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Theoretical Nuclear Physics Laboratory
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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) Systematic analysis on pygmy dipole modes with the finite amplitude method

We studied the low-lying electric dipole mode, so-called the pygmy dipole resonances (PDR), with systematic calculation of the electric dipole responses up to mass A=110 region. In light nuetron-rich nuclei, the PDRs emerge when the Fermi level is located in the loosely-bound low-angular-momentum orbital, which suggests their non-collective character. In heavier nuclei, the PDR seems to be more collective to be described by a superposition of particle-hole excitations to the loosely-bound orbitals. We also found that there is a linear correlation between the neutron skin thickness and the PDR transition strength. However, further analysis is needed to judge whether the PDR strength can be used for a measurement of the neutron skin thickness.

(2) Development of the finite amplitude method for superfluid nuclei

We have developed a new theoretical tool to apply the finite amplitude method (FAM) to nuclei with superfluidity. The implementation of the FAM on an existing spherically symmetric Hartree-Fock-Bogoliubov code (HFBRAD) in the coordinate-space representaion has been carried out. This has become a new computer program for the quasi-particle-random-phase approximation (QRPA) which can be used for a variety of modes of excitation in superfluid nuclei. In addition, we expect the method can facilitate the developments of the QRPA codes for deformed nuclei.

(3) Roles of deformation and neuron excess on the giant monopole resonance

Roles of deformation on the giant monopole resonance (GMR), particularly the mixing of the giant quadrupole resonance (GQR) and the effects of the neutron excess in Zr isotopes were investigated by means of the deformed QRPA employing the Skyrme and the local pairing energy-density functionals. In the drip-line nuclei, the neutron excitation is dominant over the proton excitation. We found for an isovector excitation the GMR has a four-peak structure due to the neutron excess as well as the mixing of the $K^{\pi}=0^{+}$ component of the isovector GQR.

(4) Giant dipole resonance in the rare-earth nuclei with shape changes

Photoabsorption cross sections of Nd and Sm isotopes from spherical to deformed even nuclei were systematically investigated by means of the QRPA based on the Hartree-Fock-Bogoliubov ground states using the Skyrme energy density functional. The gradual onset of deformation in the ground states as increasing the neutron number leads to characteristic features of the shape phase transition. The calculations well reproduce the isotopic dependence of broadening and emergence of a double-peak structure in the cross sections without any adjustable parameters.

(5) Application of the canonical-basis TDHFB method to calculation of the photoabsorption cross sections in heavy deformed nuclei

We proposed the Canonical-basis time-dependent Hartree-Fock-Bogoliubov (Cb-TDHFB) method for studies of nuclear dynamics of nuclei with superfluidity. The computer program with the Skyrme functional has been developed and applied it to heavy deformed nuclei for the first time. The linear-response calculation for ^{172}Yb indicates that the method can reproduce the result of the QRPA calculation and significantly saves the computational cost. Roughly speaking, it reduces the computational task by a factor of 1/1,000.

(6) Microscopic description of large-amplitude quadrupole collective dynamics in low-lying states

We studied the large-amplitude collective dynamics in low-lying states using the five-dimensional collective Hamiltonian constructed with the constrained-Hartree-Fock-Bogoliubov (CHFB) + local QRPA method. Various collective deformations associated with the deformed magic numbers appear in the sd-shell region. We analyzed the large-amplitude axial and triaxial quadrupole collective dynamics in low-lying states of 24Mg, 26Mg, 24Ne, and 28Si. We could reproduce well the prolate ground state and gamma vibrational band in 24Mg, oblate ground state and beta vibrational band in 28Si. We also analyzed the neutron and proton quadrupole transition matrix elements in 26Mg, and found an E2 transition where the proton matrix element is strongly suppressed by the large-amplitude collective dynamics in triaxial (gamma) direction. These results indicate the importance of the triaxial degree of freedom in low-lying states.

Neutron-rich Mg isotopes around 32Mg locates in the “island of inversion” where collective deformation develops, and the structure and dynamics in their low-lying states are an important current topic. Using the CHFB + local QRPA method, We successfully reproduced the excitation energies, B(E2)'s of the yrast bands. As neutron number increases, the structure of ground state changes from spherical to prolate shape. Especially in 32Mg, the potential energy surface shows spherical-prolate shape coexistence. Associated with the change of ground states, excited 0+ changes from shape coexistence to beta-vibration of a prolate ground states. We also showed that the potential energy surface becomes soft against the triaxial deformation as neutron number increases, and the energies of the excited 2^+ state (gamma vibration) come down.

We have also applied the method to oblate-prolate shape coexistence phenomena in the low-lying states of proton-rich Se and Kr isotopes. The results of our calculation show that the inclusion of the time-odd components of mean field, which are ignored in the widely-used Inglis-Belyaev cranking formula, increases the inertial masses and yields a better agreement with experimental data. The results of the calculation also show the importance of large-amplitude shape fluctuation in the triaxial shape degree of freedom and rotational motion for the shape mixing dynamics. The calculation for neutron-rich Cr isotopes is under progress.

(7) Extra-push energy in heavy-ion fusion reaction studied with the TDHF simulation
It is known for a long time that the fusion probability is hindered for heavy ions. This is often referred to the extra-push energy, which means that the incident energy much higher than the Coulomb barrier height is necessary for heavy nuclei with $Z_1*Z_2 > 1800$ to fuse. We are investigating whether the microscopic time-dependent Hartree-Fock (TDHF) calculation

quantitatively reproduces the extra-push energy for the fusion reaction, including the criterion for the mass combination of projectile and target. We study these issues in heavy-ion fusion reactions with TDHF theory employing the full Skyrme force and without any geometric symmetry restrictions. We found that for light systems the TDHF fusion threshold, interaction barrier with frozen-density energy density functional (FD-EDF) method and experimental Coulomb barrier have a quite good agreement, which imply extra push is not needed for light systems. However for heavy system, the TDHF fusion threshhold is higher than the interaction barrier with FD-EDF method. One may make a conclusion that an extra push energy above the interaction barrier is needed in order to achieve the fusion for heavy systems. In order to give more confidential answers to those issues on the fusion dynamics, more systematic calculations for heavy systems are now under progress.

(8) Deformed and clustering states in ^{42}Ca

Characteristics of deformed states and alpha cluster correlations are studied using the anti-symmetrized molecular dynamics (AMD) and the generator coordinate method. A ground-state band and a deformed band built on the $J^{\pi}=2^{+}$ state are reproduced. A deformed band built on the $J^{\pi}=3^{+}$ contains significant clustering-structure components, which is consistent with experimental results of ^{38}Ar(^{6}Li, d) reactions. Combinations of particle-hole configurations that protons and neutrons cause those coexistence of various deformed states.

(9) Adiabatic inter-nucleus potentials and sub-barrier fusion

The inter-nucleus potential for the adiabatic nuclear reaction was investigated. A method to derive adiabatic inter-nuclear potentials is proposed using the AMD, and effects of valence neutrons are clarified using the potentials. Valence neutrons of ^{18,22}O gain additional attractive force, which enhance probability of tunneling effects and sub-barrier fusion.

(10) Chemical potential beyond the quasi-particle mean field

The effects of quantal and thermal fluctuations beyond the BCS quasi-particle mean field on the chemical potential are studied within a model, which consists of N particles distributed amongst doubly folded equidistant levels interacting via a simple pairing force. The results obtained at zero and finite temperatures T within several approaches, which include the fluctuations beyond the BCS theory, are compared with the exact results. The chemical potential, defined as the Lagrangian multiplier to preserve the average number of particles, is compared with the corresponding quantity, which includes the effect due to fluctuations of particle and quasi-particle numbers beyond the BCS quasi-particle mean field.

(11) Canonical ensemble treatment of pairing within BCS and quasi-particle random phase approximation

A description of pairing properties in finite systems is proposed within the canonical and microcanonical ensembles. The approach is derived by solving the BCS and self-consistent QRPA with the Lipkin-Nogami particle-number projection at zero temperature. The obtained eigenvalues are embedded into the canonical and microcanonical ensembles. The results obtained are found in quite good agreement with the exact solutions of the doubly-folded equidistant multilevel pairing model as well as the experimental data for ^{56}Fe nucleus. The merit of the present approach resides in its simplicity and its application to a wider range of particle number, where the exact solution is impracticable.

(12) Thermodynamic properties of hot nuclei within the self-consistent quasi-particle random-phase approximation

The thermodynamic properties of hot nuclei are described within the canonical and microcanonical ensemble approaches. These approaches are derived based on the solutions of the BCS and self-consistent quasi-particle random-phase approximation at zero temperature embedded into the canonical and microcanonical ensembles. The obtained results agree well with the recent data extracted from experimental level densities by Oslo group for ^{94}Mo, ^{98}Mo, ^{162}Dy and ^{172}Yb nuclei.

(13) Black-sphere model for total reaction cross sections

In the framework of the contemporary black-sphere model, we examine total reaction cross sections between heavy nuclei, such as ^{56}Fe+^{208}Pb (or ^{238}U) where the Coulomb dissociation may contribute. Along this study, we point out that several semi-empirical parameterizations in simulation codes may contain terms leading to different energy and/or mass-number dependence from the empirical behavior. Further study to pin them down is now in progress.

(14) Transparency parameter for total reaction cross sections

We propose a unified parameterization of the transparency parameter in the well-known Kox and Shen models, which are two of the popular semi-empirical parameterizations for total reaction cross sections in several simulation codes due to their good reproducibility of a variety of available data. This study is aiming at allowing these models to be used at energies below 30 MeV per nucleon, where the parameterization of these models is missing. The transparency parameter is responsible for describing the energy dependence of the cross sections in the models. We also give the recommendation that the models should be used so that the lighter nucleus is always treated as projectile, no matter what the actual case might

be, because these models contain the asymmetry in exchanging the mass number of target and projectile.

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