NEW TRENDS IN PARTICLE THEORY

PROCEEDINGS OF THE JOHNS HOPKINS WORKSHOP
ON
CURRENT PROBLEMS IN PARTICLE THEORY 9

Florence, 1985
(June 5-7)

NEW TRENDS IN PARTICLE THEORY

Edited by
L. Lusanna

World Scientific

Published by

World Scientific Publishing Co Pte Ltd.
P. O. Box 128, Farrer Road, Singapore 9128
242, Cherry Street, Philadelphia PA 19106-1906, USA

PROCEEDINGS OF THE 9TH JOHNS HOPKINS WORKSHOP ON CURRENT PROBLEMS IN PARTICLE THEORY — NEW TRENDS IN PARTICLE THEORY

ISBN 9971-50-044-2

Printed in Singapore by Kyodo-Shing Loong Printing Industries Pte Ltd.

FOREWORD

This is the ninth in a series of Workshops on Current Problems in Particle Theory. As in the past, the purpose of the Workshop has been to provide a forum for theoretical physicists from all over the world to discuss outstanding problems of theoretical particle physics in an informal atmosphere. Therefore, the format has also followed the established pattern of concentrating the discussion around invited talks. The latter were given by recognized experts of each topic discussed; the speakers both summarized the state of the act and presented their own results.

The title of this Workshop was "New Trends in Particle Theory". It became clear during the last year that many of the theories as discussed, for instance, at the last Workshop face difficulties which may prove to be insurmountable. A new hope is now being offered by string models, which, while retaining all the good features of previous theories (such as gauge theories in general and supersymmetric theories in particular), appear to cure all the diseases of the former. If correct, such theories will bring an unexpected and exceptionally beautiful synthesis of theoretical ideas advanced in the past two decades or so. It is therefore not surprising that the newly found enthusiasm of theoretical physicists is reflected in the Proceedings of this Workshop. Most speakers discussed some aspect or another of string models, including even their possible cosmological consequences. What emerged as a result of the discussions is that, probably, theoretical particle physics is entering an era of new and exciting developments; however, a great deal of work will have to be done before one's hopes for an internally consistent and phenomenologically acceptable theory will be realized. We hope that this volume will contribute to this development by stimulating new ideas in the minds of its readers.

The Workshop took place in the beautiful setting of the Villa Spelman of Johns Hopkins University, overlooking the historic city of Florence, where modern physics as we know it today, was born through the works of Galileo. We wish to thank all those colleagues of ours who generously contributed their time and efforts to bring this Workshop to a successful conclusion. It was the first one which took place under a recently concluded agreement between the University of Florence and Johns Hopkins University.

As yet another development, efforts are now being made to further broaden the base of the Workshops by including physicists from the People's Republic of China, besides those from Europe and the United States, in this cooperative venture. In this spirit, members of the "old" Organizing Committee had the pleasure of welcoming Professor Yi-Shi Duan who joined the Committee this year.

We thank the Comune di Firenze, the Instituto Nazionale di Fisica Nucleare, the Johns Hopkins University, Regione di Toscana and Università di Firenze for financial support. Particular thanks are due to Deans George W. Fisher (the Johns Hopkins University) and Mario Primicerio (Università di Firenze) for their understanding and support of these Workshops.

We also wish to thank Miss Silvia Cappelli for her able and dedicated help with the organization and editorial work connected with the Workshop and to Dr. K. K. Phua and the staff of the World Scientific Publishing Co. for their understanding and encouragement in producing this volume.

The Organizing Committee

CONTENTS

Report Number DOE/ER/40033B-79
RU85/B/120

PHYSICS IN 10 AND 11 DIMENSIONS

Peter G. O. Freund *
The Rockefeller University
New York, New York 10021

The University of Chicago
Chicago, Illinois 60637

ABSTRACT

Unifications of gravity with all other forces and forms of matter in an 11-dimensional supersymmetric local field theory and in 10-dimensional supersymmetric string theories are presented. The phenomenological and conceptual advantages of the latter and some open problems are noted.

It had long been realized that nature presents us with four basic forces: strong electromagnetic, weak and gravitational. In spite (or maybe even because) of early, quite unsuccessful attempts at unifying electromagnetism and gravity, a kind of "consensus of modesty" emerged, to the effect that one should stick to one force at a time and leave unification for later. Remarkably, a consistent (viz. renormalizable) theory of the weak interactions inextricably involved electromagnetism and ended up in the partially unified electroweak theory. Strong interactions were thrown in soon thereafter, resulting in so-called grand unified theories. Alas, these grand unifications leave important questions unaswered or even unasked. Here are three such questions.

I) Any group from Cartan's infinite list of simple compact Lie groups qualifies as a grand unification gauge group. What is the theoretical criterion whereby a given group (e.g. the phenomenologically promising SU(5) or O(10)) is chosen.

II) Granting the choice of gauge group, one right away knows the gauge boson sepctrum. But what about spin 0 and 1/2 matter fields? A priori there are many possible assignments for them. Phenomenology, "simplicity", anomaly cancellation, supersymmetry all place constraints on these assignments, but do not suffice to uniquely specify them. A related question has repeatedly been asked by Einstein for gravity. In the Einstein equations $R_{\mu\nu}-1/2g_{\mu\nu}R=-8\pi\kappa\theta_{\mu\nu}$, the left hand side is geometrical and unique (just like the Yang-Mills part of ordinary gauge theory), whereas the energy momentum tensor $\theta_{\mu\nu}$ on the right hand side is arbitrary. How is one to fix this $\theta_{\mu\nu}$?

---

*Work supported in part under the Department of Energy Contract Grant Number DE-AC02-81ER40033B and National Science Foundation Grant Number PHY 83-01221.

III) In grand unification, scales near the Planck scale of gravity are involved. How is one to include gravity into this unification?

To nail down the fermion spectrum, some, presumably gauged, supersymmetry is to be invoked. This automatically brings along gravity, thus answering question III. Yet to get anywhere with questions I and II, one must start from N-extended supergravity with $N>4$. Maximally extended N=8 supergravity has been tried[1], though again with rather modest success. Instead of increasing the extent (N) of the supersymmetry in 4-dimensional space-time, it looks more promising to stick to unextended N=1 supersymmetry but increase the dimension d of space-time instead[2]. This immediately raises a number of new questions.

IV) Why is the observed dimensionality ($d_{obs}=4$) of space-time smaller than its true dimensionality d?

V) With gravity included, the quantum version of the d-dimensional theory is not renormalizable. To be consistent it must then be finite. Is it?

VI) What is the true dimensionality d of space-time and why?

Supersymmetry goes a long way towards answering this last question. It requires[3] $d \leq 11$. Otherwise, among the massless fields we would encounter the d-dimensional counterparts of spin $j > 2$, which is currently believed (though not rigorously demonstrated) to lead to inconsistencies.

The first natural example in the direction of higher dimensions is 11-dimensional supergravity.[4] I will briefly discuss it here in order to see how it tackles questions I-VI. Difficulties on question V then point the way to superstring theories in ten dimension which we shall discuss. Unlike four dimensions where both the graviton and the gravitino have 2 degrees of freedom, in 11-dimensions the graviton has 44 degrees of freedom, the gravitino 128. Supersymmetry requires equal members of Bose and Fermi degrees of freedom and thus calls for an additional 84 Bose degrees of freedom. Supersymmetry then forces these 84 degrees of freedom to be supplied by a massless antisymmetric tensor field A_{MNP} of rank 3. Being massless, these A_{MNP} admit gauge transformations, and the gauge invariant quantities are not the potentials A_{MNP} but their curl F_{MNPQ}. Now if either the tensor

F or its dual *F is to have a vacuum expectation value on a maximally symmetric space-time, then F or *F must be proportional to the totally antisymmetric Levi-Civita symbol on that space-time. But supersymmetry forced F to have 4 indices so that *F has 11-4=7 indices and therefore, the appearance of such a vacuum expectation value <F> (<*F>) is only possible if the space time is 4(7) dimensional.[5] Once <F> ≠ 0 (or <*F> ≠ 0 it is readily shown that the remaining 7 (4) dimensions develop a curvature of the right sign to present a compact Einstein manifold. In other words they do indeed curl up.[5] While there is no clear argument to exclude the 7-dimensional space-time, it is interesting that a realistic 4-dimensional space time is possible, and that this dimensionality is dialed by supersymmetry which set the number of indices of F. Question IV is then answered (modulo this 4/7 ambiguity). Question VI is also answered in that d=11 is maximal. Question III is answered, as we deal with a supergravity which has a unique way of incorporating gravity. The answers to questions I and II depend on the shape of the small 7-manifold M_7. For instance[6] for a 7-sphere we get N=8 supersymmetries and a SO(8) gauge group, for a squashed 7-sphere N=1 supersymmetry V and SO(5) x SO(3) gauge group, for a parallelized 7-sphere no supersymmetry N=0, etc.... Which, if any of these is the true vacuum is a delicate dynamical question. In all these cases the fermion and scalar spectra are also readily available.

There are however serious difficulties. At the phenomenological level, the fermion spectra are non-chiral[7], at odds with all experimental data (heavy "mirror fermions" cannot be excluded, but are unlikely on the basis of our present day experimental knowledge). Space-time is anti-de-Sitter rather than Minkowski and displays an enormous cosmological constant, 120 orders of magnitude too large! Whether "foam"[8] can be successfully invoked to unload this enormous cosmological constant remains to be seen. Finally, at a deeper level, a one loop accident notwithstanding, the prospects for a finite quantum supergravity in 11-dimensions are not the best. Question V then spells trouble!

It is this observation that over the last year has revised interest in superstring theories. Supergravity theories, of the type discussed above, are local field theories which describe pointlike objects. Once one is willing to increase the dimension d of the host space-time, one may as well entertain the possibility that the objects living in this space-time are not pointlike, but rather extended, in the simplest case strings then. We increase, as it were, the intrinsic dimension δ of these objects from δ=0 to δ=1. The extended δ=1 string then has infinitely many superheavy excited modes which, roughly speaking, temper the ultraviolet behavior of gravity, in a way similar to that in which the intermediate bosons of electroweak theory temper the ultraviolet behaviour of weak interactions.

Whereas point particles can live in a space of arbitrary dimensionality, strings cannot. To maintain Lorentz invariance at the quantum level it turns out that the dimension of the host space-time must take a certain critical value d_c [9], d_c=26 for bosonic strings,[10] or d_c=10 for supersymmetric strings[11,12], or superstrings for short. Question VI thus again receives a clear answer. The bosonic string theories in 26 dimensions are afflicted with problems: their spectra contain tachyons, and they can develop fatal one loop infinities.[13] We shall therefore restrict ourselves to the 10-dimensional superstrings. At first one may feel uneasy about considering extended objects, as this may involve violations of cherished ideas concerning the locality of fundamental interactions. Fortunately, while the strings themselves are nonlocal extended objects, they interact in a local way.[14] For instance an open string breaks at some point yielding two open strings. Conversely one end of an open string meets an end of another open string and they fuse to one open string. the two ends of the same open string can fuse yielding a closed string. Finally a closed string can split into two closed strings and vice versa, again at a point, as illustrated in fig. 1. We thus see that one can have open and closed strings, closed strings by themselves with fig. 1 type interaction, but not open strings by themselves, for the same interaction that fuses two strings can close up one string.

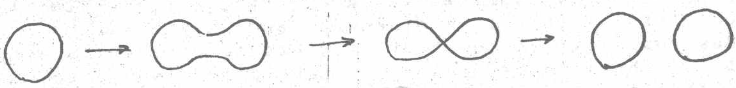

Fig. 1

In all these cases superstring theory is thus an infinitely multilocal theory.

At low energies one may neglect the spatial extension of the strings, and thus obtain an approximate local field theory of their interactions.[14]

Much as one would want a unique superstring theory, if such a theory is to play the role of ultimate, fundamental theory, as of now we have to contend with five such theories and there may be more.

First of all there are two closed superstring theories[12] endowed with N=2 extended supersymmetry in 10-dimensions. One of these is chiral the other non-chiral (the local limit of the latter is the same as the dimensional reduction of 11-dimensional supergravity to 10-dimensions). The chiral theory seems to preferentially compactify to 5 rather than 4 dimensions, although it admits[15] of more elaborate dimensional descent scenarios which might bring it down to 4 dimensions. Neither of these theories promise much to the phonomenologist. Their main virtue resides in the inclusion of gravity in consistent quantum theories[16], a highly non-trivial virtue at that. Neither of these theories have any anomalies.

Next there is a theory of unoriented open and closed superstrings, in which the open strings carry "flavor" quantum-members corresponding to a gauge group G at their two ends[11,12]. Such theories can be constructed for G any orthogonal or symplectic group.[12] But, in general such superstrings develop gauge, gravitational and mixed anomalies and thus lead to inconsistent quantum theories.[17] It was the crucial observation of Green and Schwarz,[18], that in one and only one case do these anomalies cancel: for G=SO(32). By studying the corresponding local field theory and including a few more string dictated terms in the low energy expansion it was then noted[18,19] that the group need not be SO(32) but could equally well be E_8 x E_8. (barring some trivial alternatives, involving products of hundreds of U(1) factors). There are no open and closed string theories involving $E_8 x E_8$. This has led to a search for a new type of string theories involving E_8 x E_8.

The theory of a point particle is a "field" theory in one time and zero space dimensions. (i.e. on the world line of the point), with the point particle's coordinates being the time-dependent (there is no space dependence in zero space dimensions) "fields". In the same way a string theory is a field theory on the two dimensional (one time + one space dimensional) world sheet of the string. The string fields X^μ (σ,τ) are the coordinates in the host space-time of the point (σ,τ) on the string's world sheet. This is a less trivial theory, a genuine field theory: a two-dimensional σ-model. As such a two-dimensional field theory, it can develop a conformal anomaly, and corresponding inconsistencies (ghosts) at the quantum level. Assume for the moment that the host space-time is a group mainfold. Allowing in the σ-model lagrangian, for a Wess-Zumino term with minimal non-vanishing value of its quantized coefficient, the conformal anomaly will vanish[20] if the rank r (not the dimension!) of the group whose manifold describes the host space-time equals the critical dimension of the string theory, r=26 in the non-supersymmetric case. Minkowski space in d-dimensions is R^d (R = reals) and as such an abelian group of rank d.

Hence, 26-dimensional Minkowski space will do, as was well known since the seventies. But a new possibility is opened, that of Minkowski space in a lower number of dimensions d' times a compact group $G_{26-d'}$ of rank 26-d': $R^{d'} \times G_{26-d'}$. This suggests a string theory in a 4-dimensional host space-time with some rank 22 gauge group say SO(44). On the face of it a new string theory has been obtained. However this SO(44) gauge invariance can be come by in a less dramatic way as well,[20,21]. Start from the ordinary 26-dimensional bosonic string and compactify 22 of the host space-time dimensions on a torus with all 22 radii equal. This torus is the quotient R^{22}/Λ_{22} of 22-dimensional euclidean space by the hypercubic lattice Λ_{22}. With unit lattice spacing Λ_{22} will contain (22x21x4)/2 = 924 vectors of length square two (the diagonals of the fundamental plaquettes). They span the root diagram of the Lie algebra so(44). It is not hard, using some recent very elegant mathematical techniques, to show that this theory actually exhibits a gauged SO(44) symmetry. The trick was that the rank of SO(44) equaled the difference between the critical dimension (26) of the host space-time and the dimension of its noncompact Minkowski component (the rest being curled up into the torus). It has therefore been suggested[22] that one repeat this construction but curling up only 16 of the 26 dimensions, thus leaving a 10-dimensional Minkowski space and a gauge group of rank 16. Both $E_8 \times E_8$ and SO(32) have rank 16 and in fact the only self-dual even lattices in 16 dimensions are[23] the weight lattices of $E_8 \times E_8$ and Spin $(32)/Z_2$. This all looks very promising in that it offers a possible unified picture of the $E_8 \times E_8$ and SO(32) strings as originating in 26 dimensions, were it not for one central fact: superstrings involve fermions in spinorial representations of the 10-dimensional Lorentz group Spin (9,1). It was originally hoped that these might somehow emerge as solitons in the bosonic theory. Whether this is possible is still are open question. Yet the 26 → 10 compactification has led to the construction of the remarkable heterotic string.[24] One starts from closed strings. One then has left and right moving modes which can be treated separately. For the left movers choose a closed 26-dimensional bosonic string compactified on a 16-torus as just explained. For the right-movers, on the other hand, chose a supersymmetric string which brings along the fermions! The left movers provide the rank 16 gauge symmetry, the right movers the supersymmetry. This theory yields anomaly free, finite quantum theories which incorporate gravity and are free of tachyons and ghosts gravity. The $E_8 \times E_8$ theory, further compactified from 10 down to 4 dimensions, on Calabi-Yau spaces holds out[23] very exciting phenomenological prospects. One gets realistic answers to questions I and II. For instance, the grand unification-like group turns out to be E_6, although full E_6 invariance is a 10-dimensional affair, and there are E_6 breakings in 4-dimensions not envisioned in grand unification.

We have given here the basic ideas that are involved in the construction of viable superstring theories. At this point it may be profitable to point out some of the open problems which will have to be settled before this theory assumes its definitive shape.

First and foremost, all the fancy mathematics notwithstanding, at present we still lack a compelling, hopefully geometrical, principle underlying superstring theory. The situation here is rather the opposite of the one prevailing during the development of general relativity. There, based on the equivalence principle, Einstein realised early on that general covariance must be the geometrical principle underlying a viable relativistic theory of gravity. It took then quite some effort to translate this beautiful principle into concrete dynamics. Here, on the contrary, we have a full fledged dynamical theory, but have yet to identify the geometrical principle underlying it. This involves geometry in an infinite-dimensional space, the space of all string configurations in the host spa e-time, i.e the host space-time's loop space (in the case f closed strings).

Of course we also need a criterion to narrow down the range of possible superstring theories so as to obtain uniqueness at this fundamental level. Five "theories of the world" are four theories of the world too many.

Concerning compactifications from 10 down to fewer dimensions, again a mechanism of "preferential" compactification[3] towards 4 dimensions is needed. A priori the 10-dimensional host space of superstring theory could compactify towards dimensions other than 4. Still with Calabi-Yau mainfolds, compactifications to 6-dimensions have already been found.[26] But one could come down equally well to 8 or 2 dimensions, or if (modulo certain constraints) one were to allow vacuum expectation values for the Kalb-Ramond, Yang-Mills and scalar field strengths, then to other dimensions as well.

Superstrings are usually treated in perturbation theory. The local approximation involves a supergravitating gauge theory for which nonperturbative effects can be important, e.g. solitons, such as monopoles. How are these to be reproduced in superstring theory? This suggests the existence of a yet to be discovered soliton sector of superstrings. At the same level one may ask whether, with superstrings, black-hole type singularities so puzzling in Einstein theory, would somehow be regulated.

The zero mode spectrum involves a wealth of scalar modes. This is quite similar to what happens in other supergravity theories. But there, these scalar modes parametrize a coset space. This yields a nonlinearly realized "hidden" gauge invariance. Is there such a hidden gauge invariance for superstrings, and if yes, does it develop gauge bosons at the quantum level? This could have important phenomenological repercussions.

To obtain a finite quantum theory of gravity, one had to replace local fields with superstrings, thus increasing the intrinsic dimensionality of the basic dynamical objects from $\delta=0$ to $\delta=1$, as noted above. But why stop at $\delta=1$? Could one go on to membranes, $\delta=2$, or even more extended objects? There are arguments[27] that as δ increases, the critical dimension d_c of space-time decreases until we eventually reach a situation in which the host-space can no longer accommodate these objects. In fact this situation seems to occur for $\delta\geq 4$ in the supersymmetric and $\delta\geq 6$ in the nonsupersymmetric case. Membranes ($\delta=2$) are thus tolerated, and one may consider them as well.[28] Reparameterizations of the membrane's world manifold yield an infinite algebra, although the conformal algebra is finite-dimensional in this case. It has been proposed[29] that certain anomaly-free supergravity-super-Yang-Mills systems in 6 dimensions, may represent the local limit ofsuch membranes or of related internally symmetric strings.[30] In other words, not only do we have to select one - hopefully the $E_8 \times E_8$ heterotic - superstring as the "only" one, we also have to show that what this best of superstrings can do, can not be accomplished with membranes or other such more extended objects.

To conclude, let me recall that strings and superstrings were first considered in pre-QCD hadronic physics with its emphasis on flavor symmetries. There, superstrings were less than successful. But then, the original Yang-Mills proposal also concerned flavor symmetries (isospin, eightfold-way SU(3),...) and it only really took off in its reincarceration as a renormalizable gauge theory of the weak and electromagnetic interactions. Maybe the corresponding phase in superstring theory involves a finite theory of gravity, such as is now being explored.

1) See J. Ellis, M.K. Gaillard and B. Zumino, Phys. Lett 94B, 343 (1980).

2) See T. Appelquist, A. Chodos and P.G.O. Freund "Modern Kaluza-Klein Theory";(Benjamin/Cummins, Reading Mass., 1985).

3) W. Nahm, Nucl. Phys. 135B, 149 (1978).

4) E. Cremmer, B. Julia and J. Scherk, Phys. Lett. 76B, 409(1978).

5) P.G.O. Freund and M.A. Rubin, Phys. Lett. 97B, 233 (1980).

6) M.J. Duff, Nucl. Phys. B219, 389(1983); M.A. Awada, M.J. Duff and C.N. Pope, Phys. Rev. Lett. 50, 294 (1983); F. Englert, Phys. Lett. 119B, 339(1982).

7) E. Witten, Princeton preprint 1983, to be published.

8) S.W. Hawking, Nucl. Phys. B144, 349 (1978).

9) C. Lovelace, Phys. Lett. 34B, 500 (1971). P.Goddard and R.E. Waltz, Nucl. Phys. B34, 99 (1971). P. Goddard, J. Goldstone, C. Rebbi and C. Thorn, Nucl. Phys. B56, 109 (1973).

10) G. Veneziano, Nuovo Cim 57A, 190 (1968). Y. Nambu in Proceed. Int. Conf. on Symmetries and Quark Models, Wayne Univ. (Gordon & Breach, N.Y. 1970) p. 265. T. Goto Progr. Theor. Phys. 46, 1560 (1971). L. Susskind, Nuovo Cim. 69A, 457(1970), H.B. Nielsen, unpublished (1970).

11) P. Ramond, Phys. Rev. D3, 2493 (1971); A. Neveu and J.H. Schwarz Nucl. Phys. B31, 86(1971).

12) J.H. Schwarz, Phys. Rep. 89, 223 (1982).

13) E. Witten and D.J. Gross, private communication (1984).

14) J. Scherk, Nucl. Phys. B31, 222(1971).

15) M. Gell-Mann and B. Zwiebach, Phys. Lett. 147B, 111(1984).

16) S. Mandelstam, to be published.

17) L. Alvarez-Gaumé and E. Witten, Nucl. Phys. B234,269 (1983).

18) M.B. Green and J.H. Schwarz, Phys. Lett. 149B, 117(1984).

19) L. Dixon, J. Harvey and E. Witten unpublished, J. Thierry-Mieg unpublished.

20) E. Witten, private communication; see also D. Nemeschansky and S. Yankielowicz, Phys. Rev. Lett. 54, 620(1985).

21) I.B. Frenkel and V.G. Kac Inv. Math. 62, 23 (1980). P. Goddard and D. Olive, in Vertex Operators in Mathematics and Physics J. Lepowsky et. al. editors, (Springer N.Y., Berlin, 1985) p. 51.

22) P.G.O. Freund, Phys. Lett. 151B, 387 (1985).

23) E. Witt, Abh. Math. Sem. Univ. Hamburg 14, 323 (1941)

24) D.J. Gross, J. Harvey, E. Martinec and R. Rohm, Phys. Rev. Lett. 52, 502 (1985).

25) P. Candelas, G. Horowitz, A. Strominger and E. Witten, ITP Sta. Barbara preprint,(1982).

26) M.B. Green, J.M. Schwarz and P.C. West, Caltech preprint (1984).

27) P.G.O. Freund and F. Mansouri, Z.f. Physik 14C 279, (1982).

28) A. Sugamoto, Nucl. Phys. B215, 381 (1983). P.A. Collins and R.W. Tucker, Nucl. Phys. B112, 150 (1976). P.Howe and R.W. Tucker, J. Math. Phys. 19, 981 (1978).

29) S. Randjbar-Daemi, A. Salam, E. Sezgin and J. Strathdee, Trieste preprint IC/84/218.

30) F. Ardalan and F. Mansouri, Phys. Rev. D9, 3341 (1974).