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 a 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) Correlation between the pygmy dipole strength and neutron skin thickness

We have been studying the low-lying electric dipole mode, so-called the pygmy dipole resonances (PDR) in neutron-rich isotopes, with systematic calculation of the electric dipole responses up to mass A=110 region. In this year, we investigate correlation between the PDR and the neutron skin thickness. The PDR distributions show a remarkable linear correlation with the neutron skin thickness for each isotopic chain with N=28-34 and N>50, with a universal slope of 0.18-0.20 fm^{-1}. On the other hand, the correlation is weak outside of these regions. We also discussed parameter dependence of such correlation and found same conclusion.

(2) Finite amplitude method for evaluation of the RPA matrix

The explicit evaluation of the matrix of random-phase approximation (RPA) is known to be very demanding task in realistic nuclear energy functionals. We have developed a new methodology to do this using the finite amplitude method (FAM). The method was tested with a code we developed last year using an existing spherically symmetric Hartree-Fock-Bogoliubov code (HFBRAD) in the coordinate-space representation. It turns out to be very efficient with a capability to turn an existing HF(B) code into the (Q)RPA code, very easily.

(3) Properties of the giant resonances in spherical and deformed nuclei

Roles of deformation on the giant resonance were systematically investigated by means of the deformed QRPA employing the Skyrme and the local pairing energy-density functionals. Particularly, deformation effects, the mixing of the giant resonances with different multipolarities, and dependence on the effective mass are discussed and clarified.

(4) Studies of nuclear responses in heavy deformed nuclei using the canonical-basis TDHFB method

The canonical-basis TDHFB method is suitable for studies of dynamical properties of nuclei

with superfluidity. The computer program with the Skyrme functional was developed and used for the systematic linear response calculations of heavy deformed nuclei. We have calculated the photoabsorption cross sections in nuclei along the r-process path and have found significant increase of low-energy E1 strength in isotopes with N>82. This may give a great impact on the nucleosynthesis in supernovae explosions.

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

In this study, we have studied large-amplitude quadrupole deformation dynamics using the five-dimensional quadrupole collevtive Hamiltonian. We determine the collective potential and inertial functions with the constrained Hartree-Fock-Bogoliubov plus local quasiparticle random-phase-approximation method. We have applied this method to low-lying states in neutron-rich isotopes around ^{64}Cr, where the recent experimental data suggest the onset of deformation. The calculated results are in good agreement with the available data and indicate that the shape transition from spherical and prolate may occur from ^{60}Cr to ^{64}Cr. With this method, we also have studied ^{110}Mo, whose new excited states have been observed in the experiment at RIKEN. In this region of Mo isotopes, a shape transition from prolate, via gamma-soft (unstable against axially asymmetric deformation), to oblate was predicted theoretically. Our calculation has reproduced the experimental data for ^{110}Mo well and showed that the low-lying states in ^{110}Mo are rather gamma-soft.

(6) Mean-field calculation including proton-neutron mixing

Proton-neutron (p-n) pairing is one of the open problems in nuclear physics and expected to play some role in various phenomena in medium and heavy mass region. In spite of the recent experimental progress, it is still unclear what the fingerprint of the p-n pairing is and how like-particle and p-n correlations interplay in the p-h and p-p channels. The aim of this study is to elucidate the role of p-n pairing on basis of the nuclear energy density functional theory. As a first step toward the calculation based on the density functional theory including p-n pairing, we have developed a numerical code for the Hartree-Fock calculation based on the Skyrme energy density functional which incorporates an arbitrary proton-neutron mixing in the p-h channel. In this calculation, the single-particle states are described as a mixture of protons and neutrons and the energy density functional is generalized to the form with the p-n mixed density. We are now performing test calculations for nuclei around the N=Z line in the light and medium-mass regions.

(7) Extra-push energy in heavy-ion fusion reaction studied with the TDHF simulation

We have studied extra push dynamics in heavy ion fusion reactions. Our purpose is to investigate 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 above which the extra push is needed, and how much the extra push energy is. We study these issues in heavy-ion fusion reactions with TDHF theory employing the full Skyrme energy functional and without any geometric symmetry restrictions. We performed a systematic investigation with a variety of projectile-target combinations and 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 threshold is higher than the interaction barrier with FD-EDF method. This is consistent with empirical law of the necessity of the extra-push energy for heavy systems.

(8) Enhancement of ^{16}O+^{18}O sub-barrier fusion cross sections by distortion of valence neutrons in ^{18}O

Effects of valence neutrons in ^{16}O+^{18}O sub-barrier fusions are investigated in a potential model using adiabatic potentials obtained by a method of anti-symmetrized molecular dynamics (AMD) with a constraint on internuclear distance. We found that the sub-barrier fusion cross sections of ^{16}O+^{18}O are enhanced because of distortion of valence neutrons in ^{18}O.

(9) Separation of a Slater determinant wave function with a neck structure into spatially localized subsystems

A method to separate a Slater determinant wave function with a two-center neck structure into spatially localized subsystems is proposed. An orthonormal set of spatially localized single-particle wave functions is obtained by diagonalizing the coordinate operator for the major axis of a necked system. Using the localized single-particle wave functions, the wave function of each subsystem is defined. Therefore, defined subsystem wave functions are used to obtain density distributions and mass centers of subsystems. The present method is applied to the separation of Margenau-Brink cluster wave functions of alpha + alpha, ^{16}O + ^{16}O, and alpha + ^{16}O into their subsystems, and also to the separation of anti-symmetrized molecular dynamics (AMD) wave functions of ^{10}Be into alpha + ^{6}He subsystems.

(10) Coexistence of various rotational bands and alpha clustering in ^{42}Ca

Coexistence of various low-lying rotational bands in ^{42}Ca have been investigated using the deformed-basis AMD. The parity and angular momentum projections and the generator coordinate method (GCM) obtained low-lying states. Energy variations with constraints on quadrupole deformation parameter and intercluster distance between alpha and ^{38}Ar clusters obtained the GCM basis. The rotational band built on the second 0+ (1.84 MeV) state was reproduced, and coexistence of two more 0+ rotational bands and side bands of them due to triaxial deformation was predicted. Variety of combinations of particle-hole configurations for protons and neutrons develops rich structures in ^{42}Ca.

(11) Ab initio calculation for photoabsorption reaction in 4He in collaboration

There are some discrepancies in the low energy data on the photoabsorption cross section of ^{4}He. In order to resolve this controversy, we calculate the cross section with realistic nuclear forces and explicitly correlated Gaussian functions. Final state interactions and two- and three-body decay channels are taken into account. The cross section is evaluated in two methods: With the complex scaling method and the microscopic R-matrix method. Both methods give virtually the same result. The cross section rises sharply from the 3H+p threshold, reaching a giant resonance peak at 26–27MeV. Our calculation reproduces almost all the data above 30MeV. We stress the importance of ^{3}H+p and ^{3}He+n cluster configurations on the cross section as well as the effect of the one-pion exchange potential on the photonuclear sum rule.

(12) Systematic analysis of total reaction cross sections in unstable nuclei

Exploring nuclei has been making rapid progresses beyond the p-, sd-shell region. Recently, the

total reaction and interaction cross sections, which are closely related to the nuclear size properties, are measured in neutron-rich Ne and Mg region. They exhibit some exotic structures, for example, halos, skins deformations etc. and motivate us to make a systematic analysis of the total reaction cross sections. We employ the Glauber model which is widely used for analyzing high energy nuclear reactions. In order to describe exotic deformations, input densities are generated from the wave functions obtained by the Skyrme-Hartree-Fock Method in a fully three-dimensional coordinate space. The calculated total reaction cross sections of Ne isotopes consistently agree with the very recent measurement and imply importance of deformations for reproducing a large increase of the cross section as increasing a neutron number. Predictions for Mg and Si isotopes are made. A detail analysis is underway and will be reported soon.

(13) Thermal nuclear pairing within the self-consistent quasiparticle RPA
The self-consistent quasiparticle RPA (SCQRPA) is constructed to study the effects of fluctuations on pairing properties in nuclei at finite temperature and z-projection M of angular momentum. Particle-number projection (PNP) is taken into account within the Lipkin-Nogami method. Several issues such as the smoothing of superfluid-normal phase transition, thermally assisted pairing in hot rotating nuclei, extraction of the nuclear pairing gap using an improved odd-even mass difference are discussed. A novel approach of embedding the PNP SCQRPA eigenvalues in the canonical and microcanonical ensembles is proposed and applied to describe the recent empirical thermodynamic quantities for iron, molybdenum, dysprosium, and ytterbium isotopes.

(14) Shear-viscosity to entropy-density ratio from giant dipole resonances in hot nuclei
The Green-Kubo relation and fluctuation-dissipation theorem are employed to calculate the shear viscosity η of a finite hot nucleus directly from the width and energy of the giant dipole resonance (GDR) of this nucleus. The ratio η/s of shear viscosity η to entropy density s is extracted from the experimental systematics of the GDR in copper, tin, and lead isotopes at finite temperature T . These empirical results are then compared with the predictions by several independent models as well as with almost model-independent estimations. Based on these results, it is concluded that the ratio η/s in medium and heavy nuclei decreases with increasing temperature T to reach (1.3–4) x $1/(4\pi)$ (in the units of hbar by k_B) at T = 5 MeV.

(15) Pairing reentrance in hot rotating nuclei
The pairing gaps, heat capacities, and level densities are calculated within the BCS-based quasiparticle approach, including the effect of thermal fluctuations on the pairing field within the pairing model plus non-collective rotation along the z axis for 60Ni and 72Ge nuclei. The analysis of the numerical results obtained shows that, in addition to the pairing gap, the heat capacity can also serve as a good observable to detect the appearance of the pairing reentrance in hot rotating nuclei, whereas such a signature in the level density is rather weak. The test calculations by using the same single-particle configuration as that used in the recent calculations within the Shell-Model Monte Carlo (SMMC) approach, but obtained within the Woods-Saxon potential, reveal that the neutron pairing reentrance in 72Ge is an artifact, which is caused by the use of the same single-particle spectrum for both protons and neutrons, whereas the irregularity on the curve for the logarithm of level density, reported in the SMMC calculations, is caused by unphysically large values of the heat capacity at low T within the SMMC approach.

(16) Black-sphere-model study on energy dependence of nucleon-nucleon total cross section

In the framework of the contemporary black-sphere model, we examined the energy dependence of nucleon-nucleon total cross section. We have found that the new parameterization by Bertulani and De Conti is precise enough to calculate total reaction cross sections, which differs from the standard one in the proton-proton total cross section for the energies less than 300 MeV. This is due to the lack of precise data in this energy region. We calculate total reaction cross section of carbon-carbon reaction in the black-sphere model with two different parameterizations, one is given by Bertulani and De Conti and the other is the one by the SAID program of the version "SP07". The difference between the two curves appears clearly, and the curve obtained by the one by Bertulani and De Conti reproduces the precise data very good. It is hard to distinguish one from the other if we would use proton-carbon reactions.

(17) Size of excited states

We systematically derive a length scale characterizing the size of a low-lying, beta-stable nucleus from empirical data for the diffraction peak angle in the proton inelastic differential cross section of incident energy around 1 GeV. We have found that for ^{12}C, ^{58,60,62,64}Ni, and ^{208}Pb, the value of a_l, the black-sphere radius of spin l, obtained from the inelastic channel is generally larger than the value obtained from the elastic channel and tends to increase with E_x, with a few exceptions in which case the black sphere radius decreases with E_x in its central value but can be regarded as unchanged allowing for the error bars. This is consistent with the behavior of the transition radii obtained systematically from electron inelastic scattering off ^{208}Pb. The increase is remarkable for the Hoyle state, a feature consistent with the alpha clustering picture. We hope that the present analysis could develop into a systematic drawing of the black-sphere radii of isomers and nuclei in other characteristic excited states over a chart of the nuclides.