Usage Report for Fiscal Year 2016

**Project Title:**

# Nucleon calculations for particle and nuclear physics

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## 1. Background and purpose of the project, relationship of the project with other projects

Nucleons are basic building blocks of our visible universe, and understanding how quarks and gluons interacting via Quantum Chromodynamics (QCD) give rise to their rich structure is a central focus of both theory and experiment. Quarks can also participate in yet undiscovered interactions beyond the commonly accepted Standard Model (SM).

Lattice gauge theory, a numerical method to solve quantum field theory on a discrete space-time grid, is a bridge between fundamental theory of strong interactions of quarks and gluons, on one side, and observable properties of hadrons and predicting the experimental effects of interactions beyond the Standard Model, on the other. We calculate the hadron structure functions with electromagnetic and axial vector currents, from which the proton radius, spin content, nucleon current charges can be determined from a first principle. In the current period of our project, we focus on the calculation the CP-odd nucleon matrix elements induced by the chromo electric dipole moment. This measurement covers more exploratory calculation relevant for searches for new physics in decays of ultra-cold neutrons, CP violation, and neutron electric dipole moment.

## 2. Specific usage status of the system and calculation method

At present, the most sensitive probes for the CP-violating interactions are electric dipole moment searches in hadronic, atomic, and molecular systems. In this proposal, we use nucleon four-point correlation functions to determine the effect of quark chromo-electric dipole moments (cEDMs)

$$L_{cEDM} = -i\sum_q \delta_q \bar{q}(\lambda G^a_{\mu\nu} T^a)\sigma^{\mu\nu}\gamma_5 q$$

on the nucleon EDM, which can be detected from the P-, T-odd electric dipole form factor (F3),

$$< N_{p'} | \bar{q}\gamma^\mu q | N_p >= \overline{u_{p'}}[F_1\gamma^\mu + F_2\frac{i\sigma^{\mu\nu}q_\nu}{2m} - F_3\frac{\gamma_5\sigma^{\mu\nu}q_\nu}{2m}]u_p \quad ,$$

Fortunately, our technique to compute nucleon form factors can be naturally extended to compute the CP-violating form factor F3. A schematic algorithm for the 4pt function in terms of quark diagram is shown below using so-called (doubly) sequential source method for each of quark's vector current (dots) and cEDM interactions (crosses) (Fig.1).

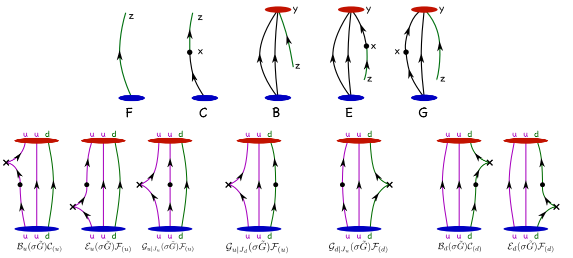


Figure 1: Quark-connected contractions of the nucleon, quark's vector current, and cEDM operators.

The chiral symmetry is crucial for the measurement of the CP-odd quantities to avoid an unphysical operator mixing contribution due to the lattice artifact, which gives a large systematic uncertainty, so that we use mobius Domain wall fermions as a chiral symmetric quark action that do not have O(a) discretization errors and no such a mixing.

Since the previous period of our project G15038, we have been developing a scheme for computing quark contribution of quark chromo-EDM to the nucleon correlation functions and a code. The most demanding computational cost comes from solving the linear Dirac equation using the Conjugate-Gradient algorithm. In these computations, it is vital to reduce the cost. We have employed various recent lattice QCD techniques such as an approximation of the fermion operator (which we refer as "zMobius" ), deflation of low-Dirac eigen-mode, an improved sampling method or all mode averaging (AMA), and the coherent trick for the quark backward propagators. We have tested these techniques in GW-MPC at HOKUSAI, and we checked that they actually works well to reduce the computational cost.

## 3. Result

Using the gauge ensembles with chiral symmetric domain wall quarks generated by the RBC/UKQCD international lattice collaboration, which includes the RIKEN-BNL computing group, we have measured F3 form factor. Meanwhile we have also found that there is a problem in the conventional formula to extract the F3 form factor commonly used in the previous lattice EDM calculations which use the nucleon-current correlation functions. In our publications [1, 2], we have pointed out that the conventional F3 form factor receives a spurious mixing due to the additional CP-violating effect that need to be subtracted, and derived a new formula that subtracts the spurious mixing effect of the F3. Based on our new formula, we have performed computations of the F3 form factor, from which we successfully extract the "correct" F3 form factor, see Fig. 2

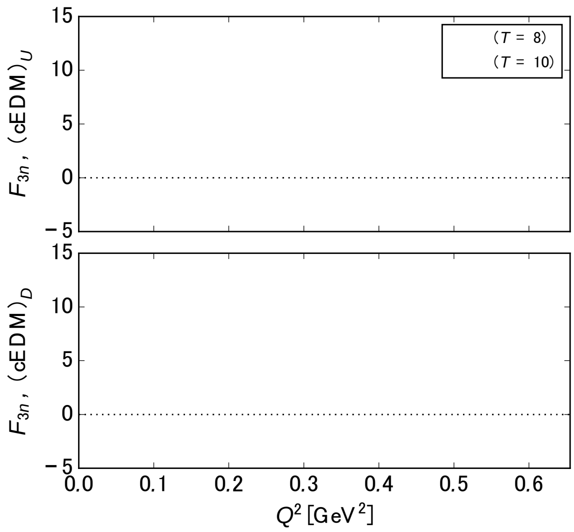


Figure 2: Result of the F3 form factor for the cEDM-induced nucleon EDM on 24 cube lattice.

Alternatively we have measured the energy shift in an uniform electric background with cEDM operator insertion. This energy shift method is free from the above spurious mixing problem, so that we can explicitly test the consistency of our methodology. As shown in Fig. 3, two results between the new F3 form factor formula and the energy shift method are consistent with each other. This is one of our main results in this project.

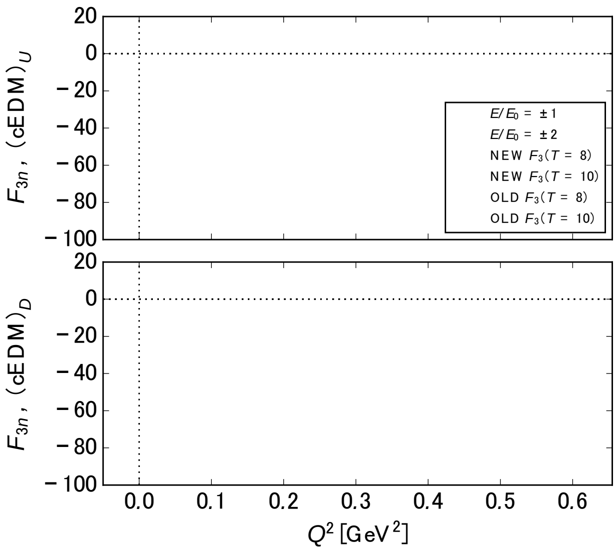


Figure 3: Comparison of the neutron EDM computed with the conventional formula and new formula to the one from the energy shift. For details, see our publications [1, 2].

4． Conclusion

We have demonstrated that the previous EDM lattice computations which use the quark-current form factor receive a contribution from the spurious mixing effect by both theoretically and numerically computations of the CP-odd form factor and the energy shift using the CP violating cEDM operator. It is also found that its contribution to the theta EDM is sub-dominant, and after correction the resulting theta EDM may be compatible to zero with larger error. Thus it becomes more difficult to constrain the QCD theta parameter from the first principle calculations and EDM experiments. Our findings would give a big impact on the (lattice) QCD as well as particle phenomenology and experiments.

5． Schedule and prospect for the future

From our findings, the importance and urgency of first-principles lattice calculation should be emphasized. However, our results on a lattice are obtained without the operator renormalization, and far from physical point, so that we require various improvements. In the next FY, we plan to advance the previous calculations. First we will calculate the theta EDM and cEDM from both quark connected and disconnected contributions on a physical point quark mass. We also study the operator mixing and the renormalization of the CP violating operators by using non-perturbative RI-MOM scheme. For those measurement, we will accumulate high statistics O(10^4). From the above computations with high statistics, we also aim to improve the current determination of the theta EDM.

Our preliminary results of the theta EDM and cEDM will be presented in coming Japan physical society meeting on March, 2017. [Hiroshi Ohki, "核子(chromo)EDM 演算子の格子 QCD 計算", Osaka University, 19 March, 2017]

Usage Report for Fiscal Year 2016

**Fiscal Year 2016 List of Publications Resulting from the Use of the supercomputer**

## [Publication]

[1] M. Abramczyk, S. Aoki, T. Blum, T. Izubuchi, H. Ohki, S. Syritsyn, “On Lattice Calculation of Electric Dipole Moments and Form Factors of the Nucleon”, arXiv:1701.07792[hep-lat], submitted to the journal of Physical Review D.

## [Proceedings, etc.]

[2] T. Izubuchi, M. Abramczyk, T. Blum, H. Ohki, S. Syritsyn, “Calculation of Nucleon Electric Dipole Moment Induced by Quark Chromo-Electric Dipole Moments”, arXiv:1702.00052 [hep-lat], PoS LATTICE2016 (2016) 398.

## [Oral presentation at an international symposium]

[3] Sergey Syritsyn, “Lattice Calculation of Neutron and Proton EDMs”, KITP Conference: Symmetry Tests in Nuclei and Atoms, kavli Institute for Theoreteical Physics, University of California, Santa Barbara, September 22, 2016.

## [Others (Press release, Science lecture for the public)]

[4] Hiroshi Ohki, talk “物質優勢宇宙の謎解明のための核子構造精密計算”, 2016 年度理研シンポジウム『スーパーコンピュータ HOKUSAI と Shoubu、研究開発の最前線』, June 8, 2016.

[5] Hiroshi Ohki, Sergey Syritsyn, poster presentation “Nucleon EDM from Chromo EDM using Domain-Wall Fermion”, The 34th International Symposium on Lattice Field Theory (Lattice 2016), 26 July, 2016.