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PHASE TRANSITION FROM QUARK-GLUON PLASMA TO MATTER AFTER THE BIG BANG

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Abstract

The dependence of the energy density distribution around a quark and an antiquark as a function of temperature has been studied in this work. Temperature range was 0.7-1.3 times the critical temperature of the phase transition from a hadronic matter to quark gluon plasma. Using Monte Carlo numerical simulation we have found that above the critical temperature we can observe a quark as a single particle.

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I. INTRODUCTION

Since the days of the early Greek philosophers, science has been on a continual quest to find the smallest piece — the most fundamental building block forming the substance of the universe. The most fundamental building blocks of nature known so far are quarks and gluons. Everything we see and use is made of quarks and gluons. Theory holds that for a brief time at the beginning of the universe there were no protons and neutrons, only free quarks and gluons. However, as the universe expanded and cooled, the quarks and gluons bound together and for the next 13 billion years remained virtually inseparable. Investigating the behavior of matter in the vicinity of the critical temperature of the deconfinement transition and at high temperature is a major goal of current and planned heavy ion collision experiments. Motivated by the confinement problem at zero temperature [1, 2, 3, 4], interesting questions arise at high temperature, concerning the behaviour of the flux tube when QCD undergoes a phase transition. What steps will the flux tube pass through and how does it behave to go to the quark-gluon plasma phase? To have answers to these questions we need to do the finite or high temperature study. To see how the flux tube melts into the quark-gluon plasma phase one has to look into the details of the interaction between quark pairs studying the distribution of the chromoelectric and chromomagnetic components of gluon fields which compose energy and action density of the flux tube.

II. THE THEORY OF STRONG INTERACTION AND LATTICE QCD

Quantum Chromodynamics (QCD) is a field theory of basic quark and gluon constituents. At short distances QCD is weakly coupled and can be studied analytically using perturbation theory, while at large distances it is strongly coupled and in most cases it can not be studied analytically. In order to study physical processes that are controlled by large-distance, nonperturbative effects of QCD, in 1974 Kenneth Wilson introduced Lattice Gauge Theory in which the space-time continuum is discretized on a lattice with lattice points or sites (See Fig. 1).

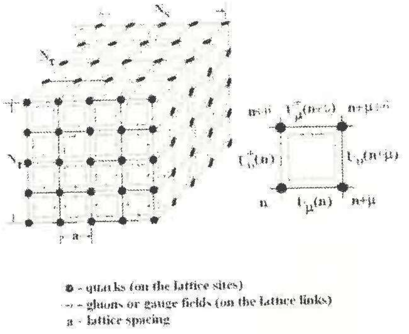


Figure 1. Space-time lattice.

In the lattice formulation the quark fields are only defined at the sites of the lattice. Two adjacent sites are connected by an oriented link. Instead of a vector potential as in the continuum case, the gauge field variables are defined on the links of the lattice and correspond to the parallel transport along the edge which takes on values in the Lie group. Hence to simulate QCD, for which the Lie group is $SU(3)$, there is 3×3 special unitary matrix defined on each link. The gauge connection, the so-called link variable replaces the continuum gauge field. The lattice regularization has a temporary role only. At the end, regularization should be removed and the final predictions will not depend upon the specific regularization used. Flux tubes connect quarks and antiquarks on the lattice. In contrast to quantum electrodynamics (QED), where the field lines connecting a pair of opposite charges are allowed to spread, one expects that the quarks within a hadron are the sources of chromoelectric flux which is concentrated within narrow tubes connecting the constituents. A model of the flux tube has been shown on the Fig. 2.

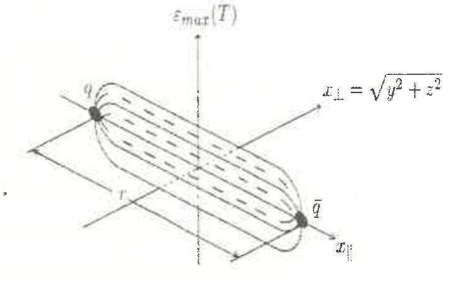


Figure 2. Flux tube model.

The distribution of gluon fields in the flux tube is measured as follows. Time propagation of the two static quarks sitting in the ends of the flux tube are represented by Polyakov loop L and its conjugate which are located at distance r from each other on the lattice. The plaquette variable, with the orientation μ,ν, which has six different values $(2,3), (1,3), (1,2), (1,4), (3,4), (2,4)$ measures the field strength. Flux tube profiles can thus be extracted from the correlation of a plaquette with the Polyakov loops [5],

$$f_{\mu\nu}(r,x)=\frac{\beta}{a^4}\left[\frac{\langle L(0)L^+(r)P_{\mu\nu}(x)\rangle}{\langle L(0)L^+(r)\rangle}-\langle P_{\mu\nu}\rangle\right],$$

by varying the distance x and the orientation of the plaquette with respect to the Polyakov loops. Six different combinations define the six components of electric and magnetic fields in the flux tube:

$$f_{12}\to\frac{1}{2}(-B^2{}_\perp),$$

$$f_{24}\to\frac{1}{2}E^2{}_\perp,$$

$$f_{13}\to\frac{1}{2}(-B^2{}_\perp),$$

$$f_{34}\to\frac{1}{2}E^2{}_\perp,$$

$$f_{23}\to\frac{1}{2}(-B^2{}_\parallel),$$

$$f_{14}\to\frac{1}{2}E^2{}_\parallel.$$

Total - magnetic and electric field strengths, respectively, are

$$\mathrm{M}=-(f_{12}+f_{13}+f_{23}),$$
$$\mathrm{E}=f_{24}+f_{34}+f_{14}.$$

Combinations of M and E define the total energy and action density,

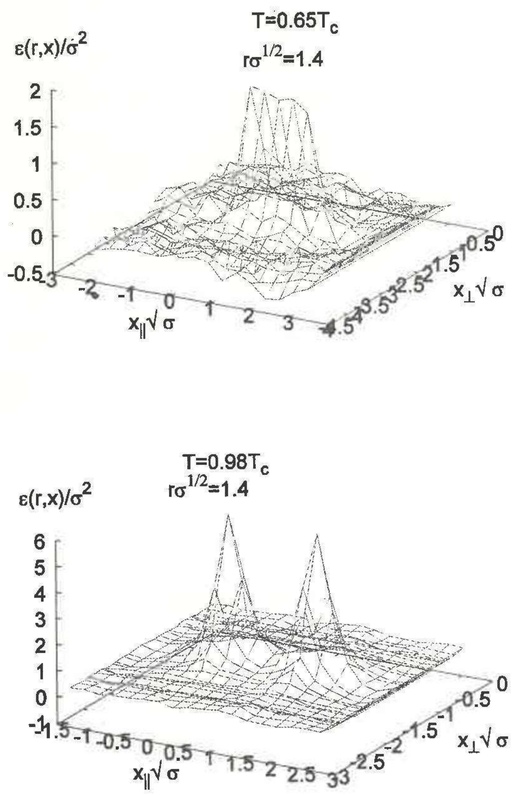
$$\varepsilon=\mathrm{E}+\mathrm{M},$$
$$\delta=\mathrm{E}-\mathrm{M}.$$

III. SIMULATION

Numerical method that is known as Monte Carlo method has been used successively in this work. In Monte Carlo simulation, some physical or mathematical system can be described in terms of probability distribution functions. In essence, the physics and mathematics are replaced by random sampling of possible states from probability distribution functions that describe the system. One can read the details about this method in [6, 7]. Wilson's lattice gauge theory with gauge group SU(2) on a four dimensional simple hypercubic lattice with periodic boundary conditions has been used in the simulation. We used one heatbath update followed by four overrelaxation steps to obtain a new gauge configuration. Measurements of the observables were performed after each sweep. In order to thermalize the gauge configurations we allowed 2000 sweeps and then carried out between 20000 and 40000 measurements.

IV. RESULTS

After the simulation performed on parallel supercomputers (TERAFLOPS) we have obtained our data with quite good accuracy. Table of parameters as well as the details of the statistics of the measurements are presented in [5]. Here we show only the surface plots of the energy density distribution in Fig. 3 and their longitudinal profiles in Fig. 4.



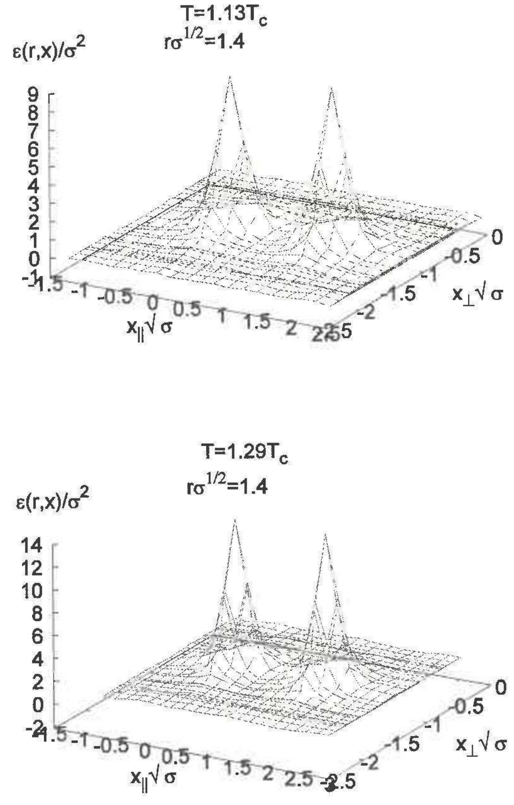


Figure 3. The energy density distribution around the two quarks.

In Fig. 3, distribution surfaces obtained for the energy density show the expected general feature that they are symmetric with respect to the quark and an antiquark axis as well as the middle plane between the pair. We see the two peaks at the two quark sources and the field strengths decreasing as it goes away from the sources.

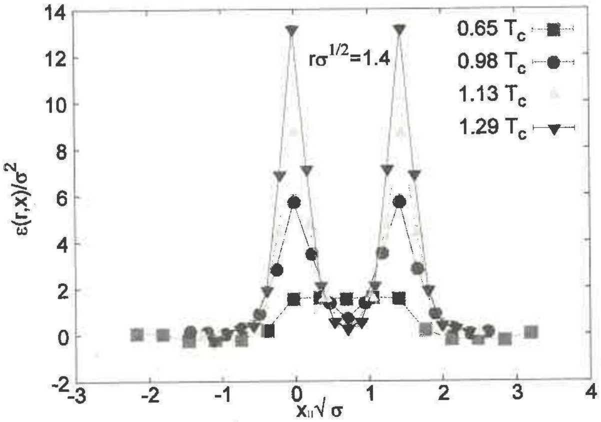


Figure 4. Longitudinal profiles of the surfaces in Fig.

From Fig. 4 one can see that the energy density in the middle point between the two quarks is decreasing from about 0.75 to 0.3 when the temperature varies from $T = 0.65T_c$ to $1.29T_c$. It tells us that the flux tube melts when the temperature reaches T_c. The same quantitative estimation can be done for the action density. We have also simulated the width of the flux tube as a function of temperature and it has been shown in Fig. 5.

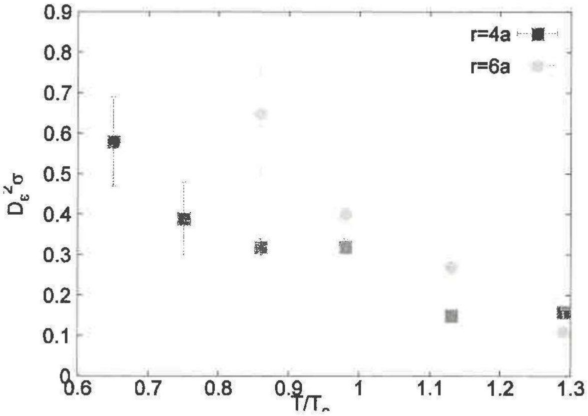


Figure 5. The width of the flux tube as a function of temperature.

On the Fig. 5 we see that the width of the flux tube also decreases when the temperature increases. The quark separation was $4a$, $6a$ in this case. a is the lattice spacing.

V. CONCLUSION

We have studied field distributions around a static quark and an antiquark pair at high temperature using Polyakov loop plaquette correlations at physical separations up to 1.4. The temperature range was $0.7T_c - 1.3T_c$. There are 3 factors that lead the field strength value to decrease when the values of those factors or parameters increase, plaquette distance, quark separation and temperature.

The decrease with increasing temperature of the width and the height of the transverse profiles at the same time shows the gradual disappearance of the flux tube when the temperature approaches the critical temperature of the phase transition from the confined phase to the deconfined phase. This means that one can observe a single quark above the critical temperature. In other words, shortly after the Big Bang, when the universe was very hot quarks existed as separate constituents.

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Ажлын товч утга

Энэ ажилд кварк, антикваркийн хосын эргэн тойрон дахь энергийн нягтын тархалт температураас хамаарах хамаарлыг судалсан. Температурын муж нь адронон төлвөөс кварк-глюоны плазман төлөв рүү шилжих фазын шилжилт болдог критик температурыг 0.7 – 1.3 дахин авсантай тэнцэх утгууд байв. Монте Карло аргыг хэрэглэн тоон симуляци хийн гарган авсан үр дүнгүүд критик температураас дээш кварк дангаараа оршдог болохыг харуулав.