Usage Report for Fiscal Year 2017

**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. High precision nuclear physics is a vital part of searches for new physics that can manifest itself in violation(s) of fundamental symmetries. In particular, observation of permanent electric dipole moments (EDMs) of nucleons and nuclei would be direct evidence for violation of CP symmetry. Connecting the quark- and hadron-level effective interactions is a task for lattice QCD. It will also directly impact key measurements in the RHIC-Spin program and a future electron-ion collider (eRHIC), thus it is very important and timely calculation for RIKEN's experimental program at BNL.

Using lattice QCD to calculate the structure of nucleons from first principles is one of the most important theoretic counterparts to these experimental efforts. Our precision calculations of hadron structure at the physical pion mass will for the first time enable predictions with broad physics impact. Approximately most of resources requested in our proposal have been used for computing electric dipole moments (EDMs) of protons and neutrons induced by effective quark-gluon interactions violating fundamental CP symmetry. Violation of this symmetry is required for baryogenesis, otherwise there would be no nuclear matter in the Universe. However, there is no presently known source of such violation at a required level, which is a strong promise for a discovery. The strong motivation for searches of CP violation is reflected in the Long range plan in its recommendation for a targeted program on fundamental symmetries, and it specifically emphasizes fundamental symmetry violations as the key question in understanding the origin of matter. Searches for permanent electric dipole moments of nucleons and nuclei are the most sensitive experiments that can detect the required CP violation. 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 and theta-term.

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

The EDM is the forward limit of the P-,T-odd electric dipole form factor (EDFF) $F_3(Q^2)$

$$< N(p^{'})|\bar{q}\gamma^{\mu}q|N(p) \geq \bar{u}\left[F_1(Q^2)\gamma^{\mu} + F_2(Q^2)\frac{i\sigma^{\mu\nu}q_{\nu}}{2M} - F_3(Q^2)\frac{\gamma_5\sigma^{\mu\nu}q_{\nu}}{2M}\right]u,$$

where $q = p' - p$ and $F_{1,2}$ are the regular parity-even Dirac and Pauli form factors.

The EDM $d_n = \frac{e}{2M}F_3(0)$ leads to P- and T- odd coupling of the nucleon spin and electromagnetic field with energy $\Delta E = -d_N\,(S \cdot E)$. Such an interaction can be induced by effective CP-violating interactions at the quark-gluon level represented by effective operators of increasing dimension and suppressed by the corresponding scale(s) of BSM physics. The only renormalizable (dimension=4) CP interaction is the QCD $\bar{\theta}$-term that may be present in the SM,

$$\mathcal{L} = \bar{\theta}\frac{1}{64\pi^2}\varepsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma},$$

where $\bar{\theta}$ is the anomaly-invariant combination of the QCD θ angle and quark mass phases. The most sensitive probes for the CP-violating interactions are electric dipole moment searches in hadronic, atomic, and molecular systems. In this proposal, we have measured nucleon 3- and 4-ponit correlation functions to determine the effect of quark chromo-electric dipole moments (cEDMs),

$$\mathcal{L}_{cEDM} = -i\sum_{q=u,d,s}\frac{\delta}{2}\bar{q}G^a_{\mu\nu}\varepsilon^{\mu\nu}\gamma_5 q,$$

and θ-induced nucleon EDMs, which can be detected from the P-, T-odd electric dipole form factor ($F_3$). Fortunately, our technique to compute nucleon form factors can be naturally extended to compute the CP-violating form factor $F_3$. 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).

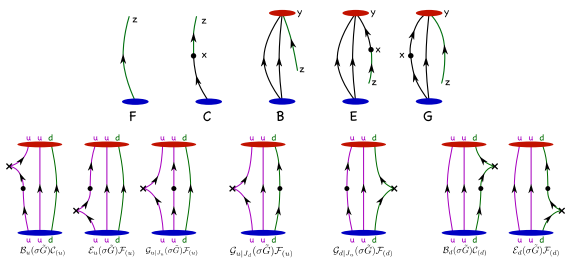


Figure 1: (Top) Sequential propagators required for computing four-point correlators and (Bottom) Fully-connected four-point correlation function for computing cEDM-induced nucleon electric dipole moment. Points indicate quark vector current and crosses show quark chromo-EDM operator insertions.

In addition, 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 (CG) algorithm. In these computations, it is vital to reduce the computational 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 employed these techniques in GW-MPC at HOKUSAI, and they actually successfully reduce the computational cost.

## 3. Results

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 $F_3$ form factor. So far, most of lattice effort has been concentrated on nucleon EDMs induced by the θ-term, using either the background electric field method or $Q^2 \to 0$ extrapolation of the $F_3(Q^2)$ form factors, with results 1-2 orders of magnitude larger compared to QCD sum rules and chiral perturbation theory estimates. We have 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. Thus form factor calculations in previous literature suffered from unphysical contributions due to parity rotation of $e^{i\alpha_5\gamma_5}$ nucleon spinors not accounted for correctly, which lead to mixing of nucleon electric and magnetic moments and spurious contribution to the EDM. See Fig. 2 for the comparison of two EDM results ($F_3$) between our correct formula and the

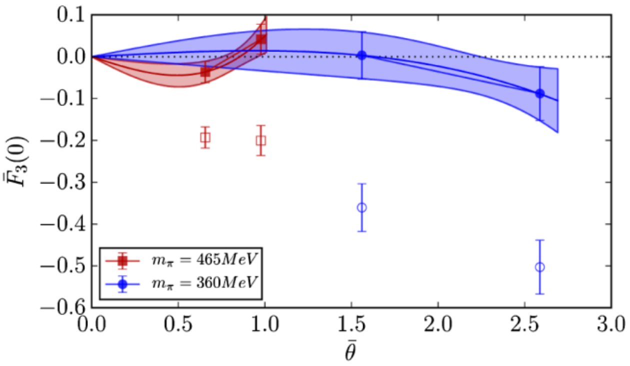


Figure 2: Corrected (filled symbols) and original (open symbols) values for the neutron form factors $F_3$ at a nonzero imaginary θ angle from Ref. [2].

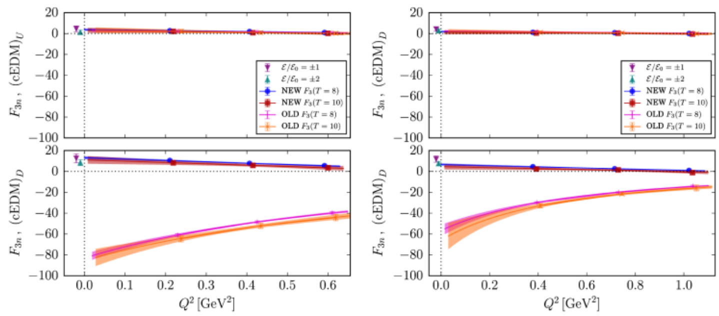


Figure 2: Comparison of the neutron $F_3$ computed with the conventional ("OLD") and the "NEW" formula to the neutron EDM computed from the energy shift. Results are shown for the $24^3 \times 64$ (left) and $16^3 \times 32$ (right) lattices.

conventional formula.

Alternatively, we have measured the spin-dependent 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. We perform calculations with identical statistics in both methods and can directly compare the central values and the uncertainties of the results. In order to check how the spurious mixing affects the results, in Fig. 3 we also plot the values of form factors computed with the old formula used. We find that the EDM results agree if the new formula for extraction of the $F_3$ is used. The agreement between the new form-factor extraction formula and the energy-shift method is one of the main results of our paper (Ref. [1]), which was selected as one of editor's suggestions in the journal of Physical Review.

## 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.

## 5. Schedule and prospect for the future

As we pointed out, after appropriate corrections, all these previous results are compatible with zero within statistical error, and the true θ-induced nucleon EDM will be much harder to calculate. While we are testing a recent technique of the truncation of space-time region of the topological charge source to reduce the fluctuation of the EDM on lattice, it is not yet sufficient to find a statistically significant nucleon EDM signal at the physical pion mass. Also, this procedure introduces a systematic error that needs a careful assessment. To control this systematic error and to further improve the statistical signal, in 2018, we plan to propose a different strategy: generating a QCD gauge ensemble with an RHMC algorithm using a QCD action with a dynamical θ term. In this method, the θ angle is analytically continued to an imaginary value θ to keep the Boltzmann weight positive definite. By adjusting the value θ, we can control the induced net topological charge. We plan to perform imaginary θ simulations including ones at the physical pion mass and with QCD chiral lattice quarks. From the computations with high statistics, we aim to improve the current determination of the theta EDM.

[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”, Phys. Rev. D 96, no. 1, 014501(2017 ).

[2] F. K. Guo, R. Horsley, U.-G. Meißner, Y. Nakamura, H. Perlt, P. E. L. Rakow, G. Schierholz, A. Schiller, and J. M. Zanotti, Phys. Rev. Lett. 115, 062001 (2015).

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**Fiscal Year 2017 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", Phys. Rev. D 96, no. 1, 014501 (2017 ), selected one of Editor's Suggestions.

**[Proceedings, etc.]**

[2] M. Abramczyk, Sinya Aoki, Tom Blum, Taku Izubuchi, Hiroshi Ohki, and Sergey Syritsyn, "Computing nucleon EDM on a lattice" , proceedings of the 35th International Symposium on Lattice Field Theory, June 18-24, 2017, Granada, Spain.

**[Oral presentation at an international symposium]**

[3] **(invited talk)** Hiroshi Ohki, "Nucleon Electric Dipole Moments from Lattice QCD", talk at 10th International Workshop on Fundamental Physics Using Atoms (FPUA), January 8, 2018.

[4] **(invited talk)** Hiroshi Ohki, "Nucleon Electric dipole moments from lattice QCD", talk at The 7th KIAS Workshop on Particle Physics and Cosmopology and The 2nd KEK-NCTS-KIAS Workshop on Particle Physics Phenomenology, November 10, 2017.

[5] **(invited talk)** 大木洋 "格子 QCD による核子構造の研究と標準模型を越えた物理", 日本物理学会企画講演, September 14, 2017.

[6] Sergey Syritsyn, "Computing nucleon EDM on a lattice", talk at The 35th International Symposium on Lattice Field Theory (Lattice 2017). June 21, 2017.

[7] Michael Abramczyk, Tom Blum, 出渕卓, 大木洋, Sergey Syritsyn, "核子(chromo)EDM 演算子の格子 QCD 計算" ,一般講演, 日本物理学会第 72 回年次大会, March 19, 2017.

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

[8] Sergey Syritsyn, "CP symmetry and baryon number violation in nucleons on a lattice", theory seminar, University of Kentucky, Nov 20, 2017.