Complex Plasmas as a Model for the Quark-Gluon-Plasma Liquid

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The quark-gluon plasma, possibly created in ultrarelativistic heavy-ion collisions, is a strongly interacting many-body parton system. By comparison with strongly coupled electromagnetic plasmas (classical and non-relativistic) it is concluded that the quark-gluon plasma could be in the liquid phase. As an example for a strongly coupled plasma, complex plasmas, which show liquid and even solid phases, are discussed briefly. Furthermore, methods based on correlation functions for confirming and investigating the quark-gluon-plasma liquid are presented. Finally, consequences of the strong coupling, in particular a cross section enhancement in accordance with experimental observations at RHIC, are discussed.

1. Strongly coupled plasmas

Plasmas are ionized gases forming 99% of the visible matter in the universe. Plasmas can be produced by high temperatures, e.g., in stars, by electric fields, e.g., in neon tubes used for illumination, or by radiation, e.g., in interstellar plasmas. Plasmas can be classified according to the following properties:

1. A plasma can be non-relativistic or relativistic. In the latter case the velocity of the plasma particles is close to the speed of light. Examples are the electron-positron pair plasma in a supernovae or the quark-gluon-plasma (QGP) in ultrarelativistic heavy-ion collisions.

2. A plasma can be classical or quantum mechanical. In the latter case the de Broglie wave length of the particles becomes of the order of the interparticle distance or larger, which is the case, for instance, for the QGP. In particular, in degenerate plasmas, such as in white dwarfs, quantum effects are dominant.

3. A plasma can be ideal or strongly coupled. In the latter case the interaction energy between the particles becomes of the order of the kinetic particle energy or larger. As we will show this is the case for the QGP. Another interesting example are complex plasmas, which we will discuss in the following.

Most plasmas in nature and in the laboratory are non-relativistic, classical, weakly coupled (ideal) plasmas. As a matter of fact, strongly coupled plasmas are hard to produce, since they require low temperatures and high densities, at which a strong recombination sets in.

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For non-relativistic, classical electromagnetic plasmas the Coulomb coupling parameter

$$\Gamma = \frac{Q^2}{dT}, \tag{1}$$

where Q is the plasma particle charge, d the interparticle distance, and T the plasma temperature, distinguishes between weakly and strongly coupled plasmas. In the latter case $\Gamma \geq O(1)$ holds. Most plasmas are ideal with $\Gamma < 10^{-3}$. Examples for strongly coupled plasmas are the ion component in white dwarfs [1] or short-living high-density plasmas produced with heavy-ion beams on solid state targets at GSI [2].

Obviously, strongly coupled plasmas require a non-perturbative description, e.g., molecular dynamics in the classical case. This has been used for computing the equation of state of one-component plasmas with a pure (repulsive) Coulomb interaction. It turned out that for $\Gamma > 172$ a Coulomb crystal forms [3], i.e., it is energetically more favorable if the particles arrange in a regular structure.

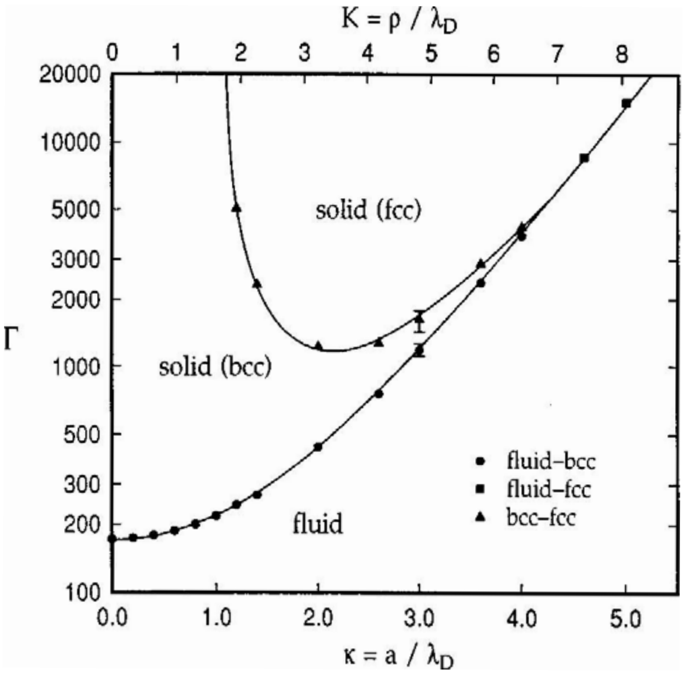

Fig.1: Phase diagram of a strongly coupled Yukawa system from Ref.[4].

Under most circumstances, however, Debye screening cannot be neglected and plasmas are Yukawa systems with an interaction potential

$$V(r) = \frac{Q}{r}\, e^{-r/\lambda_D} \tag{2}$$

with the Debye screening length λ_D. Then it is convenient to introduce a second parameter $\kappa = d/\lambda_D$. In Fig.1 the phase diagram in the Γ - κ plane for a repulsive, one-component Yukawa system is shown [4]. One recognizes a solid state, either bcc or fcc, for large Γ and small κ. Otherwise a liquid phase exists. Note, however, that in the case of a purely repulsive interaction there is no gas-liquid transition but only a supercritical fluid, i.e., a clear distinction between the gaseous and the liquid state is not possible. However, in the strongly coupled case, $\Gamma > O(1)$, the system behaves more like liquid than a gas, as we will discuss below.

2. Complex Plasmas

Dusty or complex plasmas are multi component plasmas containing ions, electrons, neutral gas, and microparticles, e.g., dust grains. Such a situation can be studied, for example, in a low temperature noble gas discharge plasma, in which micron size particles, e.g., monodisperse plastic spheres with a diameter of 1 - 10 μm, are injected. Due to the high mobility of the electrons, the microparticles collect mostly electrons on their surface, leading to a large negative charge of the microparticles between 10^3 and 10^5 e depending on the grain size and electron temperature ($T_e = 1 - 10$ eV). Since the interparticle distance is typically of the order of 200 μm and the kinetic energy of the particles corresponds to room temperature due to friction with the neutral gas, $\Gamma \gg 1$ (up to values of 10^5) can easily be reached. Therefore, in 1986 it was predicted that a regular ordering in the charged microparticle system, regarded as a massive plasma component, could exist in complex laboratory plasmas [5]. This prediction triggered experimental efforts to search for this new state of matter, the so called plasma crystal, which was discovered for the first time in 1994 at the Max-Planck-Institute for Extraterrestrial Physics [6] and almost at the same time at other places [7,8].

An image (top view) of such a plasma crystal is shown in Fig.2. Here a plasma chamber with an extension of a few centimeters is used, in which a low-temperature argon plasma is ignited by a rf discharge. After injecting the microparticles a plasma crystal is formed within a few seconds. For observation a single horizontal layer is illuminated by a laser sheet and the scattered light (Mie scattering) is recorded by a CCD camera. Clearly a hexagonal structure with lattice defects similar as in a real crystal can be observed.

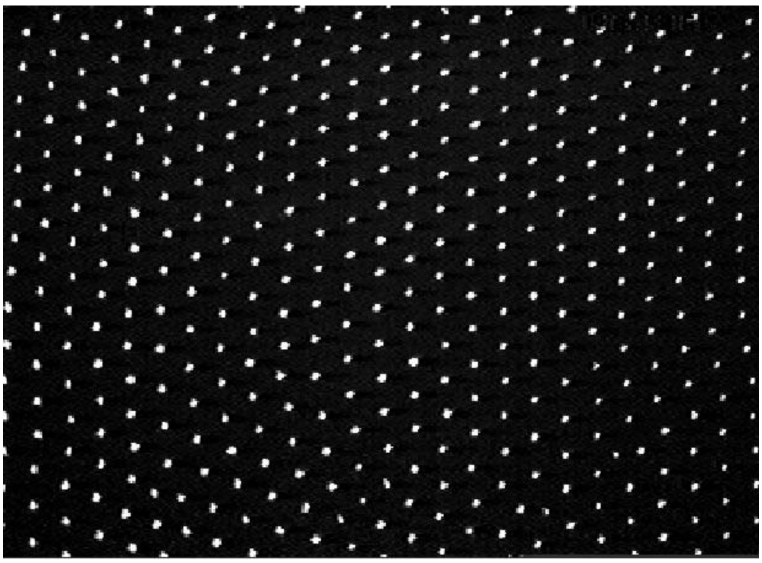

Fig.2: Top view of the plasma crystal.

Phase transitions to the liquid phase and the disordered gas phase can be observed by reducing the pressure [9]. This leads to a reduction of the neutral gas friction and hence an increase of the temperature of the microparticle system. At the same time the electron temperature decreases leading to a reduction of the charge of the microparticles. Hence the Coulomb coupling parameter (1) decreases and can become smaller than its critical value for crystallization. Indeed reducing, for instance, the pressure from about 60 Pa, in which a crystal structure exists, to 30 Pa, the microparticles show a liquid behavior. Going to even lower pressure, e.g., 10 Pa, the velocity of the particles is increased by a factor of about 200 compared to the solid phase, in which the thermal lattice oscillations correspond to particle velocities of the order of 0.2 mm/s. Thus at 10 Pa the system resembles a gas.

The equation of state of a complex plasma and the value of the Coulomb coupling parameter can be determined by the so called pair correlation function, defined as

$$g(\mathbf{r}) = \frac{1}{N}\, \langle \sum_{i \neq j}^{N} \delta(\mathbf{r} + \mathbf{r_i} - \mathbf{r_j}) \rangle, \tag{3}$$

where N is the particle number and $\mathbf{r_i}$ and $\mathbf{r_j}$ the positions of the particles.

In the case of a regular crystal structure, where a long range order exists, the pair correlation function shows pronounced peaks at the locations corresponding to the nearest neighbors, next to nearest neighbors and so on. Of course, due to thermal fluctuations and defects the peaks have a finite width and their height decreases with increasing distance. In the case of a liquid, where only a short range order corresponding to a fixed interparticle distance in the incompressible fluid is present, the pair correlation function exhibits only one clear peak and some times one or two small and broad additional peaks. Finally, in a gas corresponding to a disordered system no peaks show up in the pair correlation function.

Before we turn to the QGP, let me mention that the investigation of complex plasmas is hampered by the presence of gravity in the laboratory. The microparticles can be suspended against gravity only by an electric field (typically a few V/cm) in a small region of the plasma chamber, the plasma sheath above the bottom where the field can be strong enough. Hence only small systems in vertical directions, e.g., quasi 2-dimensional crystals, can be built up. Furthermore, the plasma conditions in the plasma sheath are very complicated rendering the interpretation of the results difficult. Finally, the gravitational force is comparable to the interparticle force, thus strongly disturbing the system, e.g., the crystal structure, and making some measurements even impossible. Therefore we perform experiments with complex plasmas also under microgravity conditions, i.e., in parabolic flights, in sounding rockets, and on board of the International Space Station where we installed the first scientific experiment (PKE-Nefedov) [10].

Finally, let me discuss some applications of complex plasmas. Beside investigating the plasma crystal and its melting a large variety of different experiments can de conducted, e.g., phonons and plasma waves can be excited, instabilities can be observed, shock waves and Mach cones can be produced, shear flow can be studied, etc. In general, complex plasmas are ideal model systems to study the dynamical behavior of solids, liquids, and plasmas on the microscopic level in real time. In addition, charged dust systems and dust-plasma interactions play an important role in astrophysics (comets, interstellar clouds, planet formation, etc.), in environmental research (chemical reactions involving micrometeorites in the ionosphere), as well as in plasma technology (dust contamination in the micro-chip production using plasma etching, dust in fusion reactors, etc.).

3. Applications to the quark-gluon plasma

For applying the ideas and methods used for strongly coupled electromagnetic plasmas, such as complex plasmas, to the physics of the QGP, we first estimate the interaction parameter. In the case of QCD it reads [11]

$$\Gamma \simeq 2\frac{C\alpha_s}{dT}, \tag{4}$$

where $C = 4/3$ or $C = 3$ is the Casimir invariant of quarks or gluons, respectively. The factor 2 in (4) comes from the fact that in ultrarelativistic systems the magnetic interaction is as important as the electric. Assuming a temperature $T = 200$ MeV which corresponds to a coupling constant $\alpha_s = 0.3$ to 0.5 and an interparton distance d of about 0.5 fm, we find $\Gamma = 1.5$ - 6. Hence the QGP is a strongly coupled plasma at temperatures which can be reached in accelerator experiments, and it is conceivable that it behaves more like a liquid than a gas. Indeed RHIC data (elliptic flow, particle spectra) [12], which can be described well by hydrodynamics with a negligible viscosity and which suggest a fast thermalization, indicate such a behavior [13–16].

Therefore the phase diagram of hot hadronic matter could be possibly extended by another phase transition from the liquid to the gas phase of the QGP at a temperature of maybe a few hundred MeV as sketched in Fig.3. However, this requires an attractive as well as repulsive component of the potential, e.g., a Lennard-Jones type potential, which is not the case in QCD where the interaction between partons in the various channels is either attractive or repulsive [17]. However, it is known that in a strongly coupled plasma purely repulsive forces can obtain an attractive component at certain distances due to non-linear effects [18]. Hence it might be worthwhile to look for a gas-liquid transition in heavy-ion collisions, in particular at LHC. Regardless whether this phase transition exists or whether there is only a supercritical QGP liquid, the QGP should behave more like a liquid at temperatures close to the deconfinement transition and like a gas at temperatures far above this transition.

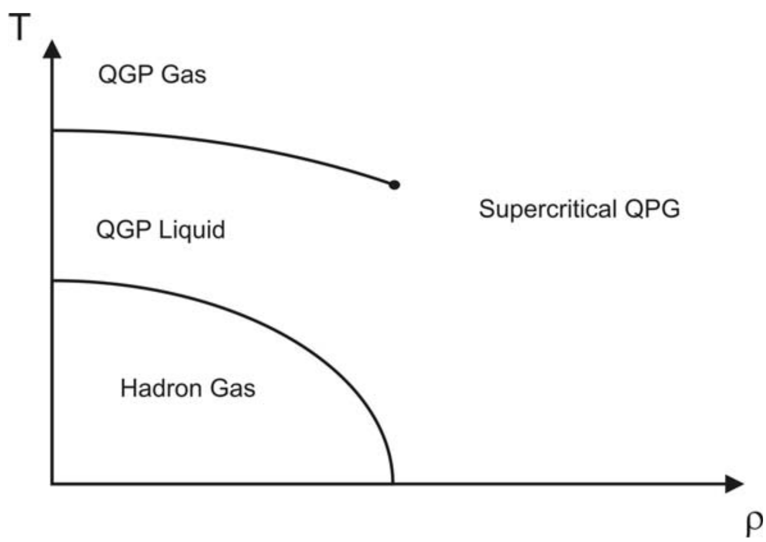

Fig.3: Sketch of a phase diagram of hadronic matter with a possible gas-liquid transition in the QGP phase.

For verifying and investigating the liquid state quantitatively one could consider experimentally as well as theoretically the so called static structure function which is closely related to the Fourier transform of the pair correlation function (3). The static structure function is a standard tool for the experimental and theoretical analysis of liquids [19]. The qualitative behavior of the static structure functions for liquids and gases is shown in Fig.4. In the case of a liquid the static structure function shows oscillations with decreasing amplitudes for large momenta. For an interacting gas, on the other hand, the static structure function increases monotonically reaching quickly a saturation value.

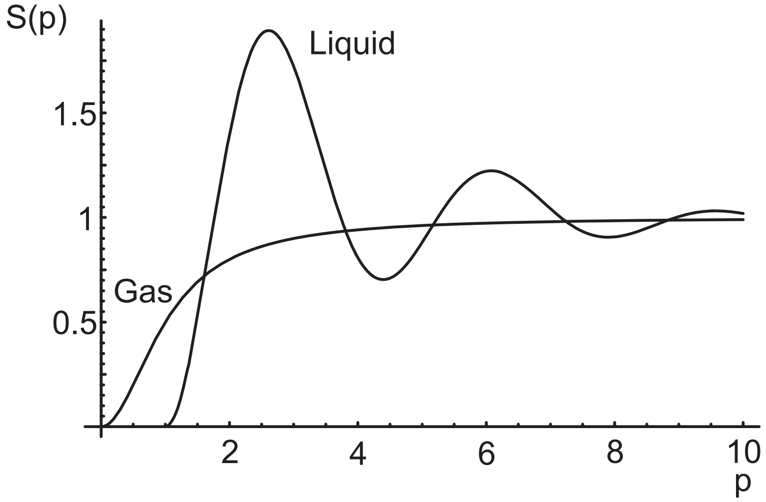

Fig.4: Qualitative behavior of the static structure functions for a liquid and a gas.

In Ref.[20] we defined the static structure function for the case of the QGP and showed that it is related to the longitudinal part of the QCD polarization tensor. Furthermore we argued that QCD lattice simulations should be able to prove the liquid behavior of the strongly coupled QGP by computing the static structure function. To demonstrate the use of this definition and as a reference for lattice calculations, we have calculated the static structure function within the Hard Thermal Loop (HTL) approximation, yielding [20]

$$S(p) = \frac{2N_f T^3}{n} \frac{p^2}{p^2 + m_D^2}, \tag{5}$$

where N_f is the number of light quark flavors, n the parton density, and $m_D = 1/\lambda_D$ the Debye screening mass which is proportional to gT in the HTL approximation. This p-dependence clearly belongs to an interacting gas which is not surprising as the HTL approximation is based on the high-temperature assumption, $T \gg T_c$.

The pair correlation function follows from the Fourier transform of $S(p) - 1$ as

$$g(r) = -\frac{N_f T^3}{2\pi n} \frac{m_D^2}{r} e^{-m_D r}, \tag{6}$$

showing no peaks which corresponds, of course, also to the gas phase.

Finally, we want to point out that strongly coupled plasmas show in general a cross section enhancement for the interaction of the particles within the plasma. The reason is that the Coulomb radius, defined by $r_c = Q^2/E$ with the particle energy E, in a strongly coupled plasma is of the order of the Debye screening length or even larger. Hence the standard Coulomb scattering theory has to be modified since due to the strong interaction particles outside of the Debye sphere contribute significantly and the Debye screening length cannot be used as an infrared cutoff. This modification leads, for example, to the experimentally observed enhancement of the so called ion drag force in complex plasmas which is caused by the ion-microparticle interaction [21].

In the QGP at $T \simeq 200$ MeV, the ratio $r_c/\lambda_D = 1$ - 5, leading to a parton cross section enhancement in the QGP by a factor of 2 - 9 [11] compared to perturbative results. Additional cross section enhancement could come from non-linear (modification of the Yukawa potential to a power law potential at large distances) and non-perturbative effects. An enhanced parton cross section leads to a reduced mean free path λ of the partons in the QGP which corresponds to a small viscosity $\eta \sim \lambda$ and a fast thermalization as indicated by RHIC experiments.

A cross section enhancement of the elastic parton scattering by an order of magnitude compared to perturbative results has also been postulated in Ref.[22] by considering elliptic flow data and particle spectra observed at RHIC. The assumption of a strongly coupled QGP, which requires an infrared cutoff smaller than the Debye mass and in which non-linear and non-perturbative effects are important, gives a natural explanation for this enhancement.

Another consequence would be the enhancement of the collisional energy loss

$$\left(\frac{dE}{dx}\right)_{\rm coll} \simeq \frac{\Delta E}{\lambda}, \tag{7}$$

where ΔE is the energy transfer per collision. This contribution to the total energy loss receives an enhancement from the soft part due to the mean free path reduction for low-energy partons [23]. On the other hand, it can be expected that the radiative energy loss is suppressed in the strongly coupled QGP by the Landau-Pomeranchuk-Migdal effect. In the case of a dense and strongly coupled plasma the emission of gluons could be suppressed by this formation time effect. Indeed experimental indications for explaining jet quenching with a significant contribution from the collisional energy loss have been discussed recently [24,25].

4. Conclusions

Within the last years strongly coupled plasmas became of increasing interest in fundamental research as well as in technology applications. The QGP as well as complex plasmas are important examples of strongly coupled plasmas. Definitely, the QGP is the most challenging strongly coupled plasma from the experimental as well as theoretical point of view. Complex plasmas, on the other hand, can easily be produced and studied. Therefore they can be used as ideal models to investigate fundamental aspects of other many-body systems, such as the dynamic evolution of phase transitions on the microscopic level. Complex plasmas can also be used to learn some interesting lessons about the QGP by analogy, such as the existence of a possible liquid phase and a gas-liquid transition, the use of correlation functions for investigating the equation of state, or cross section enhancement in a strongly coupled plasma.

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