Proceedings of RIKEN BNL Research Center Workshop

Volume 24

Physical Society of Japan Biannual Meeting

Symposium On

QCD PHYSICS AT RIKEN BNL RESEARCH CENTER

MATSUE, JAPAN

September 23, 1999

Organizers

Koichi Yazaki, Hideto En'yo and Shigemi Ohta

RIKEN BNL Research Center

Building 510, Brookhaven National Laboratory, Upton, NY 11973, USA

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- Volume 22 - OSCAR II: Predictions for RHIC - BNL-
- Volume 21 - RBRC Scientific Review Committee Meeting - BNL-52568
- Volume 20 - Gauge-Invariant Variables in Gauge Theories - BNL-
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- Volume 8 - Fermion Frontiers in Vector Lattice Gauge Theories - BNL-65634
- Volume 7 - RHIC Spin Physics - BNL-65615
- Volume 6 - Quarks and Gluons in the Nucleon - BNL-65234
- Volume 5 - Color Superconductivity, Instantons and Parity (Non?)-Conservation at High Baryon Density - BNL-65105
- Volume 4 - Inauguration Ceremony, September 22 and Non-Equilibrium Many Body Dynamics - BNL- 64912
- Volume 3 - Hadron Spin-Flip at RHIC Energies - BNL-64724
- Volume 2 - Perturbative QCD as a Probe of Hadron Structure - BNL-64723
- Volume 1 - Open Standards for Cascade Models for RHIC - BNL-64722

Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" RIKEN of Japan. The Center is dedicated to the study of strong interactions, including hard QCD/spin physics, lattice QCD and RHIC physics through nurturing of a new generation of young physicists.

During the first year, the Center had only a Theory Group. At present, the Theory Group has an active Visiting Scientist program and consists of 5 Postdocs and 4 Fellows. In addition, the Center organizes workshops centered on specific problems in strong interactions.

Now, at the Physical Society of Japan's Biannual Meeting, Matsue, Japan, we have an active Experimental Group with several scientific collaborators, one Postdoc and one Fellow. The construction of a 0.6 teraflop parallel processor, which was begun at the Center on February 19, 1998, was completed on August 28, 1998. In addition, a new Tenure Track Strong Interaction Theory RHIC Physics Fellow Program is under way. To this date nine institutions have joined this initiative. The Center has held twenty workshops since its inception.

Each workshop speaker is encouraged to select a few of the most important transparencies from his or her presentation, accompanied by a page of explanation. This material is collected at the end of the workshop by the organizer to form proceedings, which can therefore be available within a short time.

T. D. Lee
November 1, 1999

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The symposium “QCD Physics at RIKEN-BNL Research Center” was held at Shimane University, Matsue, Japan on September 23rd, 1999, both as a topical symposium of the biannual meeting of the Physical Society of Japan and a RIKEN-BNL Research Center (RBRC) workshop. The RBRC was founded as a joint project of the Institute of Physical and Chemical Research (RIKEN), Wako, Japan, and the Brookhaven National Laboratory (BNL), Upton, New York, in the fall of 1997. Since then it has dedicated itself, under the director Prof. T.D. Lee’s leadership, to promote young physicists in the field of the strong interaction in general, and in particular RHIC/QGP and RHIC/Spin physics.

Prof. Lee himself opened the symposium with a review of where the strong interaction physics stands now: Quantum Chromodynamics has been established as the fundamental theory of the strong interaction, and both experimental and theoretical means are ready to convert the field into a precision science. Only a couple of weeks after the meeting one of the main experimental apparatus, the Relativistic Heavy Ion Collider (RHIC) was dedicated at BNL. Timely reviews of its ability by Drs. Grosse Perdekamp (spin) and Shigaki (QGP) are found in these proceedings. Recent progress in making the corresponding theories more precise were reviewed by Drs. Fujii (QGP) and Yasui (spin). As the fact that three (Fujii, Grosse Perdekamp and Yasui) of these four young physicists are the current or former RBRC members tells, many important contributions were made at RBRC in the past couple of years.

Another important contribution RBRC made is in numerical lattice QCD. By the first anniversary in the fall of 1998, RBRC had completed its 0.6-TFLOPS QCDSP supercomputer in collaboration with Columbia University. Since then the collaboration evolved into RIKEN-BNL-Columbia QCD Project which pioneered numerical applications of the domain-wall-fermion and non-perturbative renormalization methods. These are applied to the first complete first-principle calculation of the ϵ' parameter of the direct CP-violation in neutral kaon. This interesting progress is reviewed here by Prof. Mawhinney.

Thus, at RIKEN-BNL Research Center, the research of the strong interaction is rapidly becoming a precision science. We hope these proceedings are useful in understanding how this development is happening. Especially important is that the young physicists are playing the central roles: RBRC just filled six joint tenure-track positions with six US institutions, has three fellows of its own and seven postdocs. In contrast all the senior staffs including the director himself are volunteers. Young physicists are encouraged to apply for the positions at RBRC as it is hiring a few more of each category. Please visit our web site at <http://penguin.phy.bnl.gov/www/riken.html>.

We thank the Physical Society of Japan, RIKEN, Brookhaven National Laboratory and to the U.S. Department of Energy for providing the facilities essential for the completion of this work.

Hideto En’yo, Physics Department, Kyoto University
Shigemi Ohta, Institute for Particle and Nuclear Studies, KEK
Koichi Yazaki, Arts and Sciences, Tokyo Woman’s Christian University

序

“QCD Physics at RIKEN BNL Research Center”シンポジウムは日本物理学会1999年秋の分科会のシンポジウムとして、また理研BNL研究センター(RBRC)ワークショップとして、9月23日に島根大学で開催されました。RBRCは理化学研究所とブルックヘイヴン国立研究所(BNL)の共同事業として1997年秋にブルックヘイヴンに設立されました。以来李政道(T.D.Lee)センター長の指導の下で若い物理学者による研究活動の重要性を協調しつつ、強い相互作用全般の研究、中でもRHIC/QGPおよびRHIC/Spin実験に関わる研究に力を注いで来ました。

シンポジウムは李センター長による強い相互作用研究の現状のレビューから始まりました：量子色力学が強い相互作用の基礎理論として確立し、この分野を精密科学とする準備が実験理論両面で整いつつあります。本シンポジウムの直後に実験面での主要装置となるべきRelativistic Heavy Ion Collider (RHIC)がBNLにおいて完成しました。本シンポジウムでもこの装置の性能についての時宜にかなったレビューがGrosse Perdekamp (Spin)、志垣(QGP)両博士によって与えられています。これらの実験に対応する理論面での精密化の進展は藤井(QGP)、安井(Spin)両博士によってレビューされました。この4人の若い物理学者のうちの3人(藤井、Grosse Perdekamp、安井)がRBRCの元または現メンバーであることが示すように、この面での多くの重要な寄与がRBRCのわずか数年の活動から生まれています。

強い相互作用研究においてRBRCがなしたもう一つの重要な寄与は格子QCD数値計算の画期的発展です。1998年秋の設置1周年の時点でコロンビア大学との協力により完成したRBRCのQCDSP型0.6テラフロップススーパーコンピュータは、その後理研BNLコロンビアQCDプロジェクト共同研究の主要装置として、ドメインウォールフェルミオン法および非摂動繰り込み法の発展に大きく寄与しました。これらの画期的新手法はK中間子崩壊の直接CP非保存過程を記述する ϵ' パラメータの初めての完備した計算に適用され大きな反響を呼びました。これについては本シンポジウムでMawhinney教授によるレビューが与えられました。

このように、強い相互作用研究は理研BNL研究センターにおいて精密科学へと急速に変貌しつつあります。本プロシーディングズがこの進展に関する皆様の理解を深めることに役立つことを願っております。最後に特に強調したいことは、この進展において若い物理学者が果たす役割の大きさです：RBRCはごく最近合衆国の他の研究機関・大学と共同で創設した六つのテニュアトラック職への任用を行い、他に3人のフェローと7人のポストドック研究者を抱えています。これとは対照的に、センター長を含めすべてのシニア職は他機関から出向のヴォランティアによっています。センターはさらに上記の若手物理学者向けの職位の全てにおいて公募を行っておりますので、奮って御応募下さい。詳細はウェブサイト<http://penguin.phy.bnl.gov/www/riken.html>からたどることができます。

御援助いただいた日本物理学会、理化学研究所、ブルックヘイヴン国立研究所および合衆国エネルギー省に感謝いたします。

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東京女子大学文理学部 矢崎紘一

Professor K. Yazaki
Chair, First Session

**Physical Society of Japan Biannual Meeting
Matsue, Japan
September 23, 1999**

Symposium on

QCD Physics at RIKEN-BNL Research Center

1:30 pm - 5:35 pm

1st half, Chair Professor Koichi Yazaki (Tokyo Woman's Christian Univ.)

1. Physics at RBRC, 60 min, T.D. Lee (RBRC/Columbia)
2. Heavy Ion Physics (theory), 20 min, Hiro Fujii (U of Tokyo)
3. Heavy Ion Physics (experiment), 40 min, Kenta Shigaki (KEK)

Break, 3:30pm - 3:45pm

2nd half, Chair Professor Hideto En'yo (Kyoto U)

4. Spin Physics at RHIC, 40 min, M. Grosse Perdekamp (RBRC)
5. Hard QCD and Spin Physics, 20 min, Yoshi Yasui (RBRC)
6. Computer and Lattice QCD, 30 min, R.D. Mawhinney (RBRC/Columbia)
7. Summary, 20 min, S. Ohta (KEK/RBRC)

The Challenge of Physics

and

Research at RBRC

T. D. Lee

Japan Physics Society, September 23, 1999

Distinguished Chairman and Colleagues:

I wish to thank the Japan Physical Society for arranging this special session on the physics research at the RIKEN BNL Research Center (RBRC). I am also proud to have this opportunity to introduce to you several of my brilliant young colleagues, who will be presenting the main body of this session:

Hirotsugu Fujii, Heavy Ion Physics (Theory)

Kenta Shigaki, Heavy Ion Physics (Experimental)

Matthias Grosse Perdekamp, Spin Physics at RHIC

Yoshiaki Yasui, Hard QCD and Spin Physics

Robert Mawhinney, Computer and Lattice QCD

Shigemi Ohta, Summary of Theory Group

It may be appropriate for me to review briefly some of the major events that led to the founding of the Center.

In 1996, Dr. Akito Arima, the President of RIKEN and Dr. Nicholas Samios, the Director of BNL, signed a Memorandum of Understanding (MOU) on the RHIC Spin Physics Research. On May 16th and 17th, the same year, I made my first visit to RIKEN. Dr. Arima discussed with me the possibility of establishing a Center near the RHIC accelerator. (An account of that visit was recorded in Volume 13 of the Proceedings of RBRC, BNL 66299 (1998)). The Inauguration of the RIKEN BNL Research Center was held at BNL on September 22, 1997. On February 19, 1998, we began the construction of the 0.6 Teraflop Supercomputer, which was completed six months later on August 28 the same year, and was awarded the SC 98 Gordon Bell Prize for Price Performance. In this talk, I will discuss some of the physics results obtained by RBRC members using this supercomputer.

The major problems in physics are:

- Theories based on symmetry, but experiments violate symmetries
- Half of the elementary particles are never free
- Lack of precision QCD calculations (Spin Problem)
- CP Violation

Relativistic Heavy Ion Physics

Fujii, Shigaki

Spin Physics

Yasui, Perdekemp

CP Violation

Mawhinney, Ohta

Need for Precise QCD Calculations

Q C D S P

(RBRC - BNL - Columbia)

*Why do we believe in
symmetry?*

*The world we live in is filled with
asymmetry.*

*Perhaps
Maximum asymmetrical possibilities
= perfect symmetry*

BUCKLING (Euler)

$$F = \frac{\pi^2 EI}{l^2}$$

$$F = 0$$

E = elastic constant
 I = moment of inertia
 l = length of the rod

Possible Buckling Directions	Cross-sections
∞
2
1

BUCKLING

- Circular cross section gives maximum possibility of asymmetrical buckling.
- These different asymmetrical buckling directions are connected through rotation.
- Consequently, there is a zero energy excitation (analog of Goldstone-Nambu boson).

- Theories based on symmetry, but experiments violate symmetries

The buckled rod is the analog of the _____ for particle physics.

- Half of the elementary particles are never free

Boundary conditions are always determined by experimental probes, separate from the equation of motion.

- the boundary condition of QCD is volume-dependent

quarks and gluons

hadrons

An effective experimental probe to explore these volume- and energy-dependent boundary conditions is:

Au - Au at 100 GeV/nucleon (v20 TeV/Au)

With quarks

$$\frac{S}{T^3} \approx \frac{1}{2} (16 + 2 \cdot 2 \cdot 3 \cdot 3) = 52/2$$

Columbia (N. Christ et al)

(i) SUDDEN ENTROPY CHANGE

→ volume expansion in hadronization

(ii) SUDDEN DENSITY CHANGE

→ new coherence parameter

→ discrete symmetry violation/collision

Entropy vs. Temperature
 $16^3 \times 4$ Lattice, $\beta = 1.9$, Staggered

Columbia

RHIC (100 GeV/nucleon)

before

Is Vacuum a Physical Medium?

T.D.L. and G.C. Wick, Phys.Rev. **D9**, 2291 (1974).

after

(quark-antiquark
gluon plasma)

Sudden entropy change

Conversion of particle signals to volume measurements (Hanbury-Brown/Twiss)

$$| \text{Amp} |^2 \propto | e^{i \vec{k}_1 \cdot \vec{r}_1} + e^{i \vec{k}_2 \cdot \vec{r}_2} + e^{i \vec{k}_2 \cdot \vec{r}_1} + e^{i \vec{k}_1 \cdot \vec{r}_2} |^2$$

$$= 1 + \cos \vec{q} \cdot \vec{r} . \text{ (varies from 1 to 2)}$$

$$\vec{q} = \vec{k}_1 - \vec{k}_2 \quad \& \quad \vec{r} = \vec{r}_1 - \vec{r}_2$$

Here, π can be any bosonic channel.

For fermionic channel:

$$| \text{Amp} |^2 \propto 1 - \cos \vec{q} \cdot \vec{r}$$

parity violation per RHIC

collision to detect coherence:

$O(x)$ is parity odd

$\langle O(x) \rangle \neq 0$ per collision

over $|x| \sim 5$ fm

$\langle O(x) \rangle = 0$ over all collisions

examples: 1. $O = \vec{E} \cdot \vec{B}$

or 2. $O = qq$ in $\bar{3}$

Kharzeev et.al.

Rischke, Pisarski

signal	experimental accuracy
$(\vec{k}_1 \times \vec{k}_2) \cdot \vec{k}_3$	$10^{-4} - 10^{-5}$ (for π 's)

Disagreement between Sum Rules and Experiment in Spin Physics

THE BJORKEN SUM RULE

$$\underbrace{\int_0^1 g_1^p(x, Q^2) dx}_{I_p} - \underbrace{\int_0^1 g_1^n(x, Q^2) dx}_{I_n} = \frac{1}{6} \left| \frac{g_A}{g_V} \right| \left\{ 1 - \frac{\alpha_s}{\pi} - \dots \right\}$$

22

THE ELLIS-JAFFE SUM RULES

$$\int_0^1 g_1^p(x, Q^2) dx = \frac{1}{12} \left| \frac{g_A}{g_V} \right| \left\{ 1 + \frac{5}{3} \times \frac{3F/D - 1}{F/D + 1} \right\} \left\{ 1 - 1.8 \frac{\alpha_s}{\pi} - \dots \right\}$$

$$\int_0^1 g_1^n(x, Q^2) dx = \frac{1}{12} \left| \frac{g_A}{g_V} \right| \left\{ -1 + \frac{5}{3} \times \frac{3F/D - 1}{F/D + 1} \right\} \left\{ 1 + 0.22 \frac{\alpha_s}{\pi} - \dots \right\}$$

where $F = 0.459 \pm .008$ and $D = 0.798 \pm .008$ from hyperon β -decay

EXP	target	Year	$\langle Q^2 \rangle$ (GeV/c) ²	Integral $\int_0^1 g_1 dx$
EMC/SLAC	proton	1988	10.7	$I_p = 0.126 \pm .010 \pm .015$
SMC	deuteron	1993	5	$I_d = 0.023 \pm .020 \pm .015$
E142	neutron (He3)	1993	2	$I_n = -0.022 \pm .007 \pm .009$
SMC	proton	1994	10	$I_p = 0.136 \pm .011 \pm .011$
E143	proton	1994	3	$I_p = 0.129 \pm .004 \pm .009$
E143	deuteron	1994	3	$I_d = 0.042 \pm .003 \pm .004$
SMC	deuteron	1995	10	$I_d = 0.034 \pm .009 \pm .006$

$Q^2 = 3 \text{ GeV/c}^2$

The Importance of CP and T Violations

The Big Bang is presumably CP symmetric.

The present universe is not; it consists predominantly of nucleons and electrons. This is why we can exist.

CP violation

- CP violation
- Lack of precision QCD calculations

$$\frac{\text{Rate}(K_L^0 \rightarrow \pi^+ \pi^-)}{\frac{\text{Rate}(K_S^0 \rightarrow \pi^+ \pi^-)}{\text{Rate}(K_L^0 \rightarrow \pi^0 \pi^0)}} = \left| \frac{\epsilon + \epsilon'}{\epsilon - 2\epsilon'} \right|^2 \equiv 1 + 6 \text{Re}(\epsilon'/\epsilon)$$

$$\text{Rate}(K_S^0 \rightarrow \pi^+ \pi^-) \approx 10^{-4} \text{ s}^{-1}$$

experimental results	theoretical estimates (based on CKM matrix)
• 28 ± 4 (FNAL)	$4.6 \pm 3.0 \pm 0.4$ (Rome '97)
• $23 \pm 3.6 \pm 5.4$ (NA31)	3.6 ± 3.4 (Munich '97) $(10.4 \pm 8.3 \text{ if } m_s \sim 100 \text{ MeV})$
$7.4 \pm 5.2 \pm 2.9$ (E731)	17^{+14}_{-10} (Trieste '98)

- First Lattice QCD study using domain wall fermions (QCDSP)

$$-(330 \pm 160) \eta_{\text{CKM}} \equiv -122 \pm 68$$

RIKEN • BNL • Columbia

Quantum Chromodynamics (QCD) Project

Quantum Chromodynamics (QCD) Project

Total Peak Speed: 1100.8 Gflops

Given the enormous computational demands of quantum field theory and the easily parallelized nature of this problem, it is natural to design and build massively parallel machines whose design is optimized for this type of calculation.

The QCDSP (*Quantum Chromodynamics on Digital Signal Processors*) computers designed at Columbia are such machines.

RIKEN • BNL Research Center

Columbia University Center

SC₉₈

Gordon Bell Prize "WINNER" for Price Performance

Columbia:

Dong Chen, Ping Chen, Norman Christ, George Fleming, Alan Gara, Chulwoo Jung, Adrian Kaehler, Yubing Luo, Catalin Mallureanu, Tim Klassen, Robert Mawhinney, John Parsons, Gabi Siegert, Chengzhong Sui, Pavlos Vranas, Lingling Wu, Yuri Zhestkov

RIKEN (R B R C)

Tom Blum, Shigemi Ohta Shoichi Sasaki Matthew Wingate

Brookhaven:

Michael Creutz, Chris Dwason, Amarjit Soni

Other Collaborators:

Robert Edwards (SCRI), Sten Hansen (Fermilab)
Anthony Kennedy (SCRI), Greg Kilcup (OSU), Jim Sexton (Dublin)

Quark Mass Renormalization

RIKEN-BNL-Columbia QCD Collaboration

No Chiral Mixing

domain wall lattice (QCDSP)

$$O_{LL} = (V-A) \cdot (V-A) = VV + AA - VA - AV$$

ζ -fermion vertex

Blum

$$\epsilon \propto \gamma \cdot B_K$$

$$B_K = \frac{\langle \bar{K} / O_{LL} / K \rangle}{\frac{8}{3} f_K^2 m_K^2}$$

$$O_{LL} = \bar{s} \gamma_\mu (1 - \gamma_5) d \bar{s} \gamma_\mu (1 - \gamma_5) d$$

(and $m_K \rightarrow 0$)

From One to Ten Teraflops

• Faster Processor:

- Texas Instruments TMS320C64 [QCDSP: C31]
- 0.67 Gflops [0.05Gflops]
- 32 Kwords on-chip memory [2Kwords]
will hold a 4^4 lattice.
- ≤ 2 Watts [0.7 Watts]
- $\approx \$100$ [\$62 $\rightarrow$ \$36]

• Faster communications.

- 200 MHz, serial [50 MHz]
- Phase locked loop.

• Larger memory: ≥ 16 Mbyte [2 Mbyte]

• Performance cost/performance improvement: \$10/Mflops [\$10/Mflops]

• Target machine: 16,384 processors, 10 Tflops [20,480 processors, 1 Tflops]

The Japanese initiatives: B-facility at KEK, the large hadron facility and the lattice QCD projects (CP-PACS at KEK and QCDSF at RBRC) form a three-prong exploration of the CP problem. For B-physics, the relevant part of the CKM matrix is the first (ud, cd and td) and third (ub, cb and tb) columns; the vectors formed by these two columns are orthogonal to each other, yielding the top triangle in the following triangle. For K-physics, we consider the first and second (us, cs and ts) columns, whose orthogonality is represented by the second (very narrow) triangles. The non-zero value of the areas of these triangles gives CP violation. The standard electroweak model (via the CKM matrix) yields equal areas for these two triangles. Test of the first triangle requires B-facilities, and the test of the second triangle requires the rare K-decays at the large hadron facility.

UNITARITY TRIANGLE

$$J_{13}^{\text{CP}} = 2 \times \text{Area}$$

$$J_{12}^{\text{CP}} = 2 \times \text{Area} = 5.60 [\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu})]^{1/2}$$

[+ new picture may emerge from QCDSP,
Rare K decay and $B \rightarrow 2\pi$ type expts]

20th Century Physics

Reductionism: Search for the smallest

35

21st Century Physics

Holism: Union of the microscopic system
and the macroscopic world

Beginning with J. J. Thomson's discovery of the electron at the turn of the century, and Rutherford's discovery of the atomic nucleus, 20th century physics has been driven by the quest for the increasingly small. We believed through studying the smallest things, understanding of all larger ones would naturally follow. The dominance of such "reductionism" is further reinforced by our ability to make precise predictions based on quantum theory, and accurate measurements through experiments.

However, the dichotomy between the symmetry in our theories and its violations in our observations, and the puzzle of quark-confinement force us to treat the physical vacuum as an independent macroscopic medium, which embeds the microscopic world of elementary particles. At present, we are poised at the threshold of a new revolution in physics, moving from "reductionism" to "holism." Again, our future successes will be based on new theories capable of making precise predictions which must be confirmed by new accurate measurements.

Our successful century-long voyage searching for the small and fundamental encouraged Max Delbruck, Francis Crick and others to extend the same approach to biology. The result has been the fundamental discoveries of DNA, RNA and other basic sub-cellular units. However life is a macroscopic phenomenon. Sooner or later, biologists would have to shift to the study of life as a whole. They must, like us, also turn from "reductionism" to "holism."

In the 21st century, as we make future discoveries that unite the microscopic world of particle physics with the macroscopic state of the physical vacuum, new precise and accurate capabilities will naturally be developed. These capabilities should again bridge over to our colleagues in other fields of sciences. The next century can again be the Century of Physics.

逍 遙 游 莊 子

Boundless Freedom (The Big Bang)

Praise the bird that named Peng (鵬)
Whose body extended several thousand miles long.

When Peng flew, glorious to behold,
His wings were the clouds in the sky,
And all heaven rode on his back,
Nothing could contain him

Zhangzi

Relativistic Heavy Ion Physics — Theory —

H. FUJII (U. of Tokyo)

Sept. 23, 1999

P L A N

1. PHYSICS MOTIVATION
2. QCD THERMODYNAMICS
3. COLLISION DYNAMICS
4. SIGNATURES OF NEW PHASE
5. CONCLUSION

PHYSICS MOTIVATION

We have the fundamental theory of the strong interaction
QCD

QGP predicted just after QCD (asympt. free) established

RHIC offers an opportunity to change QCD 'vacuum'
to Create the QCD parton (q & g) matter
to Study the properties of the Excited QCD system

Two directions of theoretical efforts:

1. Explore the QCD phase diagram and its properties
2. Describe the coll. dynamics of QCD matter

QCD THERMODYNAMICS (in eqbm)

LQCD, hot gauge theory, Eff. models

Critical behavior of transition depends on

In-medium properties;

$m(T, \mu)$, $\Gamma(T, \mu)$ of h,q,g
behavior of UA(1) breaking, etc.

New topics;

Color supercond., Tricritical pt.

COLLISION DYNAMICS

involves various aspects of QCD: from hard to soft, in/out of equilibrium and QGP pt. hopefully!

Unified description of RHIC

XN Wang, Phys. Rept.

Bjorken, PRC27(83)140, $dN_R/dy \sim 0$

Pb+Pb@SPS: $dE_T/dy \sim 400 \text{ GeV}$ of strings

HIJING/B $\bar{B}$, $dN_R/dy \sim 20$

Au+Au@RHIC: $dE_T/dy \sim 1 \text{ TeV}$ of minijets

Vance-Gyulassy-Wang, PLB443(98)45

NB: There is no unified model which describes the whole time evolution

Strings; $K=1-4$ GeV/fm

Mini jets; pQCD, $p_0=1-2$ GeV

Classical Yang-Mills Fields

Parton cascade towards equilib.

modes, screening, $\alpha_s \dots$

Kinetic eqbm, but chemical non-eqbm;

fluid-dyn. w/rate eqns to chem eqbm

local equilib

fluid dyn. w/EoS with the transition

$Q \rightarrow H$ fragm., Cluster

out-of-equilib

Eff. fields (DCC)

ideal: fluid to free gas abruptly

real: decoupling by hadronic cascade

Medium effects: m_{eff} , μ_{eff}

$Q \rightarrow H$

"A Code = A Model" ? Y. PANG

[OSCAR: Open Standard Codes and Routines]

established at a RHIC Workshop 97 (Y.Pang, M Gyulassy)

List of Codes

- 1. Partonic/String Transport
HIJING HIJING/BB MPC neXus PCPC VNI VNlb ZPC
- 2. String/Hadronic Transport
ART BEM BNC HSD JAM JPCIAE LEXUS LUCIAE RQMD
UrQMD

3. ...

...	
Code Name:	HIJING - Heavy Ion Collision
Authors:	Miklos Gyulassy and Xin-Nian Wang
Description:	Monte Carlo Model for Heavy Ion Collisions w/ emphasis on hard
Home page:	http://www-nsdth.lbl.gov/~xnwang/hijing/ - verified Fri Jul 30 12..
Accessibility:	Versions 1.3 to 1.36 are available for dwnload from the home page
User Manual:	Shost on-line description
Code Ref:	HIJING 1.0 published in Comp. Phys. Comm.
Physics Ref:	Phys.Rept
...	
Code Name:	JAM - Jet AA Microscopic Transport Model
Author:	Yasushi Nara, see his talk!
Description:	In JAM, hadrons and their excited states are explicitly ...
Home page:	http://hadron31.tokai.jaeri.go.jp/jam.html - verified Wed Sep 8 20...
Accessibility:	Version 1.009h available from the above home page.
Copyright:	This program is a free software under the terms of GNU General P...
User Manual:	in preparation

Y. NARA

SIGNATURES OF NEW PHASE

Abrupt change in observables as fns. of $\{\sqrt{s}, \text{impact param.}, A\}$

high density, low temperature, color deconfinement

Standard:

1. hadron yields — $\sim \exp(-m_s/T)$
"m_s"

2. flow — radial, dir. flow, elliptic
"EOS"

3. dileptons;

J/ψ suppression,

Kharzeev, HF

in-medium meson masses

Schaffner

Example

• Disoriented Chiral Cond.

• parity odd bubble in hot QCD

Kharzeev-Pisarski-Tytgat

3. parity violation thru color-supercond ($\mu_B \neq 0$)

Alford-Rajagopal-Wilczek,
Rapp-Shafer-Shuryak-Velkovsky,
Pisarski-Rischke, Son, etc.

Standard

E.g.

- Strangeness: Ω enhancement

Parity odd bubble in hot QCD

KHARAZMI, SARSA, T. 1347, PRL 97, 031601 (2006)

- Strong interactions at finite temperature T are described by the QCD Lagrangian
- Can this system exhibit a phase transition?

- Consider the vacuum of the non-linear σ model

$$U(\phi_i) = f_\pi^2 \left[- \sum_i \mu_i^2 \cos \phi_i + \frac{a}{2} \left(\sum_i \phi_i - \theta \right)^2 \right] \quad (\theta \approx 0)$$

when $T \uparrow T_c$, topological suscept.

$a \downarrow$

- Experimental signatures:

Measure global
P-odd obs.

→ constructed from
 p_π 's on the EbE
basis

E.g.

$$\sum (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}) \cdot \hat{z}$$

$\frac{\sigma_z}{k}$

Parity violation thru color-super.

The diagram illustrates the experimental setup. A participant is seated at a table, looking at a monitor. On the table is a 3D model of a hand. A target is indicated on the monitor. The participant is instructed to move the hand to the target. The setup includes a screen, a hand model, and a target. The participant's eye is positioned to view the hand and the target simultaneously. The hand is moved towards the target, and the target is updated in real-time. The participant's hand position is tracked, and the target is moved accordingly. The participant is instructed to move the hand to the target, and the target is updated in real-time. The participant's hand position is tracked, and the target is moved accordingly. The participant is instructed to move the hand to the target, and the target is updated in real-time. The participant's hand position is tracked, and the target is moved accordingly.

- OGE between qq is attractive in $[\bar{3}]$ -channel

$\Rightarrow$

—

variational calculations with mean fields

$$\Delta_{g,\alpha\beta} \equiv \langle \psi_{g,\alpha} \psi_{g,\beta} \rangle \neq 0 \quad \begin{array}{l} g=1, \dots, N_f \\ \alpha, \beta=1, \dots, 4 \end{array}$$

- Gap eq. or RG analysis $\mathbb{R}^d - \mathbb{C}^d \rightarrow \mathbb{C}^d$

$(\text{BCS}, \mu b \exp(-c/g^2))$

- $T_c \sim 1.13\phi(T=0) \sim 0.15\mu$

- $\phi^+_{+} = e^i \phi^+_{-}$

fixed by condensate!

$\Rightarrow$ Spontaneous breaking of $U_A(1)$!

CONCLUSION

1. QCD phase diagram may be more interesting than expected before, and RHIC will create new phase!
2. No unified model which describes the whole evolution of a coll.
⇒ Reliable picture (description) is strongly needed!
(by combining people's efforts!)
(E.g. OSCAR, Open Standard Codes and Routines)
3. Standard signatures will reveal interesting physics, but keep eyes open for qualitatively new effects!
(E.g. Parity violation)
4. RBRC is leading these activities

Past RBRC Workshops – HI phys. –

- Open Standards for CAscade models for Rhic (OSCAR) I ('97 summer)
OSCAR II: Predictions for RHIC ('99 summer)
- Non-Equilibrium Many Body Physics ('97 fall)
Color Supercond., Instantons, and P (Non?)-Conservation at High μ_B
- Quarkonium Production in Relativistic Nuclear Collisions
- High Density Matter in AGS, SPS and RHIC collisions
- QCD Phase Transitions, Quantum Fields In & Out of Equilibrium, etc

***Experimental Relativistic
Heavy Ion Physics
at BNL-RHIC
with a focus on PHENIX Experiment***

Kenta Shigaki (KEK)

at

JPS Symposium “QCD Physics at RBRC”

in

Matsue, Shimane, Japan

on

September 23, 1999

Presentation Outline

- Relativistic Heavy Ion Physics at RHIC
- RHIC Accelerator
- RHIC Experiments
- Physics Strategies of PHENIX Experiment
- Upcoming Physics from PHENIX
- Electron Measurement in PHENIX
- Summary

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Physics at RHIC

- QCD in extreme conditions and scales
 - high energy density limit (relativistic heavy ion physics)
 - high Q^2 limit (high energy spin physics)
- relativistic heavy ion physics
 - search for and characterize deconfined quark gluon plasma phase
- high energy spin physics
 - elucidate spin structure of nucleon

asymptotic freedom at short
range / high energy

Relativistic Heavy Ion Physics at RHIC

- Bevalac/SIS/AGS/SPS
 - from high density regime to high energy density (“*temperature*”) regime
- RHIC
 - reproduction of universe a few μsec after big-bang

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Recent Hot Topics from SPS and AGS

- J/Ψ “anomalous” suppression
 - SPS NA50
- low-mass dielectron enhancement
 - SPS NA45 (CERES)
- flavor equilibrium
 - AGS E866, E877
 - SPS NA49, WA97
- collective radial/directed/elliptic flow
 - AGS E866, E877, E895, E917
 - SPS NA45, NA49, NA52, WA98
- onsets of QCD phase transition ?

J/Ψ “Anomalous” Suppression

- observed in central Pb+Pb collisions by SPS NA50
 - predicted by T.Matsui and HSatz

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Debye screening ?

Low-Mass Dielectron Enhancement

- excess over known hadronic sources observed in S+Au and Pb+Au collisions by SPS NA45
- theoretical approaches *e.g.* ρ enhancement/melting

September 23, 1999

K.Shigaki at JPS Symposium "QCD Physics at RBRC" in Matsue

Flavor Equilibrium

- phase diagram of hadronic matter based on hadro-chemical analysis
 - P.Braun-Munzinger, J.Stachel *et al.*

- hadro-chemical freeze-out points approach phase boundary at AGS and SPS
- RHIC and LHC expected to show clearer signal of QCD phase transition

Collective Radial/Directed/Elliptic Flow

- radially flowing thermal source explains mass dependence of “*temperature*” parameters
 - theory by U.Heinz *et al.* ; phenomenology by N Xu *et al.*
- directed/elliptic flow as an excitation function
 - information on shadowing, equation of state

RHIC (Relativistic Heavy Ion Collider) Accelerator

Configuration	Two Concentric Superconducting Magnet Rings	
Circumference	3.8 km	
Interaction Point	6	
Number of Bunch	60; 120 in enhanced mode	
Ion Species	ranges from p to Gold, $p+A$ is possible	
	pp	$Au+Au$
Injection	Linac $\rightarrow$ Booster $\rightarrow$ AGS	Van de Graaf $\rightarrow$ Booster $\rightarrow$ AGS
E_{cm} (Maximum)	500 GeV	200A GeV
Luminosity	$2 \times 10^{32} \text{ cm}^{-2}\text{sec}^{-1}$	$2 \times 10^{26} \text{ cm}^{-2}\text{sec}^{-1}$
Polarization	70%	~
Completion	Expected in June 1999	

- ultimate tool with:
 - 2 superconducting rings
 - 3.8 km circumference
 - 6 intersecting locations
 - AGS complex as injector
- heavy ion collider
 - up to Au+Au at 200 A GeV
 - current max.: 18 A GeV (SPS)
 - capable of $p+p$, $p+A$, $A+B$
- polarized proton collider
 - up to 500 GeV
 - current max.: 20 GeV (FNAL)
 - RIKEN - BNL collaboration

Status of RHIC Accelerator

- construction phase finished in August, 1999
- physics run starting in January, 2000

RHIC Experiments

- complimentary set of experiments
- 2 large experiments
 - STAR at 6 o'clock
 - PHENIX at 8 o'clock
- 2 small experiments
 - BRAHMS at 2 o'clock
 - PHOBOS at 10 o'clock
- 2 open collision points for future experiments

STAR (sphenoidal tracking HIC) Experiment

- ~ 440 collaborators, 36 institutions, 7 countries
- large TPC-based detector system
 - event-by-event recording of hadrons and jets

September 23, 1999

K.Shigaki at JPS Symposium "QCD Physics at RBRC" in Matsue

Status of STAR Experiment

- baseline construction completed in June, 1999

beam-gas interaction event

September 23, 1999

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BRAHMS (Broad Range Hadron Spectrometer) Exp.

- ~ 50 collaborators, 12 institutions, 6 countries
- identified charged hadrons over wide kinematics
- focus on reaction dynamics

Status of BRAHMS Experiment

- baseline components ready on both arms

September 23, 1999

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PHOBOS Experiment

- ~ 80 collaborators, 9 institutions, 3 countries
- 10K element 4π detector for $d^2N/d\eta d\phi$
- two-arm small silicon pad spectrometer
- high rate capability, minimum bias events to tape

Status of PHOBOS Experiment

- all silicon detectors assembled and tested
 - multiplicity and vertex detectors
 - one spectrometer arm

PHENIX (pioneering high energy nucl. on E p.) Exp.

- ~ 430 collaborators, 42 institutions, 11 countries
 - wide collaboration for wide physics

Physics Strategies of PHENIX

- wide variety of probes with same systematics
 - sensitivity to many signatures and essentially all time-scales
 - color Debye screening
 - chiral symmetry restoration
 - change of vector meson properties
 - disoriented chiral condensation
 - thermal radiation of hot gas
 - heavy quark (s, c) production
 - jet quenching
- emphasis on transparent probes
 - photon and vector meson via γ , γ^* , l^+l^-

PHENIX Detector System

- 2 central arms for photon, electron, hadron
 - tracking chambers
 - RICH, ToF, EMCal
- 2 forward arms for muon
 - tracking chambers
 - muon identifier
- global detectors for event characterization
 - beam/beam counter
 - multiplicity/vertex detector

Japanese Contributions to PHENIX (1)

- beam/beam counter
 - Hiroshima U.
- ring imaging Cherenkov detector
 - CNS, U.Tokyo, KEK, Waseda U., Nagasaki IAS
- time of flight counter
 - U.Tsukuba
- south muon spectrometer
 - RIKEN, Kyoto U., TIT

Japanese Contributions to PHENIX (2)

- central magnet coil, drift chamber readout chip
 - KEK
- regional computing center in Japan
 - RBRC, RIKEN, CNS, Kyoto U., KEK, etc.
- other hardware/software activities
 - on EMCal beam test
- RHIC (not only PHENIX) polarimeter
 - RBRC, RIKEN, Kyoto U.

PHENIX—J Members at BNL

September 23, 1999

K.Shigaki at JPS Symposium "QCD Physics at RBRC" in Matsue

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Status of PHENIX Experiment (1)

- west central arm
 - loaded with DC, PC, RICH, EMCAL
 - tested with beam in June-August, 1999

beam/gas interaction event
in beam/beam counter

Status of PHENIX Experiment (2)

- east central arm
 - being assembled for installation in March, 2000
 - will have DC, PC, RICH, TEC, ToF, EMCal
- south/north muon arms
 - identifiers installed
 - trackers in year 2/3

beam/gas interaction event
in two planes of TEC

Chronological Strategies of PHENIX

- priorities in year 1 (2000) in descending order
 - first physics from Au+Au at 200 A GeV
 - > 120 M unbiased events ($> 20\mu\text{b}^{-1}$ integrated luminosity)
 - polarized proton commissioning in one ring
 - ~ 4 weeks
 - p+p running to characterize baseline physics
- year 2
 - greater sensitivity to rare probes in Au+Au
 - first results on spin physics
- year 3 and later
 - continuing program of heavy ion and spin discoveries

Upcoming Physics from PHENIX

- physics and time scales accessible in year 1
 - initial hard process
 - jet, hard photon
 - deconfinement
 - high-mass vector meson J/Ψ , Ψ'
 - high p_t photon from π^0 , η , η'
 - chiral restoration
 - low-mass vector meson ρ , ω , ϕ
 - thermalization
 - soft photon, non-resonant dielectron
 - open charm via single electron
 - hadronization
 - hadron spectra, strangeness, HBT interferometry
 - hydro-dynamics
 - transverse energy, dN/dy

Electron Measurement in PHENIX

- probes of particular importance
 - dielectron spectra
 - single electron spectra
- “*background*” sources
 - Dalitz decay
 - heavy quarks
 - photon conversion
 - hadron mis-identification
- requirements for eID
 - roughly $10^2 \sim 10^4$
 - physics goal dependent
 - p_t dependent

expected e/π ratio

Electron ID in PHENIX Central Arms

- charged particle tracking
 - DC, PC, TEC
 - (RICH, ToF, EMCal)
- electron identification
 - RICH
 - ring finding
 - EMCal
 - energy / momentum matching
 - time of flight
 - shower shape
 - TEC
 - energy deposit

PHENIX RICH Detector

schematics of PHENIX RICH

- primary electron identification device
- full coverage of central arm acceptance
- threshold gas Cherenkov
 - C_2H_6 ($\gamma_{\text{th}} \sim 25$)
 - CO_2 ($\gamma_{\text{th}} \sim 35$) for year 1
 - eID p_t range : $0.2 \sim 4 \text{ GeV}/c$
- PMT array readout
 - 5,120 channels in 2 arms
 - $\sim 1 \text{ degree} \times 1 \text{ degree}$ pixels

PHENIX RICH Group

- CNS, U.Tokyo H.Hamagaki, S.Nishimura, K.Oyama,
T.Sakaguchi
- Florida State U. R.Chappell, D.Crook, A.D.Frawley
- KEK Y.Akiba, K.Shigaki
- Nagasaki IAS K.Ebisu, H.Hara, Y.Tanaka, T.Ushiroda
- ORNL M.S.Emery, S.Frank, J.P.Jones, C.Moscone,
J.W.Walker, A.L.Wintenberg, G.R.Young
- SUNY at SB R.Begay, J.Burward-Hoy, J.Ferriera,
T.K.Hemmick, R.Hutter, S.Salomone
- U.Tokyo R.S.Hayano
- Waseda U. M.Hibino, S.Kametani, J.Kikuchi,
T.Matsumoto, M.Tamai

Status of PHENIX RICH Detector

- both arms of RICH completed
- first arm installed on PHENIX west arm

PMT array in RICH gas vessel

PMT arrays reflected on mirrors;
before installation of front window

Electron Capability of PHENIX

- hadron rejection power of RICH
 - 10^4 level for single track
 - 200 ~ 1,500 in central Au+Au
- hadron contamination in electron measurement
 - ~ 20 % for single electron
 - ~ 50 % for dielectron
- signal to background ratio for vector mesons
 - ~ 1/10 for ϕ
 - ~ 1/15 for ω
 - < 1/100 for ρ

Summary

- RHIC is a unique facility to study QCD in extreme conditions and scales through two-fold approaches
 - relativistic heavy ion physics
 - high energy spin physics ()
- construction phase of RHIC has finished; operation started in 1999
- first physics run starts in January, 2000
- experiments are ready to look at Au+Au collisions
 - aiming at discovery of quark gluon plasma phase
- be prepared...

August 12-18, 1999, Volume 3 Number 32, Long Island's only news, arts and entertainment weekly - www.livoice.com

HERNANDEZ

FREE

long island
VOICE

THE

WORLD
ENDS

HERE
THE EARLY
MOVES
FOR
BNL'S
BIG BANG

Spin Physics at RHIC

- Polarized Structure Functions

- Experimental Situation

Current Status

Future Experiments

- The RHIC Spin Program

Polarized Protons

Polarization Measurement

PHENIX and STAR

Polarized Proton Structure

Proton

Quark (Parton)-
distribution functions:

$$\Delta f(x) = f^{\uparrow}(x) - f^{\downarrow}(x)$$

Probability that a quark
of flavor f has momen-
tum x and spin parallel
to the proton spin

Quark Spin:

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s}$$

$$= \sum_{i=u,d,s} \int_0^1 \Delta f_i(x) dx \approx 0.2 \rightarrow \text{"Spin Crisis"}$$

Spin

$$\frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta G + L_z$$

Quark Spin Gluon Spin Orbital Angular Momentum

Polarized Proton Structure in Deep Inelastic Scattering

- k, k' : Lepton four momenta
- $Q^2 = -(k - k')^2$: Four momentum transfer
- $\nu = E - E'$: Energy transfer
- $x = Q^2 / 2M\nu$: Bjorken scaling variable
- $y = \nu / E$: Fractional energy transfer
- $\gamma = \sqrt{Q^2} / \nu$

Cross Section

$$\frac{d\sigma}{dx dQ^2} = \text{unpol.} [F_1(x, Q^2), F_2(x, Q^2)]$$

$$= \frac{1}{2} \left[(y - 2) g_1(x, Q^2) + y \gamma^2 g_2(x, Q^2) \right]$$

$$+ \frac{1}{2} \left[y g_1(x, Q^2) + 2 g_2(x, Q^2) \right]$$

Polarized Structure Functions:

$$F_1(x) = \frac{1}{2} \sum_{i=u,d,s} e_i^2 f_i(x) \quad (\text{unpolarized})$$

$$g_1(x) = \frac{1}{2} \sum_{i=u,d,s} e_i^2 \Delta f_i(x) \quad (\text{longitudinal spin})$$

$$h_1(x) = \frac{1}{2} \sum_{i=u,d,s} e_i^2 \Delta_T f_i(x) \quad (\text{transverse spin})$$

Experimental Spin Asymmetries

Photo absorption:

Cross Section:

Proton and photon spin antiparallel:
Quarks with spin parallel contribute

$$\sigma^{\uparrow\downarrow} \propto \gamma^{\uparrow} P^{\downarrow} \propto \sum_{i=u,d,s} e_i^2 q_i^{\uparrow}$$

$$\sigma^{\uparrow\uparrow} \propto \gamma^{\uparrow} P^{\uparrow} \propto \sum_{i=u,d,s} e_i^2 q_i^{\downarrow}$$

Proton and photon spin parallel: Quarks
Quarks with spin anti-parallel contribute

➔ Measure Double Spin Asymmetry

$$A_{LL} = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} \equiv A_1 = \frac{g_1}{F_1}$$

Virtual photon Asymmetry

Polarized Proton Structure in polarized pp Scattering

Cross Section:

$$\Delta\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2 \Delta f_i(x_2) \Delta f_j(x_2) \Delta\sigma_{ij}(x_1 P_1, x_2 P_2)$$

Example: Gluon Compton Scattering

The related double spin asymmetry:

$$A_{LL} = a_{LL}(qg \rightarrow q\gamma) \cdot \frac{\Delta g(x_1)}{g(x_1)} \cdot \frac{\sum_{i=u,d,s} e_i^2 \Delta f_i(x_2)}{\sum_{i=u,d,s} e_i^2 f_i(x_2)}$$

$$= a_{LL}(qg \rightarrow q\gamma) \cdot \frac{\Delta g(x_1)}{g(x_1)} \cdot A_1(x_2)$$

Current Experimental Situation

$g_1(x)$: World Data

QCD Analysis of available Data Sets:
(SMC Phys, Rev. D58:112002, 1998)

$$g_1(x, Q^2) = \frac{1}{6} \sum_{i=u,d,s} e_i^2 \int_x^1 \frac{dy}{y} \left[C_S^q\left(\frac{x}{y}, \alpha_s\right) \Delta\Sigma(x, Q^2) + 6C_S^g\left(\frac{x}{y}, \alpha_s\right) \Delta g(x, Q^2) + C_{NS}^q\left(\frac{x}{y}, \alpha_s\right) \Delta q_{NS}(x, Q^2) \right]$$

where

$$\Delta\Sigma(x, Q^2) = \sum_{i=u,d,s} \Delta q_i(x, Q^2)$$

$$\Delta q_{NS}(x, Q^2) = \sum_{i=u,d,s} \left(\frac{e_i^2}{\frac{1}{3} \sum_j e_j^2} - 1 \right) \Delta q_i(x, Q^2)$$

Results on Quark and Gluon Spin Contributions

Quark Spin Contribution:

$$\Delta\Sigma = \int_0^1 \Delta\Sigma(x, Q^2 = 1 \text{ GeV}^2) dx = 0.23 \pm 0.07$$

(QPM expectation = 0.58)

Gluon Spin Contribution:

$$\Delta G = \int_0^1 \Delta g(x, Q^2 = 1 \text{ GeV}^2) dx = 0.99^{+1.2}_{-0.3}$$

↑ Proton Spin Puzzle remains unsolved!
 $\Delta\Sigma$ constrained, need to measure ΔG

New Experiments for ΔG Measurements

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Polarized pp		Polarized DIS	
RHIC/BNL		HERA/DESY and CERN/SPS	
π^0 Production $A_{LL}(gg, gq \rightarrow \pi^0 + X)$	PHENIX	pQCD at low x	$A_1(x, Q^2)$
Heavy Flavors $A_{LL}(gg \rightarrow c\bar{c}, b\bar{b} + X)$			
Direct Photon $A_{LL}(gq \rightarrow \gamma + X)$		Photon Gluon Fusion $A_{LL}(\gamma g \rightarrow q\bar{q})$	
Jet Photon $A_{LL}(gq \rightarrow \gamma + Jet + X)$			
Jet Jet $A_{LL}(gq \rightarrow Jet + Jet + X)$			
STAR		H1 + ZEUS	
		COMPASS	
		HERMES

The Relativistic Heavy Ion Collider at Brookhaven National Laboratory

RHIC will accelerate heavy ion beams up to 100 A · GeV and

Two large detectors PHENIX and STAR have extensive

RHIC as polarized Proton Collider

RHIC Spin Accelerator Collaboration

I. Alekseev (ITEP) C. Allgower (ANL) M. Bai (Indiana U., ANL, BNL)
Y. Batygin (RIKEN) L. Bozano (U. Genova) K. Brown (BNL) G. Bunce (BNL)
P. Cameron (BNL) E. Courant (BNL) S. Erin (IHEP) J. Escallier (BNL)
W. Fischer (BNL) R. Gupta (BNL) K. Hatanaka (RCNP, Osaka U.)
H. Huang (BNL) K. Imai (Kyoto U.) M. Ishihara (RIKEN) A. Jain (BNL)
V. Kanavets (ITEP) T. Katayama (INS, U. Tokyo) T. Kawaguchi (RIKEN)
E. Kelly (BNL) S. Y. Lee (Indiana U.) A. Luccio (BNL) G. Mahler (BNL)
Y. Makdisi (BNL) F. Mariani (BNL) W. McGahern (BNL) G. Morgan (BNL)
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V. Ptitsin (BINP) L. Ratner (BNL) T. Roser (BNL) N. Saito (RIKEN)
H. Satoh (KEK) Y. Shatunov (BINP) H. Spinka (ANL) M. Syphers (BNL)
S. Tepikian (BNL) T. Tominaka (RIKEN) N. Tsoupas (BNL) D. Underwood (ANL)
A. Vasiliev (IHEP) P. Wanderer (BNL) E. Willen (BNL) H. Wu (RIKEN)
A. Yokosawa (ANL)

Spokesperson: T. Roser
Project Manager: M. Syphers

July 1998

RIKEN BNL Research Center

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Siberian Snakes

Effects of depolarizing resonances are averaged out by rotating the proton spin by large angles on each turn

Snake: Helical dipole magnet, the direction of the dipole field rotates by 180 degrees

Completion of First Snake: July 1999

Target: Snakes for 1 ring for the 1999 run

Polarimetry: News from E950

Argonne, BNL, IUCF, Kyoto, MEPHI, RIKEN,
RIKEN BNL Research Center, UNM

Coloumb Nuclear Interference Polarimeter:

Very forward polarized proton carbon scattering

$$0.003 < -t = q^2 \leq 0.01 \text{ GeV}^2/c^2$$

AGS test run in March 1999:

Detection of CNl carbon recoil

Measure analyzing power A

RHIC polarimeter?

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Junji Tojo's talk, Saturday 9.00am

Predicted Analyzing Power:

E950 Setup

ΔG from Prompt Photon Production

Gluon Compton (85% of σ)

Annihilation (15% of σ)

Double Spin Asymmetry

$$A_{LL} = a_{LL}(qg \rightarrow q\gamma) \cdot \frac{\Delta g(x_1)}{g(x_1)} \cdot \frac{\sum_{i=u,d,s} e_i^2 \Delta f_i(x_2)}{\sum_{i=u,d,s} e_i^2 f_i(x_2)}$$

$$= a_{LL}(qg \rightarrow q\gamma) \cdot \frac{\Delta g(x_1)}{g(x_1)} \cdot A_1(x_2)$$

Prompt Photons with PHENIX: EMCal!!

EMCal Resolution

$$\Delta\phi\Delta\eta \approx 0.01 \times 0.01 \quad \text{in } |\eta| \leq 0.35$$

$\pi^0 \gamma$ separation up to $\approx 30 \text{ GeV}/c$

The PHENIX Collaboration

42 Institutions with 430 physicists and engineers

Canada	Mc Gill University	Russia	Joint Institute for Nuclear Research
China	China Institute of Atomic Energy	Russia	Kurchatov Institute of Atomic Energy
China	Institute of High Energy Physics - Beijing	Russia	Petersburg Nuclear Physics Institute
China	Peking University	Russia	St. Petersburg State Technical University
Germany	University of Muenster	Sweden	Lund University
India	Banaras Hindu University	USA-AL	University of Alabama, Huntsville
India	Bhabha Atomic Research Centre	USA-CA	Lawrence Livermore National Laboratory
Israel	Weizmann Institute	USA-CA	University of California at Riverside
Japan	Center for Nuclear Study-U.Tokyo	USA-FL	Florida State University
Japan	Hiroshima University	USA-GA	Georgia State University
Japan	KEK, High Energy Accelerator Research Org.	USA-IA	Iowa State University / Ames Laboratory
Japan	Kyoto University	USA-LA	Louisiana State University
Japan	Nagasaki Institute of Applied Science	USA-NM	Los Alamos National Laboratory
Japan	RIKEN, Institute of Physical and Chemical Research	USA-NM	New Mexico State University
Japan	Tokyo Institute of Technology	USA-NM	University of New Mexico
Japan	University of Tokyo (Physics Department)	USA-NY	Brookhaven National Laboratory
Japan	University of Tsukuba	USA-NY	Columbia University / Nevis Laboratory
Japan	Waseda University	USA-NY	State Univ. of New York at Stony Brook
Korea	Korea University	USA-TN	Oak Ridge National Laboratory
Korea	Yonsei University	USA-TN	University of Tennessee
Russia	Institute of High Energy Physics - Protvino	USA-TN	Vanderbilt University

Prompt Photon A_{LL}

Model Calculation using PYTHIA and polarized PDFs from
Gehrmann, Sterling Combined Luminosities from years 2 and 3

A_{LL} in π^0 Production

Use high p_T π^0 in order to tag Jet

Model Calculation using PYTHIA and polarized PDFs from Gehrmann, Sterling 10% of design Luminosity year 2

STAR: Photon Jet

End Cap EMCalorimeter $1.07 \leq \eta \leq 2.0$

Barrel EMCalorimeter $|\eta| \leq 1$

The STAR Collaboration

37 Institutions with 400 physicists and engineers

Argonne National Laboratory
University of Arkansas
University of Birmingham
Rudjer Boskovic Institute
Brookhaven National Laboratory
University of California, Davis
University of California, Los Angeles
Carnegie Mellon University
Creighton University
Laboratory of High Energy Physics, Dubna
Particle Physics Laboratory, Dubna
University of Frankfurt
Indiana University
The Johns Hopkins University
Institut de Recherches Subatomiques (IReS) de
Strasbourg
Kent State University
Lawrence Berkeley Laboratory
Massachusetts Institute of Technology

Max-Planck-Institut fuer Physics
Michigan State University
Moscow Engineering Physics Institute
City College of New York
University of Notre Dame
Ohio State University
Pennsylvania State University
Institute of High Energy Physics, Protvino
Purdue University
Rice University
Instituto de Fisica da University de Sao
Paulo
Space Sciences Laboratory
SUBATECH, Nantes
University of Texas, Austin
Warsaw University
Warsaw University of Technology
University of Washington
Wayne State University
Yale University

STAR: Photon Jet

Fit uncorrected $\Delta G(x)$ reconstructed from 200 + 500 GeV simulations with Gehrmann-Stirling functional form $\Rightarrow$

$$\int_0^1 \Delta G_{\text{recon}}(x) dx = 1.62 \pm 0.23$$

Engineering Run 1999: STAR and PHENIX

Beam Gas Event in PHENIX TEC

Beam Gas Event in Star TPC

Conclusions

Very rich Spin Physics Program
at PHENIX and STAR

Gluon Polarization
Polarized Quark DFs

Successful Accelerator and Detector
Engineering Run last June to August

One Ring with Polarized
Protons for 1999/2000 Run

Spin Physics Starts with
the 2000/2001 run

Hard QCD and RHIC Spin Physics

Yoshiaki Yasui
RIKEN BNL research Center

Who carries the Nucleon's Spin?

1

Spin Structure Functions and/or Distribution Functions

(What is) the Spin Crisis (?)

First Moment of g_1

$$\int_0^1 g_1^p(x) dx = (\pm \frac{1}{15} a_1 + \frac{1}{36} a_2) C_{NS} + \frac{1}{9} a_3 C_S$$

Flavor Singlet Part

$$\Delta q = q^\uparrow - q^\downarrow$$

$$a_3 = \Delta \Sigma = \Delta u + \Delta d + \Delta s = 1 \quad \text{QPM}$$

$$\sim 0.1!! \quad \text{EMC Data}$$

PLB 328(1989)1

$\Rightarrow$ Quarks do not carry the proton spin ?

Gluon Component

Altarelli and Ross

$$a_3 = \Delta \Sigma_{(AB)} - n \cdot \frac{\alpha_s}{2\pi} \Delta G$$

Scheme Dependence and Anomaly

Kodaira

Measurement of the gluon component

Theoretical Issues

Fragmentation Photon

Higher Order Corrections

Resummation of the Soft gluon

Vogelsang et.al.

Loop Calculation

Transverse Spin

Measurement of the Transversity

DY ($PP \rightarrow \mu\mu X$)

$$\sigma \sim \delta q(x_1) \delta \bar{q}(x_2)$$

Semi-Inclusive DIS Collins

($eP \rightarrow ehX$)

$$\sigma \sim \delta q(x_1) \delta \hat{q}_h(z)$$

Two-Meson Fragmentation

$eP \rightarrow e\pi^+\pi^-X$ Jaffe et.al.

$$\vec{k}_\perp \times \vec{k}_\perp \cdot \vec{S}_\perp$$

$\Rightarrow PP \rightarrow \pi\pi X$

Higher Twist

$1/Q^2$ Expansion = Twist Expansion

$g_2(x, Q^2)$ and $h_L(x, Q^2)$ Twist3 in the LO

Uematsu, Kodaira and Y.Y.

Jaffe et.al., Balitsky et.al., Shuryak et.al., Koike et.al.

But, Experimental Data $\Rightarrow g_2$ is very small

HERMES Data $\Rightarrow h_L$ contribution?

Semi-Inclusive DIS $eP \rightarrow e\pi X$

Collins, Mulder et.al., Oganessyan et.al. $\leftrightarrow$ Boer (at RHIC?)

Spin Physics at “RHIC” and “RBRC”

Frontiers in Lattice QCD

Robert D. Mawhinney
Columbia University and
RIKEN-BNL Research Center

Japanese Physical Society Meeting, Matsue
September 23, 1999

1. The lattice approach to QCD
2. Progress and problems
3. Domain Wall Fermions
5. Domain Wall Fermion Results from QCDSF
 (a) Full QCD thermodynamics
 (b) Calculating matrix elements for CP violation
6. QCDSF-10

Collaborators

(7/99)

Columbia University:

Ping Chen, Calin Cristian, George Fleming, Xiaodong Liao,
Guofeng Liu, Lingling Wu, Yuri Zhestkov (students)

Chulwoo Jung, Adrian Kaehler, Yubing Luo, Catalin Malureanu
Chengzhong Sui (former students)

Tim Klassen, Gabi Siebert (postdocs)

Norman Christ, Robert Mawhinney, Pavlos Vranas

RIKEN-BNL Research Center (RBRC):

Tom Blum, Shigemi Ohta (KEK), Shoichi Sasaki, Matthew Wingate

BNL:

Mike Creutz, Chris Dawson, Amarjit Soni

QCDSP Computer and staggered fermion physics:

Alan Gara (IBM) and John Parsons - CU Nevis Laboratory
Igor Arsenin, Dong Chen (IBM) (former students)
Robert Edwards, Tony Kennedy (Edinburgh) - SCRI
Sten Hanson - FNAL
Greg Kilcup - OSU
Jim Sexton - Dublin

RBC Collaboration: RBRC/BNL/Columbia

Basics of Lattice QCD

- Numerically evaluate path integral

$$\begin{aligned}
 Z &= \int [dU] \exp \left\{ \sum_n [-\beta S_g + \text{quark}] \right\} \\
 &= \int [dU] \exp \left\{ \sum_n (-\beta S_g) \right\}
 \end{aligned}$$

- $\beta = 6/g^2$
- Number of integrals $\sim 10^7 - 10^8$
- Leave out quenched

quenching removes

- $\mathcal{D}$ is $\sim 10^8 \times 10^8$ sparse matrix. Different lattice choices are.
 1. Wilson
 2. staggered
 3. domain wall

Scales in Lattice QCD

- Discretized space and time.
- Finite volume.

- grid scale $\ll$ physics scales $\ll$ box size
- Output results are dimensionless numbers
- Physical input needed to set overall scale.
 1. m_ρ , m_N , or f_π , etc. determine coupling
 2. m_π fixes light quark masses (degenerate)
 3. m_K fixes strange quark mass.

Measuring particle masses:

For fundamental particles - like Higgs

$$\langle \Phi \Phi \rangle$$

For composite particles - like proton or pion

proton

$$\langle \epsilon^{abc} \ q^a \ q^b \ q^c \ \epsilon^{abc} \ \bar{q}^a \ \bar{q}^b \ \bar{q}^c \rangle$$

Hadron Mass Spectrum from Quarks and Gluons

N = (u,d,d)
Λ = (u,d,s)
K = (d,s̄)

Hadrons are the constituents of atomic nuclei. The computation of their mass spectrum from the dynamics of more fundamental quarks and gluons has been a principal subject of interest in particle physics.

In this figure, the results from the CP-PACS and from a previous computation are compared with experiment. Experimental results are reproduced to within about 5–10%. With the precise data from the CP-PACS, we further clarify a limitation of the widely adopted "quenched" approximation, answering a long-standing question since 1981.

Fermions and Symmetries

1. Continuum:

2. Wilson:

$$SU_V(N_f) \otimes U(1) \quad (a \neq 0)$$

3. staggered:

$$U'(1) (\subset SU_A(N_f)) \otimes U(1) \quad (a \neq 0) \\ + \text{ discrete flavor symmetries}$$

4. domain wall:

$SU_V(N_f) \supset SU_A(N_f) \supset U(1) \supset U_A(1)$ with
breaking of $SU_A(N_f) \supset U_A(1)$ going as $\exp(-aL_s)$,
even for finite a .

L_s behavior for quenched QCD with DWF

$8^3 \times 32$ and $16^3 \times 32$ lattices, $\beta = 5.7$, $m_0 = 1.65$

Quantum Chromodynamics (QCD) Project

Total Peak Speed: 1100.8 Gflops

RIKEN-BNL Research Center

Columbia University Center

The QCDSF Computer

- Design and construction
 - Design started in May, 1993
 - CU: 0.4 Tflops (8,192 node) online 4/98
 - RBRC: 0.6 Tflops, (12,288 node) online 10/98
- Funding
 - Research and development funded by US DOE
 - Columbia machine funded by US DOE
 - RIKEN-BNL machine funded by RIKEN
 - Total hardware cost $\sim$ \$4.5 M
- Currently used exclusively for QCD calculations
 - 3 Ph.D's and 6 Ph.D. students at Columbia
 - 7 Ph.D.'s at RIKEN/BNL
- Demonstrates utility of architecture
 - 4-D network simple and efficient
 - Modest memory not serious limitation
 - 20,000 nodes can run reliably

Current Results for T_c

Weak Matrix Elements with QCDSF

- First project of RBRC-BNL-Columbia (RBC) Collaboration
- What we did: calculated lattice matrix elements and non-perturbative renormalization parameters for $\Delta S = 1$ and 2 operators between pseudoscalar states.
- What we found:
 1. $\Delta S = 2$ results for B_K agree with others.
 2. $\Delta S = 1$ operators generally agree with others, except for O_6 , which is very different.
- What it means:
 1. Complete lattice calculation is possible.
 2. Must improve lattice systematics.
 3. Problems in current theoretical framework?
 4. Opening for new physics?

CP Violation in the K^0 - $\bar{K}^0$ System

First discussed by Lee, Oehme and Yang (1957) before parity violation seen experimentally

$\bar{s}\gamma_5 d$ meson is a neutral kaon and $CP|K^0\rangle = -|\bar{K}^0\rangle$.
QCD respects CP, so CP eigenstates (only QCD)

$$K^0 = \frac{1}{\sqrt{2}}(K^+ - K^-)$$

Electroweak interactions violate strangeness

$|K^0\rangle \Leftrightarrow |\bar{K}^0\rangle$ transitions possible

If electroweak interactions violate CP, eigenstates are

$$|K_{\pm}^0\rangle = \frac{1}{\sqrt{1+p^2+q^2}}(p|K^0\rangle \pm q|\bar{K}^0\rangle)$$

$$\left. \begin{array}{l} |K_+^0\rangle \rightarrow 2\pi \\ |\bar{K}_+^0\rangle \rightarrow 3\pi \end{array} \right\} \text{phase space} \Rightarrow \left\{ \begin{array}{l} |K_S^0\rangle \equiv |K_+^0\rangle \\ |\bar{K}_S^0\rangle \equiv |\bar{K}_+^0\rangle \end{array} \right.$$

$K^0 - \bar{K}^0$ CP Violation Experiments

Two parameters:

ϵ CP violation from mixing

ϵ' CP violation from decays

Two amplitudes:

$$\eta_{+-} = \frac{A(K_L^0 \rightarrow \pi^+ \pi^-)}{A(K_S^0 \rightarrow \pi^+ \pi^-)} = \epsilon + \epsilon'$$

$$\eta_{00} = \frac{A(K_L^0 \rightarrow \pi^0 \pi^0)}{A(K_S^0 \rightarrow \pi^0 \pi^0)} = \epsilon - 2\epsilon'$$

Measurements of 2 real numbers needed:

$$|\epsilon|$$

$$|\eta_{00}/\eta_{+-}|^2 \approx 1 - 6 \operatorname{Re}(\epsilon'/\epsilon) \approx 1 - 6 \epsilon'/\epsilon$$

Values are:

$$|\epsilon| = (2.266 \pm 0.017) \times 10^{-3} \quad (\text{Barnett, et. al. 1996})$$

$$\epsilon'/\epsilon = (2.1 \pm 0.46) \times 10^{-3} \quad (\text{Fabbriches, QCD 1999})$$

CP Violation in the Standard Model

quark electroweak eigenstates $\neq$ quark mass eigenstates

$$\text{QCD: } m_u \bar{u}u + m_d \bar{d}d + m_s \bar{s}s + \dots$$

$$\text{Weak: } d' = V_{ud}d + V_{us}s + V_{ub}b$$

Cabbibo-Kobayashi-Maskawa (CKM) matrix relates these eigenstates

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ & V_{cd} & V_{cb} \\ & V_{td} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3 \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3 & -A\lambda^2 & 1 \end{pmatrix}$$

$$\lambda = \sin \theta_C = 0.230 \pm 0.003, \quad = \rho + i\eta, \quad A, \rho, \eta \text{ real.}$$

From the SM to Experiment: ϵ

Need hadronic matrix elements of CP-violating operator which causes $K^0 - \bar{K}^0$ mixing.

ϵ depends on a matrix element B_K through

$$|\epsilon| = 3.4 \times 10^{-3} A^2 B_K \left[1 + 1.3 A^2 (1 - \rho) \left(\frac{m_t}{m_W} \right)^{1.6} \right]$$

$$B_K \equiv \frac{\langle K^0 | (sd)_{(V-A)} (\bar{s}d)_{(V-A)} | K^0 \rangle}{4f_K^2 m_K / 3}$$

$\Delta S = 2$ Box Diagrams

W^- W^+

u, c, t

u, c, t

$$= \frac{G_F^2}{16\pi^2} M_W^2 (\bar{d} \gamma^\mu s)_L (\bar{d} \gamma_\mu s)_L \times (\text{known factors})$$

$\Delta S = 1$ and 2 Hamiltonians

- $\Delta S = 2$ Hamiltonian

$$H_{\Delta S=2}^{eff} = \frac{G_F^2}{16\pi^2} M_W^2 (\bar{d}\gamma_L^\mu s)(\bar{d}\gamma_{\mu L} s) \\ \times (\lambda_c^2 F(x_c) + \lambda_t^2 F(x_t) + 2\lambda_c \lambda_t F(x_c, x_t))$$

- $\lambda_q = V_{qi} V_{qf}^*$ where i and f label initial and final states.
- $x_q = m_q^2/M_W^2$ and the F 's are known functions.

- $\Delta S = 1$ Hamiltonian

$$H_{\Delta S=1}^{eff} = \frac{G_F}{\sqrt{2}} V_{ud} V_{us}^* \sum_{i=1}^{10} [z_i(\mu) + \tau y_i(\mu)] O_i(\mu)$$

- z_i and y_i are Wilson coefficients. $z_i \simeq 0$ for $i > 3$ and $y_i \simeq 0$ for $i = 1, 2$.
- $\tau \equiv -V_{td} V_{ts}^*/V_{ud} V_{us}^*$

From the SM to the Lattice

Continuum

Lattice

$$\mathcal{L}^{\text{EW}}$$

$$\Downarrow$$

$$\sum_i C_i(M_W) O_i$$

$$\Downarrow$$

$$\sum_i C_i(\mu) O_i$$

$$\Downarrow$$

$$\langle q(p) | O_i | q(p) \rangle_{\text{tree}}$$

$$\Rightarrow$$

$$\langle q(p) | O_j^{\text{lat}} | q(p) \rangle_{p^2 = -\mu^2}$$

$$\langle \pi\pi | O_i | K \rangle$$

$$\Leftarrow$$

$$\langle \pi\pi | O_j^{\text{lat}} | K \rangle$$

$$\Uparrow$$

$$\langle \pi\pi | O_i^{\text{lat}} | K \rangle$$

$$\Uparrow$$

$$\langle \pi | O_i^{\text{lat}} | K \rangle$$

$$\langle 0 | O_i^{\text{lat}} | K \rangle$$

Kaon B parameter ($\mu=2\text{GeV}, \text{NDR}$)

CKM mixing matrix

Particle Data Group, C. Caso et. al.

Conventions

- Let $\delta_{0,2}$ be the phases for 2 π 's in final state
- Define isospin amplitudes

$$A_{0,2}e^{i\delta_{0,2}} \equiv \langle (\pi\pi)_{I=0,2} | H_W | K^0 \rangle$$

- The $\Delta I = 1/2$ rule is

$$\omega = \text{Re}A_0/\text{Re}A_2 \simeq 22$$

- The direct CP violation parameter ε'

$$\varepsilon' = \frac{ie^{i(\delta_2-\delta_0)}}{\sqrt{2}} \frac{\text{Re}A_2}{\text{Re}A_0} \left(\frac{\text{Im}A_2}{\text{Re}A_2} - \frac{\text{Im}A_0}{\text{Re}A_0} \right)$$

or

$$\varepsilon' = \frac{ie^{i(\delta_2-\delta_0)}}{\sqrt{2}\omega\text{Re}A_0} (\omega\text{Im}A_2 - \text{Im}A_0)$$

- Recent experiments have now given a value for

$$\text{Re} \frac{\varepsilon'}{\varepsilon} \simeq \frac{G_F}{2\omega|\varepsilon|\text{Re}A_0} \text{Im} \lambda_t [\Pi_0 - \omega \Pi_2],$$

which is $(21.2 \pm 4.6) \times 10^{-4}$ (Buras, Kaon99).

- The operators contributing to each isospin amplitude can be written as

$$\Pi_0 = \sum_i y_i \langle (\pi\pi)_{I=0} | O_i^{(0)} | K^0 \rangle (1 - \Omega_{\eta+\eta'}) \quad (1)$$

$$\Pi_2 = \sum_i y_i \langle (\pi\pi)_{I=2} | O_i^{(2)} | K^0 \rangle \quad (2)$$

- $\text{Im} \lambda_t \equiv \text{Im} V_{td} V_{ts}^*$
- $\Omega_{\eta+\eta'} \sim 0.25 \pm 0.05$ takes isospin breaking into account (Buras and Gerard (1987)).

Conventional Expectations

- Buras has presented a crude formula for ε'/ε (Buras, Kaon99)

$$\varepsilon'/\varepsilon = 13 \cdot \text{Im}(V_{ts}^* V_{td}) \left[\frac{110 \text{ MeV}}{m_s(2 \text{ GeV})} \right]^2 \left(\frac{\Lambda_{\overline{\text{MS}}}^{(4)}}{340 \text{ MeV}} \right) \cdot \left[B_6^{(1/2)} (1 - \Omega_{\eta+\eta'}) - 0.4 \cdot B_8^{(3/2)} \left(\frac{m_t}{165 \text{ GeV}} \right)^{2.5} \right]$$

- Appears that cancellation between $B_6^{(1/2)}$ and $B_8^{(3/2)}$ is important.

$\Delta S = 1$ Diagrams

exchange
and
spectator

QCD
penguin

Electroweak
penguin

$\Delta S = 1$ Diagrams

Diagram	Chirality	Color	Operator	Isospin
<p>A Feynman diagram showing a $\bar{s}$ quark and a u quark interacting via a W boson. The $\bar{s}$ quark emits a W boson and becomes a $\bar{u}$ quark. The u quark absorbs the W boson and becomes a d quark.</p>	L-L	unmix	0_1	$1/2, 3/2$
<p>A Feynman diagram showing a $\bar{s}$ quark and a d quark interacting via a W boson. The $\bar{s}$ quark emits a W boson and becomes a $\bar{u}$ quark. The d quark absorbs the W boson and becomes a u quark. A gluon (g) is exchanged between the final state $\bar{u}$ and u quarks.</p>	L-L, L-R	unmix	$0_3, 0_5$	$1/2$
<p>A Feynman diagram showing a $\bar{s}$ quark and a d quark interacting via a W boson. The $\bar{s}$ quark emits a W boson and becomes a $\bar{u}$ quark. The d quark absorbs the W boson and becomes a u quark. A photon (γ) or Z boson is exchanged between the final state $\bar{u}$ and u quarks.</p>	L-L, L-R	mix	$0_4, 0_6$	$1/2$
<p>A Feynman diagram showing a $\bar{s}$ quark and a u quark interacting via a W boson. The $\bar{s}$ quark emits a W boson and becomes a $\bar{u}$ quark. The u quark absorbs the W boson and becomes a d quark. A photon (γ) or Z boson is exchanged between the final state $\bar{u}$ and d quarks.</p>	L-R, L-L	unmix	$0_7, 0_9$	$1/2, 3/2$
<p>A Feynman diagram showing a $\bar{s}$ quark and a d quark interacting via a W boson. The $\bar{s}$ quark emits a W boson and becomes a $\bar{u}$ quark. The d quark absorbs the W boson and becomes a u quark. A photon (γ) or Z boson is exchanged between the final state $\bar{u}$ and u quarks.</p>	L-R, L-L	mix	$0_8, 0_{10}$	$1/2, 3/2$

$\Delta S = 1$ Diagrams

Diagram	Four Quark Operators
$O_1 = (\bar{s}_\alpha \gamma_\mu d_\alpha)_L (\bar{u}_\beta \gamma^\mu u_\beta)_L$
$O_2 = (\bar{s}_\alpha \gamma_\mu d_\beta)_L (\bar{u}_\beta \gamma^\mu u_\alpha)_L$
$O_{3,9} = (\bar{s}_\alpha \gamma_\mu d_\alpha)_L \sum_q (\bar{q}_\beta \gamma^\mu q_\beta)_L,$
$O_{4,10} = (\bar{s}_\alpha \gamma_\mu d_\beta)_L \sum_q (\bar{q}_\beta \gamma^\mu q_\alpha)_L,$
$O_{9,10} = \frac{3}{2} (\bar{s}_\alpha \gamma_\mu d_\alpha)_L \sum_q e_q (\bar{q}_\beta \gamma^\mu q_\beta)_L,$
$O_{10,9} = \frac{3}{2} (\bar{s}_\alpha \gamma_\mu d_\beta)_L \sum_q e_q (\bar{q}_\beta \gamma^\mu q_\alpha)_L,$

$\Delta S = 1$ effective operators

$$O_1 = (\bar{s}_\alpha \gamma_\mu (1 - \gamma_5) d_\alpha) (\bar{u}_\beta \gamma^\mu (1 - \gamma_5) u_\beta)$$

$$O_2 = (\bar{s}_\alpha \gamma_\mu (1 - \gamma_5) d_\beta) (\bar{u}_\beta \gamma^\mu (1 - \gamma_5) u_\alpha)$$

$$O_3 = (\bar{s}_\alpha \gamma_\mu (1 - \gamma_5) d_\alpha) \sum_q (\bar{q}_\beta \gamma^\mu (1 - \gamma_5) q_\beta)$$

$$O_4 = (\bar{s}_\alpha \gamma_\mu (1 - \gamma_5) d_\beta) \sum_q (\bar{q}_\beta \gamma^\mu (1 - \gamma_5) q_\alpha)$$

$$O_5 = (\bar{s}_\alpha \gamma_\mu (1 - \gamma_5) d_\alpha) \sum_q (\bar{q}_\beta \gamma^\mu (1 + \gamma_5) q_\beta)$$

$$O_6 = (\bar{s}_\alpha \gamma_\mu (1 - \gamma_5) d_\beta) \sum_q (\bar{q}_\beta \gamma^\mu (1 + \gamma_5) q_\alpha)$$

$$O_7 = \frac{3}{2} (\bar{s}_\alpha \gamma_\mu (1 - \gamma_5) d_\alpha) \sum_q e_q (\bar{q}_\beta \gamma^\mu (1 + \gamma_5) q_\beta)$$

$$O_8 = \frac{3}{2} (\bar{s}_\alpha \gamma_\mu (1 - \gamma_5) d_\beta) \sum_q e_q (\bar{q}_\beta \gamma^\mu (1 + \gamma_5) q_\alpha)$$

$$O_9 = \frac{3}{2} (\bar{s}_\alpha \gamma_\mu (1 - \gamma_5) d_\alpha) \sum_q e_q (\bar{q}_\beta \gamma^\mu (1 - \gamma_5) q_\beta)$$

$$O_{10} = \frac{3}{2} (\bar{s}_\alpha \gamma_\mu (1 - \gamma_5) d_\beta) \sum_q e_q (\bar{q}_\beta \gamma^\mu (1 - \gamma_5) q_\alpha)$$

Landau Gauge RI Wilson Coefficients at 2 GeV

Ciuchini, et., al. (1995)

$\Delta S = 1$ Contractions

figure
eight

eye
(one-spin
trace)

eye
(two-spin
trace)

$\Delta S = 1$ Contractions

Diagram	Value		Isospin	
	0_6	0_8	0_6	0_8
X	X	$1/2$	$1/2, 3/2$
Y	$-Y/2$	$1/2$	$1/2$
Z	0	$1/2$	$1/2, 3/2$

K- $\pi\pi$ Matrix Elements from RBC Collaboration

hep-lat/9908025

$\beta=6.0$

Systematic Errors

We have done a complete calculation of

$$\frac{\langle \pi^+ | O_i^{\text{lat}} | K^+ \rangle}{\langle 0 | O_i^{\text{lat}} | K^+ \rangle}$$

and Z factors for quenched QCD with $a^{-1} \sim 2$ GeV in a 1.6 fermi box.

Charm quarks integrated out in this work. Currently simulating with charm as propagating quark. Full mixing with lower dimensional operators not finished

Estimate of systematic errors:

Effect	Error	Reduced by computing
Perturbative $C_i(\mu)$	20 %	no
$K \rightarrow \pi$	25 %	possible
a	25%	yes
renormalization scale	10 %	yes
quenching	10 %	yes
isospin breaking	15 %	yes
finite volume	15 %	yes

Results

Using lattice calculation values for $\text{Im}(A_0)$ and $\text{Im}(A_2)$ gives:

$$\text{Re} \left(\frac{\epsilon'_{\text{DWF}}}{\epsilon_{\text{exp}}} \right) = (-3.3 \pm 0.3(\text{stat}) \pm 1.6(\text{syst})) \times 10^{-2} \eta$$

Using $\eta \approx 0.37 \pm 0.15$ we find:

$$\text{Re} \left(\frac{\epsilon'_{\text{DWF}}}{\epsilon_{\text{exp}}} \right) = (-12.2 \pm 6.8) \times 10^{-3}$$

Using $\text{Re}(\epsilon'/\epsilon)_{\text{DWF}}$ and also from experiment gives:

$$\rho = 7.9 \pm 3.9$$

($\rho = 0.20 \pm 0.22$ is a representative phenomenological value)

Current data for $\Delta I = 1/2$ rule show indications of an enhancement. More running currently underway

QCDSP	QCDSP-10																				
<ul style="list-style-type: none"> Faster processor <table> <tr> <td>TI C31</td><td>TI C67</td></tr> <tr> <td>0.05 Gflops</td><td>0.67 Gflops</td></tr> <tr> <td>2 Kwords on chip</td><td>32 Kwords on chip</td></tr> <tr> <td>0.7 Watts</td><td>≤ 2 Watts</td></tr> <tr> <td>\$62 $\Rightarrow$ \$36</td><td>$\sim$ \$100</td></tr> </table> Faster communications <table> <tr> <td>50 MHz serial synchronous</td><td>200 Mhz serial phase locked loop</td></tr> </table> Larger memory <table> <tr> <td>2 Mbyte</td><td>≥ 16 Mbyte</td></tr> </table> Cost/performance <table> <tr> <td>\$10/Mflops</td><td>\$1/Mflops</td></tr> </table> Target machine <table> <tr> <td>20,480 processors</td><td>16,384 processors</td></tr> <tr> <td>1 Teraflops peak</td><td>10 Teraflops peak</td></tr> </table> 	TI C31	TI C67	0.05 Gflops	0.67 Gflops	2 Kwords on chip	32 Kwords on chip	0.7 Watts	≤ 2 Watts	\$62 $\Rightarrow$ \$36	$\sim$ \$100	50 MHz serial synchronous	200 Mhz serial phase locked loop	2 Mbyte	≥ 16 Mbyte	\$10/Mflops	\$1/Mflops	20,480 processors	16,384 processors	1 Teraflops peak	10 Teraflops peak	
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Conclusions

- QCDSF and domain wall fermions have opened the door to important areas.
- Matrix elements vital for understanding CP violation in kaon systems are now calculable. Many checks remain and errors must be reduced.
- Full QCD calculations are possible for some quantities, but must be extended to many more
- Increased computer power (like QCDSF-10) is vital to achieve precision calculations.

References

Domain Wall Fermions - Theoretical foundation

- Kaplan, 1992
- Shamir and Furman 1993, 1995
- Narayanan and Neuberger 1993, 1994

Domain Wall Fermions - First simulations

- Blum and Soni 1997
- Vranas 1998

Perturbative Wilson Coefficients

- Buras, *et. al.* 1992, 1993
- Buchalla, *et. al.* 1996
- Ciuchini, *et. al.* 1994

Non-perturbative renormalization

- Martinelli, *et. al.* 1995

Pioneering lattice work ($\sim$ 1985-present)

- Bernard, Soni, *et. al.*
- Gupta, Kilcup, Sharpe, *et. al.*
- Martinelli, *et. al.*

QCD Physics at RIKEN BNL Research Center

Shigemi Ohta (KEK*and RBRC†)

September 23, 1999, Matsue

RIKEN-BNL Research Center (RBRC) is pioneering precision QCD: test QCD in greater detail,

- Spin physics as an outcome of QCD,
- QGP as a QCD prediction,
- e^+e^- to test the standard model.

RBRC promotes young physicists:

- Majority of people are young: postdocs, fellows and joint tenure track positions.
- Senior people are volunteers from BNL, Columbia, KEK, MIT, RIKEN, Tokyo, etc.

*Institute of Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki 305-0801, Japan

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Spin Physics (Grosse-Perdekamp, Yasui)

To further establish QCD:

- PDF to higher accuracy,
- so as to be sensitive to scheme dependence.

Ongoing active research in polarimetry (Grosse-Perdekamp).

Tools for more accurate calculations are being developed:

- 5-gluon vertex and beyond, also with EW spin-off (Yasui, this morning),

- lattice with DWF, being prepared by RBC.

Quark-Gluon Plasma (Shigaki, Fujii)

Quark-Gluon Plasma (QGP) : signals not yet established,

- different behavior in well-known QCD phenomena (jets and Drell-Yang),

Quark-Gluon Plasma (QGP) : signals not yet established,

Higher accuracy in wide vinty required:

- J/ψ suppression, , flavor equilibrium, collective flow, ...
 - RHIC experiments are ready.
- event generation/simulation along the
 - with as few unwarranted assumptions as possible.

Some new approaches initiated/helped by RBRC

Quark-Gluon Plasma (QGP) : signals not yet established,

Quark-Gluon Plasma (QGP) : signals not yet established,

- RHIC and related activities.

Lattice QCD (Mawhinney)

Kaon CP-violation parameter ϵ' calculation as an example of precision QCD

- made possible by LLL 'twisted' (DWF, chiral symmetry, NPR)
- pushed the standard model to the limit: wrong sign in $\text{Re}(\epsilon'/\epsilon)$
- QCD still to will decide.

QCD corrections are not reliable in anything beyond the standard model: no charm!

Also necessary for spin physics, QCD, quark mass, ...

- conventional quark mass estimates are not so reliable.
- lattice estimates are revolutionizing our views in spin and QGP physics.

RIKEN-BNL-Columbia Collaboration

RBRC promotes young physicists:

- postdocs,
 - fellows,
 - joint tenure-track positions.
- Senior people are volunteers: from BNL, Columbia, KEK, MIT, RIKEN, Tokyo, etc.
 - Balanced mixture of
 - : OSCAR, color superconductor, DWF. ... with prompt proceedings publication
 - and ... are operational.

Exciting opportunities, see

- <http://www.raaf.riken.go.jp/raaf/rhic/bnl/>
- <http://penguin.phy.bnl.gov/www/riken.html/>

Summary

Shigemi Ohta

KEK, Tsukuba, Ibaraki 305-0801, Japan,

and

RBRC, BNL, Upton, NY 11973, USA

As is clear from Prof. Lee's opening talk, by now quantum chromodynamics (QCD) has been established as the fundamental theory of the strong interaction and it is now becoming a precision science.

Our knowledge of spin-independent proton structure is obtained from hard QCD processes like lepton deep-inelastic scattering, Drell-Yan reaction and jet phenomena. Helped by the next-to-leading order perturbation calculations in QCD we now know very well about this, even to a level where some of our interpretations are now scheme dependent. At the soon-to-start RHIC/Spin experiments, we will extend the reach of our knowledge to spin-dependent proton structure. Dr. Grosse Perdekamp gave a review of this experimental program with an emphasis on a recent and important progress in polarimetry. Dr. Yasui reviewed corresponding theory, including his own contribution in making higher-order QCD perturbation calculations feasible.

Another very important outcome of QCD is its prediction of a new phase, the quark-gluon plasma: unlike in ordinary low-temperature and low-density hadronic matter where these building blocks are confined within hadrons, at high enough temperature or density they would be more or less freely propagating. The original RHIC experiments were designed to probe this possibility. Dr. Shigaki gave a review of these experiments, with emphasis on leptonic and electromagnetic probes that should not suffer contamination from hadronization and hadronic final-state interactions. Yet theoretical clarifications about which of these and other contamination is understood or not is important, and Dr. Fujii reviewed the latest development which is revolutionizing the field.

Also important is to refine our ability in extracting QCD predictions through the non-perturbative lattice method. The QCDSP supercomputer built by RBRC in collaboration with Columbia University is now used as the main apparatus of the RIKEN-BNL-Columbia QCD collaboration. The collaboration successfully pioneered lattice-QCD numerical calculations using domain-wall fermions and non-perturbative renormalization, and then applied the new methods to the first complete calculation of the ϵ' parameter in the direct CP violation process in neutral kaon. This important development was reviewed by Prof. Mawhinney.

This summary was given in Japanese.

R - K E N 様

Forthcoming RIKEN BNL Center Workshops

Title: **Prediction and Uncertainties for the RHIC Spin
Physics Program**
Organizer: W. Vogelsang and J. Qiu
Date: March 6–31, 2000

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RIKEN BNL RESEARCH CENTER

PHYSICAL SOCIETY OF JAPAN BIENNIAL MEETING

SYMPOSIUM ON

QCD PHYSICS AT RIKEN BNL RESEARCH CENTER

MATSUE, JAPAN

SEPTEMBER 23, 1999

Li Keran

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*Nuclei as heavy as bulls
Through collision
Generate new states of matter.*
T. D. Lee

Speakers:

H. Fujii
R. Mawhinney
Y. Yasui

M. Grosse Perdekamp
S. Ohta

T.D. Lee
K. Shigaki

Organizers: Koichi Yazaki, Hideto En'yo and Shigemi Ohta