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海外特別研究員最終報告書

独立行政法人日本学術振興会 理事長　殿

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（氏名は必ず自署すること）

海外特別研究員としての派遣期間を終了しましたので、下記のとおり報告いたします。
なお、下記及び別紙記載の内容については相違ありません。

記

1. 用務地（派遣先国名）用務地：　Raleigh, North Carolina　（国名：　アメリカ　）

2. 研究課題名（和文）※研究課題名は申請時のものと違わないように記載すること。
新たなアノマリーマッチングを用いた量子ゲージ理論の解析

3. 派遣期間：平成　３１年　４　月　１　日　～　令和　２　年　３　月　31　日

4. 受入機関名及び部局名
Physics department, North Carolina State University

5. 所期の目的の遂行状況及び成果…書式任意　**書式任意（A4 判相当 3 ページ以上、英語で記入も可）**
（研究・調査実施状況及びその成果の発表・関係学会への参加状況等）
（注）「6. 研究発表」以降については様式 10－別紙 1～4 に記入の上、併せて提出すること。

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The purpose of this research project is to understand strongly-coupled nature of non-Abelian gauge theories by using recent developments of anomaly matching condition and reliable semi-classical analysis. I will report on the progress of this project.

Let me start with a review of the motivation of this study. In the current energy scale, our nature is well described by the Standard Model of particle physics, which consists of the Weinberg-Salam theory unifying electromagnetism and weak interaction and quantum chromodynamics (QCD) describing the strong interaction. Quantum field theory (QFT) is the underlying technique for its description, and the electroweak part of this model enjoys quite accurate calculation based on perturbative QFT. However, QCD becomes strongly coupled at low energies, leading to confinement of quarks and chiral symmetry breaking, and the perturbative analysis does not capture these important phenomena. Because of its nature, our understanding about QCD has been based on the model analysis, such as the Nambu-Jona-Lasinio model, or on the numerical analysis with Monte Carlo simulation for its lattice version. It is still a far-reaching dream to get an analytic understanding of confinement and chiral symmetry breaking of QCD.

About a decade ago, an important progress was made on this problem by Mithat Unsal, who is my host researcher of this project at North Carolina State University. He showed that a deformed version of Yang-Mills theory with S^1 compactification has non-vanishing mass gap with confinement of electric test particles. Moreover, a lot of expectations given in 4d can be shown rigorously in 3d effective theory, so this semiclassical method provides a new way for analytic studies of non-perturbative gauge theories. A good point of this method is its applicability to a wide class of asymptotically-free theories. The Monte Carlo simulation has a limitation due to the sign problem, so it is applicable only if the model satisfies certain properties. The semiclassical method can provide a way to analyze theories with sign problems, such as the theta angle, chiral fermions, etc. On the other hand, the semiclassical method has to be free from infrared divergence, and S^1 compactification is almost always mandatory for an interesting class of gauge theories in order to evade this problem. The continuity between 4d dynamics and 3d dynamics has to be ensured, or at least inspected, by other methods, which is usually a hard task.

Here, anomaly matching comes in. When a global symmetry of QFT cannot be promoted to a local gauge redundancy, we say that this symmetry has an anomaly (or, especially, ’t Hooft anomaly). Importantly, the anomaly enjoys the non-renormalization theorem, and the anomaly computed with high-energy degrees of freedom must be the same with that of low-energy degrees of freedom up to the local counter terms. This was noticed in ’80s for continuous symmetry of chiral fermions, but the recent development of topological phases of matter enlarges its validity to any symmetries. Based on this development of anomaly matching, I previously showed that S^1 compactified theories by Unsal enjoy the same anomaly matching condition of uncompactified theories. This ensures that nontrivial degeneracy of the ground states has the same origin in 3d compactified and 4d uncompactified theories. Since the anomaly matching is kinematical constraint, this argument is not strong enough to ensure the continuity between 4d and 3d dynamics, but it still provides a useful inspection for its continuity conjecture.

It is therefore important to develop our non-perturbative understanding of field theories by combining the semiclassical method and the anomaly matching. Broadly speaking, there are two complementary directions of this research project:

1. Applying both the semiclassical method and anomaly matching to exactly solvable systems, we get a better and solid connection between these techniques.
2. Studying a new class of theories with these methods, we get a new insight about dynamics of non-perturbative field theories.

The first point is important to establish the connection between these two techniques. Comparison with exactly solvable models provides a nontrivial test for these techniques. The second point is important to find a new prediction by these methods. For example, chiral gauge theories belong to a difficult class of QFTs, since any known methods including numerical Monte Carlo techniques are not applicable. After careful identification of symmetry and anomaly, we can claim a nontrivial consistency condition for low-energy dynamics, and its confirmation from semiclassical analysis is giving a useful hint to pick up a reasonable scenario among various consistent possibilities.

To establish the first point, two-dimensional field theories often provide useful models that are exactly solvable while containing nontrivial low-energy dynamics. With Tatsuhiro Misumi at Akita University and Mithat Unsal, I studied the charge-p (>1) version of the multi-flavor Schwinger model. This model is exactly solvable, so we can compute the structure of ground states and various correlation functions. We compare the anomaly constraint and its ground-state structure under S^1 compactification with several flavor twisted boundary conditions. In 2d, there are p disconnected vacua and the low-energy behavior on each vacuum shows scale invariance, described by SU(N) level-1 WZW conformal field theory. Under compactified setup with the specific flavor twisted boundary condition, this conformal behavior is replaced by N degenerate vacua, and this satisfies the requirement of discrete anomaly matching condition. When the circle size is small, the semiclassical method with quantum instanton reproduces the exact results. In this model, we confirmed the conjectured relationship between anomaly constraint and semiclassics explicitly.

With Aleksey Cherman, Theodore Jacobson at University of Minnesota and Mithat Unsal, I studied two-dimensional QCD with adjoint Majorana fermion based on semiclassics and anomaly. Unlike the 2d Schwinger model, this is not exactly solvable, but it has many similarities with 4d QCD about confinement and chiral symmetry breaking. By anomaly matching condition, we showed that chiral symmetry has to be spontaneously broken in this theory, and we confirmed it explicitly using the semiclassical method on the circle compactification. Furthermore, as a requirement of anomaly, the domain wall connecting these chiral broken vacua turns out to have the color-electric charge N/2. As a consequence, the center symmetry has to be partially broken, which means partial deconfinement due to the existence of massless fermions.

In order to find the extension of these observations in 4d QFTs, Mithat Unsal and I considered the Yang-Mills theory with restricted topological sectors. We have shown that many of the above observations have a nice and straightforward extension to this setup by using the anomaly matching condition, and this is explicitly confirmed by the semiclassical method, too. I would like to emphasize that this becomes possible by combining analyses both from anomaly and semiclassics.

Above works and some others are already announced as preprints, and most of them are already published or accepted in peer-review journals. I gave presentations on these works in international conferences/workshops. Mithat Unsal and I are still working together on other 4d gauge theories, and we hope that those results will also come out soon.