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Light hadron spectrum in 2+1 flavor full QCD by CP-PACS and JLQCD Collaborations *

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CP-PACS and JLQCD Collaborations are carrying out a joint project of the 2+1 flavor full QCD with the RG-improved gauge action and the non-perturbatively $\mathcal{O}(a)$-improved Wilson quark action. This simulation removes quenching effects of all three light quarks, which is the last major uncertainty in lattice QCD. In this report we present our results for the light meson spectrum and quark masses on a $20^3 \times 40$ lattice at the lattice spacing $a \simeq 0.10$ fm.

1. Introduction

Three-flavor full QCD simulation is a current crucial task of lattice QCD, as it would enable us, for the first time, to study hadron physics based on principles of QCD with no approximations. To achieve this, the CP-PACS and JLQCD Collaborations are carrying out simulations with dynamical degenerate u, d quarks and a s quark with different quark mass.

In our previous work presented at Lattice 2003, we made a exploratory study at a lattice spacing $a \simeq 0.10$ fm on a small lattice $16^3 \times 32$ [1]. In this article we report the new results for the light meson spectrum and quark masses on a larger lattice of $20^3 \times 40$ at $a \simeq 0.10$ fm. We note that the analysis procedures have been made more systematic over these adopted at the time of Lattice 2004, and results are, albeit qualitatively the same, numerically different.

2. Strategy of the project

We employ the RG-improved gauge action and the non-perturbatively $\mathcal{O}(a)$ improved Wilson quark action determined for this gauge action [2], and plan to perform simulations at three lattice spacings, $a \simeq 0.07$ fm, 0.10 fm, and 0.122 fm, which are at even intervals in a^2, with a fixed physical volume $\sim (2.0\text{fm})^3$. We take five u, d quark masses for chiral extrapolations in the range of $m_{PS}/m_V \simeq 0.78 - 0.62$, and two s quark masses around $m_{PS}/m_V \simeq 0.7$ for interpolations. These parameters are chosen from our experience of simulations at $a \simeq 0.10$ fm on a $16^3 \times 32$ lattice.

An estimate of computational resources available to this project, including the Earth Simulator, and performance of the polynomial hybrid Monte Carlo program [3, 4] we use indicates that we can accumulate at least 5000 trajectories at $a \simeq 0.10$ fm and 0.122 fm and 2000 trajectories at $a \simeq 0.07$ fm, within two to three years, of which

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Table 1
κ parameters, statistics and measured meson masses (in lattice unit).

κ_{ud}	κ_s	traj.	$m_{PS,LL}$	$m_{PS,LS}$	$m_{PS,SS}$	$m_{V,LL}$	$m_{V,LS}$	$m_{V,SS}$
0.13580	0.13580	5000	0.5390(09)	–	–	0.7024(17)	–	–
0.13610	0.13580	6000	0.4943(07)	0.5098(07)	0.5249(07)	0.6656(19)	0.6764(18)	0.6871(18)
0.13640	0.13580	7500	0.4460(06)	0.4788(06)	0.5100(05)	0.6189(19)	0.6414(17)	0.6635(15)
0.13680	0.13580	8000	0.3786(08)	0.4382(07)	0.4921(06)	0.5642(27)	0.6029(22)	0.6410(18)
0.13700	0.13580	8000	0.3384(09)	0.4140(08)	0.4799(07)	0.5300(19)	0.5776(16)	0.6243(14)
0.13580	0.13640	5200	0.5254(09)	0.4947(10)	0.4626(11)	0.6853(14)	0.6636(15)	0.6416(17)
0.13610	0.13640	8000	0.4804(07)	0.4643(07)	0.4477(07)	0.6451(14)	0.6340(15)	0.6229(16)
0.13640	0.13640	9000	0.4324(05)	–	–	0.6045(17)	–	–
0.13680	0.13640	9000	0.3614(06)	0.3867(06)	0.4107(06)	0.5441(18)	0.5598(16)	0.5754(15)
0.13700	0.13640	8000	0.3221(07)	0.3625(07)	0.3994(06)	0.5164(24)	0.5396(21)	0.5625(19)

we are in the second year.

In this project, our first interest is the meson spectrum and light quark masses, because our physical volume $(2.0\text{fm})^3$ is not sufficiently large for baryons.

3. Results at $a \simeq 0.10$ fm

3.1. Simulations and analyses

Among three lattice spacings, calculations at $a \simeq 0.10$ fm have been completed by simulations carried out at $\beta = 1.9$ with $c_{\mathrm{SW}} = 1.715$ on a $20^3 \times 40$ lattice. In Tab. 1 we show the hopping parameters κ_{ud} and κ_s for u, d (Light) quarks and s (Strange) quark. Meson masses are calculated for Light-Light (LL), Light-Strange (LS) and Strange-Strange (SS) combinations of valence quark masses, and are given in the table. They are determined by a single hyperbolic-cosine correlated fit with $t_{\min} = 10$. Masses are stable against a variation of $t_{\min}$.

Chiral fits are made to LL, LS and SS masses simultaneously ignoring correlations among these masses. We adopt polynomial functions in quark masses up to quadratic terms. χ^2/d.o.f. (1.1 for PS and 0.9 for V) is acceptable. We also test the fits using masses normalized by Sommer scale and find that the meson spectrum and quark masses are stable against the change.

3.2. Light meson spectrum

The physical point is determined from experimental values of m_π, m_ρ, m_K (K-input) or m_π, m_ρ, m_ϕ (ϕ-input). The inverse of the lattice spacing $a^{-1} = 1.97(4)$ GeV is independent of inputs for the s quark mass.

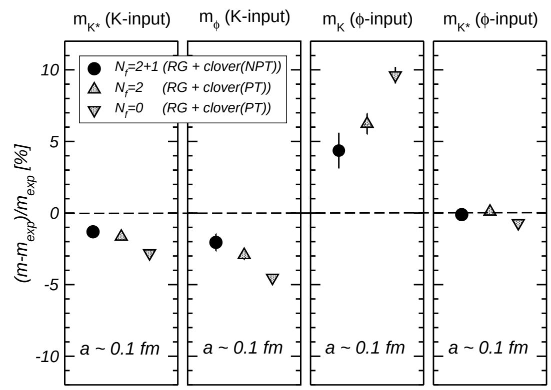

Figure 1. Deviation of the meson spectrum from experiment at $a \sim 0.1$ fm.

Light meson masses turn out to be

$$\begin{aligned} m_{K^*} &= 884.4(3.0)\ \text{MeV} && \text{(K-input)}, \\ m_\phi &= 998.5(5.9)\ \text{MeV} && \text{(K-input)}, \\ m_K &= 519.4(6.2)\ \text{MeV} && (\phi\text{-input}), \\ m_{K^*} &= 895.1(0.3)\ \text{MeV} && (\phi\text{-input}). \end{aligned} \quad (1)$$

In Fig.1 we show the deviation of the meson spectrum from experiment comparing with our results in $N_f = 2$ and 0 QCD [5] at the same lattice spacing $a \sim 0.1$ fm. We find that the spectrum in $N_f = 2+1$ QCD is closer to experiment than that in $N_f = 2$ and 0 QCD at this lattice spacing.

3.3. Quark masses

Light quark masses are determined by the axial-vector Ward identity. The matching to the $\overline{\mathrm{MS}}$ scheme is performed by using the mean-field improved one-loop calculation [6] at the scale $\mu = a^{-1}$. The renormalized quark masses are evolved to $\mu = 2$ GeV using the 4-loop beta function.

Results for quark masses are

$$\left\{\begin{array}{ll} m_{ud} = 3.05(6) & \mathrm{MeV} \\ m_s = 80.4(1.9) & \mathrm{MeV} \end{array}\right. \quad \text{(K-input)},$$

$$\left\{\begin{array}{ll} m_{ud} = 3.04(6) & \mathrm{MeV} \\ m_s = 89.3(2.9) & \mathrm{MeV} \end{array}\right. \quad (\phi\text{-input}). \qquad (2)$$

Fig. 2 presents quark masses in $N_f = 2+1$ QCD comparing with $N_f = 2$ and 0 QCD at a similar lattice spacing $a \sim 0.1$ fm. We find that quark masses in $N_f = 2+1$ QCD are smaller than those in $N_f = 2$ and 0 QCD. Since the non-perturbatively improved clover coefficient is used, we speculate that the values of quark masses at this lattice spacing do not change sizably in the continuum limit.

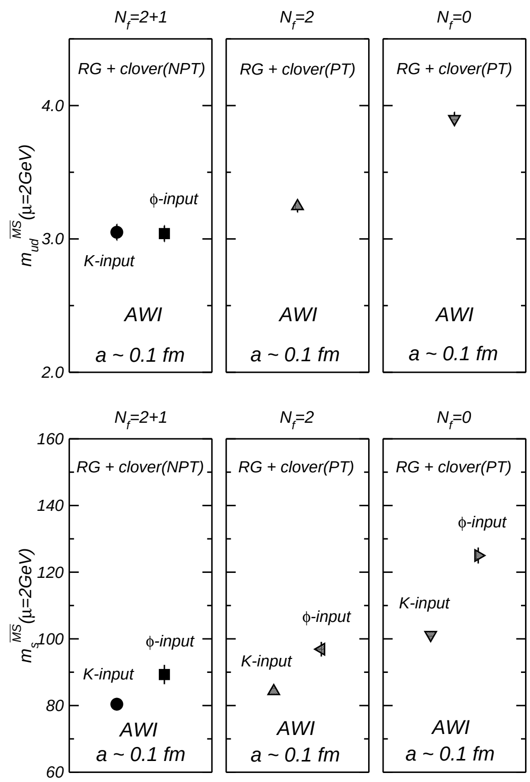

Figure 2. u and d quark masses (top) and s quark mass (bottom) at $a \sim 0.1$ fm.

4. Conclusions and future plans

As far as we compare the spectrum and quark masses at $a \sim 0.1$ fm, we observe the difference between $N_f = 2+1$ and 2. At this stage we cannot conclude whether this effect is due to dynamical strange quark or non-perturbatively determined c_{SW}. This point should become clear in the continuum limit.

Coupling values and hopping parameters for the coarser ($a \simeq 0.122$ fm) and finer ($a \simeq 0.07$ fm) lattices have already been fixed and production runs are in progress. We hope to report results in the continuum limit in near future.

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