1 Title of research

"Theoretical and numerical study of QCD phase – What do high energy nuclear experiments tell us ?"

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3 Period of research

Aug/2019 - March/2021

4 Main location of collaboration implementation

RCNP, Osaka University

5 Publication list including any kinds of papers, talks and so on

Papers:

1. M. Wakayama, Seung-il Nam and A. Hosaka
   "The use of the canonical approach in effective models of QCD", e-Print: 2003.13556 [hep-ph], submitted to Phys.Rev. D
2. M. Wakayama, V. G. Bornyakov, D.L.Boyda, V.A.Goy, H.Iida, A. V. Molochkov, A. Nakamura and V. I. Zakharov,
   "Lee-Yang zeros in lattice QCD for searching phase transition points", Phys. Lett. B793, (2019) 227
3. V.G. Bornyakov, D. Boyda, V.A. Goy, A. Molochkov, A. Nakamura,
   "Canonical partition functions in lattice QCD at finite density and temperature", PoS(LATTICE2019)271
4. D. Boyda V.G. Bornyakov, V.A.Goy, A. Molochkov and A. Nakamura,
   "Extracting High-Density QCD Properties from Heavy Ion-Collisions at J-PARC Energy Regions", Proceedings of 13th International Conference on Nucleus-Nucleus Collisions, accepted for the publication on Sept.18, 2019.

Talks and seminars:

1. S.i. Nam,
   "QCD phase diagram via the canonical method in the PNJL model with complex quark chemical potential", 2020 Korea Physical Society meeting on Apr. 2020 (delayed due to COVID-19)
2. D. Boyda,
   "Analysis of RHIC experiment data with Canonical Approach based on LQCD data", HaPhy-CENuM joint workshop at Pusan, 05.09.2019 - 08.09.2019
3. D. Boyda,
   "Canonical Approach: Analysis of RHIC data with LQCD", at HaRP workshop "Hadrons and dense matter from QCD", 19.11.18 - 26.11.18

4. M. Wakayama,
   "Search of QCD phase transitions at finite density with the canonical approach" Heavy Ion Meeting 2019-10, APCTP, Oct. 2019.

5. M. Wakayama,
   "The canonical approach in the NJL and PNJL models toward an understanding of QCD at finite density", Different approaches to the hadron and nuclear physics from the high density and temperature perspectives, Inha University, Oct. 2019.

6. M. Wakayama, S. Nam, A. Hosaka,
   "Study of QCD phase diagram from the PNJL model with the canonical method" The Physical Society of Japan 75th Spring Meeting, Nagoya University, Mar. 2020.

7. M. Wakayama,
   "The canonical approach in the PNJL models toward an understanding of QCD at finite density", Sun Moon University, Jan. 2020.

6 Description of the outputs

The project is intended to reveal the phase structure of QCD by making use of numerical analysis of the lattice QCD **and** theoretical models. Although the lattice QCD simulation is the first principle calculation, but there are the limication because of the finite size, finite spacing and finite quark mass. It is based on the Eucledian formulation and has less powerful for dynamical reactions.

In addition, the lattice QCD simulations at finite baryon density suffer from the 'sign problem'. We have beaten the sign problem by the canonical approach.

In Paper 1, N-JL (Nambu-Jona-Lasinio)model and the Polyakov model at finite temperature and density are formulated in the framework of the canonical approach.

In Paper 2, Lee-Yang zeros behavior at finite temperature and density are studied for studying the QCD phase structure by avoiding the sign problem. The number densities,$\langle n \rangle$, are calculated at the pure imaginary chemical potential $i\mu_I$, where no sign problem occurs. Then, the canonical partition functions, $Z_C(n, T, V)$, up to some maximal values of n are estimated through fitting theoretically motivated functions to $\langle n \rangle$, which are used to compute the Lee-Yang zeros. We study the temperature dependence of the distributions of the Lee-Yang zeros around the pseudo-critical temperature

In Paper 3, it is demonstrated that the sign problem is overcome by our new cannonical approach, where the RHIC energy scan data are compared with lattice QCD results.

In Paper 4, we compare higher moments of baryon numbers measured at the RHIC heavy ion collision experiments with results by the lattice QCD canonical calculations. The energy range covers from $\sqrt{s}_{NN}$ =19.6 and 200 GeV,

In this project, we visited quite often to other institutes as
S. Nam, A. Molochkov, V. Goy and N. Gerasimenyuk visited RCNP, Osaka.
D. Boyda, A. Hosaka, M. Wakayama and A. Nakamura visited Pukyong National Univ., Pusan
A. Hosaka visited FEFU, Vladivostok. It was very valuable to promote the project.
These travels were possible because of the budget from RCNP, Pukyong National University and FEFU.

So far we have developed

- Lattice QCD code for the finite baryon density system
- Lee-Yang zero codes to detect the phase transition, which is tested for the NJL model.

On-going projects

- N. Gerasimenyuk, A. Korneev
  "Lee-Yang zeros for determining the QCD phase transition point"
- V. Goy, A. Hosaka and A. Nakamura, "Hadrons at finite baryon density"
- A. Molochkov, A. Hosaka and V. Goy, "Hadrons at finite box"
- S-i.Nam, "QCD phase structures vs. effective models with complex quark chemical potential",
  "LQCD inputs for effective models",
  "EoS for neutron star".