Present status and perspectives of superheavy element research at RIKEN

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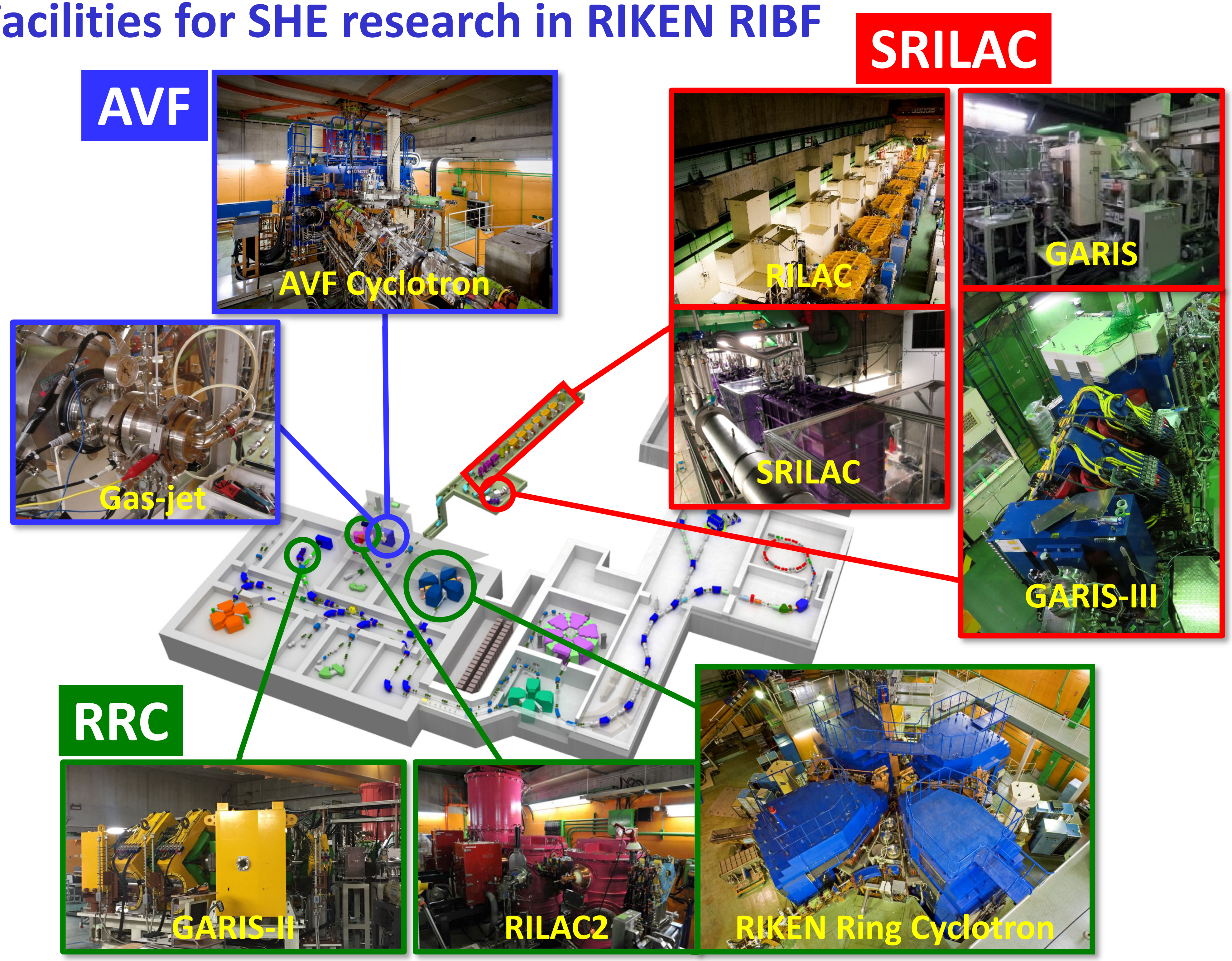
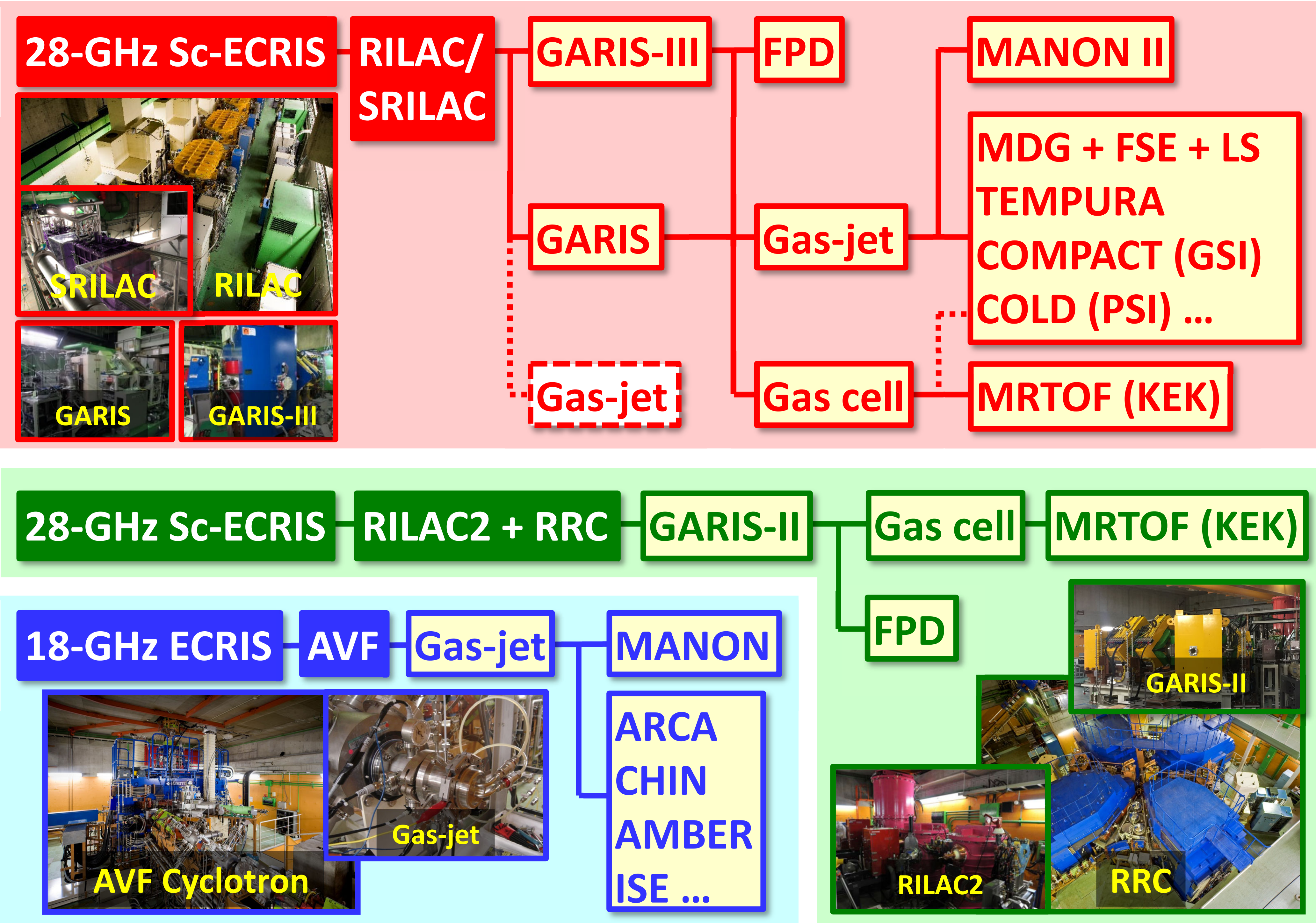
1. Facilities for SHE research in RIKEN RI Beam Factory

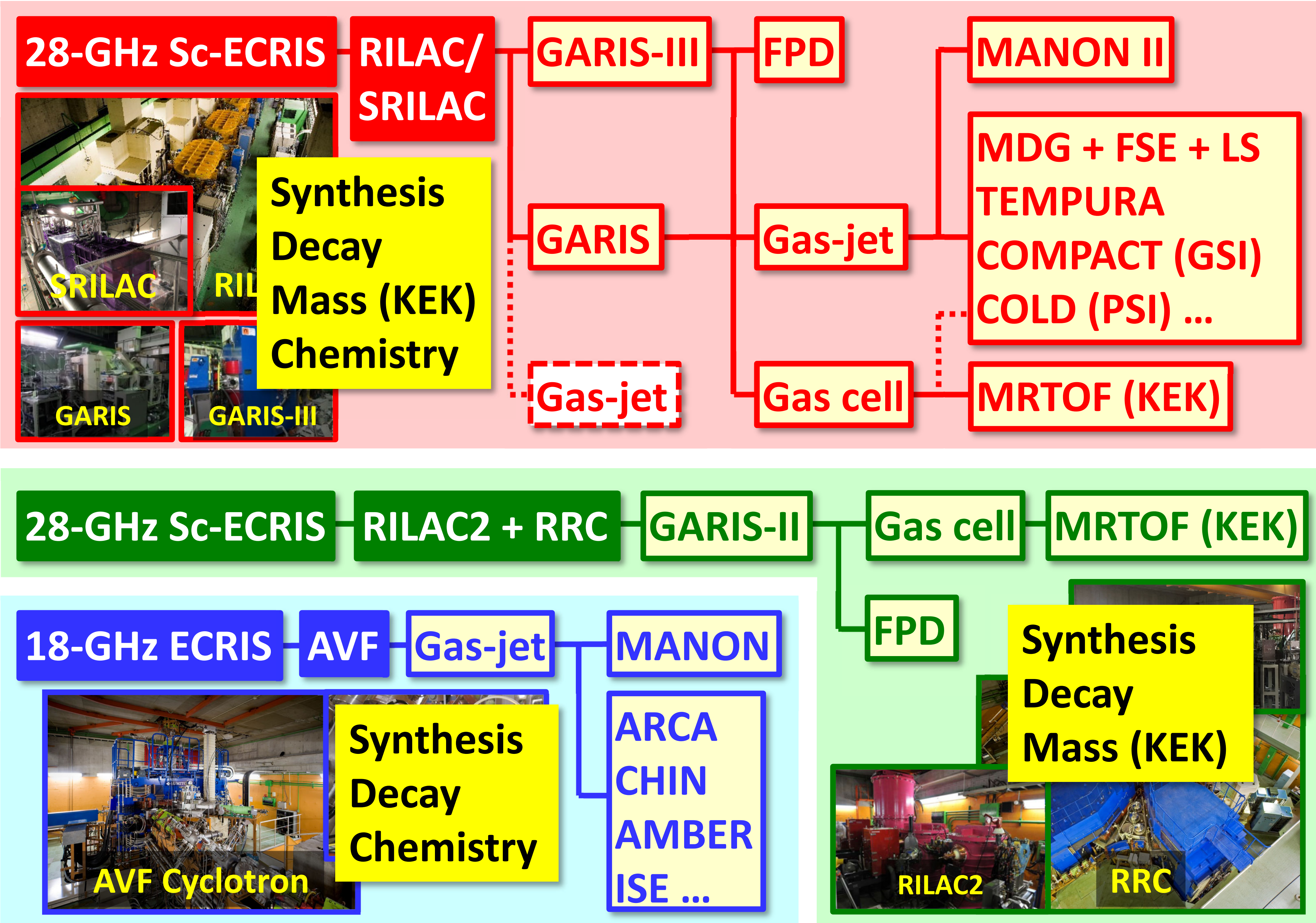
Facilities for SHE research in RIKEN RIBF



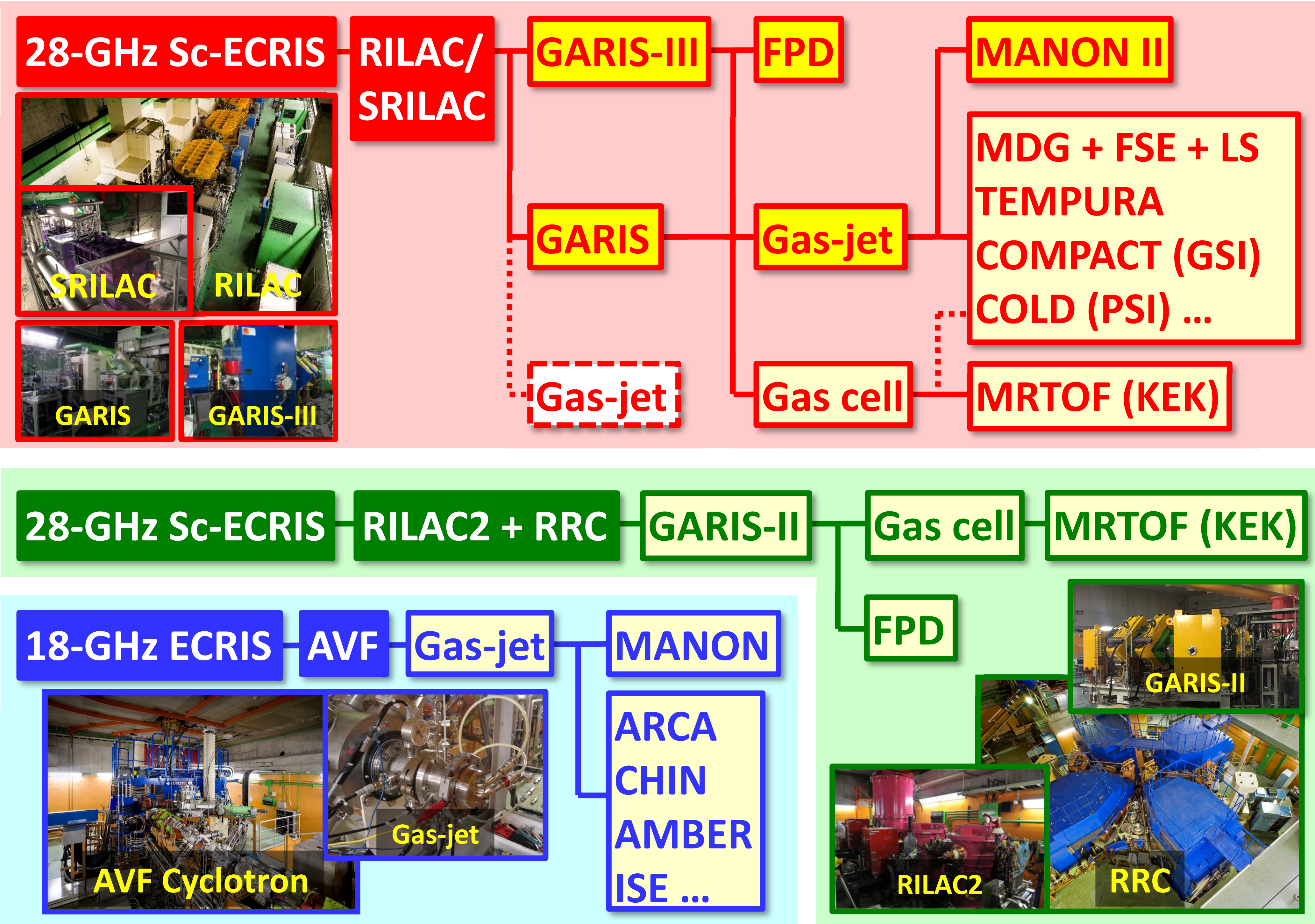
Facilities for SHE research in RIKEN RIBF



Facilities for SHE research in RIKEN RIBF

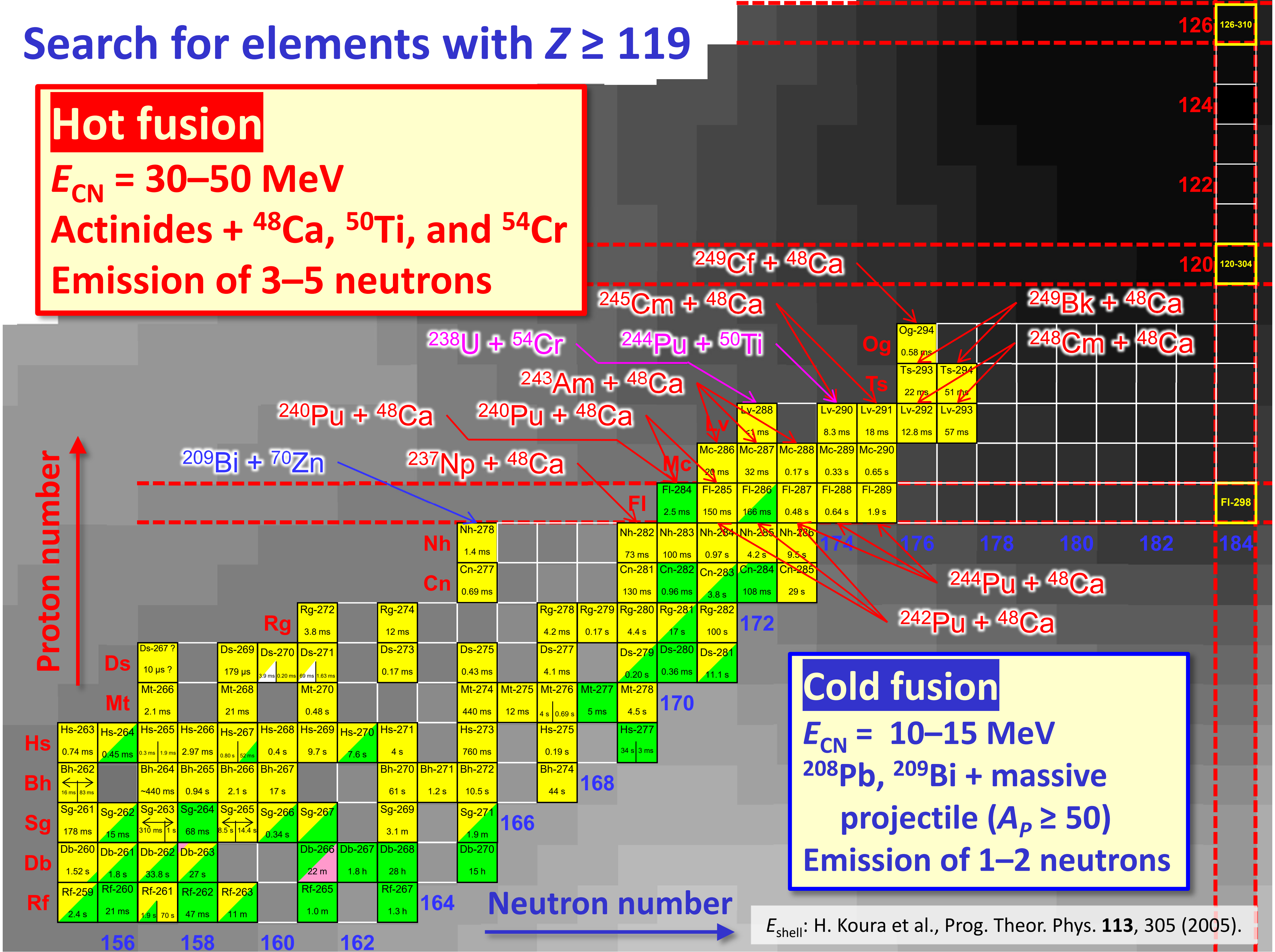


Facilities for SHE research in RIKEN RIBF



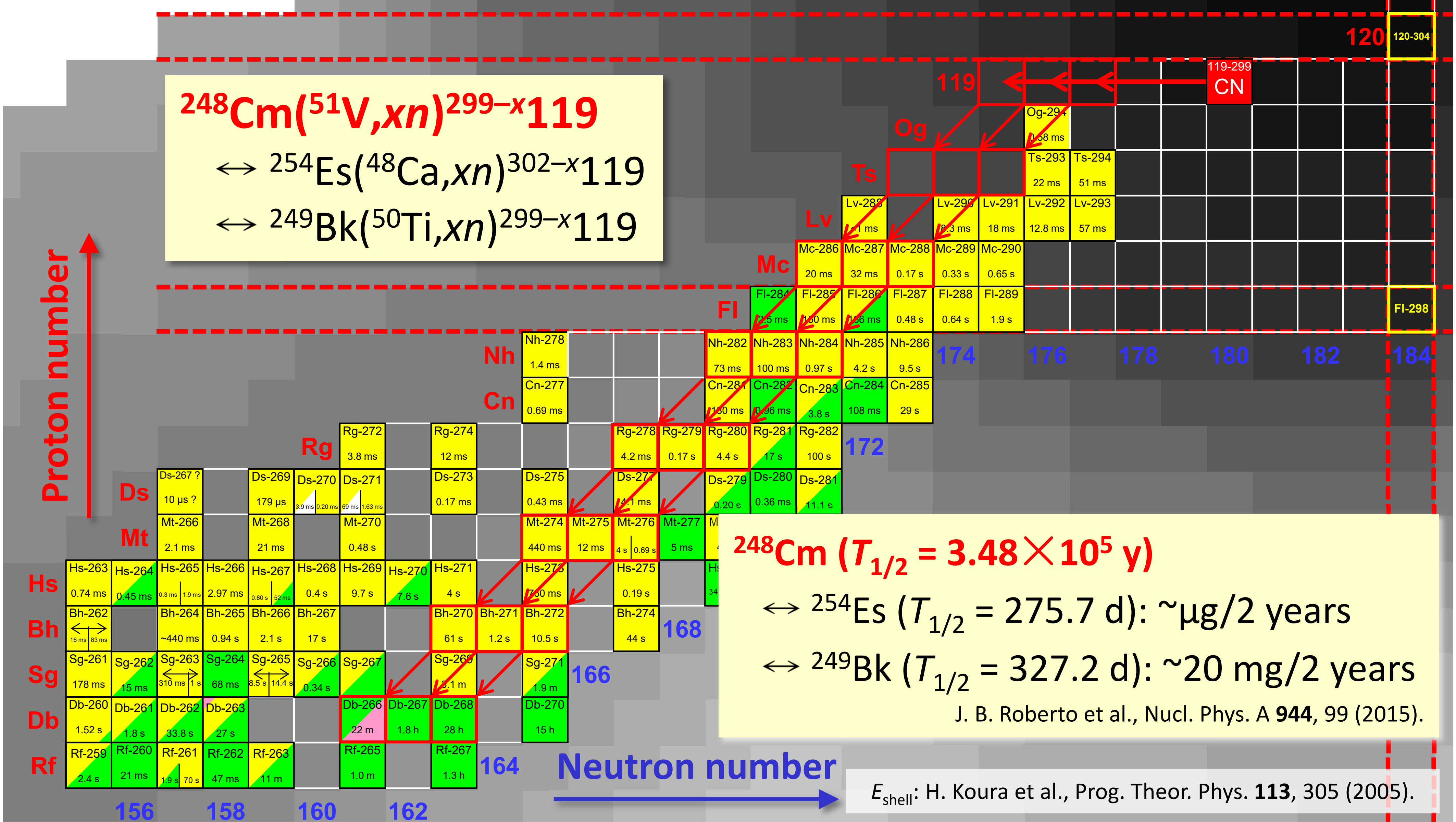
2. Search for element 119 in the $^{248}Cm(^{51}V,xn)^{299-x}119$ reaction

Search for elements with $Z \geq 119$



Search for element 119 at RIBF

RIKEN – ORNL – UTK - Kyushu Univ. – Niigata Univ. – Saitama Univ. – Osaka Univ. – Tohoku Univ. – JAEA – Yamagata Univ. – IPHC – IMP – ANU – NCBJ Collaboration



^{248}Cm(^{51}V,*xn*)$^{299-x}$119

↔ ^{254}Es(^{48}Ca,*xn*)$^{302-x}$119

↔ ^{249}Bk(^{50}Ti,*xn*)$^{299-x}$119

^{248}Cm ($T_{1/2}$ = 3.48×10^5 y)

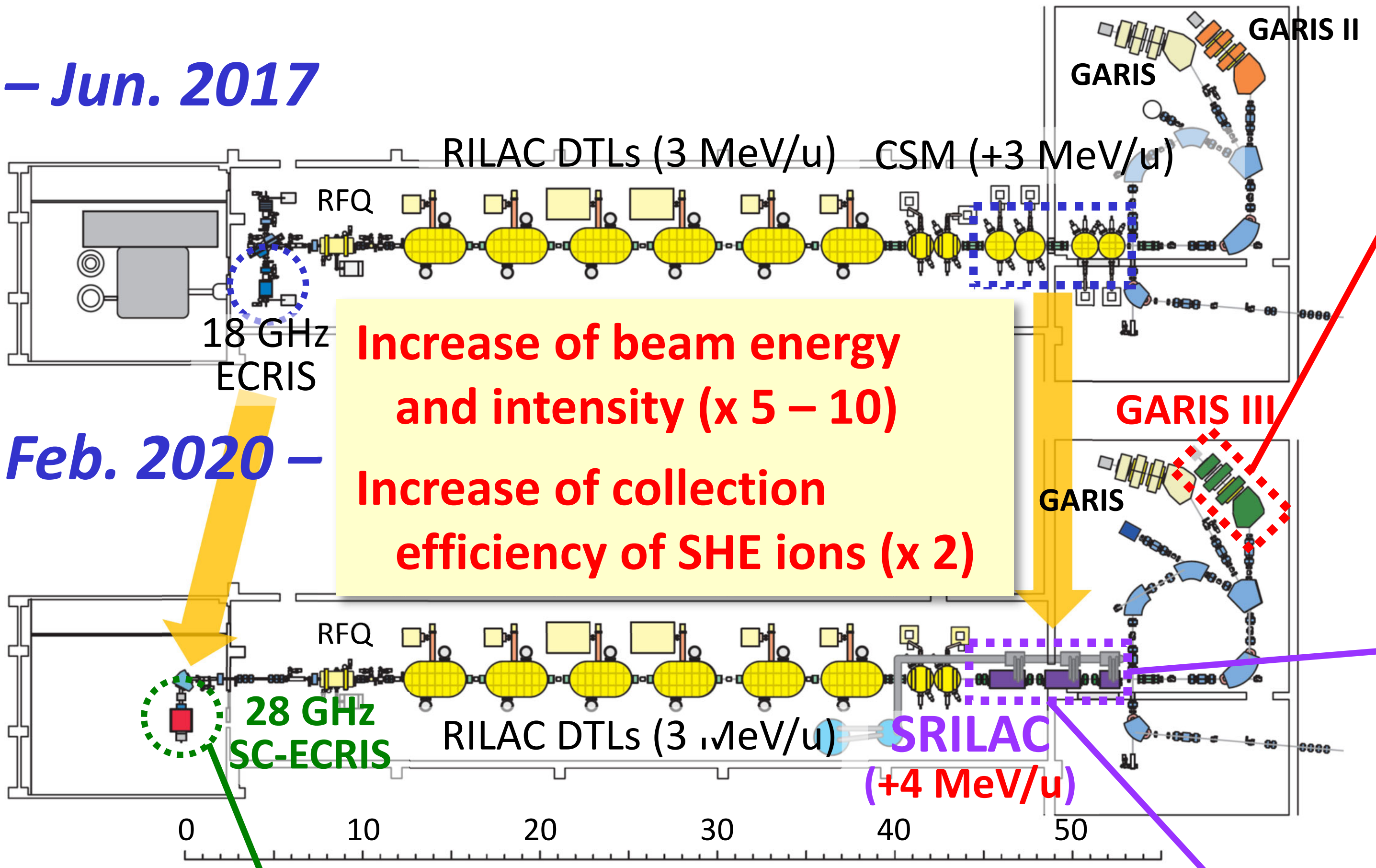
↔ ^{254}Es ($T_{1/2}$ = 275.7 d): ~μg/2 years

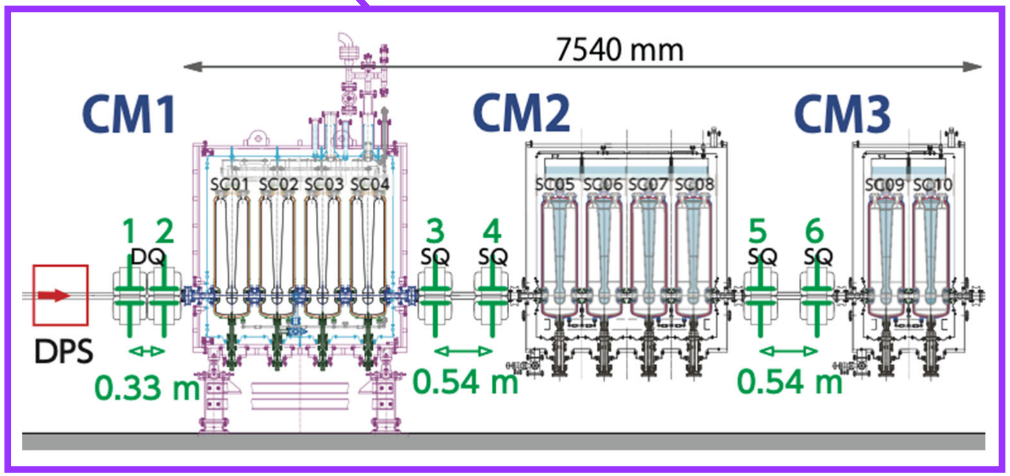
↔ ^{249}Bk ($T_{1/2}$ = 327.2 d): ~20 mg/2 years

J. B. Roberto et al., Nucl. Phys. A **944**, 99 (2015).

E_{shell}: H. Koura et al., Prog. Theor. Phys. **113**, 305 (2005).

Upgrade of RILAC (June 2017–February 2020)

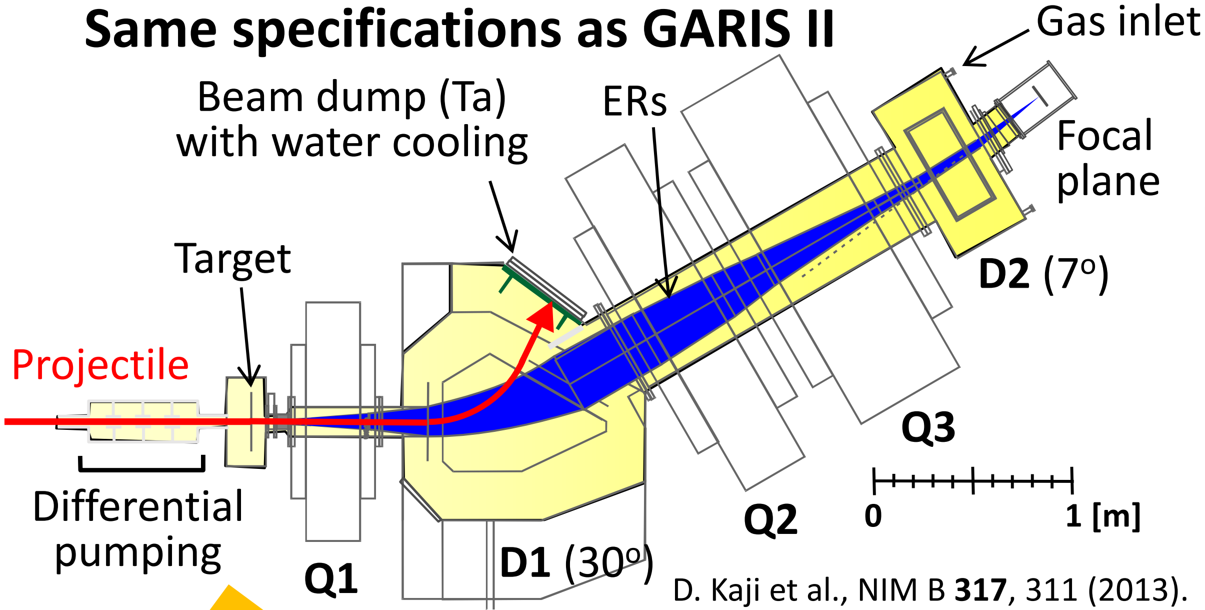




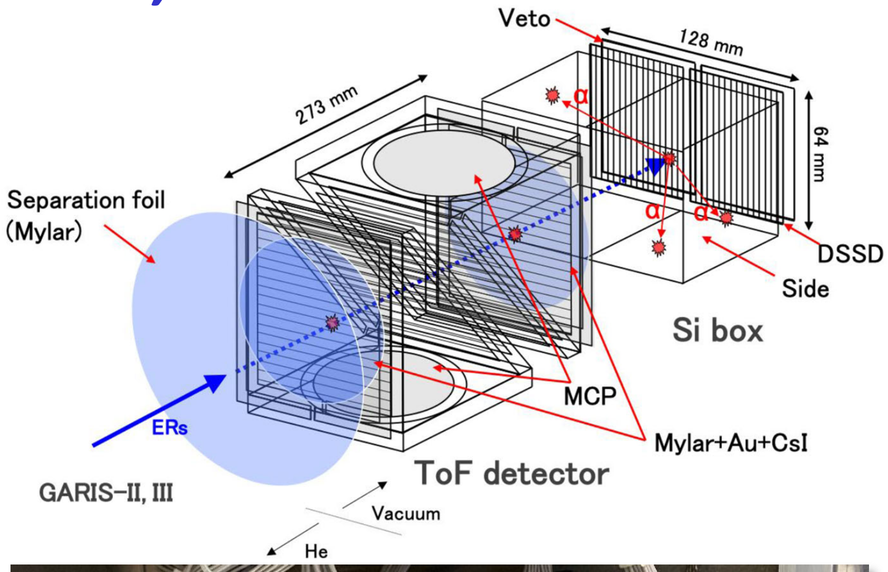
N. Sakamoto and T. Nagatomo, Nucl. Phys. News **32**, 21 (2022).

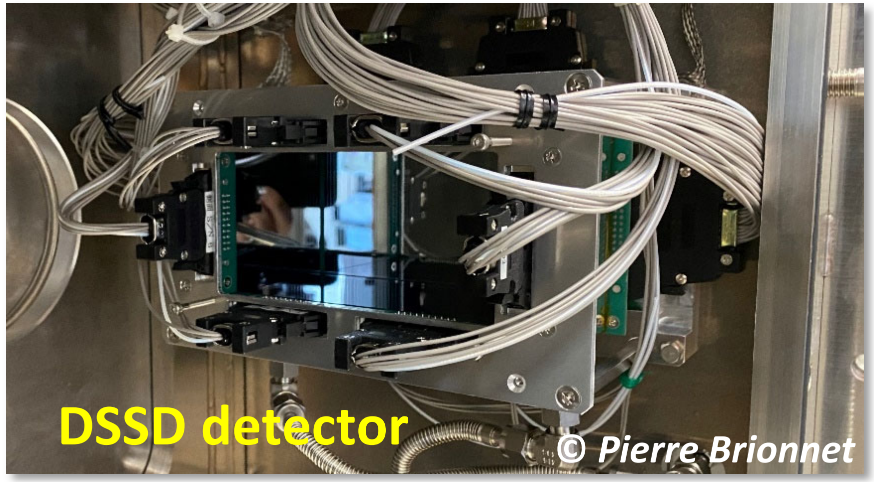
Gas-filled recoil ion separator, GARIS III, for hot fusions

Same specifications as GARIS II

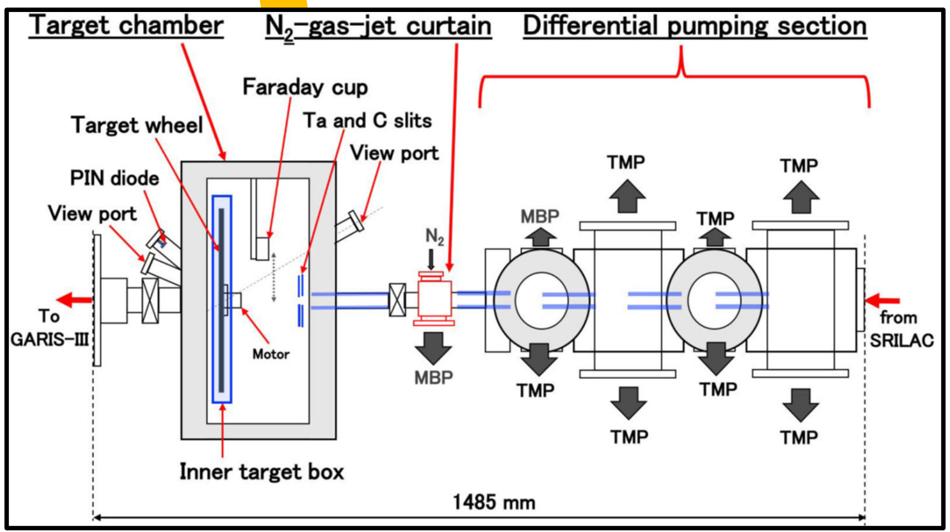


D. Kaji et al., NIM B **317**, 311 (2013).





	GARIS	GARIS II&III
Δθ (mrad)	±67	±55
Δϕ (mrad)	±58	±120
ΔΩ (msr)	≈12	≈20



Hamamatsu Photonics K. K.

- DSSD: 320 μm, 60 x 123 mm^2, 64 x 64 strips
  pixel size: ~1 x 2 mm^2
- Side detector: 320 μm
  Small: 60 x 60 mm^2; Large: 60 x 123 mm^2
- Veto detector: 650 μm, 60 x 123 mm^2 (4 pads)

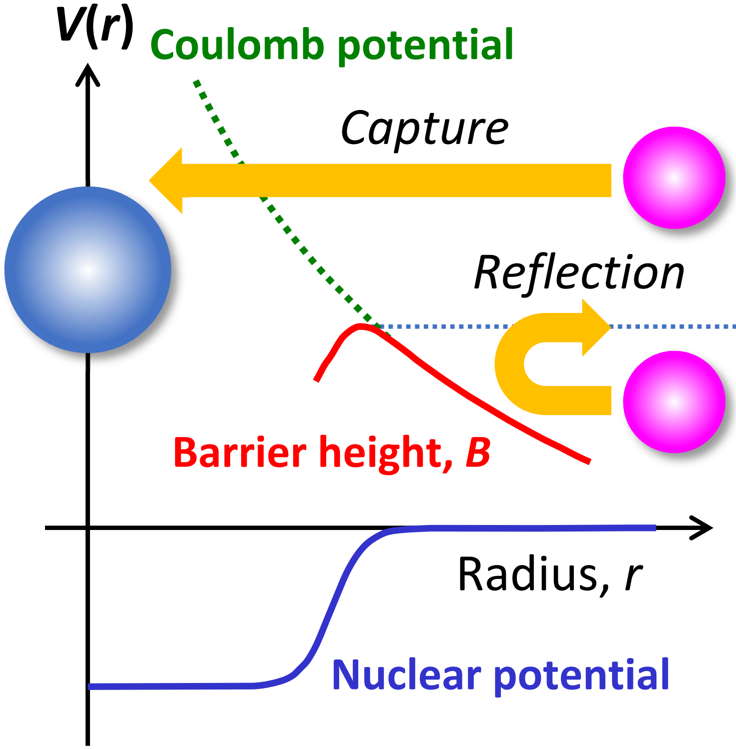
What is the optimal reaction energy ?

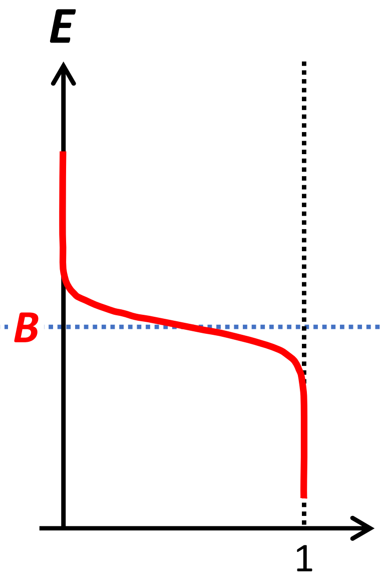
$$\sigma_{ER} = \sigma_{cap} \times P_{CN} \times P_{surv}$$

Capture | *CN formation* | *Survival of ER*

Measurement of excitation function of quasielastic backscattering to Rutherford scattering ($d\sigma_{QE}/d\sigma_{Ruth}$) by detecting non-captured projectiles

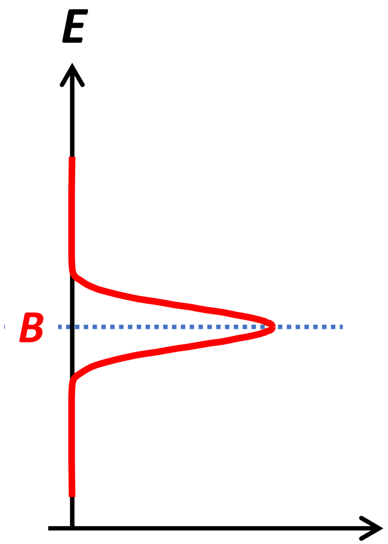
→ Optimal reaction energy for capture process





Reflection probability, $R(E)$

$$R(E) = \frac{d\sigma_{QE}}{d\sigma_{Ruth}}$$

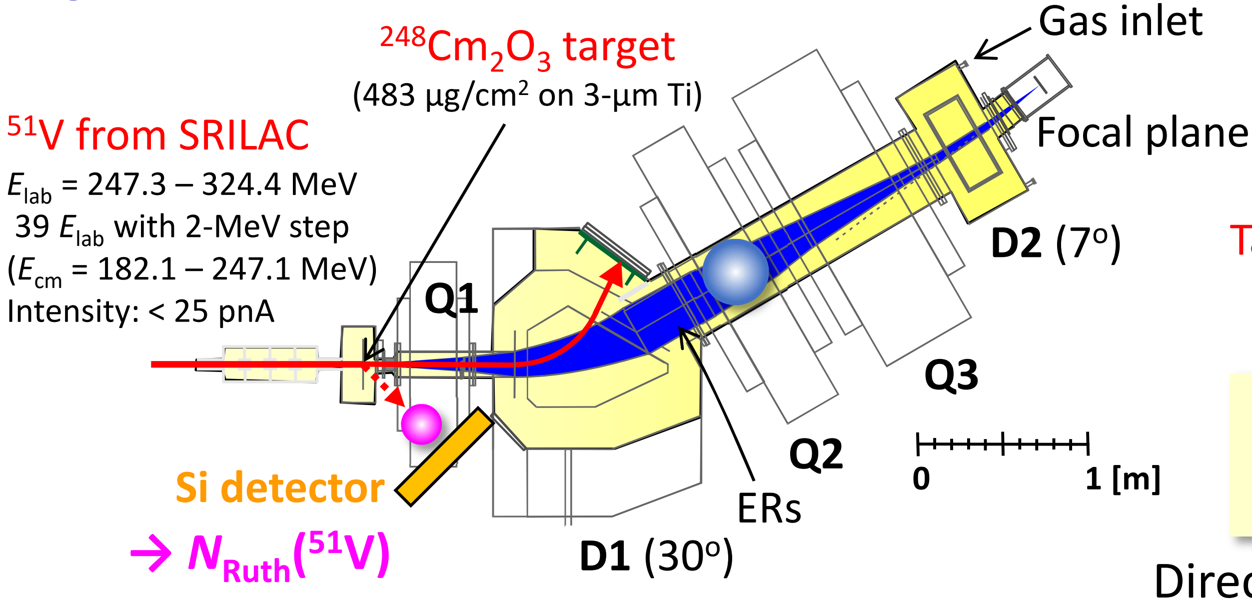


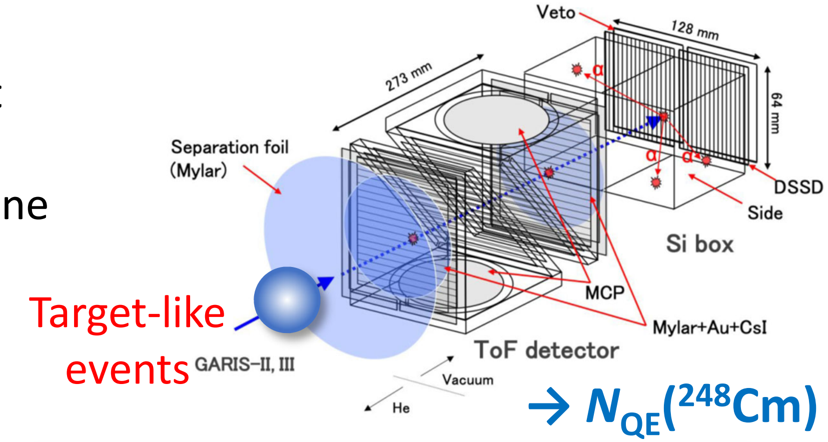
Barrier distribution, $D(E)$

$$D(E) = -\frac{dR(E)}{dE}$$

M. Tanaka, TASCA22, GSI, May 10, 2022.

Experimental method

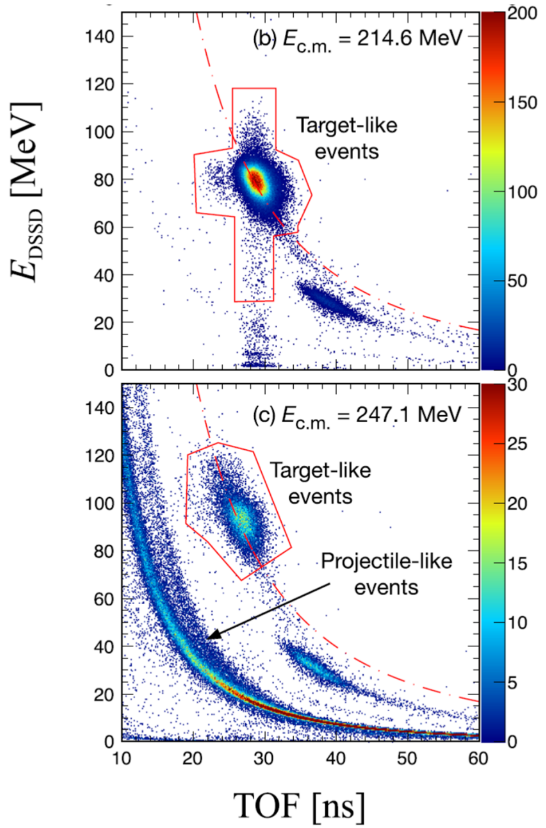


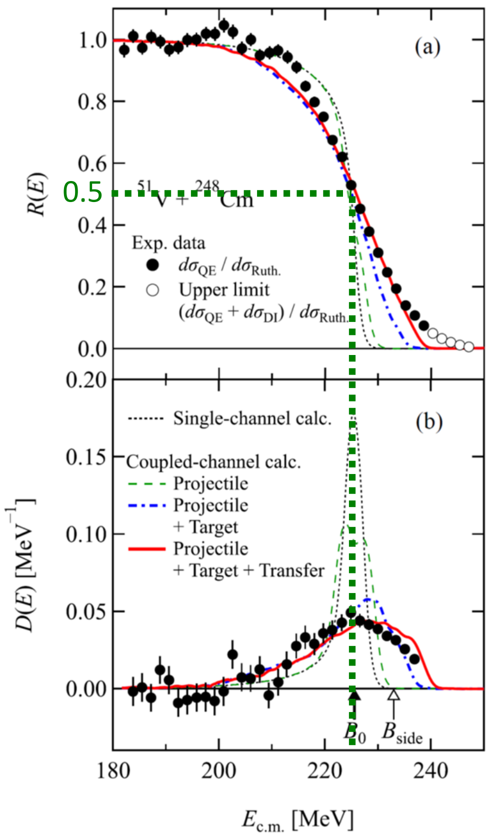


$$R(E) = \frac{d\sigma_{QE}}{d\sigma_{Ruth}} \propto \frac{N_{QE}(^{248}\mathrm{Cm})}{N_{ruth}(^{51}\mathrm{V})}$$

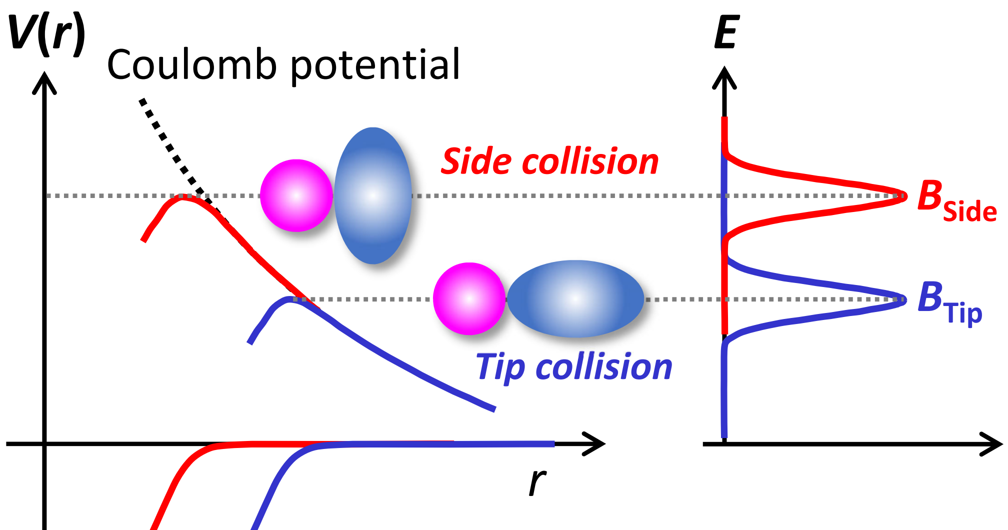
Direct measurement of QE barrier at L ~ 0

T. Tanaka et al., J. Phys. Soc. Jpn. **87**, 014201 (2018).
T. Tanaka et al., Phys. Rev. Lett. **124**, 052502 (2020).
M. Tanaka et al., J. Phys. Soc. Jpn. **91**, 084201 (2022).

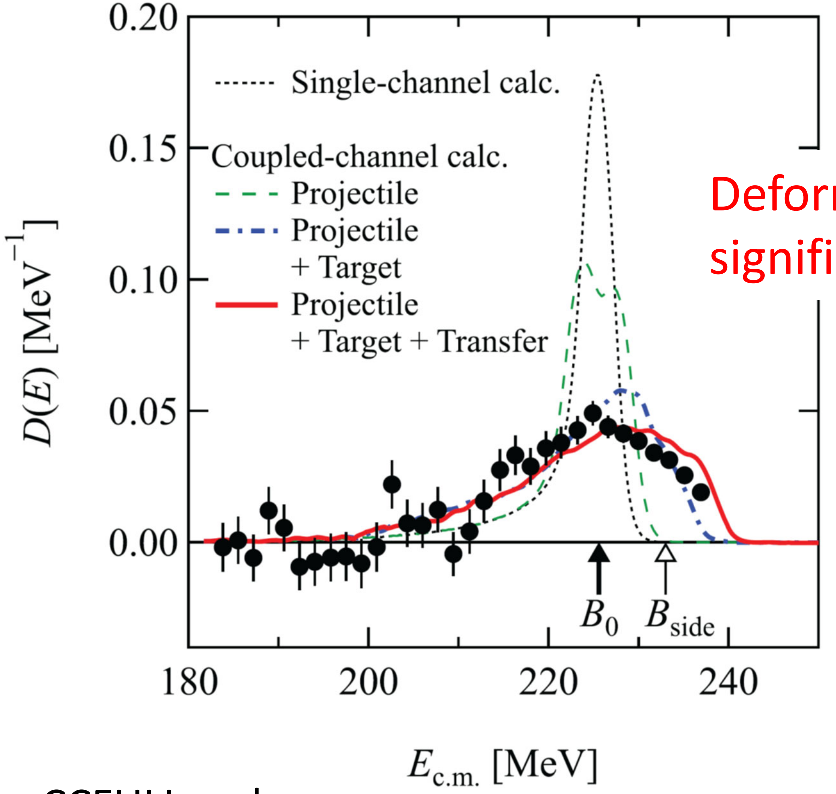




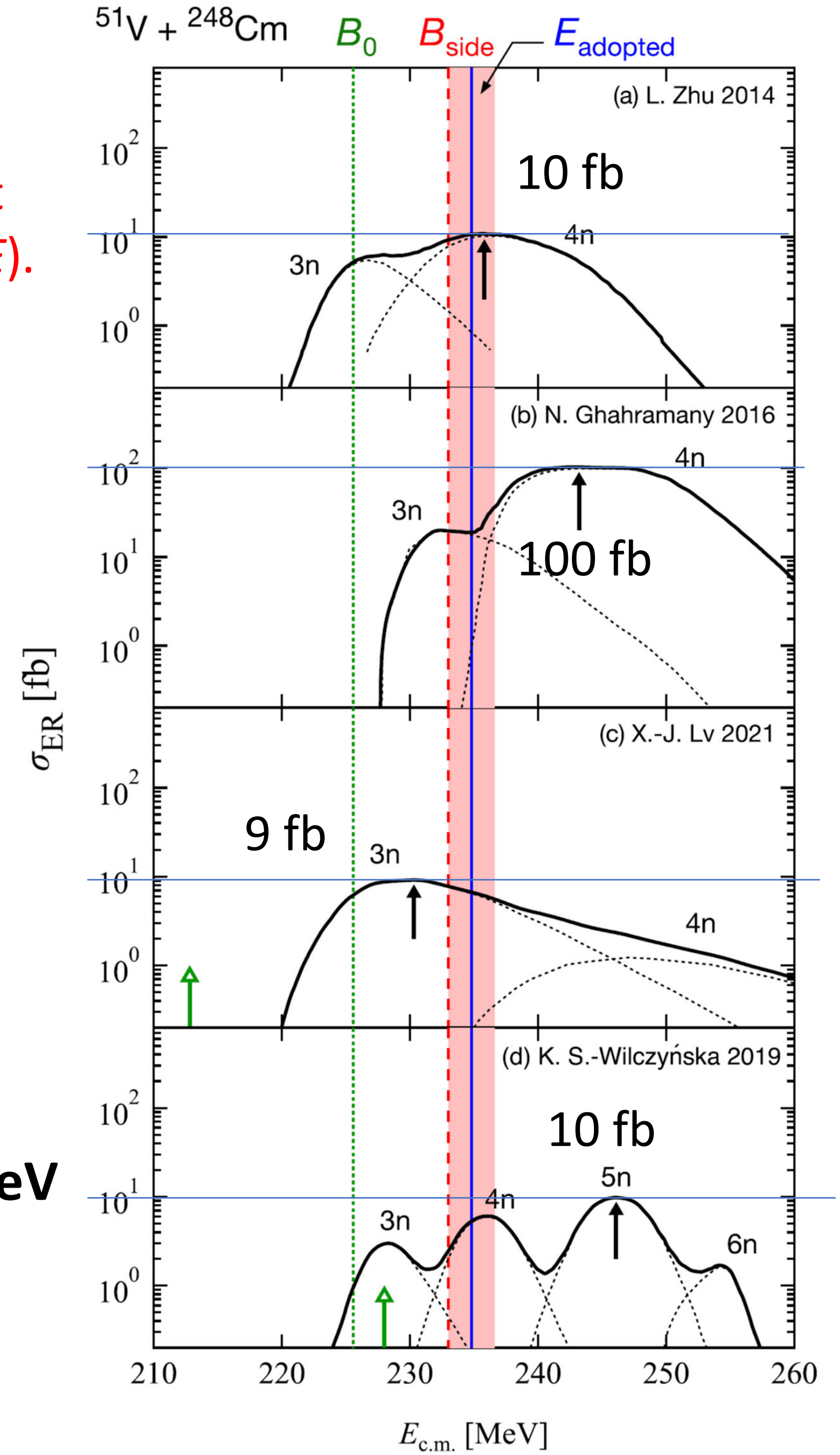
Favorable side collision in hot fusion



ex.) D. J. Hinde et al., PRL **74**, 1295 (1995).
K. Nishio et al., PRC **62**, 014602 (2000).



Deformed ^{248}Cm target significantly affects $D(E)$.



M. Tanaka et al., JPSJ **91**, 084201 (2022).

CCFULL code:

K. Hagino et al., Comput. Phys. Commun. **123**, 143 (1999).

- Average barrier height: B_0 = **225.6(2) MeV**
- Side-collision energy: B_{side} = **233.0(2) MeV** from optical potential $V(r,\vartheta)$ in CC calculation
- Uncertainty between E_{opt} & B_{side}: ΔE_{opt} = **+3.5 MeV** from the ^{48}Ca + ^{248}Cm system (+1.5% for B_{side})

T. Tanaka et al., PRL **124**, 052502 (2020).

→ Adopted energy for the ^{51}V + ^{248}Cm system

$E_{adopted} = B_{side} + 0.5 \times \Delta E_{opt}$ = **234.8 MeV**

Search for element 119 at RIBF

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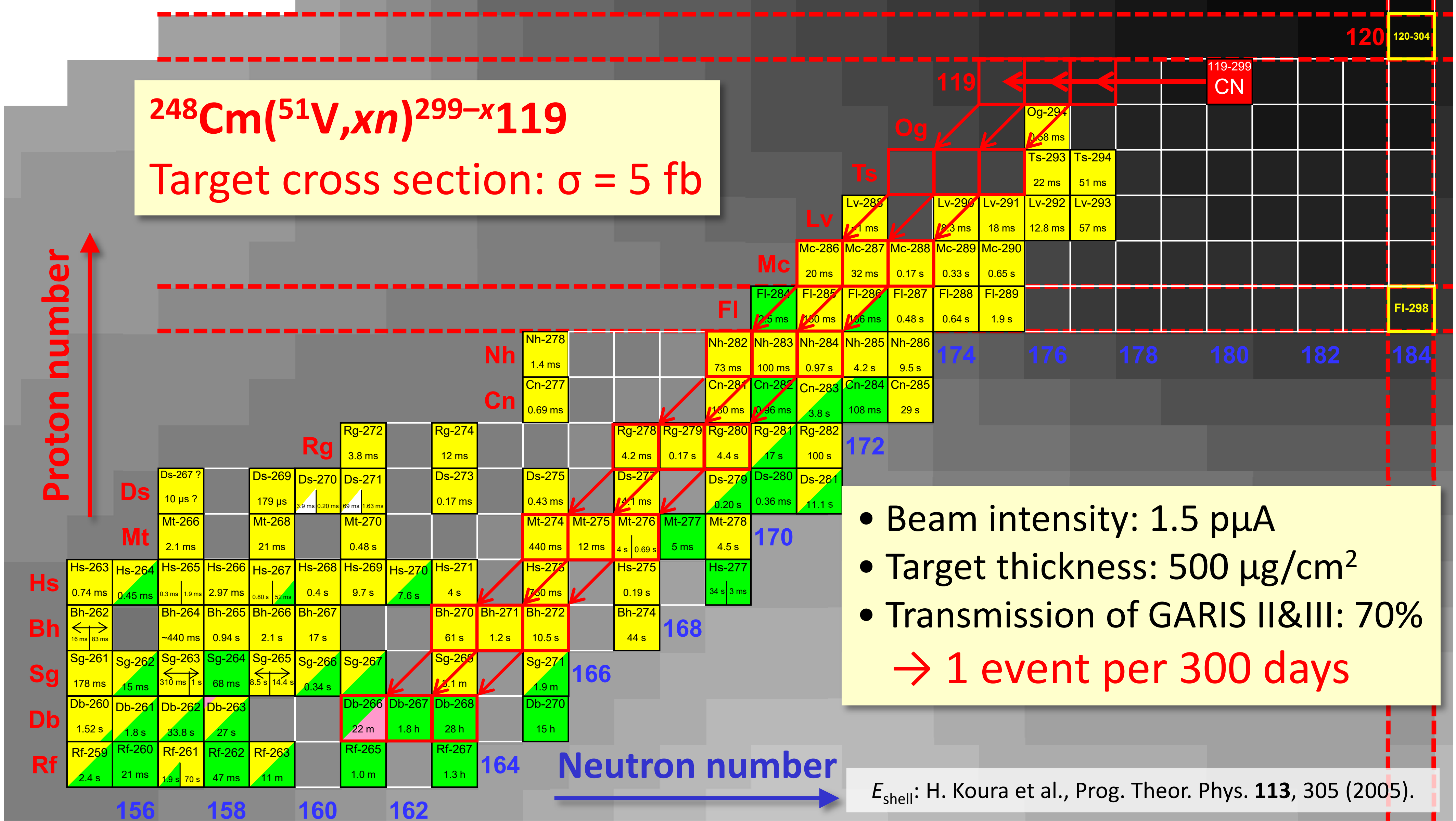
$^{248}Cm(^{51}V,xn)^{299-x}119$

Target cross section: σ = 5 fb



- Beam intensity: 1.5 pμA
- Target thickness: 500 μg/cm²
- Transmission of GARIS II&III: 70%

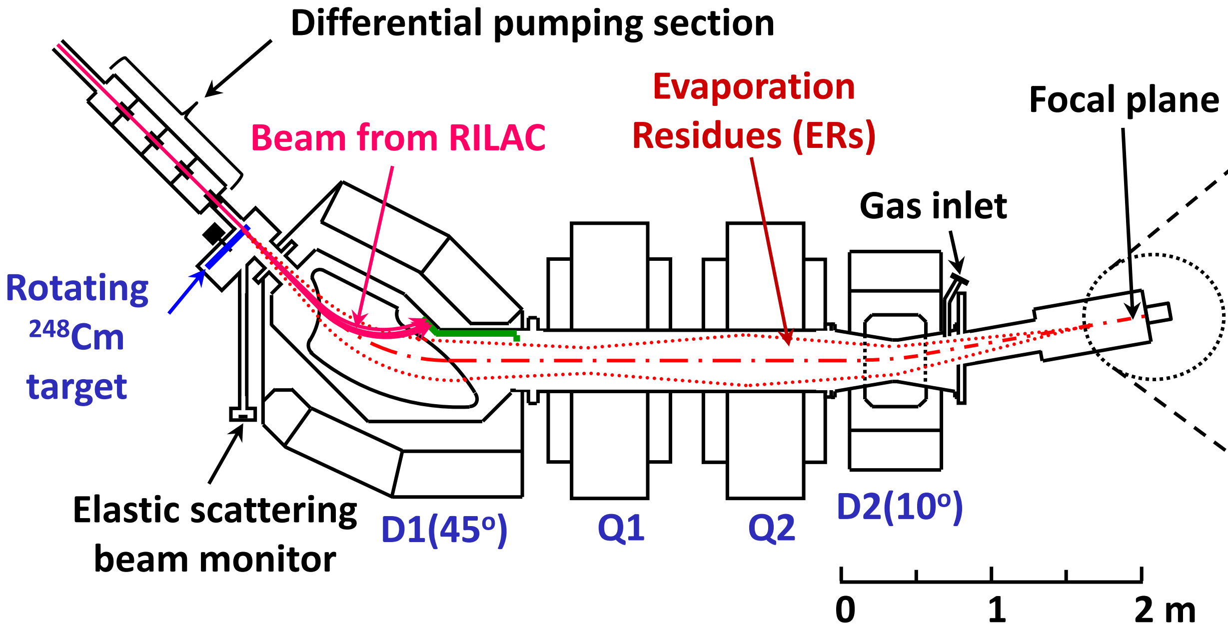
→ 1 event per 300 days

E_{shell}: H. Koura et al., Prog. Theor. Phys. **113**, 305 (2005).

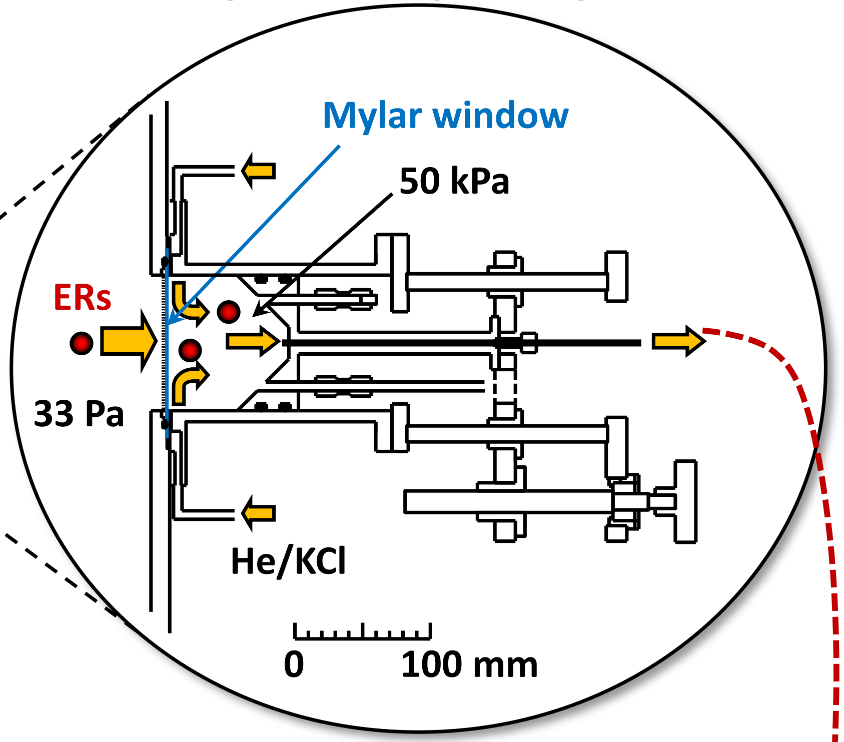
3. Production and decay studies of ^{261}Rf, ^{262}Db, ^{265}Sg, and ^{266}Bh

GARIS + gas-jet + MANON

RIKEN GARIS



Gas-jet transport system

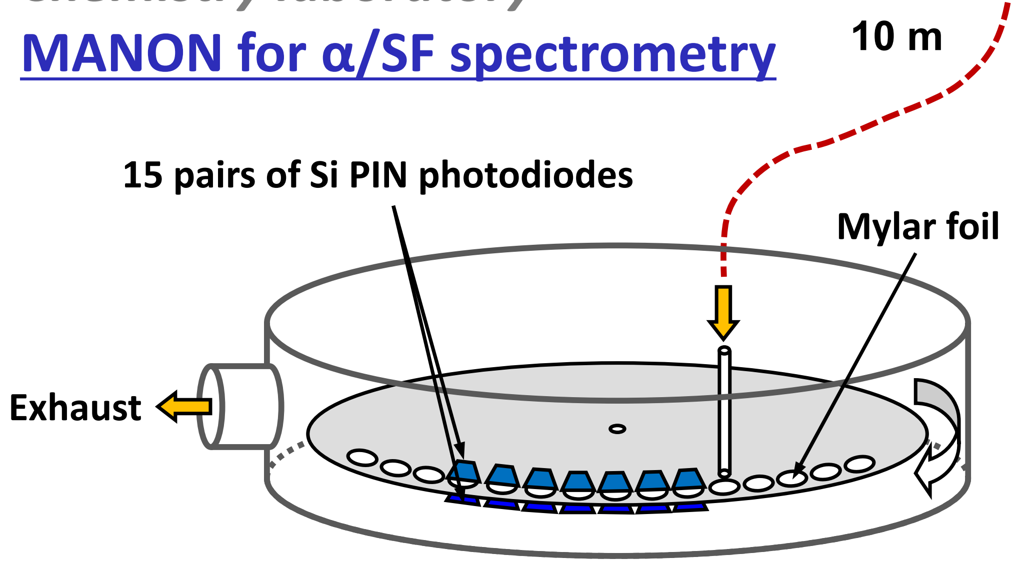


Breakthroughs in SHE chemistry

- Chemistry experiments under low background radiation
- Stable and high gas-jet transport yield
- New chemical reactions

Chemistry laboratory

MANON for α/SF spectrometry



Production and decay studies of ^{261}Rf, ^{262}Db, ^{265}Sg, and ^{266}Bh

Nuclide	^{261}Rf^{a,b} (Z=104)	^{262,263}Db (Z=105)	^{265}Sg^{a,b} (Z=106)	^{266,267}Bh (Z=107)
Half-life	68, 3 s[1)]	34 s, 27 s[2)]	8.9, 16.2 s[1)]	1.7 s, 17 s[4)]
Reaction	^{248}Cm(^{18}O,5n)	^{248}Cm(^{19}F,5;4n)	^{248}Cm(^{22}Ne,5n)	^{248}Cm(^{23}Na,5;4n)
Cross section (nb)	12[3)], ?	1.5[3)], ?	0.2–0.3[1)] ?	0.05[5)] ?
Beam energy (MeV)	95	103, 97.4	118	135, 131, 126, 121
Beam intensity (pμA)	7	4	3	3
$^{248}Cm_2O_3$ target (μg/cm^2)	280, 230	230, 290, 330	230, 280	290, 260, 270
Magnetic rigidity (Tm)	1.58–2.16	1.73–2.09	1.73–2.16	2.12
GARIS He (Pa)	33	32	33	33
GARIS transmission (%)	7.8±1.7	8.1±2.2	13	15
RTC Mylar window (μm)	0.5	0.5	0.7	0.7
Honeycomb grid (%)	78/84	84	72/84	78
Gas-jet He (kPa)	49	47	49	80
Chamber depth (mm)	20	20	40	20
He flow rate (L/min)	2.0	2.0	2.0	5.0
KCl generator (^{o}C)	620	620	600/605	620
MANON step interval (s)	30.5, 2.0	15.5	20.5, 10.5	5.0, 8.5, 15.0

1) Düllmann and Türler, PRC **77**, 064320 (2008). 2) Firestone and Shirley, *Table of Isotopes*, 8th ed. (Wiley, New York, 1996).
3) Nagame et al., JNRS **3**, 85 (2002). 4) Wilk et al., PRL **85**, 2697 (2000). 5) Morita et al., JSPS **78**, 064201 (2009).

Production and decay studies of ^{266,267}Bh

^{22}Na beam energy (MeV)	Thickness of $^{248}Cm_2O_3$ target (μg/cm^2)	Beam integral (×10^{18})	MANON Step interval (s)
121	257	10.20	8.5
126	256	9.26	8.5
131	290	4.96	5.0
	290	3.99	15.0
	257	8.90	8.5
	257	9.02	8.5
135	256	11.21	8.5

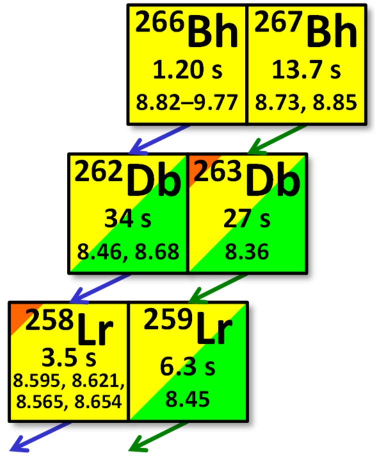
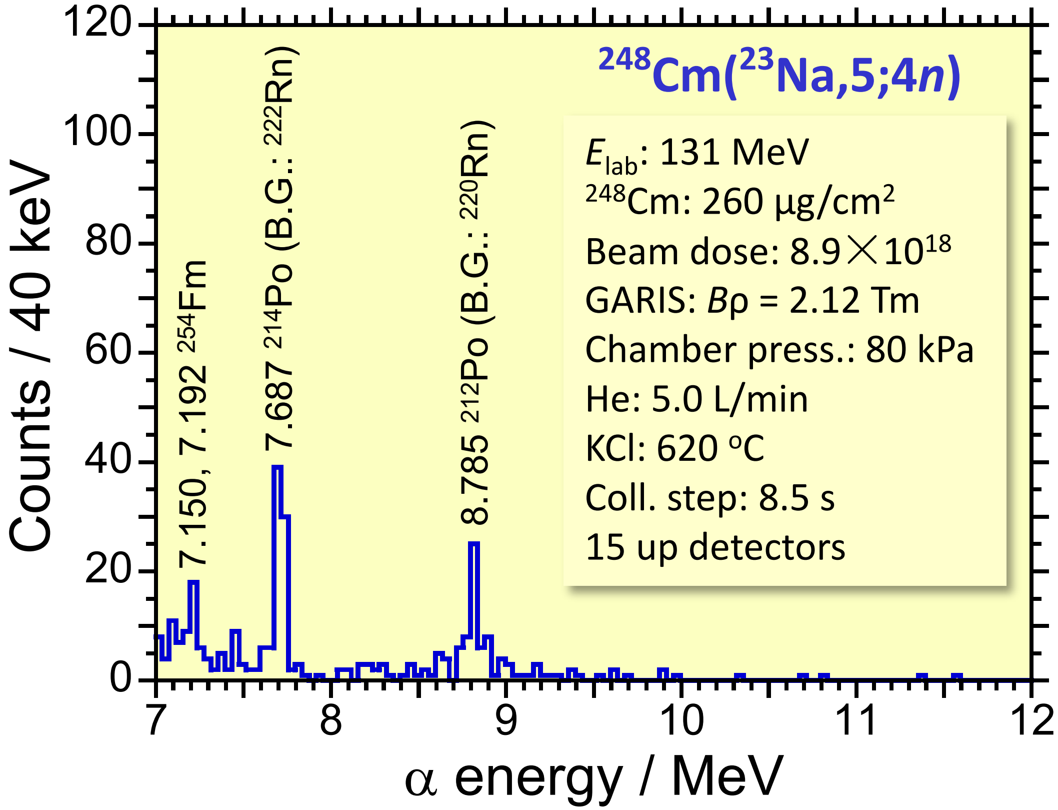


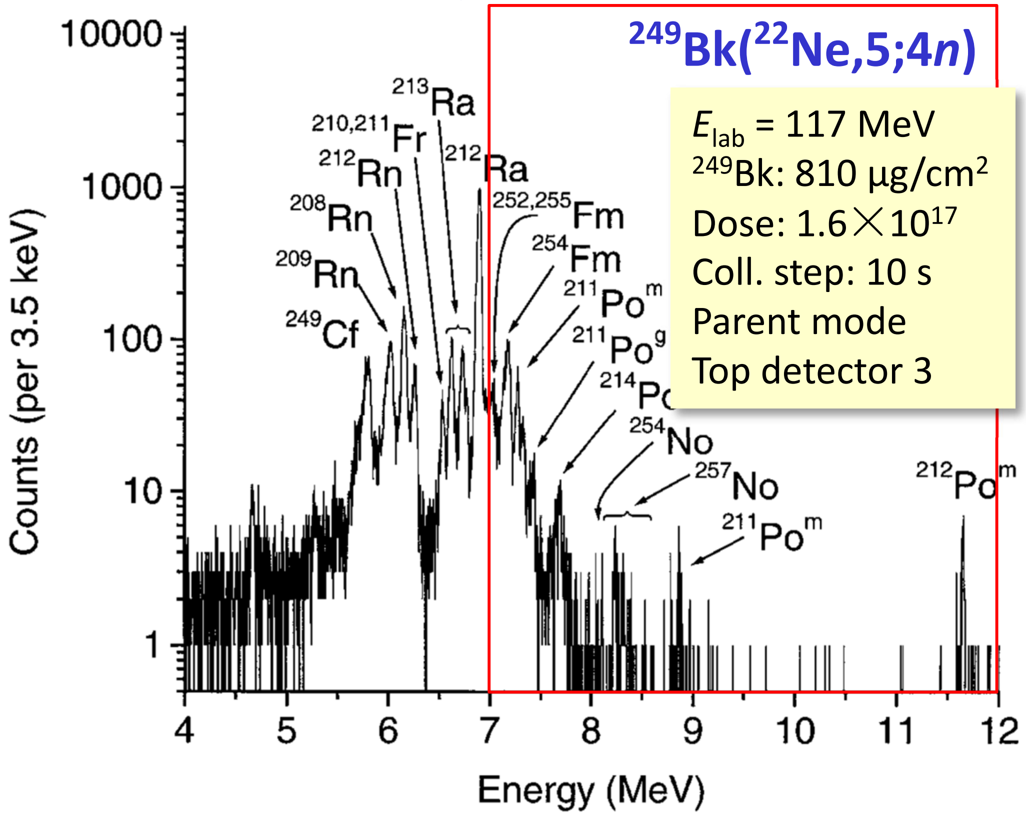
Table of Isotopes, 8th ed. (1996).
Wilk *et al.*, PRL **85**, 2697 (2000).
Eichler *et al.*, Nature **407**, 63 (2000).
Gan *et al.*, EPJA **20**, 385 (2004).
Qin *et al.*, NPR **23**, 400 (2006).
Morita *et al.*, JSPS **78**, 064201 (2009).
Morita *et al.*, JSPS **81**, 103210 (2012).
Haba *et al.*, PRC **89**, 024618 (2014).

GARIS + gas-jet + MANON II



H. Haba et al., Phys. Rev. C **102,** 024625 (2020).

Gas-jet + MG



P. A. Wilk et al., Phys. Rev. Lett. **85**, 2697 (2000).

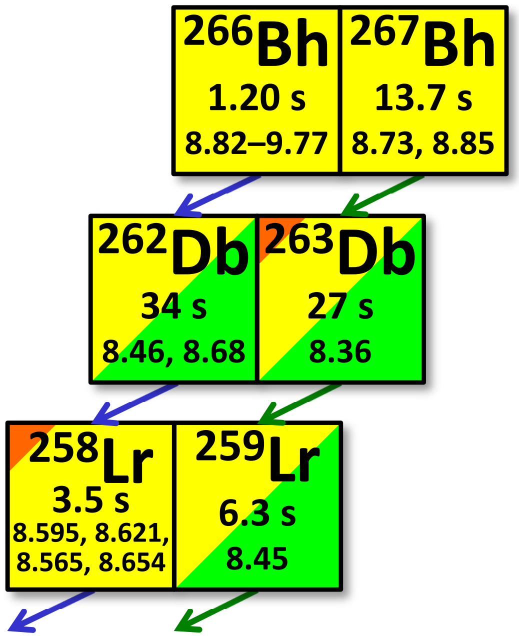
Search for α-α/SF correlations

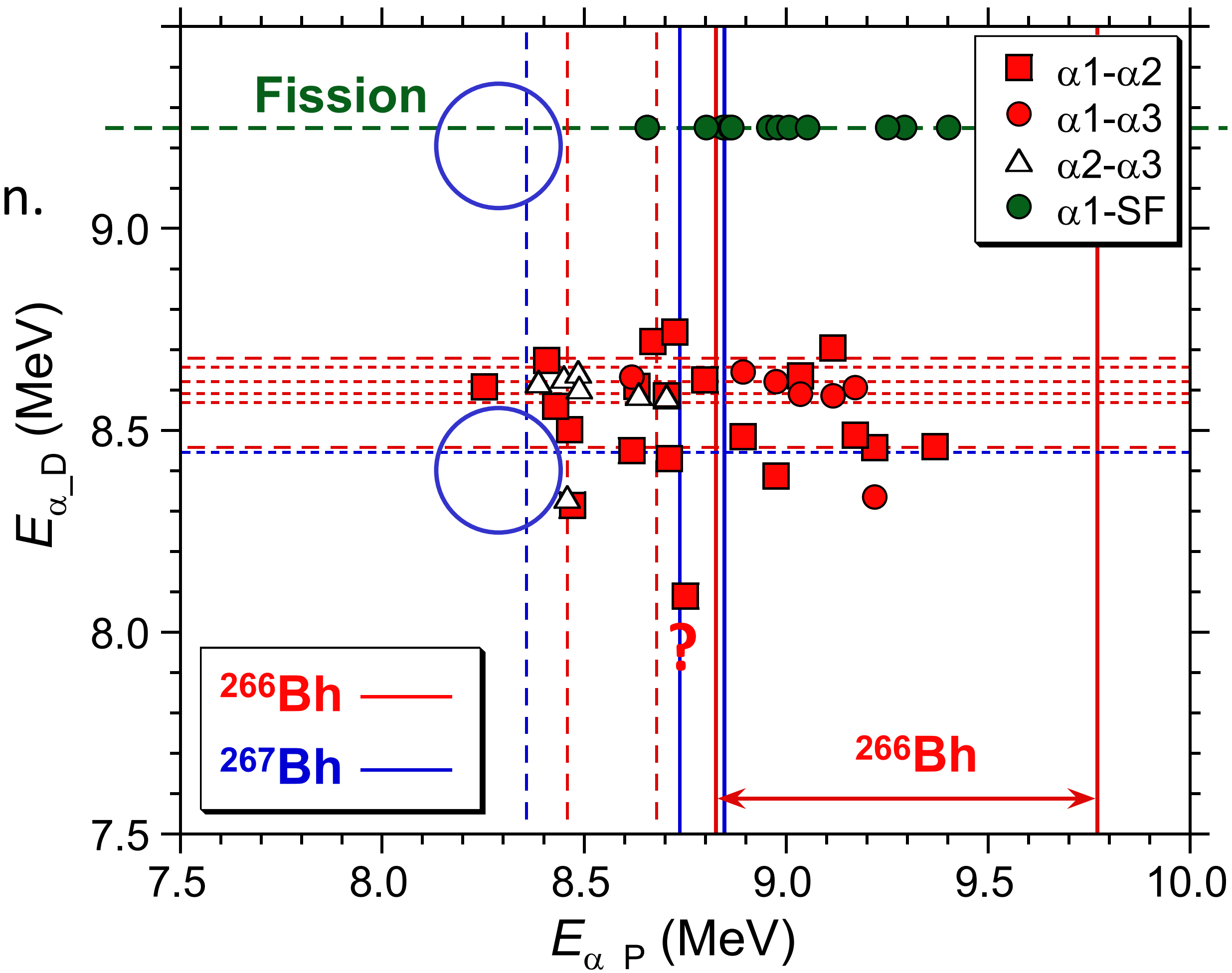
$E_{\alpha 1}$ = 8.00–10.00 MeV

$E_{\alpha 2;\, \alpha 3}$ = 8.00–8.77 MeV

E_{SF} ≥ 20 MeV; Si top & bottom coin.

$\Delta T \leq 340$ s [= 10 $T_{1/2}(^{262}Db)$]





Energy (MeV)	α-α-α		α-α		α-SF		α-α-SF	
	Obs.	RDM	Obs.	RDM	Obs.	RDM	Obs.	RDM
121	**0**	<0.00	**0**	<0.15	**0**	<0.02	**0**	<0.00
126	**0**	<0.00	**1**	<0.16	**3**	<0.03	**0**	<0.00
131	**5**	<0.00	**21**	<1.09	**10**	<0.13	**0**	<0.00
135	**2**	<0.00	**9**	<0.15	**0**	<0.02	**0**	<0.00
Total	**7**	<0.00	**31**	<1.55	**13**	<0.19	**0**	<0.00

Decay properties of ^{266}Bh

- E_α of ^{266}Bh: E_α = 8.62–9.40 MeV.
  ↔ E_α = 8.82–9.77 MeV in Refs.

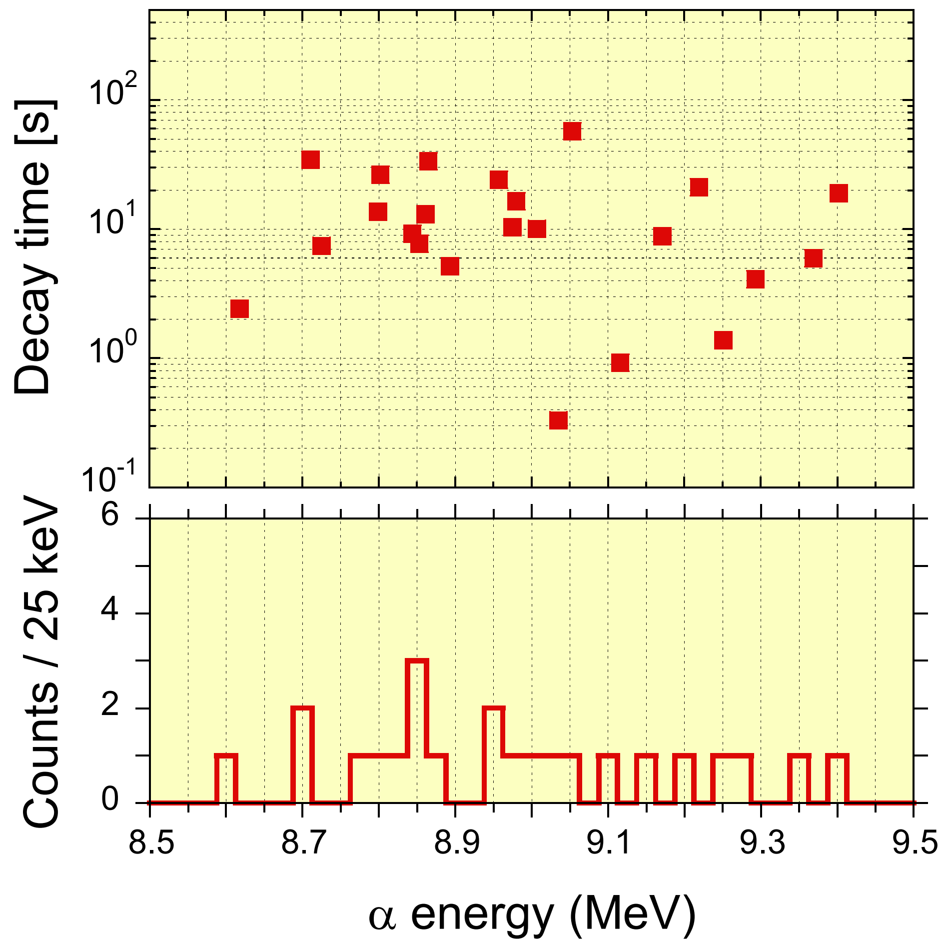
- $T_{1/2}$ = 10.0 s in this work is longer than those of ^{266}Bh in Refs.

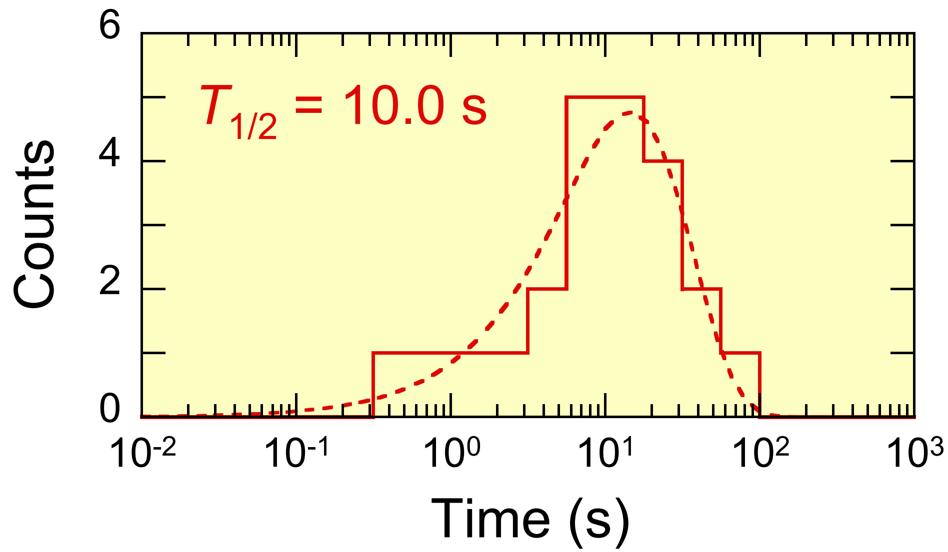
Nuclide	This work		Refs. [1–4]	
	N	$T_{1/2}$ [s]	N	$T_{1/2}$ [s]
^{266}Bh	**23**	**$10.0^{+2.6}_{-1.7}$**	**8**	**$1.20^{+0.66}_{-0.31}$**
^{267}Bh	**0**	**–**	**11**	**$13.7^{+5.9}_{-3.2}$**

[1] ^{249}Bk(^{22}Ne,5;4n)^{266,267}Bh (N = 1, 5): Wilk *et al.*, PRL **85**, 2697 (2000).
[2] ^{249}Bk(^{22}Ne,4n)^{267}Bh (N = 6): Eichler *et al.*, Nature **407**, 63 (2000).
[3] ^{243}Am(^{26}Mg,3n)^{266}Bh (N = 4): Qin *et al.*, Nucl. Phys. Rev. **23**, 400 (2006).
[4] ^{209}Bi(^{70}Zn,n)^{278}113 → ^{266}Bh (N = 3): Morita *et al.*, JPSJ **81**, 103201 (2012).

- Existence of an isomeric state in ^{266}Bh? Miss assignment of ^{266}Bh to ^{267}Bh in the previous experiments?

- The long half-life of ^{266}Bh is good for Bh chemistry.

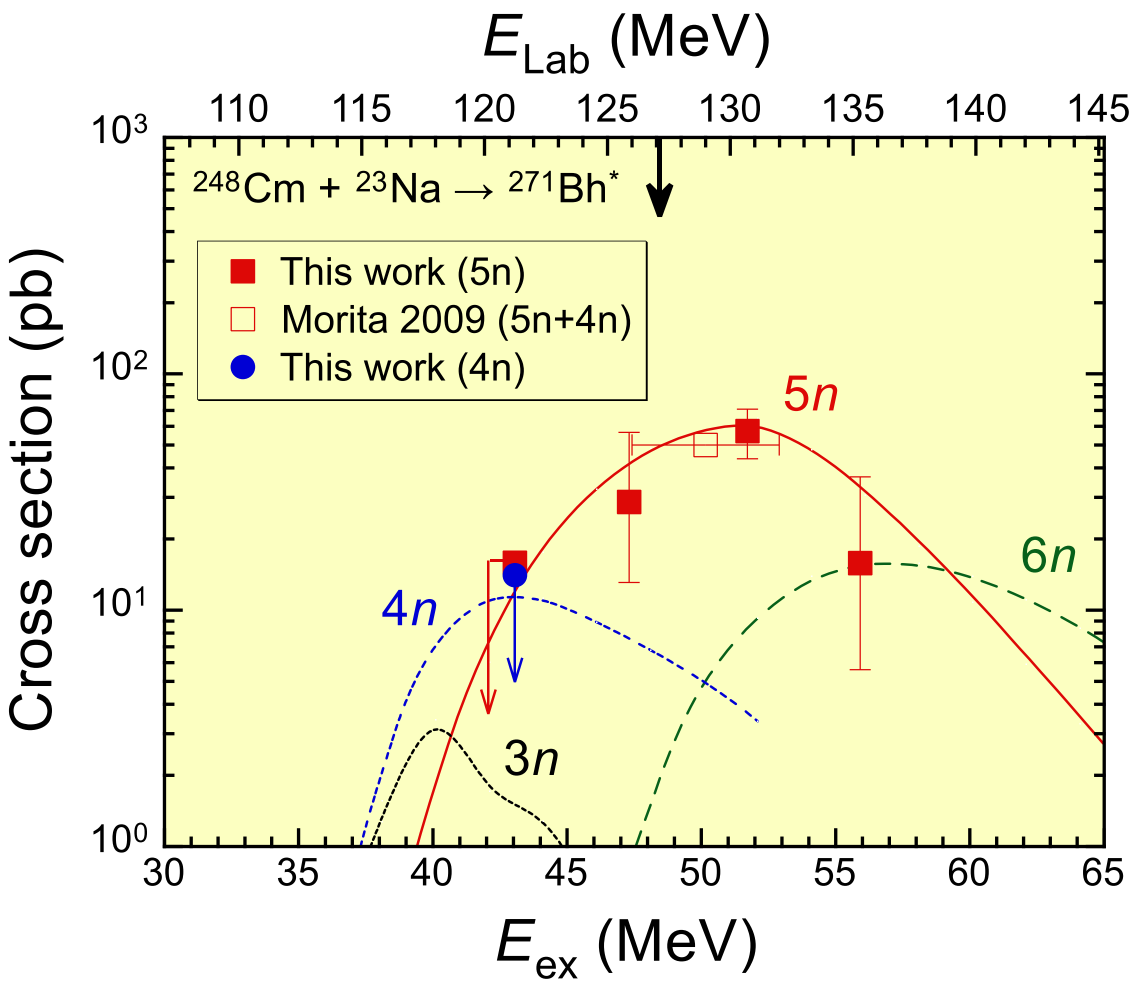




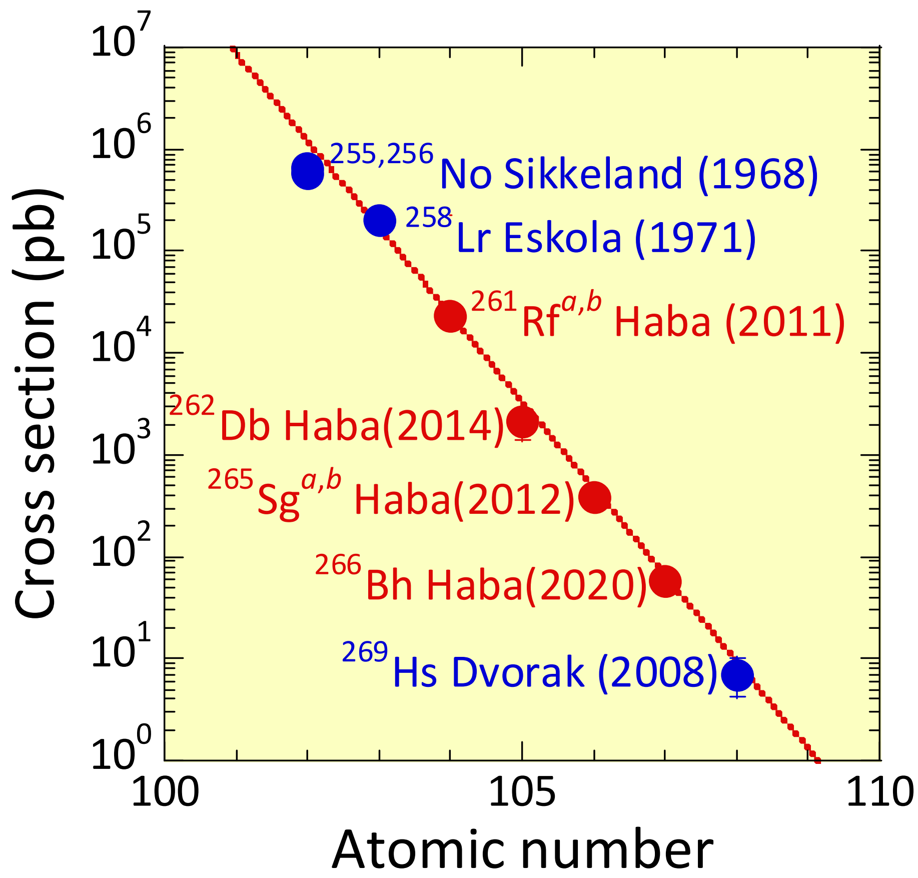
Cross section of ^{248}Cm(^{23}Na,5*n*)^{266}Bh

Reaction	Cross section at 131 MeV	Reaction*	Cross sections* at 117/123 MeV
^{248}Cm(^{23}Na,5*n*)^{266}Bh	**57 ± 14 pb**	^{249}Bk(^{22}Ne,5*n*)^{266}Bh	-/25–250 pb
		^{249}Bk(^{22}Ne,4*n*)^{267}Bh	$58^{+33}_{-15}/96^{+55}_{-25}$ pb

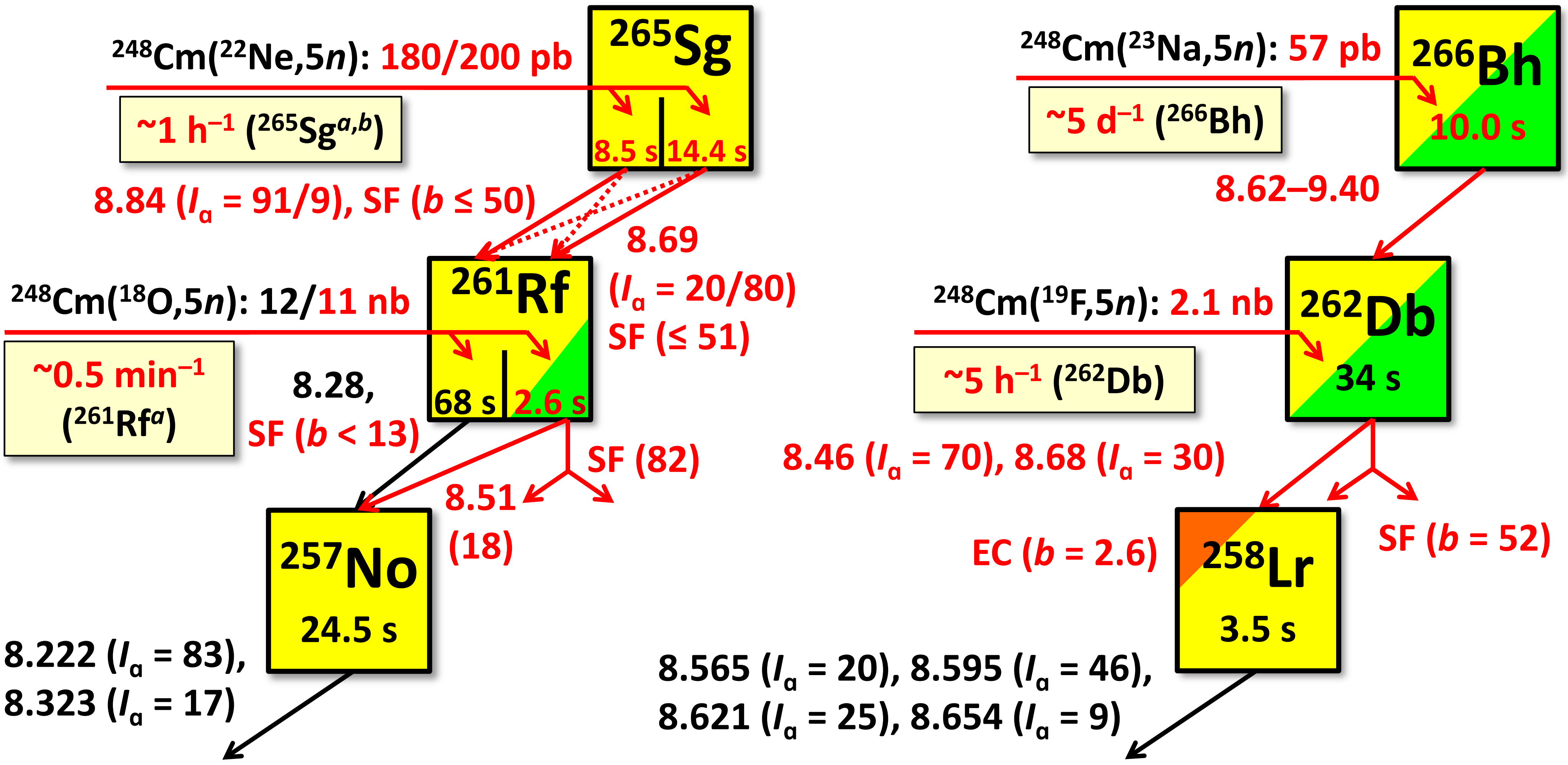
*Wilk *et al.*, PRL **85**, 2697 (2000).



Cross sections for ^{248}Cm(*X*,5*n*)



Production and decay studies of ^{261}Rf, ^{262}Db, ^{265}Sg, and ^{266}Bh



H. Haba et al., Chem. Lett. **38**, 426 (2009).
H. Haba et al., Phys. Rev. C **83**, 034602 (2011).
H. Haba et al., Phys. Rev. C **85**, 024611 (2012).
M. Murakami et al., Phys. Rev. C **88**, 024618 (2013).
H. Haba et al., Phys. Rev. C **89**, 024618 (2014).
H. Haba, EPJ Web Conf. **131**, 07006 (2016).
H. Haba et al., Phys. Rev. C **102,** 024625 (2020).

Pre-separated SHE RIs are ready for chemistry experiments.

4. Summary

- Present status of RIKEN RIBF facilities for SHE research was introduced.
- RILAC was upgraded as SRILAC to search for elements with $Z \geq 119$.
- A synthesis experiment of element 119 is ongoing in the $^{248}Cm(^{51}V,xn)^{299-x}119$ reaction using GARIS III at SRILAC.
- Production and decay properties of ^{261}Rf, ^{262}Db, ^{265}Sg, and ^{266}Bh were investigated using the GARIS gas-jet system coupled to the rotating wheel apparatus for α and SF spectrometry.