Present Status and Perspectives of SHE Researches at RIKEN

RIKEN Nishina Center

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for RIKEN SHE Collaboration

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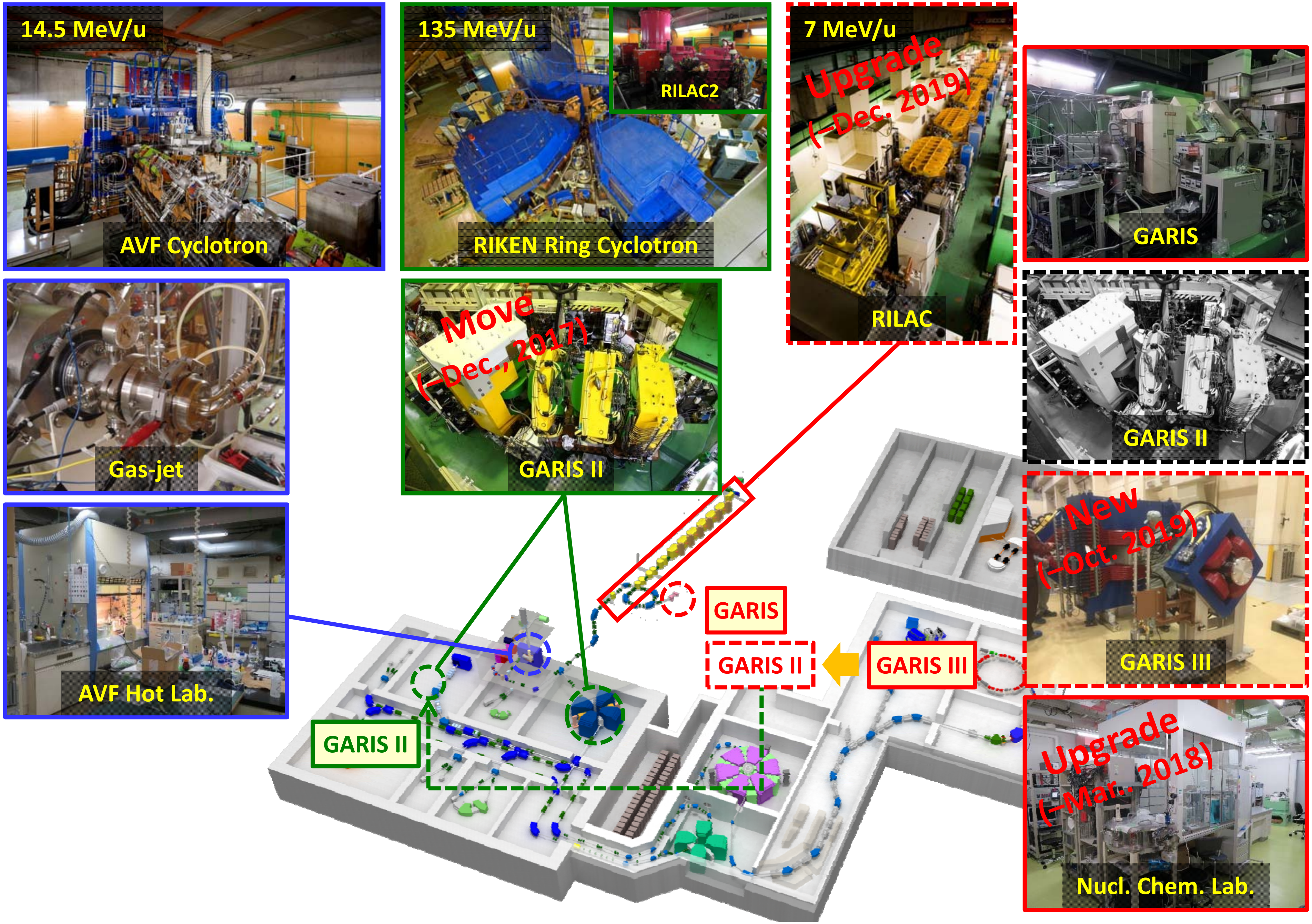
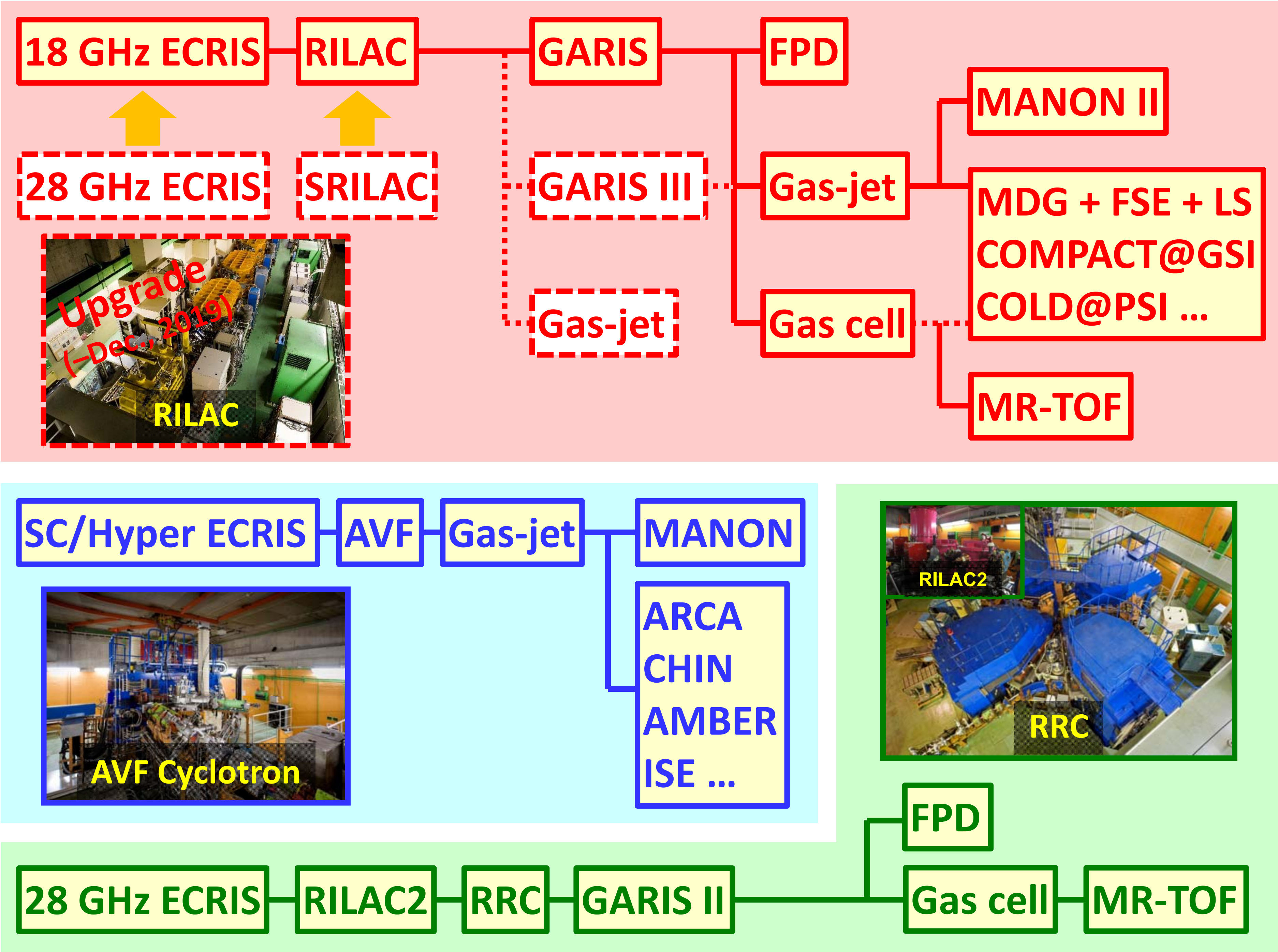
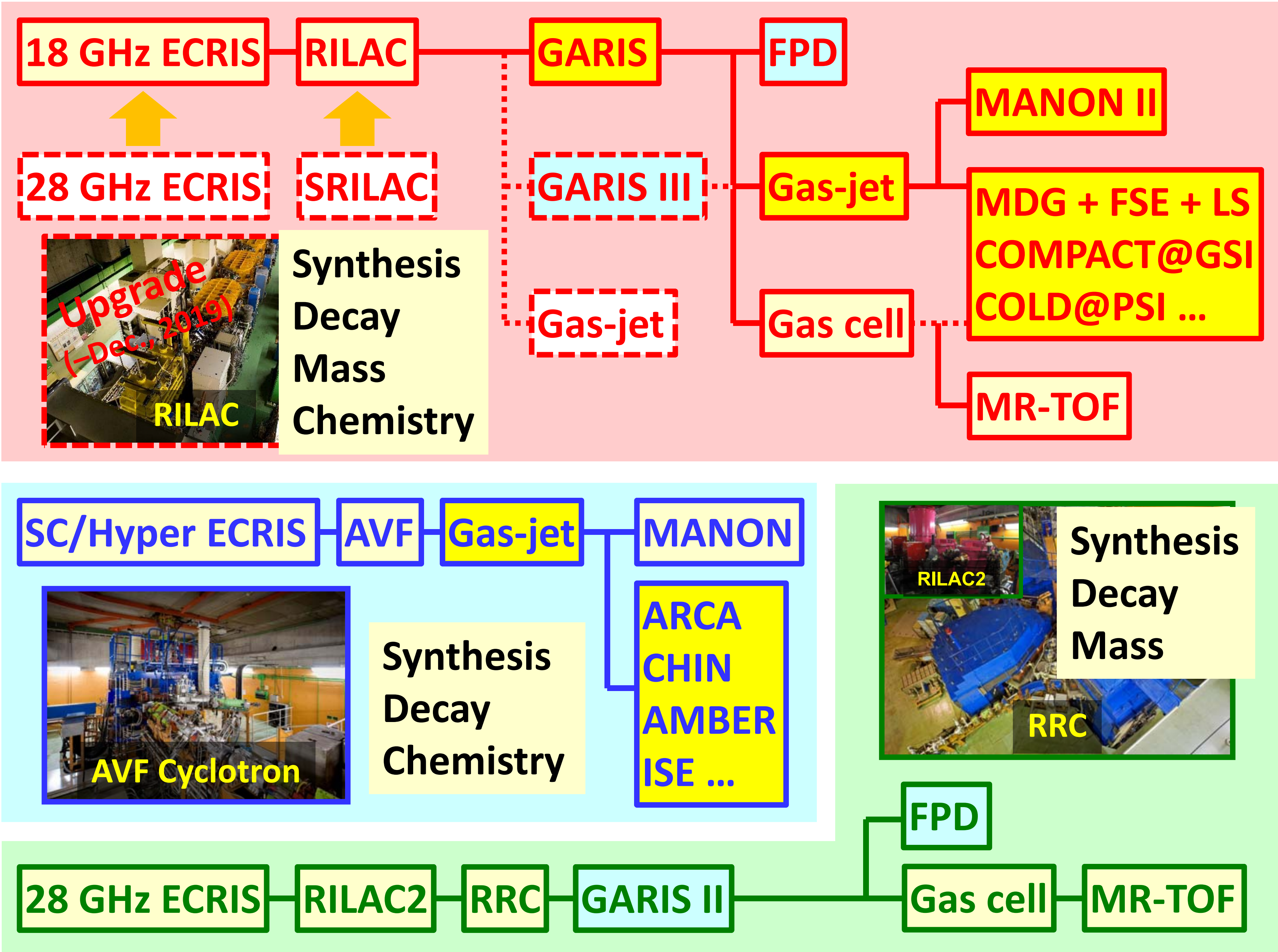
1. RIKEN RIBF for SHE researches

Present status of RIBF for SHE studies




18 GHz ECRIS
RILAC
GARIS
FPD
MANON II
28 GHz ECRIS
SRILAC
GARIS III
Gas-jet
MDG + FSE + LS
COMPACT@GSI
COLD@PSI …
Upgrade
(–Dec., 2019)
RILAC
Gas-jet
Gas cell
MR-TOF
SC/Hyper ECRIS
AVF
Gas-jet
MANON
ARCA
CHIN
AMBER
ISE …
AVF Cyclotron
RILAC2
RRC
FPD
28 GHz ECRIS
RILAC2
RRC
GARIS II
Gas cell
MR-TOF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RILAC
Synthesis
Decay
Mass
Chemistry
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MR-TOF
SC/Hyper ECRIS
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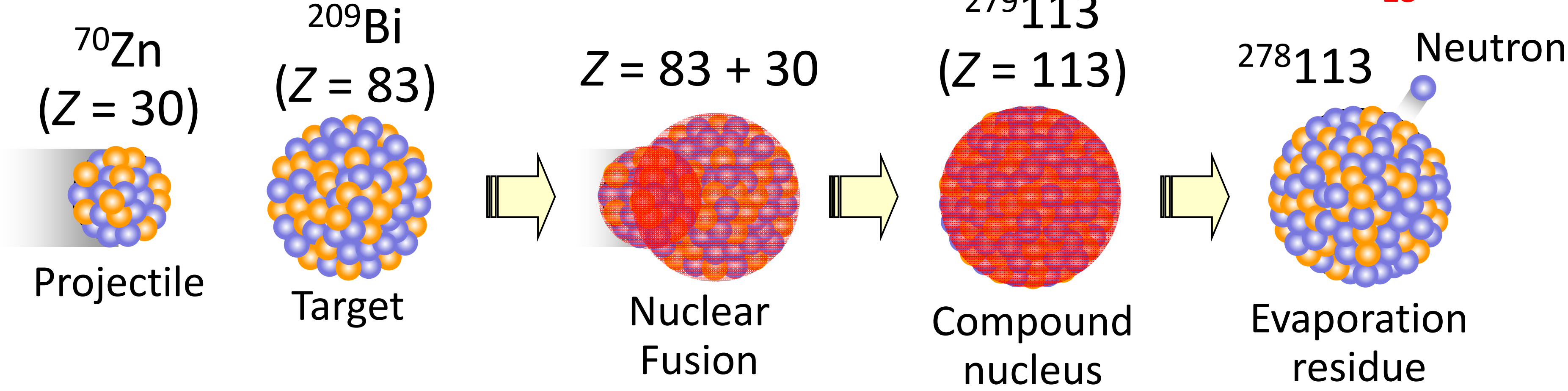
MANON
ARCA
CHIN
AMBER
ISE …
AVF Cyclotron
Synthesis
Decay
Chemistry
RILAC2
RRC
Synthesis
Decay
Mass
FPD
28 GHz ECRIS
RILAC2
RRC
GARIS II
Gas cell
MR-TOF

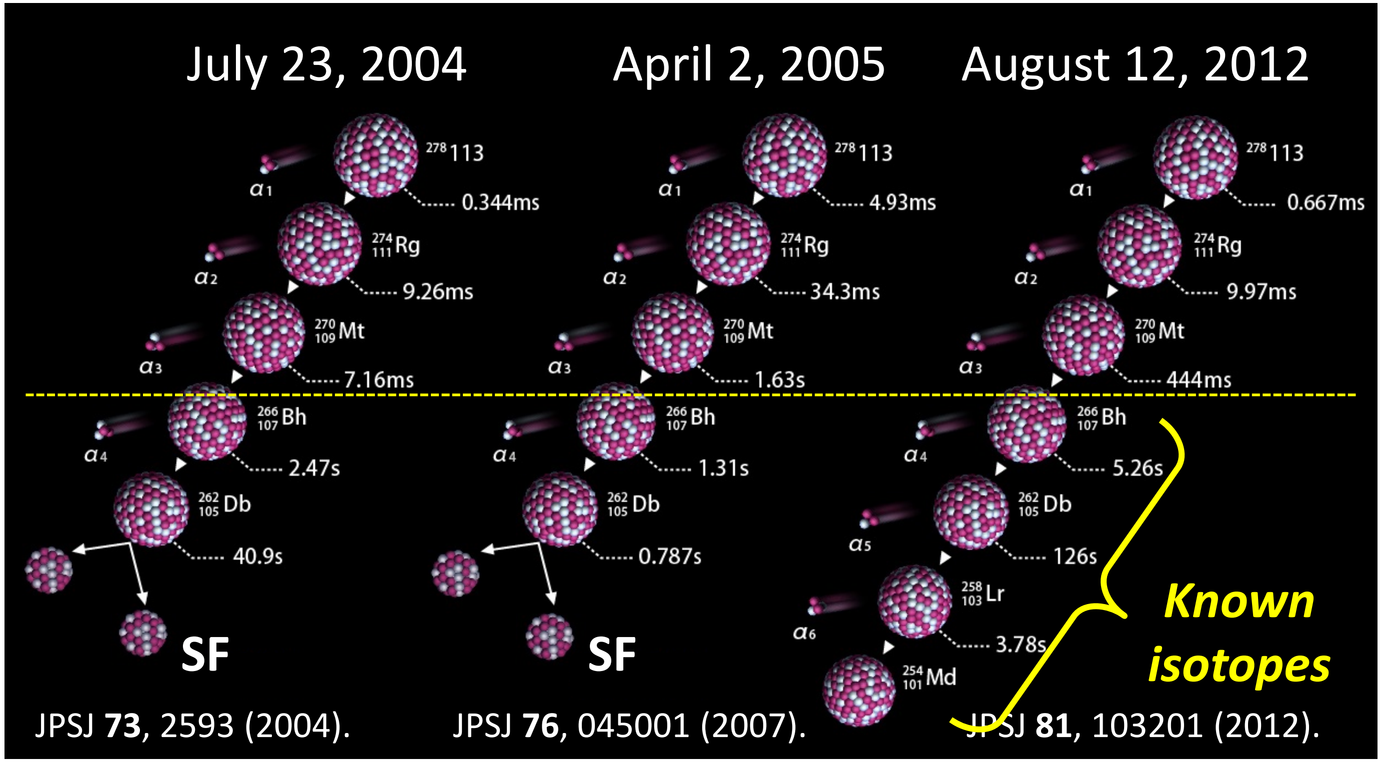
2. Search for element 119

Production of element 113 at RIBF

Cold fusion reaction of $^{209}Bi(^{70}Zn,n)^{278}113$

$\sigma = 22^{+20}_{-13}$ fb





Nihonium – *The first element discovered in Asian countries* –

INTERNATIONAL UNION OF
PURE AND APPLIED CHEMISTRY

Advancing Chemistry Worldwide

For Immediate Release 30 November 2016

IUPAC Announces the Names of the Elements 113, 115, 117, and 118

Elements 113, 115, 117, and 118 are now formally named nihonium (Nh), moscovium (Mc), tennessine (Ts), and oganesson (Og)

Research Triangle Park, NC (USA): On 28 November 2016, the International Union of Pure and Applied Chemistry (IUPAC) approved the names and symbols for four elements: nihonium (Nh), moscovium (Mc), tennessine (Ts), and oganesson (Og), respectively for element 113, 115, 117, and 118.

Naming ceremony in Tokyo, March 14, 2017

Atomic number	Element name	Element symbol
113	nihonium	Nh
115	moscovium	Mc
117	tennessine	Ts
118	oganesson	Og

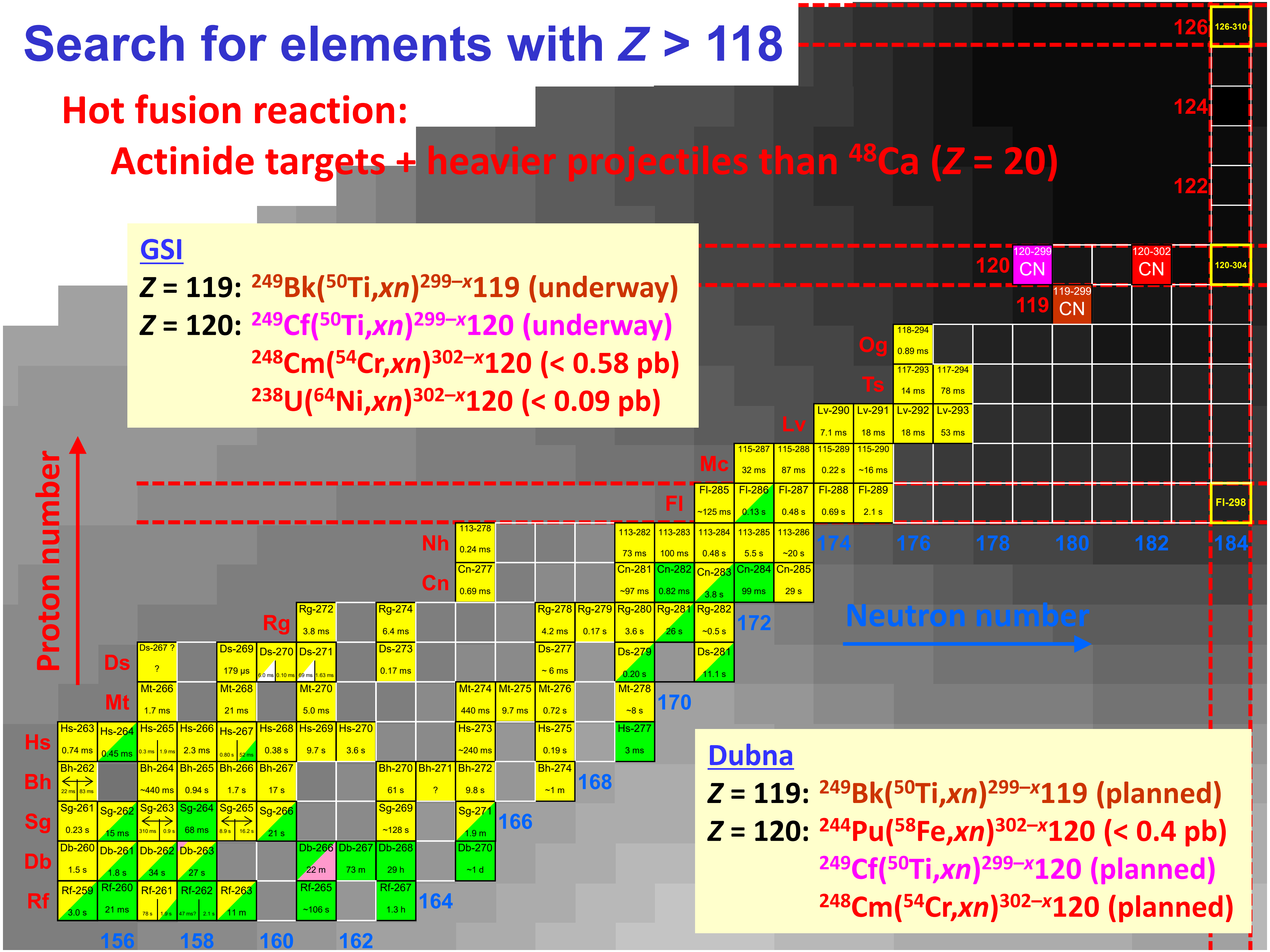
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57-71 *	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89-103 †	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

*Lanthanoide	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
†Actinoide	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Search for elements with $Z > 118$

Hot fusion reaction:

Actinide targets + heavier projectiles than ^{48}Ca ($Z = 20$)



GSI

Z = 119: ^{249}Bk(^{50}Ti,xn)$^{299-x}$119 (underway)

Z = 120: ^{249}Cf(^{50}Ti,xn)$^{299-x}$120 (underway)

^{248}Cm(^{54}Cr,xn)$^{302-x}$120 (< 0.58 pb)

^{238}U(^{64}Ni,xn)$^{302-x}$120 (< 0.09 pb)

Dubna

Z = 119: ^{249}Bk(^{50}Ti,xn)$^{299-x}$119 (planned)

Z = 120: ^{244}Pu(^{58}Fe,xn)$^{302-x}$120 (< 0.4 pb)

^{249}Cf(^{50}Ti,xn)$^{299-x}$120 (planned)

^{248}Cm(^{54}Cr,xn)$^{302-x}$120 (planned)

Search for element 119

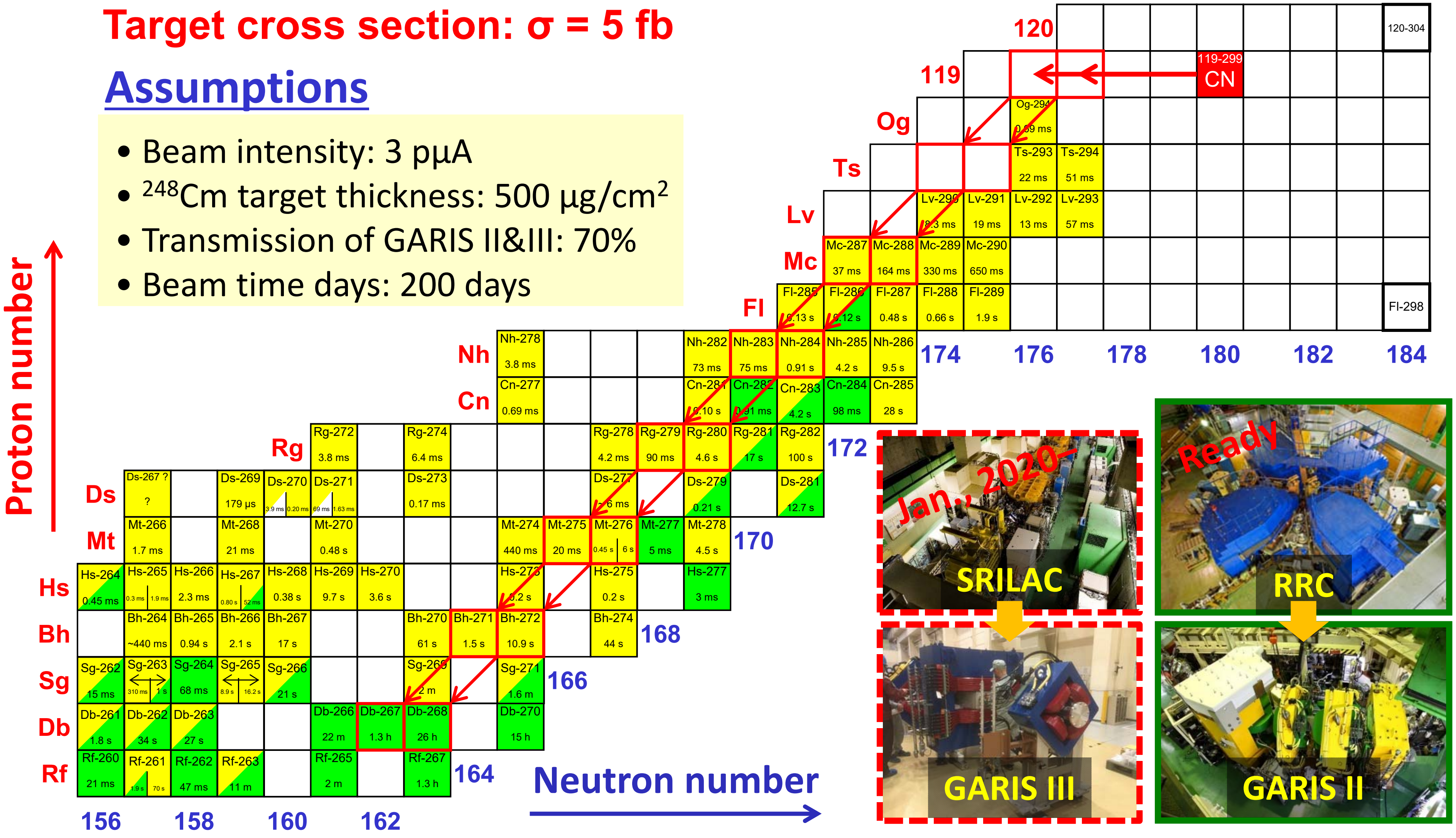
RIKEN – ORNL – JINPA – UTK - Kyushu Univ. – Niigata Univ. – Saitama Univ. – Osaka Univ. – Tohoku Univ. – JAEA – Yamagata Univ. – IPHC – IMP Collaboration

^{248}Cm(^{51}V,*xn*)$^{299-x}$119 ↔ ^{249}Bk(^{50}Ti,*xn*)$^{299-x}$119

Target cross section: σ = 5 fb

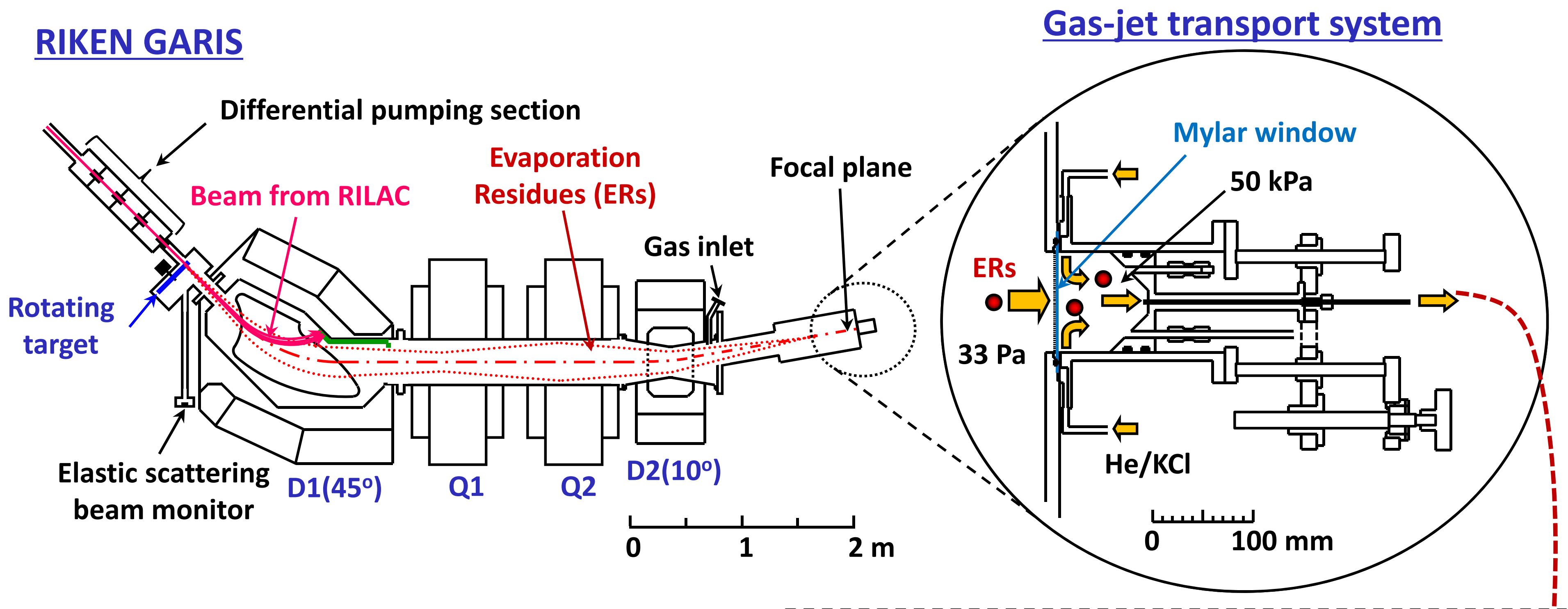
Assumptions

- Beam intensity: 3 pμA
- ^{248}Cm target thickness: 500 μg/cm^2
- Transmission of GARIS II&III: 70%
- Beam time days: 200 days



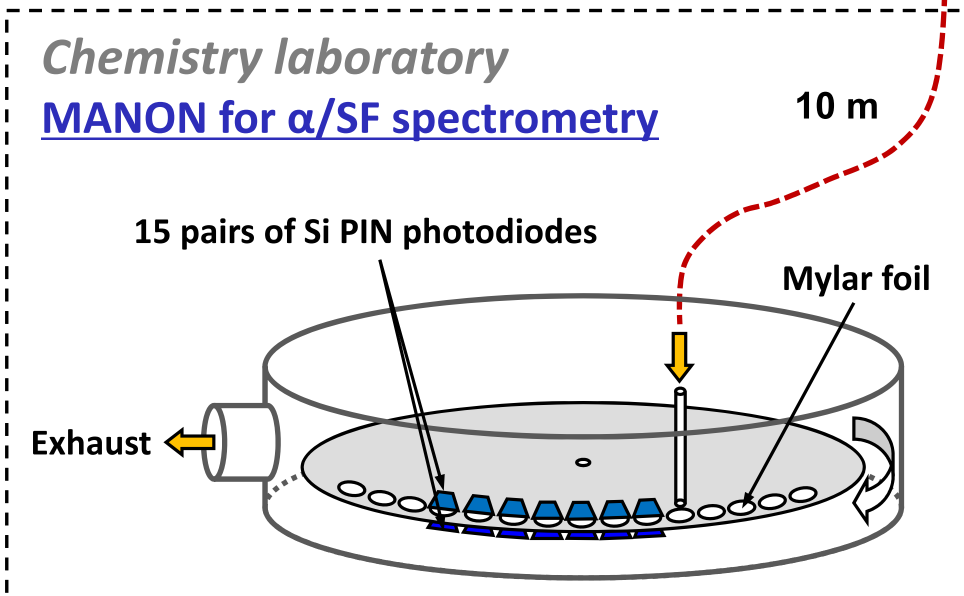
3. SHE chemistry behind GARIS

Coupling SHE chemistry to GARIS

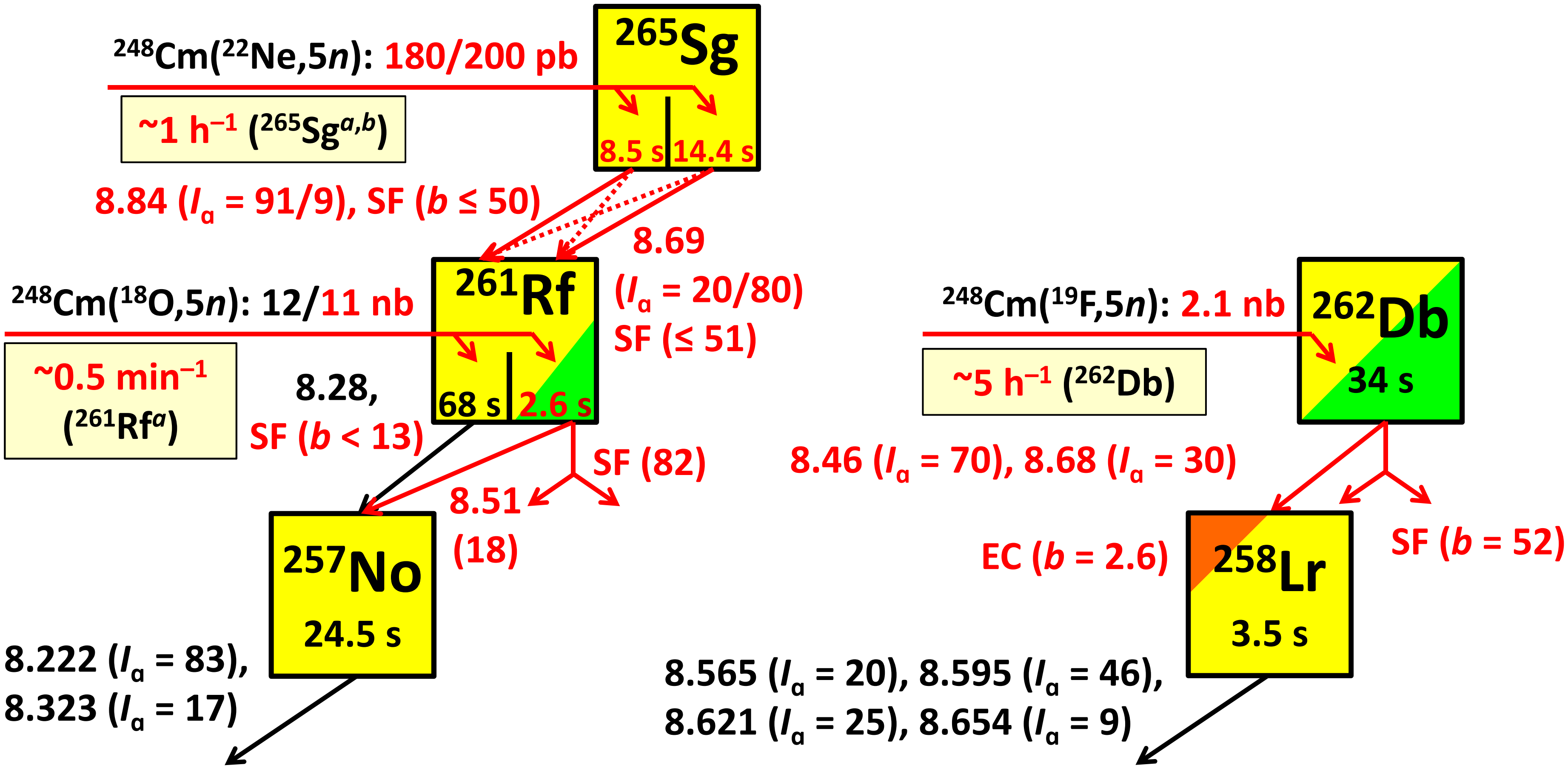


Breakthroughs in SHE chemistry

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



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



Haba et al., Chem. Lett. **38**, 426 (2009).
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Haba et al., Phys. Rev. C **85**, 024611 (2012).
Murakami et al., Phys. Rev. C **88**, 024618 (2013).
Haba et al., Phys. Rev. C **89**, 024618 (2014).
Haba, EPJ Web of Conferences **131**, 07006 (2016).

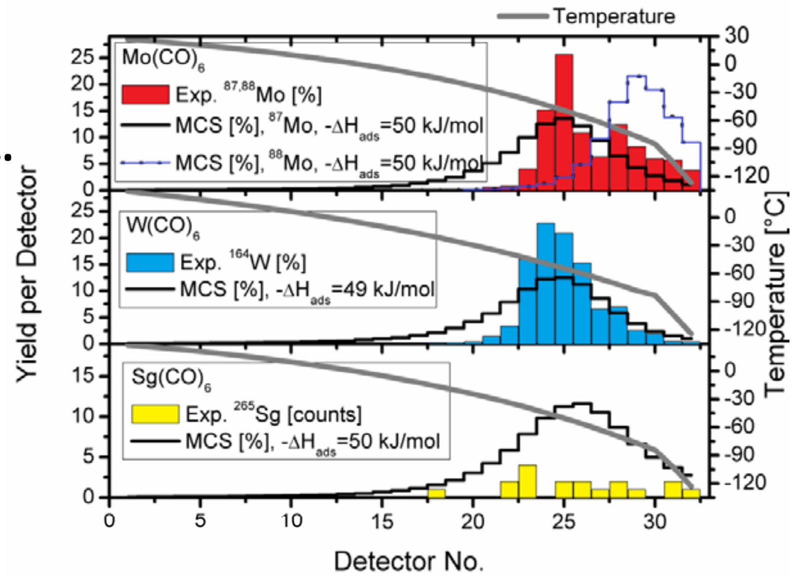
Pre-separated SHE RIs are ready for chemistry experiments.

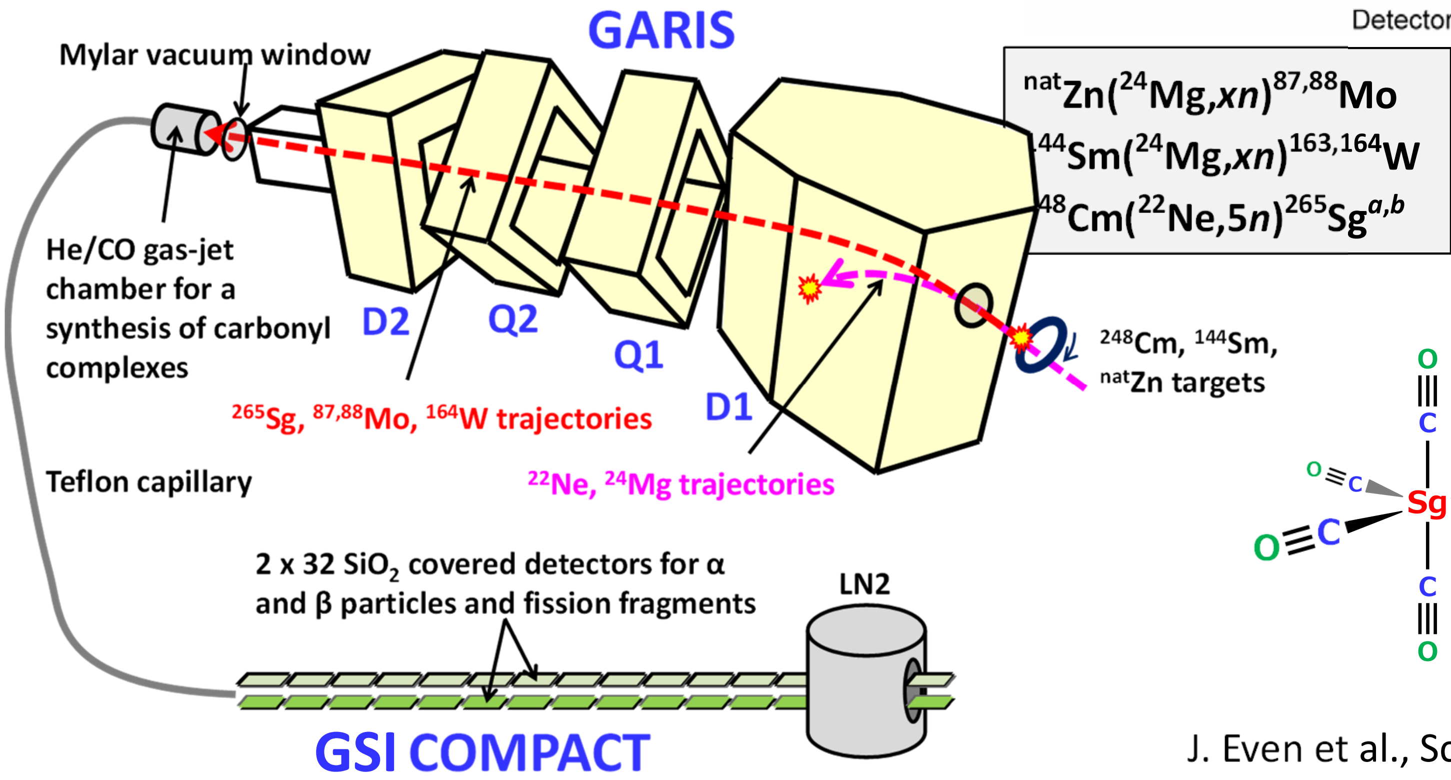
(a) Synthesis of carbonyl complexes of SHEs

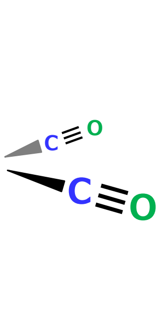
$Sg + 6CO \rightarrow Sg(CO)_6$

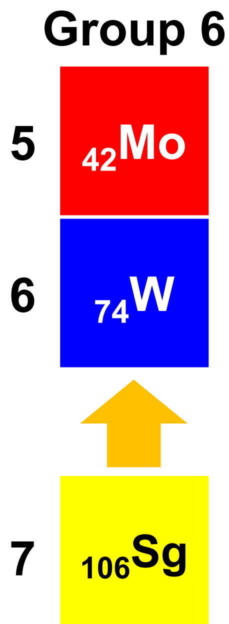
CO collaboration: HIM, Mainz Univ., GSI, RIKEN, …

- First organometallic compound of SHEs
  Sg(0) – C chemical bonding
- Adsorption enthalpy (ΔH_{ads}) on SiO_2
  $\Delta H_{ads}(Sg) \approx \Delta H_{ads}(Mo) \approx \Delta H_{ads}(W)$







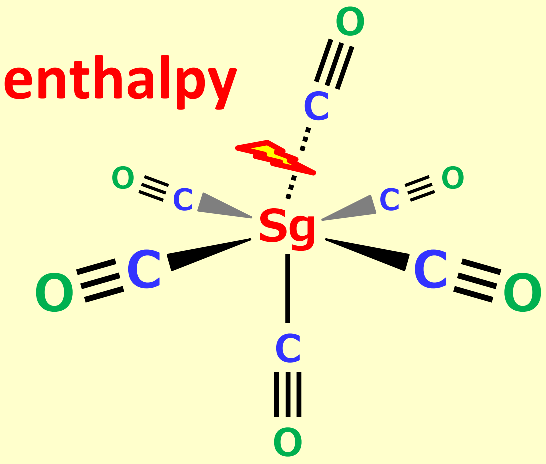


J. Even et al., Science **345**, 1491 (2014).

Systematic studies of carbonyl complexes of SHEs

(i) Metal-carbon bond stability in $Sg(CO)_6$

Decomposition studies → First bond dissociation enthalpy



- **$Mo(CO)_6$** and **$W(CO)_6$** with GARIS
  Usoltsev *et al.*, Radiochim. Acta **104**, 141 (2016).
- **$Sg(CO)_6$** with GARIS
  Eichler *et al.*, under study.

(ii) Basic studies for carbonyl complexes of Bh, Hs, and Mt

Synthesis of carbonyl complexes of homologues

→ Adsorption enthalpy on Teflon/quartz and chemical yields

- **$Tc(CO)_5$** with a ^{252}Cf SF source at IMP
  Wang *et al.*, Phys. Chem. Chem. Phys. **17**, 13228 (2015).
- **$Ru(CO)_5$** and **$Rh(CO)_4$** with a ^{252}Cf SF source at IMP
  Cao *et al.*, Phys. Chem. Chem. Phys. **18**, 119 (2016).
- **$Re(CO)_5$** with GARIS
  Wang *et al.*, under review.

	6	7	8	9
5	Mo	Tc	Ru	Rh
6	W	Re	Os	Ir
7	Sg	Bh	Hs	Mt

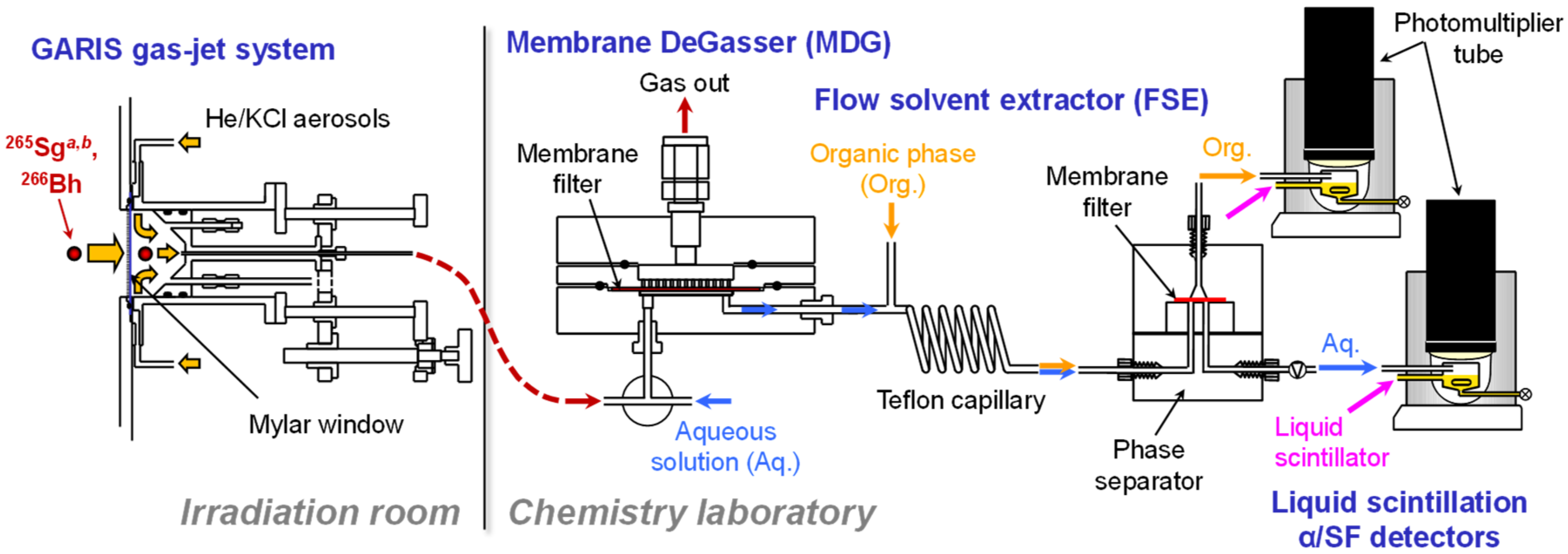
(b) Aqueous chemistry of the heaviest elements

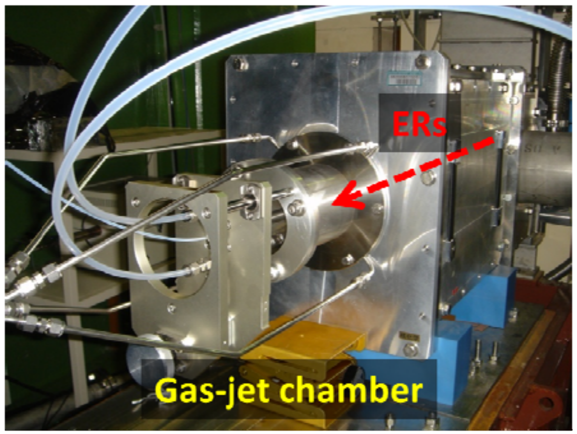
Development of a rapid solvent extraction apparatus

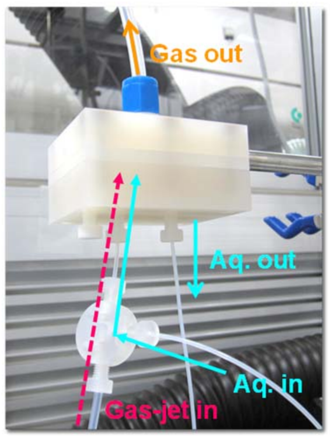
RIKEN–Niigata Univ.–JAEA–Osaka Univ.–Tohoku Univ. –IMP–Univ. Oslo collaboration

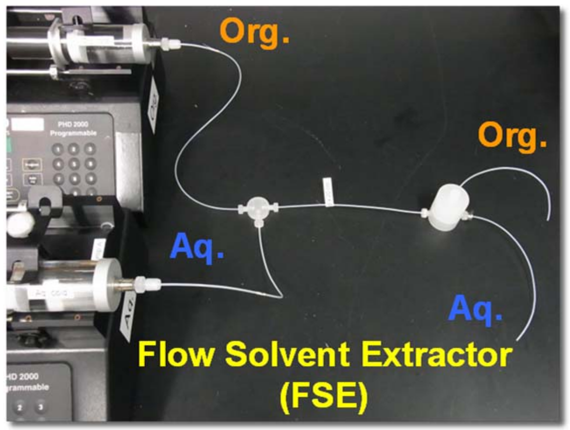
Continuous dissolution, solvent extraction, and radiation detection with LS

→ *Increase of event rates of $^{265}Sg^{a,b}$ and ^{266}Bh: x 100*



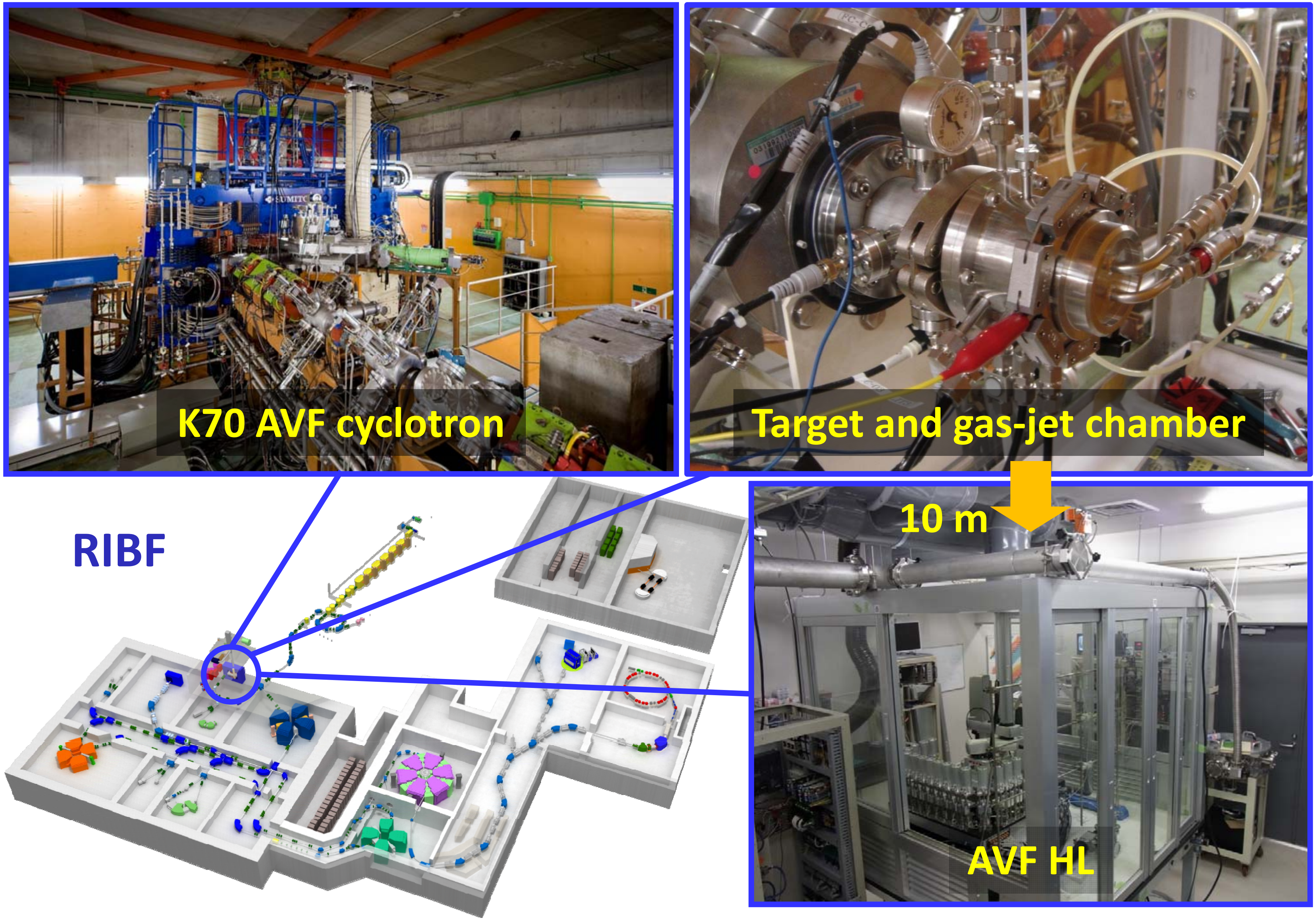






4. SHE chemistry at AVF

SHE RI production system at RIKEN AVF cyclotron

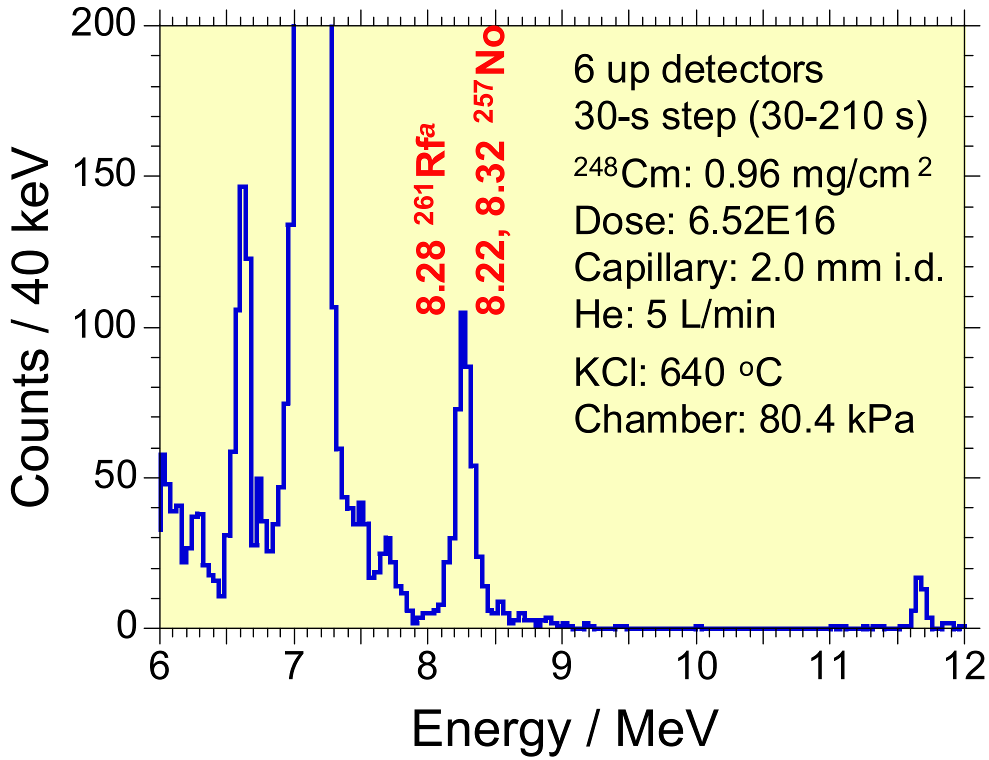


Conventional target and gas-jet system for production of SHE RIs

- **Heavy-ion beams (~1 pμA):** ^{18}O, ^{19}F, ^{22}Ne, and ^{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	$^{248}Cm(^{18}O,5n)^{261}Rf^{a}$	68 s
105	$^{248}Cm(^{19}F,5n)^{262}Db$	34 s
106	$^{248}Cm(^{22}Ne,5n)^{265}Sg^{b}$	14.4 s
108	$^{248}Cm(^{26}Mg,5n)^{269}Hs$	9.7 s

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



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**
$^{261}Rf^{a}$	96.4	0.870	3.34	865*	63	17	**5**

* 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 and 569 μg/cm² for ^{255}No and $^{261}Rf^{a}$, respectively.

Recent studies on SHE chemistry at AVF

Aq. chem. apparatuses

- ARCA (JAEA)
- CHIN (Osaka Univ.)
- AMBER (Osaka Univ.)
- ISE (Osaka Univ.)

\+

$_{104}Rf$

- **Reversed-phase TTA extraction of Rf with ARCA** (Kanazawa Univ.)
  Yokoyama et al., Radiochim. Acta **107**, 27 (2019). → **Rf < Zr ≈ Hf**
- **Chloride complex formation of Rf with AMBER and ISE** (Osaka Univ.)
  Kasamatsu et al., Radiochim. Acta **103**, 513 (2015).
  Yokokita et al., Dalton Trans. **45**, 18827 (2016). → **Rf > Zr > Hf**
- **Hydroxide co-precipitation of Rf with CHIN** (Osaka Univ.)
  Kasamatsu et al., J. Nucl. Radiochem. Sci. **14**, 7 (2014).
  Kasamatsu et al., Appl. Radiat. Isot. **118**, 105 (2016).
  Kasamatsu et al., to be submitted. → **Rf > Zr ≈ Hf**

$_{105}Db$

- **Reversed-phase TBP extraction of Db with ARCA** (Niigata Univ.)
  Murakami et al., to be submitted. → **Db ≈ Nb, Db ≠ Ta**

5. Summary

- Present status of RIKEN RI Beam Factory for SHE researches was introduced.
- Research program for element 119 was introduced.
- The gas-jet transport system was installed in GARIS for SHE chemistry.

  → Production and decay properties of ^{261}Rf, ^{262}Db, ^{265}Sg, and ^{266}Bh were investigated.

  → Synthesis of $Sg(CO)_6$ was successful.

  → Decomposition of $Sg(CO)_6$ is underway.

  → Syntheses of carbonyl complexes of Tc, Ru, Rh, and Re are underway for future studies on Bh, Hs, and Mt.
- A rapid solvent extraction apparatus is under development for aqueous chemistry of Sg and Bh.
- Aqueous chemistry studies of Rf and Db are underway with the conventional gas-jet transport system at AVF.