

Production and applications of radioisotopes at RIKEN RI Beam Factory

– Chemistry of new elements through diagnosis and therapy of cancer –

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We are developing production technologies of radioisotopes (RIs) for application studies at RIKEN RI Beam Factory (RIBF). More than 100 RIs produced at the AVF cyclotron, RIKEN Linear Accelerator, and RIKEN Ring Cyclotron have been used in research fields of physics, chemistry, biology, engineering, medicine, pharmaceutical and environmental sciences. In this paper, RIs for superheavy element chemistry and targeted alpha therapy at RIBF are emphasized. Purified RIs such as ^{65}Zn , ^{67}Cu , and ^{109}Cd are delivered to universities and research institutes through Japan Radioisotope Association. Short-lived RIs such as ^{88}Zr , ^{175}Hf , and ^{211}At are also distributed to researchers through the platform for short-lived RI distribution, supported by JSPS KAKENHI.

1. Introduction

Due to its high sensitivity, the radioactive tracer technique has been successfully applied for investigations of the behavior of elements in the fields of physics, chemistry, biology, engineering, medicine, pharmaceutical and environmental sciences. At RIKEN RI Beam Factory (RIBF), we have been developing production technologies of radioisotopes (RIs) for application studies using the AVF cyclotron (AVF), RIKEN Linear Accelerator (RILAC), and RIKEN Ring Cyclotron (RRC). In this paper, the production and applications of RIs at RIBF are reported with focus on RIs for superheavy element chemistry and targeted alpha therapy. Distributions of RIs through Japan Radioisotope Association and Supply Platform of Short-lived Radioisotopes for Fundamental Research are introduced.

2. Production of RIs at RIBF

First of all, reliable excitation functions are necessary to effectively and quantitatively produce RIs of interest and to reduce contamination of undesired by-products. We have been systematically investigating the excitation functions especially for the d- and α -induced reactions on various targets at AVF in collaboration with Sunway University, Malaysia, International Atomic Energy Agency, Austria, Hokkaido University, and Institute for Nuclear Research (ATOMKI), Hungary. The excitation functions are compared in detail with the previous ones as well as the theoretical model calculations such as the TALYS code taken from the TENDL online database [1]. Then, we develop RI production apparatuses on the beam lines of AVF, RRC, and RILAC. We also develop chemical separation procedures to obtain

RIs with high radionuclidic purity, specific radioactivity, and chemical purity. Finally, radioactivity and chemical purity of RIs are specified by γ -ray/ α -particle spectrometry and Inductively Coupled Plasma Mass Spectrometry (ICP-MS), respectively.

RIKEN RIs developed for application studies since 2002 are summarized in Table 1. With light- to heavy-ion beams from the AVF cyclotron, we produce more than 100 RIs from ^7Be (atomic number $Z = 4$) to ^{262}Db ($Z = 105$) [2,3]. RIs for superheavy element chemistry such as $^{265\text{a,b}}\text{Sg}$ ($Z = 106$) and ^{266}Bh ($Z = 107$) are produced using a gas-jet transport system coupled to the GAs-filled Recoil Ion Separator (GARIS) at RILAC [4]. On the other hand, RIs of a large number of elements, called multitracer, are simultaneously produced from metallic targets such as $^{\text{nat}}\text{Ag}$ and ^{197}Au irradiated with a 135 MeV/u ^{14}N beam from RRC [5].

3. Application studies with RIKEN RIs

The RIKEN RIs have been used in the application studies in collaboration with many researchers in the world as annually reported in RIKEN Accelerator Progress Reports [6] (See the section “Nuclear chemistry and Radiochemistry”) and the references therein. In this paper, we focus on RIs used in chemistry of superheavy elements and targeted alpha therapy.

3.1. Superheavy element chemistry

Chemical characterization of newly-discovered superheavy elements (SHEs, atomic numbers $Z \geq 104$) is an extremely interesting and challenging subject in modern nuclear and radiochemistry [7]. To start up the SHE chemistry at RIBF, we installed a gas-jet transport system to the focal plane of GARIS [4]. This system is a promising approach for exploring new frontiers in the SHE chemistry: the background radiations from unwanted products are strongly suppressed, the intense primary heavy-ion beam is absent in the gas-jet chamber, and hence the high gas-jet extraction yield is attained. Furthermore, the beam-free condition makes it possible to investigate new chemical systems. Long-lived SHE RIs of $^{261\text{a,b}}\text{Rf}$ ($Z = 104$), ^{262}Db , $^{265\text{a,b}}\text{Sg}$, and ^{266}Bh were produced in the $^{248}\text{Cm}(^{18}\text{O},5\text{n})^{261\text{a,b}}\text{Rf}$, $^{248}\text{Cm}(^{19}\text{F},5\text{n})^{262}\text{Db}$, $^{248}\text{Cm}(^{22}\text{Ne},5\text{n})^{265\text{a,b}}\text{Sg}$, and $^{248}\text{Cm}(^{23}\text{Na},5\text{n})^{266}\text{Bh}$ reactions, respectively, and their decay properties were investigated in detail using a rotating wheel apparatus for α and SF spectrometry [8–11]. The decay properties determined for $^{261\text{a,b}}\text{Rf}$, ^{262}Db , $^{265\text{a,b}}\text{Sg}$, and ^{266}Bh are shown in Figure 1.

Using the GARIS gas-jet system, the first chemical synthesis and gas-chromatographic analysis of $\text{Sg}(\text{CO})_6$ were successfully conducted under an international collaboration lead by GSI Helmholtzzentrum für Schwerionenforschung GmbH, Helmholtz Institute Mainz, and University of Mainz, Germany [12]. A detailed experiment to investigate the stability of the metal carbon bond in $\text{Sg}(\text{CO})_6$ is in progress with a thermal decomposition setup developed by Paul Scherrer Institute, Switzerland [13]. Also, syntheses and properties of Tc, Ru, Rh, and Re carbonyls are under study at Institute of Modern Physics (IMP), China and RIBF for future studies on Bh, Hs ($Z = 108$), and Mt ($Z = 109$) carbonyls [14–16]. To realize aqueous chemistry studies of Sg and Bh, we have been developing a continuous and rapid solvent extraction apparatus which consists of a continuous dissolution apparatus Membrane DeGasser (MDG), a Flow Solvent Extractor (FSE), and a liquid scintillation detector for α /SF-spectrometry [17].

A conventional target/gas-jet system for the production of SHE RIs is also available at AVF [18]. The automated batch-type solid-liquid extraction apparatus for repetitive experiments of transactinides

Table 1. List of radioisotopes developed for application studies at RIBF since 2002.

Nuclides	Z	$T_{1/2}$	Accelerator	Reactions	Nuclides	Z	$T_{1/2}$	Accelerator	Reactions
^7Be	4	53.29 d	AVF	$^{nat}\text{Li}(p,xn)$	^{139}Ce	58	137.640 d	AVF	$^{nat}\text{La}(p,xn)$
^{24}Na	11	14.9590 h	AVF	$^{nat}\text{Mg}(d,x)$					$^{nat}\text{La}(d,xn)$
^{28}Mg	12	20.91 h	AVF	$^{27}\text{Al}(a,3p)$	^{141}Ce	58	32.501 d	AVF	$^{nat}\text{Ba}(a,x)$
$^{42,43}\text{K}$	19	12.360 h, 22.3 h	AVF	$^{nat,43,44}\text{Ca}(d,x)$	$^{141m}\text{Nd}^*$	60	62.0 s	AVF	$^{141}\text{Pr}(d,2n)$
^{44m}Sc	21	58.6 h, 3.927 h	AVF	$^{nat}\text{Ti}(d,x)$	^{143}Pm	61	265 d	AVF	$^{141}\text{Pr}(a,x)$
				$^{nat,44}\text{Ca}(d,x)$	$^{143}\text{Sm}^*$	62	66 s	AVF	$^{144}\text{Sm}(d,p2n)$
^{44}Ti	22	49 y	AVF	$^{45}\text{Sc}(d,3n)$	$^{143,144}\text{Eu}^*$	63	2.63 min, 10.2 s	AVF	$^{144}\text{Sm}(d,xn)$
^{48}V	23	15.9735 d	AVF	$^{nat}\text{Ti}(p,xn)$	^{146}Gd	64	48.27 d	AVF	$^{144}\text{Sm}(a,2n)$
$^{48,51}\text{Cr}$	24	21.56 h, 27.702 d	AVF	$^{nat}\text{Ti}(a,xn)$	$^{162,163}\text{Yb}^*$	70	18.87 min, 11.05 min	AVF	$^{nat}\text{Gd}(^{12}\text{C},xn)$
^{48}Cr	24	21.56 h	AVF	$^{46}\text{Ti}(a,2n)$	$^{163,164}\text{W}^*$	74	2.75 s, 6.0 s	RILAC	$^{144}\text{Sm}(^{24}\text{Mg},xn)$
$^{52,54}\text{Mn}$	25	5.591 d, 312.3 d	AVF	$^{nat}\text{Cr}(p,xn)$	$^{169}\text{Hf}^*$	72	3.24 min	AVF/RILAC	$^{nat}\text{Gd}(^{18}\text{O},xn)$
$^{56,57,58}\text{Co}$	27	77.27 d, 271.79 d, 70.82 d	AVF	$^{nat}\text{Fe}(d,xn)$	^{170}Ta	73	6.76 min	AVF/RILAC	$^{nat}\text{Gd}(^{19}\text{F},xn)$
^{61}Cu	29	3.333 h	AVF	$^{nat}\text{Zn}(d,x)$	$^{170}\text{Re}^*$	75	9.2 s	RILAC	$^{152}\text{Gd}(^{23}\text{Na},5n)$
^{65}Zn	30	244.26 d	AVF	$^{nat}\text{Cu}(p,xn)$	$^{173}\text{Hf}^*$	72	23.6 h	AVF	$^{nat}\text{Yb}(a,xn)$
				$^{nat}\text{Cu}(d,xn)$	$^{173}\text{W}^*$	74	7.6 min	AVF/RILAC	$^{nat}\text{Gd}(^{22}\text{Ne},xn)$
$^{66,67}\text{Ga}$	31	9.49 h, 3.2612 d	AVF	$^{nat}\text{Zn}(d,xn)$	$^{174}\text{Re}^*$	75	2.40 min	RILAC	$^{nat}\text{Gd}(^{23}\text{Na},xn)$
				$^{70}\text{Zn}(p,a)$	^{175}Hf	72	70 d	AVF	$^{nat}\text{Lu}(p,xn)$
^{67}Cu	29	61.83 h	AVF	$^{70}\text{Zn}(d,an)$					$^{nat}\text{Lu}(d,xn)$
^{69m}Zn	30	13.76 h	AVF	$^{nat}\text{Zn}(d,x)$	$^{177,178a,179}\text{Ta}$	73	56.56 h, 2.36 h, 1.82 y	AVF	$^{nat}\text{Hf}(p,xn)$
^{74}As	33	17.77 d	AVF	$^{nat}\text{Ga}(a,x)$					$^{nat}\text{Hf}(d,xn)$
				$^{75}\text{As}(p,n)$	$^{177}\text{W}^*$	74	135 min	AVF	$^{nat}\text{Hf}(a,xn)$
^{75}Se	34	119.779 d	AVF	$^{75}\text{As}(d,2n)$	$^{178a}\text{Ta}^*$	73	2.36 h	AVF	$^{nat}\text{Hf}(d,xn)$
				$^{nat}\text{Ge}(a,xn)$	$^{179m}\text{W}^*$	74	6.40 min	AVF	$^{nat}\text{Ta}(d,xn)$
^{85}Sr	38	64.84 d	AVF	$^{nat}\text{Rb}(p,xn)$	$^{180}\text{Re}^*$	75	2.44 min	AVF	$^{nat}\text{Ta}(a,xn)$
				$^{nat}\text{Rb}(d,xn)$	^{181}W	74	121.2 d	AVF	$^{nat}\text{Ta}(p,xn)$
$^{85z}\text{Zr}^*$	40	7.86 min	AVF/RILAC	$^{nat}\text{Ge}(^{18}\text{O},xn)$					$^{nat}\text{Ta}(d,xn)$
				$^{nat}\text{Sr}(p,xn)$	$^{181}\text{Re}^*$	75	19.9 h	AVF	$^{nat}\text{W}(d,xn)$
^{88}Y	39	106.65 d	AVF	$^{nat}\text{Sr}(d,xn)$	^{182}Ta	73	114.43 d	AVF	$^{nat}\text{Hf}(a,x)$
				$^{nat}\text{Rb}(a,xn)$	$^{182a,183,184m,184b}\text{Re}$	75	12.7 h, 70.0 d, 169 d, 38.0 d	AVF	$^{nat}\text{W}(d,xn)$
$^{88,89}\text{Zr}$	40	83.4 d, 78.41 h	AVF	$^{89}\text{Y}(p,xn)$	^{183}Re	75	70.0 d	AVF	$^{nat}\text{Ta}(a,xn)$
				$^{89}\text{Y}(d,xn)$	^{185}Os	76	93.6 d	AVF	$^{nat}\text{Re}(p,xn)$
				$^{89}\text{Y}(p,n)$	^{186}Re	75	90.64 h	AVF	$^{186}\text{W}(d,2n)$
$^{89m}\text{Zr}^*$	40	4.18 min	AVF	$^{89}\text{Y}(d,2n)$					$^{nat}\text{Os}(a,xn)$
				$^{nat}\text{Sr}(a,xn)$	$^{188,189,191}\text{Pt}$	78	10.2 d, 10.87 h, 2.802 d	AVF	$^{nat}\text{Ir}(d,xn)$
$^{88m,88}\text{Nb}^*$	41	7.8, 14.5 min	AVF/RILAC	$^{nat}\text{Ge}(^{19}\text{F},xn)$	^{203}Pb	82	51.873 h	AVF	$^{203}\text{Pb}\text{I}(p,n)$
				$^{nat}\text{Zr}(p,xn)$	^{206}Bi	83	6.243 d	AVF	$^{nat}\text{Pb}(p,xn)$
$^{90m,90}\text{Nb}^*$	41	18.81 s, 14.60 h	AVF	$^{nat}\text{Zr}(d,xn)$					$^{nat}\text{Pb}(d,xn)$
$^{90}\text{Mo}^*$	42	5.67 h	AVF/RILAC	$^{nat}\text{Ge}(^{23}\text{Ne},xn)$	$^{206}\text{Fr}^*$	87	15.9 s	RILAC	$^{169}\text{Tm}(^{40}\text{Ar},3n)$
				$^{nat}\text{Zr}(p,xn)$	$^{209}\text{Fr}^*$	87	50.0 s	RILAC	$^{197}\text{Au}(^{18}\text{O},6n)$
$^{92m,95}\text{Nb}$	41	10.15 d, 34.975 d	AVF	$^{nat}\text{Zr}(d,xn)$	^{211}At	85	7.214 h	AVF	$^{209}\text{Bi}(a,2n)$
$^{92,94}\text{Tc}^*$	43	4.23 min, 293 min	AVF	$^{nat}\text{Mo}(d,xn)$	$^{212}\text{Fr}^*$	87	20.0 min	AVF	$^{206,207,208}\text{mPb}(^{11}\text{B},x)$
				$^{93}\text{Nb}(p,n)$	$^{214}\text{Ac}^*$	89	8.2 s	RILAC	$^{197}\text{Au}(^{22}\text{Ne},5n)$
$^{93m}\text{Mo}^*$	42	6.85 h	AVF	$^{93}\text{Nb}(d,2n)$	^{223}Ac	89	10.0 d	RRC	$^{232}\text{Th}(^{14}\text{N},xnyp)$
				$^{nat}\text{Zr}(a,xn)$	^{229}Pa	91	1.50 d	AVF	$^{232}\text{Th}(p,4n)$
$^{93,94}\text{Tc}^*$	43	2.75 h, 293 min	AVF	$^{93}\text{Nb}(a,xn)$	^{229}Np	93	1.54×10^5 y	AVF	$^{232}\text{Th}(^7\text{Li},3n)$
$^{95,96}\text{Tc}$	43	20.0 h, 4.28 d	AVF	$^{nat}\text{Mo}(d,xn)$	$^{245}\text{Fm}^*$	100	4.2 s	RILAC	$^{208}\text{Pb}(^{40}\text{Ar},3n)$
				$^{95}\text{Mo}(p,n)$					$^{238}\text{U}(^{22}\text{Ne},5n)$
^{95m}Tc	43	61 d	AVF	$^{nat}\text{Mo}(d,xn)$	$^{255}\text{No}^*$	102	3.1 min	AVF/RILAC	$^{248}\text{Cm}(^{12}\text{C},5n)$
				$^{93}\text{Nb}(a,2n)$	$^{257}\text{Lr}^*$	103	22 s	RILAC	$^{209}\text{Bi}(^{48}\text{Ca},2n)$
^{99}Mo	42	65.94 h	AVF	$^{nat}\text{Zr}(a,xn)$	$^{257}\text{Lr}^*$	103	0.646 s	AVF	$^{248}\text{Cm}(^{14}\text{N},5n)$
^{99}Rh	45	16.1 d	AVF	$^{99}\text{Ru}(p,n)$	$^{259}\text{Lr}^*$	103	6.3 s	AVF	$^{248}\text{Cm}(^{15}\text{N},4n)$
$^{100m}\text{Pd}^*$	46	4.696 min	AVF	$^{nat}\text{Pd}(d,x)$	$^{261a,b}\text{Rf}^*$	104	68, 1.9 s	AVF/RILAC	$^{248}\text{Cm}(^{18}\text{O},5n)$
$^{104m,9}\text{Ag}^*$	47	33.5 min, 69.2 min	AVF	$^{nat}\text{Pd}(d,xn)$	$^{262}\text{Db}^*$	105	34 s	AVF/RILAC	$^{248}\text{Cm}(^{19}\text{F},5n)$
^{111}Ag	47	7.45 d	AVF	$^{nat}\text{Pd}(d,xn)$	$^{265a,b}\text{Sg}^*$	106	8.5, 14.4 s	RILAC	$^{248}\text{Cm}(^{22}\text{Ne},5n)$
^{100}Cd	48	462.6 d	AVF	$^{nat}\text{Ag}(p,xn)$	$^{266}\text{Bh}^*$	107	10.0 s	RILAC	$^{248}\text{Cm}(^{23}\text{Na},5n)$
				$^{nat}\text{Ag}(d,xn)$	Multitracer	<22		RRC	$^{nat}\text{Ti}(^{14}\text{N},xnyp)$
^{124}Sb	51	60.20 d	AVF	$^{nat}\text{Sn}(d,x)$	Multitracer	<29		RRC	$^{nat}\text{Cu}(^{14}\text{N},xnyp)$
				$^{nat}\text{Sn}(a,xn)$	Multitracer	<47		RRC	$^{nat}\text{Ag}(^{14}\text{N},xnyp)$
^{121m}Te	52	154 d	AVF	$^{nat}\text{Sb}(d,xn)$	Multitracer	<72		RRC	$^{nat}\text{Hf}(^{14}\text{N},xnyp)$
				$^{124}\text{Te}(d,2n)$	Multitracer	<73		RRC	$^{nat}\text{Ta}(^{14}\text{N},xnyp)$
^{124}I	53	4.1760 d	AVF	$^{133}\text{Cs}(a,x)$	Multitracer	<79		RRC	$^{197}\text{Au}(^{14}\text{N},xnyp)$
				$^{nat}\text{La}(d,x)$	Multitracer	<83		RRC	$^{209}\text{Bi}(^{14}\text{N},xnyp)$
^{135m}Ba	56	28.7 h	AVF		Multitracer	<90		RRC	$^{232}\text{Th}(^{14}\text{N},xnyp)$

* RIs produced with the gas-jet system.

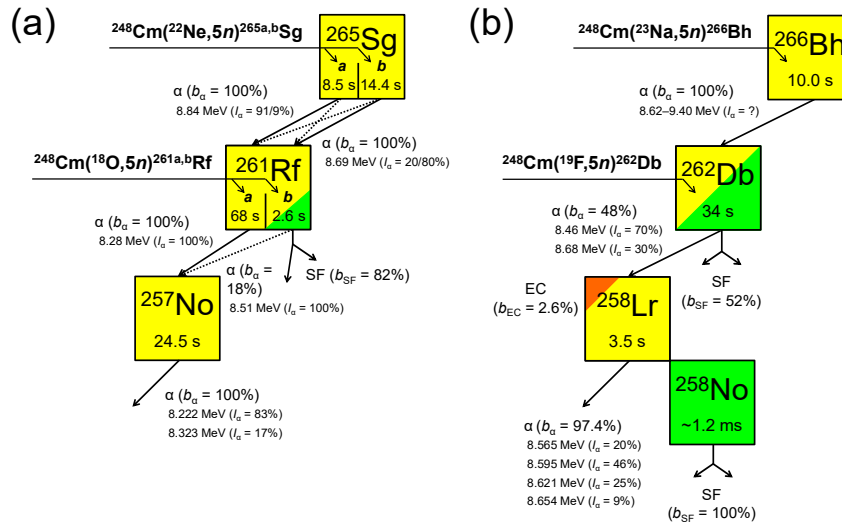


Figure 1. Decay pattern for the chains (a) $^{265\text{a,b}}\text{Sg} \rightarrow ^{261\text{a,b}}\text{Rf} \rightarrow ^{257}\text{No} \rightarrow$ and (b) $^{266}\text{Bh} \rightarrow ^{262}\text{Db} \rightarrow ^{258}\text{Lr} \rightarrow ^{258}\text{No} \rightarrow$ [8–11].

(AMBER) was developed by Osaka University, and distribution coefficients of Rf were determined in HCl [19]. Reversed-phase extraction behavior of Rf with thenoyltrifluoroacetone in HF/HNO₃ was investigated using Automated Rapid Chemistry Apparatus (ARCA) developed by Japan Atomic Energy Agency [20]. Recently, co-precipitation of Rf in basic solutions containing NH₃ or NaOH was investigated in collaboration with Osaka University using a semiautomatic suction filtration apparatus, CHIN [21].

3.2. Production of ^{211}At for Targeted Alpha Therapy

In recent years, the needs for α -particle-emitting RIs for targeted alpha therapy (TAT) is rapidly increasing in the world. The α particles have a shorter range (40–100 μm) in living tissues than β particles (0.05–12 mm), and have a high linear energy transfer (~ 80 keV/ μm), so they are highly cytotoxic. Thus, medicines labeled with α -particle-emitting RIs are considered to be effective in treating disseminated cancer, blood cancer, micrometastasis cancer, and microcancer remaining in a postoperative site. ^{211}At decays to the stable nuclide ^{207}Pb by emitting an α particle with the half-life of 7.214 h. ^{211}At is produced in the $^{209}\text{Bi}(\alpha,2n)^{211}\text{At}$ reaction by irradiating a metallic ^{209}Bi target with α particles accelerated by a cyclotron. The optimum incident beam energy for the production is ~ 28 MeV in order to minimize the production of ^{210}At in the $^{209}\text{Bi}(\alpha,3n)^{210}\text{At}$ reaction: ^{210}At decays to the long-lived and toxic ^{210}Po by an electron capture. Since the half-life of ^{211}At is very short, it is difficult to import ^{211}At from abroad and domestic production is essential. In order to realize the radionuclide therapy with ^{211}At in Japan, it is necessary to establish a platform for the production and supply of ^{211}At among domestic accelerator facilities that have large accelerators. Since 2015, we have been developing a production technology of ^{211}At at AVF and distributing it to 16 research groups in Japan [22].

Figure 2 shows a schematic and photos of the ^{211}At production system developed at RIBF. The metallic ^{209}Bi target is irradiated with α particles accelerated to 29.0 MeV by AVF. The beam energy is controlled with an accuracy of $\pm 1\%$ using a time-of-flight (TOF) beam energy measuring device. The metallic ^{209}Bi target in 20 mg/cm² thickness is prepared by a vacuum evaporation method on an Al plate. Since the melting point of the Bi metal is low (271.5 °C), the target placed at an angle of 15° with respect

to the beam axis is effectively cooled by water (1.5 L/min) and He (30 L/min). In addition, the beam axis is rotated at 120 rpm by an electromagnet (beam wobbler) to reduce heat load on the target. The current setup can accept a beam intensity up to 40 μA to produce 2 GBq of ^{211}At in 1 h. After irradiation, as shown in Figure 2 (c), the Bi target is placed on a Cu boat in a quartz tube (i.d. 30 mm \times L180 mm), and O_2 is passed through the tube (20 mL/min). The quartz tube is heated up to 850 $^\circ\text{C}$ with an electric furnace. ^{211}At sublimated from the ^{209}Bi target is transported to a PFA tube (i.d. 1 mm \times L1000 mm) bound in a spiral and cooled to -100 $^\circ\text{C}$ with a chiller. After collecting ^{211}At , the inside of the PFA tube is washed with a few hundred μL of pure water, methanol, chloroform, etc. to recover ^{211}At . The chemical yield is $>80\%$. The purified ^{211}At is shipped to universities and research institutes in Japan to develop novel nuclear medicines for cancer therapy [23–25].

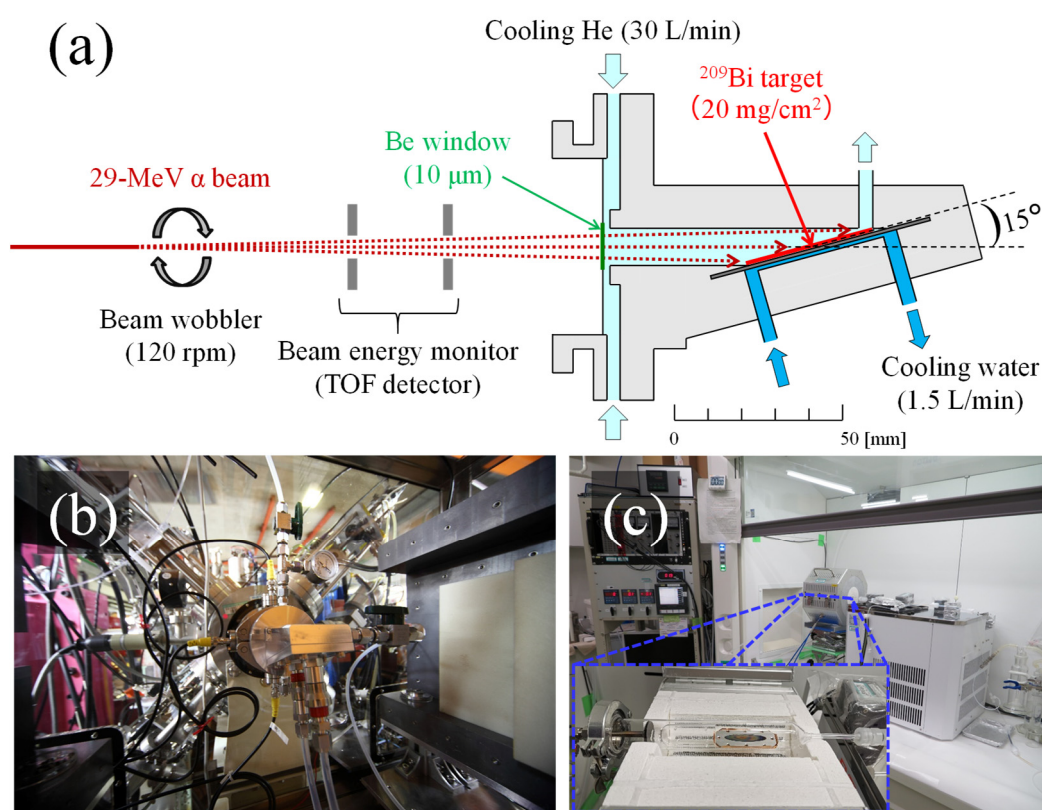


Figure 2. (a) Schematic of the target chamber for ^{211}At production. (b) Photo of the target chamber. (c) Photo of a dry distillation apparatus for ^{211}At separation.

^{225}Ac is also one of the most promising α -particle-emitting RIs for TAT. However, a stable supply system of ^{225}Ac has not yet been established in Japan even at the basic research scale (~ 100 MBq). Thus, we started to develop the production technologies of ^{225}Ac in the $^{232}\text{Th}(^{14}\text{N}, \text{xny})^{225}\text{Ac}$ and $^{226}\text{Ra}(\text{p}, 2\text{n})^{225}\text{Ac}$ reactions using RRC and AVF, respectively.

4. Distributions of RIKEN RIs

Since 2007, the purified RIs of ^{65}Zn , ^{67}Cu , ^{85}Sr , ^{88}Y , and ^{109}Cd are delivered to Japan Radioisotope Association for fee-based distribution to more than 40 universities, research institutes, and companies in

Japan. More than 150 deliveries have been conducted until March, 2020. The RIKEN RIs such as ^{88}Zr , ^{95}Nb , ^{175}Hf , ^{179}Ta , and ^{211}At are also available under the JSPS KAKENHI program “Supply Platform of Short-lived Radioisotopes for Fundamental Research” in collaboration with Research Center for Nuclear Physics, Osaka University, Cyclotron and Radioisotope Center and Research Center for Electron Photon Science, Tohoku University, National Institute of Radiological Sciences and Takasaki Advanced Radiation Research Institute, National Institutes for Quantum and Radiological Science and Technology [26]. Until March, 2020, RIBF accepted a total of 99 orders for 23 research projects.

5. Summary

Present status of the production and applications of RIs at RIBF is briefly reviewed. RIs for SHE chemistry and TAT are highlighted. Very recently, the RILAC facility was upgraded as SRILAC with a 28 GHz superconducting ECR ion source, a super-conducting quarter-wavelength resonator, and a new gas-filled recoil ion separator (GARIS III) being installed. The SRILAC facility is expected to open the next generation RI applications at RIBF with an order of magnitude larger production yields. Using Superconducting Ring Cyclotron and the fragment separator BigRIPS, RIBF can generate more than 3,000 RI beams with the world’s highest intensity. In near future, the RI beams will be used for application studies by implanting them into various materials such as water and pharmaceuticals.

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