SHE experiments with GARIS-I/-II at RIKEN

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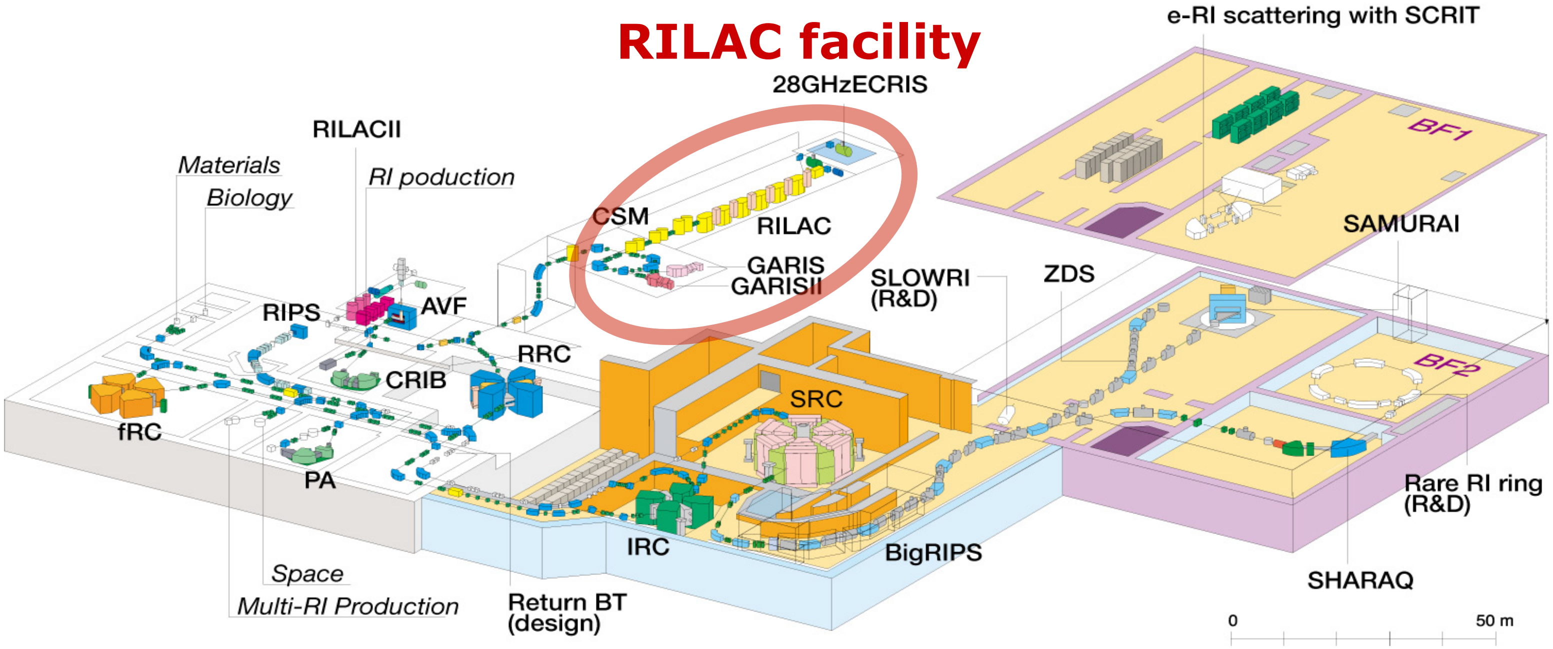
RIBF (RI Beam Factory)

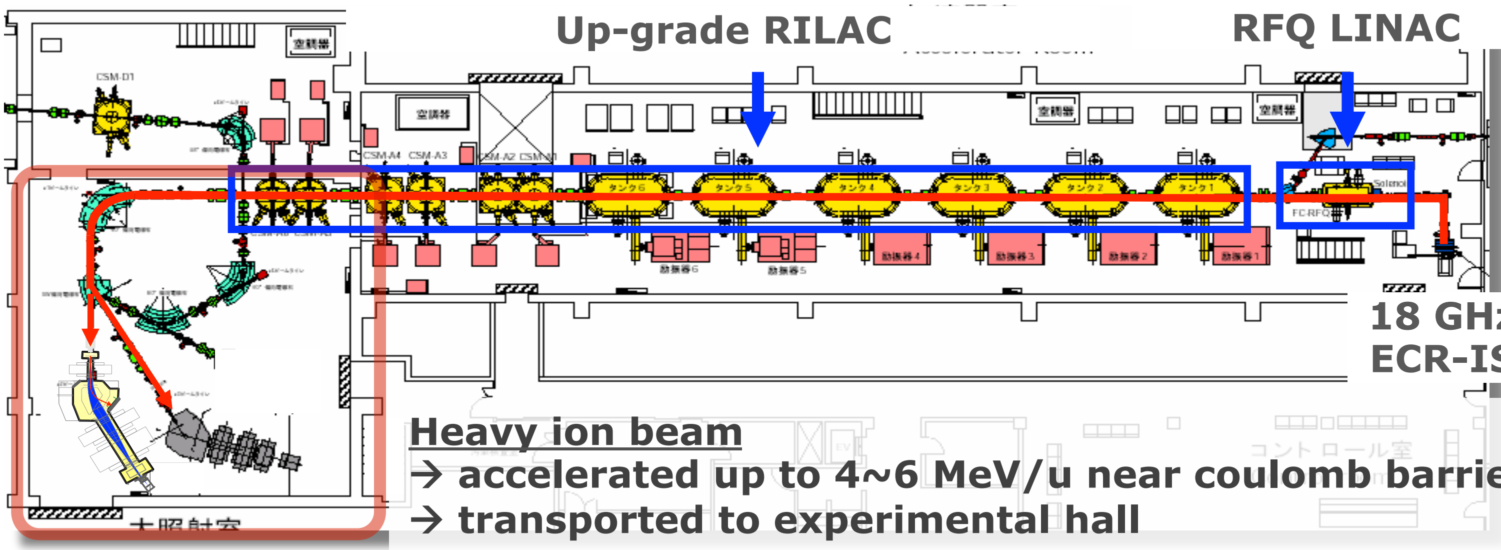


- **SHE study** is mainly performed at **RILAC facility**.
- ***High-intense heavy-ion beam** is powerful to produce SHE nuclides.*
- ***RILAC can operate stand-alone,***
  because RILAC-II was installed as an injector for SRC at 2010.
- ***Long MT is available for SHE study.***

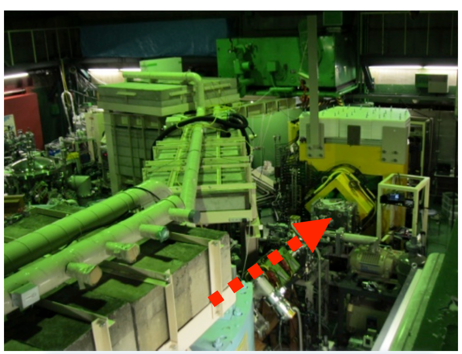
RILAC

RIKEN heavy-Ion Linear ACcelerator

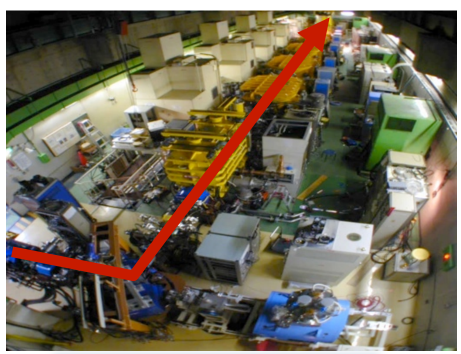
EXP hall



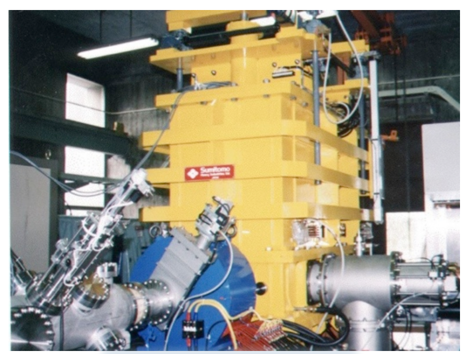
Heavy ion beam
→ accelerated up to 4~6 MeV/u near coulomb barrier
→ transported to experimental hall



GARIS & GARIS-II



Upgrade RILAC

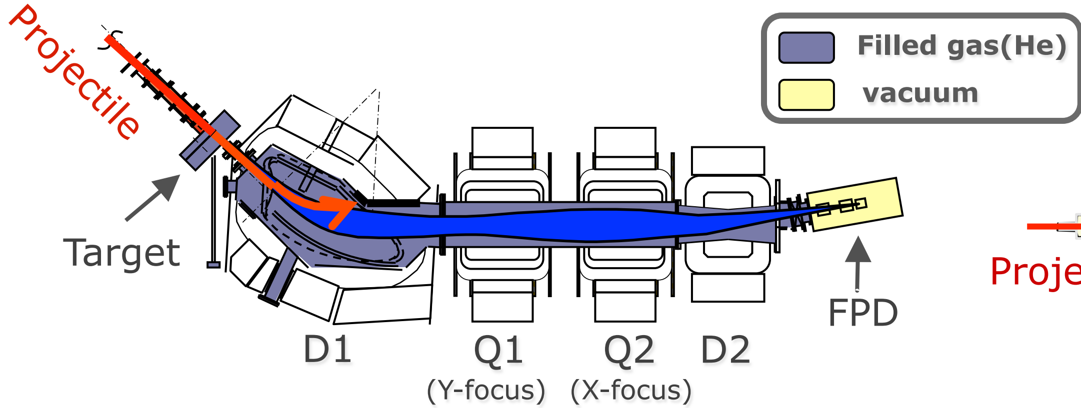


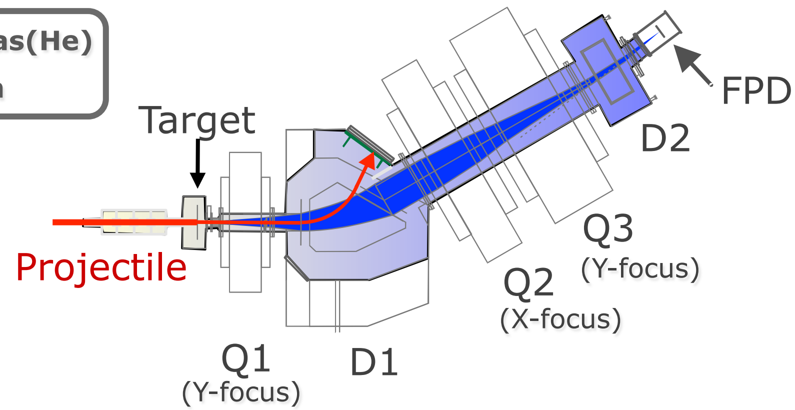
RFQ LINAC

18 GHz ECR-IS

GARIS & GARIS-II

GAs-filled **R**ecoil **I**on **S**eparator





Reaction product recoiled out of target is separated from projectiles and other *BG*, and then it is transported to FPD (focal plane detector).

Large transmission under low BG-level

Gas-filled type

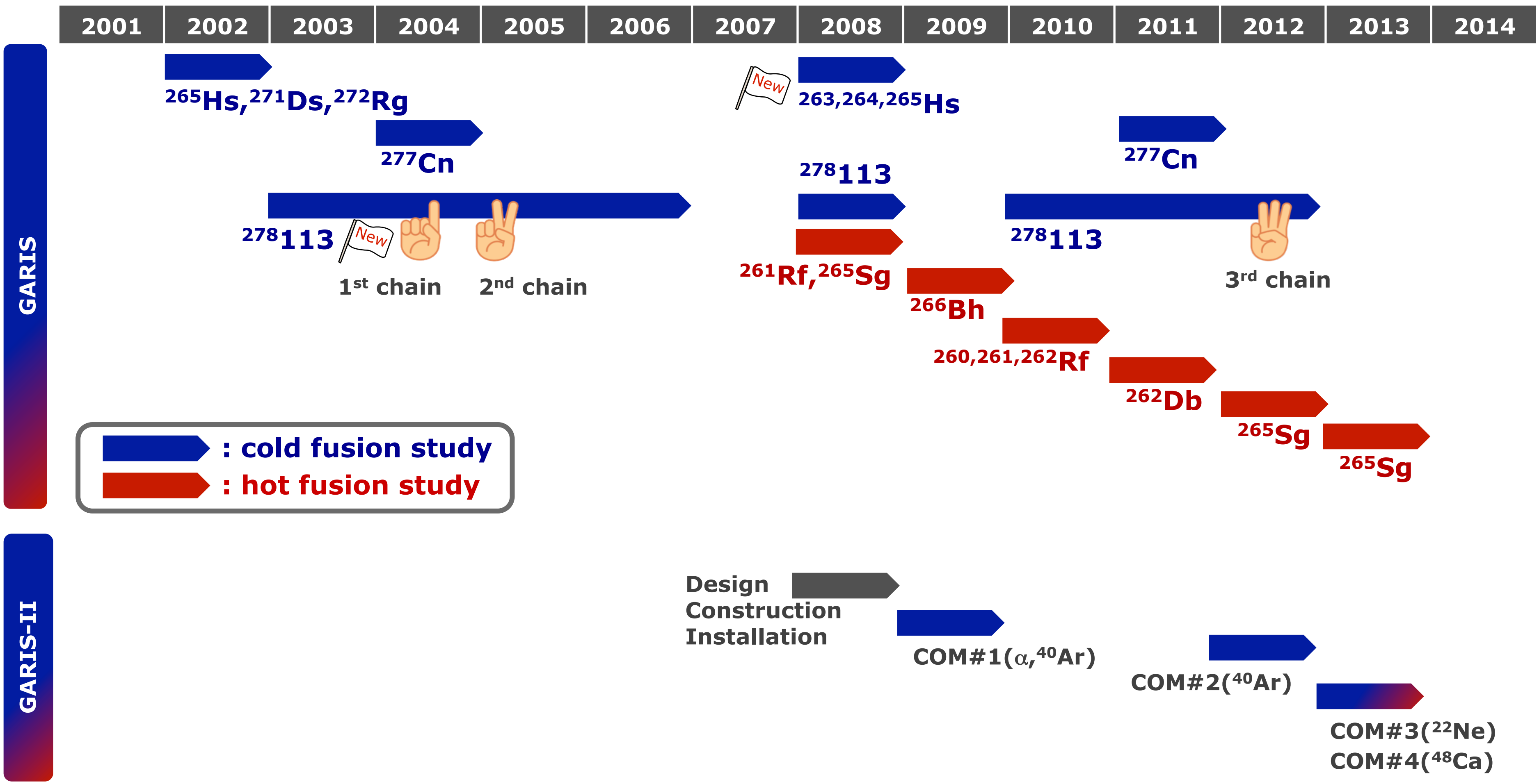
Large bending angle
Deep structure of beam-dump
2-dipoles to suppress *BG* particles

Possible to stand against high-intense beam

Windowless operation of GARIS & gas-cooling of target by differential pumping

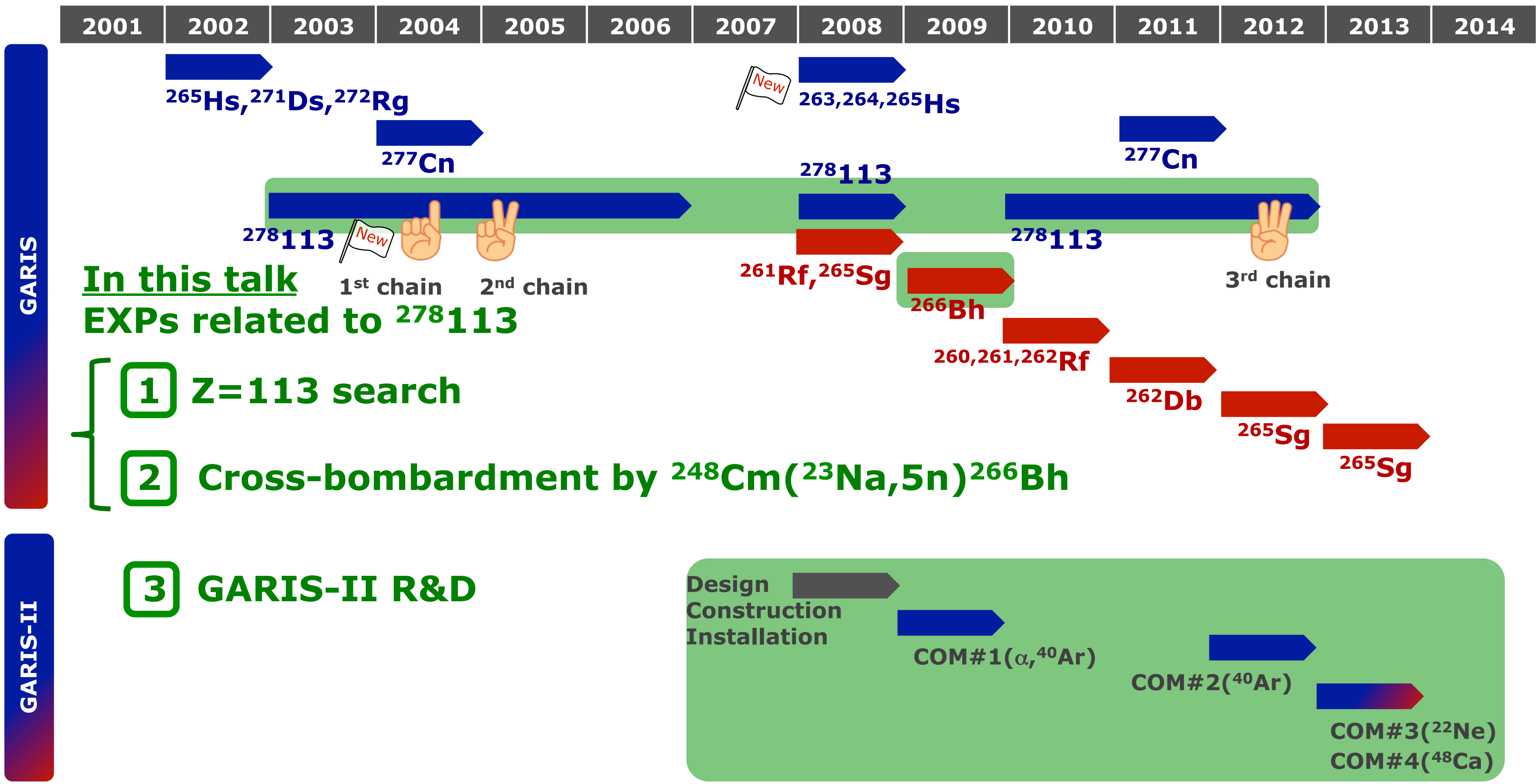
Timeline

SHE experiments with GARIS-I/-II



Timeline

SHE experiments with GARIS-I/-II



In this talk

EXPs related to ^{278}113

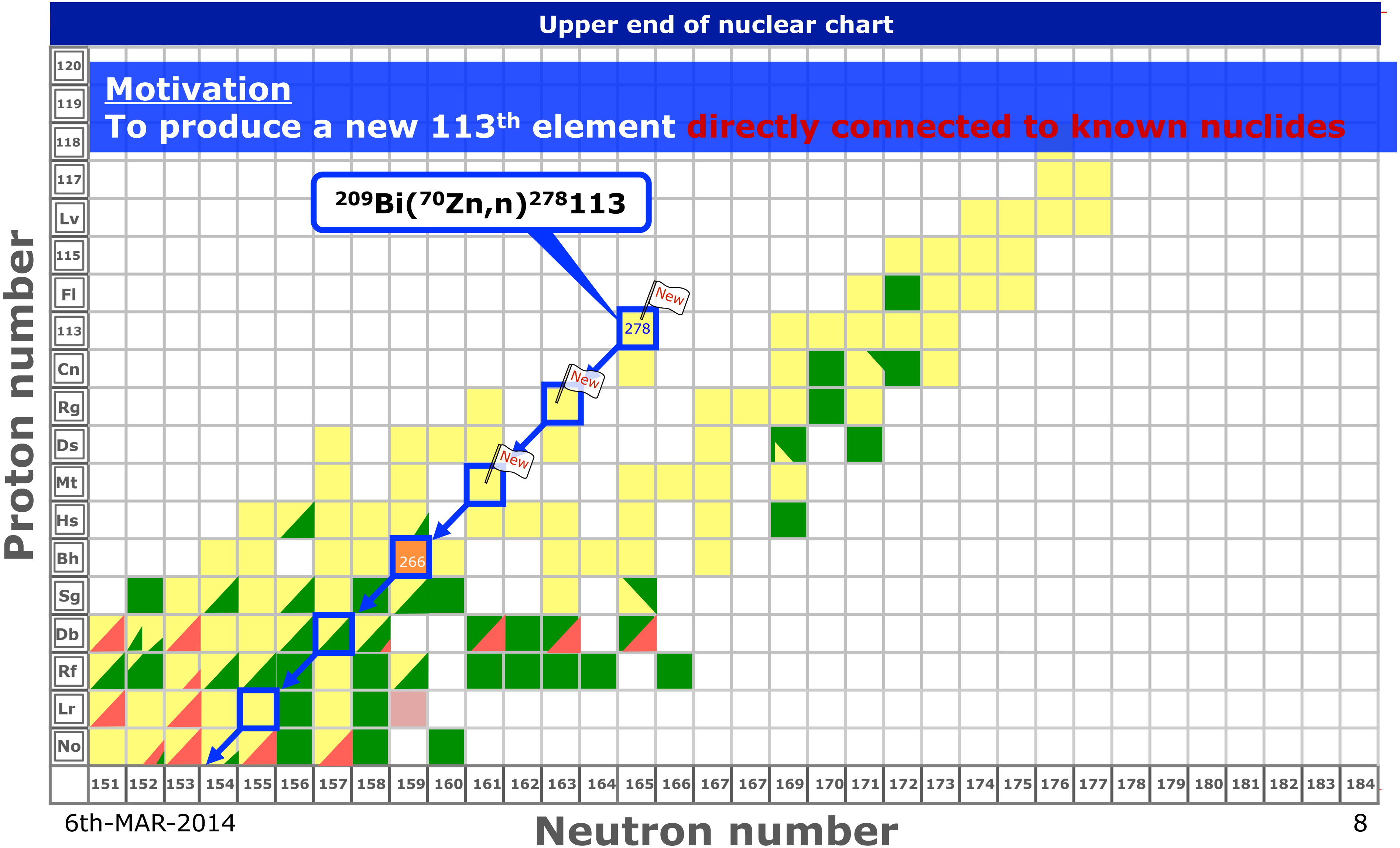
1. **Z=113 search**
2. **Cross-bombardment by $^{248}Cm(^{23}Na,5n)^{266}Bh$**
3. **GARIS-II R&D**

① Z=113 search

[1] K. Morita, K. Morimoto, D. Kaji et al., JPSJ 73, 2593(2004).
[2] K. Morita, K. Morimoto, D. Kaji et al., JPSJ 76, 045001(2007).
[3] K. Morita, K. Morimoto, D. Kaji et al., JPSJ 81, 103201(2012).

[SHE Experiments with GARIS]

Z=113 search

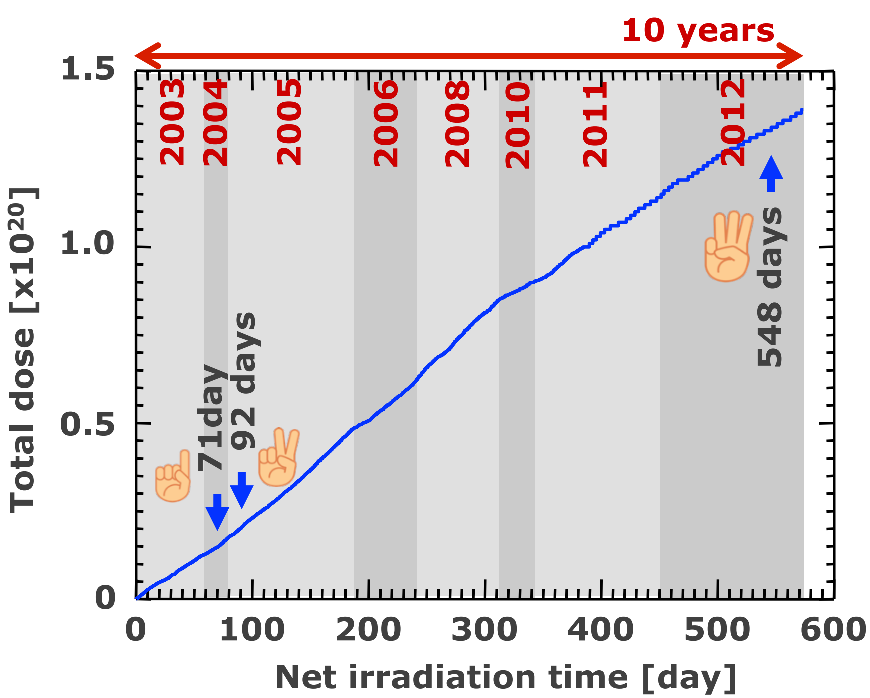


[Experimental conditions]

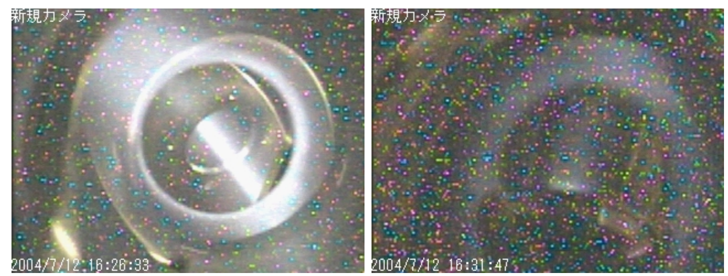
Irradiation

Nuclear reaction : $^{209}Bi(^{70}Zn,n)^{278}113$
Experimental period : 5th-SEP-2003 ~ 1st-OCT-2012 (**10 years in total**)
Net irradiation time : 576 days

Beam energy : 349 MeV @ middle of target
Beam intensity (Average) : 0.5 pμA
Dose : 1.4×10^{20}



Appearance of irradiation



D. Kaji et al. Nucl. Instr. and Meth. A737, p.19 (2014).

During irradiation,
we observed 3 decay chains in total.

$\sigma = 22^{+18}_{-12}$ fb (the lowest in SHE study)

[Experimental conditions]

Target

Preparation

by vacuum evaporation on 30~60 μg/cm² C backing foil

D. Kaji et al. Nucl. Instr. and Meth. A590, p.198 (2007).

Target thickness

0.45 mg/cm²

→ The 16 sector targets were mounted on a rotating wheel of 300 mm in diameter.

→ The wheel was rotated at 3000 rpm during irradiation.

[Experimental conditions]

Operation of GARIS

Magnetic field ($B\rho$)	**: 2.09 Tm (based on empirical formula of q_{ave})**
Filled gas	**: He at 86 Pa**
Transmission of GARIS	**: 80%**

Empirical formula on q_{ave} of recoil ion moving in a *He* gas

For cold fusion

$$q_{ave} = 0.625 \times (v/v_0) \times Z^{1/3}$$

$$9.1 \leqq (v/v_0) \times Z^{1/3} \leqq 19.1,\ Z \geqq 82]$$

Application

^{263264,265}Hs, ^{271}Ds, ^{272}Rg, ^{277}Cn, ^{278}Uut

For hot fusion

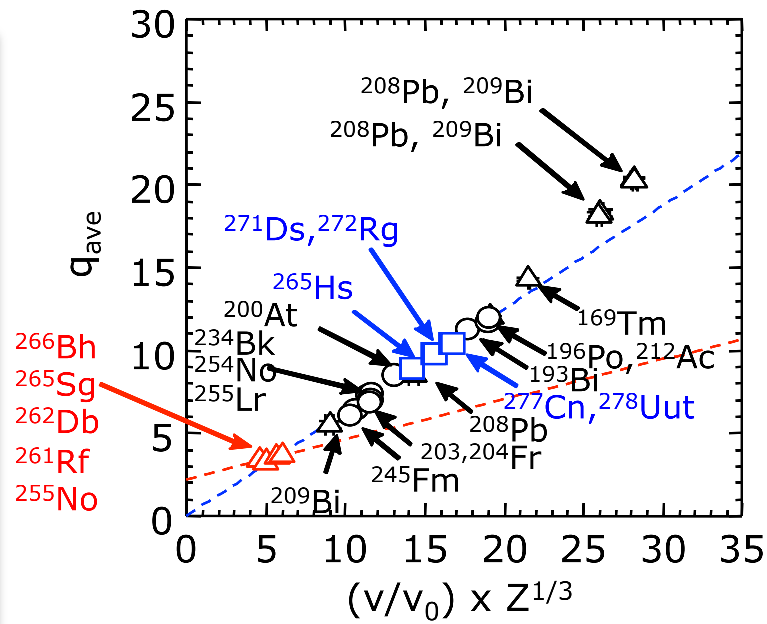
$$q_{ave} = 0.242 \times (v/v_0) \times Z^{1/3} + 2.19$$

$$4.6 \leqq (v/v_0) \times Z^{1/3} \leqq 6.0,\ Z \geqq 102]$$

Application

^{266}Bh

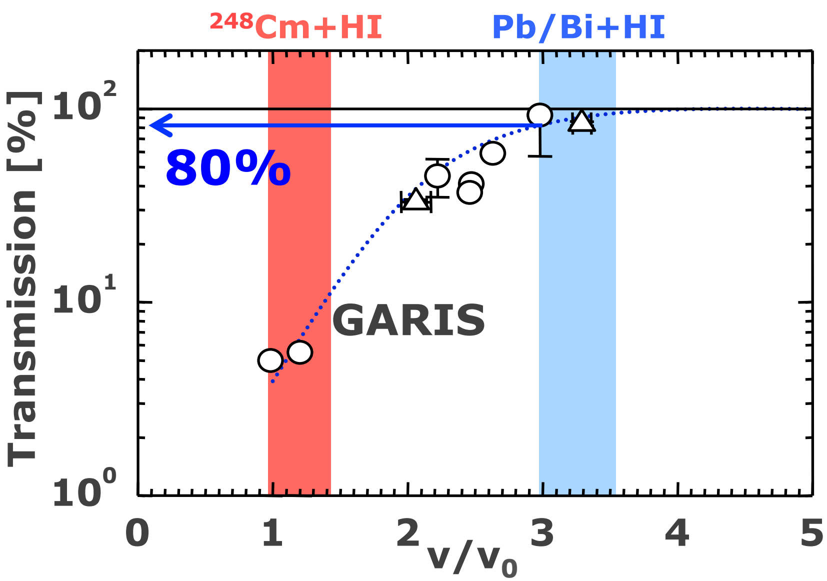
D. Kaji, et al., Proc. Radiochim. Acta 1, 105 (2011).

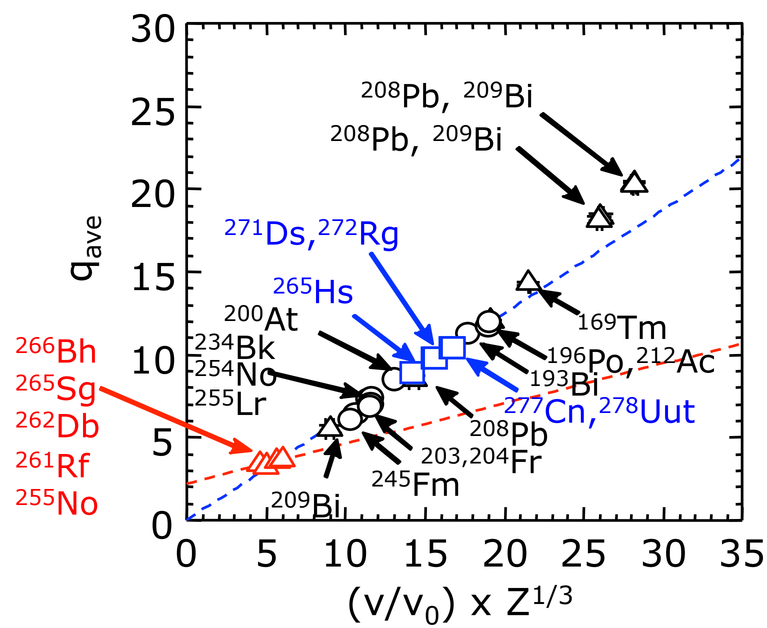


[Experimental conditions]

Operation of GARIS

Magnetic field ($B\rho$) : **2.09 Tm (based on empirical formula of q_{ave})**
Filled gas : **He at 86 Pa**
Transmission of GARIS : **80%**

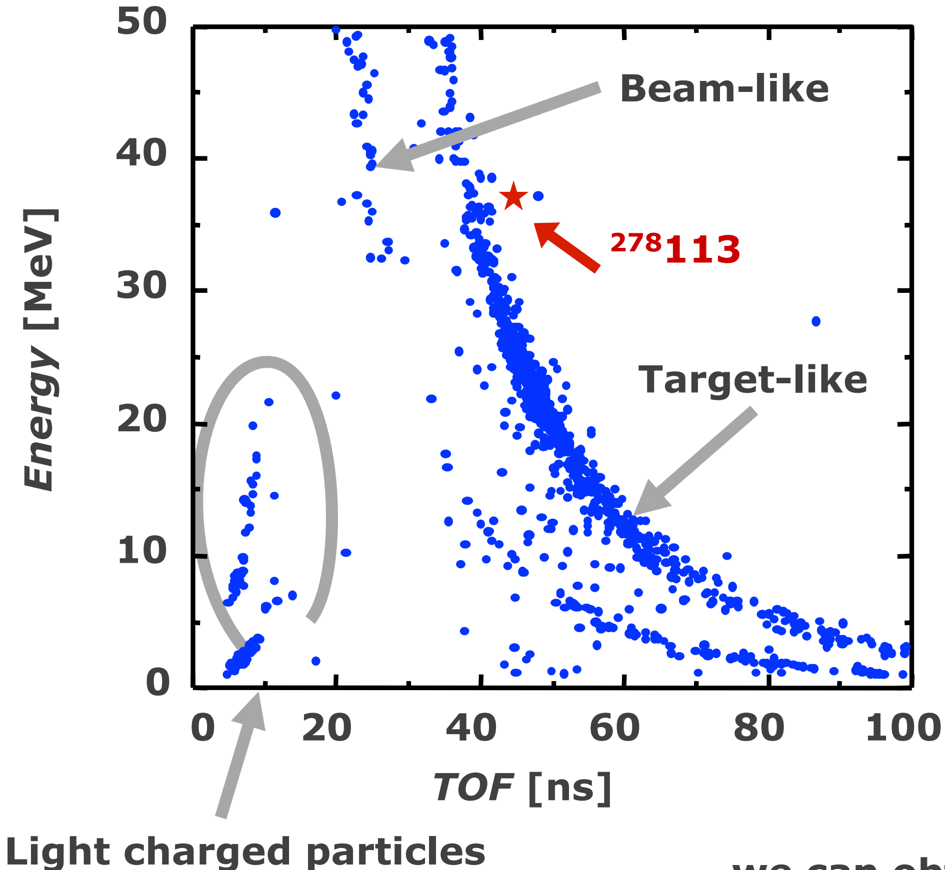


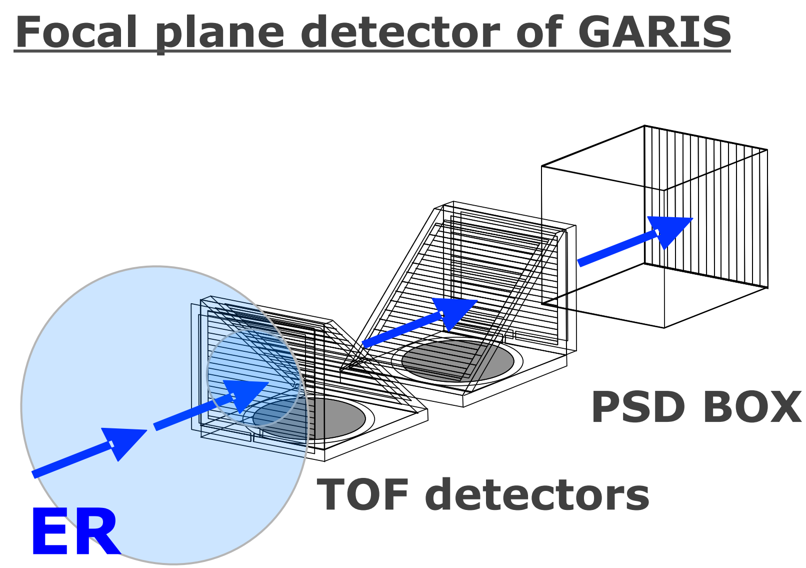


→ GARIS has the best performance for cold fusion reaction.

[Data quality]

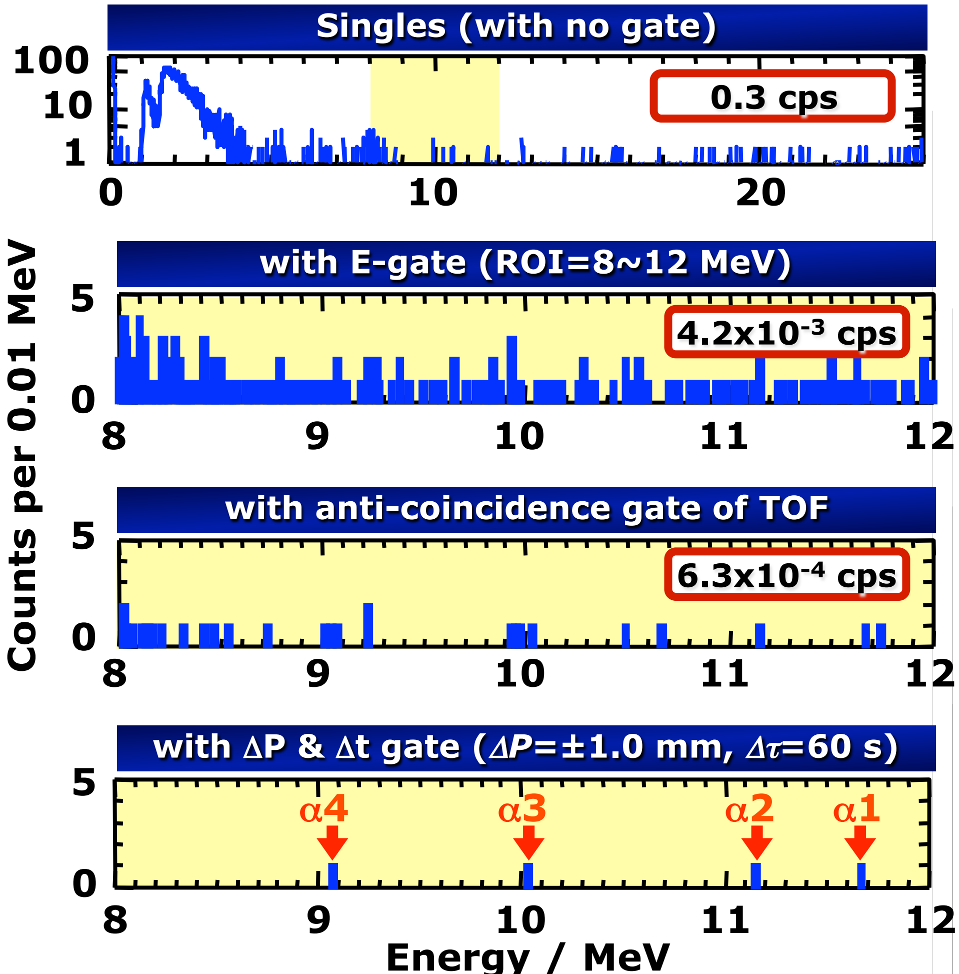
TOF-Energy PLOT





we can obtain rough mass information.
→ ER was clearly separated from BG particles.

Correlation analysis



Trigger rate @ FPD was extremely low.

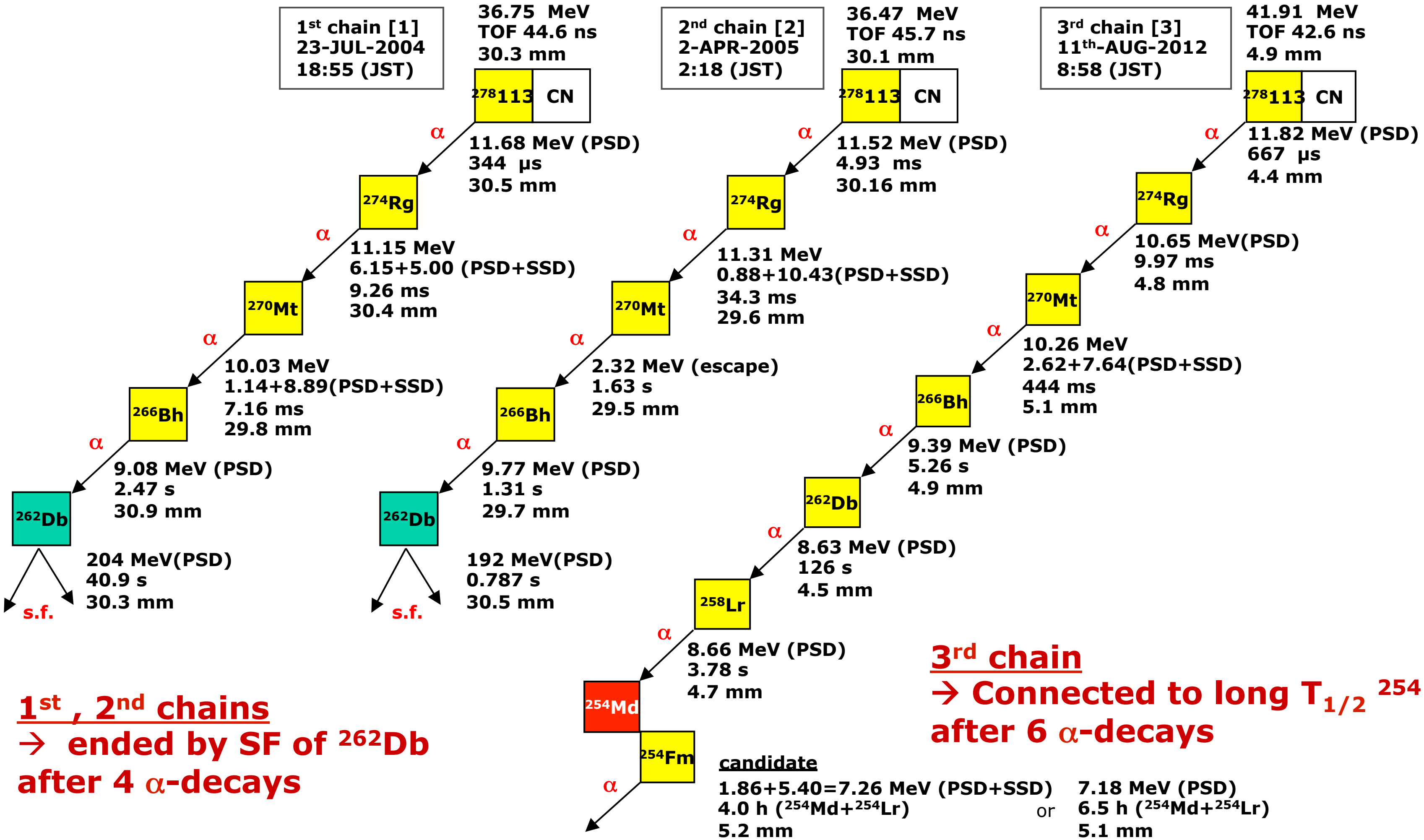
Decay-like event was also low rate.

There are no BG except for true events.

[1] K. Morita et al., JPSJ 73, 2593(2004).
[2] K. Morita et al., JPSJ 76, 045001(2007).
[3] K. Morita et al., JPSJ 81, 103201(2012).

High quality experiment enables to observe

3 decay chains due to $^{278}113$

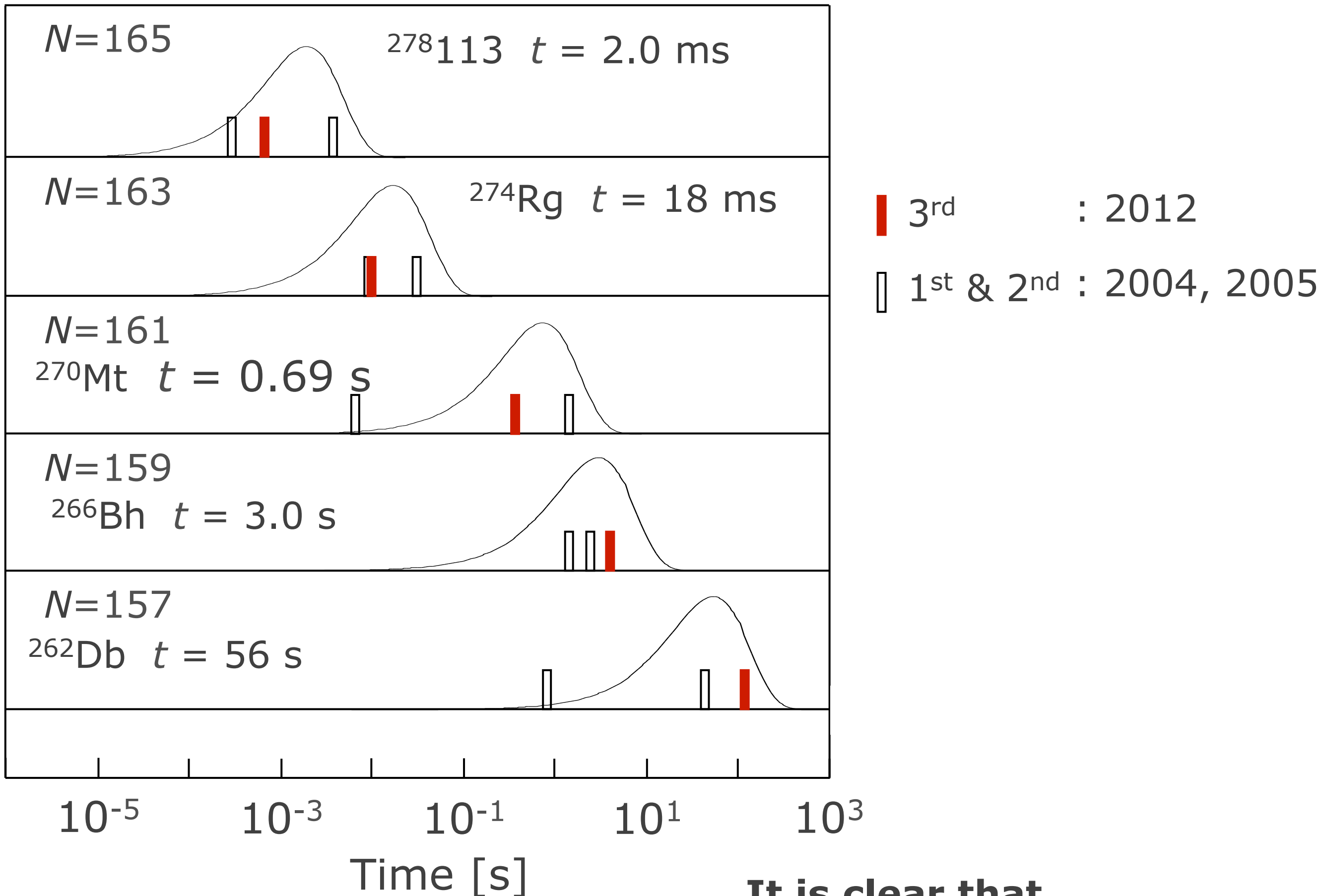


1^{st}, 2^{nd} chains
→ ended by SF of ^{262}Db after 4 α-decays

3^{rd} chain
→ Connected to long $T_{1/2}$ ^{254}Md after 6 α-decays

In order to check whether these chains are identical or not…

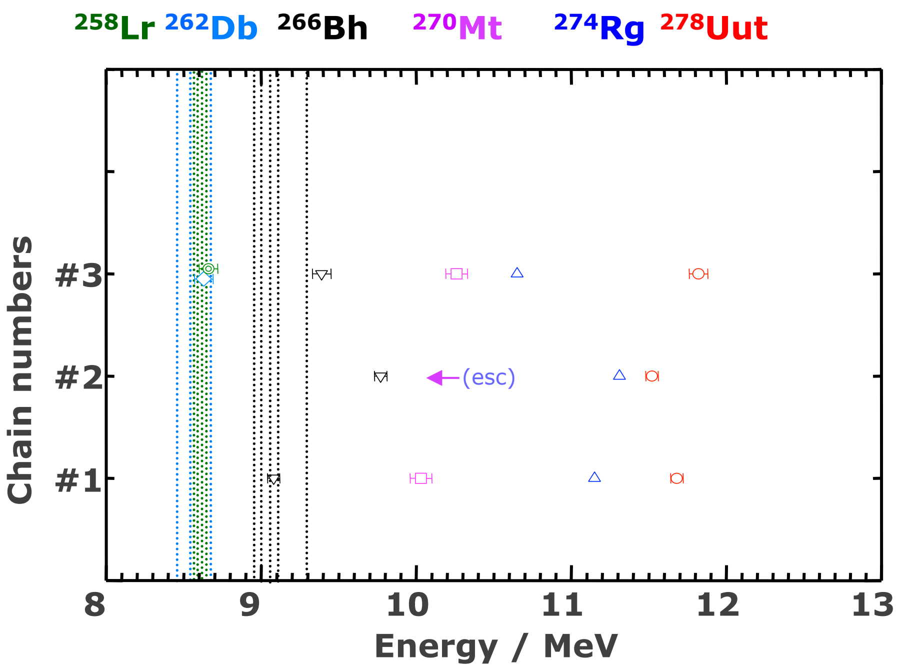
Decay time distributions (with Log scale)



It is clear that
all decay chains are identical.

In order to check whether these chains are identical or not…

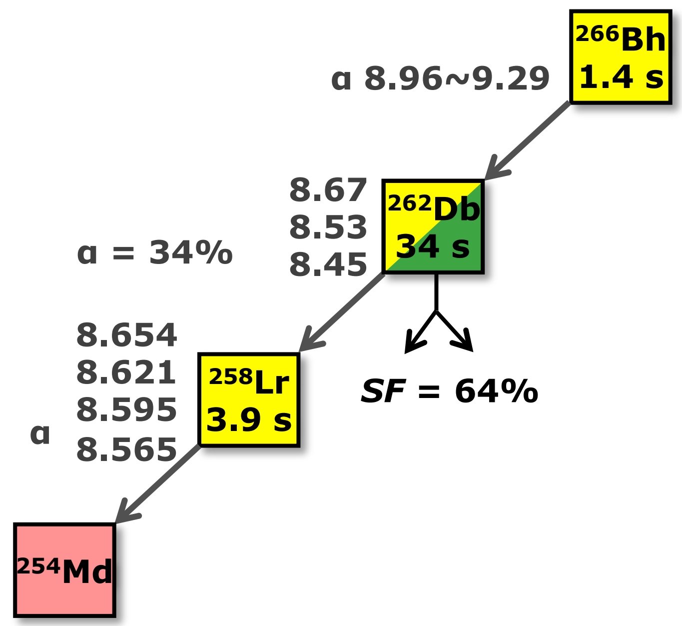
α-decay energy distributions



However, IUAC/IUPAP JWP assessed that
the statistics of ref. data are not enough.

1 event : $^{249}Bk(^{22}Ne,5n)^{266}Bh$ @ LBNL
4 events : $^{243}Am(^{26}Mg,3n)^{266}Bh$ @ IMP

Pure Appl. Chem. Vol.83, 1485 (2011).



Guide lines : reference data

^{266}Bh : PRL 85, 2697(2000)
^{266}Bh : Nucl. Phys. Rev. 23, 400 (2006)
^{262}Db & ^{258}Lr : *Table of Isotopes 8th ed*, (Wiley and Sons, New York, 1996).

It looks like that
the 1st & 3rd chains are connected to know nuclide.

2 Cross bombardment by $^{248}Cm(^{23}Na,5n)^{266}Bh$

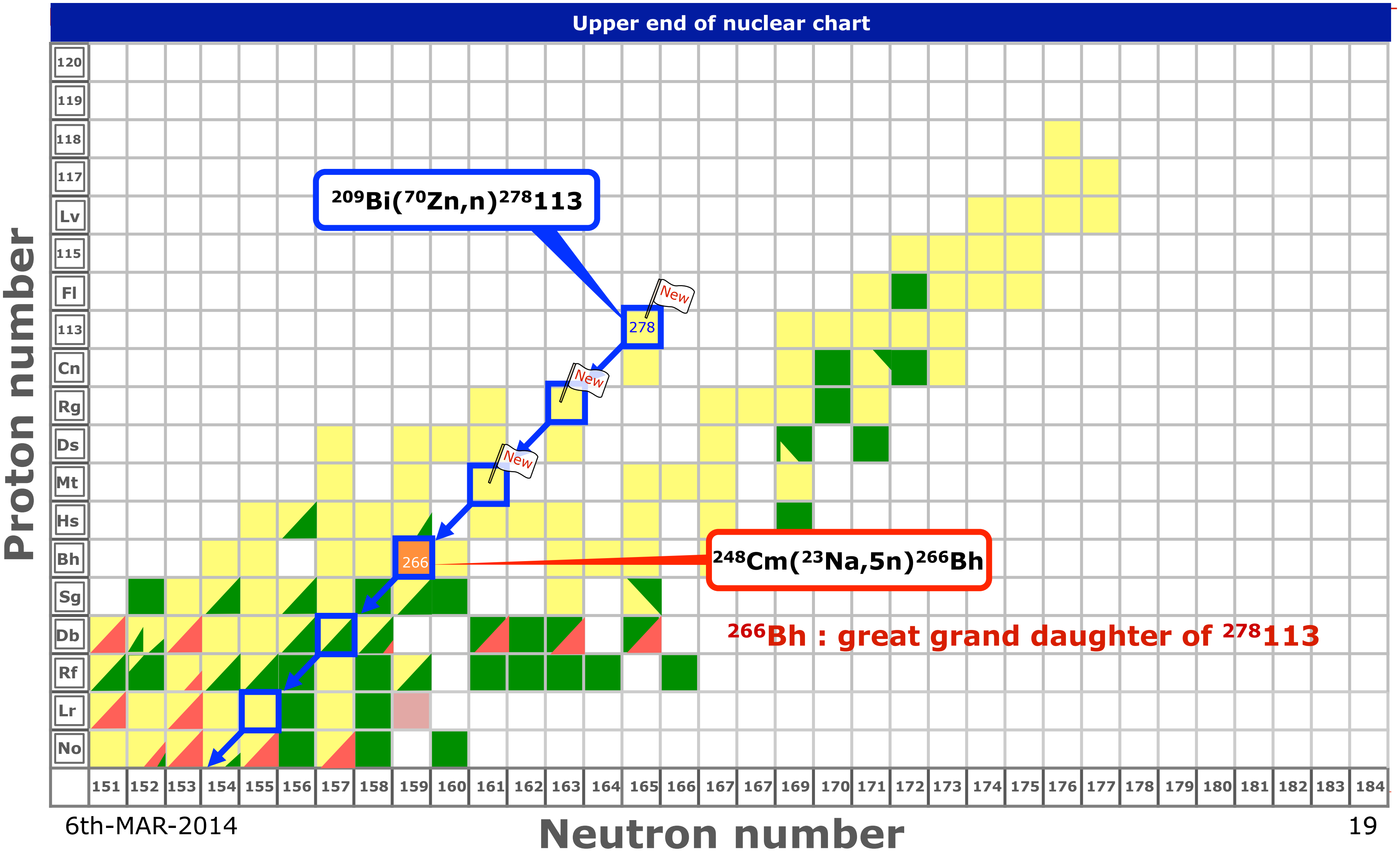
Motivation

- **To make strong the information on anchor nuclides in 113 decay chains**
- **To confirm results studied on reactions $^{249}Bk(^{22}Ne,5n)^{266}Bh$ at LBNL [1] & $^{243}Am(^{26}Mg,3n)^{266}Bh$ at IMP [2]**

[1] Wilk et al., PRL 85, 2697 (2000).
[2] Z. Qin et al., Nucl. Phys. Rev. 23, 400 (2006)

[SHE Experiments with GARIS]

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



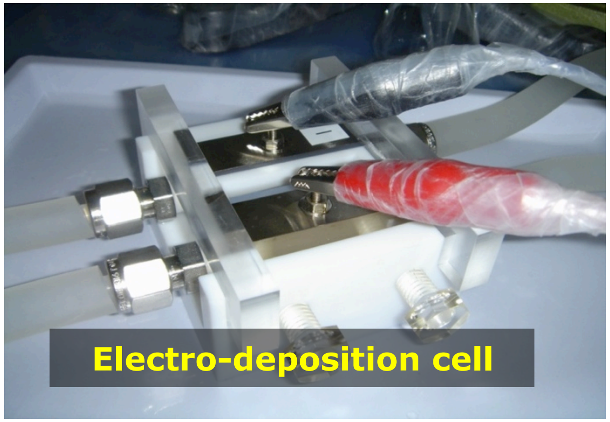
Target

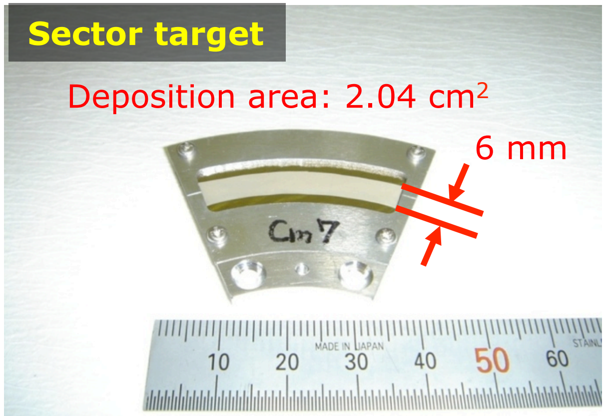
Preparation
by Electrodeposition on 2 μm Ti backing foil
Y. Kudo et al., RIKEN Accel. Prog. Rep. (2009).

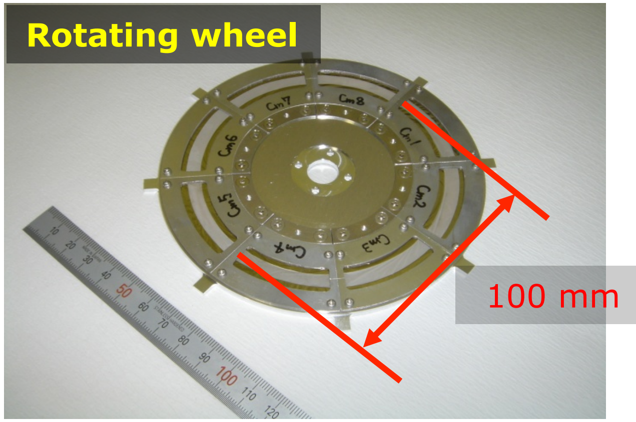
Target thickness
0.35 mg/cm^2 (as $^{248}Cm_2O_3$)

Isotopic abundance
96.64% ^{248}Cm, 0.04% ^{247}Cm, 3.17% ^{246}Cm, 0.13% ^{245}Cm, and 0.02% ^{244}Cm

→ The 8 sector targets were mounted on a rotating wheel of 100 mm in diameter.
→ The wheel was rotated at 1000 rpm during irradiation.







[Experimental conditions]

FPD for ^{266}Bh search

We used PSD box without TOF detectors & beam ON/OFF method.

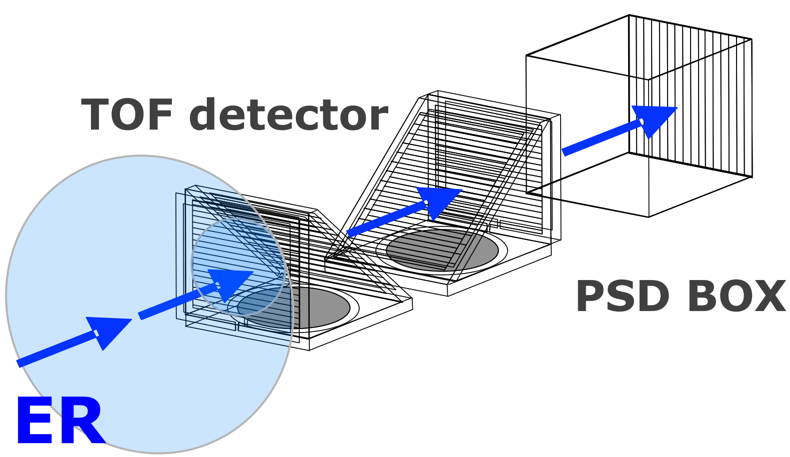
Because…

- **Recoil energy is too low to pass through MYLAR window of TOF.**
- **Counting rate during beam-ON is high.**

Z=113 search

(Cold fusion)

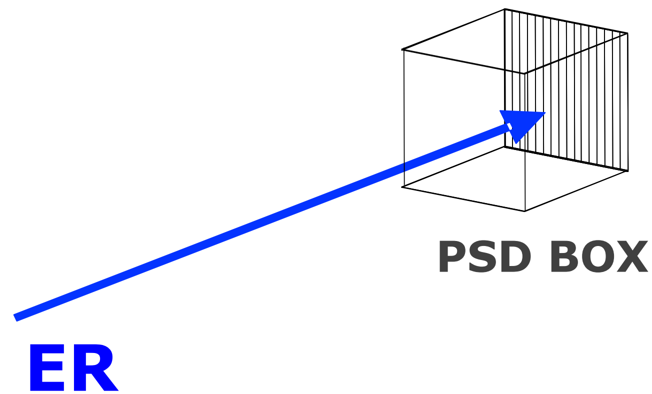
→ **Full-time beam ON**



^{266}Bh search

(Hot fusion)

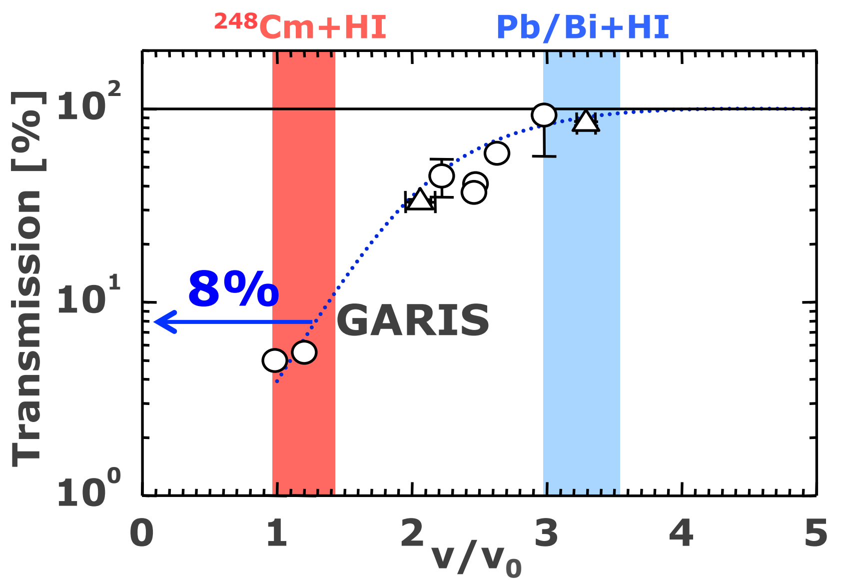
Time Structure : **3 s Beam ON/3 s Beam OFF**

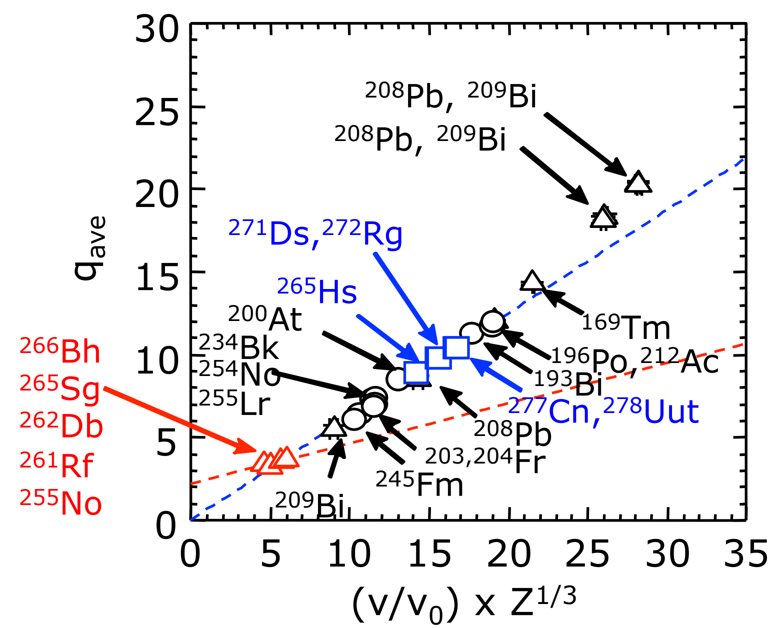


[Experimental conditions]

Operation of GARIS

$B\rho$ setting : **2.07~2.19 Tm (based on empirical formula of q_{ave})**
Filled gas : **He at 33 Pa**
Transmission of GARIS : **8%**





Transmission is not so high
due to MS with filed gas for hot fusion.

Decay information

obtained in the reaction $^{248}Cm(^{23}Na,xn)^{271-x}Bh$

Table I. Summary of decay chains observed in the reaction of ^{23}Na on ^{248}Cm.

ID	E_{beam} (MeV)	Strip	E(M) (MeV)	FWHM (MeV)	E(D) (MeV)	FWHM (MeV)	dPos (mm)	τ(D) (s)	E(GD) (MeV)	FWHM (MeV)	dPos (mm)	τ(GD) (s)	Group	Assignment
1	126[a]	2	9.05	0.11	8.71[s]	0.18	−0.45	54.91	8.71	0.11	0.98	9.23	AC	$^{266}Bh \to ^{262}Db \to ^{258}Lr$
2	130[b]	11	9.12[s]	0.16	8.74[s]	0.16	3.53	13.76	8.60	0.09	−7.16	9.36	AC	$^{266}Bh \to ^{262}Db \to ^{258}Lr$
3	132[a]	7	9.20	0.07	8.67	0.07	0.86	13.71	8.70[s]	0.14	−0.22	4.72	AC	$^{266}Bh \to ^{262}Db \to ^{258}Lr$
4	132[a]	7	8.82	0.07	8.54[s]	0.14	1.45	95.45	8.69	0.07	−1.45	3.94	BC	$^{266}Bh \to ^{262}Db \to ^{258}Lr$
5	132[b]	13	8.84[s]	0.12	8.42	0.05	−0.12	11.95	169.5[s]		−0.53	27.22	DGI	$^{267}Bh \to ^{263}Db \to ^{259}Lr$
6	130[b]	3	9.14	0.12	8.70	0.12	−0.06	66.23					A	$^{266}Bh \to ^{262}Db$ or ^{258}Lr
7	132[a]	6	9.23	0.07	8.65	0.07	0.43	22.04					A	$^{266}Bh \to ^{262}Db$ or ^{258}Lr
8	132[a]	8	9.14[s]	0.13	8.60	0.06	3.50	7.29					A	$^{266}Bh \to ^{262}Db$ or ^{258}Lr
9	132[b]	12	9.22[s]	0.11	8.61	0.04	−0.66	60.40					A	$^{266}Bh \to ^{262}Db$ or ^{258}Lr
10	130[b]	10	8.60[s]	0.17	8.70	0.10	−1.72	6.93					C	$^{262}Db \to ^{258}Lr$
11	130[b]	6	8.55	0.09	8.57	0.09	0.12	2.53					C	$^{262}Db \to ^{258}Lr$ tentative
12	130[b]	10	8.40	0.11	8.80[s]	0.18	2.99	3.73					C	$^{262}Db \to ^{258}Lr$
13	132[a]	4	8.43	0.10	8.69	0.10	−0.08	5.69					C	$^{262}Db \to ^{258}Lr$
14	132[b]	8	8.84	0.04	8.51	0.04	0.77	82.15					B	$^{266}Bh \to ^{262}Db$ tentative
15	126[a]	1	9.07	0.07	154.6[s]		0.52	5.67					E	$^{266}Bh \to ^{262}Db$
16	130[b]	9	9.09[s]	0.15	157.9		−0.56	5.34					E	$^{266}Bh \to ^{262}Db$
17	132[b]	8	9.23	0.06	180.4		1.89	121.53					E	$^{266}Bh \to ^{262}Db$
18	126[a]	7	8.99	0.09	185.8[s]		0.16	8.42					F	$^{266}Bh \to ^{262}Db$ tentative
19	126[a]	11	8.97	0.05	157.1		1.53	141.86					F	$^{266}Bh \to ^{262}Db$ tentative
20	126[a]	12	8.95[s]	0.13	162.8		−1.56	68.35					F	$^{266}Bh \to ^{262}Db$ tentative
21	126[a]	7	8.93	0.08	173.9[s]		0.61	84.30					F	$^{266}Bh \to ^{262}Db$ tentative
22	130[b]	7	8.97	0.08	131.1		−1.20	43.99					F	$^{266}Bh \to ^{262}Db$ tentative
23	132[a]	1	8.95	0.06	107.5		−0.06	151.36					F	$^{266}Bh \to ^{262}Db$ tentative
24	132[b]	13	8.98	0.04	162.8		−0.72	156.99					F	$^{266}Bh \to ^{262}Db$ tentative
25	[illegible]	10	8.95[s]	0.14	132.8		3.05	26.85					F	$^{266}Bh \to ^{262}Db$ tentative
26	126[a]	4	8.76	0.10	124.3[s]		0.14	112.21					H	$^{267}Bh \to ^{263}Db$ tentative
27	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]					[illegible]	[illegible]
28	132[b]	11	8.75	0.07	139.9[s]		−0.49	55.57					H	$^{267}Bh \to ^{263}Db$ tentative
29	132[b]	10	8.44	0.07	89.4		0.64	35.96					I	^{263}Db or ^{258}Lr
30	130[b]	12	8.84	0.04	173.8[s]		0.76	176.77					G	$^{267}Bh \to ^{263}Db$ or ^{259}Lr
31	132[a]	7	8.09	0.07	161.7[s]		−1.52	294.39					J	not assigned
32	132[b]	14	8.09[s]	0.13	164.8[s]		0.28	208.30					J	not assigned

a) Bρ of GARIS was set to 2.19
b) Bρ of GARIS was set to 2.07
s) Sum of PSD and SSD signals

32 correlation events were observed in total.
14 events were assigned to decay chains due to ^{266}Bh.

K. Morita, K. Morimoto, D. Kaji et al., JPSJ 78,064201(2009).

Summary of decay chains due to ^{266}Bh

& comparison with reference data reported by LBNL & IMP group

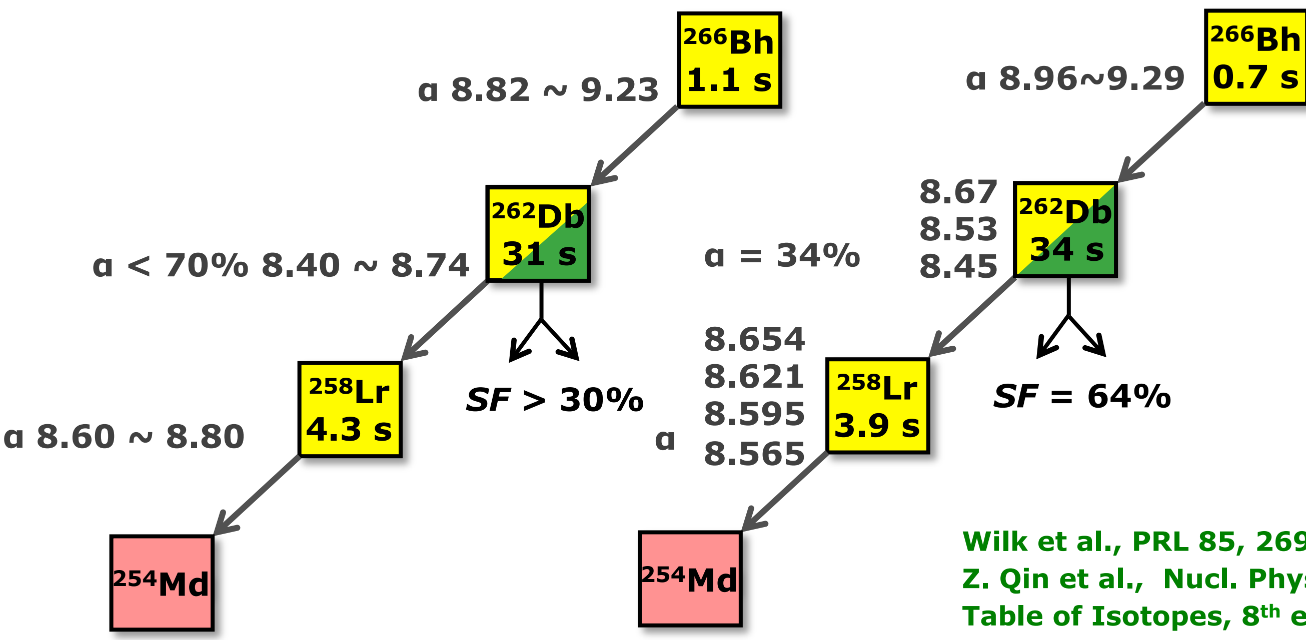
This work

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

Reference data

^{249}Bk(^{22}Ne,5n)^{266}Bh @ LBNL

^{243}Am(^{26}Mg,3n)^{266}Bh @ IMP



Wilk et al., PRL 85, 2697 (2000).
Z. Qin et al., Nucl. Phys. Rev. 23, 400 (2006)
Table of Isotopes, 8th ed. (1996).

It is clear that
observed decay energies & half-lives well agree with reference data.

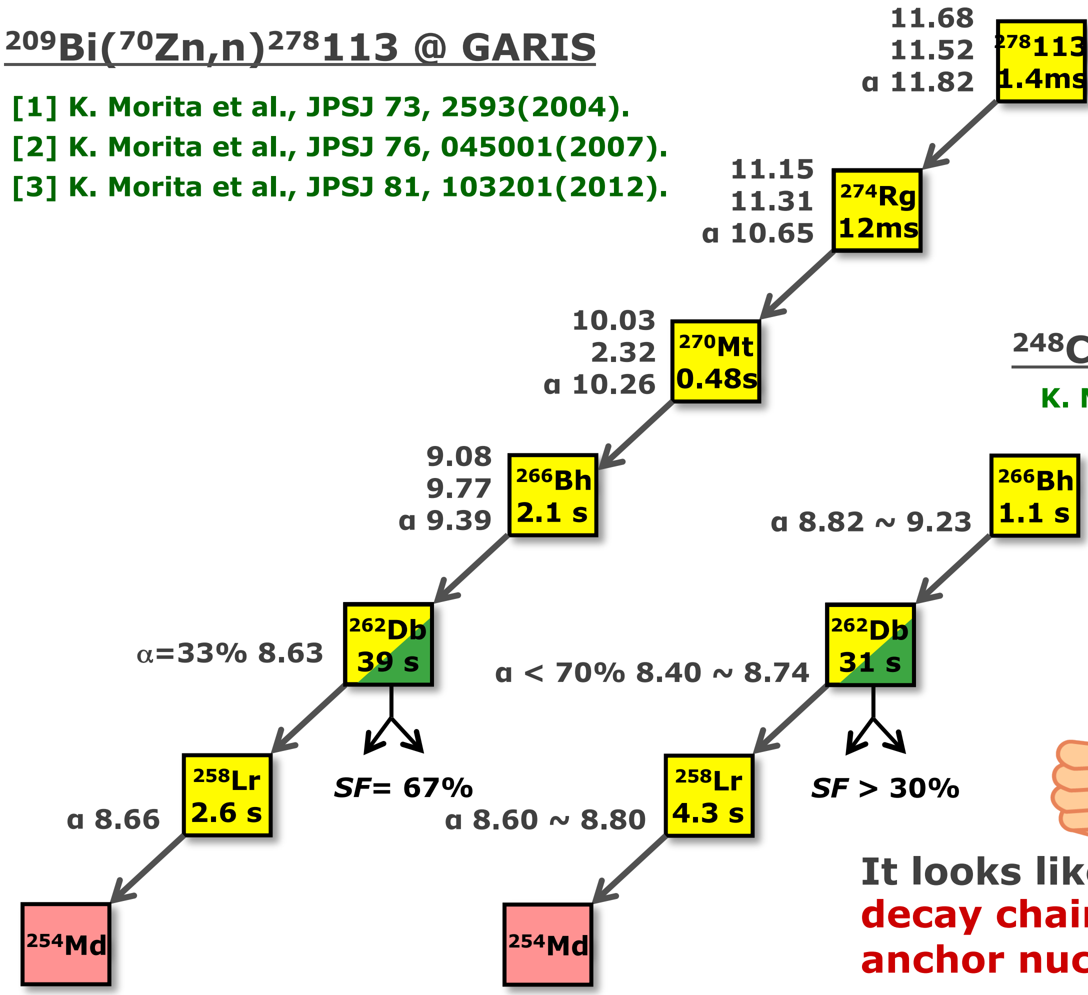
Compared with decay chains due to $^{278}113$

$^{209}Bi(^{70}Zn,n)^{278}113$ @ GARIS

[1] K. Morita et al., JPSJ 73, 2593(2004).
[2] K. Morita et al., JPSJ 76, 045001(2007).
[3] K. Morita et al., JPSJ 81, 103201(2012).

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

K. Morita et al., JPSJ 78,064201(2009).



It looks like that
decay chains from $^{278}113$ are connected to anchor nuclides of ^{266}Bh, ^{262}Db, and ^{258}Lr.

Summary

Experiments related to $^{278}113$

$^{209}Bi + ^{70}Zn \rightarrow ^{278}113 + n$ (2003 - 2012)

3 decay chains due to $^{278}113$ were observed during irradiation time of 576 days.
The 1st & 2nd chains were ended by SF of ^{262}Db.
The 3rd chain was connected to long $T_{1/2}$ ^{254}Md after 6 alpha decays.

Observed decay properties from 3 decay chains were consistent each other.

The productions of $^{278}113$ were clearly confirmed.

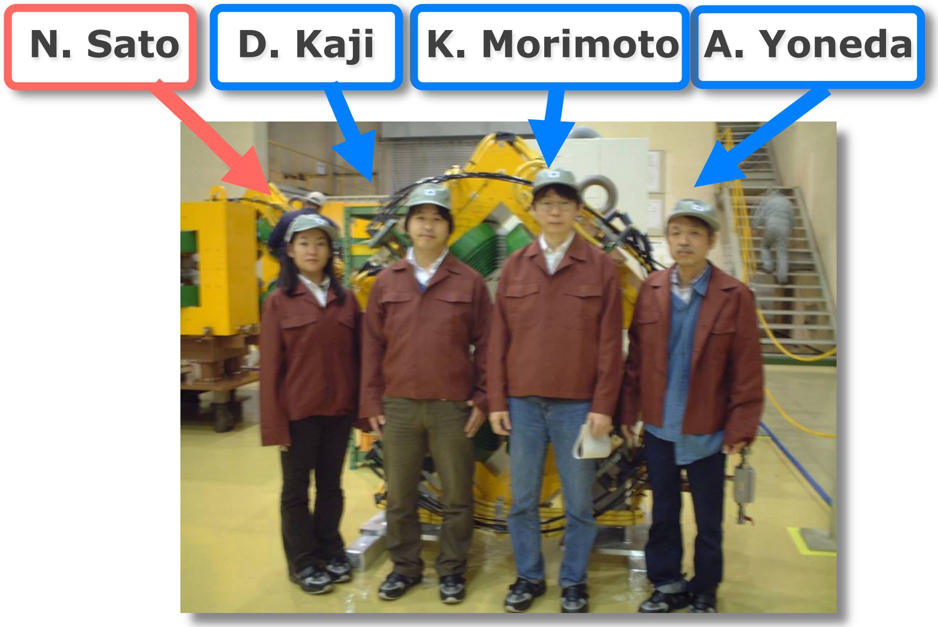
$^{248}Cm + ^{23}Na \rightarrow ^{266}Bh + 5n$ (2009)

14 events were assigned to decay chains from ^{266}Bh.
The identification was based on a genetic link to the known daughter nucleus ^{262}Db by alpha-decay.

Decay chains from ^{266}Bh were well established.
Decay chains from $^{278}113$ were clearly connected to the anchor nuclides.

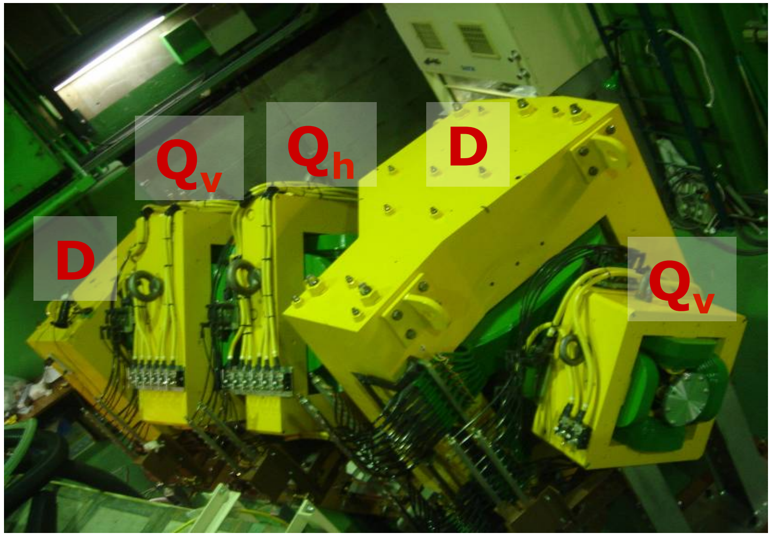
At last, the Z=113 search was finished in OCT-2012.

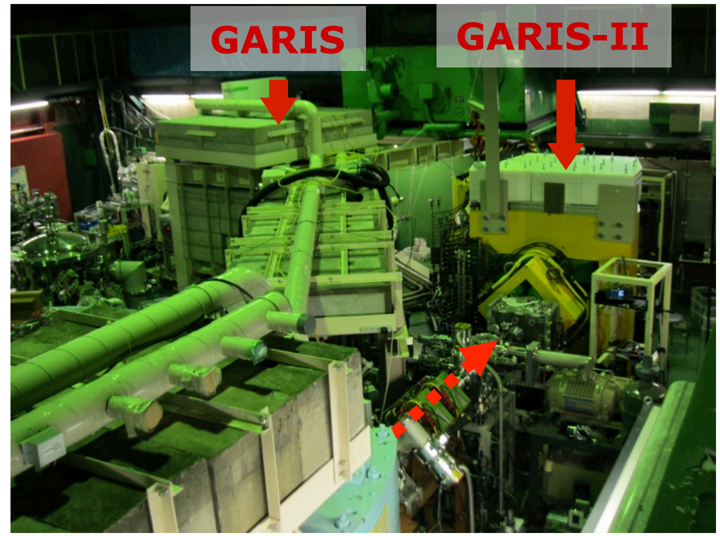
③ GARIS-II R&D



GARIS-II

New gas-filled recoil ion separator toward next generation SHE study
Big project since the birth of GARIS @ 1992





Configuration Q_v-D-Q_h-Q_v-D → 1st design & construction for SHE study (unique design)

Purpose Developed for **actinide-based fusion study**

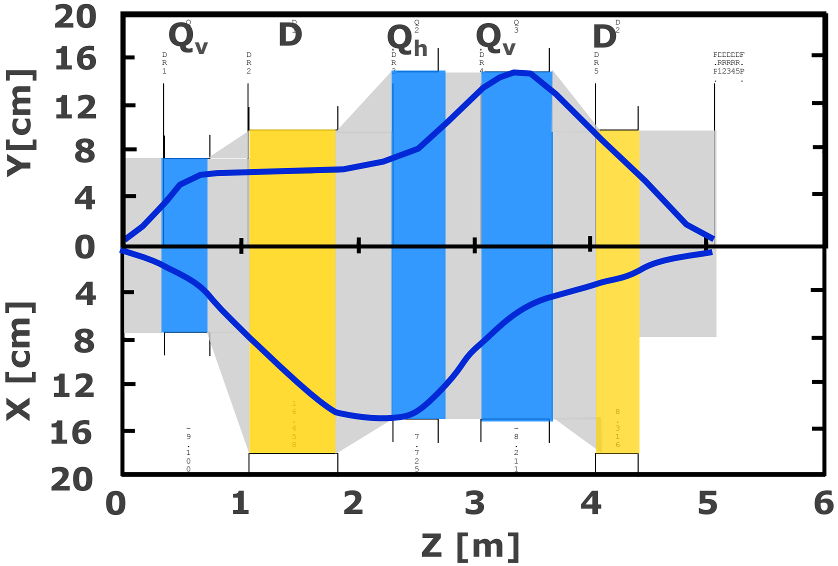
Installation Exp. Hall @ RILAC facility

D. Kaji et al., NIM B317, 311 (2013).

Basic characteristics of GARIS-II

are given in table compared with GARIS

Beam envelope analyzed by TRANSPORT



[Ex.] $^{238}U(^{48}Ca,3n)^{283}Cn$

Cross section : 2.5 pb *
Intensity : 1 puA
Target (x 2) : 500 ug/cm^2
Trans. (x 2) : 70%

* Yu. Ts. Oganessian et al., Nucl. Phys. A 734, 195 (2004).

By assuming typical EXP conditions,
Expected yield : 8 atoms/week

	GARIS	GARIS-II
Configuration	DQ_vQ_hD	$Q_vDQ_hQ_vD$
Bending angle	45° + 10°	30° + 7°
Path length	5.76 m	5.06 m
Solid angle	12.2 msr	18.5 msr
Max *Bρ*	2.17 Tm	2.43 Tm
Dispersion	9.8 mm/%	19.3 mm/%
Filled gas	He	He or $He\text{-}H_2$

① Configuration : little bit change
Difference : 1st Q magnet for vert. focusing
→ Enables a large solid angle

② Large solid angle gains 2 advantages
about *target thickness* & *Trans*.

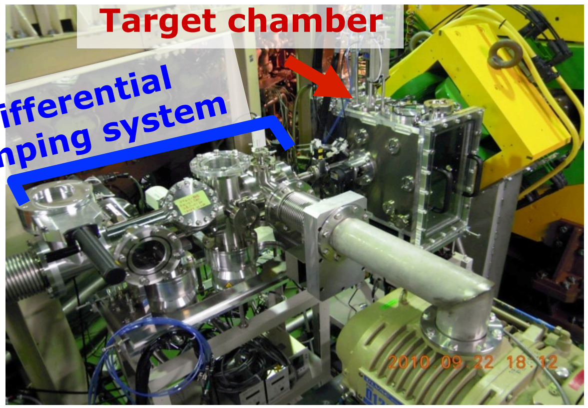
Yield is expected to be 4 times higher than GARIS

③ Max *Bρ* becomes high (from 2.17 to 2.43 Tm).
GARIS-II can use $He\text{-}H_2$ mixture as a filled gas.
→ The usage is important to reduce *BG level.*

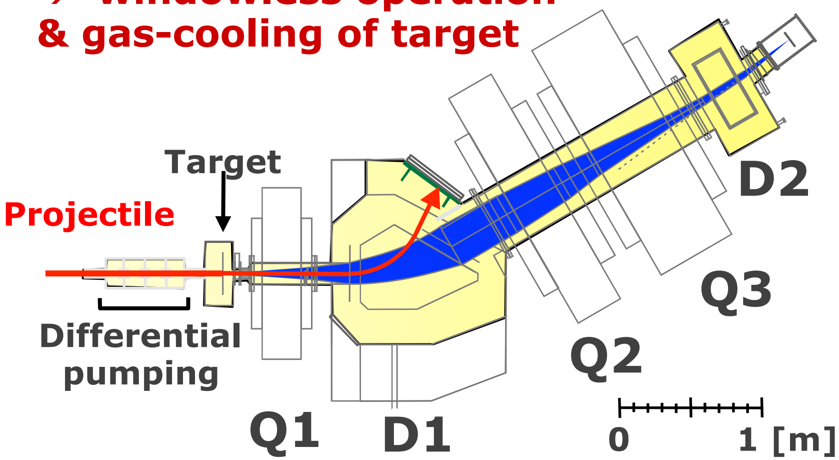
Devices around GARIS-II

Gas-cooled rotating target & Focal plane detector

Gas cooled rotating target system
to stand against high intense beam

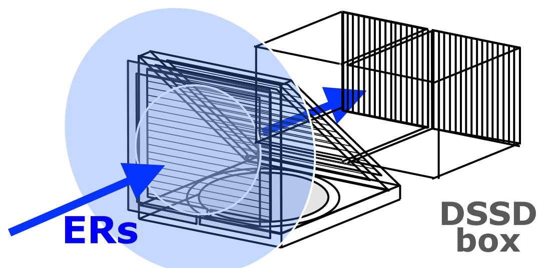


→ windowless operation & gas-cooling of target

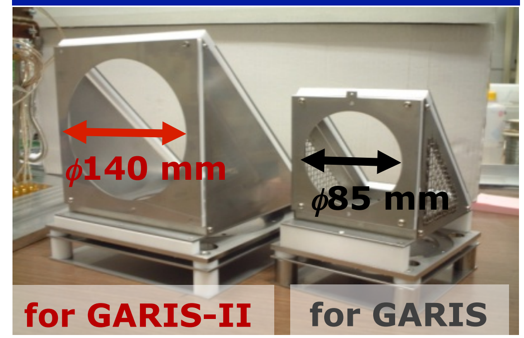


Focal plane detector
to identify ER & its successive decays

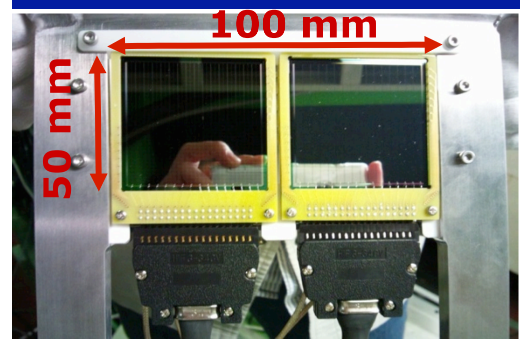
After passing through D2 magnet, ERs transit 0.5 um MYLAR as a vacuum foil and TOF detector, and later implanted into DSSD.



TOF detector



DSSD

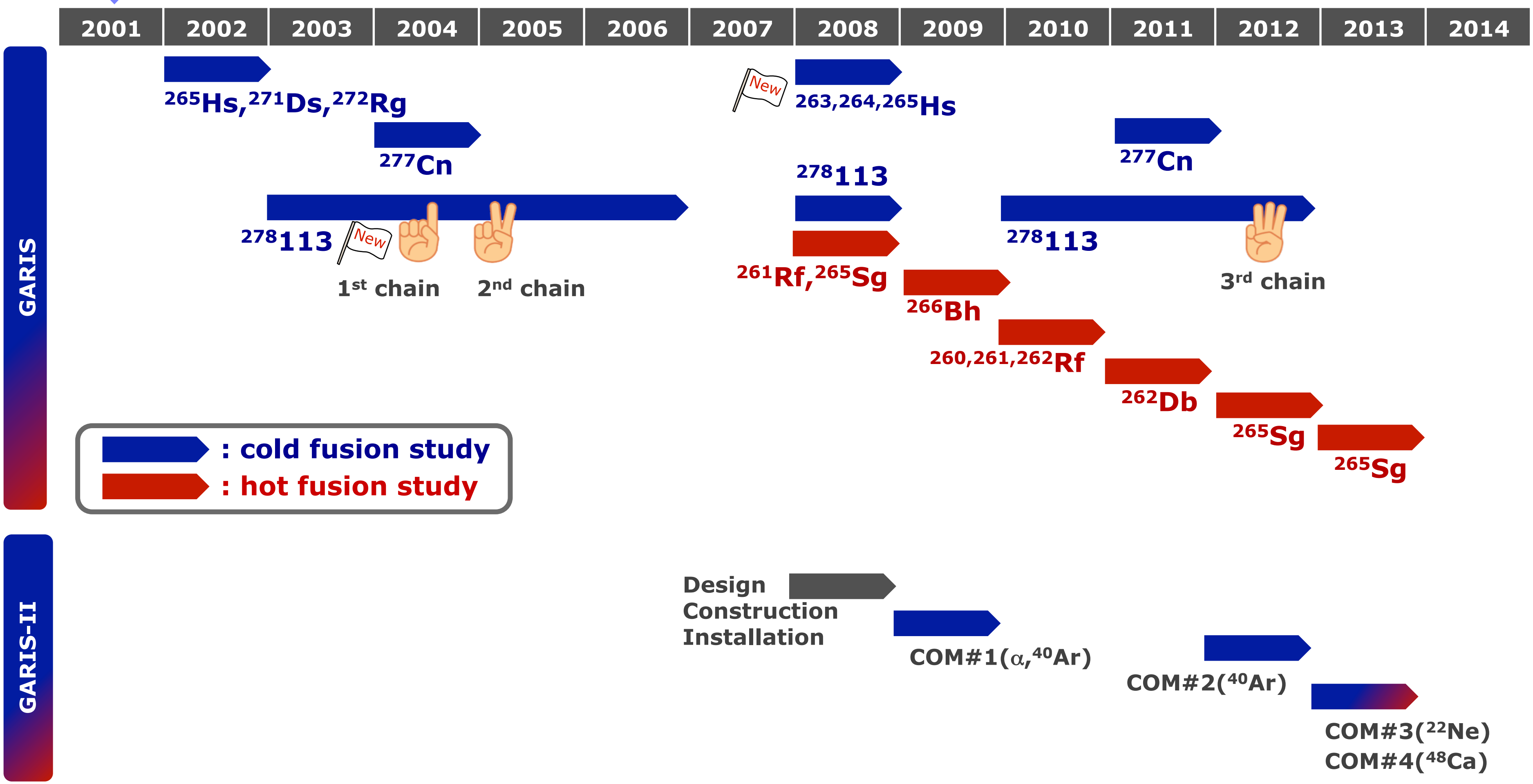


D. Kaji et al., JPSJ (2013). [Proceedings of APPC12]
D. Kaji et al., RIKEN Accel. Prog. Rep. 45, (2012).

Timeline

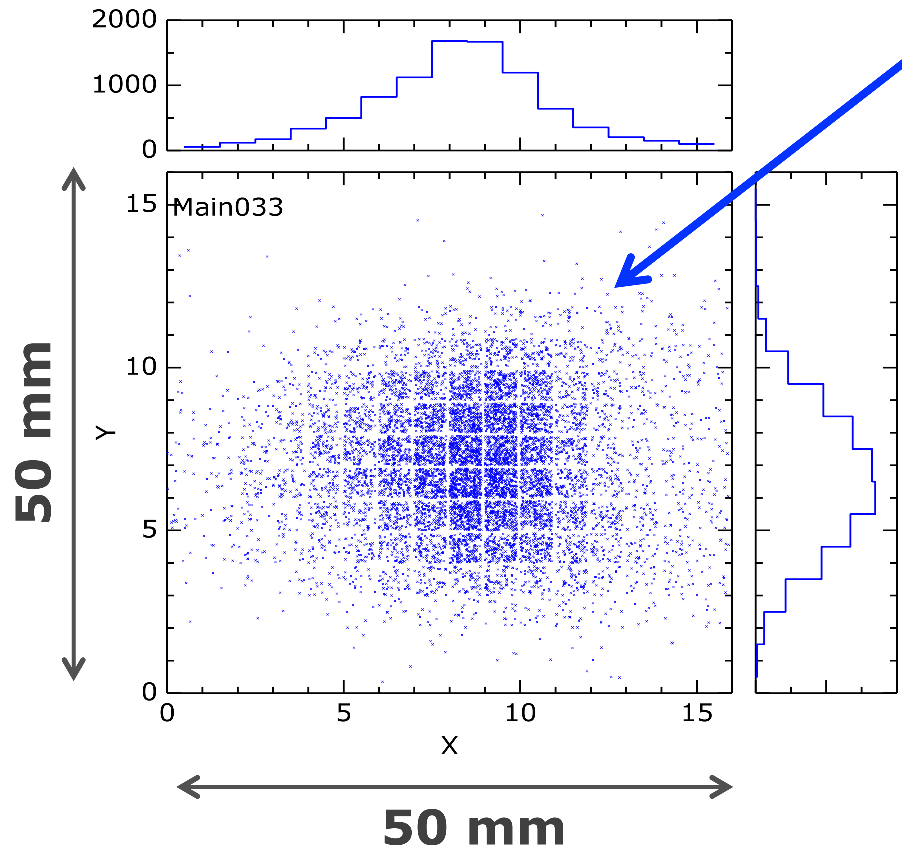
SHE experiments with GARIS-I/-II

I have participated in SHE EXP at 2001.



Solid angle

Image @ focal plane of GARIS-II



α-particles moving from target to focal plane were implanted to FPD.

Ω = 18.2 msr

well agree with design value (Ω=18.5 msr)

It is clear that
GARIS-II has a large solid angle.

[Performance of GARIS-II]

High Transmission under Low BG level

$^{208}Pb(^{40}Ar,3n)^{245}Fm$

$^{40}Ar^{11+}$, E=197 MeV

Beam ON/OFF : 5s/15s (x 616)

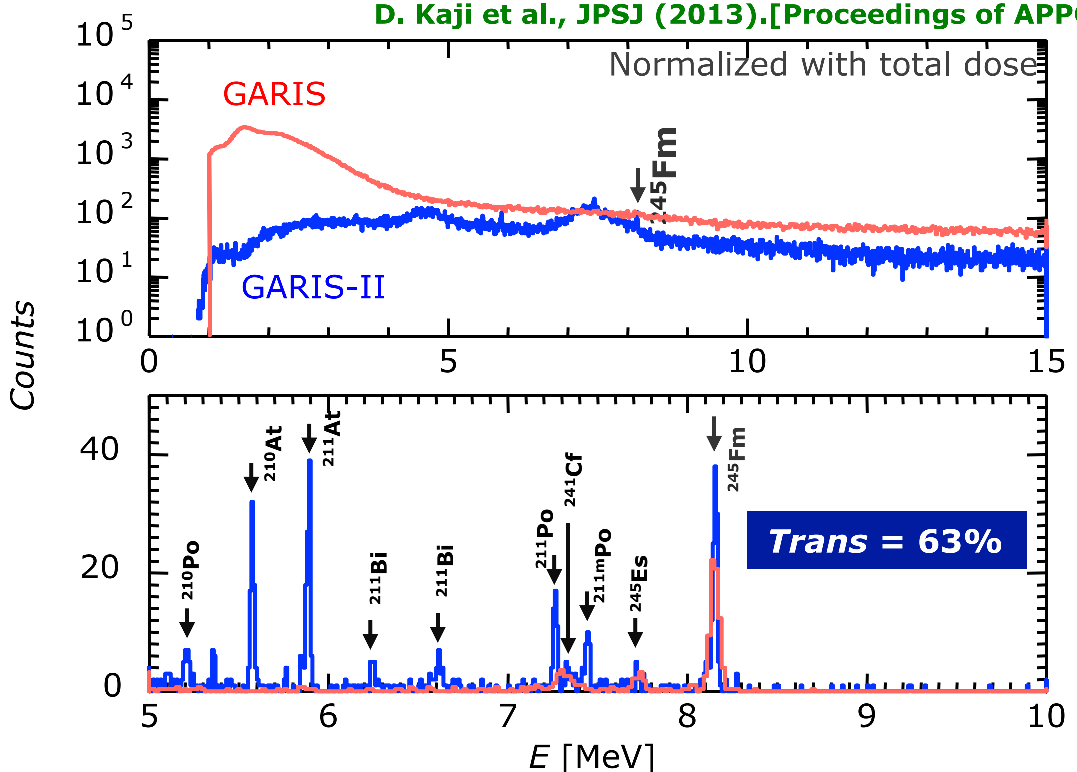
dose=2.4×10^{15}

$C/^{208}Pb$ = 60/ 280 ug/cm^2

P_{He} = 70 Pa

$B\rho$ = 2.01 T·m

D. Kaji et al., JPSJ (2013).[Proceedings of APPC12.]



Succeeded in the observation of ^{254}Fm produced by $^{208}Pb(^{40}Ar,3n)^{245}Fm$.

Also observed α-peak due to ^{245}Fm in singles!

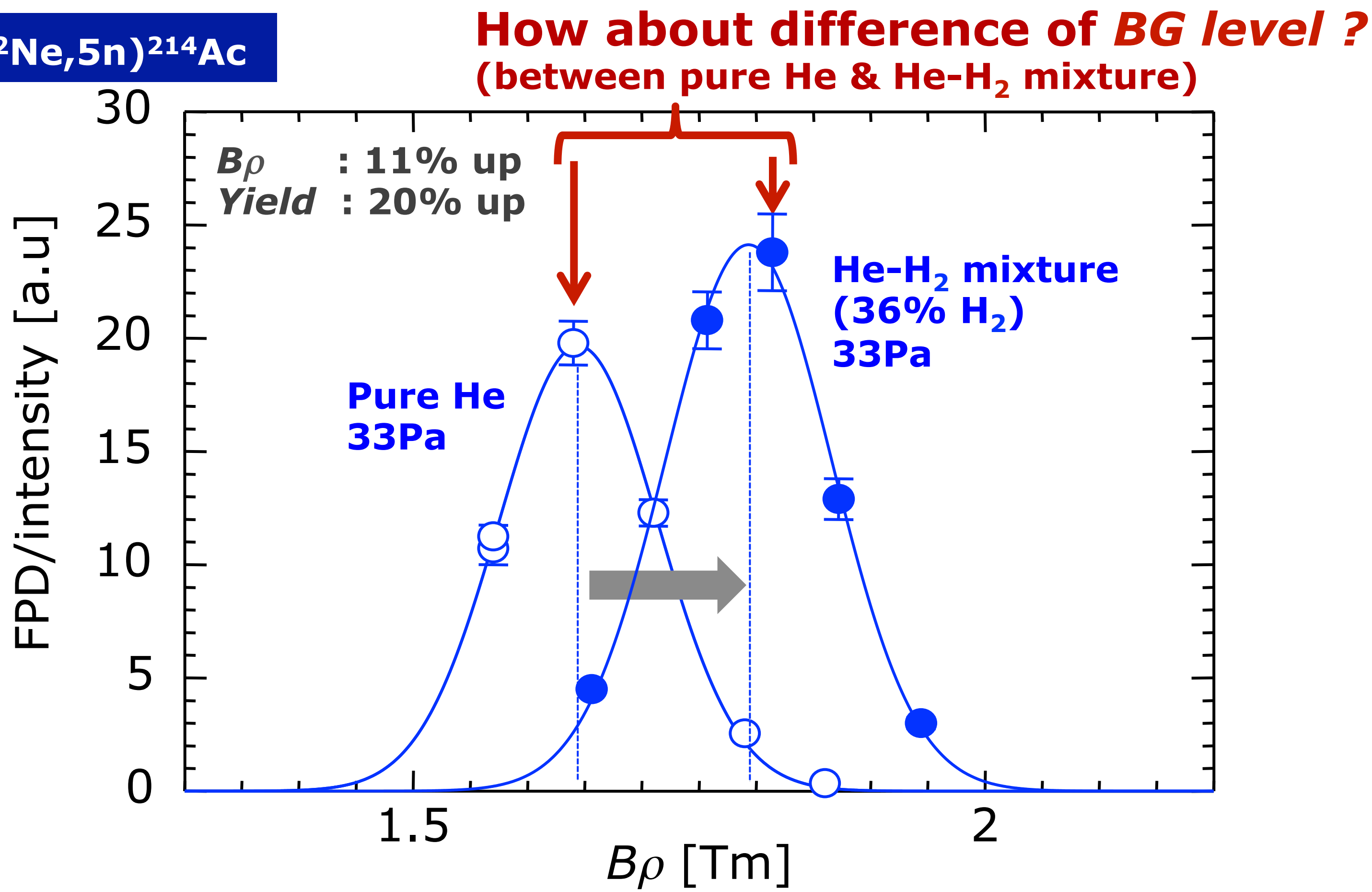
Compared with data from GARIS

Trigger rate **was about 5 times lower than GARIS,**

nevertheless ***Trans*** **of GARIS-II was 1.5 times higher than GARIS.**

1^{st} trial by using He-H_2 mixture

$^{197}Au(^{22}Ne,5n)^{214}Ac$

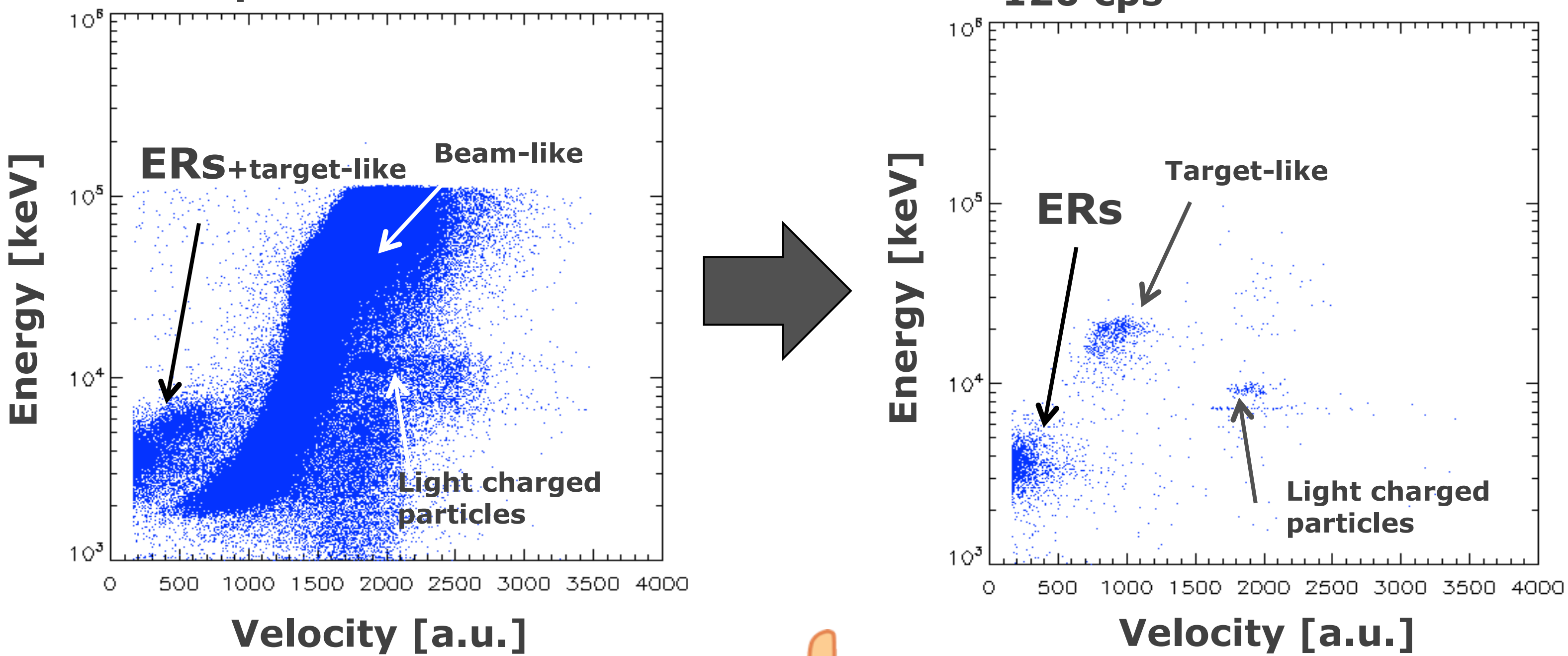


At first, we searched for optimum *Bρ* by using pure He.
After that, we changed the filled gas.

Improvement of *BG level*

Pure He
589 cps

He:H_2 = 2:1
120 cps



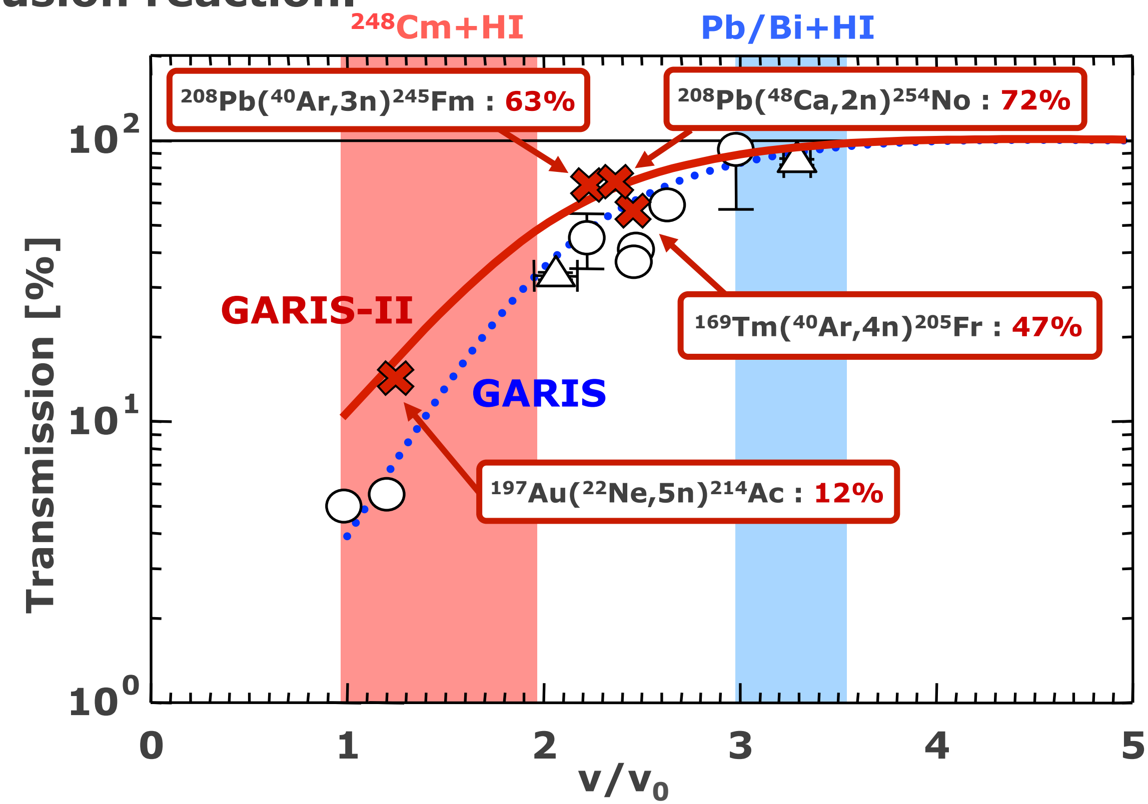
BG level **: down to 1/5**
Yield **: 20% up**

It is clear that
He-H_2 mixture is very promising for SHE study.
→ We will perform more feasibility tests by using He-H_2 mixture near future.

Summary

GARIS-II R&D

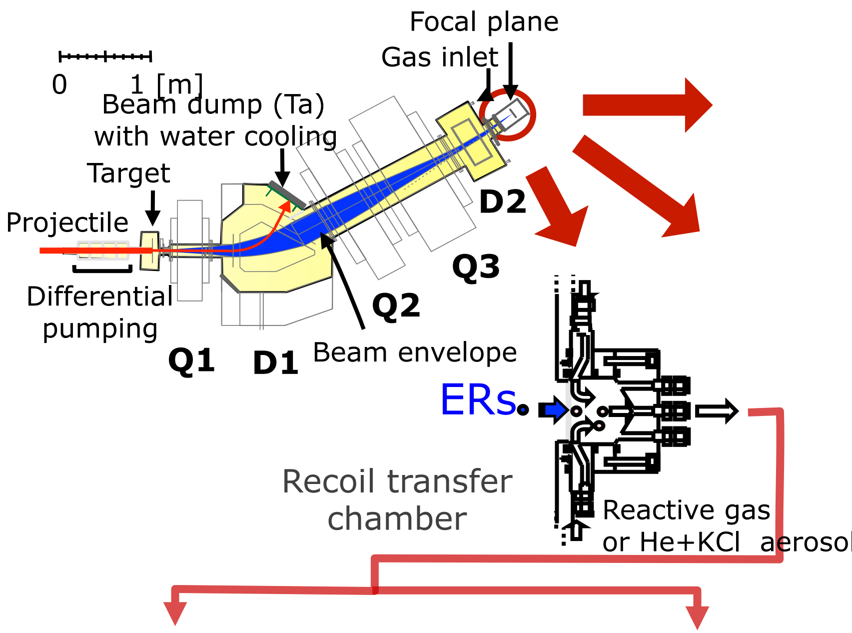
Performance of GARIS-II was investigated by using ^{40}Ar-,^{22}Ne-, ^{48}Ca-induced fusion reaction.



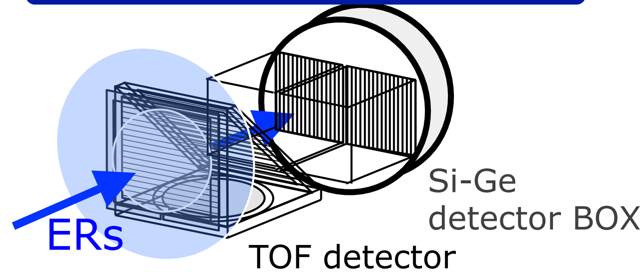
- **ERs were collected to FPD by GARIS-II with *high Trans under low BG.***
- **He-H_2 mixture is very promising for SHE study.**

Experimental plans

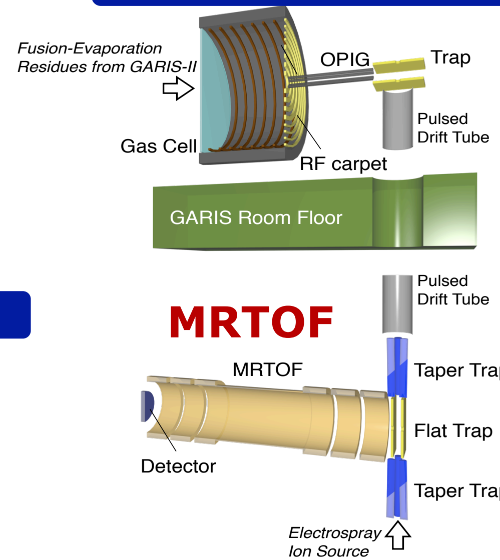
GARIS-II will use for
a new SHE search, precise mass measurement, SHE chemistry, SHE spectroscopy.



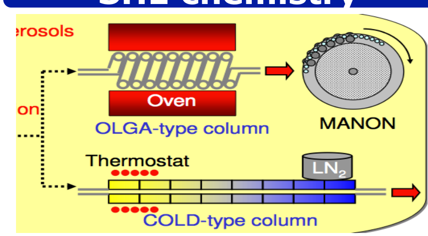
New SHE search



Mass measurement



SHE chemistry



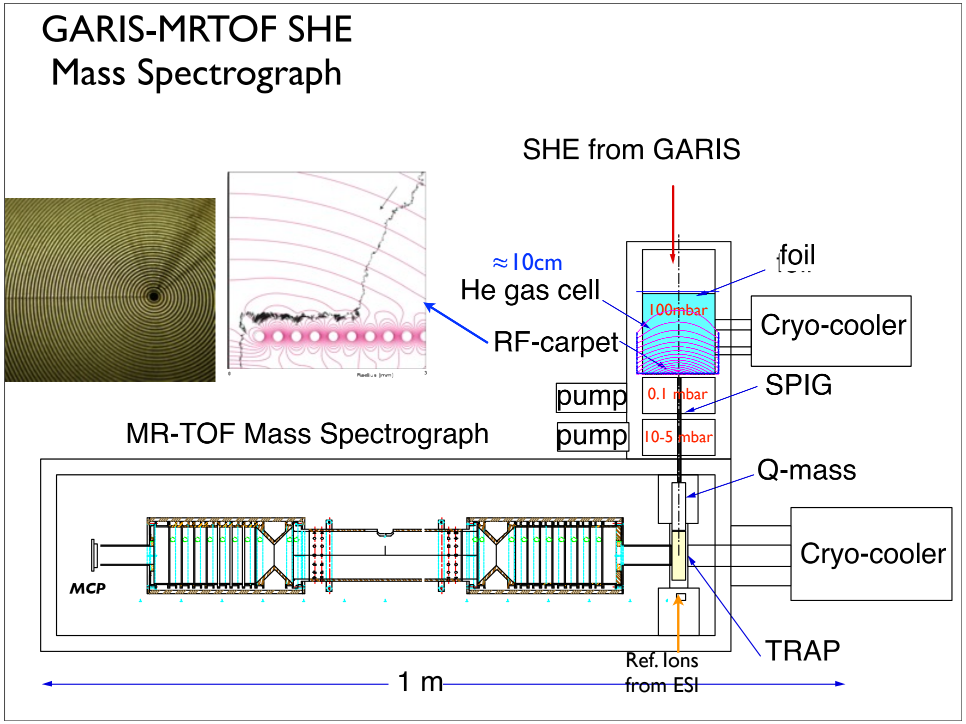
SHE spectroscopy

GARIS-II+MRTOF

Direct mass measurement gives the answer for assignment of SHE nuclides produced by hot fusion reactions

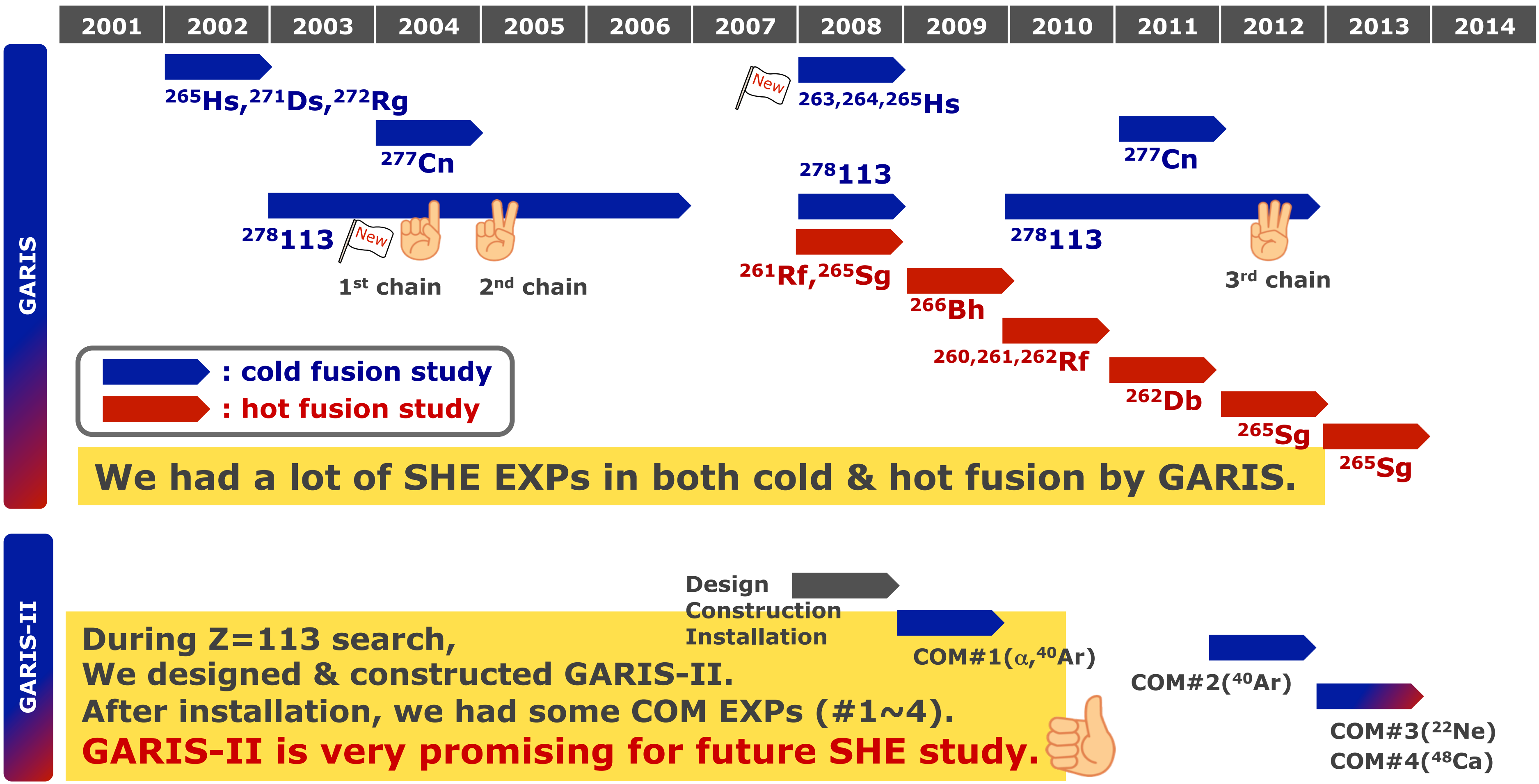
GARIS R&D team started to collabore with Wada's group @ RIKEN.
MRTOF has already moved to just downstairs of GARIS-II.
The 1st commissioning of GARIS-II+MRTOF will start in SEP-2014.

$T_{1/2}$~10ms nuclei with sub-ppm $\delta m/m$, Eff_{total}=1~30%



Summary

SHE experiments with GARIS-I/-II at RIKEN



We had a lot of SHE EXPs in both cold & hot fusion by GARIS.

During Z=113 search,
We designed & constructed GARIS-II.
After installation, we had some COM EXPs (#1~4).
GARIS-II is very promising for future SHE study.

Collaborators

Experiments related to $^{278}113$

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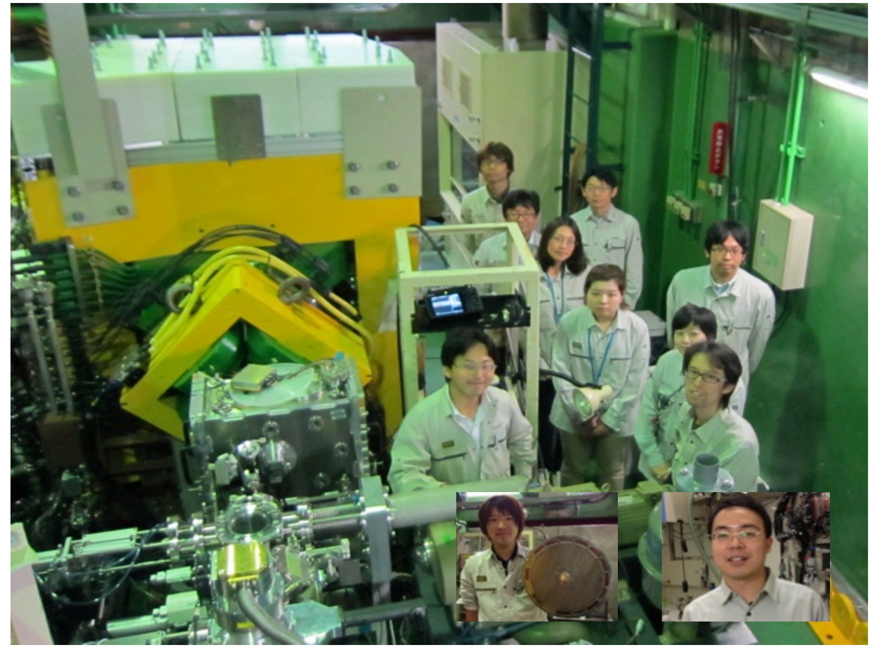
TOKYO UNIVERSITY OF SCIENCE

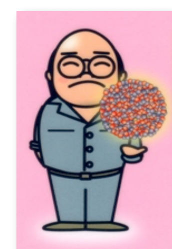
M Takeyama

山形大学 YAMAGATA UNIVERSITY

S. Yamaki

Saitama University





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- GARIS-II was constructed by Sumitomo Heavy Industry ltd.
- The experiment was performed at the RI Beam Factory operated by the RIKEN Nishina Center and CNS, University of Tokyo. The authors are grateful to the accelerator staff members for their cooperation and assistance during the experiment.
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- We would like to thank our family for continuous encouragement and hearty support.

Thank you for your kind attention !