Some possible analogies in the description of the "classical" plasma and quark-gluon plasma

V. COVLEA, A. JIPA[a*], C. BEŞLIU[a], M. CĂLIN[a], T. EŞANU[a], V. PAVEL, B. ILIESCU[a], D. ARGINTARU[b],
I. S. ZGURĂ[c], E. STAN[c], C. MITU[c], M. POTLOG[c], M. CHERCIU[c], A. SEVCENCO[c], A. SCURTU[a]
Optics, Spectroscopy, Plasma and Lasers Chair, Faculty of Physics, University of Bucharest, ROMANIA
[a]*Atomic and Nuclear Physics Chair, Faculty of Physics, University of Bucharest, ROMANIA*
[b]*Sciences and Mathematics Chair, University of Civilian Marine Constanţa, ROMANIA*
[c] *Institute of Space Sciences Bucuharest-Măgurele, ROMANIA*

Recent experimental results on the possible formation of the quark-gluon plasma in Au-Au collisions at the maximum energy of the **R**elativistic **H**eavy **I**on **C**ollider (RHIC) from the **B**rookhaven **N**ational **L**aboratory (BNL), USA, opened the discussions on the possibility to use notions, phenomena and specific parameters from the Plasma Physics in the description of the quark-gluon plasma, trying to exceed the differences between the different nature of the basic interactions in the two types of states of the matter. The present work is such attempt. We discuss the possibility to describe the observed quark-gluon plasma at the RHIC maximum energy, supposed in liquid phase, using the parameters for dusty plasmas, strongly coupled plasmas, mainly Coulomb parameter and different wave lengths. The analogies lead at the idea that there are the common behaviours of the parameters sustaining the formation of the quark-gluon plasma in liquid state.

1. Introduction

The idea of the existence of the fourth state of the matter was introduces by Crookes in a lecture given at the British Association for the Advancement of the Science, in 1879 [1]. Almost 50 years after this first mention of the fourth state of the matter, it was called *plasma* by Lagmuir and coworkers [2]. The definition given is the following: *Plasma is a quasi-neutral electric system formed by neutral and charged particles, photons and electromagnetic fields, with a collective behaviour.*

Taking into account some common aspects that can be included in the definitions for both plasmas, "classical" plasma and quark-gluon plasma, we begun some efforts for identification of some common parameters for their characterization [3-6]. This work present a few of the parameters that we considered for beginning the analogy between the two plasma types. Therefore, the present work has been structured as follow: a general presentation of the most important parameters used in characterization of the "classical" plasma, some important results on the quark-gluon plasma formation and decay, common parameters for both plasmas and their estimated values, as well as some conclusions on hydrodynamic behaviour of the quark-gluon plasma and its liquid state.

2. Parameters used in characterization of the "classical" plasma. Connections with quark gluon-plasma parameters

The main parameters used in "classical" plasma characterization that we believe that can be considered for quark-gluon plasma characterization could be grouped in a few major categories. A first category is related to the densities of the different plasma components [7-9]. The second takes into account the dimensions associated with different processes in plasma [10,11]. The third is that which consider the parameters used to describe mainly strong coupled dusty plasma [12-14].

The main physical quantities from the first category are: neutral particle density, n_n, electron density, n_e, ion density, n_i. The energy distributions can be added to thee densities. They help in the definition of other interesting quantities. For example, *plasma ionization degree* can be defined as the ratio between the number of charged particles form the volume unit and the total number of particles from the same volume unit. Using this definition a complete ionized plasma is those for that the neutral particle density is $n_n = 0$, and the value of the ionization degree is equal with unit. For ordinary "classical" plasma, namely plasmas at low pressures, the ionization degree is in the range $10^{-6} - 10^{-3}$. The presence of a confining magnetic field the ionization degree for these plasmas could increase up to 10^{-2}.

Based on the energy distributions of the plasma components, the temperatures of each component can be estimated. It is important to mention that a "classical" plasma is a system formed by different particles with different electric charges and different masses. Therefore, the following hypothesis can be introduced: "classical" plasma has minimum 2 subsystems, with different

temperatures, in each subsystem being thermal equilibrium; in such plasma, the first subsystem is formed by electrons, with temperature T_e; the second subsystem is formed by ions, with temperature T_i, neutral atoms and molecules, with temperature T_{neut}; usually, $T_{neut} \neq T_i$. It must stress here that in a plasma there are many other temperatures, like: gas temperature, T_g, (for heavy particles), excitation temperature, T_{ex}, ionization temperature, T_{ion}, dissociation temperature, T_d, radiation temperature, T_r. Into a plasma, the thermodynamic equilibrium is established if the following condition is respected:

$$T_g = T_{ex} = T_{ion} = T_d = T_r = T_e \qquad (1)$$

It is very difficult to have global equilibrium in a "classical" plasma. The main difficulties are related to the important differences between "core" and "halo". Therefore, the establishing of the *local thermodynamic equilibrium* is more probable.

It is important to say here that in an ordinary "classical" plasma there are not accomplished such conditions. Therefore, the temperature of electrons is the most important thermodynamic parameter used usually in the plasma characterization.

A plasma contains different charged particles. These particles impose the presence of the electric fields. A interesting physical quantity which takes into account the screening created by other charged particles is the *Debye screening length, λ_D*. This parameter describing the effect of the decreasing of the initial electric field is from the second category of physical quantities. The electrons having highest mobility react first of all. The excess of a type of charged particles leads to the restoring of the electric field. This field tries to keep the quasi-neutrality of the plasma. The following relation can be written:

$$E = \frac{e.n}{3\varepsilon_0} R \frac{\Delta n}{n_0}, \qquad (2)$$

where n_0 is plasma concentration (density), R is the radius of the sphere containing the deviation from the quasi-neutrality in a given plasma.

Main charges in a plasma are from electrons and positive ions. Therefore, the total charge density can be estimated from the following relation:

$$\rho = e(n_i - n_e) + q\delta(r). \qquad (3)$$

Solving Poisson equation for restoring electric field, in the *hypothesis that the electrons are in thermodynamic equilibrium* at their common temperature T_e, the following solution is obtained:

$$n_e = n.e^{e.V/k_B T_e}, \qquad (4)$$

For $eV \ll k_B T_e$ the Debye screening length can be written as follows:

$$\lambda_D = \sqrt{\frac{\varepsilon_0}{n_e} \cdot \frac{k_B T_e}{e^2}}. \qquad (5)$$

The "classical" plasma modifies the potential of a charge in vacuum, and the modification is observed on a length that is the Debye length. Therefore, a particle in rest in a plasma can not act on a long distance around. The Coulomb potential is strongly affected and can be neglected for some distances. Therefore, it is assumed that *plasma can isolate any perturbation in system, stopping the perturbation propagation in whole system*. The protective space charge length is of the order of the Debye screening length, λ_D. Generally, the potential energy of a Debye sphere, with radius λ_D, is smaller than the thermal agitation energy. For isothermal plasmas, namely when $T_e \cong T_i = T$, the number of the uncompressed electrons in the Debye sphere is:

$$N_D = \frac{4}{3}\pi\lambda_D^3 n_D, \qquad (6)$$

with n_D the number of these electrons from the volume unit of the Debye sphere. Another interesting quantity from the same category is *the Landau length, λ_L*. Landau length gives the average distance among the charged particles those electrostatic interaction energy in vacuum is equal with the average kinetic energy of these particles. The following relationship can be written:

$$\lambda_L = \frac{e^2}{4\pi\varepsilon_0 k_B T}. \qquad (7)$$

The Landau length permits to establish the conditions to approximate an ionized gas with an ideal gas, namely: *plasma behaves as an ideal gas when the electrostatic interaction energy can be neglected in comparison with the thermal energy*, namely:

$$\lambda_L \ll d, \qquad (8)$$

with d the average distance among charged particles.

Langmuir frequency is a quantity related to the electron oscillations. These oscillations can be consider as an answer to the existence of the perturbations and the apparition of the restoring electric fields to keep the quasi-neutrality of the plasma because there is the possibility to have microscopic deviations from the quasi-neutrality in volumes smaller than the Debye sphere volume. The Langmuir frequency has the following form:

$$\nu_p = \frac{1}{2\pi} \cdot \left(\frac{n_e}{m_e} \cdot \frac{e^2}{\varepsilon_0}\right)^{1/2}, \qquad (9)$$

where m_e is the electron rest mass.

The Langmuir frequency and the Debye length are related by the following relationship:

$$\lambda_D . \omega_p = \left(\frac{k_B T}{m_e} \right)^{1/2} . \qquad (10)$$

The condition that a ionized gas to be a plasma is the following:

$$\lambda_D << L , \qquad (11)$$

where L is the characteristic dimension for a plasma.

The *collision frequency in plasma, ω*, is a parameter from the second category, too. If charged particles have a *very high collision frequency* with plasma neutral components their movements are controlled by the *hydrodynamic forces* not by the electromagnetic forces. Let be τ the average time among the collisions of the charged particles with the neutral components; then, the condition for plasma behaviour of the gas is:

$$\omega . \tau = 1 , \qquad (12)$$

It is important to remark here that almost all the matter from the Universe is in the plasma state (stars, interstellar gas etc), with very large ranges of densities and temperatures (Fig.1) [9].
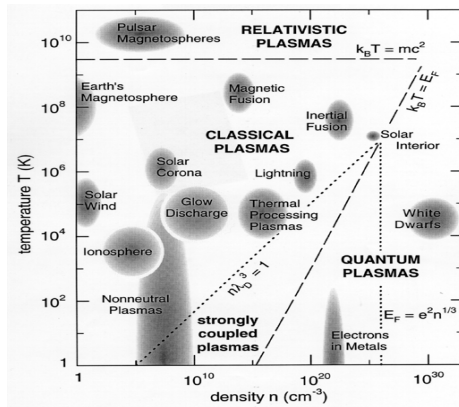

Fig.1. Electrons temperatures and densities for different "classical" plasmas.

In the same figure are included information on the "dusty" and strongly coupled "classical" plasmas. On the specific parameters we discuss later in this paper.

2.1 "Classical " plasma types

In agreement with the parameters considered previously, the following plasma types can be considered: *(i) plasma in complete thermodynamic equilibrium* or *CTE plasma, (ii) plasma in local thermodynamic equilibrium* or *LTE plasma (thermal plasma), (iii) cold plasma* or *non – LTE plasma.*

A *plasma in complete thermodynamic equilibrium* is a plasma in which all temperatures are the same, namely the relation (1) is respected. Such plasmas there are in nature, in some stars, in controlled violent explosions - for very short times - , but not in laboratory controlled conditions.

In a *plasma in local thermodynamic equilibrium* the temperatures for all components are the same, *in small volumes of the plasma*, excepting the radiation temperature, T_r. The *thermodynamic equilibrium is not attained in a cold plasma*. Here must remarked the fact that plasmas produced in research laboratories for Plasma Physics are thermal plasmas and cold plasmas.

The *conditions for thermal plasma formation* are related to the following specific situations: (i) heavy particles have high energies, at temperatures in the range 10^6-10^8 K (10^2 - 10^4 eV); (ii) atmospheric pressure and temperature around 10^3 K.

The explanation is the next: an increase in the pressure value involves an increase in the number of collisions between electrons and heavy components of the plasma; therefore, at pressures around atmospheric pressure the two components have the tendency to attain the thermodynamic equilibrium. An example is related to the electric arcs plasma jets, at atmospheric pressure, where $T_e = T_g$. The gas temperatures have values in the range [20000 K, 30000 K].

Into a *cold plasma* the following condition for the temperatures of the plasma components is achieved: $T_e >> T_i$. The electron temperatures are around 10^4 K - 10^5 K (1 - 10 eV), and the gas temperature is equal with the room temperature, with a average temperature around *25 meV* .

Much of the matter in the Universe is in the plasma state. This is true because stars, as well as most interstellar matter are plasmas. Although stars are plasmas in thermal equilibrium, the light and heavy charged particles in low pressure processing discharges are *almost never* in thermal equilibrium, either between themselves or with their surroundings. Because these discharges are electrically driven and are weakly ionized, the applied power preferentially heats the mobile electrons, while the heavy ions efficiently exchange energy by collisions with the background gas; hence, $T_e >> T_{ion}$ [7].

A few significant examples are the following:
(a) Solar wind considered as a continuum flux of charged particles with the following general parameters for electron: $n_e = 5$ cm^{-3}, $T_e = 10^5$ K.
(b) Interstellar matter sees as a hydrogen plasma with a density around *1 cm^{-3}*.
(c) Ionosphere is the low ionized plasma with density around 10^5 cm^{-3} and an electron temperature around 10^3 K, placed in the range *50 km - 500 km* from the Earth surface.
(d) Stars have in their evolution a plasma state, when the surface temperatures are in the range *[5000 K, 70000 K]*. There is a very hot core and an external halo, partially ionized. A good example is our star, the *Sun*. The temperature in the Sun core is around *10^7 K*. The nuclear fusion reaction between deuterium and tritium nuclei has a enough high cross section for kinetic energies of the two types of nuclei higher than 5 keV (around 6.10^7 K). For a *controlled thermonuclear fusion reaction* electron

temperatures higher than 10^8 K and ion densities around 10^{11} cm^{-3} are necessary. In a Tokamak fusion reactor the ion temperatures are around $T_i = 35$ keV and the electron temperatures are around $T_e = 15$ keV. In laboratory has been obtained, up to now, a glow discharge with a electron temperature $T_e \in [10^4 K, 10^5 K]$ and electron density $n_e \in [10^{10} cm^{-3}, 10^{11} cm^{-3}]$.

The present cosmological scenarios suggest that at a few microseconds after the "Big Bang" a quark-gluon plasma has been existed. Different other plasma types have been formed in the hadronization and nucleosynthesis stages.

2.2. Quark-gluon plasma

The quark-gluon plasma is a state of the matter existing at a few microseconds after "Big Bang" [15,16]. This state can be formed, in specific conditions, in nucleus-nucleus collisions at relativistic and ultrarelativistic energies (Fig.2).
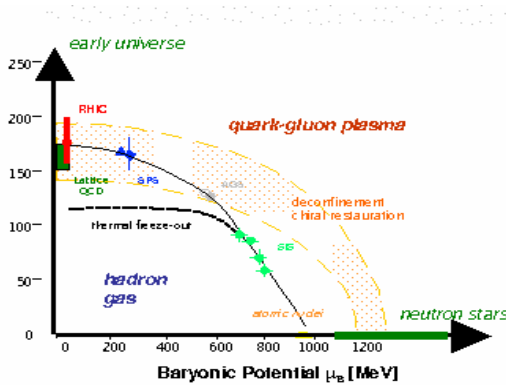

Fig.2. Phase diagram of the nuclear matter.

There are considered different ways for establishing of the specific signals for formation and decay of the quark-gluon plasma [17-21]. A relative new way, namely: *connections with classical plasmas,* has been introduced in the study of the quark-gluon plasma formed in nucleus-nucleus collisions at high energies [22, 3-6].

This new form of the nuclear matter evidenced experimentally recently [17-20], quark-gluon plasma, has a collective behaviour, at thermodynamic equilibrium, local or global. The collective behaviour is well reflected in the hydrodynamic flow of the nuclear matter. Therefore, the analogies with the behaviour of the "classical" plasmas, mainly with the strongly coupled plasmas, could help at the description of this new state of the nuclear matter: quark-gluon plasma, in liquid or gaseous phase. Our attempts are focused in the finding of a few physical quantities for establishing such connections among quark-gluon plasma and "classical" plasmas.

2.3 Characterization of the quark-gluon plasma with specific parameters of the "classical" plasma

In a "classical" plasma the Coulomb interaction is the predominant interaction. Therefore, are important those parameters related to this interaction. Such parameter is the Coulomb coupling parameter. This parameter is used, usually, in the characterization of the strongly coupled plasmas. In this type of plasma the interaction energy among plasma constituents is higher than their thermal interaction

The Coulomb coupling parameter, Γ can be defined as follows [22,23]:

$$\Gamma = \frac{Q^2}{d.T}, \qquad (13)$$

where Q is the electric charge of the plasma constituents, d is the distance among plasma constituents, and T is the plasma temperature. The quantities included in the equation (13) are in the natural system units. A plasma is strongly coupled if the Coulomb coupling parameter has a value $\Gamma > 1$. The properties of the specific phase of the plasma are related to the values range of the strongly coupling parameter. For example, a plasma with a single constituent type that is characterized by a Coulomb coupling parameter $\Gamma > 172$ a phase transition from the liquid phase to the solid phase is possible; this state is called Coulomb crystal. If the Coulomb coupling parameter has a value in the range $\Gamma \in [10,32]$ the plasma is in the liquid phase. For applying this parameter in the quark-gluon plasma characterization some modifications are necessary [23]. These modifications are related to the different nature of the interactions in the two types of plasma. Therefore, the quantities reflecting the strong interactions among the quark-gluon plasma constituents are used to define a similar parameter. The electric charge is changed by the product between the coupling constant for the strong interaction, g_s, and the Casimir invariant, C. A similar relationship with equation (13) can be written, namely:

$$\Gamma_s = \frac{C g_s^2}{d.T}. \qquad (13')$$

In the new Coulomb coupling parameter for quark-gluon plasma, Γ_s, the Casimir invariant for quarks is $C_q = \frac{4}{3}$, and the Casimir invariant for gluons is $C_g = 3$. The coupling constant for strong interaction, g_s, is related to the "fine structure constant", α_s, through the following relation ship: $\alpha_s = \frac{g_s^2}{4\pi}$.

If strong interactions exist in plasma, then the Coulomb

radius for a particle with an energy E ($r = \dfrac{Q^2}{E}$) is smaller than the Debye screening length Debye ($\lambda_D = \dfrac{1}{m_D}$, with m_D the Debye screening mass).

Also, the existence of the correlations into a plasma could offer some useful connections for characterization of the quark-gluon plasma in the liquid state. Usually, it is expected a maximum in the correlation function for some particle pairs. If additional hypothesis are introduced, like the existence of some binding states in the quark-gluon plasma at a temperature around critical temperature for a phase transition, then some changes in the maximum form are expected. For example, at the passing from temperatures below critical temperature at temperatures beyond critical temperature, qualitative changes in behaviour are observed, for example, broadening of the maximum in the correlation function.   Some connections with collision centrality could offer additional support in the analysis of the signals of the quark-gluon plasma formation. The collision parameter, b, depends on Debye screening length. The following relationship can be written: $b = 4.6\lambda_D$ [22,23]. The quark-gluon plasma formation is related to the available energy in the Center of Mass System (CMS). The next relationship can be considered: $\sqrt{s} \cong \sqrt{(1.5\mathrm{T}^2)}$. In these conditions, for example, the transport cross section increases significantly.

It is important to stress here that there are a few error sources in these analogies, but the results are not significantly affected.

3. Some estimation for quark-gluon plasma formation using specific parameters of the "classical" plasma

Taking into account that the four collaborations working at the *Relativistic Heavy Ion Collider* (RHIC) from the *Brookhaven National Laboratory* (BNL), Upton, Nw York, USA, announced in 2005 the quark-gluon plasma formation in Au-Au collisions at maximum RHIC energy [17-20], we tried during the time to do estimations for these collisions [3-6]. In this work we summarize the first estimations using adapted parameters of the "classical" plasma for these collisions.

Because some of the research group are members of the BRAHMS Collaboration, we refer mainly to the experimental results obtained in the frame of this collaboration.

During the runs, since 2000 up to 2006, the following collisions have been studied: (a) Au-Au, at $\sqrt{s_{NN}} = 62,4\, GeV$, $\sqrt{s_{NN}} = 130\, GeV$ and $\sqrt{s_{NN}} = 200\, GeV$; (b) d-Au at $\sqrt{s_{NN}} = 200\, GeV$; (c) Cu-Cu at $\sqrt{s_{NN}} = 62,4\, GeV$ and $\sqrt{s_{NN}} = 200\, GeV$;

(d) p-p at $\sqrt{s_{NN}} = 62.4\, \mathrm{GeV}$, $\sqrt{s_{NN}} = 130\, GeV$ and $\sqrt{s_{NN}} = 200\, GeV$.

We focus in this paper on the Au-Au collisions $\sqrt{s_{NN}} = 200\, GeV$. Three charged particle types can be identified with the BRAHMS experimental set-up, namely: pions, kaons and protons. [17,24-27]. Its momentum spectra have been used to estimate the inverse slopes or temperatures at the emission of the three types of particles. The temperature values are in the range from 200 MeV, for pions, to 400 MeV, for protons. The rapidity distributions are used for the energy density estimation using Bjoerken relationship. The values are around 5,00 GeV/Fm³. The estimated distance among quark-gluon plasma constituents for these value ranges of the parameters is around 0,5 Fm ($d \propto \left(n_b\right)^{-1/3}$). Also, the coupling constant for strong interaction, g_s, is estimated in the range [1,5;2,5], related to the "fine structure constant", α_s, estimated between 0,2 and 0,5. Using the equation (13'), the estimated values of the Coulomb coupling parameter are in the range $\Gamma_s \in [10,30]$. Taking into account these values range, we can affirm that the *quark-gluon plasma has a liquid behaviour, not a gas behaviour*.

The estimations for the Debye length in Au-Au collisions at $\sqrt{s_{NN}} = 200\, GeV$ given, for a screening mass $m_D \propto 6T$, a value $\lambda_D \cong 0.2\, \mathrm{Fm}$. With this value a impact parameter around 5.0 Fm can be estimated. It can be used for a future estimations of the standard and modified Coulomb logarithms, taking into account the fact that its depend on collision parameter

$$L_{C_s} = \frac{1}{2}\ln\left(1 + \frac{1}{b^2}\right) \quad , \quad L_{C\mathrm{mod}} = \frac{1}{2}\ln\left(1 + \frac{1}{b}\right) \quad ,$$

respectively. Also, its can be related to the transport cross sections and, therefore, to the hydrodynamic behaviour of the quark-gluon plasma.

A significant increase of the transport cross section could be in agreement with the results from the elliptic flow in Au-Au collisions at RHIC maximum energy. In this case, a very fast thermalization is necessary, according to the momentum spectra behaviours. Some estimations are in progress.

4. Conclusions

In the previous analogies other interaction types were neglected. Also, these analogies supposed that the quark-gluon plasma is strong coupled. There is the possibility that the relativistic effects could affect this results. In a "classical" plasma the quantum effects are important for de Broglie wavelength for "thermal" de Broglie wavelength higher than the distance among plasma constituents. Also, the "thermal" de Broglie wave-length,

defined as: $\lambda_B^{th} = \dfrac{1}{m^*}$ l$_{th}$ =1/m*, where m* is the effective

mass of the parton in the quark-gluon plasma, is strongly

related to the temperature (for gluons: $m_g^* = \dfrac{g_s T}{\sqrt{3}}$, for

quarks: $m_q^* = \dfrac{g_s T}{\sqrt{6}}$, respectively).

In Au-Au collisions at $\sqrt{s_{NN}} = 130\ GeV$, $\sqrt{s_{NN}} = 200\ GeV$, respectively, the de Broglie thermal wavelengths are around *1 Fm.* These estimations are the same order of magnitude with the interpartonic distances and, therefore, the quantum effects are important.

For these collisions Fermi energy values for quarks are around 350 MeV and can affect the estimated values; quark-gluon plasma could be a degenerate plasma, but the liquid state is preserved.

Non-relativistic strongly coupled classical plasma are difficult to produce, because there are huge difficulties in the obtaining of high particle densities at relative low temperatures. In nature, only "white dwarfs" can have the ion components in these conditions. On the other hand, there is the possibility to have dense plasmas in the relativistic and ultrarelativistic nuclear collisions.

The experimental results obtained in Au-Au collisions at RHIC maximum energy, $\sqrt{s_{NN}} = 200\ GeV$, led to the conclusion that the observed quark-gluon plasma has a liquid behaviour, not a gas behaviour. This result is in agreement with the hydrodynamic description of the relativistic nuclear collision dynamics. The existence of the quark-gluon plasma in liquid phase could offer qualitative explanations for hydrodynamic flow, growth of the cross sections and fast thermalization of the partons (quarks and gluons).

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*Corresponding author: jipa@brahms.fizica.unibuc.ro