RIKEN Accelerator Research Facility (RARF) – The predecessor of Nishina Center –

M. Ishihara[*1,*2,*3]

RARF was an organization formed under the authorization of the RIKEN President to help promote scientific activities using the RIKEN facility of accelerator complex, which may be called RARF as well. The complex consisted of the central accelerator, RIKEN Ring Cyclotron (RRC), and its alternate injectors, RIKEN Linear ACcelerator (RILAC) and the AVF Cyclotron with $K = 70$ MeV. Effectively, RARF served as a research center for accelerator-driven science, and thus can be regarded as the predecessor of Nishina Center. It was organized upon the completion of RRC by the initiative of H. Kamitsubo, who was the original leader of the RRC project. It functioned from 1990 to 2001 under equal partnership among all the RIKEN Laboratories involved in the utilization of the RARF accelerators. Pursuit of a common research program entitled Multidisciplinary Researches on Heavy Ion Science was the central objective of RARF, while it also took charge of realizing the next-generation facility as it launched the RIBF project in 1995.

Naturally, the Director of RARF was elected from among the associated Chief Scientists. Thus, I served as the first Director during 1990–1997, being succeeded by I. Tanihata (1997–2001). During my term of office Y. Awaya and Y. Yano served as Deputy Directors, respectively representing the researchers other than the nuclear physicists and the accelerator staff while I represented nuclear physicists.

RARF originally involved 13 RIKEN Laboratories, of which 3 were associated with nuclear physics and 10 with other disciplines of science. Among those, the Cyclotron Laboratory led by Y. Yano played a special role by taking the full responsibility for the construction, development, and operation of the entire accelerator facility, except for the part of RILAC that was under the charge of the relevant group of the Linear Accelerator Laboratory led by M. Kase. The total beam time was shared almost evenly between nuclear physics and non-nuclear physics groups; the former primarily used RRC, while the latter also employed the injector accelerators in their stand-alone mode.

Research activities at RARF were highlighted by the following principal programs conducted with RRC. They involved 4 projects for nuclear physics; NP-1) RIPS project, NP-2) GARIS-IGISOL project, NP-3) SMART project, and NP-4) ASHURA project, and 4 projects for other scientific disciplines; OS-1) muon science project named Large Ω, Os-2) atomic physics project on multiply charged ions, OS-3) nuclear chemistry program by means of rapid chemistry, and OS-4) radiation biology program via heavy-ion irradiation.

All of these projects were approved in the mid-1980s and facilitated upon the commissioning of RRC in 1989. It is worth noting that each of these programs was proposed and conducted under the strong initiative and leadership of the respective Chief Scientists, symbolizing the spirit and principle of the traditional RIKEN system of Chief Scientists, which prevailed in the institutional operation throughout the 1990s. For some nuclear physics programs, prominent scientists from outside of RIKEN were invited to serve as Visiting Chief Scientists, and took charge of the programs of their own proposal. This arrangement was realized upon an official request by the Nuclear Physics Forum of Japan to the RIKEN President that the RRC facility be open for scientists outside of RIKEN. As it turned out, acceptance of outside researchers was very effective in enlarging the scope of scientific activities with RARF utilities. Formally, these outside users were affiliated to relevant RIKEN Laboratories, being given the status of Visitors of RIKEN. The other RIKEN systems of Special Postdoctoral Researcher and Junior Research Associate were also useful to attract young talent from universities.

It is delightful that most of the above-quoted programs were extremely successful in generating/developing novel sub-fields of atomic and subatomic science, thereby leaving a great legacy for the current research activities at Nishina Center.

Firstly, the RIPS project (NP-1) led by myself accomplished a major step forward in advancing the rising filed of RI-beam (RIB)-driven nuclear physics. The main vehicle employed was a separator called the RIKEN Projectile-fragment Separator (RIPS), which produced RIBs of epoch-making intensities. The achievements of the RIPS project were so great that they immediately triggered worldwide enthusiasm for promotion of RIB science. At RARF, the success of the RIPS project stimulated the promotion of the RIBF project to serve as the third-generation RIB facility. Thus, a variety of research fields cultivated with RIPS are now in full bloom with BigRIPS at RIBF.

Secondly, the GARIS project of NP-2) led by T. Nomura (INS, the University of Tokyo (UT)) aimed at the synthesis of super-heavy elements (SHE) by implementing a high-performance Gas-filled Recoil Ion Separator (GARIS) for the first time in the world. This was the first Japanese attempt to look for SHE with

*1 Director of RARF (1900–1997)
*2 Project Supervisor of RARF/RIBF Project Head Office (2001–2004)
*3 Chief Scientist of Radiation Laboratory (1984–2000)

contemporary accelerator facilities. While its campaign with RRC did not succeed in finding any new elements, it has left an ample set of matured expertise and advanced instrumentation. This has afforded a strong basis for a later campaign with the upgraded RILAC facility, resulting in the successful synthesis of nihonium (Nh). The Ion-Guided Isotope Separator On Line (IGISOL) project under the leadership of T. Inamura has also left a legacy in the research field with slow and stopped RIs, which is currently progressing with the SLOWRI project at RIBF.

Thirdly, the SMART project of NP-3) was initially led by H. Ohnuma (Tokyo Institute of Technology) and later by H. Sakai (UT). It addressed particle spectroscopy with intermediate-energy heavy-ion direct reactions by incorporating a magnetic analyzer named SMART. The project was drastically reinforced when a spin-polarized deuteron beam was installed through the efforts of the Sakai group. This led to the finding of a significant effect of nuclear three-body interaction, which served to invoke the currently prevalent worldwide campaign to explore the nature and influence of higher-order interactions. The current SHARAQ project under the auspice of Center for Nuclear Study (CNS), UT, is supposed to succeed this tradition of particle spectroscopy, which is to be applied to RIB-induced reactions at RIBF.

The ASHURA project led by S. Lee (Tsukuba University) aimed at the investigation of hot/dense nuclei. The destiny of this project was exceptional; it was terminated before it became ripe because of the then emerging thrust towards relativistic-energy phenomena.

The projects in the other disciplines were also rich in novelty. The Large Ω project of OS-1) led by K. Nagamine aimed at the promotion of muon-driven science by establishing a facility of strong secondary beams of muons. For that purpose, a solenoidal magnet device with a large solid angle was constructed and named as Large Ω. After the initial attempt at RRC to produce negative muons from deuteron-induced reactions, the facility site was moved to ISIS at Rutherford Appleton Laboratory (RAL), UK, as described later.

The atomic physics project of OS-2) led by Y. Awaya addressed the investigation of multiply charged ions of medium-heavy elements, which was an emerging field in those years as promoted by the advent of intermediate-energy heavy-ion beams. After initial successes with RRC, an advanced version of the ECR ion source became the major facility for this project. The low-energy beam of highly charged ions provided a unique means to analyze single and multiple electron capture processes, thereby facilitating the spectroscopy of highly excited atomic levels.

The nuclear chemistry project of OS-3) led by F. Ambe made use of the rapid transportation system of RI products from the RRC bombardment site down to the specific area for hot chemistry. This capability readily produced useful mixtures of short-lived RIs to be used to study the features of element circulation in a variety of circumstances. This novel method named "Multi-tracer method" allowed simultaneous injection of different elements into a common host sample, yielding results fairly free from the sample individualities. Thus, it was widely applied for the study of element circulation through biological bodies and in different environmental situations.

The radiation biology project led by F. Hanaoka and F. Yatagai established an irradiation system dedicated to biological samples, which allows irradiation in the air over a wide field of homogeneous dose distribution. This facility has been used for various purposes including the pilot experiment to validate the irradiation methods for heavy-ion cancer therapy to be practically used at the HIMAC facility at National Institute of Radiological Sciences (NIRS). The irradiation system was also used intensively for a project of biological transmutation promoted by S. Yoshida and T. Abe. This project is still being undertaken in full swing at RRC, as it has been so successful in generating useful variants of flowers and grains.

The research activities of RARF were also extended to programs conducted in international collaboration. Firstly, I. Tanihata launched a set of international programs on RIB physics, for which experiments were performed using the FRS facility at GSI, Germany and the RIBLL facility at IMP, China in collaboration with researchers on site. At RIPS, a Russian group from Kurchatov Institute was invited collaboratively to conduct a unique program of synthesizing super-heavy hydrogen and helium isotopes. These programs, which were significantly productive, served well to spread RIB physics worldwide.

The major undertaking of implanting a RIKEN facility at a foreign institution started when a muon facility was constructed at RAL to produce intense secondary beams of muons by incorporating high-power proton beams from the ISIS accelerator. The facility has been in operation since 1995 under the auspices of the RIKEN Facility Office at RAL, as originally directed by K. Nagamine. It is a powerful facility open for outside users, hence widely used internationally. The central activities have been on material science, where the method of muon spin rotation, relaxation, resonance (μSR) was primarily employed to investigate electron motion or spin correlation in a variety of materials. Uniquely, the facility was also committed to R&D works for the muon-catalyzed d-t fusion.

Another project in international collaboration soon followed. In 1995, the Radiation Laboratory directed by myself took the initiative to realize the Spin Physics Program to be conducted with the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory (BNL). In starting this program, the Radiation Laboratory has strongly contributed financially to the installation of Siberian snakes and spin rotators at RHIC, which are essential for the acceleration and manipulation of spin-polarized protons. It has then been committed to play a major role in the Spin Physics Program conducted in the framework of the PHENIX Collaboration. The primary aim of this program was to elucidate the so-called spin puzzle by clarifying the role of gluons in making up the nucleon spin of 1/2. Experimental runs with RHIC polarized proton beams started in 2001 when the Radiation Laboratory accepted a new Chief Scientist, H. En'yo. After several runs on double-helicity asymmetry, the integrated contribution of gluons over the accessible range of Bjorken's x was found to be compatible with the quark contribution. Thus, the quest for the remaining contributions, possibly from smaller-x gluons and/or from the parton orbital angular momenta, has provided a strong cause for proposing the next-generation US accelerator facility, Electron Ion Collider (EIC).

The RIKEN BNL Research Center (RBRC) was created in 1997 originally to support the RIKEN activities for the Spin Physics Program, while its objective was soon extended to nursing young talents of QCD theorists under the strong initiative of T. D. Lee, the first Director of RBRC.

Promotion of international cooperation on the basis of institutional agreement was another consistent policy undertaken by RARF. In this context the 1st agreement was effectively formed with Institute of Modern Physics (IMP), Lanzhou, China as early as 1979 for collaboration on accelerator issues. A series of Japan-China Joint Symposium on Accelerators for Nuclear Physics and Their Applications thus realized through 1980–1996 greatly contributed to establishing close relations between the relevant communities of the two countries. In 1988 the agreement was formalized also to cover activities on nuclear physics. Since then a couple of postdoctoral researchers from IMP were regularly invited to stay and work at RARF through 1990s. It is delightful to see that many of those colleagues are, nowadays, playing leading roles in the Chinese community of nuclear physics.

The 2nd agreement was established with a US institution, Cyclotron Laboratory, Texas A&M University (TAM) in 1982, while the collaborative experimental program using the TAM facility was already initiated in 1978. The success of this fairly early engagement stimulated later collaboration with several European institutions, including IN2P3 (France), INFN (Italy), GSI (Germany), Flerov Laboratory and Kurchatov Institute (Russia). Among those the agreement with IN2P3 started in 1985 provided a unique scheme of cooperation, essentially allowing participation of any nuclear physicists in both the countries. Indeed it has developed a blessed tradition of close partnership between the two communities, through the conduct of many collaborative works both at GANIL and RARF and of a series of Japan-France Joint Symposium (1987–1994) on Heavy-ion Science. Long-lasting collaboration with INFN has been conducted similarly since 1991.

RARF as well pursued cooperation with domestic institutions. Most importantly, intensive cooperation with CNS was started in 2000 when it moved in the Wako campus of RIKEN so that its researchers could readily join the utilization of the RARF facility. Nowadays this collaboration has grown so far as to practice joint operation of RIBF.

The research programs/projects described thus far were started before the mid-1990s. On approaching and entering the 21 century, the configuration of RARF members was considerably changed with the addition of newly assigned Chief Scientists in return for the retirement of most of the Chief Scientists originally involved. Nevertheless, most of the research enterprises mentioned above have remained to be the central involvements in the following years to come not only for RARF but also for Nishina Center.

RARF was also committed to the realization of the next-generation facility. Thus, the RIBF project was launched in 1995 under the auspices of RARF, while the construction of RIBF was performed under the leadership of Y. Yano, who led the newly organized system called Cyclotron Center. To coherently promote the construction of RIBF and the daily operation of RARF, a new organization named RARF/RIBF Project Head Office was operated through the fiscal years of 2001–2004. It effectively accommodated the entire system of the old RARF, while I. Tanihata (2001–2003) and T. Motobayashi (2003–2005) served as the Director of the Accelerator-based Research Group. It was closed in 2005 when a transient system functioning similarly to RARF was created within the framework of the RIKEN Frontier Research System. Finally, RIKEN Nishina Center for Accelerator-Based Science (RNC) was started in 2006, and Y. Yano became its first Director. Incidentally, RIBF was commissioned in the same year.