超並列計算機 CP-PACS を用いた格子上の素粒子標準理論の研究の展開

課題番号 09304029

平成 9 年度 – 平成 11 年度
科学研究費補助金 (基盤研究 (A)(2))
研究成果報告書

平成 12 年 3 月

研究代表者

岩崎 洋一（筑波大学）

はしがき Preface

文部省科学研究補助金（基盤研究 (A)(2)）の研究課題「超並列計算機 CP-PACS を用いた格子上の素粒子標準理論の研究の展開」は平成 9 年度から 11 年度の 3ヶ年にわたり実施された。本報告書はその終了にあたり研究成果をまとめたものであり、研究成果概要、発表論文リスト、論文別刷からなる。

本研究課題は、筑波大学計算物理学研究センターを主たる研究拠点として、直接の研究分担者に加えて、多数の研究協力者を得て実施された。その中に合計 6 名の外国人研究者が含まれていること、及び関連分野の外国研究者の便宜などを考慮して、研究成果概要については英語を用いることとした。

本報告書を通じて、超並列計算機 CP-PACS を用いた格子上の場の理論の研究、特に格子量子色力学の研究が、どのような成果をあげているかをお知らせすることが出来れば幸いである。

平成 12 年 3 月

岩崎洋一

This report presents a summary of research carried out under the Grant-in-Aid of the Ministry of Education, Science, Sports and Culture entitled "*Development of Research of the Standard Model on the Lattice using the Massively Parallel Computer CP-PACS*" (Grant No. 09304029). The grant was allocated over a three year period from JFY 1997 to JFY 1999. The report consists of a research summary, a list of publications, and reprints of papers.

The research presented in this report was conducted through a collaboration consisting of the members listed in the Grant and a number of other collaborating researchers, with the Center for Computational Physics of University of Tsukuba serving as the main base. Since six researchers of the collaboration were from countries outside Japan, and for convenience of colleagues in the related fields abroad, the research summary is presented in English.

We hope that this report conveys the achievements that have been obtained on lattice field theory with the massively parallel computer CP-PACS, in particular those in lattice quantum chromodynamics.

March 2000

Yoichi Iwasaki

研究組織

研究代表者： 岩崎 洋一 （筑波大学副学長（研究担当））

研究分担者： 宇川 彰 （筑波大学物理学系（計算物理学研究センター）教授）

研究分担者： 金谷 和至 （筑波大学物理学系（計算物理学研究センター）助教授）

研究分担者： 吉江 友照 （筑波大学物理学系（計算物理学研究センター）助教授）

研究分担者： 青木 慎也 （筑波大学物理学系助教授）

研究分担者： 石塚 成人 （筑波大学物理学系（計算物理学研究センター）助手）

研究分担者： 青木 保道 （筑波大学物理学系（計算物理学研究センター）助手）

研究分担者： Burkhalter Rudolf （筑波大学物理学系（計算物理学研究センター）助手）

研究分担者： 金児 隆志 （筑波大学計算物理学研究センター COE 研究員）

研究分担者： 大川 正典 （高エネルギー加速器研究機構素粒子原子核研究所助教授）

研究分担者： 蔵増 嘉伸 （高エネルギー加速器研究機構素粒子原子核研究所助手）

研究分担者： 橋本 省二 （高エネルギー加速器研究機構計算科学センター助手）

（ 研究協力者：福来 正孝 （東京大学宇宙線研究所教授））

（ 研究協力者：出渕 卓 （金沢大学理学部助手））

（ 研究協力者：谷口 祐介（筑波大学物理学系助手））

（ 研究協力者： Ali Khan Arifa （筑波大学計算物理学研究センター未来開拓研究員））

（ 研究協力者：江尻 信司（筑波大学計算物理学研究センター学振研究員 PD））

（ 研究協力者： Shanahan Hugh （筑波大学計算物理学研究センター学振研究員））

（ 研究協力者：長井 敬一（筑波大学計算物理学研究センター学振研究員 PD））

（ 研究協力者： Boyd Graham （筑波大学計算物理学研究センター学振研究員））

（ 研究協力者： Manke Thomas （筑波大学計算物理学研究センター未来開拓研究員））

（ 研究協力者： Guertler Martin （筑波大学計算物理学研究センター外国人研究者（DAAD Fellow））

研究経費

平成9年度	15,707千円
平成10年度	7,302千円
平成11年度	9,502千円
計	32,511千円

目次

第 I 部

Members of the CP-PACS Collaboration

CP-PACS Collaboration

31 March, 2000

Arifa Ali Khan[a]
Sinya Aoki[b](*)
Yasumichi Aoki[a,b](*)
Graham Boyd[a] (November 1996 – December 1998)
Rudolf Burkhalter[a,b](*)
Shinji Ejiri[a]
Masataka Fukugita[c]
Martin Güertler[a]
Shoji Hashimoto[d](*)
Naruhito Ishizuka[a,b](*)
Taku Izubuchi[e]
Yoichi Iwasaki[a,b](*)
Kazuyuki Kanaya[a,b](*)
Takashi Kaneko[d](*)
Yoshinobu Kuramashi[d](*)
Thomas Manke[a](June 1998 – January 2000)
Keiichi Nagai[a]
Junichi Noaki[b]
Masataka Okamoto[a]
Masanori Okawa[d](*)
Hugh P. Shanahan[a]
Yusuke Taniguchi[b]
Akira Ukawa[a,b](*)
Tomoteru Yoshié[a,b](*)

[a]Center for Computational Physics, University of Tsukuba, Tsukuba, Ibaraki 305-8577, Japan
[b]Institute of Physics, University of Tsukuba, Tsukuba, Ibaraki 305-8571, Japan
[c]Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo 188-8502, Japan
[d]High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan
[e]Department of Physics, Kanazawa University, Kakuma, Kanazawa 920-1192, Japan

(*) Members of the Grants-in-Aid "Development of Research of the Standard Model on the Lattice using the Massively Parallel Computer CP-PACS" (Grant No. 09304029)

第 II 部

Summary of Research

1 Overview

This report presents a summary of research carried out under the Grant-in-Aid of the Ministry of Education, Science, Sports and Culture entitled "*Development of Research of the Standard Model on the Lattice using the Massively Parallel Computer CP-PACS*" (Grant No. 09304029). The grant was allocated over a three year period from JFY 1997 to JFY 1999.

The CP-PACS is a massively parallel computer developed at the Center for Computational Physics, University of Tsukuba, for advancing research in computational physics. Its name stands for "Computational Physics with Parallel Array Computer System". The development of the CP-PACS started in 1992, and was completed in September 1996. At that time the theoretical peak performance of 614GFLOPS and the performance of 368.2GFLOPS for the Linpack Benchmark both broke the world record.

The research program reported here aimed to exploit this computational power for significantly advancing the study of the non-perturbative aspects of the Standard Model using the space-time lattice formulation of field thery and numerical simulations. Particular emphasis was laid on the study of Quantum Chromodynamics that describes hadrons and their strong interactions based on quarks and gluons.

Numerical studies of lattice QCD have been pursued since the early 1980's. Consequently there had been much development in these studies, both in breadth and depth. At the time of the start of the program, however, there remained several fundamental issues which had not been satisfactorily answered, and are crucial for further progress of lattice QCD. We have set up the research program with a focus on these issues. Specifically, the program decided to concentrate effort on the following subjects:

- Light hadron spectrum in quenched lattice QCD
- QCD simulation with two flavors of dynamical quarks
- Finite-temperature phase transition and equation of state
- Domain-wall QCD

In the remainder of this overview, we briefly describe the reasons and the focus of these subjects. A summary of results obtained through the program will be given in the following chapters.

1.1 Light hadron spectrum in quenched QCD

Deriving the spectrum of hadrons from first principles of QCD has the fundamental importance for establishing the validity of QCD in the low-energy non-perturbative domain, and also for checking the reliability of numerical methods for extracting the predictions of QCD.

The first step toward achieving this goal is a precision calculation of the spectrum in quenched QCD; this is a subject continuously pursued since 1981. Building upon the large body of work made on this issue over the years, we have made a major attempt at determining the quenched light hadron spectrum. The principal result from this study is that the quenched light hadron spectrum deviates clearly and systematically from the experiment if examined at a precision better than a 10% level. This effort and its outcomes are described in Sec. 2.

1.2 QCD simulation with two flavors of dynamical quarks

Our study of the quenched light hadron spectrum has clearly pointed toward the importance of full QCD study including effects of dynamical quark. Exploiting the computer power of the CP-PACS, we have carried out a systematic attempt at full QCD with two flavors of light dynamical quarks, to be identified as degenerate u and d quark, treating s and heavier quark in the quenched approximation. As will be described in detail in Sec. 3 this study involves a number of subjects, both from the computational and physical point of view:

- Choice of action
  Since simulations with dynamical quarks are computationally much more intensive than quenched calculations, a preparatory study on the strategy to follow in the actual simulations was carried out. This has led to our choice of a renormalization group improved action for gluons and the "clover" improvement of the Wilson action for quarks. Some details of our action choice and parameters of simulations are described in Sec. 3.1.

- Light hadron spectrum
  Once full QCD configurations are generated taking into account effects of sea quarks, there are a number of interesting physics questions that can be addressed. Whether the disagreement between the quenched spectrum and experiment is resolved is one such problem, to which we found affirmative results (Sec. 3.2).

- Light quark masses
  Masses of quarks are one of the fundamental constants of nature. A byproduct of the spectrum calculation is a determination of the masses for u, d and s quarks. The results turned out to be very interesting; the values predicted through full QCD are 20–30% smaller than those in the quenched QCD. In particular the strange quark mass in two-flavor full QCD is 90 ± 10 MeV, which is significantly smaller than the

phenomenological value ≈ 150 MeV often used in hadron phenomenology. These results are described in Sec. 3.3

- η' meson mass and $U(1)$ problem
  Another important issue in hadron phenomenology is the mechanism for a large mass of the η' meson. Our results on this $U(1)$ problem are introduced in Sec. 3.4, where our study of topology is also summarized.

- Sea quark effects in the decay constant of B meson
  Physics of heavy b quark is a focus of recent particle physics research, both in experiment and in theory, as it promises to provide vital information on the question of CP-violation in weak interactions and possibly into physics beyond the standard model. Lattice QCD can contribute in this effort by providing the values of b-quark related matrix elements. The simplest and yet a very important matrix element is the decay constant of the B meson.

  Our full QCD simulation enables us to examine how much the value of the decay constant depends on dynamical sea quarks. A comparison of the decay constant for two-flavor full QCD and in quenched QCD was carried out using the same set improved quark and gluon actions. The results show an increase of 10–20% due to two flavors of dynamical quarks both with the clover quark action for heavy quark (Sec. 3.5) and with NRQCD (Sec. 3.6).

- Sea quark effects in the heavy quarkonium spectrum
  The question of sea quark effects has also been examined for the spectrum of heavy quarkonia using NRQCD for heavy quark. A clear signature of such effects were found for the hyperfine splitting. A large scaling violation was also observed at the same time, as described in Sec. 3.7. In this section we also describe an attempt at the hybrid spectrum using space-time anisotropic lattices, and a recent result on sea quark effects in the spectrum.

1.3 Finite-temperature phase transition and equation of state

Elucidating the physics of quark-gluon plasma is another of the major goal of lattice QCD. We have made a set of studies in this direction with the improved gluon and quark actions employed in the zero-temperature full QCD simulations. One such study concerned the equation of state in the pure gluon sector (Sec. 4.1). The results in the continuum limit showed a good agreement with that obtained with the standard plaquette action. This work has been extended to full QCD with two flavors of quarks. As described in Sec. 4.2, the phase structure for the improved clover quark was explored, and the equation of state was calculated on an $N_t = 4$ lattice.

1.4 Domain-wall QCD

A difficulty with conventional lattice quark actions is explicit breaking of chiral symmetry which is intimately tied with the necessity for avoiding doublers. This is a serious shortcoming, particularly for simulations of weak matrix elements such as B_K, for which chiral symmetry often plays an important role.

Domain-wall QCD offers an interesting possibility to resolve this problem. As a first step to establish its viability a careful study of chiral property as a function of various parameters of the formalism, including the size of the extra dimension, has been carried out. Results of this examination are described in Sec. 5. Work with domain wall is now extended to calculations of physical matrix elements relevant for CP violation studies.

2 Light hadron spectrum in quenched QCD

papers: 6-16, 7.1-(5,7), 7.2-(1, 5, 8)
(see Sec. III for reference)

Among various subjects pursued by lattice QCD, deriving the light hadron spectrum has been regarded as a key issue of lattice QCD, because it would be the most convincing demonstration on the validity of QCD in the low energy non-perturbative domain. It would also provide us with confidence when we apply lattice QCD to calculations of other physical quantities. Accordingly, numerous number of studies have been devoted to this issue since 1981 when the first attempt to calculate the spectrum was made.

Although lattice QCD formulation provides us with a straight-forward method to derive the spectrum, it was revealed afterwards that we have to overcome several difficulties to obtain numerically precise results.

Because of a limitation of computer power, most of studies had to employ *quenched approximation*, in which one ignores effects due to pair creation and annihilation of quarks and anti-quarks. One expects that the quenching error is not so large, because valence quark models describe qualitatively the observed spectrum. However, it is not known a priori to what level of precision the quenched QCD reproduces the experimental spectrum and how quenching distorts it.

In addition, calculations aiming at precise results have to have good control over the systematic errors which are specific to lattice QCD simulations. The lattice prediction for the real world can be obtained only after the infinite volume and continuum limit is taken. Moreover, because computational cost rapidly becomes very large as the quark mass decreases, one has to extrapolate results obtained at heavy quark masses to the physical up and down quark masses.

The first step toward the goal of the spectrum calculation is therefore to obtain the definitive result for the quenched QCD spectrum, by controlling all systematic errors arising from extrapolations mentioned above. The best work prior to our effort was obtained by Weingarten and collaborators with the GF11 computer in 1991-1992. Performing extrapolations in terms of quark masses and lattice spacings, supplemented by corrections from the finite lattice size, they carried out the first systematic calculation of the quenched hadron mass spectrum in the continuum limit. The results from this calculation are shown in Fig. 1. The main conclusion was that the calculated spectrum turned out to be consistent with experiment within one standard deviation, or 1–9 %, depending on the particle.

In spite of these promising results, we were not quite satisfied. First, the entire spectrum was not covered as masses of hadrons consisting of non-degenerate quarks were determined with an assumption on mass formulae for non-degenerate cases. Second, the errors were still too large to answer the the question in what manner the quenched spectrum deviates

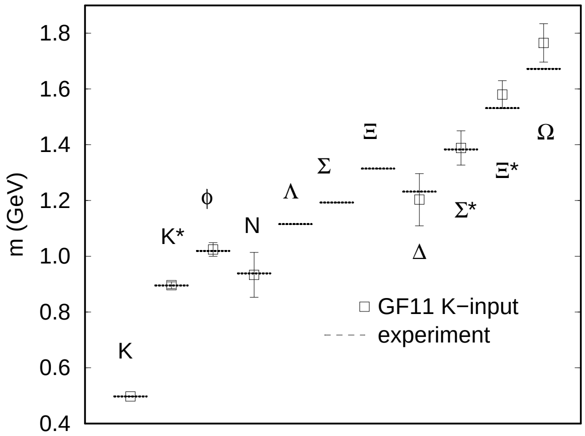

図 1: Quenched QCD spectrum reported by the GF11 collaboration in 1994. Masses of π,ρ and K were taken as input.

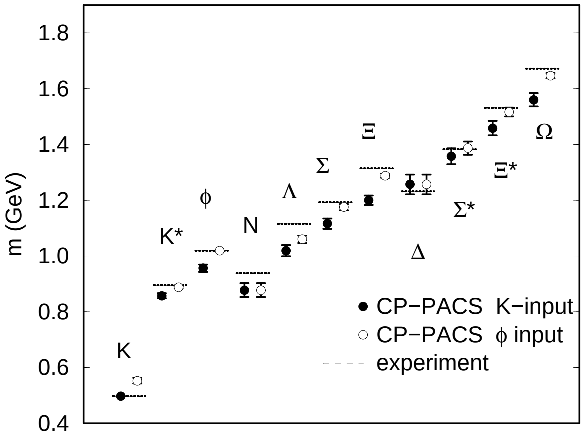

図 2: CP-PACS results for the quenched QCD spectrum obtained in 1998. Masses of π,ρ and K (or ϕ) were taken as inputs.

from experiment.

In view of this situation, we have carried out an extensive quenched simulation aiming to obtain the entire spectrum with a precision reliably better than 5%, thereby establishing the quenched spectrum and simultaneously exploring the limitation of the quenched approximation. To avoid the assumption on mass formulae, we have calculated hadron masses for both degenerate and non-degenerate cases.

The strategy we have chosen is to employ the standard method of lattice QCD simulations, and carry out, as much as the computing power of the CP-PACS allows, a measurement of hadron masses down to small quark masses at small lattice spacings employing large lattices and high statistics.

Ingredients of our calculations are summarized as follows. 1) We employed the standard plaquette gauge action and the Wilson quark action. 2) We employed four lattice spacings covering the range $a = 0.1$–0.05 fm, which was pushed closer toward the continuum limit than the range $a = 0.14$–0.07 fm used by GF11. 3) We employed lattices with a physical size of $La \approx 3$ fm, which is known to be large enough to avoid size effects beyond 1% level, as compared to $La \approx 2.3$ fm of GF11. 4) We selected five quark masses ranging over $125 \geq m_q \geq 23$ MeV, reducing the smallest quark mass by a factor 2 from $m_q \approx 40$ MeV of any previous works with the Wilson quark action. 5) Statistics were much improved.

From these simulations together with detailed systematic analyses, we have succeeded to determine the quenched QCD spectrum with statistical errors of about 1–2% for mesons and 2–3% for baryons. All of systematic errors except that due to quenching are smaller or at worst comparable to the statistical error. In Fig. 2, we show our quenched prediction for hadron masses which are much better in quality than any previous results.

The results of our calculations cover a wide range of issues in hadron physics. The

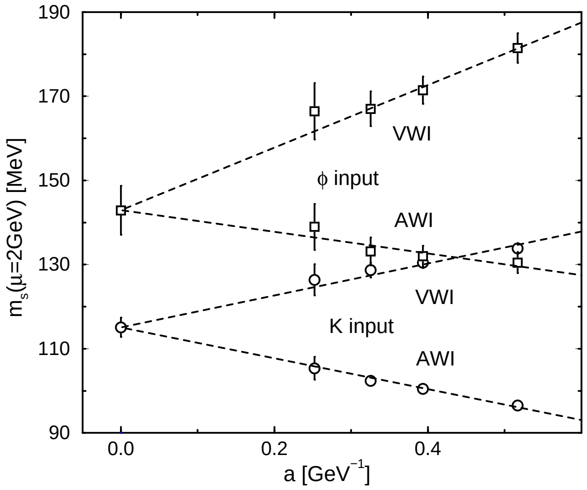

図 3: Strange quark mass in quenched QCD as functions of the lattice spacing.

major results can be summarized as follows.

- A discrepancy between quenched hadron masses and their experimental values is unambiguously established, with precisions amounting up to 7 σ for several particles. In particular, the hyperfine meson mass splitting (K–K^* mass splitting) is about 10% smaller than experiment, irrespective of the choice of input (K or ϕ) to fix the strange quark mass.

- On the other hand, the magnitude of this discrepancy is at most 10%, which is consistent with theoretical estimations of the quenching error.

- The quark mass dependence of pseudo scalar meson masses and decay constants is consistent with a prediction of the quenched chiral perturbation theory with the coefficient $\delta \approx 0.1$ of quenched singular terms.

- Light quark masses determined from either the vector Ward identity (VWI) or the axial-vector Ward identity (AWI), differing at finite lattice spacings, converge to a common value in the continuum limit. (See Fig. 3 for the results of the strange quark mass.) This behavior is compatible with our expectation that the chiral symmetry of the Wilson quark action is recovered in the continuum limit.

- The strange quark masses determined with either kaon mass or ϕ meson mass exhibit a 20% disagreement even in the continuum limit. The discrepancy originates from the small meson hyperfine splitting, and hence represents a quenching effect.

Our principal conclusion is that the quenched light hadron spectrum systematically deviates from the experimental spectrum when examined with a precision better than a

10% level. The magnitude of systematic deviation due to the quenched approximation far exceeds those of the other systematic errors and the statistical error. In this sense we consider that our study has established the quenched hadron mass spectrum.

3 QCD with two flavors of dynamical quarks

3.1 Choice of action and numerical simulation

papers: 6-(5, 15), 7.1-7, 7.2-(4, 6, 16)

Simulation of full QCD is computationally much more demanding than simulation of quenched QCD. A rough estimate shows that about a factor of $O(100)$ or more increase of computer time is needed. This means that even with a TFLOPS-class computer such as CP-PACS, a full QCD simulation with similar lattice sizes and lattice spacings as our quenched simulation is not possible. We therefore decided to explore the use of improved actions designed to have reduced cutoff errors. This allows us to do calculations on coarser lattices and correspondingly smaller lattice sizes and smaller computational costs and still remain roughly at the same physical lattice size.

The question, how much the use of improved actions leads to better scaling behavior had not yet been fully studied in the context of full QCD. As our first project in full QCD we therefore decided to first do an examination of this question. For this purpose we compared the influence on improving the gauge and/or the quark action on various quantities.

For the gauge action we compared the standard Wilson plaquette action with an improved action including a 1×2 Wilson loop with a coefficient determined by an approximate renormalization group analysis (RG-action). For the quark action, on the other hand, we compared the standard Wilson quark action with the so-called clover action, where we also compared various choices of the clover coefficient c_{SW}. We did a systematic comparison, using all four possible combinations of gauge and quark actions.

For hadron masses we found the improvement of the quark action and the use of a mean-field improved c_{SW} to be crucial for better scaling behavior. This finding is illustrated in Fig. 4. The quality of the rotational symmetry of the static quark-antiquark potential, on the other hand, was found to depend mainly on the improvement of the gauge action. Together we found that the improvement of both the gluon and the quark action is important. This is the reason why we chose to use the RG gauge action and the clover quark action with a perturbatively mean-field improved clover coefficient for our full QCD production runs.

Our full QCD simulations were carried out with two flavors of sea quarks, to be identified with the degenerate u and d quarks, while the strange and heavier quarks are treated in the quenched approximation. The parameters of the simulations are summarized in Table 1.

For continuum extrapolation we cover the range of lattice spacings $a \approx 0.2 - 0.1$ fm and use lattices with a physical spatial extent of about 2.5 fm. It turned out that an initial run at $\beta = 2.2$ results in a spatial size of 2.06 fm which is significantly smaller than for the rest of the simulations. This run was therefore replaced by another calculation

表 1: Parameters in full QCD and quenched simulations with improved actions. The scale a_σ is fixed by $\sqrt{\sigma} = 440$ MeV. Quenched runs have 200 configurations for each β.

Full QCD simulations

lattice	β	c_{SW}	a [fm]	La [fm]	$K_{\rm sea}$	#traj.	m_π/m_ρ	a_σ [fm]
$12^3\times24$	1.80	1.60	0.215(2)	2.58(3)	0.1409	6250	0.807(1)	0.289(3)
					0.1430	5000	0.753(1)	0.152(2)
					0.1445	7000	0.694(2)	0.269(3)
					0.1464	5250	0.547(4)	0.248(2)
$16^3\times32$	1.95	1.53	0.155(2)	2.48(3)	0.1375	7000	0.804(1)	0.204(1)
					0.1390	7000	0.752(1)	0.193(2)
					0.1400	7000	0.690(1)	0.181(1)
					0.1410	5000	0.582(3)	0.170(1)
$24^3\times48$	2.10	1.47	0.110(2)	2.64(5)	0.1357	2000	0.810(2)	0.1342(6)
					0.1367	2000	0.757(3)	0.1259(5)
					0.1374	2000	0.693(3)	0.1201(5)
					0.1382	2000	0.571(6)	0.1128(3)
$24^3\times48$	2.20	1.44	0.086(3)	2.06(6)	0.1351	2000	0.800(2)	0.1049(2)
					0.1358	2000	0.754(2)	0.1012(3)
					0.1363	2000	0.704(3)	0.0977(3)
					0.1368	2000	0.629(5)	0.0947(2)

Quenched simulations

$16^3\times32$			$24^3\times48$		
β	a_σ [fm]	a_ρ [fm]	β	a_σ [fm]	a_ρ [fm]
2.187	0.2079(15)	0.2004(20)	2.416	0.1359(7)	0.1446(18)
2.214	0.1977(13)	0.1903(19)	2.456	0.1266(13)	0.1328(13)
2.247	0.1853(9)	0.1807(18)	2.487	0.1206(9)	0.1284(14)
2.281	0.1727(10)	0.1765(20)	2.528	0.1130(9)	0.1206(13)
2.334	0.1577(9)	0.1632(16)	2.575	0.1065(7)	0.1130(11)

at $\beta = 2.1$. For extrapolations in the quark mass four values of the sea quark hopping parameter corresponding to $m_{PS}/m_V \approx 0.8$, 0.75, 0.7 and 0.6 and five values of the valence quark hopping parameter κ_{val} corresponding to $m_{PS}/m_V \approx 0.8$, 0.75, 0.7, 0.6 and 0.5 were chosen.

Runs were made with the hybrid Monte Carlo algorithm. To speed up calculations several algorithmic improvements like a higher order discretization scheme for molecular dynamics or the even/odd BiCGStab algorithm for inversions of the quark matrix have been implemented.

Measurements of light hadron propagators were made every fifth trajectory. Masses were extracted from hadron propagators with the standard correlated χ^2 fit. Errors were estimated with the jackknife procedure with a bin size of 50 trajectories, a choice resulting from the analysis of autocorrelations.

In order to make one-to-one comparisons between quenched and full QCD results from

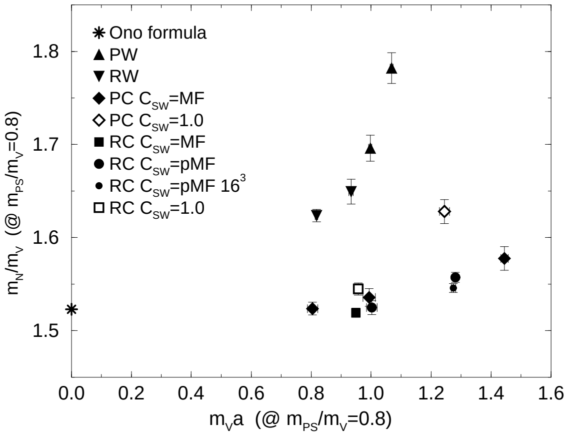

図 4: Scaling behavior of $m_{\rm N}/m_{\rm V}$ at fixed $m_{\rm PS}/m_{\rm V} = 0.8$ as function of $m_{\rm V}a$.

simulations with similar parameters, we made additional runs in quenched QCD using the same improved actions. Simulations were made at 10 values of β chosen so that the lattice spacing fixed by the string tension matches that of our full QCD runs for each simulated value of sea quark mass and for the chiral limit of $\beta = 1.95$ and 2.1. Ranges of quark masses were chosen to match the range of valence quark masses in our full QCD runs. Parameters of these quenched runs are also given in Table 1.

3.2 Light hadron spectrum

papers: 7.1-7, 7.2-(9, 10, 21)

The most interesting result in the light hadron spectrum concerns the value of meson masses. Fig. 5 shows a comparison of our results in full QCD with the ones in quenched QCD with the standard quark and gluon action (see Sec. 2) and with improved actions.

Concentrating first on the case for quenched QCD, we found that the results for the two different actions agree in the continuum limit within error bars. Note that for this comparison we analyzed the data in both cases in the same way, namely using polynomial functions for chiral extrapolations. If we did the analysis in the same way as described in Section 2, using formulae from quenched chiral perturbation theory, our conclusion that they are consistent is not changed.

An additional feature in the analysis of the chiral behavior of our full QCD data is that hadron masses depend on both the sea and valence quark masses. We took this into account by employing combined quadratic fits. The results, displayed in Fig. 5, show clearly that the discrepancies in the quenched meson spectrum are reduced in two-flavor full QCD. The remaining difference might be caused by the quenching of the third light

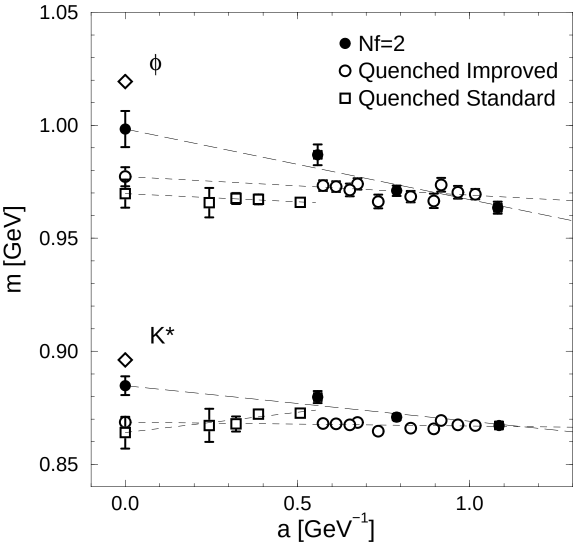

図 5: Continuum extrapolation of vector meson masses m_ϕ and m_{K^*} in full and quenched QCD. The experimental value of the K meson has been used to fix the strange quark mass.

(strange) quark.

Sea quark effects on baryons are less clear than for mesons. The main reason for this is that statistical errors for baryons in full QCD are too large to reliably discuss continuum extrapolations. On the other hand, we find quenched results with standard and improved actions to be consistent in the continuum limit also for baryons.

3.3 Light quark masses

papers: 7.1-7, 7.2-(8, 9, 21)

Masses of light quarks belong to the most fundamental parameters of the Standard Model. Because quarks are confined in hadrons, their values have to be indirectly inferred from hadron masses. This can be achieved within lattice QCD by using the functional relation between hadron masses and quark masses obtained in spectrum calculations.

We calculated quark masses both in quenched QCD and in full QCD using the spectrum results described in Sections 2 and 3.2. In Fig. 6 and 7 we show our results for the average up and down quark mass and the strange quark mass as function of the lattice spacing and after extrapolation to the continuum limit.

On the lattice several definitions of the quark mass are possible by employing the Ward identity for axial vector currents (AWI) or the Ward identity for vector currents (VWI). Due to the explicit breaking of chiral symmetry, different methods give different values at

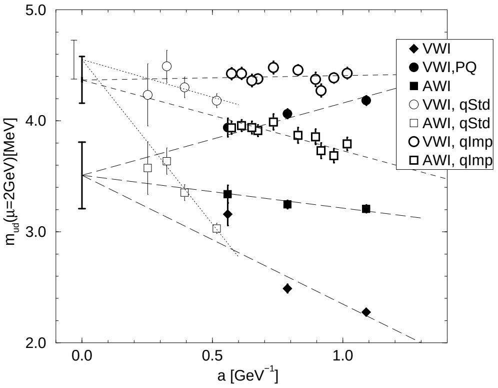

図 6: Continuum extrapolation of the average up and down quark mass m_{ud} for full QCD (filled symbols) and quenched QCD (thick open symbols) obtained with the improved action, and quenched results with the standard action (thin open symbols). Continuum values and lines show combined fits linear in a.

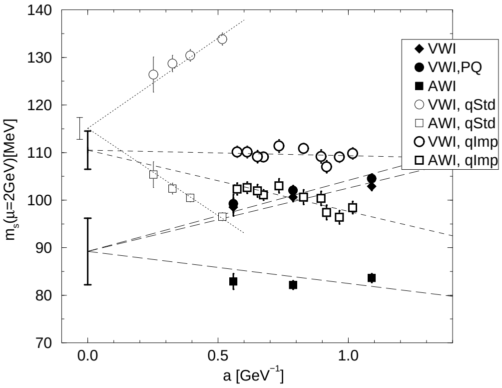

図 7: Continuum extrapolation of the strange quark mass m_s using M_K as input. Symbols have the same meaning as in Fig. 6.

finite lattice spacings. We found, however, that they converge toward the continuum limit and consequently employed combined continuum extrapolations, requiring a unique value in the continuum. Results after continuum extrapolations are summarized in Table 3.3.

Comparing the results from quenched simulations with the standard action with the ones from improved actions we found a nice agreement, confirming the universality of the continuum limit. Our full QCD results, however, tend to be significantly lower. We found that two flavors of dynamical quarks reduce quark masses by about 25%.

The strange quark mass can be determined by using either the K meson mass or the ϕ meson mass as experimental input. As can be seen in Table 3.3, the strange quark mass in the quenched approximations depends on the choice of input, differing by about 20-30%. This is a systematic error of the quenched approximation. The discrepancy is reduced to a 10% level for two-flavor full QCD.

表 2: Results for quark masses

	m_{ud} (MeV)	m_s (MeV) (M_K input)	m_s (MeV) (M_ϕ input)
$N_f = 0$ standard	4.55(18)	115(2)	143(6)
$N_f = 0$ improved	4.4(2)	110(4)	132(3)
$N_f = 2$	3.5(3)	89(7)	99(5)

In full QCD we obtained a quark mass of about $90-100$ MeV. This is significantly smaller than previous estimates from phenomenological models. This finding can have a strong impact on the determination of fundamental parameters of the Standard Model. A possible implication concerns the magnitude of direct CP-violation, for which recent experimental results favor smaller strange quark mass.

3.4 $U(1)$ problem and topology

papers: 7.2-18

One of the long-standing problems of QCD is the U(1) problem why the flavor singlet meson has a mass significantly heavier than the flavor octet mesons and how this relates to $U(1)$ anomaly and gluon field topology.

Computationally, propagators of flavor non-singlet meson consist of a loop of valence quark propagator. Propagators of flavor singlet meson have an additional contribution with two disconnected valence quark loops. Experimentally, the flavor singlet meson η' is much heavier than the corresponding non-singlet meson π. This means that, for the η' propagator, the two-loop contribution should exactly cancel the π pole of the one-loop contribution, leaving the heavy η' pole. This is a critical test of QCD and can be answered using lattice QCD.

Calculation of the two-loop contribution requires a large amount of computations. For this reason only limited results were available before our study. We performed the first systematic investigation in full QCD including continuum extrapolations.

We first tested two different methods for the calculation of the disconnected propagator. The first method uses a volume source without gauge fixing. For the second method we employed a U(1) volume noise source with 10 random noise ensembles for each color and spin combination. By comparing the results of the two methods we found them to be consistent with each other. Furthermore we found for both methods the behavior of the ratio of disconnected to connected diagrams to be consistent with theoretical expectations.

Using the first method, we computed the mass of the flavor-singlet $u\bar{u}+d\bar{d}$ meson in an approximation omitting the mixing with the $s\bar{s}$ state. We performed systematic extrapolations to the physical light quark mass and to the continuum limit, as presented in Fig. 8. We obtained values which are much larger than the flavor non-singlet pion mass. An extrapolation to the continuum limit gives $m_{u\bar{u}+d\bar{d}} = 863(86)$ MeV. In the real world, the $u\bar{u}+d\bar{d}$ state mixes with the $s\bar{s}$ state to lead to $\eta(547)$ and $\eta'(958)$ mesons. The fact that our value is slightly smaller than the experimental value 958 MeV is quite encouraging. We are planning to extend the study to investigate the effects of the mixing.

In a related study we investigated the topological charge in full QCD. Previous studies have encountered the problem that topological modes have a very long auto-correlation time.

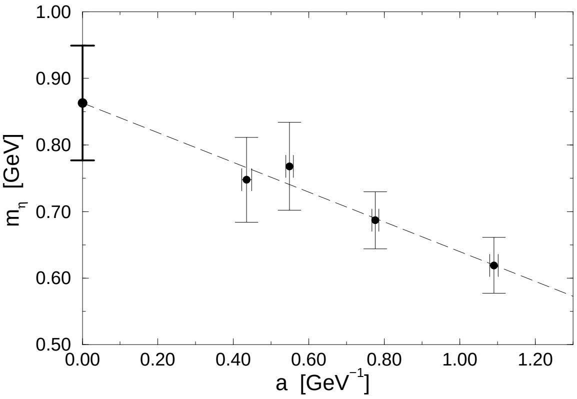

図 8: Continuum extrapolation of η' mass.

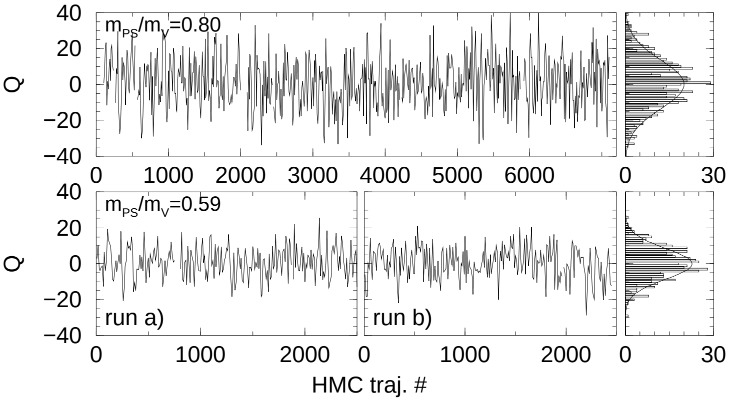

図 9: Time history and histogram of topological charge at $\beta = 1.95$.

In our work we employed the field theoretic definition of the topological charge together with cooling. In a pilot study we showed within pure SU(3) gauge theory that ambiguities due to the charge definition and the cooling procedure vanish in the continuum limit. As a side result we obtained the value $\chi_t = (178(9)\,\mathrm{MeV})^4$ for the topological susceptibility, in agreement with previous studies.

In full QCD we have measured the topological charge only at $\beta = 1.95$ up to now. In Fig. 9 we show the time history of the topological charge at two quark masses, the heaviest and the lightest one. We found auto-correlation times to be encourageably small even for the smallest quark mass, a fact which might be partly explained by the coarseness of our lattice. A more systematic investigation of this point is planned by extending measurements to gauge configurations at other values of the gauge coupling β.

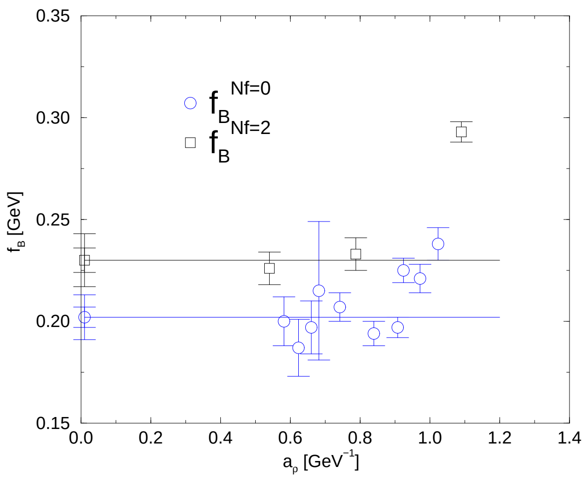

図 10: The decay constant f_B as a function of a_ρ for the relativistic clover action for the quenched ($N_f = 0$) and two flavor ($N_f = 2$) case.

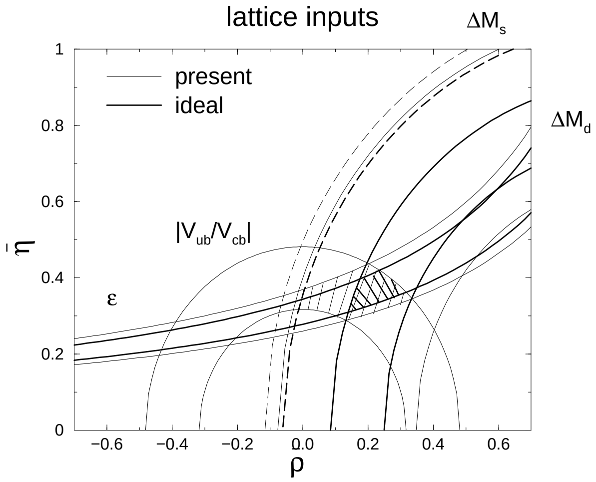

図 11: The parameters $\overline{\rho} = \rho(1 - \lambda^2/2)$ and $\overline{\eta} = \eta(1 - \lambda^2/2)$ constrained by experimental and lattice results, quoted from paper 7.1-9.

3.5 *B* meson decay constant with clover heavy quark action

papers: 7.2-(11, 22)

The accurate calculation of the CKM matrix is an important goal in particle phenomenology. Potentially useful observables are the axial decay constants f_B and f_{Bs}. An accuracy of 5 to 10% for these quantities (and their ratio) would constrain significantly the CKM matrix elements $|V_{ts}|$ ($A\lambda^2$ in the Wolfenstein parameterization) and $|V_{td}|$ ($A\lambda^3|1 - \rho - i\eta|$) which at present have uncertainties of approximately 55% and 15% respectively. A determination of the "bag parameter" B_B which tests the accuracy of a vacuum saturation approximation in $\overline{B} - B$ mixing is also necessary. Almost all previous groups have computed these decay constants in the quenched approximation (we refer to this as $N_f = 0$ lattice QCD) where the effect of sea quarks have been eliminated. While the size of the error due to this approximation is debatable for all observables, analytic calculations indicate that they may be very large in this case. For these reasons it is an important goal to obtain a more precise measurement of f_B, f_{Bs}, B_B and B_{Bs} where the quenched approximation is progressively eliminated.

The CP-PACS collaboration is at present completing a calculation of f_B and f_{Bs} in the quenched approximation of lattice QCD and where the effect of two degenerate flavors of light sea quark on the gluon field are included (referred to as $N_f = 2$ lattice QCD). We employ a relativistic formalism that has been employed successfully by a group based at Fermilab and the JLQCD collaboration in the quenched approximation. This involves using the same fermion action as the light spectrum calculation but where the operators

	$N_f = 0$	$N_f = 2$
f_B[MeV]	202(5)(11)	230(6)(13)
f_{B_s}[MeV]	229(3)(13)	272(6)(16)
f_{B_s}/f_B	1.123(33)(8)	1.185(41)(14)

表 3: Results for the decay constants from clover heavy quark action.

and field definitions are redefined and a different meson mass definition is employed. The current results indicate a significant shift of approximately 15% in the decay constants, as can be seen in Fig. 10. These results are consistent to within 1-2 standard deviations of the non-relativistic NRQCD results (see Sec. 3.6). Our present results are given in Table 3.

In conjunction with experimental data and other lattice data, this can be used to constrain the CKM matrix. To illustrate the present status of the constraint, we quote an analysis from a review by Sinya Aoki (paper 7.1-9) in Fig. 11. The parameters ΔM_s and ΔM_d are proportional to $B_B f_B^2$ and $B_{Bs} f_{Bs}^2$ respectively. The value $f_B = 210(30)$MeV employed for the anlysis incorporates a higher value of f_B for two-flavor full QCD indicated by our results obtained with clover action for heavy quark and with NRQCD (see Sec. 3.6 for the latter). As one can see, this almost constrains ρ to be positive.

3.6 B spectrum and leptonic decay constants from NRQCD

papers: 7.2-27

First principles calculations of leptonic B decay constants are important for the determination of CKM matrix elements from $B\bar{B}$ mixing experiments. Lattice calculations of the b hadron spectrum provide an important test of the lattice implementation of the hadrons. For some states, predictions can be made which can help to guide experimental analysis. CP-PACS is performing the first systematic study in full QCD.

The b quark inside a heavy-light meson can be thought of as essentially non-relativistic. Non-relativistic formulations, such as NRQCD and the Fermilab reinterpretation of relativistic heavy quark actions, are useful lattice implementations for heavy quarks where discretization errors are mass-dependent but dominated by the momentum of the heavy quark which is small inside the B meson. They are expected to have different systematic errors, and the CP-PACS collaboration is performing calculations using both heavy quark formalisms in parallel.

In the calculation using the non-relativistic heavy quarks, we use an NRQCD Lagrangian that is corrected through $O(1/M)$. In the simulation, five heavy quark masses around the b mass are used. Our light valence quarks are tree-level tadpole-improved

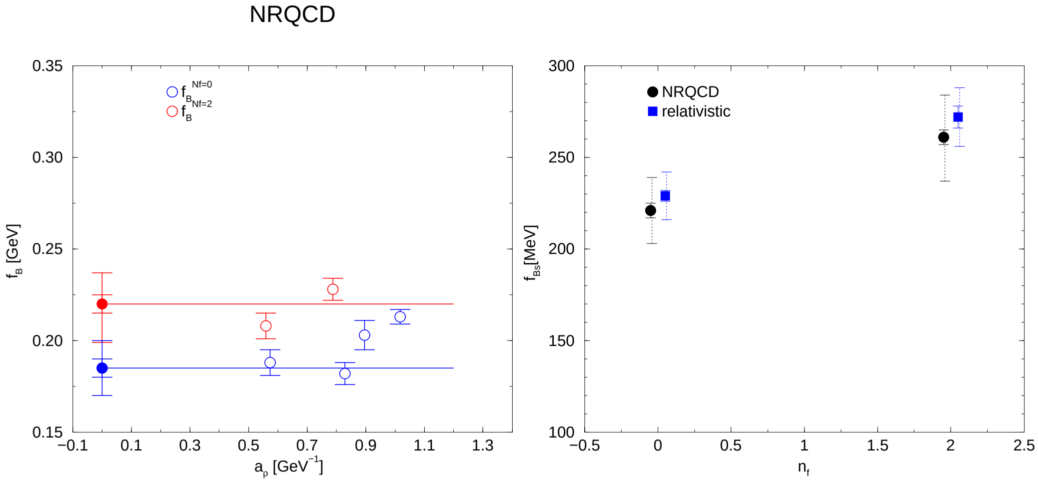

図 12: On the left, f_B from NRQCD is shown as a function of the lattice spacing. Lines indicate a constant fit. The filled symbols are the results of the fit; both the statistical and systematical errors of the results are shown. On the right, we compare f_{B_s} from NRQCD and relativistic heavy quarks, both for quenched and full QCD. The solid error bars show statistical, and the dashed ones, systematical errors.

clover, at five masses m in the range $0.5m_s \leq m \leq 3m_s$. For the gauge fields, we use a renormalization-group improved action. Simulations have been done at $\beta = 1.95$ and 2.1, for four sea quark masses, each. To enable a systematic study of quenching effects, we performed quenched runs at similar lattice spacings using the same gauge and quark actions.

In Fig. 12 we present results for f_B from NRQCD as a function of the lattice spacing (determined from the ρ mass). For lattices with $a \leq 0.8\text{GeV}^{-1}$, we assume f_B and f_{B_s} to be in a scaling window, and extract our final results using a constant fit in this region. The results are presented in Table 4, including the statistical and systematic errors. The latter are taken to include scaling violations, $O(\alpha_s^2)$, $O(1/M^2)$, and the uncertainty in the determination of the strange quark mass.

We observe a systematic upwards shift ($\sim 15-20\%$) of f_B and f_{B_s} with two dynamical light quarks. For f_{B_s}/f_B, we do not resolve a significant difference between $N_f = 0$ and $N_f = 2$.

The NRQCD results are within the error bars in agreement with the relativistic action, which corroborates the expectation that the heavy quark discretization errors are under control. A comparison between f_{B_s} from NRQCD and relativistic heavy quarks, both for $N_f = 0$ and 2, is also shown in Fig. 12.

	$N_f = 0$	$N_f = 2$
f_B[MeV]	$185(5)(15)$	$220(5)(^{+17}_{-21})$
f_B[MeV]	$221(4)(18)$	$261(4)(^{+23}_{-24})$
f_{B_s}/f_B	$1.180(16)(^{+39}_{-34})$	$1.190(14)(^{+15}_{-14})$

表 4: Results for the decay constants from NRQCD.

3.7 Spectrum of Heavy Quarkonia from NRQCD

papers: 6-9, 7.2-(17,25)

The study of heavy quark systems on the lattice is complicated by discretization errors from the large momentum scales. To circumvent this problem on conventional lattices, alternative formulations have been developed, in which the heavy quark propagation is described by an effective Hamiltonian. For heavy quarkonia there is also a wealth of experimental data, against which the accuracy of such an approach can be estimated. The ultimate goal is to devise an efficient non-perturbative framework for first-principle predictions in heavy quark phenomenology.

Effects of Dynamical Sea Quarks in Heavy Quarkonia

Prior to our work there was little known about the vacuum polarization effects in heavy quarkonia. Using ensembles of quenched and unquenched gauge field configurations at several different lattice spacings, we were able to resolve such effects against other systematic errors. In Fig. 13 we compare the spin-structure in Bottomonium with two dynamical sea quarks ($N_f = 2$) to the results from a quenched simulation ($N_f = 0$). It can be seen that the hyperfine splitting is particularly sensitive to this change. Our investigation has clearly established the need of unquenched simulations to control the systematic uncertainties in lattice calculations to a similar degree as the statistical errors.

Excited States on Anisotropic Lattices

The coarse dynamical lattices of the previous section are not well suited to resolve high excitations above the ground state. To this end one needs a much better resolution in the temporal direction. Among the most interesting states are gluonic excitations of the ground state, which are predicted by QCD, but which have yet to be discovered in experiment.

Here we studied non-relativistic hybrid quarkonia on anisotropic lattices with a fine temporal discretization. This approach has led to very accurate first-principle determinations of spin-averaged hybrid states as well as other excited states with higher orbital angular

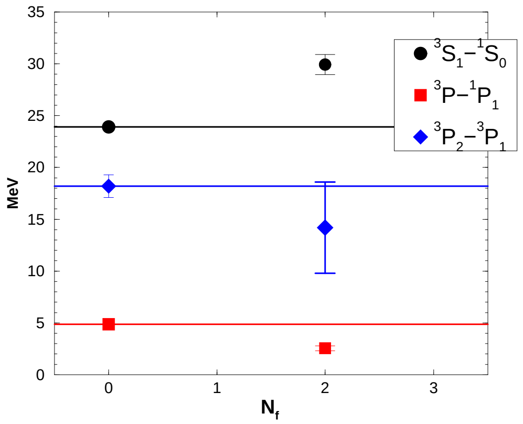

図 13: Bottomonium spin structure for $N_f = 0$ and $N_f = 2$.

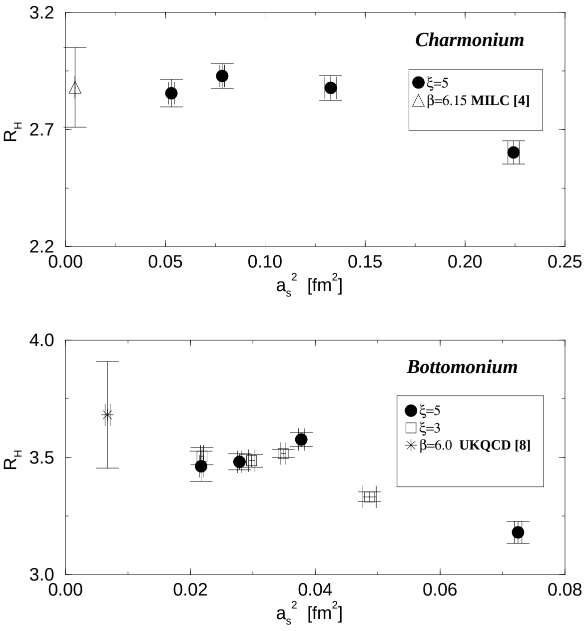

図 14: Ratio $R_{\rm H} = (H-S)/(P-S)$ against the squared spatial lattice spacing. We also show the results from previous calculations on isotropic lattices (charmonium = triangle, bottomonium=burst).

momentum. Using spatially coarse and anisotropic lattices, we could also study other systematic errors such as mass dependence, relativistic corrections, finite volume effects and lattice spacing artifacts. In Fig. 14 we present our scaling analysis which demonstrates an unprecedented control over statistical errors and stability against discretization errors.

Encouraged by those results we extended the formalism to also investigate the spin-structure of heavy quarkonia on anisotropic lattices. It became clear that the coupling between spin and gluon angular momentum results in potentially large splittings of up to 100 MeV. Ultimately one should also study dynamical sea quarks on anisotropic lattices. However, an exploratory study on isotropic lattices shows little quenching effect for the hybrid spectrum.

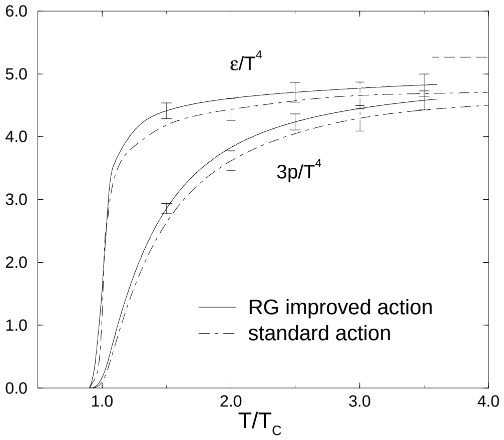

図 15: Equation of state for pure gluon system in the continuum limit with the RG-improved action (solid lines) and the plaquette action (dash-dotted lines). Dashed horizontal line on the top-right shows the free gluon gas value in the high temperature limit.

4 Finite-temperature QCD

4.1 Thermodynamics of pure gluon system

papers: 6-14, 7.2-23

At sufficiently high temperatures, the quark-confinement property is expected to be lost so that hadrons dissolve into the quark-gluon-plasma (QGP). Since such transition is a non-perturbative phenomenon, understanding QGP transition numerically is one of major goals of lattice QCD.

An important subject toward this goal is calculation of equation of state, namely the energy density ϵ and pressure p as a function of temperature T, which is needed in a variety of phenomenological analyses. As a first step toward this goal in full QCD, we studied the equation of state for pure gluon system using a renormalization-group improved action. We employed the integration method for p and the operator method for $\epsilon - 3p$:

$$\left.\frac{p}{T^4}\right|_{\beta_0}^{\beta} = \int_{\beta_0}^{\beta} \mathrm{d}\beta' \Delta S \ , \quad \frac{\epsilon - 3p}{T^4} = T\frac{\mathrm{d}\beta}{\mathrm{d}T}\Delta S \ , \tag{1}$$

where β is a gauge coupling and $\Delta S \equiv N_t^4(\langle S\rangle_T - \langle S\rangle_0)$ with $\langle S\rangle_T$ and $\langle S\rangle_0$ expectation values of action density S at $T > 0$ and $T = 0$ respectively. The energy density and pressure were calculated on a $16^3 \times 4 (N_t = 4)$ and a $32^3 \times 8 (N_t = 8)$ lattice. Temperature scales were fixed through the string tension of the static quark potential $\sqrt{\sigma}$.

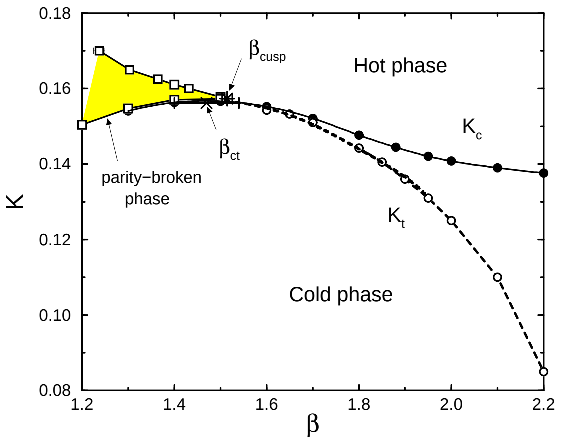

図 16: Phase diagram for $N_t = 4$. The solid line represents the critical line $K_c(\beta)$ of vanishing pion mass at $T = 0$. The Dashed line $K_t(\beta)$ is the location of finite-temperature transition. The shaded region is the parity-broken phase.

Extrapolating the results to the continuum limit ($N_t = \infty$), we found that the energy density and pressure are in good agreement with those obtained with the standard plaquette action within the error of 3–4% as shown in Fig. 15. This provides a concrete support for the expectation that results in the continuum limit are not sensitive to the choice of lattice actions. We also observed that the energy density and pressure at finite N_t overshoot those in high temperature limit calculated from one-loop perturbation theory. Understanding the origin of this behavior is reverved for further investigations.

4.2 Phase diagram and thermodynamics for two flavors of dynamical quarks

papers: 7.2-24

In the past full QCD studies of QCD thermodynamics have been made mainly with the Kogut-Susskind quark action, particularly for the equation of state. In order to test the reliability of the results, it is important to make a study also with Wilson-type quark actions. In this study, we present the first result of the equation of state from Wilson-type quarks.

As the first step, we studied the system for two flavors of quarks on $N_t = 4$ lattices. Since lattice artifacts in thermodynamical quantities are known to be severe for the combination of the plaquette gauge and Wilson quark actions. we adopt a renormalization-group (RG) improved gauge action and a meanfield-improved clover quark action employed in the zero-temperature simulations.

In Fig. 16, we show the phase diagram at $N_t = 4$. The line of finite-temperature transition K_t denoted by a dashed curve is determined by the Polyakov loop and its

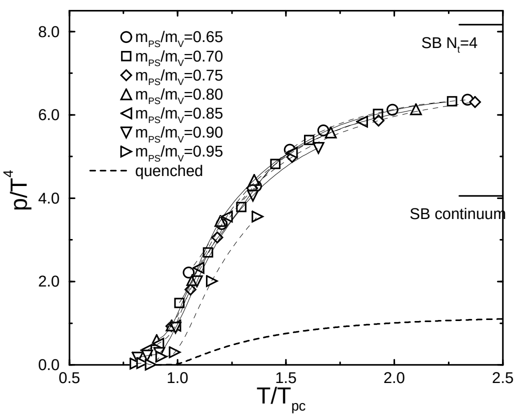

図 17: Pressure on a $16^3 \times 4$ lattice as a function of T/T_{pc}. The dashed curve shows pressure for pure gauge theory with the RG-improved action on a $16^3 \times 4$ lattice.

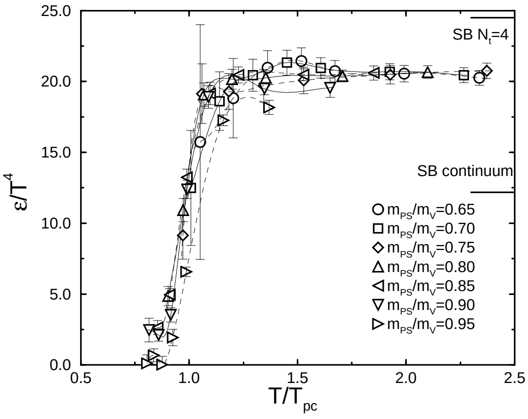

図 18: Energy density on a $16^3 \times 4$ lattice as a function of T/T_{pc}.

susceptibility. The shaded region is the parity-broken phase, which is determined by measuring the pion screening mass. The cusp of the parity-broken phase is located at $\beta_{\rm cusp} \approx 1.51$.

We studied the scaling properties of the chiral phase transition of two-flavor QCD, which is expected to belong to the universality class of O(4) spin model. In particular, we investigated a scaling relation for the magnetization of the spin model, identifying the chiral condensate defined by axial Ward identities with the magnetization. We found that the scaling ansatz works well. The best fit is obtained when the chiral transition point is $\beta_{ct} = 1.47(7)$. When we directly extrapolate the transition curve K_t to the chiral limit assuming the O(4) critical exponents, we obtain $\beta_{ct} \sim 1.43 - 1.59$. These values are consistent with $\beta_{\rm cusp}$, indicating that the cusp locates very close to the chiral transition point.

For investigation of the equation of state, we adopt the integral method to compute the pressure p as in our study of the pure-gluon case. The quark contributions to the derivatives of the free energy are evaluated by the U(1) noise method. In full QCD, the integration path can be arbitrarily chosen in the parameter space (β, K). We checked that the result for p is independent of the choice of the integration path. We also found that the error of the pressure obtained from the integration path along the K-direction is smaller than that along the β-direction.

We computed $\epsilon - 3p$ by the operator method. This method requires the derivatives of β and K with respect to the lattice spacing a. We determined these quantities from values of pseudo scalar ($m_{\rm PS}$) and vector (m_V) meson masses.

Figure 17 and 18 show the pressure and the energy density as functions of T/T_{pc} at fixed $m_{\rm PS}/m_{\rm V}$ obtained on a $16^3 \times 4$ lattice. Here T_{pc} is the pseudo-critical temperature at the same value of $m_{\rm PS}/m_{\rm V}$. The temperature scale is set by $m_{\rm V}$ through $T/T_{pc} = m_{\rm V}(\beta_{pc})/m_{\rm V}(\beta)$ with β_{pc} the pseudo-critical coupling.

We found that the pressure for fixed T/T_{pc} depends only weakly on the quark mass even for relatively heavy quark in the range $m_{\rm PS}/m_{\rm V} = 0.65$–$0.8$. For heavier quark masses, the pressure decreases toward the pure gauge value (dashed line) as expected.

We also noticed that the magnitude of pressure and energy density overshoot the Stefan-Boltzman value in the continuum at high temperatures. These features are probably a result of large discretization errors at small N_t. Indeed the Stefan-Boltzman values on an $N_t = 4$ lattice shown at the top-right in Fig. 17 and Fig. 18 are much larger than that in the continuum limit. In order to remove this discretization error, we have to extend the simulation to lager N_t.

5 Domain-wall QCD

papers: 6-(7, 13), 7.2-(19,20)

Domain-wall QCD (DWQCD) is a new development employing the domain-wall fermion formalism for quarks. Domain-wall fermion is a 5-dimensional Wilson fermion with free boundaries in the fifth dimension, with the action given by

$$\begin{aligned} S_{\mathrm{DW}} &= \sum_n \sum_{s=1}^{N_s} \Bigg[\frac{1}{2} \sum_\mu \left(\overline{\psi}(n)_s (1+\gamma_\mu) U_\mu(n) \psi(n+\mu)_s + \overline{\psi}(n)_s (1-\gamma_\mu) U_\mu^\dagger(n-\mu) \psi(n-\mu)_s \right) \\ &\quad + \frac{1}{2} \left(\overline{\psi}(n)_s (1+\gamma_5) \psi(n)_{s+1} + \overline{\psi}(n)_s (1-\gamma_5) \psi(n)_{s-1} \right) + (M-5) \overline{\psi}(n)_s \psi(n)_s \Bigg] \\ &- m_f \sum_n \left(\overline{\psi}(n)_{N_s} P_R \psi(n)_1 + \overline{\psi}(n)_1 P_L \psi(n)_{N_s} \right), \end{aligned} \tag{2}$$

Here n is a four dimensional space-time coordinate and s is an extra fifth dimensional or "flavor" index. The fifth dimensional Dirac mass or domain-wall height M is a parameter of the theory which we set within $0 < M < 2$ to realize massless fermion at tree level. The parameter m_f is the physical quark mass. It is important to notice that we have boundaries for the flavor space, $1 \le s \le N_s$, and we assume N_s to be even.

At each of the boundaries either the left- or right-handed chiral mode is expected to be localized exponentially. In the DWQCD the zero mode of domain-wall fermion is extracted by the "physical" quark field defined by the boundary fermions

$$\begin{aligned} q(n) &= P_R \psi(n)_1 + P_L \psi(n)_{N_s}, \\ \overline{q}(n) &= \overline{\psi}(n)_{N_s} P_R + \overline{\psi}(n)_1 P_L. \end{aligned} \tag{3}$$

where $P_{R/L}$ is a projection matrix $P_{R/L} = (1 \pm \gamma_5)/2$.

DWQCD would realize exact chiral symmetry in the large N_s limit if the mixing between two zero modes at each of the boundaries is suppressed exponentially. CP-PACS collaboration decided to check whether this property of DWQCD indeed holds, and to investigate how the explicit chiral symmetry breaking at finite N_s depends on β, M and the choice of the gauge action.

In order to check the chiral property of DWQCD, we examined the pion mass m_π and the anomalous quark mass m_{5q} defined by

$$m_{5q} = \frac{\left\langle j_{5q}^a(n) P^b(x) \right\rangle}{\left\langle P^a(n) P^b(x) \right\rangle}, \tag{4}$$

where

$$P^a(n) = \overline{q}(n) T^a \gamma_5 q(n), \tag{5}$$

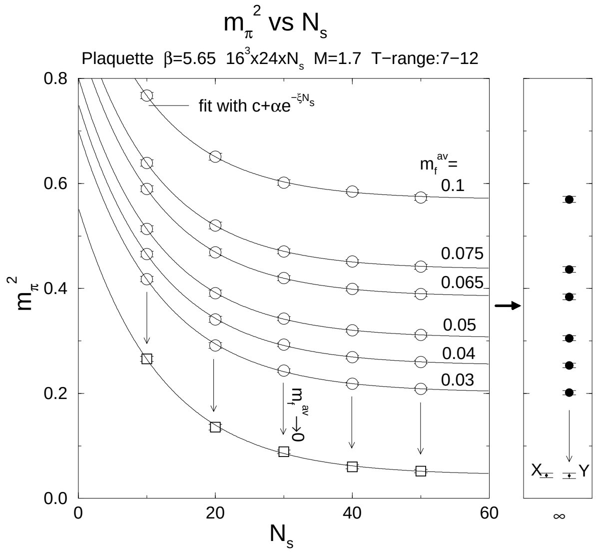

図 19: Pion mass squared as a function of the linear extra dimension N_s at $M = 1.7, \beta = 5.65$ of plaquette action on $16^3 \times 24 \times N_s$ lattice. Two limits $m_f \rightarrow 0$, $N_s \rightarrow \infty$ and their combinations are also plotted here.

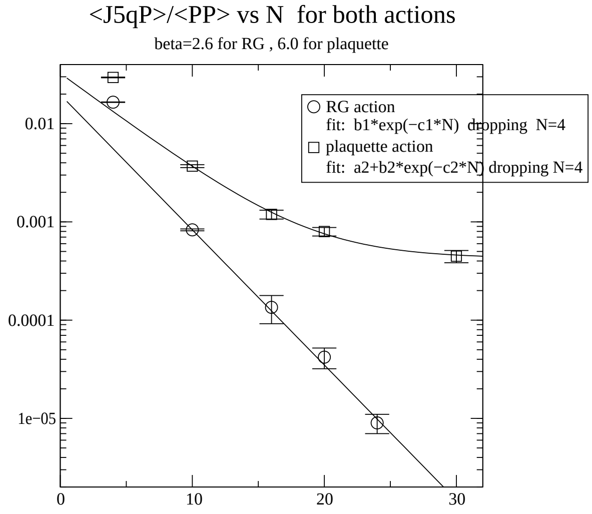

図 20: Anomalous quark mass in the chiral limit $m_q \rightarrow 0$ as a function of N_s. The circle represents the RG action and square for plaquette action. The fitting is done ignoring the point at $N_s = 4$ for both the action.

is the pion operator, and

$$J^a_{5q}(n) \;=\; \frac{1}{2}\left(\overline{\psi}(n)_{\frac{N_s}{2}} T^a(1+\gamma_5)\psi(n)_{\frac{N_s}{2}+1} - \overline{\psi}(n)_{\frac{N_s}{2}+1} T^a(1-\gamma_5)\psi(n)_{\frac{N_s}{2}}\right). \qquad (6)$$

is the anomalous term of the axial Ward-Takahashi identity.

At given quark mass m_f and the size of the fifth dimension N_s, these quantities should behave as

$$m_\pi^2 = C + \alpha \exp[-\xi N_s] + \gamma m_f + O(m_f^2), \qquad (7)$$

$$m_{5q} = C_5 + \alpha_5 \exp[-\xi_5 N_s] + \gamma_5 m_f + O(m_f^2). \qquad (8)$$

Here $C = C_5 = 0$ means that the chiral symmetry becomes exact in DWQCD.

We measure m_π^2 and m_{5q} at both $a^{-1} \sim 1$ GeV and 2 Gev, employing the plaquette action and RG improved action for gauge fields and varying m_f, N_s and M. The result for m_π^2 for the plaquette gauge action at $a^{-1} = 1$ GeV ($\beta = 5.65$) is best summarized in Fig. 19 . This figure shows that $C \neq 0$ and thus exact chiral symmetry is not be realized at $a^{-1} = 1$ GeV for the plaquette gauge action. We found that this conclusion also holds for the RG-improved gauge action. Therefore we conclude that DWQCD fails to realize exact chiral symmetry even in the $N_s \rightarrow \infty$ limit at coarse lattices at $a^{-1} \approx 1$ GeV.

At finer lattices ($a^{-1} \approx 2$ GeV), on the other hand, the behavior looks different. In Fig. 20 m_{5q} at $m_f = 0$ is plotted as a function of N_s. From this figure it is clearly seen that m_{5q} at $m_f = 0$ decreases exponentially in N_s for the RG improved gauge action, suggesting $C_5 = 0$ in this case. However, for the plaquette action, it seems that $C_5 \neq 0$ though the remaining constant is very small, corresponding to quark mass of less than 1 MeV.

The main conclusion from our study is that DWQCD realizes exact chiral symmetry for sufficiently fine lattices satisfying $a^{-1} \gtrsim 2$ GeV, while it does not work at coarse lattices such as $a^{-1} \sim 1$ GeV. The RG-improved gauge action shows improved chiral symmetry. Accordingly we start to measure weak matrix elements, for which the chiral symmetry is essentially important, using DWQCD with the RG-improved gauge action at $1/a \gtrsim 2$ GeV.

第 III 部

List of Publications

⋆ 印の文献は第 IV章に収録
(papers marked with ⋆ are collected in Sec. IV)

6 Journal papers

⋆ 1. Y. Taniguchi, A. Ukawa,
Perturbative calculation of improved coefficients to $O(g^2a)$ for bilinear quark operators in lattice QCD,
Phys. Rev. D 58, No.11 (1998) ref.114503, pp.1-8

⋆ 2. S. Aoki, K. Nagai, Y. Taniguchi, A. Ukawa,
Perturbative Renormalization Factors of Bilinear Quark Operators for Improved Gluon and Quark Actions in Lattice QCD,
Phys.Rev. D 58, No.7 (1998) ref.074505, pp.1-10

3. S. Ejiri, Y. Iwasaki, K. Kanaya,
Non-perturbative determination of anisotropy coefficients in lattice gauge theories,
Phys. Rev. D 58, No.9 (1998) ref.094505, pp.1-8

4. T. Izubuchi, J. Noaki, A. Ukawa,
Two-dimentional lattice Gross-Neveu model with Wilson action at finite temperature and chemical potential,
Phys. Rev. D 58, No.11 (1998) ref.114507, pp.1-12

⋆ 5. S. Aoki, R. Frezzotti, P. Weisz,
Computation of the improvement coefficient c_{sw} to 1-loop with improved gluon actions,
Nucl. Phys. B540, No.1-2 (1999) 501-519

6. S. Aoki, Y. Taniguchi,
One loop calculation of QCD with domain-wall quarks,
Phys. Rev. D 59, No.5 (1999) ref.054510, pp.1-13

⋆ 7. S. Aoki, T. Izubuchi, Y. Kuramashi, Y. Taniguchi,
Perturbative Renormalization Factors of Quark Bilinear Operators for Domain-wall QCD,
Phys. Rev. D 59, No.9 (1999) ref.094505, pp.1-11

8. S. Aoki, Y. Taniguchi,
One loop renormalization for the axial Ward-Takahashi identity in Domain-wall QCD,
Phys. Rev. D 59, No.9 (1999) ref.094506, pp.1-9

⋆ 9.CP-PACS Collaboration: T. Manke, H.P. Shanahan, A. AliKhan, S. Aoki, R. Burkhalter, S. Ejiri, M. Fukugita, S. Hashimoto, N. Ishizuka, Y. Iwasaki, K. Kanaya, T.

Kaneko, Y. Kuramashi, K. Nagai, M. Okawa, A. Ukawa, and T. Yoshié,
Hybrid Quarkonia on Asymmetric Lattices,
Phys. Rev. Lett. 82, No.22 (1999) 4396-4399

10. Y. Aoki, F. Csikor, Z. Fodor, A. Ukawa,
The end point of the first-order phase transition of the SU(2) gauge-Higgs model on a 4-dimensional isotropic lattice,
Phys. Rev. D 60, No.1 (1999) ref.013001, pp.1-8

⋆11. S. Aoki, R. Burkhalter, K. Kanaya, T. Yoshié, T. Boku, H. Nakamura, Y. Yamashita,
Performance of lattice QCD programs on CP-PACS,
Parallel Computing 25, No.10-11 (1999) 1243-1255

⋆12. A. Ukawa for the CP-PACS Collaboration,
Lattice QCD results from the CP-PACS computer,
Parallel Computing 25, No.10-11 (1999) 1257-1280

⋆13. S. Aoki, T. Izubuchi, Y. Kuramashi, Y. Taniguchi,
Perturbative renormalization factors of three- and four-quark operators for domain-wall QCD,
Phys. Rev. D 60, No.11 (1999) ref.114505, pp.1-13

⋆14. CP-PACS Collaboration: M. Okamoto, A. AliKhan, S. Aoki, R. Burkhalter, S. Ejiri, M. Fukugita, S. Hashimoto, N. Ishizuka Y. Iwasaki, K. Kanaya, T. Kaneko, Y. Kuramashi, T. Manke K. Nagai, M. Okawa, A. Ukawa, T. Yoshié,
Equation of state for pure SU(3) gauge theory with renormalization group improved action,
Phys. Rev. D 60, No.9 (1999) ref.094510, pp.1-8

⋆15. CP-PACS Collaboration: S. Aoki, G. Boyd, R. Burkhalter, S. Hashimoto, N. Ishizuka, Y. Iwasaki, K. Kanaya, T. Kaneko, Y. Kuramashi, M. Okawa, A. Ukawa, and T. Yoshié,
Comparative study of full QCD hadron spectrum and quark potential with improved actions,
Phys. Rev. D 60, No.11 (1999) ref.114508, pp.1-17

⋆16. CP-PACS Collaboration: S. Aoki, G. Boyd, R. Burkhalter, S. Ejiri, M. Fukugita, S. Hashimoto, Y. Iwasaki, K. Kanaya, T. Kaneko, Y. Kuramashi, K. Nagai, M. Okawa, H.P. Shanahan, A. Ukawa, and T. Yoshié,
Quenched light hadron spectrum,
Phys. Rev. Lett. 84, No.2 (2000) 238-241

17. T. Izubuchi and K.-i. Nagai,
Two-dimansional lattice Gross-Neveu model with domain-wall fermions,
Phys. Rev. D 61, No.9, (2000) ref.094501, pp.1-16

7 Conference proceedings

7.1 Invited review papers

⋆ 1. Y. Iwasaki,
The CP-PACS Parallel Computer Project,
Proc. International Conference on “Multi-Scale Phenomena and Their Simulation”, eds. F. Karsch, B. Monien and H. Satz, World Sci. (1997) 80-90

⋆ 2. A. Ukawa,
The CP-PACS Parallel Computer,
Proceedings of CHEP'97, Computer Physics Communications 110 (1998) 220-224

⋆ 3. Y. Iwasaki,
The CP-PACS Project and Computational Physics,
Proc. International Symposium on “Parallell Computing in Engineering and Science”, Science and Technology Agency (1997)

4. K. Kanaya,
Order of the finite temperature QCD phase transition on the lattice,
Proc. 3rd Intern'l Conference "Physics and Astrophysics of Quark Gluon Plasma" (ICPA-QGP '97), eds. B.C. Sinha, D.K. Srivastava and Y.P. Voyogi, Narosa Pub., New Delhi (1998) 89-98

⋆ 5. T. Yoshié,
Light hadron spectroscopy,
Nucl. Phys. B (Proc. Suppl.) 63 (1998) 3-15

⋆ 6. Y. Kuramashi for the CP-PACS Collaboration,
CP-PACS results for light hadron spectrum in quenched and two flavor full QCD,
APS, DPF '99 (1999)

⋆ 7. R. Burkhalter for the CP-PACS Collaboration,
Recent results from the CP-PACS Collaboration,
Nucl. Phys. B (Proc. Suppl.) 73 (1999) 3-15

⋆ 8. T. Yoshié,
Hadron spectroscopy from lattice QCD,
Nucl. Phys. A (1999) in press

⋆ 9. S. Aoki,
Lattice Calculations and Hadron Physics,
Proc. Lepton-Photon 1999 (2000) in press

⋆10. T. Yoshié for the CP-PACS Collaboration,
Light hadron spectrum from the CP-PACS,
Nucl. Phys. A (2000) in press

⋆11. Y. Iwasaki,
The CP-PACS Project and Lattice QCD Results,
Prog. Theor. Phys. (Suppl.) 138 (2000) in press

7.2 Original papers

⋆ 1. CP-PACS Collaboration: S. Aoki, G. Boyd, R. Burkhalter, S. Hashimoto, N. Ishizuka, Y. Iwasaki, K. Kanaya, Y. Kuramashi, M. Okawa, A. Ukawa, and T. Yoshié,
CP-PACS results for quenched QCD spectrum with the Wilson action,
Nucl. Phys. B (Proc. Suppl.) 60A (1998) 14-25

2. S. Aoki,
Phase Structure of Lattice QCD with Wilson fermion at Finite Temperatre,
Nucl. Phys. B(Proc. Suppl.) 60A (1998) 206-219

⋆ 3. Y. Iwasaki for the CP-PACS Collaboration,
The CP-PACS project,
Nucl. Phys. B (Proc. Suppl.) 60A (1998) 246-254

⋆ 4. CP-PACS Collaboration: S. Aoki, G. Boyd, R. Burkhalter, S. Hashimoto, N. Ishizuka, Y. Iwasaki, K. Kanaya, T. Kaneko, Y. Kuramashi, M. Okawa, A. Ukawa, and T. Yoshié,
Full QCD simulation on CP-PACS,
Nucl. Phys. B (Proc. Suppl.) 60A (1998) 335-340

⋆ 5. CP-PACS Collaboration: S. Aoki, G. Boyd, R. Burkhalter, S. Hashimoto, N. Ishizuka, Y. Iwasaki, K. Kanaya, Y. Kuramashi, M. Okawa, A. Ukawa, and T. Yoshié,
CP-PACS results for the quenched light hadron spectrum,
Nucl. Phys. B (Proc. Suppl.) 63 (1998) 161-163

⋆ 6. CP-PACS Collaboration: S. Aoki, G. Boyd, R. Burkhalter, S. Hashimoto, N. Ishizuka, Y. Iwasaki, K. Kanaya, T. Kaneno, Y. Kuramashi, M. Okawa, A. Ukawa, and T. Yoshié,
Hadron spectroscopy and static quark potential in full QCD: A comparison of improved actions on the CP-PACS,
Nucl. Phys. B (Proc. Suppl.) 63 (1998) 221-226

7. S. Aoki, Y. Taniguchi,
One loop calculation of QCD with domain-wall quarks,
Nucl. Phys. B (Proc. Suppl.) 63 (1998) 290-292

⋆ 8. CP-PACS Collaboration: S. Aoki, G. Boyd, R. Burkhalter, S. Ejiri, M. Fukugita, S. Hashimoto, Y. Iwasaki, K. Kanaya, T. Kaneko, Y. Kuramashi, K. Nagai, M. Okawa, H.P. Shanahan, A. Ukawa, and T. Yoshié,
Quenched Light Hadron Spectrum with the Wilson Quark Action: Final Results from CP-PACS,
Nucl. Phys. B (Proc. Suppl.) 73 (1999) 189-191

⋆ 9. CP-PACS Collaboration: S. Aoki, G. Boyd, R. Burkhalter, S. Ejiri, M. Fukugita, S. Hashimoto, Y. Iwasaki, K. Kanaya, T. Kaneko, Y. Kuramashi, K. Nagai, M. Okawa, H.P. Shanahan, A. Ukawa, and T. Yoshié,
Full QCD light hadron spectrum from the CP-PACS,
Nucl. Phys. B (Proc. Suppl.) 73 (1999) 192-194

⋆10. CP-PACS Collaboration: S. Aoki, G. Boyd, R. Burkhalter, S. Ejiri, M. Fukugita, S. Hashimoto, Y. Iwasaki, K. Kanaya, T. Kaneko, Y. Kuramashi, K. Nagai, M. Okawa, H.P. Shanahan, A. Ukawa, and T. Yoshié,
The static quark potential in full QCD,
Nucl. Phys. B (Proc. Suppl.) 73 (1999) 216-218

⋆11. CP-PACS Collaboration: S. Aoki, R. Burkhalter, S. Ejiri, M. Fukugita, S. Hashimoto, Y. Iwasaki, K. Kanaya, T. Kaneko, Y. Kuramashi, K. Nagai, M. Okawa, H.P. Shanahan, A. Ukawa, and T. Yoshié,
Heavy quark Physics in $N_f = 2$ QCD,
Nucl. Phys. B (Proc. Suppl.) 73 (1999) 375-377

12. S. Ejiri, Y. Iwasaki, K. Kanaya,
Non-perturbative determination of anisotropy coefficients and pressure gap at the deconfining transition of QCD,
Nucl. Phys. B (Proc. Suppl.) 73 (1999) 411-413

13. T. Izubuchi, J. Noaki, A. Ukawa,
Two-dimentional lattice Gross-Neveu model with Wilson action at finite temperature and density,
Nucl. Phys. B (Proc. Suppl.) 73 (1999) 483-485

14. Y. Aoki, F. Csikor, Z. Fodor, A. Ukawa,
The end point of the first-order phase transition of the SU(2) gauge-Higgs model on

a four-dimensional isotropic lattice,
Nucl. Phys. B (Proc. Suppl.) 73 (1999) 656-658

$\star$15. S. Aoki, K. Nagai, Y. Taniguchi, A. Ukawa,
One-loop renormalization factors and mixing coeffecients of bilinear quark operators for improved gluon and quark action,
Nucl. Phys. B (Proc. Suppl.) 73 (1999) 912-914

$\star$16. S. Aoki, R. Frezzotti, P. Weisz,
Computation of the improvement coefficient c_{sw} to 1-loop with improved gluon actions,
Nucl. Phys. B (Proc. Suppl.) 73 (1999) 915-917

$\star$17. T. Manke for the CP-PACS Collaboration,
Exotic quarkonia from anisotropic lattices,
Nucl. Phys. B (Proc. Suppl.) (2000) in press

$\star$18. CP-PACS Collaboration: A. AliKhan, S. Aoki, R. Burkhalter, S. Ejiri, M. Fukugita, S. Hashimoto, N. Ishizuka, Y. Iwasaki, K. Kanaya, T. Kaneko, Y. Kuramashi, T. Manke, K. Nagai, M. Okawa, H.P. Shanahan, A. Ukawa, T. Yoshié,
Eta meson mass and topology in QCD with two light flavors,
Nucl. Phys. B (Proc. Suppl.) (2000) in press

$\star$19. S. Aoki, T. Izubuchi, J. Noaki, Y. Kuramashi, Y. Taniguchi,
Perturbative renormalization factors of quark operators for domain-wall QCD,
Nucl. Phys. B (Proc. Suppl.) (2000) in press

$\star$20. CP-PACS Collaboration: A. AliKhan, S. Aoki, Y. Aoki, R. Burkhalter, S. Ejiri, M. Fukugita, S. Hashimoto, N. Ishizuka, Y. Iwasaki, T. Izubuchi, K. Kanaya, T. Kaneko, Y. Kuramashi, T. Manke, K. Nagai, M. Okawa, H. P. Shanahan, Y. Taniguchi, A. Ukawa, T. Yoshié,
Quenched QCD with domain-wall fermions on coarse lattices,
Nucl. Phys. B (Proc. Suppl.) (2000) in press

$\star$21. CP-PACS Collaboration: A. AliKhan, S. Aoki, G. Boyd, R. Burkhalter, S. Ejiri, M. Fukugita, S. Hashimoto, N. Ishizuka, Y. Iwasaki, K. Kanaya, T. Kaneko, Y. Kuramashi, T. Manke, K. Nagai, M. Okawa, H.P. Shanahan, A. Ukawa, T. Yoshié,
Light hadron spectrum and quark masses in QCD with two flavors of dynamical quarks,
Nucl. Phys. B (Proc. Suppl.) (2000) in press

$\star$22. CP-PACS Collaboration: A. AliKhan, S. Aoki, R. Burkhalter, S. Ejiri, M. Fukugita, S. Hashimoto, N. Ishizuka, Y. Iwasaki, K. Kanaya, T. Kaneko, Y. Kuramashi, T. Manke, K. Nagai, M. Okawa, H.P. Shanahan, A. Ukawa, T. Yoshié,
Heavy-light decay constants from clover heavy quark action in QCD with two flavors of dynamical quarks,
Nucl. Phys. B (Proc. Suppl.) (2000) in press

$\star$23. CP-PACS Collaboration: A. AliKhan, S. Aoki, R. Burkhalter, S. Ejiri, M. Fukugita, S. Hashimoto, N. Ishizuka, Y. Iwasaki, K. Kanaya, T. Kaneko, Y. Kuramashi, T. Manke, K. Nagai, M. Okamoto, M. Okawa, A. Ukawa, T. Yoshié,
Equation of state for SU(3) gauge theory with RG improved action,
Nucl. Phys. B (Proc. Suppl.) (2000) in press

$\star$24. CP-PACS Collaboration: A. AliKhan, S. Aoki, R. Burkhalter, S. Ejiri, M. Fukugita, S. Hashimoto, N. Ishizuka, Y. Iwasaki, K. Kanaya, T. Kaneko, Y. Kuramashi, T. Manke, K. Nagai, M. Okamoto, M. Okawa, H.P. Shanahan, A. Ukawa, T. Yoshié,
Equation of state in finite-temperature QCD with improved Wilson quarks,
Nucl. Phys. B (Proc. Suppl.) (2000) in press

$\star$25. CP-PACS Collaboration: A. AliKhan, S. Aoki, R. Burkhalter, S. Ejiri, M. Fukugita, S. Hashimoto, N. Ishizuka, Y. Iwasaki, K. Kanaya, T. Kaneko, Y. Kuramashi, T. Manke, K. Nagai, M. Okawa, H. P. Shanahan, A. Ukawa, T. Yoshié,
Heavy quarkonia from anisotropic and isotropic lattices,
Nucl. Phys. B (Proc. Suppl.) (2000) in press

26. S. Aoki, T. Izubuchi, Y. Kuramashi, Y. Taniguchi,
Lattice QCD with Domain-Wall Fermions,
Nucl. Phys. B (Proc. Suppl.) (2000) in press

$\star$27. CP-PACS Collaboration: A. AliKhan, S. Aoki, R. Burkhalter, S. Ejiri, M. Fukugita, S. Hashimoto, N. Ishizuka, Y. Iwasaki, K. Kanaya, T. Kaneko, Y. Kuramashi, T. Manke, K. Nagai, M. Okawa, H.P. Shanahan, A. Ukawa, T. Yoshié,
Heavy-light spectrum and decay constant from NRQCD with two flavors of dynamical quarks,
Nucl. Phys. B (Proc. Suppl.) (2000) in press

28. T. Izubuchi and K.-i. Nagai,
Lattice Gross-Neveu model with domain-wall fermions,
Nucl. Phys. B(Proc. Suppl.) (2000) in press

8 学会・研究会報告一覧

1. 金谷 和至 「Finite temperature QCD on the lattice with dynamical quarks」 International Workshop on “Physics of Relativistic Heavy Ion Collisions” (YITP, Kyoto Univ., Kyoto, Japan, June 9-11, 1997)
2. Burkhalter, Rudolf 「Full QCD hadron spectroscopy – A comparison of improved actions」 The XV International Symposium on Lattice Field Theory ”Lattice 97” (Edinburgh, Scotland, July 22-26, 1997)
3. 吉江 友照 「Light hadron spectroscopy」 The XV International Symposium on Lattice Field Theory ”Lattice 97” (Edinburgh, Scotland, July 22-26, 1997)
4. 金児 隆志 「The static quark potential in full QCD with improved actions」 The XV International Symposium on Lattice Field Theory ”Lattice 97” (Edinburgh, Scotland, July 22-26, 1997)
5. 金谷 和至 「CP-PACS results for the quenched QCD spectrum with the Wilson quark action」 The XV International Symposium on Lattice Field Theory ”Lattice 97” (Edinburgh, Scotland, July 22-26, 1997)
6. 岩崎 洋一 「Many-flavor QCD」 2nd German-Japanese Workshop on ”The Simulation of Quantum Field Theories on Massively Parallel Computers” (Bielefeld, Germany, July 29-Aug. 2, 1997)
7. 吉江 友照 「Details on CP-PACS quenched hadron spectra」 2nd German-Japanese Workshop on ”The Simulation of Quantum Field Theories on Massively Parallel Computers” (Bielefeld, Germany, July 29-Aug. 2, 1997)
8. 金谷 和至 「Comparative study of improved full QCD actions」 2nd German-Japanese Workshop on ”The Simulation of Quantum Field Theories on Massively Parallel Computers” (Bielefeld, Germany, July 29-Aug. 2, 1997)
9. 青木 慎也 「Phase structure of QCD with Wilson fermions」 2nd German-Japanese Workshop on ”The Simulation of Quantum Field Theories on Massively Parallel Computers” (Bielefeld, Germany, July 29-Aug. 2, 1997)
10. Burkhalter, Rudorf 「Full QCD hadron spectroscopy – A comparison of improved actions」 日本物理学会 (東京都立大学、八王子, Sep. 20-23, 1997)
11. 吉江 友照 「CP-PACS results for the quenched QCD spectrum with the Wilson quark action」 日本物理学会 (東京都立大学、八王子, Sep. 20-23, 1997)

12. 金児 隆志 「Static quark potential in full QCD with improved actions」 日本物理学会 (東京都立大学、八王子, Sep. 20-23, 1997)
13. 江尻 信司 「非等方格子を用いたグルーオンの熱力学」 日本物理学会 (東京都立大学、八王子, Sep. 20-23, 1997)
14. 長井 敬一 「Domain-wall model with Majorana coupling」日本物理学会 (東京都立大学, 八王子, Sep.20-23, 1997)
15. 金谷 和至 「Introduction to the lattice formulation of finite temperature QCD」 1997 Yukawa international seminar on ”Non-Perturbative QCD – Structure of the QCD Vacuum –” (YKIS'97) (YITP, Kyoto Univ., Kyoto, Japan, Dec. 2-12, 1997)
16. 金谷 和至 「Many flavor QCD」 1997 Yukawa international seminar on ”Non-Perturbative QCD – Structure of the QCD Vacuum –” (YKIS'97) (YITP, Kyoto Univ., Kyoto, Japan, Dec. 2-12, 1997)
17. 江尻信司 「QCD Thermodynamics on Anisotropic Lattices」 1997 Yukawa International Seminar (YKIS'97) (YTP, Kyoto Univ., Kyoto, Japan, Dec. 2-12, 1997)
18. 江尻信司 「非等方格子を用いたモンテ・カルロ・シミュレーションによるクォーク・グルーオン・プラズマの研究」基研研究会「熱場の理論とその応用」 (京都大学基礎物理学研究所、京都、 Jan. 12-14, 1998)
19. 吉江 友照 「CP-PACSにおける格子ＱＣＤプログラムの高速化」 筑波大学計算物理学研究センター研究会「計算物理学における超大型シミュレーションの技法」 (CCP, Univ. Tsukuba, Tsukuba, Japan, Mar. 25-27, 1998)
20. Burkhalter, Rudorf 「Full QCD hadron spectroscopy from high statistics simulations on CP-PACS」 日本物理学会第５３回年会 (東邦大学・日本大学、船橋, Mar. 30-Apr. 2, 1998)
21. 吉江 友照 「クエンチ格子ＱＣＤの軽いハドロン質量の連続極限」 日本物理学会第５３回年会 (東邦大学・日本大学、船橋, Mar. 30-Apr. 2, 1998)
22. 金児 隆志 「Full QCD static quark potential from high statistics simulations on CP-PACS」 日本物理学会第５３回年会 (東邦大学・日本大学、船橋, Mar. 30-Apr. 2, 1998)
23. 江尻 信司 「非等方格子上のＱＣＤ熱力学」 日本物理学会第５３回年会 (東邦大学・日本大学、船橋, Mar. 30-Apr. 2, 1998)

24. Burkhalter, R 「Recent results from the CP-PACS Collaboration」 The XVI International Symposium on Lattice Field Theory "Lattice 98" (Boulder, USA, July 13-18, 1998)

25. Shanahan, H.P. 「Heavy quark Physics in $N_f = 2$ QCD」 The XVI International Symposium on Lattice Field Theory "Lattice 98" (Boulder, USA, July 13-18, 1998)

26. 吉江 友照 「Quenched Light Hadron Spectrum with the Wilson Quark Action: Final Results from CP-PACS」 The XVIth International Symposium on Lattice Field Theory "Lattice 98" (Boulder, USA, July 13-18, 1998)

27. 金児 隆志 「The static quark potential in full QCD」 The XVI International Symposium on Lattice Field Theory "Lattice 98" (Boulder, USA, July 13-18, 1998)

28. 金谷 和至 「Full QCD light hadron spectrum from the CP-PACS」 The XVIth International Symposium on Lattice Field Theory "Lattice 98" (Boulder, USA, July 13-18, 1998)

29. 江尻 信司 「Nonperturbative determination of anisotropy coefficients and pressure gap at the deconfining transition of QCD」 The XVI International Symposium on Lattice Field Theory "Lattice 98" (Boulder, USA, July 13-18, 1998)

30. 青木 慎也 「Computation of the improvement coefficient $c_{\rm SW}$ to 1-loop with improved gluon actions」 The XVI International Symposium on Lattice Field Theory "Lattice 98" (Boulder, USA, July 13-18, 1998)

31. 青木 保道 「The end point of the first-order phase transition of the SU(2) gauge-Higgs model on a four-dimensional isotropic lattice」 The XVI International Symposium on Lattice Field Theory "Lattice 98" (Boulder, USA, July 13-18, 1998)

32. 野秋 淳一 「Two-dimentional lattice Gross-Neveu model with Wilson action at finite temperature and density」 The XVI International Symposium on Lattice Field Theory "Lattice 98" (Boulder, USA, July 13-18, 1998)

33. Burkhalter, Rudolf 「Dynamical quark effects on the light hadron spectrum」 日本物理学会 (秋田大学、秋田, Oct. 3-6, 1998)

34. 岡本 昌高 「「くりこみ群により改良された作用」を用いた Pure SU(3) gauge 系の熱力学の数値シミュレーション」 日本物理学会 (秋田大学、秋田, Oct. 3-6, 1998)

35. 金児 隆志 「Dynamical quark effects on the static quark potential」 日本物理学会 (秋田大学、秋田, Oct. 3-6, 1998)

36. 青木 保道 「格子 SU(2) ゲージ・ヒッグス模型における電弱理論の有限温度１次相転移の終点」 日本物理学会 (秋田大学、秋田, Oct. 3-6, 1998)

37. 野秋 淳一 「Lattice Gross-Neveu model の有限密度・有限温度相構造 II」 日本物理学会 (秋田大学、秋田, Oct. 3-6, 1998)

38. 吉江 友照 「Hadron Spectroscopy from Lattice QCD」 KEK-Tanashi International Symposium on Physics of Hadrons and Nuclei (Tokyo, Japan, Dec. 14-17, 1998)

39. 金谷 和至 「Phase structure of QCD at high temperatures」 研究会「高温高密度における非摂動現象」 (広島テクノプラザ、東広島, Dec. 3-4, 1998)

40. 江尻 信司 「New analysis of equation of state」 研究会「高温高密度における非摂動現象」 (広島テクノプラザ、東広島, Dec. 3-4, 1998)

41. Burkhalter, Rudolf 「Lattice QCD Results from CP-PACS」 筑波大学計算物理学研究センター研究会「ＣＰ－ＰＡＣＳによる計算物理学」 (筑波大学計算物理学研究センター、つくば, Feb. 16-17, 1999)

42. Burkhalter, Rudolf 「Full QCD light hadron spectrum on CP-PACS」 日本物理学会第５４回年会 (広島大学、東広島, Mar. 28-31, 1999)

43. Burkhalter, Rudolf 「Lattice QCD Results from CP-PACS」 Sapporo Winter School in Niseko '99 (北海道, Mar. 18-19, 1999)

44. 岡本 昌高 「Pure SU(3) gluon thermodynamics with RG-improved action」 日本物理学会第５４回年会 (広島大学、東広島, Mar. 28-31, 1999)

45. 金児 隆志 「Sea quark effects on the hadron spectrum」 日本物理学会第５４回年会 (広島大学、東広島, Mar. 28-31, 1999)

46. 江尻 信司 「clover クォーク作用によるフレーバー数 2 の full QCD 熱力学」 日本物理学会第５４回年会 (広島大学、東広島, Mar. 28-31, 1999)

47. 野秋 淳一 「Glasgow アルゴリズムによる有限密度格子 QCD の研究」 日本物理学会第５４回年会 (広島大学、東広島, Mar. 28-31, 1999)

48. 長井 敬一 「Lattice Grass-Neveu model on domain-wall fermion」日本物理学会 (広島大学, 東広島, Mar.28-31, 1999)

49. 吉江 友照 「Hadron spectroscopy from lattice QCD」 PANIC 99 (Uppsala, Sweden, June 10-16, 1999)

50. Ali Khan, Arifa 「Heavy-light spectrum and decay constant from NRQCD with two flavors of dynamical quarks」 The XVII International Symposium on Lattice Field Theory ”Lattice 99” (Pisa, Italy, June 29-July 3, 1999)

51. Burkhalter, Rudolf 「Eta meson mass and topology in QCD with two light flavors」 The XVII International Symposium on Lattice Field Theory ”Lattice 99” (Pisa, Italy, June 29-July 3, 1999)

52. Manke, T. 「Heavy quarkonia from anisotropic and isotropic lattices」 The XVII International Symposium on Lattice Field Theory ”Lattice 99” (Pisa, Italy, June 29-July 3, 1999)

53. Shanahan, H.P. 「Heavy-light decay constants from clover heavy quark action in QCD with two flavors of dynamical quarks」 The XVII International Symposium on Lattice Field Theory ”Lattice 99” (Pisa, Italy, June 29-July 3, 1999)

54. 岡本 昌高 「Equation of state for SU(3) gauge theory with RG improved action」 The XVII International Symposium on Lattice Field Theory ”Lattice 99” (Pisa, Italy, June 29-July 3, 1999)

55. 金児 隆志 「Light hadron spectrum and quark masses in QCD with two flavors of dynamical quarks」 The XVII International Symposium on Lattice Field Theory ”Lattice 99” (Pisa, Italy, June 29-July 3, 1999)

56. 江尻 信司 「Equation of state in finite-temperature QCD with improved Wilson quarks」 The XVII International Symposium on Lattice Field Theory ”Lattice 99” (Pisa, Italy, June 29-July 3, 1999)

57. 出淵 卓 「Lattice QCD with Domain-Wall Fermions」 The XVII International Symposium on Lattice Field Theory ”Lattice 99” (Pisa, Italy, June 29-July 3, 1999)

58. 青木 保道 「Quenched QCD with domain-wall fermions on coarse lattices」 The XVII International Symposium on Lattice Field Theory ”Lattice 99” (Pisa, Italy, June 29-July 3, 1999)

59. 谷口 裕介 「Perturbative renormalization factors of quark operators for domain-wall QCD」 The XVII International Symposium on Lattice Field Theory ”Lattice 99” (Pisa, Italy, June 29-July 3, 1999)

60. 長井 敬一 「Lattice Gross-Neveu model with domain-wall fermions」 The XVII International Symposium on Lattice Field Theory “LATTICE 99” (Pisa, Italy, June 29-July 3, 1999)

61. Manke, Thomas 「Exotic quarkonia from anisotropic lattices」 QCD 99 International Euroconference in Quantum Chromodynamics (Montpellier, France, July 7-13, 1999)

62. 江尻信司 「格子QCDによるクォーク・グルーオン・プラズマの研究」基研研究会「素粒子物理とその将来像」(京都大学基礎物理学研究所、京都、 July 13-16, 1999)

63. 長井 敬一 「Lattice Grass-Neveu model with domain-wall fermions」基研99年度前期研究会「素粒子物理学の新展開」(京都大学 基礎物理学研究所, 京都, July 13-16, 1999)

64. 江尻信司 「数値シミュレーションによるフレーバー数2 full QCD の研究」基研研究会「熱場の理論とその応用」(京都大学基礎物理学研究所、京都、 Aug. 25-27, 1999)

65. 青木 慎也 「Lattice Calculations and Hadron Physics」 19th International Symposium on Lepton and Photon Interactions at High Energies (Stanford, USA, Aug. 9-14, 1999)

66. Ali Khan, Arifa 「B decay constant and spectroscopy from lattice QCD」 日本物理学会 (島根大学、松江, Sept. 23-26, 1999)

67. Burkhalter, Rudolf 「eta' mass in QCD with two light flavors」 日本物理学会 (島根大学、松江, Sept. 23-26, 1999)

68. Guertler, Martin 「Determination of the pion-nucleon sigma term」 日本物理学会 (島根大学、松江, Sept. 23-26, 1999)

69. Manke, Thomas 「Exotic quarkonia」 日本物理学会 (島根大学、松江, Sept. 23-26, 1999)

70. 岡本 昌高 「Nf=2 full QCD の相転移温度の決定」 日本物理学会 (島根大学、松江, Sept. 23-26, 1999)

71. 金児 隆志 「Hevy-light decay constants from relativistic Nf=2 QCD」 日本物理学会 (島根大学、松江, Sept. 23-26, 1999)

72. 江尻 信司 「改良された作用を用いたフレーバー数2 full QCD の状態方程式の研究」日本物理学会 (島根大学、松江, Sept. 23-26, 1999)

73. 青木 慎也 「B-parameters with lattice NRQCD」 日本物理学会 (島根大学、松江, Sept. 23-26, 1999)

74. 青木 保道 「Quenched QCD with domain-wall fermions」 日本物理学会 (島根大学、松江, Sept. 23-26, 1999)

75. 谷口 裕介 「One loop calculation of SUSY Ward-Takahashi identity on lattice」 日本物理学会 (島根大学、松江, Sept. 23-26, 1999)

76. 野秋 淳一 「Domain-wall QCD におけるスケーリングの摂動論的評価」 日本物理学会 (島根大学、松江, Sept. 23-26, 1999)

77. Burkhalter, R. 「Eta' meson and topology in full QCD」 Japanese-German Seminar '99 "Lattice Field Theories on TFLOPS Supercomputers" (Kanazawa, Japan, Oct. 15-17, 1999)

78. 宇川 彰 「Aspects of next generation parallel computers」 Japanese-German Seminar '99 "Lattice Field Theories on TFLOPS Supercomputers" (Kanazawa, Japan, Oct. 15-17, 1999)

79. 岩崎 洋一 「The CP-PACS Project and Lattice QCD Results」 5th International Conference on Computational Physics (ICCP5) (Kanazawa, Japan, Oct. 11-13, 1999)

80. 吉江 友照 「Light hadron spectrum and quark masses from CP-PACS」 Japanese-German Seminar '99 "Lattice Field Theories on TFLOPS Supercomputers" (Kanazawa, Japan, Oct. 15-17, 1999)

81. 金児 隆志 「Heavy quark physics from CP-PACS」 Japanese-German Seminar '99 "Lattice Field Theories on TFLOPS Supercomputers" (Kanazawa, Japan, Oct. 15-17, 1999)

82. 江尻 信司 「Full QCD theomodynamics from CP-PACS」 Japanese-German Seminar '99 "Lattice Field Theories on TFLOPS Supercomputers" (Kanazawa, Japan, Oct. 15-17, 1999)

83. 青木 慎也 「Domain wall QCD from CP-PACS Collaboration」 Japanese-German Seminar '99 "Lattice Field Theories on TFLOPS Supercomputers" (Kanazawa, Japan, Oct. 15-17, 1999)

84. 金谷 和至 「Lattice Simulation of Large Flavor QCD」 TMU-Yale Symposium on Dynamics of Gauge Fields (Hachioji, Tokyo, Japan, Dec. 13-15, 1999)

85. 金児 隆志 「CP-PACS を用いた数値シミュレーションによる QCD の研究」 計算物理学研究センター研究会「CP-PACS による計算物理学 1999」 (筑波大学、つくば, Feb. 8, 2000)

86. 金谷 和至 「Hadronic properties from lattice QCD」 International Conference on Quark Nuclear Physics (Adelaide, Australia, Feb. 21-25, 2000)

87. 長井 敬一 「Domain-wall fermion and zero modes」研究会「超対称性、カイラル対称性と格子ゲージ理論」(新潟大学 自然科学研究科, 新潟, Nov. 17-19, 1999)

88. Ali Khan, Arifa 「B decay constants in Nf = 2 lattice QCD from the CP-PACS collaboration」 Sapporo Winter School in Niseko '00 (ニセコ・アンヌプリ、札幌, Mar. 2-6, 2000)

89. Burkhalter, Rudolf 「Lattice QCD Results from CP-PACS」 Sapporo Winter School in Niseko '00 (ニセコ・アンヌプリ、札幌, Mar. 2-6, 2000)

90. Guertler, Martin 「Nucleon matrix elements on CP-PACS」 Sapporo Winter School in Niseko '00 (ニセコ・アンヌプリ、札幌, Mar. 2-6, 2000)

91. Shanahan, Hugh 「A study of SU(2) gauge theories with adjoint Higgs in 2+1 d」 Sapporo Winter School in Niseko '00 (ニセコ・アンヌプリ、札幌, Mar. 2-6, 2000)

92. 谷口 裕介 「Chiral Limit of Domain wall Fermion」 Sapporo Winter School in Niseko '00 (ニセコ・アンヌプリ、札幌, Mar. 2-6, 2000)

93. 金谷 和至 「Thermodynamics of Nf=2 QCD with Wilson-type quarks」 International Conference on Quark Nuclear Physics (Univ. of Washington, Seattle, USA, Mar. 13-19, 2000)

第 IV 部

Reprints of papers