.(17), for the final state of a quark-gluon system:

$$T = 134MeV;\, u_u = 155MeV;\, u_d = 174MeV$$

$$n_u = 0.06fm^{-3};\ n_d = 0.05fm^{-3}; n_s = 0.09fm^{-3} \tag{18}$$

These values are shown in Fig.3.

Inclusion of hydrodynamical expansion of a quark-gluon system leads to the fact that the energy density falls more rapidly than the baryonic number density. It means that having reached the critical curve the density of baryonic number is a little higher and the temperature is a little lower than without taking into consideration the hydrodynamical expansion stage. Moreover, the different elements of an expanding system at $\varepsilon = \varepsilon_{cr}$ have, generally speaking, various n_b values, i.e. we obtain a finite piece of this curve instead of one point as at final state.

6 Signals for Quark-Gluon Plasma

(1) The idea that the genuine information about quark-gluon plasma can be obtained directly from photons and lepton pairs is known rather for a long time [37,38]. These colourless particles escape freely the quark-gluon system at every stage of its existence and an analysis of their spectra may be very informative. The relevant calculations have already been performed [33,39]. But a large background for lepton pairs formed in the plasma is from Drell-Yan pairs produced in the initial AA collisions. Their contribution to AA collisions are expected to enhance by $A^{1/3}$ relative to surface production of low p_t hadrons. The plasma contribution dies off as an exponential of the pair mass M. A proper resolution of this signal deserves careful theoretical and experimental study. The parameters which may yield a resolution of this signal involves studying the p_t and M^2 dependence of the pair production.

(2) Prompt photons also yield information about the plasma dynamics. A background to prompt photons produced in the plasma is provided by prompt photons produced in the initial AA collisions. The contribution of these prompt photons may be reduced by techniques discussed for reducing Drell-Yan pair background.

(3) As to the spectra of secondary hadrons, the possibilities to discover here some signals of quark-gluon plasma existence are unclear for the present. First of all it seems to us that some peculiarities of the quark-gluon plasma behaviour originates from nonzero baryonic number of a system (these peculiarities are absent in the central rapidity region where even if quark-gluon plasma is formed, we have $n_b = 0$). As we have already seen, the presence of nonzero values of u_u and u_d leads to a rather unexpected inequality $n_{\bar{s}} > n_{\bar{q}}$. So it is interesting to discuss the possibility to observe hadrons evaporated [40] by the surface of an expanding quark-gluon system. An abnormally large part of these will be the strange particles.

At the critical point, corresponding to Eq.(13), the share of strange quarks per unit baryonic number is already not so large. If we consider that all s and $\bar{s}$ quarks, which are available in a quark-gluon plasma at the moment of a phase transition into hadrons, are participating in the strange hadron formation, then we have the following estimates for the number of strange particles per nucleon:

$$\frac{n_s + n_{\bar{s}}}{n_b} = 0.6 \tag{19}$$

It is interesting to remark that if there is no quark-gluon formation (due to nucleon-nucleon collisions of colliding nuclei only) we should obtain the number of K-mesons in this kinematical region ~ 0.2 per nucleon according to the estimation of Ref.[41]. It should be expected here that $\bar{s}$ quarks are basically utilized to form $K^+(u\bar{s})$ and $K^0(d\bar{s})$ mesons, and s quarks are utilized to form the strange baryons (q_1, q_2, s) [41], as $n_u \gg n_{\bar{u}}$ and $n_d \gg n_{\bar{d}}$ (some other aspects concerning strangeness production are discussed in Ref.[42]). The small number of $\bar{u}$ and $\bar{d}$ quarks in quark-gluon plasma argues that the dominant part of π-mesons are produced by the decay of massive hadron systems (in particular, baryonic resonances) and, perhaps, of massive gluon systems (glueballs). The number of "direct" π-mesons (produced just by q and $\bar{q}$ quarks of plasma) is extremely small and a transitory stage of massive bags-fireballs is most important.

In spite of the scantiness of our knowledge about the confinement mechanism, we understand very well that most of the information about the hot and dense phase of AA-collisions is lost when we analyze the spectra of secondary hadrons. So we must presumably study the strangeness production in AA-collisions, and that abundant production of strange baryons, in our opinion, may be the most reliable signal of quark-gluon plasma. The situation, of course, leaves space for any speculations. For example, in Ref. [43] the idea is voiced that all the so-called"abnormal" events in cosmic ray physics originate from the quark-gluon plasma formation in heavy nucleus collisions.

Finally we would like to attract attention to the cumulative effects in relativistic nuclear physics. The formation of quark-gluon fireballs with large masses may lead, as known, to the possibility of a production of secondaries in the kinematical region which is forbidden in nucleon-nucleon collisions [44]. It seems to us that a study of photons and lepton pairs directly emitted from quark-gluon plasma is, therefore the most interesting process.

(4)In this paper, we discuss and elaborate the proposal [45] that a study of the J/ψ peak in the spectrum of lepton pairs emitted in nuclear collisions can in fact provide the necessary information.

The physical picture leading to J/ψ suppression as test for quark deconfinement in nuclear collisions is quite simple. Within a deconfining medium, quarks cannot bind to form hadrons. if a nuclear collision produces such a medium , then this subsequently expands, cools off, and after passing the confinement point T_c, it hadronises: now the quarks and antiquarks combine to form mesons and baryons. heavy quark-antiquark pairs $(c\bar{c}, b\bar{b})$ are produced by hard, pre-thermal interactions at a very early stage in the collision. In a confining medium, such as the physical vacuum, they subsequently undergo soft hadronic interactions to bind to charmonium $(J/\psi.\psi' \ldots)$ or bottonium $(Y, Y', \ldots)$ states, respectively. In a deconfining medium, this binding process is not possible, so the $c\bar{c}$ (or the $b\bar{b}$) just "fly apart". At hadronization, the presence of additional thermal c or b quarks is strongly suppressed:

$$\exp(-m_c/T_c) \simeq 0.6 \times 10^{-3}, \text{ with } m_c \simeq 1.5GeV, T_c \simeq 0.2GeV \ .$$

Hence at this stage, a heavy quark cannot find another heavy partner; it instead has to combine with a common light quark to make an open charm or open beauty meson, such as D(cu, etc.) or B (bu, etc.) Plasma formation thus leads to enhanced open charm or beauty production, at the expense of charmonium or bottonium states. Since in a normal hadronic interaction, the production of open charm is much more abundant than that of J/ψ's, such an enhancement is not likely to be seen. The resulting reduction of J/ψ formation should, however, be clearly observable and hence provide us with a test for quark deconfinement in nuclear collisions. Another way of telling this story is the following [46]:

In a confining medium the confining potential is

$$V_{con} = \frac{\alpha}{r} + \sigma r$$

and it forces confinement. This happens because there is always a minimum for th energy

$$E = \frac{1}{m\langle r^2 \rangle} + \langle V(r) \rangle$$

at some finite $\langle r^2 \rangle$. The confining potential always takes over the repulsive effect of the kinetic energy term (see Fig.4) and a bound state exists.

In a non-confining medium (plasma) the screening of colour charges modifies the potential,

$$V \simeq -\frac{\alpha}{r} e^{-u(T)r} + \sigma r \frac{1 - e^{-u(T)r}}{u(T)r}$$

where $u(T) \sim \frac{1}{D}$ is the Debye mass. Pure confinement, no screening, corresponds to $u = 0$. What happens is that screening "bends"the potential at large r. Above some $\mu_{crit.}$ (or some $T_{crit} > T_c$) no minimum of the energy can be found; bound states are lost (see Fig. 5).

7 Problem of Phase Transition Between Hadrons and Quarks

We discuss here the qualitative consequences of the phase transition model developed in papers of Ref.[47]. For the sake of simplicity, we begin disregarding the dependence on baryonic number. This model [47] gives a united analytical description both for the hadron (bag) phase and quark-gluon plasma phase. At low temperatures a hadron gas behaves approximately as an ideal gas, and with T increasing to the order ≤ 100 MeV pion creation sets in. When T increases further the hadron resonances and massive fireballs are produced. Finally when T becomes very large and hence particle production is so intensive that the energy density of a system reaches the value of the energy density of hadron constituents, a phase transition into quark-gluon plasma occurs at temperature T_{cr} (Fig.6). At $T > T_{cr}$ the energy density behaves as:

$$\varepsilon = \sigma T^4 + B$$

The temperature region $T \leq T_{cr}$ is a matter of maximum interest of course. In this region our system is a gas of massive bags, average masses of which have to be bounded when $T \to T_{cr}$. At $T = T_{cr}$ a discontinuity of energy density appears, as schematically shown in Fig.7.

There is one more specific temperature T_0 ($T_0 < T_{cr}$) in this picture. It is the temperature of a single isolated bag when the pressure of its constituents balances the vacuum pressure B. In section III we took just this temperature approximately as the temperature of a phase transition (at $u_q = 0$).

The physical picture of the evolution of a quark-gluon system which is produced in heavy ion collisions arises in the following form. Cooling down to the critical temperature T_{cr} the quark-gluon plasma undergoes a phase transition to the phase of bags (fireballs). This transition is accompanied by a spasmodic decrease in the energy density. The next stage is then the fireball decay to final hadrons (it includes, of course, the decays of known resonances too, but it is not the only mechanism). At this stage we observe another temperature T_0 which characterizes the "interior" of a single bag and defines the spectra of secondary hadrons. Just this T_0, but not T_{cr} corresponds to the so-called Hagedorn temperature.

Taking into consideration a baryonic number we have to curves instead of two points T_{cr} and T_0 on the plot of Fig.8. The solid curve is the critical (phase transition) curve and the dashed one corresponds to th equilibrium condition $P(n_b, T) = B$ of an isolated quark-gluon bag.

Correct inclusion of colour degrees of freedom of quarks and gluons is quite important for a statistical description of quark-gluon systems. The conventional approach is to multiply the number of internal degrees of freedom by the factor $N_c = 3$ for quarks and by $N_c^2 - 1 = 8$ for gluons. It means that we take equal weights summing over all colour states of quark-gluon system. But this approach is inconsistent with the hypothesis of colour confinement which says that only colourless states (singlets of $SU(N_c)$-group) can be observed. In particular, all allowed states of quark-gluon plasma produced by heating and compressing the uranium nucleus, for example, have to be colourless, too. The problem of colour confinement is beyond our present discussion, but phenomenologically the confinement effects are taken into account by introducing the parameter B. Of course, it is a very crude step and does not distinguish between the colour and colourless states. So at th present level of description we consider the requirement of colourlessness of allowed quark-gluon system states as a subsidiary postulate. It has been taken into consideration by the group theory methods in Ref.[48].

8 Experimental aspects

Results obtained by NA34, NA36, NA38, WA80, E-803 and Helios collaborations, on particle production in the energy range below 200 GeV/nucleon, are reported in Ref.(29). Increase, for example, in the transverse momentum $\langle p_t \rangle$ dependence on transverse energy E_t of photons and pions was not observed (WA80,NA34 collaborations). Particle ratios (π, for instance) were determined by time of flight measurements (E-802, collaborations) and di-muon studies (NA38 results). Nothing very striking, in view of collecting evidence for the quark-gluon plasma, was found. The NA38 collaboration, however, obtained preliminary results showing that the ratio $R = \sigma_{J/\psi}/\sigma_{DY}$ in Oxygen-Uranium collisions decreases substantially when the transverse energy E_t of the collision increases. This phenomena had been predicted in Ref.(45) as a consequence of the formation of large E_t (i.e. for central collisions) of a quark-gluon plasma – the suppression of the J/ψ signal, with respect to the Drell-Yan continuum being a consequence of colour screening.

In another experiment (30) performed by NA35 collaboration at CERN beams of O^{16} at 60- geV/nucleon and 200 geV/nucleon were used. The aim was to study particle production (cross-section, multiplicities), rapidity distribution and transverse momentum (p_t) distribution. Three different types of triggers were used: a Minimum Bias Trigger (MBT), A Forward Energy Veto Trigger (FET) and a Transverse Energy Trigger (TET). Results are illustrated by Figs.9-11. In Fig.9(a) the multiplicity distribution of all charged particles produced in minimum bias $O^{16}-Au$ interactions at 200 GeV/nucleon and emitted within $\theta_{lab} < 60°$ is presented. The shaped is similar to the transverse energy distribution for O^{16}-Pb collisions shown in Ref.30a and is consistent with a geometrical picture of impact parameter dependence (24). The low multiplicity peak corresponds to peripheral events, the plateau reflects the diving-in of the O^{16}nucleus into the Au-target nucleus resulting in a continuous increase of the participants at constant cross-section, and the high multiplicity fall-of contains the less probable hard events with very large number of produced particles. The prediction of the dual parton model (24) and the Fritiof model (28) describe the general shape of the distribution qualitatively. The multiplicity distribution of all charged particles obtained with a forward energy veto trigger selecting central O^{16}-Au reactions at 200 GeV per nucleon, are emitted within $\theta_{lab} < 60°$, is shown in Fig.9(b). The Fritiof model reproduced the data quite well, whereas the dual parton model overestimates the width slightly. The mean rapidity $\langle y \rangle$ as a function of n^-, the multiplicity for negative particles produced in O^{16}-Au interactions at 200 GeV/nucleon, is shown in Fig.10. Comparison with 200 GeV p-Au and 200 GeV pp data for low multiplicities indicates that for large impact parameters nucleon-nucleon characteristics seem to be dominating, where for small impact parameters phenomena characterizing nucleus-nucleus collisions might occur. From Fig.10(a,b) it may be seen that Fritiof model prediction (solid line) shows the same dependence, but predict $\langle y \rangle$-values larger than those extracted from experimental data over the whole multiplicity range. An increase of the mean transverse momentum $\langle p_t \rangle$ with increasing multiplicity was proposed to be

an indication for the transition from a hadronic to a quark-gluon plasma phase (49). To study this effect, $\langle p_t \rangle$ as function of n^- is presented in Fig.11(a,b). No increase of $\langle p_t \rangle$ with n^- is observed in the rapidity interval $0.5 \leq y \leq 4.5$ for th two energies 200 GeV/nucleon and 50 GeV/nucleon. The observations are qualitatively reproduced by the Fritiof model (solid lines). Another interpretation towards the quark-gluon plasma was proposed for the observation of extraordinary high $\langle P_t \rangle$ values of high energy cosmic ray events (50). In Fig.12 the mean p_t distribution determined every by event $(\langle p_t \rangle_{event})$ for central O^{16} interactions with Au at 200 GeV/nucleon is shown. There is no high $\langle p_t \rangle_{event}$ tail visible.

In the recent emulsion experiments (31), performed with 200 GeV/nucleon O^{16} and S^{32} ion beams, both the multiplicities of shower particles and the extent of target fragmentation have been studied for varying degrees of disruption of the projectile nuclei. The results, it has been shown, may be explained within a simple Glauber (geometrical) model.

Let us now review the latest situation from 1987 onward. On theoretical side not much work has been done on cascade mechanism which is characterised by the number of intranuclear collisions. The Lund model (28,58,59) based on the fragmentation of strings between quark and antiquark has incorporated the cascading (rescattering). Out of its rather two dissimilar versions for hadronic interactions the Fritiof model (28) has nicely accounted for the experimental data, but the second version PYTHIA model (60) probably has not been tried. The parameter which determine cascading is r_0, i.e. when two particles come closer than r_0 they interact. Thus r_0 play a valid role in determining energy density with reference to quark-gluon plasma formation. The simplified version of dual parton model VENUS (61) has also been tried to explain nuclear data concerning cascading. In emulsion experiments at 60 GeV/ nucleon and 200 GeV/ nucleon energies it has been concluded (62) that forward correlation are well reproduced by Lund model Fritiof. According to Curuthers and Shih (63) the correlation between hadrons produced in the forward and backward hemisphere provide information regarding the reaction dynamics according to standard information theory. The data on multiplicity and η-distribution of shower particles in emulsion experiments at ultra-relativistic energies (64) are found to compare well with the VENUS model. This model also explains the multiplicity and angular distributions of target associated particles at CERN and BNL energies but fails to account for the black particle data in emulsion (65,66). In Helios emulsion collaboration (67) the interaction of O^{16} and S^{32} at 200 geV/nucleon have been studied in emulsion and in emulsion-tungsten chamber targets at CERN. Some global parameters have been compared with the expectations of dual parton model (22). The correlation between transverse energy, multiplicity and rapidity density in different rapidity intervals have been investigated for O^{16}-emulsion, S^{32}-emulsion as well as for $S^{32} - W$ (emulsion plus a thin tungsten foil W) interactions at the same energy of 200 geV/nucleon. The distribution shown in Fig. 13 (q,b) for emulsion target have broad peak close to η-values expected for $A_{eff}(Ag)$ where,

$$A_{eff} = (3/2)A_p^{2/3} \cdot A_t^{2/3} ,$$

in a simple geometrical picture at zero impact parameter for O^{16} and S^{32} projectile on heavier targets, while A_p, A_t stand for atomic mass of projectile and target nucleus respectively. In the case of W, Fig. 13(c), a peak at $\eta(A_{eff} \rightarrow A_t)$ shows up at the highest E_t. This result could signal violent reinteraction processes, following a central collision on a large target buy the former spectators producing hundreds of secondaries in the target fragmentation region. Results of interaction have been described in prescription of dual parton model (22). Charged particle rapidity distributions are superimposed in Fig. 13(d,e,f) corresponding to the same selection used for emulsion. Fitting of the data show that the model tends to underestimate the dependence of rapidity density distribution $dN/d\eta$ on the atomic mass of the target, whereas the dependence on the atomic mass of the projectile, as well as the charged particle multiplicity, are somewhat overestimated.

An increase of strange particles have been observed in some experiments (68,69). The K^+/π^+ ratio is found to be a least by a factor of four larger than in protoproton interactions. Enhanced production of strange particles in heavy ion collisions should be good indication of plasma formation (70). Enhanced $\emptyset$ meson production has also been suggested as a possible signal for quark-gluon plasma formation (71). Although there is agreement that for central heavy ion collisions at 200 GeV/nucleon the $\emptyset/(\rho+w)$ is about three time greater than proton interactions (72,73) expectations other than quark gluon plasma formation have been suggested (71).

The multiplicity and hence η-distribution in central events provide important information about the collision dynamics. In emulsion experiments at energies from 14.6 GeV/nucleon to 20 GeV/nucleon the η-distribution in central collisions exhibit a Gaussian characteristic (62,74).

The NA38 collaboration at CERN has further studied (75,76) the production of J/ψ in nucleus-nucleus collisions at 200 GeV/nucleon via its decay $J/\psi \to u^+u^-$. At these energies charm production is a rare event with a cross section of about 0.3 mb as compared to the total cross section of the order of 400 mb. This J/ψ suppression is a possible signal for quark-gluon plasma, but there are different competing mechanisms for J/ψ suppression (77) which have been proposed, and it is still difficult to draw definite conclusion about the physical significance of the observed J/ψ suppression. It has been concluded (78) that, since inelastic part of proton-proton cross section only varies with a few percent in the 1 GeV to 1 TeV range, the geometry in ultrarelativistic heavy ion collisions is basically independent of the incident energy. It has actually been found that both the slow target associated particles (74,79), the projectile fragments (80) as well as the particles produced in the fragmentation region (68,81) show energy independent features. Thus nuclear geometry is said to be energy independent over a large range of energy, and a clean cut participant-spectator picture may well be used as a guiding hypothesis for ultra-relativistic heavy ion collisions as assumed in most of the models (82,83). Projectile mass independence has also been shown in the emulsion experiments (66). The WA80 collaboration (83-85), using a simple geometrical approach, calculated average transverse momentum $\langle p_t \rangle$ per participating nucleon in different type of interactions. The results from analyses clearly indicate that, for a given geometry, the number comes out essentially the same independent of the target mass, projectile mass, and centrality.

E802 collaboration measured E_{tot} distribution for silicon induced interaction on four targets (69). The distributions were not found to change from silver to gold target. At CERN energies the tail of distribution continue to move outwards as the target mass increases, and no saturation effects are observed (69, 84, 85). In Helios experiment (67) the rapidity distribution of the ratio E_t/N_{ch} has been measured in a limited pseudorapidity interval backward in the cm frame for events of different centrality. It is found constant in restricted rapidity bin, even at the tail of the differential cross section as a function of the transverse energy. However, the distribution of E_t/N_{ch} is not at all flat in the considered region, and its shape depends on the target and projectile system and the centrality of

the interaction. It indicates the role being played by the nuclear stopping power.

Bialas and Peschanski (86) first introduced the term intermittency to high energy heavy ion collisions to offer a convenient way to refer to the self-similar property. It signifies the power law dependency of multiplicity fluctuations on the width of the rapidity intervals, in varying rapidity intervals. This idea has gathered much interest in the recent years, because what causes intermittency may lead to the fundamental question about the production mechanism of relevant particles, which is highly desirable to understand the reaction dynamics for quark-gluon plasma formation. Evidence for this has been found in nucleus-nucleus collisions (87, 88).

The results described in preceding paragraphs clearly indicate that experimental situation is still not clear. Model calculations cannot completely explain the experimental results and evidence for quark-gluon plasma is also still being awaited.

9 Conclusions

1. The history of particular equilibrium system during heavy ion collisions can be predicted as shown in Fig.14.

Theoretical answers as to the energy density, thermalization and clear signal problems have been given in this review following strictly the line adopted in Ref. (51) with some modifications. According to these, and some other model calculations (52, 53), the critical temperature is to be 200 MeV, which implies that energy density values of 2.0-2.5 GeV/fm^3 are necessary for deconfinement. Temperature of about 200 MeV sand energy density of about 2 GeV/fm^3 are already achieved using S^{32} ions at 200 GeV/nucleon at CERN (89). It remains now to see which ions and which energies would give the indication of the much sought quark-gluon plasma.

It is argued (54) that there occurs one more phase transition, the so-called chiral phase transition (apart from a deconfinement phase transition) in quark-gluon system at $T_{chir} = 1.3T_{crit}$, based on Monte Carlo lattice gauge theory (55). It is displayed in Fig.15. Also the statistical fluctuations play an important role in the η-distributions. Therefore, the new concept of intermittency should be probed as a possible signal for quark-gluon plasma. For the same projectile nucleus at a given energy, a decrease in intermittency strength is observed with increase in multiplicity in interactions of varying mass projectiles (90). There is not a clear answer for the origin of these fluctuations and most of the models do not make accurate prediction of the intermittency. Models thus need to be improved to account for the self-similar and hence observed intermittency effects.

2. Number of observations have been made depending on the mass of two colliding nuclei. An important question is whether these observations are of importance for the detection of quark-gluon plasma. Is it possible to create such conditions in nucleus-nucleus collisions as to reach the most appropriate energy density and thermalization for quark-gluon plasma formation?

To answer this question one should keep in mind that the energy density scale for the transition must be of the order of (or larger than) nuclear energy density, i.e. ~ 0.15 GeV/fm^3. The problem then is how to increase the energy density. Essentially, there are two ways: either by heating or by compressing. With the heating procedure one tries to increase the temperature of the system by injecting more energy. This is the reason why high energies are required. In the compressing procedure one tries to increase, in a given volume, the baryon number density (chemical potential). This is one of the reasons why heavy ions are useful. Moreover, in a collision the Bjorken prescription (56) is usually followed, which states that for AA collisions in central region $\varepsilon \sim A^{1/3}$ GeV/nucleon, i.e. an increase in ε with the projectile atomic mass number.

3. So far as the signals for QGP are concerned, they might have been observed (57), but *it is necessary to understand them. Direct photon or dilepton signals from* QGP phase have problems associated to them due to prompt photons from initial AA collisions and Drell-Yan background respectively. These signals, therefore, require further investigations. The particle production in AA collisions is fairly explained by models of multi-interacting type, i.e. the dual parton model (22) and Fritiod model (28), but still they fail to explain certain important features like p_t distribution and $dN/d\eta$ dependence on projectile and target atomic mass in 200 GeV/nucleon collisions of 0^{16} and S^{32}. The competition between these models is still going on, but other similar models may also describe some of the features of AA collisions and hence should be tried. Fluctuations *in central multiplicities and rapidity distributions are not exactly known. This is an* important question for which an interplay of experimental results and theoretical analysis is very much needed.

So far as the strangeness production is concerned, it has been shown that the K^+/K^- will increase as the baryon density increases (91). It may thus be said that, since at mid-rapidity the baryon density is high at the BNL than at CERN, the $K^+ + K^-$ yield be considered when discussing strangeness enhancement.

The experimental observation of J/ψ suppression is an extremely great achievement of the NA38 collaboration. However, in view of its importance as a possible signal of QGP *formation, it has to be understood with more conventional physics. In order to do so, one* should first understand the A-dependence of the J/ψ and Drell-Yan continuum inclusive cross-section that have been observed in hardon-nucleus collisions. This may be done by considering two different effects: (a) J/ψ absorption within the colliding nuclei and (b) strong screening corrections in the initial state- assuming that, for some unknown reasons, it would be present in J/ψ production and absent in Drell-Yan pair production. A. Capella (29) has computed in the framework of the dual parton model, (22) the J/ψ suppression resulting from J/ψ absorption in nuclear matter based on the value for the inelastic cross section $\sigma^{abs}_{\psi N}$ corresponding to final state. He obtained a J/ψ suppression of 70% to be compared with the experimental value of 40% obtained by the *NA38 collaboration. The* J/ψ suppression measured by NA38 collaboration cannot be explained, therefore, by J/ψ absorption within the colliding nuclei. According to view put forward individually by Capella and Satz (29), final state interactions of the J/ψ (absorption) in nuclear matter could explain the suppression and it is not unreasonable to think that probability of final state interaction decreases with p_t. There is no doubt that absorption generates an effect of the type of the NA38 collaboration. The problem is that no one was able to obtain by absorption a suppression of J/ψ of the order of 40% between large E_t and small E_t events. On the other hand, in final state interaction models, the effect should already be present in proton-uranium collisions but that does not seem to be the case. A simultaneous and detailed experimental study of J/ψ production in pp, pA and AA collisions is mostly needed.

In NA38 the J/ψ and its p_t dependence has been studied. In order to understand this suppression one has to consider states of matter with extremely high densities although it might be possible to explain the observed effects without invoking the actual creation

of quark-gluon plasma.

As to the question of deciding what to measure in the future experiments and what to conclude from the results, following J.D. Deus (29), the answers are summarized below:

	Feature	Probe
(a)	Energy density	Multiplicities and energies of secondaries; E_t; nuclear stopping
(b)	Thermal equilibrium	spectrum and polarization of lepton pairs
(c)	Initial temperature	Thermal dilepton spectrum
(d)	Chemical equilibrium	Particle ratios
(e)	Quark deconfinement	J/ψ suppression
(f)	Plasma expansion and hardonization	Momentum distribution of secondiaries; vs dN/dy

4. *Concluding this rapid survey of the physics of QGP and heavy ion collisions*, one may say that there is little doubt about the existence of a phase transition although the exact form which it takes is not known yet precisely. There is also practically no doubt that the energy density achieved in heavy ion collisions, with incident beam energy in the 200 GeV/nucleon range and above, should reach the critical value. This makes experimentation with heavy ion beams at higher energies and/or larger ions all the more interesting and challenging.

A variety of detection and identification systems have been applied so far. The most important among them have been the calorimeters, vertex detectors, drift chambers, wire chambers *and scintillatic counters etc.An improvement on these detection system should* be expected for the future experimental investigations, as it may become possible to get a new injector at CERN giving beams of Ca and/or Pb of energies up to 177 GeV/ nucleon (in case of Pb ions). The nuclear emulsion also offers itself as the most important technique both as target an detector, highly recommendable for off-line measurements, without requiring improvement or sophisticated electronics. This technique has, in addition, the following special characteristics: (a) accuracy and high sensitivity in recording the charged particle tracks, (b) insensitivity to photons, (c) high resolving power, (d) high degree of isotropy and uniformity of response, (e) retains experimental information over extended periods of time, and (f) always records very high incoming fluences with 100% efficiency. In all future experimental investigations on AA collisions the application of nuclear emulsion technique may, therefore, yield interesting and all the more useful results.

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References

[1] L.S. Schroeder and M. Gyulassy, Proc. Quark matter 1986, Asilmer, Nucl. Phys. **A461** (1987) and references therein.

[2] H. Satz et al, Proc. Quark Matter 1987, Nordkirchen, Z. Phys. **C38** (1988) and references therein.

[3] (a) Ya. B. Zeldovich, JETP **37** (1959) 569;
(b) F. Pacini, Nature **209** (1966) 389;
(c) D. Ivanenko and D.E. Kurdgelaidze, N. Cimento Lett. **2** (1969) 13;
(d) N. Itoh, Prof. Theoret. Phys. **44** (1970) 291.

[4] (a) J.C. Collins and M.J. Perry, Phys. Rev. Lett. **34** (1975) 1353;
(b) G. Baym and S.A. Chin, Phys. Lett. **63HB** (1976) 241;
(c) T. Celik and h. Satz, Z. Phys. **C1** (1979) 163;
(d) G. Baym, Physica **96A** (1979) 131;
(e) F. Karsch and H. Satz, Phys. Rev. **D22** (1980) 480;
(f) R. Hagedorn and J. Rafaelski, **97B** (1980) 180.

[5] J. Juti, J. Polonyi and K. Szlachanyi, Phys. Lett. **98B** (1981) 199.

[6] L.D. McLerran and B. Svititskuy, Phys. Lett. **98B** (1981) 199.

[7] J. Engels, P. Karsch, I. Montvay and JH. Satz, Phys. Lett. **101B** (1981) 89.

[8] A. Bialas and W. Czyz, GSI 81-6, 1981, p. 417.

[9] L. Landau, Proc. Acad. Sci. USSR Physical Science, **17** (1953) 51.

[10] R. Hagedorn, CERN Report 71-12, 1971.

[11] J.D. Bjorken, Proc. DESY Intern. Summer Institute on Theoretical Physics, Hamburg, 1976, p. 93.

[12] K. Gottfried, Proc. 5th Intern. Conf. on High Energy and Nuclear Structure, Uppsala 1975.

[13] A. Bialas, Proc. I Workshop on ultra-relativistic nuclear collisions, 1979.

[14] R. Anishetty, P. Koehler and L. McKLerran, Phys. Rev. **D22** (1980) 2793.

[15] A. Bialas and W. Czyz, Nucl. Phys. **B194** (1982) 21.

[16] V. V. Anisovich, Yu. M. Shabelskuy and V.M. Shekter, Nucl. Phys. **B135** (1978) 477.

[17] N.N. Nikolaev, Phys. Lett. **B70** (1977) 95.

[18] V.V. Shuryak, Phys. Rev. **61** (1980) 71.

[19] A. Capella et al., Phys. Lett. **81B** (1979) 68.

[20] A. Capella et al., Particle and Fields **3** (1980) 329.

[21] A. Capella and J. Tran Thanh Van, Phys. Lett. **93B** (1980) 146.

[22] A. Capella and J. Tran Thank van, Phys. Lett. **114B** (1982) 450.

[23] H. Minakatam, Phys. Rev. **D20** (1979) 1656.

[24] A. Capella, et al., Phys. Rev. **D35** (1987) 2921.

[25] K. Werner et al., Z. Phys. **C37** (1987) 57.

[26] K. Werner et al., Phys. Lett. **B183** (1987) 385.

[27] K. Werner et al., Z. Phys. **C38** (1988) 193.

[28] B. Andersson et al, Nucl. Phys. **B281** (1987) 289.

[29] Proc. IX Autumn School on Quark-Gluon Plasma, Lisbon, 1987, Ed. J.D. Deus and S.C. Ramos.

[30] NA 35 Collaboration: (a) A. Momberger et al, Phys. Lett. **B104** (1987) 271; (b) H. Strobele et al, Quark Matter 1987, Nordkirchen

[31] G. Baroni et al, Helios Emulsion Collaboration (private communication).

[32] S.A. Chin, Phys. Lett. **78B** (1978) 552.

[33] G. Domokog and J.I. Goldman, Phys. Rev. **D23** (1981) 203.

[34] R. Hagedorn and J. Rafaelski, Proc. Statistical Mechanics of Quarks and Hadrons 1981, p. 253.

[35] J. Kuti et al, Phys. Lett. **95B** (1980) 75.

[36] J. Rafaelski, preprint UFTP 52/1981, p. 1.

[37] E.L. Feinberg, N. Cimento **34A** (1976) 391.

[38] E.V. Shuryak, Phys. Lett. **78B** (1978) 150.

[39] K. Kajantie and H. Miettinen, Z. Phys. **C9** (1981) 341.

[40] M.I. Gorenstein, V.P. Shelest and G.M. Zinojev, Phys. Lett. **60B** (1976) 283.

[41] D.V. Anchishkin et al, Phys. Lett. **108B** (1982) 47.

[42] J. Rafaelski and M. Danos, Phys. Lett. **97B** (1980) 279.

[43] F. Halzen and H.C. Liu, preprint MAD/PH/17, 1981, p. 1

[44] M.I. Gorenstein and G.M. Zinovjev, Phys. Lett. **67B** (1977) 100.

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

[46] J.D. Deus, Proc. IX Autumn School on Quark-Gluon Plasma, Lisbon, 1987, p. 299.

[47] M.I. Gorenstein, V.K. Petrov and G.M. Zinovjev, Phys. Lett. **106B** (1981) 327.

[48] M.I. Gorenstein et al, preprint ITP-82-107 E, p. 1.

[49] L. Van Hove, Phys. Lett. **118B** (1982) 167.

[50] T.H. Burnett et al.: (a) Phys. Lett. **51** (1983) 1010; (b) JACEE Collaboration, II Intern. Conf. on Nucleus-Nucleus Collisions, Visby, 1985, Sweden.

[51] M.I. Goldstein and G.M. Zinovjev, ITP-82-109E.

[52] H. Satz, Ann. Rev. Nucl. Part. Sci. **35** (1985) 245.

[53] J. Engels, F. Karsch, I. Montvay and H. Satz, Bielfield preprint BI-TP 81/05, 1987.

[54] E.V. Schuryak, Phys. Lett. **107B** (1981) 103.

[55] J. Engels, F. Karsch and H. Satz, preprint BI-TP 82/8, 1982.

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

[57] E.V. Schuryak and O.V. Zhirov, Phys. Lett. **89B** (1980) 253.

[58] J. Ranft, Phys. Rev. **D57** (1988) 1842.

[59] A. Capella, J. Tran Thanh Van, Z. Phys. **C38** (1988) 177.

[60] T. Sjostrand and M. van Zijl, Phys. Rev. **D36** (1987) 43.

[61] K. Werner, Phys. Lett. **B208** (1988) 502.

[62] K. Sengupta, G. Singh and P.L. Jain, Mod. Phys. Lett. **A6** (1990) 285.

[63] P. Corruthers and C.C. Shih, Phys. Rev. Lett. **62** (1989) 2073.

[64] P.L. Jain et al, Z.Phys. **C52** (1991) 465.

[65] P.L. Jain and G. Singh, Phys. Rev. **C43** (1991) R 2027.

[66] K. Sengupta et al, Mod. Phys. Lett. **A6** (1991) 29.

[67] Helios Emulsion Collaboration, 1990, Private communication courtesy Prof. D.H. Davis, UCL, England.

[68] T. Abbott et al., Phys. Lett. **A498** (1989) 262.

[69] G. Odynice et al., Intern. Workshop on Relativistic Aspects of Nuclear Physics (World Scientific, 1990), p. 175.

[70] H.C. Eggers and J. Rafaelski, Intern. J. Mod. Phys. **A6** (1991) 1067.

[71] J.B. Kinson, Invited Talk at QMATHIC International Conference, D.I. Khan, Pakistan, January 1992.

[72] O. Drapier, Quark Matter 1991, Gatlinburg.

[73] V. Goerlech, Quark Matter 1991, Gatlinburg.

[74] I. Otterlund, Extrapolation of EMU01 data, Lund University Report LUIP 9105, June 1991.

[75] J.Y. Grossiord et al, Nucl. Phys. **A498** (1989) 249c.

[76] C. Baglin et al, Phys. Lett. **220B** (1989) 471.

[77] C. Adami, Phys. Lett. **B217** (1989) 5.

[78] E. Stenlund, Mod. Phys. Lett. **A5** (1990) 1159.

[79] M.I. Adamovic et al, Phys. Lett. **244B** (1990) 180.

[80] M.I. Adamovic et al., Phys. Rev. **C40** (1989) 66.

[81] M.I. Adamovic et al., Phys. Rev. Lett. **62** (1989) 2801.

[82] M.I. Adamovic et al., Phys. Lett. **223B** (1989) 262.

[83] T.C. Awes and S.P. Sorensen et al., Nucl. Phys. **A498** (1989) 123c.

[84] F. Plasil et al, International Workshop on Relativistic Aspects of Nuclear Physics (World Scientific 1990) p. 105.

[85] J. Schiroff et al., Nucl. Phys. **A498** (1989) 79c.

[86] A. Bialas and R. Peschanski, Nucl. Phys. **B308** (1988) 803

[87] E. Stenlund, Nucl. Phys. **A498** (1989) 541.

[88] P.L. Jain and G. Singh, Phys. Rev. **C44** (1991) 854.

[89] H. Satz, Plenary talk at the Joint International Lepton-Photon Symposium and Europhysics Conference on High Energy Physics, Geneva, July 1991.

[90] K. Sengupta et al., Phys. Lett. **B236** (1990) 219.

[91] J. Cleymens, Nucl. Phys. **A525** (1991) 205.