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Hadron Spectrum of Quenched QCD on a $32^3 \times 64$ Lattice*

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Preliminary results from a hadron spectrum calculation of quenched Quantumchromodynamics on a $32^3 \times 64$ lattice at $\beta = 6.5$ are reported. The hadron spectrum calculation is done with staggered quarks of masses, $m_q a = 0.01, 0.005$ and 0.0025. We use two different sources in order to be able to extract the Δ mass in addition to the usual local light hadron masses. The numerical simulation is executed on the Intel Touchstone Delta computer. The peak speed of the Delta for a 16×32 mesh configuration is 41 Gflops for 32 bit precision. The sustained speed for our updating code is 9.5 Gflops. A multihit metropolis algorithm combined with an over-relaxation method is used in the updating and the conjugate gradient method is employed for Dirac matrix inversion. Configurations are stored every 1000 sweeps.

Calculating the hadron mass spectrum of QCD from the first principles of quantum field theory has been a major challenge from the inception of lattice QCD, and is an important benchmark for the validity of lattice QCD simulation method. However, achieving such a goal within reasonable numerical accuracy has been elusive so far. The nucleon to rho mass ratio always comes out too large. There may be several reasons why this is so. The current consensus is that the finite volume effect seems to be more significant for the nucleon mass[1–3] than for the ρ mass and having too large a quark mass makes this ratio too large. Therefore, it is desirable to simulate lattice QCD on a series of large lattice volumes and to see how each hadron mass is affected by the finite lattice volume. However, simulating QCD on a large lattice volume with light dynamical fermions is computationally expensive, which makes exploratory quenched simulation study attractive. Also, in recent years it is been noted that efforts in quenched QCD spectroscopy simulations seem to lag somewhat behind those in full QCD spectroscopy simulations[4], which begs for renewed efforts in the direction of large volume quenched QCD spectroscopy.

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Thus we decided to simulate quenched QCD on a $32^3 \times 64$ lattice at $\beta = 6/g^2 = 6.5$ which is large enough to see asymptotic scaling. A 10 hit Metropolis algorithm and over-relaxation method are used in updating the gauge field configuration. For the first 10000 sweeps (10 configurations), 4 Metropolis steps to 1 over-relaxation step were used. Afterwards, we use an 1 to 1 ratio. At every 1000 sweep check point, a gauge field configuration is stored and various hadron propagators have been calculated using inverted Dirac matrices with $m_q a = 0.01, 0.005$ and 0.0025 staggered quarks for each source in each gauge field background. Two kinds of wall sources are used : one is the corner source and the other is all the even points source. The mass of the $\pi, \pi_2, \rho, a_1, b_1, \rho_2, \sigma$, N and its parity partner are measured with the former source. The N, the N parity partner, the Δ, and the Δ parity partner masses are measured using the latter source following[5, 6]. A point sink is used. The measurements started from the configuration number 31 and continue onwards. The total number of configurations we have at the moment is 71 and the total number of hadron propagators sets used for our analysis is 41. As a fitting procedure, we use the CERN library minimization routine MINUIT to find the minimum of the correlated χ^2 in parameter space. The correlations between average propagators at different time separations are included. Since the number of propagators is small, auto-correlation of measurements has not been taken into cosideration. Except in the case of the π, we use a 2 particle with opposite parity (4 parameter) fitting formula. For the π, a single particle (2 parameter) fitting formula is used. The error bar quoted in all the data reflects the necessary parameter changes to increase $\chi^2 \rightarrow \chi^2 + 1$. For the π effective mass plot, we use jack-knife method error bars which we have checked to be in agreement with the correlated χ^2 method.

The numerical simulation is done using the Intel Touchstone Delta computer. The Delta has 16×33 mesh structure and we use a 16×32 mesh configuration for our simulation. Since the computing node is based on Intel i860 64-bit microprocessor, the peak speed for 16×32 configuration is 41 Gflops if 32 bit arithmetic is used in the calculation. The machine has 16 Mbyte DRAM per node (total 8.4 Gbytes) and 64 1.5 Gbyte hard disks. The tested communication bandwidth is 135 μsec + 6.5 Mbytes/node/sec for ring topology[7]. The sustained speed of our code is 9.5 Gflops for gauge field updating and the link update time is 0.48 μsec. To take advantage of pipelining and the dual instruction mode of i860 microprocessor as well as to manage its data cache, most of our code is written in i860 assembly language. The top level main routine and setup and control subroutines are written in ordinary Fortran.

Table 1 is a summary of particle masses we obtained for $m_q a = 0.01, 0.005$ and 0.0025 respectively. p.p stands for parity partner and t_{min} means the minimum fitting radius we choose for the best confidence level and error bar behavior of each fit. We fit from t_{min} to $t = 24$.

However, there is a chance that the error bar is underestimated. There may be long relaxation time fluctuations we are missing because we have small data set, and when a fit is poor, the error estimate from $\chi^2 \rightarrow \chi^2 + 1$ tends to underestimate the errors. Since our project is an on-going one, the statistics will be improved in the near future. Let us discuss how each particle fit behaves. As usual, fitting for π behaves excellently. Fig 1 shows the effective mass plot for π for three quark masses. m_π^2 is found to be proportional to m_q, as predicted by PCAC. Note also that with $m_q a = 0.0025$, the π mass is less than a half of ρ mass.

Table 1
hadron masses for $m_q a = 0.01, 0.005$ and 0.0025

$m_q a$	particle	t_{min}	mass
0.01	π	14	0.1557(15)
	π_2	11	0.1566(19)
	ρ	14	0.2432(37)
	ρ_2	9	0.2457(33)
	a_1	6	0.3441(51)
	b_1	14	0.3563(249)
	σ	7	0.3007(96)
	N_1	6	0.3793(34)
	N_1p.p.	6	0.4375(54)
	N_2	9	0.3515(37)
	N_2p.p.	9	0.4392(104)
	Δ	8	0.4168(42)
	Δp.p.	8	0.4825(72)
0.005	π	14	0.1090(22)
	π_2	11	0.1081(26)
	ρ	14	0.2268(57)
	ρ_2	8	0.2241(43)
	a_1	8	0.3225(96)
	b_1	14	0.3851(569)
	σ	4	0.2819(123)
	N_1	7	0.3383(54)
	N_1p.p.	7	0.4293(129)
	N_2	11	0.3186(93)
	N_2p.p.	11	0.3555(301)
	Δ	9	0.3902(82)
	Δp.p.	9	0.4589(171)
0.0025	π	14	0.0777(29)
	π_2	11	0.0785(38)
	ρ	14	0.2007(56)
	ρ_2	9	0.2135(71)
	a_1	8	0.3206(167)
	b_1	8	0.3046(230)
	σ	4	0.2660(205)
	N_1	6	0.3530(247)
	N_1p.p.	9	0.4105(446)
	N_2	9	0.2885(124)
	N_2p.p.	8	0.3334(378)
	Δ	8	0.3717(133)
	Δp.p.	9	0.4608(368)

For other particles, hadron propagators are contaminated at small t by excited states and at large t, noise dominates the signal. We found that it is hard to fit far out especially for the $m_q a = 0.0025$ case. Fig 2 is the effective mass plot for ρ with three different quark masses.

Fig 3 is the effective mass plot for N from the corner source method and that from all the even points source method for $m_q a = 0.01$. The signal for nucleon from the second source method behaves better than that from the first source. There is less contamination due to excited states at small t and the plateau lasts longer in the signal from the second source. However, the signals from the two different sources seems to come together at large t although the error bars are significant there. It will be interesting to see whether the results from improved statistics can confirm this trend. If it is indeed the case, a systematic error introduced by different choices of sources in the nucleon mass may become smaller with large time extent.

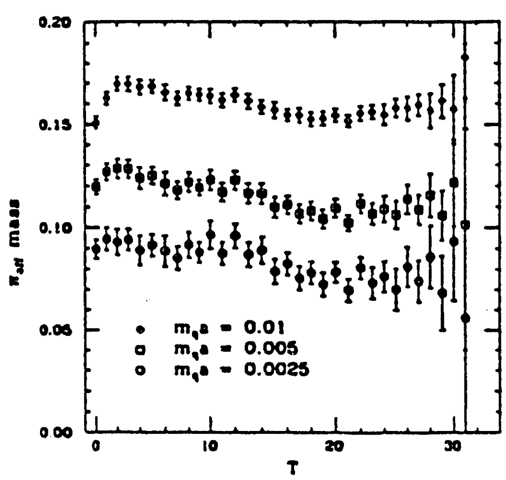

Figure 1. effective mass plot for π.

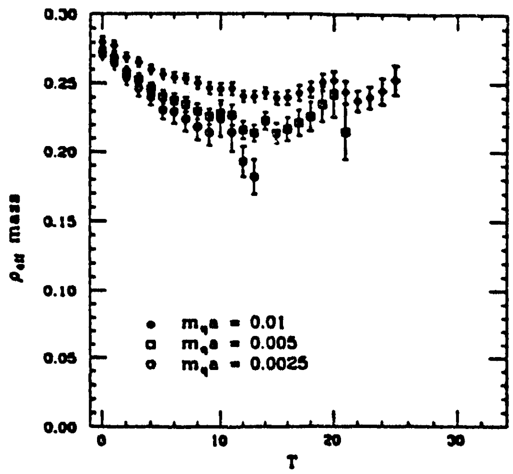

Figure 2. effective mass plot for ρ.

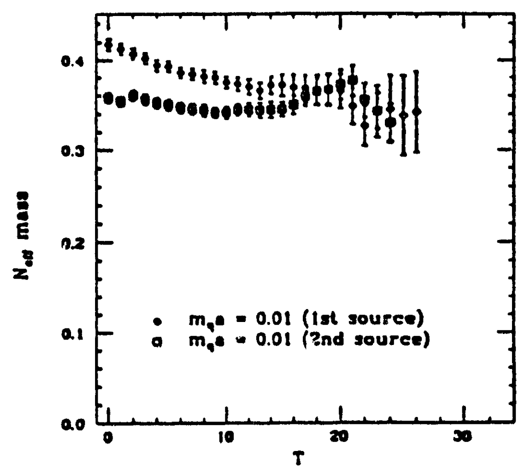

Figure 3. effective mass plot for N with $m_q a = 0.01$.

The Δ particle has a reasonable signal. We get better Δ-N splittings than previous quenched QCD spectrum calculations by other groups : our $\frac{\Delta - N}{N}$ is 0.29(6) for $m_q a = 0.0025$ and the experimental value is 0.31. Fig 4 is the Boulder plot which shows the Δ-N splitting.

With $\beta = 6.5$, the flavor symmetry appears to be restored in that the π mass is equal to the π_2 mass and the ρ mass is equal to the ρ_2 mass within statistical errors. It appears that the current choice of $\beta = 6.5$ is large enough that the system is in the scaling limit[8]. Also we may

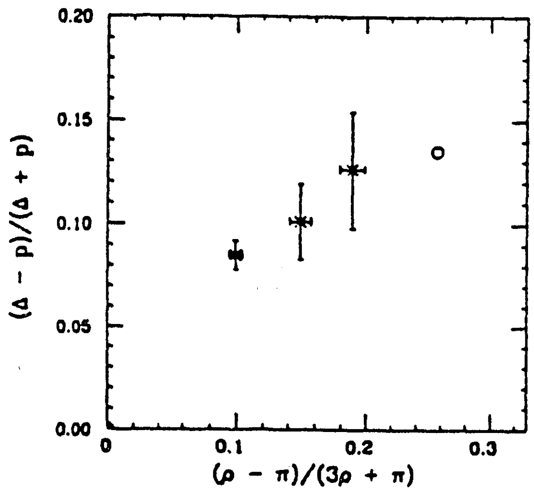

Figure 4. plot for Δ-N splitting.

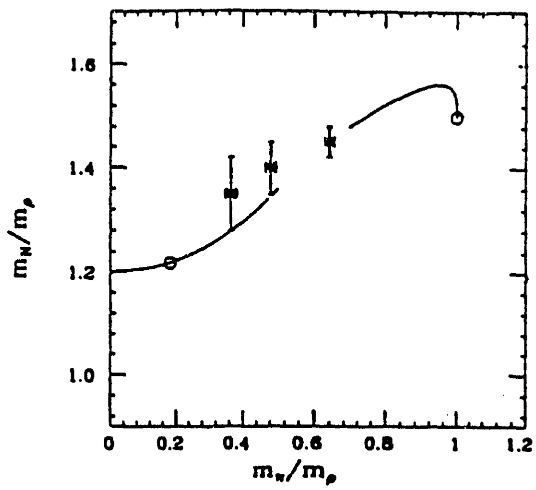

Figure 5. Edinburgh plot.

have to worry less about the systematic error resulting from the choice of quark sources. However, the nucleon to ρ mass ratio is still larger than the experimental value (bigger by $\sim 11\%$ for $m_q a = 0.0025$ although the Edinburgh plot (Fig 5. We thank R.Gupta for providing us the guiding curve based on model calculations.) shows a promising behavior. Thus we hope that spectrum calculations on a larger lattice volume at similar β with smaller quark mass will approach the physical value of hadron masses in the near future. We also intend to perform simulations on the same size lattice ($32^3 \times 64$) at $\beta = 6.0$ where the larger physical volume will permit us to study finite volume effects and permit smaller (physical) quark masses.

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