Activities related to SHE target production and aqueous chemistry of SHEs at RIKEN

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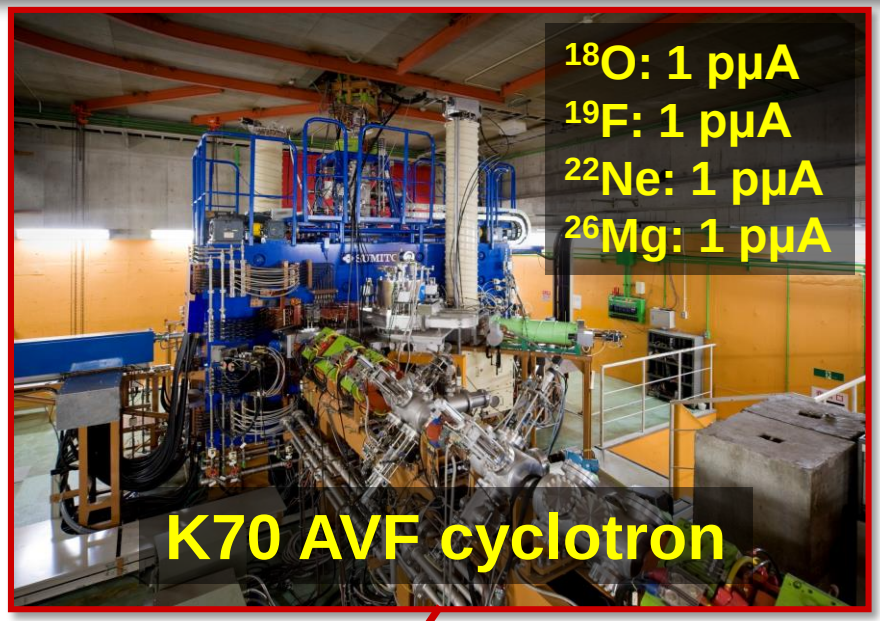
NUSPRASEN SHE-Workshop on Feb. 26, 2019 at GSI

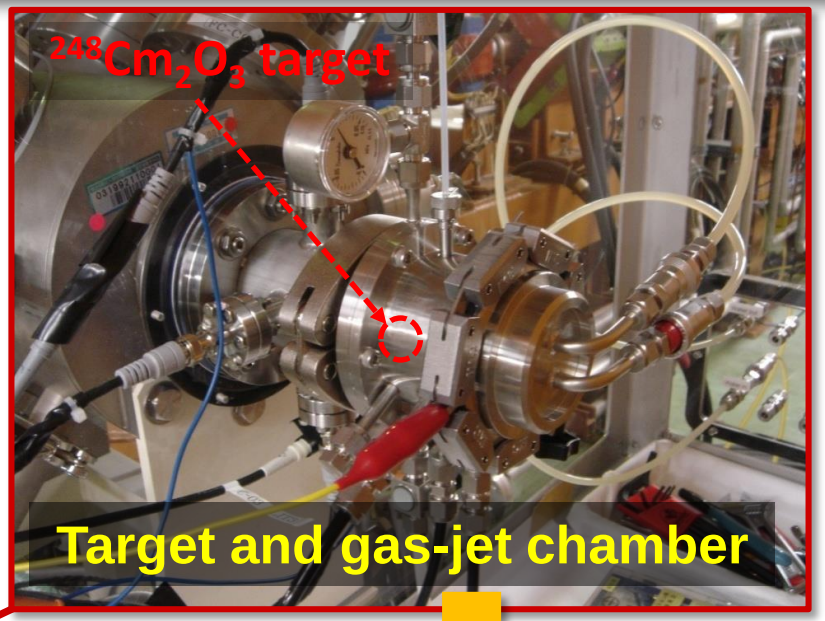
Outline

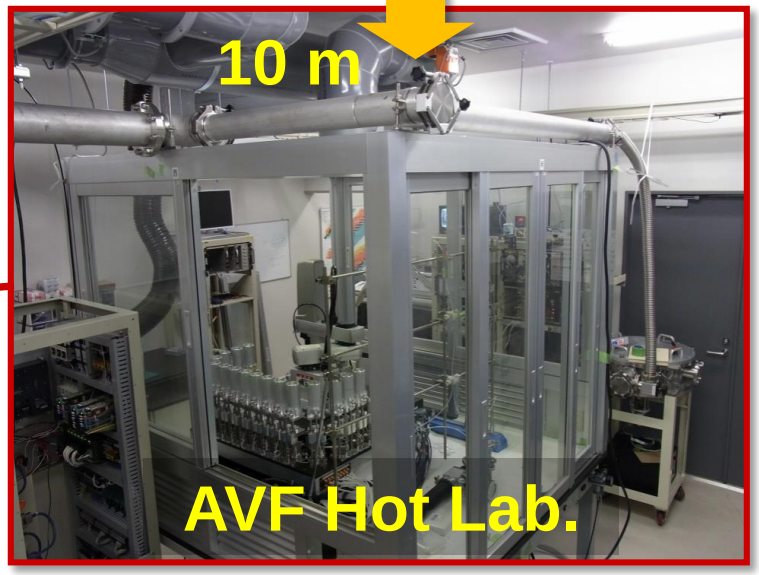
1. Target preparation and aqueous chemistry studies at AVF cyclotron
2. Target preparation and SHE production for chemistry studies at RIKEN Linear Accelerator (RILAC)
3. Summary and future perspectives

1. **Target preparation and aqueous chemistry studies at AVF cyclotron**

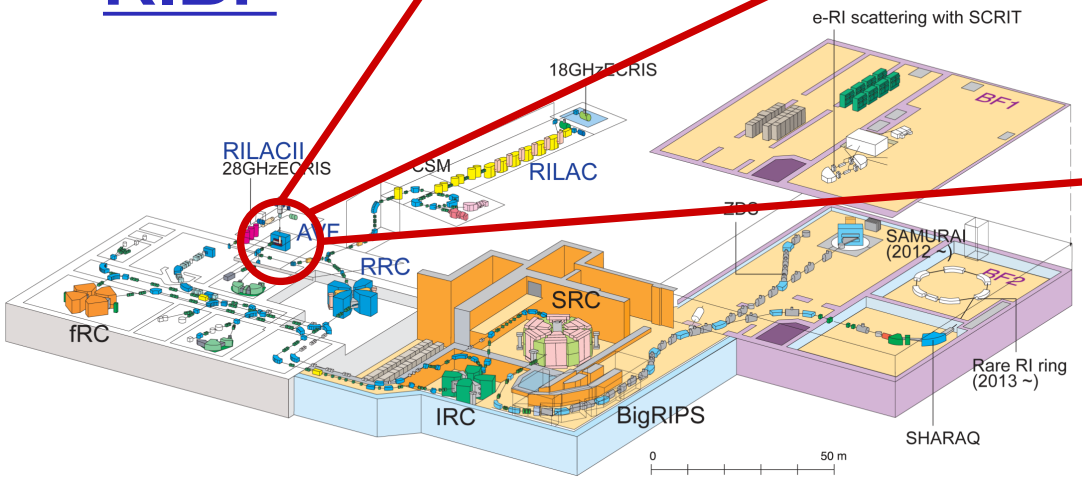
AVF cyclotron and gas-jet transport system







RIBF



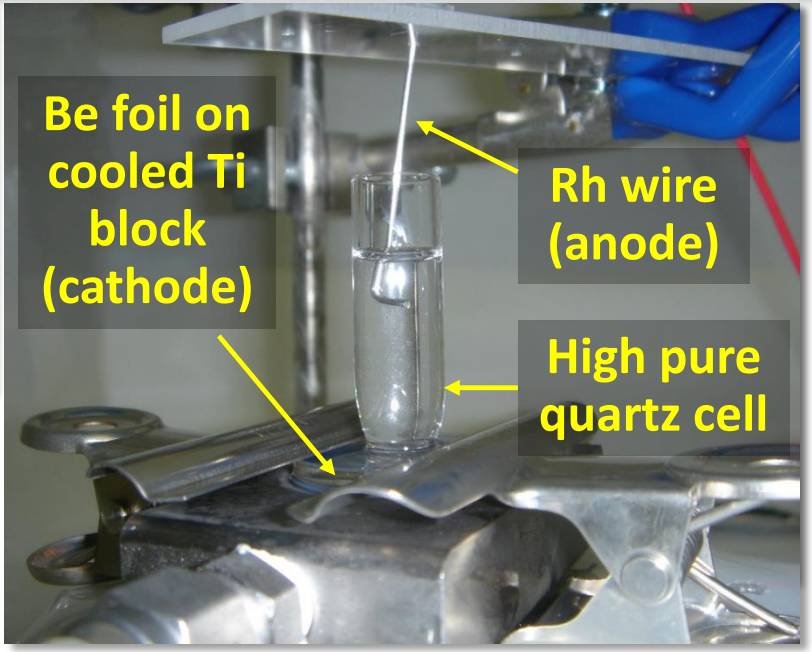
Preparation of a ^{248}Cm target for AVF

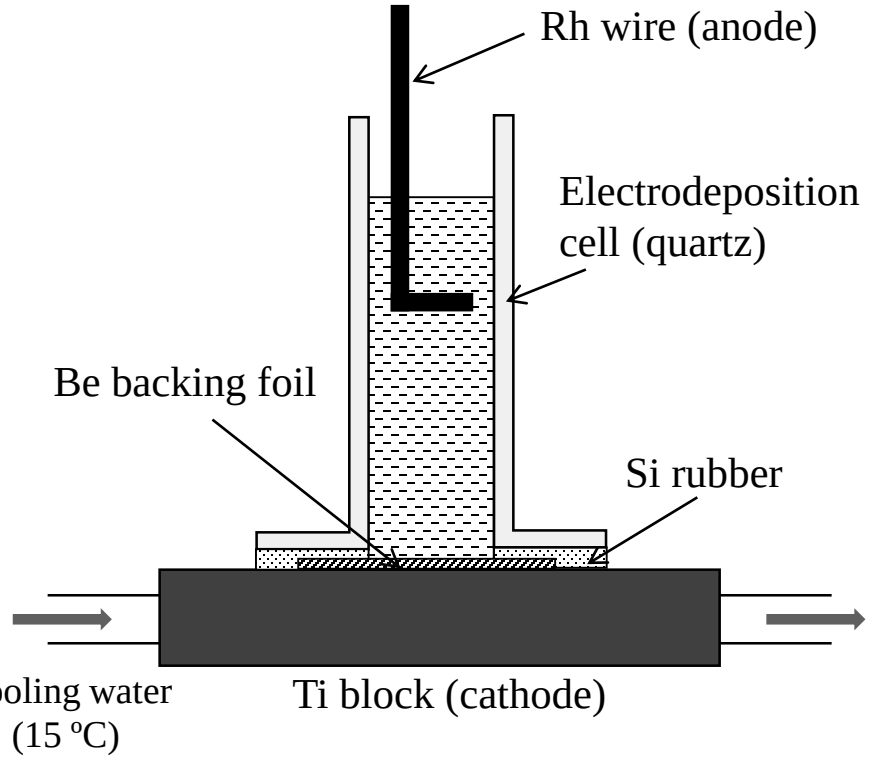
Electrodeposition conditions

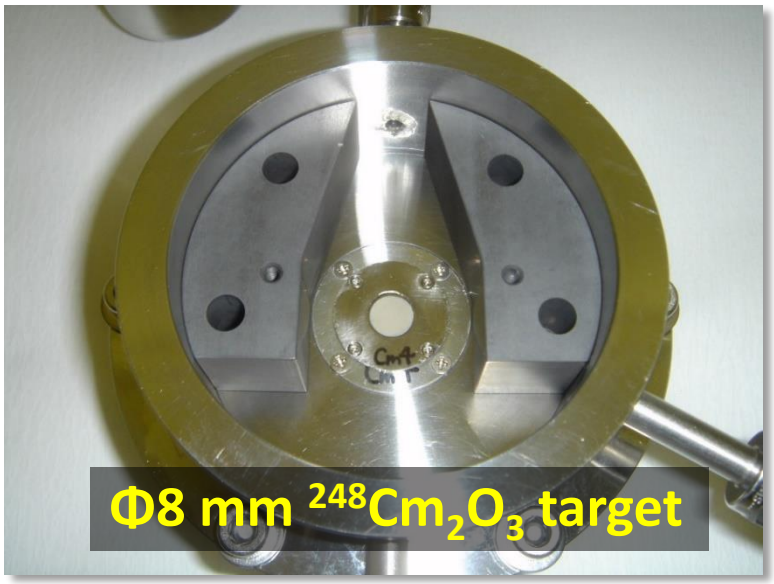
0.15 mg of ^{248}Cm in 10 µL 0.2 M HNO_3 + 2 mL 2-propanol

950 V x 4.7 mA/cm^2 for 20 min x 4

→ 850 µg/cm^2 $^{248}Cm_2O_3$ on 10-µm Be



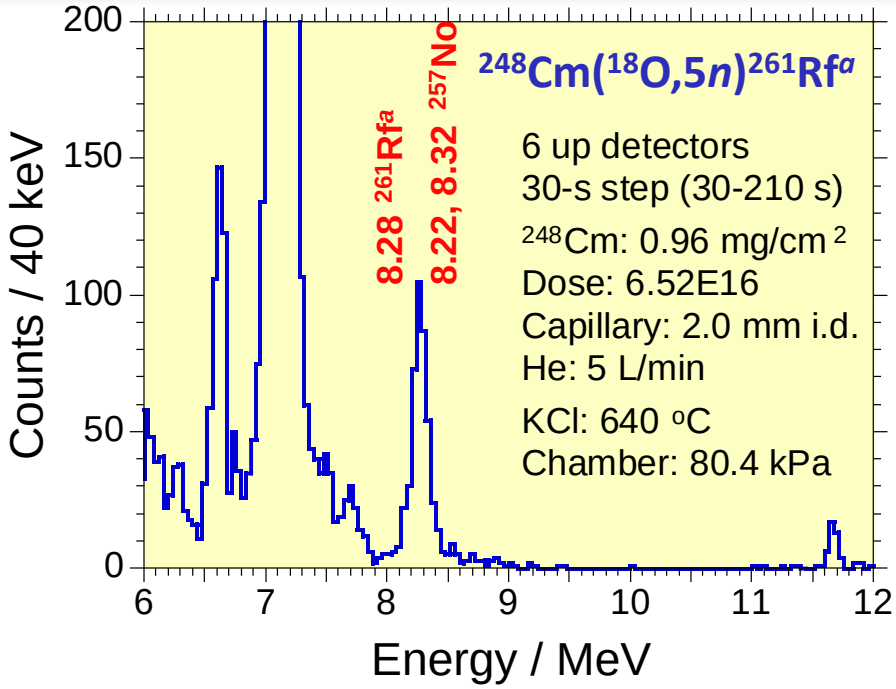




Production of SHEs using AVF + gas-jet

- Heavy-ion beam (~1 pμA):
  ^{12}C, ^{18}O, ^{19}F, ^{22}Ne, ^{26}Mg …
- High production yields without a recoil separator

Z	Reaction	Half-life
102	$^{248}Cm(^{12}C,5n)^{255}No$	3.52 min
104	$^{248}Cm(^{18}O,5n)^{261}Rf^{\alpha}$	68 s
105	$^{248}Cm(^{19}F,5n)^{262}Db$	34 s



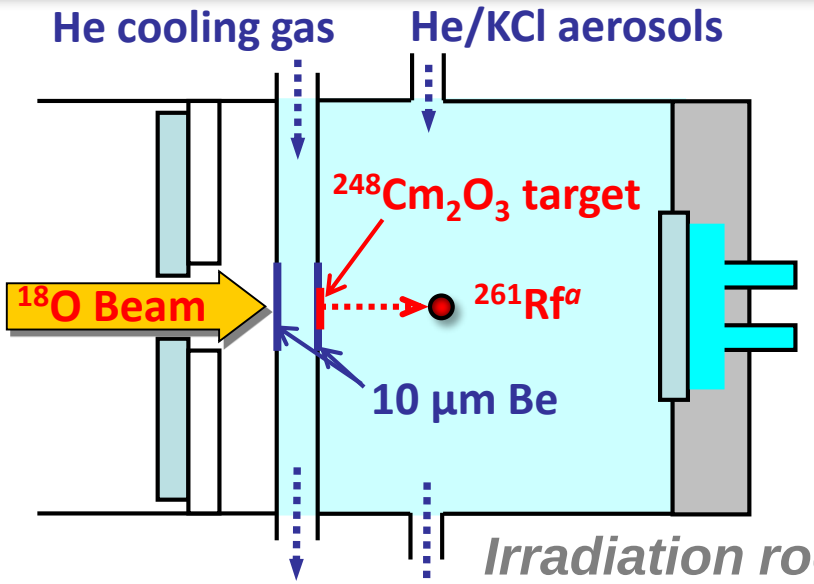
Exp.	Beam [MeV]	Beam [pμA]	Irrad. [h]	No. of α events	Gas-jet eff.** [%]	σ*** [nb]	Yield at AVF HL [atoms/min]
^{255}No	79.1	0.944	1.09	2689	46	900	**200**
$^{261}Rf^{\alpha}$	96.4	0.870	3.34	865*	63	17	**5**
^{262}Db	103.1	0.870			63	2.1	**0.6 (Calc.)**

* Including α particles of ^{257}No.

** Estimated from the gas-jet efficiencies of ^{169}Hf produced in $^{nat}Gd(^{18}O,xn)^{169}Hf$.

*** The target thicknesses were assumed to be 325, 569, and 569 μg/cm^2 for ^{255}No, $^{261}Rf^{\alpha}$, and ^{262}Db, respectively.

Aqueous chemistry of SHEs using AVF + gas-jet

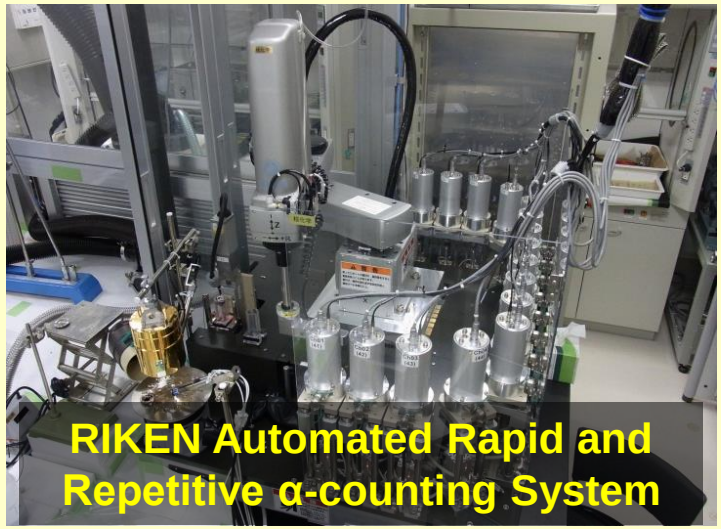


- Partition methods with single atoms
  e.g. Ion-exchange chromatography, solvent extraction, and reversed-phase extraction
  → **Distribution coefficient (K_d)**
  → **Complex formation and chemical species**

Aqueous chemistry apparatuses

- ARCA (liquid chromatography)
- CHIN (co-precipitation)
- AMBER (solid-liquid extraction by batch method)
- ISE (flow solvent extraction)

+


RIKEN Automated Rapid and Repetitive α-counting System

Aqueous chemistry of Rf and Db using AVF + gas-jet

Kanazawa Univ.

- Reversed-phase TTA extraction chromatography of Rf from HF/HNO_3 (with ARCA) Yokoyama et al., Radiochim. Acta **107**, 27 (2019).

  ⇒ K_d: Rf < Zr ≈ Hf

Osaka Univ.

- Solid-liquid extraction of Rf in Aliquat 336/HCl system (with AMBER*) **⇒ Rf > Zr > Hf** Yokokita et al., Dalton Trans. **45**, 18827 (2016).

  *Kasamatsu et al., Radiochim. Acta. **103**, 513 (2015).

- Hydroxide co-precipitation of Rf and No (with CHIN**)

  ⇒ Rf > Zr ≈ Hf Kasamatsu et al., to be submitted.

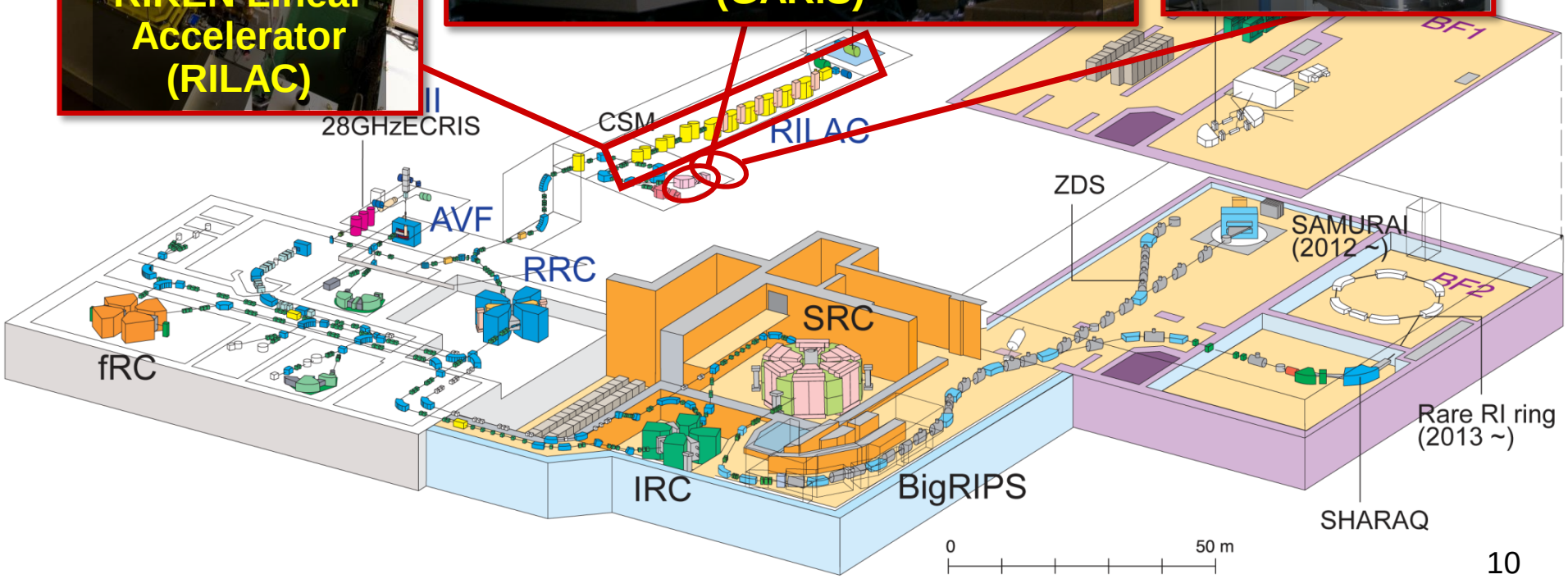
  Kasamatsu et al., J. Nucl. Radiochem. Sci. **14, 7 (2014).

Niigata Univ.

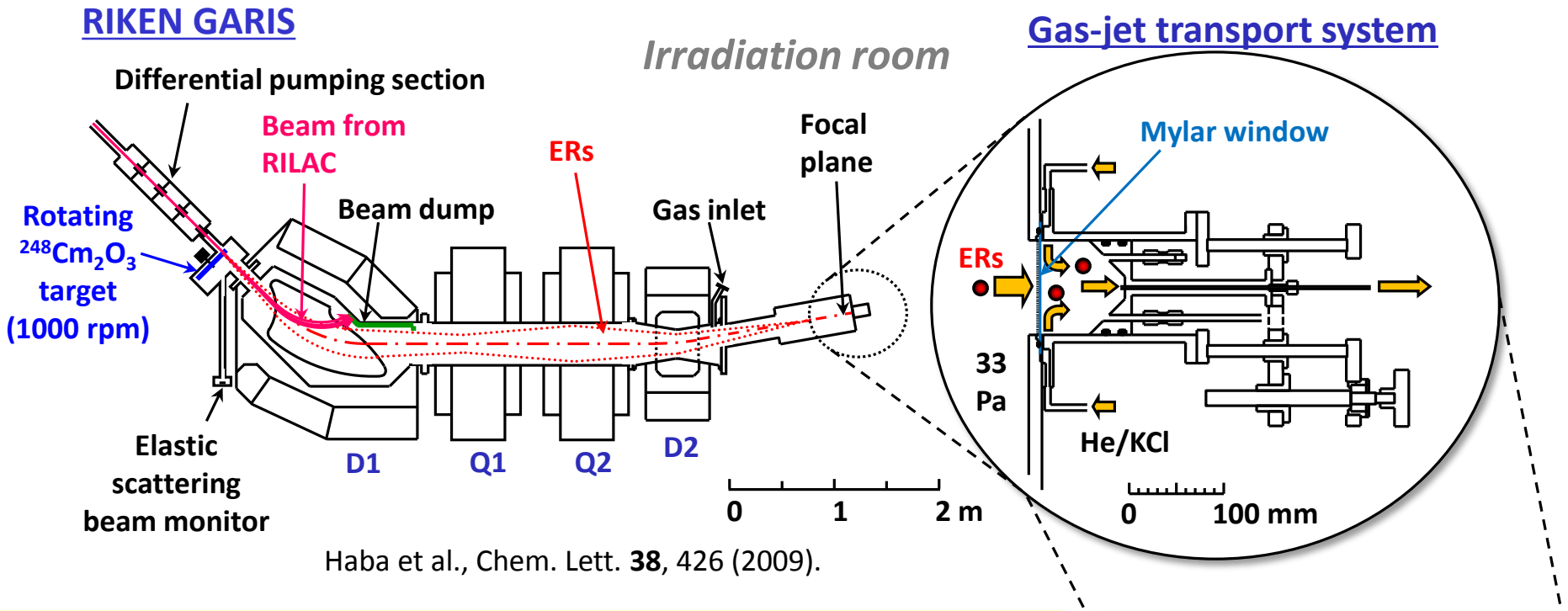
- Reversed-phase TBP extraction chromatography of Db from HF (with ARCA) **⇒ Db ≈ Nb < Ta** Murakami et al., to be submitted.

2. Target preparation and SHE production for chemistry studies at RILAC

RILAC and GARIS



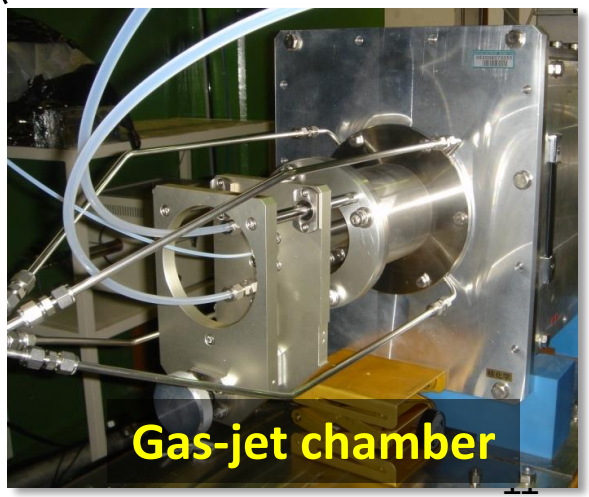
RIKEN GARIS gas-jet system for SHE chemistry



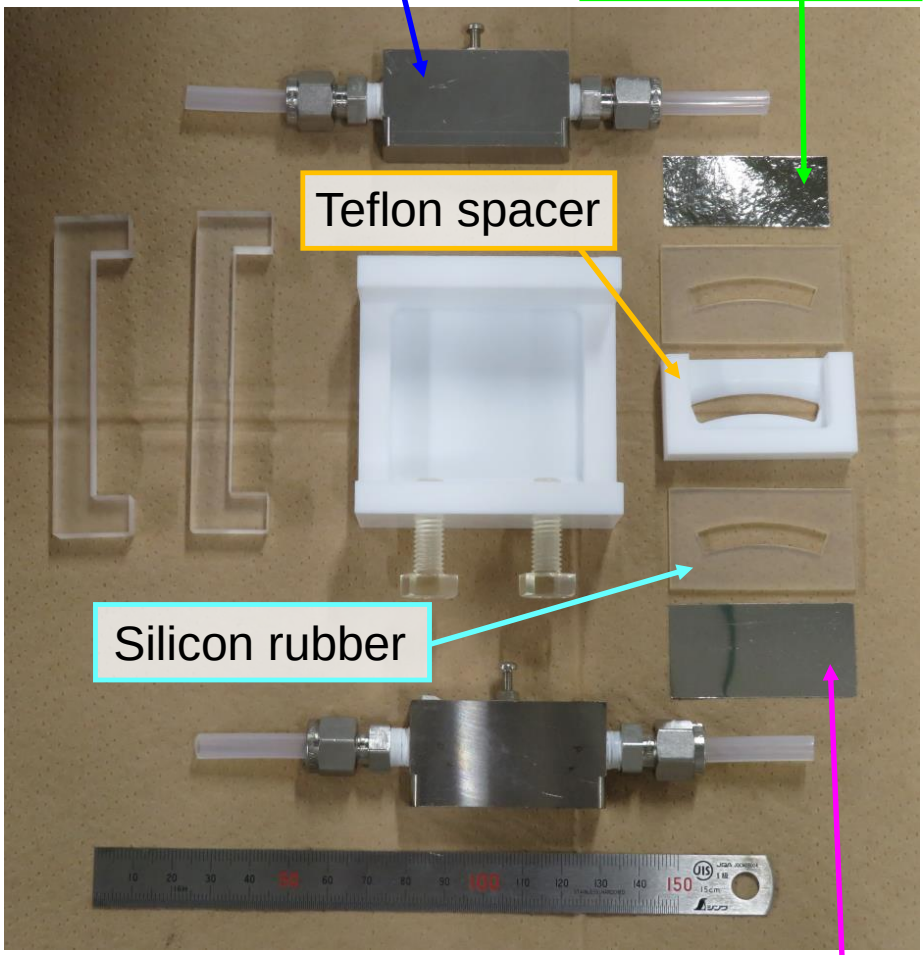
Haba et al., Chem. Lett. **38**, 426 (2009).

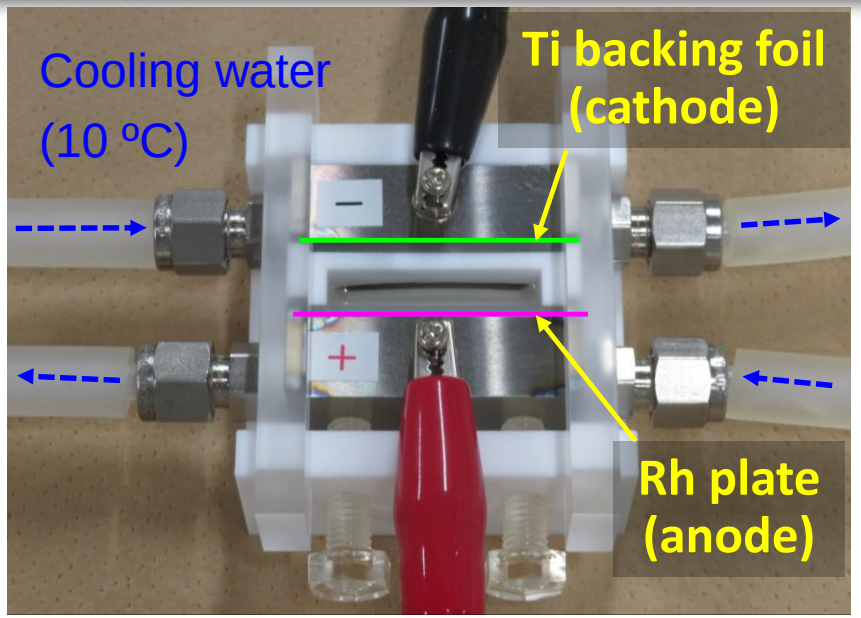
Advantages of gas-jet system coupled to GARIS

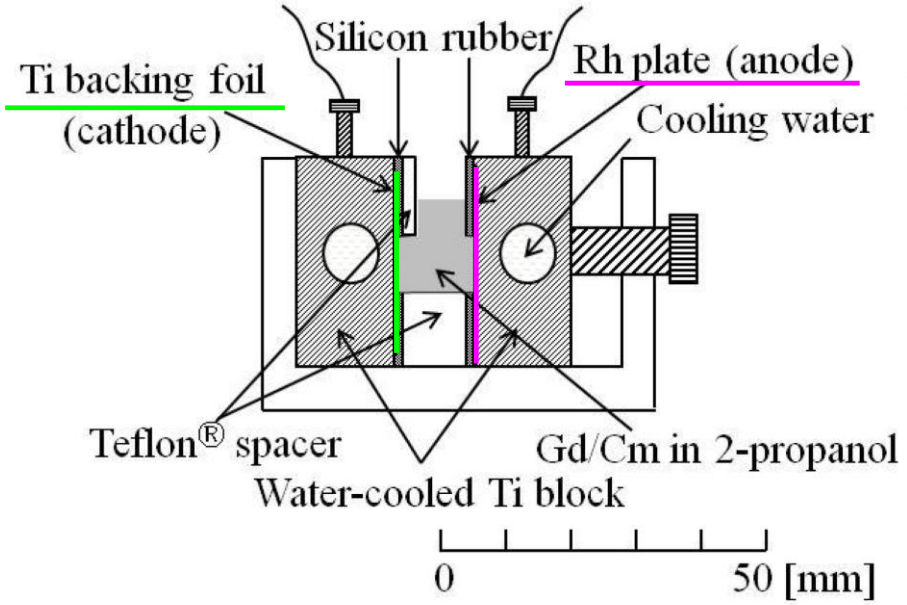
- Low background condition for α/SF spectrometry
- High gas-jet transport efficiency at intense beams
- New chemical reaction



Preparation of rotating ^{248}Cm targets

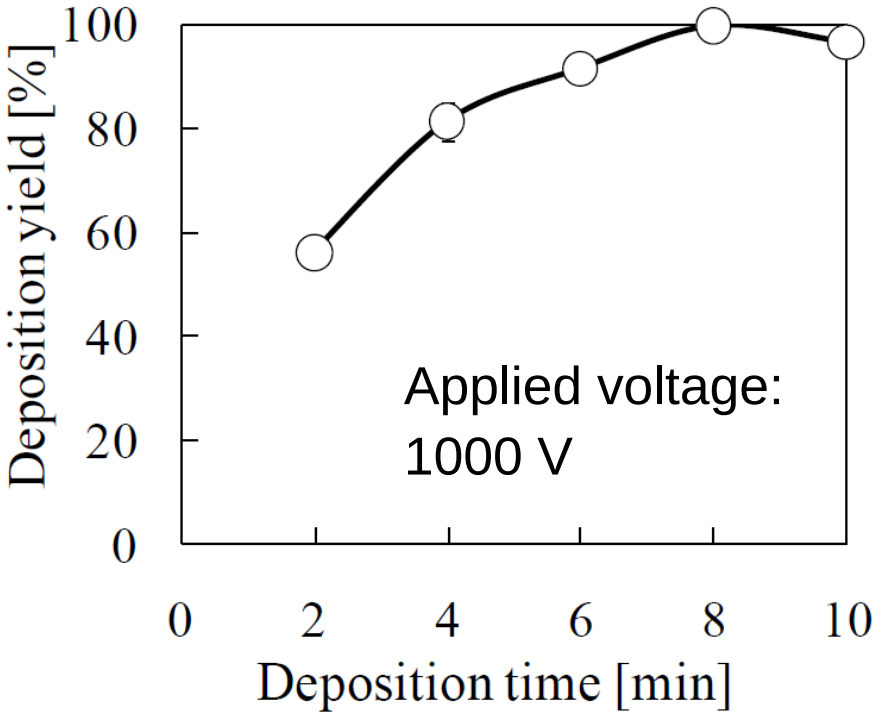


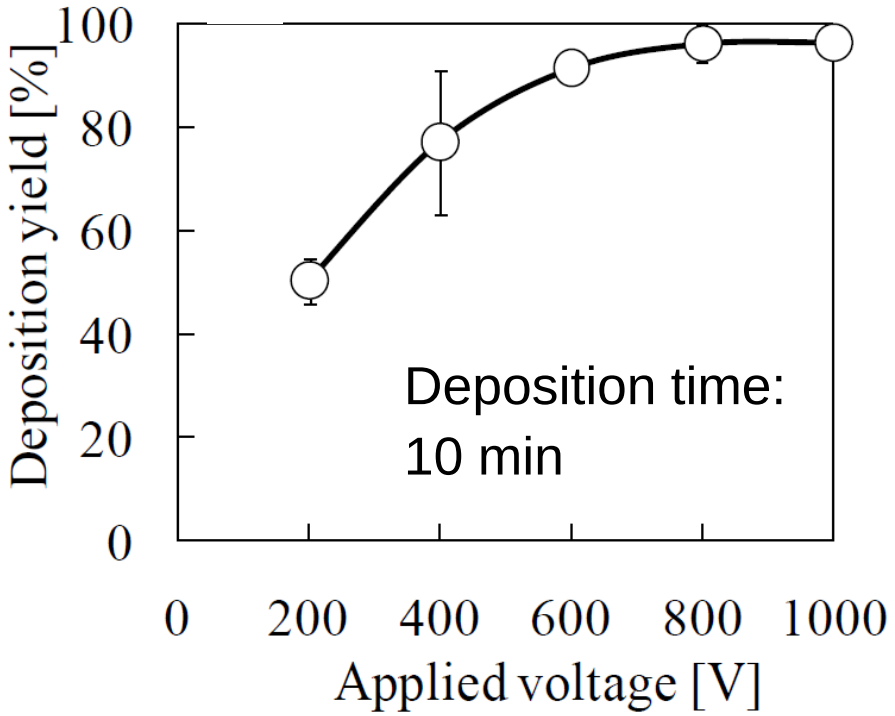




Optimization of electrodeposition conditions

20 µL of 0.2 M HNO_3 containing 650 µg of ^{nat}Gd + ^{88}Y tracer was mixed with 5.5 mL of 2-propanol.





Kudou et al., RIKEN Accel. Prog. Rep. **42**, 265 (2009).

$^{nat}Gd_2O_3$ target thickness: 350 ± 10 µg/cm^2 (10 min, 1000 V)

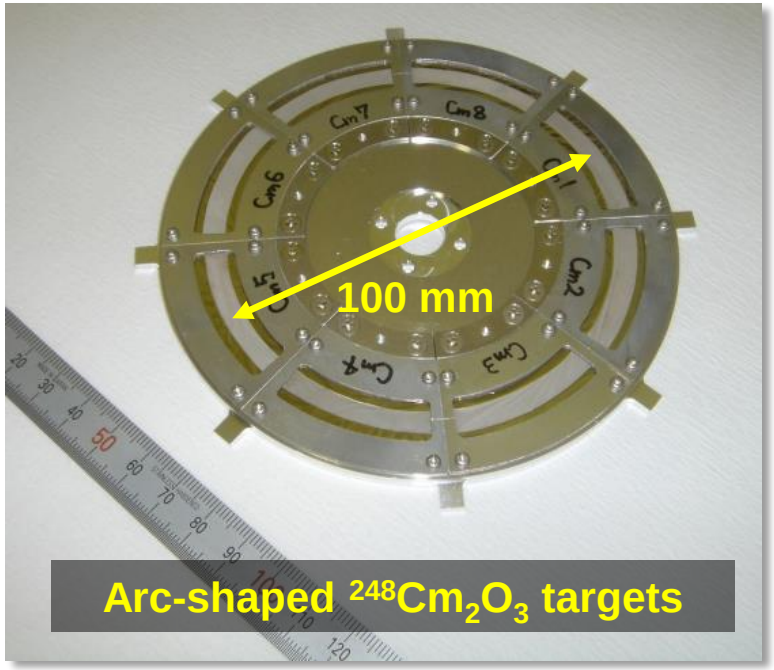
→ **Deposition time: 10 min, applied voltage: 1000 V for ^{248}Cm**

→ **Deposition yield: ~100%**

Electrodeposition of ^{248}Cm

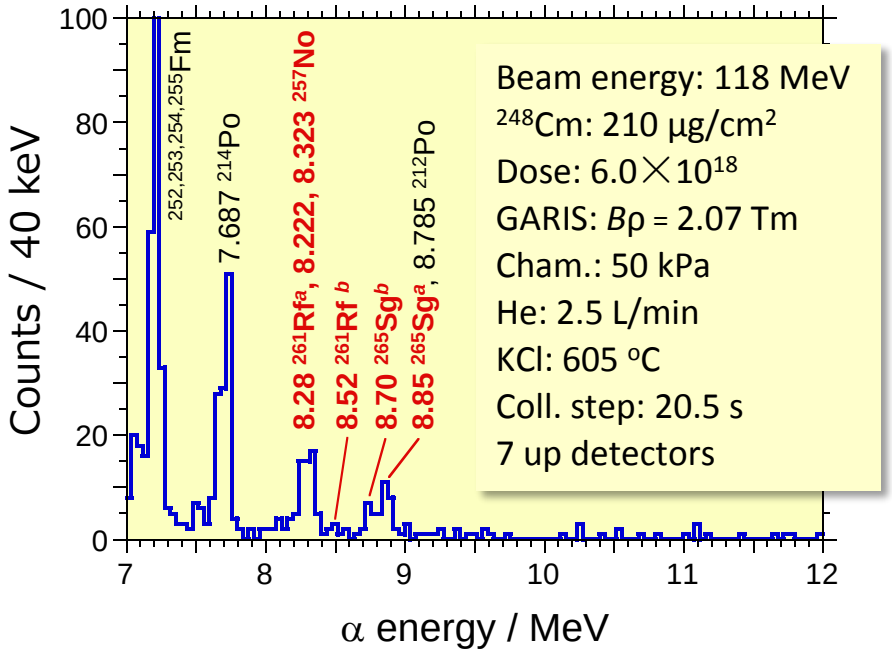
Electrodeposition conditions

Solution	0.53 mg of ^{248}Cm in 20 µL 0.2 M HNO_3 + 5.5 mL 2-propanol
Applied voltage	1000 V
Current density	8–11 mA/cm^2
Deposition time	10 min
Backing material	2-µm Ti
Deposition area	2.04 cm^2
Target thickness*	280 ± 10 µg/cm^2 $^{248}Cm_2O_3$
Deposition yield	98 ± 2%

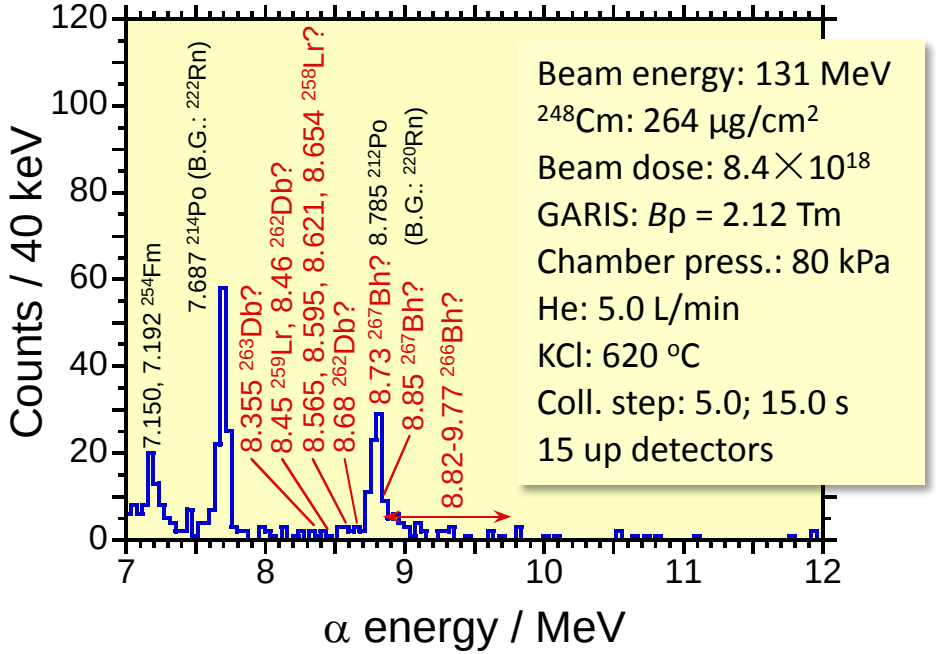


Production of $^{265}Sg^{a,b}$ and ^{266}Bh using GARIS gas-jet

$^{248}Cm(^{22}Ne,5n)^{265}Sg^{a,b}$



$^{248}Cm(^{23}Na,5n)^{266}Bh$



Nuclide	$T_{1/2}$* [s]	σ* [pb]	Target [μg/cm²]	Beam [pμA]	GARIS eff. [%]	Grid [%]	Gas-jet eff. [s]	Yield at Chem. Lab. [atoms/d]	
$^{265}Sg^{a}$	8.5	180	300	4	13	78	50	**11**	**25**
$^{265}Sg^{b}$	14.4	200	300	4	13	78	50	**14**	
^{266}Bh	10.0	57	300	4	15	78	50	**4**	

*Haba et al., Phys. Rev. C **85**, 024611 (2012).; EPJ Web of conferences **131**, 07006 (2016).

Assumption: gas-jet transport time: 2.7 s

Towards aqueous chemistry of Sg and the heavier SHEs

Pioneering cation-exchange studies of Sg in HNO_3/HF and HNO_3

Schädel et al., Radiochim. Acta **77**, 149 (1997).; Radiochim. Acta **83**, 163 (1998).

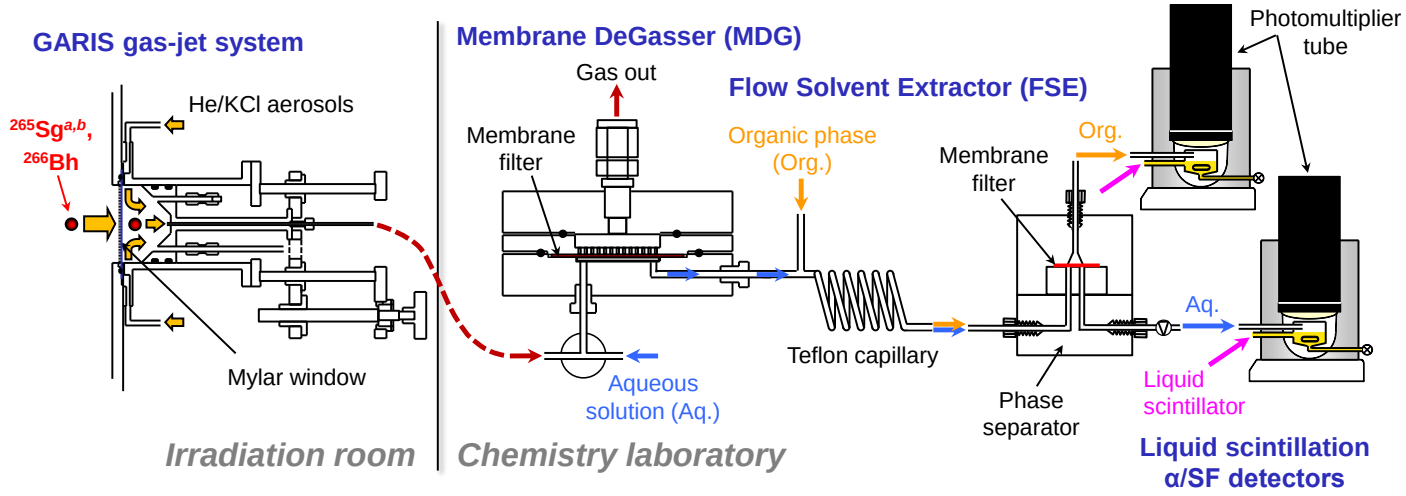
- Batch-wise column chromatography apparatus (ARCA) with Si detectors

  4 α-α correlations of ^{261}Rf → ^{257}No →

- No aqueous chemistry studies of Sg and the heavier elements have been reported since 1998.

Development of a continuous rapid solvent extraction apparatus

RIKEN–Niigata Univ.–JAEA–Osaka Univ.–Tohoku Univ.–IMP–Univ. Oslo collaboration



Continuous dissolution, solvent extraction, and α/SF detection with LS

→ **Event rates of ^{265}Sg^{a,b} and ^{266}Bh can be increased by 50-100 times**

3. Summary and future perspectives

Summary

(1) AVF + gas-jet

- Aqueous chemistry studies of Rf and Db are ongoing using the stational $^{248}Cm_2O_3$ target and gas-jet transport system.

(2) RILAC + GARIS + gas-jet

- A rotating $^{248}Cm_2O_3$ target for GARIS was prepared by a molecular plating method.
- We successfully produced $^{265}Sg^{a,b}$ and ^{266}Bh and extracted them to the chemistry laboratory using the GARIS gas-jet system.
- A continuous rapid solvent extraction apparatus is under development for the future aqueous chemistry of Sg and Bh.

Future perspectives

(1) Increase of production yields of SHEs

Upgrade of RILAC: 28 GHz ECR & SC-QWR

- **Beam intensity of RILAC: X 5**
- **Thickness of target: X 1.5**
- **GARIS III: X 1.5**

} **Production yields of SHEs: X10**

⇒ Precision chemical data based on enough counting statistics

(2) Development of target preparation techniques

- Development of durable targets for long-term and highly intense beam irradiations
- Preparation of other actinide targets (e.g. ^{238}U, ^{243}Am, ^{244}Pu) for Cn, Nh, and Fl chemistry

(3) Development of a new aqueous chemistry apparatus and experimental methods

- Development of a continuous rapid extraction apparatus

Collaborators

RIKEN	**H. Haba, T. Yokokita, N. Sato, Y. Wang, K. Morimoto, D. Kaji, T. Tanaka, K. Morita, D. Mori, A. Yoneda, M. Osanai**
JAEA	**M. Asai, Y. Nagame, K. Nishio, T. K. Sato, K. Tsukada,**
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Tohoku Univ.	**H. Kikunaga**
Niigata Univ.	**S. Goto, H. Kudo**
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Thank you for your kind attention.