HADRON SPECTROSCOPY WITH THREE-FLAVOR DYNAMICAL KOGUT-SUSSKIND FERMION

ON A LATTICE

Yuji KOIKE[†]

Department of Physics, University of Tokyo

Tokyo 113, Japan

Masataka FUKUGITA

Research Institute for Fundamental Physics, Kyoto University

Kyoto 606, Japan

Akira UKAWA^{††}

CERN, CH-1211 Geneva 23, Switzerland

Abstract

We present a Langevin simulation of the hadron mass spectrum with the three-flavor Kogut-Susskind quark action for the quark masses, $m_q a = 0.05$ and 0.1 at $\beta = 5.6$ on a $10^3 \times 20$ and an $8^3 \times 18$ lattices. The effects of the vacuum quark loops were found to be absorbable into the shift of the coupling, and hence a large m_N/m_ρ still holds. Our analysis shows that at $\beta = 5.6$ the system with $N_f = 8$ passes through the critical point for finite size ('finite temperature') effects between $m_q a = 0.05$ and 0.1 , and the $N=10$ system is always in confined phase for $m_q a > 0.05$.

[†] JSPS fellow. Address from September: Center for Theoretical Physics, MIT, Cambridge, MA 02139, USA
^{††} On leave from Institute of Physics, University of Tsukuba, Ibaraki 305, Japan

1. Introduction

Several reports are already available for the hadron mass spectrum calculation with the complete inclusion of dynamical quark loops in lattice QCD both with Wilson^[1] and the Kogut-Susskind(KS)^[2-6] fermion actions. In these studies it has been found that the effect of the vacuum quark loops significantly reduce the hadron masses, but that they can be mostly absorbed into the shift of the bare coupling in the quenched calculation, at least within presently achieved statistical errors. The number of parameter sets so far used for such calculations, however, is too few to clarify the structure of the theory, e.g. N_f - and β -dependences etc. Furthermore the dynamical fermion calculation is generally quite time consuming and this makes it usually not easy to carry out a fully satisfactory error analysis. In fact, if we closely examine each data, full consistency is not yet established.^[7] Clearly more data with a variety of simulation parameters are necessary, especially for those with which the quark loop effect becomes larger.

The purpose of this article is to report the results of the hadron mass spectrum for three-flavor KS fermion action. We have carried out the Langevin simulation at $\beta = 5.6$ on an $8^3 \times 18$ and a $10^3 \times 20$ lattices with $m_q a = 0.05$ and 0.1 . We found that the general trend of our result is what we expected from previous spectroscopic analyses for $N_f = 2$ and $N_f = 4$. A spectroscopic calculation with the three-flavor KS fermion has previously been made by Campostrini et al. ($\beta = 5.7$ on a $10^3 \times 32$ lattice)^[5] using the pseudofermion method to include the vacuum quark loops. Our results differs substantially from theirs. We consider that this is due to the fact that the simulation of ref. [5] underestimates the effect of the vacuum quark loops as well as it suffers from fake loop effects. One of our interesting results, pertaining to the latter points, concerns the finite temperature transition. Our analysis shows that the

system with $N_g = 8$ ($N_g^3 \times N_t$; $N_g \times N_t$) at $\beta = 5.6$ passes through the critical point when the quark mass decreases from $m_q a = 0.1$ to 0.05. This critical coupling is somewhat larger than that expected from previous studies. In the 'unconfined' side, the hadron spectrum clearly shows the restoration of chiral symmetry.

2. Simulation

The formalism of the Langevin method is well known.^[8] We have employed a bilinear noise scheme with a multiplicative factor $3/4$ in the bilinear noise term to yield an $N_f = 3$ simulation. We have used the partial second order algorithm explained in ref. [1] to minimize the systematic errors arising from the finite step size $\Delta\tau$. The standard one-plaquette action is used for the gluon field. The lattice size we used was $10^3 \times 20$ which is the largest one practically feasible on HITAC S-810/10 at KEK. We made the simulation for two values of the quark mass, $m_q a = 0.1$, 0.05 at $\beta = 5.6$. The periodic boundary condition was imposed both in spatial and temporal directions. Langevin time step was chosen to be $\Delta\tau = 0.01$. It is known^[9] that the systematic error due to a finite $\Delta\tau$ is considerably smaller for the KS fermion compared to the Wilson fermion and the effective shift of β due to $\Delta\tau$ is only of the order of $\Delta\beta = 0.025(0.01)$ at $m_q a = 0.05(0.1)$.^[9] Therefore, we did not attempt to make $\Delta\tau$ extrapolation in the present work.

We used the conjugate residual algorithm for the solver of the linear equation $Dx = \xi$ with D the lattice Dirac operator and ξ the white noise for the fermion. During the gauge sweep we chose the stopping condition $|Dx - \xi|/\sqrt{N} < r$ (N is the number of degrees of freedom) to be $r = 0.002$ for $m_q a = 0.05$ and 0.01 for $m_q a = 0.1$. With this choice, we needed about 22 seconds for $m_q a = 0.05$ and 9 seconds for $m_q a = 0.1$ for a solution $Dx = \xi$ in the thermalized stages of the gauge sweep on HITAC S-810/10 vector computer.

The thermalization was monitored by inspecting the Wilson loops and the hadron propagators, which were calculated at every $\delta\tau = 0.25$ and 1.0 respectively, and the first 3500(4500) sweeps were discarded for $m_q a = 0.1$ ($m_q a = 0.05$). We carried out 8500(12500) sweeps for $m_q a = 0.1(0.05)$ and took the averages in the interval $\tau = 35-85$ (45-125). As a further check, averages of Wilson loops over the interval $\delta\tau = 10$ were calculated to detect a systematic drift with long periods and we did not find any such drift. We did not find sizable correlations between hadron propagators calculated on successive configurations beyond $\tau_c = 2$. In fact, if τ_c is defined as the time at which the autocorrelation function first decreases to the value expected for a random sequence without correlation ($= 1/\sqrt{N}$ with N the sample size), we found $\tau_c = 1-2$ depending on physical quantities. We therefore estimated the error of hadron propagators using $\tau_c = 2$. Hadron masses for $m_q a = 0.05$ were calculated in the two subintervals, $\tau = 45-95$ and $95-125$, and a good agreement between them was obtained for all hadrons within the errors. We also made 10000 pure gauge sweeps at $\beta = 5.6$ on an $8^3 \times 18$ lattice and 7500 sweeps at $\beta = 5.93$ on a $10^3 \times 20$ lattice, using the standard pseudo-heatbath technique in order to compare the full QCD results with the quenched ones. The hadron propagators were calculated at every 100 sweeps in these runs. As a stopping condition for the CR solution in the calculation of the hadron propagator and the chiral order parameter, we adopted the condition $|Dx - b| < 10^{-5}$ where b is a point source $b_n = \delta_{n, n_0}$ with $n_0 = (\vec{0}, t_0)$. In order to improve the symmetry of the data under $t \rightarrow N - t$ (see eqs. (1) and (2) below) in the hadron propagators, we calculated them for three values of t_0 , $t_0 = 0, 6, 13(12)$ on a $10^3 \times 20(8^3 \times 18)$ lattice and took their averages regarding them as independent.

In full QCD simulations we have to pay particular attention to the effect of fake dynamical quark loops wrapping around the lattice in the spatial

directions. As a check we closely examined the scatter plot of the Polyakov line Q in the spatial directions. We observed that it distributed almost spherically around the origin of the complex plane and we hardly find a signature for the fake loop effect on a $10^3 \times 20$ lattice both at $m_q a = 0.1$ and 0.05 . The average value of $\langle Q \rangle$ is of the order of 10^{-3} , which is considerably smaller than the typical width of the scatter ($\sim 10^{-2}$). We also made runs on an $8^3 \times 18$ lattice with the same choice of the parameters; $\beta = 5.6$, $N_f = 3$ and $m_q a = 0.05$ ($\tau = 75$, $\Delta\tau = 0.01$) and 0.1 ($\tau = 115$, $\Delta\tau = 0.01$). On this size of the lattice we observed that for $m_q a = 0.05$ the scatter plot deviates substantially towards $\pm 120^\circ$ directions and their averages are of the order of 10^{-2} (see fig.1), the same order of magnitude as the width of the scatter, which is taken as a signature of the finite size ('finite temperature') effect. The run for $m_q a = 0.1$ already shows, albeit less conspicuous, a similar trend. The direction of the distortion can be understood, if we recall that with the periodic boundary condition the quark determinant gives a weight in favor of negative sign for the Polyakov line. Whether the Polyakov line distributes around $\pm 120^\circ$ axis or around negative axis depends on the strength of the quark loop contribution.

3. Hadron Spectroscopy on a $10^3 \times 20$ lattice

For the extraction of the masses of hadrons with definite spin and parity we followed the same procedure as our previous study.^[3] The hadron propagators were fitted to the form,

$$M(t) = \sum_i A_i [\exp\{-m_i t\} + \exp\{-m_i a(N_t - t)\}] + \sum_i A'_i [(-1)^t \exp\{-m'_i t\} + (-1)^{N_t-t} \exp\{-m'_i a(N_t - t)\}], \quad (1)$$

for mesons, and

$$B(t) = A [\exp\{-m a t\} + (-1)^t \exp\{-m a(N_t - t)\}] + A' [(-1)^t \exp\{-m' a t\} + \exp\{-m' a(N_t - t)\}], \quad (2)$$

for baryons. In fitting the pion propagator, we neglect the contribution from the opposite parity states. For other mesons and baryons, we carried out a two-pole fit except for the case of the ρ -meson in the quenched calculation with $\beta = 5.6$ and $m_q a = 0.05$, where we used the single-hyperbolic cosine form. The hadron masses obtained together with their fitting ranges are shown in table 1 and fig. 2. Here $\rho'(\pi')$ stands for the opposite parity partner of $1^{++}(0^{++})$ that appears in the same propagator. The gross feature of hadron masses is the same as in the preceding studies.^[2-6] The pion mass in full QCD does not differ much from the quenched one, while the other hadron masses are substantially lowered by the vacuum quark loops. If one looks closely at fig. 2(a), however, one notices that the full QCD pion mass is slightly larger than the quenched value.^[3] This is due to a feature of the KS action that the pion mass in the quenched calculation increases from $\beta = 5.5$ to $\beta = 5.7$ and then seems to decrease towards $\beta = 6.0$.

A conspicuous feature of full QCD hadron mass spectra found in the previous studies is that the most of the effect of the vacuum quark loops can be absorbed into a shift of the bare coupling in the quenched QCD.^[1-6] The magnitude of the shift can be estimated by matching the Wilson loops of full QCD to those of the pure gauge theory, and we record in table 2 the resulting estimate. In general the shift of the coupling is larger for larger size Wilson loops, for lighter quarks and for more number of flavors. The results of the quenched calculation at $\beta = 5.93$, which was chosen by the matching of the

5x5 Wilson loop of the full QCD simulation with $\beta=5.6$, $N_f=3$ and $m_q=0.05$, are depicted in figs. 2 (a) and (b). A good agreement with the full QCD results is achieved for the present case of $N_f=3$ as well, although the quenched results are slightly smaller. With the choices $\beta=5.91-5.92$, which matches the 4x4 Wilson loop, we would expect an almost complete agreement between the full and the quenched calculations at $m_q=0.05$.

Let us turn to the discussion of spectroscopic parameters. For this purpose we extrapolate the hadron masses to $m_q=0$, assuming the form $m_\pi = A\sqrt{m_q} + B_\pi$ for the pion and $m_{\rho,N} = A_{\rho,N}m_q + B_{\rho,N}$ for the ρ -meson and nucleon with the results shown in table 3. The lattice spacing for $\beta=5.6$ determined from the ρ -meson mass at $m_q=0$ with $m_\rho=770$ MeV as input is,

$$a^{-1} = 1.21 \pm 0.06 \text{ GeV } (N_f=3),$$

$$a^{-1} = 0.73 \pm 0.11 \text{ GeV } (N_f=0).$$

This means that our smallest quark mass $m_q=0.05$ corresponds to $m_q = 61$ MeV.

Our lattice size $N_s a/2=0.83$ fm may be large enough to accommodate a nucleon. If we assume scaling, the above lattice constants are translated into the QCD scale parameter on the lattice or in the $\overline{MS}$ scheme,^[10]

$$\Lambda_{L,KS} = 1.02 \pm 0.06 \text{ MeV } (\Lambda_{\overline{MS}} = 57.9 \pm 3.2 \text{ MeV }) (N_f=3),$$

$$\Lambda_{L,KS} = 2.70 \pm 0.39 \text{ MeV } (\Lambda_{\overline{MS}} = 77.8 \pm 11.2 \text{ MeV }) (N_f=0).$$

The smallness of the Λ parameters may be ascribed to the fact that $\beta = 5.6$ is not yet in the scaling region.

We note here that the m_N/m_ρ ratio is substantially larger than the empirical value as given by the Fermi interaction model.^[11] Our values are $(m_N/m_\rho) = (0.78 \pm 0.01, 1.66 \pm 0.04)$ at $m_q=0.1$ and $(m_N/m_\rho, m_N/m_\rho) = (0.72 \pm 0.02, 1.75 \pm 0.08)$ at $m_q=0.05$. A linear extrapolation of ρ and N masses with respect to m_q yields $m_N/m_\rho = 1.89 \pm 0.23$ at $m_q=0$ (We obtain 1.79 ± 0.57 for the quenched calculation at $\beta=5.6$). Such a large value of m_N/m_ρ is what we

have known in spectroscopy with the quenched approximation (our value is actually even larger), and is also consistent with other full QCD results.[†]

We also listed in table 1 and fig. 3 the chiral order parameter $\langle \bar{\chi}\chi \rangle = \langle \text{Tr} D^{-1} \rangle/3$. We see indication of a nonvanishing value of the parameter at $m_q=0$ and hence of a spontaneous breakdown of chiral symmetry. Using the current algebra relation $m_\pi^2/f_\pi^2 = 3/m_q \langle \bar{\chi}\chi \rangle$ and setting $m_\pi^2/m_q = A_\pi^2$, we find $f_\pi = 0.090 a^{-1} = 109$ MeV for full QCD and $f_\pi = 0.22 a^{-1} = 160$ MeV for quenched QCD at $\beta=5.6$.

4. Hadron Spectroscopy on an $8^3 \times 18$ lattice

Our results on this lattice provide information concerning the finite temperature effect. As noted above, the Polyakov line on $8^3 \times 18$ for $m_q=0.05$ shows a signature for the 'finite temperature' phase. The chiral order parameter $\langle \bar{\chi}\chi \rangle$ on an $8^3 \times 18$ lattice is smaller than that on a $10^3 \times 20$ lattice at this m_q (fig.3). We also calculated the hadron masses, which are shown in figs. 2 (a) and (c) (also in table 1). We observe that the pion mass has a large deviation from zero as $m_q \rightarrow 0$ (fig. 2(a)), and the masses of the parity partners, i.e., $(\pi, 0^{++})$, $(\rho, 1^{++})$, $(N, \frac{1}{2}^{+})$, $(N, \frac{1}{2}^{-})$, exhibit a strong tendency of degeneracy at $m_q=0.05$ (fig. 2(c)). These are taken as signals for the chiral symmetry restoration as noticed by DeTar and Kogut and then by Gottlieb et al.^[12]

At $m_q=0.1$ $\langle \bar{\chi}\chi \rangle$ on $8^3 \times 18$ agrees well with that on $10^3 \times 20$, and meson masses also show a very good agreement between the $8^3 \times 18$ and $10^3 \times 20$ data. (The disagreement seen in baryon masses is likely to be ascribed to the finite size effect that baryons are not confined in the lattice with $N_s=8$.) We have noticed, however, that the Polyakov line starts to show some distortion

[†] Gottlieb et al.^[2] claims a fast decrease of m_N/m_ρ with decreasing m_q in a smaller m_ρ/m_π region.

already at this quark mass.

From these observations we may conclude that the $N_s=8$ system at $\beta=5.6$ and $m_q a=0.05$ receives the finite size effect due to the fake quark loop wrapping around the spatial lattice, and that $m_q a=0.1$ is a marginal value where the system starts to show the finite size effect. We may provisionally identify the onset of finite size effect with the finite temperature phase transition, bearing in mind, however, that we are using the periodic boundary condition and our lattice $8^3 \times 18$ is not thermodynamic ($N_t \gg N_s$). The system with $N=8$ at $\beta=5.6$ undergoes a finite temperature phase transition between $m_q a=0.1$ and 0.05 .

This value of β_c is somewhat larger than that expected from the available data: The relevant values of β_c at $m_q a=0.05$ for $N_f=0, 2$ and 4 are $\beta_c=5.7(N=4)$, $5.88(N=6)$, $6.0(N=8)$, $6.08(N=10)$ for $N_f=0$; [13] $\beta_c=5.32(N=4)$, [2,9,14] $5.47(N=6)$ [21] for $N_f=2$; $\beta_c=5.05(N=4)$, [15] $5.175(N=6)$, [16] $5.25(N=8)$ [6] for $N_f=4$. These data fall on approximately a straight line in a plot of $\log(N)$ vs. β_c (with a slope larger than that for scaling), and an extrapolation leads to an estimate $\beta_c(N_f=2)=5.58-5.75$, $\beta_c(N_f=4)=5.28-5.32$ at $m_q a=0.05$ for $N=10$. For the case of $N_f=3$, taking $\beta_c=5.1-5.2$ for $N=4$ (We interpolate values for $N_f=0, 2$ and 4), we estimate $\beta_c=5.35-5.45$ at $N=8$ and $5.45-5.55$ at $N=10$ for $m_q a=0.05$. However, our simulation clearly indicates that $\beta_c > 5.6$ for $N_s=10$ as confirmed in the previous sections. For $N_s=8$ the critical coupling for $m_q a=0.05$ probably lies between 5.55 and 5.6 . If we adopt $\beta_c=5.55-5.6$ at $N_t=8$, we obtain $T_c=125-150$ MeV.

5. Comparison with the BNL analysis.

Campostrini et al. [15] have made a full QCD simulation for $N_f=3$ at $\beta=5.7$ on a $10^3 \times 32$ lattice for the quark masses $m_q a=0.1, 0.05$ and 0.02 with the vacuum

quark loop included by the pseudofermion technique. They found the shift of the coupling $\Delta\beta=0.236$ for $m_q a=0.05$ by adjusting their full QCD hadron masses to quenched results. This value is significantly smaller than our value $\Delta\beta=0.31-0.32$. A similar trend can also be seen in the $\Delta\beta$ value from the Wilson loop matching: their values $0.20(1 \times 1)$, $0.23(2 \times 2)$, $0.255(3 \times 3)$ and $0.265(4 \times 4)$ at $\beta=5.7$ are to be compared with our values at $\beta=5.6$ for $10^3 \times 20$ listed in table 2. (The latter values change little for $8^3 \times 18$.) For the former we expect larger shifts due to a higher choice of β , while the latter values agree with our expectation from other analyses for $N_f=2$ and 4 . [2-4,6,7] This comparison would cast doubt that their simulation might have underestimated the effect of the quark loop. In fact, they have noticed a very slow convergence or long periodicity fluctuations in making thermalized configurations. A similar slow convergence of a high-acceptance pseudofermion simulation has also been pointed out in ref. [17]. It seems to us that the use of the pseudofermion algorithm at a small quark mass is problematic. This insufficient incorporation of the quark loop explains their heavy ρ -meson mass compared with what we expect from other hadron mass analyses. [7] We should also note that our results indicate the onset of finite size effect on a $N_s=10$ lattice at $\beta=5.6-5.7$ for $m_q a=0.05$. Hence we suspected that their data at $m_q a=0.05$ suffers from finite size effects as well, and more strongly so at $m_q a=0.02$.

Acknowledgement

The numerical calculation for the present work was carried out on the HITAC S810/10 at KEK. We would like to thank the Theory Division of KEK for its warm hospitality. This work is supported in part by the Grants-in-Aid for Scientific Research of the Ministry of Education (Nos. 62790109 and 61460019).

References

- [1] M. Fukugita, Y. Oyanagi and A. Ukawa, Phys. Rev. Lett. 57 (1986) 953; Phys. Rev. D36 (1987) 824; Phys. Lett. 203B (1988) 145.
- [2] S. Gottlieb, W. Liu, D. Toussaint, R.L. Renken and R.L. Sugar, Phys. Rev. Lett. 59 (1987) 1513.
- [3] M. Fukugita, S. Ohta, Y. Oyanagi and A. Ukawa, Phys. Lett. 191B (1987) 164.
- [4] A. Billoire and E. Marinari, Phys. Lett. 184B (1987) 381.
- [5] M. Campostrini, K. Moriarty, J. Potvin and C. Rebbi, Phys. Lett. 193B (1987) 78; in Proc. of the International Symposium "Field Theory on the Lattice", Seillac, 1987, Nucl. Phys. B(Proc. Supple.) 4 (1988) 140.
- [6] M.P. Grady, D.K. Sinclair and J.B. Kogut, Phys. Lett. 200B (1988) 149.
- [7] M. Fukugita, in proc. of the International Symposium "Field Theory on the Lattice", Seillac, 1987, Nucl. Phys. B(Proc. Supple.) 4 (1988) 105.
- [8] A. Ukawa and M. Fukugita, Phys. Rev. Lett. 55 (1985) 1854; G.G. Batrouni, G.R. Katz, A.S. Kronfeld, G.P. Lepage, B. Svetitsky and K.G. Wilson, Phys. Rev. D32 (1985) 2736.
- [9] M. Fukugita and A. Ukawa, Kyoto University preprint, RIFP-734(1988), Phys. Rev. D in press.
- [10] H.S. Sharatchandra, H.J. Thun and P. Weisz, Nucl. Phys. B192 (1981) 205.
- [11] S. Ono, Phys. Rev. D17 (1978) 888.
- [12] C. DeTar and J. Kogut, Phys. Rev. Lett. 59 (1987) 399; Phys. Rev. D36 (1987) 2828;
- S. Gottlieb, W. Liu, D. Toussaint, R.L. Renken and R.L. Sugar, Phys. Rev. Lett. 59 (1987) 1881.
- [13] N. H. Christ and A. E. Terrano, Phys. Rev. Lett. 56 (1986) 111; S.A. Gottlieb et al. Phys. Rev. Lett. 55 (1985) 1958;
- A.D. Kennedy, J. Kuti, S. Meyer and B.J. Pendleton, Phys. Rev. Lett. 54 (1985) 87.
- [14] M. Fukugita, S. Ohta, Y. Oyanagi and A. Ukawa, Phys. Rev. Lett. 58 (1987) 2515.
- [15] S. Gottlieb, W. Liu, D. Toussaint, R.L. Renken and R.L. Sugar, Phys. Rev. D35 (1987) 3972.
- [16] J. B. Kogut, Phys. Rev. Lett. 56 (1986) 2557.
- [17] R.V. Gavai and F. Karsch, Nucl. Phys. B261 (1985) 273.

Table 1. Values of hadron masses in units of a^{-1} . Numbers in parentheses stand for the t range of fitting.

hadron	$m_q=0.05(10^3 \times 20)$	$m_q=0.1(10^3 \times 20)$	$m_q=0.05(8^3 \times 18)$	$m_q=0.1(8^3 \times 18)$
π	$0.603(4-16)$ ± 7	$0.821(4-16)$ ± 4	$0.698(5-13)$ ± 10	$0.837(5-13)$ ± 8
ρ	$0.843(4-16)$ ± 14	$1.051(4-16)$ ± 10	$0.936(4-14)$ ± 20	$1.089(4-14)$ ± 17
1^{+-}	$0.860(4-16)$ ± 151	$1.097(4-16)$ ± 247	$0.895(4-14)$ ± 131	$1.030(4-14)$ ± 217
π'	$0.714(3-17)$ ± 70	$0.921(4-16)$ ± 48	$1.082(5-13)$ ± 584	$0.921(4-14)$ ± 80
0^{++}	$0.863(3-17)$ ± 7	$1.102(4-16)$ ± 10	$0.779(5-13)$ ± 11	$1.069(4-14)$ ± 11
ρ'	$0.849(3-17)$ ± 24	$1.056(4-16)$ ± 23	$0.886(4-14)$ ± 56	$1.047(4-14)$ ± 35
1^{++}	$1.217(3-17)$ ± 31	$1.314(4-16)$ ± 48	$0.997(4-14)$ ± 30	$1.302(4-14)$ ± 57
$N(1/2^+)$	$1.473(4-16)$ ± 41	$1.746(4-16)$ ± 25	$1.619(4-14)$ ± 59	$1.851(4-14)$ ± 46
$N(1/2^-)$	$1.570(4-16)$ ± 61	$1.860(4-16)$ ± 54	$1.633(4-14)$ ± 69	$1.956(4-14)$ ± 78
$\langle \bar{\chi}\chi \rangle$	0.105 ± 3	0.177 ± 3	0.0959 ± 20	0.174 ± 3

Table 1. (continued)

hadron	$m_q=0.05$	$g=5.6$ ($8^3 \times 18$) $m_q=0.1$	quenched $m_q=0.05$	$g=5.93$ ($10^3 \times 20$) $m_q=0.1$
π	$0.597(3-15)$ ± 3	$0.816(3-15)$ ± 3	$0.585(4-16)$ ± 4	$0.807(4-16)$ ± 3
ρ	$1.209(4-14)$ ± 74	$1.369(3-15)$ ± 21	$0.809(4-16)$ ± 9	$1.013(4-16)$ ± 6
1^{+-}	—	$2.191(3-15)$ ± 287	$0.787(4-16)$ ± 129	$1.082(4-16)$ ± 115
π'	$1.191(3-15)$ ± 361	$1.407(3-15)$ ± 147	$0.707(3-17)$ ± 41	$0.923(3-17)$ ± 20
0^{++}	$1.235(3-15)$ ± 81	$1.404(3-15)$ ± 47	$0.889(3-17)$ ± 6	$1.096(3-17)$ ± 4
ρ'	$1.364(3-15)$ ± 185	$1.448(3-15)$ ± 73	$0.864(3-17)$ ± 16	$1.048(3-17)$ ± 9
1^{++}	$2.137(3-15)$ ± 288	$2.202(3-15)$ ± 174	$1.214(3-17)$ ± 21	$1.395(3-17)$ ± 17
$N(\frac{1}{2}^+)$	$2.009(3-15)$ ± 162	$2.141(3-15)$ ± 55	$1.419(4-16)$ ± 24	$1.713(4-16)$ ± 14
$N(\frac{1}{2}^-)$	$2.136(3-15)$ ± 466	$2.659(3-15)$ ± 205	$1.522(4-16)$ ± 40	$1.851(4-16)$ ± 30
$\langle \bar{\chi}\chi \rangle$	0.226 ± 4	0.270 ± 4	0.103 ± 2	0.167 ± 2

Table 2. Effective shift of the gauge coupling constant $\Delta\beta$ estimated by matching the Wilson loop.

$m_q a$	1x1	2x2	3x3	4x4	5x5
0.05	0.225 ± 10	0.270 ± 10	0.295 ± 15	0.310 ± 20	0.330 ± 20
0.1	0.210 ± 10	0.245 ± 10	0.265 ± 15	0.280 ± 15	0.310 ± 20

Table 3. Coefficients for extrapolation of hadron masses in $m_q a$.

hadron	full QCD ($10^3 \times 20$) $\beta=5.6$		quenched $\beta=5.6$		quenched $\beta=5.93$	
	A	B	A	B	A	B
π	2.35 ± 9	0.0784 ± 217	2.37 ± 4	0.0681 ± 100	2.39 ± 5	0.0504 ± 132
ρ	4.17 ± 34	0.634 ± 290	3.20 ± 1.53	1.05 ± 15	4.08 ± 20	0.605 ± 18
N	6.45 ± 96	1.20 ± 9	2.63 ± 3.43	1.88 ± 33	5.89 ± 56	1.12 ± 5

Figure captions

Fig. 1. Distribution of Polyakov lines in the spatial directions averaged over its transverse directions during the course of gauge sweeps for $m_q a=0.05$. (a)-(c) are data for a run on a $10^3 \times 20$ lattice and (d)-(f) those on an $8^3 \times 18$ lattice.

Fig. 2. (a) Pion masses as a function of $\sqrt{m_q a}$ for full (solid circles for $10^3 \times 20$ and solid triangles for $8^3 \times 18$) and quenched (open circles and squares) QCD.

(b) ρ -meson and nucleon masses as a function of $m_q a$. The meaning of the symbols is the same as in (a).

(c) Masses of parity partners, $(\pi, 0^{++})$, $(\rho, 1^{++})$ and (N_2^{1+}, N_2^{1-}) as a function of $m_q a$ on a $10^3 \times 20$ and an $8^3 \times 18$ lattices.

Fig. 3. Chiral order parameter $\langle \bar{\chi}\chi \rangle = \langle \text{tr} D^{-1} \rangle / 3$ as a function of $m_q a$. The meaning of the symbols is the same as in fig. 2.

Fig. 1

Fig. 2 (a)

Fig. 2 (b)

Fig. 2 (c)

Fig. 3