

# CP-PACS Result for the Quenched Light Hadron Spectrum\*

CP-PACS Collaboration: S. Aoki<sup>a</sup>, G. Boyd<sup>b</sup>, R. Burkhalter<sup>b</sup>, S. Hashimoto<sup>c</sup>, N. Ishizuka<sup>a,b</sup>, Y. Iwasaki<sup>a,b</sup>, K. Kanaya<sup>a,b</sup>, Y. Kuramashi<sup>d</sup>, M. Okawa<sup>d</sup>, A. Ukawa<sup>a</sup> and T. Yoshié<sup>a,b</sup>

<sup>a</sup>Institute of Physics, University of Tsukuba, Tsukuba, Ibaraki 305, Japan

<sup>b</sup>Center for Computational Physics, University of Tsukuba, Tsukuba, Ibaraki 305, Japan

<sup>c</sup>Computing Research Center, High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305, Japan

<sup>d</sup>Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305, Japan

The quenched hadron spectrum in the continuum obtained with the Wilson quark action in recent simulations on the CP-PACS is presented. Results for the light quark masses and the QCD scale parameter are reported.

## 1. Introduction

Ever since the pioneering work of Hamber and Parisi[1] and of Weingarten[2], the calculation of the light hadron spectrum has been regarded as a fundamental subject in lattice QCD. The extensive simulations on the GF11 computer[3] have established that the quenched spectrum agrees with experiment within 5–10%. The next, and final, step within quenched QCD would be to further advance the calculational accuracy so that possible deviations from the experimental spectrum are made manifest. In this article we report the main results recently obtained with the CP-PACS computer towards this goal.

## 2. Simulation

Our calculation is made with the plaquette gluon action and the Wilson quark action. We employ a spatial size of  $L_s a \approx 3$  fm to avoid finite-size effects, and  $a^{-1} \gtrsim 2$  GeV to facilitate the continuum extrapolation. These requirements lead to the selection of  $\beta$  and lattice sizes listed in Table 1. Gauge configurations are generated with the over-relaxation and heat bath algorithms mixed in a 4:1 ratio. Hadron propagators are calculated for the five quark masses correspond-

\*Talk presented by K. Kanaya at Lattice97, Edinburgh, Scotland, 22–26 July 1997.

Table 1  
Parameters of simulation.

$\beta$	lattice	$a^{-1}$ [GeV]	$L_s a$ [fm]	$N_{\text{conf}}$
5.90	$32^3 \times 56$	1.97(1)	3.21(2)	800
6.10	$40^3 \times 70$	2.60(1)	3.04(2)	600
6.25	$48^3 \times 84$	3.12(2)	3.03(2)	420
6.47	$64^3 \times 112$	4.16(4)	3.03(3)	91

ing to  $m_\pi/m_\rho \approx 0.75, 0.7, 0.6, 0.5$  and  $0.4$ , the last point being a step closer to the chiral limit than hitherto attempted. All unequal quark mass combinations allowed for degenerate  $u$  and  $d$  quarks are taken. We smear the quark source with the function  $\Psi(r) = A \exp[-B(m_\rho, m_q)r]$ , with  $B \approx 0.33$  fm. Hadron masses are extracted by uncorrelated fits together with a single elimination jackknife procedure for estimating errors.

## 3. Meson spectrum

We find  $m_{PS}^2$  for pseudoscalar and  $m_V$  for vector mesons to be well described by a linear function of  $1/K$ , which we adopt for our chiral fits. The physical point for the degenerate  $u$  and  $d$  quarks is fixed by  $m_\pi(135)$  and  $m_\rho(769)$ , and we use  $m_K(498)$  or  $m_\phi(1019)$  for the  $s$  quark.

In Fig. 1 we show the continuum extrapolation of strange vector meson masses with the  $m_K$  as input. A linear fit in  $a$  yields the continuum value

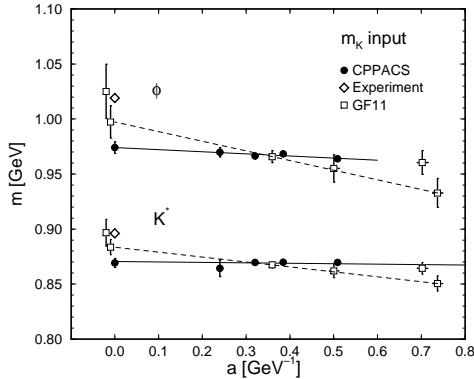


Figure 1. Continuum extrapolation of  $K^*$  and  $\phi$  masses with the  $m_K$ -input. GF11 estimate for infinite volume[3] is plotted left at  $a = 0$ .

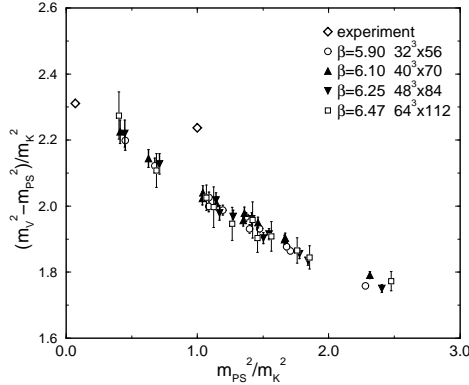


Figure 2. Meson hyperfine splitting.

which is smaller than the experimental value by 3% for  $K^*$  and by 4% for  $\phi$ , to be compared with the statistical error of 0.5%. If we take  $m_\phi$  as the input for the  $s$  quark,  $m_{K^*}$  agrees with experiment to 0.6%, while  $m_K$  is higher by 9%.

The origin of the discrepancy can be traced to the hyperfine splitting shown in Fig. 2. Our results, which scale well, decrease too fast as meson mass increases. The slope  $b$  of the curve is related to the  $J$  parameter through  $J = (1 + b)/2$ . A fast decrease translates into a small value of  $J$ ; we obtain  $J = 0.377(11)$  in the continuum limit.

#### 4. Baryon spectrum

We show our typical chiral extrapolation for baryon masses in Fig. 3. We find all baryon masses to be linear in  $1/K$  except for  $m_N$  and

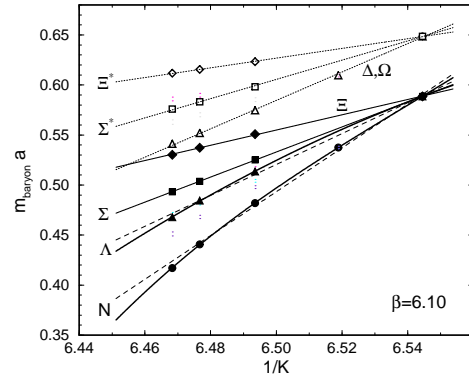


Figure 3. Baryon masses as a function of  $1/K$  for the light quark at  $\beta = 6.1$ . For non-degenerate baryons, results with the heavier  $s$  quark ( $m_\pi/m_\rho \approx 0.75$ ) are plotted.

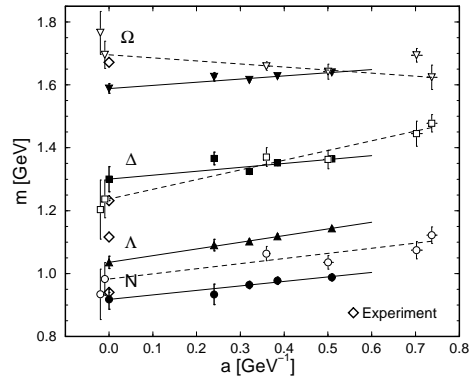


Figure 4. Continuum extrapolation of baryon masses. Open symbols show GF11 results.

$m_\Lambda$ , which show a clear negative curvature. We choose a fit cubic in  $1/K$  for  $m_N$ , quadratic for  $m_\Lambda$ , and linear for the other baryon masses.

The negative curvature significantly lowers the nucleon mass compared to previous results at a finite lattice spacing, as shown in Fig. 4. The continuum value obtained from a linear extrapolation is smaller than experiment by 2.3%, albeit consistent within the statistical error of 3%. The mass of  $\Delta$  is 6% higher, with a statistical significance of 1.7 standard deviations.

The nucleon mass at each  $\beta$  depends on the form adopted for the chiral extrapolation. Including the form from quenched chiral perturbation theory, the continuum values, however, agree within 3%.

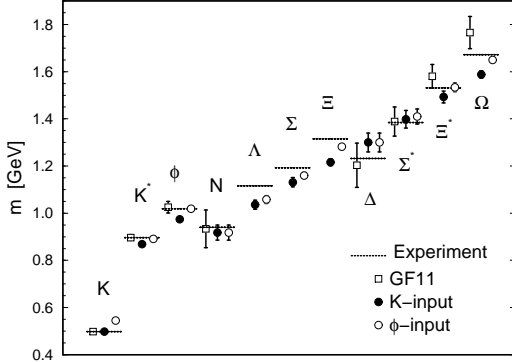


Figure 5. Quenched hadron spectrum in the continuum limit.

The extraction of the continuum value is most uncertain for the nucleon,  $\Delta$ , and  $\Sigma^*$  masses, for which the errors in the continuum limit are about 3%. For all the other channels a linear chiral extrapolation (quadratic for  $m_\Lambda$ ) followed by a linear continuum extrapolation fits our data very well, resulting in errors of 1–2%.

Our final result for the baryon spectrum is shown in Fig. 5, together with the meson spectrum for completeness.

In the octet the strange baryon masses are lower than experiment, by 5–8% using  $m_K$  as input, and by 3–5% for  $m_\phi$  as input. The Gell-Mann-Okubo (GMO) relation, however, is well satisfied, at 1% for both cases.

For the decuplet the GMO relation takes the form of an equal spacing rule. This is also well satisfied with our results, the three spacings mutually agreeing within 5–10%. The average spacings, however, are too small by 30% with  $m_K$  as input and by 20% for  $m_\phi$  as input.

The agreement of the baryon spectrum with experiment is generally better if we use  $m_\phi$  as input, particularly for the decuplet. However, we have to remember that the  $K$  meson mass differs from experiment by 9% in this case, which is a 7 standard deviation effect.

## 5. Light quark masses

We calculate light quark masses with the perturbative definition  $m_q a = Z_m(1/K - 1/K_c)/2$  and with those based on the axial Ward iden-

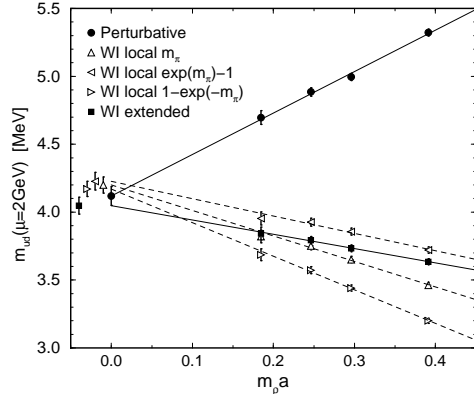


Figure 6.  $\bar{m} = (m_u + m_d)/2$  at 2 GeV in the  $\overline{\text{MS}}$  scheme calculated by various definitions.

tity  $\nabla_\mu A_\mu = 2m_q a P$ . The two methods give results considerably different at finite lattice spacings. However, extrapolated linearly in the lattice spacing, they converge to a common value within 5% as shown in Fig. 6. For average  $u, d$  quark mass at 2 GeV in the  $\overline{\text{MS}}$  scheme, we obtain  $\bar{m} = 4.1(2)$  MeV. For the  $s$  quark mass, we find  $m_s = 135(7)$  MeV and  $111(4)$  MeV using  $m_\phi$  and  $m_K$ . The discrepancy reflects the quenching error in the strange meson spectrum.

## 6. QCD scale parameter

We estimate  $\Lambda_{\overline{\text{MS}}}$  using  $\alpha_P(3.40/a)$  and  $\alpha_{\overline{\text{MS}}}(\pi/a)$  including the 3-loop correction in the  $\Lambda$  parameter and the scale determined from  $m_\rho$ . The couplings are estimated from the average plaquette with 2-loop perturbation theory. A linear continuum extrapolation of the two results converge and yields  $\Lambda_{\overline{\text{MS}}} = 230(5)$  MeV where the error includes extrapolation uncertainties.

This work is supported in part by the Grants-in-Aid of Ministry of Education (Nos. 08NP0101, 08640349, 08640350, 08640404, 092462-06, 09304029, 09740226). GB and RB are supported by JSPS.

## REFERENCES

1. H. Hamber and G. Parisi, Phys. Rev. Lett. 47 (1981) 1792.
2. D. Weingarten, Phys. Lett. 109B (1982) 57.
3. F. Butler *et al.*, Nucl. Phys. B430 (1994) 179.