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Kadir Utku Can

Electromagnetic Form Factors of Charmed Baryons in Lattice QCD

Doctoral Thesis accepted by
the Tokyo Institute of Technology, Tokyo, Japan

Springer

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Supervisor's Foreword

Our universe is composed of atoms, which are made of a nucleus and electrons circulating around the nucleus. The nucleus is further a composite object of elementary particles called hadrons. The most popular hadron is the proton, the nucleus of the hydrogen atom. Heavier nuclei contain multiple protons and also some neutrons, which are the neutral sibling of the proton. The last half of the twentieth century was an era for discoveries of new particles beyond the electron, proton, and neutron, which lead to the standard model of elementary particles. There the quark and gluon are introduced to describe the structure and dynamics of the hadrons (and thus the nucleus).

Analyzing the hadron structure in terms of quarks and gluons is one of the main subjects in the hadron physics. The fundamental theory of their dynamics is known as the quantum chromodynamics (QCD), which is a part of the standard model. According to QCD, quarks and gluons interact with each other through color-dependent force or the color–gauge interaction. Although QCD is as simple as expressed by a single-line Lagrangian, its outcome has full of surprises. At low energy, the color-coupling strength is so strong that the quark and the gluon cannot be isolated, but instead are completely confined in color neutral (singlet) hadrons. Furthermore, light quarks get dynamical masses due to the (chiral symmetry breaking) quark condensate in the strongly correlated vacuum. These features of the strong interaction make the analysis of QCD and comparison with experiment quite complicated.

In this thesis work, the author, Kadir Utku Can, studies the hadron structure from QCD, focusing on the baryons that contain at least one charm quark (charmed baryons). Utku's work was motivated by recent rapid developments of experimental studies in the spectroscopy of heavy-quark (charm and bottom) hadrons at various high-energy particle accelerators. In 2003, the Belle detector experimental group at KEK, Japan, found a new resonance state in the region of the charmonium spectrum. This state happens to be quite exotic; *i.e.*, it cannot simply be a charm–anti-charm bound state, but it should contain more quarks. This was followed by many other candidates of "exotic" hidden-charm multi-quark states. The theorists started to reconsider a simple picture of charmonium states and have developed new ideas, such as di-quark correlation, hadron molecule, strong channel coupling.

What is special in heavy quarks? The intriguing aspect is that the inner dynamics of charmed baryons is supposed to be distinguished from their light counterparts, *i.e.*, that of the nucleon. This is caused by the large mass of the charm quark and the asymptotic freedom, the key property of QCD. In order to investigate such properties, Utku calculated the electromagnetic form factors of the lowest lying charmed baryons. The form factors can represent, after the Fourier transform, the charge densities coming from the quarks of each flavor.

As the hadrons are formed at the low-energy regime of QCD, the effective coupling constant is significantly large and perturbative approaches are inapplicable. Then, a state-of-the-art numerical method, called lattice QCD, was applied to this study, which is the most powerful, ab initio, and non-perturbative method of QCD. The lattice QCD is a method in which quarks and gluons are regarded as dynamical variables defined on a discretized space-time lattice. They move around on the lattice according to the dynamics of QCD and form bound states, *i.e.*, hadrons. Their motion is described as a multi-dimensional path integral, which is evaluated numerically by an importance sampling method. After 30 years of its proposal, the technique has been advanced with the help of development of fast and large supercomputers. Recent calculations have achieved good accuracy that can be compared with available experimental data.

Utku has applied the lattice QCD technique to calculate the mass and form factors of heavy baryons. The thesis is based on series of papers which Utku and his collaborators published in these several years. The work required two important developments, (1) to properly implement the charm quark on the lattice and (2) to calculate three-point (vertex) functions with finite momenta. The combination of these two components has been achieved for the first time in this thesis work. He successfully obtained the form factors of the charmed baryons and estimated the distribution and the radius (extension size) of each flavor of quarks. His analysis shows a systematic behavior of the quark distributions for the charmed baryons. Most notably, he shows that the expectations of the (naive) quark model and effective field theory calculations of heavy systems are qualitatively consistent with the first principle calculations. For instance, the spin-flavor correlation of quarks in the baryon agrees qualitatively to simple (nonrelativistic) quark models. On the other hand, the quantitative results often deviate from the model calculations. This thesis contains the details of his analyses of the lattice QCD results. His results also provide insights into the dynamics of yet unobserved charmed baryon systems.

This is the first step to investigate the charmed (and in future also bottomed) hadron structure from the first principle. Utku plans to extend his calculation of the form factors further for the so-called heavy exotic hadrons, which are regarded as multi-quark resonance states.

Kadir Utku Can came from Turkey and became a graduate student at Tokyo Institute of Technology (Tokyo Tech.) under my supervision. His former supervisor, Güray Erkol, Professor at Ozyegin Univ., Istanbul, is also a long-term collaborator of mine, since he was a JSPS Postdoctoral Fellow at Tokyo Tech.

Toru Takahashi, Professor at the National Institute of Technology, Gunma College, is another key collaborator of this work. Utku's study at Tokyo Tech. was based on the collaboration between Turkey and Japan and has been very fruitful. We thank all the collaborators of our work and hope to continue the fruitful collaboration in future.

Tokai, Japan
November 2017

Prof. Makoto Oka

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