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) Energy-density-functional calculation including proton-neutron mixing
We have performed mean-field calculation based on the Skryme energy density functional (EDF) including arbitrary mixing between protons and neutrons. Isobaric analogue states (IASs) were calculated using the isocraking method. Through the calculations for IASs in A=14 and 40-56 isobars, we demonstrated that our model is capable of qualitative description of the excited IASs. The T=1 IAS in the A=14 exhibits asymmetry between the relative energy of the T_z=1 state and that of the T_z=-1 states measured from the T_z=0 state, which may be related to charge asymmetry and independence of the NN interaction. To investigate this point, we also started a systematic calculation of the T = 1 triplets in the A=10-58 region. We also performed a benchmark calculation by comparing the results obtained with our 3D EDF solver and those obtained with an axial EDF solver.

(2) Finite amplitude method in covariant density functional theory
The first step of this project is to prove the feasibility of combining the covariant density functional theory (DFT) and the finite amplitude method (FAM). Different from the non-relativistic counterpart, the effects of negative-energy spectra, i.e. the Dirac sea, must be taken into account in the relativistic random phase approximation (RPA). It is non-trivial for applying iterative algorithms to a system with infinite positive- and negative-energy eigenstates. Furthermore, the rearrangement terms because of the density-dependent nucleon-nucleon couplings in the covariant framework are usually much more complicated than those in the non-relativistic framework, and these sophisticated rearrangement terms cause heavy computations. On the other hand, the covariant density functionals hold the Lorentz invariance as well as the isospin symmetry (except for the Coulomb part). This leads to the unification of the time-even and time-odd parts in the corresponding functionals, and also makes the extension of FAM to the charge-exchange channels relatively easy. In the recent studies, we have demonstrated the feasibility of the FAM for the covariant DFT. In addition, it is found that the effects of the Dirac sea can be automatically taken into account in the coordinate-space representation and the rearrangement terms due to the density-dependent couplings can be implicitly calculated without extra computational costs.

(3) Reaction cross section and electric dipole excitations in ^{22}C
The ^{22}C nucleus is currently of significant interest, since its halo structure with extremely weak binding was suggested by experiments. We have performed the Glauber analysis on this nucleus based on the density distribution calculated with the Skyrme energy density functional. To reproduce the large experimental cross section, we need to readjust the t_0 parameter of the Skyrme functional. It is desirable to have new experimental data on the reaction cross section with higher bombarding energy which should be available in current RIBF. In addition, we calculated the electric dipole modes of excitation with the RPA using the finite amplitude method (FAM). The computer code was previously developed, however, we need a very large space to treat such a weakly bound nucleus. The calculation with the 3D coordinate space of radius of 100 fm has been carried out, thanks to available high performance computing systems. It suggests that a very strong low-energy peak does not consist only of weakly bound s-wave neutrons, but also of sizable amount of d-wave components.

(4) Systematic study on pygmy dipole strength in heavy isotopes
We have systematically studied the low-lying electric dipole mode, so-called the pygmy dipole resonances (PDR) in neutron-rich isotopes in a region of nuclei with N<90, using the linear response calculation with the Skyrme energy density functional. The strong neutron shell effects have been found, which suggest several magic numbers for the enhancement of

the PDR strength. We also investigate the deformation effect on the PDR. The K=0 component of E1 strength become dominant in Sr and Zr isotopes with prolate deformation. However, it is not associated with the orientation dependence of the neutron skin thickness. In fact, it is opposite, namely, the neutron skin thickness along the symmetry axis si smaller than that in the perpendicular directions. The close examination of the PDR strength in nuclei beyond N=82 indicates different characters for the peaks at E > 5 MeV and those at E < 5 MeV. The low-energy dipole states appearing at very low energies (E < 5 MeV) indicates no hindrance of the E1 strength from the pure single-particle strength. This suggests that these PDR peaks are completely decoupled from the giant dipole resonance (GDR).

(5) Deformed nuclei in the black-sphere approximation
In order to study the value of the density derivative *L* of the symmetry energy of nearly symmetric nuclear matter, the total reaction cross section, σ_R, of neutron-rich nuclei is one of the most important observables. We focus on the reactions involving the isotopes of Ne and Mg using the black-sphere approximation of nuclei. In this region of nuclei, we have to face the nuclear deformation. We change the black sphere into a spheroid of the same volume in order to take into account nuclear deformation before the discussion of *L* dependence. The values of the deformation parameter, β, are taken from microscopic nuclear structure models. Before drawing conclusion, we have to check the interaction dependence by adopting SkM*, SLy4, KTUY etc. The study is now in progress.

(6) Giant dipole resonance in ^{88}Mo at finite temperature and angular momentum
The line shapes of giant dipole resonance (GDR) in the decay of the compound nucleus 88Mo, which is formed after the fusion-evaporation reaction 48Ti + 40Ca at various excitation energies E* from 58 to 308 MeV, are generated by averaging the GDR strength functions predicted within the phonon damping model (PDM) using the empirical probabilities for temperature and angular momentum. The average strength functions are compared with the PDM strength functions calculated at the mean temperature and mean angular momentum, which are obtained by averaging the values of temperature and angular momentum using the same temperature and angular-momentum probability distributions, respectively. It is seen that these two ways of generating the GDR linear line shape yield very similar results. It is also shown that the GDR width approaches a saturation at angular momentum $J \geq 50\hbar$ at T= 4 MeV and at $J \geq 70\hbar$ at any T.

The evolution of the GDR width and shape at finite temperature T and angular momentum J is described within the the PDM. The PDM description is compared with the established experimental systematics obtained from heavy-ion fusion and inelastic scattering of light particles on heavy target nuclei, as well as with predictions by other theoretical approaches. Extended to include the effect of angular momentum J, its strength functions have been averaged over the probability distributions of T and J for the heavy-ion fusion-evaporation reaction, which forms the compound nucleus ^{88}Mo at high T and J. The results of theoretical predictions are found in excellent agreement with the experimental data. The predictions by PDM and the heavy-ion fusion data are also employed to predict the viscosity of hot medium and heavy nuclei.

(7) Study of pygmy dipole resonance with the exact treatment of the pairing
The strength functions of giant dipole resonance (GDR) in oxygen $^{18-24}$O, calcium $^{50-60}$Ca, and tin $^{120-130}$Sn isotopes are calculated within the phonon damping model under three approximations: without superfluid pairing, including BCS pairing, and exact pairing gaps. The analysis of the numerical results shows that exact pairing decreases the two-neutron separation energy in light nuclei, but increases it in heavy nuclei as compared to that obtained within the BCS theory. In neutron-rich medium and heavy nuclei, exact pairing significantly enhances the strength located at the low-energy tail of the GDR, which is usually associated with the pygmy dipole resonance (PDR). The line shape of the GDR changes significantly with increasing the neutron number within an isotopic chain if the model parameter is kept fixed at the value determined for the stable isotope.

(8) Microscopic analysis of fusion hindrance in heavy systems
We study the reaction mechanism of fusion reactions and analyze origins of fusion hindrance in heavy systems with microscopic time-dependent Hartree-Fock (TDHF) theory. We have developed a method to directly extract nucleus-nucleus potential and energy dissipation from the relative motion of colliding nuclei to nuclear intrinsic excitations in fusion reactions from TDHF trajectories. We show that the Coulomb barrier disappears in potentials obtained in heavy systems and they monotonically increase as relative distance decreases, which are different from those of light, medium-mass systems. Further analysis shows that main origin of fusion hindrance is a dynamical change of extracted potential at short relative distance.

(9) Nuclear β-decay half-lives and r-process matter flow
Nucleosynthesis via rapid neutron capture, i.e., the r-process, is a major mechanism for producing the elements heavier than Fe in Universe. Understanding this process requires knowledge of properties such as masses, β-decay half-lives, and neutron-capture cross sections for a large number of extremely neutron-rich nuclei far from the stability line. In order to

reliably predict the β-decay half-lives of thousands of unknown nuclei relevant to the r-process, the full self-consistency of the quasi-particle RPA (QRPA) approach is essential. Meanwhile, the proton-neutron pairing correlations in both isovector (T = 1) and isoscalar (T = 0) channels must be taken into account properly. In a very recent work, we established a fully self-consistent charge-exchange QRPA with both T = 1 and T = 0 proton-neutron pairing, based on the relativistic Hartree-Fock-Bogoliubov (RHFB) framework. Then, we systematically investigated the β-decay half-lives of neutron-rich even-even nuclei with 20 ≤ Z ≤ 50. It is shown that the available data are well reproduced, where the isospin-dependent T = 0 proton-neutron pairing is one of the most important ingredients. With the calculated β-decay half-lives, a classical r-process calculation has been performed with neutron density n_n = 1022-1024 cm^{-3} and temperature T = 1.5×109 K, and a remarkable speeding up of r-matter flow is predicted. This leads to enhanced r-process abundances of elements with A ≥ 140, an important result for understanding the origin of heavy elements in Universe.

(10) Pseudospin symmetry in nuclear single-particle spectra

In nuclear single-particle spectra, pairs of single-particle states with quantum numbers (n-1, l+2, j=l+3/2) and (n, l, j=l+1/2) are always found to be quasi-degenerate. Arima et al. and Hecht et al. introduced in 1969 the so-called pseudospin symmetry (PSS) to explain this phenomenon. Although it has been already more than 40 years since the suggestion of PSS in atomic nuclei and comprehensive efforts have been made, the origin of PSS is still a puzzle. Recently, we suggested that it is promising to understand PSS and its breaking mechanism in a fully quantitative way by combining the similarity renormalization group technique, supersymmetric (SUSY) quantum mechanics, and perturbation theory. We took the Schrödinger equation as an example, which corresponds to the lowest-order approximation in transforming a Dirac equation into a diagonal form by using the similarity renormalization group. It is shown that while the spin symmetry-conserving term appears in nuclear single-particle Hamiltonian, the PSS-conserving term appears naturally in its SUSY partner Hamiltonian. The eigenstates of these two Hamiltonians are exactly identical except for the so-called intruder states, which have no pseudospin partners. In such a way, the origin of PSS deeply hidden in the original Hamiltonian can be traced in its SUSY partner.

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