Activity report of the second-term (2014–2021) RIBF Theory Forum

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Preface

Recent advancements in radioactive-isotope (RI) beam technology have opened up the research field of the physics of exotic nuclei. Since the RIBF started operation in 2007, our experimental capabilities have been significantly expanded, including neutron- and proton-rich nuclei as well as superheavies. With increasing experimental data for a vast mass region of the nuclear chart, nuclear structure and reaction theories are expected to play a more important role in interpreting the data and in profoundly understanding atomic nuclei. A mission of the second-term Theory Forum (TF2) is to discuss physics in the future of RIBF. Taking over the discussions in the first-term Theory Forum (TF1) (2006–2014), we have been working through various activities. Although most of the members were renewed, Dr. Y. Utsuno, Dr. K. Ogata, and Dr. S. Wanajo acted as mediators to bridge the activities of TF1 and TF2. We would like to express our gratitude to them. This report summarizes our activities over the last seven years to facilitate handover to the third-term Theory Forum. Because of the limited space in this progress report, details about our activities are provided on a web page.[1)]

Short reports from WGs

TF2 was divided into several working groups (WGs) to discuss physics cases intensively. We also had intergroup discussions regularly. Here, we present short summaries of these activities, which are categorized into three subjects: nuclear astrophysics, the physics of superheavy elements, and the physics of nuclear many-body problems. More details on each subject can be found on the website.

Nuclear astrophysics: r-process, EOS, and nuclear matter

In the field of nuclear astrophysics, discussions were started with two WGs. The primary purpose of the r-process WG was to improve the current theoretical calculations of nuclear properties, including the masses, decay half-lives, neutron-capture reaction rates, and nuclear fission rates for the r-process nucleosynthesis calculations. The possibility of updating these rates used in the nucleosynthesis community was discussed, particularly to reflect the latest results from nuclear theory groups in Japan. A novel mass model based on the Bayesian neural-network method was proposed to assess the model uncertainty and to evaluate the impact of new measurements on the prediction. The significance of direct reaction on the neutron capture rates was investigated through a microscopic approach. Furthermore, we found a compelling difference between the phenomenological fission distributions widely used in the nucleosynthesis calculations and the results obtained using a dynamical model based on the Langevin model in the neutron-rich r-process region. This shows the necessity of considering dynamical fission in the data on systematic fission yields for better r-process calculation.

The equation of state (EOS) and nuclear matter WG aimed to determine the nuclear-physics constraints on the nuclear EOS. The connection between the astrophysical observations and the nuclear properties revealed at RIBF has been explored. We found that we can construct a model that can account for the indication of GW170817 if the symmetry energy at twice the saturation density of nuclear matter is 40–60 MeV. The symmetry energy in this density region can be constrained from the collision experiment of neutron-rich heavy ions measured by the SAMURAI spectrometer at RIBF.

In addition to these activities focusing specifically on theoretical nuclear physics, we organized a series of workshops to bring together nuclear physicists and astrophysicists motivated by the discovery of an r-process event (kilonova) associated with the gravitational-wave detection by the Advanced LIGO–Advanced Virgo from merging neutron stars. The workshops were held at RNC (June 2018), YITP Kyoto University (May 2019), and NAOJ (October 2020).

Superheavy elements

The main purpose of the superheavy element and fission WG (SHE/Fission WS) was to give theoretical suggestions and make proposals for experiments on new superheavy elements conducted at RIBF. A primary interest in the physics of superheavy elements is to synthesize new elements exceeding $Z = 118$, and to produce nuclei at the center of the island of stability located around $Z = 114$ and $N = 184$. For the former, heavier projectiles and stable actinide targets are being promoted. For the latter, there is no available set of stable projectiles and targets because the center of the island of stability is located in the neutron-rich region.

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It is thus desirable to estimate the possibility of new-element synthesis based on the theoretical calculation and to propose new experiments.

To synthesize superheavy elements, we proposed the optimum incident energy and the combination of a target and projectile based on the calculated evaporation-residue cross section. We also calculated the properties of new superheavy elements: lifetime, deformation, nuclear structure, fission barrier height, decay proprieties, etc. We then suggested a new approach to the synthesis of superheavy nuclei.

We (co)organized the RIBF ULIC mini-WS in August 2016 as a kick-off meeting and subsequently held a WS entitled "New developments in superheavy element research" at Kyushu University in July 2018.

Nuclear structure, collective motion, many-body correlations, and halo

The nuclear systems under extreme conditions are expected to reveal new facets associated with the correlations among nucleons. A uniqueness of drip-line nuclei was discussed in view of the nuclear interactions and the strong correlations in a dilute system, such as the multi-neutron halo and its condensation. A possibility of measuring the many-body correlations was also discussed through the nuclear responses and reactions. The connections between the nuclear responses and the EOS of nuclear matter or the reaction (decay) rates relevant to the r-process were investigated.

The true pleasure in nuclear physics is the diversity of research topics. Thus, we realized the importance of offering an opportunity to young colleagues, particularly students and post-docs, where we can frankly discuss nascent plans of physics research. To provide such an environment and to explore important physics for future experiments at RIBF in a variety of research subjects covered in the WG, we decided to organize "Hodan-kai" meetings. In contrast to the style of an ordinary workshop, the Hodan-kai aims to facilitate the exchange of unmatured ideas among young researchers. To concentrate on physics discussions, the venue was a relatively isolated place, and the presentation files are not open to the public.

The first Hodan-kai was held from July 31 to August 2, 2017 and focused mainly on the latest theoretical research on nuclear physics. The second and third meetings were held in February 2019 and 2020, respectively. The topics discussed were extended in the second and third meetings, as listed in Table 1. In the third meeting, in addition to talks given in the regular Hodan-kai style, two "panel discussion" sections consisting of introductory talks by organizers and 5–7 short talks by invited panelists were newly organized to facilitate interaction among the participants. The program and summary of the Hodan-kai are shared on their respective websites.[2–4)]

Table 1. Number of talks by theoretical and experimental nuclear physicists and researchers from other fields, as well as participants in the successive Hodan-kai meetings.

	Date	Theor.	Exp.	Other	Participants
1st	Aug 2017	22	1	0	49
2nd	Feb 2019	6	7	12	42
3rd	Feb 2020	6	7	4	43

Collaboration and Perspective

In addition to the collaborations among the TF2 members, collaborative works with other researchers have been conducted, and further collaborations are expected in the near future. We have already co-authored 4 papers on the experiments performed at RIBF, 2 proposals to the RIBF PAC, 24 papers on the theoretical analysis of the RIBF data, and 30 papers on the physics expected in the future RI beam facilities. Furthermore, 30+ invited talks on the physics of RI beams have been delivered by the TF2 members during this term.

We have been discussing nuclear fission with experimentalists of the Japan Atomic Energy Agency (JAEA). The measurement of nuclear fission processes and the formation of nuclei in the actinide region using the multinucleon transfer reaction have been intensively studied at the tandem facility of JAEA. Through joint research between JAEA and Kindai University, we have published a number of co-authored papers that have advanced the analysis of experimental data and the interpretation of experimental data. Students of Kindai University attended the summer training school at JAEA. These young students are expected to lead the physics of exotic nuclei in the future. This activity will thus be a starting point for further collaborative research in the physics of superheavy nuclei and fission.

The JSPS-NRF-NSFC A3 Foresight Program "Nuclear Physics in the 21st Century" started in 2019. A microscopic understanding of the r-process is one of the main projects, and theoretical collaboration among the A3 countries is key to success. The activities in TF2 would set a foundation for the extended collaboration. A plan for the construction of a microscopic nuclear data library based on nuclear density-functional theory is described in Ref. 5).

References

1) https://www.nishina.riken.jp/RIBF/TheoForum/index.html.
2) 1st Hodan-kai, https://indico2.riken.jp/event/2509/.
3) 2nd Hodan-kai, https://indico2.riken.jp/event/2864/.
4) 3rd Hodan-kai, https://indico2.riken.jp/event/3157/.
5) K. Yoshida, in this report.