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QCD WITH 2 LIGHT QUARK FLAVOURS: THERMODYNAMICS ON A $16^3 \times 8$ LATTICE AND GLUEBALLS AND TOPOLOGICAL CHARGE ON A $16^3 \times 32$ LATTICE *

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The HTMCGC collaboration has been simulating lattice QCD with two light staggered quarks with masses $m_q = 0.0125$ and also $m_q = 0.00625$ on a $16^3 \times 8$ lattice. We have been studying the behaviour of the transition from hadronic matter to a quark-gluon plasma and the properties of that plasma. We have been measuring entropy densities, Debye and hadronic screening lengths, the spacial string tension and topological susceptibility in addition to the standard order parameters.

The HEMCGC collaboration has simulated lattice QCD with two light staggered quarks, $m_q = 0.025$ and $m_q = 0.010$ on a $16^3 \times 32$ lattice. We have measured the glueball spectrum and topological susceptibilities for these runs.

1. INTRODUCTION

Studies of the thermodynamics of lattice QCD are directed at understanding the nature of the transition from hadronic matter to a quark-gluon plasma and determining the temperature at which it occurs. In addition, they can measure the properties of this quark-gluon plasma, which distinguish it from cold hadronic matter and which might, therefore, be used as a signature for its production. It is hoped that this transition and consequently the quark-gluon plasma will be observable in heavy ion collisions at RHIC. Since the early universe was presumably in this high temperature phase, understanding of this plasma phase and the nature of the transition are also important in understanding the development of the early universe.

Measurement of the hadronic spectrum from lattice QCD simulations is an important test of

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lattice QCD as a calculational tool and could ultimately test the validity of QCD. In addition to calculating the masses of the known hadrons, we can predict the masses and decay parameters of as yet unobserved (or unidentified) hadrons, such as glueballs (pure glue states). Unlike normal hadrons they cannot be modeled by the simple quark model, which makes lattice methods more important. It is desirable to measure the properties of these states in the presence of dynamical quarks, to determine whether their mixing with mesons render them so broad as to be effectively absent from the hadron spectrum.

In section 2, we describe our simulations of QCD with two flavours of staggered quarks on a $16^3 \times 8$ lattice. We have performed simulations with $m_q = 0.0125$ and are now extending this to $m_q = 0.00625$. Since the results of the $m_q = 0.0125$ runs have been reported elsewhere [1], we shall concentrate on the new results at $m_q = 0.00625$ in this report. Preliminary results for $\langle\bar{\psi}\psi\rangle$ and the Wilson/Polyakov line are reported as functions of $\beta = 6/g^2$, yielding an estimate for the position of the transition. Measurements of the entropy densities, Debye screening and spacial string tension are also reported. In section 3, we describe preliminary measurements of the glueball spectrum and string tension on a $16^3 \times 32$ lattice with two light quark flavours with quark masses $m_q = 0.025$ and with quark masses $m_q = 0.010$. Estimates of the topological susceptibility are also given for these lattices. Both our simulations used the hybrid molecular dynamics method with noisy quarks to allow the number of flavours to be tuned to two.

2. THERMODYNAMICS

We (the HTMCGC collaboration) have carried out our lattice QCD simulations on a $16^3 \times 8$ lattice using the CM-2 at the Pittsburgh Supercomputer Center. Our simulations have used $m_q = 0.0125$ and $m_q = 0.00625$. Simulations on the same lattice size for $m_q = 0.004$ were reported by the Columbia group at this meeting [2]. The reader should consult recent reviews [3, 4] for reference to related work. At $m_q = 0.0125$ we had observed a transition at $\beta = 5.54(2)$ yielding a transition temperature $T_c = 155(9) MeV$, where the quoted error does not include an estimate of the systematic errors which could be as large as 20% [1]. Although we found no evidence for first order behaviour there were some abrupt jumps in the time evolution of the order parameters. (Similar jumps were reported by the Columbia group which they felt might be associated with a first order transition for their lower mass.)

Let us now turn to a discussion of the results of our ongoing runs at $m_q = 0.00625$. Here most of our running has been with a time increment $dt = 0.005$. To date, we have run for 1000 time units at $\beta = 5.55$ and $\beta = 5.525$, 380 time units at $\beta = 5.5$ and 450 time units at $\beta = 5.45$. In Figure 1 we plot the Wilson/Polyakov line and $\langle\bar{\psi}\psi\rangle$ as functions of β for these runs along with the $m_q = 0.0125$ data for comparison. From this

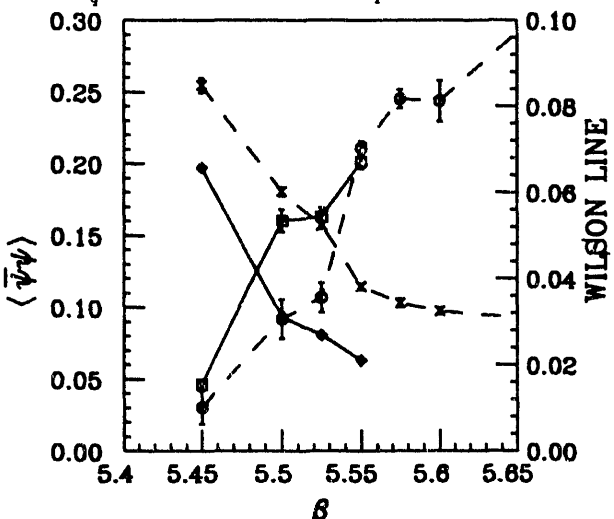

Figure 1. Wilson/Polyakov line and $\langle\bar{\psi}\psi\rangle$. The continuous lines are for $m_q = 0.00625$ the dashed lines for $m_q = 0.0125$.

we conclude that the transition occurs at $\beta = 5.50(5)$ and estimate $T_c = 138(21) MeV$ where as before the quoted error is purely statistical.

We have estimated the partial entropy densities s_g and s_{ud} for the gluons and quarks, respectively, including the one loop corrections from the formulae [5]

$$s_g T = \frac{4}{3}\left(1 - \frac{1.022}{\beta}\right)\beta(P_{st} - P_{ss})$$

$$s_{ud}T = \frac{4}{3}(1-\frac{1.279}{\beta})\frac{n_f}{4}\left[\langle\bar{\psi}\underset{0}{\not{D}}\psi\rangle - \frac{3}{4} + \frac{1}{4}m_q\langle\bar{\psi}\psi\rangle\right]$$

where P_{st} and P_{ss} are the average space-time respectively space-space plaquettes. We plot these quantities, divided by the ratio of their free field lattice to continuum values as an attempt to remove some of the finite lattice size/lattice spacing effects, in Figure 2. For the lowest two β values at $m_q = 0.00625$ we clearly have insufficient statistics to yield reliable results. However, the indications are that the partial entropy densities increase rapidly as T is increased through T_c.

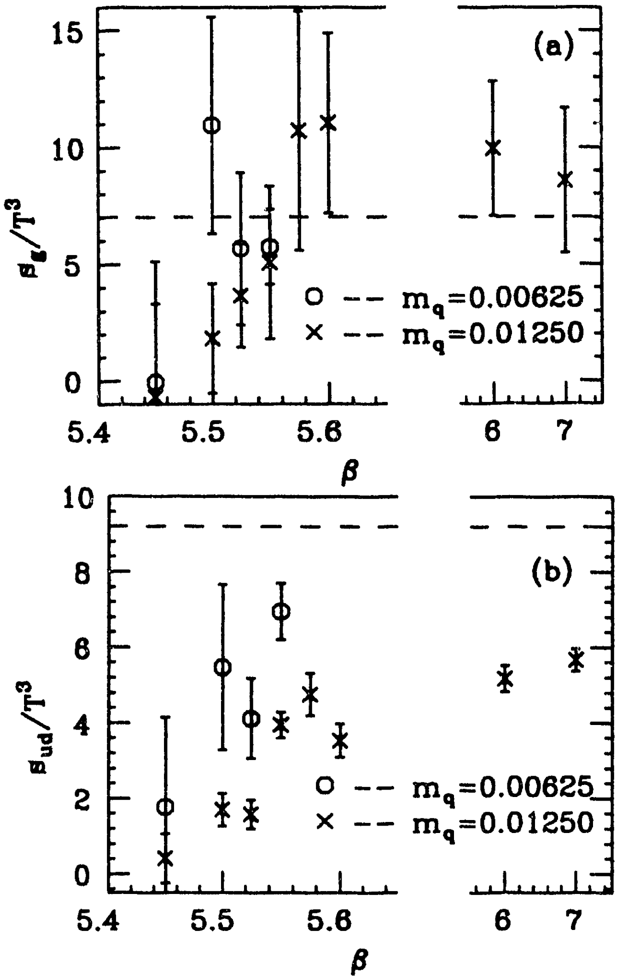

Figure 2. Entropy densities. a) Gluons. b) Quarks. Dashed lines indicates the Boltzmann limits.

We have measured correlation functions of "fuzzy" [6] temporal Wilson/Polyakov lines. The exponential decay of these yields a screening mass μ which perturbatively is twice the Debye screening mass. (See Ref. [4] for a discussion of Debye screening.) This is plotted in Figure 3. Its value appears to be of such a size to have potential relevance to ψ/J production in the plasma. Measurement of spacial Wilson Line correlations

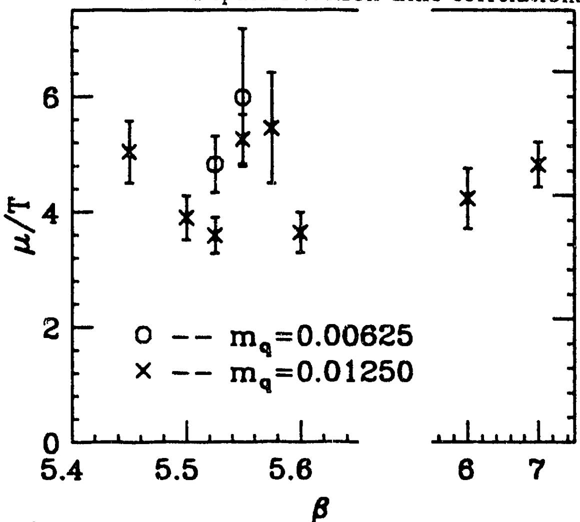

Figure 3. Screening masses for thermal Wilson Lines.

at $\beta = 5.525$ and $\beta = 5.55$ for $m_q = 0.00625$ yield spacial string tensions (0.074(7) and 0.061(5)) comparable with those for $m_q = 0.0125$.

We will measure the hadronic screening lengths for low mass hadrons including the effects of a valence strange quark with realistic mass (~ 0.03 at T_c) for this lighter quark mass to better understand the nature of the excitations in the plasma and the manner in which chiral symmetry is restored. Measurement of the entropy density for this strange quark should shed light on strangeness production in the plasma phase. We will also measure the topological susceptibility which probes chiral symmetry and anomalies in lattice QCD. Finally we will measure baryon number susceptibility as a prelude to understanding nuclear matter with its finite baryon number density.

It will be necessary to run much longer in the vicinity of β_c to accurately determine the position and nature of the transition. Larger lattices with a larger ratio of spacial to temporal extent are needed to fully understand the thermodynamics of continuum QCD. Since the Debye screening length at T_c is such that the question of ψ/J suppression is dependent on the precise form of the potential in the plasma phase, it will be necessary to perform high statistics runs in order to measure this potential directly [4].

3. GLUEBALLS AND TOPOLOGY

The HEMCGC collaboration has carried out simulations with two light staggered quark flavours ($m_q = 0.025$ and $m_q = 0.010$) on a $16^3 \times 32$ lattice at $\beta = 5.6$ to measure the hadron spectrum [7] using the CM-2 at SCRI. We have also measured glueball correlation functions based on the "fuzzy" operators of [6]. In Table 1, we present 0^{++} and 2^{++} glueball masses based on a blocked simple plaquette operator, and string tensions (κ) from blocked Wilson/Polyakov line correlations. T indicates the range of separations fit. These results are in good agreement with what we found on smaller lattices [8], and do not show the dependence on quark masses reported by Kuramashi et al. [9], which they interpreted as evidence for glueball-meson mixing.

Table 1
Glueball effective masses and string tensions. For comparison $m_\rho = 0.640(3)$ and $m_N = 0.946(5)$ at $m_q = 0.025$ while $m_\rho = 0.507(5)$ and $m_N = 0.749(3)$ at $m_q = 0.010$.

	T	$m_q = 0.025$	$m_q = 0.010$
$m_{0^{++}}$	1-2	0.76(7)	0.82(5)
$m_{2^{++}}$	1-2	1.31(8)	1.12(7)
$\sqrt{\kappa}$	1-2	0.243(4)	0.227(3)
	2-3	0.236(9)	0.209(5)
	3-4	0.233(21)	0.195(12)

We have measured the "fuzzy" wave-functions for several different templates and blocking levels. We will use these to perform a variational calculation of glueball masses, and to measure glueball-Wilson line mixing which gives us an indirect measurement of glueball-meson mixing. We also have meson wave-functions which will enable us to measure glueball-meson mixing directly.

Finally, we have measured the topological charge Q for our configurations using the cooling method [10]. From these measurements we have calculated the topological susceptibility $\chi = \langle Q^2 \rangle / V$. Preliminary results are $\chi = 6.4(1.7) \times 10^{-5}$ for $m_q = 0.010$ and $\chi = 6.4(1.5) \times 10^{-5}$ for $m_q = 0.025$. While the former is in good agreement with the results from smaller lattices [8] and with the Ward identity, the second is in worse agreement with the small lattice results. Worse still, while the Ward identity requires $\chi \propto m_q$, no evidence for such a mass dependence is seen. Although our errors are probably underestimated we have, as yet, no explanation for this behaviour.

Acknowledgements

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