String Theory: Physics or Metaphysics?

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ABSTRACT

I will give arguments for why the enormous progress made during the last century on understanding elementary particles and their fundamental interactions suggests strings as the truly elementary constituents of Nature. I will then address the issue of whether the string paradigm can in principle be falsified or whether it should be considered as mere metaphysics.

1. THE CENTURY OF PHYSICS?

Very likely the 20th century will go down in history as the century of physics. In my opinion no other field of human knowledge has undergone, in that century, so much progress and so many revolutionary changes. Its very beginning was marked by three developments that shook forever as many scientific beliefs:

- The belief in *absolute determinism* when, in 1900, Max Planck, in order to eliminate an infinity in the energy emitted by a black body, introduced a constant, h, that still carries his name. This marked the beginning of the quantum revolution whose indeterminism was nicely embodied later in Heisenberg's uncertainty principle,

  (1) $$\Delta_q \Delta_p \geq h$$

  that bounds from below the product of position and momentum uncertainties.

- The belief in *absolute time* when, in 1905, Albert Einstein, starting from the invariance of the speed of light in vacuum, c, introduced Special Relativity and his much celebrated relation between mass and energy:

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$$E = mc^2 \quad (2)$$

- The belief in an *absolute geometry* when, only ten years later, again Einstein formulated the theory of General Relativity according to which matter "curves" spacetime and bodies simply move along geodesics (i.e., minimal-length paths) in the ensuing non-trivial geometry. In General Relativity Newton's constant, *G*, controls the amount by which mass and energy affects the surrounding geometry of spacetime.

These three breakthroughs fed all subsequent developments of that branch of 20th century physics that aims at uncovering the laws of physics at their deepest level. In particular, the efforts made in the twenties and thirties to combine Quantum Mechanics and Special Relativity led physicists to formulate, in the forties, a very successful framework known as Quantum Field Theory (QFT). The first successful application of QFT was Quantum Electrodynamics (QED for short), a theory describing electromagnetic phenomena at the quantum level with incredible accuracy (better than 10 parts in a billion in the case of the anomalous magnetic moments of the electron and the muon).

During the fifties and the sixties physicists tried to extend that framework to the description of two of the other known forces, the strong (or nuclear) force, responsible for binding protons and neutrons inside the atomic nuclei, and the weak force, responsible for radioactivity. Such experimental and theoretical effort was rewarded in the early seventies when physicists formulated the so-called Standard Model of elementary particles, a milestone that will certainly stay in the books of physics. Many tests of the Standard Model, carried out in the seventies, eighties, and nineties, have so far confirmed the validity of the Standard Model with no exception (the discovery that neutrinos do have mass can be easily incorporated in the Standard Model without any basic change on its structure).

Rather than describing what the Standard Model is, I will simply emphasize its beauty in terms of the conceptual unification it brings about. The Standard Model asserts that *all* non-gravitational interactions are described by one and the same special class of QFTs, known as gauge theories. This was a known fact for the QED description of electromagnetic interactions, but is a highly non trivial – and even surprising – claim for the other two forces. The reason why the same kind of theory, a gauge theory, can lead to such diverse phenomena like Coulomb's law, the short range force responsible for nuclear binding, and the slow process of radioactive decay, is due to the fact that the underlying symmetry of a gauge theory (called gauge invariance) can be realized in different ways, or phases, not unlike the way water can manifest itself as a solid, a liquid, or a gas.

What is this single gauge principle underlying so many diverse phenomena? The answer is quite simple: all these interactions are induced, at the most fundamental level, by massless spin-1 particles.[1] Gauge theories are the mathematical way to describe such kind of elementary particles. Thus, if we wish to extract a single message from the incredible success of the Standard Model, I would put it as follows:

Nature likes spin-1 massless particles
and therefore She likes Gauge Theories.

But then what about the fourth fundamental force known to us, gravity? For several decades particle theorists were not very interested in gravity, since gravitational forces are completely negligible for elementary particles in normal situations (in the hydrogen atom, for instance, the ratio of the gravitational and electromagnetic force between the electron and the proton is a miserable 10^{-40}). Actually, physicists were quite happy to leave gravity to Einstein's General Relativity. Also, since gravity is relevant only for macroscopic bodies, they were happy to treat it "classically", i.e., without any appeal to quantum mechanics. However, when looked at more carefully, also gravity reveals itself as a sort of gauge theory where the "gauge" symmetry is replaced by Einstein's equivalence principle, an invariance under a generic change of the coordinate system. Even more amazingly, one finds that the symmetries of General Relativity are what they are precisely because the quantum of gravity (called graviton in analogy with the electromagnetic photon) is a massless particle of spin 2 (angular momentum $2\,\hbar$). In other words, we can add gravity to our previous reasoning by slightly enlarging the message that Nature is sending to us:

Nature likes spin-1 and spin-2 massless particles
and therefore She likes Gauge Theories and General Relativity.

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[1] Spin-1 means an angular momentum $J = \frac{h}{2\pi} \equiv \hbar$. We recall that Quantum Mechanics implies that angular momentum is an integer or half-integer multiple of $\hbar$.

What remains to be explained is why Nature likes precisely such kind of massless particles.

2. CLASSICAL VS QUANTUM STRINGS

I will now argue that Relativistic Quantum String Theory (RQST) explains in a very natural way the existence of those massless spinning particles that Nature appears to like so much. What is RQST? It is simply what one obtains by adding to the basic principles of Special Relativity and Quantum Mechanics (whose combination, as I said, led to QFT) a third crucial ingredient: the assumption that all truly elementary particles, rather than being pointlike, are instead one-dimensional objects: strings.

By combining this assumption with special relativity and quantum mechanics results in arguably the richest theory ever constructed by physicists, RQST. The three ingredients: Relativity, Quantum Mechanics and Strings, of RQST are all essential, but I will concentrate my discussion on the latter two, Quantum Mechanics and Strings. I will argue that Quantum Mechanics is essential to make string theory a candidate theory of elementary particles and fundamental interactions by comparing the properties of classical, deterministic strings with those of their quantum mechanical analogues.

A classical relativistic string is a well defined system containing a single physical parameter, the so-called string tension *T*. The string tension plays, in string theory, the same role that mass plays in point-particle theory. Mass can be converted into energy via Einstein's eq. (2), whereas *T* denotes the energy per unit length stored in the string. Its physical dimensions are thus $E \cdot l^{-1} = m \cdot l \cdot t^{-2}$. A classical non-interacting pointlike particle moves along a trajectory that minimizes its length (the already mentioned geodesic); similarly, the classical string motion is such as to minimize the area of the two-dimensional surface it sweeps during its motion.

Classically, neither point-particle nor string theory have a fundamental length built in. At the quantum level, however, we can associate to the mass of a particle a quantum length (so-called Compton wavelength) given by: $\lambda_C = \frac{h}{mc}$. Of course, such a wavelength is not a universal constant since it varies from particle to particle according to its mass. Similarly, we can associate with *T* a quantum length-scale, called the string length:

$$\lambda_S = \sqrt{\frac{\hbar c}{T}} \tag{3}$$

except that there is just a single T for all possible strings and therefore λ_S unlike λ_C, is a truly universal length scale. We can say that the three fundamental constants c, h and λ_S represent, respectively, the three basic ingredients underlying RQST: Relativity, Quantum Mechanics and Strings.

Here comes the punch line: classically, string theory is scale-free. Given a possible classical string motion we can always construct another one by rescaling all lengths by a common factor. As a consequence, the mass of the string gets rescaled by exactly the same factor. We can go to the limit in which we rescale the size of the string to zero size and the string will become both massless and spinless. The last property is physically very obvious: classically we cannot have angular momentum without having both a finite mass and a finite size (and indeed under a rescaling of the string size by a factor k its angular momentum gets rescaled by a factor k^2). Actually, one can prove a strict inequality stating that $J \leq \frac{M^2}{2\pi T}$, which immediately implies that massless spinning strings cannot exist classically!

Let us now turn on h, i.e., Quantum Mechanics. Its consequences are truly amazing, even miraculous. They can be partly understood by the quantum mechanics of known systems. Take for instance the hydrogen atom: the classical theory had great problems in explaining its stability. The single electron of the hydrogen atom would like to emit electromagnetic radiation (like a charged particle circulating in an accelerator at CERN), would lose energy and slow down, and eventually "fall" on the nucleus (a proton in this case). But the uncertainty principle of Quantum Mechanics, Eq.(1), intervenes and tells us that falling on the nucleus would make the relative position of the electron and the proton very precisely determined at the cost of a lot of momentum uncertainty, hence of a large kinetic energy. Quantum Mechanics tells us which the best compromise is: the optimal (i.e., energy minimizing) average distance between the electron and the proton is given by the so-called Bohr radius:

$$a_0 = \frac{\hbar}{\alpha m_e c} \sim 10^{-8}\, cm \tag{4}$$

where $\alpha \sim 1/137$ is the so-called fine-structure constant.

A similar mechanism is at work with a quantum string. In analogy with a classical string it does not like to have a large size (since this costs a lot of tension energy) but, unlike a classical string, it does not like to be very small either since, in that case, its very small Δx forces a very large Δp i.e., a very large kinetic energy (again the uncertainty principle at work!). Not surprisingly, the best compromise happens to be for a quantum string to have a size of order λ_s, the only length scale available. Thus quantum strings acquire, through Quantum Mechanics, a characteristic size, a minimal length. That minimal length is essential for resolving the long-standing short-distance problems with quantization of Einstein's General Relativity.

A second, no less important, miracle comes from the fact that the classical inequality $J \leq \frac{M^2}{2\pi T}$ suffers a quantum correction which is insignificant for large J and M but essential when these are small. The inequality becomes:

$$J \leq \frac{M^2}{2\pi T} + a\hbar \qquad (5)$$

where a can take integer or half integer values up to and including $a = 2$. Thus, as a quantum effect, massless strings of spin 1 and 2 become not only possible but, actually, *inevitable* in RQST!

In conclusion, the combination of the two above-mentioned miracles potentially makes RQST a realistic theory of all fundamental interactions which, furthermore, is free from the UV infinities that plague ordinary QFTs and that make quantization of General Relativity virtually impossible.

3. IS THIS PHYSICS?

Physicists have a definite criterion for deciding whether a certain theory can be considered to be a scientific one: the theory has to make testable predictions so that it can be falsified, at least in principle, by experiments. (On the contrary, a theory can never be proven to be correct, since it is impossible to exclude that an alternative explanation of the same phenomena can be found.) When this criterion is applied to string theory it is converted into something slightly more demanding. Indeed, everybody would agree that string theory makes definite predictions, like for instance the existence of very heavy (by particle physics standards) "string excitations", or modifications of gravity at very short distances. What is under dispute is whether any *conceivable* experiment, now or in the foreseable future, will ever be able to test those predictions.

Several respectable physicists have taken a negative attitude towards that question. According to them RQST is a beautiful construction whose predictions will never be accessible to experimental verification: hence RQST is *"not even wrong"* to quote a sentence by famous physicist Wolfgang Pauli. The reason underlying this statement is simply that the fundamental length of RQST, λ_s, is, most likely, of the same order of magnitude (or perhaps just a factor 10 larger than) the so-called Planck length, a length scale that can be constructed out of the three fundamental constants we introduced at the very beginning, c, ħ, and G:

$$L_p = \sqrt{\frac{G\hbar}{c^3}} \sim 1.6 \times 10^{-33}\ cm \tag{6}$$

But then, it is argued, such a length scale is so tiny that there will never be a way to distinguish a string of that size from a zero-size point. Hence, it will be impossible to compare the predictions of a RQST from those of some suitable QFT if we only have experiments of limited energy and thus, by the uncertainty principle, of limited spatial resolution. Indeed, the possibility of building an accelerator capable of testing distances such as those in eq. (6) is definitely out of question.

That reasoning appears to be awed on (at least) two grounds:

- There is in Nature a very powerful accelerator: the Universe itself. Because of its expansion, the Universe has been cooling down since the big bang. On the contrary, if we go back in time, the Universe was hotter and hotter as we proceed towards the big bang. Thus, the physics of the very early Universe, and even the very existence of a Big Bang as the beginning of time, should have been strongly affected by the characteristic properties of quantum strings and would much differ from what would come out of more conventional theories like General Relativity.

  It is generally accepted today that the quantum properties of the early Universe left an imprint on the large scale structures of the Universe that we observe today: stars, galaxies, clusters. Therefore, it is all but excluded that RQST can be tested through its cosmological implications. Any possible modification of physics at the string scale has been stretched to macroscopic (or even astronomical) distances by the expansion of the Universe. At present, the problem with such a way of testing string theory is that it is very hard to solve it in extreme regimes like the one that must have prevailed around the big bang epoch. Techniques are being developed to study such regimes, but are not yet at the level of providing robust predictions.

- There is an even stronger argument against the claim that RQST cannot be falsified. It is enough to recall how the first version of string theory was abandoned at the beginning of the seventies. That original string theory, born in the late sixties and thus predating the construction of the Standard Model, was not invented for the purposes for which it is studied now: it was instead an attempt to describe the physics of the strong interactions outside the framework of conventional QFT (at that time QFT looked inapplicable to strong interactions). At the beginning string theory led to great hopes, but then it proved to be too tight and constrained a framework and, in particular, it kept predicting the existence of massless particles of spin up to 2. When the purpose of string theory was to describe the world of protons, neutrons and pions, there was no room for such massless particles. This was certainly one of the main reason for abandoning the old string theory in the early seventies in favour of the theory of quarks and gluons, now known as Quantum-ChromoDynamics (or QCD in analogy with QED).When the purpose of string theory was not to describe the carriers of gauge and gravitational interactions but rather the world of protons, neutrons and pions, there was no place for such massless particles. This was certainly one of the main reasons for abandoning the old string theory in the early seventies in favour of the theory of quarks and gluons, now known as Quantum-ChromoDynamics (or QCD in analogy with QED).

Could history repeat itself? Well, hopefully not, but nothing is less clear at the moment. At a first, crude level of approximation RQST provides not only the nice massless spinning particles we like and need so much: it also gives us, in a single package, a bunch of massless spinless particles generically called "moduli". Some of them are related to the sizes and shapes of the extra dimensions of space in which quantum strings like to evolve. This is, by the way, another "gift" of quantum mechanics, we cannot just take what we like and refuse the rest: string theory comes as a package deal: take it all or leave it all!

One can show that these undesired massless strings produce new unobserved long-range forces whose strength is similar to that of gravity but which, unlike gravity, do not obey the equivalence principle of General Relativity and thus lead, for instance, to unacceptable violations of the universality of free fall, a property now tested with exceedingly high precision. Hopefully, that first approximation is indeed too crude and the moduli become massive particles by the time the theory's full solution is worked out. This will make the new forces short-ranged and thus avoid contradiction with experiments.

So, not only string theory is falsifiable, the real question is: *why is it not already falsified?* The answer, once more, is that the theory is not developed enough to be able to answer such questions since they lie outside the regimes in which string theory can be studied by presently available techniques. We should not forget, in this respect, that RQST is an entirely new and relatively young theoretical construction. It took many decades to develop QFT to such an extent that it could be successfully applied to actual experiments, or even to understand that the non-observation of free quarks was not in contradiction with QCD. Indeed, the problem of proving quark confinement turned out to be extremely hard to solve analytically and, even today, can only be addressed numerically through powerful dedicated computers.

The conclusion stemming from both arguments given above is that RQST is so constrained by its mathematical and physical consistency that, in principle, its test should be easy. Only our present inability to draw firm predictions from its complicated equations is preventing us from saying today whether it has any chance to survive. It is not an improvement in experimental techniques, but rather of the theory itself, that will tell us whether this beautiful theory has any chance to survive as a physical theory, or whether it will remain forever a beautiful construction in search of experimental confirmation.