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MACROSCOPIC CONSTRAINTS ON STRING UNIFICATION*

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Abstract

The comparison of string theory with experiment requires a huge extrapolation from the microscopic distances, of order of the Planck length, up to the macroscopic laboratory distances. The quantum effects give rise to large corrections to the macroscopic predictions of string unification. I discuss the model-independent constraints on the gravitational sector of string theory due to the inevitable existence of universal Fradkin-Tseytlin dilatons.

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The purpose of my talk is to explain how Newton's Law – one of the best-understood and most-respected laws of physics – provides some interesting constraints on string theory[1], which has been recently developed in the first serious attempt to unify all known particles and interactions. This talk is based on the results of works[2][3] done in collaboration with Gabriele Veneziano from CERN.

Newton's Law, formulated circa A.D. 1680, provides a very good description of the *classical non-relativistic* gravitational attraction of massive bodies at distances ranging from the typical laboratory scales of 1m, up to the interplanetary distances of order 10^{12}m, and far beyond. On the other hand, string theory, formulated three hundred years later, provides *quantum relativistic* description of gravitational forces. The typical scale of such a theory must be the Planck length $L_P = (\hbar G_N/c^3)^{1/2} \approx 10^{-35}$m, thirty five orders of magnitude smaller than the distances testable by the classical laboratory experiments. It is clear that extraction of macroscopic predictions from string theory requires a huge extrapolation.

The forces emerging in the classical limit of string theory can be best classified according to the spin of intermediate bosons. To be specific, I will discuss the content of the heterotic theory of closed strings[4], as the most promising candidate for string unification. The spin-1 vector bosons mediate the standard electro-weak and strong interactions. They may also mediate some yet undiscovered GUT-type gauge interactions. The corresponding coupling constants are dimensionless numbers. The gravitational interactions are carried by spin-2 massless gravitons, whose coupling constant G has dimension $(length)^2$ (from now on I set $\hbar = c = 1$). The only dimensionful parameter of string theory is the string "radius" $(\alpha')^{1/2}$, therefore $G \sim \alpha'$. In addition, string theory brings at least one spin-0 massless scalar particle, the so-called Fradkin-Tseytlin dilaton[5], which induces the interactions that are the main topic of my discussion.

In string unification, the elementary particles arise from the quantization of transverse string "oscillations", much in a way like the photons arise from quantizing the transverse degrees of freedom of a freely propagating electromagnetic wave. The same "oscillation" that produces the graviton, produces also the dilaton, a totally gauge-neutral massless scalar particle. The existence of dilatons is one of the most solid model-independent prediction of string theory. It does not matter whether the theory is formulated directly in four dimensions, or compactified from a higher number of dimensions – the presence of Fradkin-Tseytlin dilatons is an inevitable universal property of string unification.

In a *non-relativistic* system of slowly moving massive bodies, the dilaton exchanges give rise to the extra forces that are undistinguishable from the gravitational attraction. The effective Newton's constant contains the equal spin-2 and spin-0 contributions: $G_N = G + G'$, where G' is the dilaton coupling constant. String theory predicts[5)] $G' = G$, ignoring the quantum corrections which will be discussed later. The difference between the spins of gravitons and dilatons matters only for the *relativistic* processes involving particles moving with the velocities close to the speed of light. The graviton, which corresponds to the rank-2 tensor field, couples to the *energy-momentum* tensor density induced by a moving particle, whereas the scalar dilaton field couples to its rest *mass*. This is the reason why the electromagnetic waves of massless photons interact with the graviton sources, but do *not* interact with the dilaton sources.

Notice that in order to yield the right value of G_N, the fundamental string scale must be of order of the Planck length, $\alpha' \sim L_P^2$, as I have already pointed out before.

The corresponding momentum scale is the Planck mass $M_P = 1/L_P \approx 10^{19}$GeV. On the other hand, the momenta involved in gravitational, and even in accelerator experiments, are much smaller than M_P. In order to make any contact with the experiment, it is necessary to study the string physics, in particular the scattering amplitudes, at momenta $Q \ll M_P$. There exists a very familiar example of a theory whose behaviour changes drastically from one momentum scale to another. QCD, the theory of free quarks and gluons at momenta much larger than the proton mass, provides also a good description of quark confinement and other low-energy phenomena. The reason why this is possible is that as a result of quantum corrections, more precisely, due to the quantum loop effects, the QCD coupling constant "runs" from one momentum scale to another. A similar "running" occurs in string theory as well, due to the string loop effects[2)3)6)].

The crucial property of string theory, as contrasted with quantum field theory, is that all Feynman diagrams are ultra-violet finite, even if the loops are present. The string "radius" $(\alpha')^{1/2}$ acts as a physical short-distance cutoff for the loop diagrams. This means that $(\alpha')^{n/2}$ is the natural order of magnitude for a coupling constant of dimension $(length)^n$. Only in the presence of some symmetries, like supersymmetry, one may expect some unusual cancellations of loop corrections. For the processes at momenta $Q \ll (\alpha')^{-1/2}$, the dominant loop corrections contain the factors of $\log(Q^2\alpha')$. The dominant logarithmic contributions can be evaluated by using the effective low-energy field theory approximation[2)]. It turns out that the "running" of string coupling constants is due entirely to the quantum processes involving gauge interactions. In particular, the processes involving creation of virtual gravitons and dilatons, which is possible via non-gauge interactions only, are negligible. The momentum-dependence of the effective coupling constants is discussed below.

For a generic gauge coupling constant g, the effective coupling constant $g(Q)$ is given by:

$$g^{-2}(Q) \;=\; g^{-2} + \beta_0(4\pi)^{-2}\log(Q^2\alpha')\,, \tag{1}$$

where the coefficient β_0 is determined by the gauge representations of the particles with masses $m^2 < Q^2$. Eq.(1) can be rephrased by saying that the string ultraviolet cutoff $1/\alpha' \sim M_P^2$ provides a natural renormalization scale for the effective field theory.

The effective graviton coupling constant does *not* run:

$$G(Q) \;=\; G\,. \tag{2}$$

The gauge corrections to the graviton-matter couplings can be completely absorbed into the redefinitions of masses of the particles interacting with the graviton. The effective *gravitational* masses obtained in this way turn out to be *equal* to the radiatively corrected *inertial* masses. As expected, the gauge interactions do not violate the equivalence principle of Einstein's tensor theory of general relativity. Even for strongly coupled systems, like the nucleons, whose masses receive large contributions from gauge interactions that are beyond the scope of the QCD perturbation theory, the equivalence principle ensures the equality of the gravitational and inertial mass. This means, for example, that the nucleon mass m_n, evaluated say in lattice gauge theory, determines its non-relativistic potential energy in the graviton field; the coupling G is mass-independent.

The effective dilaton coupling constant *runs*[3]. As I have already pointed out before, the dilaton couples to the massive particles only. The effective dilaton coupling to a particle of mass m is given by:

$$G'(m) \;=\; K^2(m)\,G\,. \tag{3}$$

For a heavy quark of mass m, the perturbative QCD contribution to the factor K is:

$$K(m) - 1 \;=\; -\frac{2}{\pi}\,\alpha_s(m)\,\log(m^2\alpha')\,, \tag{4}$$

where α_s denotes the QCD coupling constant. The typical value of this correction, for a quark with $m \sim 10\text{GeV}$, is $K - 1 \approx 6$. The electro-weak effects are at least one order of magnitude smaller. Eq.(4) follows from the more general relation[3], whose validity extends beyond the perturbation theory:

$$K(m) - 1 \;=\; 2\alpha_s\,\frac{\partial \log m}{\partial \alpha_s}\,, \tag{5}$$

where the logarithm of the effective mass is differentated with respect to the QCD coupling constant at the string unification scale $1/\alpha' \sim M_p^2$. Eq.(5) allows a nice estimate of the factor K in the more interesting case of the dilaton-nucleon coupling. QCD predicts that the nucleon mass is of order of the strong interaction scale $\Lambda_s \sim (\alpha')^{-1/2}\exp(-c/\alpha_s)$, where c is a known constant. The experimental value of $\Lambda_s \sim 1\text{GeV}$ implies $c/\alpha_s \approx 44$. By substituting $m_n \approx \Lambda_s$ into eq.(5), one obtains:

$$K(m_n) \;=\; 1 + 2c/\alpha_s \;\approx\; 89\,. \tag{6}$$

Thus the strong interaction effects lead to the considerable enhancement of the dilaton couplings to hadrons; this was already indicated by the perturbative calculation of the heavy quark coupling. The dilaton coupling $G'(m_n)$ is approximately 8×10^3 times *stronger* than the corresponding graviton coupling $G(m_n) = G$ to the nucleons, see eqs.(3) and (6). The origin of this spectacular effect can be traced back to the different structures of spin-2 and spin-0 couplings to gluons.

The main lesson, which can be drawn from my discussion of the effective coupling constants, is that the quantum effects give rise to large corrections to the macroscopic predictions of string unification. In particular, the presence of "strongly" coupled dilatons creates a very serious phenomenological problem for string theory. The newtonian forces are completely dominated by the spin-0 component of the gravitational attraction:

$$G_N \;=\; G + G' \;\approx\; G'(m_n) \;\approx\; 8\times10^3 G \tag{7}$$

On the other hand, as explained before, only the spin-2 component $G \approx \frac{1}{8}\times10^{-3}G_N$ contributes to the *relativistic* coupling of gravitation to the electromagnetic radiation. Due to this almost entirely *scalar* nature of gravitational interactions at large distances, the string theory predictions for the values of the angle of light deflection and the time of radio echo delay by Sun[7] are *smaller* than the predictions of Einstein's *tensor* theory of general relativity by the factor of $\frac{1}{8}\times10^{-3}$. Since the measurements agree with Einstein's predictions within 1% of experimental errors, the existence of massless Fradkin-Tseytlin dilatons is ruled out. More precisely, for the massless dilatons, the laboratory, geophysical and astronomical data exclude[8] $G' \gtrsim 10^{-3}G_N$.

The only way in which string theory may avoid the dilaton "dominance" problem, is that due to some yet unknown mechanism, the dilaton acquires a mass large enough to prevent it from contributing to the newtonian forces. The classical tests of Newton's Law, based on the variations and refinements of the classical experiment of Cavendish, provide the constraint[8] $G'(m_n)\exp(-m_d\times 1\text{mm}) \lesssim 10^{-3}G_N$, which corresponds to the lower bound on the dilaton mass: $m_d \gtrsim 3\times10^{-3}$eV. Some cosmological considerations lead to additional constraints on the dilaton mass and couplings[9].

The dilaton mass generation presents a difficult problem for string theory. As a manifestation of the string excitation that creates the graviton, the Fradkin-Tseytlin dilaton is a genuinely massless particle. At the field theoretical level, however, the zero dilaton mass does not seem to be protected by any symmetry except for supersymmetry, which must be broken anyway in the realistic string models. Satisfactory mechanisms for supersymmetry breaking and the dilaton mass generation still remain to be discovered.

In spite of many phenomenological problems, one of which I discussed here, string theory remains a very attractive, and so far unique, candidate for the unification of all particles and interactions. All phenomenological problems of string theory, like mass generation, supersymmetry breaking *etc.*, are in general some variations of the symmetry breaking problem. It took many years before a similar problem was solved in gauge theories, opening the way for the standard model of electroweak and strong interactions. There are many ongoing theoretical efforts in the direction of understanding symmetry breaking in string theory and hopefully, a more successful confrontation with the experiment will soon be possible.

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