Usage Report for Fiscal Year 2019

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. In particular, observation of permanent electric dipole moments (EDMs) of nucleons (nEDMs) and nuclei would be direct evidence for violation of CP symmetry. 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.
Using lattice QCD to calculate the structure of nucleons from first principles is one of the most important theoretic counterparts to these experimental efforts. Most of lattice effort has been concentrated on nEDM induced by the θ-term with results 1-2 orders of magnitude larger compared to QCD sum rules and chiral perturbation theory estimates.

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) $F_3(Q^2)$

$$< N(p')|\bar{q}\gamma^{\mu}q|N(p) \geq \bar{u}\left[F_1(Q^2)\gamma^{\mu} + F_2(Q^2)\frac{i\sigma^{\mu\nu}q_{\nu}}{2M} - F_3(Q^2)\frac{\gamma_5\sigma^{\mu\nu}q_{\nu}}{2M}\right]u \quad (1)$$

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. 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 θ¯-term. The most sensitive probes for the CP-violating interactions are electric dipole moment searches in hadronic, atomic, and molecular systems. In the previous period, we have found that there is a problem in the previous lattice calculations in which the conventional F_3 form factor receives a spurious mixing due to the additional CP-violating effect that

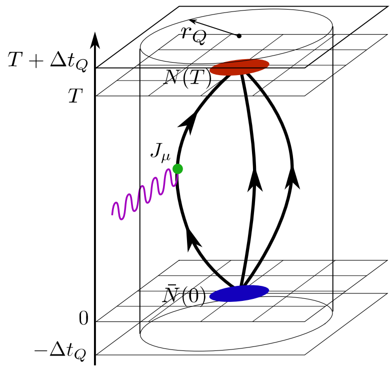

Figure 1: Constrained sampling of the topological charge density Eq. (2) for reducing the statistical noise in the CP-odd three-point correlation functions, as well as the CP-odd two-point correlation functions.

need to be subtracted, and derived a new formula that subtracts the spurious mixing effect of the $F_3(Q^2)$. It is also suggested that the truncation of the topological charge sum at large distances may reduce fluctuations of the nEDM on a lattice while still capturing most of the signal [1]. The global topological charge is zero on average in the current simulation because our QCD action is CP-even. However, its correlation with the nucleon charge distribution has large noise due to its density fluctuations not suppressed with distance. It is interesting to test a time- and space- truncation of the topological charge. We restrict the topological charge estimator separately in time and space to a cylindrical volume V_Q (Figure 1),

$$\tilde{Q}(\Delta t_Q, r_Q) = \frac{1}{16\pi^2} \sum_{x \in V_Q} \mathrm{Tr}\big[\hat{G}_{\mu\nu}\tilde{\hat{G}}_{\mu\nu}\big]_x ,$$

$$(\vec{x}, t) \in V_Q : \begin{cases} |\vec{x} - \vec{x}_0| \le r_Q , \\ t_0 - \Delta t_Q < t < t_0 + t_{\mathrm{sep}} + \Delta t_Q , \end{cases} \quad (2)$$

where t_0 is the location of the nucleon source and $t_0 + t_{\mathrm{sep}}$ is the location of the nucleon sink. The *CP*-odd correlation functions are computed entirely inside the region defined in the above equation where *CP* violation is present. We have performed initial calculations using physical-quark ensembles with m_π=139MeV. However, we observe no signal for the neutron EDFFs, and the results are consistent with zero with the statistical uncertainty.

To control the systematic error and to further improve the statistical signal, we have proposed a different strategy: the matrix element of the topological charge density operator with background electric field. In this method we calculate the three-point function of the nucleon in the presence of the background electric field,

$$\Delta C_{3pt}(T,\tau) = \langle N(T)\bar{Q}(\tau)\bar{N}(0)\rangle_{\vec{\mathcal{E}}}, \quad (0 < \tau < T),$$

where N is a nucleon operator, and $\bar{Q}$ is the topological charge density operator. Performing the spectral decomposition of the above three-point function,

$$\begin{aligned}\Delta C_{3pt}(\tau,\vec{\mathcal{E}}) =& \langle N(T)\bar{Q}(\tau)\bar{N}(0)\rangle_{\vec{\mathcal{E}}} \\ &\sim \sum_{n,m} e^{-E_n(T-\tau)-E_m\tau}\langle 0|N|n\rangle\langle n|\bar{Q}|m\rangle\langle m|\bar{N}|0\rangle_{\vec{\mathcal{E}}} \\ =& |Z_N|^2 e^{-m_N T}\langle N|\bar{Q}|N\rangle_{\vec{\mathcal{E}}} + (\text{excited states}),\end{aligned}$$

we obtain the matrix element of the nucleon states with electric background. Note that this matrix element can be non-zero if there exist the background electric fields $\vec{\mathcal{E}}$. This quantity has the following spin vector structure,

$$\langle N|\bar{Q}|N\rangle_{\vec{\mathcal{E}}} = \delta E = d_n \times \vec{\Sigma}\cdot\vec{\mathcal{E}}, \quad (3)$$

where δE is the energy shift which should be given in terms of the EDM coefficient d_n with electric field. Using this formula we can directly calculate the EDM from the matrix element of the topological charge density itself.

3. Result

We have computed the nucleon correlation function with background electric fields in the current period of the GW-MPC at HOKUSAI. We use gauge ensembles of 16^3 x 32 and 24^3 x 64 lattices with unphysical heavy pion mass ~ 340 MeV. To reduce the gauge noise of the topological charge density operator we use the gradient flow method to smear the gluonic operator. We take the ratio of the three-point and two-point functions which corresponds to the energy shift,

$$\frac{\Delta C_{3pt}(T,\tau)}{C_{2pt}(T)} \to \delta E \quad (T \to \infty) . \quad (4)$$

EDFF $F_3(0)$ can be extracted by dividing the magnitude of the electric field,

$$|F_{3n}(0)| = \frac{2m_N \delta E}{|\vec{\mathcal{E}}|} .$$

We plot the results of the spin components of the ratio in the left panel of Figure 2. Taking the difference between spin up (or positive $\vec{\mathcal{E}}$) and spin down (or negative $\vec{\mathcal{E}}$) contributions of the ratios is important to improve the signal as shown in the right panel of Figure 2. Figure 3 shows the gradient flow time dependence of the matrix elements for each sink-source time separation *T*. As expected, increasing the flow time, we obtain better signals.

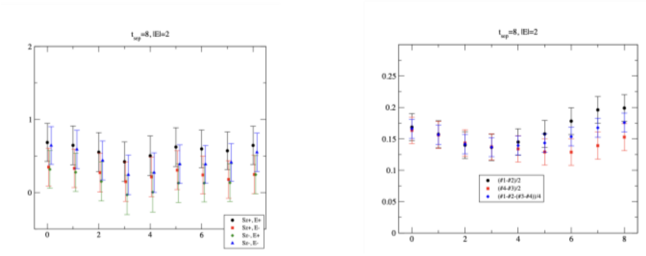

Figure 2: (Left) Spin components of the ratio in Eq.(4). The horizontal axis shows the position of the topological charge density (τ). We use the sink and source separation time T=8. (Right) The result on average over spin and electric field.

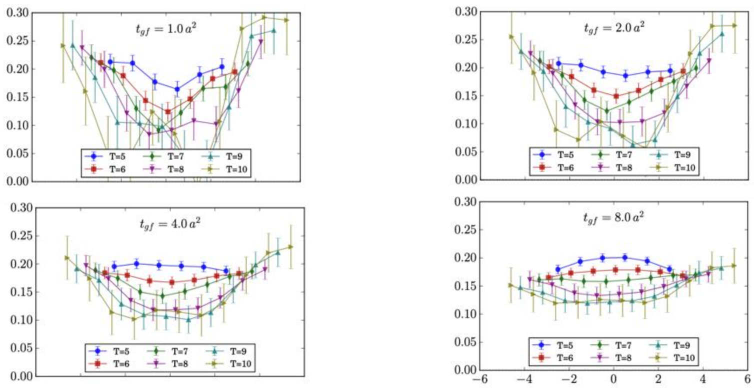

Figure 3: The gradient flow time dependence of the matrix element.

4. Conclusion

We have studied nucleon EDM operators induced by QCD θ-term. In this project we have proposed a new method to calculate the EDFF in zero-momentum limit $F_3(0)$: the matrix element of the topological charge density operator in the presence of the background electric field. We have tested this method using a QCD gauge ensemble with heavier pion masses. Our results are consistent with the result of $F_3(0)$ from the form factor methods.

5. Schedule and prospect for the future

From our findings, the importance and urgency of first-principles lattice calculation of θ_{QCD}-induced EDM at the physical point will be challenging due to the statistical noise of the topological charge. In the case of the form factor method, direct calculations at the physical point may be at the limit of the current computing capabilities since our preliminary result which has indicated that the expected signal-to-noise ratio ~ 0.2 at physical point. To control this systematic error and to further improve the statistical signal, we have proposed a new method using the matrix element with background electric fields: Our preliminary results has demonstrated that we can achieve statistically-significant signal for θ_{QCD}-induced nucleon EDM. These are our preliminary results obtained in a series of our projects. We will continue to compute the θ-induced nucleon EDM on 24^3 x 64 lattice at physical pion masses. Combing these results, we plan to publish papers in near future.

Reference

[1] J. Dragos, T. Luu, A. Shindler, J. de Vries and A. Yousif, "Confirming the Existence of the strong CP problem in Lattice QCD with the Gradient Flow", arXiv:1902.03254[hep-lat].

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Fiscal Year 2019 List of Publications Resulting from the Use of the supercomputer

[Conference Proceedings]

[1] S. Syritsyn, I. Taku, and H. Ohki, "Calculation of Nucleon Electric Dipole Moments induced by Quark Chromo-Electric Dipole Moments and the QCD theta-term", Pos Lattice 2018, 121 (2019)

[Oral presentation]

[1] (Invited talk) H. Ohki, "Computing Nucleon Electric Dipole Moments in Lattice QCD", Frontiers in Lattice QCD and related topics, Yukawa institute for Theoretical Physics, Kyoto University, April 26, 2019.

[2] (Plenary talk) H. Ohki, "Computing Nucleon Electric Dipole Moments from Lattice QCD", The 37^{th} International Symposium on Lattice Field Theory, Wohan, China, June 20, 2019.

[3] H. Ohki, "Calculation of Electric Dipole Moments of the Nucleon", 2019 Lattice X Intensity Frontier Workshop, Brookhaven National Laboratory, USA, September 23, 2019.