Subnuclear System Research Division
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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 $a_e(\text{theory}) = 1\,159\,652\,181.606\,(11)(12)(229) \times 10^{-12}$, 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: $\alpha^{-1}(\text{Cs}) = 137.035\,999\,046\,(27)$. 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 $\alpha^{-1}(\text{Cs})$. 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) Lorentzian conformal field theories through sine-square deformation
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 reexamined two-dimensional Lorentzian conformal field theory using the formalism previously developed in a study of sine-square deformation of Euclidean conformal field theory. We

construct three types of Virasoro algebra. One of them reproduces the result by Luscher and Mack, while another type exhibits the divergence in the central charge term. The other leads the continuous spectrum and contains no closed time-like curve in the system.

(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) Most charming dibaryon near unitarity

The interaction between Ω_{ccc}–Ω_{ccc} in the S-wave and spin-0 channel was studied from the (2 + 1)-flavor lattice QCD with nearly physical light-quark masses and the relativistic heavy quark action with the physical charm quark mass. The time-dependent HAL QCD method was employed to extract the $\Omega_{ccc}\Omega_{ccc}$ potential from the lattice QCD data of two-baryon spatial correlation, and the scattering observables were calculated. The potential was found to be attractive at mid-range and weakly repulsive at short-range. Taking into account the Coulomb repulsion with the charge form factor of Ω_{ccc} as well, the scattering length $a_0^{\rm C} \sim= 19$ fm and the effective range $r_{\rm eff}^{\rm C} \sim= 0.45$ fm were obtained. The ratio $r_{\rm eff}^{\rm C}/a_0^{\rm C} \sim= -0.024$, whose magnitude is considerably smaller than that of the dineutron (−0.149), indicates that $\Omega_{ccc}\Omega_{ccc}$ is located in the unitary region.

(3-2) d^*(2380) dibaryon from lattice QCD

The $\Delta\Delta$ dibaryon resonance $d^*(2380)$ with $(J^\pi, I) = (3^+, 0)$ was studied from the 3-flavor lattice QCD with heavy pion masses (m_π = 0.68, 0.84, 1.02 GeV). The central $\Delta\Delta$ potential in $^7S_3$ channel obtained by HAL QCD method shows a strong short-range attraction, so that a quasi-bound state corresponding to d*(2380) is formed with the binding energy 25–40 MeV below the $\Delta\Delta$ threshold for the heavy pion masses. The tensor part of the transition potential from $\Delta\Delta$ to NN was also extracted. Although the obtained transition potential is strong at short distances, the decay width of $d^*(2380)$ to NN in the D-wave was found to be kinematically suppressed.

(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. In contrast, the nucleons have finite charge distributions, while this is not considered in DFT calculation. Because it is indispensable to treat the Coulomb interaction more accurately to achieve high-accuracy nuclear effective interaction, we consider such finite-size effects to nuclear DFT, and we reveal that such effects give a non-negligible contribution to nuclear binding energies. In nuclear structure calculation, both non-relativistic and relativistic schemes of DFT are used, while the connection between them, especially in terms of the effective interaction, is not understood well. To reveal it, we also develop the efficient non-relativistic reduction of the many-body systems.

(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.

(5-3) One-dimensional Bose and Fermi gases with contact interactions

We investigate local quantum field theories for one-dimensional (1D) Bose and Fermi gases with contact interactions, which are closely connected with each other by Girardeau's Bose-Fermi mapping. While the Lagrangian for bosons includes only a two-body interaction, a marginally relevant three-body interaction term is found to be necessary for fermions. Because of this three-body coupling, the three-body contact characterizing a local triad correlation appears in the energy relation for fermions, which is one of the sum rules for a momentum distribution. In addition, we apply in both systems the operator product expansion to derive large-energy and momentum asymptotics of a dynamic structure factor and a single-particle spectral density. These behaviors are universal in the sense that they hold for any 1D scattering length at any temperature. The asymptotics for the Tonks-Girardeau gas, which is a Bose gas with a hardcore repulsion, as well as the Bose-Fermi correspondence in the presence of three-body attractions are also discussed.

(5-4) Mesoscopic spin transport between strongly interacting Fermi gases

We investigate a mesoscopic spin current for strongly interacting Fermi gases through a quantum point contact. Under the situation where spin polarizations in left and right reservoirs are same in magnitude but opposite in sign, we calculate the contribution of quasiparticles to the current by means of the linear response theory and many-body T-matrix approximation. For a small spin-bias regime, the current in the vicinity of the superfluid transition temperature is strongly suppressed due to the formation of pseudogaps. For a large spin-bias regime where the gases become highly polarized, on the other hand, the current is affected by the enhancement of a minority density of states due to Fermi polarons. We also discuss the broadening of a quasiparticle peak associated with an attractive polaron at a large momentum, which is relevant to the enhancement

(5-5) Optical spin conductivity in ultracold quantum gases

Measurement of frequency-resolved spin transport is a subject of much interest in condensed matter physics. Here we show that the optical spin conductivity, which is a small AC response of a spin current, can be measured with existing methods in ultracold atom experiments. We point out that once interatomic interactions are turned on, the optical spin conductivity becomes nontrivial even in clean ultracold atomic gases and thereby can be a probe of generic quantum states of matter. This is a sharp contrast to the optical mass conductivity which becomes trivial in typical cold-atom systems without disorder and lattice potential. For systems with arbitrary spin degrees of freedom, we construct a general formalism of the optical spin conductivity and derive the f-sum rule. To demonstrate the availability of the optical spin conductivity, our formalism is applied to a spin-1/2 Fermi superfluid and a spin-1 Bose-Einstein condensate. It turns out that both superfluids show nontrivial responses that cannot be captured with the Drude conductivity. The application of our proposed method to generic ultracold atomic gases with spin degrees of freedom is feasible.

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List of Publications & Presentations

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[Original Papers]

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