Available online at www.sciencedirect.com
ScienceDirect
Nuclear Instruments and Methods in Physics Research B 254 (2007) 295–299
NIM B
Beam Interactions with Materials & Atoms
www.elsevier.com/locate/nimb

Development of the RF-IGISOL at CYRIC

Tetsu Sonoda [a,*], Masahiro Fujita [a], Akiyoshi Yamazaki [a], Takuya Endo [a], Tsutomu Shinozuka [a], Yuji Miyashita [b], Nozomi Sato [b], Atsushi Goto [b], Eiji Tanaka [a], Tomokazu Suzuki [b], Toru Miyake [a], Minoru Tanigaki [c], Michiharu Wada [d]

[a] *Cyclotron and Radioisotope Center, Tohoku University, Sendai 980-8578, Japan*
[b] *Department of Physics, Tohoku University, Sendai 980-8578, Japan*
[c] *Research Reactor Institute, Kyoto University, Kumatori, Osaka 590-0494, Japan*
[d] *Riken, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*

Received 1 September 2006; received in revised form 25 October 2006
Available online 10 January 2007

Abstract

An rf ion guide for mass separation of fission fragments has been developed as a new type of the ion-source of an ion guide isotope separator on-line (IGISOL). Fission fragments from an uranium target are thermalized in a large helium gas cell and extracted by a combination of dc and inhomogeneous rf electric fields. They are subsequently mass separated by an electromagnetic mass separator. Test experiments with a radioactive α-source and with fission fragments produced in the proton-induced fission of ^{238}U reveal that the yields of mass-separated radioactive ion beams are enhanced, due to the dc and rf electric fields in the gas cell.

PACS: 29.25.Rm; 29.25.Ni; 41.85.Ar

Keywords: IGISOL; Rf ion guide; Proton-induced fission; Nuclear spectroscopy

1. Introduction

The study of medium-mass neutron rich nuclei far from the valley of beta-stability is an important step toward the understanding of nuclear structure and astrophysical r-process. A sufficiently high yield of mass-separated low-energy ion beams is required to determine the static properties of such exotic nuclei. The proton-induced fission of ^{238}U coupled with an ion guide isotope separator on-line (IGISOL) is one of the most effective methods to produce such exotic nuclear ion beams.

The IGISOL method was first developed at the University of Jyväskylä based on the He-jet technique [1]. This method has been widely applied to extract radioactive isotopes of many elements including refractory elements. The IGISOL system at the Tohoku University CYRIC (Cyclotron and Radioisotope Center) was installed in 1987 [2]; it has been used to study nuclei in the *fp*-shell region [3] and medium-mass neutron-rich nuclei produced by proton-induced fission [4–6] using an old $K = 50$ MeV cyclotron. During 1998–2001, the old cyclotron has been replaced to a new $K = 110$ MeV cyclotron. Then, the new project for the development of the rf ion guide system has been started [7,8].

In the target chamber of an ion guide system, recoiling nuclei from the target are stopped in a buffer gas and the thermalized ions are extracted from the exit nozzle of the chamber by a gas flow. When the ion guide method is used for fission products, which have a typical kinetic energy of 1 MeV per nucleon, the stopping efficiency in thermalization becomes crucial. A typical ion guide chamber has a volume of 5–100 cm^3. which is limited in order to ensure that the ions can be evacuated within a short time by the

* Corresponding author. Present address: Department of Physics, University of Jyväskylä, P.O. Box 35 (Y5), FIN-40351 Jyväskylä, Finland. Tel.: +358 14 260 2350; fax: +358 14 260 2351.
E-mail address: tetsu@phys.jyu.fi (T. Sonoda).

0168-583X/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.nimb.2006.10.084

gas flow. However, the stopping capability of such a small gas cell is as low as ≈10 keV per nucleon; it is significantly less than the recoil energy of fission fragments. Therefore,only a small fraction of fragments can be thermalized in the gas and many others are lost in the wall of the cell or in the target.

In order to enhance the stopping capability, it is essential to increase the cell size. However, a long transport time is required to extract the thermal ions from a large cell, since gas flow is the only medium of transport in the cell. This causes severe ion losses not only due to the short lifetime of radioactive nuclei, but also due to any loss processes in the cell such as neutralization, molecular formation and diffusion to the walls. In an rf ion guide, a large gas cell can be used, since it is equipped with dc and inhomogeneous rf electric fields that guide the ions quickly toward the exit hole by preventing any contact between the ions and the wall of the cell. This rf ion guide method was first developed at RIKEN to obtain a low-energy beam from energetic RI beams of a projectile fragment separator [9].

2. Experimental apparatus

In order to enhance the stopping capability of the gas cell while maintaining a high extraction efficiency for the ions of fission products, a large ion guide chamber with dc and rf electric fields has been developed. The volume of the new gas cell is 10^4 cm^3, which is ~1000 times larger than the old one. Fig. 1 shows a schematic diagram of the new gas cell; it has an inner diameter of ~300 mm and a length of ~400 mm. It contains an arrangement of 80 ring electrodes forming a parabolic tapered cylinder. Each ring electrode is fixed by four insulation supports made of an engineering plastic (Delrin). DC gradient potentials are produced by resistors between adjacent ring electrodes that cause the ions to drift toward the exit of the cell with a relatively high velocity of ≈5 m/s. An rf carpet is installed around the exit of the cell, in order to guide the ions to a small exit nozzle without any losses. This rf carpet consists of 100 concentric ring electrodes with an interval of 0.6 mm and a thickness of 200 μm; they are fabricated using a printed circuit board technique. The diameters of the outer electrode and the exit nozzle are 60 mm and 1.6 mm, respectively. Furthermore, rf voltage of ~50 V_{pp}, 2.2 MHz and dc offset voltage are applied to the rf carpet. The rf voltage is phase shifted by 180° between adjacent electrodes to form an ion barrier, while the dc offset voltage guides the ions to the center of the carpet. The fine structure of the rf carpet ensures that the effective ion-barrier is produced by a large repulsive force to the surface, which is inversely proportional to the third power of the distance between the electrodes (see Eq. (12) in [9]).

In order to maintain the vacuum condition of the primary beam line from the cyclotron, the gas cell is separated from them by two windows made of a HAVAR foil with a thickness of 10 μm. The target region is also separated from the gas cell by a thin aluminum foil with a thickness of 6 μm in order to separate the high electron density region around the primary beam and the stopping region, since the ions of interest can be neutralized in the high electron density region. The fission fragments, however, can pass through the foil and are thermalized in the gas cell.

The distribution of thermalized recoil ions in the gas cell is calculated using a numerical simulation code TRIM [10]. We assume that the fission fragments of 131 MeV ^{116}Pd are

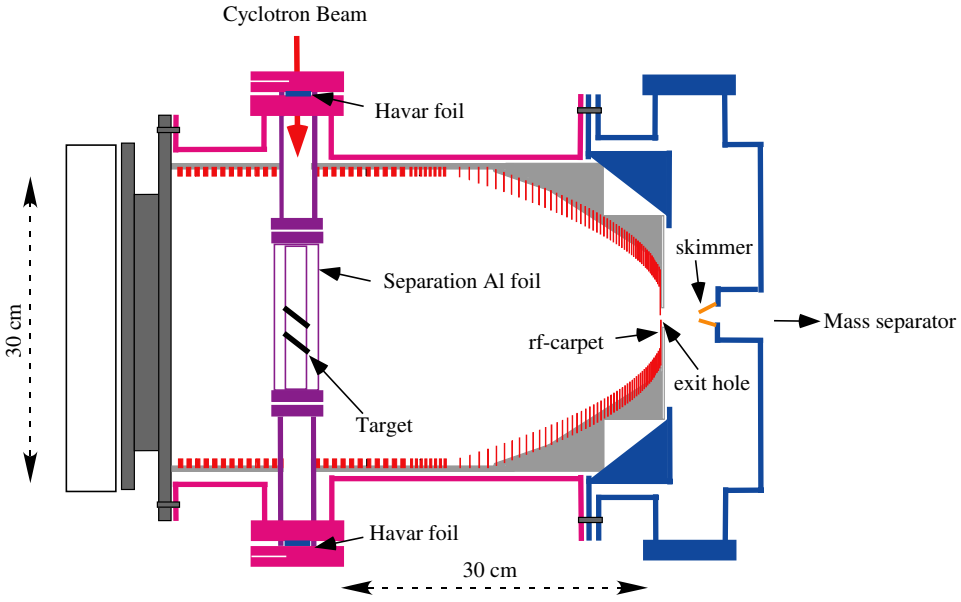

Fig. 1. Cross-sectional view of the rf ion guide gas cell attached to the ISOL. Fission fragments are stopped in the He buffer gas and are extracted by a combination of dc and rf electric fields. The ions that pass through the skimmer are accelerated for 50 keV and mass-separated by the dipole magnet of the on-line isotope separator.

Table 1
Stopping efficiencies of the old and present ion guide gas cell for ^{116}Pd fission fragment

Pressure (hPa)	40	133	267
Old CYRIC ion guide chamber (%)	0.5	1.7	5.5
Present rf ion guide chamber (%)	8.5	26.0	50.5

isotropically emitted from two uranium targets with a thickness of 20 mg/cm^2, which are located on the beam with a tilt angle of 45°, and injected into the gas cell through a 6 μm aluminum window. The stopping efficiency is defined as the ratio of the number of stopped ions in the He buffer gas to the number of ions recoiling out from the target. Table 1 compares the stopping efficiency of the old IGISOL gas cell with that of the present rf ion guide gas cell. A 15-fold increase in the stopping efficiency is expected if the buffer gas pressure is 133 hPa.

3. Results and discussion

3.1. Off-line tests

Off-line test experiments were performed using an ^{227}Ac source. ^{219}Rn ions recoiled out of the source with an energy of ≈100 keV and were thermalized in the gas cell. They were subsequently transported by the dc and rf electric fields to the nozzle and mass-separated by the ISOL. A silicon surface barrier detector was placed at the focal plane of the ISOL to detect α-particles from ^{219}Rn. Thus, we have measured the total efficiency of the RF-IGISOL system as the ratio of the number of transported ^{219}Rn ions to the number of recoiling ^{219}Rn ions from the source. Fig. 2 shows the total efficiency as a function of the distance between the source and the exit nozzle for transporting the ions with and without the dc and rf electric fields. In these experiments, gas pressure was 40 hPa; it corresponded to the distribution of the recoil ions in a sphere with a diameter of 20 mm around the source. A large enhancement in the efficiency, due to the presence of the dc and rf electric fields was observed, particularly when the distance between the source and the exit was long. It should also be noted that the efficiency monotonously decreased with an increase in the distance. The phenomenon is considered to be due to some loss processes such as molecular formation and charge exchange with impurities in the gas during the drift period.

The electric fields in the cell were defined by three parameters: the rf voltage (V_{rf}), the difference in the dc potential across the rf carpet (V_{dc}), and the dc voltage between the target and the carpet (D_{cell}). These parameters were optimized for each measurement.

3.2. On-line tests

On-line test experiments have been done for the fission products from the proton-induced fission of ^{238}U. Two

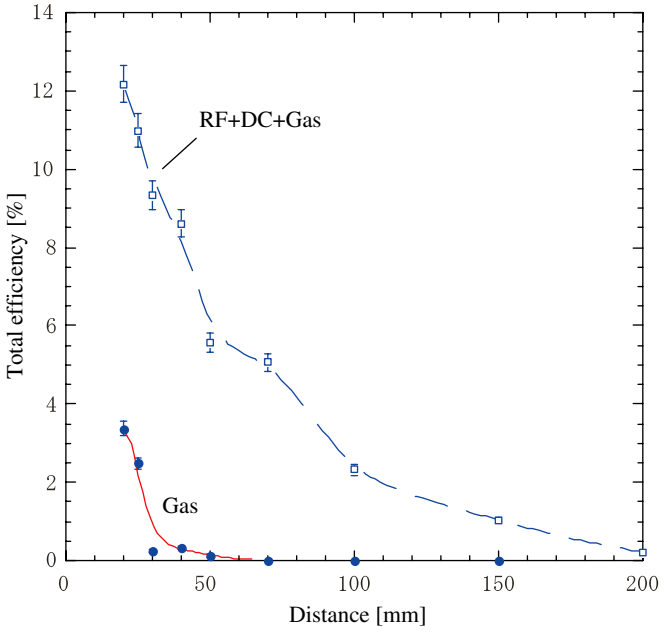

Fig. 2. Total efficiency of the entire RF-IGISOL system as a function of the distance between the source and the exit hole at the off-line test experiments using an ^{227}Ac source.

metallic uranium foils with a thickness of 20 mg/cm^2 were irradiated by a 50 MeV proton beam from the cyclotron. The fragments were thermalized in the gas cell, extracted by the rf ion guide, and injected into the ISOL. The mass-separated fragment ions were transferred into a tape transport system in which the radioactivities were detected by plastic scintillation counters for β-rays and by a high-pure germanium detector for γ-rays.

Since the detection efficiency for β-rays was considerably higher, the β counting rate was used to optimize the rf ion guide parameters and the ion optics of the ISOL. On the other hand, γ-rays were used to identify the obtained nuclides, although the detection efficiency was low. It should be noted that the identification was performed not only for the nuclides, but also for their charge states and mass numbers. Thus, the molecular ions were clearly excluded from the evaluation of the total efficiency.

Fig. 3 shows the experimental results for the fission fragments of $A = 100$ detected by the β counters. The intensity of the primary proton beam was 60 nA and the pressure of the gas cell was 40 hPa. The counting rates were plotted as functions of V_{rf} and V_{dc} for different values of D_{cell} voltage. The effects of the rf ion-barrier fields and the dc fields were clearly observed; in particular a gain of factor 4 was obtained by using an appropriate value of D_{cell}. This implies that the long transportation of stopped ions in a region far from the exit nozzle was fairly realized by the dc field. Furthermore, the yields obtained in this case were 20 times greater than those obtained when no electric fields were applied.

To compare the performance of the present RF-IGISOL setup with that of our old IGISOL setup, we have

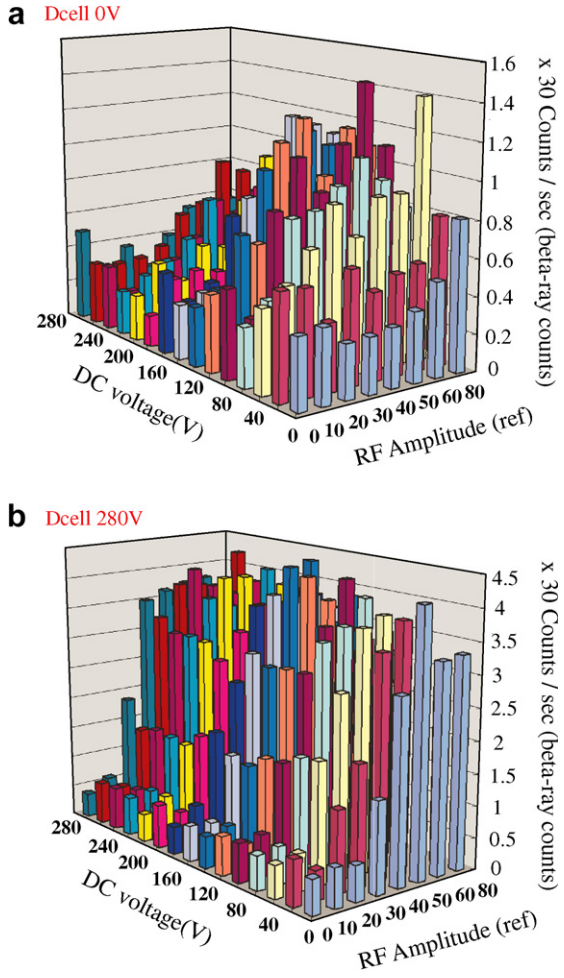

Fig. 3. Experimental results for the yields of the $A = 100$ fragment detected by β-ray detector. The counting rates are plotted as functions of the rf voltage (V_{rf}) and the dc voltage across the rf carpet (V_{dc}) for different dc voltage between the target region and the rf carpet (D_{cell}). (a): $D_{cell} = 0$ V and (b): $D_{cell} = 280$ V, which corresponds to an electric field of ≈10 V/cm.

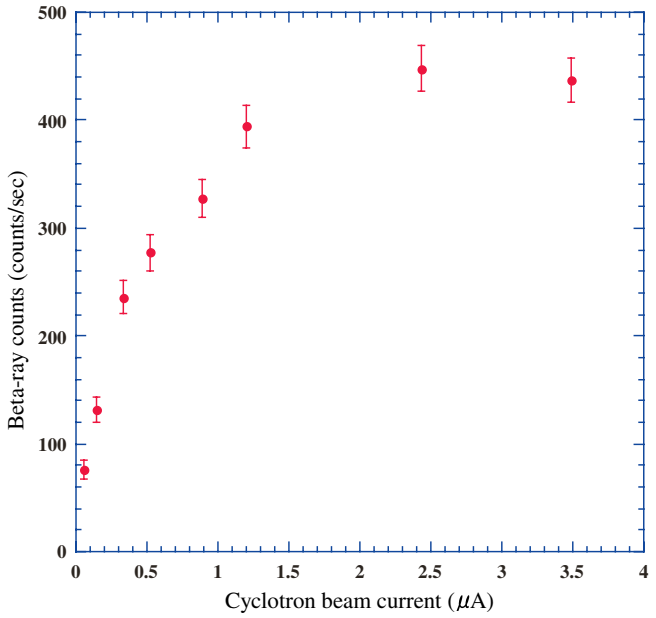

Fig. 4. Intensity dependence of separation yields of the fission fragments. The counting rate is plotted as a function of the primary proton beam intensity.

measured the separation yield of ^{116}Pd by using the γ-detectors. We obtained ≈200 $^{116}Pd^{+}$ ions/s at the end of the mass separator when the proton intensity was 0.5 μA; this corresponded to a gain of factor 3 in comparison with that of the old setup. However, this value was less than that expected for the increase in the stopping efficiency of the gas cell. One reason was that the gas pressure was only 40 hPa, which should result in a reduction of 1/3 in the stopping efficiency against 133 hPa (Table 1). The gas pressure was limited because the pressure in the acceleration region of the mass separator should be less than 10^{-4} hPa and the strength of the rf ion-barrier field was not sufficient to operate at above 40 hPa. Although, we considered the limited gas pressure, the separation yield was still less than the expected value. Another considerable reason for the loss would be neutralizations or molecular formations that occurred when the ions drifted in the gas cell. Since, there were many plastic insulators in the gas cell, the purity of the gas was not as good as that in the old setup.

A common problem of the ion guide system is that the efficiency depends on the beam intensity [11–13]. We measured the separation yield of the fission fragments as a function of the primary beam intensity, as shown in Fig. 4. It has shown the saturation effect around the intensity of 1.5 μA.

We intend to modify the present RF-IGISOL setup in order to improve the overall performance. For solving the primary intensity dependence problem, which is now explained as a space charge effect [13], all surfaces of the gas cell should be covered with rf ion barriers. To solve the chemical reaction problem, we have to replace most of the plastic insulators with ceramic ones and cool the gas cell to a lower temperature in order to reduce the amount of outgas from the materials. Finally to solve the stopping efficiency problem, we intend to reduce the residual gas around the acceleration region by installing an rf six-pole ion beam guide (SPIG) [14,15] in the skimmer region.

4. Summary

For the first time, we have introduced an rf ion guide in the IGISOL in order to increase the yields of the proton-induced fission fragments of ^{238}U. The off-line results show that the rf ion guide successfully transports the ions that stop in a large volume of the gas cell. The on-line tests also reveal that the efficiency is enhanced, due to the introduction of the rf ion guide in the IGISOL. However, the improvements in the overall performance is less than that

expected for the gain in the stopping efficiency of the large gas cell. Further development should be required to modify the rf ion guide in order to obtain significantly higher yields of the fission fragments, particularly for nuclides far from stability.

Acknowledgements

The authors thank Prof. T. Mitsugashira, Prof. T. Ohtsuki, Dr. K. Takamiya and Dr. H. Yuki for providing us an ^{227}Ac source.

References

[1] J. Ärje, J. Äystö, H. Hyvönen, P. Taskinen, V. Koponen, J. Honkanen, A. Hautojärvi, K. Vierinen, Phys. Rev. Lett. 54 (1985) 99.
[2] M. Yoshii, H. Hama, K. Taguchi, T. Ishimatsu, T. Shinozuka, M. Fujioka, J. Ärje, Nucl. Instr. and Meth. B 26 (1987) 410.
[3] T. Shinozuka, M. Fujioka, H. Miyatake, M. Yoshii, H. Hama, T. Kamiya, Phys. Rev. C 30 (1984) 2111.
[4] M. Tanikawa, H. Kudo, H. Sunaoshi, M. Wada, T. Shinozuka, M. Fujioka, Z. Phys. A 347 (1993) 53.
[5] H. Kudo, M. Maruyama, M. Tanikawa, M. Fujita, T. Shinozuka, M. Fujioka, Nucl. Instr. and Meth. B 126 (1997) 209.
[6] H. Kudo, M. Maruyama, M. Tanikawa, T. Shinozuka, M. Fujioka, Phys. Rev. C 57 (1998) 178.
[7] T. Shinozuka, M. Fujita, A. Terakawa, A. Yamazaki, M. Tanigaki, T. Misu, M. Fujioka, H. Orihara, CYRIC Annual Report (2000) p. 19.
[8] T. Shinozuka, RIB projects of Sendai new cyclotron, in: Proceedings of the 4th Italy–Japan Symposium on Perspective in Heavy Ion Physics, Tokyo, 2001.
[9] M. Wada, Y. Ishida, T. Nakamura, Y. Yamazaki, T. Kambara, H. Ohyama, Y. Kanai, T.M. Kojima, Y. Nakai, N. Ohshima, A. Yoshida, T. Kubo, Y. Matsuo, Y. Fukuyama, K. Okada, T. Sonoda, S. Ohtani, K. Noda, H. Kawakami, I. Katayama, Nucl. Instr. and Meth. B 204 (2003) 570.
[10] J.F. Ziegler et al., SRIM, The Stopping and Range of Ions in Matter,<http://www.srim.org/index.htm>.
[11] K. Morita, T. Inamura, T. Nomura, J. Tanaka, H. Miyatake, M. Fujioka, T. Shinozuka, M. Yoshii, H. Hama, K. Taguchi, K. Sueki, Y. Hatsukawa, K. Furuno, H. Kudo, Nucl. Instr. and Meth. B 26 (1987) 406.
[12] M. Huyse, M. Facina, Y. Kudryavtsev, P. Van, Duppen, ISOLDE Collaboration, Nucl. Instr. and Meth. B 187 (2002) 535.
[13] A. Takamine, M. Wada, Y. Ishida, T. Nakamura, K. Okada, Y. Yamazaki, T. Kambara, Y. Kanai, T.M. Kojima, Y. Nakai, N. Oshima, A. Yoshida, T. Kubo, S. Othani, K. Noda, I. Katayama, P. Hostain, V. Varentsov, H. Wollnik, Rev. Sci. Instr. 76 (2005) 103503.
[14] H.-J. Xu, M. Wada, J. Tanaka, H. Kawakami, I. Katayama, S. Ohtani, Nucl. Instr. and Meth. A 333 (1993) 274.
[15] S. Fujitaka, M. Wada, H. Wang, J. Tanaka, H. Kawakami, I. Katayama, K. Ogino, H. Katsuragawa, T. Nakamura, K. Okada, S. Ohtani, Nucl. Instr. and Meth. B 126 (1997) 386.