FEATURE

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Research Area: Theoretical Physics

Proton, Neutron, and D-brane

1. Prologue

One day, we were chatting about how to explain the importance of the recent research in string theory to the general public. Somebody asked about the "D-brane," which has played crucial roles in the recent development of string theory, saying, "For example, what is a good way to explain the reason why the research on D-branes is important?" My answer was, "That's easy. Because, we are made of D-branes." You may think that I was just kidding. But, I was fairly serious. Yet, I exaggerated a bit. More precisely, I should have said, "Particles like protons and neutrons in atoms, which are the basic ingredients of our body, can be described as D-branes in string theory." What is D-brane? How can that be possible? I'd like to talk about these topics here.

2. Quarks and QCD

I suppose you have learned in middle school or high school that an atom consists of a tiny lump called a nucleus made of protons and neutrons, and electrons circulating around it. If you take physics courses in college, you probably learn that protons and neutrons are composite particles made of three smaller particles, called "quarks."[1]

In addition, particles called "pions" flit about in the nucleus. The pion was introduced by Professor Hideki Yukawa to explain the force among protons and neutrons, and confirmed by the later experiments. It is now known that the pion is a composite particle made of a quark and an antiquark. Here, the antiquark is a partner of the quark, whose properties are almost the same as a quark except that its charge has the opposite sign.

The particles made of quarks and antiquarks are called "hadrons," and there are many kinds of hadrons. Actually, the number of species of hadrons confirmed in the experiments is more than hundreds. And almost all of them, except for some rare exotic ones, are made of three quarks or a pair of a quark and an antiquark. A hadron made of three quarks, such as the proton and the neutron, is called a "baryon," and that made of a quark-antiquark pair, such as the pion, is called a "meson" (Figure 1).

Quarks want to be confined in a trio (baryon) or a couple (meson), and in particular, nobody has ever succeeded in extracting an isolated quark in the experiments. The reason is that there is an extremely strong force called "strong force" among quarks and antiquarks, created by the exchange of another particle called the "gluon." The theory of strong force including quarks and gluons is called "QCD."[2]

QCD is a surprisingly simple and beautiful theory —something that I really admire. But, it is known to

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[1] Up to now, six kinds of quarks are found in the experiments, and they are called up, down, strange, charm, bottom, and top. In this article, we mainly focus on light quarks, in particular, up quarks and down quarks.

[2] QCD is an acronym of "Quantum Chromodynamics."

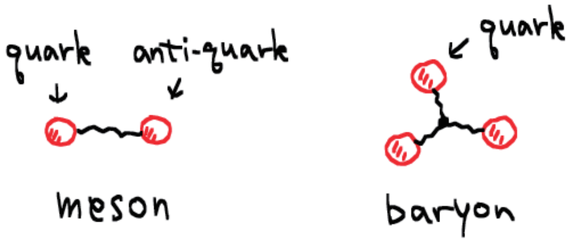

Figure 1. Meson and baryon in the quark model

be very difficult to analyze. It is almost impossible to calculate by hand the properties of hadrons, such as masses, radius, strength of the interaction, etc., and people have developed efficient methods to calculate them using supercomputers. As a result, it was shown that the predictions of QCD agree well with the experimental data, and nowadays QCD is considered to be the fundamental theory of hadrons. I am very much impressed by the fact that mankind has reached QCD, even though no experiments have ever found isolated quarks and gluons, and the theoretical calculations are extremely difficult.

3. Particle or String

As explained in the previous section, protons and neutrons are particles made of three quarks. You might wonder, then, whether there is a possibility that quarks are also made by even smaller particles. This is an interesting question, but there is no experimental evidence that suggests it to be the case. This kind of particle—considered to be a point particle without any further smaller structure—is called the elementary particle. Examples of elementary particles include quarks, gluons, electrons, photons (particles of light), etc.

So far, various kinds of elementary particles are found in the experiments. The reason why there are many different kinds of elementary particles is one of the big mysteries that remain to be solved. As history tells us, significant progress in physics will be made when complicated objects are found to be made of more fundamental and simple ingredients. This happened, for example, when people realized that all ordinary matter is made of atoms (atomism); all the atoms are made of protons, neutrons and electrons (atomic model); hadrons are made of quarks (quark model). Physicists are dreaming of finding a simple principle that deduces all the elementary particles in a unified way.

"String Theory" is a theory that is expected to solve this mystery. It is based on the assumption that the elementary particle is not a point particle but an extremely tiny string (Figure 2).

The fundamental object in string theory is only one species of string. This string can oscillate and spin, and it behaves as a particle with different properties when the state of the string is different. It poses the interesting possibility that all the different kinds of elementary particles are represented by the same string. Furthermore, surprisingly, it turned out that the spectrum of particles created by the string contains the "graviton," which is the elementary particle that mediates gravity. Unlike the other elementary particles, the graviton has a special property that makes it difficult to be incorporated in the theory of elementary particles, and constructing a consistent theory of gravity was a long-standing dream of physicists. String theory unexpectedly turned out to be an elegant solution to this problem.

One of the most surprising predictions of string theory is that space-time is ten dimensional (one time and nine spatial dimensions). In our daily life, we can only recognize four dimensions (one time and three spatial dimensions), but string theory predicts that there are six additional spatial directions that we cannot see.[3]

[3] The number of space-time dimensions corresponds to the number of coordinates we have to specify to meet somebody precisely. When we say, "Let's meet at the position 100 m north and 50 m east of here, 30 m above the ground, 10 minutes from now," for example, we specify four numbers (100, 50, 30, 10). In this case, we say the space-time is four dimensional. In string theory, four numbers are not enough and ten numbers are needed to specify the location in space-time.

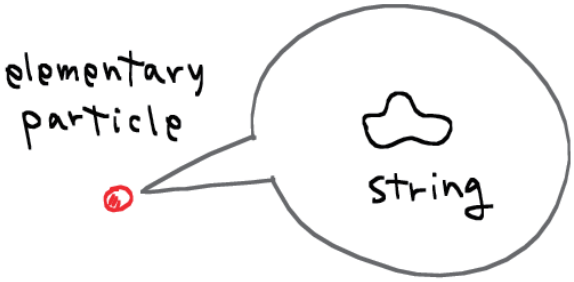

Figure 2. Elementary particle and string

The hidden six dimensions are called “extra dimensions.” The particles realized in string theory depend on the shape of the extra dimensions. In other words, the complicated structure of elementary particles can be realized thanks to the existence of the extra dimensions. Although we have unfortunately not yet reached a consensus on how the shape of the extra dimensions should be selected, it has been shown that particle contents very close to those found in the experiments can be realized with some choices of the extra dimensions. In string theory, it is not allowed to include the particles we want in the theory by hand because of severe consistency conditions. It appears to be a miracle that such theory includes the graviton naturally and reproduces the elementary particles found in the experiments. For these reasons, string theory attracted a great deal of attention among physicists, and it was called a promising candidate of “the ultimate unified theory,” or, “the theory of everything.” These developments were made around the middle of the 1980s. There were a number of surprising discoveries at that time, and people refer to this era as the first string revolution.

Even now string theory remains to be an attractive possibility as the ultimate unified theory, and many physicists are trying to make it complete. It is, however, still under construction. Since I don’t want to disappoint you later, I’d like to state clearly here that I’m not going to discuss the ultimate unified theory below. The main goal of this article is to explain recent attempts to describe QCD or hadron physics discussed in section 2 using string theory. It is now possible to describe hadrons in string theory and calculate various physical quantities that can be compared with the experimental data. In order to achieve such technology, we had to wait for another string revolution.

4. Gauge/String Duality

In the latter half of the 1990s, string theory again encountered an era of great development called the second string revolution. The development was mainly more theoretical, such as the non-perturbative effects in string theory, and it may not sound as glorious as the ultimate theory. The researchers are very much excited, however, because the development has drastically overturned some of the basic concepts in physics such as “dimensions of space-time,” or “elementary particle.” In particular, the “gauge/string duality” was one of the most striking discoveries during the second string revolution.

The main claim of the gauge/string duality is that gauge theory and string theory are equivalent in certain situations. Here, the gauge theory is a theory with an elementary particle mediating force, like the gluon in QCD, introduced by imposing certain symmetry. It is known that the theory of strong force, weak force, and electromagnetic force are all described by gauge theory. QCD is a typical example of gauge theory.

The surprising features of the gauge/string duality are as follows. Gauge theory is a theory of elementary particles living in a four dimensional space-time, while string theory is a theory of strings living in a ten dimensional (curved) space-time. The fundamental degrees of freedom and even space-time dimensions are different. Apparently, they look completely different, but, nevertheless, the duality suggests that they can be equivalent. Everyone was

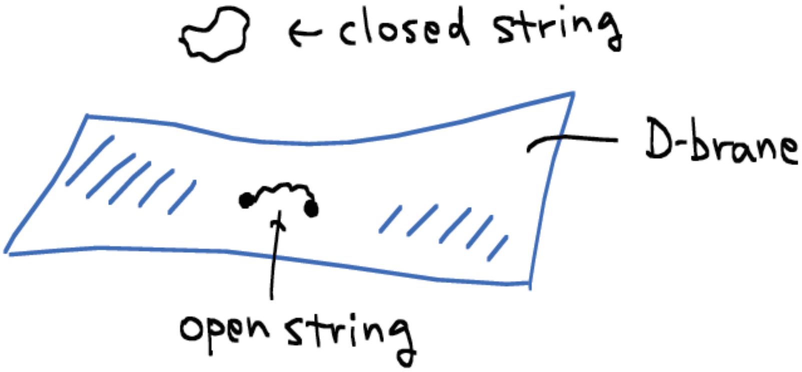

Figure 3. D-brane, open string, and closed string

surprised when Maldacena conjectured this duality in 1997, because it was totally unexpected.

How can gauge theory and string theory be equivalent? In order to explain this, we have to introduce the "D-brane." A D-brane is an extended object in string theory. There are various types of D-branes. If it is extended along the time direction and *p* dimensional spatial directions, it is called a D*p*-brane. For example, the D2-brane is a membrane embedded in ten-dimensional space-time. It can take various shapes, e.g., a spherical one as a soap bubble, or an infinitely extended planar D-brane can also exist. The characteristic property of the D-brane is that the end points of strings can be attached to it. There are two possible types of strings in string theory. One of them is called a "closed string," which looks like a rubber band without end points, and the other is called an "open string," which has two end points like a rubber band cut by scissors. As depicted in Figure 3, closed strings can be separated from the D-brane, while open strings cannot, since the end points are attached on the D-brane.

Though this D-brane might look strange, it is now well established that such objects exist in string theory. The importance of the D-brane was recognized in the mid 1990s, and it played crucial roles in the second string revolution. One of the reasons was that the D-brane provided an easy way to realize gauge theories in string theory. It can be shown that the open strings attached on the D-brane contain particles that mediate forces and a gauge theory is realized on the D-brane. At this stage, this is still a theory of strings, but it is possible to tune a parameter of the theory to make the length of the strings to zero and then, the theory becomes a theory of point particles. For example, in the case of a D3-brane, which is extended in three spatial dimensions, we obtain a gauge theory in a four dimensional space-time.

On the other hand, according to Einstein's theory of general relativity, when there is a D-brane, the space-time around it will be curved. Let us briefly explain what it means for those who are not familiar with the notion of curved space-time. Imagine a soft rubber sheet with horizontal and vertical lines like a graph paper. The vertical line corresponds to the time axis and the horizontal line corresponds to a spatial axis, and a free particle moving with a constant speed corresponds to a straight line on it. When the rubber sheet is bent out of shape, the straight line will be curved. The idea of Einstein's general relativity is to interpret this curved line as the track of a particle moving under the influence of gravity. In some cases, the gravitational effect of D-branes can be captured in a good approximation by replacing the D-branes with the corresponding curved background. It can then be shown that the parameter tuning considered above does not lead to zero string length limit, and the system we obtain is a theory of strings living in a certain curved space-time.

Figure 4. Meson and baryon in string theory

In this way, two descriptions of the system are obtained, one of them is a four dimensional gauge theory, and the other one is string theory in a curved space-time. Since they are obtained from the same D-brane system, it is natural to expect that they are physically equivalent. This is the basic idea of the gauge/string duality. Although this argument motivates us to believe that the duality holds, it does not mean that the duality is proven in a satisfactory way. Therefore, it is important to investigate concrete examples in detail and check whether the predictions of the duality are satisfied. After a lot of works done in this direction, a huge number of non-trivial evidences supporting the duality have been found and now the gauge/string duality is widely believed to be true.

5. Holographic QCD

What can we learn from the gauge/string duality, if it is applied to QCD? The string theory description equivalent to QCD under the gauge/string duality is called "holographic QCD."[4]

Up to now, a string theory description completely equivalent to QCD has not been found yet. But, there is a string theory set up equivalent to a gauge theory that agrees with QCD at low energies in a good approximation. The following discussion is based on this string theory description. It can be shown that hadrons like protons, neutrons, and pions discussed in section 2 are successfully realized in the holographic QCD. I'd like to provide a glance at the main points here.

Following the discussion given in the previous section, the holographic QCD is obtained by first constructing a D-brane system that realizes QCD, and then, by replacing part of the D-branes with the corresponding curved space-time. As a result, we obtain a system with a D8-brane embedded in a curved ten-dimensional space-time. How can hadrons be realized in this set up?

Since there is a D8-brane in the system, open strings with end points attached on it can exist. These open strings are interpreted as mesons. If you compare Figure 4 with Figure 1, you will see that the pictures of the open string and the meson look similar.

In section 3, I explained the possibility that various elementary particles can be obtained from just one string. Applying exactly the same idea to this open string, it is natural to expect that various kinds of mesons can be obtained from the open string. In fact, it can be shown that the meson spectrum predicted from this open string reproduces not only the pion, but also a lot of other mesons found in the experiments. Furthermore, it is possible to estimate the masses and strength of interactions of the mesons, and the predictions of holographic QCD turned out to be in reasonable agreement with the experimental data, although the approximation

[4] This name came from holography which is a technology to record three dimensional images in a film, since the duality predicts the equivalence of four dimensional QCD and ten-dimensional string theory.

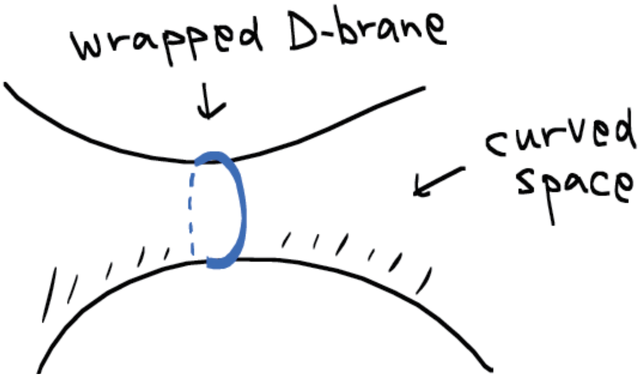

Figure 5. D-brane wrapped on the extra dimensions

made for the calculation is still crude.

Note that the role of strings in holographic QCD is a bit different from what we saw in section 3, in which elementary particles are made of tiny strings. Here, an open string corresponds to a meson, which is a composite particle made of a quark and an antiquark. In addition, this string theory description is not meant to be a theory that is more fundamental than the theory of elementary particles. Under the gauge/string duality, gauge theory and string theory are considered to be equivalent and both of them are on an equal footing. These are new viewpoints that gauge/string duality brought us.

What about baryons? As I already told you at the beginning, baryons are identified as D-branes. There exists a D4-brane wrapped on a four dimensional space along the extra dimensions and trapped as depicted in Figure 5.

The D4-brane is an object extended along one time direction and four spatial directions. Now, since all the four spatial directions on this D4-brane are along the extra dimensions, it behaves as a particle extended only in the time direction in the four dimensional space-time in which we are living. This particle is interpreted as a baryon. Interestingly, it can be shown that this D4-brane necessarily have three open strings attached on it, due to an effect of a field called RR field in the background. As you can see comparing Figure 1 and Figure 4, a baryon made of three quarks resembles a D4-brane with three strings.

By analyzing the spectrum of the states obtained from this D4-brane, it has been shown that the states identified as protons and neutrons are found as expected. Moreover, a lot of other baryons, such as excited states of nucleons, are reproduced. More detailed analyses have revealed that various properties of protons and neutrons such as the magnetic moment, electric charge distribution, etc., calculated in the holographic QCD agree with the experimental data quite well.

6. Epilogue

We have learned that the hadrons living in nuclei can be described by string theory, and mesons and baryons correspond to open strings and D-branes, respectively. In this description, the world looks a bit different from the traditional view. In particular, since protons and neutrons account for more than 99.9% of our weight, I was tempted to say "We are made of D-branes." Don't you think it is a bit amusing to step on the scales, if you know that you are measuring the weight of the D-branes in your body?

Actually, the topic I have discussed so far is only a small piece of the charm of the D-brane. The D-brane appears in various situations in string theory. It can describe black holes, or even the entire universe in some scenarios. I hope there will be other occasions to discuss these topics.