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Study of Bulk Properties of QCD Matter by the Relativistic Heavy Ion Collisions

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We review the present understandings of the bulk properties of strong interacting matter obtained from Relativistic Heavy Ion collision processes and the origin of collective flow. We discuss some open questions in the hydrodynamical approach to these processes.

Keywords: Relativistic hydrodynamics; QGP formation

I. INTRODUCTION

The existence of phase transitions of strongly interacting bulk matter predicted by the quantum chromodynamics (QCD) should relfects itself in variety of physical scenarios such as the evolution of inhomogeneities in the early universe, structure of compact stars, spectra of particles from nuclear collisions at ultra-relativistic energies, etc. In particular, the relativistic heavy ion collisions are the unique possibility of observing such phase transitions of the QCD bulk matter in laboratories, permitting us to extract the properties of the matter at extremely high temperature and energy density.

It is now almost three decades since the basic idea of using ultra relativistic heavy ion collisions to achieve the new phase of the matter, quark-gluon plasma (QGP), was proposed[1]. By colliding two nuclei at relativistic energies, a huge amount of energy is expected to be concentrated in a small space-time region which would lead to this new phase. At first sight, one may think that a more simple system such as a single hadron-hadron collision rather than nucleus-nucleus collision could also achieve such a state and if so, it would be easier to study the QCD dynamics. In fact, heavy ion collisions are much more complicated and expensive than hadronic collisions for the same energy. Furthermore, the final states of the system become orders of magnitude more complex due to the corresponding large number of degrees of freedom involved. Therefore, methods of data storage and their analysis also become complex. However, when we want to investigate the thermodynamical signals of a system, we should first establish the thermodynamical equilibrium. This necessarily requires large interaction time and volume so that only in a macroscopic system we can approach the thermal equilibrium. In hadron-hadron collisions, the system is too small to attain the thermal equilibrium. Thus the complexity of heavy ion collision is the price we have to pay to study the possible phase transition phenomena of the QCD bulk matter.

The relativistic heavy ion collision program started with the incident energy $\sim 1 GeV$ per nucleon using the Bevalac, in Berkeley, just before the 80's. Subsequently, in Brookhaven and Dubna, fixed target nuclear collisions at relativistic energies have been studied. In the 90's, a heavy ion program with fixed target started at the CERN SPS accelerator. The center of mass energy then was of the order of a few tens of GeV per nucleon pairs. In the end of the year 2000, the Relativistic Heavy Ion Collider (RHIC) at BNL began to work, with energies of $100-200\ GeV$ at the center of mass, and in the next year (2007) the Large Hadron Collider (LHC) at CERN will be in operation for a heavy ion program in the energy range of a few $TeVs$.

In early times, a clear-cut first order phase transition from hadronic matter to QGP was expected so that it was hoped that one might observe well-defined signals of phase transition such as the identification of latent heat by the construction of caloric curves (entropy density vs. temperature), but this was not so easy. During these two decades, especially from the experiments realized at SPS and RHIC, a lot of new data have been obtained and is still being accumulated. They revealed the extremely complex nature of the physical processes involved in heavy ion collisions. Instead of the initial naive QGP signals, necessities of more sophisticated observables have been recognized.

Although the nature of the transition from the hadronic phase to the QGP phase is still not well understood, the overall "picture" of relativistic heavy ion collisions is now being configured. In addition to the experimental data, advances in theoretical studies also enriched understandings of the properties of the strong interacting matter[2]. In particular, recent developments in the lattice-QCD calculations are very significant[3]. We now believe that there exists a tri-critical point in the (T,μ) phase diagram[4]. For (almost) baryon-antibaryon symmetric matter achieved in the central collisions of relativistic heavy ion reactions (or in the cosmological scenario) the phase transition from the color deconfined phase to confined phase will not be of the first order but higher order one or more smooth cross-over.

In this short review, we report the present status of the ultra-relativistic heavy ion collision physics, in particular, the collective flow phenomena which is considered as a robust signal of the formation of new state of hadronic matter. We also discuss some of open problems of hydrodyanamical approach.

II. COLLECTIVE FLOW AS A SIGNAL OF FORMATION OF NEW STATE OF THE HADRONIC MATTER

Nowadays, no one raises any serious objections against QCD as the theory of strong interactions and, of course, to the existence of quarks of gluons (it was not so only 40 years ago and ideas of relativistic heavy ion collisions were even out of question). Therefore, when we say "QGP signals", we are not talking about a mere observation of the presence of quark-gluon degrees of freedom, but how they become deconfined and behave as the real carriers of the thermodynamical energy and momentum. That is, we are talking about dynamical mobilities of quarks and gluons.

First, let us consider the structure of hadrons in terms of quarks and gluons. In the QCD picture, a hadron is a bound state of quarks which may be illustrated as in Fig.1.

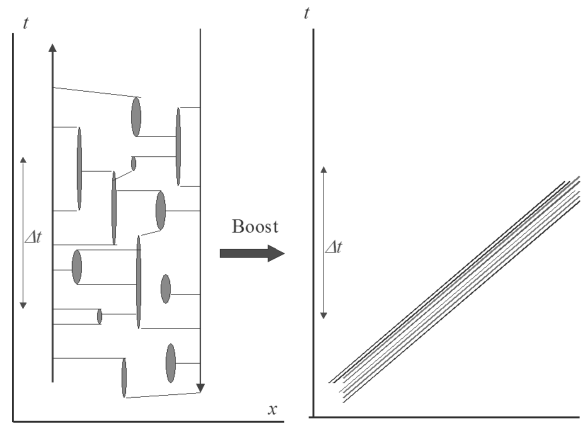

FIG. 1: Many virtual quarks and gluons form dressed valence particles in a hadron (left). These virtual particles behaves as real particles in a short time and distances (right).

In the left-hand side of this figure, a hadron (in this case, a meson) structure is illustrated in terms of two (valence) quark lines where the vertical direction represents the time and horizontal direction the space. Between the two lines many (infinite) virtual bubbles formed by quark-antiquark pairs are connected with gluon exchanges.

Suppose we need a certain minimum time interval Δt to observe the structure of this hadron. All virtual lines which are shorter than this time interval are strongly correlated so that they are not observable as individual degrees of freedom. Only their average behavior reflects the observed hadron properties. When the hadron is boosted near the speed of light (the right-hand side of the figure), then due to Lorentz dilation of time all these short-living bubbles elongate and the effect of correlation among them becomes irrelevant within the time interval Δt. In fact, all these virtual quarks and antiquarks, together with gluons, can be regarded as independent particles within this short interaction time interval. Therefore, it is these "independent particles" that are responsible for the first interactions among high energy hadron collisions. They are called "partons". Then we expect that the number of these partons will increase when the incident energy increases, since for higher energies we can "see" more uncorrelated virtual lines within a given interaction time Δt. How the number of partons increases as a function of the incident energy depends on the interaction which generates the virtual pairs in a hadron, i.e., depends on the ground state of the system. In practice, this energy (momentum) dependence of the number of partons is observed as the structure functions of a hadron in deep inelastic collisions.

After the first instant of the collision in hadron-hadron collisions, these partons are shot out from their initial configurations and materialized. Several QCD based models (parton cascade, string fragmentation, Brigov-Regge theory, etc) have been constructed to simulate the high energy hadronic and nuclear collisions[5]. Recently, the theory of color glass condensate has been applied to calculate the initial energy density distribution in the case of nucleus-nucleus collisions[6]. A huge number of partons is produced so that if interactions among them are sufficiently effective, thermalization of the partonic gas will be attained very quickly. This is the QGP and the most of partons are taken out from the vacuum which consitutes the hadron. In this sense, the QGP formed in high energy nucleus-nucleus collisions can be viewed as a consequence of "melting" nucleons at high energy density. Since these partons are nothing but the basic ingredients which constitute the background for the nucleon's proper existence, i.e., the physical vacuum itself, we may also say that the QGP is a melted state of the physical vacuum.

Unfortunately, the melted vacuum cannot be observed directly, since any observables are in the form of hadrons far after their formation at the melting point. The QGP formed expands rapidly in space and cooled down to hadron gas, again. Therefore, we have to find some way to deduce the properties of the melted matter as QGP using only after the observable hadronic final states. This is also exactly the case of the modern observational cosmology, where we try to find out signals of the initial melted state of matter just after the Big-Bang in terms of the present-day signals.

It may be illustrative to classify possible QGP signals into two major categories. One which is related directly or indirectly to the thermodynamical or hydrodynamical properties of the QGP dynamics. The other are the effects of the deconfined quark and gluon matter on the way of propagation of some probe particle in the QGP. In the first category, we may list the particle abundances, especially the strangeness enhancement, the collective flow properties and azimuthal asymmetry parameters, etc. In the second category, we may classify the J/ψ suppression, dilepton production, direct photons, jet quenching and possible generation of shock waves by jets[25]. In both cases, there exist some intrinsic problems. For example, as we mentioned in the Introduction, the concept of thermal equilibrium becomes delicate when we deal with a small system within a short time scale. In a strict sense, we never expect the true thermal equilibrium in nucleus-nucleus collisions. Therefore, the signals of QGP in the first category may be spoiled by this finite size effect. The signals of the second category have the advantage of being free from the necessity of the ideal thermal equilibrium. We just want to verify the formation of finite domains where the quarks and gluons are deconfined. However, this depends on how effectively the hot and dense deconfined quarks and gluons interact with the probing particles and how this process can be distinguished from the one where one has a collection of hadrons instead of the QGP. An extensive studies have been carried out using the above ideas to examine the data of SPS and RHIC experiments and despite the needs of several caveats which should be considered with care, a large amout of convincing facts that indicate the formation of the QGP phase in the early phase of nuclear collisions have been accumulating[7].

Among these signals, the one which brought a new insight is the emergence of collective flow in the final state of exploding particles. Suppose that a very high energy density domain has been created in the nuclear collision. If the mean-free path of partons are sufficiently short compared with the size of this domain, then the matter inside tends to create a collective pressure which acts the system to expand. This is exactly the situation we expect in the hydrodynamical motion of a fluid. Since the acceleration of the expansion is proportional to the pressure gradient, the particles in the final state should have larger momentum in the direction in which initially the largest pressure gradient.

To make clear the meaning of the collective flow, let us here review the basic structure of the relativistic hydrodynamics. Let $T^{\mu\nu}$ be the energy-momentum tensor of the matter. Then the dynamics of the system should obey the conservation law of this tensor,

$$\partial_\mu T^{\mu\nu} = 0. \tag{1}$$

For the case of a perfect fluid in local equilibrium, we can write

$$T^{\mu\nu} = (\varepsilon + p)\, u^\mu u^\nu - p g^{\mu\nu},$$

where ε, p and u^μ are, respectively, the proper energy density, pressure and four-velocity of the fluid element. Eq.(1) should be complemented by the continuity equations for conserved currents such as the baryon number,

$$\partial^\mu (n u_\mu) = 0,$$

and also the equation of state which describe the thermodynamical properties of the matter. The equation of state may be given by

$$\varepsilon = \varepsilon(n, s),$$

where n and s are the baryon number and the entropy densities, respectively. For ideal fluid, the endropy is also conserved,

$$\partial^\mu (s u_\mu) = 0.$$

These hydrodynamical equations can also be derived from the action principle[10]. They can be solved numerically to give the space-time development for the thermodynamical variables and the fluid velocity u^μ[11].

To analyze the physical observables in terms of the hydrodynamical scenario, we have to construct the particle spectra from the hydro solution. As the hydrodynamical expansion proceedes, the fluid becomes cooled down and also becomes rarefied, occurring finally the *decoupling* of the constituent particles, that is, they don't interact any more until their detection (Long-lived resonances and other unstable particles may decay on the way to the detector after this instant of decoupling phase). In the standard hydrodynamical models, one introduces the concept of freeze-out, which assumes that particle emission occurs on a sharp three-dimensional surface (defined for example by the local temperature, $T(x,y,z,t) =$ constant). Before crossing it, particles have a hydrodynamical behavior, and after they free-stream toward the detectors, keeping memory of the conditions (flow, temperature) of where and when they crossed the three dimensional surface. The Cooper-Frye formula [15] gives the invariant momentum distribution in this case

$$Ed^3N/dp^3 = \int_\sigma d\sigma_\mu p^\mu f(x,p). \tag{2}$$

$d\sigma_\mu$ is the surface element 4-vector of the freeze out surface σ and f the thermal distribution function of the type of particles considered. The space-time dependence comes from those of thermodynamical parameters, such as temperature and chemical potential. This is the formula implicitly used in all standard thermal and hydrodynamical model calculations (see [16] and the discussion in the next section for different approach of hadron production from the thermal gas). It is found that the hydrodynamical description can describe very well the many observables[9][19].

As menioned above, one of the most important observables in the hydrodynamical approach is the collective flow parameter. For non-central collisions, anisotropic hot matter is created in between the colliding nucleus and this should lead to the anisotropic azimuthal distribution of particle momenta with respect to the reaction plane as illustrated below.

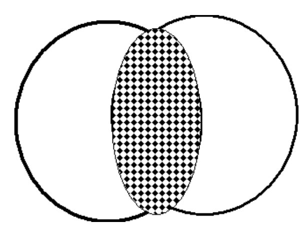

FIG. 2: Non central collision of two nuclei creates an anisotropic distribution of hot and dense matter which expands hydrodynamcally.

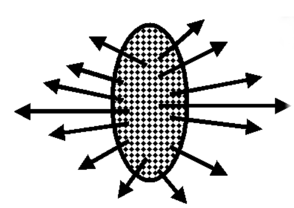

FIG. 3: Due to the sharp pressure gradient, the final state particles attain the anisotropic momentum distrubution.

Such anisotropy can be expressed by the coefficients of Fourier expansion of the azimuthal distribution of particles. In practice, the determination of these coefficients from the experimental data is not trivial since the reaction plane is not given a priori. In the hydro case, of course, the reaction plane is given from the beginning. We define the theoretical elliptic flow for a given transverse momentum window as

$$v^{(2)}\left(p_T\right)=\frac{\left\langle \int d\phi\,\left[d^2N/dp_T^2d\phi\right]\cos 2\left(\phi-\phi_{\vec{b}}\right)\right\rangle}{\left\langle \int d\phi\,\left[d^2N/dp_T^2d\phi\right]\right\rangle},$$

where p_T is the transverse momentum, and ϕ and $\phi_{\vec{b}}$ are, respectively, the azimuthal angles of the particle and of the impact parameter vector with respect to a some space-fixed coordinate system.

The finite positive value of this coefficient v_2 is referred to as the elliptic flow and, from the point of view of hydrodynamics, it is sensitive to the initial pressure gradient of the system. In Figs.4 and 5, hydro calculations of the elliptic flow for different equation of states are shown together with the experimental data. In these figures, we can see clearly that the elliptic flow reaches to the hydrodynamical limit for RHIC energies (Fig.5) whereas for lower energies (SPS - Fig.4) the flow is much less than that expected from the hydro model. This can be understood as, while the hadronic gas behaves as a viscous dissipasive matter, the QGP has much less dissipative energy per unit entropy and offers a large initial pressure gradient, and the elliptic flow reaches to its ideal fluid dynamical limit, as seen from Fig.5.

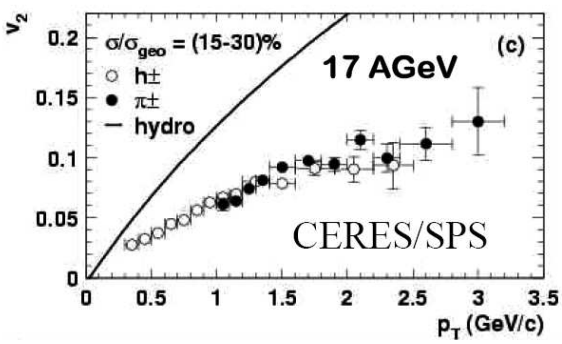

FIG. 4: Elliptic flow at SPS energies as function of transverse momentum, compared to the simple idela fluid hydrodynamical calculation. The observed values of elliptic flow are below the hydro values. Figure adapted from the presentation of M. Gyulassy at International Symposium on Heavy Ion Collisions, Frankfurt, April, 2006.

These hydro calculations, together with the other observables, such as pion interferometry (HBT[12]) measurements indicate that the thermal equilibrium of QGP is attained at a very early stage of the nucleus-nucleus collisions[13][23].

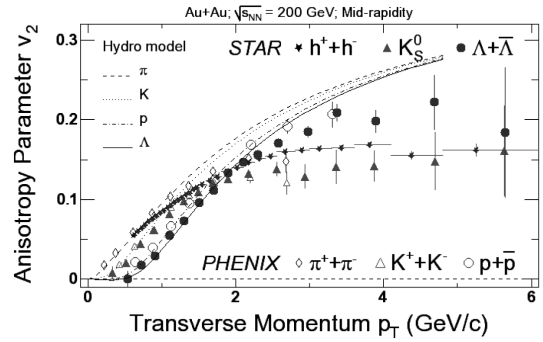

FIG. 5: Elliptic flow at RHIC energies as function of transverse momentum, compared to the simple idela fluid hydrodynamical calculation. Figure adapted from the presentation of M. Gyulassy at International Symposium on Heavy Ion Collisions, Frankfurt, April, 2006.

III. SOME OPEN PROBLEMS OF RELATIVISTIC HYDRODYNAMICS

We may summarize the present general picture for the formation of QGP in the relativistic heavy ion collisions at RHIC energies. I)-Hadronic abundances are well described in terms of chemical equilibrium among hadronic resonances, which in turn indicate the temperature and chemical potential of this stage. Temperatures as high as 170 MeV in the chemical freeze-out are obtained in RHIC data, which indicate that the temperature achieved during the collision must have much exceeded the critical temperature predicted by the lattice QCD calculation. II)-Ideal hydrodynamical calculations work basically well. This approach indicates the very early equilibration of the partonic gas. III)-In particular, the large elliptic flow observed at RHIC energies is consistent with the ideal fluid calculation, and when compared to the SPS cases, this fact strongly indicates that the new state of matter has been formed at the early stage of the collision at RHIC energies which flow as an ideal fluid. IV)-HBT measurements also indicate a short equilibration time. V)-Some indications of non-equilibrium processes reflecting in multi-strangeness enhancement. J/ψ and heavy quark observations. IV)-Observations of jet-quenching, distribution of mono-jets, and their dependence on system size effect (jet tomography) are consistent with the emergence of hot and dense deconfined quark and gluon domain. VII)- The nature of the QGP seems rather a strongly interacting fluid (sQGP) than a ideal parton gas, although the corresponding Reynold´s number is very large, close to the ideal fluid[18].

As shown above, although the evidences are yet circumstancial, a lot of convincing indications are accumulating to believe that the QGP phase has been attaind in the RHIC experiments. However, we still do not know the precise nature of the QGP and its formation dynamics. In the coming LHC experiment (ALICE), observations of the hard components (jets), possible generation of shock waves and heavy quark production will be the central issue, in addition to other interesting possibilities such as the large extra dimension of the space-time.

For such energies, the hydrodynamic description should become still more reliable for the description of the bulk dynamics of the QGP. On the other hand, as mentioned before, there exist several open problems in the interpretation of data in terms of the hydro model. These questions require careful examination to extract quantitative and precise information on the properties of QGP. For example, it has been pointed out that the effect of even-by-event fluctuations due to the different initial conditions are crucial for quantitative studies of observables[17].

Furthermore, several very different physical scenarios within the hydro calculation (e.g. continuous emission, sudden freeze-out, rQMD cascade, some drastically simple hydro models, etc) can give rise equally good results in reproducing the observables with suitable choices of parameters. In a way, one may say that the hydro signature is "robust", but on the other hand, this could be a synonym of "insensitive", so that in order to extract some quantitative information on the properties of the quark-gluon plasma. For a better and quantitative understanding of the mechanism of phase transition in the bulk QCD matter, we should clarify these points and refine the physical parameters used in these models.

With respect to this point, one should remind a important point of the collective flow. While we use the equation of state, hydrodynamical equations are meaningful only when the approximation of local thermal equilibrium is reasonable. On the other hand, as far as Eq.(1) is concerned, it is nothing but the local conservation of energy and momentum density. Therefore, it may be possible that a system which is completely out of local thermal equilibrium can also manifest a flow pattern. For example, as a well-known example, we may recall that the Schrödinger equation

$$i\hbar\frac{\partial\psi}{\partial t}=-\frac{\hbar^2}{2m}\nabla^2\psi+V\psi$$

can also be written just as if the form of hydrodynamics,

$$\frac{\partial}{\partial t}\vec{v}+(\vec{v}\cdot\nabla)\,\vec{v}=-\frac{1}{m}\nabla p_q-\frac{1}{m}\nabla V,$$
$$\frac{\partial n}{\partial t}+\nabla\cdot(n\vec{v})=0,$$

where

$$\vec{v}=\frac{1}{m}\nabla\left(\arg\psi\right),$$
$$n=|\psi|^2$$

and

$$p_q=-\frac{1}{2m}\frac{1}{|\psi|}\nabla^2\,|\psi|$$

serves as the pressure, but nothing to do with the thermal equilibrium. That is, a flow phenomena does not necessarily indicates the validity of the local thermodynamical equilibrium.

We may list several crucial points of the hydrodynamical approach to the relativistic heavy ion reactions.

1. How to establish the initial condition for the hydrodynamical motion in relativistic heavy ion reactions.

In particular, the process of thermalization of the partonic excitation, and understand how the early thermalization can be attained. Several new concepts have been proposed. For example, as the mechanism of quick isotropization from the initial momentum distribution of partons (which is predominantly longitudinal), the so-called Weibel instabilities known in plasma physics is shown to be effective also in the case of QCD. However, the isotropization itself is not suffice for the thermal equilibrium. With respect to the mechanism of thermalization, another interesting notion, called prethermalization is recently developed. In a scalar field theoretical model, it is shown that when the system is set to an excited state, the validity of equation of state (the functional relation between energy density and pressure) is attained well before the real thermal equilibrium is reached[21]. With respect to this point, we have discussed a possible relation between the mechanism of early thermalization to the non-extended statistical mechanics[20]. Furthermore, the approach from the color glass condensate may provide an initial momentum distribution easy to achieve a quick thermalized state of partons because of saturation mechanism. As mentioned, several investigations based on the CGC approach to calculate the initial energy distribution have been carried out.

2. How to estimate the effects of finite size of the system and event-by-event fluctuations.

Even the mechanism of thermalization is fast enough, the initial condition attained by the nuclear collision must be far from smooth and fluctuates collision by collision. Furthermore, strictly speaking, the hydrodynamics is the zero mean-free path approximation but for the nuclear collisions, this is not a trivial approximation. As we know that the nuclear ground state has finte surface thickness (of the order of 3 fm) but if we try to describe the density distribution in terms of zero mean free-path hydrodynamics, we would have zero surface thickness for the ground state mass distribution. The parameter which characterizes the degree of approximation with respect to the finite size of the system would be

$$x=\frac{\lambda_{MFP}}{\lambda_{Hydro}}$$

where λ_{MFP} is the tipical mean-free path of the constituent particles and λ_{Hydro} is the hydrodynamical inhomogenity scale, which is tipically

$$\lambda_{Hydro}\simeq\left|\frac{1}{\rho}\nabla\rho\right|^{-1}.$$

Hydrodynamics is valid for $x\ll 1$, that is, if the inhomogenity scale is of the order of the mean-free path, the hydrodynamics should break down. On the other hand, as we mentioned above, the hydrodynamical equations can be decomposed into two parts, one simply states the conservation laws, and other, to relate the force and energy density in hydro cell. If we can express the force acting on the hydro cell taking into account for the inhomgenity scale, then we could still use the hydrodynamical scheme. In other words, we need an equation of state of the matter which depends on the size of the system.

Such an effort is being done and recently that the effect of finite size of the system on the properties of chiral phase transition has been estimated using the multiple reflextion expansion method within the frame work of Nambu-Jona-Lasinio model, showing explicitly the dependence of the equation of state (EoS) on the system size parameter. The basic idea is to introduce the density of state in the expression of the thermodynamical potential within the mean-field approximation as

$$\omega = \frac{m^2}{4G} - \nu \int_0^{\Lambda_{\rm UV}} dk \rho_{MRE}(k,\kappa,R)$$
$$\left\{ E_k + \frac{1}{\beta} \ln \left[1 + e^{-\beta(E_k+\mu)} \right] \left[1 + e^{-\beta(E_k-\mu)} \right] \right\},$$

where

$$\rho_{MRE} = \frac{k^2}{2\pi^2} \left[1 + \frac{6\pi^2}{kR} f_S\left(\frac{k}{\kappa}\right) + \frac{12\pi^2}{(kR)^2} f_C\left(\frac{k}{\kappa}\right) \right],$$

is the density of state given by the multiple expansion method, and

$$f_S(x) = -\frac{1}{8\pi}\left(1 - \frac{2}{\pi}\arctan x\right), \tag{3}$$

$$f_C(x) = \frac{1}{12\pi^2}\left[1 - \frac{3}{2}x\left(\frac{\pi}{2} - \arctan x\right)\right]. \tag{4}$$

R and κ are parameters related to the radius and surface thickness. In Fig.6, we show how the structure of the phase diagram is affected by the radius parameter R, with $\kappa = 0$. The solid and dotted lines represents the critical lines of the first order and second order phase transitions, respectively. These lines represent the critical lines of (a) $R = \infty$, (b) 20, (c) 10 and (d) 5.7 fm from the out-most one, respectively. One can see that the transition temperature of the chiral phase transition is lowered as the system size is reduced. The reduction of the temperature is remarkable already at $R = 20$ fm. The dashed line represents the trajectory of the tricritical point as a function of R. One can easily see that the temperature and the chemical potential of the tricritical point are reduced as the R is decreased.

Although the example shown here is a very simplified estimate, but the effect of inhomgenity on the equation of state can be very important for the hadronization mechanism of the QGP formed in the relativistic heavy ion collisions.

3. How to estimate the viscosity and its effect on collective flow phenomena for the QCD matter.

The comparison of flow phenomena to the ideal fluid calculation indicates that the emergence of ideal-fluid type behavior at RHIC energies. This idea that the QGP behaves a real ideal fluid raised an interesting question which may have its orgin in supersymmetric gravity theory[24]. On the other hand, Hirano and Gyulassy argue that this is due to the the entropy density of the QGP which is much larger than the hadronic phase[6]. To be precise, a precise and consistent analysis of the viscosity has not yet been done. This is because the introduction of dissipative phenomena in relativistic hydrodynamics casts difficult problems, both conceptual and thechnical. It is known that the formalism of Landau[3] of relativistic vicous fluid leads to acausal wave propagation. To cure this problem, the second order thermodynamics was developed by Israel, Stewart and Miller[4]. However, this theory is too general and contains many unknown parameters which make difficult the application of the theory to practical problems. Several works have been done in this direction.

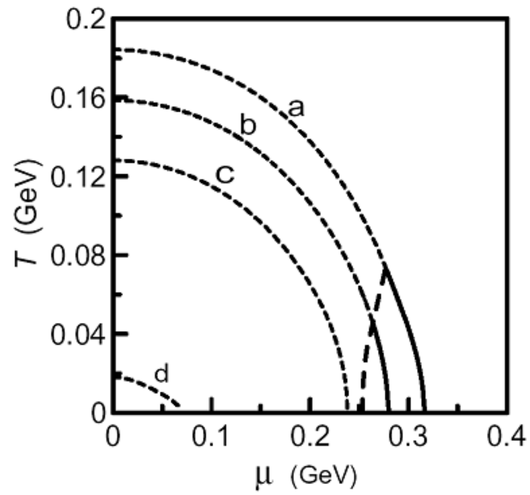

FIG. 6: Change of phase diagram with respect to the size parameter of the system. Curves a, b, c and d correspond to the critical temperature as function of the chemical potential for different size parameter R (see the text).

4. How to obtain the final hadron spectra from the hydrodynamical model.

The usual method of sudden freeze-out described by Cooper-Frye formula Eq.(2) is not only an idealization but also contains some problems such as conservation of energy and momentum, negative flux and artificial entropy creation. To remedy this approach several approaches which couples the transport approach to the hydrodynamical final state configurations. Usually these calculations are rather complex and time consuming in practice. The continuous emission approach still uses the equilibrium momentum distribution of particles but they can be emitted continuously during the hydrodynamical evolution of the system. It also takes into account the absorption effects while the emitted particle from the inside traverses the surrounding hadronic matter. This accounts for the finite size of the system in the final particle spectra. In contrast to the usual sudden freeze-out, final hadrons can be emitted from any temperature. It should be emphasized that the two extremely cases, a sharp temperature surface of sudden freeze-out and almost flat distribution of temperature of the continuous emission scenario give equally good description of the observed spectra and flow.

IV. SUMMARY

The hydrodynamics is found to be a very successful tool for the description of the relativistic heavy ion collisions. A very simple, idealized form of this approach revealed that at the RHIC energies there emerges a new phase for the dense and hot matter which flows as if an ideal fluid. This may be identified as the QGP. On the other hand, from the quantitative point of view, the present hydrodynamical approach still contains many uncertainties and also some conceptual problems. When these questions are clarified, we will have much more detailed knowledge about the dynamics and properties of the new states of strongly interacting matter.

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