Development of atomic physics under the contribution of RIKEN Accelerator Research Facility, during 1972–1997 period

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In this report, I will describe how the studies of atomic physics using the RIKEN Accelerator Research Facility was started and grew up, from my personal viewpoint. I will also describe a little about the "new RIKEN" started in 1958, and early days of the 160 cm Cyclotron. I suppose this may be worth to write, since people who know that time are not so many now.

When a personal name is listed, the title will be omitted and when his/her name appears in the second time, only the family name is shown. Laboratory is abbreviated as Lab. In parentheses after the laboratory, the name of its Chief Scientist is shown when it is necessary.

1 The 160 cm Cyclotron

In 1959, after half a year when RIKEN changed to a non-profit research institute sponsored by the Science and Technology Agency (STA) from a private company Kaken, I (Y. Enomoto at that time) joined the Irradiation Lab.(K. Shinohara),[a] RIKEN in Komagome, Tokyo where an electron Van de Graaff accelerator was working and was used to study the irradiation effect on polymers and so forth. Around the end of that year, I belonged to the Radiation Lab. (F. Yamasaki[b]) under the agreement between Shinohara and Yamasaki, which pleased me too. In the Radiation Lab., A. Hashizume and Y. Tendow had been mainly studying β-γ spectroscopy and K. Izumo on the theory of nuclear physics. The small cyclotron constructed in 1952 in RIKEN had been working under members of the Radiation Lab., S. Motonaga, S. Konno, M. Hemmi, and A. Shimamura. I became a member of the β-γ spectroscopy group, but also participated in experiments of direct nuclear reaction made by the group of Y. Nogami Lab., Univ. of Tokyo, using the cyclotron of the Institute for Nuclear Study (INS), Univ. of Tokyo in 1960–1961, and later in that done by K. Matsuda-group of INS.[c]

In May of 1962, the construction plan of the Cyclotron[d] including facilities was prepared and proposed to STA (representative was Yamasaki at first, but soon changed to Hiroo Kumagai). In this plan, I took responsibility for a particle analyzer and a target chamber. For the construction of the Cyclotron, M. Odera, T. Karasawa, Y. Miyazawa and T. Fujisawa joined the Radiation Lab. and soon, in June 1962, the Cyclotron Lab. (Kumagai) was founded. Four staffs mentioned above, and also Motonaga, Hemmi and Shimamura moved to this new laboratory from the Radiation Lab. Yamasaki and T. Hamada (Senior Scientist of the Radiation Lab.) supported Kumagai, who had double position of INS and RIKEN, about the construction of the Cyclotron so much. At the beginning of designing the main magnet, Tendow and I estimated the distribution of magnetic field between the pole pieces, and calculated trajectory of ion beams under Karasawa, but this job was taken over by N. Nakanishi (Cyclotron Lab.). K. Matsuda joined the Cyclotron Lab. leaving INS in 1965, and H. Kamitsubo did leaving the Institute of Solid State Physics of the Univ. Tokyo in 1966.

The Radiation Lab. got new staff members for the β-γ spectroscopy group, T. Katou in 1966 and T. Inamura, who transferred to the Cyclotron Lab. a few years later, in 1967.

The first beam of the Cyclotron was obtained in 1966. At very beginning of starting experiments of nuclear physics, three groups (headed by Odera, Matsuda, and Kamitsubo) were organized to study the elastic scattering of ^{3}He, as the acceleration of ^{3}He was one of the special features of the Cyclotron. Target elements were Al (Odera), Ca (Matsuda) and Ni (Kamitsubo). Only once, an experiment using a tritium beam was made, that was $^{100,98}\mathrm{Mo(t,p)}^{102,100}\mathrm{Mo}$.[2,3] After that, tritium was never accelerated again because it contaminated the Cyclotron itself. Another nuclear-physics group studied in-beam spectroscopy (Hashizume-group). This mainly consisted of the β-γ spectroscopy group of the Radiation Lab. except for me. I belonged to the Matsuda-group but continued the study of β-γ spectroscopy at the Radiation Lab.

Yamasaki retired from RIKEN in 1968. Hamada became the Chief Scientist of the Radiation Lab. and after a while the Radiation Lab. moved to Yamato-machi (now, Wako-shi) from Komagome.

In March 1971, just after Matsuda was nominated for the Chief Scientist of the Cyclotron Lab., he met an accident during enjoying skiing and passed away, and Kamitsubo became the Chief Scientist of the Cyclotron Lab.

2 So-called "Atomic Physics Group"

The measurement of X rays from atoms excited by slow heavy-ions was made in 1934 by using a Van de

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*1 Chief Scientist of Atomic Physics Laboratory (1990–1997)

a) Shinohara changed the name of his Lab. to the Atomic Physics Lab. in 1960. He retired from RIKEN in 1966. In these days, they call the laboratory after the Chief Scientist's name, for example, Shinohara-Lab.

b) When his family name is written by Chinese character, they usually read it as "Yamazaki." He had been a scientist of the Nishina Laboratory since old (before 1945) RIKEN and engaged in the construction of the 60" cyclotron before the War.

c) I got the degree of Dr. Sci. from Univ. of Tokyo, by one of this group's studies.[1]

d) In the documents, the expression of "160 cm Cyclotron" was not used.

Graaff accelerator, but extensive studies using heavy-ion accelerators were started in early 1960s. In these days, heavy-ion accelerators were constructed, and some of them were used for studies of beam-foil spectroscopy, which analyzed photons from fast heavy ions excited by passing through a thin foil. Heavy-ion atom collision studies were started around middle of 1960s.

Learning the worldwide trend of studies in the atomic physics and considering the ability of the Cyclotron to accelerate heavy ions, I was very interested in the studies of atomic physics by using it. In 1972, at a meeting of the Radiation Lab (T. Hamada), I proposed the study of inner-shell ionization processes in heavy-ion atom collisions by measuring X rays. The first experiment was made on October 25–26, 1972, by the group consisted of members of the Radiation Lab., Hamada, Awaya, M. Okano, Hashizume, T. Takahashi, Izumo, Tendow, Katou, Hidekazu Kumagai and M. Nishida. Kumagai took part of electronic counting systems mainly, and Nishida worked on the data handling at the computer. Experiments were made at the No. 4 beam line in the small experimental area using the target chamber for in-beam spectroscopy. A sketch of the experimental rooms with the beam lines of the Cyclotron is shown in Fig. 1 and a photograph of the control desk taken from the counting area in Fig. 2. At the beginning, we met many problems to make the experiment because of the large difference of the cross sections between the nuclear reaction and the inner-shell ionization. We needed very low-intensity beams and found that the current integrator which had been used for the nuclear reaction experiments was of no use, and thus Kumagai designed a new current integrator by using a pico-ammeter. Operators struggled to transport the beams and to make collimation at the target position because they could not detect the beams on their way. Later they made a nice devise to solve this problem. The background radiation from a collimator/slit before the target was too high to make the measurements. We paid many efforts to reduce it. Tendow designed a new small rectangular target chamber made of aluminum and we set it downstream of the in-beam target chamber in May of 1973. We bombarded ten target elements between Cr and Bi with 5 MeV/nucleon α-particles and N^{4+} ions, and measured K- and L-X rays emitted from the targets by using a Si(Li) detector. The aim of the experiment was to study the K- or L-shell ionization processes induced by α-particles and by N^{4+} ions, from the viewpoint of ${Z_1}^2$-dependence of the inner-shell ionization cross section, where Z_1 is the atomic number of the incidents ions. We also obtained the data on the K and L X-ray energies and the width of each X rays in the energy spectra.[4,5]

This group was called as X-ray group at first, but soon called as ion-atom collision group or atomic physics group. So, to avoid a confusion the name of "atomic physics group" will be used hereafter. The first RIKEN Symposium on atomic physics using accelerators, "Excitation of Inner Shell Electrons" was held in January 1974 hosted by the Radiation Lab.

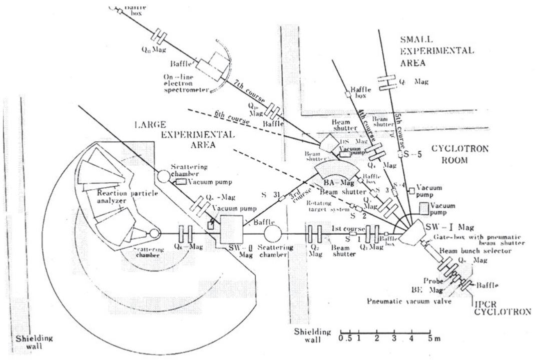

Fig. 1. Layout of the 160 cm Cyclotron beam lines.

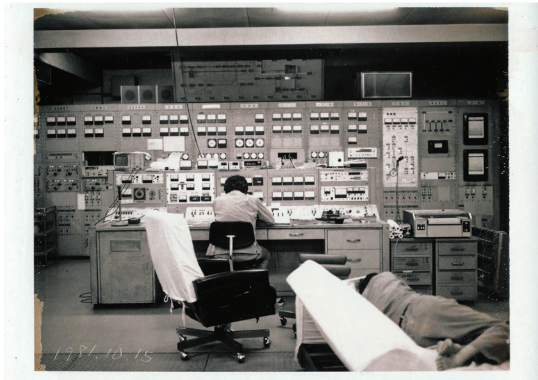

Fig. 2. A photograph of the control desk of the 160 cm Cyclotron taken from the data acquisition area.

We wanted to have a step-scanning crystal spectrometer for measuring X-ray spectra with high energy-resolution to study the multiple inner-shell ionization processes in heavy-ion atom collisions. In 1974, by getting the supplementary budget, we constructed an on-line step-scanning crystal spectrometer.[6] Kumagai designed a control system for step scanning.[7]

In 1975, M. Akiba, got the special researcher position at the Radiation Lab., and joined atomic physics group. We had a visitor, H. Tawara of Kyushu Univ. who took his gas-target system. We studied the ionization processes of Ar atoms by C^{4+}-ions impact by setting his gas-target system on the 6th beam line in the large experimental area[8] in June 1975, and in November, we installed the step-scanning X-ray spectrometer on this line.

We studied simultaneous K- and L-shell ionization processes and simultaneous L- and M-shell ones by measuring K and L X-ray spectra using the crystal spectrometer, for various combinations of target elements including gaseous elements and species of heavy ions. The incident energy of the heavy ions was also changed.[9,10] In 1975, the Linear Accelerator Lab. (M. Odera) was established and T. Tonuma, who moved from the Cyclotron

Table 1. The Budget of the 160 cm Cyclotron in 1975 (in unit of thousand yen).

Item	Budget	Working Budget
Nuclear Physics	30,110	28,900
Atomic & Molecular Physics	3,744	3,590
Nuclear Chemistry	6,770	6,500
Radiation Chemistry	1,800	1,730
Radiation Biology	1,720	1,650
Solid State Physics	3,800	3,650
Cyclotron Body	26,140	25,100
Common Facilities	20,060	19,260
Total	94,144	90,380

(The total Budget of RIKEN: 5,066 million yen.)

Lab. to this laboratory, joined the atomic physics group in 1976. He prepared the gas-target system for these experiments.[11)]

Analyzing all the data, we found the ionization probabilities of L-shell and M-shell electrons in multiple-ionization were fitted to a theoretical universal curve when we chose a proper scaling-factor.[12)] Awaya made a 30 min. oral presentation about this work at the XIth Int. Conf. on the Physics of Electronic and Atomic Collisions (ICPEAC) in Kyoto, 1979, held by Science Council of Japan and by the Society for Atomic Collision Research, and this was a good chance to debut the RIKEN atomic physics group to the worldwide community of atomic collision study.

Talking about the budget for study, the budget for Special Research "General Research using 160 cm Cyclotron" had been authorized, and we wanted to have the item concerning to atomic physics in it. In 1975, the committee of Cyclotron users agreed to add the item "studies of atomic and molecular physics" in this budget document. Table 1 shows the items in the budget document and the budget shared among them, as of 1975. Afterwards, the item concerning to study of atomic physics was included in the special budget for the accelerators, namely, "General Research using Heavy-ion Linear Accelerator" and "General Research of Heavy-ion Science."

The step-scanning crystal spectrometer had been very useful but it took a long time to get X-ray spectra as the Bragg angle had to be changed step by step. Learning that a position sensitive gas-flow proportional counter became commercially obtainable, I got an idea to make a "Broad-Range Crystal Spectrometer" by combining this counter and a flat crystal, for the first time. Considering the position resolving power of the detector, the uniformity of a flat crystal, and the size of beam spot on the target, it was concluded that this new crystal spectrometer would satisfy the aimed energy-resolving power by covering a Bragg-angle range of approximately 20° at once. We constructed this spectrometer getting the budget to Grants-in-Aid for Scientific Research.[13)] Kumagai designed the data-taking system for this spectrometer. The test of this broad-range crystal spectrom-

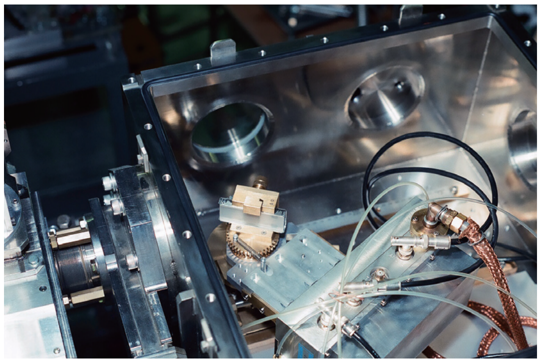

Fig. 3. Photograph of the broad-range crystal spectrometer in the chamber of (4) in Fig. 5 (shown later). This chamber was connected to the X-ray target chamber (3) with bellows.

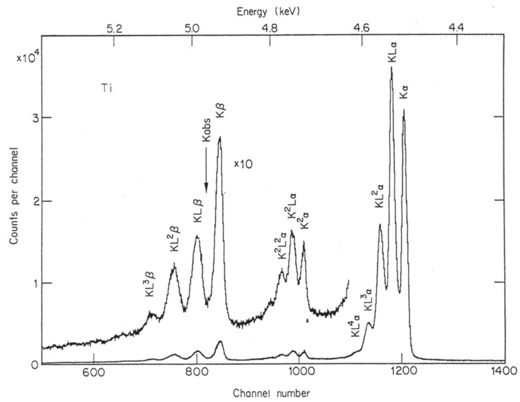

Fig. 4. Spectrum of Ti K-X rays induced by 81 MeV N ions obtained by the broad-range crystal spectrometer. The symbol K^mL^n denotes the m K-shell and n L-shell vacancies in the initial state.

eter was made in the large experimental area of the Cyclotron by setting it in the middle-size scattering chamber in 1980.[14)] Its energy-resolving power was almost equal to the step-scanning one, and its data-taking time was approximately 1/20 compared to that one. In addition to them, it was handy and easy to move to the places where experiments would be done. Figure 3 is a photograph of the broad-range crystal spectrometer and Fig. 4 shows a spectrum of Ti X rays induced by an 81 MeV N-ion bombardment measured with this spectrometer. A. Hitachi (special researcher of the Radiation Lab.) studied angular distribution of Ti K-X rays and Sn L-X rays induced by 81 MeV N-ion bombardments using the broad-range crystal spectrometer.[15)] From that time to 1997, we made many experiments using this unique and strong tool to study heavy-ion atom collisions where high-resolution spectra of K-, L-, or M-X rays emitted from either target atoms or projectile ions were requested.

T. Kambara (Linear Accelerator Lab.) joined the atomic physics group in 1979 and in next year he started to study the collisional quenching of 110 MeV Ne^{9+} ions in gaseous targets. The energy spectra of the Lyman series X rays (np→1s: $n = 2$, 3, 4 and 5) emitted by Ne^{9+} were measured by the broad-range crystal spectrometer with a crystal of RAP in this experiment.[16,e]

Studies of radiative electron capture (REC) processes (the inverse process of photoionization) were made by measuring the REC X rays emitted from 5.5 MeV/nucleon Ne ions collided with a gaseous target.[17] M. Kase (Linear Accelerator Lab.) and I. Kohno (Cyclotron Lab.) participated in this experiment. In 1980, Tonuma et al. made a device to analyze the recoil-ion charge states from collisions of heavy-ions and gaseous atoms. They succeeded to get charge distribution of recoil Ar^{n+} ($n = 1$–7) ions from an Ar-gas target bombarded by 84 MeV N ions[18] and made some studies at the Cyclotron. Awaya et al. designed and constructed a target chamber for measuring angular distribution of X rays by a Si(Li) detector.[19] J. Takahashi (special researcher of the Radiation Lab.) et al. measured the angular distribution of L-X rays from Sn bombarded by 82 MeV N ions from the Cyclotron using this chamber to study anisotropy of L X-ray emission.[20] This chamber was moved to the experimental room of RILAC later.

From around 1980 many people became busy to prepare beam lines with experimental equipment in the experimental area of the RIKEN Heavy-ion Linear Accelerator (RILAC). This machine could accelerate ions from He to Pb, and studies using these heavy ions were very attractive for atomic physicists. Special researchers of both the Radiation Lab. and the Linear Accelerator Lab., cooperated with this preparation, too. In 1981, Kumagai and I held an additional post at the Linear Accelerator Lab. I became the Senior Scientist of the Radiation Lab. in 1982. Kumagai et al. constructed the on-line data taking system and data processing system at the counting room of RILAC.[21]

Figure 5 shows the layout of the RILAC beam lines (as of 1993). Experimental setup installed during 1980–1984 in the experimental area of RILAC are listed below. Most of them are shown in Fig. 5, but some were prepared later. The number in parentheses after the equipment corresponds to that in Fig. 5.

⟨A1 beam line⟩

Kohno et al. designed and installed a 100 cm diameter target chamber (1) on the A1 beam line. Originally it was constructed for universal use in the nuclear scattering and reaction experiments,[22] however, this chamber was often used for study of atomic physics.

⟨A2 beam line⟩

Tonuma et al. set the recoil-ion charge analyzer (2), which was revised frequently according to the purpose of their experiments since then.

e) By this work, Kambara got the degree of Dr. Sci from Kyoto Univ.

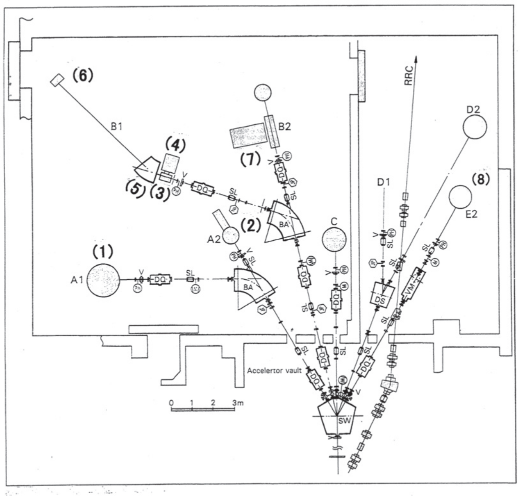

Fig. 5. Layout of the RILAC beam lines.

⟨B1 beam line⟩

An X-ray target chamber, a copy of that designed by Tendow in 1973, was installed to measure X rays with a Si(Li) detector through a thin Be window at 90° against the beam (3). A chamber for the broad-range crystal spectrometer (4) was constructed in 1981 by Awaya et al. and was connected to the X-ray target chamber at the opposite side of the Be window. The setting of B1 beam line, however, was changed very often according to the purpose of the experiments. The target chamber for measuring angular distribution of X rays by a Si(Li) detector was moved from the Cyclotron and set at downstream of (3) some time after 1984, though it is not shown in Fig. 5. The instruments (5) and (6) were installed afterwards: (5) was a broad-range charge analyzer constructed in 1986,[23] and (6) was a two-dimensional Parallel-Plate Avalanche Counter (PPAC).

⟨B2 beam line⟩

K. Mori and K. Ando, who were members of the Thermonuclear Fusion Lab. (K. Mori), installed a beam-foil spectrometer (7), which consisted of a foil-moving system and a grazing-incident spectrometer (McPherson-247).[24] At the downstream of (7), K. Kimura (Chemical Dynamics Lab.) installed his setup for studies of radiation chemistry.

⟨C beam line⟩

This beam line was dedicated to a PIXE group of the Solid State Chemistry Lab.

⟨D1 and D2 beam lines⟩

These beam lines were dedicated to solid-state physics.

⟨E2 beam line⟩

A. Yagishita (Linear Accelerator Lab.) et al., installed an Auger- electron spectrometer.[25]

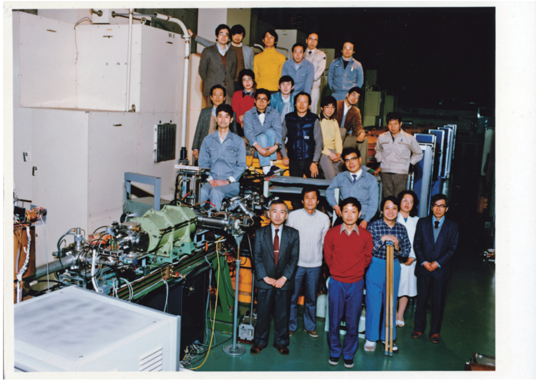

Fig. 6. Photograph of M. Odera and members of Linear Accelerator Lab. with RILAC, taken one day of March, 1985.

In February 1982, RILAC started to supply heavy-ion beams to the proposed experiments. As the basic instruments to make the experiments were ready, works were done eagerly from this time to 1997 by using beams of RILAC. Figure 6 is a photograph of Odera and the staff of the Linear Accelerator Lab. taken in March 1985 at the RILAC accelerator. The experimental works made during 1982–1997 will be introduced later.

3 Atomic Processes Laboratory

At the end of March 1982, K. Mori, Chief Scientist of the Thermonuclear Fusion Lab., retired from RIKEN. T. Watanabe (Univ. Tokyo), a theorist of atomic processes, was nominated for this position in November 1982. Among the staff of the Thermonuclear Fusion Lab., Ando and S. H. Be remained in this laboratory. Watanabe invited me to his laboratory so as to make the laboratory contribute to both the theoretical and the experimental atomic physics. So, Nishida and I moved to this new laboratory from the Radiation Lab., just after T. Hamada, Chief Scientist of the Radiation Lab., retired from RIKEN at the end of March 1983. At the same time, Katou moved to Safety Control Affairs Center. Most of other members remained in the Radiation Lab. (M. Ishihara), so the atomic physics group originated in the Radiation Lab. broke up.

Watanabe changed the name of laboratory to Atomic Processes Lab. in 1983. Tonuma and Kambara held double positions of the Linear Accelerator Lab. and the Atomic Processes Lab. Be moved to the Cyclotron Lab. The Atomic Processes Lab. got new members; in 1983, I. Shimamura, a theorist, who was promoted to the Senior Scientist in next year, and in 1985, Y. Kanai, an experimentalist. M. Odera, the Chief Scientist of the Linear Accelerator Lab., retired from RIKEN in March, 1985, and in 1986, Kambara moved to the Atomic Processes Lab., whereas Tonuma stayed at the Linear Accelerator Lab. (I. Tanihata) keeping the double position.

Watanabe managed the general administration of the laboratory and the theoretical group and I did most of the management of the experimental group consulting with him. Though the theoretical group made excellent works but I will describe here about only the experimental group except for some studies in which both group collaborated. Watanabe was eager to promote the international collaboration.

Visitors of experimentalist to the Atomic Processes Lab., were S. M. Shafroth (Univ. North Carolina), R. Schuch (Heidelberg Univ.), P. Mokler (GSI), N. Stolterfoht (Hahn-Meitner Inst.), B. Sulik (ATOMKI – Inst. Nucl. Study, Hungarian Academy of Sciences, Debrecen, Hungary), T. Papp (ATOMKI), H. Schmidt-Böcking (Frankfurt Univ.), and R. Dörner (Frankfurt Univ.). Visiting researchers whose living expenses supported by RIKEN for more than one year, were M. M. Ismail (Cairo Univ.) and G. H. Vogt (Heidelberg Univ.). The experimental group wanted to use a Semi-Classical Approximation program coded by a theorist D. Trautmann (Basel Univ., Switzerland) and invited him to the laboratory. Domestically, we had many visitors. Main visitors were: A. Danjo (Niigata Univ.), A. Hitachi (Waseda Univ.), Y. Itoh (Josai Univ.), T. Koizumi (Rikkyo Univ.), H. Shibata (Res. Cent. Nucl. Sci., Univ. Tokyo), Matsuo (Tokyo Med. Dent. Univ.), T. Mizogawa (Saitama Univ.), S. Ohtani, K. Sato and H. Tawara (Inst. Plasma Phys., Nagoya Univ.), K. Okuno (Tokyo Metropolitan Univ.), K. Shima (Tsukuba Univ.), H. Suzuki and K. Wakiya (Sophia Univ.), S. Tsurubuchi (Tokyo Univ. of Agric. Tech.), J. Urakawa (KEK), S. Takagi (Toho Univ.), Y. Yamazaki (Nucl. Reactor, Tokyo Inst. Tech.) and M. Yoshino (Shibaura Inst. Tech.).

Kambara stayed at Max-Planck Institute (MPI) for Nuclear Physics (Heidelberg) supported by Nishina Memorial Foundation for one year, and also joined experiments at MPI and UNILAC, GSI.

In 1986, we constructed a beam line for the study of atomic physics in the E2 room of the RIKEN Ring Cyclotron (RRC), as is shown in Fig. 7. We installed a target chamber to measure the angular distribution of X rays, a 100 cm-diameter target chamber for universal use, and a broad-range magnetic charge analyzer that can be rotated from 0° to 60° relative to the beam direction. In order to reduce the background radiation, there were no slits or baffles in the experimental room. A charge stripper setup was installed in the RRC vault to provide different charge-state projectile ions. The beam line was designed so as to get a vacuum better than 10^{-8} Torr.

Another facility for atomic physics was constructed in the ion source vault of the AVF cyclotron in 1988 to use low-energy highly-charged heavy ions from the ECR ion source. Schematic diagram of this beam line including a 0° electron spectrometer is shown in Fig. 8.

The Synchrotron Radiation Facility Design Group (Head: H. Kamitsubo) for the SPring-8 project was organized at RIKEN in 1988 and Watanabe chaired its user-groups in which I was included. A workshop on the

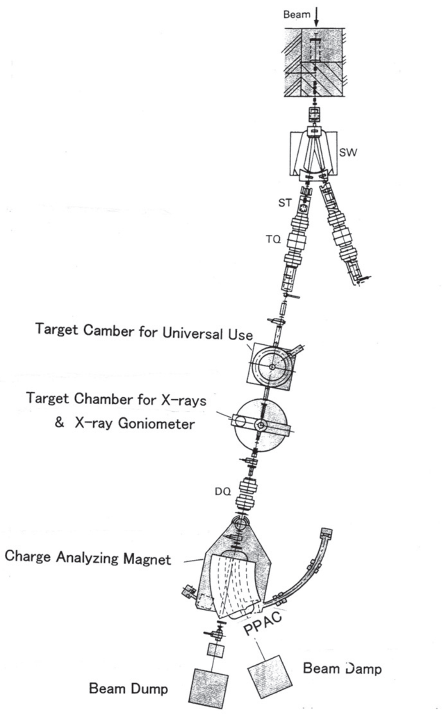

Fig. 7. Experimental setup for atomic physics in the E2-experimental room of RRC.

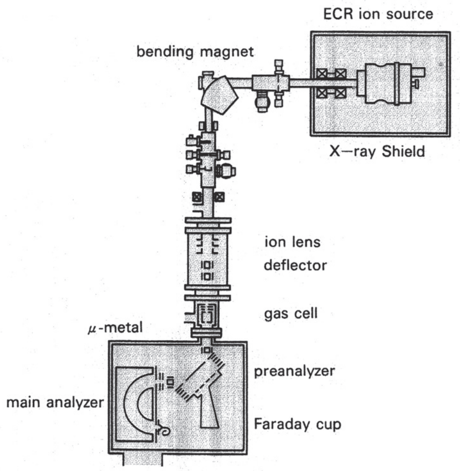

Fig. 8. Experimental setup at the AVF ECR ion source. The 0° tandem-type electron spectrometer is installed.

studies of atomic physics using this high brilliant synchrotron radiation was held among the atomic physicists of Japan in December 1988, and it was decided to organize a working group which would be managed by M. Kimura of Osaka Univ., and I. Up to the end of 1990, five meetings were held and the research and development for future studies were discussed. Some R&D plans were proposed to R&D program of the SPring-8 Project.

Fig. 9. Photograph of Atomic Physics Building (right) and Cyclotron Building (left).

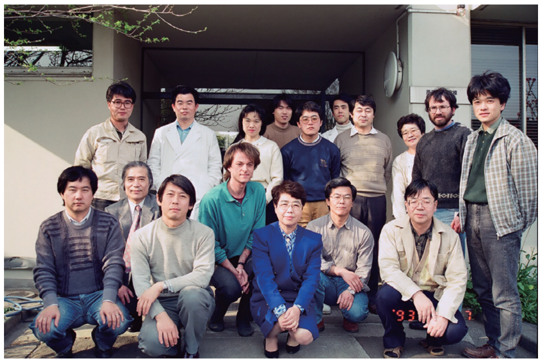

Fig. 10. Photograph of members of the Atomic Physics Lab. at the entrance of the Atomic Physics Building, taken in April of 1993.

4 Atomic Physics Laboratory

In February 1990, the Atomic Processes Lab. moved from the main research building to “Cyclotron Research Building” near “Cyclotron Building.” At the end of March Watanabe retired from RIKEN. I was nominated for the Chief Scientist of this laboratory taking over everything from him, except for the name of laboratory, which was changed to “Atomic Physics Laboratory.” The building was renamed as “Atomic Physics Building.” A photograph of Atomic Physics Building (right) and Cyclotron Building (left) located across a street each other, and that of members of the Atomic Physics Lab. taken at the entrance of Atomic Physics Building in April of 1993 are shown in Fig. 9 and Fig. 10, respectively. Both buildings were demolished to construct the RIBF Building later.

The Atomic Physics Lab. welcomed three new members for experimental studies: M. Oura in 1991, Y. Nakai in 1992 and T. Kojima in 1994. In addition to these three staff members, two special researchers of basic science program, Naoki Watanabe and M. Kitajima joined the experimental group. We had also visiting researchers, Y. Zou (Jiao Tong Univ. China), P. Bengtsson (Lund Univ.), B. Nyström (Lund Univ.), R. Hutton (Lund Univ.), S. Kravis, T. Mizogawa, T. Niizeki, K. Soejima and M. Sano. Kambara became a Senior Scientist in 1993. Four special researchers of basic science program, H. Fukuda, T. Yoshida, J. Tang, and A. Igarashi, and visiting researcher, M. R. Harston joined the theoretical group. Shimamura made the management of theoretical group.

Oura moved to Synchrotron Radiation Center in 1996 keeping the position of the Atomic Physics Lab.

Collaboration with the domestic and foreign research groups were performed positively.

Agreements of collaboration on studies of atomic physics were made with Kansas State University (KSU) in 1991, Dept. of Physics, Goethe (Frankfurt) University in 1992, Lund University in around 1995 and GSI (since the Atomic Processes Lab.). There was an exchange program of scientists between Hungary and the Japan Society for the Promotion of Science, and the Atomic Physics Lab. accepted experimentalists from ATOMKI by this program. T. Papp, B. Sulik, J. Pálinkás and D. Berenyi visited RIKEN and T. Papp and B. Sulik joined the experiments.

H. Schmidt-Böcking (Frankfurt Univ.), I. Martinson (Lund Univ.), C. D. Lin (KSU, theorist) were invited to the laboratory by Eminent Scientist program of RIKEN. Every year, a post-doc of Frankfurt Univ. stayed at the laboratory for approximately two months and joined experiments. They were R. Dörner, J. Euler, S. Lencinus, L. Spielberger, O. Jagutzki, V. Mergel, M. Jeager and M. Achler. From KSU, we had five visitors, B. DePaola, C. P. Bhalla (theorist), P. Richard, L. C. Cocke and M. P. Stöckli. DePaola often visited the laboratory and joined experiments and Bhalla participated in the analysis of experimental data, calculating the fluorescence yields for the cases of multiple inner-shell vacancies existed in initial states. Visitors from Lund Univ. participated in the beam-foil experiments. They were, Martinson, S. Huldt, L. Engeström, and I. Kink. P. Spädke of GSI visited RIKEN taking his program code "AXEL," which we wanted to use to simulate the ion trajectory in the R&D research for SPring-8.

Domestically, most of the visitors at the Atomic Processes Lab. continued the collaboration with us. S. Ohtani, T. Mizogawa, and Y. Yamazaki changed their affiliations and new ones were Inst. Laser Center/Univ. Electro-Commun., Nagaoka Coll. Tech. and Coll. Arts Sci./Univ. Tokyo, respectively. Additional main visitors were T. Azuma and K. Komaki (Coll. Arts Sci., Univ. Tokyo), Keishi Ishii (Kyoto Univ.), Akio Itoh (Kyoto Univ.), K. Kuroki (Natl. Res. Inst. Police Sci.), T. Mitamura, T. Sekioka and M. Terasawa (Himeji Inst. Tech.), and T. Takayanagi (Sofia Univ.).

The Cyclotron was shut down in 1990. The RIKEN symposium "Studies using 160 cm Cyclotron – Its contribution to the accelerator science –" was held in December of that year. In this symposium two talks were given on "The sequence of events of getting the Cyclotron": one was given by T. Hamada, the former Chief Scientist of the Radiation Lab. from the viewpoint of RIKEN, and the other by K. Nagara, the former executive director, who had handled the Cyclotron budget at the STA, from the viewpoint of STA. The supplement of RIKEN Accelerator Progress Report – The 160 cm Cyclotron 1966–1990 – was published. The ceremony of demolishing of the Cyclotron was held on the 26th of February, 1999. A Photograph of that time is shown in Fig. 11.

Fig. 11. Ceremony of demolishing of the 160 cm Cyclotron was held on the 26th of February, 1999. A photograph of participants with the 160 cm Cyclotron.

In 1991, H. Kamitsubo became the director of Synchrotron Radiation Project, and Y. Yano was appointed to the Chief Scientist of the Cyclotron Lab. RIKEN Accelerator Research Facility (RARF), which included both RILAC and RRC, was organized preliminary in 1991 and next year it was established. The facility director was Ishihara and vice facility directors were Awaya (myself) and Yano. From the Atomic Physics Lab., Kambara and Kanai contributed to this facility as members of experimental support division. The chairperson of steering committee of this facility was Tanihata. Two Project Advisory Committees (PACs) were organized for RRC: a PAC for nuclear physics and that for other fields.

In September 25–28 in 1994, Advisory Meeting for the future project "RIKEN RI Beam Factory (RIBF)" was held at RIKEN. Atomic physicist, Martinson was a member of the advisory committee. At this meeting, I presented the achievements of atomic physics at RARF, and Kambara gave a talk at the session of the proposals of RIBF.

We held "The Forth RIKEN Winter School-Atomic and Molecular Processes" in January 8–12, 1995 at Tsunan, Niigata. Lecturers were T. Åberg (Helsinki Univ. Tech.), Y. Hatano (Tokyo Inst. Tech.), P. Mokler (GSI), and H. Tawara (Nat. Inst. Fusion Sci.). This winter school was hosted by RARF and held annually from 1992.

5 Experimental studies during 1982–1997

Here, I will introduce some main subjects of the experimental works at the Cyclotron, RILAC, RRC, and the

ECR ion source made during the period of the Atomic Processes Lab. and the Atomic Physics Lab., briefly. As there were so many works and space is limited, only the subjects will be mentioned in most cases and limited numbers of papers are quoted.

5.1 Studies using heavy ions from 160 cm Cyclotron

The isotope effect of REC X-ray yield

The theoretical group of the Atomic Physics Lab., K. Hino et al., had formulated the REC process and predicted so called "isotope effect" where the REC cross section depended on the mass of a target. According to isotope-effect prediction, the ratio of REC cross sections between collision systems, $Ne^{q+}+{}^3He$ and $Ne^{q+}+{}^4He$ would be close to two.[27] The experimental group checked this prediction by measuring the REC X-ray yields for 110 MeV Ne ions from the Cyclotron incident on ${}^3He$ and ${}^4He$ gas targets. Contrary to the prediction, the difference was within 7%.[28,29] Theorists reconsidered their formulation.[30]

5.2 Studies using heavy ions from RILAC

Table 2 shows the annual trend of the beam time of RILAC and how it was shared among the user's groups. As is seen in this table, approximately 1/3–1/4 of beam time were used by atomic physics.

Studies will be introduced what was done at each beam line, which is shown in Fig. 5. Names of experimental members of each study were abbreviated in most cases, but collaborated organizations are listed.

A1 and B1 beam lines

1) Studies of multiple ionization process and electronic states of target atoms or projectile heavy ions with multiple inner-shell vacancies

   The various kind of studies were made from 1982–1997, using the broad-range crystal spectrometer. Main subjects were as follows, where Z_1, q and E denote the atomic number, the charge, and the incident energy of the projectile ions, respectively. Z_2 is the atomic number of the target atoms and x is the thickness of the target foils.

   a) Systematic studies of multiple inner-shell ionization processes of the target atoms for various collision systems (Z_1, q, E, and Z_2 were changed)[31,32]

      X-ray spectra of the excited target atoms were measured in most cases, but that of the exited projectile ions were also measured if necessary.

   b) Electronic state of the projectile ions during passing through a thin foil[33]

      X rays from the projectile ions were measured by changing q, E, and x, so as to make clear how the projectile ions got equilibrium charge state, and the outer-shell vacancies contributed to the formation of the inner-shell vacancy during passing through a target foil.

   c) Studies of angular distribution of L-X rays[34]

      Measurements were made by a Si(Li) detector at first, and then by the broad-range spectrometer to resolve the L satellite lines. Studies were made for different Z_1, q, E, and Z_2. The M2/E1 mixing of L-X rays were studied.

   d) Radiative electron rearrangement transition following multiple K- and L-shell ionizations[35]

      The RER satellite lines were observed for the first time.

2) Studies on impact parameter dependence of inner-shell ionization

   This studies developed with advancement of experimental setup and technique.

   In 1985, the impact-parameter dependence of K-shell ionization of the target atoms was investigated for He^+ + Ca, Cr and Cu systems.[36] The target K-X rays were measured with a Si(Li) detector in coincidence with the scattered ions detected with a PPAC at approximately 2 m downstream of the target. The beam was collimated to 1 mm × 1 mm with a divergence of 0.02°. Later, using the same set up, target-thickness dependence of the K-vacancy production probabilities $P_K(b)$, where b was the impact parameter, and the total cross sections were studied for 40.6 MeV Ar ions + Ca and Cu systems. The obtained $P_K(b)$ for Ar ions on Ca target were compared with that of 21 MeV Cl ions on Ar target obtained at Max Planck Inst., Heidelberg, to study a solid-gas effect in the K-vacancy production in the near symmetric collision systems.[37]

   In 1986, the broad-range charge analyzer was installed (cf. Fig. 5). Charge distribution of projectile ions scattered by thin target foils, and next, by gaseous targets was measured using the two dimensional PPAC mounted at the exit of charge analyzer.[38] A four-jaw slit was set upstream of the target to make a parallel beam.

   In 1988, studies on K X-ray emission probability $P(b, \phi)$ for projectile ions with different charge states were made, where b was the impact parameter and ϕ was the angle between the scattering plane and the X-ray emission direction, using a coincidence method between signals of X-ray detector and that of the two dimensional PPAC. The b was estimated from scattering angle θ of the projectile ions.[39] The setup is shown Fig. 12. Then, studies on inner-shell ionization and transfer processes in close collisions followed, by coincidence measurements between the scattered projectiles and charge-analyzed recoil ions.

   A high-resolution recoil-ion momentum spectrometer had been developed.[40] When a very cold and localized supersonic gas jet target (internal temper-

Table 2. Beam time of RILAC and that for individual research group (in unit of day).

Year	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Beam Time (days)	144	167	155	155	175	151	176	174	123	177	164	170	167	174	105	182
Atomic Physics	◎	◎	◎	66	62	36	31	41	33	63	44	41	43	60	37	45
Nuclear Physics				5	17	1	0	21	0	0	0	0	0	6	14	2
Others (*)				69	77	40	44	40	52	43	56	44	28	24	16	26
Accelerator research				15	18	11	21	5	4	7	11	16	25	6	2	16
Beam transportation to RRC				0	0	63	80	67	34	64	53	69	70	78	36	93

Others (*) is the sum of beam time for Solid state physics, Nuclear chemistry, Radiation chemistry, and Radiation biology.
◎ There are no data about the individual research group but atomic physics group used the beams in the year marked by this symbol.

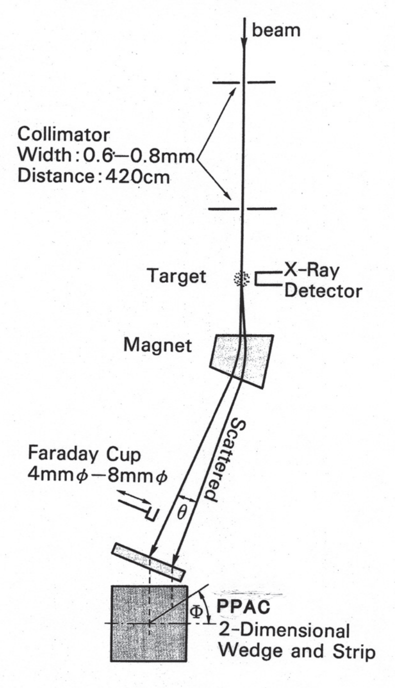

Fig. 12. Experimental setup prepared at B1 beam line for scattering angle dependent measurement.

ature as low as a few mK) and this high-resolution recoil momentum spectrometer were combined, one could obtain recoil-ion momentum with resolution of better than 0.1 au. This experimental technique was called as COLd Target Recoil Ion Momentum Spectroscopy (COLTRIMS). The detection efficiency was nearly 4π, and simultaneously the three-dimensional components of the recoil-ion momentum after a collision were obtainable. This equipment was placed at the gas-cell in Fig. 12 in 1994. Final-state selective measurements of the differential cross sections of single-electron capture and target single-ionization process were made for 8.7 MeV O^{7+}-He collisions by using this equipment under the collaboration of the Atomic Physics Lab., Frankfurt Univ. and Kansas State Univ.[41] Afterwards, some works for different collision systems were made by COLTRIMS.[42]

3) Study of the fragment-ion distribution of C_{60} in close collision with fast C ions

The experimental setting was similar to that shown in Fig. 12. A C_{60} vapor target produced by an oven was placed at the position of the target in Fig. 12. Instead of the X-ray detector, a TOF spectrometer was placed at 90° respect to the beam and analyzed the mass-to-charge ratio of the fragment ions. Close collisions were selected by the change of the projectile charge state, using the coincidence method between the signals of the TOF spectrometer and that of the PPAC.[43] This work was made in collaboration with Kyoto Univ. group.

4) Trial of studies on collisional process of electrons and heavy ions by a merged electron-ion beam method (1985–1986)

New trial of studies were started in 1985 under the collaboration with Inst. Plasma Phys./Nagoya Univ., Tokyo Metropolitan Univ., Rikkyo Univ., Josai Univ., Tokyo Univ. of Agric. Tech., Res. Center Nucl. Sci. Tech./Univ. Tokyo, and Toho Univ. An Electron Beam Ion Source (EBIS) apparatus, so-called "proto-NICE" developed at Inst. Plasma Physics/Nagoya Univ. was rebuilt in the experimental room of RILAC.[44] After testing, it was installed on the beam line (B1). A 1.24 MeV/nucleon Ar^{4+} ions entered the interaction region through an axial 2-mm-diameter hole in the cathode of the electron gun of the Proto-Nice. The electron-ion collision energy was changed by varying the electron energy, and the charge distribution of the Ar ions was measured by a magnetic charge-state analyzer and a PPAC. The data on the charge state of the Ar ions merged with the electrons (on state) and without the electrons (off state) are measured and accumulated. The observed ratio Ar^{3+}/Ar^{4+} was about 3×10^{-6} and almost same between the "on state" and "off state." Therefore it should have originated in the Ar^{4+}-residual gas (10^{-7} Torr. × 6 m) collisions. Large effort was made to reduce the amount of residual gas in the beam ducts, but finally we had to give up this trial. But as a byproduct, we experienced that the Ar-ions were focused by the electron beam.[45]

A2 beam line

Various kinds of experiments concerned to recoil ions (cluster ions) were made. An apparatus to measure the net ionization cross sections of rare gas targets by collisions of heavy ions was made adopting the condenser plate method in 1983.[46] In 1987, a target gas cell and recoil ion detection system were designed and installed. The charge state of the recoil ions was analyzed by a time-of-flight spectrometer and that of the projectile ions was analyzed by an electrostatic analyzer and a PPAC Coincidence measurements between the charge-analyzed recoil ions and the projectiles were performed.[47] The production of recoil charged ions and molecules were studied by using a molecule target.[48] Around 1990, they started to study charged recoil ions, molecules and clusters produced when heavy ions collided with a frozen rare gas or molecule target on a thin foil at the liquid-nitrogen temperature.[49] This work was made for various combination of target and incident heavy ions. In 1996, they planned to investigate the electron loss from H^- ions under the highly ionized MeV/nucleon ion impact and prepared a setup for it.[50]

B2 beam line

An experiment of beam-foil spectroscopy was started in 1983. At first, the determination of the relative sensitivities of the detection system including a grazing incidence monochromator and a channel electron multiplier (Ceratron) with a secondary electron converter was made by using 14.8 MeV N ions from RILAC.[51] Visitors from Inst. Plasma Phys./Nagoya Univ. and Tokyo Univ. Agric. Tech, and S. Kohmoto (Cyclotron Lab.) joined the experiment. During 1984–1987, beam-foil spectra of Al ions were studied. New lines of Al XII, Al XI and Al X were identified and their energies were obtained. The lifetime of $2s2p^1P$ state of Al X was determined and a transition array of Al X 2p3d-2p4d was identified.[52] During 1988–1993, the Mg IX 3s3d-2s4f transition of beam-foil spectra was measured and analyzed. The lifetimes of the $2p^53p$ and $2p^53d$ levels in Ne-like Ti, Cr, and Fe ions were systematically studied.[53]

During 1994–1997, following studies were made. The transition probabilities for Na-like Nb^{30+}, and Mg-like Nb^{29+} were investigated.[54] The lifetime of the 3p $^2P_{3/2}$ level in Na-like Kr^{25+} were determined. The wave lengths of intercombination lines in Al- and Si-like ions from Kr to Nb and the lifetime of the intercombination transitions in Be-like and B-like Iron were studied. These works were done in collaboration with the group of Lund Univ. During the same period, beam-foil spectra of highly charged Ne ions and that of highly charged Ar ions were measured in visible regions by collaborating with the group of Kyoto Univ. Many lines were observed and identified for Ne and Ar.

E2 beam line

1) Auger electron spectroscopy (1982–1986)

Spectroscopic studies on the L-MM Auger electrons from highly ionized target Ar^{q+} ($q = 7,\ 6\,5$) atoms excited by Ar ions, those from Ar excited by He, C, Ne, Al ions, and the M-NN ones from Kr bombarded by He, N, Ne and Ar ions by using Auger electron spectrometer.[55] In 1987, N. Stolterfoht (Hahn-Meitner Inst.) visited RIKEN with a 0° electron spectrometer. K-LL Auger electrons emitted from projectile N ions were studied for collision system 1.33 MeV/nucleon N^{2+} ions on He and Ne target by using this spectrometer. Highly energy-resolved spectrum was obtained because of the emission angle of Auger electrons was 0° (without Doppler broadening). By this reason, this type of electron spectrometer was used to measure electrons hereafter.

2) Study of high charge state Rydberg ion (1990–1994)

A Rydberg-state analyzer was taken by B. DePaola (KSU) and combined with the 0° electron spectrometer of RIKEN. After 2.5 MeV/nucleon N ions colliding with a target foil, hydrogen-like N ions in Rydberg states of $n{\sim}160$ were obtained. The Rydberg electrons were ionized in the electric field of the Rydberg analyzer, and were measured by the 0° electron spectrometer. A beat structure was expected in the spectra of electrons from high charge Rydberg ions. The observed period of the beats roughly agreed with that predicted by a simple model. As this study was made under collaboration with KSU, Kanai and DePaola mutually visited the partner labs.[56] Kanai also collaborated with KSU-group, on the study of the electron capture process of multiply charged ions colliding with Rydberg state target ions.

3) Systematic studies of binary electrons (1992–1994)

Binary encounter electron peaks were measured in collision of Bi^{q+} (q = 10, 14, 16 and 32) on H_2, He, and Ar at 0° with changing the incident energy; 0.56, 0.8 and 1.2 MeV/nucleon for q = 16 and 32, and 0.8 MeV/nucleon for q = 10 and 14. The binary-encounter peak shift and the double-differential cross section were obtained as functions of the incident energy. Experimental peak shift was compared with Bohr-Lindhard model and adiabatic tunneling model.[57]

5.3 Studies using heavy ions from RRC

1) Studies on radiative electron capture process

Immediately after the beams of RRC were available, angular distribution of K- and L-REC X rays were studied for 20.5 MeV/nucleon Ar ions on a Be target. Experimental results fit well to $\sin^2\theta$ distribution which was theoretically predicted, where θ

is the angle of the X ray relative to the beam. By analyzing the K-REC spectra, the width of K-REC peak was consistent with capture of a 2s electron of Be. This width reflected the momentum distribution of the 2s electron of Be and was compared with that obtained by Compton scattering for the first time.[58] The yields of K-REC X rays of 26 MeV/nucleon $Ar^{13,\ 18+}$ ions passing through a C foil were studied by changing the foil thickness from 10–80 $\mu g/cm^2$. It was found that single collision condition was valid even in the case of foil targets as the ion energy was high. The REC cross sections for 26 MeV/nucleon Ar^{18+} ions were obtained and compared with Bethe Salpeter theory.[59] Ratio of the REC cross section to the total electron capture cross section was studied for 77 MeV/nucleon Ar^{18+} ions in 23 and 44 $\mu g/cm^2$ carbon foils.

2) Studies of charge distribution of ions after passing through foils

Charge distribution of 26 MeV/nucleon Ar^{13+} ions after passing through a carbon foil was measured by changing the thickness of the foil (10, 20, 40, 80, 160, 200 $\mu g/cm^2$ and 4.2 mg/cm^2),[60] and that for 77 MeV/nucleon Ar^{q+} ions by changing the thickness of carbon foil (10 $\mu g/cm^2$–4.27 mg/cm^2) and the incident charge state ($q = 16$–18).[61] The magnetic charge analyzer and PPAC were used (cf. Fig. 7). The electron capture and loss cross sections were obtained for 77 MeV/nucleon Ar^{q+} ions. This offered also an important basic data to get heavy ions with requested charge value.

3) Systematic studies on multiple inner-shell ionization of target elements by heavy ion

Up to that time, systematic-studies were made with heavy ions from the Cyclotron and RILAC, and data at higher impact energies were desired. K_α satellite, hyper-satellite and K_β satellite X-ray spectra of target elements (Ti, Fe, Ni and Cu) excited by 26 MeV/nucleon N ions were measured, and those of target elements (Ti, V, Fe, Ni and Cu) excited by 92 MeV/nucleon Ar^{17+} were done. The broad-range crystal spectrometer was used to get spectra. All the data obtained at the Cyclotron, RILAC, and RRC were analyzed and discussed.[62]

4) Study of radiative electron rearrangement (RER) process

By using the broad-range crystal spectrometer, RER X rays from the 36.6 MeV/nucleon Ar^{14+} ions impinging on thin carbon foils were measured. The thicknesses of the foils were 10, 22, 39 and 85 $\mu g/cm^2$. At the same time, the charge distribution of the Ar ions after passing through the C-foil were measured by the magnetic charge analyzer with the PPAC.[63]

5) Studies on binary encounter electrons

Peaks of binary encounter electrons by 93 MeV/nucleon Ar^{q+} ($q = 17$, 18) passing through a thin carbon foil were studied by changing q and the thickness of the carbon foils (22–83 $\mu g/cm^2$) at the emission angle of 0°. Momenta of the electrons were analyzed by a magnetic electron spectrometer.[64]

6) Studies of heavy-ion irradiation effect on the superconducting materials, such as $La_{2-x}Sr_xCuO_4$

This work started in 1993 under collaboration with a group of Himeji Inst. Tech.[65] Irradiation had been made at a large target chamber shown in Fig. 7 but it took a long time to change the samples at this chamber. Kambara et al. made a setup for material irradiations on the E5A beam line of RRC in 1995.[66]

7) Collaboration to a few subjects proposed by the group of Univ. Tokyo

5.4 Studies using beams of AVF ECR Ion source

Energy levels and production mechanisms of doubly-excited states of projectile ions were studied by measuring emitted electrons with high energy resolution. A 0° Auger electron spectrometer was used. The doubly-excited states of ions were produced by double-electron capture from target gases. Study group of Sofia Univ. and visitors from Niigata Univ. and Shibaura Inst. Tech. joined this study.

1) Measurements of ejected electrons from He-like Carbon ions

$^{13}C^{6+}$ ions at 90, 66.7, 46.2 keV and $^{11}B^{5+}$ ions at 65, 50, 37.5 keV from the ECR ion source collided with a He gas target. Auger electrons from He-like states of C^{4+**} $(2lnl')$ $n = 3$–6 and B^{3+**} $(2lnl')$ $n = 2$–6 were observed. C^{4+**} $(2l2l')$ states were not produced in this experimental conditions, which could be explained by Niehaus' reaction window. Auger-electron spectra from C^{4+**} $(2l2l')$ and B^{3+**} $(2lnl')$ $n = 2$, 3 were measured with high energy resolution and compared with theoretical calculations.[67]

2) Studies of ejected electron spectra from O^{4+**} $(1s^2 3l3l')$

Excited state O^{4+**} $(1s^2 3l3l')$ were produced by the double electron transfer from target gas to 60 keV O^{6+} ions. Ar, Ne, He, O_2, N_2 and H_2 were used as the target. Spectra of the ejected electrons varied depending on the targets. Production mechanisms of singlet/triplet states of the doubly-excited states were discussed.[68]

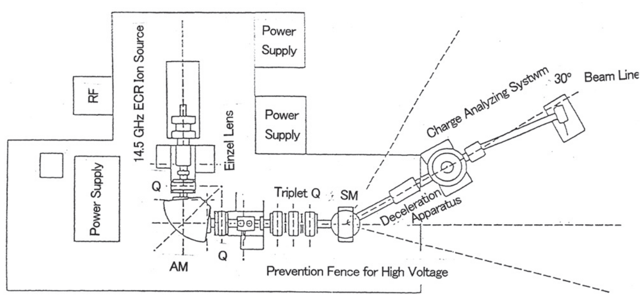

Fig. 13. Layout of the 14.5 GHz ECR ion source and setup for experiment.

6 Other studies at Atomic Physic Laboratory

1) Construction of 14.5 GHz ECR ion source

As the ECR ion source of the AVF cyclotron was an excellent facility for our studies, we desired to have one dedicated to atomic physics, and to get lower energy highly charged ions by decelerating the ions extracted from an ECR ion source. Getting the supplementary budget for construction of ion source under the name of shared-use equipment, we got a 14.5 GHz ECR ion source, Caprice, and installed it in the large experimental area of the Cyclotron.[69,70] Its beam line and instruments for studies were prepared by Special Coordination Funds for Promoting Science and Technology (representative: Awaya) since 1993 to at least 1997. Schematic Drawing of this facility, as of 1996, is shown in Fig. 13. Group of Sofia University joined the test experiments.[71]

2) R&D research works for SPring-8

As was described before, the working group of atomic physics for SPring-8 made proposals to R&D program of SPring-8 Project and got budgets for them.[72] These works were made by the members of working group, but the Atomic Physics Lab. became the base of them.

a) Development of merging beam method for photoionization of ions

T. Koizumi, Rikkyo Univ. and Y. Itoh, Josai Univ. were leading this project and many visitors from outside as well as some members of the Atomic physics Lab. joined them.

A collinear ion-photon merging-beam system was designed and constructed. The ions produced in an ion source were accelerated up to 1–2 keV and deflected by 90° through an electrostatic quadrupole ion deflector. The ions transported through a pair of orifices of 2 mm in diameter to the interaction region with photons, length of that was 15 cm. Then ion beams were analyzed by a parallel-plate ion-charge analyzer, which has a Faraday cup and two electron multipliers (Ceratron) as an ion detector. The computer code, AXCEL, developed in GSI was used to simulate the ion trajectories. The interaction region was biased to 800 V to distinguish the charged ions produced in this region from those in other regions. This equipment was completed in 1992. The use of a compact ECR ion source as the ion source was desirable, but impossible at that time. Therefore, an ion source of surface ionization type was used. In 1993, this equipment was moved to Photon Factory (PF), KEK and experiments on photoionization of ions were made. During 1993–1997, the studies on following target ions were made. Ba^+, Sr^+, Xe^+, Xe^{2+}, Xe^{3+} and Eu^+.[73–76]

b) Construction of an EBIS for use with synchrotron radiation to study the photoionization process of highly charged ions

S. Kravis, visiting researcher of the Atomic Physics Lab., was a main person of this project, and some staffs of the Atomic Physics Lab., especially N. Watanabe collaborated with him. Among the members of the working group, Okuno and Ohtani joined this work.

The highly charged ions are formed through successive ionization by electron impact while ions are trapped inside of the source by electric field. This EBIS was much smaller than typical EBIS which required liquid He for a superconducting solenoid, because of adopting the liquid nitrogen-cooled solenoid, instead of the superconducting ones. At liquid-nitrogen temperature, the resistance of copper is almost 1/10 of that at room temperature, so the power consumption was reduced. When the solenoid was cooled, the vacuum reached 10^{-10} Torr.[77] This equipment had a possibility to study the PHOBIS concept by replacing electron beams from electron gun with photon beams from SPring-8. In 1995, the test operation of this equipment was made at PF, KEK as a target of multiply charged ions and as the PHOBIS mode.[78]

3) Development of readout technique for two-dimensional position-sensitive detectors

A new technique for two-dimensional position readout from one electrode plane was proposed by T. Mizogawa.[79] This technique was applicable to a wide range of detector types, such as a gas-filled counter and a micro-channel plate This method was a combination of two one-dimensional position-readout techniques; the back-gammon method and weighted coupling capacitor method, and named as "modified backgammon method with weighted coupling capacitors (MBWC)." The patent department of RIKEN got the patent for this technique and a private com-

Fig. 14. Photograph of the opening ceremony of HCI-96.

pany “Optima” commercialized it.

At the end

In September 23–26, 1996, The 8th International Conference on the Physics of Highly Charged Ions (HCI-96) was held at Sonic City Hall in Omiya, hosted by RIKEN (Atomic Physics Lab.), and sponsored by The Japan Society for Promotion Science, Saitama Prefectural Government, Saitama Foundation for Culture and Industry and The Society of Atomic Collision Research. Akito Arima, the president of RIKEN, and Mariko Bando, the Vice Governor of Saitama Prefecture, (both the titles are of the time) gave addresses of welcome. I chaired the conference, Kanai worked as the conference secretary and Kambara was in charge of editing the proceedings of the conference, which was published by Physica Scripta.[80] A photograph of the opening ceremony is shown in Fig. 14.

This is a personal thing, but during the conference I had 60th birthday and I got an unexpected gift: in accordance with the session chairperson, HP. Winter (TU Wien), all participants sang the song “Happy Birthday” for me. In addition to this, I got another present in this year: The Physics Section, Royal Swedish Academy of Sciences and the Nobel Foundation invited me to the Nobel Prize Ceremony and Banquet, in view of my services to Swedish physics.

I retired from RIKEN in March 1997 and Y. Yamazaki took over the Atomic Physics Lab.

“There is a time for everything” is one of my favorite saying. I think that the experimental study of atomic physics using energetic highly-charged heavy ions got its time at RIKEN Accelerator Research Facility in the last quarter of the 20th century.

I am most grateful to former Chief Scientists, T. Hamada, M. Odera, T. Watanabe, and H. Kamitsubo for their understanding and support to experimental studies of Atomic Physics. I thank to the former members of RIKEN Accelerator Research Facility, especially for technical staffs, for their help to make experiments. I would like to express my gratitude to T. Kambara for his proofreading of this report and his advice. I am indebted to Y. Kanai and Y. Nakai for their comments for preparing this report.

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