QUANTUM ASPECTS OF GRAVITATION*

ABHAY ASHTEKAR

Départment de Physique, Université de Clermont-Fd., 63170 Aubière, France

ABSTRACT

The interface between general relativity and quantum theory has been an exciting area of research ever since the two theories were introduced. However, it is only over the past few years that the activity in this area has become intense and the problem of unification of the two theories has come to be recognized, more or less universally, as one of the most—if not the most—fundamental open problems in theoretical physics. The purpose of this article is to present the current state of the art in broad terms. It should be emphasized that the article is addressed to non-specialists—say, advanced undergraduate or post-graduate students—and is intended to be an introduction to the field rather than a thorough review thereof.

1. INTRODUCTION

A PHYSICAL theory describes a certain aspect of Nature. Electrodynamics is a familiar example: it describes physical properties common to all charged particles and fields. Quantum mechanics, in this sense, is not a physical theory. Rather, it is a body of laws to which *all* physical theories must, apparently, submit. These laws require, for example, that (pure) states of any system be represented by rays in a Hilbert space; observables, by self-adjoint operators on this space; etc.: quantum mechanics is a general framework which claims to be all-pervading, in terms of which we must formulate the description of *all* aspects of Nature. In particular, therefore, one might expect that the 'correct' description of gravitational interactions should fit in this framework.

The best theory of gravitation, available today, is general relativity. This description of gravitation does not fit in the framework of quantum mechanics: there is no Hilbert space, no self-adjoint operators; one uses the language of differential geometry rather than that of functional analysis. The common belief therefore is that although general relativity does describe gravitation very accurately on a large scale, it fails to do so on a microscopic scale. Stated differently, one says that general relativity is the correct 'classical' theory of gravity and seeks a more accurate, 'quantum' version thereof.

However, among all classical theories, general relativity is unique: it also describes space-time geometry. Consequently, it makes claims on the formulation of other theories of Nature. For example, it requires that *any* physical field be described by a geometrical object—typically a tensor or a spinor field- on a differential manifold; that its evolution be described by hyperbolic differential equations; etc.: general relativity, like quantum mechanics, provides an all-pervading body of laws. One cannot, therefore, hope simply to subject general relativity to the framework of quantum mechanics. Rather, one is forced to seek a unification of the two frameworks; unification which will provide not only a more accurate description of gravitation, but also a more complete basis for describing *all* theories of physics.

Inspite of the fact that the efforts at achieving this goal began as early as 1930's, I think it is fair to say that one is a long way away from obtaining a satisfactory solution.

Why is the problem so difficult? The reasons fall into two broad categories. First is the lack of observational data. No experiment has ever been performed to probe the quantum effects associated with the gravitational interaction. And indeed the present-day technology will have to improve at least by 25 orders of magnitudes before one can conceive of an experiment. Thus, the situation here is just the opposite of that in strong interactions. In this respect, there is a curious similarity between the current state of affairs in theoretical physics and the developments at the beginning of this century which led to the discovery of general relativity and quantum mechanics. As in the case of quantum mechanics, there exist piles of data waiting to be explained by the future theory of strong interactions. The contradiction, when it arises, is the one between experimental facts and simple theoretical models. Consequently, the progress in the field of strong interactions is following, broadly, the same path that led to quantum mechanics: first, one does phenomenology, seeking patterns and putting order in the accumulated data; then, one constructs simple models to explain the main features; and, finally, one looks for a complete theory which is to remove the ad-hoc assumptions in the various models. In quantum gravity, as was the case for general relativity, the difficulty is not too

*Based on a colloquium given at the Raman Research Institute, Bangalore, on 30th July 1979.

much data, but *no* data! Here, the problem is solely a conceptual one; the clash is between two sets of theoretical principles. Consequently, a step by step approach, using experimental data as a constant guide, is simply not available! As in the case of general relativity, one must use instead, only one's physical intuition and mathematical ingenuity. Obviously, this makes the problem very hard. The second major difficulty arises from the fact that, unlike other physical fields, the gravitational field dictates the structure of space-time itself. Physical theories, as a general rule, assume that space-time is given, once and for all, serving as the background for phenomena of interest. Thus, space-time is like a stage on which the drama of evolution unfolds, the actors being the various particles and fields encompassed by the theory of interest. The situation is drastically different in general relativity. Here, the gravitational field is identified with the curvature of space-time: the stage just disappears and the space-time geometry joins the group of actors. It is no more fixed, immune to surroundings; it also participates in the drama of evolution. This loss of kinematical background causes a host of problems, both conceptual and technical.

Inspite of these difficulties, one can speculate on the structure that the desired theory should have. First and the most obvious feature would be the presence of three fundamental constants of Nature: the velocity of light c, Planck's constant $\hbar$ and Newton's constant G. One expects the theory to reduce, in an appropriate sense, to general relativity in the limit when $\hbar$ goes to zero and to the Minkowskian quantum field theory, in the limit when G tends to zero. The genuinely new predictions are most likely to emerge on scales characterized by all three constants, *e.g.*, at 10^{-33} cms ($\sim c^{-3/2}\, G^{1/2}\, \hbar^{1/2}$), which is the unique quantity with dimensions of length that one can construct from the three fundamental constants. One hopes, for example, that the quantum fluctuations of the geometry would provide a natural cut-off at this length so that the theory would be automatically free of the ultra-violet divergences which plague Minkowskian quantum field theories. Similarly, one hopes that the quantum effects will cure general relativity of its singularities: singularity theorems of the classical theory assume that the stress-energy tensor of matter should satisfy certain inequalities which, inspite of being very natural in the classical domain, are violated by quantized matter fields. Next, consider the various conservation laws. The strong interaction conserves I-spin, parity, strangeness, baryon number, energy-momentum and charge, while the electromagnetic interaction conserves only the last five and the weak interaction, only the last three. If this pattern—weaker the interaction, less the number of conservation laws—is any indication, further violations are to be expected in quantum gravity. Indeed, recent investigations concerning black-hole evaporations strongly suggest that the baryon number will not be conserved: baryons could be eaten up by black holes which, on evaporation, would produce equal number of baryons and anti-baryons! It is *not* unlikely that there will be other, even more interesting predictions with a bearing already on the day-to-day laboratory physics. For example, the theory would permit, via quantum fluctuations, non-trivial topologies thereby providing new quantum numbers of topological origin for classifying the elementary particles. More generally, the theory would presumably replace the present-day notion of space-time by something that is radically different and this will certainly have a profound impact on all of physics. As the history, *e.g.*, of special relativity, indicates, the most dramatic aspects of this impact will be precisely those which could never have been guessed before!

The review is organized as follows. Section 2 summarizes the efforts at obtaining the required theory by traditional means. Broadly, the conclusion reached is a negative one: traditional methods run into difficulties which, at least at the moment, seem to be unsurmountable. Section 3 discusses the recent developments in a simpler but related issue: that of quantizing other fields in presence of an external gravitational field. It is these developments that have given a new impetus to research in this area. Their implications on the required theory of quantum gravity as well as some possible avenues to the desired goal are sketched in Section 4.

To conclude this section, let me make a qualifying remark that applies to the entire discussion that follows. A review of a subject in progress is bound to show the prejudices of the author *via* the selection of the material: without such a selection, the review would amount to little more than a bibliography of the literature on the subject! In the case of quantum gravity, not only is the subject in progress, but there is still considerable disagreement even on the basic issues. Selection-effects are therefore all the more significant. Broadly, the view-points expressed in this article are those of relativists, in contrast to say, particle physicists. Thus, for example, it is assumed that general relativity is the 'correct' classical theory of gravitation and the vast literature on alternate theories of gravitation and their quantization—is simply overlooked.

2. Traditional Approaches

The space-time metric plays a dual role in general relativity: on the one hand, it determines the space-time geometry thereby providing a kinematical arena for all of physics, and, on the other hand, it serves as the gravitational potential, thereby participating in dynamics. It is this duality, as was remarked in the Introduction, that makes the problem of quantization so very difficult. For example, a central assumption in the quantum description of fields in Minkowski space is that of micro-causality: physical observables associated with a region of space-time must commute with those associated with another if the two regions are space-like separated. The assumption has a simple operational meaning and is therefore very basic from a physical view-point. Unfortunately, it cannot even be formulated in the gravitational case: since the space-time metric, in its role as a dynamical variable, is to be subjected to quantum fluctuations, a background geometry to decide whether or not the two given regions are space-like separated is simply not available! Thus, the special role of the gravitational field makes it difficult to guess the algebra of observables in quantum gravity. The situation is no better with quantum states. In Minkowskian theories, quantum states of fields are wave functions which represent probability amplitudes for fields to acquire various values. In quantum gravity, one is then led to consider wave functions of metrics and probability distributions for space-time geometries. How is one to interpret such a distribution? How is one to describe the physical systems, *e.g.*, particles and fields—if one has only a probability distribution of geometries rather than a fixed geometry as a background?

The traditional approaches to quantum gravity may be divided into two broad classes depending on one's attitude towards these problems: covariant frameworks and canonical methods.

In the covariant approach, one adopts the attitude that since it is the dual role of the metric that causes the problems, one ought to begin by splitting the two roles. Thus, one starts as in Minkowskian field theories by fixing, once and for all, a 4-manifold M, topologically R^4, equipped with a flat metric η_{ab}. Then, given any other metric g_{ab} on M, one defines a tensor field h_{ab} via $g_{ab}=\eta_{ab}+h_{ab}$. This decomposition splits the two roles played in general relativity by g_{ab}: η_{ab} is to provide the required kinematical arena and h_{ab} is to be the dynamical variable, representing the gravitational potential. Einstein's equation on g_{ab} provides a non-linear hyperbolic equation on h_{ab}. Thus, the situation is reduced to that in familiar field theories in Minkowski space: conceptual problems mentioned above simply disappear! One therefore mimics the quantization procedure applicable to these field theories. The first step is to linearize the equation on h_{ab} and to construct from the space of solutions to the linear equation a Fock space of quantum states. These states provide a unitary representation of the Poincaré group—the symmetry group of (M, η_{ab})-corresponding to mass $m=0$ and spin $|s|=2$. (Irreducible representations of the Poincaré group can be classified by values of m and s). One therefore concludes that gravitons are zero rest mass spin-two particles. Next, one returns to the full non-linear equation on h_{ab}. Using this equation, one introduces, formally, a Hamiltonian operator on the Fock space which is to describe, in quantum theory, the dynamical evolution corresponding to Einstein's equation. Finally, from this Hamiltonian, one attempts to construct the S-matrix, *i.e.*, to compute the probability amplitudes for scattering processes involving gravitons.

The scheme has two types of drawbacks. First, it seems not to lead to a meaningful S-matrix. More precisely, the resulting quantum theory appears* not to be renormalizable. This means that in the perturbation series in powers of the coupling constant for scattering amplitudes, individual terms diverge in such a way that a systematic procedure for absorbing infinities by renormalizing the constants appearing in the theory is not possible. Put differently, there exist an infinite number of arbitrary parameters in the theory and hence the theory has *no* predictive power! The second drawback—which may well be the real source of the first—is that the flat background metric, introduced by hand, pervades the entire framework. The introduction of this background injures the very spirit of general relativity; a basic lesson of Einstein's theory is that there exists a single space-time metric which serves simultaneously as the gravitational potential. One may argue that the split $g_{ab}=\eta_{ab}+h_{ab}$ should be treated merely as a mathematical convenience similar to the choice of a gauge condition in electrodynamics. This viewpoint would be justifiable. However, as the framework stands, the split seems to play a dominant role in the resulting theory: the name 'covariant approach' itself refers to the Poincaré covariance of the theory! Furthermore, the price paid for the convenience seems to be too high: right from the beginning, one is forced to restrict oneself to space-times which are topologically R^4 and to ignore the fascinating non-perturbative phenomena such as the quantum fluctuations of topology at Planck length. In particular, this rules out the investigation of processes such as black hole formation and evaporation which require non-trivial topologies. And, one would expect that

* In principle, it is possible that the numerical coefficients in front of all undesired counter-terms turn out to be zero for all orders in the coupling constant. This would, however, be truly miraculous since no physical principle—such as gauge invariance or symmetry—is available which requires such a cancellation.

it is precisely through such qualitatively new processes that quantum gravity would make its impact felt. Indeed, the numerical predictions of scattering amplitudes that have played an important role in the developments concerning other interactions are, at the present stage, quite unimportant in quantum gravity, given the current feasibilities in experimental physics. The issues of immediate interest are therefore the conceptual ones. And, by imitating the procedure adopted in other interactions, covariant methods are forced to ignore precisely these issues. As Roger Penrose puts it, "if we remove the life from Einstein's beautiful theory by steamrolling it first to flatness, and linearity, then we shall learn nothing from attempting to wave the magic wand of quantum theory over the resulting corpse".

The canonical approach, on the other hand, does respect the geometrical aspect of general relativity. Thus, not only is a splitting of the dual role of the metric is avoided, but the emphasis is on investigating, already at the classical level, the ways in which general relativity differs from other field theories due to this duality. Here, the main idea is to cast the classical theory in a Hamiltonian form and to subject the 'basic' canonically conjugate variables to the Heisenberg commutation relations. To this goal, one begins with the initial value formulation of Einstein's equation. What information must one specify at an 'initial instant of time', which, when evolved *via* field equations, would lead to a unique solution to these equations? Note that even this issue is more complicated in general relativity than in other field theories. For, not only are the field equations more involved but the space-time itself is to emerge as the *end-product* of the evolution! Nonetheless, the issue is completely resolved: given a 3-surface S equipped with symmetric tensor fields q_{ab} and p_{ab} subject to certain constraints, there exists a unique (maximal) 4-manifold M with a solution g_{ab} of Einstein's (vacuum) equation such that S is a space-like 3-surface in (M, g_{ab}) with intrinsic metric q_{ab} and extrinsic curvature p_{ab}. Thus, the pair (q_{ab}, p_{ab}) on S is the initial data for Einstein's equation. Hence, in analogy with Minkowskian field theories, one may wish to treat the pair as the basic canonically conjugate variables. Unfortunately however, since q_{ab} and p_{ab} are subject to constraints, the pair contains a lot of redundant information. Thus, one must first isolate the true, physical degrees of freedom of the gravitational field by solving the constraint equations, or equivalently, by factoring out the gauge freedom. The fields representing the true degrees of freedom would then serve as the required canonically conjugate variables. Unfortunately, however, the nature of the constraint equations is such that a natural extraction of these fields is not possible in the present framework. Can one not invent schemes to quantize constrained Hamiltonian systems? Afterall, constraints arise naturally in the Maxwell theory—Div $\bar{E} = 0$, Div $\bar{B} = 0$—and yet a simple quantum description of the electromagnetic field *is* available. It turns out that the constraints in general relativity are qualitatively different from those in electrodynamics reflecting the fact that the diffeomorphism group in Einstein's theory is vastly more complicated than the Abelian gauge group of Maxwell's theory. Hence, one cannot use ideas from electromagnetism. One must look for other models. A considerable effort has been made in this direction. Of particular interest are the so called quantum cosmologies where one freezes all but a finite number of degrees of freedom of the gravitational field and subjects the rest to quantization. These models have led to number of insights. However, the results have not appreciably simplified the situation in full general relativity. In particular, although a number of proposals for passing from the constrained Poisson-bracket formalism to Heisenberg quantization now exist, the issue of constructing a Hilbert space of quantum states has remained almost entirely unexplored. Thus, although canonical methods have shed light on a number of issues in general relativity at the classical level, the programme has simply not 'taken-off' in the quantum domain.

To summarize, although the two traditional approaches take entirely different stands on the problems raised by the dual role of the metric, in the end, both run into major difficulties. Overall, one has the feeling that covariant frameworks are pragmatic but not sufficiently deep while the canonical methods are broader in their goal but not sufficiently supple to manoeuvre.

3. Quantization in Curved Backgrounds

The main stream of research on quantum effects of gravity changed its course abruptly in mid-seventies when it was realized that the external potential approximation to quantum gravity is a physically interesting as well as mathematically feasible enterprise. The idea here is to investigate the effects of a classical, background gravitational field on quantized matter. In a sense, the spirit is contrary to the original goal: instead of quantizing the gravitational field, one tries to 'general-relativize' quantum field theory. Nonetheless, there exist two reasons which indicate that the results obtained in this framework will contribute to our understanding of full quantum gravity. First, in quantum electrodynamics, the external potential calculations often provide excellent approximations to the predictions of the full theory. The second and more important reason is that, as we shall see, some of the insights provided by this framework are so compelling that it is difficult to believe that they are mere quirks of the approximation scheme.

In this framework, one gives oneself a classical gravitational field of physical interest and investigates its effects on quantum matter fields. The background gravitational field induces several interesting quantum processes: not only are the matter fields scattered in a non-trivial fashion, but there can also occur a spontaneous as well as stimulated emission of particles. Thus contrary to the situation in familiar Minkowskian quantum field theories, the vacuum state of the matter fields is unstable in the S-matrix description, the incoming vacuum state can evolve to an outgoing many particle state. This phenomenon is not peculiar to gravity; it is a general feature of the external potential frameworks. Normally, the stability of vacuum is ensured by the conservation of energy. In the presence of external potentials, on the other hand, the energy of the quantized fields, by itself, need not be conserved; energy can be transferred from the background potential to the quantum fields. To illustrate how such a transfer may come about in the gravitational case, one can construct a simple phenomenological model. One can envisage the vacuum state of matter fields as being filled with a sea of freely falling virtual particle-antiparticle pairs. Due to the tidal forces induced by the background curvature, any given pair can be torn apart as it falls. If the curvature is strong enough, the pair may be torn apart to such an extent that the gravitational potential energy gained in the process exceeds twice the rest mass of the quanta associated with the given matter field. When this occurs, it is energetically possible for the two virtual particles 'to become real'; there is a spontaneous emission. This model of particle-production is, of course, very heuristic. Nonetheless, it makes the phenomenon plausible and is also useful in making order of magnitude estimates. Finally, note that the nature of the approximation is such that one ignores the reaction of the created particle back on the gravitational background. Thus, the background, as the name suggests, participates in dynamics only partially; it affects the evolution of matter fields but is itself immune to changes.

The detailed mathematical formalism describing these processes turns out to require a non-trivial generalization of the machinery available in Minkowskian field theories. This is because the gravitational field, being geometric, affects the very notion of field quanta. For example, whereas an external static, electric field can give rise to spontaneous emission of charged paricles, an external, static, gravitational field cannot. The reason behind this disparity can be traced back to the fact that whereas the energy of charged fields fails to be conserved in time in presence of a static electric background, the energy *is* conserved in presence of a static gravitational background, thanks to the geometric nature of gravity. Mathematically, difficulties arise because Fourier transforms, which play a dominant role not only in calculations but in the very definitions of particle and antiparticle states in Minkowskian frameworks, are simply not available in curved space-times. In spite of these problems, the S-matrix theory is now well-understood. Thus, if the gravitational background is asymptotically well-behaved, one can introduce well-defined incoming and outgoing states, give necessary and sufficient conditions for the existence of the S-matrix, and, in the case when it exists, write down the expression of the S-matrix in a closed form. These expressions have led to explicit formulae for number of particles created *via* spontaneous and stimulated emission in any desired state.

The most important prediction of the framework is the *Hawking effect* which occurs in presence of black hole backgrounds. Let me first summarize the situation in classical general relativity where black holes have, already, fascinating properties. Among these are the so-called 3 laws of black hole mechanics: (i) the surface gravity κ—the analogue of g of Newton's theory—is a strict constant on the surface of the black hole; (ii) if δM and δA denote, respectively, differences in the mass and the area of two nearby black hole configurations in equilibrium, then* $\delta M = \left(\frac{\kappa c^2}{8\pi G}\right)\delta A$; and, (iii) the area A of a black hole can never decrease. The analogy between these laws—proved rigorously using only classical general relativity—and the 3 laws of thermodynamics is striking: κ plays the role of temperature and A of entropy. Unfortunately, however, in classical general relativity, the analogy remains only a formal one. For, the black hole, being black, must be at *zero* temperature rather than at κ. Similarly, since entropy is dimensionless whereas A has dimensions of (length)^2, a relation between the two quantities must involve a fundamental length and no such quantity can be constructed out of G and c, the only fundamental constants available in classical general relativity. It turns out, miraculously, that quantum theory intervenes and takes care of all these problems! Detailed calculations, carried out in the framework of quantum field theory on black hole backgrounds show that black holes do radiate *via* spontaneous emission of particles. Since the gravitational interaction is universal, all species of particles are produced. Furthermore, the spectrum is exactly Planckian with temperature $T = \hbar\kappa/2\pi c$; a black hole radiates as if it were

* For simplicity, I have restricted myself here to uncharged, non-rotating black holes.

a black body. Due to this emission, the hole loses mass and can eventually just evaporate. Finally with Planck's constant $\hbar$ at disposal, one *can* construct a quantity with dimensions of length and relate the area A to entropy $S : S = (c^3/4G\hbar) A$! Thus, if quantum effects are included, one can unify the 3 laws of black hole mechanics and the 3 laws of thermodynamics to obtain 3 laws of *black hole thermodynamics*. In this result, the principles of quantum theory, general relativity and statistical mechanics are so delicately interwoven that one is compelled to believe that it cannot but represent an essential germ of truth, even though a number of approximations have been used in its present derivation to give an anology, this result may well be to the final theory of quantum gravity what Bohr atom was to non-relativistic quantum mechanics.

4. Outlook

Apart from providing a new impetus to the field, the era of external potential approximations has given rise to a number of ideas for full quantum gravity which are now being pursued. First, there is the work in cosmological context. The standard cosmological model exhibits an initial singularity representing the big-bang. Thus, the gravitational field was very strong in the early universe. Hence, a significant amount of spontaneous emission of particles must have occurred. It is tempting to conjecture that *all* matter came into existence *via* this process: In the beginning, there was Gravitational Field and Quantum Gravity said "Let there be matter" and there was matter. . Unfortunately, however, detailed calculations in the external potential approximation are full of ambiguities since one must specify initial conditions (*e.g.*, the incoming vacuum) on a singularity. Moreover these calculations invariably predict that an infinite number of particles was created since the gravitational field grows unboundedly as one recedes to earlier and earlier times. The problem here is simply that the external potential approximation breaks down; one must take into account the reaction of the created particles back on the gravitational field. That is, one must attempt to solve a self-consistent problem in which the gravitational field continuously produces particles which continuously modify the gravitational field. One must develop approximation schemes to handle the *coupled* system; one cannot afford the luxury of a background field method. A lot of effort is being made in this direction. Another off-shoot of quantum theory in curved space-times is the investigation of the role of space-time topology in quantum phenomena. Already in the external potential approximation, non-trivial topologies provide new quantum numbers for labelling elementary particles. It is an attractive hypothesis that many—if not all—of the so-called internal quantum numbers may really be of topological origin. Finally, the results obtained using black-hole backgrounds have opened another avenue: finite temperature quantum gravity. A key role in this research is played by the so-called gravitational instantons which are the Euclidean solutions (*i.e.*, metrics with signature $++++$ rather than $-+++$) to Einstein's equation with finite action. It is believed that these instantons represent-in the semi-classical approximation—states of thermal equilibrium of the gravitational field and effort is being made to gain insight into issues such as the permissible transitions between two such states.

What is the status of issues raised by the traditional approaches to quantum gravity? The renormalization problem faced by covariant approaches has led to the theory called supergravity. This theory has several mathematically attractive features and has in fact opened new areas of research in pure mathematics: supermanifolds and graded groups. From a physical viewpoint, however, significant progress is yet to appear. In particular, although the original motivation was that of obtaining a re-normalizable theory, the status of this issue is still unclear. Furthermore, the theory requires the introduction of a fundamental spin—3/2 field called gravitino—and no such field is observed in Nature. Hence, as the matter stands—*i.e.*, in the absence of qualitatively new, deep and compelling results—the basic scenario of supergravity seems somewhat artificial. A more recent and much less explored approach is the so-called asymptotic quantization scheme. The point of departure here is the theory of gravitational radiation in exact general relativity; one quantizes the radiative modes of the gravitational field. The idea is to place oneself 'in between' the two traditional methods. Thus, as in the covariant approach, the emphasis is on the S-matrix description while, as in the canonical approach, the passage to quantum theory is *via* a Hamiltonian formulation. However, at no stage does one introduce a background metric or linearize Einstein's equation; non-trivial topologies are permissible. Gravitons, for example, arise as asymptotic entities in the exact theory rather than as spin-2 quanta on a Minkowskian background. Also, the Hamiltonian framework, being based on *null* rather than space-like 3-surfaces, is free of constraints! Consequently, unlike in the canonical approach, the programme does 'take-off' in the quantum domain: one can construct the Hilbert spaces of 'in' and 'out' states and introduce physically interesting operators on them. However, the issue of dynamics—*i.e.*, that of the actual construction of the S-matrix—is yet to be explored; one has available only a kinematic framework which is free of the obvious drawbacks of the traditional approaches.

While all these ideas are bound to give new insights and may even go a long way towards the desired theory, in my opinion, they are unlikely to go all the way; as Bohr might have said, they are not "crazy enough". To be crazy enough, one must, I feel, abandon the use of space-time as the point of departure; space-time should emerge as a 'derived' concept, a macroscopic, averaged-out object. In this respect, two directions seem to be particularly promising. The first is provided by the notion of space-time foam; one begins with a microscopic model of space-time, consisting of a foam-like structure perpetually undergoing topological changes depicting quantum fluctuations. The second and more profound approach is the one involving spin-networks and twistors. Here, one takes the operational view that particles are more fundamental than space-time; space-time is recovered from spin-networks and twistor space which are themselves built directly from the momentum-angular momentum structure of particles.

1. Feynman, R. P. and De Witt, B. S., "Covariant approach," in *Proceedings on Theory of Gravitation* (*Warszawa Conference*) (Guthier Villars, Paris, 1964). Discussions between the participants to the conference, reported in this volume, provide an excellent view of the conceptual problems in quantum gravity.
2. Bergmann, P. G., "Canonical approach," *Riddle of Gravitation* (Charles Scribner's Sons, N.Y., 1968) Part III; C. W. Misner, K. S. Thorne and J. A. Wheeler, *Gravitation* (Freeman, San Fransisco, 1973) Ch. 43.
3. Hawking, S. W., "Black hole evaporation," *Nature*, 1974, **248**, 30; D. W. Sciama, *Vistas in Astronomy*, 1976, **19**, 385; Wald, R., *American Scientist*, 1977, **65**, 585.
4. Wheeler, J. A., "Space-time foam," in *Battelle Rencontres*, Eds. C. M. De Witt and J. A. Wheeler (Benjamin, N.Y., 1967); Hawking, S. W., in *General Relativity : An Einstein Centenary Survey*, Eds. S. W. Hawking and W. Israel (Cambridge, U.P., London, 1979).
5. Penrose, R., "Spin networks and twistors," in *Quantum Theory and Beyond*, Ed. T. Bastin (Cambridge, U.P., London, 1971); *Magic without Magic*, Ed. J. Klauder (Freeman, San Fransisco, 1972); *New Scientist*, 1979, **82**, No. 1157, 734.
6. "General Reference," *Quantum Gravity*, Eds. C. J. Isham, D. W. Sciama and R. Penrose (Oxford U..P, Oxford, 1975). Introductory sections of the articles in this volume provide an excellent non-technical survey of the entire field. A second, more up-to-date volume, based on the 1980 Quantum Gravity Conference, will be published by the Oxford University Press early next year.

A NEW TANNIN FROM YOUNG STEM BARK OF *CAESALPINIA PULCHERRIMA*

K. K. AWASTHI*, ANOOP KUMAR AND (MRS.) K. MISRA**
Chemistry Department, Allahabad University, Allahabad 211 002, *India.*

ABSTRACT

From the inner stem bark of three months old plants of *Caesalpinia pulcherrima* a new ellagitannin has been isolated which is unique in having a combination of condensed and hydrolysable tannin units in the molecule. Its structure has been established on the basis of analytical, degradative and spectroscopic evidences.

CAESALPINIA PULCHERRIMA[1] (subfamily: Caesalpinaceae, family : Leguminosae) known in Hindi as 'Guletrura' is a garden variety. In our earlier publications[2-5] we have reported the presence of β-sitosterol, sebacic acid, quercimeritrin, leucodelphinidin and two ellagitannins (A) and (B) from the stem bark. This bark is highly astringent and the astringency goes on decreasing with the age of the plant. We have studied the bark at different stages of growth in order to assess the chemical changes taking place specially in the polyphenols. In our earlier publication the bark of full-grown plants was studied. We now report the components of the younger bark.

The fresh inner stem bark of three months old plants of *C. pulcherrima* was extracted with alcohol free acetone. The concentrated extract was fractionated into petrol, ether and ethyl acetate soluble fractions. Petrol removed chlorophyll and β-sitosterol. Ether extracted gallic acid, sebacic acid and quercimeritrin; and ethyl acetate extracted mainly leucodelphinidin

* Present address : Chemistry Department, Christ Church College, Kanpur, India.
** For correspondence.