Nonlinear Dynamics and Applications. Vol. 13 (2006) 282 - 286

First-order QGP⇒hadrons phase transition in heavy-ion collisions

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We study the multiplicity distributions of charged particles through the generalized Ginzburg-Landau model for first order QGP→hadron phase transition. Fitting of the experimental data is discussed. The free parameters of the Ginzburg-Landau model are found.

PACS numbers: 25.75.-q, 12.38.Mh, 73.43.Nq
Keywords: heavy-ion collisions, quark-gluon plasma, phase transition, Ginzburg-Landau model, multiplicity distribution

1. Introduction

The quark gluon plasma (QGP) is a novel state of matter conjectured to is formed during ultrarelativistic heavy-ion collisions and to have existed when the Universe was about 10 μsecs old. Ultrarelativistic heavy-ion experiments at SPS-CERN, RHIC-BNL and the forthcoming LHC at CERN seek to create this state in collisions of heavy ions such as Pb and Au up to $\sqrt{S} \sim 200$ $Gev/nucleon$ at RHIC and 5 $Tev/nucleon$ at LHC. Current theoretical ideas suggest that a QGP in local thermodynamic equilibrium is formed on a time scale of the order of $\sim 1fm/c$ after the collision when the partons in the colliding nuclei are liberated. The QGP contains quarks and gluons, just as normal (hadronic) matter does. The difference between these two phases of QCD is the following: In normal matter each quark either pairs up with an anti-quark to form a meson or joins with two other quarks to form a baryon (such as the proton and the neutron). In the QGP, by contrast, these mesons and baryons lose their identities and make a much larger mass of quarks and gluons. In normal matter quarks are confined; in the QGP quarks are deconfined [1].

Parton-parton collisions during a pre-equilibrium stage is then conjectured to lead to a state of local thermodynamic equilibrium that expands hydrodynamically and eventually undergoes a hadronization phase transition at a temperature of order ~ 160 Mev [2].

One of the theoretical aims is to find a signal about the phase transition. Unfortunately, the theoretical description of the QGP from first principles is extremely difficult as the interaction between quarks and gluons in the QGP, described by QCD, is strong. Therefore, perturbative QCD is not applicable. Only at extremely high temperatures the interaction becomes weak due to asymptotic freedom, allowing a perturbative treatment of the QGP. As is well-known, fluctuations are large for statistical systems near their critical points.

Thus the study of fluctuations in the process might reveal some features for the phase transition [2, 3].

Monte Carlo simulations [4] on intermittency [5] without phase transition for pp collisions [6] show quantitatively different results on multiplicity fluctuations from theoretical predictions with the onset of phase transition [5]. These different results stimulated a lot of theoretical works on multiplicity fluctuations with phase transition of second-order [7, 8] and first-

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order [9, 10] within Ginzburg-Landau model which is suitable for the study of phase transition for macroscopic systems.

The order of a phase transition is one of the basic thermodynamic characteristics. A phase transition is said to be of first order if there is at least one finite gap in the first derivatives of a suitable thermodynamic potential in the thermodynamic limit. A transition is said to be of second order if there is a power-like singularity in at least one of the second derivatives of the potential.

As the collision energy is increased in modern accelerator experiments, the role of collective effects in the interaction of high-energy particles becomes more noticeable. Despite of successes achieved in describing these processes within perturbative QCD [11], the perturbation theory cannot reproduce all particular properties of quark-gluon interaction; in particular, collective aspects of the behavior of the parton system [12]. In addition, there is still a gap between QCD computations and the long-distance regime where hadrons are observed.

Another aspect of the problem consists in technical difficulties of the analysis of the large particle multiplicities with the essentially random peculiarities of multi-particle production. Methods of the statistical physics are fruitful because the mathematical apparatus used at investigation of the multiplicity distribution and particle correlations is common both for the statistical physics and for the processes of the multi-particle production [13]. For statistical systems, the fluctuations are large near critical points. Therefore the multiplicity fluctuations of hadrons produced in high-energy heavy-ion collisions can be used as indication of whether a quark-gluon system undergoes a phase transition. Up to now the question concerning the order of the parton-hadron PT in high-energy collisions is opened. Lattice gauge calculations indicate that for two flavors the PT is most likely to be of the second order [14, 15]. When strange quarks are included, a weak first-order PT may occur [16].

Ginzburg-Landau (GL) formalism, both for the second-order [3, 7] and first-order [9, 10] PT is applicable. One of the differences between second- and first- order phase transitions is the hysteresis phenomenon which is typical for the first-order phase transitions only [9].

The latest RHIC experimental data is shown that the QGP is indicated as strongly coupled quark-gluon liquid of very low viscosity rather than a gas of weakly interacting quarks and gluons [17]. Therefore QGP-hadrons phase transition should be a first order phase transition of the liquid-gas type. In present paper, the quark-gluon plasma is described phenomenologically and the transition from QGP to hadrons is considered as a first-order phase transition.

2. Ginzburg-Landau model for the first-order phase transition

We give first a very brief review of the usual method in the GL approach to hadronic observables. The GL theory of the phase transitions is based on the expansion of the free energy in powers of the order parameter. The allowed terms in this expansion are further selected by symmetry reasons. Phase transitions can be classified according to the transformation behavior of their order parameters under the symmetry transformation. We discuss only an order parameter described by a complex scalar field ψ.

The Ginzburg-Landau free energy is given by

$$F[\psi] = \int dz \left[\gamma \left| \frac{\partial \psi(z)}{\partial z} \right|^2 + \beta |\psi(z)|^2 + \alpha |\psi(z)|^4 + c|\psi(z)|^6 \right], \tag{1}$$

where $\psi(z)$ is the complex order parameter which characterizes a hadron phase, $|\psi(z)|^2$ is associated with the hadronic multiplicity density of the system, the parameters γ, β, α are some functions of global characteristics of the system (temperature, density, etc.), $c = const > 0$, z denotes the variables of the d-dimensional phase space.

Let us consider a simple case of uniform ψ which is equivalent to setting $\gamma = 0$ in (1). Then the Ginzburg-Landau free energy is

$$F[\psi] = c \int dz \left(b|\psi|^2 + a|\psi|^4 + |\psi|^6 \right), \quad b = \frac{\beta}{c}, \quad a = \frac{\alpha}{c}. \tag{2}$$

The term $|\psi|^6$ is included to allow the first-order phase transition. The phase transition takes place due to the change of the control parameters a, b with temperature. In Fig. 1 and Fig. 2 we show the plane of the control parameters a, b of the potential (2) and the dependence of the ground state $|\psi_0|$ upon the parameters a, b respectively. The plane of the control parameters a, b has four regions with different form of potentials which are shown in corresponding places in the Fig. 1. As control parameters change along lines 1 and 2, we have the first and the second-order phase transition respectively. Hysteresis takes place when the physical process is not completely reverse, i.e. direct and reverse phase transitions occur at different values of the control parameters. In Fig. 2 a loop of hysteresis is shown. The existence of hysteresis phenomenon must lead to the difference between critical temperatures of direct T_{C1} and reverse T_{C2} phase transitions. In case of the first-order phase transition $T_{C1} > T_{C2}$ and we have delay of the system in the quark-gluon plasma state. In case of the second-order phase transition such difference does not take place. The theoretical and experimental search for differences between manifestations of the first- and second-order phase transitions can lead to important results for registration of quark-gluon plasma in nuclear collisions.

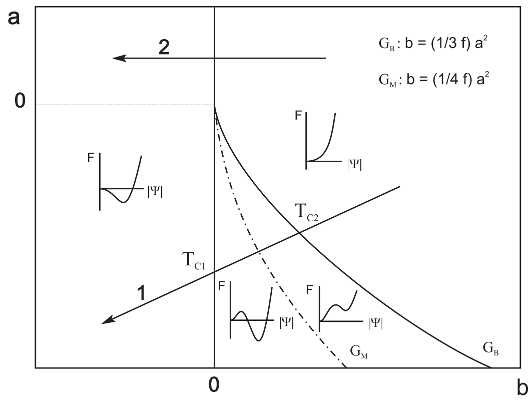

FIG. 1. The plane of control parameters of the potential (2)

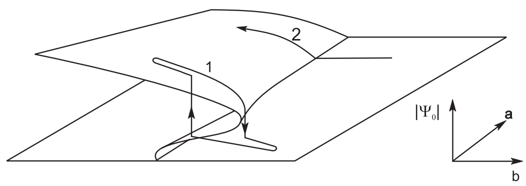

FIG. 2. The dependence of the ground state $|\psi_0|$ upon the control parameters a, b

The fluctuation of hadron density takes place due to the fluctuation of order parameter from ground state. The probability of this fluctuation $W[\psi]$ is given by

$$\begin{aligned} W[\psi] &= Z^{-1} \exp(-F[\psi]) \,, \\ Z &= \int D\psi \exp(-F[\psi]) \,, \end{aligned} \tag{3}$$

where $F[\psi]$ is the free energy of the system and Z is the partition function. Here we assume that the phase transition is of first-order and it is described by the generalized Ginzburg-Landau free energy with $|\psi|^6$ term included in (1).

Then the hadron multiplicity distribution can be given by the functional integral [13]

$$P_n = Z^{-1} \int D\psi P_n^0 e^{-F[\psi]}, \tag{4}$$

where P_n^0 is the probability density of finding n particles, in the state far from the phase transition. As simple approximation we can use for P_n^0 Poisson distribution [7, 9]

$$P_n^0 = |\langle n|\psi(z)|^2 = \frac{1}{n!}\ \exp\left\{-\int\limits_V |\psi(z)|^2 dz\right\} \left(\int\limits_V |\psi(z)|^2 dz\right)^n . \tag{5}$$

We also assume that $|\psi|$ does not depend on z [7, 9]. Making the appropriate substitutions for (4) we obtain

$$P(n,\alpha,\beta,c) = \frac{1}{Z}\int_0^\infty \mathrm{d}x\ \frac{(x)^n e^{-x}}{n!} e^{-(c\ x^3+\alpha\ x^2+\beta\ x)}, \qquad Z = \int_0^\infty \mathrm{d}x\ e^{-(c\ x^3+\alpha\ x^2+\beta\ x)}. \tag{6}$$

3. The fitting of experimental data in heavy-ion collisions

The formula (6) has three free parameters $\alpha,\ \beta,\ c$.

To define these we can use a experimental data of multiplicity distribution. In paper [18] have been presented the experimental data of multipicity distributions of negative charged particles of 5% most central $Au+Au$ collisions for $\sqrt{S_{NN}} = 130\ GeV$, $P_\perp > 100\ MeV/c$,$|\eta| < 0.5$ We fitting this data by formula (6). For parameters $\alpha,\ \beta,\ c$ we found the values

$$\alpha = -1.35\cdot 10^{-3},\quad \beta = 1.62\cdot 10^{-1},\quad c = 2.589\cdot 10^{-6}. \tag{7}$$

The result of fitting is shown on Fig. 3

We assume that the constant c characterize of a type of heavy-ion collisions ($Au+Au$, $Pb+Pb$) and α, β is depend on the other parameters of collision such as energy, centrality, etc. If we fit experimental data of multiplicity distributions for other energies $\sqrt{S_{NN}}$ and centrality $\mathcal{C}, (0 < \mathcal{C} \leq 1)$, we can obtain the parameters $\alpha,\ \beta$ as function of $\alpha(\sqrt{S_{NN}},\ \mathcal{C})$ and $\beta(\sqrt{S_{NN}},\ \mathcal{C})$.

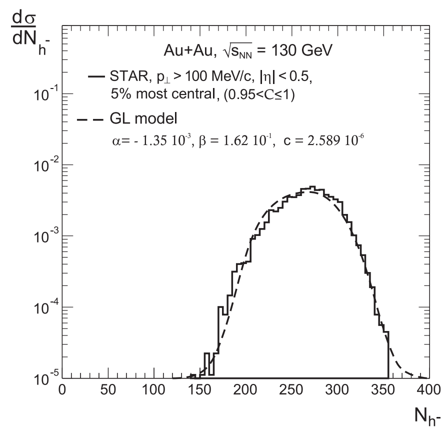

FIG. 3. The result of comparison of GL model (dashed line) and experimental data (solid line) of multiplicity distributions of charged particles in $Au+Au$ collisions

4. Conclusion

In this paper we apply the phenomenological Ginzburg-Landau theory to describe the first-order QGP-hadron phase transition. We show that this model can describe the multiplicity distributions in high energy heavy-ion collisions. We fit experimental data of multiplicity distribution of charged particles. The values of parameters of the generalized Ginzburg-Landau model are found.

Acknowledgments

This research was supported in part by the BRFFR-Grant F06R-209 (Minsk, Belarus).

References

[1] J.W. Harris, B. Muller. Annu. Rev. Nucl. Part. Sci. 46, 71 (1996); B. Muller in Particle Production in Highly Excited Matter, edited by H.H. Gutbrod, J. Rafelski, NATO ASI series B, vol. 303 (1993); H. Elze, U. Heinz, Phys. Rep. 183, 81 (1989); H. Meyer-Ortmanns, Rev. Mod. Phys. 68, 473 (1996); H. Satz, in Particle Production in Highly Excited Matter, edited by H.H. Gutbrod and J. Rafelski, NATO ASI series B, Vol. 303 (1993); B. Muller. The Physics of the Quark-Gluon Plasma, Lecture Notes in Physics. Vol. 225 (Springer-Verlag, Berlin, 1985); L.P. Csernai. Introduction to Relativistic Heavy Ion Collisions (John Wiley and Sons, England, 1994); C.Y. Wong. Introduction to High-Energy Heavy Ion Collisions (World Scientific, Singapore, 1994).

[2] A. Bialas, R.C. Hwa. Phys. Lett. B253, 436 (1991).

[3] R.C. Hwa, M.T. Nazirov. Phys. Rev. Lett. 69, 741(1992).

[4] R.C. Hwa, J.C. Pan. Phys. Rev. D45, 106(1992).

[5] A. Bialas, R. Peschanski. Nucl. Phys. B273, 703(1986); B308, 857(1988).

[6] M. Adamus et al. (NA22 Collaboration). Phys. Lett. B185, 200 (1987); I.V. Ajinenko et al. (NA22 Collaboration). Phys. Lett. B185, 222, 306(1989); 235, 373(1990); N.M. Agababyan et al. Phys. Lett. 261, 165(1991).

[7] R.C. Hwa. Phys. Rev. D47, 2773(1993); R.C. Hwa, J.C. Pan. Phys. Lett. B297, 35(1992).

[8] X. Cai, C.B. Yang, Z.M. Zhou. Phys. Rev. C54, 2775 (1996).

[9] L.F. Babichev, D. V. Klenitsky, V. I. Kuvshinov. Proceed. 3d Int. Seminar "Nonlinear Phenomena in Complex Systems" (14-16 February, 1994, Polatsk, Belarus), Minsk, Institute of Physics, 1995, 149; L.F. Babichev, D.V. Klenitsky, V.I. Kuvshinov. Phys. Lett. B345, 269(1995);

[10] R.C. Hwa. Phys. Rev. C50, 383(1994); I.A. Lebedev, M.T. Nazirov. Mod. Phys. Lett. A9, 2999(1994); A.K. Mohanty, S.K. Kataria. Phys. Rev. Lett. 73, 2672(1994).

[11] Yu. L. Dokshitzer, V. A. Khoze, A. H. Mueller, S. I. Troyan. Basics of perturbative QCD. Frontièrs, France, 1991.

[12] I. M. Dremin, A. V. Leonidov. Usp. Fiz. Nauk 165, 759 (1995).

[13] D. J. Scalapino, R. L. Sugar. Phys. Rev. D8, 2284 (1973).

[14] S. Gottlieb, Nucl. Phys. B20, 247 (1991).

[15] H. Gausterer, S. Sanielevici, Phys. Lett. B 209, 533 (1988).

[16] F. Wilzcek, Int. J. Mod. Phys. A7, 3911 (1992).

[17] M. Gyulassy. Preprint nucl-th/0403032 (2004)

[18] C. Adler at al.(STAR Collaboration). Multiplicity distribution and spectra of negatively charged hadrons in Au+Au collisions at $\sqrt{S_{NN}} = 130\ GeV$; nucl-ex/0106004 (2001) 6 pages.