Present status and future plans of SHE researches at RIKEN

RIKEN Nishina Center

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1. Production and decay studies of RIs for SHE chemistry

(a) ^{248}Cm(^{19}F,5n)^{262}Db (Z = 105)

(b) ^{248}Cm(^{23}Na,5;4n)^{266,267}Bh (Z = 107)

2. Toward syntheses of the heaviest elements

^{248}Cm(^{48}Ca,xn)$^{296-x}$Lv (Z = 116)

3. Future plans of SHE researches at RIKEN

1. Production and decay studies of RIs for SHE chemistry

Coupling SHE chemistry to recoil separators

Breakthroughs in SHE chemistry

- **Chemical and physical experiments under low background condition**
- **Stable and high gas-jet transport efficiency**
- **New chemical reactions**

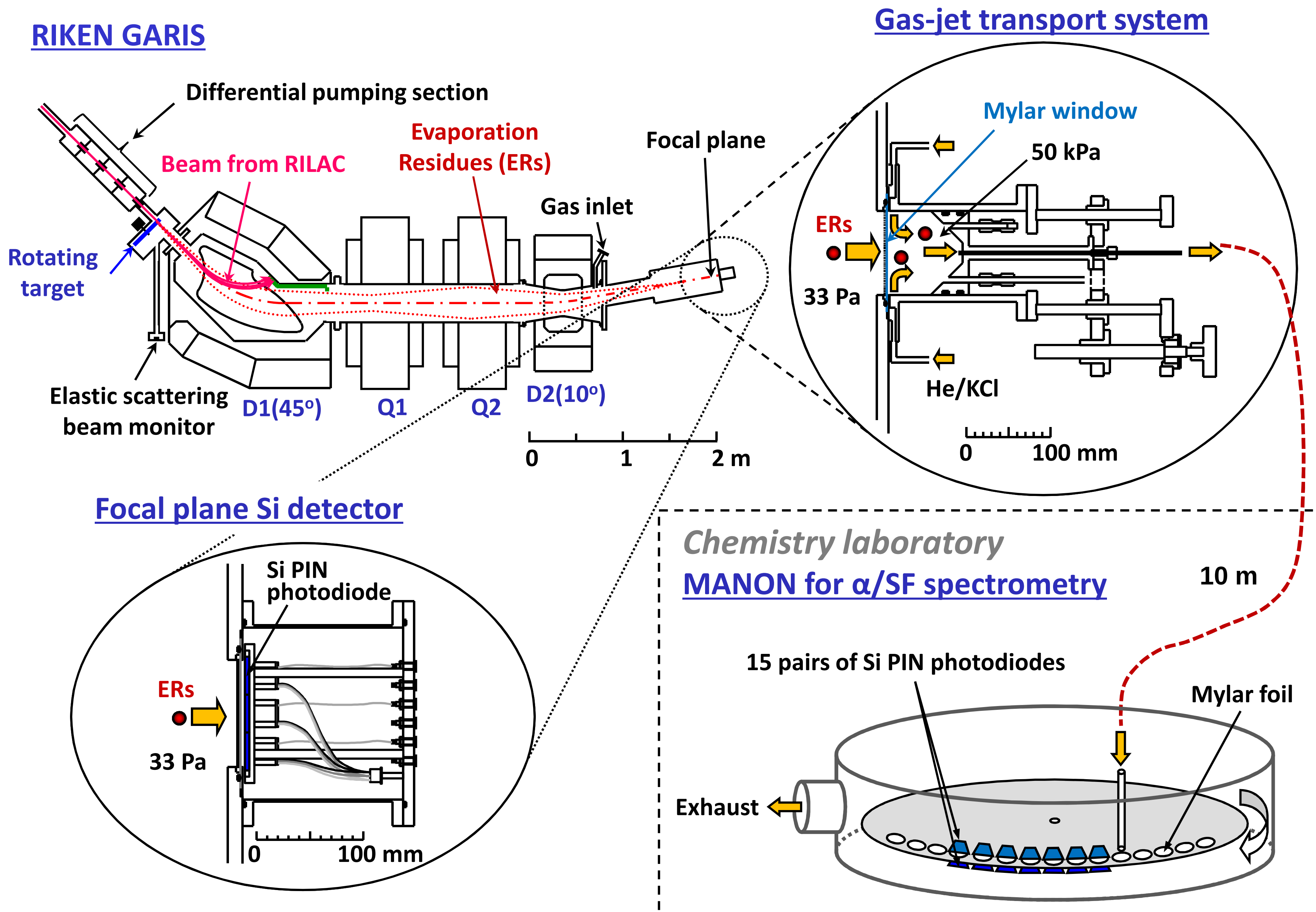
Development of a gas-jet transport system coupled to GARIS

- **^{169}Tm(^{40}Ar,3*n*)^{206}Fr**; **^{208}Pb(^{40}Ar,3*n*)^{245}Fm** [JNRS **8**, 55 (2007); EPJD **45**, 81 (2007)]
- **^{238}U(^{22}Ne,5*n*)^{255}No** [JNRS **9**, 27 (2008)]

Production and decay studies of RIs for chemical studies

- **^{248}Cm(^{18}O,5*n*)^{261}Rf^{a,b}** [Chem. Lett. **38**, 426 (2009); PRC **83**, 034602 (2011)]
- **^{248}Cm(^{22}Ne,5*n*)^{265}Sg^{a,b}** [PRC **85**, 024611 (2012)] → **$Sg(CO)_6$ chemistry** (Julia's talk)
- **^{248}Cm(^{19}F,5*n*)^{262}Db** [PRC **89**, 024618 (2014)]
- **^{248}Cm(^{23}Na,5;4*n*)^{266,267}Bh** [in progress]

Experimental setup



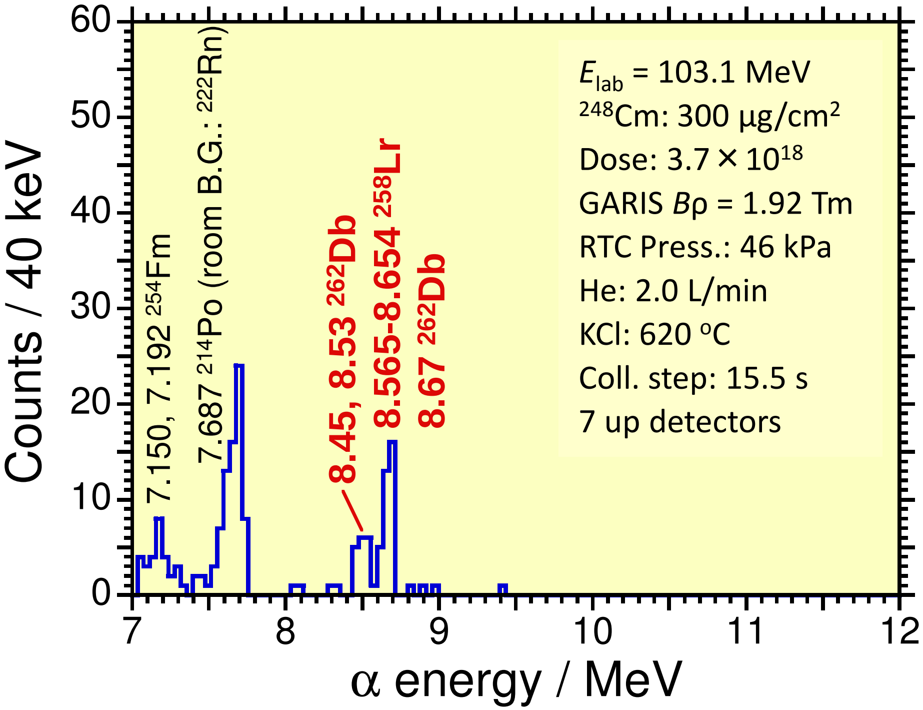
Production of ^{262,263}Db and ^{266,267}Bh using the GARIS gas-jet system

Nuclide	^{262,263}Db (Z=105)	^{266,267}Bh (Z=107)
Half-life	34 s, 27 s[1)]	1.7 s, 17 s[2)]
Reaction	^{248}Cm(^{19}F,5;4n)	^{248}Cm(^{23}Na,5;4n)
Cross section (nb)	1.5[3)], ?	0.05[4)] ?
Beam energy (MeV)	103, 97.4	130.6
Beam intensity (pμA)	4	3
$^{248}Cm_2O_3$ thickness (μg/cm^2)	230/290/330	290
Magnetic rigidity (Tm)	1.73–2.09	2.12
GARIS He (Pa)	32	33
RTC Mylar window (μm)	0.5	0.7
Honeycomb grid (%)	84	78
Gas-jet He (kPa)	47	80
Chamber depth (mm)	20	20
He flow rate (L/min)	2.0	5.0
KCl generator (^{o}C)	620	620
Step interval of MANON (s)	15.5	5.0, 15.0

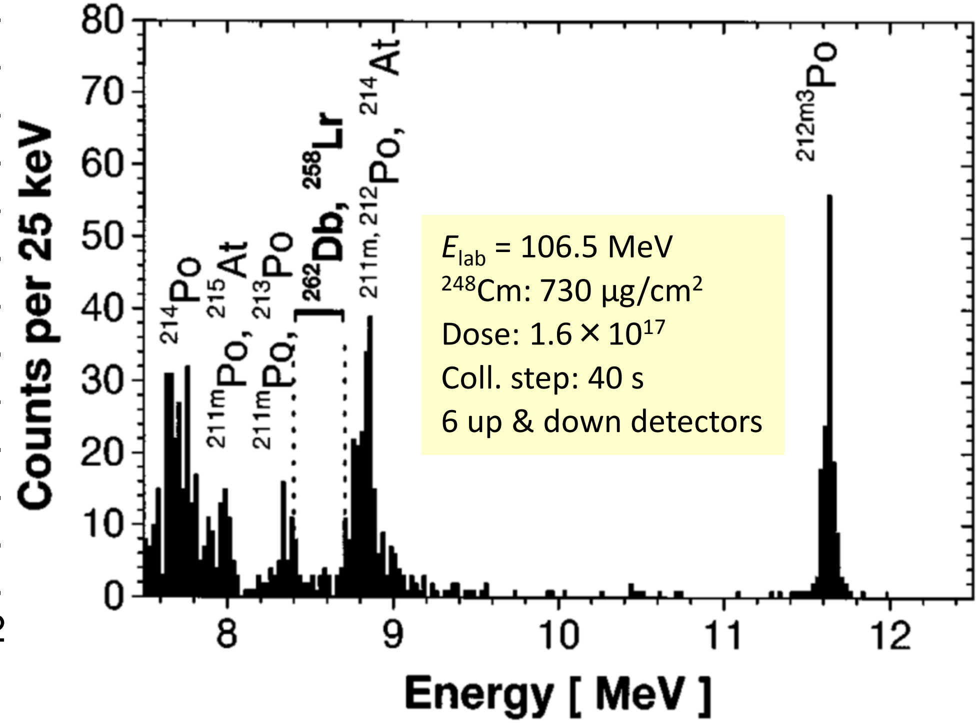
1) Firestone and Shirley, *Table of Isotopes*, 8th ed. (Wiley, New York, 1996).
2) Wilk *et al.*, PRL **85**, 2697 (2000). 3) Nagame *et al.*, JNRS **3**, 85 (2002). 4) Morita *et al.*, JSPS **78**, 064201 (2009).

(a) ^{248}Cm(^{19}F,5n)^{262}Db

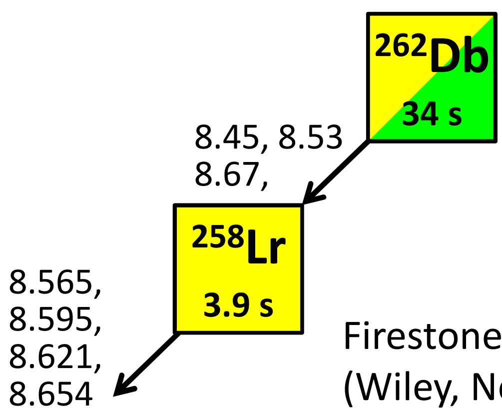
GARIS gas-jet



Conventional gas-jet



Dressler *et al.*, Phys. Rev. C **59**, 3433 (1999).



Firestone and Shirley, Table of Isotopes, 8th ed.
(Wiley, New York, 1996).

Search for correlations

E_α = 8.0–9.0 MeV; $E_{SF} \geq 30$ MeV

$\Delta T \leq 58.5$ s

	Observed	Random
α-α	**75**	< 2.9
α-SF	**2**	< 0.6

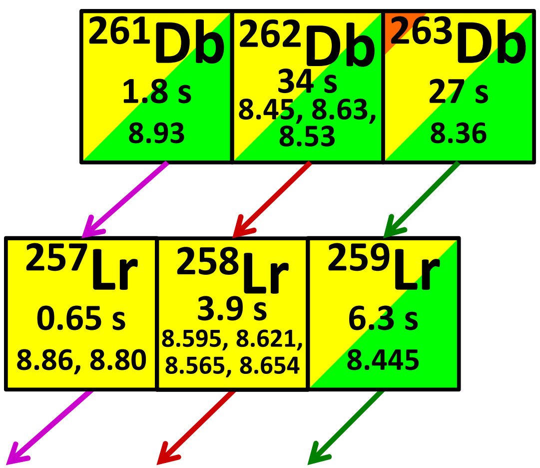
$^{248}Cm(^{19}F,5n)^{262}Db \rightarrow ^{258}Lr$: 76

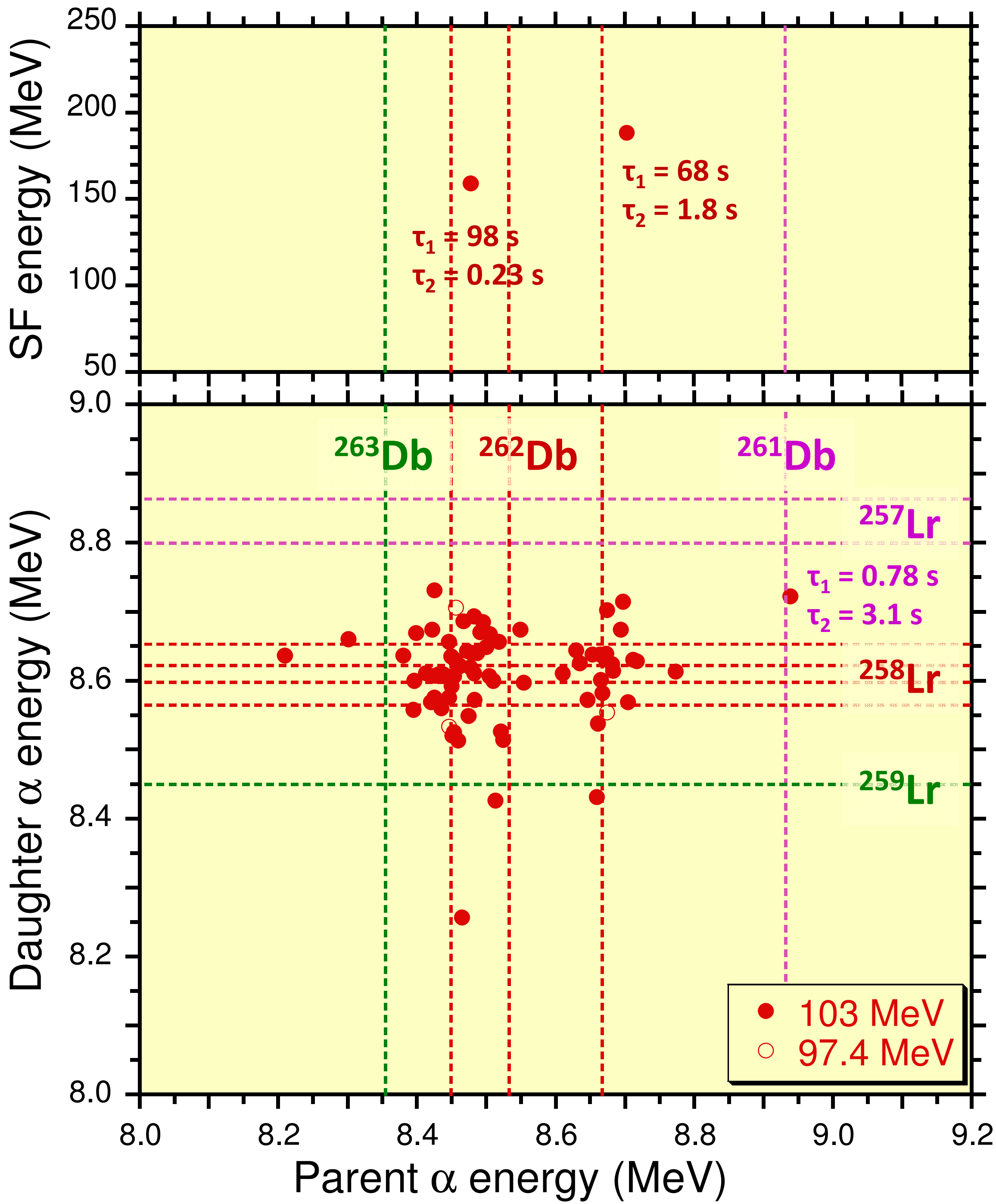
$^{248}Cm(^{19}F,6n)^{261}Db \rightarrow ^{257}Lr$: 1

$^{248}Cm(^{19}F,4n)^{263}Db \rightarrow ^{259}Lr$: 0

Single SF events: 123

***Table of Isotopes*, 8th ed.**

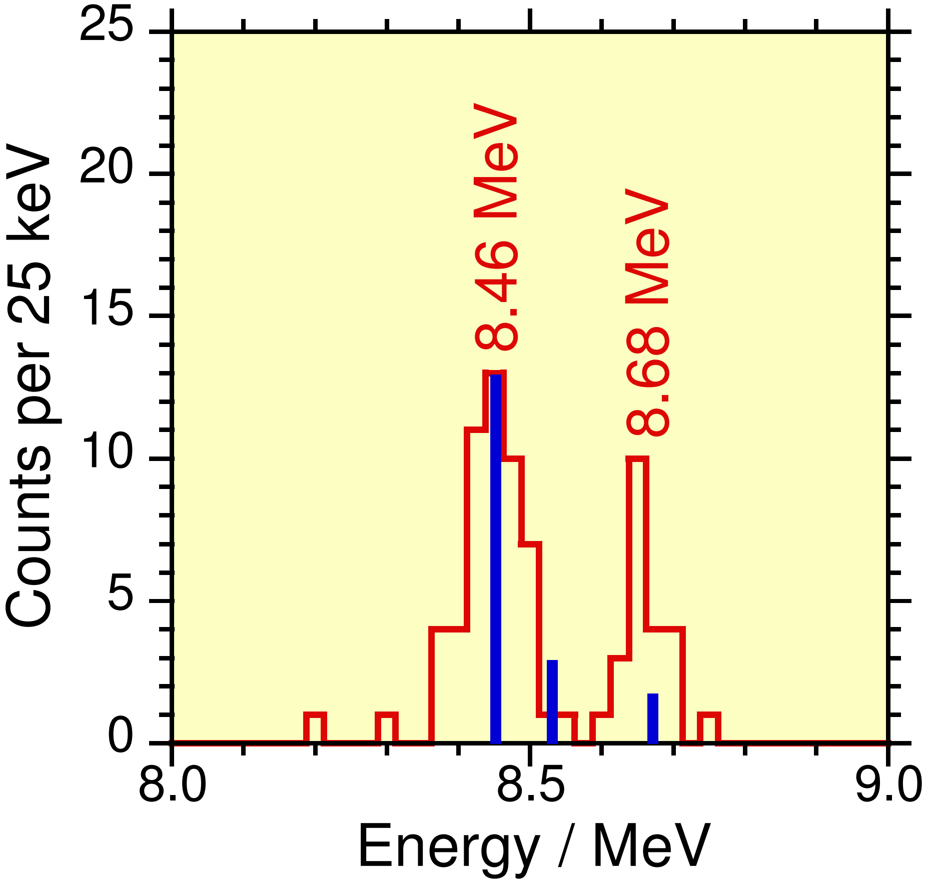




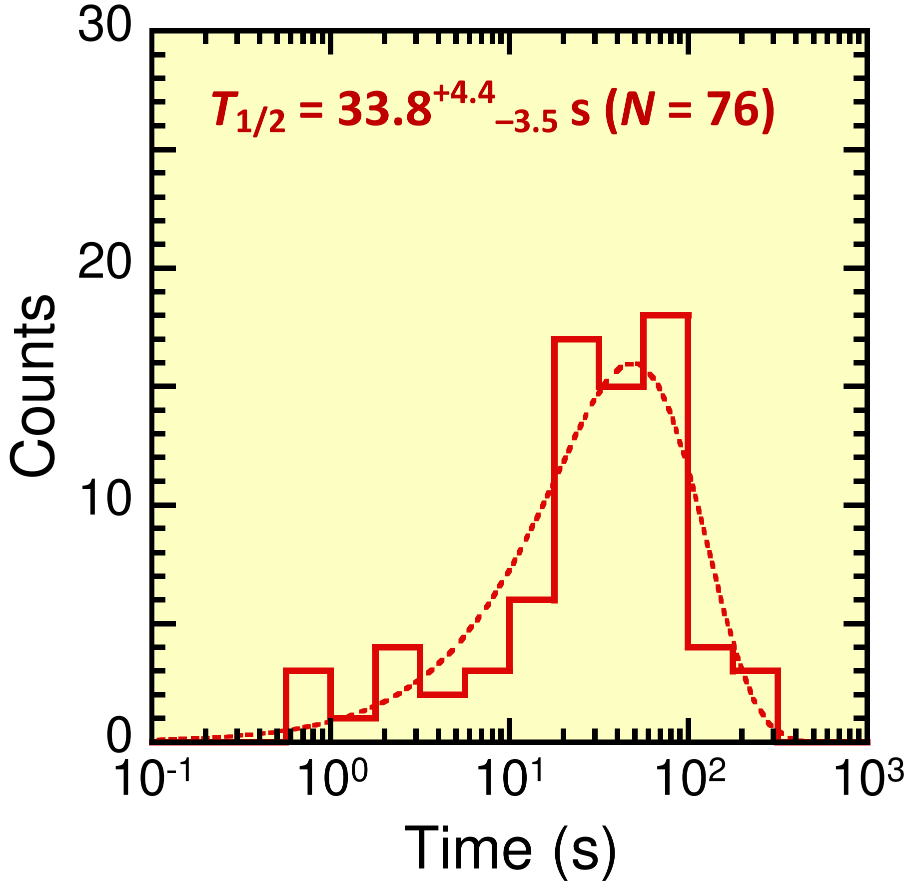
α energy and half-life of ^{262}Db

This work				Table of Isotopes 8th ed.			
$T_{1/2}$ [s]	E_α [MeV]	I_α [%]	b_{SF} [%]	$T_{1/2}$ [s]	E_α [MeV]	I_α [%]	b_{SF} [%]
	8.46±0.04	**70±5**			8.45±0.02	75	
$33.8^{+4.4}_{-3.5}$			**52±4**	34±4	**8.53±0.02**	**16**	**≈33**
	8.68±0.04	**30±5**			8.67±0.02	9	

α spectrum of ^{262}Db

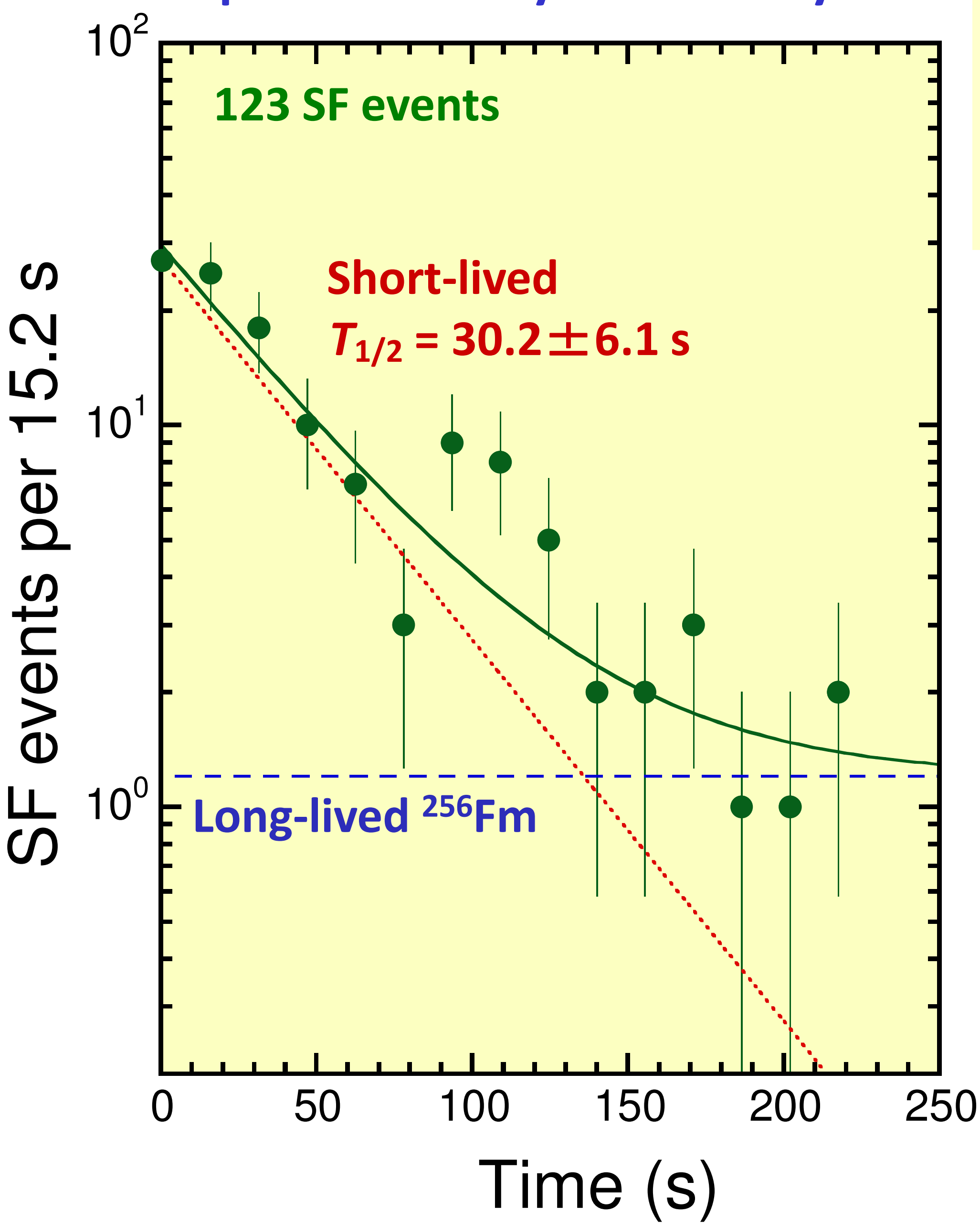


Decay time spectrum of ^{262}Db



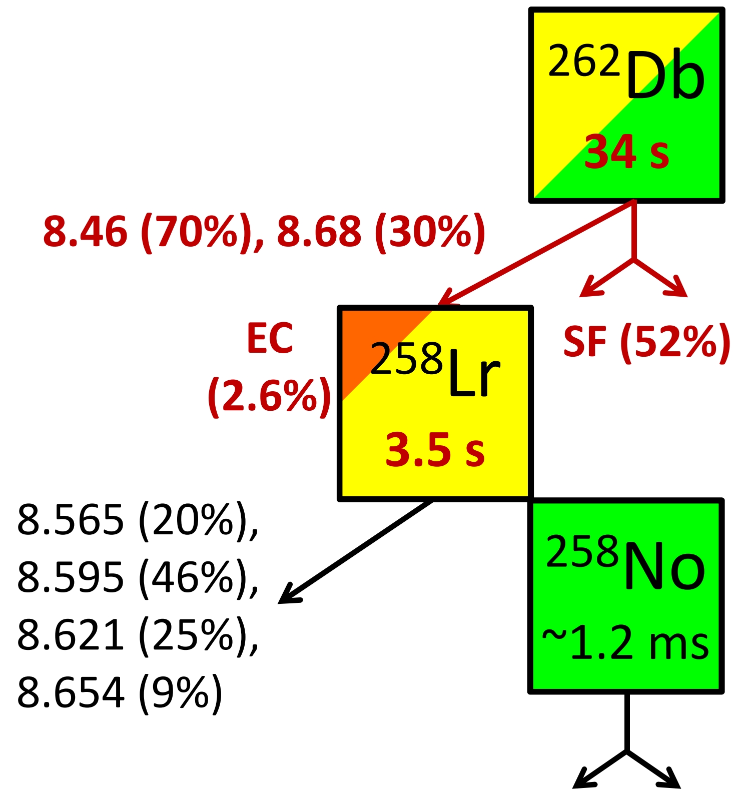
Single SF events

2-components decay curve analysis



- $T_{1/2} = 33.8^{+4.4}_{-3.5}$ s from α decay of ^{262}Db
- No α events of ^{263}Db (b_α = 43%)
  → Negligible SF of ^{263}Db (b_{SF} = 57%)

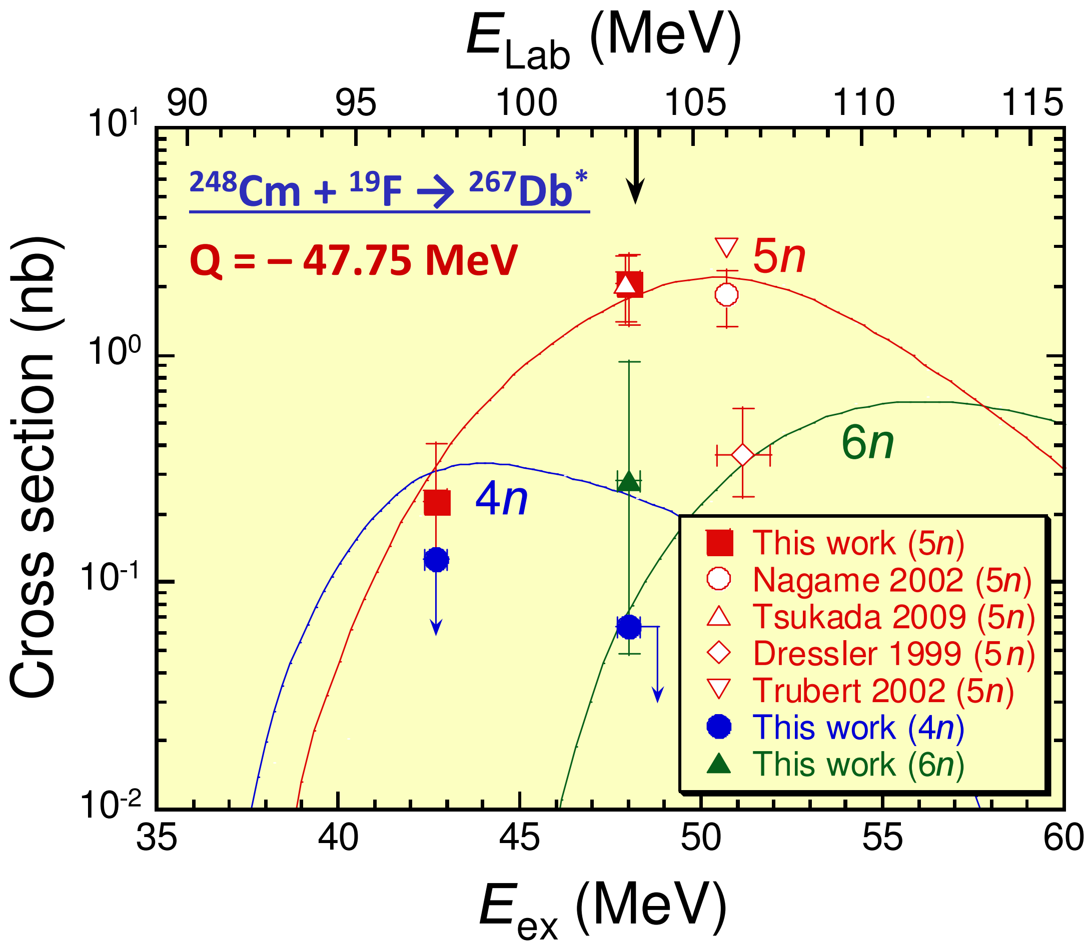
SF branch of ^{262}Db:
b_{SF} = 52±4%
↔ b_{SF} = ≈33% (adopted)



Excitation functions for $^{248}Cm(^{19}F,xn)^{267-x}Db$

- New decay data of ^{262}Db and ^{258}Lr
  $b_{SF}(^{262}Db) = 52\%$; $b_{EC}(^{258}Lr) = 2.6\%$
- Nagame *et al.*, JNRS **3**, 85 (2002).
  σ = 1.5±0.4 nb at 103 MeV
  for $^{248}Cm(^{19}F,5n)^{262}Db$

Products	Cross sections [nb] 103.1 MeV	Cross sections [nb] 97.4 MeV
^{261}Db (6*n*)	$0.28^{+0.65}_{-0.23}$	< 0.10
^{262}Db (5*n*)	2.1±0.7	$0.23^{+0.18}_{-0.11}$
^{263}Db (4*n*)	< 0.064	< 0.13

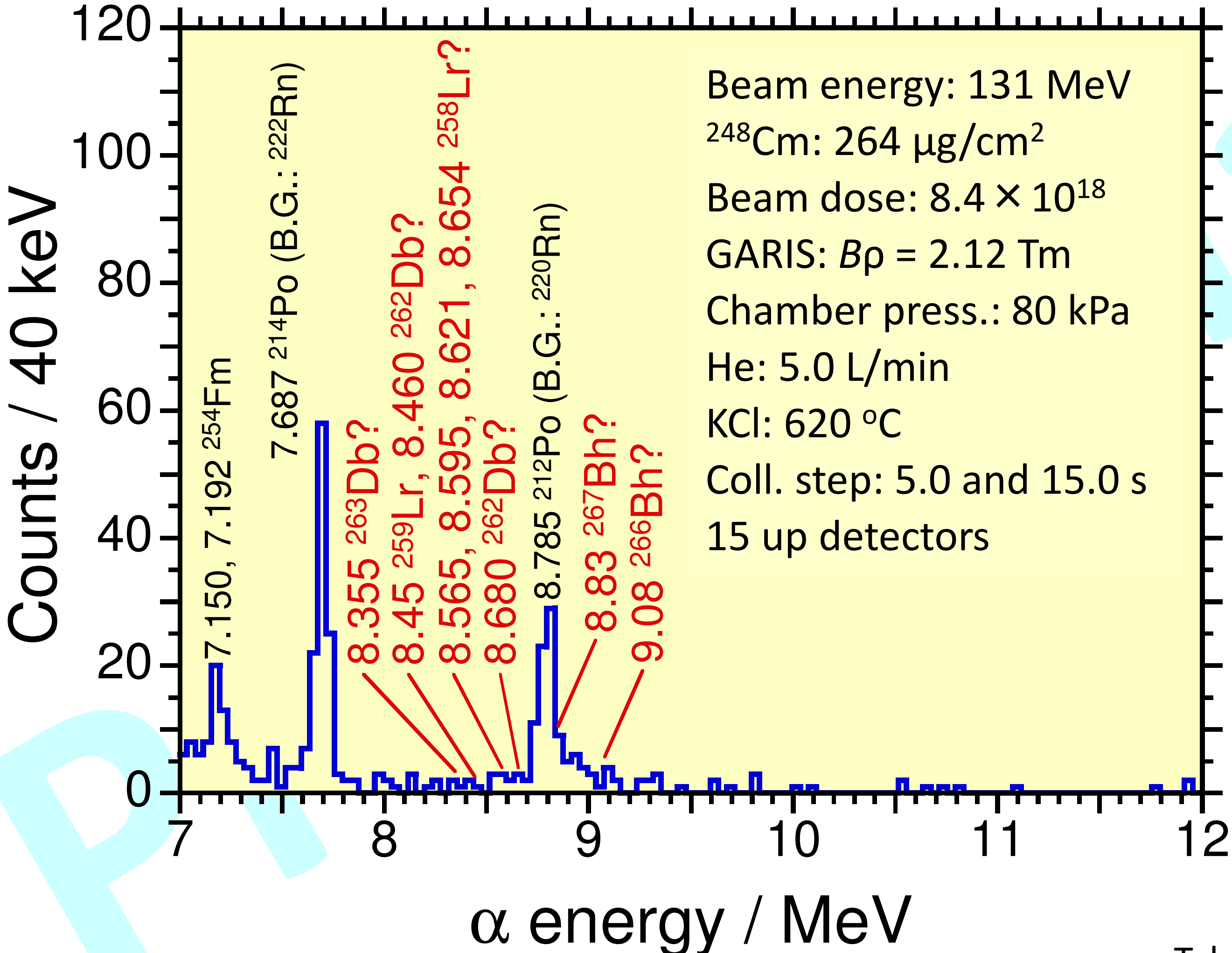


HIVAP calculation

Reisdorf and Schädel, ZPA **343**, 47 (1992).
Nishio *et al.*, PRL **93**, 162701 (2004).
Nishio *et al.*, PRC **82**, 024611 (2010).

(b) ^{248}Cm(^{23}Na,5;4n)^{266,267}Bh

α-particle spectrum



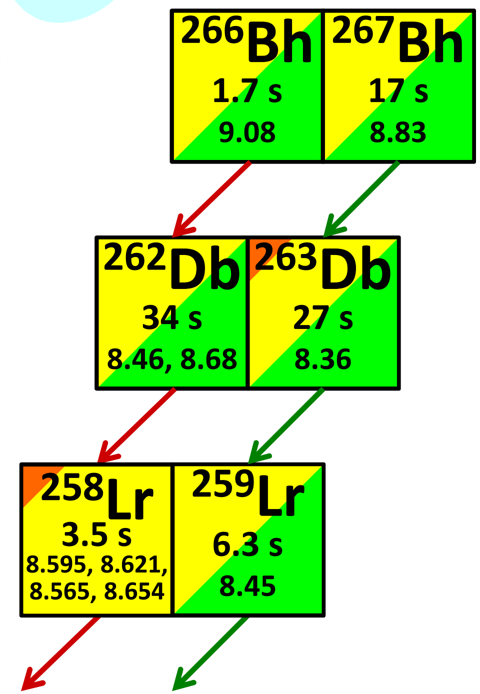


Table of Isotopes, 8th ed. (1996).

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

Haba *et al.*, PRC **89**, 024618 (2014).

Search for correlations

E_α = 7.5–10.0 MeV; $E_{SF} \geq 30$ MeV

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

No. of the observed correlations

	Observed	Random
α-α-α	1	< 0.01
α-α	5	< 1.4
α-SF	5	< 0.05

Tentative assignments

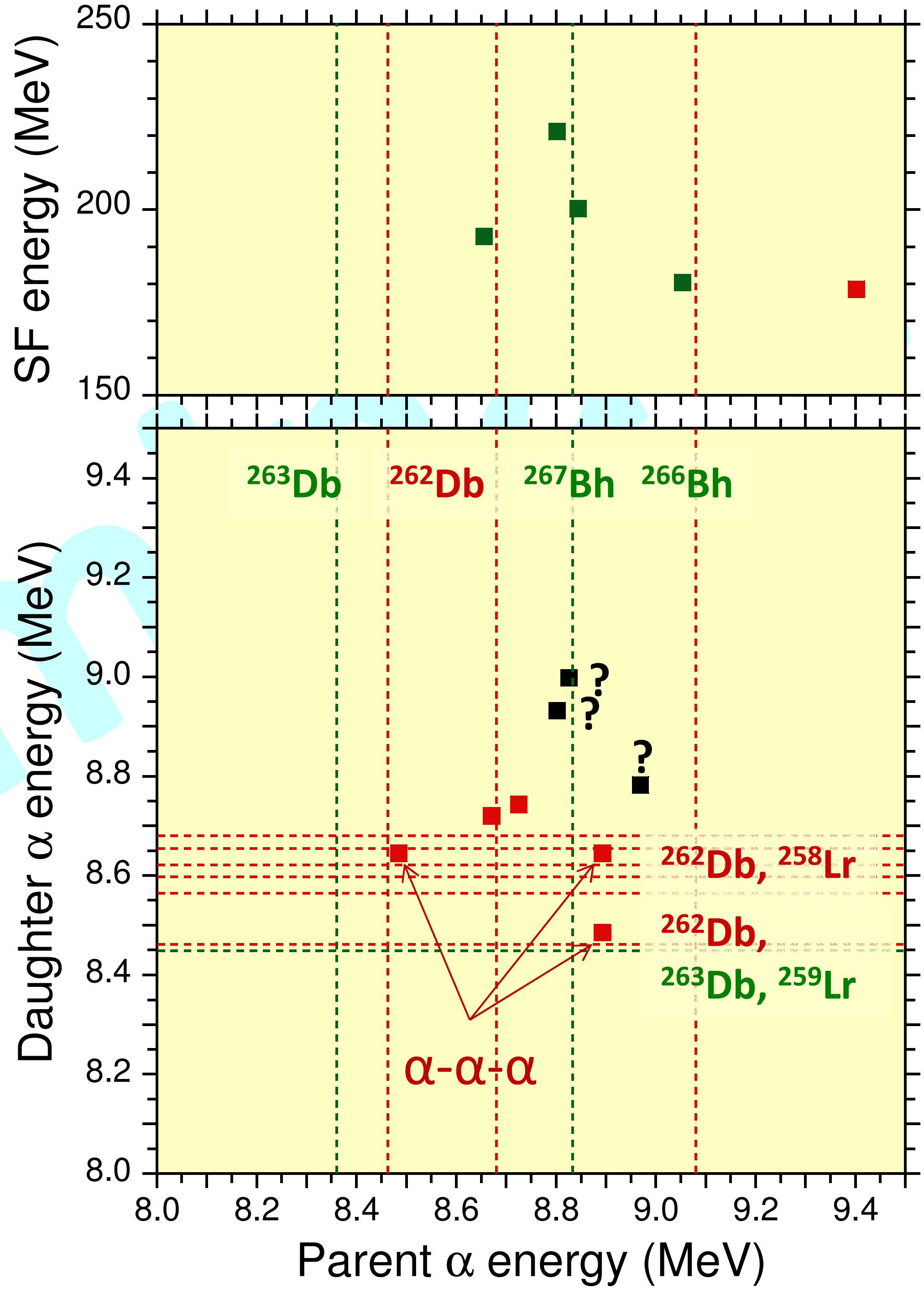
$^{248}Cm(^{23}Na,5n)^{266}Bh$: 4

$^{248}Cm(^{23}Na,4n)^{267}Bh$: 4

Not assigned: 3 (accidental?)

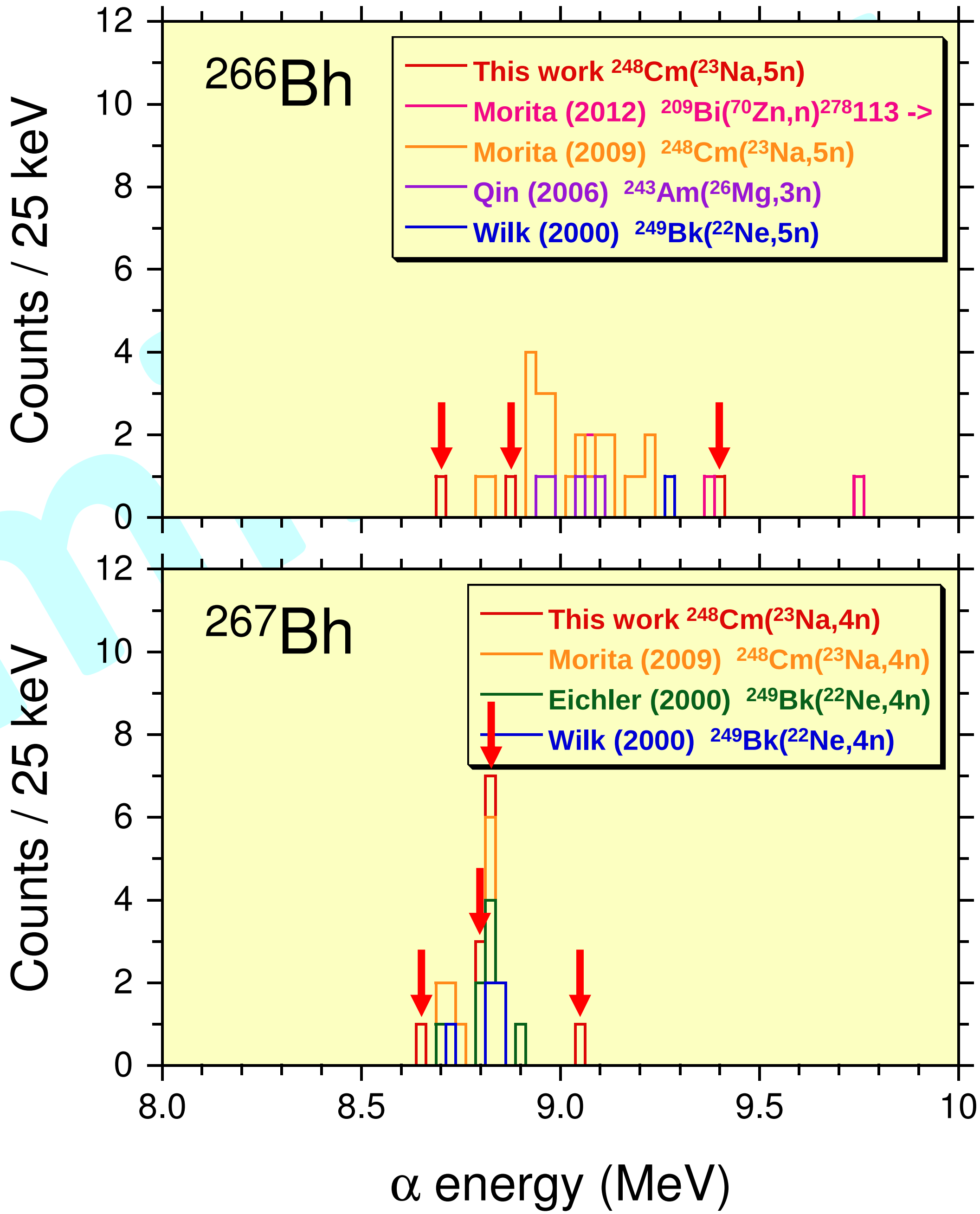
Single SF events

No. of single SF events: 7



α-particle energies of ^{266,267}Bh

- **The α energies of ^{266}Bh spread widely in the range of E_α = 8.72–9.77 MeV.**
- **The α spectrum of ^{267}Bh shows peaks at 8.84 MeV (I_α = ~70%) and 8.72 MeV (I_α = ~30%).**



References

[1] ^{249}Bk(^{22}Ne,5;4*n*)^{266,267}Bh (*N* = 1, 5):
Wilk *et al.*, PRL **85**, 2697 (2000).

[2] ^{249}Bk(^{22}Ne,4*n*)^{267}Bh (*N* = 6):
Eichler *et al.*, Nature **407**, 63 (2000).

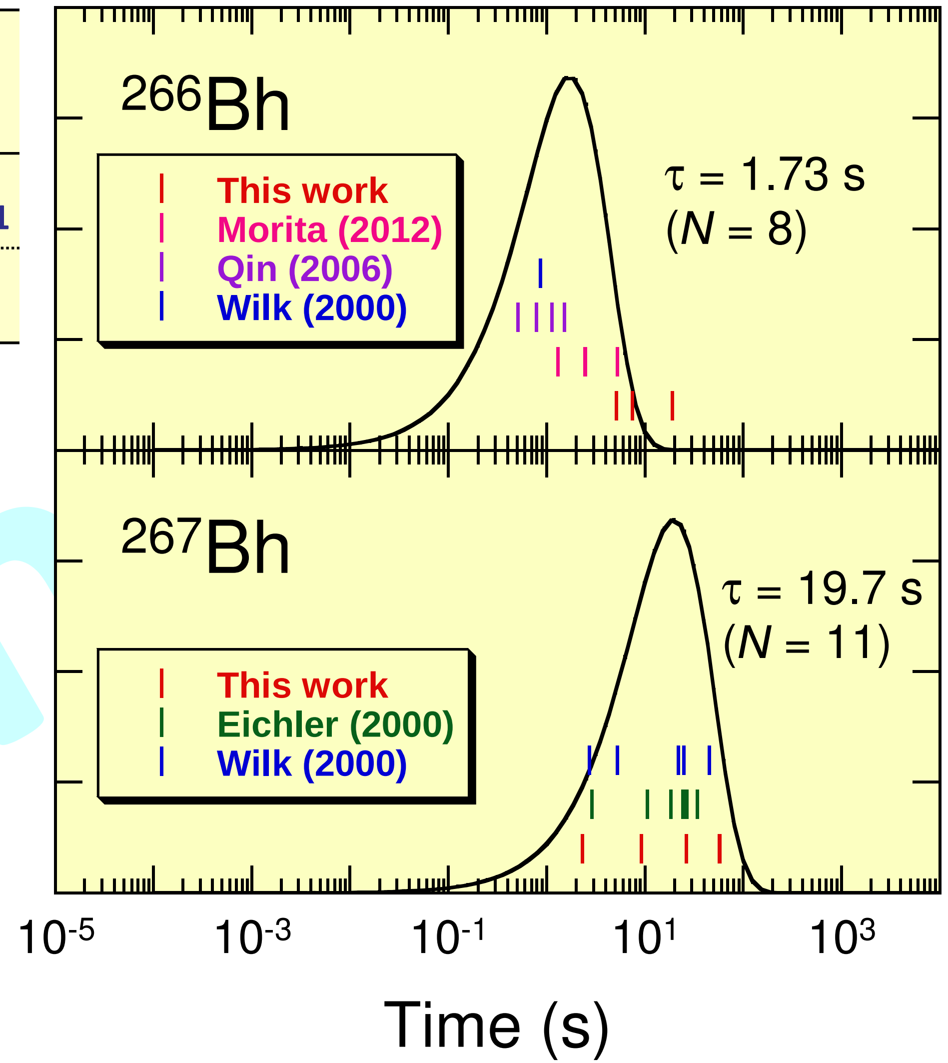
[3] ^{248}Cm(^{23}Na,5;4*n*)^{266,267}Bh (*N* = 20, 5):
Morita *et al.*, JPSJ **78**, 064201 (2009).

[4] ^{209}Bi(^{70}Zn,*n*)^{278}113 → ^{266}Bh (*N* = 3):
Morita *et al.*, JPSJ **81**, 103201 (2012).

Half-lives of ^{266,267}Bh

Nuclide	This work		Refs. [1–4]	
	N	$T_{1/2}$ [s]	N	$T_{1/2}$ [s]
^{266}Bh	3	**$7.3^{+10.0}_{-2.7}$**	8	**$1.20^{+0.66}_{-0.31}$**
^{267}Bh	4	**$16.5^{+16.5}_{-5.5}$**	11	**$13.7^{+5.9}_{-3.2}$**

- **The lifetimes of ^{266}Bh measured recently at RIKEN are longer than those in the literatures.**
- **The longer-lived ^{266}Bh would be good for chemistry studies of Bh.**
- **The half-life of ^{267}Bh agrees with that in the literatures.**



References

[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).

Excitation functions for $^{248}Cm(^{23}Na,xn)^{271-x}Bh$

Reactions	Cross sections at 130.6 MeV	Reactions*	Cross sections* at 117/123 MeV
$^{248}Cm(^{23}Na,5n)^{266}Bh$	53^{+42}_{-25} pb	$^{249}Bk(^{22}Ne,5n)^{266}Bh$	-/25–250 pb
$^{248}Cm(^{23}Na,4n)^{267}Bh$	33^{+26}_{-16} pb	$^{249}Bk(^{22}Ne,4n)^{267}Bh$	$58^{+33}_{-15}/96^{+55}_{-25}$

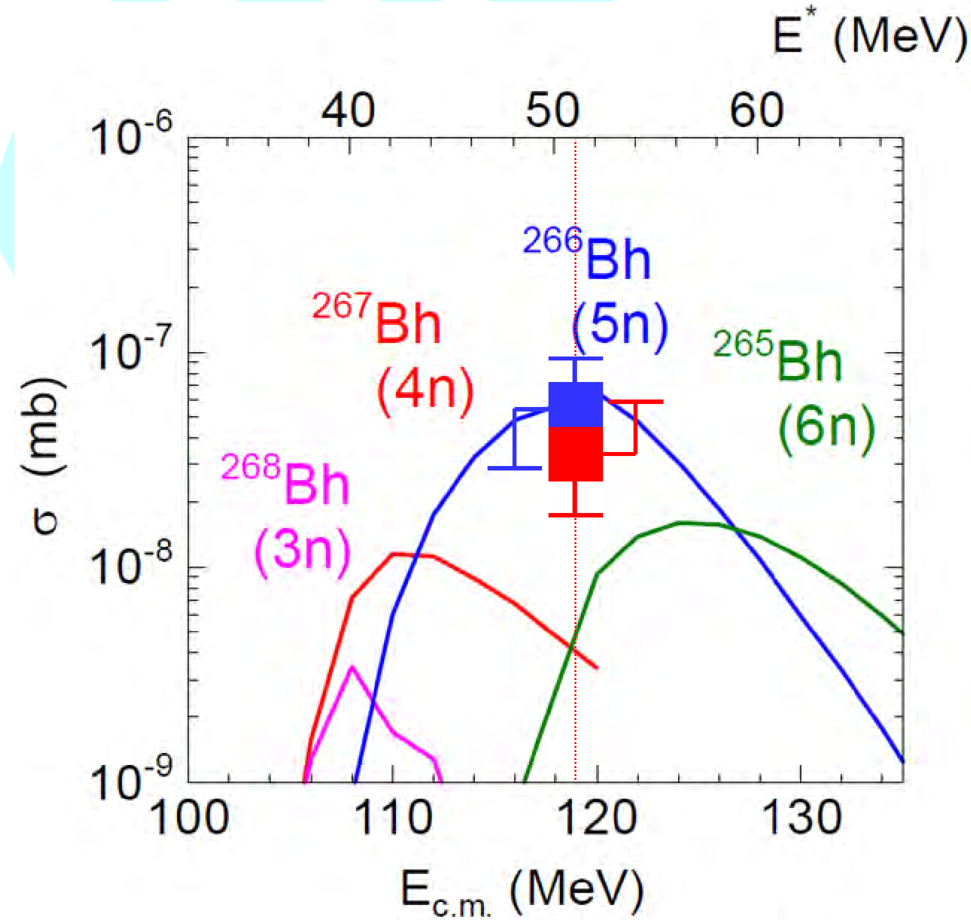
*Wilk *et al.*, PRL **85**, 2697 (2000).

Assumptions

- $T_{1/2}(^{266}Bh)$ = 7.3 s
- $T_{1/2}(^{267}Bh)$ = 16.5 s
- GARIS transmission: 15%
- Gas-jet transport time: 2.7 s

HIVAP calculation

Reisdorf and Schädel, ZPA **343**, 47 (1992).
Nishio *et al.*, PRL **93**, 162701 (2004).
Nishio *et al.*, PRC **82**, 024611 (2010).



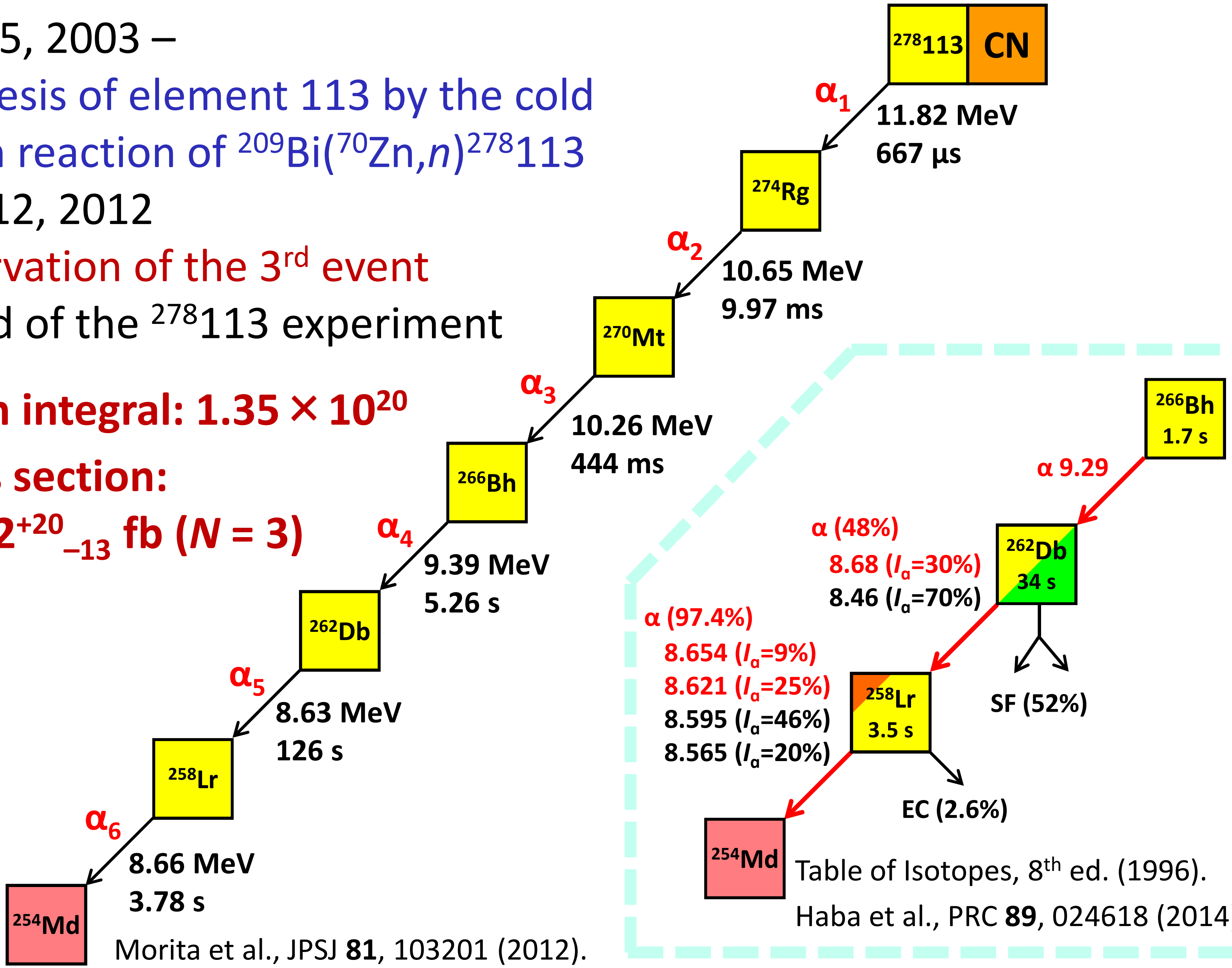
2. Toward syntheses of the heaviest elements

- Sept. 5, 2003 –
  Synthesis of element 113 by the cold fusion reaction of $^{209}Bi(^{70}Zn,n)^{278}113$
- Aug. 12, 2012
  Observation of the 3rd event
  → End of the $^{278}113$ experiment

Beam integral: 1.35 × 10^{20}

Cross section:

$\sigma = 22^{+20}_{-13}$ fb (N = 3)



Morita et al., JPSJ **81**, 103201 (2012).

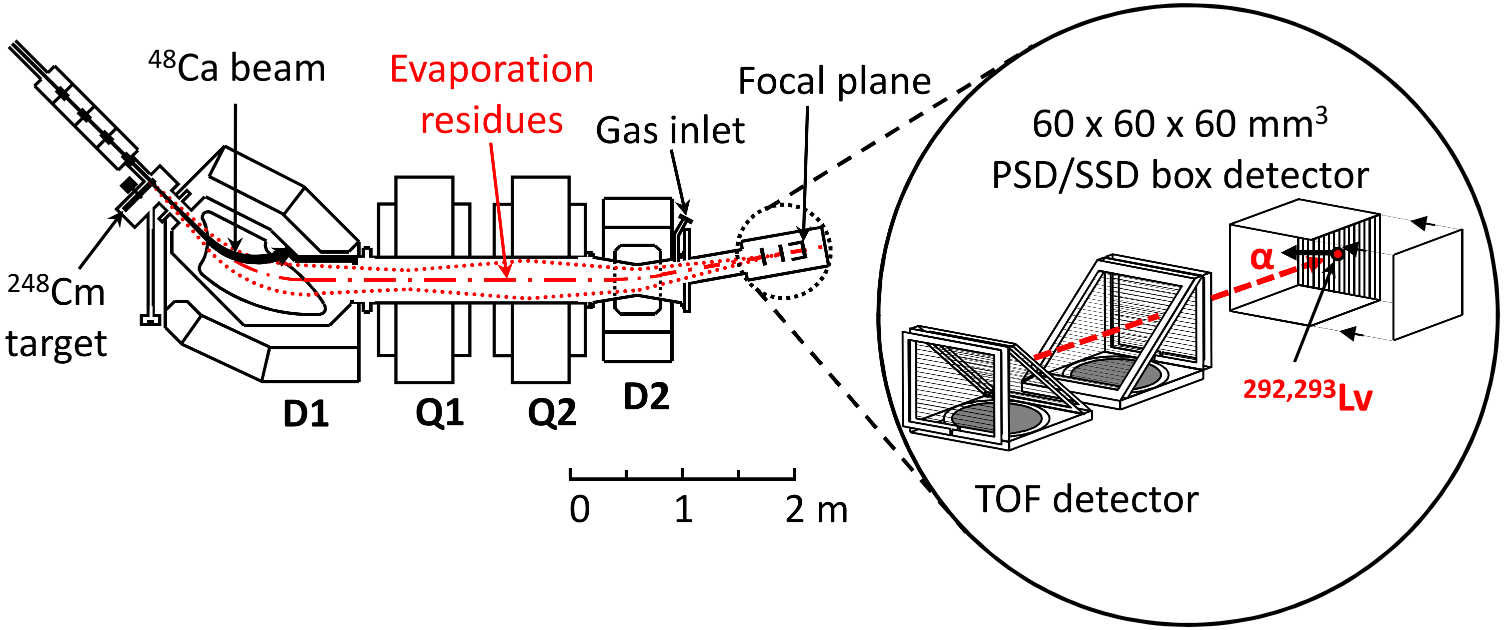
Table of Isotopes, 8th ed. (1996).

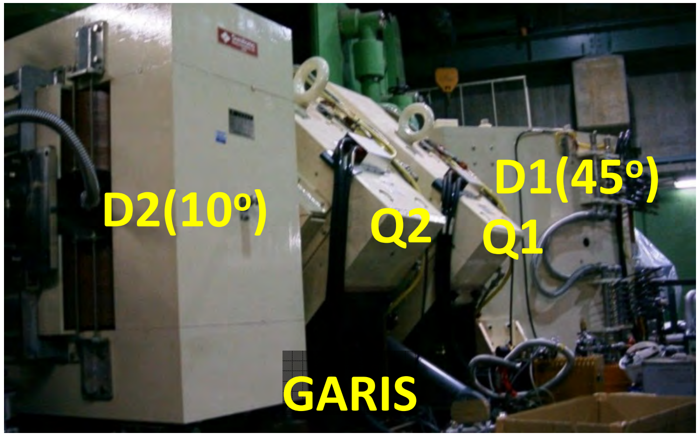
Haba et al., PRC **89**, 024618 (2014).

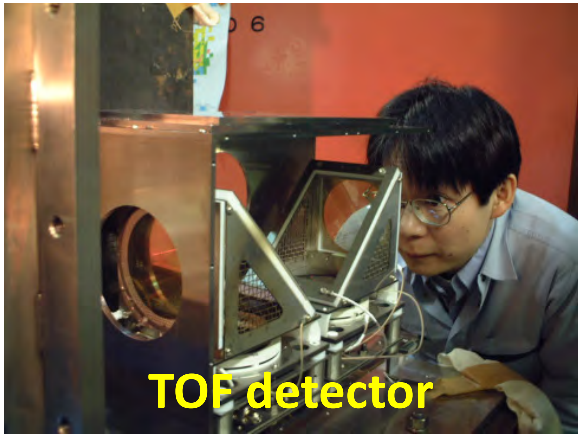
Synthesis of the heavier elements by hot fusion reactions

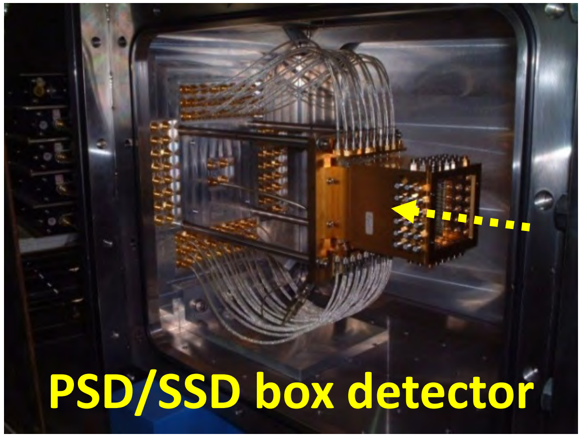
$^{248}Cm(^{48}Ca,xn)^{296-x}Lv$ as the first step

Refs. DGFRS: Oganessian *et al.*, Phys. Rev. C **63**, 011301 (2000).
Oganessian *et al.*, Phys. Rev. C **70**, 064609 (2004).
SHIP: Hofmann *et al.*, Eur. Phys. J. A **48**, 62 (2012).









Experimental conditions

Reaction	$^{248}Cm(^{48}Ca,xn)^{296-x}Lv$
Period	Dec. 1, 2013 – Dec. 12, 2013
Beam energy	250 MeV in the middle of the target
Beam intensity	ave. 0.8 pμA
Beam integral	4.3×10^{18}
Target thickness	0.29 mg cm^{-2} $^{248}Cm_2O_3$
Target backing	0.90 mg cm^{-2} Ti
Magnetic rigidity	2.17 Tm
He pressure in GARIS	73 Pa
GARIS eff.	36%
PSD + SSD eff.	94%

α-particle energies of ^{292,293}Lv and their daughters

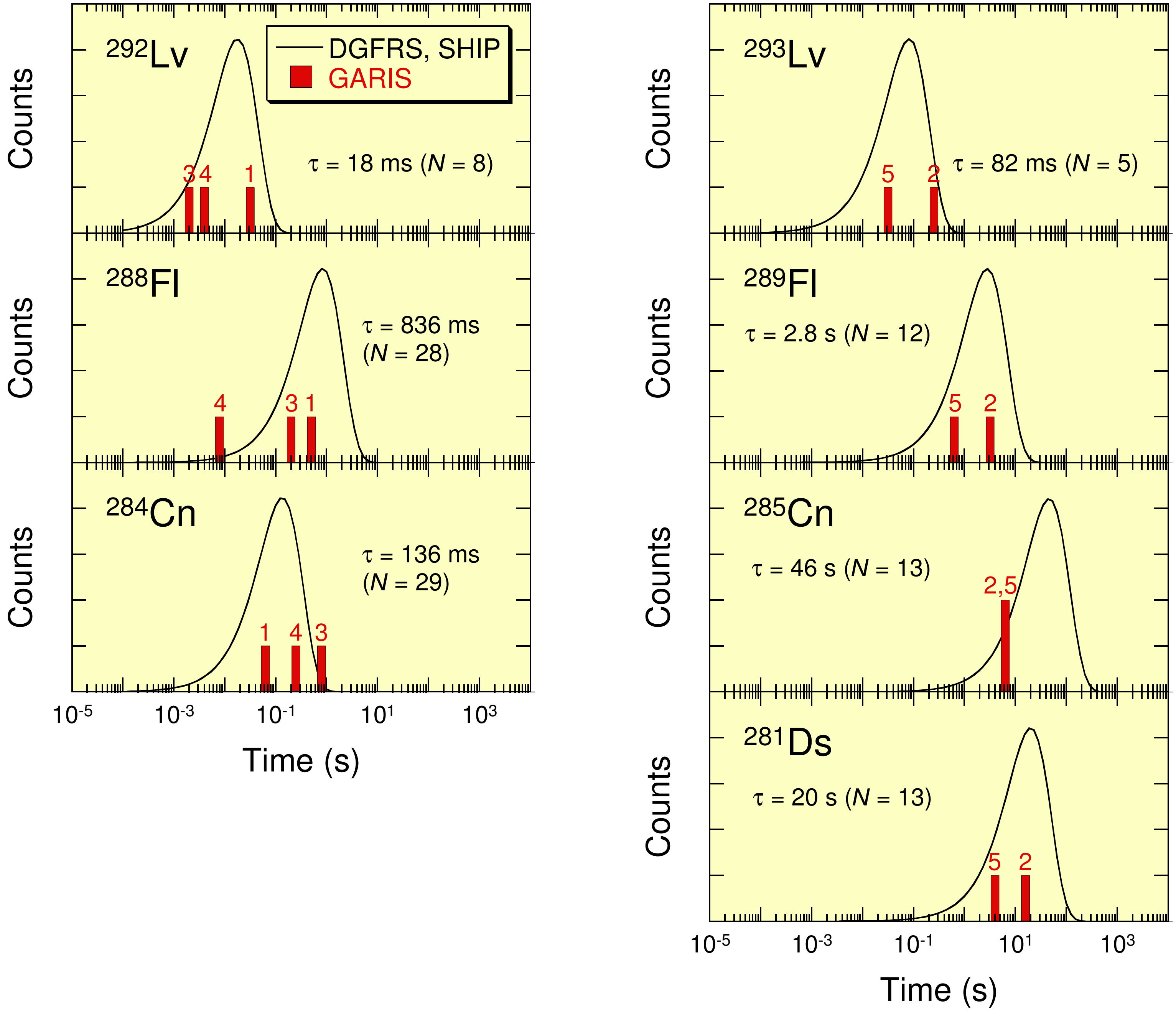
	Chain 1	Chain 3	Chain 4	Ref.*
^{292}Lv	E_α = 10.79 MeV τ = 32 ms	(E_α = 2.77 MeV) τ = 2.0 ms	E_α = 10.66 MeV τ = 4.1 ms	E_α = 10.66 ± 0.07 MeV $T_{1/2} = 18^{+16}_{-6}$ ms
^{288}Fl	E_α = 9.89 MeV τ = 0.548 s	E_α = 9.99 MeV τ = 0.243 s	(E_α = 0.83 MeV) τ = 0.0090 s	E_α = 9.95 ± 0.07 MeV $T_{1/2} = 0.80^{+0.32}_{-0.18}$ ms
^{284}Cn	E_{SF} = 232 MeV τ = 65 ms	E_{SF} = 182 MeV τ = 832 ms	E_α = 9.09 MeV τ = 282 ms	$T_{1/2} = 101^{+41}_{-22}$ ms
^{280}Ds			E_{SF} = 163 MeV τ = 9.6 ms	

* Oganessian et al., PRC **70**, 064609 (2004).

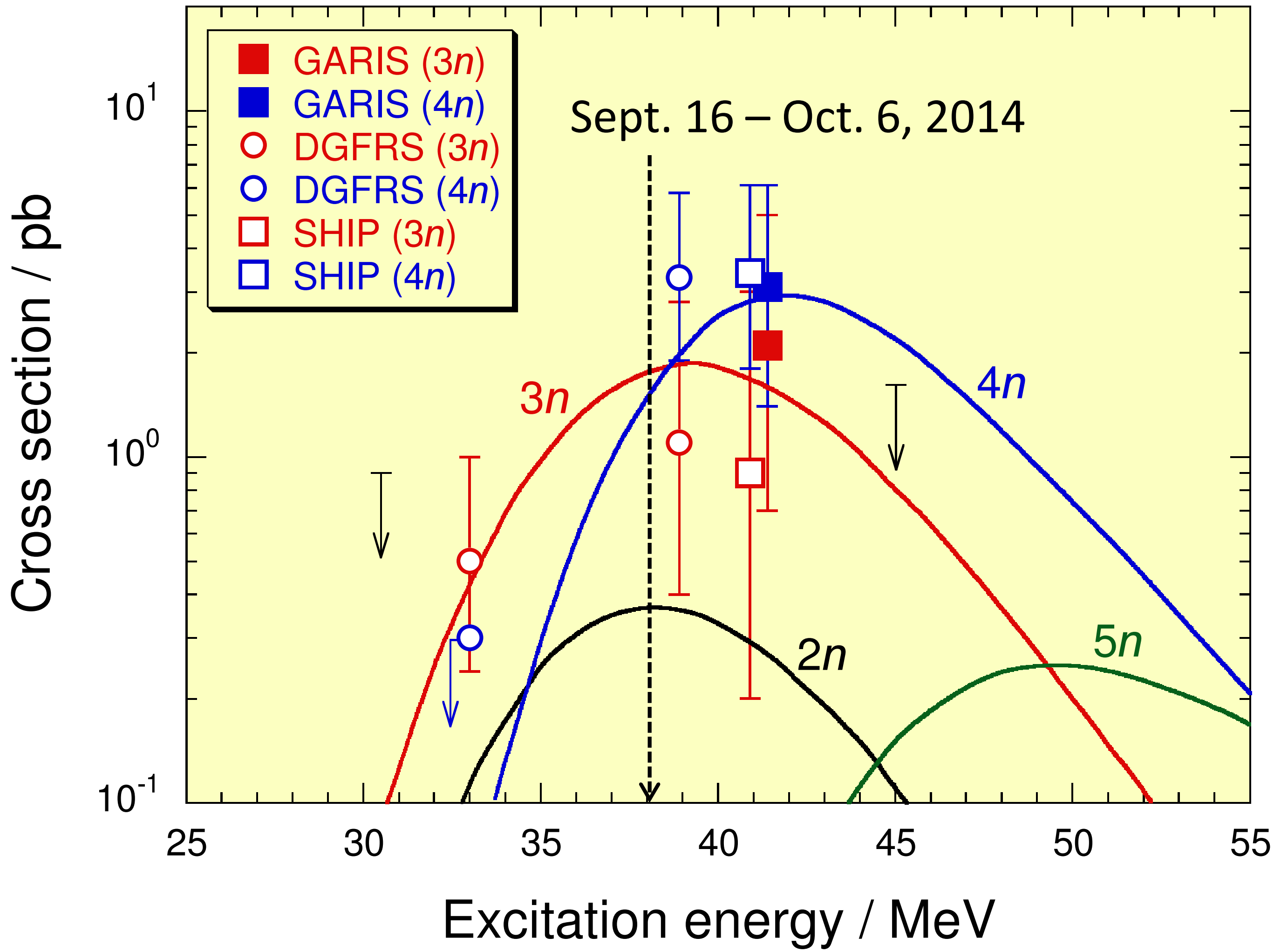
	Chain 2	Chain 5	Ref.*
^{293}Lv	E_α = 10.47 MeV τ = 253 ms	(E_α = 7.76 MeV) τ = 32 ms	E_α = 10.53 ± 0.06 MeV $T_{1/2} = 53^{+62}_{-19}$ ms
^{289}Fl	E_α = 9.89 MeV τ = 3.97 s	E_α = 9.72 MeV τ = 0.666 s	E_α = 9.82 ± 0.06 MeV $T_{1/2} = 2.7^{+1.4}_{-0.7}$ s
^{285}Cn	(E_α = 2.46 MeV) τ = 7.76 s	(E_α = 1.64 MeV) τ = 7.56 s	E_α = 9.16 ± 0.06 MeV $T_{1/2} = 34^{+17}_{-9}$ s
^{281}Ds	E_{SF} = 195 MeV τ = 19.8 s	E_{SF} = 221 MeV τ = 4.63 s	$T_{1/2} = 9.6^{+5.0}_{-2.5}$ s

* Oganessian et al., PRC **70**, 064609 (2004).

Lifetimes of $^{292,293}Lv$



Excitation functions for $^{248}Cm(^{48}Ca,xn)^{296-x}Lv$



DGFRS: Oganessian et al., Phys. Rev. C **63**, 011301 (2000).
Oganessian et al., Phys. Rev. C **70**, 064609 (2004).
SHIP: Hofmann et al., Eur. Phys. J. A **48**, 62 (2012).
Theoretical calculation: Zagrebaev, Nucl. Phys. A **734**, 164 (2004).

3. Future plans of SHE researches at RIKEN

Chemistry using preseparated $^{261}Rf^{a}$, ^{262}Db, and $^{265}Sg^{a,b}$

- $^{248}Cm(^{23}Na,xn)^{271-x}Bh$ (in progress)
- Aqueous chemistry of Sg and Bh by solvent extraction with LS
- Gas chemistry by direct complexation without aerosols

  Organometallic compounds of SHEs

Syntheses of the heaviest SHEs

- $^{248}Cm(^{48}Ca,xn)^{296-x}Lv$ (in progress)
- $^{248}Cm(^{50}Ti,xn)^{298-x}118$ (scheduled in 2015)

  ^{50}Ti-MIVOC with $Cp^{*50}TiMe_3$ from Univ. Strasbourg (Aug., 2014–)

  9 mg of ^{248}Cm from ORNL (Jan., 2015)

  Commissioning of GARIS II (in progress)

High precision mass measurement of SHE nuclei ($\delta m/m$ ~ 0.5 ppm)

- GARIS II + RF-Carpet + MRTOF Spectrograph (Aug., 2014–)

Collaborators for the GARIS gas-jet experiment

Nishina Center for Accelerator-Based Science, RIKEN

M. Huang, D. Kaji, J. Kanaya, Y. Komori, K. Morimoto, K. Morita, M. Murakami, M. Takeyama, K. Tanaka, Y. Wakabayashi, S. Yamaki, and A. Yoneda

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Tohoku Univ.

H. Kikunaga

Niigata Univ.

R. Aono, H. Kudo, K. Ooe, and S. Tsuto

Advanced Science Research Center, JAEA

K. Nishio, A. Toyoshima, and K. Tsukada

Kyushu Univ.

T. Tanaka

Collaborators for the $^{248}Cm + ^{48}Ca$ experiment

RIKEN	K. Morita, K. Morimoto, D. Kaji, Y. Wakabayashi, H. Hasebe, M. Huang, J. Kanaya, A. Yoneda, A. Yoshida, and K. Katori
Yamagata Univ.	M. Takeyama, F. Tokanai, and T. Yoshida
Saitama Univ.	S. Yamaki and T. Yamaguchi
Tokyo Univ. Sci.	K. Tanaka
Niigata Univ.	M. Murakami
IMP	Z. Gan and L. Ma
GSI	H. Geissel, S. Hofmann, and Y. Maurer
Kyushu Univ.	K. Fujita, Y. Narikiyo, T. Tanaka, and S. Yamamoto
JAEA	M. Asai