【Grant-in-Aid for Scientific Research (S)】

Broad Section B

Title of Project : Chemical Composition of Disk Forming Regions of Solar-type Protostars and its Evolution to Planetary Systems

Satoshi Yamamoto
(The University of Tokyo, Graduate School of Science, Professor)

Research Project Number : 18H05222　Researcher Number : 80182624
Keyword : Radio Astronomy

【Purpose and Background of the Research】

A detailed understanding of the evolution of matter during star and planet formation is of fundamental importance in elucidating the origin of the Solar System. In this project, we will explore the chemical diversity of protostellar sources and its evolution to planetary systems through high-resolution radio observations with ALMA. The main goals are (1) to reveal an entire view of the chemical diversity by observations of about 20 protostellar sources, (2) to resolve the transition zone from the envelope to the disk for a few representative sources at the highest angular resolution of ALMA, and (3) to investigate the origin of the chemical diversity in a statistical way by observing many protostellar sources in a single molecular cloud complex. For the 5 year term of this project, we are going to reveal basic laws of the chemical evolution of protostellar sources for an understanding of our origin in the universe.

【Research Methods】

To achieve the above goals, we are going to conduct extensive observations of molecular lines with a full use of ALMA.

(1) Evolution of Chemical Diversity: So far, the observational data with a resolution of a few 10 au have been delivered for a few sources. We are going to analyze these data, and to prepare proposals for further ALMA observations. For 5 years, we will eventually explore about 20 protostellar sources, and reveal basic laws of the chemical evolution. In addition, we will study chemical processes in disk forming regions by chemical network calculations.

(2) Chemical and Physical Processes in Disk Forming Regions: Complex physical and chemical processes, including a launch of outflows, seem to occur around the centrifugal barrier of the infalling-rotating envelope gas. We will reveal its detailed structure at the highest angular resolution.

(3) Origin of Chemical Diversity: Observations of a number of protostellar sources in the Orion and Perseus clouds have already been conducted with ALMA. Chemical diversity and its origin will be studied in a statistical way by using the CH_3OH and CCH lines. We will propose ALMA observations of other molecular complexes for comparison.

In parallel to the observational studies, we are going to conduct laboratory measurements of rest frequencies of molecular lines including those of isotopic species with an accuracy better than 0.01 MHz by using a new submillimeter spectrometer at RIKEN. The obtained rest frequencies will widely be used for the above ALMA analysis.

【Expected Research Achievements and Scientific Significance】

This is the first attempt of systematic studies of chemical evolution in disk forming regions by a full use of ALMA. The result will provide us with crucial information on how chemical diversity of the envelope is inherited into planetary systems. It will significantly contribute to our understanding of the initial chemical environment of the Solar System in combination with results expected from exploration of small Solar System bodies

【Publications Relevant to the Project】

・Sakai et al., 2014, Nature, 507, 79-80.
・Oya et al. 2016, Astrophys. J. 824, 88 (19 pp).
・Sakai et al. 2017, Mon. Not. R. Astr. Soc. 467, L76-L80.

【Term of Project】 FY2018-2022

【Budget Allocation】 144,500 Thousand Yen

【Homepage Address and Other Contact Information】

http://www.resceu.s.u-tokyo.ac.jp/~submm/

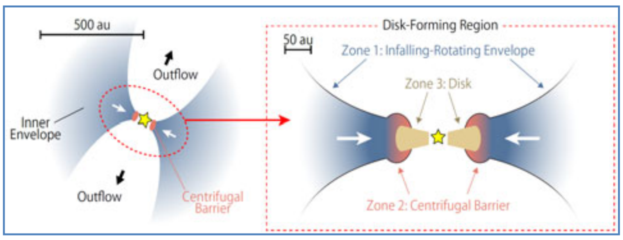


Figure 1: Schematic illustration of a disk forming region to be studied with this project.

Title of Project : Identifying the origin of the type-Ia supernova by observations just after the explosion

Mamoru Doi
(The University of Tokyo, Graduate School of Science, Professor)

Research Project Number : 18H05223 Researcher Number : 00242090
Keyword : Type Ia supernova, Progenitor, Explosion Mechanism, Standard Candle, Dark Energy

【Purpose and Background of the Research】

The type Ia supernova (SNIa) provides important heavy elements of the universe such as Iron, and also a good standard candle for Cosmology being used to find acceleration of the expansion of the Universe. But the progenitor of SNIa is not identified yet. Recently we found a SNIa whose explosion was triggered by detonation of a thin Helium layer by observations about half day after its ignition, which shows that a key to unveil the progenitor of SNIa is early phase observations just after the explosion.

There are other studies which imply that SNeIa may have different explosion mechanisms and may be originated from different progenitor systems. Statistical studies of SNeIa in very early phase are promising to classify the ignition mechanisms as well as progenitors of SNIa.

In this study, we aim to obtain high quality observational data of SNeIa with newly developed instruments, and to compare observational results with theoretical models to understand diversity of color and luminosity of SNeIa and to unveil the origin of SNeIa. Simultaneously we make template spectra of SNeIa in Near Infrared wavelengths (NIR) in order to make the SNIa as a standard candle in NIR.

【Research Methods】

We complete the CMOS wide-field camera, Tomo-e, at the prime focus of the 1-m Kiso Schmidt telescope, operated by the University of Tokyo,

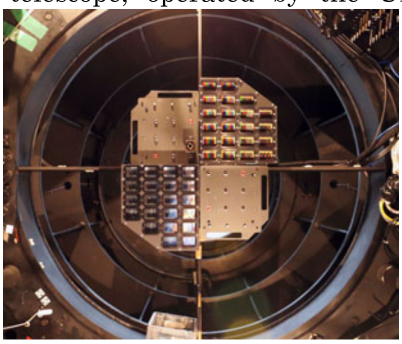


Figure 1. A wide-filed CMOS camera, Tomo-e, being built at the prime focus of Kiso Schmidt. So far, 21 sensors are installed, and more sensors are being installed.

and will use Tomo-e to find nearby SNeIa from their very early phase. Tomo-e will have 84 CMOS sensors and will be the most powerful instrument to find bright supernovae. With repeated 2-hour cadence imaging, Tomo-e can find all SNeIa in the northern sky (Dec. > -20 deg.) brighter than V=19 mag except for very crowded regions. Then we will carry out follow-up observations with a newly developed multi-band camera and an upgraded IFU spectrograph attached to the Seimei 3.8-m telescope, Kyoto University. We will compare multi-band photometry and spectra of more than 30 SNeIa with theoretical models, and will carry out statistical studies. We also make template spectra of about 30 SNeIa in NIR with a few day cadence with NICE, an Echelle spectrograph on the 6.5-m TAO telescope, operated at the world highest site, Atacama, Chile by Univ. of Tokyo.

【Expected Research Achievements and Scientific Significance】

Thus we carry out statistical photometric and spectroscopic studies of more than 30 SNeIa, and understand the progenitor and the explosion mechanism of SNIa. At the same time, a set of NIR spectroscopic template of SNeIa, which enables SNIa to be a standard candle in NIR. Overall, this study will be an important step to understand the origin of SNIa and, in the long run, the origin of the acceleration of the Universe, i.e. Dark Energy.

【Publications Relevant to the Project】

・"A hybrid type Ia supernova with an early flash triggered by helium-shell detonation", Jiang, J., Doi, M., Maeda, K.et al., Nature, 550, pp.80-83. (2017)
・"Photometric properties of intermediate redshift Type Ia supernovae observed by the Sloan Digital Sky Survey-II Supernova Survey", Takanashi, N., Doi, M. et al., MNRAS, 465, p.1274-1288 (2017)

【Term of Project】 FY2018-2022

【Budget Allocation】 147,400 Thousand Yen

【Homepage Address and Other Contact Information】

http://www.ioa.s.u-tokyo.ac.jp/~doi/doi's_project.htm

Title of Project : Material Science of Hydrogen in the deep earth and planets

Hiroyuki Kagi
(The University of Tokyo, Graduate School of Science, Professor)

Research Project Number : 18H05224 Researcher Number : 70233666
Keyword : hydrogen, the earth's interior, planetary interior, neutron diffraction

【Purpose and Background of the Research】

Hydrogen is the most abundant element in the solar system and the simplest element containing only one electron. However, the chemical property of hydrogen has a wide variety caused by its multiple bonding nature. From these reasons, hydrogen can constrain the properties and structure of materials in the deep earth and planets. In this research project, we are going to solve fundamental questions on structures, properties and behaviors of hydrogen-containing minerals in the deep earth and planets from versatile experiments at high pressure and high temperature or low temperature. The purpose of the project is to clarify the thermodynamic stability, crystal structure, chemical composition of hydrogen-beading materials in the deep earth and planets. The targets of our project cover very wide range of materials as illustrated in Figure 1.

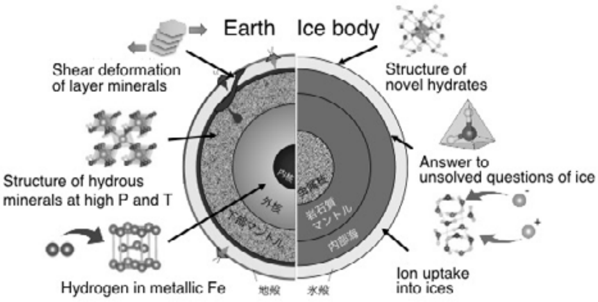


Figure 1 Targets of our research.

【Research Methods】

Main experimental method in this research project is neutron diffraction measurements at high pressure at the PLANET beamline (BL-11), MLF, J-PARC (see Figure 2). The PLANET beamline was constructed by a research consortium led by members in this research project. Crystal structures of the materials in the deep earth and planets will be solved from X-ray diffraction measurements at PF, KEK and local structure surrounding hydrogen atoms will be obtained from neutron diffraction measurements at MLF, J-PARC. In this research, laboratory-based instruments will be also installed to support the measurements at J-PARC and KEK, because beamtime distributed to us is very limited. In this project, we will solve the phase relationship of salt-water systems at high pressure and low temperature to clarify the internal structure of icy bodies. Moreover, the occupancy and local structure of hydrogen atoms in metallic iron will be clarified at high pressure and high temperature conditions.

Figure 2 BL-11 at MLF, J-PARC.

【Expected Research Achievements and Scientific Significance】

Structure and chemical compositions of the earth's core and icy planets will be clarified from this research project.

【Publications Relevant to the Project】

・Hattori et al. (2015) Design and performance of high-pressure beamline PLANET launched at pulsed neutron source at J-PARC. NIM A, 780, 55.
・Iizuka-Oku et al. (2017) Hydrogenation of iron in the early stage of Earth's evolution. Nature Comm., 8, 14096, DOI: 10.1038/ncomms14096.

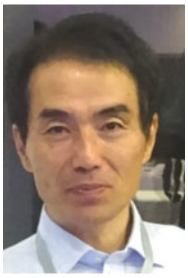
【Term of Project】 FY2018-2022

【Budget Allocation】 148,500 Thousand Yen

【Homepage Address and Other Contact Information】

http://www.eqchem.s.u-tokyo.ac.jp

Broad Section B



Title of Project : Creation of a new discipline, quantum glass, for electronic systems and its development to material science

Kazushi Kanoda
(The University of Tokyo, Graduate School of Engineering, Professor)

Research Project Number : 18H05225 Researcher Number : 20194946
Keyword : molecular solid, strongly correlated electron system, liquid and glass, soft matter

【Purpose and Background of the Research】

The physics of strongly interacting electrons has advanced into a fertile field owing to their diverse and emergent phenomena with microscopic orders of charges and spins. Recent studies, however, suggest that interaction may cause heterogeneous self-organizations of electrons on scales far larger than molecular size and their extremely slow dynamics – the very characteristics of soft matters.
In the present study, we investigate electronic systems exhibiting spatiotemporal variation on anomalously large scales in terms of soft matters, aiming to establish a new notion, "quantum glass of electrons", that possesses charge and spin of quantum nature, not available in conventional glasses. This research project tries to create a new interdisciplinary filed linking two sciences of strongly correlated electrons and soft matters, so far developed separately (Fig.1).

【Research Methods】

The project is conducted in close collaboration between three groups performing physical property measurements, material synthesis and theoretical studies, seeking quantum glass matters, their control and a new notion of electronic rheology.
The measurement group studies the spatiotemporal variation of electronic states by NMR, electron transport and permittivity measurements and scanning microspectroscopy, and further tackles non-equilibrium phase control (Fg.2). The synthesis group designs and synthesizes materials for electronic glasses by the chemical modification of molecules and the introduction of proton electron interactions. The theory group elaborates effective models for electronic glasses to elucidate the origin of the slow dynamics.

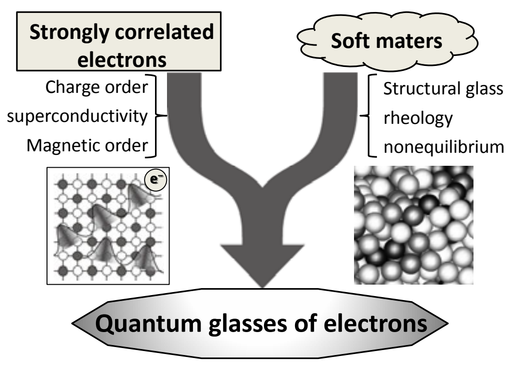


Figure 1

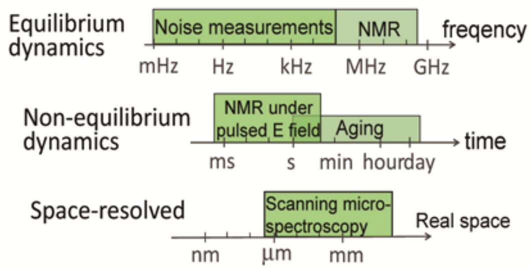


Figure 2

【Expected Research Achievements and Scientific Significance】

We aim to develop a new research area, quantum glass, which originates from interacting electrons. This project tackles an essential issue of how soft matters so-far studied in the classical framework meet electrons of quantum nature. It is expected that soft matters of quantum nature come out and novel phase control exploiting slow dynamics and non-equilibrium nature is developed.

【Publications Relevant to the Project】

・T. Sato, K. Miyagawa and K. Kanoda, "Electronic crystal growth", Science **357**, 1378-1381 (2017).
・T. Itou, E. Watanabe, S. Maegawa, A. Tajima, N. Tajima, K. Kubo, R. Kato and K. Kanoda, "Slow dynamics of electrons at a metal–Mott insulator boundary in an organic system with disorder", Sci. Adv. **3**, e1601594-1-6 (2017).

【Term of Project】 FY2018-2012

【Budget Allocation】 151,400 Thousand Yen

【Homepage Address and Other Contact Information】

http://park.itc.u-tokyo.ac.jp/kanoda_lab/

【Grant-in-Aid for Scientific Research (S)】

Broad Section B

Title of Project：Search for new symmetry violation in leptons

Toru Iijima
(Nagoya University, Center for Experimental Studies, Professor)

Research Project Number：18H05226　Researcher Number：80270396
Keyword：Experimental particle physics, lepton, accelerator, particle detectors

【Purpose and Background of the Research】

Although the Standard Model (SM) of particle physics has been established with confirmation of the Kobayashi-Maskawa theory to explain the CP violation and also discovery of the Higgs boson to explain the origin of the mass, there are still mysteries of the Universe; How the anti-matter disappeared? What is the dark matter? What is the dark energy? To solve such mysteries, discovery of New Physics (NP) beyond the SM would be the first step. Here, violation of symmetry or conservation law play important role, and there have been many findings in the quark and neutrino sectors in the past.

In fact, we have found that the B meson prefers decaying to the final state with τ ($D\tau\nu$) rather than those with e ($De\nu$) or μ ($D\mu\nu$). There are also reported deviations from the SM in rare B meson decays ($B\to K^{(*)}e^+e^-$, $B\to K^{(*)}\mu^+\mu^-$) and in the anomalous magnetic moment of the muon, $(g\text{-}2)_\mu$.

In this research, we will clarify the existence of new symmetry violations in the charged lepton sector, in data taken by SuperKEKB/Belle II experiment and the J-PARC g-2/EDM experiment (E34), and discover New Physics.

【Research Methods】

In the proposed research, we search for lepton universality violations in the tauonic B decays and rare B meson decays, and lepton flavor violation in τ decays. To achieve this goal as early as possible, we will perform R&D to improve the detector performance, and develop computing architecture to process big data samples. Moreover, we will improve the SM prediction of the $(g\text{-}2)_\mu$, by precision measurement of the e+e- cross section to estimate the contribution of the hadronic loop effect. We also plan to improve the performance of E34 by transferring expertise developed for the Belle II experiment.

【Expected Research Achievements and Scientific Significance】

We plan to accumulate data about 30 times more than presently available. Together with the detector improvement, we will clarify the lepton universality and lepton flavor violation. In parallel, we try to start the E34 experiment. If deviations are found clearly in some of these measurements, we will be able to claim NP and also elucidate the NP model from correlations.

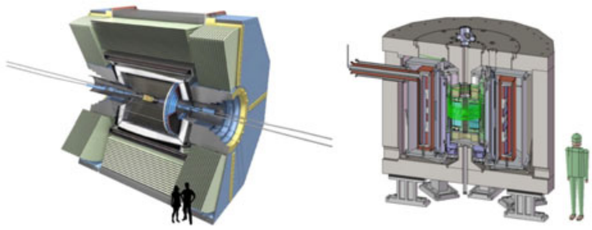


Figure 1　Belle II experimrnt (left) and J-PARC E34 experiment (right)

【Publications Relevant to the Project】

- "Measurement of the τ lepton polarization and R(D*) in the decay $B\to D^*\tau\nu$", S. Hirose, T. Iijima, K. Hayasaka et al., Phys. Rev. Lett. 118, 211801 (2017).
- "Measurement of the branching fraction of $B0\to D^*\tau\nu$ relative to $B0\to D^* l\nu$ decays with a semileptonic tagging method", Y. Sato, T. Iijima, K. Hayasaka et al., Phys. Rev. D94, 072007 (2016).

【Term of Project】 FY2018-2022

【Budget Allocation】 147,400 Thousand Yen

【Homepage Address and Other Contact Information】

http://wru.hepl.phys.nagoya-u.ac.jp/

Title of Project：Rotational Symmetry Breaking in Strongly Correlated Quantum Matters

Yuji Matsuda
(Kyoto University, Graduate School of Science, Professor)

Research Project Number：18H05227　Researcher Number：50199816
Keyword：Strongly Correlated Electrons, Quantum spin systems, Rotational Symmetry Breaking

【Purpose and Background of the Research】

Recently, nematic transition, in which electronic structure spontaneously break the underlying lattice symmetry has aroused great interest in strongly correlated systems, including cuprates, iron-pnictides, heavy fermion systems. The clarification of the origin of the nematic transition is very important because it is closely related to the long-standing central issues of condensed matter physics, such as pseudogap formation, unconventional superconductivity, hidden order and quantum criticality. Moreover, quantum spin liquid state in insulating systems, in which the long range magnetic order is destroyed by quantum fluctuations, has attracted much attention recently as a novel quantum phase. Ground states of these quantum spin liquid states, however, have been poorly explored so far. In particular, what kind of symmetry breaking occurs in these quantum spin liquid state is an unresolved issue. In this project, to clarify the rotational symmetry breaking in these novel quantum systems, we develop the ultrahigh sensitive torque magnetometry, which makes us possible to detect the magnetic anisotropy in unprecedented precision.

【Research Methods】

In a wide temperature range from 50 mK to 400 K, we develop the ultrahigh sensitive torque magnetometry, For the precise measurements of the in-plane magnetic torque, we use a system consisting of a two-dimensional vector magnet and a mechanical rotator (see Fig.1), which enables us to rotate the magnetic field **H** within the *ab* plane. Computer controlling the vector field and mechanical rotator systems, we eliminate the misalignment and rotate **H** within the *ab* plane with the accuracy better than 0.1 degree.

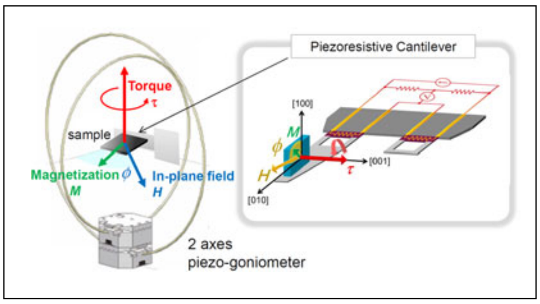


Figure 1

【Expected Research Achievements and Scientific Significance】

It has been widely recognized that strongly correlated quantum many body systems exhibit various types of symmetry breakings. In this project, we clarify the rotational symmetry breaking in strongly correlated superconductors, including heavy fermion compounds, high-Tc cuprates and iron-pnictides, correlated electron systems with strong spin-orbit interactions, including irridates, and quantum spin liquids. These studies are expected to provide a key to understanding important aspects of long-standing unresolved issue in condensed matter physics.

【Publications Relevant to the Project】

- Y. Sato, *et al.* "Thermodynamic evidence for a nematic phase transition at the onset of the pseudogap in $YBa_2Cu_3O_y$" Nature Phys. 13, 1074–1078 (2017).
- S. Kasahara *et al.* "Electronic nematicity above the structural and superconducting transition in $BaFe_2(As_{1-x}P_x)_2$" Nature 486, 382-385 (2012).
- R.Okazaki *et al.* "Rotational Symmetry Breaking in the Hidden-Order Phase of URu_2Si_2" Science 331, 439-442 (2011).

【Term of Project】 FY2018-2022

【Budget Allocation】 198,250 Thousand Yen

【Homepage Address and Other Contact Information】

http://kotai2.scphys.kyoto-u.ac.jp/index.php
matsuda@scphys.kyoto-u.ac.jp

【Grant-in-Aid for Scientific Research (S)】

Broad Section B

Title of Project : Exploration of new quantum condensed phase by exploiting orbital and spin degrees of freedom of ultracold atomic gases in an optical lattice

Yoshiro Takahashi
(Kyoto University, Graduate School of Science, Professor)

Research Project Number : 18H05228 Researcher Number : 40226907
Keyword : quantum electronics, cold atom, quantum simulation, optical lattice

【Purpose and Background of the Research】

The researches using the quantum gases have been quite active. Among them, especially interesting is quantum simulation of quantum many-body system described by so called Hubbard model using cold atoms in an optical lattice which is the periodic potentials for atoms (See Fig. 1). The cold atoms in an optical lattice are well described by the Hubbard model which consists of hopping term and on-site interaction term. This Hubbard model is an important one which describes strongly correlated electron system such as itinerant magnetism and unconventional superconductivity.

Under this background, we aim at the significant advancement of research on physical properties of quantum condensed phases by exploiting novel orbital degrees of freedom which can be realized by non-standard optical lattice, and novel spin degrees of freedom of high spin symmetry offered by two-electron atoms.

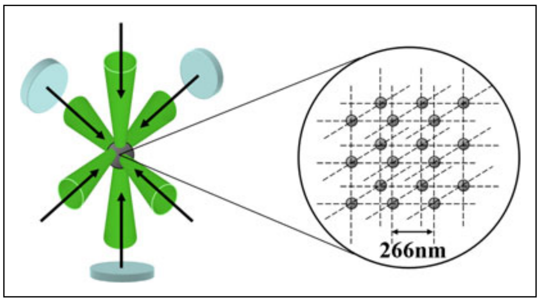


Figure 1 Optical lattice

We mainly exploit ytterbium (Yb) atomic system which possess SU(N=6) symmetry, and carry out unique experiments by constructing a Lieb optical lattice which possess flat-band and two-orbital systems of localized and itinerant characters. In addition, we develop a high-resolution imaging and controlling technique to realize a unique quantum simulator.

【Research Methods】

We plan to perform the following four research topics: "study of quantum magnetism and superfluidity realized by flat band of optical Lieb lattice", "study of two-orbital system with localized and itinerant characters", "study of SU(N) quantum magnetism", and "New possibilities on unique orbital degrees of freedom".

【Expected Research Achievements and Scientific Significance】

Our research which focuses novel multi-orbital and highly-symmetric spin degrees of freedom is quite unique, only possible by two-electron atomic system which we have been developing. We expect significant advancement of quantum simulation research as well as condensed matter theory and computational science, which will give us an important guideline of material synthesis.

【Publications Relevant to the Project】

- T Tomita, S Nakajima, I Danshita, Y Takasu, and Y Takahashi, "Observation of the Mott insulator to superfluid crossover of a driven-dissipative Bose-Hubbard system", **Sci. Advances, 3**, 2017, e1701513 (1-8).

- S. Taie, H. Ozawa, T. Ichinose, T. Nishio, S. Nakajima, and Y. Takahashi, "Coherent driving and freezing of bosonic matter wave in an optical Lieb lattice", **Sci. Advances, 1**, 2015, e1500854(1-6).

【Term of Project】 FY2018-2022

【Budget Allocation】 144,600 Thousand Yen

【Homepage Address and Other Contact Information】

http://yagura.scphys.kyoto-u.ac.jp/

Title of Project : Neutron Structural Biology for New Generation

Masaaki Sugiyama
(Kyoto University, Institute for Integrated Radiation and Nuclear Science, Professor)

Research Project Number : 18H05229 Researcher Number : 10253395
Keyword : protein dynamics, neutron scattering

【Purpose and Background of the Research】

In these days, not only structure but also dynamics has been highlighted to understand functions of biomacromolecules.

Figure 1 shows the relation between structure and dynamics, taking multi-domain protein (MurD) as an example. A hierarchic structure of the protein is shown in Fig.1(u): "amino acid reside" is a basic unit (10^{-11}-10^{-10} m), "domain" is a unit of 3D structure (10^{-10}-10^{-9} m), "whole structure" is constituted with the domains (10^{-9}-10^{-8} m), "complex / aggregates" is connected by other protein(s) and/or molecules(s) (>10^{-8} m). Next, based on MD simulation, the time range of dynamics of each structure is displayed on a spatio-temporal map (Fig.1(d)): Zones 1-4 correspond to the dynamics of amino acid reside (10^{-15}-10^{-12} s), domain (10^{-12}-10^{-9} s), whole structure (10^{-9}-10^{-6} s) and complex / aggregates (>10^{-6} s), respectively. Experimentally, there are several methods to observe the dynamics for Zones 1 and 4 but and there are not for Zones 2 and 3, namely an experimental "missing zone".

Neutron scatterings have possibilities to cover the missing zone in principle. However, the beam intensity was not enough to observe dynamics of protein in solution. Recently, the situation is going to change: J-PARC has supplied the brilliant beam and their spectrometers are having ability to observe the dynamics.

Purposes of this project are establishment of the methods to measure the protein dynamics in the

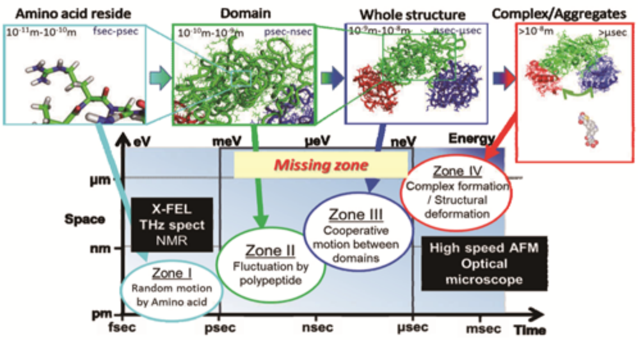


Figure 1. Relation between structure and dynamics in a multi-domain protein. (up) Hierarchic structure. (down) Dynamics of each structure on spatio-temporal map.

missing zone and development of the analyzing method coupled with MD simulation by making full use of the latest neutron spectrometers.

【Research Methods】

This project proceeds development and empirical studies. Three techniques, high level protein deuteration, measurement for protein dynamics with QENS, NSE and SANS, and data analysis coupled with MD simulation, will be developed. Then, by integrating the developed techniques, the protocol will be established to reveal protein dynamics in the missing zone. In the empirical study, the first targets are two proteins with high biological significances: MurD is a typical multi-domain protein and Hef is an intrinsically disordered protein. Then, the targets expand more.

【Expected Research Achievements and Scientific Significance】

This project will not only develop methods to cover the missing zone but also reveal dynamics of proteins with high biological significances. With these results, it is expected to reveal a transfer mechanism from random motion of amino-acid resides to cooperative motion between domains.

The developed methods will be open for all researches who are interesting of protein dynamics. Then, it is also expected that Japanese facilities such as J-PARC becomes center of neutrons biology. In addition, the most of project members are young and up-coming researches. Therefore, they will play a central role in this field in the next 10 years.

【Publications Relevant to the Project】

・P. Bernadó, M. Sugiyama, etal., BBA General Subjects, 1862 (2018) 253-274.
・R. Inoue, M. Sugiyama, etal., Sci. Rep., **6** (2016) 29208.

【Term of Project】 FY2018-2022

【Budget Allocation】 151,600 Thousand Yen

【Homepage Address and Other Contact Information】

http://www.rri.kyoto-u.ac.jp/NSBNG

Title of Project : Search for the neutron electric dipole moment and the time reversal violation

Kichiji Hatanaka
(Osaka University, Research Center for Nuclear Physics, Specially Appointed Professor)

Research Project Number : 18H05230 Researcher Number : 50144530
Keyword : Particle physics, Nuclear physics, Symmetry, Ultracold neutron, Electric dipole moment

【Purpose and Background of the Research】

The current standard cosmology describes our Universe and its evolution starting from the Big Bang and following Inflation. The early Universe was in thermal equilibrium of particle-antiparticle annihilation. The Universe was cooled down by its expansion and the small amount of matter remained. Combined charge and parity (CP) reversal symmetry violation can be related to the matter-antimatter asymmetry. The standard model (SM) of particle physics describes the CP violation in the quark sector by CKM matrix. CP violation in neutrino sector was also observed by the T2K experiments. However, they are not enough to explain the matter-antimatter asymmetry in the present Universe. A new physics beyond SM is necessary.

A permanent electric dipole moment (EDM) of a fundamental particle violates time reversal (T) symmetry and therefore also CP symmetry assuming CPT conservation. The EDM is a good probe for searching a new physics beyond SM.

【Research Methods】

Ultracold neutrons (UCN) are neutrons of which kinetic energy is remarkably small (< 300 neV). Therefore, they can be stored in a material vessel. Neutron EDM (nEDM) is measured by observing the spin precession frequency of UCN in both the magnetic and electric fields. A high density UCN source is constructed and developed at TRIUMF (see Fig. 1). The UCN source enable us to measure the nEDM in the sensitivity of 10^{-27} ecm.

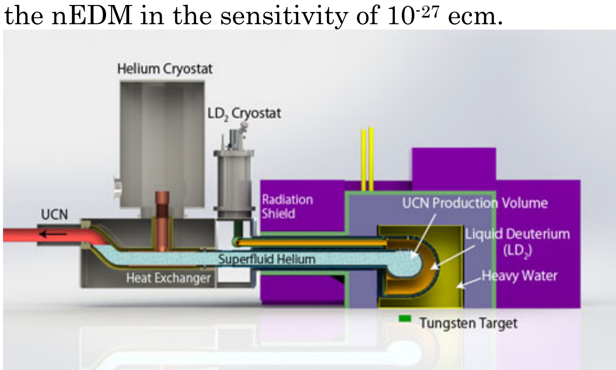


Figure 1 Schematic layout of the UCN source

Neutrons produced upon spallation reaction on the tantalum-clad tungsten target are moderated by room temperature heavy water. A large flux of cold neutrons around 1 meV is created by further moderation in 20 K liquid deuterium. Conversion to UCN happens in superfluid liquid ^{4}He around 1K where the cold neutrons are downscattered creating phonons and rotons in the liquid.

UCN are transported from the source to a storage vessel preserving their polarization. nEDM is measured by precisely observing the frequency of UCN spin precession in stable magnetic and electric fields using Ramsey resonance method. Systematic errors mainly arise from a geometric phase effect caused by gradients and fluctuations of the magnetic field. We will achieve uniform (< 1 nT/m) and stable (< 1 pT/100 s) magnetic fields by applying active compensation coils and a 4-layer shielded room.

【Expected Research Achievements and Scientific Significance】

SM predicts a nEDM at the level of 10^{-32} to 10^{-31} ecm. On the other hand, a new physics such as SUSY model predicts nEDM around 10^{-28} to 10^{-26} ecm. The current best experimental upper limit is 3×10^{-26} ecm measured with UCN at Institute Laue Langevin (ILL). We will search nEDM in the level predicted by new physics.

【Publications Relevant to the Project】

・R. Golub and J. Pendlebury, Phys. Lett. A 62, 337 (1977)
・J. M. Pendlebury et al., Phys. Rev. D. 92, 092003 (2015)
・Y. Masuda et. al, Phys. Rev. Lett. 108, 134801 (2012)

【Term of Project】 FY2018-2022

【Budget Allocation】 152,200 Thousand Yen

【Homepage Address and Other Contact Information】
http://fnp.kek.jp

Broad Section B

Title of Project : New Initiative on Search for Charged Lepton Flavor Violation with Highly Intense Muon Source

Yoshitaka Kuno
(Osaka University, Graduate School of Science, Professor)

Research Project Number : 18H05231 Researcher Number : 30170020
Keyword : Elementary Particle

【Purpose and Background of the Research】

One of the most important subjects in elementary particle physics is to search for new physics phenomena beyond the Standard Model (SM). Charged lepton flavor violation (CLFV) is known not to occur in the framework of the SM, whereas it is expected to occur in the new physics models. Therefore, CLFV is considered to be one of the best to search for new physics. One of the most important CLFV processes is muon to electron conversion (μ-e conversion) in a muonic atom. We are preparing an experiment to search for it with a factor of about 100 improvement over the previous search. This experiment is called the COMET (J-PARC E21) Phase-I experiment. In particular, in this project, we will improve its experimental sensitivity by another 8 times over the original proposal of COMET Phase-I.

【Research Methods】

The present research method is to construct the COMET Phase-I detector to carry out our research for μ-e conversion. The detector is a cylindrical drift chamber (CDC) where a muon stopping target made of aluminium is placed at the center of the CDC. In particular, in this project, we intend to make three modifications of improvement. They are as follows; (1) We will install another solenoid magnet (named the Bridge Solenoid) between the solenoids of the muon transport section (3T) and the detector solenoid (1T). It would be useful to increase a total number of muons stopped and to reduce background hits. (2) We will replace all the silicon-based photon sensors for the CDC trigger counters, by fine-mesh photomultipliers, and will place additional radiation shielding for them (3) We will make special selection of the parts and FPGA used in the frontend electronics of the CDC to make them stronger against radiation.

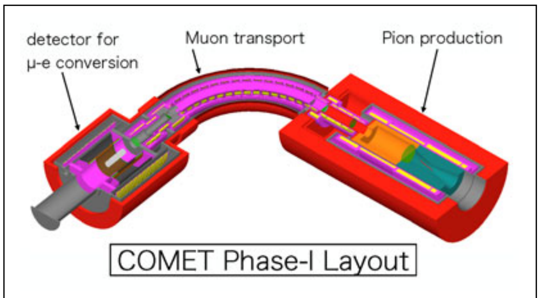


Figure 1

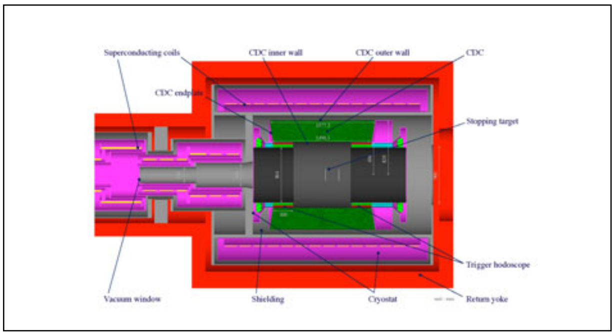


Figure 2 CDC layout

【Expected Research Achievements and Scientific Significance】

The COMET Phase-I with the proposed modifications, will intend at the 800 times improvement to aim at the discovery. If it is found, it would make a big paradigm change in the elementary particle physics.

【Publications Relevant to the Project】

- Y. Kuno, "A Search for Muon-to-electron Conversion at J-PARC: The COMET Experiment", PTEP 2013 (2013) 022C01, DOI : 10.1093/ptep/pts089
- Y. Kuno and Y. Okada, "Muon Decay and Physics beyond the Standard Model", Rev. Mod. Phys. 73 (2001) 151-202, DOI : 10.1103/Rev/ModPhys.73.151

【Term of Project】 FY2018-2022

【Budget Allocation】 148,500 Thousand Yen

【Homepage Address and Other Contact Information】

http://www-kuno.phys.sci.osaka-u.ac.jp/mlfv/

Title of Project : Experimental study on syn-deformational reaction processes at high pressures: Implications for slab weakening and deep earthquakes

Tomoaki Kubo
(Kyushu University, Faculty of Science, Professor)

Research Project Number : 18H05232 Researcher Number : 40312540
Keyword : Earth's deep material, transformation, deformation, high pressure, synchrotron radiation

【Purpose and Background of the Research】

Large deformation of subducting slabs and deep earthquakes in the mantle transition zone (Fig. 1) are still unresolved issues in mantle dynamics. Previous studies have suggested that the grain-size reduction due to non-equilibrium transformations leads to weakening and/or shear instability, which may be responsible for the slab stagnation and deep earthquakes. However, there have been few direct experimental evidences on the coupling process. We conduct synchrotron radiation and FIB-TEM studies combined with seismological investigation to constrain the role of the olivine transformations on the slab weakening and deep earthquakes.

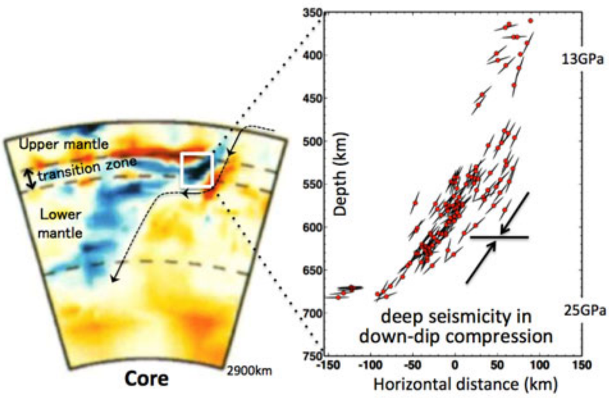


Fig. 1 Large deformation of subducting slab and distributions of deep earthquakes in mantle transition zone.

【Research Methods】

We conduct high-pressure deformation experiment at mantle transition zone conditions by using D-DIA and D-111 type apparatus. We focus on the interaction between deformation and the olivine-spinel and the post-spinel transformations. Simultaneous in-situ observations of reaction kinetics, creep behaviors, and acoustic emission (AE) activities are possible with the use of synchrotron X-ray and AE measurement system (Fig. 2). Reaction and deformation microstructures in recovered samples are examined by FIB-TEM analysis. The result is compared with that observed in shocked meteorites. We also conduct seismological studies on the field of metastable olivine, topography of the 660 km discontinuity, multiple discontinuities, and their relationships with distributions of deep earthquakes.

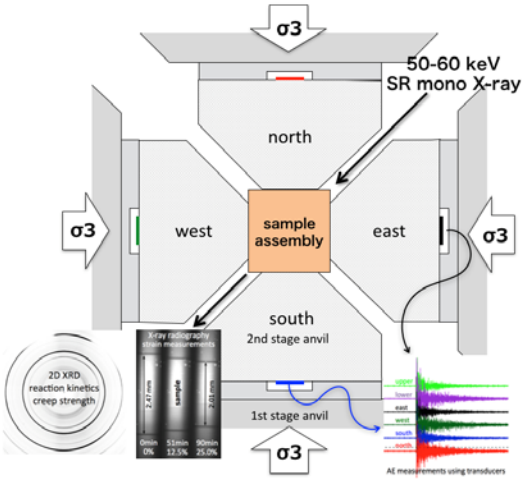


Fig. 2 D-DIA type high-pressure deformation apparatus and in-situ observations of transformation kinetics, creep behaviors, and AE activities

【Expected Research Achievements and Scientific Significance】

By using these techniques, we investigate the details of reaction-induced weakening, shear localization, and shear instability under mantle transition zone conditions. Interdisciplinary research combining high-pressure mineral physics with meteoritics and seismology is crucial to understand the slab behaviors in mantle transition zone.

【Publications Relevant to the Project】

Doi N., Kato T., Kubo T., Noda M., Shiraishi R., Suzuki A., Ohtani E., Kikegawa T., Creep behavior during the eutectoid transformation of albite: Implications for the slab deformation in the lower mantle. Earth Planet. Sci. Lett., 388, 92-97, 2014

【Term of Project】 FY2018-2022

【Budget Allocation】 108,400 Thousand Yen

【Homepage Address and Other Contact Information】

http://mineral2.geo.kyushu-u.ac.jp/saito/index.html
kubotomo@geo.kyushu-u.ac.jp

Title of Project : Strategic research to construct motivic units using new symmetry

Kenichi Bannai
(Keio University, Faculty of Science and Technology, Professor)

Research Project Number : 18H05233 Researcher Number : 90343201
Keyword : Number Theory, Arithmetic Geometry

【Purpose and Background of the Research】

Conjectures such as the Beilinson conjecture, Tamagawa Number Conjecture and Iwasawa main conjecture concerning the special values of Hasse-Weil L-functions associated to algebraic variety defined over number field is a central problem in Mathematics, especially in arithmetic geometry. The Birch and Swinnerton-Dyer Conjecture for elliptic curves is a special case of these conjectures.

When the algebraic variety is the multiplicative group, whose associated Hasse-Weil L-function is the classical Riemann Zeta function, the above conjectures were solved by effort of many mathematicians a predominant tool being a motivic unit called the cyclotomic element (cyclotomic unit). One reason that the proof of the conjectures in the other cases are notoriously difficult is that there are no known method to systematically construct motivic units which intrinsically contain information concerning both the special values of the L-function and arithmetic information of the algebraic variety.

The purpose of this research is to study the polylogarithm, which are motivic elements systematically constructed for the multiplicative group, elliptic curves, and more general higher dimensional abelian varieties, wtih an eye towards future construction of motivic units. A concrete goal is to study the polylogarithm for a certain algebraic torus, and attempt to relate its Hodge realization to special values of L-function relevant in this case.

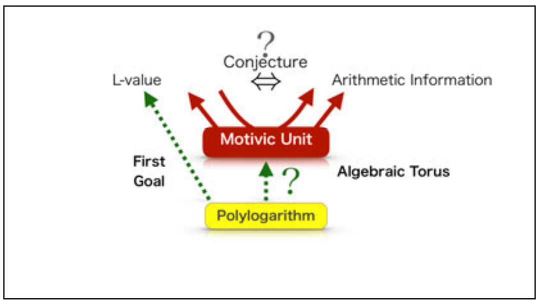


Figure 1 Concept

【Research Methods】

The research will be conducted by a team of experts including S. Yamamoto and S. Yasuda (Number Theory), S. Kobayashi (Iwasawa Theory), T. Terasoma (Motives), A. Shiho (p-adic theory) and T. Katsura (Operator Algebra). In particular, we will use techniques developed to explicitly represent higher degree cohomology classes, In order to obtain L-values from higher degree cohomology classes, it is necessary to use a theory of new symmetry called plectic structure developed by J. Nekovář and A. J. Scholl. We will first expand the theory of plectic structures for the Hodge case, and then will subsequently deal with the motivic, p-adic and étale cases.

【Expected Research Achievements and Scientific Significance】

If we succeed in explicitly determining the Hodge structure of the polylogarithm of the algebraic torus and succeed using the plectic structure to recover special values of the relevant L-function, then this would indicate the possibility that polylogarithm of the algebraic torus may be used to construct motivic units in this case.

【Publications Relevant to the Project】

- J. Nekovář and A. J. Scholl, *Introduction to plectic cohomology*, Advances in the theory of automorphic forms and their *L*-functions, Contemp. Math., vol. **664**, Amer. Math. Soc., Providence, RI, 2016, pp. 321–337.
- K. Bannai, K. Hagihara, S. Kobayashi, K. Yamada, S. Yamamoto, and S. Yasuda, *Category of mixed plectic Hodge structures* (2017), arXiv:1705.05522[math.AG].

【Term of Project】 FY2018-2022

【Budget Allocation】 91,900 Thousand Yen

【Homepage Address and Other Contact Information】

http://www.math.keio.ac.jp/~bannai/
bannai@math.keio.ac.jp

Title of Project : **High Precision Polarimetric Observation by a Balloon-Borne Solar Telescope: Revealing Conversion Processes of Magnetic Energy in the Stellar Atmosphere**

Yukio Katsukawa
(National Institutes of Natural Sciences, National Astronomical Observatory of Japan, Solar Science Observatory, Associate Professor)

Research Project Number : 18H05234 Researcher Number : 00399289

Keyword : Astrophysical Plasma, Solar Physics, Optical-IR Astronomy, Balloon instrument, International Collaboration

【Purpose and Background of the Research】

The **chromosphere** interfacing the photosphere of 6000K and the corona of over 1MK is not a simple intermediate atmospheric layer transmitting magnetic energy, but a region where strong non-linearity drives dynamic phenomena, such as turbulence, shocks, and jets. Because the dynamics are likely to be responsible for injection of non-thermal energies into the corona and the solar winds, the chromosphere is the most important target in the solar and stellar physics. In order to **understand the conversion process of the magnetic energy**, it is necessary to quantitatively observe the chromosphere together with energy generation by turbulent magneto-convection in the photosphere. In order to overcome the qualitative interpretation by conventional imaging observations, we acquire a **high-quality 3D magnetic and velocity fields for the first time by the SUNRISE balloon-borne solar telescope**. In this research, we develop a high precision spectro-polarimeter to be installed in SUNRISE. In addition, we carry out **numerical modeling of the dynamic phenomenon in the solar atmosphere**, and aim to clarify the conversion process of magnetic fields in the astrophysical plasma by direct comparison with the 3D data provided by the SUNRISE balloon observation.

【Research Methods】

(1) High resolution and precise polarization measurement by the balloon-borne solar telescope SUNRISE: SUNRISE is an international joint project equipped with a 1m optical telescope. It allows us to perform a seeing-free and continuous observation for a week in its flight from Sweden to Canada at an altitude higher than 35km. We will newly develop SCIP (SUNRISE Chromospheric Infrared spectro-Polarimeter) for precise spectro-polarimetric observation of NIR spectral lines sensitive to magnetic fields in the photosphere and the chromosphere. Its flight is planned for 2021. We aim to obtain temporal evolution of 3D magnetic and velocity structures, to capture propagation of MHD waves and a discontinuous magnetic structure suggestive of magnetic reconnection.

(2) Numerical modeling of the solar photosphere and chromosphere: We employ massive numerical simulations to reproduce key process responsible for the energy transfer and dissipation which are highly deviated from thermal equilibrium over multiple spatial and temporal scales. We plan to incorporate ionization and recombination of atoms by heating and cooling, because they are likely to affect the dynamic phenomena in the chromosphere. We apply state-of-the-art radiative transfer calculation to simulate polarized spectra radiated from the dynamic phenomena, which allows us to make direct comparison with the data taken by SUNRISE.

【Expected Research Achievements and Scientific Significance】

The Sun provides a unique site to deeply understand the conversion processes of magnetic energy by the observations with resolution, which can be applied in a wide range of astrophysical plasmas such as stellar winds and accretion disks where common processes are likely to work. Because a space-based spectro-polarimetry planned in 2020's is only SUNRISE, this research can provide the basis for a future large-scale satellite project by showing superiority of the observation.

【Publications Relevant to the Project】

・"Penumbral Microjets in Sunspot Chromospheres: Evidence of Magnetic Reconnection", Katsukawa, Y., Astrophysics and Space Science Library, 449, 201 (2018).
・"SUNRISE: Instrument, Mission, Data, First Results", Solanki, S., ApJL, 723, L127 (2010).

【Term of Project】 FY2018-2022

【Budget Allocation】 109,100 Thousand Yen

【Homepage Address and Other Contact Information】

https://hinode.nao.ac.jp/SUNRISE/
yukio.katsukawa@nao.ac.jp

Title of Project : Origin of hadron mass studied by the systematic measurement of spectral change of mesons in nuclei

Satoshi Yokkaichi
(RIKEN, Nishina Center, Senior Research Scientist)

Research Project Number : 18H05235 Researcher Number : 20360670
Keyword : Experimental Nuclear Physics, GEM, Electron ID Detector, Tracker, Chiral symmetry

【Purpose and Background of the Research】

We have already published on the signature of the spectral change of vector mesons (ρ, ω, ϕ) in nuclei in 2006-7, as results of the KEK-PS E325 experiment. These are phenomena interpreted as evidence of "the mechanism of hadron mass generation due to the spontaneous broken chiral symmetry", which is proposed by Nambu.

In order to confirm this study, we have proposed J-PARC E16. We will start the commissioning of detectors at the completion of the newly-built high-momentum beamline at J-PARC Hadron experimental facility. We will perform systematic measurements with the 10 times as much statistics as that of E325.

【Research Methods】

We construct the new spectrometer at the high-momentum beamline which is under construction now, and measure the electron-positron pairs from the vector-meson decays. We radiate the primary proton beam (30 GeV, 1 x 10^{10} protons/pulse) from the J-PARC MR to very thin targets (C 400 μm, Cu 80 μm, Pb 30 μm), whose radiation length is up to 0.5% to suppress the electron background from the target material. To cope with the high interaction rate up to 1 x 10^7 Hz at the target, we use GEM Tracker, which achieves the 100 μm of position resolution in tests, thus the evaluated mass resolution is 6-8 MeV for ϕ mesons. With the combination of two stage of electron identification detectors, Hadron Blind Gas Cherenkov Detector and Lead-glass calorimeter, we can reject background pions down to 0.03%.

【Expected Research Achievements and Scientific Significance】

As a model-independent analysis, we compare the measured invariant mass distribution of mesons with the vacuum-expected shape and difference between the two will be examined systematically. The amount of difference could be depend on the meson velocity and nuclear size, namely, the number of modified meson could be much for more slowly-moving mesons and for larger nuclei, where the probability of inside-nuclear decay is expected higher. Statistically-significant such dependences are the evidence of the spectral change of mesons in nuclei. Such analysis performed for the ϕ meson and ρ/ω mesons.

Also, we compare the data with theoretical calculations of spectral change. Once we reproduce the data shape by fitting with a model calculation, mass change of mesons at the normal nuclear density could be deduced. Particularly, mass change of ϕ meson is interpreted to the strange quark-antiquark pair condensate in nuclear matter, which is an order parameter of the chiral symmetry breaking, using in-medium QCD sum rules. Further, a momentum dependence of such mass is a dispersion relation of mesons in nuclear matter.

Namely, we re-confirm the existence of spectral change of mesons in nuclei and compare the nature of spectral change with the QCD predictions. That is an experimental elucidation of the nature of hadron as the elementary excitation on the QCD vacuum.

【Publications Relevant to the Project】

・"Evidence for In-Medium Modification of the φ meson at Normal Nuclear density", R. Muto et al. Phys. Rev. Lett. 98 (2007) 042501
・"Experimental signature of the medium modification for rho and omega mesons in 12-GeV p+A reactions", M. Naruki et al. Phys. Rev. Lett. 96 (2006) 092301
・"In-medium mass modification of vector mesons", S. Yokkaichi, Lecture notes in physics 781 (2009) pp161-193, Springer

【Term of Project】 FY2018-2022

【Budget Allocation】 150,800 Thousand Yen

【Homepage Address and Other Contact Information】
http://ribf.riken.jp/~yokkaich/E16/E16-index.html

【Grant-in-Aid for Scientific Research (S)】

Broad Section B

Title of Project : From Quarks to Neutron Stars: Challenges in QCD

Tetsuo Hatsuda
(RIKEN, Interdisciplinary Theoretical and Mathematical Sciences, Program Director)

Research Project Number : 18H05236 Researcher Number : 20192700
Keyword : Neutron star, Lattice QCD, Baryon force, Quantum many-body problem, Equation of state

【Purpose and Background of the Research】

Structure of dense matter is one of the most important unsolved problems in nuclear physics. The coalescence of binary neutron stars (GW 170817) was recently observed by the gravitational wave and electromagnetic waves simultaneously. Understandings of high-density matter inside the neutron star and the origin of heavy elements will be further accelerated by such observations in the future.

The purpose of the present project is to derive the equation of state of dense matter through the precision quantum many-body calculations combined with the baryon-baryon interactions extracted from quantum chromodynamics (QCD) simulations on the lattice.

【Research Methods】

Reseachers participating in this project have pioneered the HAL QCD method for deriving the nuclear force from lattice QCD and also have developed the cluster variation method for quantum many-body systems. We will carry out systematic calculations of the baryon-baryon interactions as well as detailed studies of the three-body interactions by using lattice QCD simulations. This will provide basic data necessary to formulate the equation of state relevant to outer and inner cores of neutron stars. Also, we construct the equation of state at finite temperature with arbitrary proton fraction by the cluster variational method.

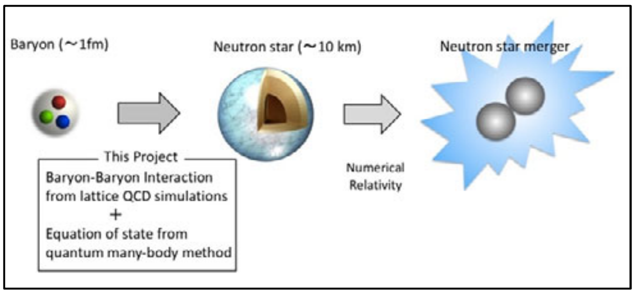


Figure 1 From quarks to neutron star mergers

【Expected Research Achievements and Scientific Significance】

Combining lattice QCD and quantum many-body method to construct a microscopic equation of state is crucial for analyzing gravitational wave from neutron star mergers. In addition, the present project is closely related to condensed matter physics for strongly correlated quantum systems such as cold atomic gases and liquid helium. The present project is also related directly to the experimental studies of dense matter using the collisions of heavy nuclei.

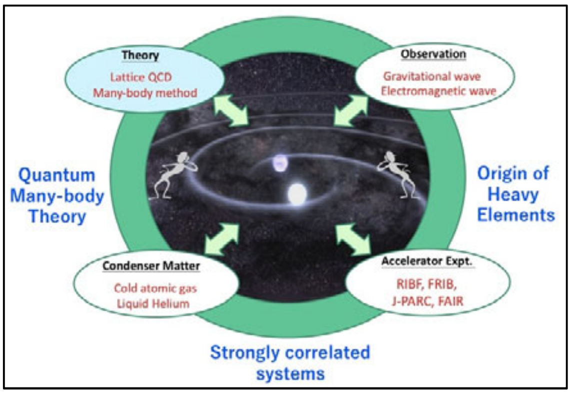


Figure 2 Interdisciplinary connections

【Publications Relevant to the Project】

- G. Baym, T. Hatsuda, T. Kojo, et. al, "From Hadrons to Quarks in Neutron Stars", Rept. Prog. Phys. vol.81, 056902 (2018).
- H. Togashi, E. Hiyama, Y. Yamamoto, M. Takano, "Equation of State for Neutron Stars with Hyperons by the Variational method", Phys. Rev. C93, 035808 (2016)

【Term of Project】 FY2018-2022

【Budget Allocation】 91,600 Thousand Yen

【Homepage Address and Other Contact Information】

https://ithems.riken.jp/
thatsuda@riken.jp