Theoretical Research Division
Theoretical Nuclear Physics Laboratory

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) Systematic calculation of *T* = 1 triplets with proton-neutron-mixed energy density functionals

We have performed a systematic calculation for the $T = 1$ isobaric analog states (IASs) based on the Skyrme energy density functionals (EDFs) including protons-neutron (*p-n*) mixing. The IASs are calculated using the isocranking method. First we performed a systematic calculation for the energies of the $T = 1$ triplets in the $A = 10 \sim 66$ region with several Skyrme parameter sets. We used the isoscalar *p-n* mixed Skyrme EDFs, which are invariant under rotation in the isospin space, together with the Coulomb energy functional. The calculated results show a systematic underestimation from the experimental data, which may be related to violation of the charge symmetry and the charge independence of the nucleon-nucleon interaction and may imply that we need to further extend the energy functionals including isospin breaking terms. Recently, we have started a calculation including the isospin breaking interactions.

(2) Three dimensional mesh calculations for covariant density functional theory

The covariant density functional theory has some numerical difficulties, such as variational collapse and the fermion doubling. Because of these problems, the three-dimensional (3D) mesh calculation was impossible for a long time. In order to realize such calculations for the first time, we proposed in a novel and practical method to solve Dirac equations in the 3D coordinate space. The variational collapse is prevented by employing a method based on the variational principle for the inverse of a single-particle Hamiltonian, while for the fermion doubling, we have extended the method of Wilson fermion, which has been widely employed in lattice QCD calculations.

Using ^{16}O as an example, we have confirmed that our strategy provides accurate solutions for self-consistent mean-field calculations without the influence of the negative-energy spectrum and the spurious solutions of a discretized Dirac equation. We have also shown with ^{24}Mg and ^{28}Si that this method is applicable to deformed solutions in the (β, γ) deformation plane. This development enables us, e.g., i) to study any complicated structure of nuclei with a single numerical code, ii) to compare directly the results of the relativistic models to those of 3D mesh calculations with the non-relativistic models, and iii) to provide reliable theoretical predictions with the relativistic models for unknown nuclei allowing symmetry-breaking solutions. It also allows a straightforward extension of the finite amplitude method within the relativistic framework for a study of nuclear excitations in deformed nuclei.

(3) Microscopic description of fusion hindrance in heavy systems

We investigate fusion hindrance in heavy systems, where the fusion probability is strongly hindered compared with that in light- and medium-mass systems, to understand the origin of the fusion hindrance from a microscopic point of view. We employ microscopic time-dependent Hartree-Fock (TDHF) model for the analysis. In TDHF simulations, we reasonably reproduce the extra-push energies estimated from experimental data for heavy systems. Then, we extract nucleus-nucleus potential and energy dissipation by combining TDHF simulations for fusion reactions with Newton equation including a dissipation term. Extracted potentials in heavy systems show monotonic increase as the relative distance of two nuclei decreases and the disappearance of an ordinary barrier structure, which are different from lighter systems. Using these properties, we analyze the origin of the extra-push energy and find that the contribution to extra-push energy from the increase in potential is larger than that from dissipated energy in most systems. We conclude from our analysis that the main origin of the fusion hindrance is dynamical increase in potential.

(4) Hidden pseudo-spin and spin symmetries and their origins in atomic nuclei

Pseudo-spin symmetry (PSS) was introduced to explain the near degeneracy between pairs of nuclear single-particle states with the quantum numbers (n-1, l+2, j=l+3/2) and (n, l, j=l+1/2). We have written a review article [arXiv:1411.6774, *Phys. Rep.* in press], and intended to provide a comprehensive overview on the recent progress of pseudo-spin and spin symmetries in a systematic way. These symmetries were discussed in various systems and potentials: from stable nuclei to exotic nuclei, from non-confining to confining potentials, from local to non-local potentials, from central to tensor potentials, from bound states to resonant states, from nucleon spectra to anti-nucleon spectra, from nucleon spectra to hyperon spectra, from spherical nuclei to deformed nuclei.

Furthermore, three of the open issues in this field were selected and discussed in detail, i.e., the perturbative nature of PSS, the puzzle of intruder states, and the supersymmetric (SUSY) representation of PSS. For the perturbative nature of PSS, we emphasized that whether or not the symmetry breaking behaves perturbatively depends on whether an appropriate symmetry limit is chosen and an appropriate symmetry-breaking term is identified. As long as an appropriate symmetry limit is chosen, the nature of PSS is indeed perturbative. For the puzzle of intruder states, we showed several different features about this puzzle. By doing that a number of "contradicting" results in the literature for the spin (pseudo-spin) partners have been clarified in an explicit way. For the SUSY representation of PSS, we pointed out one of the promising ways for understanding the PSS and its symmetry breaking, by combining the similarity renormalization group, the SUSY quantum mechanics, and the perturbation theory. Meanwhile, how to apply the SUSY technique directly to the Dirac equations, which have non-trivial scalar and vector potentials, remains an interesting and open question.

(5) "Hybrid Kurotama model" for total reaction cross sections

We have developed a new general-purpose-total-reaction-cross-section model/subroutine called ``Hybrid Kurotama". The model has been tested and compared with available data for *p*+He, *p*+nucleus, and nucleus+nucleus total reaction cross sections. The overall agreement has been found better than former published models. This model is therefore very suitable to be used in any deterministic or Monte Carlo particle and heavy ion transport code.

(6) Improved parametrization of the transparency parameter in Kox and Shen models of total reaction cross sections

The total reaction cross section is an essential quantity in particle and heavy-ion transport codes when determining the mean-free path of a transported particle. Many transport codes determine the distance a particle is transported before it collides with the target or is stopped in the target material, with the Monte Carlo (MC) method using semiempirical parametrization models for the total reaction cross sections. In order to improve the well-known Kox and Shen models of total reaction cross sections and allow the models to be used at energies below 30 MeV/nucleon, we have proposed a modified parametrization of the transparency parameter. We have also reported that the Kox and Shen models have a projectile-target asymmetry and should be used so that the lighter nucleus is always treated as the projectile.

(7) Energy and mass number dependence of total reaction cross sections of nuclei

We have systematically analyzed nuclear reaction data that are sensitive to nuclear size, namely, proton-nucleus total reaction cross sections and differential elastic cross sections, using a phenomenological black-sphere approximation of nuclei that we are developing. In this framework, the radius of the black sphere is found to be a useful length scale that simultaneously accounts for the observed proton-nucleus total reaction cross section and first diffraction peak in the proton elastic differential cross section. This framework is expected to be applicable to any kind of projectile that is strongly attenuated in the nucleus. On the basis of a cross-section formula constructed within this framework, we find that a less familiar $A^{1/6}$ dependence plays a crucial role in describing the energy dependence of proton-nucleus total reaction cross sections.

(8) Probing the critical behavior in the evolution of GDR width at very low temperatures in $A \sim 100$ mass region

The influence of giant dipole resonance (GDR) induced quadrupole moment on GDR width at low temperatures is investigated experimentally by measuring the GDR width systematically in the unexplored temperature range T = 0.8-1.5 MeV, for the first time, in $A \sim 100$ mass region. The measured GDR width, using alpha induced fusion reaction, for ^{97}Tc confirms that the GDR width remains constant at the ground state value up to a critical temperature and increases sharply thereafter with the increase in T. The data have been compared with the adiabatic thermal shape fluctuation model (TSFM), phenomenological critical temperature fluctuation model (CTFM) and microscopic phonon damping model (PDM). Interestingly, the CTFM and PDM give the similar results and agree with the data, whereas the TSFM differs significantly even after incorporating the shell effects indicating towards the inclusion of GDR-GQR coupling in the TSFM.

(9) Giant dipole resonance in highly excited nuclei

The evolution of the giant dipole resonance's (GDR) width and shape at finite temperature T and angular momentum J is described within the framework of the phonon damping model (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.

We also explore an approach that includes temperature-dependent shell effects and fluctuations of the pairing field in the thermal shape fluctuation model (TSFM). We apply this approach to study the width of GDR in ^{120}Sn, ^{179}Au and ^{208}Pb. Our results demonstrate that the TSFM that includes pairing fluctuations can explain the recently observed quenching in the

GDR width.

(10) Reentrance phenomenon of superfluid pairing in hot rotating nuclei

When a nucleus rotates (total angular momentum J and/or rotational frequency ω are not zero), the nucleon (proton and neutron) pairs located around the Fermi surface will scatter to the empty levels nearby and lead to the decreasing of pairing correlation. When the J or ω is sufficiently high, i.e., equal to the critical value J_c or ω_c, the scattered nucleons completely block the single-particle levels around the Fermi surface. Consequently, pairing correlation disappears. However, when J is slightly higher than J_c (or $\omega > \omega_c$), the increase of temperature T will relax the particles scattered around the Fermi surface and causes some levels become partially unoccupied, making them available for scattered pairs. As a result, the pairing correlation reappears at some critical value T_1. As T goes higher, e.g., at $T_2 > T_1$, the newly created pairs will be eventually broken down again. This phenomenon is called the pairing reentrance. The recently developed FTBCS1 theory that includes the effect due to quasiparticle-number fluctuations in the pairing field and angular momentum z projection at $T \neq 0$ has predicted the pairing reentrance effect in some realistic nuclei. The shell-model Monte Carlo calculations have suggested that the pairing reentrance effect can be observed in the nuclear level density in a form of a local maximum at low T (or excitation energy E^*) and high J (or ω). Recently, an enhancement of level density of ^{104}Pd at low E^* and high J has been experimentally reported. This work demonstrates that the enhancement observed in the extracted level density of ^{104}Pd is the first evidence of pairing reentrance phenomenon in atomic nuclei.