FY2009

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) Finite amplitude mothod for nuclear response calculations

We are performing a systematic calculation of nuclear photoabsorption cross section for light nuclei. The calculation is fully self-consistent and is based on the time-dependent density-functional theory with the Skyrme functional. This is achieved using the finite amplitude method we have recently developed. The key feature of the method is to obtain the matrix elements of the random-phase approximation (RPA) in a simple way avoiding explicit calculation of induced residual fields. The method is called "Finite amplitude method" (FAM). So far, even-even nuclei up to mass number A=100 have been studied.

We have also been developing a new theoretical tool to apply the finite amplitude method to nuclei with superfluidity. Then, we have been involved in the implementation of the FAM on an existing spherically symmetric Hartree-Fock-Bogoliubov code (HFBRAD) which is currently being turned into a quasi-particle-random-phase approximation (QRPA) code.

(2) Many-body green's function approaches to nuclear structure

Green's functions theory using modern realistic nuclear interactions was applied to study 56Ni and 48Ca. This allowed us to investigate the role of different types of correlations on the problem of quenching of the spectroscopic factors. Based on this success, the dependence of nuclear correlations on proton-neutron asymmetry is being investigated. The "state of the art" Green's function theory was also benchmarked on the ground state energy of 4He, where accuracies of 100-200KeV or less were found. This shows the feasibility of ab-initio studies with this method. Analogous calculations have been performed for electronic systems (atoms) to aid in developments of density functional theory.

(3) Low-lying collective modes in deformed neutron-rich nuclei

Low-frequency negative-parity excitations in deformed neutron-rich nuclei have been studied with the self-consistent Hartree-Fock-Bogoliubov and the QRPA. The Skyrme energy density functional together with the pairing energy density functional is adopted. We found a significant coupling effect between the dipole and the octupole excitations for the pygmy resonance in neutron-rich Mg isotopes.

(4) Spectroscopic study of odd-mass nuclei

The quasi-particle-vibration-coupling Hamiltonian has been derived in a framework of the nuclear density functional method to describe the low-lying properties of odd-mass nuclei in a microscopic way. We applied it to the electric-quadrupole moments of neutron-rich Al isotopes around N=20, and showed an important role of neutron pairing correlations implying a weakening of the N=20 shell gap. The results show a reasonable agreement with recent experimental data.

(5) Linear response calculation using the canonical-basis TDHFB with a schematic pairing functional

Aiming at constructing a theoretical framework that is able to analyze and predict properties of unknown nuclei, we proposed the Canonical-basis time-dependent Hartree-Fock-Bogoliubov (CbTDHFB) approach in the three-dimensional coordinate-space representation. In this approach, we assume that the time evolution can be described by the time-dependent canonical basis with the time-dependent (u,v) factors. We have shown that this can be achieved only when we use a special pairing functional. The computer program with the Skyrme functional has been developed and applied to E1 and E2 nuclear response.

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

states

We have proposed a microscopic method to calculate the vibrational and rotational inertial functions, which includes the time-odd contribution of the mean-field, in the Bohr-Mottelson collective Hamiltonian for large-amplitude quadrupole collective dynamics. The method is composed of constrained HFB and the local QRPA equations, which are derived from the adiabatic self-consistent collective coordinate method. The method is applied to shape coexistence and anharmonic vibrations in Se isotopes, and we have shown that the time-odd mean field increases the collective inertial functions and lowers the excitation energies.

(7) Phenomenological analysis of the oblate-prolate symmetry breaking in triaxial deformation dynamics

In this study, we have analyzed the effects of the oblate-prolate symmetry breaking on dynamics of triaxial deformation in oblate-prolate shape coexistence phenomena using a simple model based on the well-known quadruploe collective Hamiltonian. We have obtained a number of interesting suggestions through the numerical solutions of this model: (i) The relative energy of the excited 0+ state can be a signature of the potential shape along the γ direction. (ii) Specific E2 transition probabilities are sensitive to the breaking of the oblate-prolate symmetry. (iii) Nuclear rotation may induce the localization of collective wave functions in the quadrupole deformation space if the oblate-prolate symmetry in the moments of inertia is broken.

(8) Structures of superdeformed states in 28Si and 40Ar

Structures in 28Si and 40Ar have been studied using the antisymmetrized molecular dynamics (AMD) method. The oblate-prolate shape coexistence is reproduced and existence of superdeformed (SD) band is predicted for 28Si. The SD states contain alpha-24Mg cluster structure components. For 40Ar, the SD band is reproduced, which were experimentally identified very recently. The calculation suggests that the SD states form triaxial shapes, and a K = 2+ side band exists.

(9) Nuclear “pasta” in supernova

We aim to bridge between astrophysics and nuclear and atomic physics by solving astrophysical problems using nuclear/atomic physics and by providing interesting nuclear/atomic physics problems in astrophysical systems. This year, we have solved a long-standing problem about the formation of rod-like and slab-like nuclei referred to as "pasta" nuclei in collapsing supernova cores. In the field of cold atom physics, we have studied the critical velocity of unitary Fermi superfluids flowing in a periodic potential. Unitary Fermi gases resemble the low density dripped neutron gases in neutron stars and this work also provides useful information to study neutron star crusts and the related phenomena.

(10) Study of vortex lattices in cold Fermi gases

We are developing a theoretical framework to describe both the vortex structure in rotating condensates and the band-structure of Fermi superfluids in a periodic potential. This year, we have developed a new efficient scheme to create a Schroedinger cat-like maximally entangled state in a two-state Bose system.

(11) Phenomenological formulae for nuclear reaction cross sections

We examine the mass-number dependence of the cross section formula based on the black-sphere picture of nucleus. We find analytically that, in contrast to other formulae, our formula includes $A^{1/6}$-dependence in addition to $A^{2/3}$-dependence. The $A^{1/6}$-dependence, which comes from the optical depth of target nucleus, is one of the characteristic features of our formula.

We study the scaling properties of proton-nucleus total reaction cross sections for stable nuclei, and propose an approximate expression just in proportion to $Z^{2/3}\sigma_{pp}^{total} + N^{2/3}\sigma_{pn}^{total}$. Based on this expression, we can derive a relation that enables us to predict a total reaction cross section for any stable nucleus within at most 10% uncertainty, using the empirical value of the total reaction cross section of a given nucleus.

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