Subnuclear System Research Division
Quantum Hadron Physics Laboratory

1. Abstract

Atomic nuclei are made of protons and neutrons bound by the exchange of pion and other mesons. Also, protons and neutrons are made of quarks bound by the exchange of gluons. These strong interactions are governed by the non-Abelian gauge theory called the quantum chromodynamics (QCD). On the basis of theoretical and numerical analyses of QCD, we study the interactions between the nucleons, properties of the dense quark matter realized at the center of neutron stars, and properties of the hot quark-gluon plasma realized in the early Universe. Strong correlations common in QCD and cold atoms are also studied theoretically to unravel the universal features of the strongly interacting many-body systems. Developing perturbative and non-perturbative techniques in quantum field theory and string theory are of great importance not only to solve gauge theories such as QED and QCD, but also to find the theories beyond the standard model of elementary particles. Various theoretical approaches along this line have been attempted.

2. Major Research Subjects

(1) Perturbative and non-perturbative methods in quantum field theories
(2) Quantum computing
(3) Lattice gauge theory
(4) QCD under extreme conditions
(5) Nuclear and atomic many-body problems

3. Summary of Research Activity

(1) Perturbative and non-perturbative methods in quantum field theories

(1-1) Theory of the anomalous magnetic moment of the electron

The anomalous magnetic moment of the electron ae measured in a Penning trap occupies a unique position among high precision measurements of physical constants in the sense that it can be compared directly with the theoretical calculation based on the renormalized quantum electrodynamics (QED) to high orders of perturbation expansion in the fine structure constant α, with an effective parameter α/π. Both numerical and analytic evaluations of ae up to $(\alpha/\pi)^4$ were firmly established. The coefficient of $(\alpha/\pi)^5$ has been obtained recently by an extensive numerical integration. The contributions of hadronic and weak interactions have also been estimated. The sum of all these terms leads to a_e (theory) = 1 159 652 181.606 (11)(12)(229) $\times 10^{-12}$, where the first two uncertainties are from the tenth-order QED term and the hadronic term, respectively. The third and largest uncertainty comes from the current best value of the fine-structure constant derived from the cesium recoil measurement: α^{-1} (Cs) = 137.035 999 046 (27). The discrepancy between a_e (theory) and a_e (experiment) is 2.4σ. Assuming that the standard model is valid so that a_e (theory) = a_e (experiment) holds, we obtained $\alpha^{-1}(a_e)$ = 137.035 999 1496 (13)(14)(330), which is nearly as accurate as α^{-1} (Cs). The uncertainties are from the tenth-order QED term, hadronic term, and the best measurement of a_e, in this order.

(1-2) Transport theory of chiral fermions under external gravity and fluid field

We formulated the kinetic theory of chiral matter in external gravitational fields, based on quantum field theory. The resulting kinetic theory reveals that the Riemann curvature induces non-dissipative transport phenomena of chiral fermions. In particular, we found that the spin-gravity coupling results in the antiparallel flow of the charge current and energy current of fermions, which is never explained in the classical picture. These novel framework and phenomena takes place not only in cosmological systems involving neutrinos but also in chiral matter affected by background fluid, such as quark-gluon plasma, graphene and Dirac/Weyl semimetals. We demonstrated that a temperature gradient and fluid vorticity induce a pressure correction and charge and energy flow in Dirac/Weyl semimetals.

(1-3) Spin transport of massive fermion

We derived the spin kinetic theory under external electromagnetic and gravitational fields. We derived the global equilibrium conditions from the kinetic equations and find that the finite Riemann curvature or an external electromagnetic field is necessary to determine the spin-thermal vorticity coupling. Solving the equation of motion of axial vector part of the Wigner transformed fermion propagator, we evaluated the Pauli-Lubanski vector, which expresses the spin polarization of massive fermions, at the local equilibrium and out of equilibrium. This formula is potentially important of the Λ polarization puzzle found in heavy-ion collisions, which cannot be understood in the calculations based on global equilibrium assumption.

(1-4) Chiral vortical effect in condensed matter systems

We revisited the chiral vortical effect in condensed matter physics, by using the semiclassical wave-packet theory. In high-energy physics, the chiral vortical current is conventionally defined as the Noether current. Such a definition is however improper in the context of condensed matter systems since there potentially exists the contributions of the magnetization current. Indeed we showed that the chiral vortical current is compensated by the magnetization current. Hence the chiral vortical effect cannot be observed in pseudo-relativistic condensed matter systems, such as Dirac/Weyl semimetals. Instead, we demonstrated that the chiral vortical effect is an observable in several nonrelativistic matter, and suggested possible table-top experimental setups.

(1-5) Conformal field theories and time-developments in higher dimensions

In quantum field theories, symmetry plays an essential and exceptional role. Focusing on some proper symmetry and delving into its meaning have been proven to be one of the most fruitful strategies. We try to extend the result obtained in two-dimensional conformal field theory using the formalism developed in a study of sine-square deformation of Euclidean conformal field theory to higher dimensional conformal field theory with both Euclidean and Lorentzian metric. Here the time developments of the system are chosen to honor the conformal symmetry of the system, yet they are classified into three distinct categories, each corresponds the cases found in the study of two-dimensional conformal field theory.

(2) Quantum computing

(2-1) Hybrid quantum annealing via molecular dynamics

A novel quantum-classical hybrid scheme was proposed to efficiently solve large-scale combinatorial optimization problems. The key concept is to introduce a Hamiltonian dynamics of the classical flux variables associated with the quantum spins of the transverse-field Ising model. Molecular dynamics of the classical fluxes can be used as a powerful preconditioner to sort out the frozen and ambivalent spins for quantum annealers. It was demonstrated that the performance and accuracy of our smooth hybridization are better in comparison to the standard classical algorithms (the tabu search and the simulated annealing) by employing the MAX-CUT and Ising spin-glass problems.

(3) Lattice gauge theory

(3-1) Dibaryon with highest charm number near unitarity from lattice QCD

A pair of triply charmed baryons, $\Omega_{ccc}\Omega_{ccc}$, is studied as an ideal dibaryon system by (2+1)-flavor lattice QCD with nearly physical light-quark masses and the relativistic heavy quark action with the physical charm quark mass. The spatial baryon-baryon correlation is related to their scattering parameters on the basis of the HAL QCD method. The $\Omega_{ccc}\Omega_{ccc}$ in the $1^{\rm S}_0$ channel taking into account the Coulomb repulsion with the charge form factor of Ω_{ccc} leads to the scattering length $a_0^{\rm C} \simeq -19$ fm and the effective range $r_{\rm eff}^{C} \simeq 0.45$ fm. The ratio $r_{\rm eff}^{C}/a_0^{\rm C} \simeq -0.024$, whose magnitude is considerably smaller than that of the dineutron (−0.149), indicates that $\Omega_{ccc}\Omega_{ccc}$ is located in the unitary regime.

(3-2) Emergence of the ρ resonance from the HAL QCD potential in lattice QCD

We investigate the $I = 1$ $\pi\pi$ interaction using the HAL QCD method in lattice QCD. We employ the (2+1)-flavor gauge configurations at $m_\pi \approx 411$ MeV, in which the ρ meson appears as a resonance state. We find that all-to-all propagators necessary in this calculation can be obtained with reasonable precision by a combination of three techniques, the one-end trick, the sequential propagator, and the covariant approximation averaging (CAA). The non-local $I = 1$ $\pi\pi$ potential is determined at the next-to-next-to-leading order (N2LO) of the derivative expansion for the first time, and the resonance parameters of the ρ meson are extracted. The obtained ρ meson mass is found to be consistent with the value in the literature. This opens up new possibilities for the study of resonances in lattice QCD.

(3-3) Stress tensor around static quark-anti-quark from Yang-Mills gradient flow

The spatial distribution of the stress tensor around the quark-anti-quark pair in SU(3) lattice gauge theory was studied. The YangMills gradient flow plays a crucial role to make the stress tensor well-defined and derivable from the numerical simulations on the lattice. The resultant stress tensor with a decomposition into local principal axes shows, for the first time, the detailed structure of the flux tube along the longitudinal and transverse directions in a gauge invariant manner. The linear confining behavior of the potential at long distances is derived directly from the integral of the local stress tensor.

(4) QCD under extreme conditions

(4-1) Finite density QCD based on complex Langevin method

The complex Langevin method (CLM) is one of a promising approach to overcome the sign problem. The central idea of this approach is that the stochastic quantization does not require the probabilistic interpretation of the Boltzmann weight e^{-S} even when the action takes complex values. Although the equivalence between CLM and the familiar path integral quantization is quite nontrivial, it is pointed out that the probability distribution of the drift term can judge the correctness of the CLM. This enable us to perform lattice simulation of QCD based on CLM in the finite density region in a self-contained manner. We discussed the applicability of the CLM with four-flavor staggered fermions on a $8^3 \times 16$ lattice with quark mass $m = 0.01$. In particular, we focus on the behavior of the eigenvalue distribution of the fermion mass matrix which is closely related to the appearance of the singular drift problem.

(4-2) Non-equilibrium quantum transport of chiral fluids from kinetic theory

We introduced the quantum-field-theory (QFT) derivation of chiral kinetic theory (CKT) from the Wigner-function approach, which manifests side jumps and non-scalar distribution functions associated with Lorentz covariance and incorporates both background fields and collisions. The formalism is utilized to investigate second-order responses of chiral fluids near local equilibrium. Such nonequilibrium anomalous transport is dissipative and affected by interactions. Contributions from both quantum corrections in anomalous hydrodynamic equations (EOM) of motion and those from the CKT and Wigner functions (WF) are considered in a relaxation-time approximation (RTA). Anomalous charged Hall currents engendered by background electric fields and temperature/chemical-potential gradients are obtained. Furthermore, chiral magnetic/vortical effects (CME/CVE) receive viscous corrections as non-equilibrium modifications stemming from the interplay between side jumps, magnetic-moment coupling, and chiral anomaly.

(4-3) Hadron-quark crossover in cold and hot neutron stars

We presented a much improved equation of state for neutron star matter, QHC19, with a smooth crossover from the hadronic regime at lower densities to the quark regime at higher densities. We now use the Togashi *et al*. equation of state, a generalization of the Akmal-Pandharipande-Ravenhall equation of state of uniform nuclear matter, in the entire hadronic regime; the Togashi equation of state consistently describes nonuniform as well as uniform matter, and matter at beta equilibrium without the need for an interpolation between pure neutron and symmetric nuclear matter. We describe the quark matter regime at higher densities with the Nambu-JonaLasinio model, now identifying tight constraints on the phenomenological universal vector repulsion between quarks and the pairing interaction between quarks arising from the requirements of thermodynamic stability and causal propagation of sound. The resultant neutron star properties agree very well with the inferences of the LIGO/Virgo collaboration, from GW170817, of the pressure versus baryon density, neutron star radii, and tidal deformabilities. The maximum neutron star mass allowed by QHC19 is 2.35 MS, consistent with all neutron star mass determinations.

(4-4) Gluonic energy and momentum distribution at finite temperature

We studied the energy-momentum distribution of the gluons around a static quark at finite temperature on the basis of the effective field theory (EFT) of thermal QCD. Spatial correlations between the Polyakov loop and the energy-momentum tensor were calculated up to the next-to-leading order in EFT. The results were compared with the recent quenched lattice QCD calculation obtained by using the gradient flow formalism. The EFT results and the lattice QCD data agree quite well without any fitting parameters at high temperature above deconfinement. On the other hand, there is a substantial difference near the critical temperature especially in the distribution of the energy density, which indicates some non-perturbative effect.

(5) Nuclear and atomic many-body problems

(5-1) Density functional theory for nuclear structure

The atomic nuclei are composed of protons and neutrons interacting via the nuclear and Coulomb interactions. The density functional theory (DFT) is widely used to calculate the ground-state properties. Nevertheless, because of the lack of knowledge of nuclear interaction in medium (effective interaction), the effective interaction is fitted to experimental data, and it has been attained to develop a high-accuracy one. As the first step, the effective interaction of the charge symmetry breaking term, a part of the nuclear interaction, is proposed.

(5-2) Fundamental problems of density functional theory

The density functional theory (DFT) is one of the powerful methods to calculate ground-state properties of the quantum many-body problems, including atomic nuclei, atoms, molecules, and solids. The accuracy of the DFT depends on the energy density functional (EDF), which contains information on the interaction. We develop a method to calculate EDF for electronic systems purely microscopically using the functional renormalization group. In this method, energy density for so many various densities can be calculated, and eventually, DFT calculation can be performed without fitting energy density to some functional forms. We also develop the relativistic DFT in which the finite-light-speed correction to the Coulomb interaction is also considered to calculate the ground-state properties of super-heavy elements.

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List of Publications & Presentations

Publications

[Original Papers]

T. Naito, G. Colò, H. Liang, X. Roca-Maza, and H. Sagawa, "Toward ab initio charge symmetry breaking in nuclear energy density functionals," Phys. Rev. C **105**, L021304 (2022).

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H. Sagawa, S. Yoshida, T. Naito, T. Uesaka, J. Zenihiro, J. Tanaka, and T. Suzuki, "Isovector density and isospin impurity in ^{40}Ca," Phys. Lett. B **829**, 137072 (2022).

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[Review Article]

内藤智也, 萩野浩一, 小林良彦, 「アイソスピンの符号の慣習をめぐって」, 日本物理学会誌 **77**, 99 (2022).

Presentations

[Domestic Conferences/Workshops]

内藤智也 (招待講演), 「原子核構造で探る中性子星」～中性子星の観測と理論～研究活性化ワークショップ 2021, 埼玉県和光市 (理化学研究所), 2021 年 8 月 10 日.

内藤智也 (招待講演), 「ミュオン波動関数計算コードの開発」, RCNP 研究会 「ミューオン X 線 γ 線分光—非破壊分析, 化学, 原子核物理への新展開・ミューオン原子核捕獲反応による原子核関連研究の可能性」, 大阪府茨木市 (大阪大学 核物理研究センター), 2022 年 3 月 25 日.

T. Naito, "Isospin symmetry breaking in ground-state properties," 85th DFT Meeting, 北海道札幌市 (北海道大学大学院理学研究院物理部門), 2022 年 1 月 25 日.

板垣直之, 内藤智也, 平田雄一, 「^{11}B のクラスター構造とその応用」, 日本物理学会 第 77 回年次大会, オンライン, 2022 年 3 月 15 日.

[Seminar]

内藤智也, 「Ab initio エネルギー密度汎関数に向けて」, 酒見グループセミナー (東京大学大学院理学系研究科附属原子核科学研究センター), オンライン, 2021 年 7 月 16 日.

Award

A. Hirayama, Student Presentation Award of the Physical Society of Japan, 2021 Autumn meeting.