論文の内容の要旨

論文題目: High Energy Scattering of Hadrons in Holographic QCD

(ホログラフィック QCD によるハドロン高エネルギー散乱)

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Study of hadron scattering at high-energy began at about early 1960s with the advent of the first high-energy accelerators. In this era, the main interest was on elastic scatterings, or in general, exclusive processes in which the kinematics of all particles in the final state is reconstructed. As long as we consider that each hadron is a fundamental object, to focus on the elastic scattering was natural because the elastic scattering is the simplest process.

The theoretical foundation was S-matrix theory, which requires several mathematical axioms for the scattering amplitude. The S-matrix theory led us to several representations / transformations of scattering amplitude, by using partial wave expansion and dispersion relations. The idea of complex angular momenta is one of the most important development, which is the consequence of the Watson-Sommerfeld representation of the scattering amplitude. The Regge theory was formulated basting on the complex angular momenta, which aims to gather and collect infinite number of (t-channel) hadronic resonances all together into a single expression as "amplitude of exchange of Regge trajectory". The Regge theory can describe the high-energy small-angle scattering data (with parameter fitting), by assuming poles (=Regge trajectories) in the complex angular momentum plane. The Veneziano amplitude, which is known as the scattering amplitude of the open string today, was discovered as an explicit realization of the idea of Regge theory, along with conjectured s-t duality. This was the born of the string theory and the idea that hadron is string. However, the Regge theory, Veneziano amplitude or the other string based amplitude remained merely models of the scattering amplitude and the fundamental theory of the hadrons was still unclear.

In the 1970s, the quantum chromodynamics (QCD) began to be understood as the fundamental theory of the hadrons. One of the main reasons was discovery of narrow-resonance of J/ψ particle, which was understood as the bound state of charm and anti-charm. On the other hand, people started to consider that the string models for hadrons are inappropriate itself, because the Veneziano amplitude differs from the experimental data of large angle (=large momentum transfer) scattering (hard scattering). The string theory predicts that the scattering amplitude falls down exponentially as a function of energy; this property seems to be inevitable because a string is not a pointlike object but has a finite size, so the large angle scattering is a rare event. However, the experimental data showed that the amplitude has a power-low behavior in terms of energy, which prefers the model that there are pointlike particles inside a hadron, as in the QCD.

Once it was noticed that quarks and gluons are elementary constituents inside the hadrons, the hadron processes which people were interested in changed. The elastic scatterings are complicated processes in the viewpoint of the QCD. Instead of such exclusive scatterings, the inclusive process became main interest such as total cross section of e^+e^- to hadrons or total cross section of e^-p to hadrons, so-called deep inelastic scattering (DIS). This is because we can leave clean parton processes where QCD can be tested by the perturbation theory, by summing up all the final states and neglecting the information of individual hadrons.

Today, the QCD has been fully tested, and interests are shifting into enlarging processes in which perturbative QCD is available and unveiling non-perturbative properties of hadrons itself, such as spin structure of a hadron and spacial or momentum transverse distribution of partons in a hadron. The perturbative QCD has been established as a powerful tool for high-energy hadron scattering and is utilized to search for new physics at hadron colliders or the other high-energy experiments with parton distribution function (PDF) determined by experimental data. However, there are many high-energy hadron processes which require more complicated non-perturbative information of partons, for example, generalized parton distribution (GPD). Such parton information is taking attention not only it is needed to describe cross sections of hadron processes, but also it tells us properties of hadrons described above. To determine such non-perturbative parton information in hadrons, we need to develop theoretical understandings of non-perturbative properties, along with taking experimental data. In this context, the exclusive (elastic) scattering are taking attention again. Even today, Regge-theory based phenomenology is still useful for a variety of high-energy small-angle scatterings which perturbative QCD can not explain.

On the other hand, the string theory, which was born in order to explain hadron scattering but finally abandoned, has developed towards "theory of everything". The string theory includes D-brane as a Dirichlet boundary condition of open string, and it was noticed that D-brane can also be regarded as black hole (black brane). From this idea, AdS/CFT duality was conjectured, which states that a Yang-Mills (YM) theory corresponds to superstring theory on a warped geometry. AdS/CFT duality is an example of weak/strong correspondence, and therefore non-perturbative physics of the strongly coupled YM theory can be studied by the perturbation theory in the string theory.

Holographic QCD is an idea to study non-perturbative properties of hadron physics in the QCD by means of AdS/CFT duality. The gravity dual which is completely dual to the QCD is not known, but, several essential properties of the QCD can be implemented: confinement, breaking (eliminating) supersymmetry, adding flavor (quark), and chiral symmetry breaking, and so on. On such gravity duals, one can calculate low-energy observables in the strongly coupled gauge theory: spectra of hadrons, coupling constants among hadrons, and properties in finite temperature, and so on. So far, the holographic QCD is not good at quantitative precisions, but it is still a powerful tool which can derive several qualitative properties of hadrons and develop theoretical / conceptual understandings of non-perturbative properties of hadrons.

Although the main interest of the holographic QCD has been low-energy hadron physics, nothing prevents us from using gravitational dual descriptions to study high-energy hadron scattering. As I depicted above, even in high-energy processes, we need non-perturbative information also, and AdS/CFT duality can be exploited for it. By using AdS/CFT, we can provide theoretical grounds for the traditional Regge theory and models based on string theory, and moreover, we can study how such traditional models should be modified, corresponding to the fact that the string theory is not on a flat (four) dimensional spacetime, but on a warped ten dimensional spacetime. Polchinski-Strassler (2001) showed that large-angle hadron scattering calculated in a gravity dual shows power-law behavior; the problem of traditional string model was cured. Brower-Polchinski-Strassler-Tan (BPST) (2006) formulated the Pomeron amplitude (= the leading trajectory in the Regge theory) in the gravity dual, which has both the property of the Regge theory and BFKL theory (=perturbatively formulated Pomeron). The BPST Pomeron captures the physics in the QCD because the transition between Regge theory and BFKL theory had been anticipated also in the QCD. However, potential power of gauge/string duality in hadron scattering is far from being fully exploited so far.

In this doctoral thesis, I deepen our understandings of 2 to 2 scatterings of hadron at high-energy (small Bjorken x) in holographic QCD by utilizing and extending BPST Pomeron. Especially, I study scattering of hadron h and virtual photon γ^* ; this process is known as DIS and deeply virtual compton scattering (DVCS). From the cross sections of these processes, one can extract PDF and GPD. Although perturbative QCD can describe photon-virtuality q^2-evolution of PDF and GPD, initial data of the evolution cannot be determined by perturbation theory. Such non-perturbative initial data for PDF can be obtained from DIS experiments, but GPD cannot be determined even from experimental data, without some theoretical modeling of non-perturbative physics. GPD describes parton distribution in the transverse directions and two parton correlation in a hadron in general, hence it is an interesting object on its own. I see that gravitational dual descriptions can determine how those non-perturbative scattering amplitudes depend on kinematical variables such as center-of-mass energy, momentum transfer, impact parameter and photon virtuality. Contrary to the study by Polchinski and Strassler (2002) which stated that the DIS in a gravity dual is completely different from DIS in the QCD, I show that qualitative properties of PDF/GPD of the QCD can be captured in a gravity dual by taking large but finite $1/x$ and q^2. Gauge/gravity dual also tells us how to think about various theoretical ideas that various models of GPD have been based on.

Conceptual understandings of Regge theory are also developed. High energy behavior of elastic scattering amplitude $A(s,t)$ is characterized by poles and their residues of its partial wave amplitude $A(j,t)$ on the complex angular momentum j-plane; the poles and residues depend on momentum transfer t. The poles in the j-plane (=Regge trajectory) have often been assumed to depend linearly in t. Notable aspects for Regge theory and amplitude in string theory on a warped spacetime, however, include i) a single "Regge trajectory" of string theory on 10 dimensions gives rise to a Kaluza–Klein tower of infinite "Regge trajectories" on 4 dimensions, and ii) those trajectories do not remain linear for arbitrary negative t. The non-linear trajectories immediately result in non-Gaussian profile of GPD in the transverse directions, although Gaussian profile of GPD is often assumed in phenomenological analysis. We will also describe how the residues of the Regge poles are determined by holographic set-up, and also explain how the Kaluza–Klein tower of Regge trajectories organizes itself to become a single contribution with a form factor in momentum transfer $t < 0$.

An extra energy scale q^2 is available in photon–hadron scattering, in addition to the center of mass energy W and confinement scale Λ. This extra parameter makes theoretical understanding of the non-perturbative amplitude interesting. The scattering amplitude is dominated by a contribution from a saddle point in the complex j-plane, not from a pole, for sufficiently large $q \gg \Lambda$. The saddle point value j^* depends on kinematical variables such as W, q and t. We find, by following this dependence of j^*, instead of naively taking small x limit or large q^2 limit, that observables characterizing scattering amplitude such as $\ln(1/q)$-evolution parameter $\gamma_{\text{eff.}}$, $\ln(1/x)$-evolution parameter $\lambda_{\text{eff.}}$ and t-slope parameter B show qualitatively the same behavior in the strong coupling regime (gravity dual) as expected in perturbative QCD or observed in HERA DVCS experiment. As the saddle point value j^* and the leading poles are both given by the kinematical variables of the scattering, crossover from the saddle-point phase to the leading pole phase may also be expected, when the photon virtuality decreases to a smaller value.

I also develop the method to study skewness parameter of GPD, which relates the virtuality-difference of initial and final photon. With the full skewness dependence included in this analysis, it is also possible to use the result of this study to bridge a gap between data in such scattering processes at non-zero skewness and the transverse profile of partons in a hadron, which is encoded by the generalized parton distribution functions at zero skewness.

For this study, I found that the BPST formalism is insufficient and we have to extend it in a number of points. First, hadron matrix elements of total derivative operators are irrelevant for the h–$\gamma^{(*)}$ scattering with zero skewness (like DIS), but they do contribute to the skewed scattering amplitude. This contribution needs to be implemented in the language of gravity dual. Secondly, Pomeron/Reggeon propagators have been treated as if it were for a scalar field in BPST Pomeron, but they correspond to exchange of stringy states with non-zero (arbitrary high) spins; for the study of scattering with non-zero skewness, the polarization of higher spin state propagator should also be treated with care. Finally, this also means that infinitely many gauge degrees of freedom in string theory (which extends the general coordinate transformation of the graviton) need to be dealt with properly.