General Relativity from Strings

Tamiaki Yoneya
University of Tokyo
Strings 2015 Banquet, June 24, 2015

It is a great pleasure for me to be here, attending this wonderful meeting. I would like to thank the organizers for warm hospitality, and for a kind arrangement of this after-dinner session.

The organizers asked me to give some historical reminiscences related to my old works on the connection of string theory with gravity. So let me talk about how I happened to come to this work, as faithfully as I can remember now. Although I am not sure whether such a personal history of myself interests you, I hope that it at least would help to convey to you the now forgotten atmosphere at the genesis of string theory in the early 70s.

I became a graduate student in 1969 at Hokkaido University, Japan. That was just the year when the string theory was born. At that time, string theory was called the dual resonance model, or in short, dual model. I vividly remember big excitement, when I was first exposed to a very short but quite a stimulating paper by Susskind on the string interpretation of the Veneziano formula. I was struck by the simplicity of the idea, giving a direct physical meaning on what was originally a mere mathematical expression, something like the Planck formula, for the S-matrix elements of meson scatterings. And then I encountered a beautiful and more comprehensive paper by Nambu, and my interest in the dual model was further strengthened.

From the first encounter with the dual string model, a basic question on the relation between the dual model and ordinary quantum field theory was increasingly occupying my mind. Remember that the Veneziano formula originally emerged without any connection with field theory. There were two particular problems which I was concerning with. One was whether and how the channel duality could be compatible with the ordinary Feynman rules of field theories. Another was the meaning of the existence of massless spinning states. With respect to this second question, I expected that the dual model corresponding to open strings should be regarded as an intrinsic extension of local gauge field theories. From this viewpoint, I first tried to clarify the role of massless spin-one state in the model, by studying whether the interaction vertices of those states can be regarded as minimal interaction, just as we have in local gauge field theories which are governed by gauge principles. My thinking was that, if the interactions of these massless spinning states had non-minimal structure, the connection of the dual model with gauge principle would not perhaps be of such fundamental significance. I could confirm that in all cases of open-string models which had world-sheet conformal invariance, the corresponding vertices could indeed be derived as minimal interactions with an appropriate generalized local gauge transformation of string wave function, or string fields, in an

exact sense without making any low-energy approximation. Thus I was convinced that the dual open-string models must indeed be regarded intrinsically as an extension of gauge field theories. Needless to say, all these sound trivial from our present standpoint. But, I would like to stress that, as far as I knew at that time around the middle of 1971, no one had ever formulated explicitly such a viewpoint, and when I first submitted a paper on this to a journal, it was rejected. After a few months of this experience, I came to know by a letter I received from Masatsugu Minami that a similar viewpoint had recently been discussed independently by Neveu and Scherk, in a different way using a low-energy approximation, namely, the zero-slope limit. I was shocked by this, and I resubmitted the paper to a different journal.

By this time, I hit an idea of extending my viewpoint to closed strings. I thought, the closed-string model, which was called the Virasoro-Shapiro model at that time, should similarly be regarded as an extension of general relativity. However, in those days, the atmosphere of particle-physics community was almost totally against general relativity. I myself felt that such a connection would be a rather strange and bizarre thing. Although, as an undergraduate student, I had been quite enthusiastic about general relativity, I myself became prejudiced against gravity, after starting researches in particle physics. During that period, current algebra and S-matrix were the major stream at least in my environment at that time, so that the classical geometric theory such as general relativity seemed to be useless.

So I decided to put aside the problem of connecting closed strings to general relativity, as a possible future work. And I turned my mind to the first question of reconciling the channel duality with Feynman rules. Minami's letter was useful for me also in that he mentioned Noboru Nakanishi's work. Nakanishi studied a systematic method of decomposing integration regions of n-point dual tree amplitudes, in such a way that each decomposed region involves only pole singularities corresponding to the usual Feynman diagrams. I tried to re-formulate his rule of decomposition such that the factorization property of the amplitudes became manifest simultaneously: Then it would be possible to extend his rules to general loop amplitudes. I partially succeeded in this program, on the basis of my previous work on general Reggeon vertices. For example, this resolved the problem of an infinite multiple counting which had been a difficulty in the ordinary way of constructing non-planar loop amplitudes of open strings known at that time. I then expected that the whole rule could be recast as a quantum field theory of strings. I tried it very hard, but unfortunately could not manage it in any satisfiable and publishable way. As everyone knows, this program of constructing a covariant string-field theory was beautifully achieved after 13 years by Witten in 1985.

Actually, the failure of constructing string field theory allowed me to return my mind again to the possible connection of dual models to general relativity. I remember, that was about the beginning of 1973. Around this time, many people, especially who are phenomenologically-oriented, were departing from the dual string model. This was just the period when the gauge field theoryies were about to resurge as the fundamental theory of strong interactions, as well as of electro-weak interactions. But I felt that the dual string models must contain something deeper as a theoretical framework which was perhaps beyond the field theory, and that had not yet been fully clarified. I started thinking that as the Yang-Mills theory had turned out to be useful, general relativity might also become important even for particle physics, someday in some unexpected way.

To demonstrate the connection, the first thing to do was to exhibit a concrete correspondence of physical amplitudes in the zero-slope limit, and also to make the comparison of interaction vertices with finite α'. Another thing which I strongly wished to clarify was to establish some definite correspondence principle between the two structures. I expected that there must be some characteristic property, in analogy with the correspondence, for example, between commutation relations and Poisson brackets which played so important role in creating quantum mechanics. Although I am not completely successful, especially, in the latter program of the possible correspondence principle, I decided to publish my modest results. First paper was a brief letter which was submitted in July, 1973, and then the full paper in October. The title of the full paper was "Connection of dual models to Electrodynamics and Gravidynamics". The reason I added the word 'electrodynamics' was to discuss the similarity and contrast between the two cases of open and closed strings in a simplest possible setting, on the basis of my previous works on the case of open strings. In regard to the possible correspondence principle, I could only emphasize that the non-linear geometric structure of general relativity was replaced by and encoded into the non-locality or extendedness of strings. That was discussed in my full paper by comparing the structure of the generating functionals for tree amplitudes. This interpretation of stringy extendedness actually constituted one of the motivations behind my later proposal of the space-time uncertainty relation, which I was going to publish first in 1987 in a volume commemorating the 60th birthday of Professor Kazuhiko Nishijima. In the meanwhile, I received a preprint by Scherk and Schwarz. Their impressive works stimulated me to continue my thinking further. In fact, after my initial papers, I published two follow-up papers in the mid 70s, discussing the geometrical properties of the couplings of graviton state to fermionic strings, extending the methods I had developed in the case of gauge-string

connection.

I remember that, at the time of the first publication of my results, I was, however, not completely sure about my standpoint in interpreting the connection between dual models and gravity. There was a different and competing viewpoint, existing actually from the early 70s, on the relationship between dual strings and field theory, namely, the possibility of strings emerging as a non-perturbative object from local gauge field theories. Among such possibilities are the so-called fishnet interpretation, which was later going to be delineated by ' t Hooft's large N limit, and also the idea of relativistic vortices, as proposed by Sakita-Virasoro in the first case, and in both cases by Nielsen-Olesen. I was asking myself rather perplexingly, "If such a view were correct, would it imply that general relativity could be contained in gauge theory without gravity?". I had not been able to resolve this puzzle for many years. Of course, the holographic interpretation, being developed in recent years, is certainly providing us an entirely new perspective for this question.

These were how I came to my early works on the connection of strings to gravity, and also some of my related thoughts during this period.

Finally, as an aside, I would like to remind you that this year is, not only 100 years of General Relativity, but also 150 years from Maxwell's monumental work with the title, " A dynamical theory of the electromagnetic fields", which was published in 1865. This work can be regarded as the start of gauge field theory, in a sense that Maxwell reformulated systematically and rightly his electromagnetic field theory in terms of the vector potential, by extending various previous results given by himself and other workers, most notably, Michel Faraday. Interestingly, in the same paper, he also briefly pointed out a fundamental difficulty in extending his formulation further to gravity. In this sense, he can also be regarded as an initiator of our unification program.

To conclude: I am now convinced that the unification of gauge theory and general relativity as open and closed strings must be, at least in a broad sense, the truth of Nature. Nature must not fail to utilize such a simple and beautiful way of unifying fundamental interactions.

Thank you for your attention.

(Note added: For further accounts and references, I would like to refer the reader to my contribution, *Gravity from strings: personal reminiscences of early developments*, in the book, *The Birth of String Theory*, eds by A. Cappelli et al, Cambridge Univ. Press., 2012)