SHE researches at RIKEN

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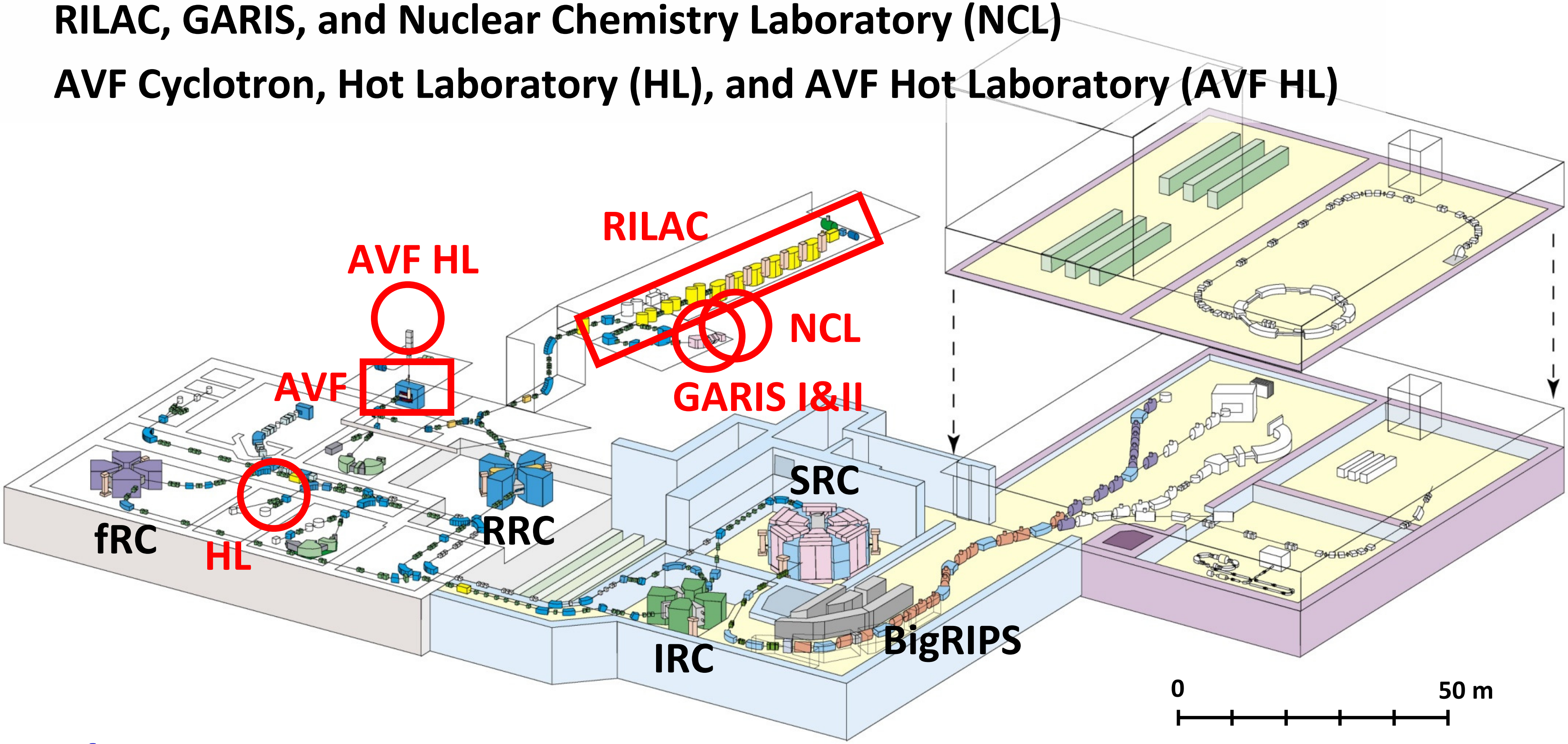
CONTENTS

1. Introduction

RIKEN facilities for SHE chemistry

RILAC, GARIS, and Nuclear Chemistry Laboratory (NCL)

AVF Cyclotron, Hot Laboratory (HL), and AVF Hot Laboratory (AVF HL)



In this presentation

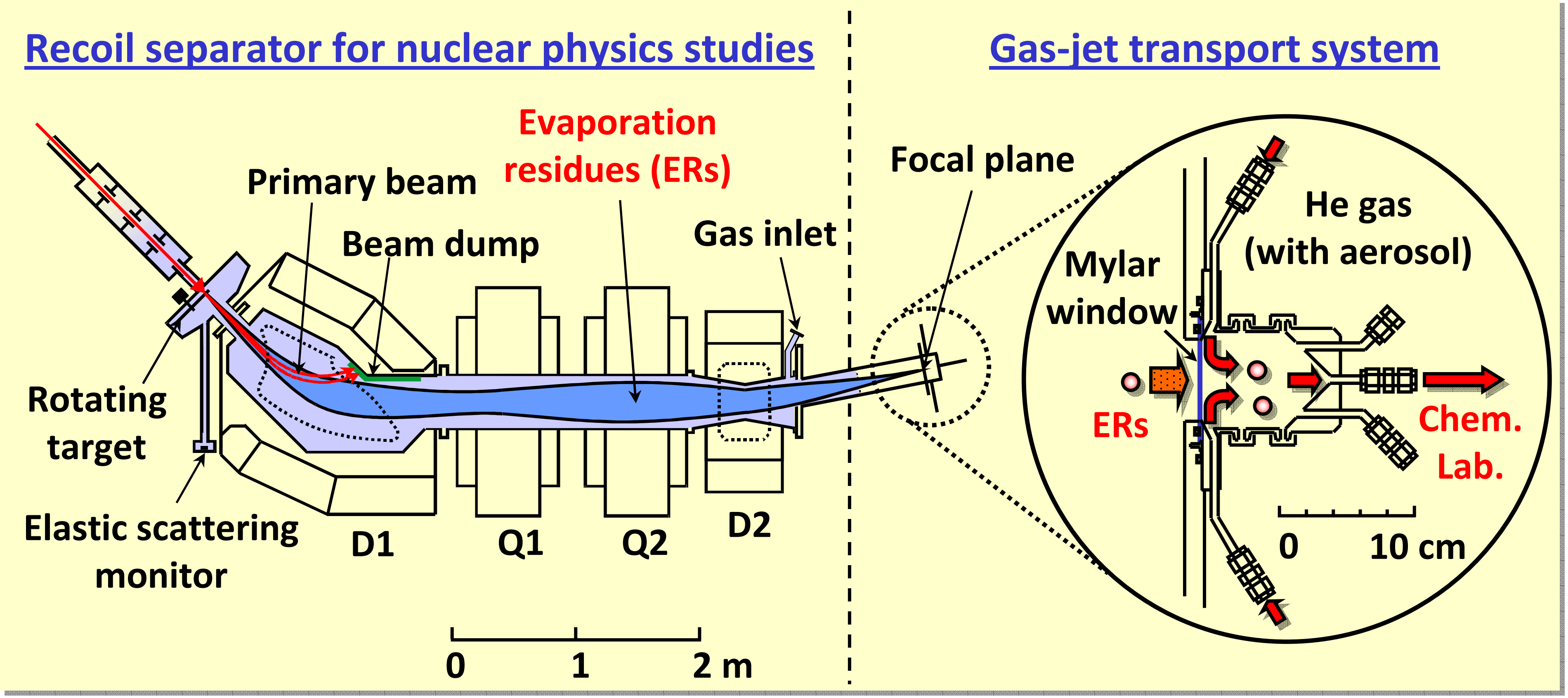
- Present status of RIKEN facilities for SHE researches: GARIS@RILAC, AVF, and HL
- Results of the ^{248}Cm(^{22}Ne,5*n*)^{265}Sg experiment at GARIS@RILAC
- Chemistry programs planned at GARIS@RILAC and AVF

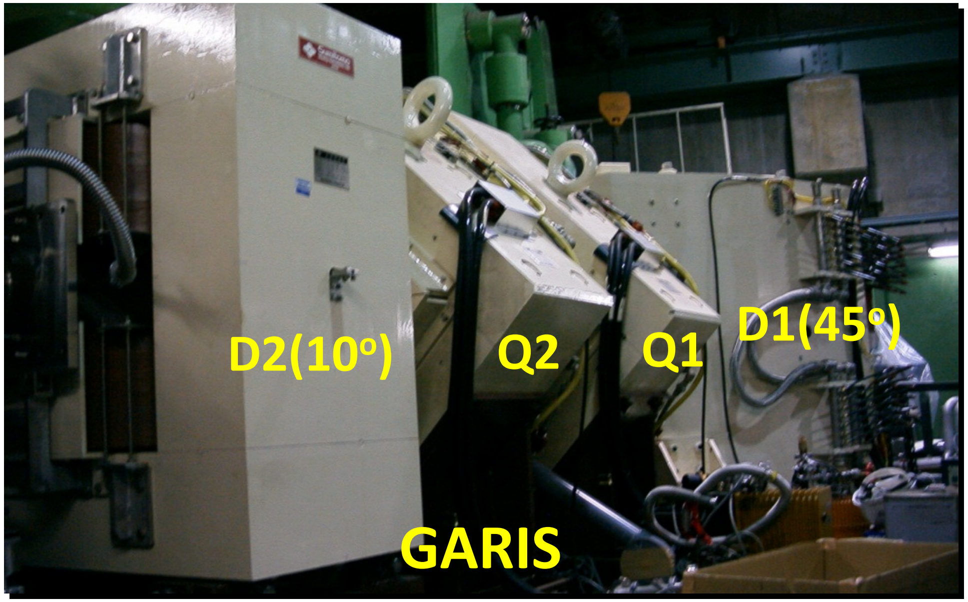
2. Present status of RIKEN facilities for SHE chemistry

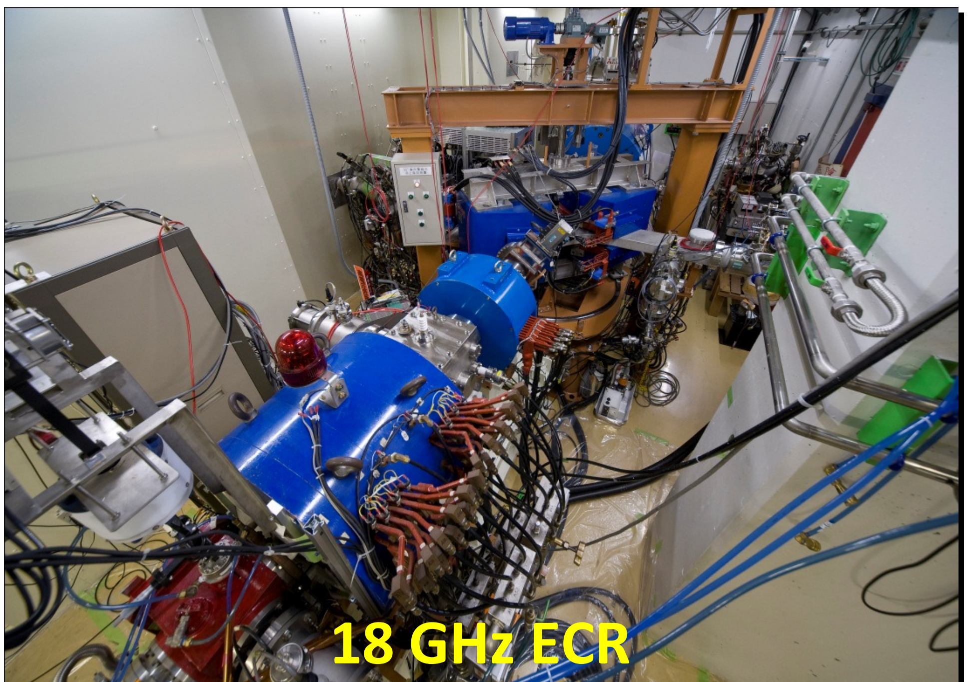
2.1. GARIS@RILAC

GARIS as a pre-separator for SHE chemistry

- Chemical and physical experiments under low background condition
- Stable and high gas-jet transport efficiency
- New chemical systems that were not accessible before




D2(10^{o})
Q2
Q1
D1(45^{o})
GARIS


18 GHz ECR


≦6.0 MeV/nucl.
RILAC

- **Commissioning of GARIS as a pre-separator for SHE chemistry**

^{169}Tm(^{40}Ar,3*n*)^{206}Fr ($Z = 87$)
^{197}Au(^{18}O,6*n*)^{209}Fr ($Z = 87$)
^{197}Au(^{22}Ne,5*n*)^{214}Ac ($Z = 89$)
^{208}Pb(^{40}Ar,3*n*)^{245}Fm ($Z = 100$)
^{238}U(^{22}Ne,5*n*)^{255}No ($Z = 102$)

→ Developments of a gas-jet transport system coupled to GARIS
Magnetic setting of GARIS
Gas-jet parameters

- **Production of ^{261a}Rf and its homologues ^{169}Hf and ^{85}Zr**

7th Workshop on the Chemistry of the Heaviest Elements, 13 Oct., 2009, Mainz

^{248}Cm(^{18}O,5*n*)^{261a}Rf ($Z = 104$)
^{nat}Gd(^{18}O,*xn*)^{169}Hf ($Z = 72$)
^{nat}Ge(^{18}O,*xn*)^{85}Zr ($Z = 40$)

→ Simultaneous chemical experiments with pre-separated ^{261a}Rf, ^{169}Hf, and ^{85}Zr

This work

- **Production of ^{265}Sg and its homologues ^{173}W and ^{90}Mo**

^{248}Cm(^{22}Ne,5*n*)^{265}Sg
^{nat}Gd(^{22}Ne,*xn*)^{173}W
^{nat}Ge(^{22}Ne,*xn*)^{90}Mo

→ Simultaneous chemical experiments with pre-separated ^{265}Sg, ^{173}W, and ^{90}Mo

- **Production and decay properties of ^{265}Sg**

Decay properties of ^{265}Sg

Düllmann and Türler: PRC **77**, 064320 (2008).

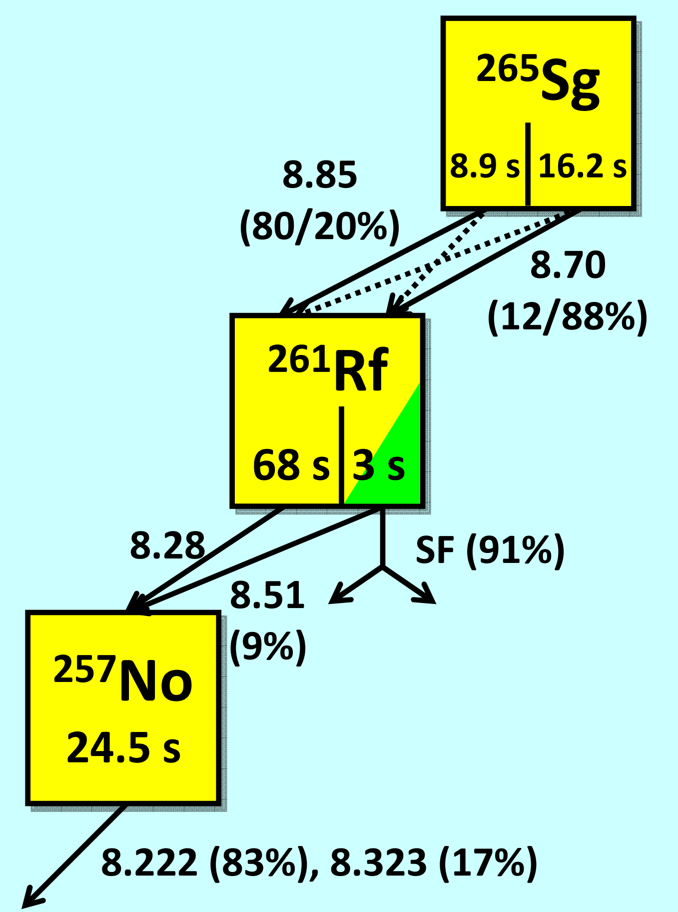
- **^{248}Cm(^{22}Ne,5*n*)^{265}Sg: Reanalysis → 36 events**
- ^{208}Pb(^{70}Zn,*n*)^{277}Cn: SHIP/GARIS + FPD → 4 events
- ^{248}Cm(^{26}Mg,5*n*)^{269}Hs: Gas-jet + COLD/CALLISTO/COMPACT → 20 events

References for ^{248}Cm(^{22}Ne,5*n*)^{265}Sg	Method	E_{beam}	No of. events	σ [pb]
Lazarev *et al.* (1994)	DGFRS	116	4$^{a)}$	80
		121	6$^{a)}$	320
Gregorich *et al.* (1996)	MG	121	3	
Türler *et al.* (1998,1999)	OLGA	121/123	19	206
Türler *et al.* (1998)	PSI Tape	119	1$^{b)}$	78
Dressler *et al.* (2000)	PSI Tape	116	1$^{b)}$	73
Hübener *et al.* (2001)	HITGAS	119	2$^{b)}$	92

a) τ(^{265}Sg) was not measured.

b) Only sensitive to α-SF chains

Decay pattern in 2008



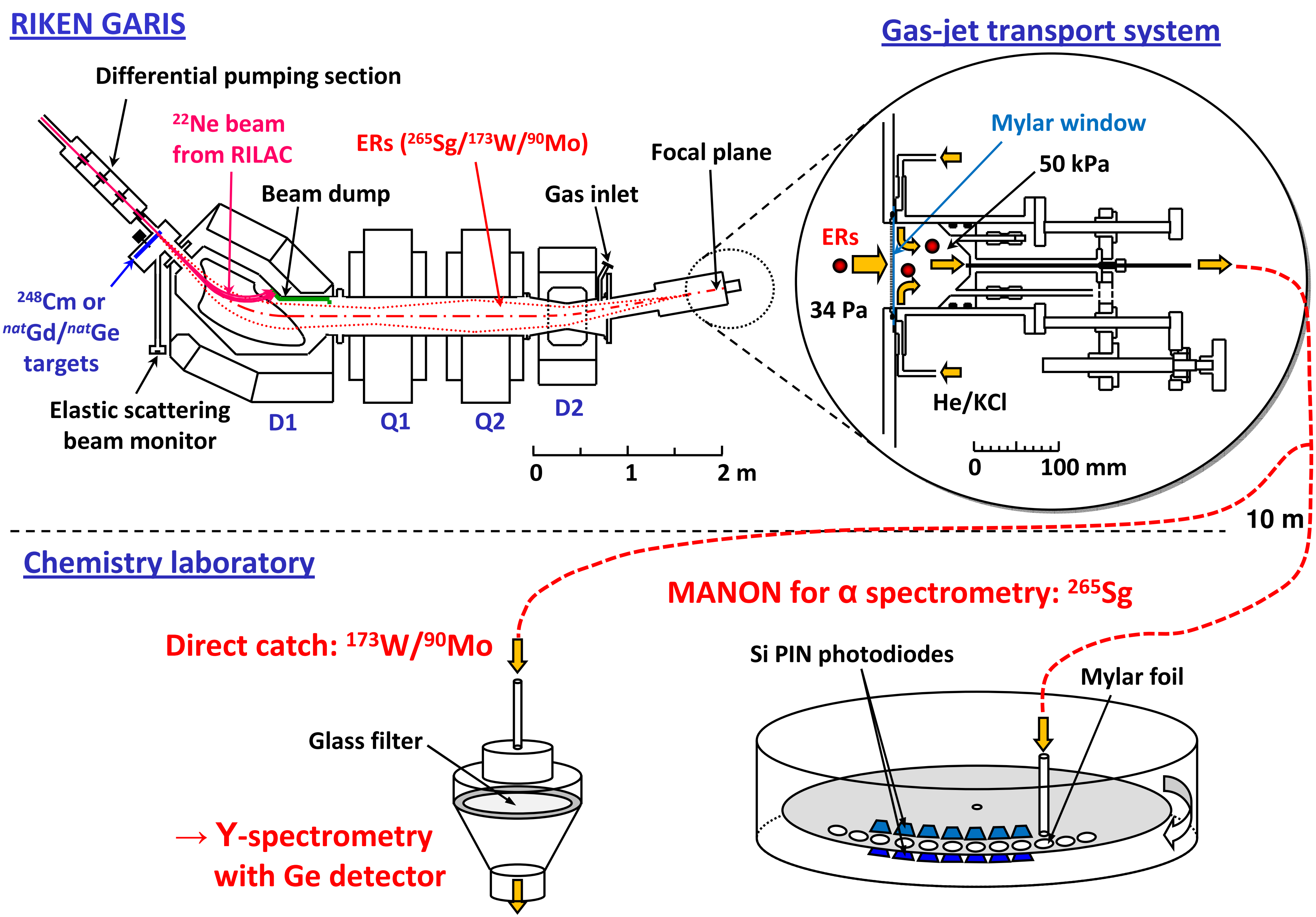
For future chemical studies of ^{265}Sg

Decay properties (E_{α} and $T_{1/2}$) ?

Cross section ?

→ Systematic studies on ^{248}Cm(^{22}Ne,5*n*)^{265}Sg

Experimental



Experimental conditions

Nuclide	$^{265a/b}$Sg (Z=106)	^{173}W (Z=74)	^{90}Mo (Z=42)
Half-life	8.9/16.2 s[a)]	7.6 min	5.67 h
Reaction	^{248}Cm(^{22}Ne,5n)	^{nat}Gd(^{22}Ne,xn)	^{nat}Ge(^{22}Ne,xn)
Cross section	0.2–0.3 nb[a)]	157 mb[b)]	17.6 mb[b)]
Beam energy (MeV)	118	←	←
Beam intensity (pμA)	4	←	0.25
Target (μg/cm^2) on 2-μm Ti	230/280 (Cm_2O_3)	340 (Gd_2O_3)	290 (Ge)
Recoil energy (MeV)	9.4	14.1	25.8
Magnetic rigidity (Tm)	1.73–2.16	1.50–1.93	0.985
GARIS He (Pa)	34	←	←
Mylar window (μm)	0.65	←	←
Honeycomb grid (%)	84	←	←
Gas-jet He (kPa)	50	←	68
Chamber depth (mm)	40	100	100
He flow rate (L/min)	2.0/2.5	2.0	4.0
KCl generator (^{o}C)	600/605	620	620
Aerosol collection (s)	20	120	300
α- or Y-spectrometry	MANON	Ge detector	Ge detector

a) Düllmann and Türler: PRC **77**, 064320 (2008).

b) Calculated with PACE4

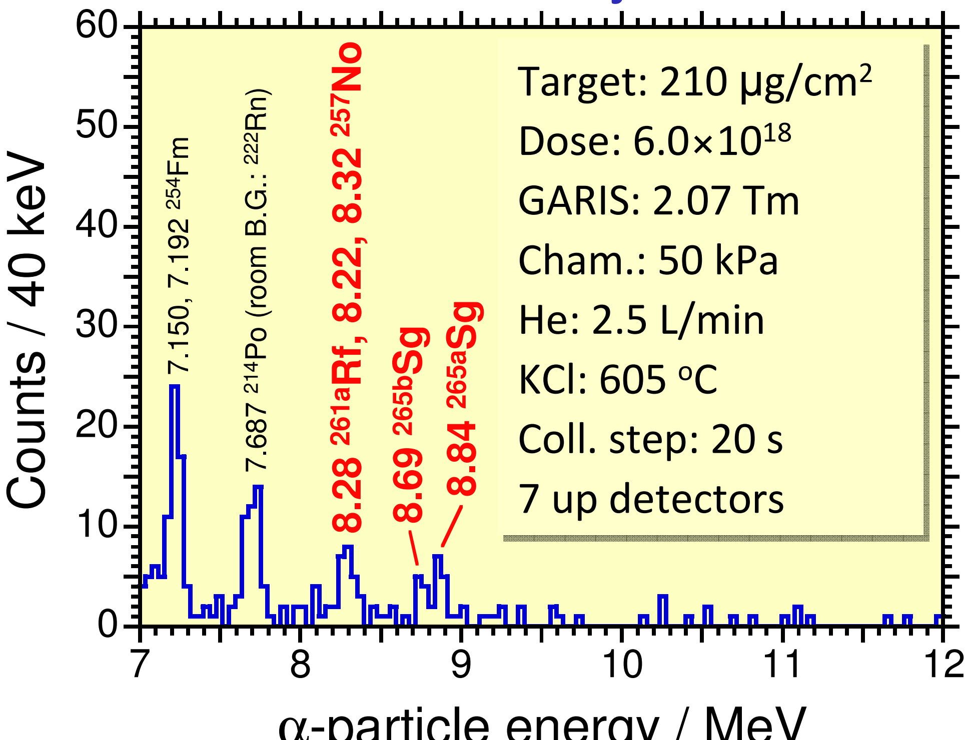
Results and discussion

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

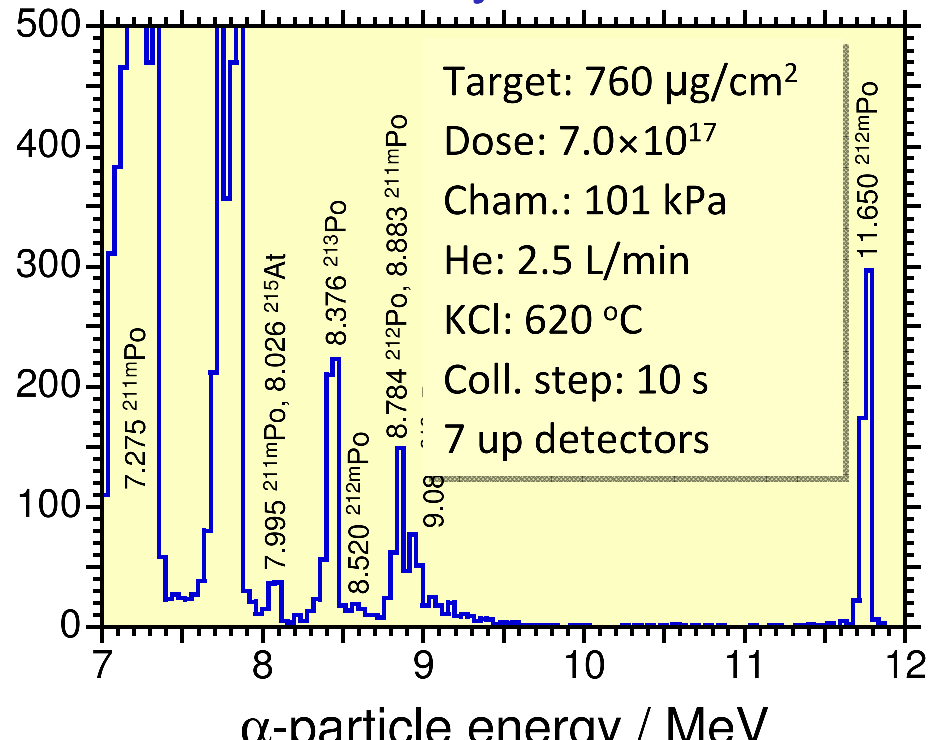
Beam time	Magnetic rigidity (Tm)	Beam dose (10^{18})
Sep. 30–Oct. 6, 2008	1.73	2.07
	1.94	1.91
	2.16	1.57
	2.04	0.639
Sep. 19–23, 2009; July 16–20, 2010	2.07	11.2

α spectra of MANON

RILAC + GARIS + Gas-jet + MANON



AVF + Gas-jet + MANON



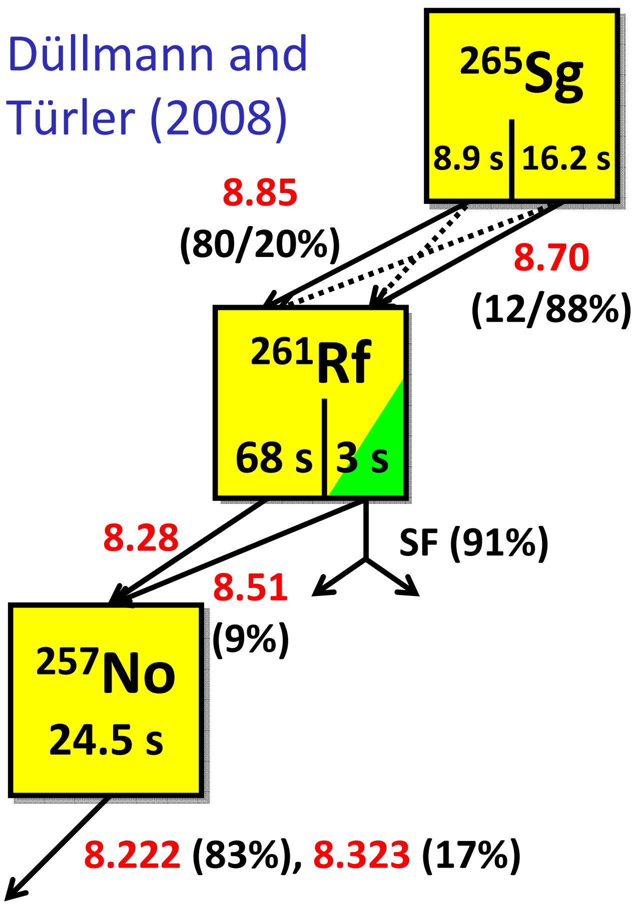
Search for α-α/α-SF correlations

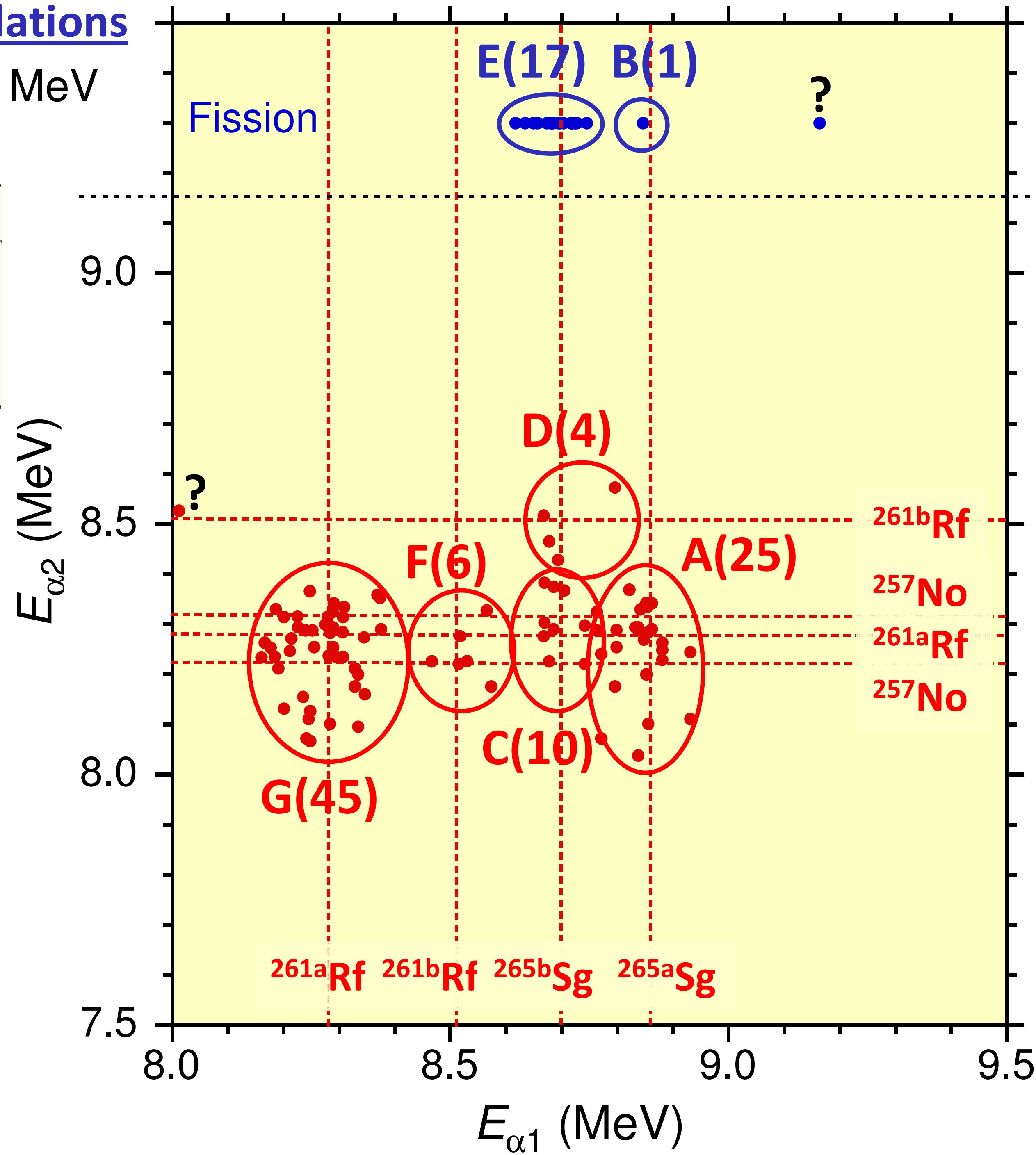
E_α = 8.0–9.5 MeV; $E_{SF} \geq 30$ MeV

ΔT = 234 s

	Observed	Random
α-α	**91**	< 5.4
α-α-α	**18**	< 0.13
α-SF	**19**	< 2.1

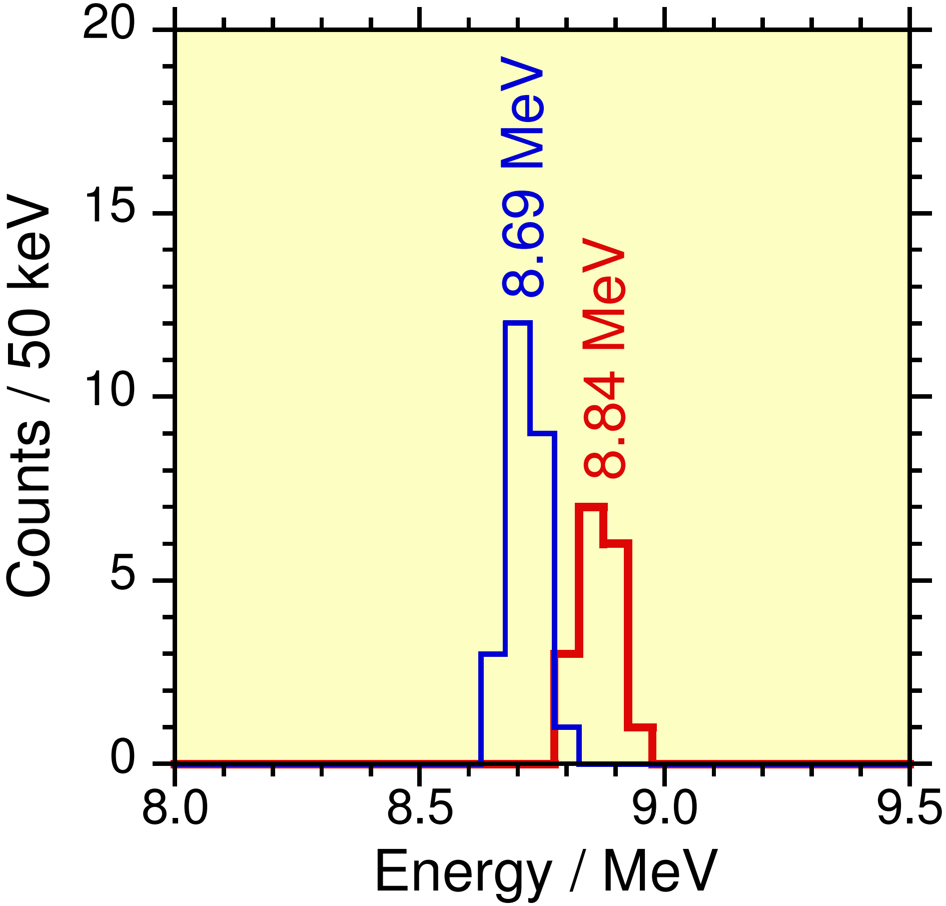
Düllmann and Türler (2008)



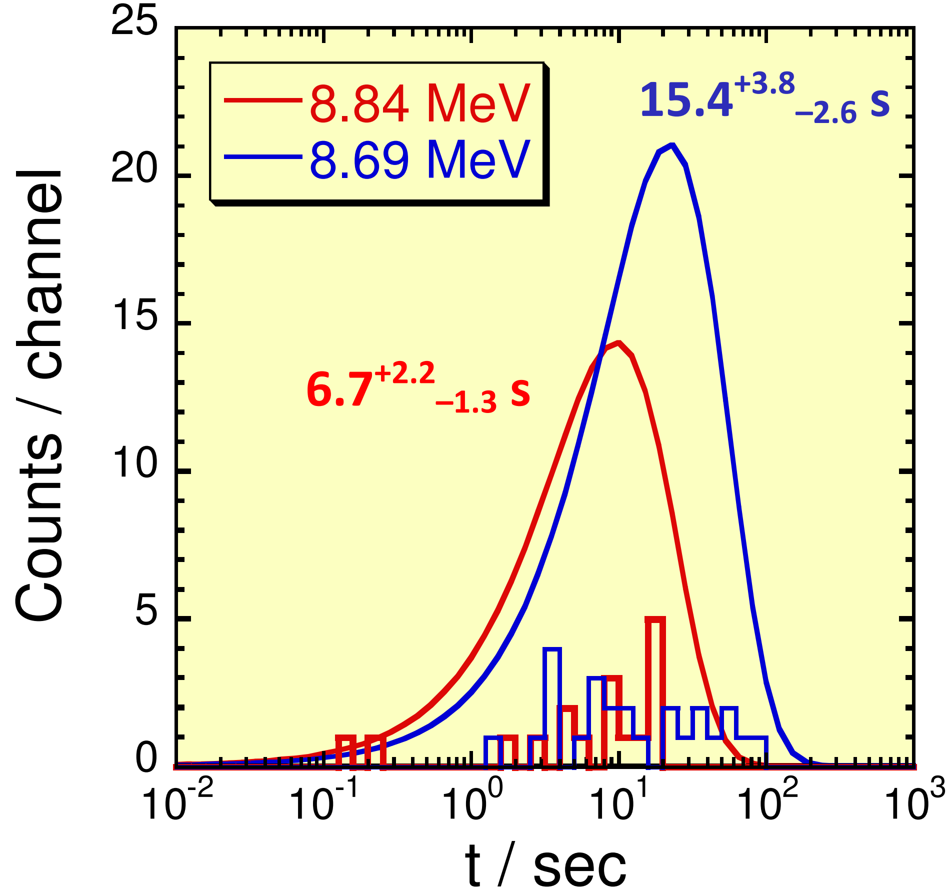


α energy and half-life of $^{265a,b}Sg$

α spectrum of $^{265a,b}Sg$



Decay time spectrum of $^{265a,b}Sg$

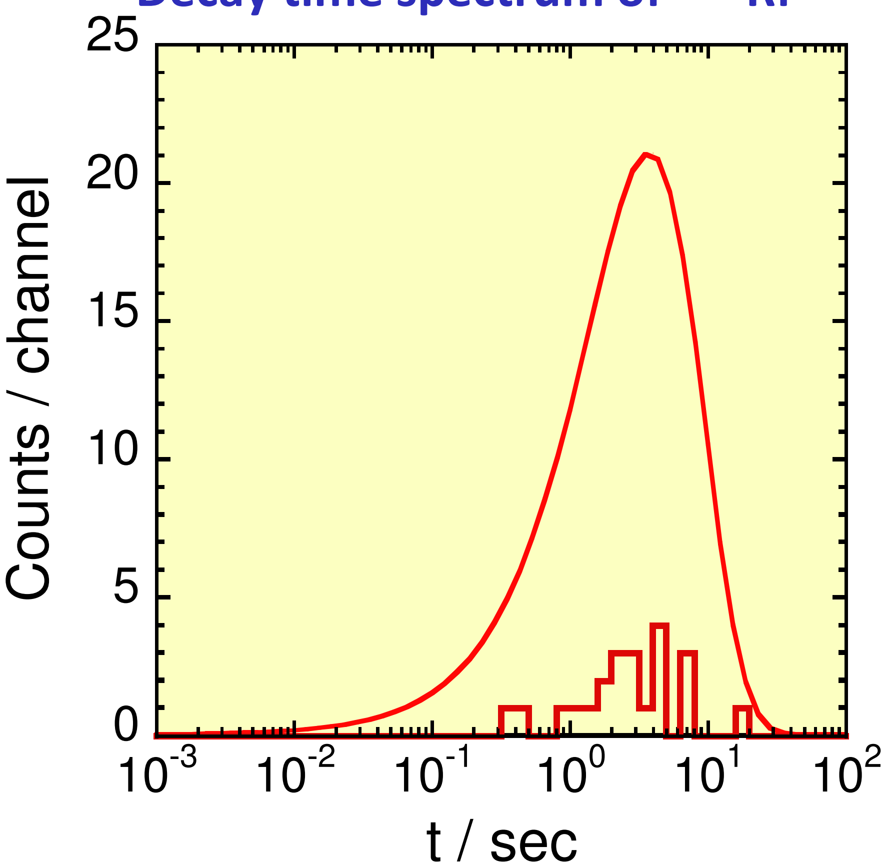


	This work			Düllmann and Türler (2008)		
	n	E_α [MeV]	$T_{1/2}$ [s]	n	E_α [MeV]	$T_{1/2}$ [s]
^{265a}Sg	**17**	**8.840.05**	**$6.7^{+2.2}_{-1.3}$**	20	8.85	$8.9^{+2.7}_{-1.3}$
^{265b}Sg	**25**	**8.690.05**	**$15.4^{+3.8}_{-2.6}$**	24	8.70	$16.2^{+4.7}_{-1.9}$

α energy and half-life of ^{261a,b}Rf and ^{257}No

	This work				References		
	n	E_α [MeV]	$T_{1/2}$ [s]	b_{SF}	E_α [MeV]	$T_{1/2}$ [s]	b_{SF}
^{261a}Rf	**48**	**8.270.05**	(33^{+12}_{-7})		8.280.02[a)]	683[b)]	< 0.11[c)]
^{261b}Rf	**25**	**8.510.05**	$\mathbf{2.6^{+0.7}_{-0.5}}$	**0.820.09**	8.52[d)]	1.90.4[d)]	0.740.06[d)]
^{257}No	**54**	**8.07–8.38**	(23^{+4}_{-3})		8.222, 8.323[e)]	24.50.5[e)]	

Decay time spectrum of ^{261b}Rf



References

a) Table of Isotopes, 8th ed.

b) Asai, private communication.

c) Kadkhodayan *et al.*, RCA **72**, 169 (1996).

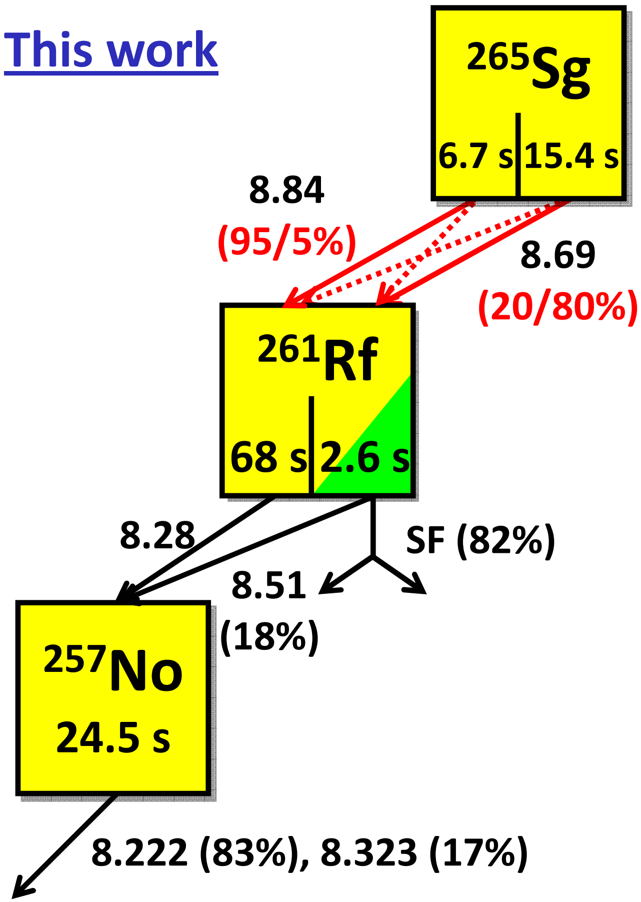
d) Haba *et al.*, 7th Workshop on the Chemistry of the Heaviest Elements, 13 Oct., 2009, Mainz.

e) Asai *et al.*, PRL **95**, 102502 (2005).

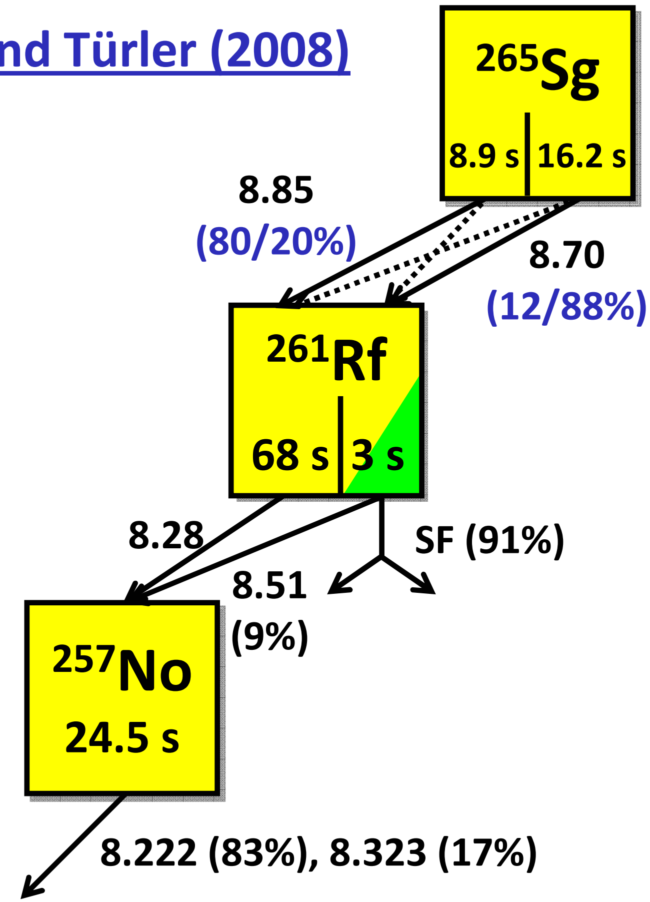
Decay patterns observed in the chain $^{265a,b}Sg \rightarrow {}^{261a,b}Rf \rightarrow {}^{257}No$

^{265}Sg state	^{265}Sg $T_{1/2}$ [s]	→	^{261}Rf state	No. of events (obs.)	No. of events (corr.)	Branching ratio [%] This work	Branching ratio [%] Düllmann and Türler (2008)
a	6.7	→	a	16	19.7	95	80
		→	b	1	1.0	5	20
b	15.4	→	a	4	5.1	20	12
		→	b	20	20.0	80	88

This work



Düllmann and Türler (2008)



Cross section

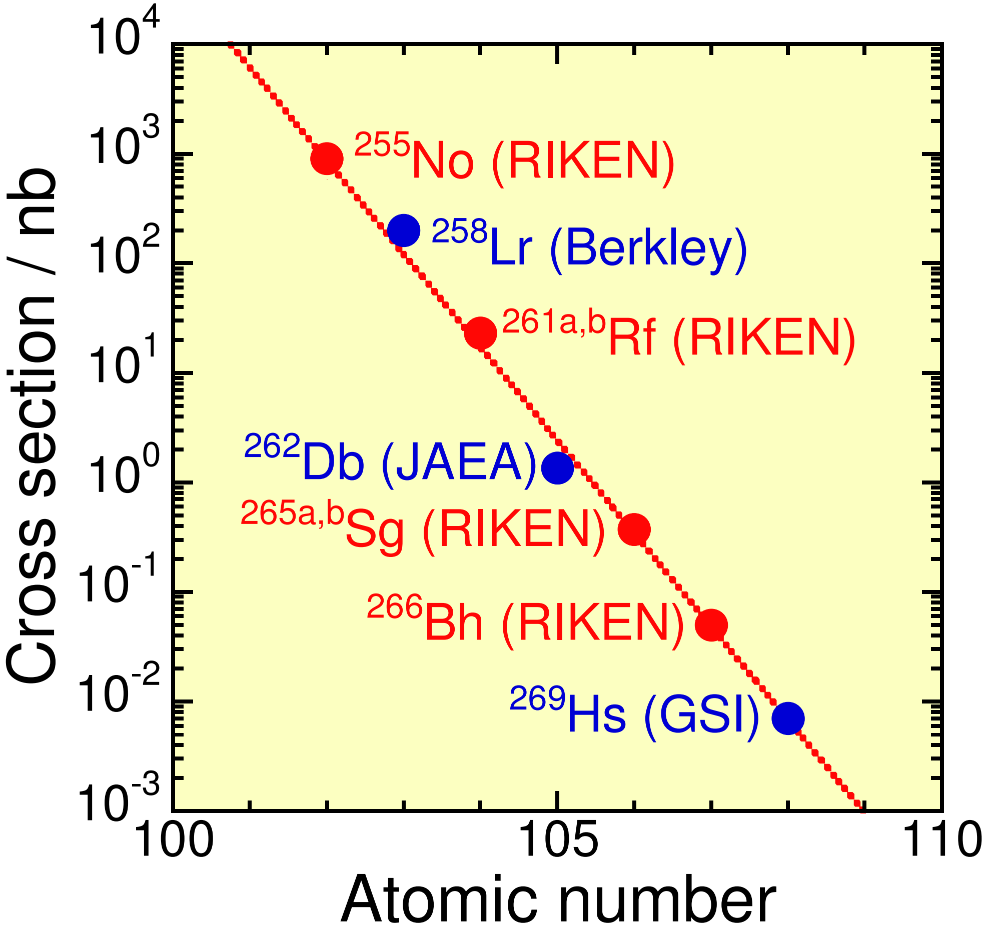
Assumptions: GARIS eff. = 15% and gas-jet eff. = 50%

	Cross section at 118 MeV [pb]
^{265a}Sg	200^{+90}_{-70}
^{265b}Sg	170^{+50}_{-40}

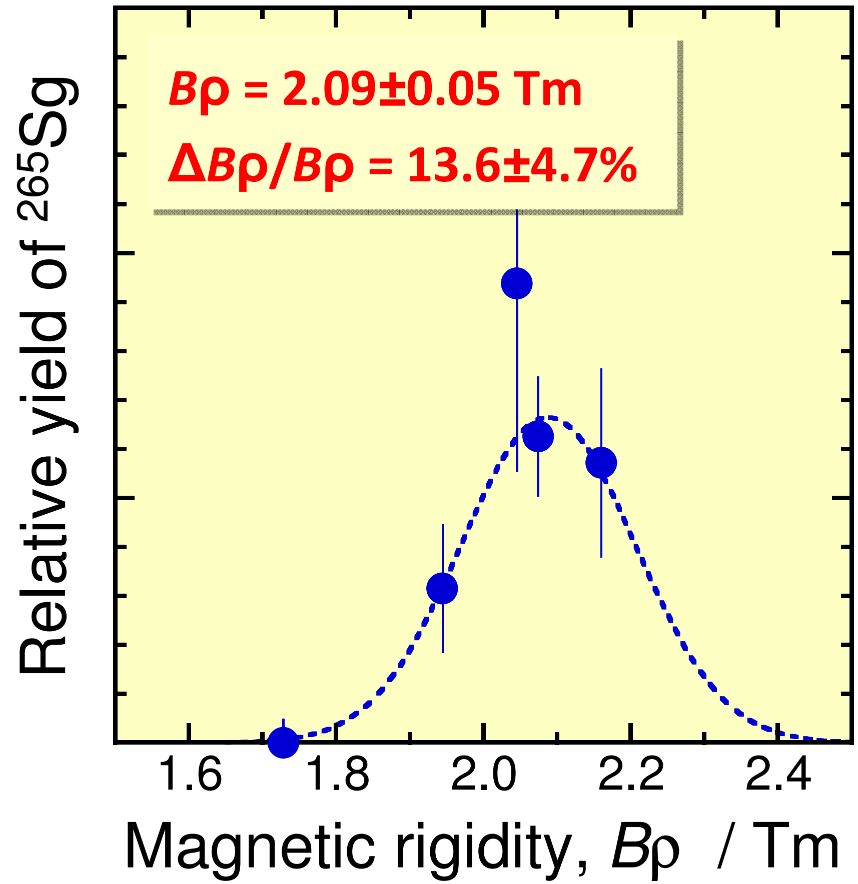
$\sigma(^{265a+b}Sg) = 370^{+90}_{-70}$ pb

$\sigma(^{265a}Sg)/\sigma(^{265b}Sg) = 1.6\pm0.7$

Cross section systematics for $^{248}Cm(X,5n)$

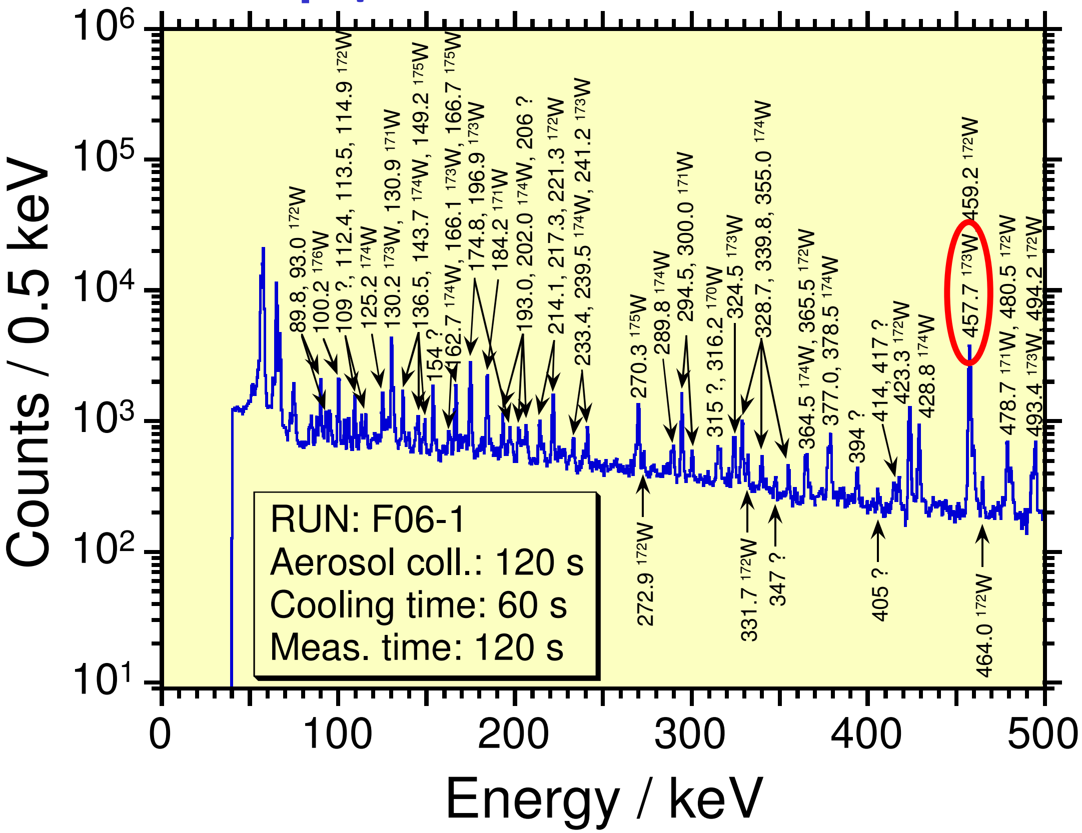


Relative yield of ^{265}Sg vs. $B\rho$

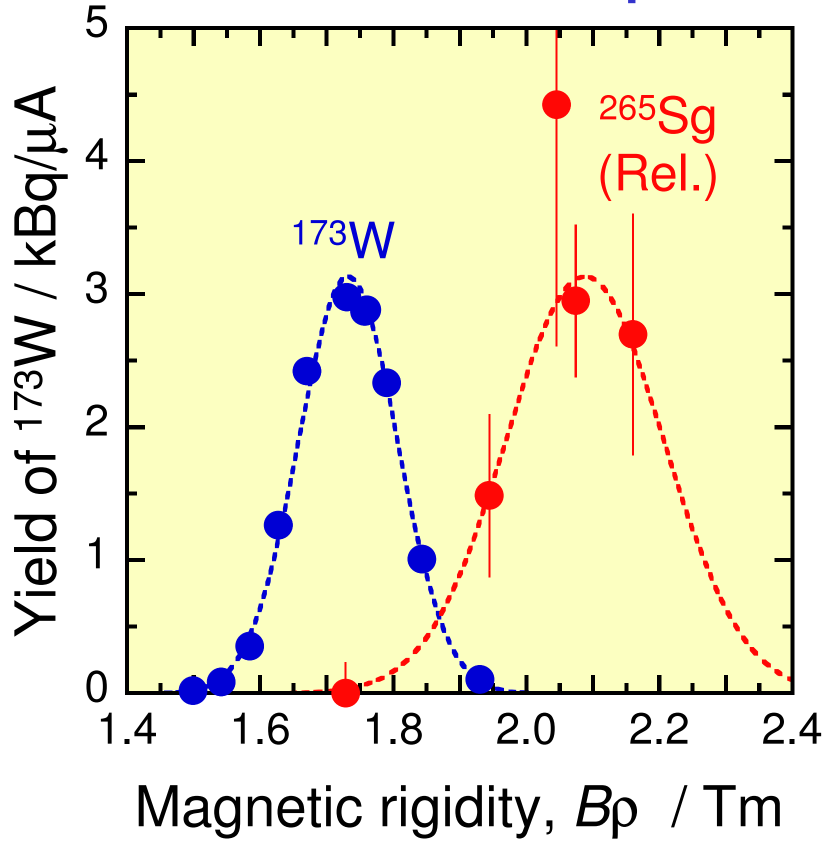


(b) $^{nat}Gd(^{22}Ne,xn)^{173}W$

γ spectrum of Ge detector



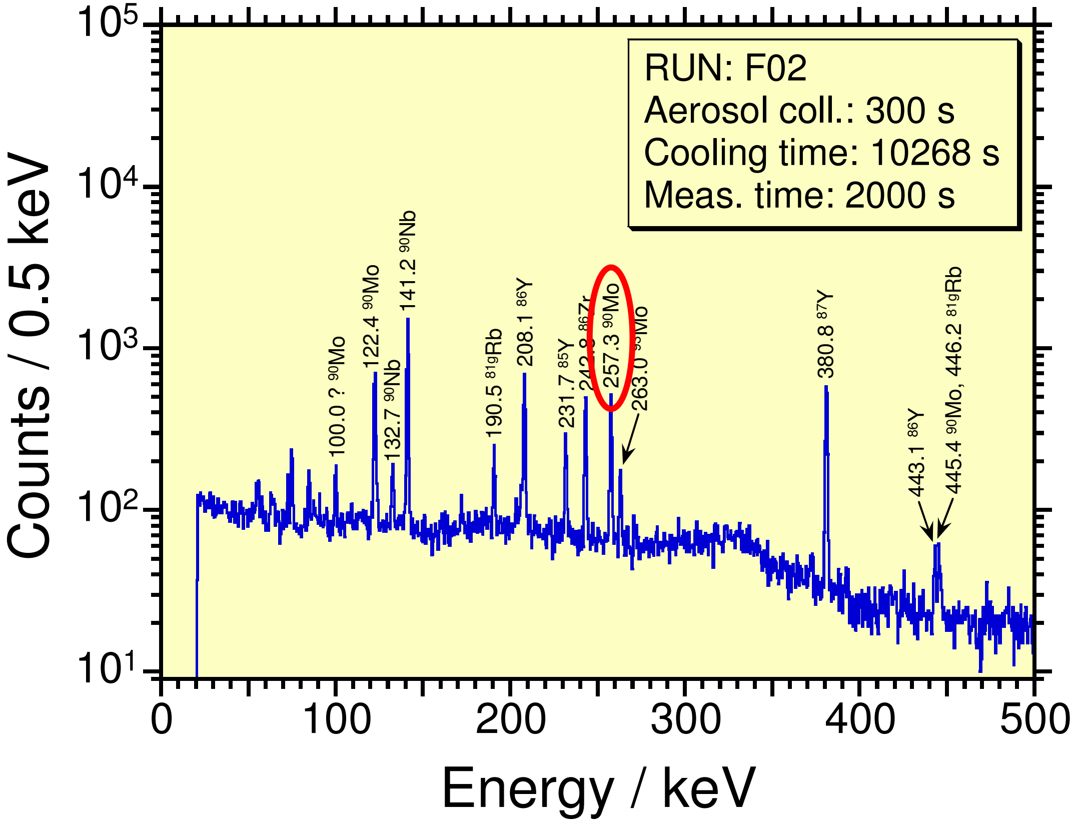
Yield of ^{173}W vs. *B*ρ



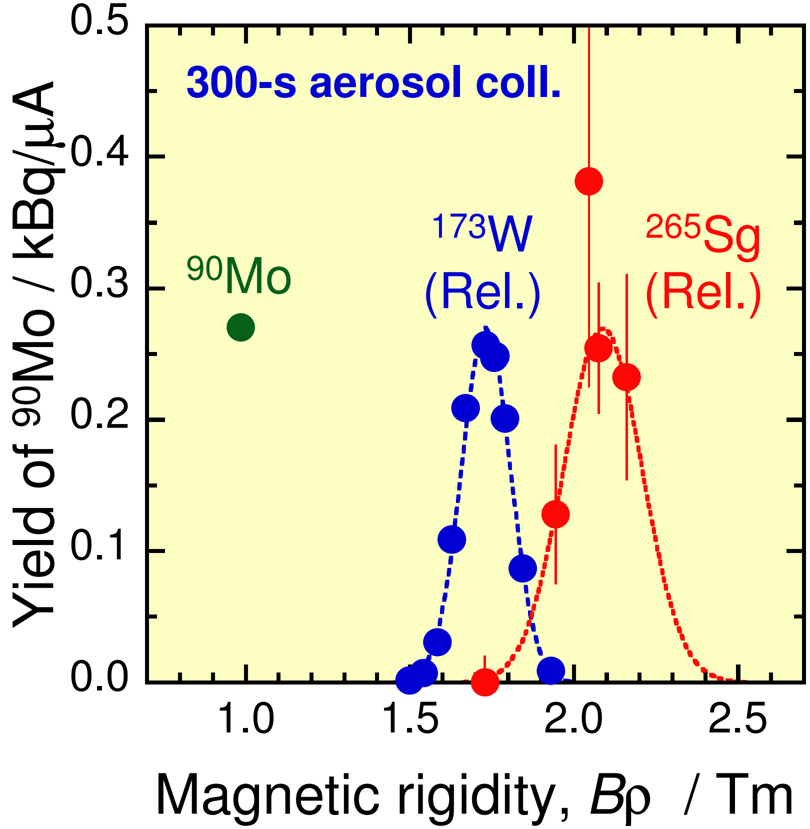
- ^{171}W ($T_{1/2}$ = 2.38 min), ^{172}W (6.6 min), **^{173}W (7.6 min)**, ^{174}W (31 min), ^{175}W (35.2 min), and ^{176}W (2.5 h)
- ***B*ρ = 1.73±0.01 Tm** and Δ*B*ρ/*B*ρ = 10.1±0.3%
- Yield at chemistry laboratory: 3.1 kBq/pμA after 120-s aerosol collection
- Gas-jet eff.: **65±1%**

(c) $^{nat}Ge(^{22}Ne,xn)^{90}Mo$

γ spectrum of Ge detector



Yield of ^{90}Mo vs. $B\rho$



- **^{90}Mo ($T_{1/2}$ = 5.67 h)**, ^{93}Mo, $^{90m,90g,89a,89b,88g,87m,87g,86g}Nb$, $^{89m,89g,87m,86,85g}Zr$, $^{89m,87m,86m,86g,85m,85g,84m}Y$, ^{83g}Sr, ^{81g}Rb, and ^{81m}Kr
- Yield at chemistry laboratory: 0.27 kBq/pμA after 300-s aerosol collection
- The optimum *B*ρ and the gas-jet efficiency will be measured in the future.

→ We are ready for chemistry experiments of Sg together with its homologues!

2.2. AVF cyclotron

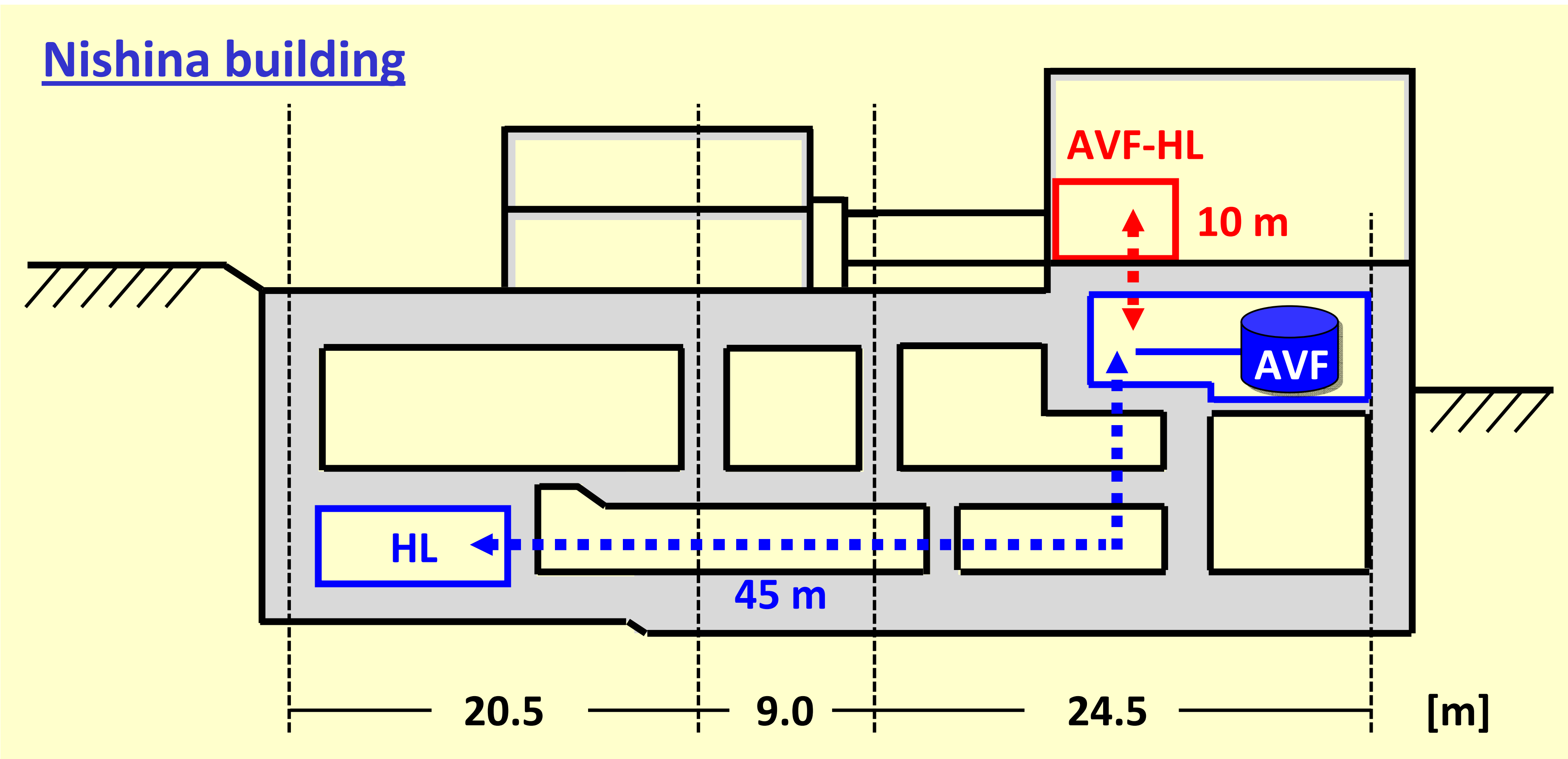
Conventional gas-jet transport system for SHE researches

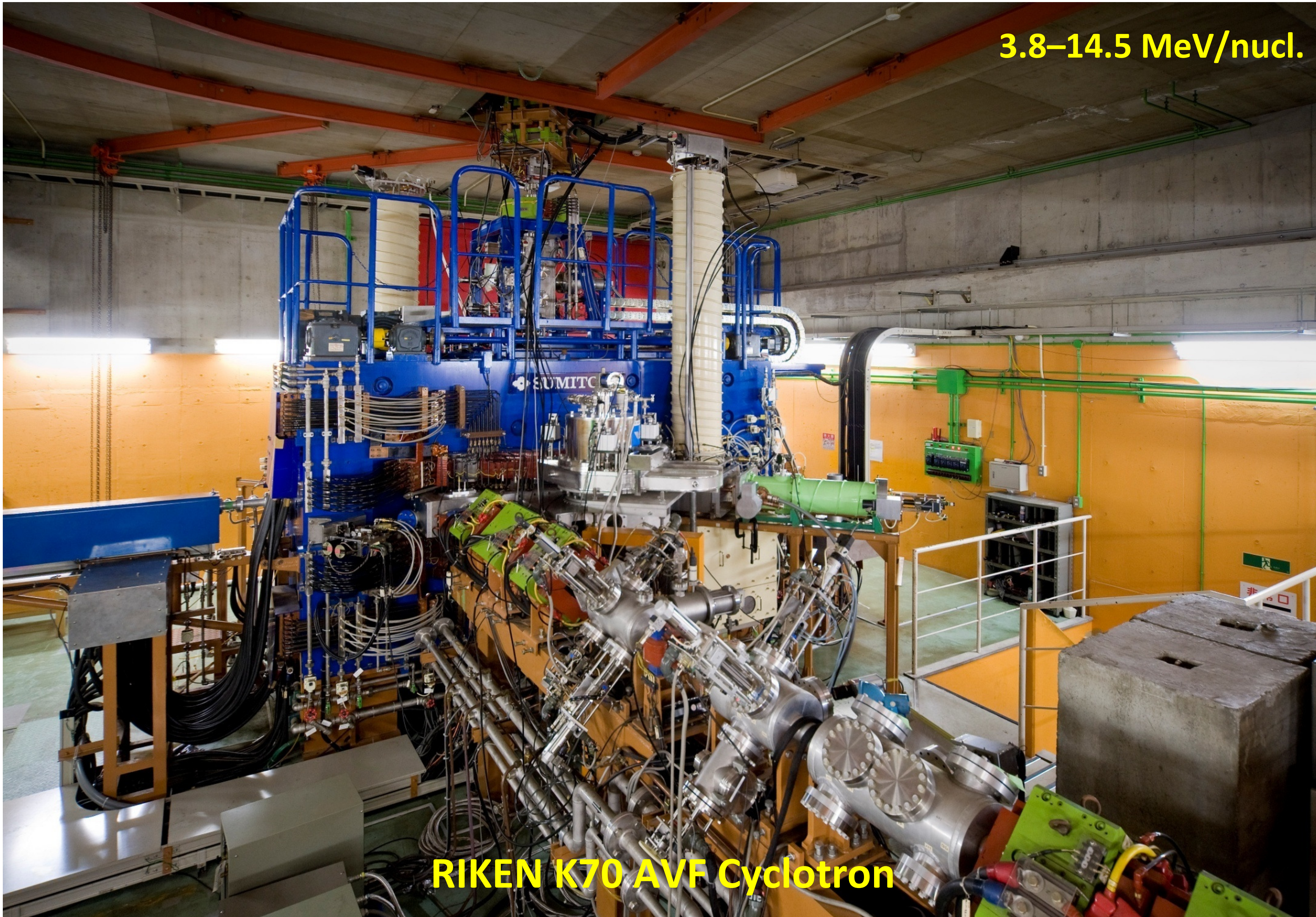
AVF C-03 → HL (45 m)

New chemistry laboratory in the upper floor of AVF (Nov. 2009–)

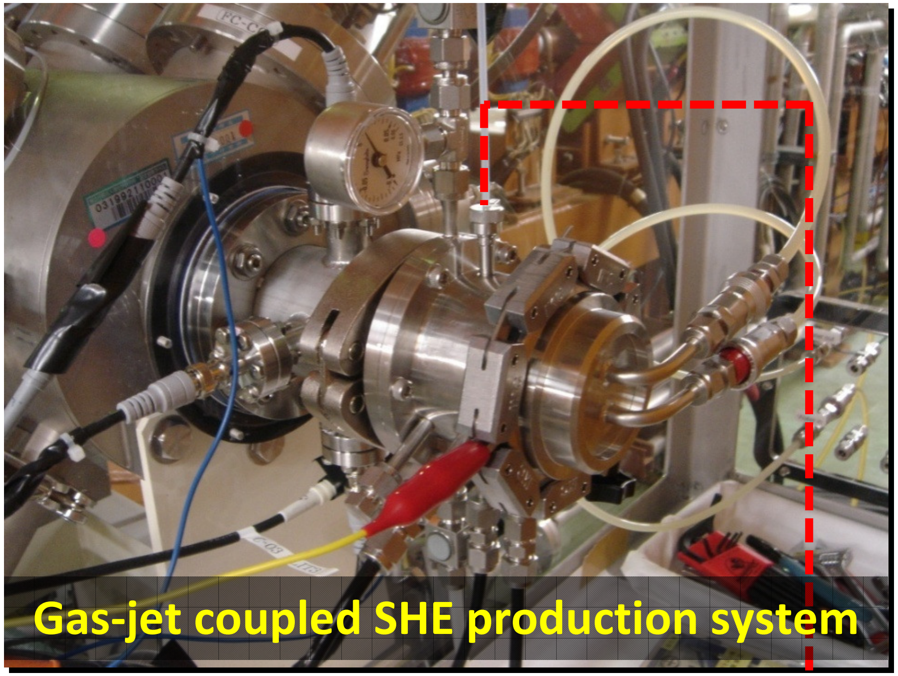
AVF C-03 → AVF-HL (<10 m)

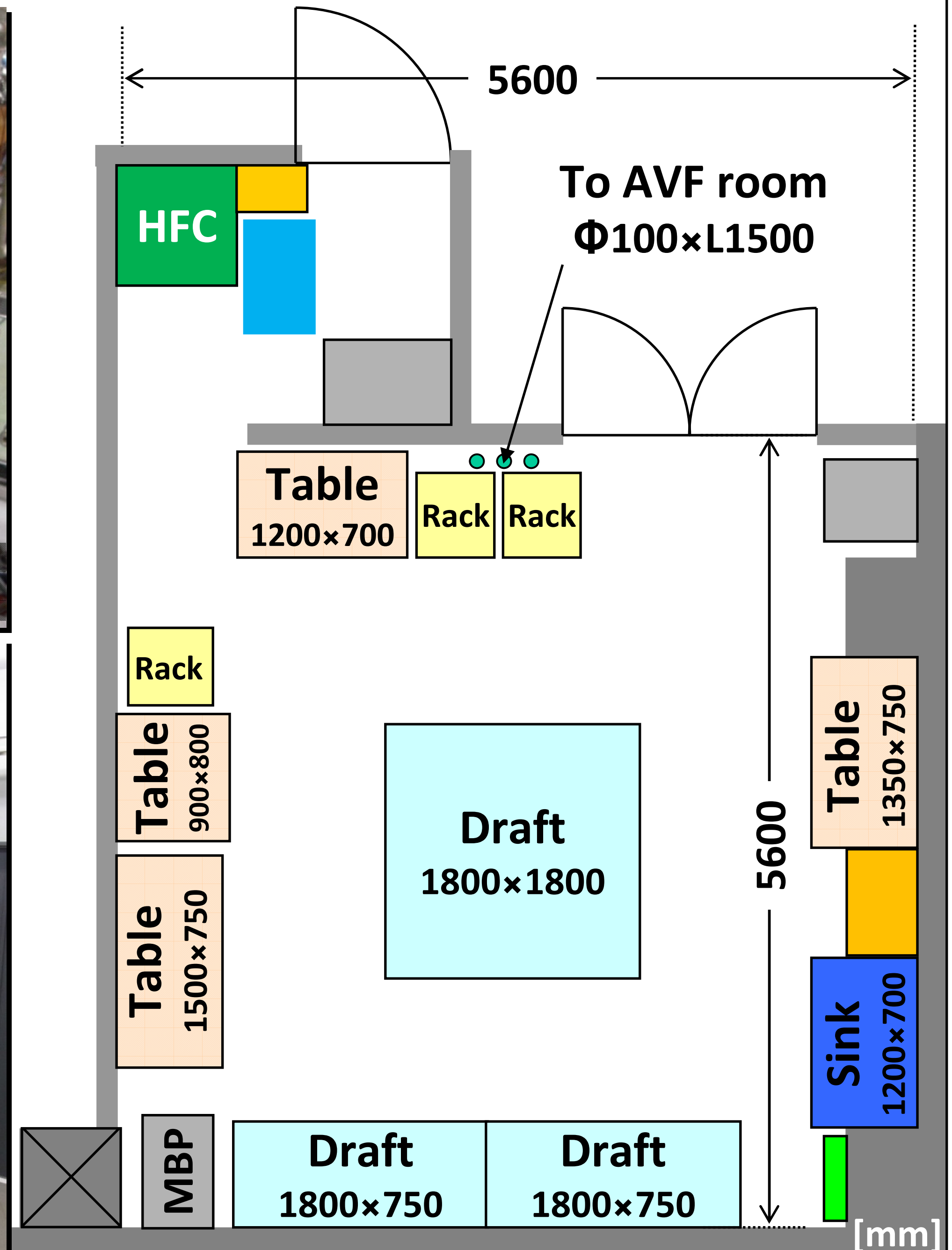
→ SHE researches up to ~Hs at AVF without recoil separators




3.8–14.5 MeV/nucl.
RIKEN K70 AVF Cyclotron

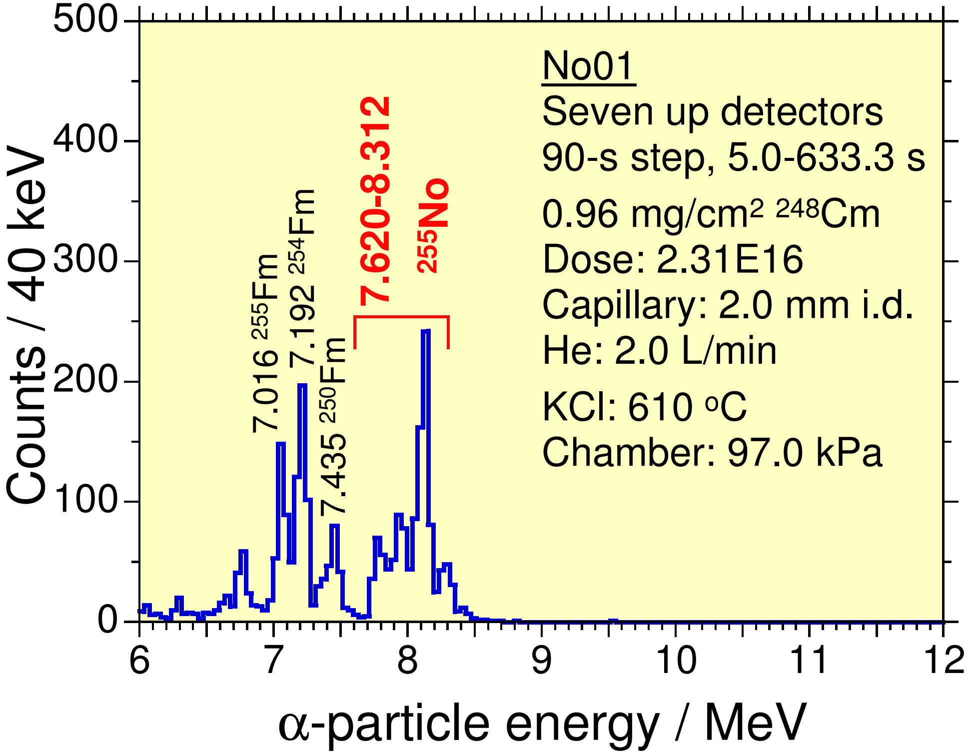
New chemistry laboratory: AVF HL (Nov. 2009 –)



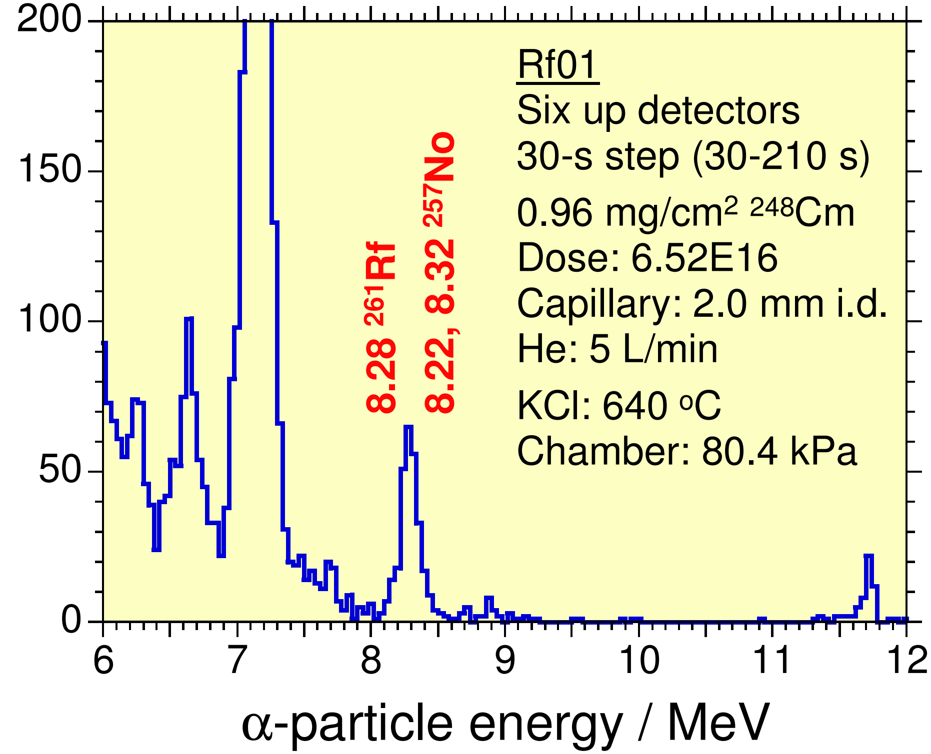


Commissioning of the new gas-jet system: AVF C-03 → AVF HL

$^{248}Cm(^{12}C,5n)^{255}No$



$^{248}Cm(^{18}O,5n)\ ^{261a}Rf$



Exp.	Beam [MeV]	Beam [pμA]	Irrad. [h]	Number 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**
^{261a}Rf	96.4	0.870	3.34	865*	63	17	**4.7**

* Including α particles of ^{257}No.

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

*** The effective target thickness of ^{248}Cm is assumed to be 325 and 569 μg/cm² for ^{255}No and ^{261a}Rf, respectively.

3. Chemistry program

(a) RILAC + GARIS + Gas-jet

– Chemistry opened by beam separation and low background condition –

- Gas phase chemistry of halide or oxyhalide of Rf (Db and Sg) with an isothermal gas chromatograph column (Niigata Univ.)
- Solvent extraction of Rf (and Sg) with a microchemical chip + LS (Osaka Univ.)
- α-fine structure spectroscopy of ^{257}Rf and ^{255g,m}Lr (JAEA)
- Production and decay properties of ^{262}Db by ^{248}Cm(^{19}F,5*n*)^{262}Db (RIKEN)

(b) AVF cyclotron + Gas-jet

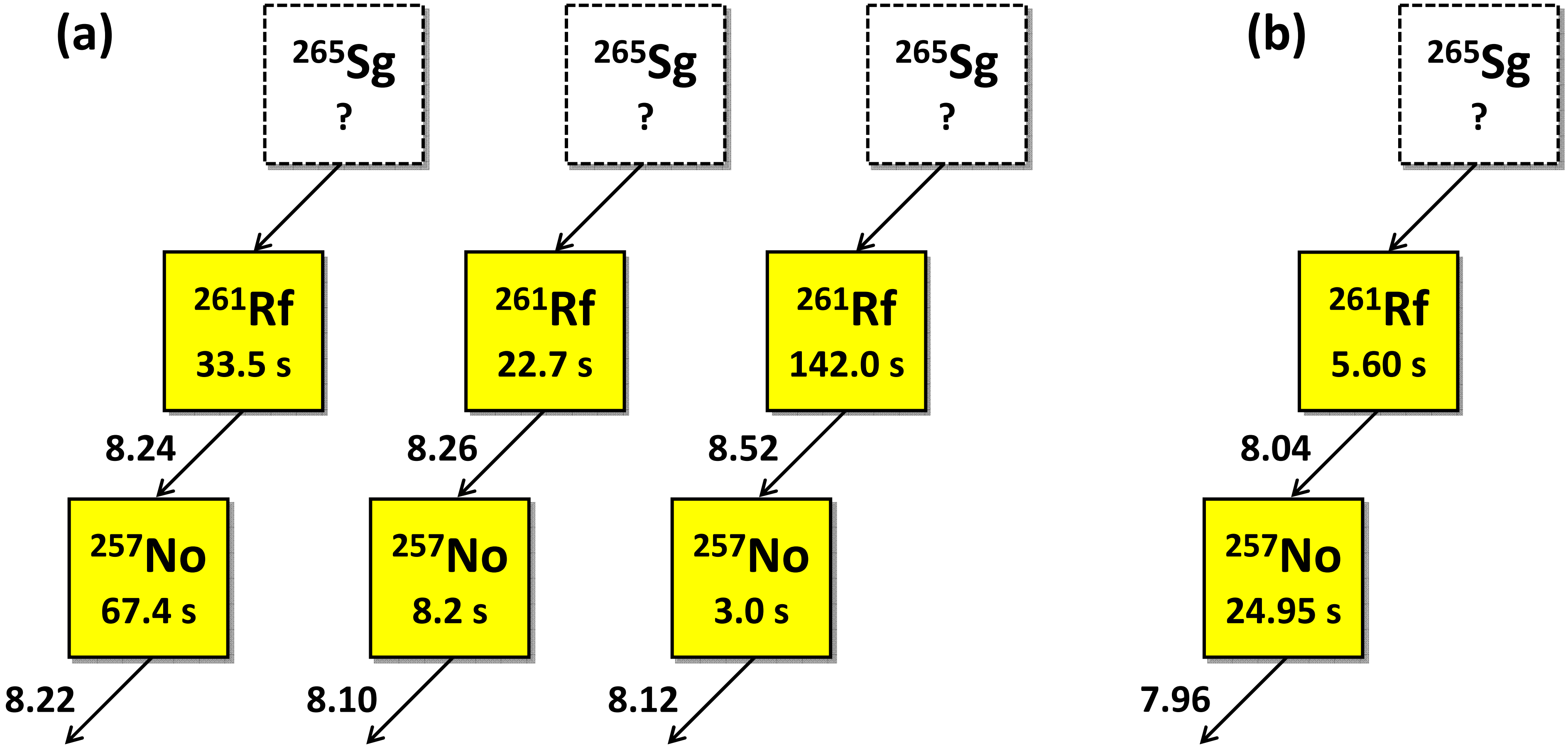
– Chemistry with a conventional gas-jet –

- Electrochemistry of No with a microchemical chip (Osaka Univ. and JAEA)
- Reversed-phase extraction of TTA complex of Rf with JAEA AIDA (Kanazawa Univ.)
- **Aqueous chemistry of Sg**

Previous aqueous chemistry of Sg

(a) Schädel *et al.*, RCA **77**, 149 (1997). ARCA CIX, 0.1 M HNO_3/5×10^{-4} M HF

(b) Schädel *et al.*, RCA **83**, 163 (1998). ARCA CIX, 0.1 M HNO_3

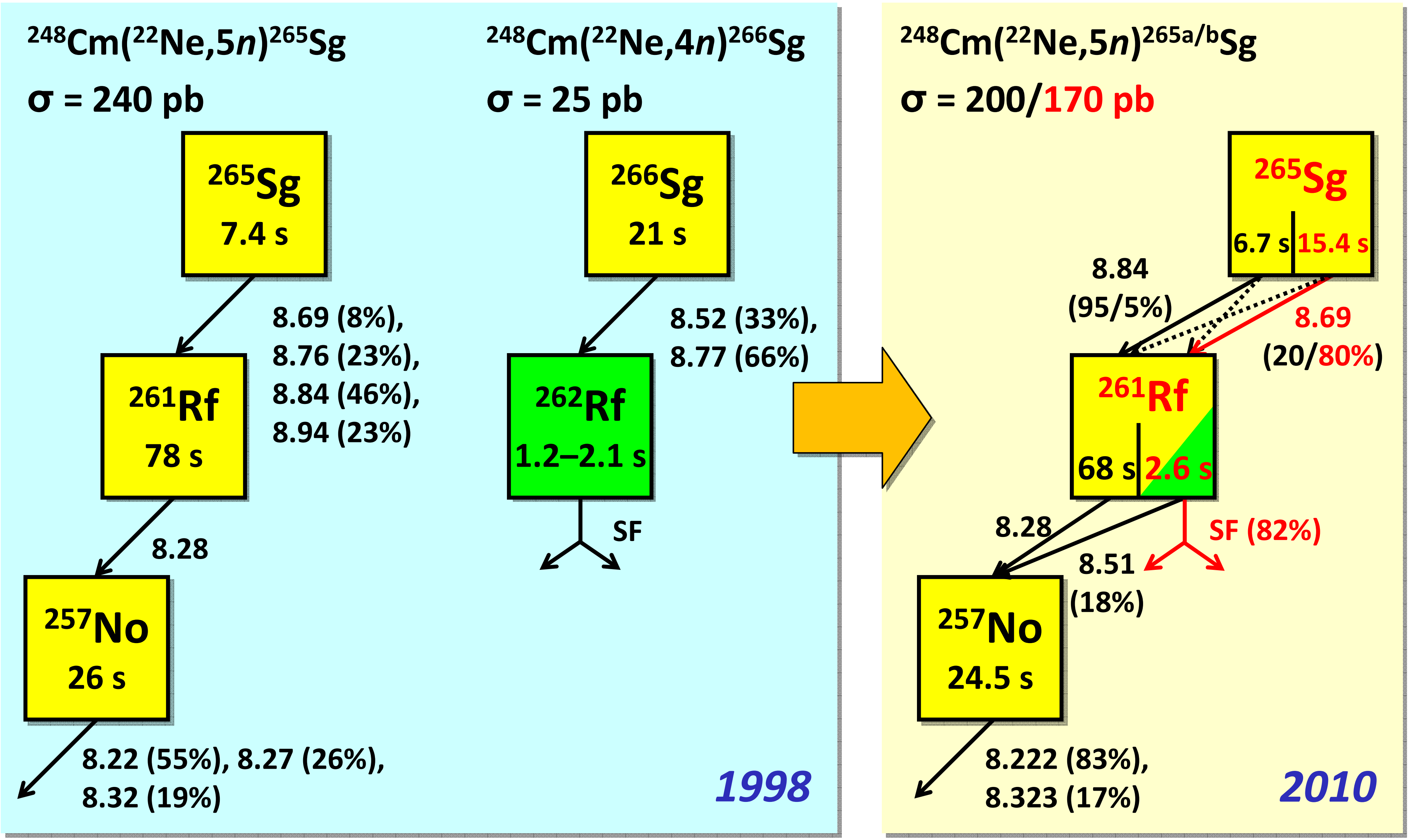


Sg^{6+} ≈ Mo, W; Sg ≠ U, Zr, Hf, Rf

SgO_2F_2 or $SgO_2F_3^-$ in 0.1 M HNO_3/5×10^{-4} M HF

Aqueous chemistry of ^{265}Sg

- ^{265b}Sg (8.69-MeV α, $T_{1/2}$ = 15.4 s) ⟶ ^{261b}Rf (SF, $T_{1/2}$ = 2.6 s)
  ⟶ Great advantage for aqueous chemistry of Sg
- Based on successful collaboration on aqueous chemistry of Rf and Db at JAEA



- **Model experiments with long-lived radiotracers of Sg homologues**

  ^{181}W ($T_{1/2}$ = 121.2 d): ^{181}Ta(p,n)^{181}W at AVF

  ^{93m}Mo ($T_{1/2}$ = 6.85 h): ^{93}Nb(p,n)^{93m}Mo at AVF

  ^{99}Mo ($T_{1/2}$ = 65.94 h): fission product of ^{252}Cf

- **Automated rapid α-particle detection system for aqueous chemistry**

16 Si PIN photodiodes (Hamamatsu S3204-09, 18×18 mm^2)

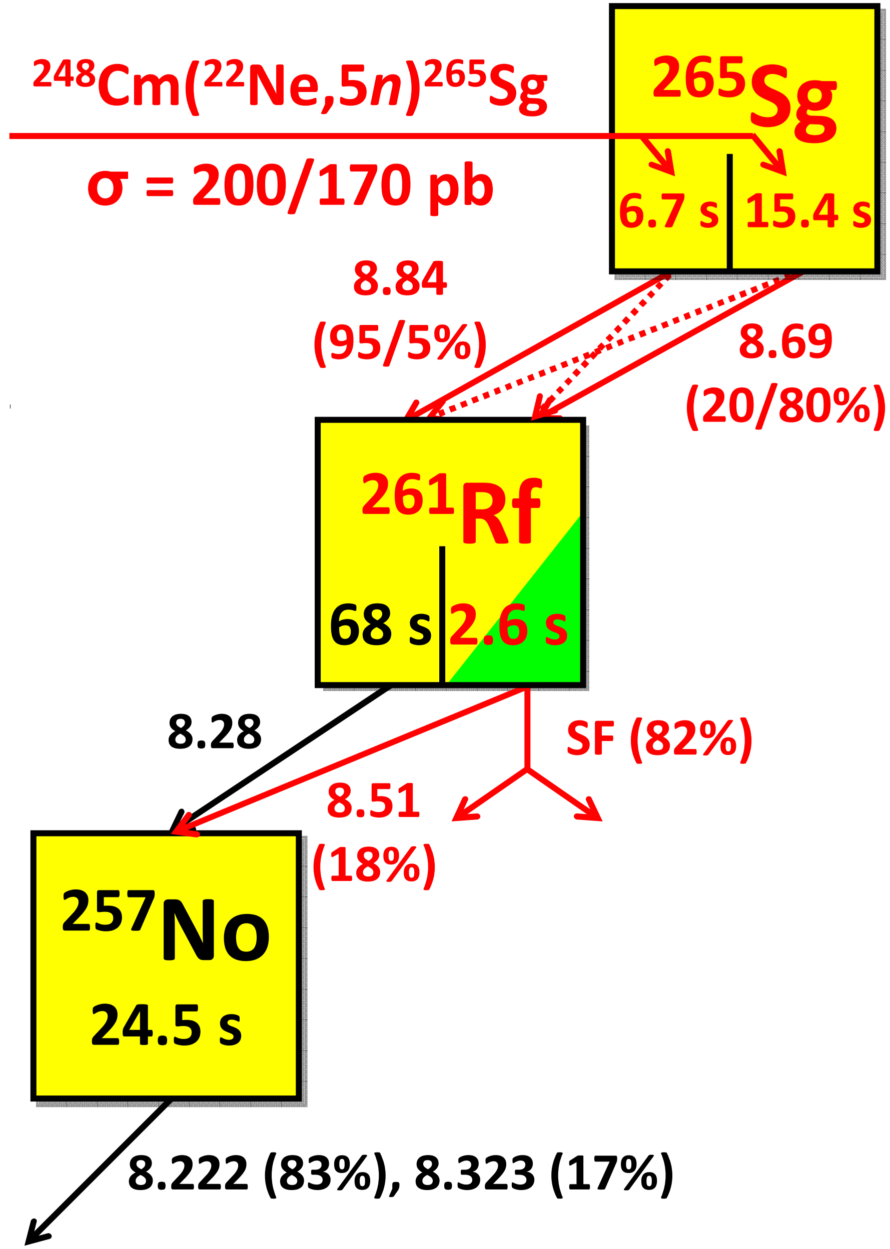
Time required to transfer samples to the detector: <4 s

4. Summary

- The gas-jet transport system has been coupled to GARIS@RILAC.
- Productions and decay properties of ^{265a,b}Sg were investigated in detail.
  ^{248}Cm(^{22}Ne,5*n*)^{265}Sg
- ^{173}W and ^{90}Mo were also extracted to the chemistry laboratory.
  ^{nat}Gd(^{22}Ne,*xn*)^{173}W/^{nat}Ge(^{22}Ne,*xn*)^{90}Mo

- The conventional gas-jet transport system has been installed at the AVF cyclotron: AVF → AVF HL.
- The commissioning of the new gas-jet line was successful with ^{255}No and ^{261a}Rf.

- Chemistry programs planned at GARIS@RILAC and AVF are introduced.



Acknowledgements

Participants in RIKEN Workshop on SHE Chemistry FY2007–FY2009

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