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Tensor Network scheme for lattice gauge theories

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Lattice QCD is expected to be an ideal tool to understand the nonperturbative dynamics of strong interactions from first principles. Both the algorithmic development and the increase of the performance of the supercomputer over past 40 years allow us to make simulations with the physical up, down and strange quark masses. We are now able to predict physical quantities associated with single hadrons with high precision. However, there exist the notorious problems inherent in the Monte Carlo approach that the lattice QCD calculations have relied on: (i) sign problem, (ii) simulation with a complex action, and (iii) computational cost to simulate fermionic systems. These are essential defects of the Monte Carlo approach in the lattice QCD simulations. In other words, fundamental solution to these problems cannot be expected as far as we play with the Monte Carlo approach.

Recently we have successfully applied the Grassmann Tensor Renormalization Group (GTRG) algorithm, which is one of the Tensor Network (TN) scheme, to the analysis on the phase structure of one-flavor lattice Schwinger model (2D QED) [Ref. 1]. The results show that the algorithm is free from the sign problem and the computational cost is comparable to the bosonic case thanks to the direct manipulation of the Grassmann variables. This was the first successful application of the TN scheme to a Euclidean lattice gauge theory including fermions. In Ref. 2 we have performed further analysis on the phase structure of one-flavor lattice Schwinger model by adding the so-called θ term. Despite of the complex action we have succeeded in reproducing the phase structure predicted by analytical calculations. This provides us an evidence that the GTRG algorithm has ability to treat complex actions. In Refs. 1 and 2 we have shown that the GTRG algorithm solves all the three problems (i), (ii) and (iii) listed above by taking the Schwinger model as a testing ground.

It is highly encouraging that the effectiveness of the algorithm has been proved for the Schwinger model, which is the simplest gauge theory including fermions. Once we develop an effective algorithm for 4D lattice QCD, we could expect revolutionary progress on research of the dynamics of light quarks, the strong CP problem and the finite density QCD.

References:

8. Y. Shimizu and Y. Kuramashi, *Phys. Rev.,* **D90**, 014508 (2014).
2. Y. Shimizu and Y. Kuramashi, *Phys. Rev.,* **D90**, 074503 (2014).