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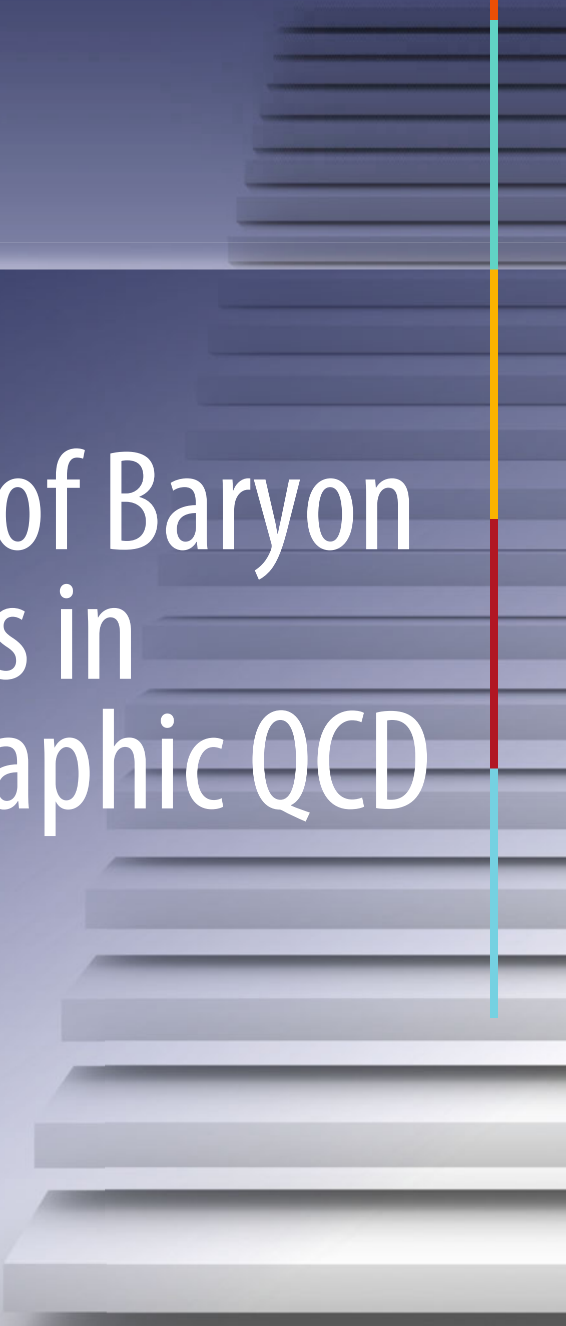

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Daisuke Fujii

Dynamical Properties of Baryon Resonances in the Holographic QCD

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Supervisor's Foreword

In his doctoral study, Daisuke Fujii worked on the structure of baryons; from their static to dynamic properties. Much effort has been devoted to electromagnetic and strong transitions of resonances.

Hadrons are composite and dynamic objects of quarks and gluons. Because of the color SU(3) gauge structure of QCD, the fundamental theory of strong interaction, the direct approach is almost unique by the simulations of discretized fields. This lattice QCD method has been successfully applied to ground state hadrons and their interactions. Yet there are many unsolved problems especially for excited states or resonances, while abundant new states have been found by large scale accelerator experiments. This is the place where models or effective theories become useful. Implementing important features of QCD with inputs from experimental and simulation data, effective theories can be applied to various physics phenomena with predictions.

The theoretical tool that Daisuke uses is a low energy theory for hadrons which is derived from QCD with the aid of the string theory. It is the top-down approach of holographic QCD proposed by Sakai and Sugimoto, resulting in a flavor gauge theory for mesons. Baryons are described by instantons in five dimensional space-time. They are collective excitations of QCD, in sharp contrast with the quark model where baryons are described as single particle excitations of quarks. The collective and single particle natures are the two opposing limits that either one of them dominates a state is determined by QCD dynamics, which should be carefully investigated for each state. Daisuke has chosen the most controversial state, the Roper resonance of the nucleon, and extensively studied its transition amplitudes. A new important has been obtained for electromagnetic transition. A significant improvement is achieved, which could not be possible in the quark model.

In the thesis, Daisuke starts with pedagogic introduction of the Sakai-Sugimoto model. He shows the derivation of the model with a detailed explanation of gauge/gravity holographic correspondence. Then he introduces instantons and their collective quantization for baryons. He also discusses the Skyrme model briefly which is useful to understand baryons as instantons. Effort has been made for the discussions of various form factors. In doing so he points out a subtle problem in the definition of the currents; a consistency between the method faithful to the holographic dictionary and the phenomenology inspired one. Daisuke compared them and found unsolved issues there that should be further investigated for the application of holographic QCD to hadron physics.

To summarize, Daisuke studied the properties of baryon resonances in a holographic model of QCD. He found new results in good agreement with data emphasizing thecollective dynamics of QCD that a naive quark model does not have. He also found difficulty in the computation of currents that should be further worked out. All these results have been achieved by Daisuke's excellent mathematical skills and physics intuitions. This book will provide a cornerstone for further studies of the structure of baryons.

Osaka, Ibaraki, Japan Prof. Atsushi Hosaka
May 2023

Preface

In this doctoral thesis, various properties of baryon resonances are investigated using the Sakai-Sugimoto model, one of the holographic QCD models. Even though the Roper resonance is one of the most experimentally established baryon resonances, it is difficult to explain its various properties theoretically. We find that the mass formula obtained from the Sakai-Sugimoto model captures the characteristics of the experimental data of Roper resonances well. Therefore, we attempted to calculate other properties of the Roper resonance, especially the electromagnetic transition amplitude and the decay width of the one pion emission. We also tried to do similar analyses for other nucleon resonances ($\Delta(1232), N^*(1535)$).

For this purpose, it is necessary to obtain the baryon wave function and chiral current in the Sakai-Sugimoto model. In the holographic QCD model, baryons appear as D-branes. In particular, in the Sakai-Sugimoto model, this D-brane is identified with an instanton on D8 brane. Therefore, we consider the motion of this instanton in moduli space and quantize it to obtain the wave function of the baryon. This is the conventional method used in the analysis of solitons and is called collective coordinate quantization. After that, we performed calculations and compared them with experimental data using the two currents defined as expectation values by using the GKP-Witten relation and the Noether current of chiral symmetry in the Sakai-Sugimoto model, respectively. On the other hand, some problems exist in the definition of chiral current, therefore we pointed out these problems.

In addition, Roper-like excitations have recently been found in heavy baryons. Therefore, we discuss the extension of the Sakai-Sugimoto model to heavy flavor for the purpose of these analyses.

Osaka, Ibaraki, Japan
May 2023

Daisuke Fujii

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Chapter 1
Introduction

Abstract Some typical low-lying states of nucleon resonance and the problems associated with them will be discussed. The Sakai-Sugimoto model is then briefly explained and the motivation for using the model to describe nucleon resonance is given. Finally, the structure of this book is presented.

The strong interactions forming the baryons that occupy more than 99% of the visible matter in our universe are described by quantum chromodynamics (QCD). However, due to their non-perturbative nature, the behavior of low-energy QCD is not always well understood. While the properties of the ground state baryons such as masses and magnetic moments of the octet baryons, are thought to be well understood, much part of them are actually governed by the flavor symmetry. The dynamics of low energy QCD is more directly reflected in the excited/resonant states of the baryons [1]. This was the case as we have seen in the developments of the atomic physics where various observations of atomic spectra revealed their origin due to the motion of electrons and their interactions. We expect a similar situation for QCD; from the study of baryon spectra we may be able to extract the information of the constituents, or effective degrees of freedom, that govern the structure of baryons and their interactions. This motivates us to study baryon resonances.

While the first-principles calculations of the ground state have been developed by Lattice QCD, the simulations of resonances is difficult, because resonances are recognized as a continuum (scattering) state. For this reason, investigation by effective models that incorporate the appropriate degrees of freedom have been useful. Among various effective models, the most standard one is the constituent quark model that describes baryon resonances as excitations of quarks that are confined inside the baryons [2–7]. The model reproduces well the properties of the ground state baryons and reasonably well the first resonant states. The model can also predicts further resonant states. However due to its simplicity the predictive power is limited, and for some resonances, the model lead serious discrepancies in comparison with experimental data. Difficulties are in many cases decay properties of resonances, which are the most important dynamical properties, for example, the decay widths and

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electromagnetic transition amplitudes [8]. This is because the quark model describe the resonances as a stable particle, although the actual baryon resonances are recognized as poles appearing in the scattering amplitudes of mesons and baryons. The dynamically coupled-channel model (DCC model) is a well-known model that respects the actual resonances [9]. This model explains the properties of resonances very well by using scattering cross-section data as input. However, it is a phenomenological model that requires a large amount of data input.

In this doctoral thesis, the dynamical properties of nucleons are discussed in the Sakai-Sugimoto model, which is the most successful holographic QCD description of low-energy QCD [10, 11]. So far, static properties such as the mass spectra have been investigated in this model by well utilizing the extra-dimensional degrees of freedom, where its success has been shown [12–16]. On the other hand, it is also essential to elucidate the dynamical properties of resonances and their interactions. In this study, as a milestone of the new development of the study of dynamical properties in the holographic model of QCD, the properties of the nucleon resonance are investigated [17, 18]. Moreover, this model describes nucleon as solitons (instantons) [12, 14], whose are resonances expressed as their collective motion excitations, namely stable particles. Here, the extra-dimensional degrees of freedom play an important role. As described below, this extra-dimension includes the degrees of freedom of the meson and its resonances. Then, from the viewpoint of our four-dimensional spacetime, this solitons (instantons), baryon, can be interpreted as a meson-baryon composite system. Considering that the actual nucleon resonance is recognized as the poles of the scattering amplitudes of the meson and baryon, this baryon picture is very interesting. From this point of view, it is worthwhile to investigate various properties of nucleon resonance using this model.

In addition, hadrons with heavy quarks and their resonances have been studied with great interest in recent years [19–24]. In particular, the existence of Roper-like heavy baryons is of intriguing concern [8]. The Roper-like excitations are observed at energies above about 500 MeV from the ground state that shows flavor-independent properties [23]. Therefore, it is desirable to extend the Sakai-Sugimoto model to cases involving heavy flavors [25–35]. This thesis also presents our work on the development of the Sakai-Sugimoto model in this direction [36].

Hadron resonance as a fundamental excitation produced by the QCD vacuum shows various aspects and opens up many interesting research areas. The nature of the resonance states can be not only theoretically understood but also experimentally verified. Therefore, theoretical and experimental investigation of the structure and properties of hadron resonance are expected to reveal the puzzle of low-energy QCD.

1.1 Nucleon Resonances

In the following, we discuss the specific resonances.

1.1.1 The **Δ(1232)** *Resonance*

The $\Delta(1232)$ resonance is a resonant state with isospin $3/2$ and spin-parity $3/2^+$ quantum numbers, with a mass of 1232 MeV and a decay width of about 100 MeV [37]. In the picture of the quark model, which describes a nucleon as three quarks, it can be interpreted as an excitation by a magnetic dipole transition that flips the spin-isospin of one quark of the nucleon.

It is the most strongly excited compared to the other nucleon resonances, and decay to a pion and a nucleon with a branching ratio of almost 100%. The quark model, which successfully explains the magnetic moment of the nucleon, was expected to reproduce the $\Delta(1232)$ resonance electromagnetic transition amplitude, but its prediction is much smaller [3, 7, 38] than the amplitude observed in experiments [39]. It has been found that a simple description of the nucleon as a three-body system of quarks is not sufficient to explain this transition amplitude, in which it is important to take into account the meson clouds produced by the strong coupling of the $\Delta(1232)$ resonance to the pion and nucleon [40]. It is now becoming clear that this picture of a meson-baryon composite system is also very important for understanding other nucleon resonances.

1.1.2 Roper Resonance

The Roper resonance is the first excited state of the nucleon, with spin-parity $1/2^+$, a mass of 1440 MeV and a decay width of about $160 \sim 190$ MeV, which is one of the most established resonances since L. D. Roper observed its existence in the 1960s [41]. Nevertheless, there are many unsolved puzzles regarding its structure and properties.

A long-standing controversial puzzle is the issue of the mass of the Roper resonance. Since the establishment of the picture of baryons composed of three constituent quarks, there have been many studies using the non-relativistic quark model. On one hand, the quark model was found to reproduce experimental values of the masses of many nucleon resonances by using harmonic oscillator-type confinement potentials. On the other hand, the mass of the Roper resonance cannot be explained by the quark model picture. Its mass smaller than the negative parity resonance $N^*(1535)$ has attracted great amount of interests because the naive quark model predicts the mass of the Roper resonance much higher than that of the negative parity state.

Turning to the dynamical properties of the Roper resonance, a further problem was unveiled. That is the fact that the quark model cannot reproduce the data obtained from the electromagnetic transitions of the Roper resonance. The electromagnetic excitations of nucleon resonances have long been studied experimentally and theoretically as an important source of information for understanding QCD. The helicity amplitudes extracted from this electro-production data distinguish competing models. In earlier years, the data were insufficiently precise and the amount of helicity amplitude data points was limited. However in recent years, mainly with the advent of the Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Facility (JLab), a large amount of precise data has been obtained [42–46]. Motivated by this, many theoretical studies [8, 9, 24, 47] have been devoted to the understanding of this process for the Roper resonance, in particular, it has been argued that the quark three-body picture is inappropriate and that it is important to consider the effect of the meson cloud [8, 9].

This is not the only problem with the Roper resonance. An almost vanishing decay width of one pion emission, which is a forbidden process in the limit of zero momentum of the outgoing pion in the non-relativistic quark model, disagrees with the large value of the experimental data. To solve these problems about electromagnetic transition and one pion emission, many theoretical efforts have been devoted. It was pointed out that relativistic effects of the confined quarks at short distance and meson cloud effects at long distance are important to improve the problems [8, 9].

It follows that these two problems about electromagnetic transition and one pion emission of the Roper resonance stem from the properties of the non-relativistic quark model. These transition processes are related to the following matrix element;

$$\left\langle \text{spin} \otimes \text{isospin} \middle| \mathcal{O}_{\text{spin,isospin}} \middle| \text{ spin} \otimes \text{isospin} \right\rangle \langle \psi^{N^*} | e^{i\vec{q}\cdot\vec{x}} | \psi^{N} \rangle \qquad (1.1.1)$$

where the $\mathcal{O}_{\text{spin, isospin}}$ is the operator of the spin and isospin, $\psi^{N(N^*)}$ is the wave function of the nucleon (the Roper resonance), $\vec{q}$ is the momentum of a pion or a photon. This transition process is forbidden in the limit of $\vec{q} \to 0$ due to the orthogonality of the wave function. However, the experimental value has a finite value in this limit, which is a contradiction.

In Ref. [47], the prediction for the helicity amplitude of the electromagnetic transition at the real photon point was improved by adding a correction for the effect of internal quark dynamics. Recently, similar results have been obtained for the decay width of one pion emission. The effect of internal quark dynamics, which is important for the solution of this problem, contributes as a relativistic correction term to the matrix elements as follows. Denoting the momentum of the internal quark as $\vec{p}$, we find that the relativistic corrections add the following terms to the matrix elements;

$$\langle \text{spin} \otimes \text{isospin} \left| \mathcal{O}_{\text{spin,isospin}} \right| \text{spin} \otimes \text{isospin} \rangle \langle \psi^{N^*} \left| \vec{p} e^{i\vec{q}\cdot\vec{x}} \right| \psi^{N} \rangle \qquad (1.1.2)$$

Due to the internal quark momentum $\vec{p}$, this matrix element is not zero even in the limit of $\vec{q} \to 0$.

The importance of the effect of the meson clouds around the quark is also remarked on for the understanding of the Roper resonance [8, 9]. As discussed below, the baryon picture of the Sakai-Sugimoto model leads us to expect that the effect of meson clouds is incorporated.

1.1.3 Negative Parity Resonance

The negative parity resonance $N^*(1535)$ is the second excited state of the nucleon with a mass slightly larger than the Roper resonance. There has been interest in studying $N^*(1535)$ from several perspectives, as follows. For example, it has been discussed that when chiral symmetry is restored at finite temperature and finite density, a degenerate pair of different parity states are observed, i.e., the existence of chiral partners. The negative parity resonance $N^*(1535)$ is considered to be a reasonable candidate for a nucleon's chiral partner [48–51]. This fact is of great interest because it indicates that $N^*(1535)$ may play an important role in understanding the chiral symmetry of QCD.

On the other hand, this resonance is known to be strongly coupled to ηN, which is an almost exclusive property of this resonance [52–54]. Therefore, the production of $N^*(1535)$ can be identified by observing the η meson. This property also allows the study of $N^*(1535)$ through meson-nucleus bound states. When the η meson-nucleus bound states are observed, the energy and structure of the bound state depend strongly on the interaction between the η meson and the nucleus, which in other words can also be said to reflect the nature of $N^*(1535)$ in the nucleus. Therefore, $N^*(1535)$ is an interesting research issue because it allows us to further understand the nucleon resonance by studying the meson-nucleus bound state. So far, the search for this resonance state has been conducted, which has not yet led to its identification [55, 56], but the above-mentioned interest has led to ongoing intensive research.

While in the quark model nucleon resonances are described as three-quark systems, in several models [57–59], the negative parity state $N^*(1535)$ may be described as composite states of a ground state baryon and a negative parity meson such as $K\Sigma$. The baryon picture of the Sakai-Sugimoto model can be interpreted as a meson-baryon composite system, and the analysis of this doctoral thesis has a very interesting possibility for the understanding of baryon resonances including $N^*(1535)$.

1.2 Sakai-Sugimoto Model

The Sakai-Sugimoto model [10, 11] has been recognized as the holographic QCD that best reconstructs strongly coupled massless QCD in the large N_c limit at low energies. In the holographic QCD, the question is how to realize QCD in the framework of string theory.

After Polchinski pointed out the importance of D-branes [60], the AdS/CFT (anti-de Sitter/conformal field theory) correspondence was conjectured by Maldacena [61]. A non-conformal, supersymmetric four-dimensional pure Yang-Mills (YM) theory and its dual gravity theory were constructed, for example by Witten, by using N_c D4 brane [62, 63]. We see that the open string with two endpoints on this N_c D4-brane corresponds to a $U(N_c)$ gluon field of $N_c \times N_c$ adjoint representations. The field of $U(N_c)$-fundamental representations corresponding to the quark is an open string with one of its two endpoints on this D4-brane. The other endpoint should be placed on the D-brane corresponding to the flavor degrees of freedom. In this way, we can introduce quarks into the pure YM theory. However, due to the addition of the new D-brane, we can no longer use the gravity solution proposed by Witten. In general, it is quite difficult to obtain a gravity solution for such a complex D-brane system. Therefore, it was proposed in Ref. [64], to introduce D-branes corresponding to the degrees of freedom of the flavor as probes (that have a negligible back reaction to the background field). This allows us to incorporate quark degrees of freedom into four-dimensional pure YM theory based on Witten's N_c D4-brane system and its dual gravity theory. Furthermore, an assignment of D-branes that reproduces the chiral symmetry and its spontaneous breaking was proposed by Ref. [10, 11]. This is the Sakai-Sugimoto model used in this thesis.

The gravity theory equivalent to massless QCD can be regarded as an effective action of the flavor gauge field in the five dimensional space (four space-time and one extra dimension), implementing the spontaneous breaking of chiral symmetry [65, 66], allowing many hadron physics predictions to be obtained with simple analytical calculations [10, 11]. For example, from this effective theory of mesons, scalar and vector meson spectra can be obtained, which well reproduce experimental data. It also shows that the model contains a pion, which is an Nambu-Goldstone (NG) boson associated with the spontaneous breaking of the chiral symmetry. This pion is massless, as one would expect from the fact that the Sakai-Sugimoto model is the gravitational theory equivalent of massless QCD. This model also contains the Skyrme model including the Wess-Zumino-Witten (WZW) term and the (axial-) vector meson. Furthermore, the chiral anomaly is reproduced from the Chern Simons (CS) term corresponding to the WZW term in this model. In addition, many other qualitative and quantitative predictions related to hadron physics are possible, such as vector meson dominance, the Kawarabayashi-Suzuki-Riazuddin-Fayyazuddin (KSRF) relation, the pion form factor, the $U(1)_A$ anomaly, and so on. Moreover, surprisingly, there are practically only two parameters in this model. Nevertheless, it has achieved great success in explaining light flavor hadron physics.

1.3 Baryons for Sakai-Sugimoto Model

In the Sakai-Sugimoto model, baryons are analyzed by soliton picture [12, 14]. T. Skyrme constructed the Skyrme model, which describes baryons as solitons of an infinite number of pions, which can explain many properties of baryons [67–71].

On the other hand, the Sakai-Sugimoto model is a hadron effective model of 1+4 dimensional spacetime, which leads the Skyrme model by projecting the model onto four-dimensional spacetime employing Atiyah-Manton's method [72]. Furthermore, the extra dimension of the model naturally accommodates various excited states of mesons. The baryons in the Sakai-Sugimoto model are known to emerge as instantons on the D8 brane [12, 14, 73–75]. The dynamics of baryons is described as the collective motion of instantons/solitons, which is a very different description from the quark model with a single-particle picture. Interestingly, as we will see below, the baryon picture of the Sakai-Sugimoto model is closely related to that of the meson cloud, which has recently been revealed in the study of Roper resonances.

For the purposes of this doctoral thesis, there are several facts that are particularly noteworthy in this model, as described below. First, the model describes baryon resonances as meson-baryon composite systems. Baryon resonances are represented using extra dimensions that play a crucial role in the realization of the description of mesons and their resonant states. When the baryon resonance is viewed from a 4-dimensional space-time perspective, the Lagrangian appears as a meson-baryon composite system. The extra-dimensional degrees of freedom are also used to represent the negative parity excitation, because the meson-baryon (soliton) composite system is critically important for the description of negative-parity states. In the quark model, we describe the negative parity excitation as an orbital excitation of a single quark. This model, which describes baryons as solitons (instantons), is similar to the baryon picture of the Skyrme model, but it is known that it is generally difficult to deal with negative parity excitation in the Skyrme model. One way is to introduce meson fluctuations around the soliton solutions i.e., meson-baryon composite system [57, 58]. Therefore, one of the unique points of this model is that it can describe the negative parity excitation by utilizing the extra dimensional degrees of freedom. Furthermore, in the obtained mass formula, the masses of the Roper resonance and the negative parity state are degenerate [12]. This is a good feature of the hadron resonance mass spectra than the quark model.

In addition to the discussions in the light flavor sector, recent experiments have also discovered Roper-like states in heavy flavors, which has stimulated some theoretical works. Under these situations, studies on the extended the Sakai-Sugimoto model to heavy flavors have been performed in Ref. [31, 36] and others. In particular, in our study Ref. [36], we find that the extra dimension again plays an important role in introducing heavy flavors to the Sakai-Sugimoto model.

Further studies of the static properties of baryons in this model have been conducted by [13, 16]. For this purpose, it is necessary to define the chiral current using this model. There are two ways to define the chiral current in this model. One is to define the current using the GKP-Witten relation from the standpoint of the AdS/CFT correspondence [16], and the other is to obtain the current as the Noether current from the standpoint of the hadron effective model [13]. The former method is a natural definition of current from the viewpoint of AdS/CFT correspondence, but it causes problems in the analysis of baryons because the current is defined as coupling with the external field in the extra-dimensional boundary. The baryons in this model are identified with instanton solutions in a 3+1 dimensional space including one extra dimension, but since instanton solutions usually have spatial SO(4) symmetry, the current becomes zero when the baryons exist. This is because the classical solution is obtained by ignoring the effect of the warp factor. In Ref. [16], they obtained an asymptotic solution at the boundary that incorporates the effect of the warp factor leading to a well-defined current evaluation. They used this current to investigate the static properties of the baryon and found that it roughly captured the experimental data. On the other hand, almost at the same time as Ref. [16], a study of nucleon resonance with the current obtained from the latter definition was carried out and found to roughly reproduce the experimental data. However, since this current has non-uniqueness in its form, they determine this non-uniqueness so that the chiral current of the Skyrme model is derived when reduced to four-dimensional space-time.

Using these currents, we investigate the dynamical properties of baryons, in particular, electromagnetic transition amplitudes and the decay width of one pion emission. They are related to the following matrix elements, using a certain function f for the soliton picture of the baryon.

$$\langle \text{spin} \otimes \text{isospin} \big| \mathcal{O}_{\text{spin,isospin}} \big| \text{spin} \otimes \text{isospin} \rangle \langle \psi_\rho^{N^*} \big| f(\vec{x}, \rho) e^{i\vec{q}\cdot\vec{x}} \big| \psi_\rho^{N} \rangle \quad (1.3.1)$$

where $\psi_\rho^{N^*}$ is the wave function for instanton monopole vibration of size ρ. Unlike (1.1.1), this matrix element has a nontrivial form and thus has the potential to solve problems concerning the dynamical properties of the Roper resonance from a different perspective in comparison to relativistic corrections. In particular, analysis of the properties of baryon resonance by the Sakai-Sugimoto model is essential to verify the validity of the description of baryon resonance and to understand its phenomenological meaning. In this doctoral thesis, we will explain both current definitions and calculate the physical quantities. The results will show that the latter definition is more effective for a comprehensive analysis of baryon resonances.

1.4 Construction of the Doctoral Thesis

The role of each chapter is described below. Chapter 2 reviews the analysis of mesons and baryons in the Sakai-Sugimoto model. In particular, we emphasize that the Sakai-Sugimoto model has a meson cloud picture. In addition, the resonances of baryons and their dynamics are expressed as the collective motion of instantons/solitons. By explaining this point, we will clarify the baryon picture as a meson-baryon complex system. In addition, Roper-like excitations have recently been found in heavy flavor baryons. Therefore, we first review the treatment of flavor SU(3) including s quark and then discuss the extensions that introduce heavy flavor to the Sakai-Sugimoto model based on Chap. 3. Furthermore, we define the chiral current to analyze the dynamical properties of the baryon resonance. Therefore, in Chap. 4, we will first discuss the definition of the chiral current, and then calculate various physical quantities and compare them with experimental data. Finally, we summarize and discuss prospects in Chap. 5.

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