RIPS Project: Pursuit of the RIB Physics Program with RIPS

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The RIB Physics Program with RIPS was initiated in 1984, when I took the office of Chief Scientist of the Radiation Laboratory. The primary objective of the job was to cultivate a novel field of nuclear physics using the RIKEN Ring Cyclotron (RRC) facility,[1)] which was then under construction since 1980 to be completed in 1989. RRC is an intermediate-energy heavy-ion facility, following predecessors such as NSCL, MSU at Michigan and GANIL at Caen. Since we were late comers, I was keen to select a research objective well distinguished from those of the preceding facilities, where studies of hot and/or dense nuclei were most intensively pursued. Our subject thus chosen was the study on exotic nuclei far from the line of stability by means of a radioactive ion beam (RIB), which was a research field still in its infancy in the 1980s. The major vehicle to drive our program was an in-fight projectile-fragment separator, RIKEN Projectile-fragment Separator (RIPS),[2)] which emerged as the world strongest RIB deliverer, marking the advent of the second-generation RIB facility.

This program was proven to be so successful that it triggered and enhanced worldwide enthusiasm towards the promotion of RIB science. Indeed, the RIPS program has attained many of the first accomplishments in terms of identifying unique scientific agendas on exotic nuclei and of cultivating novel methods for RIB experiments. These accomplishments altogether served to constitute the universal framework for the research conduct on RIB physics through the years that followed. At RIKEN, the success of the RIPS project became the cause for promoting the project of RIKEN RI-Beam Factory (RIBF), which was commissioned in 2006 to serve as the world-leading facility for the third-generation RIB science.[3)]

1 Features of RIPS

The production method of RIB by means of in-flight projectile fragments was introduced in the mid-1980s, and pioneering works with such RIBs were performed at Bevalac, LLNL to determine the radius of exotic nuclei[4)] and then at LISE, GANIL mainly to synthesize new isotopes.[5)] The finding of the neutron halo by the former work was particularly fascinating, as it revealed the exotic nature of nuclei very far from the line of stability. While these earlier studies were much stimulative, the fairly weak beam intensities inherent to those first-generation facilities severely hampered further extension of RIB physics. Thus, the RIPS project was aimed at drastically expanding the research territory by introducing reinforced RIB of unprecedented intensities. RIPS was also charged to facilitate the unique capability of producing spin-polarized RIB.[6)]

RIPS is designed to be a separator of incoming projectile fragments, delivering the resultant RIB at the exit channel. It consists of two 45° dipoles (D1 and D2) supplemented with twelve quadrupoles and four sextupoles. The system is essentially composed of two sections in cascade with their relevant focuses. The first section with D1 gives rise to a dispersive focus at F1 and analyzes the magnetic rigidity of fragments. The second section with D2 compensates for the dispersion of the first section and gives rise to a doubly achromatic focus at F2. These two sections combined, with a wedge-shaped energy degrader placed at F1, constitute a doubly achromatic spectrometer, separating the projectile fragments with respect to their A and Z (or q).

In designing RIPS, special precautions were taken to achieve the maximum intensities for the outcoming RIB. The large angular and momentum acceptances taken as 5 msr and 6%, respectively, are essential for this purpose. Also important was the adoption of a large value of 5.76 Tm for the maximum magnetic rigidity, which well exceeds the value of 3.5 Tm of RRC. Such a large bending power allows the use of the highest possible energy of the primary beam even for the production of fragments with very large magnetic rigidity. This is useful to drastically enhance the yield of neutron drip-line nuclei like ^{11}Li, since the production rate of RIB varies with the incident energy $E_{\rm int}$ of the primary beam as $E_{\rm int}^{\alpha}$, where $\alpha \fallingdotseq 3.3$. Thus, RIPS was constructed to become an epoch-making deliverer of RIBs by affording beam intensities stronger than the preceding facilities by 3–4 orders of magnitude.

Such intensities of RIPS beams served tremendously to expand the scope of the applicable experimental methods and hence of the research subjects to be addressed. Most importantly, the RIPS beams were strong enough to easily facilitate observation of a variety of direct reactions, the cross sections of which are typically of the order of several 10 mb. As closely described later this feature greatly helped to promote in-beam studies of nuclear structure and nuclear astrophysics, thereby opening up a wide research field of RIB physics.

Moreover, the capability of RIPS was extended to deliver not only ordinary RIBs but also special types of RIBs, namely spin-polarized RIBs and RIBs of isomers. Spin-polarized fragments are produced in the course of the projectile-fragmentation process. Hence, spin polarized RIBs can be readily obtained through RIPS.[6)] The spin-polarized beams thus produced provided a unique tool to determine the nuclear moments of unstable nuclei by means of an NMR method incorporating the β-decay process.

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2 Research goals with RIPS-RIB

In undertaking the RIPS project, we have chosen three major subjects on nuclear physics.[7] Firstly our focus was directed to reveal and explore exotic phenomena of nuclear structure, which are to be unique to unstable isotopes.[8] Thus, we placed our research emphasis on extremely neutron-rich nuclei, which are uniquely characterized by i) isospin asymmetry with a large excess of neutrons and ii) loose binding of valence neutrons. As is well recognized nowadays, the former feature gives rise to exotic bulk phenomena such as shell evolution resulting in appearance/disappearance of new/classical magic numbers, while the latter gives rise to the peripheral phenomena of neutron halo or skin. Such dilute neutron matter may enhance the cluster formation of the di-neutron. In general, decoupling of valence neutrons from the core may be another key property of extremely neutron-rich nuclei.

Direct reactions have been essential in exploring such exotic features because each variety of direct reactions will provide a sensible probe for a specific property of nuclear structure. Hence, various direct reactions at intermediate energies were combined to probe broad aspects of exotic nuclear properties. Among others, Coulomb excitation/dissociation, nuclear inelastic scattering, nucleon-removal reactions, and exchange reactions were most frequently employed.

The second primary subject concerned nuclear astrophysics. Nucleosynthesis in stellar environments often occurs via proton/neutron radiative capture processes involving targets of unstable nuclei. Hence, we focused on the determination of stellar reaction rates for those radiative processes by measuring cross sections of their effectively inverse reactions, i.e., Coulomb dissociation processes. Proton-induced radiative capture reactions occurring in the p-p chain and CNO cycle were chosen to be the primary objectives.

Finally the unique asset of RIPS, spin-polarized RIB, has facilitated the pursuit of the third primary subject; determination of nuclear moments of unstable nuclei, which are hardly accessible otherwise. The research programs and achievements on these three subjects will be separately described in Sections 4, 5, and 6, respectively.

3 Cultivation of experimental methods for RIB

Most of our experiments on the first and second subjects as defined above were conducted by observing RIB-induced direct reactions. When performing such in-beam experiment, one observes the reaction process in inversed kinematics, where the incoming projectile of RIB serves as the nucleus to be characterized while the target nucleus serves as a probing particle. One will then encounter several difficulties characteristic of RIB made of in-flight fragments: the wide energy spread and the deteriorated emittance in addition to the poor luminosity. Among others, the wide energy spread of RIB is most disturbing since in-beam spectroscopy generally requires the precise determination of excitation energy E_x of the final state of interest, while the missing mass method, which is standard with the primary beam, does not properly work with the poor energy resolution of RIB.

To manage this problem, we have developed the following two methods for the in-beam RIB experiment: one is to measure the gamma rays de-exciting the bound final states[9] and the other is to determine the invariant mass of the unbound final states via the measurement of 4 momentum vectors of all the particles emitted in the final channel.[10,11] Nowadays, these two methods have become prevalent as the standard experimental methods for RIB physics. The poor luminosity is partly overcome by the useful features of the intermediate-energy RIB, as the use of a thick target is allowed and a full solid angle can be readily covered by the detector assembly by virtue of the strong forward focusing of the outgoing particles owing to Lorenz boost.

4 Study on exotic nuclear structure of extremely neutron-rich nuclei

The experimental studies on exotic nuclear structure in the earlier stage were primarily performed in two regions of neutron-rich nuclei, one being around $N = 8$ isotones including ^{11}Li and ^{12}Be and the other around $N = 20$ isotones including ^{32}Mg. Both of the regions involve phenomena of significant shell quenching and of neutron halo as described below.

4.1 Study on halo nuclei

The neutron halo phenomenon was first indicated for ^{11}Li by the large interaction radius determined via the measurement of interaction cross section.[4] To further explore the nature of the phenomenon, we employed Coulomb dissociation as a probing reaction, as first applied to the study on ^{11}Be.[10] In this process, halo nuclei are strongly excited via the E1 transition, leading to the continuum final states at low excitation energies. This so-called soft dipole excitation turned out to be a powerful tool for characterizing the wave function of the halo nucleon, which is supposedly well decoupled from the core part of the nucleus. In fact, the decay spectrum, as observed in the single-neutron halo nucleus ^{11}Be with the invariant mass method, represents the square of Fourier transform of the wave function times radius. Hence the spectrum shape is dictated by the neutron separation energy S_n, with the peak appearing around $E_x \sim 8/5S_n$. The cross section is proportional to the square of the asymptotic normalization coefficient, which is gigantic for a halo neutron. Thus, the strength may well exceed the Weisskopf unit, yielding the cross section of several 100 mb.

This feature of huge cross sections for low excitation energies serves as a clear signature of any neutron halo nuclei. In fact, later experiments singly exploiting this feature newly identified several halo nuclei, including

^{19}C, ^{31}Ne, and ^{37}Mg. With complementary experiments, ^{19}C was ascribed to the s-wave halo like ^{11}Be, while ^{31}Ne and ^{37}Mg in the pf-shell region were ascribed to the p-wave halo. It is worth noting that the appearance of the p-wave halo is caused by deformation of those nuclei.[12]

For the case of a two-neutron halo such as of ^{11}Li, the occurrence of a di-neutron cluster may be conceived. This phenomenon can be identified by finding an enhanced strength of soft dipole excitation, since the total strength of the E1 excitation for the case of the two-neutron halo represents the square of the radius vector of the center of gravity of the pair of neutrons. Indeed, the observed strength for ^{11}Li clearly exceeded the upper limit for the two uncorrelated neutrons, disclosing occurrence of a di-neutron cluster in the halo area of dilute density.[13]

4.2 Disappearance of classical magic numbers as signatures of shell evolution

This quest was initially addressed to nuclei around $N = 8$ as stimulated by the notion of the $N = 7$ anomaly.[14] As pointed out by I. Talmi et al., the supposedly higher-lying neutron level of the $2s_{1/2}{}^{+}$ orbit gradually lowers with respect to the $1p_{1/2}{}^{-}$ orbit as the neutron excess increases along $N = 7$ isotones, even crossing over at ^{11}Be. To clarify the nature of this phenomenon, we first studied the level scheme of an $N = 9$ isotone, ^{14}B, by observing the β decay of ^{14}Be.[15] A large-acceptance detector assembly for β-γ spectroscopy was used together with a high-efficiency TOF detector array for delayed neutrons. It was confirmed that the evolution of level crossing with increasing neutron excess also occurs in $N = 9$ isotones, supporting the conjecture that $N = 8$ magicity is quenched in extremely neutron-rich isotones.

The systematic study on shell evolution was strongly activated when we introduced a novel method of in-beam γ ray spectroscopy,[9] by which the behaviors of the first excited 2^+ state (2_1^+) and other prominent low-lying states of even-even nuclei may be easily assessed. The first experiment of this category was performed on ^{32}Mg by incorporating the intermediate-energy Coulomb excitation process (I.E. Coulex) at $E_{\rm in}/A = 49.2$ MeV. The use of Coulex at such a high energy was a challenging attempt at that time since there had prevailed a strong prejudice that the dominance of Coulex over nuclear excitation for the case of E2 transition could be only assured when the incident energy was taken well below the Coulomb barrier. As is revealed, Coulex well dominates even at intermediate energies when a target nucleus of a heavy element such as Pb is employed. Thus, the E2 strength, $B(\text{E2}; 0^+_{\rm g.s.} \to 2_1^+)$, and the excitation energy of the 2_1^+ state, $E_{\rm x}(2_1^+)$, were unambiguously determined for ^{32}Mg. The enhanced B(E2) and the reduced $E_{\rm x}(2_1^+)$ together provided clear evidence of enhanced collectivity, assuring the quenched magicity of $N = 20$ in this extremely neutron-rich isotope.

In-beam γ-ray spectroscopy with intermediate-energy reactions is subject to a huge Doppler effect. We thus used an array of highly segmented NaI(Tl) γ-ray detectors named DALI to facilitate the Doppler shift correction. The use of the NaI(Tl) detector was helpful to increase the photo-peak efficiency, while its relatively poor energy resolution sufficed to observe the spectrum with sparse peaks owing to the stringent selectivity inherent to intermediate-energy direct reactions. In-beam γ-ray spectroscopy with I.E. Coulex thus initiated soon became the most popular method worldwide to explore the phenomena of shell evolution.

In-beam γ-ray spectroscopy with RIB marked another big step forward when we studied ^{12}Be by incorporating the proton inelastic scattering for the first time.[16] It was immediately recognized that the (p, p') reaction is equipped with several precious features to reinforce the method of in-beam spectroscopy. Firstly, the number of atoms per given target thickness in mg/cm^2 is huge for the proton target of $A = 1$, leading to the tremendous enhancement of event rate. Another indispensable feature of the (p, p') reaction is that it provides a different measure of transition strength, which is the deformation length δ. To make it more usable, the global optical potential is available for the proton scattering to be readily employed for DWBA analysis. The lowered $E_{\rm x}(2_1^+)$ and enhanced $\delta_2(0^+_{\rm g.s.}\to 2_1^+)$ thus obtained were clear signatures of the strong collectivity of ^{12}Be, confirming the occurrence of quenched magicity for this neutron-rich $N = 8$ isotone. For ^{12}Be, the first 1^- state[17] and the second 0^+ state[18] were also found close to the ground state. This implies the near degeneracy of $2s_{1/2}{}^{+}$ and $1p_{1/2}{}^{-}$ orbits, further supporting the quenched magicity.

The (p, p') reaction affords additional merits: it strongly excites the first 4_1^+ state as well as 2_1^+, in contrast to the case of I.E. Coulex, thereby providing unique information on nuclear collectivity. This feature was first exploited in the study of ^{62}Cr to assure its strong deformability.[19] It is also worth noting that the (p, p') process occurs through nuclear interaction, while Coulex occurs through electromagnetic interaction. Accordingly, the former process is more sensitive to the neutron component of the transition matrix, while the latter to the proton component. Thus, the combination of these two reactions enables us to determine the proton and neutron matrixes separately. This feature was exploited, e.g., to clarify the nature of the strongly hindered E2 strength of ^{16}C.[20] It was revealed that the effective charges of the valence neutrons are strongly suppressed, indicating their decoupling from the core nucleons.[21]

Finally, the nucleon-removal reaction was introduced as the third probe reaction, as first used for the study of ^{34}Mg.[22] It was particularly useful to broaden the accessible region of in-beam spectroscopy towards larger neutron excess. The in-RIB γ-ray spectroscopy thus developed has been intensively employed till today to explore the features of shell evolution over the broad region of the nuclear chart. So far, such endeavors worldwide have been successful to confirm the occurrence of shell quenching at $N = 28$[23] as well $N = 8$ and 20, while such quenching only occurs in the isotones located very close to the neutron drip line. In contrast, no signature of shell quenching was found for the heavier classical magic numbers of $N = 50$ and 82, even at extremely neutron-rich isotones such as ^{78}Ni[24] and ^{128}Pd.[25] For these systematic studies on shell evolution, the 2015 Nishina Memorial Prize was awarded to T. Motobayashi and H. Sakurai on behalf of the international colleagues.

5 Study on nucleosynthesis in the cosmos: Determination of astrophysical reaction rates via RIB-induced Coulomb dissociation

Nucleosynthesis in the cosmos is supposed primarily to occur in stellar burning processes that involve very-low-energy nuclear reactions with unstable nuclei. Thus, determination of reaction rates of relevant processes should provide clues in deciding among the various possible scenarios on cosmic evolution. In this context, we set up a novel program to measure the cross section of stellar reactions of radiative capture, which is the most popular process in star burning. For this purpose, we followed the suggestion[26] by G. Baur and C. A. Bertulani that one should measure the cross sections of Coulomb dissociation with an intermediate-energy RIB, which effectively serves as the inverse reaction for the radiative capture process directly feeding the ground state of the residual nucleus. The measurement of this high-energy reaction instead of the original very-low energy reaction tremendously enhances the experimental efficiency by allowing a thicker target and a wider detection acceptance as well as affording a greatly increased cross section. These effects together contribute to increase the overall efficiency by about 6 orders of magnitude, well compensating for the disadvantage of using RIBs with much reduced intensity.

The method was first applied to determine the reaction rate of the ^{13}N(p, γ)^{14}O reaction,[11] a key reaction to ignite the hot CNO cycle of hydrogen burning in stars. The observation of Coulomb dissociation of ^{14}O by means of the invariant mass method revealed the relevant resonance of 1^- located at a decay energy of approximately 545 keV with a radiative width of $\Gamma_\gamma = 3.1 \pm 0.6$ keV. This marked the first successful experiment on the astrophysical reaction rate ever performed with RIB.

The astrophysical study with I.E. Coulex was then addressed to the ^{7}Be(p, γ)^{8}B reaction, a key process in the production of high-energy solar neutrinos by the ^{8}B β^+ decay. To determine the E1 strength free from the disturbing E2 contaminant, the first experiment using the RIPS ^{8}B beam[27] was complemented by another experiment performed using RIB of a higher incident energy at FRS-GSI.[28] The S_{17} value finally determined was $S_{17} = 20.6 \pm 1.2$ (exp.) ± 1.0 (theo.), slightly smaller than the values recently obtained directly from the low-energy bombardment of protons on a ^{7}Be target.

The Coulomb dissociation method was later applied not only to proton-capture reactions but also to a neutron-capture process, ^{14}C(n, γ)^{15}C, one of the key reactions in the Big-Bang nucleosynthesis.[29]

6 Study on nuclear moments as determined with spin-polarized RIB

Our tradition of producing spin-polarized unstable nuclei with heavy-ion reactions started as early as the mid-1970s, when we obtained spin-polarized ^{12}B isotopes via the ^{100}Mo(^{14}N, ^{12}B)X reaction at $E_{\rm in} = 90$ MeV.[30] However the polarizability could be meager in the intermediate-energy projectile fragmentation since the grazing angle of such a high-energy reaction tends to approach zero. To examine this aspect, we performed a pilot experiment at GANIL in the late 1980s to find that ^{12}B produced in ^{18}O projectile fragmentation at $E_{\rm in}/A$ = 60 MeV indeed exhibited a sizable spin orientation.[31] Encouraged by this finding, a novel production scheme of spin-polarized RIB was developed.[6] RIPS was used for this purpose as well, through which the spin-polarized projectile fragments of specific nuclear species were separated and collected. To favorably collect spin-polarized fragments, two supplemental procedures were combined. One is to collect fragments emitted at angles away from zero. This was facilitated with a magnetic swinger placed upstream of the production target, which was used to tilt the direction of the incoming projectile. Secondly, the momentum bin for the in-flight fragment was selected at the intermediate dispersive focal plane so that the net polarization may be optimized. The magnitude of fragment spin polarization thus obtained is significantly large for the case of single nucleon removal, while it decreases rather rapidly as the number of removed nucleons increases.

For the measurement of g-factor, the spin-polarized β-unstable fragments were implanted into the host material, which preserves the spin orientation under an externally applied magnetic field. Meanwhile, the adiabatic fast-passage NMR method for spin reversal was applied to the implanted nucleus to find the relevant Larmor frequency and hence the g-factor of interest. The spin precession occurring across the Larmor frequency was monitored by observing asymmetric emission of β rays with respect to the spin-polarization axis. Spin-polarized unstable nuclei were also employed for the measurement of Q-moment, where a sequence of NMR procedures was applied to the fragments implanted into a host material with an adequate electric-field gradient.

Highlights in the earlier phase of the program involve firstly the determination of g-factor of ^{17}C[32] and secondly of Q-moments of ^{15,17}B isotopes.[33] The former result unambiguously confirmed the anomalous spin-parity of $3/2^+$ for this nucleus of $(d_{5/2})^3$ dominance. The latter result revealed extremely suppressed neutron effective charges of less than 0.1 as compared to the ordinary magnitude of $\sim$0.6. It was concluded that the valence neutrons of those extremely neutron-rich isotopes are strongly decoupled from the core part of the nuclei.

The campaign of this program has been continued till today. As of 2010, g-factors and Q-moments were newly determined, respectively, for 14 and 10 unstable isotopes.

7 Collaborators

As described above, the RIPS project was carried out under the auspices of the Radiation Laboratory. On the other hand, the project has covered such a broad scope of nuclear research that a large number of collaborators from outside of the Radiation Laboratory were also involved. Among others, T. Kubo from the Linear Accelerator Laboratory should be noted as the primary contributor to the construction/operation of RIPS. Regarding the pursuit of research programs, the following three groups from outside of RIKEN played a major role in the initial stage of the project: 1) a group from the University of Tokyo (UT) led by myself and assisted by S. Shimoura, 2) a Rikkyo University group led by T. Motobayashi, 3) a group from Tokyo Institute of Technology (TIT) led by K. Asahi, and 4) a Kyushu University group led by Y. Gono. Among others, group 1) played a special role by directing the entire program jointly with the Radiation Laboratory. In the later stage, 5) a group from TIT led by T. Nakamura, 6) a group from the Science Faculty, UT, led by H. Sakurai, and 7) a group from CNS, UT, led by S. Shimoura joined to expand the scope of the program. Meanwhile, Radiation Laboratory finished its commitment to this program when I retired from the Laboratory in 2000. Instead, three RIKEN Laboratories with their respective Chief Scientists, 8) T. Motobayashi, 9) K. Asahi, and 10) H. Sakurai, were newly created to pursue RIB-related nuclear physics. The Laboratory of 9) was effectively succeeded by 11) the current Laboratory led by H. Ueno.

The research program on halo nuclei was originally implanted by group 1) and dramatically developed by the leadership of group 5) in the following stage. The program incorporating the in-RIB γ-ray spectroscopy has been most prosperous. It was originally started by groups 1) and 2) and later involved many other groups 6), 7), 8), and 10). In particular, group 2) was credited with the construction of the principal device, a γ-ray Detector Array for Low Intensity radiation (DALI). The research program on astrophysical nucleosynthesis was also initiated by groups 1) and 2), and later conducted primarily by groups 2) and 8). The research program with spin-polarized RIB was started by groups 1) and 3), and later taken over by groups 3) and 9) and finally by the current group 11). Group 4) was committed to a challenging program of developing and utilizing the so-called isomer beam. It was proven that such a beam is useful in studying, e.g., properties of excited bands built on isomeric states.[34]

Finally, RIPS has been so useful that many research groups other than the above joined in the utilization of the facility. Among others the Linear Accelerator Laboratory group led by I. Tanihata set up a unique program on nucleosynthesis to exploit the extremely intense RIPS beam of ^{11}Li. This program, which was performed in collaboration with a group from Kurchatov Institute led by A. Korsheninnikov, has succeeded in the synthesis of e.g., "super heavy" helium isotope, ^{10}He.[35] Another major commitment was made by a group from Osaka University led by T. Minamisono and K. Matsuta, who intensively worked on spin-dependent β-decay issues by means of spin-polarized RIB.

Altogether, the number of researchers who have participated in the RIPS-based programs is greater than 250. In particular, the participation of graduate students from various universities was significant. As of January 2008, the RIPS project resulted in the awarding of 52 Ph.D. degrees.

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