2. Theoretical Nuclear Physics Laboratory　／中務原子核理論研究室

Associate Chief Scientist: Takashi NAKATSUKASA (D.Sci.)　／中務　孝

From August, 2007 to March, 2016

2.1 Summary of Research Activities

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.

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

Summary of Research Activity

(1) Microscopic determination of nuclear reaction path and inertial mass

Nuclear reaction at low energy is described by the quantum scattering theory. However, when many nucleons are involved in the reaction processes, the full treatment becomes impractical. In this case, it is very useful to find the optimal collective coordinate to describe the reaction. Based on the time-dependent density-functional theory, we can achieve this by solving a set of equations, the moving mean-field equation and the moving RPA equation, which we derived previously using a theory of large amplitude collective motion. This requires complicated coding and large computational resources. We have developed a computer program based on the three-dimensional real-space representation and applied this to reaction of light nuclei, such as ^{8}Be and ^{16}O. We have succeeded to derive the fission path of ^{8}Be into two alpha particles. At the same time, the inertial mass parameter for this reaction is microscopically determined. It turns out that the collective inertial mass is equal to the reduced mass in a asymptotic region and increases near the touching region of two alpha's.

(2) Energy density functional approaches to superheavy nuclei

We have performed a systematic calculation for superheavy nuclei using the energy density functional methods. A purpose of this study is to quantify the theoretical uncertainty of the energy density functional methods. Comparing the results with known experimental data, we have found nice agreement. However, in unknown territories of the superheavy nuclei, we do not know the predictive power of the method. To quantify the uncertainty, we use many different kinds of modern energy density functionals and compare the results to each other. Surprisingly, the results agree with each other in open-shell region where the nuclei are well deformed. On the other hand, in the semi-magic and the transitional regions, the predicted values are scattered. Most probably, this is associated with missing correlations, such as shape fluctuation effects, and indicates necessity of further extension of the model.

(3) 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 A1/6 dependence plays a crucial role in describing the energy dependence of proton-nucleus total reaction cross sections

(4) Deformed nuclei in the black-sphere approximation of nuclei

In order to access the information of nuclear equation of state, such as the value of L, we have studied total reaction cross sections by focusing on the empirical data of the interaction cross section measured at ~900 MeV per nucleon, as a first step. Since the data of Ne and Mg isotopes have already been obtained with the energy of ~240 MeV per nucleon at the RI Beam Factory of RIKEN, systematic analyses are indispensable. For the analyses, we adopt the black-sphere approximation of nuclei. Since we have to face the nuclear deformation in this region of nuclei, we change the black sphere into a spheroid of the same volume in order to take into account nuclear deformation. So far, we have obtained the results showing rather small effect from nuclear deformation. This study is now in progress.

(5) Giant Dipole Resonance built on hot rotating nuclei produced during evaporation of light particles from Mo-88 compound nucleus

We succeeded to show that the phonon damping model (PDM by Dang & Arima 1998), which was extended to finite angular momentum in 2012, describes very well the most recent data of the giant dipole resonance (GDR) built on hot rotating nuclei produced during evaporation of light particles from ^{88}Mo compound nucleus by the experimentalists in Krakow and Milano.

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

We applied the FTBCS1 theory (proposed and developed by Dang and Hung in 2008) at finite temperature and angular momentum to study the pairing phenomenon and level density in ^{104}Pd, of which an enhancement of level density at low excitation energy and high angular momentum has been experimentally observed by the experimentalists at BARC (Mumbai). The quantitative agreement between experiment and theory suggests that this enhancement is indeed the first experimental evidence of the reentrance of superfluid pairing in a finite nucleus.

(7) Effects of thermal shape fluctuations and pairing fluctuations on the giant dipole resonance in warm nuclei

We presented the complete formalism based on the microscopic - macroscopic approach for determining the deformation energies and a macroscopic approach which links the deformation to GDR observables. We discussed our results for the nuclei ^{97}Tc, ^{120}Sn, ^{179}Au, and ^{208}Pb, and corroborate with the experimental data available. We showed that the thermal-shape fluctuation model could explain the data successfully at low temperature only with a proper treatment of pairing and its fluctuations.

(8) Experimental investigation on the temperature dependence of the nuclear level density parameter

In collaboration with the experimentalists at the VECC (Kolkata), who studied the effect of temperature T and angular momentum J on the inverse level density parameter k by populating the compound nucleus ^{97}Tc in the reaction ^{4}He + ^{93}Nb at four incident beam energies of 28, 35, 42, and 50 MeV, we compared the T dependence of k for two angular momentum windows with different theoretical predictions as well as with the results of calculations within the FTBCS1. We found that the experimental data are in good agreement with the theoretical calculations at higher J but deviate from all the calculations at lower J.

(9) Review of three-decay study of giant dipole vibration in hot rotating nuclei

In collaboration with D. Chakrabarty and V. Datar, we have written and submitted to The European Physical Journal A – Hadrons and Nuclei an invited review article, entitled "Giant dipole vibration in hot rotating nuclei". The review has been accepted for publication and is now in production.

(10) Gauge symmetry in the large-amplitude collective motion of superfluid nuclei

The adiabatic self-consistent collective coordinate (ASCC) method is a practical method for describing the large-amplitude collective motion in atomic nuclei with superfluidity and an advanced version of the adiabatic time-dependent Hartree-Fock-Bogoliubov theory. We investigate the gauge symmetry in the ASCC method on the basis of the Dirac-Bergmann theory of constrained systems. We have shown that the gauge symmetry in the ASCC method originates from the constraint on the particle number in the collective Hamiltonian, and that it is partially broken by the adiabatic expansion. The validity of the adiabatic expansion under the general gauge transformation is also confirmed.

2.2 Projects

Project name	Category	Start in	Finish in	Awardee	Grand total 2014-2015 (Thousand yen)
Low-energy collective excitations and fusion/fission mechanism in nuclei	JSPS: Grant-in-Aid for Scientific Research(B)	2013	2015	Takashi NAKATSUKASA	0

JSPS: Japan Society for the Promotion of Science

2.3 Members

Position		Number			Name (First name FAMILY NAME) as of April 1, 2016
		March 31, 2014	March 31, 2015	March 31, 2016	
Principal Investigator (PI)		1	(1)	(1)	-
Staff scientist	Permanent employee	1	1	1	-
	Contract employee	1	1	1	-
Postdoctoral fellow		3	3	1	-
Research associate		-	-	-	-
Student trainee		-	2	1	-

Technical assistant	-	-	-	-
Visiting research staff	11	10	8	-
Student	-	-	-	-
Administrative assistant	-	-	-	-
Others	5	8	8	-

( ): Concurrent position

Research associate: young employee who drive for a doctoral degree under the supervision of a RIKEN Chief Scientist or team leader.

Student trainee: Undergraduate, Masters and PhD students hired by RIKEN to conduct their thesis research under the supervision of a RIKEN Chief Scientist or team leader.

JSPS: Japan Society for the Promotion of Science

2.4 Funding

Thousand yen

Fiscal Year	**2013**	**2014**	**2015**
Government Budget	0	0	0
Grant	3,200	0	0
Private & Others	2,200	3,000	1,000

2.5 Research Achievements [2014 年、2015 年の欄を埋めてください]

	Year	**2013**	**2014**	**2015**
Publication	international	15	17	16
	domestic	1	0	1
Oral Presentation	international	21	29	8
	domestic	16	4	7
Patent Application		0	0	0

Selected Original Papers

1. Nakatsukasa T, Matsuyanagi K, Matsuzaki M, Shimizu Y R, “Quantal rotation and its coupling to intrinsic motion in nuclei”, Phys. Scr. 91, 073008 (2016).
2. Yoon S, Dalfovo F, Nakatsukasa T, Watanabe G, “Multiple period states of the superfluid Fermi gas in an optical lattice”, New J. Phys. 18 023011 (2016).
3. Washiyama K, “Microscopic analysis of fusion hindrance in heavy nuclear systems”, Phys. Rev. C 91, 064607 (2015).
4. Ebata S, Nakatsukasa T, Inakura T, “Systematic investigation of low-lying dipole modes using the canonical-basis time-dependent Hartree-Fock-Bogoliubov theory”, Phys. Rev. C 90, 024303 (2014).
5. Liang H Z, Nakatsukasa T, Niu Z M, and Meng J, “Feasibility of the finite-amplitude method in covariant density functional theory”, Phys. Rev. C 87, 054310 (2013).
6. Sato K, Dobaczewski J, Nakatsukasa T, and Satula W, “Energy-density-functional calculations

including proton-neutron mixing”, Phys. Rev. C 88, 061301(R) (2013).
7. Dang N D, Ciemala, M, Kmiecik M, Maj A, “Giant dipole resonance in ^{88}Mo from phonon damping model’s strength functions averaged over temperature and angular momentum distributions”, Phys. Rev. C 87, 054313 (2013).
8. Iida K, Shinya Koide S, Kohama A, and Oyamatsu K,, “Proton inelastic diffraction by a black nucleus and the size of excited nuclei”, Modern Physics Letters A 27, 1250020 (2012).
9. Iida K, Oyamatsu K, Sarhan B A, Kohama A, “Proton-nucleus total reaction cross sections in the optical limit Glauber theory: subtle dependence on the equation of state of nuclear matter”, Prog. Theor. Phys. 126, 1091 (2011).
10. Dang N D, “Shear-viscosity to entropy-density ratio from giant dipole resonances in hot nuclei”, Phys. Rev. C 84, 034309 (2011).

2.6 Awards

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2.7 Collaborative Activities

Partner Laboratories in Nishina Center

Radioactive Isotope Physics Laboratory, Spin Isospin Laboratory, Nuclear Spectroscopy Laboratory, Quantum Hadron Physics Laboratory, Strangeness Nuclear Physics Laboratory, Mathematical Physics Laboratory.

Partner Institutes

The University of Tokyo
Niigata University
University of Tsukuba
Japan Atomic Energy Agency
University of Washington
Kyoto University
TRIUMF
The University of Milan
Oak Ridge National Laboratory
University of Tennessee
Zagreb University
Peking University

2.8 Future Plan

The Theoretical Nuclear Physics Laboratory has been closed at March 2016.

2.9 Curriculum Vitae (Associate Chief Scientist)

Name: Takashi Nakatsukasa

Education:	1989-1993	Graduate School of Science, Kyoto University
Degrees:	1994	Kyoto University, PhD (Physics)
Appointments:	1994	Research Associate in RCNP, Osaka University
	1994-1996	Research Associate in Chalk River Laboratory, Canada
	1996-1999	Research Associate in University of Manchester Institute of Science and Technology, UK
	1999-2001	Special Postdoctoral Researcher in RIKEN
	2001-2004	Assistant Professor in Tohoku University
	2004-2007	Lecturer in University of Tsukuba
	2009-2012	Visiting Associate Professor in Niigata University
	2013	Visiting Professor in Niigata University
	2014-present	Professor in University of Tsukuba
Academic Activities:	Editor for Progress of Theoretical Physics	
	Editor for Journal of Physical Society of Japan	
	Committee for TRIUMF SAP-EEC (Canada)	
	Steering Committee of Institute for Institute of Particle and Nuclear Studies, KEK	
Awards:	—	