Date: March, 2018
Institute Laboratories' Research Promotion Office RIKEN

Research Project Mid-term Evaluation Result

The following research project underwent a mid-term evaluation in accordance to Clause 10 and 11, Chapter 2 of the *Regulations for Research and Development Evaluations* (Regulation No. 74, October 1, 2003.)

Evaluation system:
Out of five reviewers, two experts from outside of RIKEN and tree RIKEN Science Council Research Programs Committee members were appointed as reviewers for the following research project. The reviewers evaluated the project based on the reporting session held on February 28, 2018.

Reviewers list:

External experts (alphabetical order)

1) Mikio KOZUMA, Professor, Department of Physics, Tokyo Institute of Technology
2）Yasuhiro SAKEMI, Professor, Center for Nuclear Study, The University of Tokyo

RIKEN Science Council Research Program committee member (alphabetical order)

3) Tetsuo HANAGURI, Team Leader, Emergent Phenomena Measurement Research Team
4) Takao SOMEYA, Chief Scientist, Thin-Film Device Laboratory
5) Takashi TANAKA, Chief Scientist, Advanced X-Ray Laser Laboratory

Research project brief overview

Project name: Extreme precisions to Explore fundamental physics with Exotic particles (EEE)
Project Leader: Hidetoshi KATORI
Project duration: April, 2014～March, 2020（5 years）
Budget allocated: Total of 371,400 thousand Yen（ past 4 years）
Research overview:

The pioneering project, Extreme precisions to Explore fundamental physics with Exotic particles (EEE), aims to establish a new and world-unique research group at RIKEN with three key words embedded in the title of the proposal rallying three sub-groups with cutting-edge expertise in atomic physics, quantum electronics, and nuclear physics. The titles of the research proposals and the leaders of three sub-groups are 1) Antimatter goes Quantum Logic – Ground state cooling of antiprotons for stringent CPT tests: S. Ulmer; 2) Pinning down r-process path via precise mass and lifetime measurements of extremely rare nuclei: T. Uesaka; 3) Search for exotic atomic clocks and their evaluation based on System RIKEN: H. Katori

1. <u>Comprehensive Evaluation</u> <u>(To be disclosed)</u>

1) Evaluation on five-grade scale	S	A	B	C	D
(1) Research objective:	3	2	0	0	0
(2) Implementation of research plan:	3	2	0	0	0
(3) Research achievement:	4	1	0	0	0
(4) Future research plan:	2	2	1	0	0

S Outstanding / A Excellent / B Good / C Acceptable / D Not acceptable

2) Evaluation details (reviewer's number is different from the order of the above list)

＜Reviewer 1＞

(1) Research objective

This project consists of three sub-groups, each of which has its own clear scientific goal. Dr. Ulmer's sub-group aims at comparisons of fundamental attributes of protons and antiprotons for testing the CPT invariance. Dr. Uesaka's sub-group plans to measure masses and lifetimes of neutron-rich rare nuclei to provide insights into the r-process nucleosynthesis. Dr. Katori's sub-group tries to develop novel atomic clocks to examine the constancy of the fine-structure constant. These apparently different sub-themes have two common threads; all of them target ultra-high precisions in measurements and all of the experiments are based on the particle trapping. Such commonality is strong enough to unify apparently different projects into a single project. It is (both technically and mentally) meaningful and reasonable to conduct these three projects in a harmonized manner. The mutual exchange of the expertise among the sub-groups is unique and may advance each sub-field. Nevertheless, in contrast to the clear goal of each sub-group, the unified goal of the whole project is not so clear. It would be even better if the concrete picture of the "new physics", which may emerge out of integration of the three sub-themes, could be argued.

(2) Implementation of research plan

All of the experiments planned in this project are ambitious and thus are not straightforward. I assess that the research plans are carefully designed to make these difficult experiments feasible. The expertise that is offered to/received from other subgroups is indispensable and seems to work effectively. Even though most of the experiments are in the stage of proof of concept, overall implementations so far have been conducted in reasonable ways.

(3) Research achievement

Dr. Ulmer's sub-group performed record-breaking precise measurements of the proton-to-antiproton charge-to-mass ratio and magnetic moments of proton and antiproton. They also designed a 5-Penning-trap system for sympathetic cooling of protons/antiprotons, which is about to be implemented. This new system will allow them to further improve the accuracy of the measurements. It seems that the plans are going smoothly.

Dr. Uesaka's sub-group has developed various elemental technologies that are indispensable to measure masses and lifetimes of rare nuclei. For example, they developed isotope-selective self-triggered injection technique that lifts the mismatch between the cyclotron, which supplies isotopes, and the storage ring for analyses.

Dr. Katori's sub-group conducted spectroscopic measurements on the highly charged holmium ions and ^{229}Th nuclei, which are candidate elements to construct atomic clocks for testing the constancy of the fine-structure constant. In both elements, the target transitions are yet to be observed. Apparently it is a long way to go to realize the atomic clocks using these elements. Nevertheless, given a high hurdle, the progress of the plans is reasonable.

(4) Future research plan

Each sub-group lists the future research plans in the handout. They are all reasonable and may be feasible in the remaining term of the project. I do not find any technical issue in the listed future plans. Dr. Ulmer's sub-group is about to achieve the sympathetic cooling of protons/antiprotons. Dr. Uesaka's sub-group is ready to work on unknown neutron-rich rare nuclei. Although it would be difficult to realize the atomic clocks based on highly-charged ions and ^{229}Th nuclei by the end of the project, Dr. Katori's sub-group may be able to gain important spectroscopic information on these elements for future developments.

The final goals (CPT invariance, for example) demand endless efforts for improving the experimental precisions, as one has to experimentally prove that "zero is zero", in some sense. As far as I understand, the most crucial thing is not the final goal but the quest for precision itself. Even before reaching the final goal, at each step of the improvement of precisions, a new perspective of physics would be gained. It would be even better if the prospects of such a new perspective are elaborated in the future plans.

＜Reviewer 2＞

(1) Research objective

Three world-unique groups do this project with cutting-edge expertise in atomic physics, quantum electronics, and nuclear physics. Research purposes, i.e., stringent CPT tests with cold antiprotons, pinning down r-process with extremely rare nuclei, and search for exotic atomic clocks with System RIKEN is unprecedentedly high, in other words, there is no guiding theory. For example, the new frequency standard with exotic atom would enable us to approach New Physics beyond the standard model. Another reason I evaluated the research objective as "S" is due to the fact the expertise of each group is indispensable for the rest of subgroups to materialize the research purposes. For example, Ulmer group is aiming to test the CPT symmetry employing orders of magnitude colder antiprotons, where the laser-cooling technique of Katori sub-group and 3D detector technique of Uesaka sub-group play essential roles.

(2) Implementation of research plan

The primary challenge of this project is a synergetic and close collaboration between experimental groups in atomic physics, nuclear physics and quantum optics for tackling forefront topics in precision measurements. Frankly saying, such a synergetic partnership is hard since the technique of ultra-precision metrology is exceptionally sophisticated and specialized to a particular issue. Nevertheless, members in this project have succeeded in this challenge. Ulmer's and Katori's groups shared techniques on laser cooling of Be+ and manipulation of highly charged ions. Ulmer's and Uesaka's groups synergetically utilized techniques about 3D tracking and pickups with extreme sensitivity. In the same way, Uesaka's and Katori's groups used trapping technique of short-lived nuclei. Also, I would like to emphasize that they successfully achieved promotion of young researchers through this project. They also bridged respective fields through workshops and conferences held by different leaders of sub-groups. Due to the reasons discussed above, I evaluated the implementation of research plans as "A.

(3) Research achievement

Research title of Ulmer sub-group is ground state cooling of antiprotons for tests of discrete symmetries with extreme precision. One of their impressive results is comparing the proton-to-antiproton charge-to-mass ratios with 69 ppt precision, which constitutes the most precise test of CPT invariance ever performed in the baryon sector. Research title of Uesaka sub-group is pinning down r-process path via accurate mass and lifetime measurements of extremely rare nuclei, where r-process nucleosynthesis is considered to be an origin of elements heavier than iron. Through precise and fast mass measurement, we have a chance to challenge a mystery in roots of the heavy elements. Towards the mass measurement of r-process nuclei, the team solved a lot of technical issues, e.g., they have succeeded in eliminating a substantial bottleneck in the field of storage science by establishing a novel injection method ISSI. Research title of Katori sub-group is search for exotic atomic clocks and their evaluation based on Systeme Riken. In atom spectroscopy, including "optical lattice clock" invented by Katori, one often measures transitions of an outermost electron. They are susceptible to stray electric fields because of their sizeable orbital radius and corresponding polarizability. The team investigated two new systems that are immune to such environmental perturbations, i.e., optical transitions in highly charged ions (HCIs) and nuclei. Once we can get the optical transition of HCIs or nuclei, completely new 3rd generation clock following the optical lattice clock can be provided. The team has produced a lot of fruitful results, one of which is developing a fast x-ray detector system to observe the 29 keV excitation of ^{229}Th nuclei. Since all three teams have produced a lot of unique experimental results, there is no doubt that the research achievement of the project should be "S."

(4) Future research plan

Ulmer sub-group are planning to show sympathetic cooling of protons, which will enable the team to measure a proton magnetic moment at sub-100 ppt precision. They can apply the new method to sympathetically cool antiprotons, which will lead to measurements of the antiproton magnetic moment at a comparable resolution as achieved with protons. These measurements will provide the most sensitive tests of CPT invariance in the baryon sector. Uesaka sub-group are ready to start experiments at the Rare RI ring. The first target will be a mass measurement in the region of neutron-rich 78Ni. Plans or pathways for realizing highly charged ions clocks provided by Katori are also convincing. In summary, I evaluated the future research plan of the project should be "S."

＜Reviewer 3＞

(1) Research objective

Although the research objectives of individual subgroups are quite diverse, they can be represented as a key word “high precision”. Improving the measurement precision is definitely one of the most important subjects not only in physics but also in all areas of research. Moreover, it should be emphasized that the ultimate goal of this pioneering project is, in some sense, to explore new findings, which may violate the general theories that have been accepted for a long time. Such theory-violating phenomena, if they are actually found, will eventually lead to “pioneering” a new field in physics and stimulate the discussions between theorists and experimentalists in the relevant areas. In this regard, the research objective of this project is highly evaluated.

(2) Implementation of research plan

Each subgroup has proposed a new scheme, developed relevant devices, and successfully implemented and commissioned them. It is highly evaluated that all of these steps have been completed just within four years since the project has started.

(3) Research achievement

It is too early to say something about the “achievements” of the project, because each subgroup has just finished preparation of devices and instruments that are necessary for their experiments. Even so, the advancement of the project in terms of engineering is excellent. One thing which I’d like to mention is that the synergy effect between subgroups is not very clear only from the reports and presentations for the mid-term evaluation. It is thus recommended that the subgroup leaders report the outcomes and achievements focusing more on the collaborative aspects in the final evaluation.

(4) Future research plan

Having completed the implementation, each group is now ready to perform each target experiment. This is definitely the right way for this project to proceed, and I believe that many experimental results are obtained by the end of this project.

＜Reviewer 4＞

(1) Research objective

The project entitled “Extreme precisions to explore fundamental physics with exotic particles” is aiming at producing synergetic effects with combining three unique groups who have cutting-edge expertise in high precision physics. In particular, the objective of this research is to establish a new an d unique research field in low energy fundamental physics employing single particles. All the three research groups worked independently and were known as world’s leading teams, when this proposal was submitted; thus, I believe that objectives of this proposal is appropriate as Pioneering Projects that should have carried out in RIKEN.

(2) Implementation of research plan

The project comprises three sub-projects, namely, “Antimatter goes Quantum Logic – Ground state cooling antiprotons for stringent CPT tests (Subject Lead: Dr. Stefan Ulmer)”, “Nucleosynthesis researcher with precision measurements for exotic nuclei (Subject Lead: Dr. Tomohiro Uesaka)”, and “Search for exotic atomic clocks and their evaluation based on system Riken (Subject Lead: Dr. Hidetoshi Katori)”. The lead researchers were Dr. Yamazaki from the beginning to 2016 and Dr. Katori from 2016 to the end. Both leaders have managed this project appropriately and made tremendous efforts to produce synergetic effects and create new scientific community. In particular, they have nicely guided young researchers, who have been stimulated by other research fields.

(3) Research achievement

All the three groups have made amazingly high achievements. The number of Nature and Science papers published by only one group, without counting Nature sister journals, reached five. Other groups have made scientific achievements with the similar quality and quantities.

(4) Future research plan

It is important to support these high quality and unique researches by internal and external research funds.

＜Reviewer 5＞

(1) Research objective

In this project, the fundamental physics is explored with various types of precise measurements developed at RIKEN for exotic particles. It is a highly original research project by experts who are leading internationally leading-edge research on nuclear physics, atomic physics and quantum optics.

In the Dr. Ulmer group, CPT invariance is verified with high accuracy using the charge-to-mass ratio and magnetic moment of antiproton and proton in BASE experiment at CERN. It is always acknowledged to be important to verify the CPT theorem deeply related to local field theory with Lorenz invariance.

Dr. Uesaka group aims to elucidate nucleosynthesis mechanism such as r-process with an accurate mass measurement of neutron-rich nuclei using the rare RI ring. Mass measurement of short-lived unstable nuclei can be realized for the first time by the innovative accumulation ring newly constructed at RIKEN. In addition, the theoretical researches on supernova explosion, gamma ray burst are in progress, which are related with experimental researches on nucleosysnthesis.

At the Dr. Katori group, based on the internationally renowned research by Prof. Katori on the optical lattice clock, they aim to realize the next generation clock / frequency standard using highly charged ions (HCI) and using the nuclear transition with quite low excitation energy of Th that can suppress the disturbance of the external field. This program is universally important as a definition of seconds as a metrological standard, and also greatly spreads to particle physics that leads to the study on the dark energy through the precise measurement of the change of the fundamental constants.

Every program is a research directly linked to the understanding of the evolution of the matter dominant universe, and it is regarded as an extremely challenging and attractive research project based on the world's most advanced technology developed at RIKEN.

(2) Implementation of research plan

All the groups develop and utilize the cooled and accumulated exotic particles such as anti-proton, rare RI, trapped highly charged ions (HCI), and heavy elements to study the fundamental physics. The tight collaboration of experimental technologies such as particle cooling and high precision detectors has been established between each research groups.

In BASE experiment at CERN/AD, they have pioneered experimental techniques to overcome the world's highest accuracy to measure the antiproton/proton charge-to-mass ratio and magnetic moment, and are leading this research field in the world. In the rare RI ring, in order to study the neutron capture process accompanying the supernova explosion, precise mass measurement is performed for the short-lived neutron-rich nucleus. In this project, they constructed a storage ring dedicated for the isochronous mass spectroscopy of short-lived radioactive isotopes. Furthermore, to realize the next generation clock, based on the state-of-the-art technology of the world-leading research representative of the optical lattice clock, the developments of the HCI and Th nuclear clock are in progress. This group is promoting the experiment to identify the clock transition using nuclear resonance scattering method at SPring-8.

From the viewpoint of collaboration between different fields, they are working on development of laser light source required for the sympathetic cooling, development of ion trap apparatus, creation of Th target, etc with the cooperation of research groups such as the nuclear physics, atomic physics, quantum optics, and radiation chemistry etc. It is highly evaluated that each research program has been accelerated successfully with this tight collaboration.

(3) Research achievement

By highly accurate measurement of the charge-to-mass ratio of antiproton and proton, they succeeded in verifying the most accurate CPT invariance and reported in Nature etc. Furthermore, they succeeded in improving the high precision measurement of the magnetic moment of the antiproton, reported by Nature, Science etc. This group is leading the research field of the ultra-high accuracy verification of CPT invariance in the world, and it is highly appreciated. It is expected to explore unexplored areas of the fundamental symmetry by further improving accuracy in the future.

In the rare RI ring project, a storage ring dedicated for the isochronous mass spectroscopy was successfully constructed and the stable operation was started. They also succeeded in developing a fast response kicker system and established a systematic precise mass measurement technique for short-lived nuclei. Many results about the developments of the key devices were already published and it is certain that physics outputs significant to understand the r process will be shown in the next phase.

Research on next generation clocks using HCI and Th nuclei has advanced spectroscopy experiments of holonium and development of HCI trap devices is in progress. Furthermore, the measurement of the clock transition of Th is being made using the nuclear resonance scattering method in the SPring-8. There are already many publications on developments, although this research is a quite challenging topic. The idea to realize the next generation clock is clear and the future progress is expected.

In addition, it is highly appreciated that the promotion of the young researchers active in this program were successfully achieved.

(4) Future research plan

The Dr. Ulmer group will demonstrate the sympathetic cooling technology using cooled Be ion by a coexisting Penning trap with proton, and aims to improve the accuracy of proton magnetic moment. After establishing this technique, they will introduce it to CERN /BASE experiment in the future, to achieve the improvement of accuracy of magnetic moment of anti-proton, and to verify CPT invariance by unexplored highly accurate measurement. It is no doubt that this group will lead the science of the symmetry of the matter and anti-matter in the world.

In the Dr. Uesaka group, the rare RI ring is already in operation, and aiming for the mass measurement of the important neutron-rich Ni nucleus and the second peak of A ~130 nuclear domains to study the nucleosynthesis. They are ready to perform the experiments for the important physics outputs on nucleosynthesis for the first time with rare RI ring in the world.

Dr. Katori Group will demonstrate sympathetic cooling of HCI and other components to realize the clock using HCI will be completed. In addition, they will continue the precise spectroscopy experiment to identify the Th clock transition at SPring-8 and promote the basic study to realize the nuclear clock ahead of the world.

As described above, it is highly appreciated that any plan has high originality and is driving the fundamental physics in the world. Also it is highly appreciated that the exchanging the advanced techniques between each groups has accelerated the research progress, and we strongly expect that a new academic field will be opened up by further fusion of different fields in this project.

RIKEN Science Council Research Programs Committee