T. D. Lee: Relativistic Heavy Ion Collisions and the Riken Brookhaven Center

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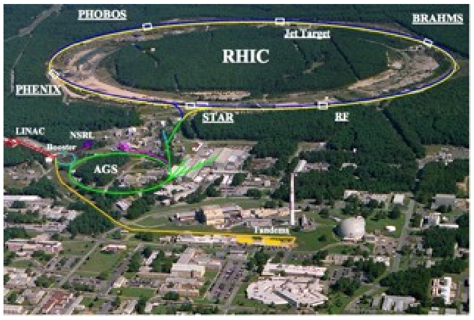
Abstract

This paper presents the history of Professor T. D. Lee's seminal work on the theory of relativistic heavy ion collisions, and the founding and development of the Riken Brookhaven Center. A number of anecdotes are given about Prof. Lee, and his strong positive effect on his colleagues, particularly young physicists.

1 Introduction

This presentation concerns Prof. T. D. Lee's seminal contributions to the study of relativistic Heavy Ion Collisions, and his achievements developing the Riken Brookhaven Center at Brookhaven National Laboratory. A picture of the Relativistic Heavy Ion Collider at Brookhaven National Laboratory is shown in Fig. 1 A. This is the most recent experimental project for the production and study new forms of matter at extreme energy density. In this field Prof. Lee made essential seminal contributions. We will describe these contributions, and their implications to date in this talk. The picture shown in Fig. 1 B is symbolic of the Riken Brookhaven Research Center's involvement in RHIC physics.. This center was conceived by Prof. Lee and Prof. Akito Arima of Tokyon University. The artistic rendition of the two



A

B

Figure 1: (A) The Relativistic Heavy Ion Accelerator (RHIC) at Brookhaven National Laboratory (BNL). (B) Heavy ions colliding: One of the artworks associated with the Riken Brookhaven Research Center (RBRC) at BNL.

bulls is illustrated by Li Karen due to original idea from Prof. Lee, and is illustrative of heavy ion collisions making a new form of matter. The Yin-Yang symbol for RBRC is also due to Prof. Lee. We will describe the formation and successes of RBRC in this talk.

In Fig. 2, Prof. Lee is shown in his office at RBRC. T. D. is a teacher, a colleague, a mentor and friend to all of us. Some of us have known him for a very long time, and some of less so, but we all know that you:

Always listen carefully to what T. D. says and you will greatly benefit..

2 The Origins of the Study of Relativistic Heavy Ion Collisions

The first serious discussions of relativistic heavy ion collisions to perhaps make new forms of matter were held at the *Workshop on Heavy Ions: How and Why* held in Bear Mountain, New York, Nov. 29 - Dec 1, 1974.[1] In the introduction and summary of the meeting, Leon Lederman and Joseph Weneser state:

The history of physics teaches us that profound revolutions arise from a gradual perception that certain observations can be accom-

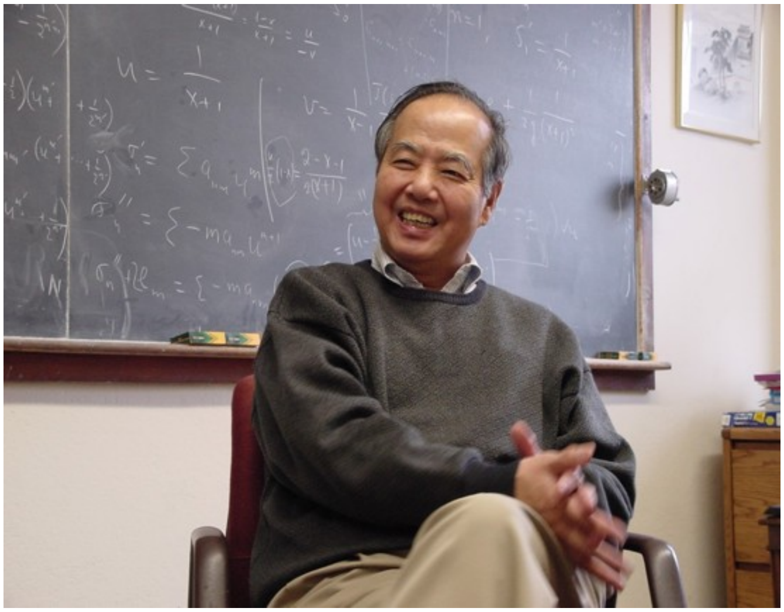


Figure 2: Professor T. D. Lee at his office at Riken Brookhaven Center.

modated only by radical departures from current thinking. The workshop addressed itself to the intriguing question of the possible existence of a nuclear world quite different from the one we have learned to accept as familiar and stable.

Prof. Lee's in his talk said

It would be intriguing to explore new phenomena by distributing high energy or high nuclear matter over a relatively large volume.

The idea that one could make new forms of matter on size scale large compared to microphysics size scales and that this might probe fundamental properties of matter at energy densities much larger than that of nuclear matter was born at this workshop. Prof. Lee described the possibility that our vacuum might be unstable with respect to another vacuum, characterized by the expectation value of a scalar field, the Lee-Wick matter.[2]. This is shown in Fig. 3 This idea led to a revolution in cosmology and in field theory at finite temperature and density. The concept of an unstable vacuum led Coleman[3] to develop techniques for computing the decay rate, and Kobzarev, Okun and Voloshin computed decays for systems at finite temper-

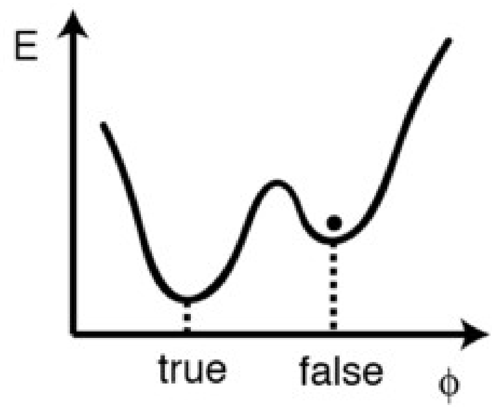


Figure 3: The unstable vacuum as invisaged by lee and Wick.

ature as might be seen in cosmology.[4] Guth and Linde used the finite energy density of a false vacuum to drive a de Sitter expansion of the universe, and developed the idea of inflation.[5] In various contexts, vacuum stability is used as an argument to constrain the properties of fundamental theories of matter.

Profs. Lee and Wick imagined making abnormal metastable states of such matter in heavy ion collisions:

In this way one could temporarily restore broken symmetries of the physical vacuum and pssibly create abnormal states of nuclear matter.

Prof. Lee's interest in such problems can be seen in some of his most early work :

- 1950: Energy Production and pp Reactions in White Dwarfs
- 1950-1952: Turbulence in Hydrodynamics and Magneto-hydrodynamics
- 1952 Statistical Theory of the Equation of State and Phase Transitions (with C. N. Yang)

Professor Lee was a student of Fermi, also a scientist with a broad range of physics interests.

In 1980, there was a workshop held at the Center for Advanced Studies at Bielefeld University, "Statistical Mehcanics of Quraks and Gluons". This meeting is a precursor to the Quark Matter meetings which are regularly held to discuss the physics of relativistic nuclear collisions. Some of the famous scientists were at the meeting are shown in Fig. 4 One of the authors of

Figure 4: T. D. Lee discussing physics with Helmut Satz and "Papa" Migdal at the Bielefeld meeting. In the background is Gordon Baym

this talk, Larry McLerran, was in Europe for the first time. There was real excitement about the possibility to use heavy ions to make a new state of matter, the Quark Gluon Plasma. The ideas for this had been largely developed after the Bear Mountain meeting, in works by Collins and Perry and by Cabibbo and Parisi.[6] (The original idea dates back to a paper by Naoki Itoh[7]) The name "Quark Gluon Plasma" was coined by Eduard Shuryak in 1978.[8]

Professor Lee gave a talk "Is the Vacuum a Physical Medium?"[9] . The first computations using lattice gauge theory to show that there was a deconfinement phase transition at finite temperature were presented.[10] There was much discussion about heavy ion collisions.

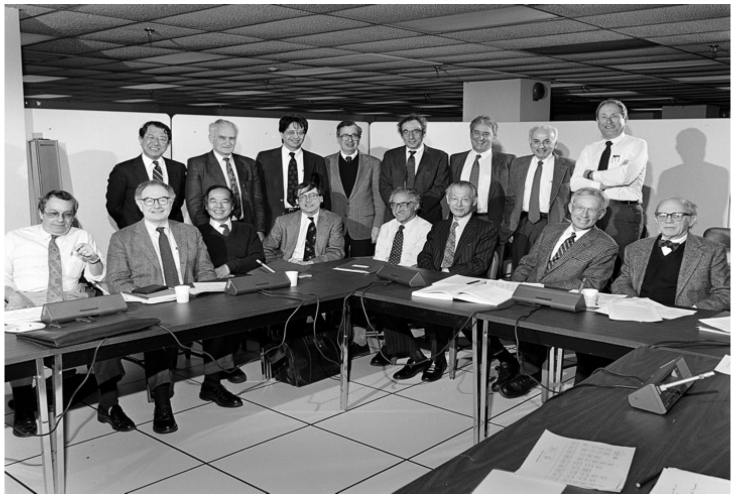


Figure 5: The RHIC Advisory Committee

3 RHIC

The Bielefeld meeting and a subsequent Snowmass Summer Study: "Relativistic Heavy Ion Colliisons and Future Physics" were crucial to the devlopment of the heavy ion program which led to experiments at the AGS at BNL, the CERN-SPS, and now at RHIC. RHIC can accelerate collide gold nuclei with total center of mass energy of 200 GeV per nucleon (20 TeV for a gold nucleus), and protons up to 500 GeV with 70% polarization.

RHIC arose in the aftermath of the cancellation in 1983 of the Isabelle accelerator. Isabelle was a 400 GeV pp collider. After the announcement of the cancellation of Isabelle, there was a Quark Matter conference held at BNL. RHIC was subsequently endorsed in the Nuclear Physics Long Range Plan, after partially constructing Isabelle. Among the innovative magnet options considered for RHIC was the innovative 2 in 1 superconducting magnet design similar to that now being used in the Large Hadron Collider (LHC). Construction was finished on RHIC in 1999, and RHIC is now carrying on a program of heavy ion physics and polarized proton-proton collisions to study the origin of the spin in a nucleon.

In Fig. 5, we show a picture of the RHIC Advisory Committe, which was set up by the then director of BNL, and one of the authors of this presentation, Nick Samios, to advise him on matter related to RHIC. This was an international group (U. S., Europe and Asia) of university and laboratory representatives. Of particular note are T. D. Lee, who was a member for ten years, H. Feshback, who was chair, (A. Bromley was the previous chair), S. Ozaki who was the RHIC Project Manager, M. Schwartz who was then Associate Director of High Energy and Nuclear Physics at BNL, and a young N. Samios.

The various Associate Directors for High Energy and Nuclear physics during the time RHIC was conceptualized and built are shown in Fig. 6.

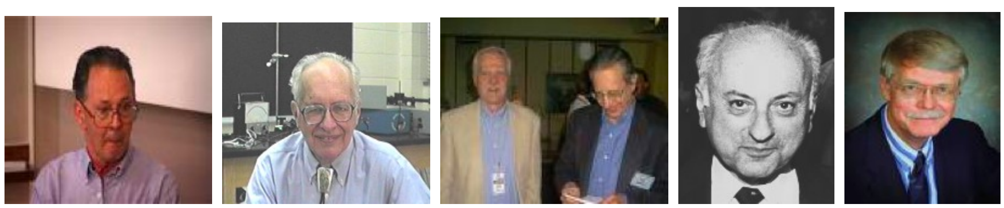


Figure 6: Associate directors for high energy and nuclear physics during the construction of RHIC. (A) Robert Palmer (B) Robert Adair (C) Larry Tureman (with Nick Samios) (D) Mel Schwartz (E) Tom Kirk

RHIC was constructed in 1999, and there have been four major experiments, Brahms, Phenix, Phobos, and Star, shown in Fig. 7. Brahms and Phobos were designed as small experiments to do quick analysis of the environment at RHIC and are no longer in operation. RHIC has about 1200 experimental physicists working at the various experiments from 50 countries. There have been more than 2000 publications arising from the RHIC experiments.

4 The Physics of Matter at Very High Density

The RHIC program has been immensely succesful, providing an experimental discovery of the strongly interacting Quark Gluon Plasma (sQGP), a very high energy state of matter near therma equilibrium composed of unconfined quarks and gluons.. It has provided hints of the Color Glass Condensate (CGC) which is very high energy density matter made from gluons with properties closely related to Bose condensate and to glasses, and of the Glasma,

Figure 7: The RHIC Experiments

a transient state of matter which transforms the CGC into an sQGP. The formation of this matter and its subsequent evolution into hadrons bears a a close resemblance to the formation of matter and radiation in cosmology and its evloution into the present universe, as visualized by Hatsuda in Fig. 8. Steffen Bass has provided another artistic rendering of the various stages of ultrarelativistic heavy ion collisions as shown in Fig. 9

The strongly interacting Quark Gluon Plasma is a new state of matter with energy densities greater than an order of magnitude larger than those atomic nuclei, $\epsilon \geq 2-3\ GeV/Fm^3 \sim 10-15 \times \epsilon_{nuclei}$. This matter has a high temperature corresponding to typical particle energies $E \geq 200\ MeV$. This matter is composed of unconfined quarks and gluons, although the interaction between these quarks and gluons is very strong. The RHIC and LHC heavy ion programs will in the future explore and develop understanding of this matter.

Prof. Lee is known for his interest in art, and after the first collisions at RHIC commisioned the artwork shown in Fig. 10. Prof. Lee looks understandably happy.

The experimental strategy for the RHIC program consisted of utilizing

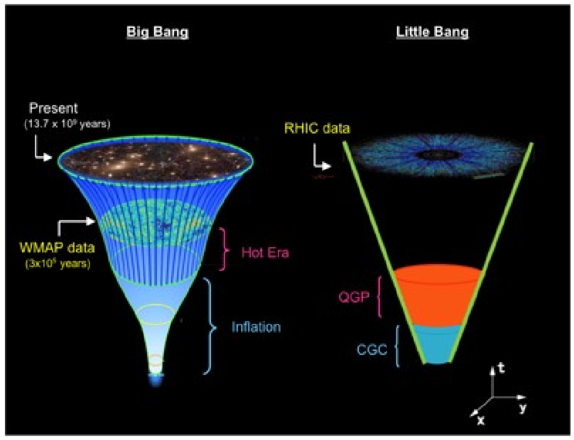


Figure 8: The Big Bang and the Little Bang as envisioned by Tetsuo Hatsuda

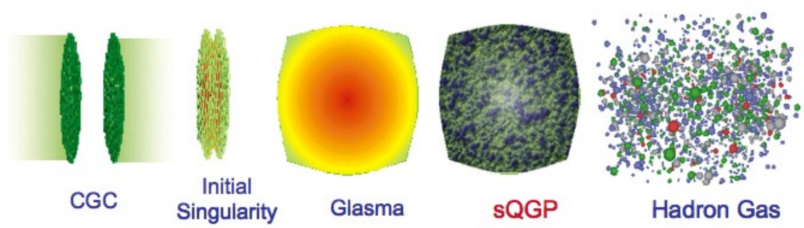


Figure 9: A collision of two nuclei as conceptualized by Steffen Bass

four detectors, two large, PHENIX and STAR, and two small, BRAHMS and PHOBOS. These all performed in a magnificent fashion and they were designed to have some appreciable overlap in their capabilities, which proved extremely useful. The evidence for the strongly interacting nature of the Quark Gluon Plasma comes from at least two sources. The first is jet suppression.[11]-[12]. One expects that the production of high momentum particles comes from elementary elastic scattering processes, where two quarks or gluons produce two high momentum quarks or gluons. These quarks and gluons subsequently fragment into jets of particles. If there is a a medium present in which these jets can interact, the jet may be slowed or quenched before escaping the medium One can trigger on one of the high momentum

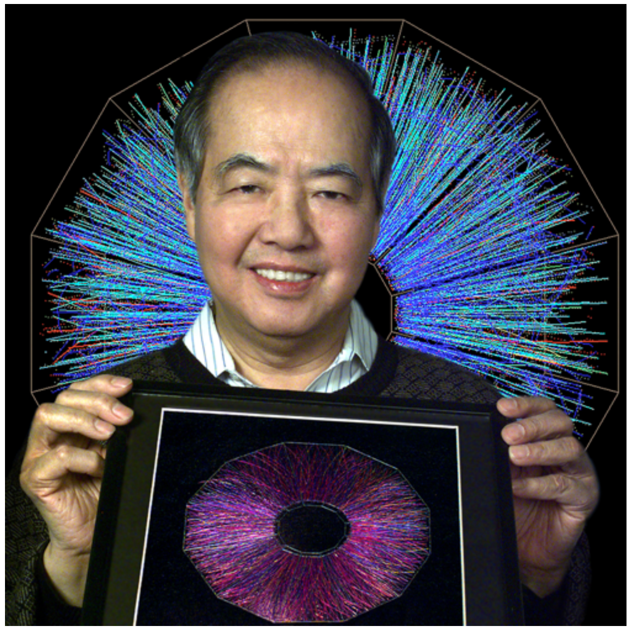
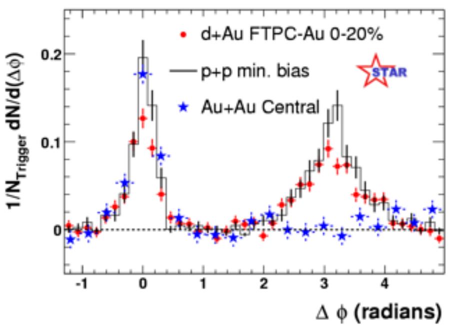


Figure 10: A artists drawing of a heavy ion collision as seen in the Star detector

produced jets and look for a corresponding jet at an azimuthal angle 180 degrees away, corresponding to the other jet. The results of the Star experiment are shown in Fig. 11 A. In pp or deuteron-Gold collisions, the jet is seen on the opposite side. In heavy ion collisions, where an sQGP is produced, there is no jet on the opposite side, so it has been quneched. In Fig. 11 B, the Phenix experiment directly measured jet production (via the measurement of single particle inclusive spectra of leading π^0 mesons) and compared them to theoretical expectations for production with no media present. They found about a factor of five suppression out to very high transverse momentum the surprise about these results is the magnitude of the suppression and that it extends out to such large transverse momentum. This can only be accommodated by having extremely strong interactions of the quarks and gluons with the media, and therefore if the media is composed of quarks and gluons, very strong interactions of the quarks and gluons in the media among themselves.

The other piece of evidence for a sQGP comes from the measurement of elliptic flow. Elliptic flow (V2) is an asymmetry in the transverse momen-



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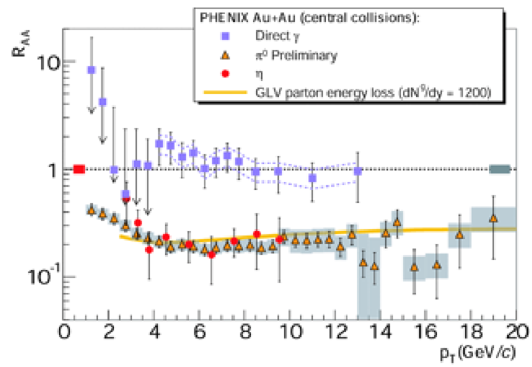

B

Figure 11: (A) The Star measurement of jet-jet angular correlations (B) The Phenix measurement of jet suppression.

tum of produced particles due to an asymmetry in the collision geometry, as shown in Fig. 12. In a nonzero impact parameter collision, the interacting matter has an asymmetry in the matter density in directions in the plane of the collisions relative to that perpendicular to that plane. This asymmetry in the matter distribution due to multiple particle interactions transforms the asymmetry in the matter distribution into that of the momentum distributions. The surprise at RHIC was that for the first time at RHIC, perfect fluid (zero mean free path) hydrodynamics computations could give the correct flow for the vast majority of particles.[11] There are deviations at high transverse momenta, where there are not so many particles, but even these can be qualitatively and semi-quantitatively understood as due to quark coalescense [13]

5 The Evolving Picture of the Structure of Matter at Very High Density

As time has evolved, theoretical conceptions of the properties of matter at very density have developed. In Fig. 13, we see that in the 1980's, one thought that there was ordinary hadronic matter and a Quark Gluon Plasma, separated by a line of first order phase transitions. By the 1990's, one believed that there was a smooth cross over between these phases. By the early

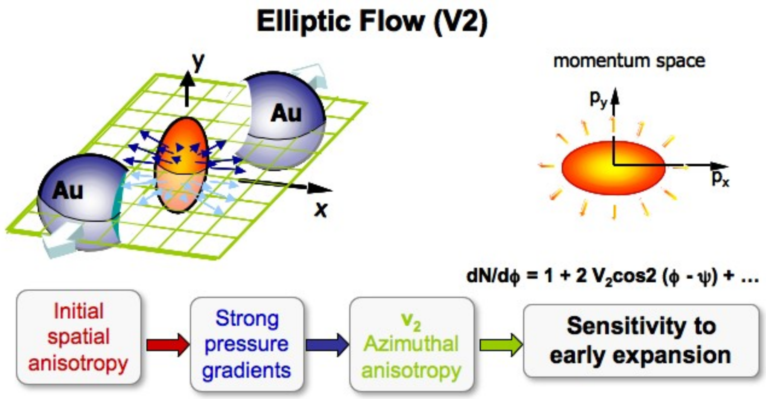

Figure 12: Flow in heavy ion collisions

2000's, the phase diagram had been com;plicated by the possible existence of color superconductivity. The most recent version of such a phase diagram has many more possibilities. The scales at which the physics is interesting were predicted correctly. The point of this figure is to show that physics is ultimately an experimental science, and nature oten times has more structure than we can imagine. This also applies to concepts such as Color Glass Condensate[14] and Glasma[15], which did not exist 20 years ago.

With facilities such as RHIC and LHC, one can test novel ideas about the structure of matter, and surely these pictures will evolve. RHIC can be run in a mode which is very low energy to test come conjectures about the properties of matter at high baryon density. By looking in the forward region of deuteron-nucleus collisions, one can gain information concerning the CGC.

6 RBRC

The Riken Brookhaven Center at BNL was established largely through the efforts of Professor T. D. Lee and Akito Arima. The center is dedicated to the study of strong interactions, which includes spin physics, lattice gauge thoery and RHIC physics. Its goal is to nurture a new generation of young physicists. In the words of Prof Lee:

In my meeting with Dr. Arima, our conversation turned to the subject of scientific creativity and the best way to nurture it. The

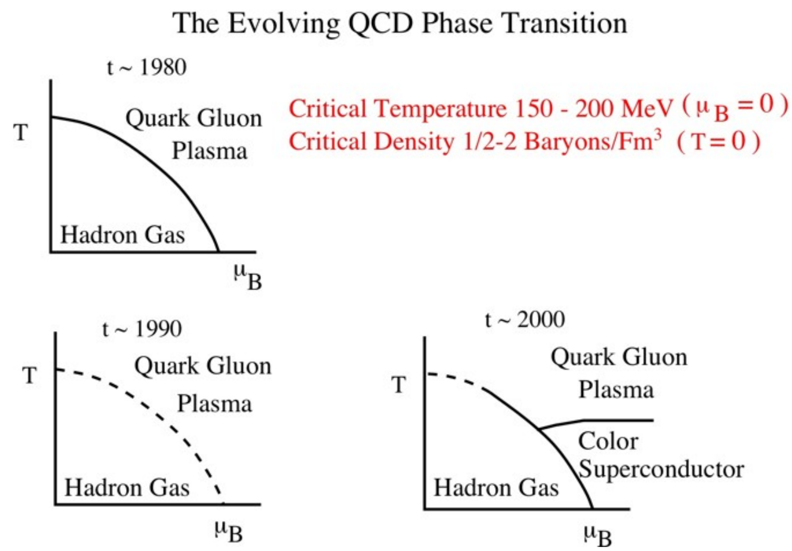

Figure 13: The conception of the phase diagram of QCD as a function of time.

Niels Bohr Institute played an essential role in the development of quantum mechanics in the 1920's. At that time, Bohr had already formulated his quantization rule, and Einstein had completed his Theory of Relativity. A new generation of physicists went through the Bohr Institute, including Heisenberg, Dirac, Pauli, Nishina and others. While Bohr and Einstein were still active at that time, they did not discover quantum mechanics. Quantum mechanics was created by this new group of young physicists, mostly in their twenties.

The RBRC center was established in 1997. In the upper left hand part of Fig. 16 is a photo of attendees at the the first RBRC workshop "Non-equilibrium Aspects of Many Body Dynamics" . Attendees included Frank Wilczek, Miklos Gyulassy, Eduard Shuryak, Berndt Muller, as well as the two writers of this talk. There was signing of the memo of understanding for RBRC with Satoshi Ozaki, Nick Samios, T. D. Lee Peter Bond, Tom Kirk and Henry Grahn shown in the lower left of Fig. 16. There was a presentation of a nameplate for RBRC by Professor Arima to Professor Lee, lower right of Fig. 16.

Figure 14: Photos of the inauguration ceremony for the RBRC center.

7 The Physics Interests of of RBRC

The RBRC Center supports the RHIC Spin experimental and theoretical effort. In particular, the spin structure of the proton is of major interest. Is the origin of spin in valence quarks, the gluons or orbital angular momentum? RIKEN augmented the RHIC program by funding a capability of polarizing the spin of protons in RHIC. This was accomplished with the addition of Siberian snakes, spin rotators and polarimeters to both the AGS and RHIC. These additions to the RHIC complex are shown in Fig. 15 The expected sensitivit to the gluon contribution to the protons spin by the PHENIX and STAR detectors is also exhibited.

There is also interest in the physics of matter at the highest energy density. This includes the Quark Gluon Plasma and cold nuclear matter which may be in a Color Superconducting state. It also includes the Color Glass

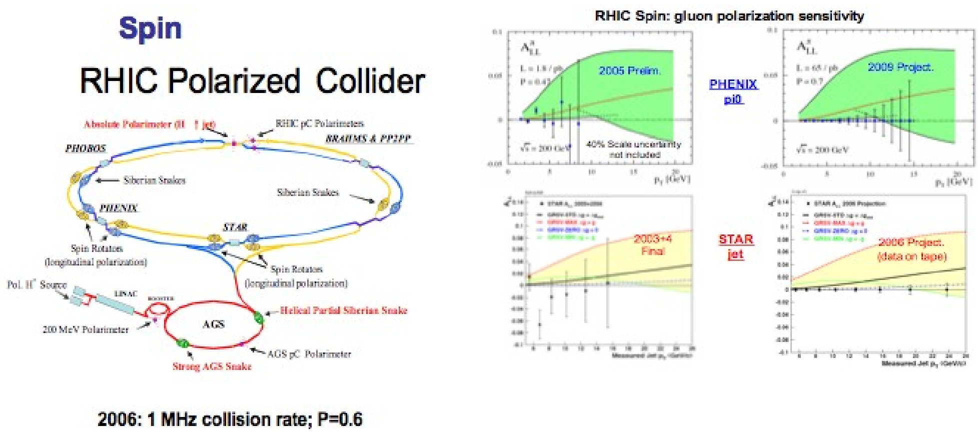

Figure 15: The spin capability at RHIC.

Condensate, the universal high density gluons matter which controls the high energy limit of QCD, and the Glasma which is produced in the collisions of sheets of colored glass at RHIC, and eventually forms the Quark Gluon Plasma.

RBRC also supports lattice gauge theory, and the construction of high speed computers such as the Quantum Chromodynamics on a Chip project, QCDOC. The deign of this machine provided a prototype for the IBM Blue-Gene computers. An earlier version of the QCDOC, the QCDSP won the Gordon Bell Prize for Computing Performance in 1998. There are now two QCDOC computers at BNL each with a peak performance of 10 Teraflops. One machine was paid for by RBRC and the other by the US Department of Energy. These machines can compute properties QCD at finite temperature, weak matrix elements which probe the nature of CP violation, and precision measurements of the propeties of strongly interacting particles.

In Fig. **??**, the QCDOC is shown. Among the participants are Drs. Doi and Kaya of RIKEN, Drs. T. D. Lee and N. Christ of Columbia, and P. Chaudhuri, E. McFadden, S. Ozaki and N. Samios of BNL.

RBRC has supported over 60 workshops on spin, the properties of high density matter and lattice gaug theory. One of its strongest workshops was New Discoveries at RHIC in May 14-15 of 2004.[11]. This workshop brought physicists from around the world to discuss the new developments at RHIC,

Figure 16: Photos of the inauguration for the QCDOC at RBRC.

and resulted in a widely quoted special edition of Nuclear Physics A. It was the initiator for whitepapers from the various experimental collaborations which summarized their accomplishments, is widely quoted, and is a also a special edition of Nuclear Physics A.[12]

RBRC now has a staff of about 15-20 theoretical physicists and 10 experimentalists. It has funded 18 RBRC University Fellows who are in joint positions with RBRC and Universities, and of these 14 have now been tenured.

8 A Poem for T. D. Lee

Alice and Larry McLerran wrote the poem below for Prof. T. D. Lee on the occasion of his 80'th birthday. It's title is Khan Tengri. Khan Tengri is a 7000 meter high mountain in the Tien Shan range just a little bit on the Kazakhstan side of the border with China. Tien-Shan can be translated from Chinese as Heavenly Mountains. Khan Tengri is a Uighar word for King of the Spirits. A picture taken by Alex Schwarzkopf of Khan Tengri is shown in Fig. 17

Figure 17: The mountain Khan Tengri

Khan Tengri
For T. D. Lee

A young man scaled the mountain Khan Tengri;
The sun wove rainbows in the blowing snow.
Entranced, he stayed there as the colors changed
Until the stars became his only light.

Some say he talked with spirits in the night,
While others thought him crazed by lack of air.
Still, in the morning he strode from the fog,
The Tien-Shan spires rising at his back.

He taught to all his love of mountain heights –
The source of streams that flow from glacial walls
Past creatures crossing meadows crisp with frost

Down to the slopes where the lofty cedars rise.

Faces turn skyward, children dream of peaks,
New climbers go in search of routes that mount
Through thinning air and wind that pierces bone
To reach the views that no eye other has seen.

The Picture 18 is of Teardrop Lake in the crater of the South Sister volcano in Oregon, taken by Kenneth Anderson.

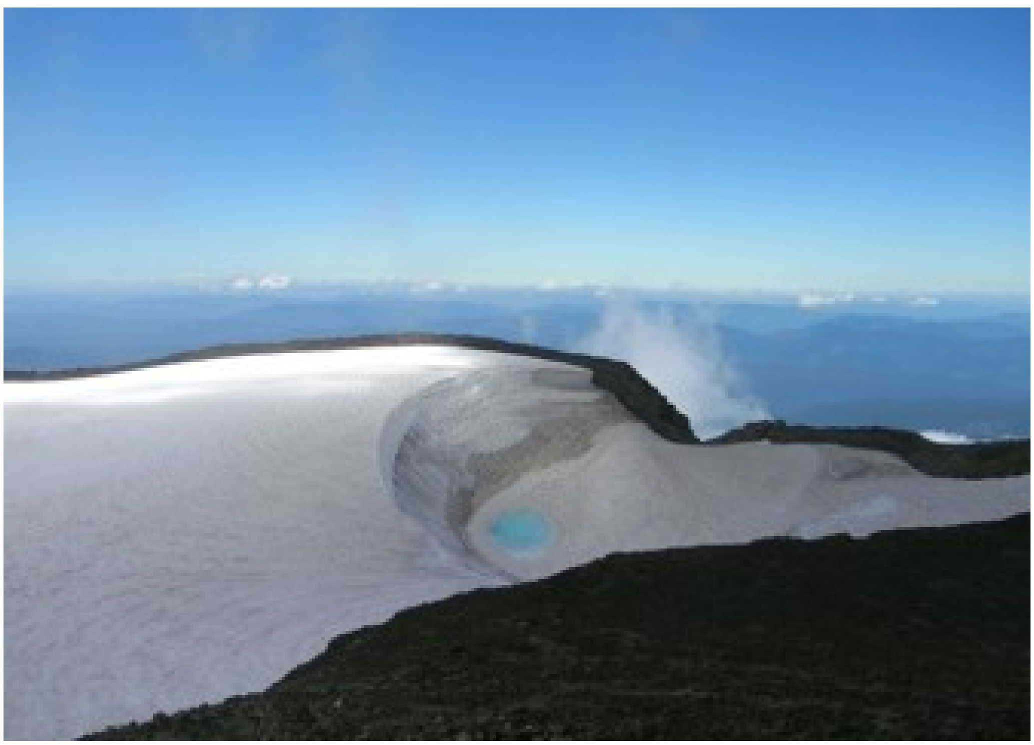

Figure 18: Teardrop lake in the crater of the South Sister volcano in Oregon.

9 Summary

Professor T. D. Lee is a physicist of the highest rank. He is a

Visionary

Strategist

Manager

Artist

10 Acknowledgments

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