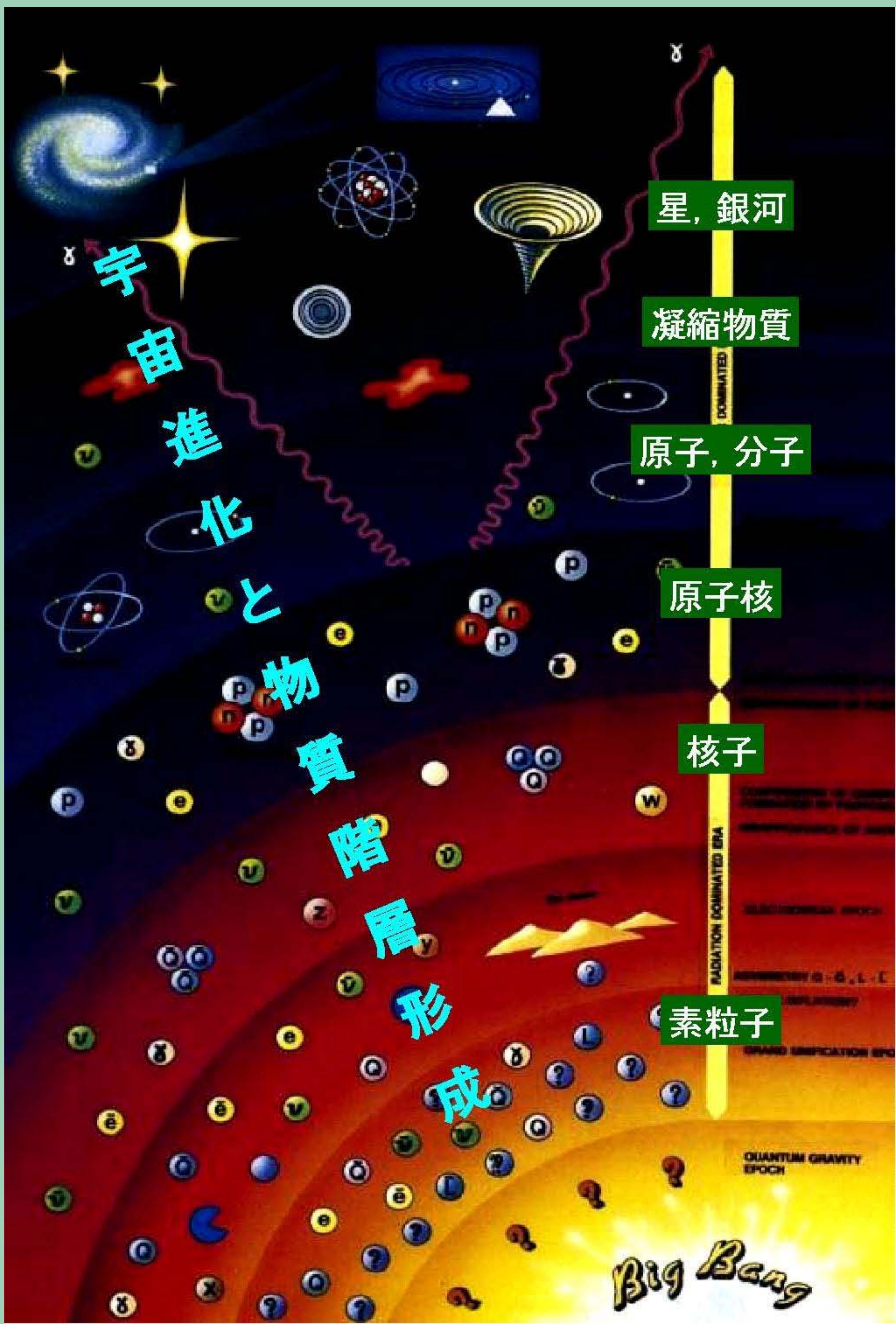
The 21st Century COE Program at Tohoku University

Exploring New Science by Bridging Particle-Matter Hierarchy



Contents

1 Introduction

Osamu Hashimoto

The 21 Century Center of Excellence Program (21COE) was established by Ministry of Education, Science, Sport (MEXT) to cultivate a competitive academic environment among Japanese universities by giving targeted support to the creation of world-standard research and education bases (centers of excellence) in 2002. It aims to uphold the level of graduate education in doctor courses.

Our 21COE program, started in 2003, was jointly proposed by Departments of Physics, Institute of Astronomy and Institute of Mathematics of the school of science together with Cyclotron & Radioisotope Center, Center for Low Temperature Science, and Institute for Materials Research of Tohoku University. We intend to explore new science ranging quark-hadron matter, quantum extreme matter, star-galaxy matter and cosmic dark matter, by bridging particle-matter hierarchy of particles, nuclei, condensed matter and cosmological universe. The emphases of the program are on (1) interdisciplinary cooperative researches in the broader fields of physics, astronomy and mathematics,(2) bi-directional, cooperative international and domestic collaboration, and (3) fostering graduate students and young scientists in a wide variety of research fields under international environment

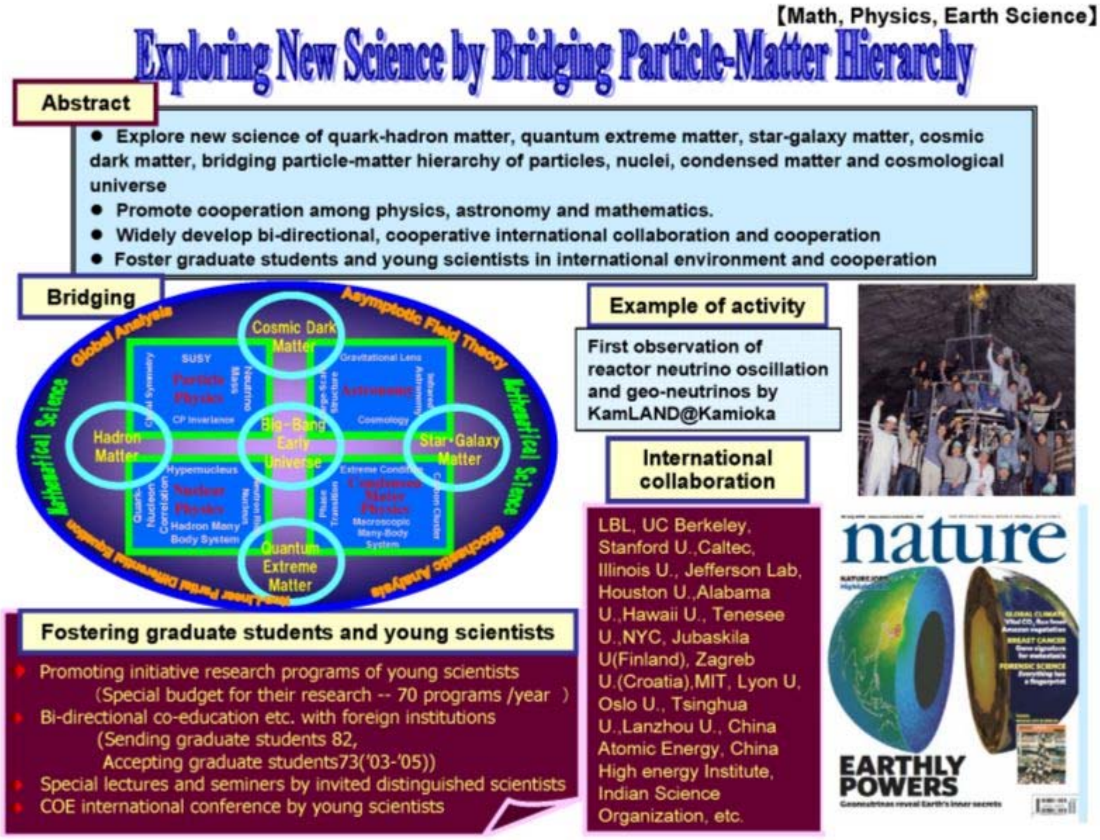
The 21COE program established graduate school curricula that bridge mathematics, physics and astronomy in addition to lecture courses or seminar series by world distinguished scientists of the related fields. In addition, through inviting many active scientists and enhancing international atmosphere on campus, young scientists found opportunities to exchange their ideas on daily basis. Doctor students and postdoctoral fellows were strongly encouraged to propose their own research projects. On a competitive basis, the COE program selected "young-scientist initiative program" and provided them special budget so that they could intensively conduct their own researches and also participate in international conferences to present their activities.

We believe our 21COE program has kept high-level research and made fruitful research outcome, in the 12 research fields of, for example, neutrino physics, hypernuclear physics, strongly-correlated condensed matter physics, and cosmological sciences as well in the field of non-linear mathematics.

In 2006, MEXT conducted an interim evaluation of the 21COE programs nationwide. Our program was recognized by the MEXT committee as one of the most successful 21COE programs in the field of Mathematics, Physics and Geo-science. We are very much encouraged as a one-page summary of our 21COE was selected and included in the COE pamphlet which MEXT prepared to explain to the public how the program was successful.

Although it is a challenging task, cooperation between physics, astronomy and mathematics has been greatly stimulated through the 21COE program. It is now more routine to communicate each other, which would not have been realized without this COE program. It is also under discussion to further unify the present curricula of the graduate courses between the department of physics and the institute of astronomy. It is also mentioned, that, based on the achievement of our COE program and the other 2 COE programs in the school of science, the school founded the Center for the basic science in April of 2007 to strengthen cooperation between the 3COEs and 6 departments and institutions of the school in education and research.

This report has been prepared to summarize the activities of our 21COE program to provide a basic material to outside reviewers and ourselves. It is our intension to seriously review our activities carried out under the 21COE program both internally and externally and prepare the next step to further accelerate the effort to establish us as one of the center of excellence in the world scientific community.



2 Outline of "Exploring New Science by Bridging Particle-Matter Hierarchy"

2.1 Steering system

Professor Atsuto Suzuki (particle physics) acted as the project leader from the start of the COE (October, 2003) to his transference (March, 2006) as the director of KEK. Professor Osamu Hashimoto (nucleus physics) succeeds the project leader from April 2006. The following table shows the list of chief investigators and their assignment.

Name	Research Assignment	Administrative Assignment
Atsuto Suzuki	Neutrino Physics	Project Leader (until 2006/3)
Osamu Hashimoto	Hyper Nuclei Physics	Project Leader (from 2006/4)
Youichi Murakami	X-ray and Neutron Physics	Chief Administrator
Toshifumi Futamase	Cosmology	Chief Administrator
Hideo Kozono	Mathematical Science	Chief Administrator
Kunio Inoue	Neutrino Physics	Steering Member (from 2006/4)
Kenichi Hikasa	Particle Physics	Steering Member
Takashi Takahashi	Photoemission	Steering Member
Yoshio Kuramoto	Condensed Matter Theory	Steering Member
Hitoshi Yamamoto	CP Violation	
Masahiro Yamaguchi	Particle Physics	
Toshio Kobayashi	Excess-Neutron Nuclei	
Hirokazu Tamura	Hyper Nuclei Physics	
Jirota Kasagi	Quark Matter	
Tsutomu Shinozuka	Excess-Neutron Nuclei	
Haruyoshio Aoki	Low-Temperature Physics	
Toshihiro Kawakatsu	Soft Matter Physics	
Hideyuki Seio	Galaxy Formation	
Takashi Ichikawa	Galaxy Structure	
Shigenori Bando	Mathematical Science	
Eiji Yanagida	Non-linear Systems	
Kazuyoshi Yamada	High Temperature Superconductivity	
Teruya Ishihara	Photonic Crystals	
Katsumi Tanigaki	Nano Network Systems	
Seiji Chiba	Dark Matter	
Makoto Hattori	Background Radiation	
Yoshiaki Taniguchi	Galaxy Structure	(until2006/3)

The steering committee, which is held every month, discusses concrete policy and decides on the activity plan. According to the necessity, members outside the steering committee, or some new professors attend the meeting.

In many cases, some of the chief investigators become members of the organizing committee. However, younger people of the assistant professor level have also joined in some case. At organization of an international conference featuring younger generation, in particular, an assistant professor served as Chairperson, and the most of the organization committees consisted of researchers less than 40 years old, and some graduate students.

On the other hand, the meeting of all chief investigators is not held so frequently. It is about one or two times in each year.

Furthermore, we have asked the following list of well-experienced scholars for evaluation and advice of the COE program. We invite these committees and the well-experienced scholars of relevant fields to the international symposia that we held, and report the activity of this COE program. The evaluation members have given useful advices on the activity of this COE program.

Jiro Arafune
(National Institution for Academic Degrees and University Evaluation, Specially Appointed Professor: Particle Theory)
Hiroyuki Shiba
(Kobe University, Professor Emeritus, Condensed-Matter Theory)
Motohiko Yoshimura
(Okayama University, Professor: Particle Theory)
Hirohito Suematsu
(Riken Harima Institute, Director: Condensed-Matter Physics)
Tadao Oda
(International Christian University, Guest Professor, Mathematics)

2.2 Major Expenses

2.2.1 Proportion of each expense to the total

The budget of this COE program in the first fiscal year (2003) is 130 million yen, and 2006 fiscal year is about 177 million yen. This amount does not include the overhead taken by the university. Each item of expenses is shown in the following tables. The unit is 1,000 Yen.

Fiscal Year	Equipment	Travel	Personnel	Miscellaneous	Education	Total
2003	7,878	31,037	32,580	38,486	20,017	130,000
2004	4,892	21,447	97,587	10,973	20,100	155,000
2005	5,445	23,869	98,313	5,874	18,450	152,000
2006	1,000	27,000	122,000	7,000	20,000	177,000

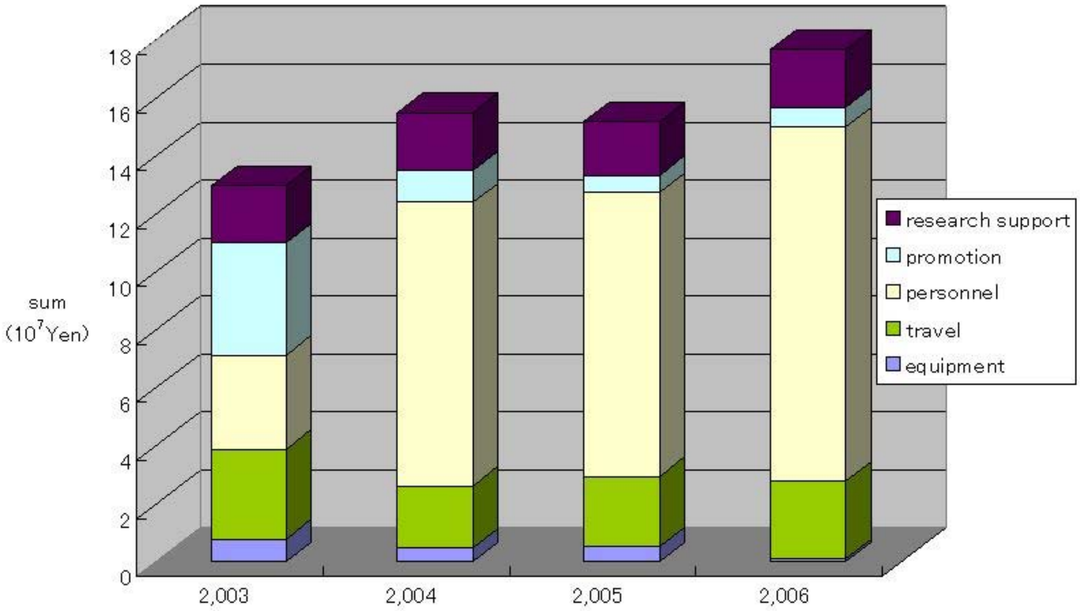
The most major expense is the personnel cost, and the next is the travel cost. The breakdown of these expenses is explained later. The proportions of costs are illustrated in the following figure.

2.2.2 Financial support of young researchers

The research support expense is given for Ph.D students and young researchers adopted as COE fellows. The amount is determined based on examination of the application that explains the research program. The details are explained later.

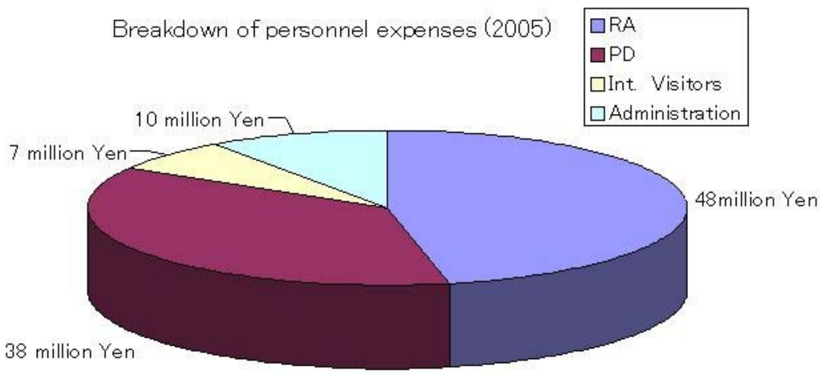
2.2.3 Breakdown of personnel expenses

The cost for paying Research Assistant (RA) for graduate students occupies a large portion of the personnel expenditure. Then the employment of post doctoral people called COE fellows needs a large amount. We have asked international professors, who are invited by the COE long-term program, to lecture in the master and the doctor's course in the graduate school.



This lecture is sometimes also given in the framework of the international graduate school course that is called IGPAS in the Faculty of Science.

Because a considerable amount of clerical work is necessary for the activity of COE, "The COE support office" has been installed in the Faculty of Science. . This office also makes the service for the other COE programs run by members in the Faculty of Science. The labor cost for this is about 10 million yen per year. The following figure illustrates the situation taking the example of 2005 fiscal year. The other fiscal years look roughly the same except for the first year.

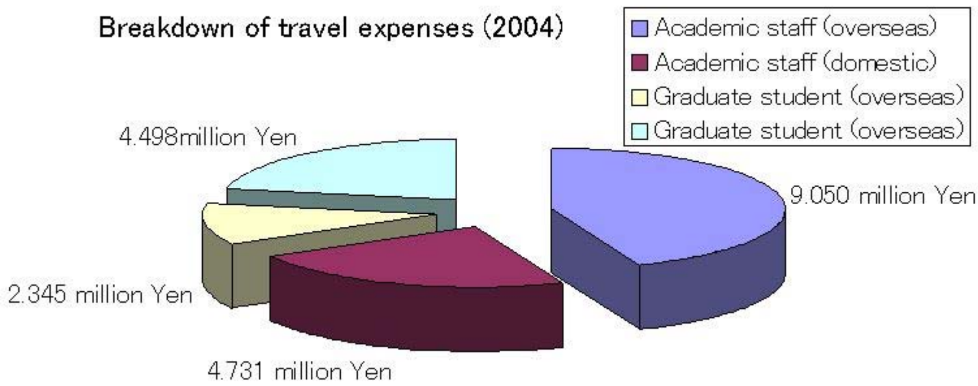


2.2.4 Breakdown of travel expenses

The foreign travel expenses of professors related to the COE occupies the largest proportion On the other hand, the domestic traveling expenses are divided almost equally into professors and graduate students. In the case of professors, the portion of cost for domestic travels is about half of the international travels. To the contrary, graduate students spend more on domestic travels than on international travels.

As can be seen from the absolute amount of the money, traveling expenses that graduate students and young researchers can use have increased very much by the COE program. This means the greatly increased occasion that results of the research can be reported inside and outside of Japan.

The breakdown of traveling expenses is shown in the following figure, taking an example of 2005 fiscal year. Other fiscal years except the first year have similar breakdowns.



2.3 The center for basic science

In April, 2007, the school of science founded the center for basic science as an organization to support the cooperation of the three COEs in the school of science. We also would like to stimulate closer cooperation in education and research among the 6 departments and institute for Mathematics, Physics, Astronomy, Geophysics, Chemistry, Earth science. The center was intended to have multiple functions partly based on the successful activities of the three 21COE such as, (1) to enhance education in global environment for basic science through the international graduate program for advanced science (IGPAS) and also exchanging graduate students internationally. (2) to further explore and promote interdisciplinary research programs among the scientists in the school, (3) to further strengthen international and domestic collaborative programs , (4) to support graduate students and young researchers to conduct their own research and/or jump into the world scientific community, (5) to interface cooperation with the International Advance Research and Education Organization of Tohoku University which was founded in 2007 as outcome of the university-wide 13 21COE programs to create new interdisciplinary areas and new intelligence, while continuing to promote research in various areas and to educate young talented researchers who can generate the intelligence. We also aim to foster future young scientists fully facilitating the new center.

3 Educational Program

3.1 Outline

Central to the 21st Century COE Program is the education of doctoral graduate course students. The largest portion of our budget is devoted to the educational program. Our COE Program features "bridging" of the three departments and "bidirectional international exchanges." The educational program is organized along these lines.

3.2 Employment of international faculties

New graduate program lecture courses "Advanced multi-scale natural science" are set up as the COE Program started. These lectures can be taken by the students of the three participating departments of the COE Program (Physics, Astronomy, and Mathematics). In line with the policy of the Program, we invite researchers from all over the world as visiting professors every year for two to six months to give the above-mentioned lectures. We list the lecturers and the subjects below.

Uhrig, G. S. (2004): Correlated fermionic systems: Fermi liquid and Luttinger liquid
Rindani, S. D. (2004): Neutrino physics
Balantekin, A. B. (2004): Topics in nuclear and particle astrophysics
Yuang, Xue Feng (2005): Macro/mesoscopic physics of soft materials
Fila, Marek (2005): Blow-up of solutions of semilinear parabolic equations
Boerner, G. (2006): Cosmology

3.3 International exchanges

We invite short-term researchers other than those visiting professors described above. The duration of each visit is between one week and one month. We have accepted about one hundred visitors since the start of the program, with full coverage of travel and local expenses. Our Kamland Neutrino Laboratory is especially attracting visitors from US and other foreign countries.

Our students are encouraged to make foreign visits with financial support from the COE program. The purpose ranges from collaboration in their researches to participation in conferences. In particular, we have close connection with Jefferson Lab, Lawrence Berkeley National Lab, and an observatory in Hawaii. These institutions have unique facilities which enables us to perform up-to-date researches. Both research associates and students make long-term visits to those institutions. Because of this, visits to the US consist the largest part of the statistics. Theory students tend to visit more varied places including Korea, China, Taiwan, Australia, and Asian countries. The statistics of foreign visits of the students is listed below.

Year	Collaboration			Conference
	America	Europe	Other	
2003	32 (7)	1 (0)	1 (1)	9 (6)
2004	19 (3)	4 (1)	2 (0)	7 (1)
2005	22 (5)	3 (1)	6 (2)	17 (3)
2006	9 (0)	8 (4)	1 (0)	13 (1)

Up to December 2006. Number of COE supported visits are in parentheses.

3.4 The International Graduate Program for Advanced Science (IGPAS)

The International Graduate Program for Advanced Science (IGPAS) is a graduate-course program in the Graduate School of Science for foreign students opened in fall 2004. The students receive education in English for the full five years of the graduate study. Five students can receive financial support from the Japanese government each year. These students must enter as master course students and the support is for five years (two years master course plus three years doctoral course). Additional students (up to ten each year) without governmental support are also admitted to IGPAS, in which case a students may start from the doctoral course. These students may receive partial support for traveling and living expenses, and are exempt of tuition and fees, which are done in connection with the COE program.

The education program of IGPAS is closely connected to the three COE Program which are operating in the Graduate School of Science. The lectures related to our COE Program are listed below. All of these lectures are in English. In addition to these lectures, the IGPAS students are required to take at least two of the three general courses "Frontiers in Science," "Information Science," and "Internship." These courses help the students to acquire general scientific knowledge with wide viewpoint. Japanese students are also allowed to take IGPAS courses, which helps them to become used to scientific communication in English.

IGPAS courses	
(common to the three departments)	(astronomy)
Advanced Multi-Scale Natural Science A-I–A-VI	Stellar Astronomy
Advanced Multi-Scale Natural Science B-I–B-VI	Galactic Astronomy
(physics)	Cosmology
Quantum Field Theory I, II	(mathematics)
Elementary Particle Physics I, II	Advanced Algebra A–I
Nuclear Physics I, II	Advanced Geometry A–F
Condensed Matter Physics I–V	Advanced Analysis A–I
Statistical Physics	Manifold Theory A–E
Solid State Physics	Advanced Applied Mathematics A–I
Strongly Correlated Material Physics	Current Topics in Mathematics A–H
Biophysics	Modern Mathematics A–H

A number of students have applied to IGPAS every year from Asia, Europe, and Africa, with the largest proportion from China. The first student in Physics Department (from China) finished the Master Course in October 2006 with excellent score and entered the Doctoral Course.

The governmental support is stopped in 2007 unfortunately. The IGPAS program operates in reduced size with partial support from the departments. The graduate school is paying efforts, with support from the university, in regaining the governmental fund.

3.5 International cooperative education program

Tohoku University made an agreement on cooperative education program in 2005 with several institutions on higher education in China and France. The participating institutions are Tsinghua University in China and Ecole Central and INSA Lyon in France. Our COE has participated in this program with the Graduate School of Science to fix and operate the program.

With the cooperative program, master course students spend one year in their own institution and visit the other for one and half years to receive master's degrees from both institutions. We have already accepted several students and promote exchanges at the faculty level.

We also have started collaboration in education and research mainly in nuclear physics area with Lanzhou University in China. We signed an official agreement between the departments in 2006.

3.6 Supporting young scientists and students

We hire young scientists who have received their Ph.D. degree as COE Research Fellows (up to 2005) and Assistant Professors (from 2006) for a term of two years. They help to promote the COE program and are also encouraged to conduct their own research.

Doctoral course students are hired as research assistants to help COE researches, with monthly payment of about 50 kYen.

COE Fellows

Kato, Jun (Math)	2003.10–2004.3
Tanaka, Hajime (Astro)	2003.10–2005.11
Taniguchi, Tetsuya (Math)	2003.10–2004.3
Shimizu, Yasuhiro (High Energy Theory)	2003.11–2005.11
Satyabrata, Raj (Cond. Matter Expt.)	2004.2–2006.1
Kikuchi, Tetsuya (Math)	2004.4–2006.3
Kira, Hiroshi (Cond. Matter Expt.)	2004.4–2006.3
Takahashi, Futoshi (Math)	2004.4–2005.9
Yoshida, Kei (Astro)	2004.4–2006.3
Koike, Takeshi (Nuclear Expt.)	2004.8–2006.6
Kiss, Annamaria (Cond. Matter Theory)	2004.8–2006.3
Takeuchi Tsutomu (Astro)	2005.12–2006.3

COE Assistant Professors

Ishiwata, Michinori (Math)	2006.2–2008.1
Kiss, Annamaria (Cond. Matter Theory)	2006.4–2008.3
Kira, Hiroshi (Cond. Matter Expt.)	2006.4–2008.3
Takeuchi, Tsutomu (Astro)	2006.4–2006.11
Takenaga, Kazunori (High Energy Theory)	2006.4–2008.3
Tsukada, Gyo (Nuclear Expt.)	2006.4–2008.3
Matsui, Hiroaki (Cond. Matter Expt.)	2006.4–2008.3
Okabe, Nobuhiro (Astro)	2006.5–2008.3
Miura, Hideyuki (Math)	2006.5–2008.3
Ito, Yosuke (Astro)	2006.7–2008.3

Ohta, Kazutoshi (High Energy Theory)	2006.10–2007.3
Nohara, Yuichi (Math)	2006.10–2008.3
Hashimoto, Katsuyuki (Cond. Matter Expt.)	2006.11–2008.3

Research Assistants

	Number				Payment (kYen)			
Year	Phys	Astro	Math	Total	Phys	Astro	Math	Total
2003	37	6	19	62	9,703	1,550	5,183	16,436
2004	39	7	23	69	22,078	4,173	13,306	39,556
2005	45	6	31	82	25,799	3,853	15,789	45,673
2006	43	5	26	74	26,641	3,244	15,789	45,673

3.7 Young Scientist Initiative Program

One of the most important program budgetwise is the Young Scientist Initiative Program. It supports doctoral course students and COE research associates with a grant (maximum 1,500 kYen per year), which enables them to pursue their own research project. The project must be related to the COE program and is to be conducted by a single person. The duration of the project is within one fiscal year.

One who receives the grant is supposed to write a report on the project at the end of the fiscal year and is required an oral presentation if he/she applies for another in the next year.

The program started in 2003 and 211 applications have been accepted in the first four years, 135 in Physics, 20 in Astronomy, 56 in Mathematics. The total amount awarded is 81,920 kYen. The breakdown to each year is shown in the table.

Young Scientist Initiative Program

	Number				Total payment (kYen)			
Year	Phys	Astro	Math	Total	Phys	Astro	Math	Total
2003	22	2	11	35	13,000	3,000	4,000	20,000
2004	29	5	14	48	13,100	3,000	4,000	20,100
2005	36	6	15	57	13,200	2,000	3,300	18,500
2006	48	7	16	71	15,640	3,050	4,632	23,321

4 Research Program

4.1 Outline

The aims of the COE are to explore new research fields by links between matter hierarchies, which are composed of quark matter, weak/strong correlated matter, stellar/interstellar matter and dark matter in the universe, as well as to develop the researches on each of these hierarchies intensively. To accomplish the projects covering such a broad range of interests, we establish the international research center for "New Science by Bridging Particle-Matter Hierarchy ".

The research system is consisted of 12 research groups. The members of each group specialize the different research field to activate the inter-hierarchies studies and collaborate with each other. The joint seminars and workshops are held many times. The research groups are divided into 5 research fields and the purposes of each field are as follows: (A) Particle physics and astrophysics Exploring the ultimate structure of matter and the fundamental principles of nature by particle physics, also the birth, evolution and end of the universe by astrophysics: Construction of the picture of the universe in cooperation with the quarks, hadrons, and condensed matter research groups (B) Quarks and hadrons Understanding the static and dynamic properties of quantum many-body systems made of finite number of particles, which are self-bound by the strong interaction: Elucidating the many-body correlation phenomena due to the increase of the particle number in cooperation with the condensed matter research group (C) Strongly correlated electrons Making new materials and understanding the generation mechanism of the novel physical properties using synchrotron and neutron scattering techniques: Theoretically studying on the strong electron correlation of the materials in cooperation with the quarks and hadrons research groups (D) New materials Exploring new materials especially nano-materials composed of carbon, silicon, germanium, and so on and searching the novel physical properties: Discovering the new physical properties producing due to new geometric structure and nano-scale processing technique like photonic crystals (E) Mathematical science Establishing the unified picture of the universe using nonlinear mathematical analysis techniques in cooperation with particle physics, astrophysics, quarks and hadrons physics, condensed matter physics research groups

4.2 Invitation of international researchers

The COE program has invited foreign researchers in the short term. There are two types of the invitations: (a) the invitation in which we pay travel and sojourn expenses: (b) the invitation in which we only pay sojourn and domestic travel expenses. The category (a) is conditional upon the stay at Tohoku Univ. more than 10 days, while the category (b) has no condition of the stay term. The imposed condition make the invited researchers have enough time to make a close relationship with our students and collaborate with each other. We invite the researcher from many different fields as the follow tables.

(1) Invitation list in 2003: We have invited many researchers that year because the year coincided with the active year of the KamLAND experiment and we had the international symposium to launch this COE program and invited many distinguished scholars.

Short-term international visitors in 2003

Dpt	Name	Affiliation	Position	Period
Phys	Evgueni Lakouchev	Univ. of Alabama	PD	2003/11/10–2004/1/9
Phys	Alan Poon	Lawrence Berkeley Nat. Lab.	Assis. Professor	2003/11/17–12/4
Math	Peter Takac	Universitat Rostok	Professor	2003/11/30–12/13
Phys	Yuri Efremenko	Univ. of Tennessee	Assoc. Professor	2003/12/1–12/11
Math	Peter Brinkmann	Univ. of Illinois	Assoc. Professor	2003/12/5
Phys	Louis Lyons	Univ. of Oxford	Professor	2003/12/9–12/12
Phys	Jesse Goldman	Lawrence Berkeley Nat. Lab.	PD	2003/12/26–1/10
Phys	Christopher Mauger	California Inst. of Tech.	PD	2003/12/28–2/3
Phys	Steven Dazeley	Louisiana State Univ.	Ph.D. program	2003/12/29–1/13
Phys	Willam Bugg	Univ. of Tennessee	Professor	2004/1/1–1/18
Phys	Hong Ding	Boston College	Assoc. Professor	2004/1/10–1/17
Phys	Glenn Horton-Smith	California Inst. of Tech.	Senior Researcher	2004/1/13–1/24
Phys	Russell E. Walstedt	Japan Atomic Energy Agency	Group Leader	2004/1/14–1/16
Phys	Petr Bydzovsky	Nucl. Phys. Inst. Acad. Sci. Czech	Sci. Researcher	2004/1/14–2/20
Phys	Miloslav Sotona	Nucl. Phys. Inst. Acad. Sci. Czech	Senior Sci. Researcher	2004/1/14–2/20
Phys	Patrice Payre	CNRS	Researcher	2004/1/14–3/31
Astro	C. S. Jeffery	Armagh Observatory	Astronomer	2004/1/16–1/24
Phys	M. P. Decowski	Univ. of California	PD	2004/1/24–2/6
Phys	Satyabrata Raj	Indian Nat. Sci. Acad.	Assis. Professor	2004/1/30–1/31
Phys	Andre H. Hoang	Max Planck Inst. for Physic	Teniored staff	2004/1/31–2/14
Phys	Segei G. Tikhodeev	General Physics Inst. RAS	Head of Lab.	2004/1/31–2/7
Phys	Kam Biu Luk	Univ. of California	Professor	2004/1/4–1/16
Phys	Steven Berridge	Univ. of Tennessee	Lecturer	2004/1/8–1/19
Astro	P. P. Wardayanti	Inst. Tech. Bandung	Assoc. Professor	2004/1/9–2/15
Phys	Willam Bugg	Univ. of Tennessee	Professor	2004/2/1–2/19
Phys	Bruce Berger	Lawrence Berkeley Nat. Lab.	PD	2004/2/10–2/22
Math	Schulz-Baldes	Technishe Universitat Berlin	Assoc. Professor	2004/2/10–2/22
Phys	Brian Fujikawa	Lawrence Berkeley Nat. Lab.	Assoc. Professor	2004/2/11–3/1
Math	Francisco Urbano	Univ. of Granada	Professor	2004/2/12–2/19
Math	George Kamberov	Stevens Inst. of Tech.	Assoc. Professor	2004/2/14–2/27
Math	I. M. C. Salavessa	Technical Univ. of Lisbon	Assoc. Professor	2004/2/14–2/29
Astro	Thomas Buchert	Technical Univ. Munich	Assoc. Professor	2004/2/14–3/15
Phys	Byron Dieterle	Univ. of New Mexico	Professor	2004/2/15–2/29
Math	H.Amann	Univ. Zurich	Professor	2004/2/15–3/8
Phys	George Tsitsishvili	Math. Inst., Georgian Sci. Acad.	Senior researcher	2004/2/22–3/19
Phys	Werner Tornow	Duke Univ.	Professor	2004/2/24–3/13
Math	Maria Specovius	Kassel Univ.	Assoc. Professor	2004/2/26–3/10
Phys	D.D.Sarma	Indian Inst. of Sci.	Professor	2004/2/28–3/12
Phys	P.R.A. Miguel	Universitat de Barcelona	Research Fellow	2004/2/29–3/19
Phys	Ryszard Czajka	Poznan Univ. of Tech.	Professor	2004/2/3–2/21
Astro	Chang Heon Young	Yonsei Univ. Observatory	Visiting Researcher	2004/2/5–2/14
Phys	Stuart Freedman	Lawrence Berkeley Nat. Lab.	Professor	2004/2/9–2/21
Phys	Karsuern Heeger	Lawrence Berkeley Nat. Lab.	Assis. Professor	2004/2/9–2/22
Phys	Petr Vogel	California Inst. of Tech.	Professor	2004/2/9–2/23
Phys	M.S.Dresselhaus	Massachusetts Inst. of Tech.	Professor	2004/3/1–3/8
Phys	Yifang Wang	Inst. of High Energy Phys.	Professor	2004/3/10–3/23
Phys	Fred Gray	Univ. of California	PD	2004/3/15–3/31
Phys	Stuart Freedman	Lawrence Berkeley Nat. Lab.	Professor	2004/3/17–3/27
Phys	Robert Svobada	Louisiana State Univ.	Professor	2004/3/18–3/31
Phys	L.Cardman	Jefferson Lab	Assoc. Director	2004/3/2–3/8
Phys	F.Steglich	Max Planck Inst.	Lab. Director	2004/3/3–3/7
Phys	Sandip Pakvasa	Univ. of Hawaii	Professor	2004/3/4–3/9
Math	Donhgo CHAE	Seoul Nat. Univ.	Professor	2004/3/5–3/7

(2) Invitation list in 2004: Extremely distinguished researchers, who are very busy, stayed at our university more than 10 days. We had the symposium, which attached importance to the domestic research that year. This is the reason why the foreign researchers invited are far short of those in other years.

Short-term international visitors in 2004

Dpt	Name	Affiliation	Position	Period
Phys	Serguey Petkov	Bulgarian Acad. of Sci.	Professor	2004/4/26–4/27
Phys	Stefan Recksiegel	Technische Universitat Munchen	PD	2004/4/5–4/8
Math	Jann-Long Chern	Nat. Central Univ.	Professor	2004/5/9–5/16
Phys	B.S. Shastry	Univ. of California	Professor	2004/6/11–6/24
Astro	T.J. Broadhurst	Tel Aviv Univ.	Professor	2004/6/11–7/14
Phys	Gerrit E. Bauer	Delft Univ. of Tech.	Professor	2004/6/12–7/14
Phys	Song Changyong	Pohang Univ. of Sci. and Tech.	PD	2004/6/21–6/29
Phys	Didier Poilblanc	Universite Paul Sabatier	Head of Lab.	2004/7/12–7/25
Phys	Chang Sany Hyeon	Yonsei Univ.	Professor	2004/7/20–8/3
Phys	Dipankar Das Sarma	Indian Inst. of Sci.	Professor	2004/9/27–10/7
Math	Hermann SOHR	Paderborn Univ.	Professor	2004/10/5–12/1
Math	Jong Sheng Guo	Nat. Taiwan Normal Univ.	Professor	2004/11/14–11/27
Phys	Hong Ding	Boston College	Assoc. Professor	2004/11/17–11/25
Phys	Teakoon Lee	Seoul Nat. Univ.	Professor	2005/1/10–2/1
Math	Li Kaitai	Xian Jiaotong Univ.	Professor	2005/1/25–2/5
Math	Helmut Abels	Max Planck Institut	Assis. Professor	2005/2/12–3/28
Phys	Sergei G. Tikhodeev	General Physics Inst. RAS	Head of Lab.	2005/2/17–2/23
Astro	Gerhard Boerner	Max Planck Institut	Professor	2005/2/21–2/23
Math	Reinhard Farwing	Darmstadt Univ. of Tech.	Professor	2005/2/6–2/20
Phys	Jin Ming Yang	Academia Sinica, China	Professor	2005/3/1–3/22
Phys	Arvind S. Vengurlekar	Tata Inst. of Fundamental Research	Professor	2005/3/17–3/18

(3) Invitation list in 2005: We have mainly invited Asian researcher in the symposium that year: In February and March, many researchers were invited from South Korea, Taiwan, and China.

Short-term international visitors in 2005

Affiliation	Name	Affiliation	Position	Period
Phys	X.R. Tata	Univ. of Hawaii	Professor	2005/4/3–4/12
Astro	Jean-Paul Kneib	Inst. of Astrophysics, Marseille	Professor	2005/5/21–5/23
Astro	Peter Hogan	Univ. College Dublin	Professor	2005/5/7–6/7
Astro	Yipeng Jing	Shanghai Observatory	Professor	2005/7/1–7/2
Math	Kim Hyunseok	Korean Inst. of Advanced Sci.	Assoc. Professor	2005/7/17–7/22
Phys	Onuttom Narayan	Univ. of California	Assoc. Professor	2005/7/18–7/29
Math	Vadim Kaimanovich	International Univ. Bremen	Professor	2005/7/2–7/17
Phys	Janos Timar	Inst. of Nuclear Research (ATOMKI)	Senior Research Fellow	2005/7/24–7/31
Astro	Wolfgang Glantzel	Univ. of Gottingen	Professor	2005/9/3–9/10
Phys	Je Geun Park	Sungkyunkwan Univ.	Assoc. Professor	2005/10/13–10/15
Phys	Margaryan Amur	Yerevan Physics Inst.	Leading Sci. Researcher	2005/12/14–12/25
Math	Jaigyoung Choe	Seoul Nat. Univ.	Professor	2006/1/2–1/19
Math	Herman Sohr	Univ. of Paderborn	Professor	2006/1/2–1/25
Math	Reinhard Farwing	Technische Universitat Darmstadt	Professor	2006/1/4–1/25
Astro	Alvio Renzini	Osservatorio Astronomica di Padova	Professor	2006/2/10–2/19
Phys	Jorg Reinhold	Florida International Univ.	Assoc. Professor	2006/2/11–2/19
Astro	Andrei Kototkov	Brown Univ.	Senior Research Assoc.	2006/2/11–2/20
Math	Yuan Lou	Ohio Univ.	Professor	2006/2/12–2/24
Phys	Horst Lenske	Univ. of Giessen	Professor	2006/2/13–2/19
Astro	Bahram Mobasher	Space Telescope Sci. Inst.	Assoc. Professor	2006/2/14–2/19
Phys	Igor S. Aranson	Argonne Nat. Lab.	Staff Physicist	2006/2/14–2/22
Phys	S. Raymond	CEA Grenoble	Sci. Researcher	2006/2/14–2/22
Phys	Daisik Kim	Seoul Nat. Univ.	Assoc. Professor	2006/2/15–2/17
Phys	Ting Kuo Lee	Academia Sinica, China	Research Fellow	2006/2/15–2/18
Phys	Je Geun Park	Sungkyunkwan Univ.	Assoc. Professor	2006/2/15–2/19
Astro	Hyung Mok Lee	Seoul Nat. Univ.	Professor	2006/2/15–2/19
Phys	Carlos Pena Garay	Inst. for Advanced Study	Assoc. Professor	2006/2/16–2/21
Phys	Ward Plummer	Univ. of Tennessee	Professor	2006/2/9–2/19
Phys	Jin Ming Yang	Academia Sinica, China	Professor	2006/3/10–3/31

(4) Invitation list in 2006: We had the symposium sponsored by young researchers of the COE on the end of June.

Short-term international visitors in 2006

学科	Name	Affiliation	Position	Period
Math	Jorg Wolf	Humboldt Universitat	Assoc. Professor	2006/4/17–4/24
Phys	Sandip Pakvasa	Univ. of Hawaii	Professor	2006/4/30–5/11
Phys	Stephen Lovesey	Rutherford-Appleton Lab.	Professor Emeritus	2006/5/15–5/17
Math	Peter Polacik	Univ. of Minnesota	Professor	2006/5/19–6/10
Astro	Bhuvnesh Jain	Univ. of Pennsylvania	Assoc. Professor	2006/6/20–7/4
Phys	Kirill Melnikov	Univ. of Hawaii	Assoc. Professor	2006/6/24–7/2
Phys	Adam Kaminski	Iowa State Univ.	Assis. Professor	2006/6/25–7/2
Math	Jason Metcalfe	Univ. of California	Assis. Professor	2006/6/25–7/3
Phys	Daniel Mannix	ESRF	Assis. Professor	2006/6/26–6/30
Phys	Manfred Sigrist	Swiss Federal Inst. of Tech.	Professor	2006/6/26–7/1
Phys	Ramin Golestanian	Univ. of Sheffield	Assoc. Professor	2006/6/26–7/6
Phys	Philippe Chomaz	Grand Accelerateur Nat. D'Ions Lourds	Sci. Director	2006/6/27–7/2
Phys	Haiyan Gao	Duke Univ.	Assoc. Professor	2006/6/29–7/1
Math	Yiannis Petridis	The City Univ. of New York	Assoc. Professor	2006/7/5–7/21
Phys	Rahul Sinha	High Energy Accelerator Research Org.	Professor	2006/8/29–8/30
Phys	S. Ramakrishnan	Tata Inst. of Fundamental Research	Professor	2006/8/9–8/26
Astro	Peter Hogan	Univ. College Dublin	Professor	2006/9/22–10/9
Astro	Yipeng Jing	Shanghai Observatory	Professor	2006/11/13–11/23
Phys	Andrei G. Lipson	Russian Acad. of Sci.s	Vice Director	2006/11/2–12/2

5 Outreach Activities

The three majors within the COE prepare a variety of materials for outreach programs as follows.

School visits

From 1993, in less than 4 years time, there have been over 70 school visits (Physics 41, Astronomy 5, Mathematics 25). This includes trips to Elementary, Middle, and High Schools, and special training workshops for High School Teachers. We have held activities at all of the central Tohoku region High Schools. Thanks to monetary support for outreach activities from Tohoku branch of the Japan Physics Conference, many of the Physics Department teachers are systematically holding classes at High Schools. Every year as Part of the "Modern Math Lecture Meetings," the Mathematics Department holds two lectures aimed primarily at High School Juniors about the fun parts of mathematics.

Lectures for general audience

In less than 4 years time, there have been 68 General Lecture Meetings (Physics 30, Astronomy 19, Mathematics 19). Six times a year, the Physics Department invites prominent researchers from the entire country to give talks on "The Leading Edge of the Physical Sciences" and in partnership with private enterprises sponsors the public symposium "Tohoku University Physics Experiment Forum (Tohoku University Physics Experimental Technique Exchange Forum)" for the exchange of experimental and computational techniques needed for performing experiments. The Astronomy Department held the "Invitation to Modern Astronomy" 3 times a year at Sendai Observatory, in cooperation to put on the heavenly body telescope observation meetings. The Mathematics Department holds the "Sendai Mathematics Seminar" every August. Regardless of Major, the entire university body helps with the "Tohoku University Science Cafe" for the citizens of Sendai. In addition, every year we hold the Science Open Campus attended by approximately 2000 High school students. The Science Open Campus includes displays, mock lectures and mock experiments.

Public exhibitions and lectures

We sponsor and cosponsor displays for the public. For example, with the Sendai Science Museum, the Physics department helped to plan and put on the "2005 Year in Physics." Over the course of 3 months 9,000 guests visited the Visiting Exhibits Floor of the Sendai Science Museum to see the displays about experiments and equipment, play with the physics toys and watch the public experiments. On holidays, University students went to explain the exhibits to the guests.

Also, as part of the Tohoku University 100 year Anniversary activities, starting on August 20, 2007, the Department of Science held 24 days of open science lectures aimed at the general public. During the first for days, eight members of the COE gave talks to an audience of 160 people.

As shown above, we have a lively outreach program through our regular programs and special activities. At the same time, these outreach activities also serve as an introduction to the COE's research. The number of participating teachers has been limited and we will make increasing the participation is a priority

6 Results of Research

Particle Physics and Astrophysics Group

Quark Hadron Group

Strongly Correlated Electrons Group

Novel Materials Group

Mathematical Science Group

Particle Physics and Astrophysics Group

The particle physics and astrophysics group pioneers new field integrating infinitesimal particle physics world and gigantic world of the universe. What it the origin of the mass? How is the large scale structure of the galaxies made? Why does the universe consist of matter and of no anti-matter? Is there a way to observe interiors of the sun and the earth directly? These fundamental questions and evolving observations can be solved/achieved only through synergies among various fields like particle physics theory / experiment, neutrino research, astronomy and nuclear physics. This group organizes active researchers in these cutting-edge fields and the achievements of this group are reported here.

Early Universe and Particle Physics

Principal Investigator : Kenichi Hikasa (Department of Physics, Professor)
Research Area : Theoretical particle physics
Homepage : *http://www.tuhep.phys.tohoku.ac.jp/*

Main Research Subjects:
*Theoretical research of high energy physics (Higgs sector, SUSY, etc.)

Experimental and Theoretical Study on Cosmic Dark Matter

Principal Investigator : Takashi Ichikawa (Department of Astronomy, Professor)
Research Area : Optical and infrared astronomy
Homepage : *http://www.astr.tohoku.ac.jp/~moircs/index_j.html*

Main Research Subjects:
*The structure and the evolution of nearby galaxies
*Galaxy evolution and distribution in the early universe
*Development of optical and infrared imaging devices

Observation of ^{7}Be Solar Neutrinos and Geo-neutrinos

Principal Investigator : Kunio Inoue (Research Center for Neutrino Science, Professor)
Research Area : Experimental physics of elementary particles
Homepage : *http://www.awa.tohoku.ac.jp/*

Main Research Subjects:
*observation and measurement of reactor-, geo- and low energy solar- neutrinos

Early Universe and Particle Physics

Principal Investigator:
Kenichi Hikasa
(Department of Physics, Professor)
Collaborators:
Masahiro Yamaguchi
(Department of Physics, Professor)
Takeo Moroi
(Department of Physics, Professor)
Toshifumi Futamase
(Department of Astronomy, Professor)
Masashi Chiba
(Department of Astronomy, Professor)
Hitoshi Yamotomo
(Department of Physics, Professor)
Makoto Hattori
(Department of Astronomy, Professor)

Purposes

Current targets of particle physics include the verification of the Higgs sector, which consists an important part of the Standard Model but remains totally untested, and searches for new physics beyond the Standard Model. Although the Standard Model provides a unified picture of the three fundamental forces as gauge interactions, gravity is outside its scope. There are observational evidences which requires physics beyond the Standard Model such as neutrino masses, particle-antiparticle asymmetry of the universe, the existence of dark matter and dark energy, and so on. Many of these are related to the early universe, which prompts collaborational studies between particle physics and astrophysics.

Meanwhile, candidates of the new physics such as supersymmetric models and models with extra dimensions contain new structure in the flavor sector of elementary particles. Test of these theories cannot be done solely at energy-frontier machines. Flavor physics at lower energies can provide complementary information which is very difficult to obtain elsewhere. Our theoretical particle physics group collaborates with astrophysics and experimental particle physics groups in these aspects.

Research Activities

(Theoretical Aspect)

Kobayashi-Maskawa mechanism of CP violation has been verified by experiments at the B factories at KEK and SLAC. Many of the CP asymmetries agree with the expectation from this source of CP violation. Some of the rare B decays caused by the neutral current transition of a bottom quark to a strange quark show deviation from the Kobayashi-Maskawa predictions, however. In supersymmetric models, this kind of deviation may arise from the mass mixing of squarks. We have found that the pattern of deviation is different for left-handed and right-handed squark mixings. The effect has the same sign in the decays $B \to \phi K$ and $B \to \eta' K$ in the former case, while the sign is opposite in the latter case [1]. These decays thus may provide important information in the flavor structure of supersymmetric particles.

The gravitino is the supersymmetric partner of the graviton. It is typically very long lived and can easily cause problems in early cosmology. In particular, primordial nucleosynthesis, one of the very successful prediction of the Big-Bang cosmology, may be disturbed by the gravitino decay. We have refined the calculation of gravitino decay processes with hadrons in the final state and found that former limits on the gravitino density should be modified drastically [2].

(Experimental Aspect)

The electron positron collider group is currently engaged in the physics analysis and upgrade of the Belle experiment at the KEK B factory, and in the preparation for ILC (International Linear Collider) . The hardware projects of the Belle experiment that the Tohoku group has worked on are the end cap muon system (KLM) and the interaction region. The Tohoku group was the main group to design and build the KLM endcap, and its maintenance continues today. The design and fabrication of the interaction region upgrade, which started about 5 years ago, was led by the Tohoku group in collaboration with KEK, and we have succeeded in reducing the radius of the collision point beampipe from 2 cm to 1.5 cm while the beam intensity increased dramatically. This improved the impact parameter resolution by roughly 25% as expected.

For Belle physics analyses, we have been pursuing measurement of the CP violating angle phi3, and search for rare decays of tau lepton and charm mesons. A Tohoku master student has discovered the flavor-changing radiative decay of charmed meson for the first time, and the result became a press release at the 2004 international confer-

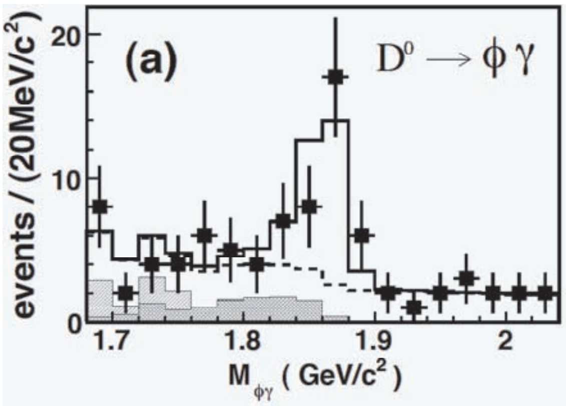


Figure 1:

ence of high energy physics [3]. The measurement of phi3 using DK mode, which is considered to be the only model-independent technique to measure phi3, is led by the Tohoku group[4].

The main goal of ILC is precision measurements of Higgs particle which is considered to be responsible for creation of masses of elementary particles. The ILC project is currently rapidly progressing and the Tohoku group is engaged in both software and hardware aspects of the project. We act as the Asian representative of the worldwide study on physics and detector of linear collider (WWS) and as the principal investigator of the JSPS creative scientific research program for development of ILC detector which accounts for a majority of the funding on ILC detector in Japan. Tohoku university is now one of the key bases of the ILC project.

Experimental and Theoretical Study on Cosmic Dark Matter

Principal Investigator:
Takashi Ichikawa
(Department of Astronomy, Professor)
Collaborators:
Toshifumi Futamase
(Department of Astronomy, Professor)
Masashi Chiba
(Department of Astronomy, Professor)
Masahiro Yamaguchi
(Department of Physics, Professor)
Yoshiaki Taniguchi
(Department of Astronomy, Professor)
Kunio Inoue
(Research Center for Neutrino Science, Professor)
Masahiro Takada
(Department of Astronomy, Assistant Professor)

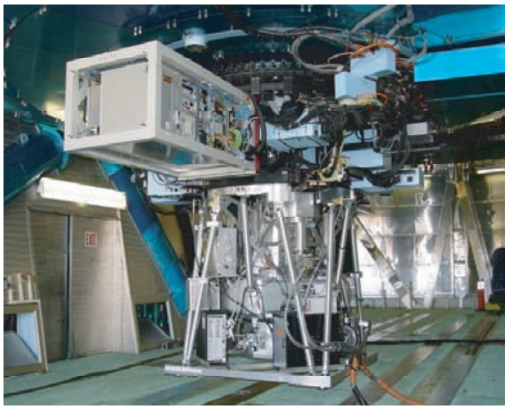


Figure 2: MOIRCS installed on the Subaru telescope

Purposes

The understanding of structure formation and the elucidation of the nature of dark matter and dark energy are unsolved problems in modern cosmology. For the understanding of these matter the astronomy group of our COE program has constructed the construction of multi-object near infrared camera and spectrograph (MOIRCS) for Subaru telescope and studied gravitational lensing.

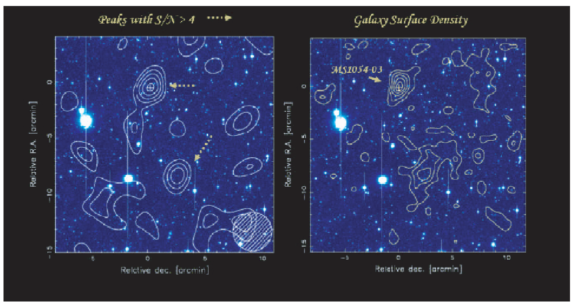


Figure 3: Gravitational lensing observation of high red-shift galaxy clusters with the Subaru telescope

Research Activities

The birth and evolution of galaxy in the early universe depends strongly on the distribution of dark matter that dominates the material context of the universe and dark halos. Although dark halos are not directly observed, we can infer their distribution from the distribution of galaxies. In particular, the distribution of small galaxies gives us a clue to know the evolution of dark halos since the small galaxies are assembled to become large galaxies. However the light from the early galaxies shift to infrared because of Doppler shift by the cosmic expansion. Furthermore most stars in galaxy emit the electromagnetic waves in the optical band, the near infrared observation is most suitable for the study of the distribution of galaxies in the early universe. Thus the group by Ichikawa at Astronomical Institute and Hawaii Observatory of National Astronomical Observatory of Japan developed multi-Object Infrared Camera and Spectrograph (MOIRCS) for Subaru telescope which has the widest field of view in the 8-10 m class telescopes. The first observation was made in 2004 and then made experimental observation for about 1 year, MOIRCS. After that we have proved that MOIRCS have the world best properties in the near infrared observation. By using MOIRCS we have been observing low mass galaxies when the universe is about 25 billion years old that was very difficult so far. We have obtained the spatial distribution of the low mass galaxies whose stellar mass is less than 10 . solar mass, and found that such a low mass galaxy was contained in a dark halo with 10 solar mass in such a young age of the universe and then evolved together with the same number density.

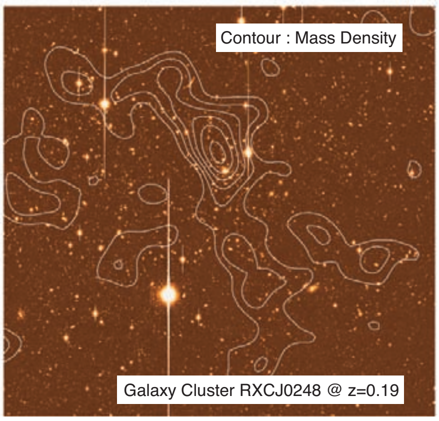


Figure 4:

As far as gravitational lensing study is concerned, we have carried out the lensing observation of nearby clusters of galaxies and the systematic study of statistical properties of their mass distribution. This is collaboration with the observation made by Hubble space telescope. Cluster of galaxies is the biggest self-gravitating system in the universe and it is regarded that the statistical nature of its mass distribution depend on process of structure formation and the nature of dark matter in the cold dark matter scenario which predicts that objects with smaller scales are assembled to larger objects. In order to accurately determine the mass distribution of clusters of galaxy from the center to the surrounding region, we use Hubble telescope that has very high resolution but small field of view to discover the lensing images in the central region of clusters and use Subaru telescope with wide field of view to observe distortions of shapes of background galaxies by gravitational lensing of clusters. We have already about 10 nearby clusters and will observe more in the near future to have precise statistical information on the mass distribution and thus we will have important information on the nature of dark matter and the details of the structure formation in the universe.

Observation of ^{7}Be Solar Neutrinos and Geo-neutrinos

Principal Investigator:
Kunio Inoue
(Research Center for Neutrino Science, Professor)
Collaborators:
Junpei Shirai
(Research Center for Neutrino Science, Professor)
Fumihiko Suekane
(Research Center for Neutrino Science, Professor)
Masayuki Koga
(Research Center for Neutrino Science, Professor)
Tadao Mitsui
(Research Center for Neutrino Science, Professor)
Yasuhiro Kishimoto
(Research Center for Neutrino Science, Assistant Professor)
Sanshiro Enomoto
(Research Center for Neutrino Science, Assistant Professor)
Nororu Takigawa
(Department of Physics, Assistant Professor)
Hideyuki Saio
(Department of Astronomy, Assistant Professor)

Purposes

Understanding properties of neutrinos propels particle physics studies like grand unified theories and also contributes to cosmology and astrophysics researches. In addition, a characteristic feature of neutrinos, "easily penetrating matter", is applicable to explore optically invisible interiors of the sun and the earth. But the application requires precise knowledge of the neutrino propagation.

Research Activities

In order to understand neutrino properties, artificial neutrino sources such as a nuclear reactor and an accelerator are quite effective. The KamLAND experiment utilizes its high sensitivity for detecting anti-neutrinos from distant nuclear reactors around 180 km. It has succeeded to observe a smoking gun evidence of the neutrino oscillation in its energy spectrum and has measured neutrino mass difference very precisely. The analysis based on the 515 days of data[7] has shown the fact that neutrinos disappear and reappear repeatedly during their propagation by investigating survival probability dependence on LE. The achieved precision on the squared neutrino mass difference with the analysis is; $\Delta m^2_{21} = 7.9^{+0.4}_{-0.3} \times 10^{-5}\,\mathrm{eV}^2$. Further improvements on the precision is going on by accumulating more data with an expanded fiducial volume and by employing an all position calibration device which will eliminate the current dominant systematic error from the fiducial volume determination.

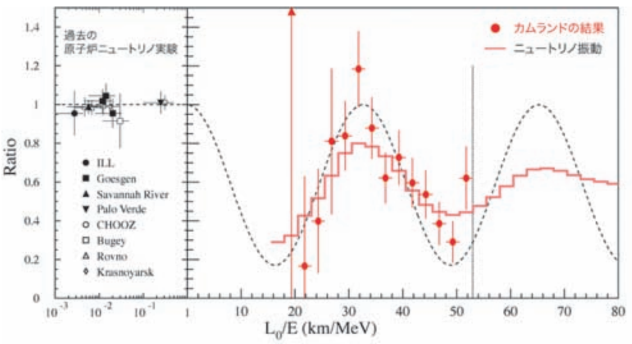


Figure 5: Oscillatory behavior of reactor neutrinos observed by the KamLAND experiment

Thanks to the precise measurement of the neutrino propagation, neutrinos are now applicable as a probe to investigate interiors of astronomical objects. The KamLAND experiment, at first, demonstrated the application to an exploration of the interior of the earth[8]. The earth is generating about 40 TW of heat supposed to mainly come from decays of radio-active isotopes. Those decays release anti-neutrinos and the heat at the same time. Detection of these anti-neutrinos is a bland-new method to observe and verify the heat generation of the earth. Although the heat generation in the earth is the most important parameter to understand the earth formation, earthquake, terrestrial magnetism and so on, it was difficult to establish a reliable chemical composition of the whole earth from the limited knowledges based on meteorite analyses and surface rock analyses. On the contrary, neutrinos can bring a global information of the heat generation and may provide a new knowledge on an elemental distribution at the deep inside of the earth. The KamLAND experiment observed an excess of 25^{+19}_{-18} events above the known backgrounds in the 750 days of data, where a model predicts 19 geo-neutrino events. It is quite important that the KamLAND experiment succeeded to establish a method to observe geologically produced anti-neutrnios. The achieved error is still large due to large background contributions from nuclear reactors and radioactive impurities. However, the KamLAND experiment is reducing radioactive impurities by a new purification method and accumulating more data and the precision will be improved in the near future.

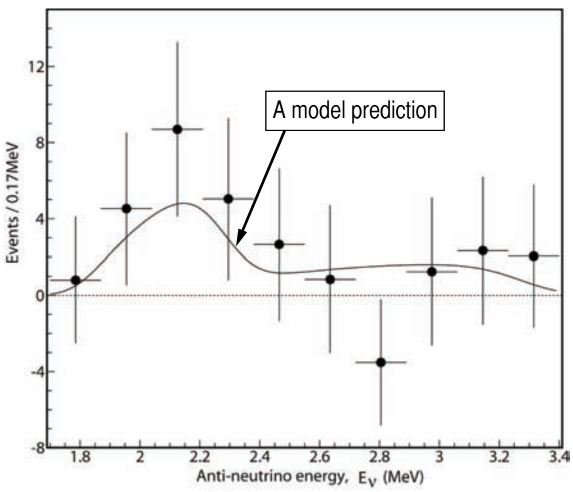


Figure 6: Observed energy spectrum of geologically produce anti-neutrinos (after background subtraction)

Another application of neutrinos is an observation of the nuclear fusion reaction taking place at the center of the sun. So far, realtime counting experiments have measured only high energy portion of ^{8}B neutrinos of which the branching ratio is only 0.02%. The KamLAND experiment has a sensitivity to low energy neutrinos and it is aiming at an observation of ^{7}Be neutrinos with 14% blanching ratio. The measurement of the dominant composition will help understanding interior of the sun more effectively. At the same time, the CNO cycle neutrinos and low-energy portion of ^{8}B neutrinos enter the scope of the KamLAND. It is expected to achieve the initial motivation of solar neutrino observation to distinguish the pp-chain and the CNO cycle, and the confirmation of the spectrum distortion due to the matter effect of the neutrino oscillation. A new purification device using distillation method has been constructed and a development of a new dead-time free electronics is proceeding well. These solar neutrino observations with KamLAND are expected to strongly propel neutrino astrophysics in the near future after a success of the background reduction.

Selected Publications

1. Recent measurements of CP asymmetries of $B \to \phi K_0$ and $B \to \eta' K_s$ at B factories suggest new CP violation in left-handed squark mixing, M. Endo et al., Phys. Lett. B **609**, 95 (2005).
2. Hadronic decay of late-decaying particles and Big-Bang nucleosynthesis, M. Kawasaki et al., Phys. Lett. **B** 625, 7 (2005).
3. Observation of the decay $D_0 \to \phi\gamma$, O. Tajima et.al. Phys. Rev. Lett. 92, 101803 (2004).
4. Study of suppressed decay $B \to (K\pi)DK^-$ and $(K\pi)D\pi^-$, M. Saigo et.al. Phys. Rev. Lett. 94, 091601 (2005).
5. MOIRCS : multi-object infrared camera and spectrograph for SUBARU Ichikawa, T et al. SPIE, 6269, 38, (2006).
6. Cosmology with High-redshift Galaxy Survey : Neutrino Mass and Inflation. M. Takada, E. Komatsu and T. Futamase, Physical Review D73, 083520 (2006).
7. Measurement of Neutrino Oscillation with KamLAND: Evidence of Spectral Distortion. KamLAND collaboration, Phys. Rev. Lett. 94, 081801 (2005).
8. Experimental investigation of geologically produced antineutrinos with KamLAND. KamLAND collaboration, Nature 436, 499-503 (2005).

Quark Hadron Group

Our world of matter began from the world made of elementary particles after the big bang, followed by the world of hadrons as quark many-body systems, and then that of atomic nuclei as hadronic many-body systems. Various nuclei (elements) were synthesized in stars, and then supernova explosion produced heavy nuclei and high density nuclear matter inside neutron stars. We aim at unified understanding of this whole history of matter evolution on quark and hadron many-body systems, through combined researches on strangeness nuclear physics, unstable nuclear physics, elementary particles and astrophysics. We also study various effects of circumstance in the upper level hierarchy influenced to quantum states in the lower level hierarchy, by investigating possible changes of nuclear reaction and decay rates in condensed matter as well as modification of hadron properties in nuclear matter.

Evolution of matter on quark and hadron many-body systems

Principal Investigator: Osamu Hashimoto (Department of Physics, Professor)
Research Area: Experimental nuclear physics
Homepage: *http://lamdba.phys.tohoku.ac.jp/*

Main Research Subjects:
- Strangeness nuclear physics
  High resolution spectroscopy of Λ hypernuclei with electron beams
  Precision γ-ray spectroscopy of hypernuclei
  Mechanism of strangeness production via electromagnetic interaction
- Unstable nuclear physics with radioactive ion beams
  Studies by proton knock-out reactions
  $E0$ giant resonance of neutron-rich nuclei by zero-degree proton inelastic scattering
  Structure of neutron-rich nuclei by Coulomb break-up reactions
- Unstable nuclear physics at the Cyclotron RI Center
  RF ion guide for on-line mass separator and heavy neutron-rich nuclei
  Nuclear structure studied by in-beam γ-ray spectroscopy

Control of reaction rates and lifetimes in quantum states

Principal Investigator: Jirota Kasagi (Department of Physics and Laboratory of Nuclear Science, Professor)

Research Area: Experimental nuclear physics
Homepage: *http://www.lns.tohoku.ac.jp/˜ hadron/*

Main Research Subjects:
- Low energy nuclear reactions in metal
- Change of nuclear lifetimes in matter
- Nucleon resonances in nuclear matter

Evolution of matter on quark and hadron many-body systems

Principal Investigator:
Osamu Hashimoto
(Department of Physics, Professor)
Collaborators:
Hirokazu Tamura
(Department of Physics, Professor)
Satoshi N. Nakamura
(Department of Physics, Associate Professor)
Toshio Kobayashi
(Department of Physics, Professor)
Tsutomu Shinozuka
(Cyclotron RI Center, Associate Professor)
Ken'ichi Hikasa
(Department of Physics, Professor)
Seiji Tanabashi
(Department of Physics, Associate Professor)
Yukinari Sumino
(Department of Physics, Assistant Professor)
Hideyuki Saio
(Department of Astronomy, Professor)
Yuu Fujii
(Department of Physics, Assistant Professor)
Mifuyu Ukai
(Cyclotron RI Center, Postdoctoral fellow)
Mizuki Sumihama
(Department of Physics, Postdoctoral fellow)

Results

(1) Strangeness Nuclear Physics

We investigate detailed structure of Λ hypernuclei (nuclei with strangeness), in order to understand the baryon-baryon interactions as the extended nuclear force and to explore high density nuclear matter in neutron stars which is expected to contain strangeness. We also study hadron reactions with strangeness as a probe to understand hadron structure as quark many-body systems.

High resolution spectroscopy of Λ hypernuclei with electron beams

In 2000 we succeeded in high-resolution spectroscopy of Λ hypernuclei using the (e, eK^+) reaction for the first time. In order to pursue this research further, we built a dedicated magnetic spectrometer for kaon momentum analysis, HKS (Fig. 1). The HKS consists of one dipole magnet and two quadrupole magnets. Together with a newly developed detector system, the HKS was installed at the Hall C in the Jefferson Laboratory in U.S., and the experiment E01-011 was performed using this spectrometer system. The preliminary analysis result showed that the HKS achieved the world-best energy resolution of ∼700 keV(FWHM) and a $^{12}_{\Lambda}$B hypernuclear spectrum was obtained with high statistical quality. We also obtained a spectrum for $^{28}_{\Lambda}$Al for the first time. Efforts are being made to improve the analysis program to achieve better resolution. In addition, we have been constructing a new spectrometer for scattered electrons, HES, to investigate heavier hypernuclei and neutron-rich hypernuclei.

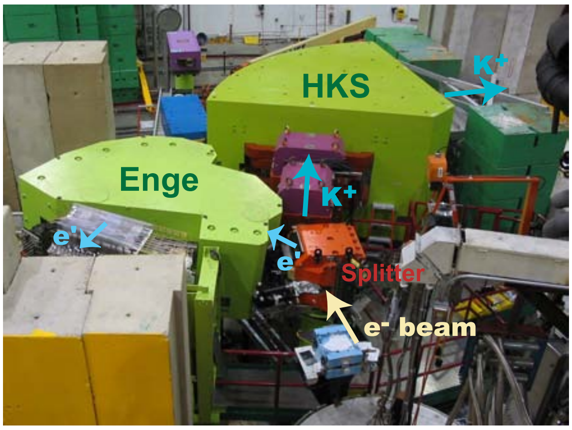


Figure 1: The high resolution kaon spectrometer (HKS) constructed for hypernuclear spectroscopy and installed at the Jefferson Laboratory.

Precision γ-ray spectroscopy of hypernuclei

Since the first success of precision γ-ray spectroscopy of Λ hypernuclei using a germanium detector array, Hyperball, we have investigated γ transitions of various *p*-shell hypernuclei at the KEK-PS and BNL-AGS accelerators. We observed two γ transitions in $^{16}_{\Lambda}$O from the 6.6 MeV excited states to the ground states doublet members. Their energy difference showed that the spacing of the doublet is only 26 keV, from which we successfully extracted the strength of the tensor interaction between a Λ and a nucleon. Thus we have determined all the spin-dependent interaction strengths including the spin-spin and spin-orbit interactions. We also succeeded in a γγ coincidence measurement and measured the $^{7}_{\Lambda}$Li$(7/2^+, 5/2^+)$ doublet spacing.

We constructed the upgraded Ge detector array, Hyperball2 (Fig. 5), performed experiments to study ${}^{11}_{\Lambda}$B and ${}^{12}_{\Lambda}$C hypernuclei, and observed their γ transitions. In addition, we have been developing and constructing a new generation Ge detector array, Hyperball-J, which will be used at the high intensity accelerator facility, J-PARC.

Mechanism of strangeness production via electromagnetic interaction

In order to understand strangeness production mechanism via electromagnetic interaction, we are investigating the $\gamma n \to \Lambda K^0$ process in the threshold region of which data have been missing. We constructed the Neutral Kaon Spectrometer (NKS) and installed it at the Laboratory of Nuclear Science. We irradiated a liquid deuterium target with tagged photon beams around 1 GeV and analyzed two charged pions from K^0 decay using the NKS. Thus we successfully measured the cross section of this process for the first time. This result gives strong restrictions to theoretical models for strangeness production reaction mechanism. We have recently built an upgraded apparatus, NKS2 (Fig. 2), and are performing an experiment which covers a wider kinematical region and allows detection of Λ decay process with higher statistics.

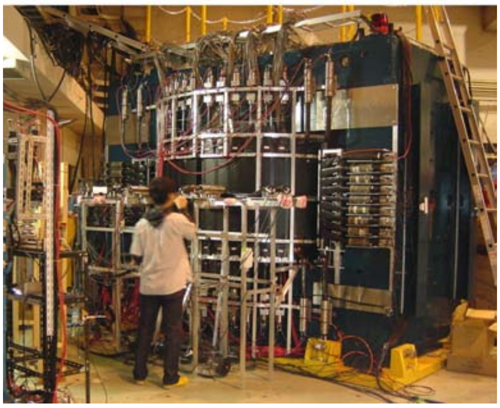


Figure 2: The second-generation Neutral Kaon Spectrometer, NKS2, constructed for the study of the $\gamma n \to \Lambda K^0$ process.

(2) Unstable nuclear physics with radioactive ion beams

Studies by proton knock-out reactions

We measured the ${}^{9-16}$C$(p, 2p)$ reaction using a detector system shown in Fig. 3 in the HIMAC accelerator facility. In these neutron-rich nuclei we systematically observed proton hole states of inner shell orbitals deeply bound by 20–45 MeV. Their momentum distributions indicate that the charge radii for the inner proton orbitals are contracted by 25% in the neutron-rich side. We also studied weakly to strongly bound outer proton orbitals and found that the effective nucleon number is increased by 60% for the weakly-bound nucleus ^{9}C.

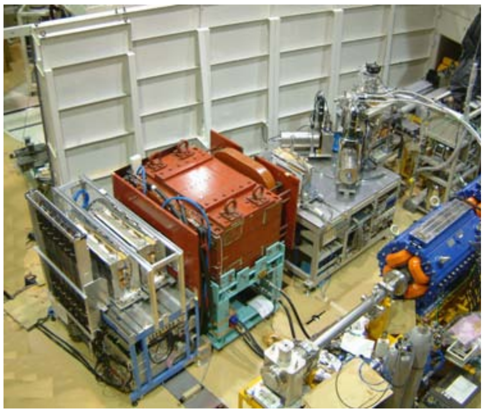


Figure 3: Detector system for proton knock-out reaction experiments installed at HIMAC.

$E0$ giant resonance of neutron-rich nuclei by zero-degree proton inelastic scattering

We have fabricated a 180^0 bending type of magnetic spectrometer and performed an experiment for a neutron-rich nucleus, ^{38}S, at the RIKEN accelerator facility. Various background processes have been reduced, and a structure observed in the excitation energy spectrum implies an E0 and E1 giant resonances.

Structure of neutron-rich nuclei by Coulomb breakup reactions

We measured the invariant mass in the Coulomb breakup reaction of ^{11}Li and found that the correlation of the weakly-bound two valence neutrons plays an important role in the ^{11}Li ground state.

(3) Unstable nuclear physics at the Cyclotron RI Center

RF ion guide for on-line mass separator and heavy neutron-rich nuclei

In order to establish the scenario of nucleosynthesis via the r-process originating in supernova

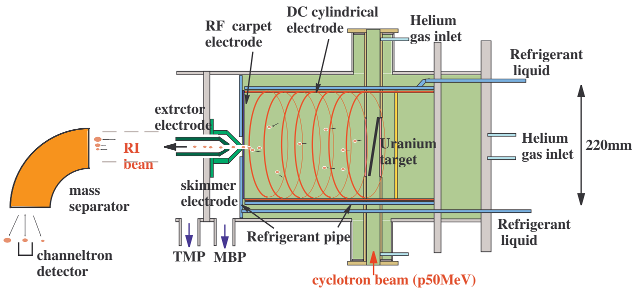


Figure 4: The developed RF ion guide (second version)

explosion, detailed investigation of neutron-rich nuclei with the mass number larger than 50 is indispensable. However, it is difficult to produce such heavy neutron-rich nuclei as radioactive isotope (RI) beams by the projectile fragmentation reaction with intermediate energy heavy ion beams, which is usually used for lighter neutron-rich nuclei. On the other hand, the RI beam production methods (ISOL) from the target fragmentation reaction with proton beams or from the fission reaction with reactor neutrons have been used to study neutron-rich nuclei of only a limited number of elements because of technical difficulties in their production and extraction. In our project, the ion guide method, which allows fast and efficient separation and transport of short-lived unstable nuclei, has been extended to the "RF ion guide method" by enlarging the volume of the isotope collection chamber and introducing DC and RF electric fields. This method enables faster and more efficient extraction of unstable isotopes into the mass separator.

After various developments we succeeded in collection and separation of neutron-rich unstable nuclei which have not been able to be separated in the previous ion source method as in ISOLDE. For example, we separated 2000 atoms/s of the ^{112}Rh isotope with a half life of 10 s. We are designing the finished type of the apparatus which is expected to achieve 10 times more yield.

The new cyclotron can deliver a high intensity proton beam as negative hydrogen ions (50 MeV 30μA). With this beam, we plan to produce high intensity fast neutron beam, which will be used to induce fission reaction of uranium and other nuclei to produce and separate short-lived neutron-rich nuclei such as ^{78}Ni.

Nuclear structure studied by in-beam γ-ray spectroscopy

We constructed a germanium detector array, Hyperball2 (Fig. 5), consisting of six Clover-type Ge detectors (the relative efficiency of each detector is 125%) and fourteen Ge detectors (the relative efficiency of 60%). We have started a research project on nuclear structure via in-beam γ-ray spectroscopy by using this apparatus and employing heavy ion beams developed in the Cyclotron RI Center.

When a nucleus has a triaxial asymmetry and the left and right handed systems are discriminated, almost degenerate two rotational bands (chiral bands) are predicted to appear. Observations of candidates for the chiral bands have also been reported. We are searching for chiral bands in the mass region around 80, by producing excited states of ^{79}Kr and ^{80}Br via fusion reactions ^{70}Zn(^{13}C, 4n) and ^{70}Zn(^{13}C, p2n) and measuring γ rays from them using Hyperball2.

In addition, the preparation of the heavy ion beams and the high efficiency detector array allows observation of high spin states with smaller production cross sections. We detected the 27/2$^-$ high spin isomer in ^{93}Mo and determined the g-factor of the 27$^-$ high spin isomer in ^{152}Dy, both of which enabled us to determine the particle configurations of these medium heavy nuclei.

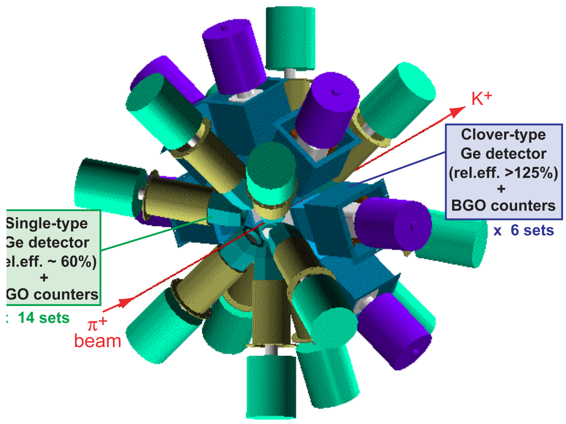


Figure 5: A large Ge detector array, Hyperball2, used for precise γ spectroscopy of hypernuclei and in-beam γ-ray spectroscopy of ordinary nuclei at the Cyclotron RI Center.

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1. High resolution spectroscopy of the $^{12}_{\Lambda}$B hypernucleus produced by the $(e, e'K^+)$ reaction,
T. Miyoshi, O. Hashimoto, S.N. Nakamura *et al.*,
Phys. Rev. Lett. **90** (2003) 232502.
2. Hypernuclear fine structure in $^{16}_{\Lambda}$O and the ΛN tensor interaction,
M. Ukai, H. Tamura, O. Hashimoto *et al.*,
Phys. Rev. Lett. **93** (2004) 232501.
3. Cascade gamma decay in the $^{7}_{\Lambda}$Li hypernucleus,
M. Ukai, H. Tamura, O. Hashimoto *et al.*,
Phys. Rev. **C 73** (2006) 012501.
4. Observation of strong low-lying $E1$ strength in the two-neutron halo nucleus ^{11}Li,
T. Nakamura, T. Kobayashi *et al.*,
Phys. Rev. Lett. **96** (2006) 252502.
5. Development of the RF-IGISOL at CYRIC,
T. Sonoda, T. Shinozuka *et al.*,
Nucl. Instr. Meth. **B 254** (2007) 295.

Control of reaction rates and lifetimes in quantum states

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Results

(1) Low energy nuclear reactions in metal

It has been found that the reaction rate of the D+D reaction is largely enhanced in metal. It is phenomenologically interpreted as a large dependence of the screening potential on the host metal. But the large screening potential more than 300 eV cannot be theoretically understood because the effect of free electrons in metal is estimated to be less than 50 eV. It is to be noted that the observed large screening potential applied to a ultra low energy D+D reaction suggests that the nuclear reaction can be observed even in room temperature. The measurement of the nuclear reaction in Pd metal at a ultra low energy is an interesting subject. Following the previous Li+D reaction experiment in Pd metal, we have started systematic experiments to measure the target temperature dependence of the Li+D reaction rate using a lithium metal target, in order to investigate the effect of circumstance of the target nuclei to the reaction rate. Figure 6 shows the ^{6}Li(d,α)^{4}He reaction rate at 60 keV beam energy as a function of temperature. We found that the reaction rate increases by a few % at the melting point of lithium metal, gradually decreases as the temperature goes up, and then rapidly increases at the temperature ($\sim$ 390^{0}C) for the liquid-gas mixed phase. Quantitative explanation is an important subject in future.

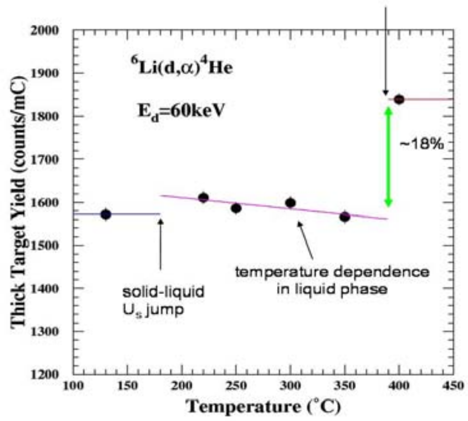

Figure 6: Reaction rate of the ^{6}Li(d,α)^{4}He reaction for 60 keV deuterons injected into Pd metal plotted as a function of the temperature.

(2) Change of nuclear lifetimes in matter

We have performed precise measurement of lifetimes of ^{7}Be nuclei inserted in a spherical molecule, C_{60} fullerene. The ^{7}Be nucleus decays via the electron capture process into the first excited state of ^{7}Li and emits 432 keV γ ray. Figure 7 shows the result of γ-ray yield measured for 160 days (Red and blue points show the yields when ^{7}Be is inserted in C_{60} and in Be metal, respectively). This result evidently indicates that the ^{7}Be lifetime decreases almost by 1% in C_{60}. A calculation from the first principle was performed and showed that the Be atom can stays in the center of the fullerene. It is suggested that in this case the electron density increases at the position of the Be nucleus and enhances the electron capture rate. In the future we plan to measure the temperature dependence of the lifetime change precisely in order to elucidate the mechanism of the lifetime change and to pursue future applications.

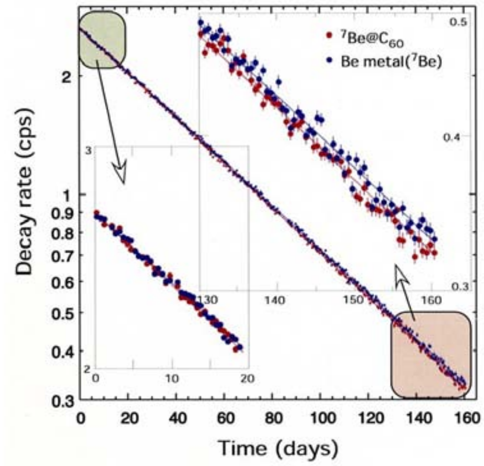

Figure 7: Decay time spectrum of ^{7}Be inserted in C_{60} fullerene and in Be metal.

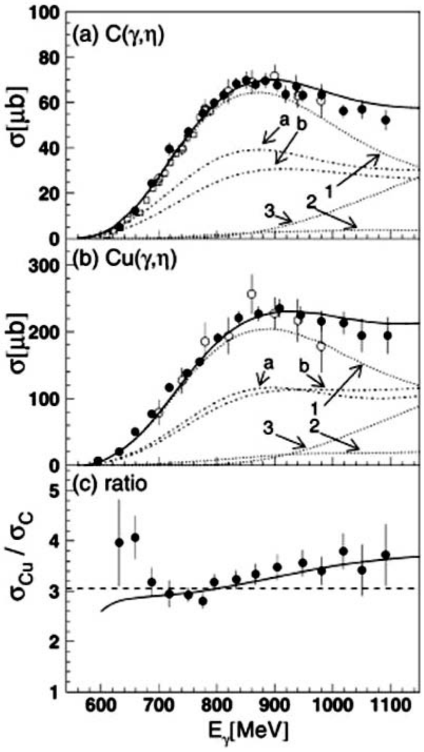

Figure 8: $\gamma N \to \eta N$ reaction cross sections measured on C and Cu nuclear targets as a function of the incident γ-ray energy. Their ratio is also shown.

(3) Nucleon resonances in nuclear matter

In order to study modification of hadron property in nuclear matter, we have investigated the process of nucleon excitation $S_{11}(1535)$ in a nucleus. We have irradiated GeV γ rays into C and Cu nuclei and studied the $\gamma N \to \eta N$ reaction on a nucleon in a nucleus. Figure 8 (a) and (b) shows the excitation curve of the reaction cross section on C and Cu targets, respectively. We observed a broad resonance peak at $E_{\gamma} \sim 900$ MeV, which includes a large contribution of the $S_{11}(1535)$ excitation. This result was compared with the calculation based on the quantum molecular dynamics model (solid curve). The experimental result cannot be reproduced if the elementary cross section is reduced due to the predicted mass reduction. The calculated curve, however, overestimates the experimental data at a higher energy region, which suggests more precise data is necessary. We are planning to employ a new detector system, FOREST, and measure the $\gamma p \to \eta p$, $\gamma n \to \eta n$ cross sections precisely.

Selected Publications

1. Strongly enhanced Li + D reaction in Pd observed for deuteron bombardment on PdLi$_x$ with energies between 30 and 75 keV,
J. Kasagi *et al.*,
J. Phys. Soc. Jpn. **73** (2004) 608.
2. Enhanced electron-capture rate of ^{7}Be encapsulated in C_{60} cages,
T. Ohtsuki, J. Kasagi *et al.*,
Phys. Rev. Lett. **93** (2004) 112501.
3. Photoproduction of η-meson off C and Cu nuclei for photon energies below 1.1 GeV,
T. Kinoshita J. Kasagi, H. Shimizu *et al.*,
Phys. Lett. **B 639** (2006) 429.
4. Photoproduction of eta mesons off protons for $E_{\gamma} <$ 1.15 GeV,
T. Nakabayashi, J. Kasagi, H. Shimizu *et al.*,
Phys. Rev. **C 74** (2006) 035202.

Strongly Correlated Electrons Group

This research group has investigated the novel properties of transition metal oxides and rare earth compounds due to the strong electron correlation. The aim of the research is to elucidate the formation mechanism of the electric and magnetic properties by observing the multipole ordered states and the fluctuation of electronic degrees of freedom. The techniques of synchrotron radiation and neutron scattering experiments have been developed to detect the ordering and the fluctuation. The experimental group closely collaborates with the theoretical group in the research and the development.

Observation of orbital and charge orderings
-Development and application of resonant x-ray scattering technique-

Principal Investigator: Youichi Murakami (Department of Physics, Professor)
Research Area: Materials Structural Physics
Homepage: *http://calaf.phys.tohoku.ac.jp/index-j.html*

Main Research Subjects:
- Charge and orbital ordering and the fluctuation studied by resonant x-ray scattering
- Development of experimental techniques in synchrotron x-ray and neutron scattering

Hierarchical structure in electronic multipole orders and fluctuations

Principal Investigator: Yoshio Kuramoto (Department of Physics, Professor)

Research Area: Condensed Matter Theory
Homepage: *http://www.cmpt.phys.tohoku.ac.jp/~qmbt/*

Main Research Subjects:
- Multipole orders and excitations probed by neutron and X-ray scatterings
- Properties associated with multipolar transitions and their hierarchy
- Interactions between multipoles and conduction electrons

Observation of orbital and charge orderings -Development and application of resonant x-ray scattering technique-

Principal Investigator:
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Collaborators:
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(Department of Physics, Research Associate)
Hiroshi Kira
(Department of Physics, Research Associate)

Results

(1) Development of resonant x-ray scattering (RXS) techniques

Resonant x-ray scattering has been developed as a powerful technique to observe the orbital ordering in correlated electron systems. However, the scattering mechanism has been controversial, especially in K-absorption edge resonance of transition metal oxides. We have made it clear by measuring the interference terms between the resonant scattering term and the Thomson scattering term, or between the resonant terms of dipolar (E1) and quadrupolar (E2) transition processes. The results indicate that the Jahn-Teller mechanism is more responsible than the Coulomb mechanism in an eg electron system ($La_{0.5}Sr_{0.5}MnO_3$ thin films) of $3d$ transition metal oxide, but it is the opposite way in a t_{2g} electron system ($YTiO_3$) of $3d$ transition metal oxides and a $4f$ electron system (DyB_2C_2). We have shown that the RXS intensities of $Y_{1-x}Ca_xTiO_3$ at Ti K-edge (main-edge) energy are determined on the basis of the scattering mechanism as shown in Fig. 1.

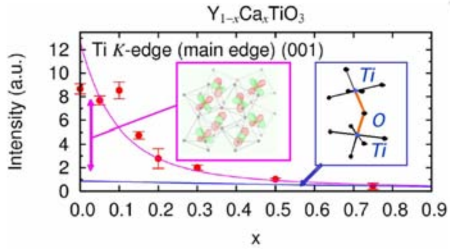

Figure 1: The Ca concentration dependence of RXS intensities at Ti K-edge energy in $Y_{1-x}Ca_xTiO_3$.

(2) Hole dynamics in spin and orbital ordered vanadium perovskites

A theory of doped perovskite vanadates with spin and orbital orders is developed. Mobile holes are strongly renormalized by spin excitations (magnons) in the spin G-type and orbital C-type (SG-OC) order, and orbital excitations (orbitons) in the spin C-type and orbital G-type (SC-OG) one. Hole dynamics in a staggered t2g orbital array is distinguished from that in the antiferromagnetic order and the eg orbital one. The fragile character of the (SG-OC) order in $Y_{1-x}Ca_xVO_3$ is attributed to the orbiton softening induced by a reduction of the spin order parameter.

(3) Orbital ordering and the impurity effect in copper fluorides

The impurity effect on the ordered states of strongly correlated electron systems has attracted a great deal of interest. We have been interested in the impurity effect on orbitally ordered systems and investigated the effect on a typical orbital ordering system $KCuF_3$ by substituting Zn ($3d^{10}$) for Cu ($3d^9$). Powder x-ray diffraction and RXS experiments were carried. The Cu concentration vs. temperature phase diagram of $KCu_xZn_{1-x}F_3$ has been determined as shown in Fig. 2. It has been found that the orbital ordering disappears at $x = 0.543 \pm 0.005$ with decreasing Cu concentration. This order-disorder concentration is much lager than that of the spin percolation threshold in the three-dimensional system. The result is consistent with the recent theoretical work. In order to study the local electronic state, the RXS was applied at Zn and Cu K-absorption edge energies. The result indicates the local orbital pseudo-spin of the Cu ions neighboring on the Zn ions is fairly tilted.

(4) Quadrupolar frustration in Shastry-Sutherland lattice of RB_4 studied by resonant x-ray scattering

Magnetic materials with geometrically frustrated magnetic interactions exhibit a wide variety of intriguing phenomena caused by fluctuating spins

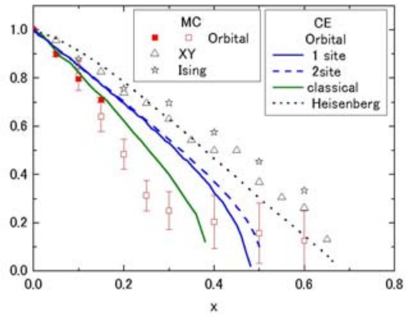

Figure 2: The Cu concentration vs. temperature phase diagram of $KCu_xZn_{1-x}F_3$.

that cannot order down to very low temperatures. These exotic phenomena are caused by the spin degree of freedom of the magnetic ions. On the other hand, there are only a few examples that suggest frustration of the orbital degree of freedom. Here we have presented direct evidence for fluctuating quadrupolar and magnetic moments in a rare-earth compound, RB_4 (R = Dy, Ho, Tb), which has a Shastry-Sutherland type geometrical frustration. The RXS at the L absorption edge of Dy was utilized in DyB_4. Analysis of the energy, polarization, temperature, and azimuthal-angle dependences of the E1 resonance of the (100) forbidden reflection show that the magnetic and quadrupolar components within the frustrated c-plane have a short-range correlation, suggesting that the moments are fluctuating. In contrast, the basic antiferromagnetic component along the c-axis has a long-range order. In HoB_4 the magnetic order is competing with the quadrupole order. It is found the magnetic order is also a short-range one in the intermediate phase.

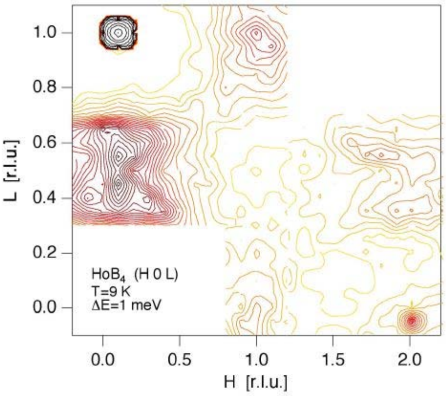

Figure 3: The magnetic scattering intensities in the paramagnetic phase of HoB_4. Two types of magnetic correlations around (0 0 0.5) and (1 0 1) coexist.

(5) Magnetic phase separation of manganite nanocrystals in mesoporous silica

Strongly correlated electron (SCE) nanocrystals are also unique objects with the new surface effect in the fundamental science. To study the characteristic structures and electronic states in the magnetic SCE nanocrystals, we have synthesized a perovskite-type manganite $LaMnO_3$ (LMO) with the average size 20 ± 5 nm by using mesoporous silica MCM-41 as a nano-size test tube. The magnetization, susceptibility, and neutron diffraction measurements have revealed that the ferromagnetism with $T_C = 260$ K coexists with the antiferromagnetism with $T_N = 90$ K. On the basis of the x-ray and neutron powder diffraction and the small-angle neutron scattering, the core/shell type phase separation model is proposed as a magnetic nanostructure where the nanocrystal is composed of the antiferromagnetic core with the short magnetic correlation and the ferromagnetic shell. The ferromagnetism in the shell is supposed to be induced by the hole doping to MnO_2 layers due to the oxidized surface effect through the double exchange mechanism. This result indicates that the SCE nanocrystals have the potential to become a new electronic state.

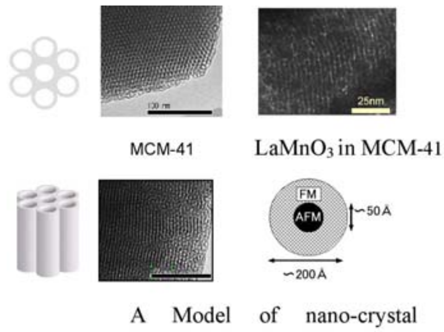

Figure 4: Electron microscopic pictures.

Selected publications

1 Randomly Diluted e_g Orbital-Ordered Systems, T. Tanaka, M. Matsumoto, and S. Ishihara, Phys. Rev. Lett. **95**, (2005) 267204.

1. Theory and experiment of orbital excitations in correlated oxides, S. Ishihara, Y. Murakami, T.Inami, K. Ishii, J. Mizuki, K. Hirota,S. Maekawa ,Y. Endoh, New Jour. Phys. **7**, (2005) 119.

2. Nobel Orbital Ordering induced by Anisotropic Stress in a Manganite thin film, Y. Wakabayashi, D. Bizen, H. Nakao, Y. Murakami, M. Nakamura, Y. Ogimoto,

K. Miyano, and H. Sawa, Phys. Rev. Lett **96**, (2006) 017202.

3. Ferro-type orbital state in Mott transition system $Ca_{2-x}Sr_xRuO_4$ studied by resonant x-ray scattering interference technique, M. Kubota, Y. Murakami, M. Mizumaki, H. Ohsumi, N. Ikeda, S. Nakatsuji, H. Fukazawa and Y. Maeno, Phys. Rev. Lett. **95**, (2005) 026401.

4. Orbitally Ordered State in $Y_{1-x}Ca_xTiO_3$ $(0 < x < 0.5)$, H. Nakao, M. Tsubota, F. Iga, K. Uchihira, T. Nakano, T. Takabatake, K. Kato and Y. Murakami, J. Phys. Soc. Jpn. **73**, (2004) 2620.

Hierarchical structures in electronic multipole orders and fluctuations

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Purpose of research

Ferromagnetism and ferroelectricity caused by magnetic and electric dipoles have been investigated for a long time as electronic orders in solids. Recently, the importance has been recognized of such orders and fluctuations in which higher-order moments play a role. The simplest example is the order of degenerate electronic orbitals in solids. This can be considered to be a quadrupole order. Our theoretical and experimental studies found cases where the octupoles order before the dipoles, or other cases where even higher multipoles such as 16- and 64-poles order. Figure 1 illustrates the idea of multipoles.

However, the mechanism of such multipole orders have not yet been fully elucidated. The purpose of this research is to clarify the hierarchical structure in dynamics of electrons through intimate cooperation between experiment and theory taking diverse condensed-matter systems from transition metal compounds to rare-earth and actinide compounds.

Results

Dynamics of multipoles have various energy scales depending on relative magnitudes of crystalline electric fields and spin-orbit interactions, and show rich hierarchical structures. The multipole degrees of freedom may be responsible for some strange phase transitions as a hidden order parameter. Furthermore, it is conceivable that the multipoles are controlling easily observable magnetism and superconductivity from behind. Our research group investigates the physics of multipoles via the following subjects.

(1) Observation of multipoles by neutron and X-ray scatterings
The cubic system $Ce_xLa_{1-x}B_6$ has been studied for a long time because of its Kondo effect and emergence of various ordered phases. In particular the order parameter of phase IV, which appears around $x \sim 0.7$, remains to be identified. We proposed a model ascribing this order to an antiferro octupole order. We have established this model through theoretical analysis of recent resonant X-ray scattering experiment. This is the first occasion of confirming the octupole order in real materials. Figure 2 shows the comparison between theoretical and experimental results.

We have shown experimentally that the magnetic state of tetragonal $_2C_2$, which exhibits anomalous susceptibility and magnetic structure, is an extremely rare case where antiferromag-

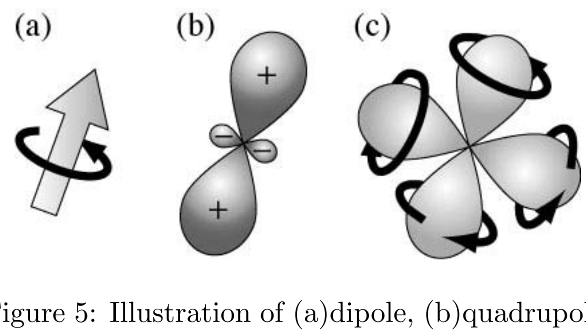

Figure 5: Illustration of (a)dipole, (b)quadrupole, (c)quadrupole+octupole. Curved arrows represent microscopic currents.

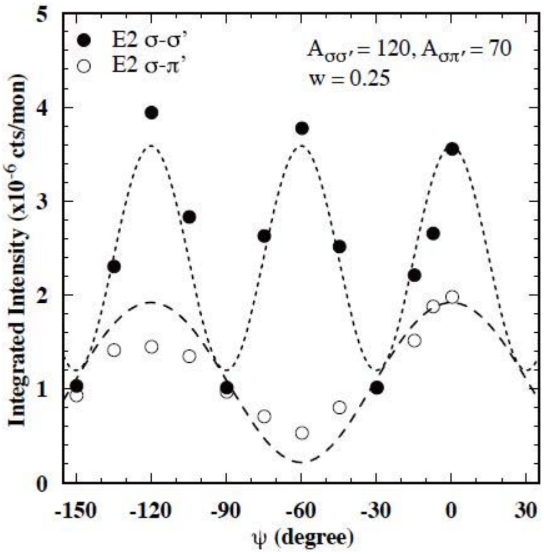

Figure 6: Azimuthal angle dependence of the intensity from resonant X-ray scattering. Experimental results (black and white circles) of the E2 (quadrupole) processes show good agreement with theoretical results (broken lines) of the octupole model, for both cases of changing (σ-π'), and non-changing (σ-σ') polarization scatterings.

netism and antiferro octupole order coexists. Figure 3 shows the phase diagram of the Gd added TbB_2C_2.

(2) Physical properties of the multipole orders and excitation spectra

We have improved the power of polarized neutron spectrometers which have been installed in JASRI by our graduate school. As a result, we could observe a tiny lattice distortion associated with multipole transitions. Furthermore, we have detected, using SPring-8 and Tsukuba synchrotron facilities, such properties as anomalous magnetic structure, diffuse magnetic scattering, anomaly in the susceptibility, and lattice softening. These are related to the electronic structures.

In particular, we have observed strong temperature dependence of crystal field excitations in $PrRu_4P_{12}$ skutterudite. By cooperation between theory and experiment, we have identified the origin as an antiferro order of electric 16-poles and 64-poles that behave as a scalar in the point-group symmetry. Figure 4 shows the temperature dependence of the scattering spectra.

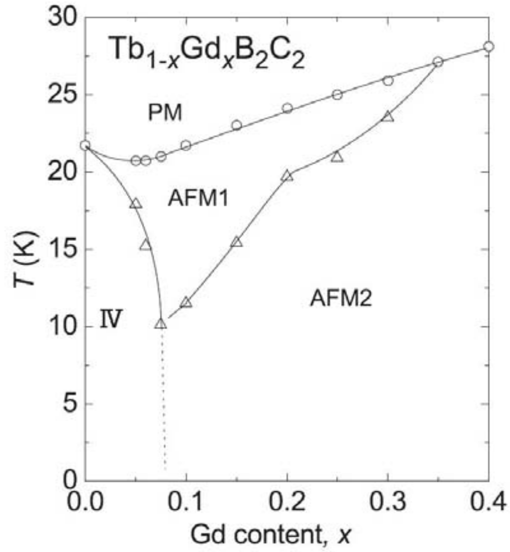

Figure 7: Phase diagram for $Tb_{1-x}Gd_xB_2C_2$. PM: paramagnetic; AFM1, AFM2: antiferromagnetic; IV: antiferro octupolar.

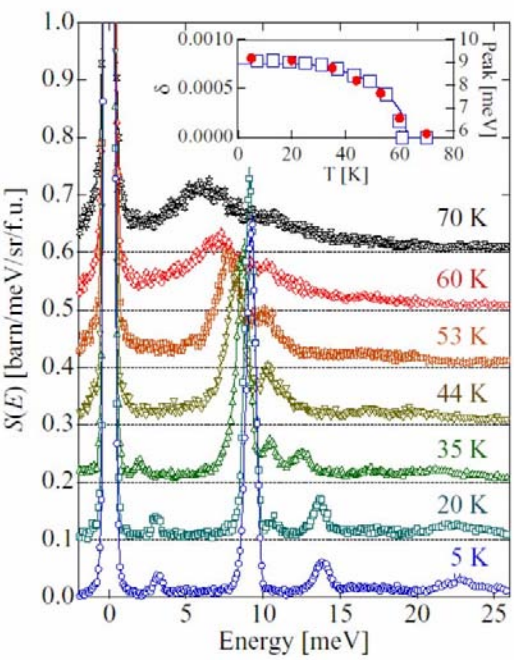

Figure 8: Inelastic neutron scattering spectra in $PrRu_4P_{12}$ skutterudite. The temperature dependence below 60 K can be understood as a scalar-type order of higher multipoles.

(3) Interaction effects between multipoles and conduction electrons

With orbital degrees of freedom, interaction between local and conduction electrons include elements of orbital polarization and fluctuation. They may be responsible for the anomalous character of Fermi liquids and non-Fermi liquids. We have studied effects of interactions between conduction electrons and local electrons with non-Kramers degeneracy, and explained the characteristic temperature dependence of the quasi-static scattering width in the inelastic neutron scattering. We have formulated a theoretical framework to approach the excitation spectrum of electrons on the border of localized and itinerant states, from both limits of crystal field excitations and the band picture.

Selected publications

1. Lattice Distortion and Octupole Ordering Model in $Ce_xLa_{1-x}B_6$,
   K. Kubo and Y. Kuramoto,
   J. Phys. Soc. Jpn. **72** (2003) 1859 .
2. Evidence for Octupole Order in $Ce_{0.7}La_{0.3}B_6$ from Resonant X-ray Scattering,
   H. Kusunose and Y. Kuramoto,
   J. Phys. Soc. Jpn. **74** (2005) 3139.
3. Possible Antiferro-Octupolar Order in Antiferromagnetic TbB_2C_2 Examined by Gd Substitution,
   E. Matsuoka, Y. Sasaki, D. Usui, M. Nakagawa, H. Onodera,
   J. Phys. Soc. Jpn. **75** (2006) 123707.
4. Evolution of 4f Electron States in the Metal-Insulator Transition of $PrRu_4P_{12}$,
   K. Iwasa, L. Hao, K. Kuwahara, M. Kohgi, S. R. Saha, H. Sugawara, Y. Aoki, H. Sato, T. Tayama, T. Sakakibara,
   Phys. Rev. B**72** (2005) 024414.
5. Evidence for Magnetic-Field-Induced Quadrupolar Ordering in the Heavy-Fermion Superconductor $PrOs_4Sb_{12}$,
   M. Kohgi, K. Iwasa, M. Nakajima, N. Metoki, S. Araki, N. Bernhoeft, J-M. Mignot, A. Gukasov, H. Sato, Y. Aoki and H. Sugawara,
   J. Phys. Soc. Jpn. **72** (2003) 1002.

Novel Materials Group

We investigate the electronic structure and the mechanism of anomalous properties of novel materials such as high-temperature superconductors and carbon-based nano-materials. We develop advanced experimental probes such as angle-resolved photoemission and neutron scattering. In addition, we synthesize high-quality single crystals and fabricate electronic devices based on the nano-meter size constituents. We also study photonic crystals and condensed polymer systems to investigate the relationship between the physical properties and the geometrical conditions of the crystals.

Elementary Excitations in Superconductors by Multi-Energy-Hierarchey Spectroscopy

Principal Investigator: Takashi Takahashi (Department of Physics, Professor)
Research Area: High-resolution photoemission spectroscopy
Homepage: *http://arpes.phys.tohoku.ac.jp*

Main Research Subjects:
- High-resolution photoemission study on high-temperature superconductors
- High-resolution photoemission study on charge-ordered electron systems
- Development of high-resolution photoemission systems

Material Properties Based on Geometrical Configuration and Unified View Points

Principal Investigator: Teruya Ishihara (Department of Physics, Professor)
Research Area: Solid State Photo-Physics
Homepage: *http://sspp.phys.tohoku.ac.jp*

Main Research Subjects:
- Generation of mesoscopic structures and the dynamics of structural phase transition
- Atomistic diffusion and cluster growth of silver atoms on a Si surface
- Optical response of geometrical structures with scales of light wavelength and sub-wavelength

Hierarchical Control and Appearance of Novel Properties in Nano Network Materials

Principal Investigator: Katsumi Tanigaki (Department of Physics, Professor)
Research Area: Nano fabrication, Thin film growth of materials, Solid state physics of Nano clusters
Homepage: *http://sspns.phys.tohoku.ac.jp*

Main Research Subjects:
- Synthesis, structure and Properties in carbon based materials
- Physical properties of silicon and germanium nano network solids
- Electronic properties of nano materials by applying field effect transistor device construction

Elementary Excitations in Superconductors by Multi-Energy-Hierarchey Spectroscopy

Principle Investigator:
Takashi Takahashi
(Department of Physics, Professor)
Collaborators:
Haruyoshi Aoki
(Center of Low Temperature Science, Professor)
Kazuyoshi Yamada
(Institute for Materials Research, Professor)
Akira Ochiai
(Department of Physics, Associate Professor)
Takafumi Sato
(Department of Physics, Assistant Professor)
Supporting Researcher:
Satyabrata Raj
(JSPS Fellow)

Results

(1) Photoemission

Electron-Hole Symmetry in High-Temperature Superconductors

To study the electronic states near the Fermi energy in electron-doped HTSC, we performed high-resolution angle-resolved photoemission (ARPES) on $Nd_{2-x}Ce_xCuO_4$ (Figure 1). We observed a pseudogap and a quasiparticle band dispersion continuously connected to each other in the momentum space. We further studied the systematic evolution of these electronic states as a function of temperature/doping, and found that the evolution of pseudogap shows a good agreement with the Cu-spin correlation. Our results suggest that antiferromagnetism strongly couples to the electronic states near the Fermi surface in electron-doped HTSC.

To study the superconducting gap symmetry in electron-doped HTSC, we performed high-resolution ARPES on the electron-doped HTSC $Pr_{0.89}Ce_{0.11}CuO_4$ (Figure 2). We measured the superconducting gap along the Fermi surface, and found that the momentum dependence of the gap is clearly deviated from the prediction from the $d_{x^2-y^2}$ wave symmetry with an anomalous enhancement in a particular momentum region on which the Fermi surface is well connected by the magnetic scattering vector. This result clearly indicates that the antiferromagnetic interaction plays an essential role in the mechanism of electron-doped high-T_c superconductivity.

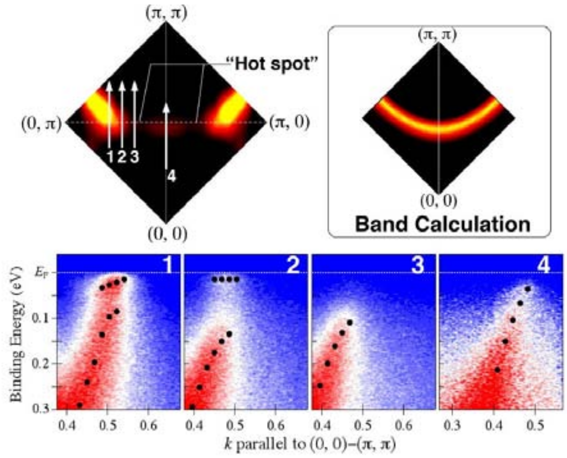

Figure 1: Fermi surface and band dispersion of NCCO.

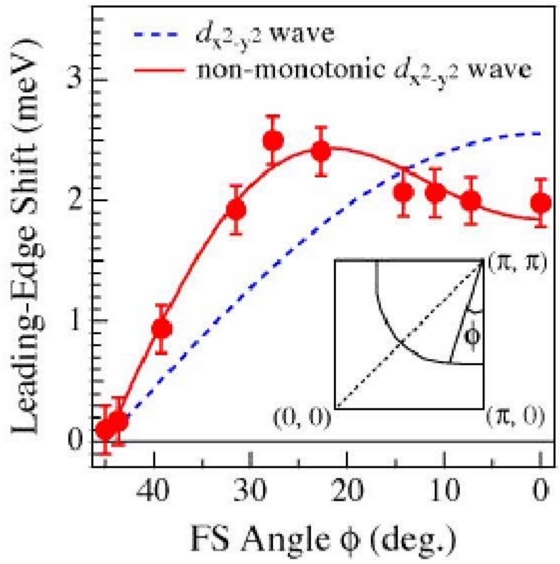

Figure 2: 1-2 Anisotropy of the superconducting gap in $Pr_{0.89}LaCe_{0.11}CuO_4$

Autocorrelation between photoemission and neutron-scattering in high-T_c superconductors

Neutron scattering and photoemission spectroscopy are complemental probes to each other. While the former probes collective excitations e.g. magnons and phonons, the latter probes kinetic states of charge carriers. In correlated electron systems, collective excitations and charge carri-

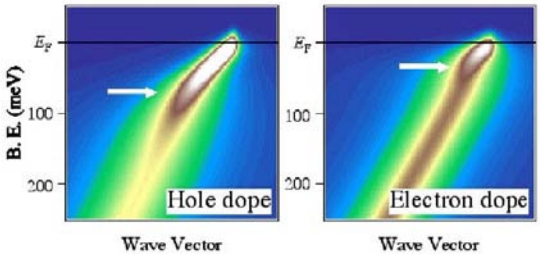

Figure 3: Simulaiton of band dispersion in electron- and hole-doped HTSC.

ers strongly couple with each other, providing a driving force for the exotic physical properties. Therefore, it is important to undrestand the inherent autocolrrelation between the neutron and photoemission spectrum produced by many-body ineractions.

We measured the electronic band dispersion in hole-doped $La_{2-x}Sr_xCuO_4$ and electron-doped NCCO at the Cu-O bonding diagonal direction by high-resolution ARPES. We observed a sudden bending of the band dispersion in each system and found that the energy scale is completely different between the electron- and hole-doped materials. To understand the experimental results, we performed a simple simulation of the bands assuming the strong coupling of holes/electrons with the spin excitations determined by inelastic neutron scattering (Figure 3). The simulated reproduced the photoemission results, suggesting that the spin excitations (magnons) are coupling to the charge carriers in both HTSC systems.

(2) Neutron scattering

We newly constructed a triple-axis neutron spectrometer AKANE on a thermal neutron beam-port of the JRR-3 in JAEA. With a new Ge monochromator AKANE provides us inelastic scattering data with the energy transfer up to 12meV. On this spectrometer we also started a neutron scattering experiment under a pulsed magnetic field up to 27 Tesla.

In addition to these experiments with reactor-beam we also performed a pulsed neutron scattering experiment to study magnetic excitation spectra over a wide energy as well as momentum space. Among them, the measurement on an electron-doped high-T_c cuprate clarified that both the magnetic excitation spectrum and its momentum dependence are far different from those of spin wave as seen in the undoped antiferromagnetic Mott insulator.

The dynamical spin-spin correlations of the electron-doped cuprate are now compared to those from a band-model using the data of ARPES measurement by Takahashis group to extract the contribution of itinerant electrons to the magnetic excitation spectrum and dispersion. As a future plan, we perform a neutron scattering experiment under high pressure to study the interplay between the itinerant and localized spins on the novel magnetic excitations in high-Tc cuprates.

A newly installed triple-axis neutron spectrometer, AKANE

Due to overage of a single-crystal diffractometer of the Institute for Materials Research (KINKEN) of Tohoku University, which had been installed more than 15 years ago at previous JRR-2 (JAEA, Tokai), we started to overhaul and upgrade the double-axis diffractometer since 2003. The main issue of this upgrade is an install of an energy analyzer before the detector, so that one can extract direct information about quasi-particles in condensed matters, such as phonons in lattice vibrations and spin waves in magnets. This time, we renamed the triple-axis neutron spectrometer AKANE (Advanced KINKEN triple-axis neutron spectrometer).

The unique feature of AKANE is the combination of a monochromator of Ge (311) and an analyzer of pylorytic graphite PG (002). Due to extinction effects of high-quality Ge crystals, which severely suppress the reflectivity, we intentionally introduced some degrees of mosaicity (h = 10'∼15') through hot-press treatments. The reflectivity of Ge crystal is considerably improved after this process, and then we can use the Ge monochromator as like a conventional PG monochromator.

Figure 5 shows typical data of inelastic scattering measurements (phonon) on AKANE. Although the sample is relatively small in volume (0.3 cc), well-defined TA-phonon group is detectable up to about 10 meV with reasonable statistics. As shown in the inset of Fig. 5, a low-lying phonon dispersion is easily determined, thus indicating a high potential of AKANE for studies on low-energy excitations ($\omega \leq 10$ meV) by use of the optimized Ge monochromator.

Figure 4: Triple-axis neutron spectrometer, AKANE.

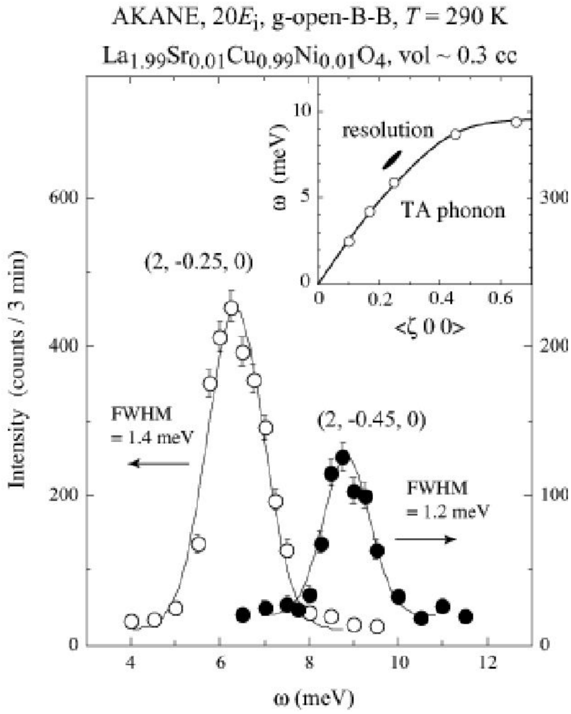

Figure 5: Energy spectra of TA-phonon mode measured on AKANE using a copper-oxide sample. The inset shows a resultant phonon-dispersion relation.

Figure 6 shows an example of Q spectra of magnetic excitations measured on AKANE (ω = 6 meV). The sample is a superconductor $La_{2-x}Sr_xCuO_4$ single crystal with 1 cc in sample volume. In spite of its small magnetic moment (0.5 mB or less), we can take high-quality data with respect to the intensity as well as the signal-to-noise ratio in a statistics of less than 10 minutes per point. We further succeeded in observing the magnetic cross section up to $\omega = 10$ meV by using the same crystal. Thus, AKANE is now available for studies on advanced condensed-matter physics, as like high-T_c superconductivity.

2-2 Neutron Diffraction Experiments under extremely high pulsed magnetic field

Magnetic field can control magnetic moments directly and precisely and is one of important parameters to understand the magnetism of materials. On the other hand, neutron scattering is a direct probe of space-time correlation of magnetic moments in materials. Thus, neutron scattering under high magnetic fields is eagerly anticipated in novel material science. Currently, the highest magnetic field for neutron scattering experiments was 25T using a repeating pulsed magnet in Neutron Science Laboratory of High Energy Accelerator Research Organization in Japan. However, neutron scattering experiments over 10T are still difficult and limited for the present. Therefore, aiming at performing neutron scattering experiments under 40T, Yamada group and Nojiri group in Institute for Materials Research (IMR) are developing easier and more diffusive techniques for neutron scattering with long pulsed magnets under collaborative research.

We have developed a pulsed magnetic field generating system which consists of a compact condenser bank and a mini-coil. In 2006, using this system, we performed neutron diffraction experiments under high pulsed magnetic filed on the neutron spectrometer AKANE of IMR. We have succeeded in observing the spin flip transition in the antiferromagnet MnF_2 at H=10T with 20T pulsed magnetic filed, and a field-induced magnetic transition in the triangular-lattice antiferromagnet $CuFeO_2$ at about 22T with 27T pulsed

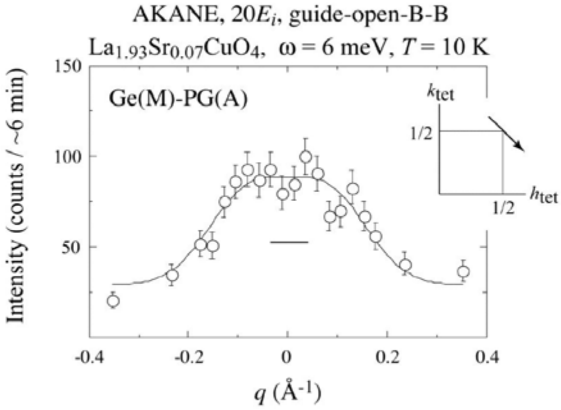

Figure 6: Magnetic inelastic scattering measured on AKANE using a copper-oxide superconductor.

magnetic filed. We note that the magnetic filed of 27T was the world record of the magnetic filed for neutron diffraction experiments. The result indicates that our magnetic field system is in practical use for neutron diffraction experiments under extremely high magnetic filed. In 2007, neutron diffraction experiments which aim at observing multi-step metamagnetic transitions in rare earth compound TbB4 between 17T and 30T are in progress.

Selected Publications

1. Direct observation of a non-monotonic $d_{x^2-y^2}$-wave superconducting gap in the electron-doped high-T_c superconductor $Pr_{0.89}LaCe_{0.11}CuO_4$,
   H. Matsui, K. Terashima, T. Sato, T. Takahashi, M. Fujita, K. Yamada,
   Phys. Rev. Lett. **95**, (2005) 017003–1-4.
2. Angle-resolved photoemission spectroscopy of the antiferromagnetic superconductor $Nd_{1.87}Ce_{0.13}CuO_4$: Anisotropic spin-correlation gap, pseudogap, and the induced quasiparticle mass enhancement,
   H. Matsui, K. Terashima, T. Sato, T. Takahashi, S.-C. Wang, H.-B. Yang, H. Ding, T. Uefuji, and K. Yamada,
   Phys. Rev. Lett. **94**, (2005) 047005–1-4.
3. Quantum magnetic excitations from stripes in copper oxide,
   J. Tranquada, H. Woo, T.G. Perring, H. Goka, G.D. Gu, G. Xu, M. Fujita and K. Yamada,
   Nature **429**, (2004) 534-538.
4. Electron-phonon coupling reflecting dynamic charge inhomogeneity in copper oxide superconductors,
   D. Reznik, L. Pintschovius, M. Ito, S. Iikubo, M. Sato, H. Goka, M. Fujita, K. Yamada, G.D. Gu and J.M. Tranquada,
   Nature **440**, (2006) 1170-1173.

Material Properties Based on Geometrical Configuration and Unified View Points

Principle Investigator:
Teruya Ishihara
(Department of Physics, Professor)
Collaborators:
Toshihiro Kawakatsu
(Department of Physics, Professor)
Tohru Sakai
(Department of Physics, Associate Professor)
Shozo Suto
(Department of Physics, Professor)

Results

In this research project, we have been studying the relation between the geometrical/topological configurations of materials on various length scales and the physical properties of these materials. "Soft matter" such as dense polymeric systems and dense colloidal suspensions are one of the suitable targets of such study. Generation of mesoscopic structures and the dynamics of structural phase transition of soft matter are studied using the self-consistent field (SCF) theory and the molecular simulation technique, both of which are based on the coarse-grained descriptions. By changing the temperature or by applying an external field (such as an external flow field or an external electric field) to the microphase separated structures, one can induce a transition between different microphase separated structures. We have simulated this process by using the dynamical SCF theory, and understood the mechanism of the transition. Figure 7 shows the transition process from a gyroid structure to a cylindrical structure induced by an externally imposed shear flow. One can observe a coexistence between the gyroid phase and the cylindrical phase, which can never be reproduced by the standard SCF technique where the density distributions of the components are expanded in the Fourier modes. We also compared this transition by shear flow with a corresponding results under an external electric field. We found that the kinetic pathways of the transition are different for the case with the shear flow and the case with the electric field.

We have studied the atomistic diffusion and cluster growth of silver atoms on a Si(111)7x7 surface using variable temperature scanning tunnel-

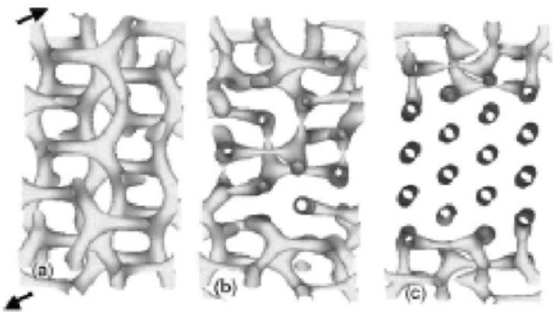

Figure 7: A simulation result of a transition from a gyroid structure to a cylindrical structure of a block copolymer under an external shear flow.

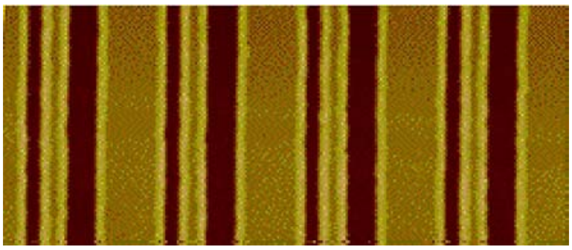

Figure 8: Atomic Force Microscope image of asymmetric metallic photonic crystal slabs with period of 1.2 mm.

ing microscope. The silver clusters bigger than three atoms attract a single silver atom like a black hole. We named the phenomena as cooperative diffusion. In order to understand the mechanism precisely, we have carried out several kinetic Monte Carlo Simulations.

We have studied opto-electric properties for geometrical configurations of the order of light wavelength. We fabricated metallic photonic crystal slabs consisting of unit cells without inversion symmetry, on which reciprocity of transmission is confirmed experimentally. Then we discovered that voltage is induced for laser pulse with normal incidence. It can be interpreted as photo-rectification due to broken inversion symmetry.

Figure 8 shows atomic force microscope image of a photonic crystal slab with asymmetric unit cell. Thick and thin grooves engraved in a Au thin film breaks the inversion symmetry. We measured voltage across the structure induced by irradiation of 5ns p-polarized laser with normal incidence. As is shown in Fig.9, the voltage can be positive or negative depending on wavelength. The dependence can be ascribed to the asymmetric diffraction due to the asymmetric photonic unit cell. We also investigated sub-wavelength Ag/Al_2O_3 multilayer systems from a metamaterial point of view.

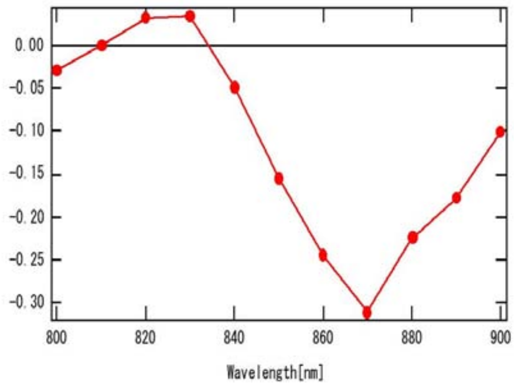

Figure 9: Photo-induced volatage at normal incidence as a function of incident wavelength.

Selected Publications

1. Epitaxial transition from gyroid to cylinder in a diblock copolymer melt,
   T. Honda and T. Kawakatsu,
   Macromolecules **39**, (2006) 2340-2349.
2. STM studies of platinum silicide formation on Si(111) by solid state epitaxy,
   A. Wawro, S. Suto and A. Kasuya,
   Phys. Rev. B **72**, (2005) 205302–1-10.

Hierarchical Control and Appearance of Novel Properties in Nano Network Materials

Principle Investigator:
Katsumi Tanigaki
(Department of Physics, Professor)
Collaborators:
Riichiro Saito
(Department of Physics, Professor)
Hiroshi Matsui
(Department of Physics, Associate Professor)
Shigeru Takagi
(Department of Physics, Associate Professor)
Ryotaro Kumashiro
(Department of Physics, Assistant Professor)

Results

The main research aim of the present group in this project is to search for new nano materials constructed from the nano-meter size building blocks with highly regulated geometry and to exploit new physical phenomena to be expected for such systems. For this purpose, this group has promoted the following research items during the project period: (1) Precise regulation of structure in nano polyhedral materials and exploitation of their novel physical properties, and (2) Exploitation of new physical properties produced by carrier controls by applying filed effect transistor device structure. The former research focuses on finding of a novel electron-phonon interactions, and the latter one is an approach to establish a new research method to control carriers physically in a different fashion from the conventional chemical carrier tuning.

(1) Precise regulation of structure in nano polyhedral materials and exploitation of their novel physical properties

Much attention has recently been paid to the materials featured by nano size structure such as skutterdites, clathrates and so forth. As shown in Fig.10, skutterdites have a general chemical formula of LnT_4X_{12}, where rare-earth elements can be encapsulated inside the cages formulated by pnicogens. Clathrates are the family of compounds expressed by the chemical formula of $A_8B_{16}C_{30}$ in type I clathrates, where alkali metal and alkaline-earth meal atoms are encapsulated inside the cages created by third- (Ga, Al, In) and fourth- (Si, Ge, Sn) groups of elements. The atoms endohedrally confined in the cages give rise to dynamic motions to produced exotic phonons with anharmonic oscillations under the inner potentials created by the outer-surrounding frameworks. Such kinds of phonons are called rattling phonons and have been drawing much attention recently to the scientific community.

The electrons in crystals show Bloch periodicity, while the rattling phonons behave as glass-like disordered states. Such unique states are called "Phonon-Glass-Electron-Crystal (PGEC)", and these could be the good guiding principle of designing new materials in the future. In the PGEC conceptual materials, new electron-phonon interactions between Bloch electrons and the rattling phonons would produce a new state, from which one can expect the unconventional electronic states to be created.

In our research project, we have studied the causality between the rattling motions of the en-

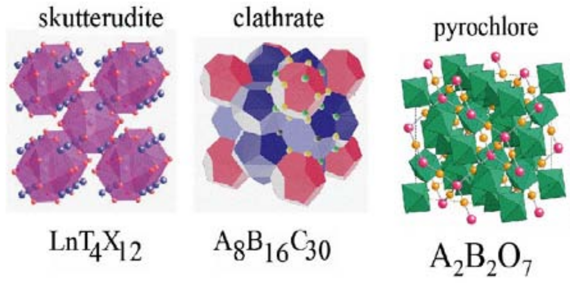

Figure 10: Structure of skutterdites and clathrates

capsulated Ba atoms, both in silicon and germanium frameworks, and the arising physical properties, and consequently have achieved the important information on this issue. Our group succeeded to find, for the first time, that both silicon and germanium clathrates with the chemical formula of $Ba_{24}IV_{100}$ (IV=Si and Ge) have the identical crystal structure and show superconductivity at low temperatures. Importantly, their electronic states are very different from each other, although the both frameworks of Si_{100} and Ge_{100} show the same crystal structure which is comprised from IVth group of elements. Actually, the electronic transport measurements show a very different evolution of conductivity as a function of temperature. Furthermore, the pressure experiments showed an opposite pressure dependence as for the superconducting transition critical temperature. We have studied the situation of the endohedral Ba atoms from the viewpoint of X ray diffraction measured at Spring-8 (Beamline BL02B2) and have analyzed by a MEM/Rietveld method. The detailed density maps determined by these analyses clearly show the five anisotropic high-density positions in the case of $Ba_{24}Ge_{100}$, while they are isotropic in the case of $Ba_{24}Si_{100}$ as shown in Fig. 11. Because the electron-phonon interactions in the category of rattling phonons shall be very intriguing to search for exotic electronic properties, the further experimental evidences as well as the sophisticated theoretical developments will be required in the future.

Another progress in this project is regarding the experiments of silicon isotope science. In the case of silicon which is very important in the field of semiconductor technology, isotopes of ^{29}Si and ^{30}Si are known to be naturally abundant isotopes of Si other than the richest abun-

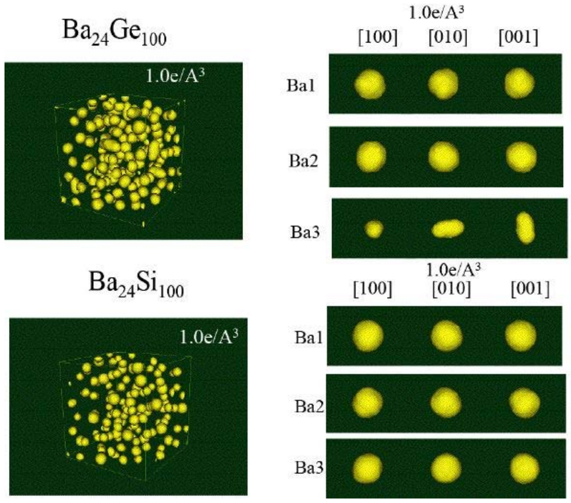

Figure 11: MEM density maps of Ba in $Ba_{24}Ge_{100}$ (IV=Si and Ge)

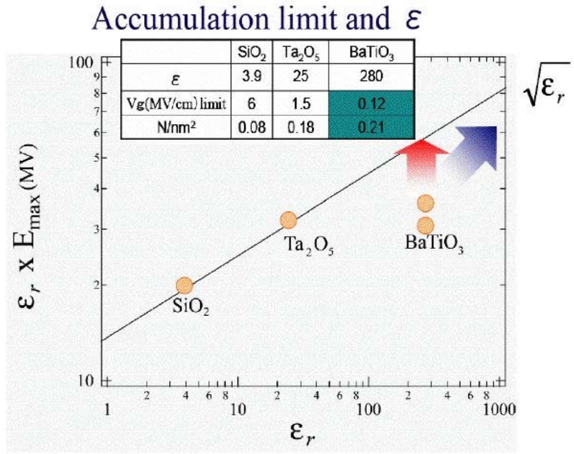

Figure 13: Correlation between the limit of carrier injection and dielectric constant

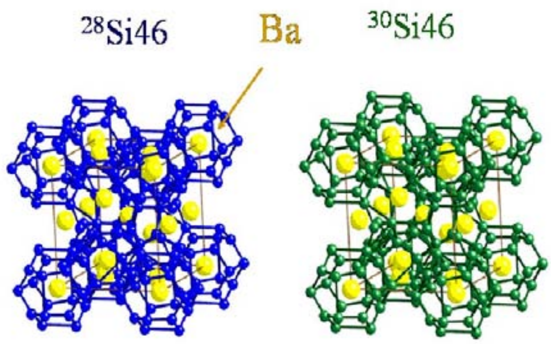

Figure 12: Nano silicon clustered crystals made from isotope ^{28}Si and ^{30}Si elements.

dant 92.2% of ^{28}Si. For controlling phonons, isotopes are very crucial. The phonon engineering for producing nano materials consisting of pure isotopes without changing the other electronic parameters is the key technology in isotope engineering and is positioned as one of the most important techniques in the future nano technology and science. Our group has succeeded, as a result in the present project, to synthesize new silicon clathrates composed of ^{28}Si and ^{30}Si isotopes as shown in Fig.12. This is the first example of silicon isotope clathrates and is expected to produce a variety of scientific fields in the future

(2) Exploitation of new physical properties produced by carrier control by applying filed effect transistor device structure

We have studied, in the present research project, the possibility for the highly regulated carrier injection using high dielectric gate insulators. As a result, we have succeeded to realize 0.1 holes per molecule close to the ultimate highest limit among the conventional organic FETs, by employing the single crystal $BaTiO_3$ thin film grown by laser ablation as the gate insulator and the rubrene single crystal as an organic semiconductor. This is the highest carrier injection so far reported to the best of our knowledge. This result may suggest that 0.2-0.3 carriers per molecule will be achieved, if the higher quality epitaxial $BaTiO_3$ gate insulator, which has the ideal physical limitations of the breakdown voltage, could be achieved. Consequently, the realization of electronic phase transitions from insulating to metallic may be possible as a future advancement.

A variety of materials showing the polyhedral network connections can be made from the IVth group of elements such as C, Si and Ge. In such a material family, IV_{20}, IV_{24}, IV_{28}, IV_{60} as well as nanotubes are considered. Among these, IV_{20}, IV_{24} and IV_{28} with electronically open shell structure formulate covalent type nano network materials, being shared with their faces. These polyhedral crystals can accommodate other atoms and molecules inside their cages and such encapsulated atoms and molecules may have unique phonon states under the potential created by the cages. These phonons having time and space dependent features, so called rattling phonons, will break the symmetry of Bloch electron states and hitherto unique unconventional electronic states may be realized via electron-phonon interactions that have not ever so far observed.

In general, the electronic states in crystals are classified as the Bloch state associated with the periodicity in the Brave lattice, while the rattling phonons described in the earlier paragraph are glass-like and have freedom in their dynamic motions. The concept of new electron-phonon interactions suggested in the present studies could be extended to the materials design that will perhaps be very fruitful and useful in generating novel materials and the new physics associated with them. In the present project, we have also studied the physical carrier modulation by employing the FET device structure and have exploited the limitation of carrier injection. We believe that we were able to show the possible future direction in nano materials science as one of the important advancements in nano materials science.

Selected Publications

1. Mechanism of superconductivity in the polyhedral-network compound Ba_8Si_{46},
   K. Tanigaki, T. Shimizu, K. M. Itoh, J. Teraoka, Y. Moritomo and S. Yamanaka,
   Nature Materials **2**, (2003) 653-655.
2. Superconductivity and physical properties of $Ba_{24}Si_{100}$ determined from electric transport, specific-heat capacity, and magnetic susceptibility measurements,
   T. Rachi, H. Yoshino, R. Kumashiro, ... and K. Tanigaki,
   Phys. Rev. B **72**, (2005) 144504–1-6.

Mathematical Science Group

We investigate mainly two topics arising from Mathmatical Physics. One is The Nonlinear Analysis such as Nonlinear PDE, Global Analysis in Differential Geometry. Another is The Theoretical Statistical Physics such as Soft Materials and Collective Dynamics of Motile Elements.

Nonlinear Analysis in Mathematical Physics
Principal Investigator: Hideo Kozono (Mathematical Institute, Professor)
Research Area: Nonlinear Partial Differential Equations
Homepage: *http://www.math.tohoku.ac.jp*

Main Research Subjects:
* Nonlinear Differential Equations
* Harmonic Analysis
* Functional Analysis
* Mathematical Physics

Nonlinear Analysis in Mathematical Physics

Principle Investigator:
Hideo Kozono
(Mathematical Institute, Professor)
Collaborators:
Eiji Yanagida
(Mathematical Institute, Professor)
Motoko Kotani
(Mathematical Institute, Professor)
Sigetoshi Bando
(Mathematical Institute, Professor)
Toshihiro Kawakatsu
(Department of Physics, Professor)
Yoshinori Hayakawa
(Department of Physics, Associate Professor)

Results

(1) Mathematical Fluid Mecanics
(H. Kozono)

(i) Extension criterion via two components of vorticity on strong solutions to the Navier-Stokes equations

In three dimensional Euclidian space $\mathbb{R}^3$, it turns out that if we control two components of vorticity, then we may treat the fluid motion as in the plane such that the vorticity behaves like a scalar field. The well-known extension criterion via vorticity on local strong solutions to the Navier-Stokes equations was obtained by Beale-Kato-Majda. Indeed, they proved that if the strong solution u on $\mathbb{R}^3 \times (0, T)$ satisfies

$$\int_0^T \sum_{i=1}^3 \|\omega_i(t)\|_{L^\infty(\mathbb{R}^3)} dt < \infty,$$

then u can be continued to the solution on $\mathbb{R}^3 \times (0, T')$ for some $T' > T$, where $\omega = (\omega_1, \omega_2, \omega_3)$ denotes the vorticity rot u. In this research, we generalize the space from L^∞ to the larger BMO, and show that even under the weaker hypothesis such as

$$\int_0^T \sum_{i=1}^2 \|\omega_i(t)\|_{BMO}\, dt < \infty$$

the same continuation of the solution can be obtained.

(ii) Strong and generalized energy inequalities of the Navier-Stokes equations in general unbounded domains

Let Ω be a general unbounded domain in $\mathbb{R}^3$ with the uniformly $C2$-boundary $\partial\Omega$. In particular, we are interested in the case when $\partial\Omega$ is *non-compact.* For weak solutions u of the Navier-Stokes equations in Ω we consider the following two types of the energy inequalities;

$$\int_\Omega |u(x,t)|^2 dx + 2\int_s^t \int_\Omega |\nabla u(x,\tau)|^2 dx d\tau \leqq \int_\Omega |u(x,s)|^2 dx \quad (1)$$

for almost every $s \geq 0$, including $s = 0$ and all t such that $s \leqq t < \infty$, and

$$2\int_0^T \int_\Omega |\nabla u|^2 \psi dx dt \leqq \int_0^T \int_\Omega \{|u|^2(\partial_t \psi + \Delta\psi) + (|u|^2 + 2p)u \cdot \nabla\psi\} dx dt \quad (2)$$

for all $\psi \in C_0^\infty(\mathbb{R}^3 \times (0, T))$ such that $\psi \geqq 0$. We call (1) and (2) the strong and the generalized energy inequalities, respectively. Leray named the weak solution with (1) the *turbulent* solution. Suppose that u is the turbulent solution in the space-time $\Omega \times (0, \infty)$. Then for the singular set $\Sigma \equiv \{t \in (0, \infty); u(t) \notin C^\infty(\Omega)\}$ in *time* of u, he showed that $\mathcal{H}^{\frac{1}{2}}(\Sigma) = 0$, where $\mathcal{H}^d$ denotes the d-dimensional Hausdorff measure. Furthermore, there exists a large T_0 such that $u(t) \in C^\infty(\Omega)$ holds for all $T_0 \leqq t$. This is a famous Leray's structure theorem for turbulent solutions to the Navier-Stokes equations.

On the other hand, Caffarelli-Kohn-Nirenberg named the weak solution with (2) the *suitable weak solution.* Let u be the suitable weak solution. For the set S of space-time singularities defined by $S = \{(x, t) \in \Omega \times (0, \infty); u \notin L^\infty(B_\rho(x, t)), \forall\rho > 0\}$, it is proved that $\mathcal{H}^1(S) = 0$, where $B_\rho(x, t) \equiv \{(y, s) \in \mathbb{R}^3 \times (0, \infty); |y - x| < \rho, |s - t| < \rho\}$. Since the uniqueness question on weak solutions of the Navier-Stokes equations is still open, it is important to investigate which kind of weak solutions has a nice property. In this respect, the notion of turbulent solutions and suitable weak solutions plays an essential role.

In the present research, we give a positive answer to the question whether these solutions exist for an arbitrary given initial data $a \in L^2_\sigma(\Omega)$. Up to now, such an existence result has been obtained under the restriction that Ω is the whole space $\mathbb{R}^3$, the half-space $\mathbb{R}^3_+$ and the domain Ω with the compact boundary $\partial\Omega$. In these cases, the L^r-theory of the Stokes operator is fully established, which enables us to make use of the technique of holomorphic semi-group and the maximal regularity theorem for the Stokes equations. Unfortunately in general unbounded domains Ω with non-compact boundary, the Helmholtz decomposition holds true only in $L^2(\Omega)$. To get around such difficulty, we introduce a larger space $L^2(\Omega) + L^r(\Omega)$ for $1 < r \leqq 2$ and establish a weaker version of the maximal regularity theorem for the Stokes equations. As an application, it turns out that the pressure p associated to the velocity u of the Navier-Stokes equations can be taken in such a way that $\nabla p \in L^{\frac{5}{4}}_{\mathrm{loc}}(0, \infty; L^2(\Omega) + L^{\frac{5}{4}}(\Omega))$. Our information on the global behaviour on Ω of the pressure p makes it possible to construct both turbulent solution and suitable weak solution for an arbitrary given initial data $a \in L^2_\sigma(\Omega)$.

Selected Publications

1. Kozono, H., Yatsu,N., Extension criterion via two-components of vorticity on strong solutions to the $3D$ Navier-Stokes equations. Math. Z. **246** (2004), 55–68.
2. Farwig,R., Kozono,H., Sohr,H., An L^q-approach to Stokes and Navier-Stokes equations in general domains. Acta Math. **195** (2005), 21–53.

(2) Reaction Diffusion Equation (E. Yanagida)

(i) With Prof. Hirokazu Ninoimya (Ryukoku University), I considered traveling front solutions of the Fisher equation. The Fisher equation is a monostable reaction-diffusion equation, for which we could observe a front as a transition layer from an unstable state to a stable state, and the dynamics of the front governs the qualitative behavior of solutions. In the singular limit as the diffusion constant tends to zero, the dynamics of the front can be described as an interface (or a moving surface), and it is an important problem to understand its dynamics.

In this research, we showed that the dynamics of the front in the singular limit can be described by using a zero level set of a Hamilton-Jacobi equation. As a consequence, behavior of the interface can be completely controlled by taking suitable initial data. This implies that the motion of the interface cannot be predicted from the shape of the interface, which is essentially different from the Allen-Cahn equation for which the motion of interfaces is described by the mean curvature flow.

(ii) With Profs. M. Fila (Comenius Univ.), J. R. King (Univ. Nottingham), and M. Winkler (RWTH Aachen), I studied the behavior of solutions of Fujita-type equation. This is a very simple nonlinear parabolic partial differential equation containing a power nonlinearity, and the structure of solutions drastically changes depending on the exponent. In this research, we consider a super-critical case. In this case, it is known that the long-time behavior of solutions is determined from a decay rate of initial data.

In this research, our aim is to derive a precise estimate of grow-up and decay rates, and to obtain quantitative description about the relation between the rate and initial data. So far, we have obtained precise description of the relation between the decay rate of initial data and the grow-up rate of solutions when the initial data decay slowly, but we have not obtained a satisfactory result in the case where the initial data decay fast. In this case, in order to investigate the behavior of solutions precisely, we used formal expansions of solutions near zero and infinity, and then we estimated the global behavior of solutions from the matching condition. Based on this formal analysis, we obtained a rigorous proof by constructing suitable super- and sub-solutions. This work is summarized in the paper [1].

(iii) With Prof. Y. Lou (Ohio State Univ.), I carried out the investigation on a minimization problem associated with an eigenvalue problem with indefinite weight. It is known in the field of mathematical ecology and population genetics that the sign of the principal eigenvalue plays a crucial role for the dynamics of solutions. In this research, we introduced a model equation with spatial inhomogeneity, and considered the minimization problem of the principal eigenvalue under some constraint. So far, only insufficient result in the simplest case has been obtained, and a more general case has been left open.

In this research, we showed the existence of a minimizer, and made clear its fundamental properties. By using these results, we gave a complete answer to the one-dimensional case. In the higher dimensional case, we have obtained only partial results, but found some important properties. These results will be published in the paper [2].

(iv) With Profs. Masato Iida (Iwate University) and Kimie Nakashima (Tokyo Marine University), I studied a boundary value problem on an unbounded interval which is related with a singular limit of competition-diffusion equations. In the limit as the inter-specific diffusion rate tends to infinity, the habitats of two species are divided by an interface, and the motion of the interface is a key to understand the dynamics of the ecological system.

In this research, we describe the behavior of solution near the interface by using a system of ordinary differential equations, and studied precisely the asymptotic behavior of solutions at infinity. Based on this analysis, we constructed suitable super- and sub-solutions, and showed that the singular limit of strong competition can be described by a sort of free boundary problem. This fact has been proved in a weak sense, but we proved the convergence in a stronger sense. This result will be published in the paper [3].

Selected Publications

1. M. Fila, J. R. King, M. Winkler and E. Yanagida, Linear behaviour of solutions of a superlinear heat equation, preprint.
2. Y. Lou and E. Yanagida, Minimization of the principal eigenvalue for an elliptic boundary value problem with indefinite weight and applications to population dynamics, Japan J. Indust. Appl. Math. **23**, No.3 (2006), 275-292.
3. M. Iida, K. Nakashima and E. Yanagida, On certain one-dimensional elliptic systems under different growth conditions at respective infinities, to appear in Advanced Studeis on Pure Mathematics.

(3) Schorödinger operators on a Crystal Lattice
(M. Kotani)

Magnetic Schorödinger operators on a crystal lattice

A crystal Lattices is a periodic discrete object. Typical examples are the square larrice, the triangluar lattice, the cubic lattice and the diamond lattice. It is originally to describe how the atoms in a crystal in $\mathbb{R}^2$, $\mathbb{R}^3$ are binded each other by internal force. Mathmatically a crysal lattice is an abstract graphs on which an Abelian group acts freely cofinitely, and hence it does not necessarily sit in either $\mathbb{R}^2$, nor $\mathbb{R}^3$.

We would like to propose a mathematical model for electrons moving on a crystal lattice under magnetic fields and analyze how spectra depend on magnetic flux class. If a crystal lattic is in a Eucridean space, we may modify the notion of the magnetic Schrödinger operator to define the magnetic transion operor, but in our case, there is no such notion of the magnetic field trivially defined.

We define a magnetic transion operator by using magnetic translations. In this way, it is considered as a "Laplacian" in a non-commutative space, and naturallt its spectra reflect symetries and self-similarities in the non-commutative space seen in the famoous Hofstadter butterfly.

Selected Publications

1. Large deviation and the tangent cone at infinity of a crystal lattice, with T.Sunada, to appear in Math.Z.**254**(2006), pp 837-870.
   We discee the large deviation property of random walks on a crystal lattice to find the relation of the rate function appearing in the large deviation and the metric space structure of the tangent cone at the infinity of the crystal lattice. This gives an explicite method to determine the metric structure by using combinatorial data of the crystal lattice.

Research Talks

1. 2006.6.13-16, Noncommutative Geometry 2006 Kyoto, Kaito International Community House, "Magnetic transition operators on a crystal lattice".
2. 2006.10.4, Large Deviation on a crystal lattice, Copenhagen University.
3. 2006.12.1, Discrete Geometric Analysis on a crysal lattice, Institute of Material Research, Tohoku University.

Symposium Organization

1. 2006.6.13–6.16, Noncommutative Geometry 2006 Kyoto, Kaito International Community House.
2. 2006.7.15–7.17, COE-Workshop, Asymptotics in Geometry, Tohoku Univerisity.
3. 2006.11.13–11.25,The 8th MSJ-IHES, & Hayashibara Forum, IHES, France.
4. 2007.1.12–1.15, COE Spring School, Randomness apears in integrable systems.

Official Trip

1. 2006. 9.27–10.6Copenhagen Univeristy, Denmark, colloborate with R.Nest.
2. 2006.11.13–11.25, IHES, France.

Outreach

1. 2006.4.26, Principle to figure spaces in Nature, Keio University.
2. 2006.5.21, Principle to figure spaces in Nature, Zonta International, Sendai.
3. 2006.6.26, What is Mathematics?, Keizai Doyukai, Japan association of corporate executives.
4. 2006.9.12 , Principle to figure spaces in Nature, Shirakasi junior high School, Rifu.

Others

1. "Women's work", Nature 442(2006), pp715.

(4) Einstein-Kähler metric (S. Bando)

In the paper below, we dealt the extension of Futaki invariant which was introduced by A. Futaki.

Futaki introduced Futaki invariant as an obstruction for a compact Kähler manifold with the positive first Chern class (Fano manifold) to admit an Einstein-Kähler metric.

An Einstein-Kähler metric has the constant scalar curvature, and E. Calabi has extended Futaki invariant to the obstruction to have the constant scalar curvature.

For a Kähler manifold, it is equivalent to have the harmonic first Chern class form and to have the constant scalar curvature, and in the paper below we have extended Futaki invariant as an obstruction to have not only for the first but for the any Chern class forms to be harmonic.

Futaki invariant can be regarded as a kind of "moment map", and its integral form has defined by T. Mabuchi, which is called K-energy. Through the works by G. Tian, S. K. Donaldson and others, it is known that K-energy has the deep connection to the stability of projective algebraic varieties, and the "Hitchin–Kobayashi correspondence" for Fano manifolds is expected.

In the studies of Futaki invariant and K-energy, the understanding of them as moment maps plays a crucial role. Kähler manifolds and spaces constructed by them naturally have symplectic structures, and the moment maps are natural objects. But if we insist on symplectic structures, then our scope would be limited, for instance, we can not deal with general Einstein manifolds which are not necessarily Kähler.

In the work of Kazdan–Warner, which was the starting point of Futaki invariant, they had dealt Riemannian manifolds, not complex manifolds, and defined a kind of obstructions. Here symplectic structures have no role. A frame work which can deal with the wider class of objects is wanted.

Recently, X. Wang has introduced the notion of moment maps for Riemannian manifolds which dose not assume symplectic structures. He defined it by focusing on the way the moment maps are used, disregarding the connection to the symplectic geometry. Since there are no symplectic geometry behind, it dose not work good enough in general. We have studied it, but we have attained no results so far.

We can find any direct connections each other, but we can observe that the embeddings to the spheres are studied in the various branches of geometry, apparently or inapparently. Fisher metric in information geometry is a good example, and the Hitchin–Kobayashi correspondence problem can be thought of the embedding problem to the complex projective spaces or to the spheres by considering their S^1-lifts. We also observe that in the study of Ricci curvature of measure–metric spaces, we have an integral quantity which is analogous to the one which appears in the study of Hitchin–Kobayashi correspondence. We try to understand if there is a geometry behind these coincidences.

Selected Publications

1. An obstruction for Chern class forms to be harmonic, Kodai Math. J. 29 (2006), 337–345.

(5) Transitions of Polymeric Systems (T. Kawakatsu)

Field Theory of Phase Transitions of Polymeric Systems

In studying phase separations and phase transitions of polymer blends and block copolymers, it is important to focus on the mesoscopic structures that are much larger than the atomic/molecular scales. In such a case, a use of the field theoretic approach based on the coarse-graining method is highly efficient. In this research project, we developed a dynamical self-consistent field (SCF) theory of the phase separation phenomena, where the conformational degrees of freedom of the polymer chains are taken into account using the path integral method.

Using the SCF theory, one can quantitatively predict the phase behavior of polymeric systems. However, the use of the SCF theory causes a considerable increase in the computational cost. Therefore, the SCF theory faces a difficulty when we try to study long-time and large scale phenomena such as the dynamics of phase separations. To eliminate such a difficulty, Ginzburg-Landau (GL) theory, where the system is further coarse-grained compared to the SCF theory. A shortcoming of the GL theory is its lower accuracy in the strong-segregation regime. This is because the GL theory approximates the free energy of the system by a few leading terms in its Taylor series expansion around the critical point. We proposed a new method where the high accuracy of the SCF theory and the low computational cost of the GL theory are compatible by hybridizing these two methods. In this new theory, the time evolution of the system is solved based on the GL theory, where the model free energy is adjusted by time to time using the accurate SCF theory.

By using this method, we succeeded in reproducing the correct phase separation dynamics of a mixture composed of polymers with complex molecular structures with a considerably reduced computational cost. In Figure, we show a simulation result of the micro phase separation of a solution of an A_{20}-B_{60}-C_{20} symmetric triblock copolymer, where the quality of the solvent is changed. A triangular lattice of the C-domains in the initial state is shown in Figs.(a)-(c). By changing the quality of the solvent, the system changes into the asymmetric domain structure shown in Fig.(d). This final structure is different from the true equilibrium state of the system is the one shown in Fig.s(e) and (f), where the A $\leftrightarrow$ C symmetry is retained. This means that the dynamical SCF theory can trace the kinetic pathway from the intial state to the final quasi-equilibrium state.

Selected Publications

1. Hybrid Dynamic Density Functional Theory for Polymer Melts and Blends,
T.Honda and T.Kawakatsu, Macromolecules, in press.
2. Computer Simulations of Nano-Scale Phenomena Based on the Dynamic Density Functional Theories,
T.Honda and T.Kawakatsu,in Nanostructured Soft Matter: Experiments, Theory and Perspectives; A. Zvelindovsky, ed., Springer-Verlag, in press.
3. Kinetic pathway of Gyroid-to-Cylinder transition in diblock copolymer melt unde electric field,
D.Q.Ly, T.Honda, T.Kawakatsu, and A.V.Zvelindovsky, Macromolecules, submitted.

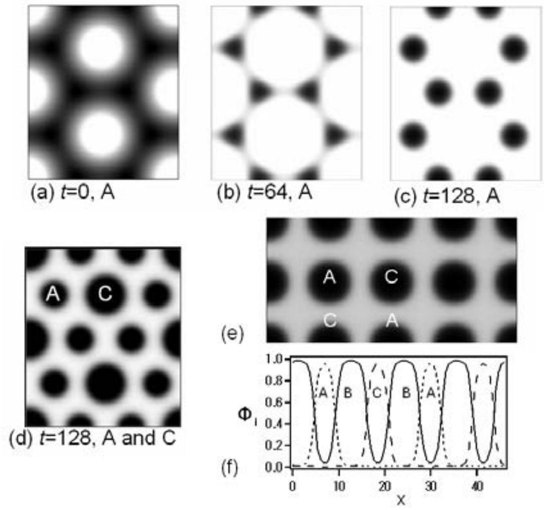

Figure 1: Various domain structures of an A-B-C type triblock copolymer obtained using the hybrid theory

(6) Modeling of Largely-deformed Fluid Systems (Y. Hayakawa)

(i) Nonlinear Dynamics in Collision

We studied colliding process of nonlinear elastic object in terms of a one-dimensional model. When the one-dimensional crystal with nonlinear interactions collides to a rigid wall, even without internal dissipative process, translational energy converts to incoherent lattice vibration resulting in an energy dissipation. Such energy dissipation increases (coefficient of restitution decreases) as the incident velocity of the object increases. We found the energy dissipation rate had a maximum at the incident velocity which is comparable to the sound velocity of the crystal. We also derived an estimation of the amount of energy dissipation as a function of the incident velocity. Furthermore, we analyzed generation process of fragment through colliding process and discussed a power-law fragment size distribution function. (Ref. 1)

(ii) Modeling of Largely-deformed Fluid Systems

We developed an SPH (Smoothed Particle Hydrodynamics) computer code in terms of the Lagrange's description of fluid in order to simulate colliding process of a three-dimensional object into fluid surface. In previous experimental studies, it had been known that there was an optimal tilt angle (about 20 degree) of the object (a rotating disc) between the disc and fluid surface to produce a bounce, which was interpreted as the optimal condition for "stone-skip". On the basis of the numerical analysis, we proposed an equation of motion of the colliding object, we found that our model theory could reproduce both experimental and numerical results quantitatively (Ref. 2).

(iii) Pattern formation of Crystal Growth

There have not been qualitative studies or theory to describe the shape selection mechanism of Kompeitoh (Japanese candy) which has a characteristic spike-like structure.

Although conventional theory of dendritic crystal growth predicts atomic-scale characteristic length for Kompeitoh, we observe spikes in macroscopic scale which is typically in millimeters. Furthermore, there seems to be some an autonomous mechanism to regulate the number of spikes. To answer these questions, we carried out systematic experimental studies of crystal growth. We found that, if started from spherical initial crystals, number of initial spikes (about 90) is gradually reduced, and finally approximately 20 spikes were selected. In these process, existence of wetting layer of sucrose solution on the crystal was crucial.

From the experimental results, we proposed a phenomenological model for Kompeitoh growth, and we gave a scenario how the characteristic shape of Kompeith is autonomously formed in a view point of mixing process of granules accompanied with crystal growth (Ref. 3).

Selected Publications

1. Shin-ichiro Nagahiro, and Yoshinori Hayakawa, "Collision of One-Dimensional Nonlinear Chains", Phys. Rev. E 67, (2003) 036609.
2. Shin-ichiro Nagahiro and Yoshinori Hayakawa, "Theoretical and Numerical Approach to "Magic Angle" of Stone Skipping", Physical Review Letters 94 (2005) 174501.
3. Isamu Sakai and Yoshinori Hayakawa, "Shape Selection of Kompeitoh, J. Phys". Soc. Jpn. Vol. 75, (2006) 104802.