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

Broad Section B

Title of Project : **Electron-proton scattering using the lowest-ever energy beam for precise determination of proton charge radius.**

SUDA Toshimi
(Tohoku University, Research Center for Electron-Photon Science, Professor)

Research Project Number: 20H05635 Researcher Number : 30202138
Keyword : Elastic electron scattering, proton charge radius, lowest-ever beam energy

【Purpose and Background of the Research】

This research aims to determine the proton charge radius by electron scattering in the least model-dependent way. We will conduct electron-proton elastic scattering using low-energy electron beam, Ee = 20 – 60 MeV, the *lowest-ever electron beam energy* used for proton-radius studies. Note that the radius is defined as the derivative of the charge form factor at $Q^2 = 0$, where Q is the momentum transfer.

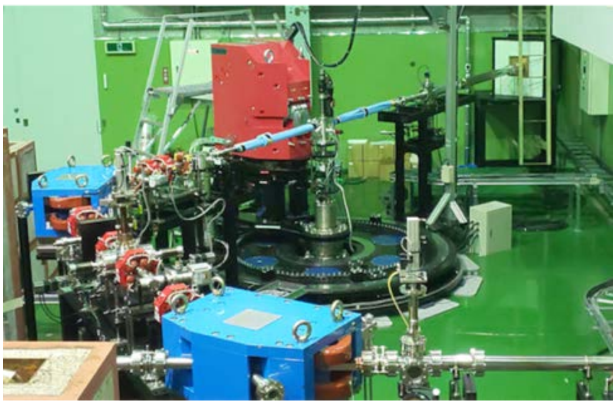
The proton radius is under debate since 2010, known today as the "*Proton Charge Radius Puzzle*". The proton charge radius provided by elastic electron scattering and the Lamb shift measurements of atomic hydrogen has been 0.88 fm, whereas the radius extracted from the spectroscopy of muonic-hydrogen atoms is found to be 0.84 fm. Since this uncertainty of the proton radius directly corresponds to the Rydberg constant in addition to obvious importance as one of the fundamental physics quantities of the proton for nuclear physics. This radius difference by electron and muon also introduces speculation for possible new physics beyond the Standard Model.

【Research Methods】

The experiments will be performed using the 60 MeV electron linear accelerator of Research Center for Electron Photon Science (ELPH), Tohoku University. Making full use of the advantages of the low-energy and small accelerator, it becomes possible to determine the charge and magnetic form factors experimentally separated by the so-called Rosenbluth separation method, which requires frequent changes of the beam energies.

The key to the success of this research is to control systematical uncertainties to be an order of 10^{-3}, since the change of $G_E(Q^2)$ in the momentum transfer range is only a few %. The CH_2 target will be employed for this purpose since the charge radius of carbon is precisely known in the 10^{-3} level. The absolute cross section for proton is determined relative to that of the known cross section for carbon. We will, thus, be able to determine absolute elastic cross section off proton with high precision by the relative measurements to that of carbon.

Installing the 2nd spectrometer for monitoring C/H ratio of the CH_2 target, which is known to change its ratio by beam irradiation, a series of elastic cross section measurements will be performed at the new beamline shown in the photo above.



【Expected Research Achievements and Scientific Significance】

Our measurements will cover the lowest momentum transfer region so that the proton charge radius is determined in the least model-dependent way. We will measure the ***absolute*** cross section, and extract the charge form factor from the cross section using the ***Rosenbluth separation***, both of which are in sharp contrast to previous electron scattering experiments. Thus, the results of our project will provide the most reliable proton radius data for those determined by electron scattering.

【Publications Relevant to the Project】

- R. Pohl et al., Nature 466 (2010) 213.
- A. Antognini et al., Science 229 (2013) 417.
- T. Suda et al., Journal of Part. Acc. Soc. Japan, 15(2018)52-59.
- T. Suda and K. Tsukada, Genshikaku Kenkyuu 61(2017) 87-98.

【Term of Project】 FY2020-2024

【Budget Allocation】 132,500 Thousand Yen

【Homepage Address and Other Contact Information】

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

Broad Section B

Title of Project： Determination of Three-Nucleon Forces via Three-Nucleon Scattering

SEKIGUCHI Kimiko
(Tohoku University, School of Science, Associate Professor)

Research Project Number: 20H05636 Researcher Number：70373321
Keyword：Three-Nucleon Force, Polarized Proton, Polarized Deuteron, Few-Body Systems, Chiral Effective Field Theory

【Purpose and Background of the Research】

Understanding the strong nuclear force is of fundamental importance to decipher the natural way of building mater in the Universe. In the last two decades, three-nucleon forces (3NFs) that appear when more than two nucleons interact have been shed light. Establishment of high-precision two-nucleon potentials and achievements of the ab-initio calculations with these forces strongly suggest the necessities of 3NFs in describing various nuclear phenomena.

Few-nucleon scattering offers good opportunities to investigate 3NFs by direct comparison between the rigorous numerical calculations and the high-precision data. Our previous study of deuteron-proton (*dp*) elastic scattering at intermediate energies (E/A～100 MeV) draws the following conclusions: i) The 3NF is clearly needed for the cross section minimum region. ii) The spin dependent parts of the current 3NF models are deficient. iii) The short-range components of the 3NFs are required for high momentum region.

Recently, remarkable theoretical work of the nuclear force based on the chiral effective field theory, the theory of low-energy QCD, opens up new possibilities of exploring detailed properties of the 3NFs, including spin, iso-spin, and short-range terms. Meanwhile, high-precision experimental data are needed to determine the low-energy constants of this theoretical framework.

The project's motivation is to establish high-precision three-nucleon forces by the experimental data of *dp* elastic scattering at intermediate energies. We perform the measurement of spin correlation coefficients for *dp* elastic scattering at the energy of interest.

【Research Methods】

Cross section minimum angular region for *dp* elastic scattering is a golden window where we can clearly pin down 3NF effects. In this project we especially focus on the measurement of spin correlation coefficients for which a few sets of data exist only. Together with this the theory group formulates the scheme to perform the rigorous numerical calculations based on the chiral EFT nuclear potentials up to the 5th order (N4LO). The experiment is performed at RIKEN RIBF where high-quality polarized deuteron beam is provided (See Fig.1). We construct the polarized proton solid target for which dynamic nuclear polarization using p-Terphenyle,$C_{18}H_{14}$ is applied. We also construct the large angular acceptance detector system to measure the azimuthal dependent polarized cross section in the wide angular range.

【Expected Research Achievements and Scientific Significance】

3NFs established by the project contain rich information of the properties of these forces, including momentum, spin, and iso-spin dependences. The potential is expected to be applied to the ab-initio calculations of nuclear structures, reactions and nuclear matter properties. The obtained results would provide deep insight for various nuclear phenomena, e.g. neutron-rich nuclei related to nucleosynthesis, and neutron star properties. The low energy constants determined by the *dp* elastic scattering data hold the information which will connect the nuclear interactions to the dynamics of quarks and gluons in the future.

【Publications Relevant to the Project】

- K. Sekiguchi, H. Sakai, H. Witala et al., Phys. Rev. C **65**, 034002 (2002).
- K. Sekiguchi, H. Witala et al., Phys. Rev. C. **96**, 064001 (2017).
- E. Epelbaum, H.-W.Hammer, and U.-G.Meissner. Rev. Mod. Phys. **81**, 1773 (2009).
- E. Epelbaum et al., Eur. Phys. J. A **56**, 92 (2020).

【Term of Project】 FY2020-2024

【Budget Allocation】 151,600 Thousand Yen

【Homepage Address and Other Contact Information】

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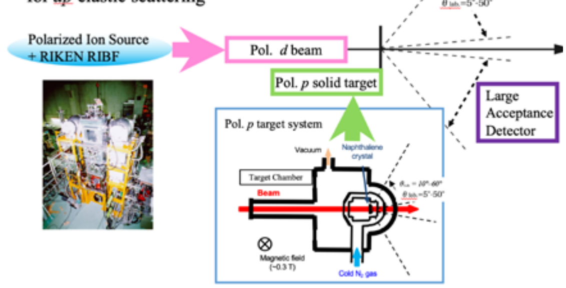
Fig.1：Layout of measurement of spin correlation coefficient for *dp* elastic scattering



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

Broad Section B

Title of Project： Study of nucleon spin structure in quark level with a large polarized target

IWATA Takahiro
(Yamagata University, Faculty of Science, Professor)

Research Project Number: 20H05637 Researcher Number：70211761
Keyword：nucleon, spin, QCD

【Purpose and Background of the Research】

How is matter built? Matter, namely atoms, are made of electrons and nucleons (proton and neutron). The electron is an elementary particle having spin 1/2 and its property is well known. In contrast, structure of the nucleon, also having spin 1/2, is not well understood. The nucleon is a composite particle composed of three quarks with orbital angular momentum (OAM)L=0. It is notable that quarks also have spin 1/2. And spin of the nucleon is created by the sum of the quark spins(in quark model).

However, it was found that the role of the quark spin is not significant. What makes the nucleon spin is not known now. This is called a mystery of the origin of the nucleon spin.

First, people considered gluon spin. Gluons having spin 1 mediating the force between the quarks can contribute to the nucleon spin. However, as related measurements are difficult, the studies have not reached a decisive conclusion. And this contribution seems not significant compared with the conventional expectations.

On the other hand, quark OAM which is never realistic in the quark model recently attracts interests. Because new experimental data are suggesting its existence.

【Research Methods】

The effect of the quark OAM is expected to appear in the left-right asymmetry of produced particles in muon induced reactions. This is called Sivers asymmetry (Fig.1). If non-zero values are observed for the asymmetry, it is considered as an evidence of the OAM.

A muon beam from SPS at CERN impinging on the COMPASS polarized target (Fig.2), and the produced

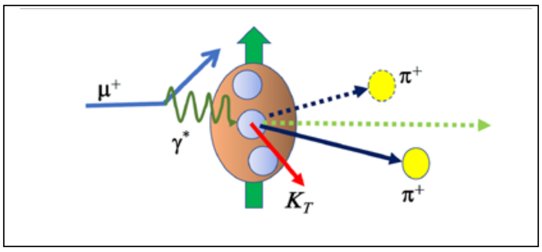


Figure 1 Sivers Asymmetry

particles are detected. Analyzing the data, the asymmetry is obtained.

Another important quantity, tensor charge (TC) of the nucleon, is also obtained. Appearance of electric dipole moment of nucleons which is expected to appear in the theories beyond standard model is affected by the TC.

【Expected Research Achievements and Scientific Significance】

Usually, OAM of constituents in a system in a lowest state do not appear in the case of the systems with atoms and nuclei. If one finds OAM of quarks in the nucleon which is the lowest state of quark system, a new paradigm is created.

The nucleon is a composite system with quarks binding strongly each other. To understand its structure, one has to rely on QCD(Quantum Choromo-Dynamics). Lattice QCD which deals with field theory in divided space-time is the unique way of calculation base on QCD. It has been partially successful in reproducing experimental results. However, they should be strictly checked with new experimental results.

Our study will provide with important quantities which

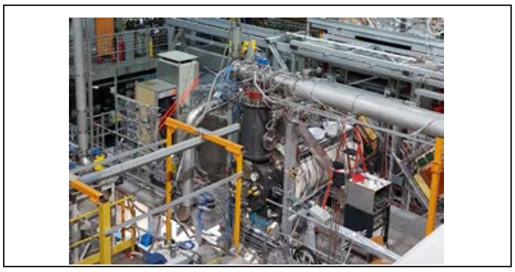


Figure 2 COMPASS apparatus

are necessary when predictions are given based on the theories beyond standard model. This leads to acceleration in searching new physics.

【Publications Relevant to the Project】

・ **Collins and Sivers asymmetries in muonproduction of pions and kaons off transversely polarised proton.,** COMPASS, C.Adolph et al., ***Phys.Lett. B744 (2015) 250-259***
Measurement of the Collins and Sivers asymmetries on transversely polarised protons. COMPASS, M. Alekseev, et al., ***Phys.Lett. B692:240-246,2010***

【Term of Project】 FY2020- 2023

【Budget Allocation】 155,200 Thousand Yen

【Homepage Address and Other Contact Information】

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

Broad Section B

Title of Project： Gluon saturation and origin of QGP probed by forward photons at LHC

CHUJO Tatsuya
(University of Tsukuba, Faculty of Pure and Applied Sciences, Lecturer)

Research Project Number: 20H05638 Researcher Number：70418622
Keyword：Color Glass Condensate, QGP, ALICE experiment, LHC accelerator, Silicon electromagnetic calorimeter

【Purpose and Background of the Research】

There is an undiscovered state in quantum chromodynamics (QCD) that describes the "strong force" acting on elementary particles. That is a "Color Glass Condensate (CGC)". This state is a high-density gluon matter predicted by QCD, and at the same time gives an initial condition of Quark Gluon Plasma (QGP) that appears in high-energy heavy ion collisions. Therefore, CGC is linked to our fundamental understanding of "strong force". Many experimental studies have been carried out so far, but no clear signal has been obtained. We have developed a highly segmented silicon electromagnetic calorimeter detector "FoCal" that can capture clear signal of CGC under high particle density.

In this study, a part of FoCal will be constructed and installed prior to the LHC-ALICE experiment, and the existence of CGC will be experimentally explored by detecting decay photons from neutral mesons by FoCal and the existing ALICE detector. We will elucidate the origin of QGP formation and the mechanism of early thermalization that appear in heavy ion reactions. This is a new international collaboration led by the Japanese team.

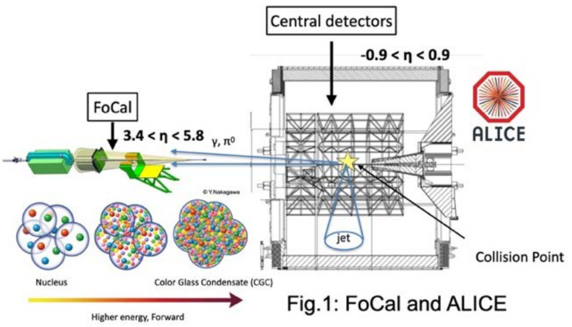

Fig.1: FoCal and ALICE

【Research Methods】

To obtain a clear signal of CGC, the following three points are important; (1) Measurement in the very forward direction (beam axis, zero degrees direction), (2) Use of high energy heavy ion beams, (3) Identification of probes sensitive to gluon density. Therefore, we use the accelerator LHC (Large Hadron Collider, CERN (Switzerland)), which provides the world's highest energy lead nucleus beams, and install FoCal in the very forward direction of the ALICE experiment to probe the gluon density of lead nucleus. This is the first time in the world to detect a photon in the very forward direction, which is a sensitive to the gluon density.

Japanese team will lead the project to produce the "FoCal-E PAD" detector, which is the main part of energy measurement in FoCal. Furthermore, in 2024 during the LHC Run-3, a part of the assembled FoCal module will be installed prior to the ALICE experiment, and initial physics measurement and the fist data analysis will be performed.

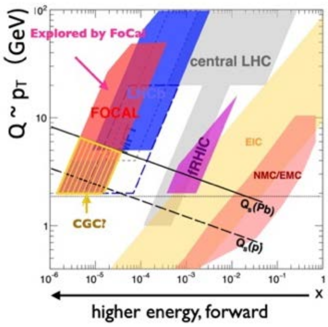

Fig. 2: New regime explored by FoCal

【Expected Research Achievements and Scientific Significance】

Using the FoCal, the following points will be clarified by the π^0 mesons and their correlation measurements. (1) Where does the saturation of gluon density appear (discovery of Color Glass Condensed), (2) Exploring the ridge structure that appears in a small collision system with a wider $\Delta\eta$ region (origin of QGP, early thermalization), (3) World's first measurement of jet suppression and QGP fluid development in the very forward region ($3.5 < \eta < 4.5$) in Pb-Pb collisions.

These findings will clarify the entire QGP creation mechanism in heavy ion collisions, and new developments in quantum chromodynamic phase diagram are expected. On the technical side, there are potential for new medical applications such as proton CT by FoCal.

【Publications Relevant to the Project】

・ Letter of Intent: A Forward Calorimeter (FoCal) in the ALICE experiment, ALICE Collaboration (T. Chujo et al.), CERN-LHCC-2020-009, LHCC-I-036, ALICE-PUBLIC-2019-005.
・ S. Acharya, T. Chujo et al., ALICE Collaboration, "Measurement of charged jet cross section in pp collisions at $\sqrt{s}$ =5.02 TeV", Phys. Rev. D 100 (2019), 092004.

【Term of Project】 FY2020-2024

【Budget Allocation】 149,800 Thousand Yen

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

Broad Section B

Title of Project：　Inclusive study on gravitational-wave astrophysics

YOKOYAMA Jun'ichi
(The University of Tokyo, Graduate School of Science, Professor)

Research Project Number:　20H05639　　Researcher Number：50212303
Keyword：Gravitational waves, data analysis, black holes, binary neutron star, kilonova, origin of heavy elements

【Purpose and Background of the Research】

Direct detection of gravitational waves from black holes and neutron stars by LIGO and Virgo has brought about a new era of gravitational wave astrophysics. The Japanese KAGRA detector is also joining the world-wide network of gravitational wave observations with its sensitivity to be improved. In this situation, this research project aims at the following scientific goals. (1) To achieve the detection of gravitational waves by KAGRA applying the independent component analysis of both gravitational-wave channel and environmental channels. (2) Using the observed data of black holes by gravitational waves and timing residuals of pulsars, we deduce the nature of these black holes to clarify if they are of primordial origin or not. (3) With regards to the binary neutron star coalescence, we clarify the dynamics and radiation processes of the kilonova phase and calculate the abundance of heavy elements produced by the r-process nucleosynthesis. We thereby advance gravitational-wave astrophysics inclusively.

【Research Methods】

First we perform joint analysis of the environmental data of KAGRA with its strain channel including the gravitational-wave signals to remove non-Gaussian noises in terms of the independent component analysis (ICA). Then we apply the GstLAL pipeline to detect gravitational wave signals from KAGRA. These analyses heavily use the computer cluster we will install with this grant.

As for the origin of black holes, we first make a volume-limited sample to extract the proper mass function of the holes. Then assuming that they are of primordial origin, we calculate the power spectrum of curvature perturbations and associated spectrum of long-wave stochastic gravitational wave background. This is compared with the pulsar timing data to constrain the mass range of primordial black holes.

The study on kilonova and nucleosynthesis will be done in the following procedure. First we calculate the initial configuration after the binary neutron star coalescence in terms of numerical relativity. Then we calculate nuclear contents and radiation processes in nonequilibrium situation to yield the abundance of heavy elements produced by the r-process nucleosynthesis using the computer cluster we will install. The results will be compared with various observations including those of Tomo-e camera.

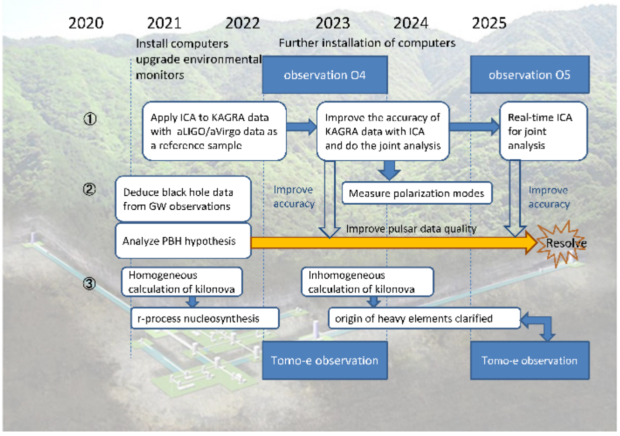

Figure 1. KAGRA and proposed timeline (without Covid-19's impact)

【Expected Research Achievements and Scientific Significance】

First KAGRA will accomplish detection of gravitational waves hopefully with the help of our analysis and the computer cluster we will install. Then simultaneous operation of four detectors in the world will improve the directional accuracy of the sources and the data quality. With increased observational data we should be able to constrain mass range of primordial black holes to judge whether these black holes are of primordial origin or from first generation of stars. Furthermore numerical analysis of kilonova and associated nucleosynthesis will uncover what fraction of heavy elements such as gold and platinum was produced in these events with the help of the observations of dwarf galaxies. This will also yield important information on elementary processes of nuclear interactions.

【Publications Relevant to the Project】

・ KAGRA collaboration "Application of the independent component analysis to the iKAGRA data" PTEP 2020(2020)053F01

【Term of Project】 FY2020- 2024

【Budget Allocation】 155,700 Thousand Yen

【Homepage Address and Other Contact Information】

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

Broad Section B

Title of Project : Novel Development of Highest Energy Gamma Ray Astronomy

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Research Project Number: 20H05640 Researcher Number : 20202161
Keyword : cosmic ray, gamma ray, muon, air shower, Cherenkov light, Bolivia

【Purpose and Background of the Research】

Cosmic rays, high-energy particles composed mainly of protons and nuclei, are flying from space. They are thought to be accelerated up to 10^{15} eV (peta electron volts, 1 PeV) around celestial bodies in the Milky Way. Various candidate bodies such as supernova remnants, pulsars, and black holes are listed as their origin, but their origin is still unknown. PeV is more than 100 times higher than the acceleration limit of 7 TeV of the highest energy accelerator Large Hadron Collider (Europe) built on the ground. The acceleration of cosmic rays should be related to extreme electromagnetic and gravity fields that cannot be realized in ground laboratories.

"What kind of celestial bodies accelerate particles by what mechanism?"

"What is happening in the extreme environment of the universe?"

are the core questions of this research. In this study, a new cosmic ray observation apparatus will be constructed in the Andes highland (4700 m in altitude) in Bolivia, South America, aiming to discover galactic celestial bodies accelerating cosmic rays up to PeV energies by the highest energy (sub-PeV region: 10^{14} eV - 10^{15} eV) gamma-ray observation. Answering the question of "what kind of celestial body" and clarifying its energy spectrum, will lead to elucidation of extreme phenomena that occur in individual celestial bodies.

【Research Methods】

We will build a new cosmic ray air shower observation apparatus near the Chacaltaya Cosmic Ray Observatory in Bolivia to explore the highest energy gamma rays from celestial bodies. The overall picture of the idea of this study is shown in Figure 1. High-energy charged cosmic rays and gamma rays are detected as "air showers," a group of particles that repeatedly generate secondary particles in the Earth's atmosphere, and the ground scintillation detectors determine the energy and arrival direction of incident particles. However, with only the ground scintillation detectors, charged cosmic-ray-induced air showers (noise) overwhelm gamma-ray-induced air showers (signal). Muons are contained in large quantities in charged cosmic ray air showers that repeat hadronic reactions, but rarely in gamma-ray air showers developed by electromagnetic interactions. Hence, underground muon detectors enable us to distinguish between charged cosmic-ray air showers and gamma-ray ones.

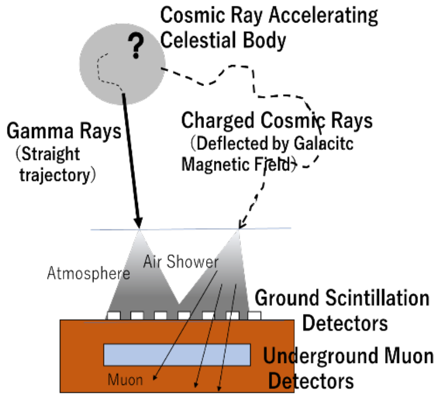

Figure 1 Overall picture of this research. Ground scintillation detectors determine the direction and energy of an air shower, while underground muon detectors discriminate charged cosmic ray noises.

【Expected Research Achievements and Scientific Significance】

This is the first experiment with sufficient sensitivity to discovery of sub-PeV gamma-ray celestial bodies in the southern hemisphere. From the southern hemisphere, important cosmic ray acceleration candidate bodies such as the galactic center and many supernova remnants can be observed, and it is expected to make a dramatic contribution to identifying cosmic-ray acceleration sites, the mystery since the discovery of cosmic rays in 1912.

【Publications Relevant to the Project】

- M. Amenomori, …, M. Takita, …, et al., “First Detection of Photons with Energy beyond 100 TeV from an Astrophysical Source”, Physical Review Letters, 123, 051101-1-6, (2019)
- T.K. Sako, …, M. Takita,…, et al., “Exploration of a 100 TeV gamma-ray northern sky using the Tibet air-shower array combined with an underground water-Cherenkov muon-detector array”, Astroparticle Physics, 32, 177-184, (2008).

【Term of Project】 FY2020-2024

【Budget Allocation】 152,300 Thousand Yen

【Homepage Address and Other Contact Information】

https://www.alpaca-experiment.org/

Title of Project： Reconfigurable topological nanophotonics

NOTOMI Masaya
(Tokyo Institute of Technology, School of Science, Department of Physics, Professor)

Research Project Number: 20H05641　　Researcher Number：50393799
Keyword：topological photonics, nanophotonics, non-Hermitian optics, photonic crystal

【Purpose and Background of the Research】

Electronic wavefunctions of solid-state materials exhibit intriguing topological properties in the momentum space, leading to various novel phenomena and materials. The topological physics is now a very active area. The Nobel Prize in physics 2016 was given to three theorists initiating this field. Recently, this concept is being applied to photonic crystals, which are artificial structures having a periodic refractive index modulation, and various intriguing optical properties have been found. This field called topological photonics is extensively studied. However, topological properties in optics are created by the pre-fabricated structure, and therefore one cannot control or change externally. In this study, we develop novel ways to dynamically control topological properties in specially-arranged nanophotonic structures, and aim for proposing novel forms of photonic processing using reconfigurable topological properties.

【Research Methods】

In this study, we explore two methods for realizing reconfigurable topological nanophotonics: loading tunable nanomaterials and use of non-Hermitian optics.

In the first approach, we load a nano-scale material whose refractive index is largely tunable, for example, a phase-change material, on a photonic crystal, and explore the possibility of photonic topological phase transition. Figure 1 (a) shows a typical example of our idea. Here we assume to employ $Ge_2Se_2Te_5$ (GST), a well-known phase change material exhibiting a large index contrast at the structural phase transition. We theoretically found that when we deliberately arrange the pattern of GST, this particular photonic crystal exhibits photonic topological phase transition by the phase transition of GST. In the present project, we explore a variety of combinations of structures and materials, and experimentally demonstrate to control various photonic topological properties with this method.

In the second approach, we employ non-Hermitian photonic periodic systems which have a periodicity in both real and imaginary parts of refractive index. Recently, it has been clarified that non-Hermitian periodic systems posses so-called exceptional points at which the band structure becomes discontinuous. Around the exceptional points, one can largely alter the band structure by changing the imaginary part (that is, absorption or gain) of the index. Recently, we have theoretically found that one can create and control the topological insulating phase solely by the variation of gain/absorption shown in Fig. 1(b). In this project, we experimentally demonstrate reconfigurable non-Hermitian topological structures with this method.

In addition, with these tuning methods, we plan to control various topological singular points appearing due to a vectorial nature of photonic topological properties.

This project is performed under a collaboration with NTT Basic Research Laboratories.

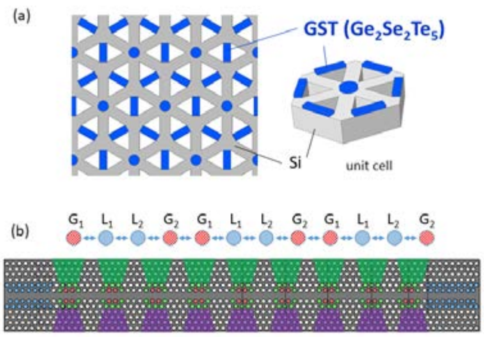

Figure 1 Reconfigurable topological nanophotonics structures. (a) GST tuning, (b) Non-Hermitian tuning.

【Expected Research Achievements and Scientific Significance】

Currently, a large number of novel properties are being found in topological photonics. Reconfigurable topological nanophotonic systems will enable us to employ these intriguing properties dynamically. We believe this will lead to a new degree of freedom to realize a novel form of photonic processing.

【Publications Relevant to the Project】

・K. Takata, and M. Notomi, "Photonic topological insulating phase induced solely by gain and loss," *Phys. Rev. Lett.* 121, 213902 (2018).
・T. Yoda and M. Notomi, “Generation and annihilation of topologically protected bound states in the continuum and circularly polarized states by symmetry breaking”, *Phys. Rev. Lett.* 125, 053902 (2020)

【Term of Project】FY2020-2024

【Budget Allocation】141,300 Thousand Yen

【Homepage Address and Other Contact Information】

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

Broad Section B

Title of Project： **Establishment of high resolution laser spectroscopy in the vacuum ultraviolet region and its application to laser cooling of anti-hydrogen**

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(University of Electro-Communications, Graduate School of Informatics and Engineering, Professor)

Research Project Number: 20H05642 Researcher Number：10251711

Keyword：single frequency tunable laser, vacuum ultraviolet wavelength region, high resolution laser spectroscopy

【Purpose and Background of the Research】

Optical science has developed inextricably with development of extreme laser technologies. Almost all of areas regarding the extreme laser technologies appear to have been explored. However, if we look closely at the whole area, we realize that there are areas of laser technology that remain completely unexplored even today, although nearly 60 years have passed after the invention of laser. The single frequency tunable laser technology in the vacuum ultraviolet region (Frontier in Fig. 1) will be one of them.

The primary goal of this research project is to construct the vuv single-frequency tunable laser technology at an application level. We also aim to establish high resolution laser spectroscopy in the vuv on the basis of such laser technology, which may also enable to construct a quantitative scenario for laser cooling of anti-hydrogen atom.

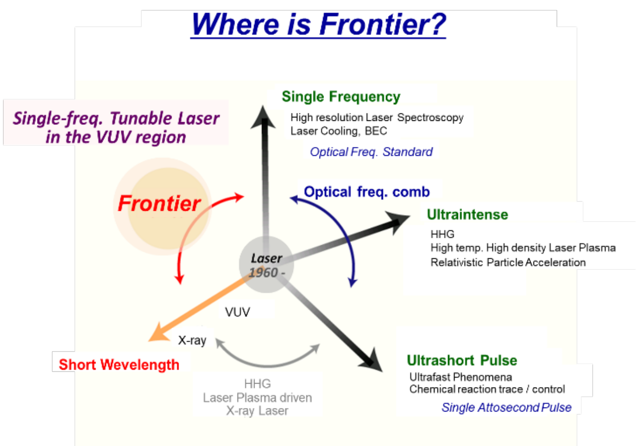

Figure 1. A variety of research fields in optical science complementary evolving to development of the extreme laser technologies.

【Research Methods】

We found that nonlinear wavelength conversions with quantum efficiency of unity can be achieved by incorporating artificial controls of optical phases in the nonlinear optical processes. So far, we have developed its theoretical framework and performed the corresponding proof-of-principle experiment. In this research project, we apply these achievements to higher-order stimulated Raman scatterings in gaseous para-hydrogen to realize a practical single-frequency, tunable laser in the vuv wavelength region. We also construct a scenario for the laser cooling of anti-hydrogen on the basis of experiments using atomic hydrogen as a test medium, where Lyman alpha transition (121.6 nm) is employed as the cooling transition.

【Expected Research Achievements and Scientific Significance】

The vacuum ultraviolet is a wavelength region where light and matter interaction is extremely strong. Establishment of the vuv single-frequency tunable laser as a practical technology will naturally pave the way to high-resolution laser spectroscopy in the vuv, which will also open a variety of frontiers in optical science, such as study of fundamental symmetries including gravity through the complementary high resolution laser spectroscopy of the laser cooled hydrogen and anti-hydrogen, study of future frequency-standard by using the nuclear transition (149 nm) in Thorium, and so on.

【Publications Relevant to the Project】

- T. Suzuki, M. Hirai, and M. Katsuragawa, Octave-spanning Raman comb with carrier envelope offset control, **Phys. Rev. Lett. 101**, 243602 (2008). ***Cover***
- J. Zheng and M. Katsuragawa, Freely designable optical frequency conversion in Raman-resonant four-wave-mixing process, **Scientific Reports 5**, 8874 (2015).
- M. Katsuragawa and K. Yoshii, Arbitrary manipulation of amplitude and phase of a set of highly discrete coherent spectra, **Phys. Rev. A**, 95, 033846 (2017).
- C. Ohae, J. Zheng, K. Ito, M. Suzuki, K. Minoshima, and M. Katsuragawa, Tailored Raman-resonant four-wave-mixing process, **Optics Express**, **26**, 1452 (2018).

【Term of Project】 FY2020-2024

【Budget Allocation】 112,800 Thousand Yen

【Homepage Address and Other Contact Information】

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

Title of Project： Solar activity over the past 10,000 years

MIYAKE Fusa
(Nagoya University, Institute for Space-Earth Environmental Research, Associate Professor)

Research Project Number: 20H05643　　Researcher Number：90738569
Keyword：Sun, Cosmic ray, Cosmogenic nuclide, tree ring, ice core

【Purpose and Background of the Research】

Solar flares and coronal mass ejections emit very high-energy particles called "Solar Energetic Particles (SEPs)." Satellites often observe rapid increases in SEP flux, a phenomenon known as a SEP event. Large-scale SEP events pose a major threat in the current space exploration era as they can damage artificial satellites, harm astronauts exposed to flux, and cause communication failures. Therefore, an understanding of SEPs is necessary. However, the long-term occurrence characteristics of SEP events, such as their occurrence rate and upper limit are poorly understood because SEP events are not directly observed and recorded before the 1940s.

Cosmogenic nuclides such as the ^{14}C of tree rings and the ^{10}Be and ^{36}Cl of ice cores are known as excellent proxy data of past extreme SEP events (tens of times larger than the largest SEP events in direct observations). We discovered signatures of extreme SEP events such as 775 CE and 994 CE from the data of cosmogenic nuclides (Figure 1). These findings indicate not only the possibility of superflares in our sun, but also indicate the possibility of extreme solar phenomena in the future, which can profoundly affect the modern society.

The purpose of this study is to identify the largest SEP event during the past 10,000 years by analyzing the ^{14}C in annual rings and ^{10}Be and ^{36}Cl in ice cores and to clarify the frequency and characteristics of extreme SEP events. To evaluate the universality and peculiarity of the Sun among the sun-like stars, we will compare the data of our sun and the stellar flares of the sun-like stars.

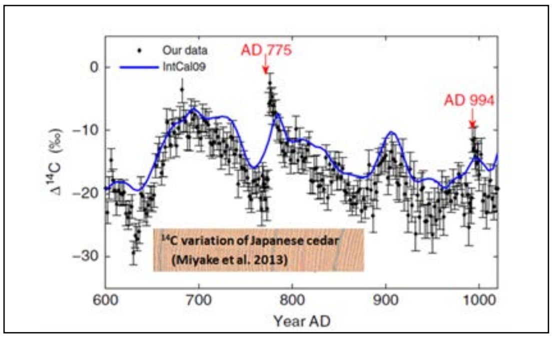

Figure 1　SEP events shown in ^{14}C data

【Research Methods】

To comprehesively detect the signatures of extreme SEP events, we will conduct a one-year resolution ^{14}C analysis of tree rings over the past 10,000 years (Figure 2). In addition, the detected events will be characterized throuh ^{10}Be and ^{36}Cl analyses of ice coress.

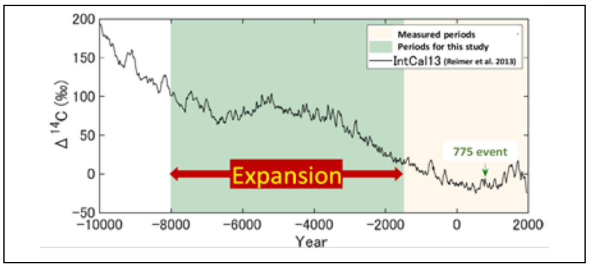

Figure 2　Measurement periods for this study

【Expected Research Achievements and Scientific Significance】

This research will provide long-term ^{14}C data over the past 10,000 years, revealing the occurrence rate of extreme SEP events and the largest SEP event during that period. Furthermore, as various solar activities have been observed during the past 10,000 years, we expect to clarify the relationship between the occurrences of extreme SEP events and solar activities.

The obtained data are not only important for investigating past solar activity, but are also potentially available for other investigations. For example, this study provides basic ^{14}C dating data. The ^{14}C spikes can be used as a one-year dating point, enabling the ultra-high-precision ^{14}C dating and one-year synchronization of ice cores and sediment cores. Such an unrestricted age indicator of regional and natural sample types is unprecedented and groundbreaking.

【Publications Relevant to the Project】

- F. Miyake, I. Usoskin, S. Poluianov (Editors), "Extreme Solar Particle Storms: The hostile Sun", Institute of Physics Publishing (2019).
- F. Miyake, K. Nagaya, K. Masuda, T. Nakamura, A signature of cosmic-ray increase in AD 774‐775 from tree rings in Japan, Nature, 486, 240-242 (2012).

【Term of Project】 FY2020-2024

【Budget Allocation】 152,400 Thousand Yen

【Homepage Address and Other Contact Information】

http://www.isee.nagoya-u.ac.jp/en/index.html

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

Broad Section B

Title of Project : **Synthesis and Development of Room-Temperature Superconducting Device**

SHIMIZU Katsuya
(Osaka University, Graduate School of Engineering Science, Professor)

Research Project Number: 20H05644 Researcher Number : 70283736
Keyword : Superconductivity, High-Pressure Synthesis, Hydride

【Purpose and Background of the Research】

In recent years, it has been experimentally clarified that hydrides exhibit superconductivity exceeding 200 K under high-pressure conditions, then we can expect "room temperature superconductivity" comes into reality. Various hydrides are predicted to become high-Tc superconductors with their transition temperatures of room temperature or high. In this research, we are investigating whether room temperature superconductivity can be realized and how high the superconducting transition temperature can be raised, by targeting hydrides. To reach the goal of "a room-temperature superconducting device", we focus (1) to synthesize a room-temperature superconductor under high pressure, and (2) to operate a superconducting device in a high-pressure cell. We are aiming to expand our technology of material synthesis and measurement of physical properties and to provide the guideline that not only to realize room-temperature superconductivity but also to connect to social implementation.

【Research Methods】

The starting materials of the hydrides are elements and hydrogen. The element is sealed together with hydrogen into a high-pressure cell: a diamond anvil cell (DAC), and compressed and heated by laser (Figure 1). Although this method has been widely used, a limited number of successive synthesis has been reported, which indicates the difficulty in handling hydrogen. We focused on the importance of searching for an appropriate synthesis (heating) method. We will challenge several new synthetic routes and methods such as; pressurize at low temperature and a Joule heating. Some ternary hydrides are predicted theoretically to be superconductors with higher temperatures. We will perform theoretical calculations and precise crystal structural analysis to make an optimal

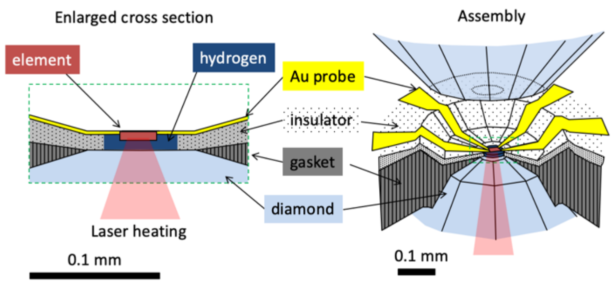

Figure 1 Schematic drawing of synthesis method.

synthesis of the superconductive hydrides.

To construct a superconducting device under high pressure, the superconductor is shaped into a device structure in a DAC. Starting the test with using existing superconductors, we will establish know-how for constructing superconducting devices under pressure.

【Expected Research Achievements and Scientific Significance】

The impact on society of "room temperature superconductivity (RTSC)" is immeasurable. The RTSC will be used widely in energy systems and electronics and communication systems. In this research, we aim to realize the RTSC by high-pressure hydride as a candidate and challenge the superconductor device under high-pressure conditions. This will provide a guideline for the social implementation of RTSC, and, in addition, will be an opportunity to develop research toward the practical use of RTSC at low pressure or ambient pressure. A high-sensitive magnetic sensor is an example of the RTSC device.

The academic background of this research is "the quest of the ultimate form of matter". The themes of this research are to answer the questions of "can RTSC be realized?" and "can RTSC be used?"

Based on the belief of the PI "essence of physics locates in extreme", we will challenge the realization of RTSC using high-pressure technology, we will answer the questions.

【Publications Relevant to the Project】

- M. Einaga, K. Shimizu *et al.*, “Crystal structure of the superconducting phase of sulfur hydride”, Nature Phys. 12, 835–838 (2016).
- M. Sakata, K. Shimizu *et al.*, “Superconductivity of lanthanum hydride synthesized using AlH_3 as a hydrogen source”, Supercond. Sci. Technol. 33 (2020) 114004 (6pp).

【Term of Project】 FY2020-2024

【Budget Allocation】 151,200 Thousand Yen

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

Broad Section B

Title of Project : The earliest stage of star formation to be studied by observing deuterated molecules

TATEMATSU Ken'ichi
(National Astronomical Observatory of Japan, Nobeyama Radio Observatory, Professor)

Research Project Number: 20H05645 Researcher Number : 40202171
Keyword : star formation, molecular cloud core, starting mechanism, deuterium

【Purpose and Background of the Research】

The importance of radio astronomy observations of deuterated molecules is increasing. First, it was found that most of molecules are depleted onto the dust grain, and therefore it is hard to observe cold (10-20 K) starless molecular cloud cores (prior to the formation of the protostar) through with the cutting-edge radio telescope ALMA, which has an extremely high spatial resolution. Then, deuterated molecules, which are less affected by depletion and can provide kinematical information through Doppler shift, are becoming valuable for the ALMA era. Second, it is becoming clear that the deuterium fraction reaches its maximum just before and after the onset of star formation. The deuterium fraction monotonically increases before star formation, and monotonically decreases afterward.

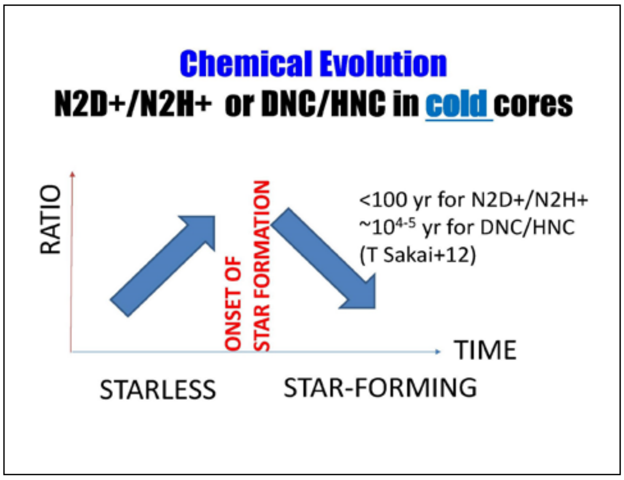

Figure 1 Schematic drawing of the change of the deuterium fraction.

【Research Methods】

For this research, we will newly develop a cutting-edge 7-beam 72-116 GHz receiver system to be installed on the Nobeyama 45-m radio telescope. We will carry out survey observations of representative star forming regions. The receiver employs 72-116 GHz low-noise amplifiers to allow 7-beam and dual-polarization observations. We will develop the receiver in the 1st and 2nd years, will make commissioning of the receiver in the 3rd year, and will conduct survey observations toward representative star forming regions in Taurus, Ophiuchus, Orion and Infrared Dark Clouds, which have different star forming activities, and make a comparative study among regions. In addition, we will make follow-up observation using ALMA.

【Expected Research Achievements and Scientific Significance】

In this research, we will employ the Chemical Evolution Factor which we introduced and established using the deuterium fraction, together with protostellar information. We will classify molecular cloud cores in to four stages: early starless, mid starless, late starless, and protostellar. Then, we will carry out statistical study of the evolution of molecular cloud cores to achieve the above purpose.

We like to pinpoint the starting mechanism of star formation. Candidate mechanisms are dissipation of turbulence, mass accretion, decrease of supporting magnetic fields, etc. If dissipation of turbulence is important, we will be able to observe its decrease along the core evolution. If mass accretion is important, we will see increase in core mass. Statistical study based on the Chemical Evolution Factor should allow us to make significant progress in this field.

【Publications Relevant to the Project】

- Ken'ichi Tatematsu, Tie Liu, Gwanjeong Kim, Hee-Weon Yi, Jeong-Eun Lee, Naomi Hirano, et al. "ALMA ACA and Nobeyama observations of two Orion cores in deuterated molecular lines," ApJ, 895, 119 (2020)
- Gwanjeong Kim, Ken'ichi Tatematsu, et al., “Molecular Cloud Cores with High Deuterium Fraction: Nobeyama Single-Pointing Survey,” ApJS, 249, 33 (2020)

【Term of Project】 FY2020- 2024

【Budget Allocation】 158,000 Thousand Yen

【Homepage Address and Other Contact Information】

https://www.nro.nao.ac.jp/~kt/html/kt-e.html

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

Broad Section B

Title of Project：Precise measurement of the mass and magnetic moment of muon using electromagnetic traps and the search for new physics

SHIMOMURA Koichiro
(High Energy Accelerator Research Organization, Institute of Material Structure Science, Professor)

Research Project Number: 20H05646 Researcher Number：60242103
Keyword：muon, muonium, Penning Trap

【Purpose and Background of the Research】

The Standard Model of elementary particles, which describes the basic building blocks of matter and their dynamics, was completed not only theoretically but also experimentally with the discovery of the Higgs boson. However, the model contains a number of problems, such as the fact that it contains too many parameters and does not include particles that are responsible for dark matter. There should be a new physics beyond the Standard Model of elementary particles that solves these problems. An experimental technique that is gaining more and more attention as an effective method to look for signs of this is the ultra-precise measurement of a single particle or two body systems. Muons, with their moderate mass and lifetime, are ideal for verifying the Standard Model to the highest degree and, above all, as probes to search for new physics. In fact, the muons have been studied for many years in the world, and nowadays, there are some physical phenomena, including the muons, that are difficult to explain by the Standard Model.

【Research Methods】

Our ultimate goal is to carry out two interrelated precision measurement on muons. The first is to measure the Zeeman sub level of muons (positive muon and electron bound system) under precise high magnetic field, to determine the hyperfine structure of muons (1 ppb) and the magnetic moment and mass of muons (about 5 ppb) with an accuracy of more than an order of magnitude higher than that of the previous studies. The other is a new measurement of single-particle muons by combining an ultra-slow muon beam and the Penning trap technique to determine the magnetic moment and mass of the muons with the highest accuracy (2 ppb), completely independent of muonium. The measurements will utilize the ultra-slow muons that have been developed at J-PARC. The muons are almost stationary and, in the case of our measurement, the generation and transport of the muons are carried out under a high magnetic field, which allows us to use a 100% polarized beam. The superconducting magnet used in the muon hyperfine structures measurement can provide a uniform static field up to 2.9 T and will be used as a spin-polarizing and trapping field for very slow muons (Fig. 1). In addition, the distance from the very slow muon source to the measurement area is as short as 50 cm, and it can be transported without beam loss at a low accelerating voltage of about 5 keV. The decay positrons are used as the muon spin signal. We ensure high accuracy by ensuring that the positron statistics are available. Preliminary simulations show that if, for example, an ultra-slow muon is rotated by a magnetic field flipper with 90° of polarization, and 10^{12} rotations under high magnetic fields are observed, the magnetic moment can be determined with an accuracy of 1 ppb from the statistics alone. This is achieved in about 100 days. The muon masses can also be measured independently with the same accuracy by measuring the 180° reversal of the muon spin in the trap.

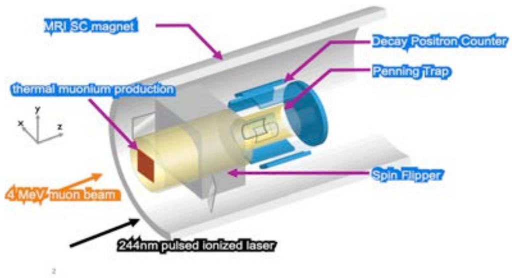

Figure 1 Concept of Muon Trap

【Expected Research Achievements and Scientific Significance】

We will synthesize these results and compare them with the ongoing muonium 1s-2s energy level difference and muon anomalous magnetic moment measurements, as well as with various theoretical models, in order to search for new physics beyond the Standard Model.

【Publications Relevant to the Project】

・K. Shimomura, *Muonium in J-PARC; from fundamental to application* Hyperfine Interactions 233,89-95 (2015)
・H. A. Torii, S. Kanda, K. Shimomura, P. Strasser *et al.* *Precise Measurement of Muonium HFS at J-PARC MUSE*, JPS Conf. Proc. 8 (2015) 025018(1-6).

【Term of Project】 FY2020-2024

【Budget Allocation】 151,100 Thousand Yen

【Homepage Address and Other Contact Information】
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Title of Project：Clear measurements of meson mass modifications in nucleus by using high intensity proton beam

OZAWA Kyoichiro
(High Energy Accelerator Research Organization, Institute of Particle and Nuclear Studies, Associate Professor)

Research Project Number: 20H05647　Researcher Number：20323496
Keyword：Origin of hadron mass, Chiral Symmetry, finite density QCD medium

【Purpose and Background of the Research】

According to a standard quark model, a proton contains three quarks. However, its mass can't be understood as a sum of the quark mass. The proton has the mass of 938MeV/c^2 and the mass of the bare quark is only a few MeV/c^2 generated by a Higgs mechanism. The difference of mass can be understood as a result of a dynamical mass generation caused by a spontaneous breaking of the chiral symmetry.

This understanding is widely accepted and several efforts were performed to measure effects of the symmetry restorations in a medium. However, there is almost no experimental evidence for detections of mass modifications directly. Measured mass is consistent with the mass in a vacuum. Modified mass in a different circumstance is not detected clearly. Thus, the main purpose of this project is a detection of the mass modification in a medium with minimal uncertainties.

In this project, we aim to show a clear mass modification of mesons in a nucleus. Here, we choose the nucleus as a finite density QCD medium and we measure mass spectra of ϕ mesons.

【Research Methods】

We will finish constructions of a beam line and detectors and collect 73000 decays of ϕ mesons. The detectors under construction are shown in Fig. 1.

Figure 1　Detectors under construction

In this experiment, a high intensity proton beam (30GeV, 0.5 x 10^{10} protons per second) is delivered from J-PARC Main Ring Accelerator. The beam is injected to thin nuclear targets (Radiation Length 0.5%, Lead 30 μm) and generate ϕ mesons. Decays of ϕ mesons are detected by large acceptance detectors. The interaction rate at the target is very high (1 x 10^7 Hz) and we use Gas Electron Multiplier (GEM) based detectors to cope with such high rate counting. The GEM tracker and a Hadron Blind Detector (HBD), which is a kind of gas Cherenkov counter for electron identifications, were already developed and tested. The performance of the detectors satisfied our requirements.

【Expected Research Achievements and Scientific Significance】

An expected mass spectrum measured by this experiment is shown in Fig. 2. In the spectrum, there are two peaks which are correspond to the mass spectra of ϕ mesons in a free space and in a nucleus. This new peak shows the first observation of a clear evidence for the hadron mass modification in a nucleus.

An amount of the strange quark condensate in the nucleus can be evaluated based on mass spectra of ϕ mesons. The quark condensate is an order parameter of the chiral symmetry. It is a parameter to evaluate a sensitivity of a dark matter search.

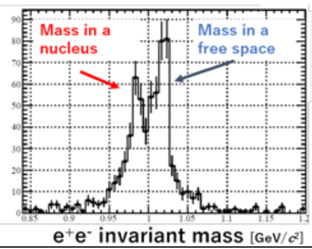

Figure 2　Expected mass spectrum

【Publications Relevant to the Project】

- "Development of a hadron blind detector using a finely segmented pad read-out," K. Kanno et al., Nuclear Instruments and Methods in Physics Research Vol. A819, 20, 24, 2016
- "Observation of ρ/ω meson modification in nuclear matter," K. Ozawa et al., Phys. Rev. Lett. 86, 5019, 5022, 2001

【Term of Project】FY2020-2024

【Budget Allocation】149,800 Thousand Yen

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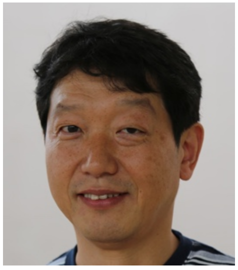

Title of Project : r-process nucleosynthesis and role of deformed nuclei

NISHIMURA Shunji
(RIKEN, Nishina Center, Senior Researcher)

Research Project Number: 20H05648 Researcher Number : 90272137
Keyword : neutron-rich nuclei, nucleosynthesis, β decay, mass, machine learning, neutron merger, supernovae

【Purpose and Background of the Research】

About half of the elements heavier than iron are originated from r-process nucleosynthesis at promising sites such as supernova explosions and binary neutron star collisions. Simultaneous observation of gravitational waves and electromagnetic radiation phenomenon (kilonova) enabled us to identify the binary neutron star collision (GW170817), and confirmed near-infrared light, indicating an evidence of lanthanoid nucleosynthesis. On the other hand, there is no evidence that gold / platinum and uranium were synthesized. The lanthanoid synthesized by the r-process has characteristic peak structure near the mass number A = 165 (Fig. 1-a). However, the mechanism of this peak formation is shrouded in mystery.

There are two hypotheses in lanthanoid nucleosynthesis: the “Nuclear Deformation Cause Theory (NDCT)”[1] and the “Actinide Asymmetric Fission Cause Theory (AAFCT)”[2]. This study focuses on the confirmation of the NDCT and collects data on the masses and β decays of lanthanoid nuclei. The obtained data will be applied to the combined theory with neutral network and deep learning method to search for anomalies. Large scale nuclear data constructed through the cooperation of experiments and theory will be put into calculation for heavy element synthesis calculation. By coordinating the above research systems, we aim to verify lanthanoid nucleosynthesis focusing on the nuclear deformation effect, and to understand comprehensive heavy element nucleosynthesis including gold and platinum associated with neutron magic number N = 126.

【Research Methods】

Uncertainties regarding neutron separation energies (masses), half-lives, and delayed neutron emissions of neutron-rich nuclei are major barriers to quantitative estimation of the r-process. Using spallation reactions of uranium and platinum at the high-intensity heavy ion accelerator facility RIBF, key neutron-rich nuclei in lanthanoid nucleosynthesis will be produced (Fig. 1-b). In order to efficiently collect information on the masses and β decays of the produced rare isotopes, we will introduce a large gas cell device and β decay measuring device. Deep learning method is incorporated into the nuclear theory that takes into account the behavior of the nuclear structure. The deformation magic of the nucleus will be investigated by the systematics and correlation among these nuclear properties. Furthermore, we will construct large-scale nuclear data expanded to unknown nuclear regions together with the uncertainties. The amount of heavy elements synthesized such as lanthanoids, gold and platinum largely depends on the strength of the r-process (electron fraction Ye). Considering the environment of binary neutron stars and supernova explosions, we will verify the lanthanoid nucleosynthesis that incorporates the constructed large-scale nuclear data.

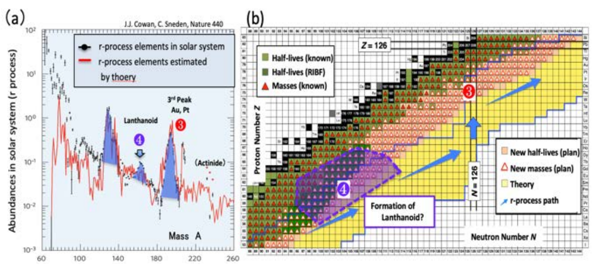

Figure 1 (a) Solar abundance, (b) r-process nuclei

【Expected Research Achievements and Scientific Significance】

The proposed verification of lanthanoid nucleosynthesis is different from the conventional r-process study with neutron magic number N = 50, 82, and 126. The key point is to investigate the anomaly in β decay and neutron separation energies associated with the deformation of nuclei. Although the research strategy focuses on the NDCT, there is a possibility that the hypothesis cannot be confirmed. In that case, the results suggest the AAFCT and indirect evidence of the synthesis of gold, platinum and uranium in GW170817. In this case, quantitative heavy element synthesis including gold and platinum will be studied.

【Publications Relevant to the Project】

・ [1] R. Surman et al., Phys. Rev. Lett. **79** (1997) 1809.
・ [2] S. Goriely et al., Phys. Rev. Lett. **111**, 242502 (2013).

【Term of Project】 FY2020- 2024

【Budget Allocation】 146,400 Thousand Yen

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