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Light hadron spectrum and quark masses in QCD with two flavors of dynamical quarks *

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We present updated results of the CP-PACS calculation of the light hadron spectrum in $N_{\rm f}=2$ full QCD. Simulations are made with an RG-improved gauge action and a tadpole-improved clover quark action for sea quark masses corresponding to $m_{\rm PS}/m_{\rm V}\approx 0.8$–$0.6$ and the lattice spacing $a=0.22$–0.09 fm. A comparison of the $N_{\rm f}=2$ QCD spectrum with new quenched results, obtained with the same improved action, shows clearly the existence of sea quark effects in vector meson masses. Results for light quark masses are also presented.

1. Introduction

Understanding sea quark effects in the light hadron spectrum is an important issue, sharpened by the recent finding of a systematic deviation of the quenched spectrum from experiment[1]. To this end, we have been pursuing $N_{\rm f}=2$ QCD simulations using an RG-improved gauge action and a tadpole-improved clover quark action [2], to be called **RC** simulations in this article.

The parameters of these simulations are listed in Table 1. The statistics at $\beta=2.2$ have been increased since Lattice'98, and the runs at $\beta=2.1$ are new. In addition we have carried out quenched simulations with the same improved action, referred to as **qRC**, for a direct comparison of the full and quenched spectrum. The β values of these runs, given in Table 1, are chosen so that the lattice spacing fixed by the string tension matches that of full QCD for each value of sea quark mass at $\beta=1.95$ and 2.1. Quenched hadron masses are calculated for valence quark masses such that $m_{\rm PS}/m_{\rm V}\approx 0.8$–$0.5$, which is similar to those in the **RC** runs.

In this report we present updated results of the full QCD spectrum and light quark masses. We also discuss sea quark effects by comparing the **RC** and **qRC** results. For reference we use quenched results with the plaquette gauge and Wilson quark action [1] as well, which we denote as **qPW**.

2. Full QCD spectrum

The analysis procedure of our full QCD spectrum data follows that in Ref. [2]: m_π and m_ρ are used to set the scale and determine the up and down quark mass m_{ud}, while the strange quark mass m_s is fixed from either m_K or m_ϕ. We tested several fitting forms for the continuum extrapolation, and found that the fit is stable; e.g., for the meson masses, linear extrapolations in a and in $a\alpha_{\overline{\rm MS}}$ are consistent with each other and a quadratic fit in a is also consistent within 2 standard deviations. Here, we present results from

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Table 1
Parameters in **RC** and **qRC** simulations. Scale a_σ is fixed by $\sqrt{\sigma} = 440$ MeV. **qRC** runs have 200 configurations for each β.

RC simulations

lattice	$K_{\rm sea}$	#traj.	m_π/m_ρ	a_σ [fm]
$12^3\times24$	0.1409	6250	0.806(1)	0.289(3)
$\beta=1.80$	0.1430	5000	0.753(1)	0.152(2)
$c_{SW}=1.60$	0.1445	7000	0.696(2)	0.269(3)
$a=0.215(2)$ fm	0.1464	5250	0.548(4)	0.248(2)
$16^3\times32$	0.1375	7000	0.805(1)	0.204(1)
$\beta=1.95$	0.1390	7000	0.751(1)	0.193(2)
$c_{SW}=1.53$	0.1400	7000	0.688(1)	0.181(1)
$a=0.153(2)$ fm	0.1410	7000	0.586(3)	0.170(1)
$24^3\times48$	0.1357	2000	0.806(2)	0.1342(6)
$\beta=2.10$	0.1367	2000	0.757(2)	0.1259(5)
$c_{SW}=1.47$	0.1374	2000	0.690(3)	0.1201(5)
$a=0.108(2)$ fm	0.1382	2000	0.575(6)	0.1128(3)
$24^3\times48$	0.1351	2000	0.800(2)	0.1049(2)
$\beta=2.20$	0.1358	2000	0.754(2)	0.1012(3)
$c_{SW}=1.44$	0.1363	2000	0.704(3)	0.0977(3)
$a=0.086(3)$ fm	0.1368	2000	0.629(5)	0.0947(2)

qRC simulations

$16^3\times32$		$24^3\times48$	
β	a_σ [fm]	β	a_σ [fm]
2.187	0.2079(15)	2.416	0.1359(7)
2.214	0.1977(13)	2.456	0.1266(13)
2.247	0.1853(9)	2.487	0.1206(9)
2.281	0.1727(10)	2.528	0.1130(9)
2.334	0.1577(9)	2.575	0.1065(7)

the linear extrapolation in a.

Fig. 1 shows an update of results for vector meson and octet baryon masses in comparison to those from the **qPW** simulation. With increased statistics at $\beta = 2.2$ and new points at $\beta = 2.1$, we find our conclusion to remain unchanged since Lattice'98, *i.e.,* meson masses in full QCD extrapolate significantly closer to experiment than in quenched QCD. For baryons, the statistical errors are still too large to draw definitive conclusions.

3. Sea quark mass dependence

In order to obtain a deeper understanding of the sea quark effect in meson masses, we investigate how their values depend on the sea quark mass. In this test, the valence strange quark mass is fixed by a phenomenological value of the ratio $m_{\eta_{\bar{s}s}}/m_\phi = 0.674$. To avoid uncertainties that may arise from chiral extrapolations, the light dynamical quark mass is set to one of the values corresponding to $m_{\rm PS}/m_{\rm V} = 0.7, 0.6$ or 0.5. The values of the masses "m_{K^*}" and "m_ρ" of fictitious mesons for such quark masses can then be determined by interpolations or short extrapolations of hadron mass results.

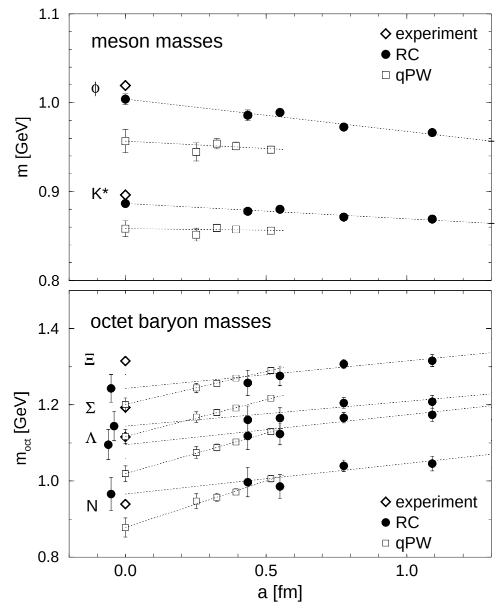

Figure 1. Typical hadron masses with m_K-input.

In Fig. 2, we plot "m_{K^*}/m_ρ" as a function of the lattice spacing normalized by "m_ρ" for different sea quark masses. Making linear extrapolations in a, we observe that the continuum limits of the two quenched simulations **qRC** and **qPW** are consistent. On the other hand, the full QCD result from **RC** exhibits an increasingly clearer deviation from the quenched value toward lighter sea quark masses. We consider that this result provides a clear demonstration of the sea quark effect on vector meson masses.

4. Quark masses

We plot our results for light quark masses in the $\overline{\rm MS}$ scheme at μ =2 GeV in Fig. 3, together with the quenched results of Ref. [1]. Contin-

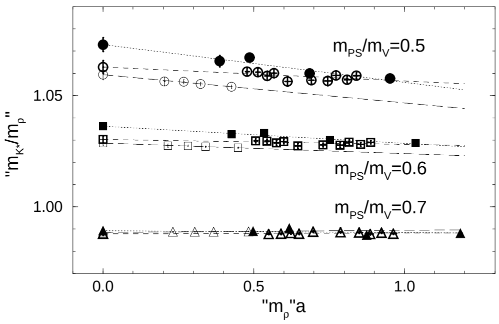

Figure 2. Fictitious mass ratio “m_{K^*}/m_ρ” defined in the text at different sea quark masses. Filled, thick open and thin open symbols are the results from **RC** , **qRC** and **qPW** simulations, respectively.

uum extrapolations are made linearly in a with the constraint that the three definitions (using axial vector Ward identity(AWI) or vector Ward identity(VWI) with either K_c from sea quarks or partially quenched K_c) yield the same value. We confirm our previous finding[2] that i) quark masses in full QCD are much smaller than those in quenched QCD, and ii) the large discrepancy in the strange quark mass determined from m_K or m_ϕ, observed in quenched QCD, is much reduced.

Our current estimate for quark masses in $N_\mathrm{f}=2$ QCD are $m_{ud} = 3.3(4)$ MeV, $m_s = 84(7)$ MeV (K-input) and $m_s = 87(11)$ MeV (ϕ-input). The quoted errors include our estimate of the systematic errors due to the choice of functional form of continuum extrapolations and the definition of the $\overline{\mathrm{MS}}$ coupling used in the one-loop tadpole improved renormalization factor.

Our results for quark masses are smaller than the values often used in phenomenology[3], though the ratio $m_{ud}/m_s = 26(3)$ is consistent with the result 24.4(1.5)[4] from chiral perturbation theory. The small values are quite interesting, especially for the strange quark mass; a smaller strange quark mass raises the prediction of the Standard Model for the direct CP violation parameter $\mathrm{Re}(\epsilon'/\epsilon)$, as strongly favored by the experimental results from the KTeV [5] and NA31 Collaborations [6].

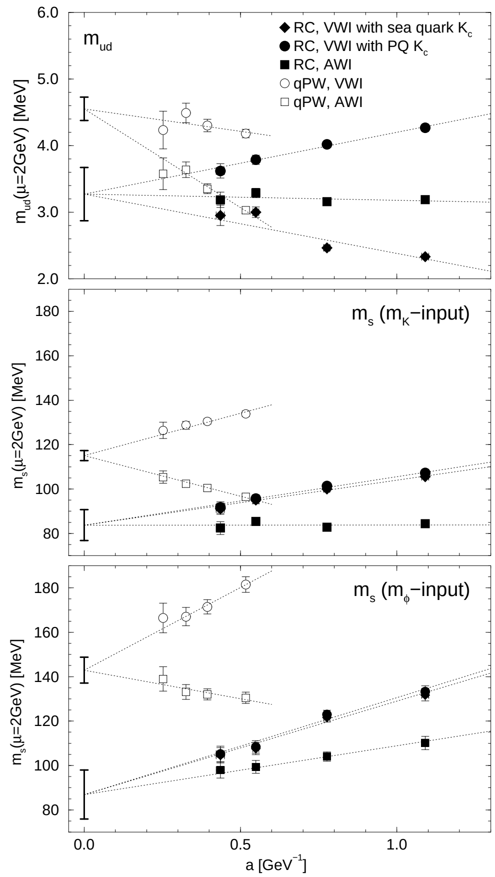

Figure 3. Continuum extrapolation of m_{ud} (top) and m_s with m_K-input(middle) and m_ϕ-input(bottom).

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