CCAST (WORLD LABORATORY)
SYMPOSIUM/WORKSHOP PROCEEDINGS
VOLUME 6

FIELDS, STRINGS AND QUANTUM GRAVITY

Edited by

HANYING GUO
ZHAOMING QIU
HENRY TYE

GORDON AND BREACH SCIENCE PUBLISHERS

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Edited by

Hanying Guo
Zhaoming Qiu
Institute of Theoretical Physics, Beijing, People's Republic of China

and

Henry Tye
Newman Laboratory of Nuclear Studies, Cornell University, Ithaca, New York, USA

Proceedings of the CCAST (World Laboratory) Symposium Workshop
held at
The Temple of the Sleeping Buddha,
Beijing, People's Republic of China
May 29-June 10, 1989 (Cancelled June 4 1989)

GORDON AND BREACH SCIENCE PUBLISHERS
New York · Philadelphia · London · Paris · Montreux
Tokyo · Melbourne

Gordon and Breach Science Publishers

Post Office Box 786
Cooper Station
New York, New York 10276
United States of America

5301 Tacony Street, Slot 330
Philadelphia
Pennsylvania 19137
United States of America

58, rue Lhomond
75005 Paris
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3-14-9, Okubo
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Japan

Post Office Box 197
London WC2E 9PX
United Kingdom

Post Office Box 161
1820 Montreux 2
Switzerland

Private Bag 8
Camberwell, Victoria 3124
Australia

Library of Congress Cataloging-in-Publication Data

CCAST (World Laboratory) Symposium/Workshop (1989: Peking, China)
Fields, strings, and quantum gravity: proceedings of the CCAST (World Laboratory) Symposium/Workshop held at the Temple of the Sleeping Buddha, Beijing, People's Republic of China, May 29-June 10, 1989 (cancelled June 4, 1989)/ edited by Hanying Guo, Zhaoming Qiu, and Henry Tye.
p. cm.—(China Center of Advanced Science and Technology (World Laboratory) Symposium/Workshop proceedings: v. 6)
Includes bibliographical references.
ISBN 2-88124-741-5
1. Field theory (Physics)—Congresses. 2. String models—Congresses. 3. Quantum gravity—Congresses. I. Guo, Hanying. II. Qiu, Zhaoming, 1946— . III. Tye, Henry. IV. Title. V. Series: CCAST (World Laboratory) Symposium/Workshop. China Center of Advanced Science and Technology (World Laboratory) Symposium/Workshop proceedings: v. 6.
QC173.68.C33 1989
530. 1'4—dc20
90–2999
CIP

 Printed in Great Britain by Bell and Bain Ltd., Glasgow.

丛　书　前　言

中国高等科学技术中心 (CCAST) 于1986年10月在北京成立．它是一个民间研究组织．它参加由意大利政府捐助建立的民间组织世界实验室并获得世界实验室的资助．它和中国的研究机构及大学建立密切的合作关系．中心的目的是在中国创造良好的研究环境，建立中国和世界各国研究机构和科学家之间的联系，以鼓励中国科学家做出有世界水平的研究成果，为全世界科学技术自由交流和发展做出贡献．

中心的主要活动之一是组织国际学术交流；每年将组织三至四次国际学术讨论会，精选与中国现有条件合适的和可发展的前沿科技领域，邀请在这方面有突出贡献的科学家介绍该学科的基础，现状，特别强调存在的问题和困难及将来可盼望的前景，使之有助于中国及世界的物理学家共同努力，推动这一学科的发展．

每一次讨论会将有一本文集，这部丛书就是这些文集的汇合．希望中国的物理学界，尤其是年轻的一代能从这部丛书中得到教益．

李政道

一九八七年五月三十一日

Preface to the Series

The China Center of Advanced Science and Technology (CCAST) was established in Beijing on October 17, 1986, to introduce important frontier areas of science to China and to promote the free exchange of scientific information between China and other nations. It is sponsored by the World Laboratory, with support from the Italian and Chinese governments.

Every year CCAST (World Laboratory) will organize three of four international symposia/workshops on subjects that are especially selected for their potential as seeds for future development in China. Each symposium brings together about 10 experts from abroad and 60–70 scientists from within China. They work very closely to discuss, in depth, the current state of the subject and to explore its future possibilities, with special emphasis on present problems within the area. It is this joint labor of fostering the growth of modern science in an ancient center of civilization that gives these symposia an especially uplifting feeling. This series of proceedings may serve as witness to these efforts on behalf of the younger generation of Chinese physicists.

T. D. Lee

Preface

When the CCAST–World Laboratory Symposium/Workshop on Fields, Strings and Quantum Gravity began on May 29, in Beijing, the student demonstrations were already in their seventh week. At that time, the governments of many nations were advising their citizens not to go to China. In spite of that, all the invited speakers came, many with their families. Within China, a number of participants were also having difficulty coming to Beijing. Nevertheless, all 92 Chinese attendees did manage to overcome the transportation problems and arrive in time for the opening session.

The meeting was held at the Temple of the Sleeping Buddha, which is located in the Fragrant Hills northwest of Beijing. The statue of the Sleeping Buddha dates from the early fourteenth century. The temple complex was largely built in the eighteenth and nineteenth centuries and features many square courtyards surrounded by one-story buildings, situated at the heart of a very large botanical garden. Recently renovated, it has more than 100 guest rooms, which enabled all of the participants to live and work together.

Zhao Xuequin, the author of the famous Qing Dynasty novel *The Dream of the Red Chamber,* used to live next to the Temple grounds. In the eighteenth century, Emperor Chien Lung sometimes went there for outings. The natural beauty, combined with the old architecture, provided a particularly tranquil setting for the pursuit of modern theoretical physics. The stellar quality of the international speakers, the active participation of the Chinese scientists and the penetrating questions posed by the young students gave life to the ancient place, and promised new hope for the China to come.

Many lecturers had arrived in Beijing a day or two before the workshop started. As a first introduction to China, we took them to Tiananmen Square. Although it was by then about a week after the declaration of martial law, one could hardly see any military presence except, a few soldiers in front of Zhongnanhai near the Square. Even the police who normally would be at all busy intersections directing traffic were absent. By this time the intensity of the period of the hunger strike had already past. Tiananmen Square is a vast area; it did not seem to be crowded even with 2,000–3,000 students camping there.

On the bulletin board of the new CCAST Institute of Theoretical Physics building was a message urging scientists and other intellectuals to participate in and celebrate the victory of the protest movement, which was set for May 30. This was supposed to be the final day. I was relieved to read this.

The very large number of participants in the mass demonstrations clearly showed the desire of the majority of people for government reform against corruption. The government had acquiesced to a nationally televised meeting with the students on May 19. The extraordinarily good behavior of the demonstrators and the restraint of the government from mid-April to the end of May impressed the world. Yet, since May 22 the slogans I saw on the streets and on the walls of many buildings were "Down with Li Peng" rather than "Anti-corruption and Democracy." There seemed to have been a change from the idealistic to the political, which worried me. During the afternoon of May 30, I saw buses and trucks carrying students and others back from the demonstration; they were chatting, laughing and waving flags. All seemed to be having a good time and there was a dreamlike, festive atmosphere. I was also happy thinking that this would be a good ending. Yet, for reasons still unclear to me, the demonstrations did not end.

The second 1989 CCAST Symposium/Workshop, on Relativistic Heavy-ions began on June 1. All the speakers came except two. For each of the two meetings, the revered Chinese artist Li Keran dedicated an original painting, reproduced on the covers of these proceedings. I visited him at his home to thank him. Li, 82, said that all of his life he had painted only peaceful subjects. At my request, he drew two fighting bulls locking horns for the Relativistic Heavy-Ion Symposium, with a poem that read:

> Nuclei as heavy as bulls
> Through collision
> Generate new states of matter.

Ever since the student occupation of Tiananmen Square, Li had been uneasy. Like the two bulls, the government and the students were locked in conflict. Neither side could retreat. How would it end?

Then the tragedy of June 4 occurred. All of us were stunned by its suddeness and enormity. It was necessary for me to arrange for the safe departure of everyone as soon as possible. However, it was the wish of the students, the speakers, and the other attendees to continue the lectures until the very last moment. In spite of the obvious difficulties, all of the lecturers completed their manuscripts.

Since 1979 I had watched China, through its open policy, make substantial progress. Ten years ago it would have been nearly impossible to have an international gathering such as ours, living together and participating in open discussions from morning until night. It is only through innumerable interactions like this, in many disciplines and over a period of years, that China can achieve modernization.

In April and May, nearly a million Chinese publicly expressed their wish for the future of China. Several hundred died on the morning of June 4; many were idealistic and innocent. To honor their memory and to express our grief, this volume is dedicated.

T. D. Lee

Invited Lecturers

Sidney Coleman	Department of Physics, Harvard University Cambridge, Massachussetts, USA
Stanley Deser	Department of Physics, Brandeis University, Waltham, Massachussetts, USA
David Gross	Department of Physics, Princeton University New Jersey, USA
Gerard 't Hooft	Department of Physics, Boston University Massachussetts, USA
H. C. Lee	Theoretical Physics Branch, Chalk River Nuclear Laboratories Ontario, Canada
Yuval Ne'eman	Institute of Advanced Studies, Tel Aviv University Ramat Aviv, Israel
Henry Tye	Newman Laboratory of Nuclear Studies, Cornell University Ithaca, New York, USA
A. Sen	Tata Institute of Fundamental Research Bombay, India
Cumrun Vafa	Department of Physics, Harvard University Cambridge, Massachussetts, USA
A. B. Zamolodchikov	L. D. Landau Institute for Theoretical Physics Moscow, USSR

CONTENTS

THREE-DIMENSIONAL GRAVITY THEORIES

S. DESER

Department of Physics, Brandeis University

Waltham, MA 02254, USA

Abstract In these lectures, we explore some properties, classical and quantum, of gravity models in 3 spacetime dimensions. Both standard Einstein theory and its extension to include a Chern–Simons term are considered.

1. INTRODUCTION

The central physical problem of constructing a consistent theory of quantum gravity, preferably within a framework which unifies it with all other interactions, is still unresolved, although it is currently hoped that string theory will provide some of the answers. Because of the difficulties involved in the full problem, one may try to gain some insights by studying models in lower dimensions where there are many simplifying features. In these lectures, I will be primarily concerned with three-dimensional theories, both Einstein's and an extension of it called topologically massive gravity that includes the now famous Chern–Simons term, unique to D=3. I will concentrate here on work in which I have been directly involved; the subject is currently being studied from many points of view, and I will not attempt a comprehensive review here.

Because Einstein's theory in its quantum aspects is not familiar to everyone, I will begin with a non-technical survey of it before discussing the D=3 models. Many details will be omitted throughout, but it is hoped that the references provided will suffice for further study.

2. QUANTUM GRAVITY

The Planck length, which supplies the scale of quantum gravity, was first obtained by Planck in his series of papers around 1900: he defined the quantity $\kappa \equiv (G\hbar c^{-3})^{\frac{1}{2}} \sim 10^{-32}$ cm, which, together with c and $\hbar$, provides natural units of length, time, and mass ($\hbar\,\kappa^{-1}\,c^{-1} \sim 10^{-5}$ gm or $10^{19} GeV$). That κ, as the basic coupling constant in gravity, would lead to ultraviolet problems because of its dimensionality was already noted in the early thirties by Heisenberg and others. Actual quantization of the gravitational field also began in the thirties through the work of Rosenfeld and of Pauli and Fierz, who studied the massless spin 2 field action which is the weak field limit of the full Einstein theory. I believe it was realized quite early on that the gravitational field, being universally coupled to all matter, could not be left classical (except as a – frequently very good – approximation), any more than could the electromagnetic field; in either case, it makes no fundamental sense to couple the field only to some expectation value of the matter sources. This means that classical geometry is an effective limiting low energy (and $\hbar \to 0$) concept, whether it emerges from quantized local Einstein theory or (more likely) from some nonlocal generalization such as string theory in which spacetime is not even a primary ingredient.

Modern work on quantization began in the fifties, where the rather peculiar dynamics of the theory (such as the absence of any extrinsic notion of time, and the fact that its conjugate, the "Hamiltonian," vanishes) associated with its gauge (= coordinate) invariance was disentangled. Although the canonical and covariant quantization of the classical theory has been better and better understood in different ways ever since, there still remain problems of regularization in the operator transcription. The covariant, diagrammatic approach to closed loops – radiative corrections – was well-understood by the early seventies when many explicit one-loop calculations were performed (with infinite results); indeed, the need for ghosts in nonabelian gauge theories was first noted here. Corresponding tree-level effects were also calculated, despite the horrible proliferation of indices in the graviton-graviton vertices. These results were all within the standard perturbative framework in which the gravitational field was developed about some background (usually flat space) and nonlinearities were expanded in a series of powers of κ. There have also been attempts at summing parts of the series or inferring non-perturbative consequences of the theory, in the hope that these would in fact lead to gravity as a universal regulator which would make everything finite, essentially because of the old hope that κ would act as a natural small-distance cutoff for all fields. Although we will mention a successful classical result in this direction, we have no well-defined closed form approach to the quantum problem. There are also a number of conceptual questions involving the path-integral formulation and the configurations to be summed over (*e.g.*, should different topologies be included, and if so with what weight), how to continue to Euclidean signature etc. as well as the meaning of the "wave-function of the universe" that are actually the basis of much current activity, particularly in connection with the cosmological constant problem and more generally with quantum cosmology which will be dealt with by Prof. Coleman. I cannot cover these important ideas, nor those regarding the quantum mechanics of black holes which Prof. 't Hooft will describe.

A completely different aspect of quantum gravity was uncovered in the then very distant context of (old-fashioned) string theory by Scherk and Schwarz and by Yonea around 1974; they noted that among the infinity of excitations described by these nonlocal systems, there appeared, for closed strings, a massless spin 2 particle, which by the uniqueness and universality

I will review, must be identified with the graviton. The notion of supersymmetry, which also evolved from string theory, led in 1976 to a profound generalization, supergravity, which is a local theory unifying spacetime and matter into a single multiplet. This was in fact a much more radical unification than the Kaluza-Klein geometrization of electromagnetism of the twenties, because fermions, and not just bosonic gauge fields, were associated with gravity. However, strings, Kaluza-Klein extensions and supergravity do have the common theme that the "true" spacetime dimensionality need not be 4, but could be higher. This is likely to remain a fruitful notion, especially if we find a compelling way to account for compactification into just the observed 4 macroscopic dimensions together with the curling up of the others. More recently, we have seen the 1984 string revolution which emphasized the role of "anomalies" associated with gauge theories, the required avoidance of which would leave (what was then thought to be) an essentially unique model whose low energy excitations correspond to the observed particles. This chapter is of course far from complete, but the deep changes in our notions of what occurs at "small distances" is likely to remain important; I am sure all this will be covered in Prof. Gross's lectures. However, one should caution that nonlocality also has its price, which is still to be completely understood.

Although Einstein arrived at classical general relativity by profound geometrical intuitions which found their setting in Riemannian geometry, it is in fact possible to arrive at it by entirely complementary means, based on the more familiar (and experimentally incontrovertible) ideas of special relativistic dynamics, particularly special relativistic quantum theory (in the tree level sense).

In the special relativistic and Galilean macroscopic world, the forces of gravity are found to have certain simple qualitative properties which require an essentially unique field for their description: there are attractive macroscopic force between static (as well as moving) masses, that the forces fall off as $\frac{1}{r^2}$, and that light is also "bent." On the other hand, all forces in special relativity are due to exchange of particles – which are characterized by two invariants – their mass (which can also be zero) and spin. All 1/2 integer spin particles are immediately excluded by the fact that the forces are macroscopic (they must then involve exchange of at least 2 fermions) and $\frac{1}{r^2}$ (such exchange implies faster falloff). Likewise, Weinberg showed that all particles of spin greater than 2 and long range (= zero rest mass) can only couple to matter "currents" which have zero static limit, so they are also excluded. This leaves spins (0,1,2). Spin 1 is excluded by the fact that like "charges" attract. [Actually, implicit in the attraction/repulsion induced by even/odd spin exchange is the requirement that the intermediate field enter with positive energy, which is in turn based on the observed stability of matter.] A scalar (spin 0) field cannot be the main gravitational intermediary, because the only local generalization of Newtonian mass density is of course the stress tensor $T^{\mu\nu}(x) = T^{\nu\mu}(x)$ of a system, and its scalar part T^{μ}_{μ} which would couple to spin 0 vanishes for the electromagnetic field, so light would not be bent. [A scalar could couple to some other quantity such as $F_{\mu\nu}F^{\mu\nu}$, but then "bending" would be radically different from that observed.]

We have almost run out of candidates: there remains only the spin 2 field, either massive or massless; being described by a symmetric tensor field $h_{\mu\nu}$, it is ideally suited for coupling to $T^{\mu\nu}$. One totally unexpected dividend here is that one can show that this field must be strictly massless (*i.e.*, of infinite range) even though there is clearly no observable solar system difference between a Yukawa potential with range the size of the universe, say, and the strictly Coulomb one. Nevertheless, it turns out (as first shown by van Dam and Veltman) that there is a discontinuity here, and that there is a 25% difference in the light bending predicted by the $m = 0$ and $m \neq 0$ choices, the observed bending leading of course to $m = 0$. This is due to the fact that the zero helicity component of a massive spin 2 field fails to decouple from matter even as $m \to 0$. Now there is only one way to describe a (positive energy) infinite range spin 2 field (just as the Maxwell action is unique under similar assumptions). In both cases, these fields are governed by actions and field equations of the gauge type, with currents/stress tensors as sources. Being gauge fields, these systems have identically conserved field operators: for Maxwell, they are $\Box A_\mu$ as leading term, minus the term $\partial_\mu \partial^\nu A_\nu$, *i.e.*, $\partial_\nu F^{\nu\mu}$. For a symmetric tensor $h_{\mu\nu}$, one similarly has $\Box\, h_{\mu\nu}$ minus analogous terms, the identically conserved combination being called $G_L^{\mu\nu}(h)$, the linearized Einstein tensor.

The respective sources $(J^\mu, T^{\mu\nu})$, (we use $\hbar = c = \kappa = 1$ units), must therefore be conserved (not identically, but by virtue of the matter field equations) not only for free sources but precisely also when their coupling to the gauge fields is included. This is indeed the case for the electric current: charge remains conserved because photons are neutral. However, the stress-tensor is a different story: it represents the energy of a system and is only conserved ($\partial_\mu T^{\mu\nu} = 0$) when that system is isolated. But it is now in interaction with the h-field and so no longer conserved; only the stress tensor of the total matter plus h-field system is. We must therefore add the term $T^{\mu\nu}(h)$ – quadratic in h – to the source side of the field equations. But this requires adding a cubic term in h in the action, which in turn changes the $T^{\mu\nu}$ of the h-field (since $T^{\mu\nu}$ is derived from the action), and so on – indefinitely. While there is no *a priori* guarantee that this series converges, *i.e.*, that a consistent self-coupling exists, it of course does. [Indeed, by a suitable choice of variables, the whole process stops at the first nonlinear (cubic) order in the h-field action.] The net result is two-fold: first, the original gauge invariance of the $h_{\mu\nu}$ field, which was the obvious generalization ($\delta h_\mu = \partial_\mu \xi_\nu + \partial_\nu \xi_\nu$) of the Maxwell $\delta A_\mu = \partial_\mu \Lambda$ becomes nonlinear, and depends on h; second, the total h-field action depends on $h_{\mu\nu}$ only in the combination $(\eta_{\mu\nu} + h_{\mu\nu})$ and does not involve the Minkowski $\eta_{\mu\nu}$ alone. This universal dependence is also true of the matter action in its coupling to $h_{\mu\nu}$ – it also only depends on the combination $(\eta_{\mu\nu} + h_{\mu\nu})$. Furthermore, the gravitational Lagrangian has a very specific form, homogeneous in second derivatives at every power of $h_{\mu\nu}$; "miraculously" this form is a purely geometric quantity – the scalar curvature density of a Riemann space with metric $g_{\mu\nu} \equiv \eta_{\mu\nu} + h_{\mu\nu}$. The underlying symmetry is just general coordinate invariance. Furthermore the result is unique, up to a possible additional part, the so-called cosmological term, and can be extended to provide a derivation of supergravity as well. [There is as yet no corresponding way to understand the "geometry" underlying closed string theory in which gravity is embedded.] This derivation of the effective (low energy) classical Einstein theory does not imply however that it is the "true" model to be quantized, anymore than one must take phonons as "true" fundamental particles.

We next illustrate both the nonperturbative function of classical general relativity as a universal "regulator," *i.e.*, as providing a physical cutoff for infinities that would otherwise be present in systems coupled to it, and the pitfalls of the perturbative expansion in strong-field problems. We emphasize that the discussion here is purely classical, but its lessons are worth bearing in mind when we come to the quantum domain. Consider first the self-energy of a simple distribution of mass and charge at the Newton-Maxwell level. We are interested in the behavior of the self-energy as the size ϵ of the particle tends to zero, *i.e.*, in the point limit. The total mass (or energy) of this system is given by

$$m = m_0 - \frac{G m_0^2}{2\epsilon} + \frac{e^2}{2\epsilon} \tag{2.1}$$