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An overview of progress in string theory

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Abstract. There has been many interesting developments in string theory in last couple of years. The purpose of this article is to present a brief account of the progress made in string theory. The two invited talks by S R Das and S Mukhi in this volume contain more detailed accounts of our understanding of black hole physics and the intimate connections between string theory and gauge theories.

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1. Introduction

There are four fundamental forces in Nature: gravitation, weak force, electromagnetism and strong nuclear force. The electroweak theory and quantum chromodynamics (QCD) provide an adequate description of the last three forces mentioned above at a microscopic level and called the standard model. The principle of gauge invariance is the most important ingredient in the construction of the standard model. The standard model is renormalizable and therefore, observable physical quantities can be computed order by order in the perturbation theory. The vast experimental data show that the standard model has passed several crucial tests. However, there are several important issues one would like to address in order to understand the nature of the fundamental interactions. There is some evidence that there might be a unified description of the three interactions, except gravity, since the three coupling constants tend to converge on a point when they are extrapolated to higher energies using the renormalization group equations. Furthermore, one would like to understand some of the parameters of the standard model from a deeper level rather than introduce them in the Lagrangian from the onset.

The general theory of relativity, in the classical regime, has successfully passed many tests and it is a very important ingredient of the standard cosmological model. On the other hand, Einstein's theory is not renormalizable and therefore, it breaks down in the quantum regime. It is desired that we understand the nature of Hawking radiation from a black hole from a microscopic theory, the derivation of the Bekenstein–Hawking formula for black hole entropy and the evolution of the Universe at early epochs.

It is accepted that string theory holds the promise of unifying the four fundamental interactions [1,2] (also see [3–7] for some topical reviews). It is possible to compute some of the parameters of the standard model, such as gauge coupling constants, the Yukawa couplings etc from the string theory at least in principle, although we have not succeeded in constructing the standard model from a string theory. It is well known that perturbative calculations of quantum gravity effects yield finite results in the string theoretic framework. Let us recapitulate some of the essential features of string theory. The string is a one dimensional object which executes motion in spacetime. There are, grossly speaking, two types of strings: open and closed strings. As the name suggests, the ends of open strings are free and they are required to satisfy suitable boundary conditions for the end points. The closed string, by definition, has its both ends glued together, forming a loop. It is well known that when a point particle evolves in spacetime, it traces out a trajectory describing its history. In case of an open string, it sweeps a two dimensional surface and similarly the closed string sweeps a surface which is that of a cylinder. The natural question is why we do not observe these strings in high energy collisions. The answer to this question lies in the fact that the strings are much smaller in size than the present accelerators can probe. If we could have accelerators which have energies of the order of 10^{19} GeV, then it will be possible to observe the dynamics of the strings directly and test the predictions of string theory at the Planckian energies. In contrast, the present day accelerators have energies of the order of TeV – almost 16 orders of magnitudes below the string scale.

The string has tension and it vibrates in an infinite number of modes. We identify each mode of the string with a particle. Of course, the string will have the lowest mode and we identify that with a particular particle. The next mode will correspond to an excited state and it is separated in energy from the lowest mode in suitable unit of string tension – separation between two neighbouring levels is order of 10^{19} GeV. It is well known that superstrings move in ten spacetime dimensions which is a consequence of the conformal invariance of the theory. The string theories of interest to us contain massless particles in their lowest mode. For example, in 10-dimensional heterotic string theory, we have graviton, antisymmetric tensor and dilaton together with the super Yang–Mills multiplets corresponding to the gauge groups SO(32) or $E_8 \times E_8$ in its massless sector. Therefore, in the low energy limit, the string theory effectively reduces to a point particle field theory (this is when we want to describe physics at the present day accessible energy scales). In other words, the zero slope limits of string theories correspond to known field theories – superstring theories go over to supergravity theories in this limit. Since string is a one dimensional extended object the string coordinate is a function of two variables: $X^{\mu}(\tau, \sigma)$. Here τ plays the same role that the invariant time parameter plays in relativistic description of a point particle and σ is another parameter due to extended nature of string. As it evolves in spacetime, the string traces out a surface: the worldsheet. The requirement that the theory be invariant under reparametrization of the worldsheet leads to the constraint that spacetime is ten dimensional. The bosonic string has spin two graviton, scalar dilaton and antisymmetric tensor in its massless sector. The superstring, contains fermionic partner of the bosonic coordinate X^{μ}. Moreover, the fermionic coordinates may satisfy two types of boundary conditions: (i) when they are periodic in σ variable, the boundary condition is called Ramond or (R) or (ii) antiperiodic boundary condition called Neveu–Schwarz (or NS). The states of the superstring belong to representations of spacetime supersymmetry once some of the unwanted one could be removed by the so called GSO projection. The dilaton plays a special role since it is the coupling constant of theory; $g_s = e^{\phi/2}$. Furthermore, the Newton's constant and the gauge couplings related to the VEV of this field. There are five perturbatively consistent string theories in ten dimensions: type I, type IIA, type IIB, heterotic string with SO(32) gauge group and heterotic with $E_8 \times E_8$ gauge group.

The anomaly cancellation requirement implies that the only admissible gauge group for the ten dimensional theories are SO(32) and $E_8 \times E_8$. Therefore, type I theory only admits SO(32) gauge group.

Since superstring theory lives in ten dimensions, it is important to ask what string theory has to say about the four dimensional world. Moreover, if the spacetime is indeed ten dimensional, then why we do not see the extra dimensions. One of the ways to understand these issues to invoke the ideas proposed by Kaluza and Klein almost seven decades ago. In the context of string theory, the extra dimensions are curled and their size is so small that we cannot expose their existence with the available energies of present accelerators. One of the interesting features of the KK proposal is that the momenta along the compact directions are quantized in units of the inverse radius of the compact circle and the momenta are related to some of the gauge coupling constants. Thus we have an explanation of the quantized nature of charges. The ideas of Kaluza and Klein have played very important role in constructing four dimensional theories starting from the ten dimensional superstring theories. Our understanding of string theories has been enriched due to duality symmetries. Let us consider a bosonic string, for simplicity, whose one of the spatial coordinates, say X^{I}, is compactified on a circle of radius R and we consider another bosonic string for which the same spatial coordinate is compactified on a circle of radius $1/R$. Then, T-duality symmetry tells us that the two string theories are equivalent, in other words a theory with one compact dimension of radius R is equivalent to the theory with the coordinate which is compactified on circle of reciprocal radius and T-duality holds good order by order in perturbation theory. Thus we can test it perturbatively. The S-duality transformation takes a theory from weak coupling domain to the strong coupling regime. In some cases, it could take one string theory to another string theory as we know heterotic theory compactified on T^4 is S-dual to type IIA compactified on K_3, although in $D = 10$ these are two distinct theories. In case of ten dimensional type IIB theory, we go from strong coupling to weak coupling phase of the same theory under S-duality. It is quite obvious that the tests of this symmetry are nonperturbative in nature. The consequences of these symmetries are very important and interesting for our understanding of string dynamics in various dimensions and in revealing the interconnections amongst the five string theories. It is argued that there is a single fundamental theory, sometimes referred to as U theory or M theory, such that all the five perturbatively consistent string theories are manifestations of different phases of the underlying theory. There is intimate relation between type IIA theory and $D = 11$ supergravity. If we compactify, one of the spatial coordinates of the eleven dimensional theory on a circle, then then the radiius of the circle, R_{11}, is related to the coupling constant of the type IIA theory:

$$R_{11} = (g_s^{(A)})^{2/3}. \tag{1}$$

Thus, in the strong coupling, (large radius limit of 11-dimensional supegravity) type IIA theory goes over to $D = 11$ supergravity. It is argued that the low energy limit of the M theory is expected to give the 11-dimensional supergravity, just as 10-dimensional supergravity theories can be realized as the low energy limits of appropriate ten dimensional superstring theories.

If we consider evolution of strings in the background of their massless excitations, then conformal invariance imposes constraints on these back grounds. These restrictions take the form of differential equations known as 'equations of motion'. Indeed, one can construct the D-dimensional effective action, D being number of spacetime dimensions, from these equations of motions. Thus, the background field configurations arising as solutions of the equations of motion are identified as vacuum configurations of the string theory. In fact one can look for solutions of equations of motion which correspond to extended objects just as we look for monopole and solitonic solutions in classical field theories. If the object is extened in p spatial directions, it is called a p-brane; for example string is 1-brane and a membrane is 2-brane. Another important ingredient in string theory is spacetime supersymmetry which is responsible for many remarkable features of the theory. Even in supersymmetric field theories, there exist the so called BPS bound saturated solutions. These states do not receive quantum corrections due to the nonrenormalization theorems in supersymmetry, they are stable objects and it costs no binding energy to form their bound states. There are special types of BPS extended objects, known as Dp-brane, which admit a conformal field theoretic description. Another important property of the Dp-branes is that open string ends can get attached to them. Thus, when two of the Dp-branes are separated away from each other, they can be connected by open strings. It costs energy when we stretch a string and it will cost more energy when Dp-branes are far apart and connected by open string. On the other hand, if two of these objects are lying on top of each other then not only it costs no energy for a string connecting these two, but also the string can begin its one end and join the other end on the same brane. As Mukhi [8] has explained in detail in his talk, for two coincident branes, the resulting gauge group is U(2). Similarly, if we have N coincident Dp-branes, we have U(N) supersymmetric Yang–Mills theories and by considering intersections of various brane configurations one can derive interesting duality properties of the supersymmetric Yang–Mills theories.

The five perturbatively consistent string theories in ten dimension: these string theories are intimately connected with each other in diverse spacetime dimensions through various duality relations. Furthermore, the Dp-branes together with supersymmetries play a very crucial role in testing some of the duality conjectures which provide a deeper understanding of the nonperturbative features of string theory.

The physics of black hole has many fascinating aspects.The classical black hole is the final stage of a collapsing heavy star. As the name suggests, matter falls into it and nothing comes out; there is an event horizon. However, deeper investigations have revealed, almost a quarter of a century ago, that there are strong similarities between thermodynamics and black hole mechanics. If M is mass of the black hole,

$$\mathrm{d}M = \frac{1}{8\pi G} k \mathrm{d}A, \quad \delta A \geq 0. \tag{2}$$

Here G is the Newton's constant, A is the area of the event horizon and k is the surface gravity. This is to be compared with thermodynamical relation,

$$\mathrm{d}E = T\mathrm{d}S, \quad \delta S \geq 0. \tag{3}$$

Hawking's startling discovery that black holes radiate with a black body spectrum of temperature $T = (\hbar k)/2\pi$, when quantum effects are accounted for, raised several important issues in black hole physics. One can also associate entropy with a black hole

$$S_{\mathrm{BH}} = \frac{A}{4G\hbar}. \tag{4}$$

The thermodynamical relations used to describe macroscopic phenomena can be derived from statistical mechanics starting with microscopic fundamental laws of physics. Since $\hbar$

appears in the black hole entropy formula, it is expected that the microscopic derivation of black hole entropy requires quantum gravity calculations. Moreover, entropy of a system, when interpreted from statistical mechanical point of view, counts the total number of degrees of freedom in the system. How do we count the number of degrees of freedom in a black hole and obtain the expression for entropy? There are more fundamental issues related to quantum mechanics when we carefully examine the implications of Hawking radiation. We can think of allowing some matter to go into the black hole, prepare the initial state as a pure quantum state to be the incident wave. However, the emitted Hawking radiation has a black body distribution and thus these are mixed states. Therefore, the S-matrix that will describe the above process will loose its unitarity property.

In the perturbative regime, string theory can provide reliable results for computations of processes involving graviton. The resulting S-matrix elements respect the required unitarity and analyticity properties. Thus, it is pertinent to ask what string theory has to offer in resolving the issues alluded to earlier. Recently, one of the important achievements of the string theory has been the microscopic derivation of the black hole entropy, for a special class of black holes that arise in string theory. We shall, initially, not set $G = 1$, to bring out a few salient points in discussions of stringy black holes and some times we shall display presence of $\hbar$ in formulas. Recall, that the Newton's constant is related to string coupling and tension as $G \sim g_{\rm str}^2/T_s$, T_s is the string tension, in four spacetime dimensions. If we have a massive string state, the gravitational field is GM_s, where M_s is mass of a string state measured in units of T_s; also some times we shall denote it as M. Thus, the field increases as string coupling increases. String states are given by the mass formula $M^2 = NT_s$ and it is well known that at a given mass there are a lot of states and the degeneracy grows exponentially with mass, i.e. e^M. Thus one might think that the excited states, if treated as black holes, will reproduce the entropy formula; however, this simple argument in not adequate since black hole entropy grows like M^2, whereas the naive argument will give $S_{\rm BH} \sim M$. There have been attempts to explain this discrepancy saying that the mass that would appear in microscopic derivation of $S_{\rm BH}$ is not the same as the one appearing in Bekenstein–Hawking formula and there might be renormalization effects to be accounted for. The perturbative string states appear in infinite levels and thus, for high enough mass, the massive elementary string state will lie inside the Schwarzschild radius associated with it. Consequently, they will require black hole descriptions. One of the ways to derive black hole entropy microscopically is to consider such BPS states, so that when string coupling gets strong, the state is unchanged. In this approach, the first step is to pick up appropriate BPS state and compute the microscopic entropy. Next, compute the Beckenstein–Hawking entropy of the BPS state, it is also an extremal black hole, and verify whether the two ways of calculating entropy are in agreement. This is the first clue that string theory might explain black hole entropy in microscopic way. However, the black holes constructed from the elementary string states had some short comings while computing the entropy. The area of the event horizon, for such black holes, tends to zero as one approaches the extremal limit; moreover, the dilaton also diverges at the horizon in this limit. This problem was encountered for string states in the NS sector.

The D-brane in RR sector can come as elementary states and there are corresponding solitonic states contained in the full spectrum. The type IIB string is endowed with S-duality symmetry, $\mathrm{SL}(2, Z)$. NS states have tensions of order 1, whereas, D-strings had mass density of the order of $1/(g_{\rm str})$. For the solitons of NS sector the mass goes as $1/(g_{\rm str}^2)$ (recall the mass formula for monopoles); but the solitons for RR sector still have mass order $1/(g_{\rm str})$. In the weak coupling regime NS solitons and RR ones are heavy. We should account for the gravitational fields they produce, which is GM. In view of the above discussions, (i) NS elementary states produce very low field and (ii) RR states also produce low field in weak coupling limit; field tends to 0 as $g_{\rm str} \rightarrow 0$. We may argue that in this regime, flat spacetime is a good description of the geometry. Since we are dealing with BPS states, as string coupling increases the mass remains unchanged, but the gravitational field keeps increasing and after some critical coupling, the spacetime is not flat any more; we must employ general theory of relativity. If these states describe black holes, then we should be able to compute the degrees of freedom associated with them. It is possible to construct black hole configuration such that the area of the horizon is not zero nor the dilaton diverges at the horizon, when we take the extremal limit. For five dimensional black holes, we need at least three charges to have nonzero area for the horizon together with constant value for the dilaton at the horizon. In case of the four dimensional black hole one needs four charges in order to satisfy the requirement of nonzero horizon area and finite value of dilaton (at the horizon).

The black holes which are of interest in this context have some special characteristics. They can be thought of as composites of many D-branes carrying Ramond charges. We have mentioned before that the BPS states have the property that mass of composite BPS state is the sum of the masses of the constituents. One starts in the weak string coupling phase with such D-branes and proceeds towards strong coupling domain when gravity becomes strong. In weak coupling regime, the degeneracy of the level can be estimated reliably and microscopic entropy can be computed. In the strong coupling domain, the D-brane is inside the horizon and one can treat this like a black hole and compute the ratio $A/4G$, which is independent of string coupling $g_{\rm str}$ since both area and Newton's constant grow like $g_{\rm str}^2$.

Let us discuss how the five dimensional black hole configuration is constructed with D-branes. We start with type IIB theory in 10-dimensions. It is well known that they admit $D1$-string and $D5$-brane. We want to make the composite object heavy; therefore, we put Q_5 number of $D5$-branes and Q_1 number of D1-strings together. Let us compactify this theory on T^5, the five dimensional torus, such that the Q_5 number of $D5$-branes are wrapped around T^5, the Q_1 $D1$-strings wrap along one of the directions of the torus. Then put some momentum along the direction in which the D-string is wrapped; this momentum will be quantized in units of inverse radius of S^1. The aim is to evaluate the microscopic entropy by counting number of degrees of freedom for this system and it involves some detailed technical steps. The astonishing result is that the entropy computed for this special type of black hole from the microscopic theory agrees with the Bekenstein–Hawking entropy formula. This aspect has been dealt more carefully in the talk by S R Das [6].

Recently, attentions have been focussed in constructing supersymmetric gauge theories by considering various configurations of branes in string theories as well as in M-theory. When we have N coincident Dp-branes, a supersymmetric U(N) gauge theory lives in world-volume of the branes. The $1/N$ expansion proposed by 't Hooft revealed several aspects of SU(N) Yang–Mills theory. According to 't Hooft, one should consider large N limit of the theory keeping $g_{\rm YM}^2 N$ fixed, $g_{\rm YM}$ being the gauge coupling constant. Then a Feynmann diagram is designated by the topological factor N^{χ}, χ being the Euler characteristic of the Feynmann diagram. When we consider, expansion in $1/N$, rather than in coupling constant, each order in $1/N$, contains diagrams to all orders in coupling constant and the leading order corresponds to the planar diagrams. Maldacena [9–13] has made remarkable conjecture regarding large N conformal gauge theories. The proposal states that large N limit of a conformally invariant theory in d dimensions is determined by supergravity theory on $d+1$ dimensional anti-de Sitter spacetimes a compact space (for a sphere it is maximally symmetric). The AdS/CFT connection has led to the generalization of the holography principle in this context which was first introduced in black hole physics in order to understand the Bekenstein entropy bound and the area law for black hole entropy. It has been argued in the past that theories with gravity differ qualitatively from theories defined on flat spacetime through the holography hypothesis. If we consider a theory in the presence of gravity in some region of spacetime manifold M and in a spatial volume V, then, according to holography the degrees of freedom of the system reside on the boundary of V. In other words, the entropy of the system is bounded by the area of the surface bounding V. If it were not so, then one could pump in sufficient amount of energy inside V, so that the radius becomes equal to the Schwarzschild radius associated with a black hole whose horizon coincides with the radius. Then, due to Bekenstein–Hawking formula, the entropy will be equal to the area of the horizon. If our earlier assertion were not true, i.e. the entropy were not related to the area, but were proportional to the volume of V, then as soon as the black hole will be formed the entropy will decrease violating the second law of thermodynamics. We note that the verification of Maldecana's conjecture is another support for the holography principle. This has been a very active area of research with interesting developments in many directions which has brought together various aspects of string theory and field theory. Thus the conjectures of Maldacena led to reveal deeper connections between string theory and superconformal gauge theories.

We have emphasized earlier that gravity is an integral part of string theory since graviton is a part of the spectrum. Moreover, gauge fields also invariably appear in string theories. Let us recapitulate a few points in order to get a perspective of AdS/CFT connections. We have seen that the heterotic strings, through their constructions, contain nonabelian gauge groups and graviton in their massless spectrum. The type II theories have graviton, coming from NS sector, in their perturbative spectrum. However, with the discovery of Dp-branes, we know that supersymmetric gauge theories can arise if we consider coincident Dp-branes in type II theories. Type I string theory admit nonabelian gauge field: this is little bit technical point and we shall not elaborate further how exactly nonabelian gauge theories are incorporated in this case. Furthermore, consistency of the type I theory requires that we have to incorporate closed string sector in order to account for nonplanar loop corrections; therefore there is gravity coming from the closed string spectrum. For this theory, when we take $\alpha' \to 0$ limit Yang–Mills theory appears automatically and since consistency requires inclusion of closed string states, gravity also will appear in the zero slope limit. In view of the preceding remarks, one might conclude that, in string theory, gravity and gauge theory invariably appear simultaneously. Thus the important question to answer is that how the string theory can describe the strong interaction among quarks and gluons. The recent developments have provided connections between string theory and gauge theories.

The configuration under consideration is N coincident Dp-branes and open strings can end on these hypersurfaces. When we look into the dynamics in the world-volume we have collection of these open strings and their excitations. Moreover, the world-volume fields have their interactions and also there exists interaction with the bulk. An interesting limit to consider is when dilaton remains at a fixed value and the slope parameter tends to zero value. Then, at low energies, the gravity decouples; but to keep the interactions in the world-volume intact, we should have gauge coupling finite, for the U(N) gauge theory. In fact, if we ignore the center of mass part, then we need to consider the SU(N) gauge theory. It is necessary to go near the horizon, $r \to 0$, to see the connection between AdS and CFT. In particular, when one considers a five dimensional extremal black hole and takes near horizon limit a very interesting situation arises and in this case the conjecture of Maldacena could be verified. For such configuration, the dilaton decouples. The ten dimensional space can be written in the factorised form as $S_5 \times \mathrm{Ad}S_5$, S_5 being the five sphere. For the case in hand, it is verified that the correlation functions computed on the bulk for the supergravity theory coincide with the correlation functions of the super Yang–Mills theory which lives on the boundary. Indeed, supersymmetric gauge theory that resides on the boundary of the $\mathrm{Ad}S_5$ is $N = 4$ supersymmetric Yang–Mills theory which is known to be conformally invariant theory. This is a remarkable result since it exhibits connection between a theory with gravity (supergravity theory living on the bulk) and the supersymmetric gauge theory. For example, on the supergravity side, the two point correlation function of the dilaton $\phi(x)$ and $\phi(y)$ is related to correlation function of two gauge invariant operators $F^a_{\mu\nu}(x)F^{\mu\nu}_a(x)$ and another F^2 at point y.

Another interesting idea which is being persued is that the size of the internal dimension could be of the order of milimeter [14–16]. In this scenario some of the excited states of string theory might have masses in the TeV range and such particles might be produced in high energy accelerators in not too distant future. The electro-weak unification scale is of the order of TeV. However, it is now well known that the gauge coupling constants of QCD and electro-weak theory converge to a point quite accurately around 10^{16} GeV when they are extrapolated by the renormalization equations from their present measured value. The existence of two such scales gives rise to gauge hierarchy problem. This can be resolved if one considers a supersymmetric version of the standard model and invokes softly broken SUSY hypothesis. Although there are alternative proposals to solve gauge hierarchy problem, the introduction of supersymmetry is the most elegant one. We have quite good understanding of the standard model up to the electro-weak scale and the predictions of the model have been tested quite accurately in laboratories. There have been very important developments in the physics at the Planck scale, in recent years, where gravity is expected to play an important role. However, the short distant properties of gravity has been experimentally explored only in the range of milimeters.

Recently, it has been proposed that there is only one scale in Nature and that is the electroweak scale M_{ew} and this is also the scale for gravitational interaction. However, we determine the Planck scale from the value of the Newton's constant, therefore, if M_{ew} is the only energy scale how will M_{Pl} appear with its usual value. This issue is resolved by invoking the presence of extra compact dimensions. Thus, for the higher dimensional theory, with say n compact dimensions,

$$M_{\mathrm{Pl}(n+4)} \sim M_{\mathrm{ew}}. \tag{5}$$

If R is the radius of compact dimensions, the Newton's law of gravity for two test masses m_1 and m_2 separated by distance r takes the form

$$V(r) = \frac{m_1 m_2}{M^{n+2}_{\mathrm{Pl}(n+4)}} \frac{1}{r^{n+1}}, \tag{6}$$

when $r << R$ i.e. when we are probing really short distance scale. On the other hand, when $r >> R$, one does not see the extra dimensions and the Newton's law takes the form

$$V(r) = \frac{m_1 m_2}{M_{\mathrm{Pl}(n+4)}^{n+2} R^n} \frac{1}{r}. \tag{7}$$

Thus the four dimensional Planck scale is to be identified as

$$M_{\mathrm{Pl}}^2 = M_{\mathrm{Pl}(n+4)}^{2+n} R^n. \tag{8}$$

Now, if we invoke that there is only one scale i.e. $M_{\mathrm{Pl}(n+4)} = M_{\mathrm{ew}}$, and use the observed value of M_{Pl} in the above equation then

$$R \sim 10^{(30/n)-17}\,\mathrm{cm}\ \left(\frac{1\ \mathrm{TeV}}{M_{\mathrm{ew}}}\right)^{1+2/n}. \tag{9}$$

If there is one extra compact dimension i.e. $n = 1$, then $R \sim 10^{13}$cm. For such a large radius compact dimension, Newtonian gravity will be affected considerably as can be inferred from observations of planetary motions. The next possibility is $n = 2$ and in this case $R \sim 100\,\mu$m and present experiments have not probed gravity quite accurately to such a distance to rule out this scenario.

We know that the standard model has been probed to the length scale of the order of $1/M_{\mathrm{ew}}$. Thus it is proposed that standard model particles do not propagate in the extra dimensions and they must be localised in the 4-dimensional spacetime. Thus, gravitons are allowed to propagate in the $(4+n)$-dimensional world. This idea provides a new ground to test string theory since the theory lives in 10-dimensional spacetime. Thus some of the dimensions must be compact. Moreover, perturbative description of string theory has two fundamental parameters: the string scale M_s and the coupling constant g_{str}. When we compactify to $D = 4$, then g_{str} and M_s can be expressed in terms of the Planck mass, M_{Pl} and the gauge coupling constant α_G at the string scale and the compactification volume $(2\pi)^6 V$. Suppose the string scale is really $M_{\mathrm{ew}} \sim$ TeV, then we can solve for V and g_{str}; but this can be trusted if $g_{\mathrm{str}} < 1$, i.e. the perturbation theory is still reliable. When one considers the weakly coupled heterotic string, V and g_{str} drop out, therefore, we are not in an advantageous situation. However, starting from 10-dimensional type I theory with SO(32) gauge group and compactifying it to 4-dimensions one can get some interesting results. It is possible to propose experimental tests for such a theory in order to verify the ideas regarding large extra compact dimensions. The duality properties of string theory plays a very important role in this approach. Some of the characteristics of TeV scale compactification scheme are:

- Production of Regge excitations, since the scale is of the order TeV, these particles, lying on Regge trajectories, will have masses in the TeV range. These will be narrow resonances.
- Regge excitations of gluons will be produced in accelerators and they might be observed in LHC.
- Gravity propagates in the bulk and consequently the graviton of the $(4+n)$-dimensional theory will be emitted into the compact dimensions. The emission of graviton will be important at energy scales higher than the scale of internal dimensions and this emission might resemble Hawking radiation.

We find that it might be possible to see the effects of extra dimensions if the proposal of large extra dimensions is tenable.

In this review, I have tried to convey to you my personal perspective of the interesting developments in string theory. We have seen that there is intimate connections between string theory and the gauge theories, leading to deeper understanding of both the areas. For a special class of black holes, it is possible to derive Bekenstein–Hawking entropy formula from an underlying microscopic theory. Furthermore, one can calculate emission of radiation from an excited, nearly extremal black hole and then show that the transition probability has the characteristics of the Hawking radiation.

I have not been able to cover rather interesting developments in topics like M(atrix) model [17,18], stable non-BPS states [19,20] and some of the phenomenological aspects of string theory. It is quite obvious that we have witnessed exciting developments in the string theory during the last couple of years.

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