Theoretical Research Division
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1. Abstract

Nuclei are finite many-particle systems composed of protons and neutrons. They are self-bound in femto-scale (10^{-15}m) by the strong interaction (nuclear force) whose study was pioneered by Hideki Yukawa. Uncommon properties of the nuclear force (repulsive core, spin-isospin dependence, tensor force, etc.) prevent complete microscopic studies of nuclear structure. There exist number of unsolved problems even at present. In addition, radioactive beam facilities reveal novel aspects of unstable nuclei. We are tackling these old problems and new issues in theoretical nuclear physics, developing new models and pursuing large-scale calculations of quantum many-body systems. We are also strongly involved in research on other quantum many-body systems, to resolve mysteries in the quantum physics

2. Major Research Subjects

(1) Nuclear structure and quantum reaction theories
(2) First-principle calculations with the density functional theory for many Fermion systems
(3) Computational nuclear physics

3. Summary of Research Activity

(1) Regularized multi-reference energy density functional calculations with new Skyrme parametrizations
Symmetry restoration and configuration mixing by use of the generator coordinate method based on energy density functionals, which are referred to as a multi-reference approach, have become widely used techniques in low-energy nuclear structure. Recently, it has been pointed out that these techniques are ill defined for standard Skyrme energy density functionals and the results can exhibit discontinuities or even divergences in the energy. Then, a regularization procedure has been proposed to remove such spurious contributions to the energy. This regularization procedure, however, imposes the use of integer powers of the density for the density-dependent terms in energy density functionals.

Therefore, we have constructed new Skyrme parametrizations that have integer powers of density dependence for multi-reference energy density functional calculations with the regularization procedure. A significant improvement of the reproduction of the experimental binding energies and charge radii for a wide range of singly-magic nuclei is observed. With our new Skyrme parametrizations, we perform regularized multi-reference calculations for a systematic study of spectroscopic properties for Mg isotopes. A good description for the B(E2:$0^+ \rightarrow 2^+$) values is obtained. However, the first 2^+ energies are overestimated for all the isotopes. One of the reasons of this overestimation can be due to neglecting time-odd terms when calculating the Hamiltonian kernel.

(2) Mean-field calculation including proton-neutron mixing
We have been developing a new code for Hartree-Fock calculation based on the nuclear density functional theory (DFT) including an arbitrary mixing between protons and neutrons. This is a first step towards the DFT calculation including proton-neutron (p-n) pairing. To treat the p-n pairing within the DFT framework, one needs to generalize the quasiparticle states as mixtures of protons and neutrons. In connection with this extension, the density functionals also should be extended to those with mixing between protons and neutrons. As a first step towards the p-n pairing, we have performed HF calculations (without pairing correlation) including the p-n mixing. Isospin of the system is controlled by a linear constraint on isospin (called the isocranking term). We have carried out test calculations for A=14 and 48 isobars. For A = 14 isobars, we have calculated the energies of the well-known isobaric analogue states (IAS's) with T = 1 in ^{14}C, ^{14}N, and ^{14}O. We have found that the IAS with Tz = 0 is described well as a state consisting of single-particle states with the p-n mixing. For A=48, we have seen that we can obtain states with different values of T and T_z by adjusting the isocranking frequency. We have also implemented in our code an improved method for optimization with constraints known as "the augmented Lagrange method", which is widely used in quantum chemistry. This can be utilized, e.g., for the calculation of the excitation energies for high-isospin states in a single nucleus, from which we can evaluate the nuclear symmetry energy.

(3) Microscopic study on the shape transition in chromium isotopes around N=40
We have investigated the nature of the quadrupole collectivity in the low-lying states of neutron-rich chromium isotopes, $^{58-66}$Cr, by solving the five-dimensional (5D) collective Schroedinger equation. We have determined the vibrational and rotational inertial functions and the collective potential in the 5D quadrupole collective Hamiltonian microscopically derived with the constrained Hartree-Fock-Bogoliubov plus local quasiparticle RPA method, which we have proposed recently. The results of calculation are in good agreement with the available experimental data and suggest that the prolate deformation remarkably develops in the chromium isotopes around N = 40. However, the results also indicate that they still possess transitional characters and the large-amplitude shape fluctuations dominate in their low-lying states. We have also

discussed similarities and dissimilarities of the quadrupole shape transition near ^{64}Cr with N = 40 and that near ^{32}Mg with N = 20.

(4) Relativistic Slater approximation for Coulomb exchange effects
The relativistic local density approximation (LDA) for the Coulomb exchange functional in nuclear systems is presented. This approximation is composed of the well-known Slater approximation in the non-relativistic scheme and the corrections due to the relativistic effects. The validity of the relativistic LDA in finite nuclei calculations is examined by comparing with the results of the relativistic Hartree-Fock-Bogoliubov theory, where the non-local Coulomb exchange term is treated exactly. The relative deviations of the Coulomb exchange energies in the relativistic LDA calculations are in general less than 5% for semi-magic Ca, Ni, Zr, Sn, and Pb isotopes from proton drip line to neutron drip line. It is also worthwhile to emphasize that the relativistic corrections to LDA are found to play substantial roles in improving the agreement with the exact results by 3~5%.

(5) Feasibility of the finite amplitude method in covariant density functional theory
The finite amplitude method in covariant density functional theory (CDFT) has been developed, including both the so-called iterative finite amplitude method (i-FAM) and matrix finite amplitude method (m-FAM). A benchmark test has been performed with the conventional random-phase approximation (RPA) code for the isoscalar giant monopole resonance (ISGMR) in ^{208}Pb. The feasibility of the FAMs for CDFT has been proved. Furthermore, the calculated results in the present study show that the existence of Dirac sea does not introduce additional difficulties for the present FAMs in the relativistic scheme, and the effects of Dirac sea can be included implicitly and automatically in the coordinate-space representation. In addition, the rearrangement terms can be calculated implicitly without extra computational costs in both m-FAM and i-FAM.

(6) Subroutine “kurotama” in PHITS
The total reaction cross section (σ_R) of nuclei is one of the most fundamental observables that characterize the geometrical size of nuclei. It is also important in numerical simulations in the fields of accelerator technology, particle therapy, and space radiation, as well as in many other fields that are related to particle and heavy-ion transport phenomena, because, in the codes for such simulations, one needs to estimate reaction rates systematically by using σ_R for various combinations of colliding particles over a wide energy range. The Particle and Heavy Ion Transport code System (PHITS) is one of the most powerful codes designed for these simulations. In order to systematically estimate σ_R for nucleus-nucleus reactions, we apply the black-sphere (BS)-cross-section formula. Due to its suitability for systematics, the BS-cross-section formula (“kurotama” in Japanese) with its extension to the energies of less than 100 MeV/nucleon is now officially incorporated into PHITS version 2.52.

(7) Black-sphere approximation of deformed nuclei
Following to the success of the black-sphere approximation of spherical nuclei for systematic analyses of the total reaction cross sections (σ_R), we extend this framework to reactions involving deformed nuclei. Instead of starting with the Fraunhofer diffraction from the circular disk for spherical nuclei, we adopt the Fraunhofer diffraction from spheroid for deformed nuclei as the starting point. The study is now in progress.

(8) Low-energy electric dipole strength and dipole polarizability
We have shown the low-lying electric dipole strength in neutron-rich isotopes is correlated with the neutron skin thickness. However, this correlation is robust only for specific nuclei. In contrast, the dipole polarizability has a universal correlation with the neutron skin thickness, especially when we subtract the contribution from the giant dipole resonance. These studies have been carried out with the canonical-basis time-dependent Hartree-Fock-Bogoliubov theory which we proposed before.

(9) Extension of the phonon damping model to non-zero angular momentum
The phonon-damping model (PDM) is extended to include the effect of angular momentum at finite temperature. The formalism is based on the description of the non-collective (single-particle) rotation of spherical systems. This implies that the total angular momentum J can be aligned along the *z*-axis, and therefore it is completely determined by its projection M on this axis alone. The numerical calculations were carried out for two spherical nuclei ^{88}Mo and ^{106}Sn. The analysis of the numerical results shows that the GDR width increases with M at a given value of T for T<3 MeV. At higher T, the GDR width approaches a saturation at M > 60 for ^{88}Mo and M > 80 for ^{106}Sn. However, the region of M > 60 goes beyond the maximum value of M up to which the specific shear viscosity η/s has values not smaller than the KSS lower-bound conjecture for this quantity. This maximum value of M is found to be equal to 46 and 55 for ^{88}Mo and ^{106}Sn, respectively, if the value $\eta(T=0) = 0.6\times10^{-23}$ MeV s fm^{-3} for the shear viscosity at T = 0 is used. A check by using the KSS lower-bound conjecture for the specific shear viscosity and the same $\eta(0) = 0.6\times10^{-23}$ MeV s fm^{-3} also shows that the experimental data

for the GDR line shape in ^{88}Mo at the the initial temperature T ~ 4 MeV and J = 44 of the compound nucleus leads to a violation of the KSS conjecture. This calls for the need of reanalyzing the recent experimental data for the GDR in ^{88}Mo at these large values of temperature and angular momentum.

(10) Description of the width of giant dipole resonance in ^{201}Tl measured at low temperature
We calculated the width and strength function of the giant dipole resonance (GDR) in ^{201}Tl at finite temperature within the framework of the quasiparticle representation of the PDM. Thermal pairing is taken into account by using the exact treatment of pairing within the canonical ensemble. This treatment allows us to calculate the exact equivalences to the pairing gaps for protons and neutrons in a nucleus neighboring a proton closed-shell one. Because of thermal fluctuations owing to the finiteness of the system, which are inherent in the canonical ensemble (CE), the exact CE thermal pairing gaps do not collapse at the critical temperature T_c of the superfluid-normal phase transition as in the case of infinite systems, but decrease monotonically as T increases and remain finite up to T as high as 5 MeV. The good agreement between the PDM predictions including thermal pairing and the recent experimental data is a clear demonstration of the manifestation of the effect owing to thermal pairing, which plays a vital role in reducing the GDR width at low T in open-shell nuclei. Under the influence of thermal pairing, the GDR width in ^{201}Tl becomes as low as around 3.7 MeV at T = 0.8 MeV, and the width $\Gamma(0)$ of the GDR built on the ground state (T = 0) can be as small as 3 MeV, which is smaller than the GDR width in ^{208}Pb (4 MeV) at T = 0. The results obtained in the present work as well as the previous predictions for the GDR width in ^{120}Sn, where the important role of neutron thermal pairing has been shown to reduce the GDR width at T < 1 MeV, confirm that, in order to have an adequate description of GDR damping at low T, a microscopic model needs to take into account thermal pairing at least up to T ~ 1.5 MeV.

(11) Specific shear viscosity in hot rotating systems of paired fermions
The Green-Kubo relation is used to calculate the specific shear viscosity from the retarded Green's function that describes the propagation of quasiparticles within the quasiparticle mean field of a classically rotating system of nucleons that interact via a monopole interaction. Thermal fluctuations are included within the improved version of the finite-temperature BCS (called the FTBCS1), whereas coupling to monopole pair vibrations is taken into account within the self-consistent quasiparticle random-phase approximation (SCQRPA). The general feature of the specific viscosity η of this system can be summarized as follows. At a given temperature T, η increases with the angular momentum M, that is a rotating system of paired fermions is more viscous. In medium and heavy systems, η decreases with increasing T at T > 2 MeV and this feature is not affected much by angular momentum. However, in light systems, it increases with T at the values of angular momentum M close to M_{max}, which is defined as the limiting angular momentum for each system. At T < 2 MeV, local minima and/or local maximum appear because of the significant change in the curvature of the temperature dependence of the thermal pairing gap. Thermal fluctuations and coupling to the quasiparticle pair vibrations within the SCQRPA significantly increases η for small N systems with N < 10, whereas η decreases for large N > 10 systems. All the results of η obtained within the schematic model as well as realistic nuclei are always larger than the universal lower bound of the specific shear viscosity up to T=5 MeV.