Mini workshop: Nuclear Astrophysics Experiments with HIAF

Opportunities For Mass and Decay Lifetime Measurements At the HIAF-SRing facility

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2025-9-3

Outline

01 **Motivations**

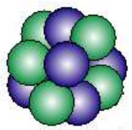
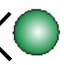
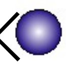
02 **Principle of Storage Ring MS**

03 **Current status of M & $T_{1/2}$ experiments**

04 **Thoughts for Day One experiments**

Motivation

$M_{nucleus} = N \bullet m_{neutron} + Z \bullet m_{proton} - (B_{nucleus})/c^2$

 $= N \times$  $+ Z \times$  $- B_{nucleus}/c^2$

$\delta m/m = 10^{-6} - 10^{-8}$

nuclear structure

High-precision mass measurements can reflect the combined effects of various interactions among nucleons within the nucleus

SLIDE FROM K. BLAUM

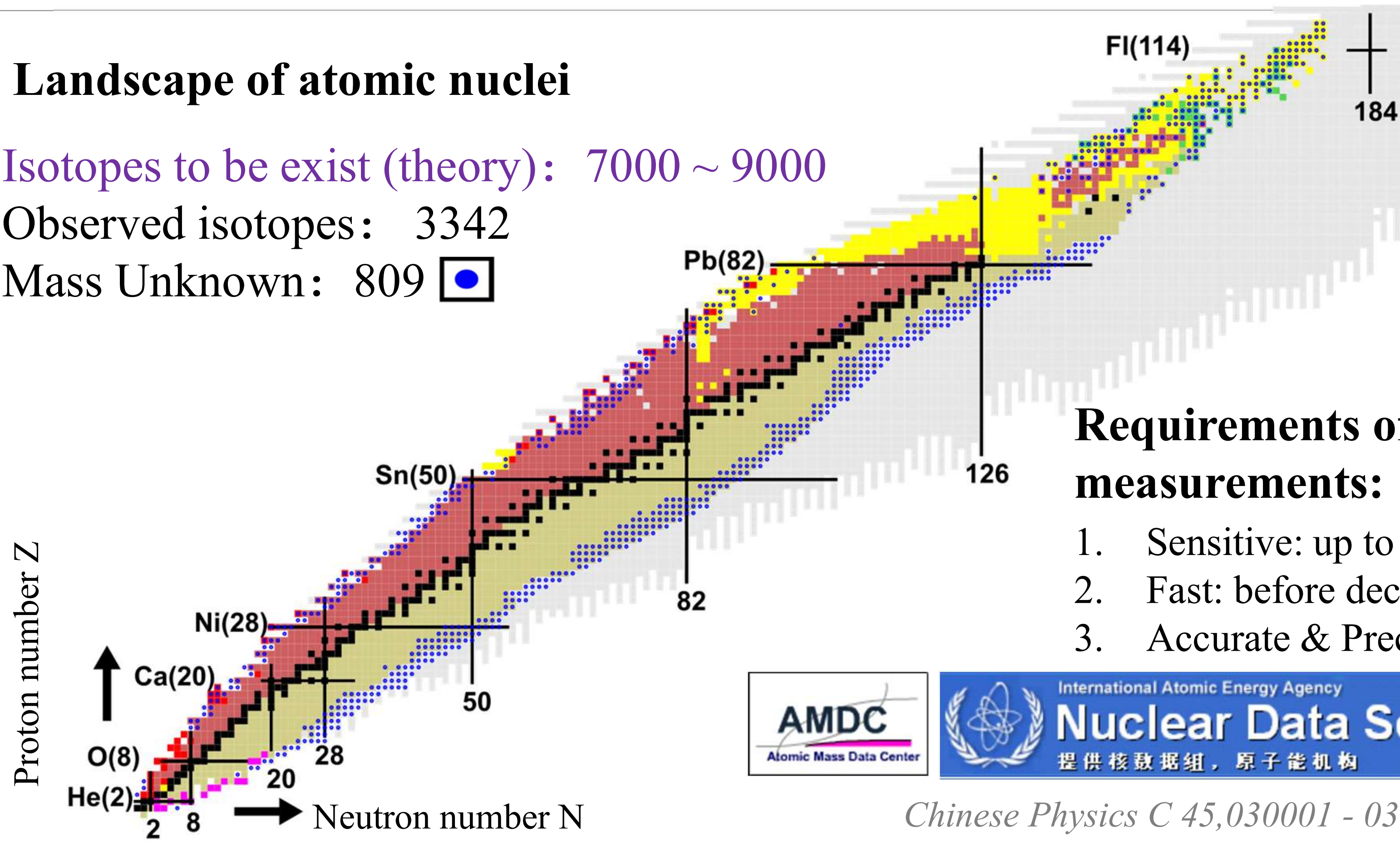
Motivation

Landscape of atomic nuclei

Isotopes to be exist (theory)： 7000 ~ 9000

Observed isotopes： 3342

Mass Unknown： 809



Requirements of mass measurements:

1. Sensitive: up to single ion
2. Fast: before decay
3. Accurate & Precision

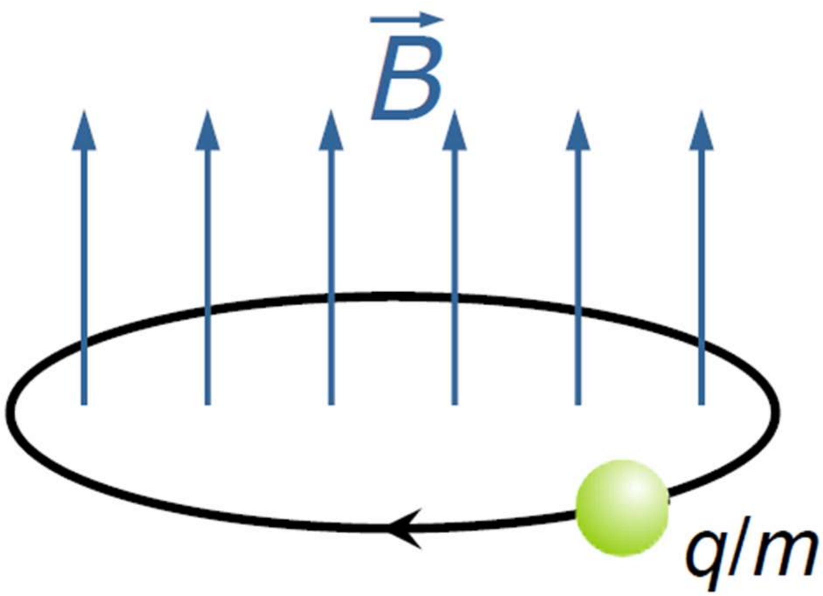
AMDC Atomic Mass Data Center

International Atomic Energy Agency Nuclear Data Services 提供核数据组，原子能机构

Chinese Physics C 45,030001 - 030003 (2021)

Outline

Principle of Storage Ring Mass Spectrometry

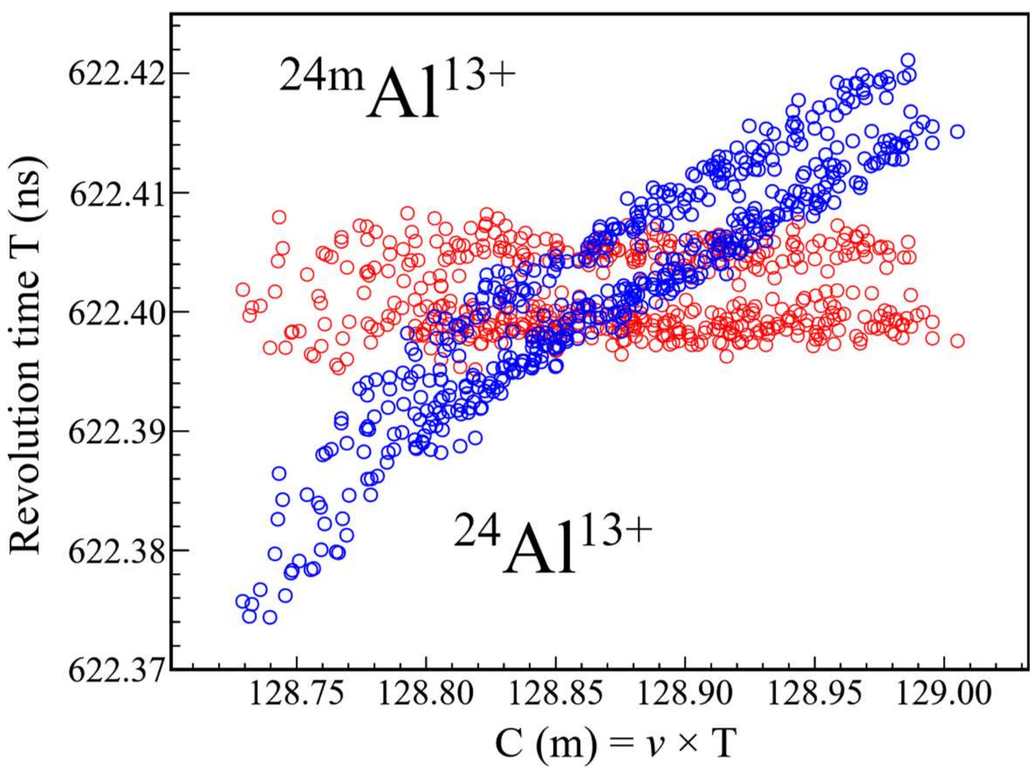


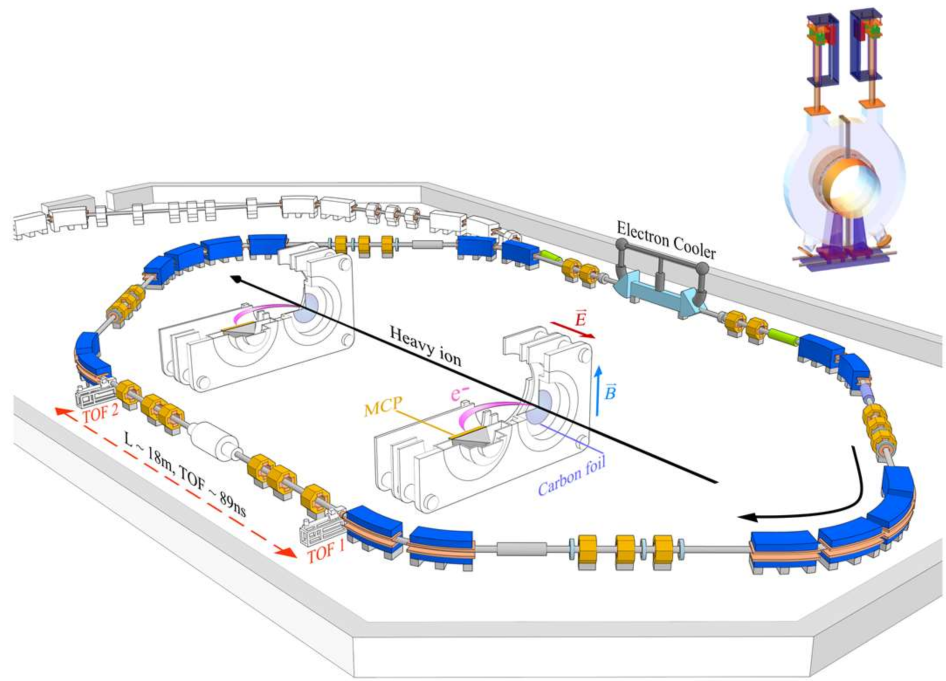
Cyclotron frequency:

$$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

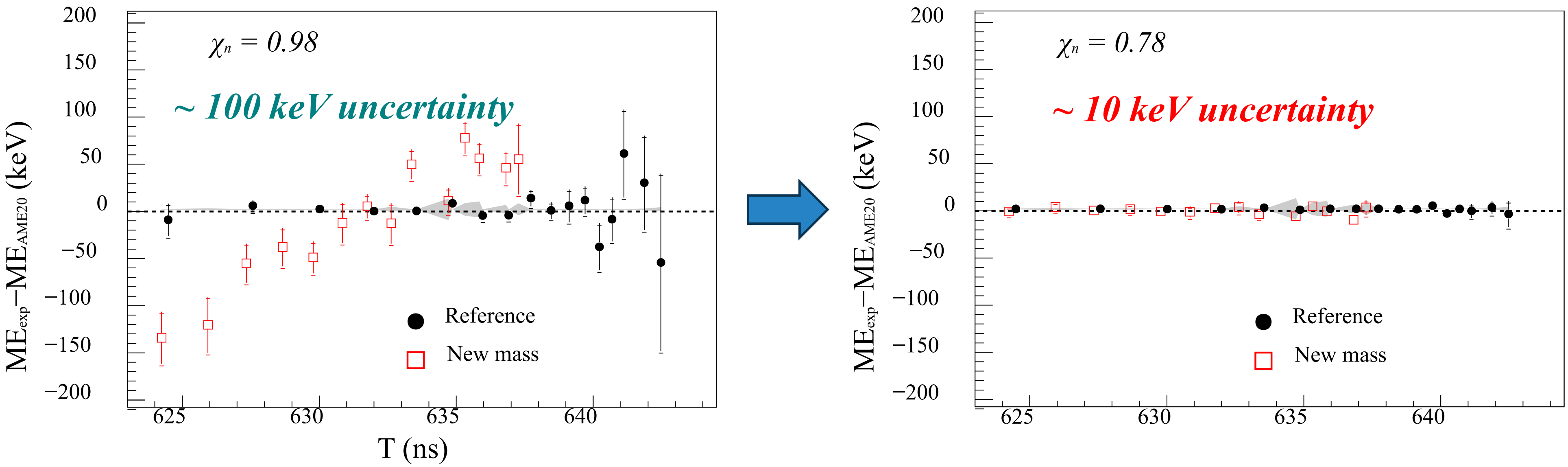
Ultrahigh vacuum: < 1 × 10 $^{-11}$ mbar
Storage time: hours to days

Principle of Storage Ring Mass Spectrometry



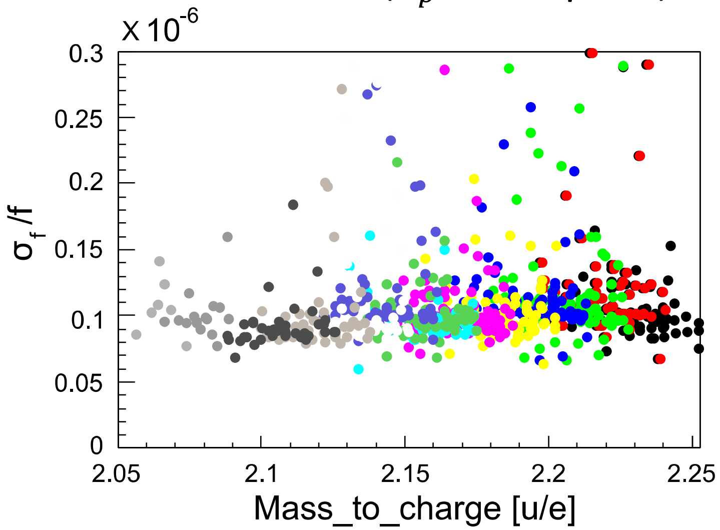


Brho-defined Isochronous Mass Spectrometry

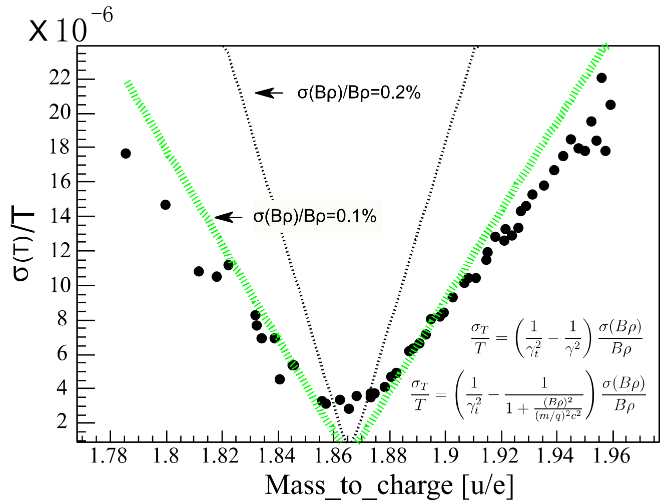


Mass resolving power

SMS@ESR (α_p~ 0.18, γ~1.4)



IMS @CSRe (α_p~ 0.5, γ~1.4)



$\sigma_T/T = (\alpha_p\gamma^2 - 1)\,\sigma_v/v \sim 10^{-7}$	$\sigma_T/T = (\alpha_p - 1/\gamma^2)\,\sigma_{B\rho}/(B\rho) > 10^{-6}$
$R \approx (\gamma^2 - \alpha_p^{-1})^{-1} v/\sigma_v/2.355$	$R \approx \left(\alpha_p\gamma^2 - 1\right)^{-1}(B\rho)/\sigma_{B\rho}/2.355$

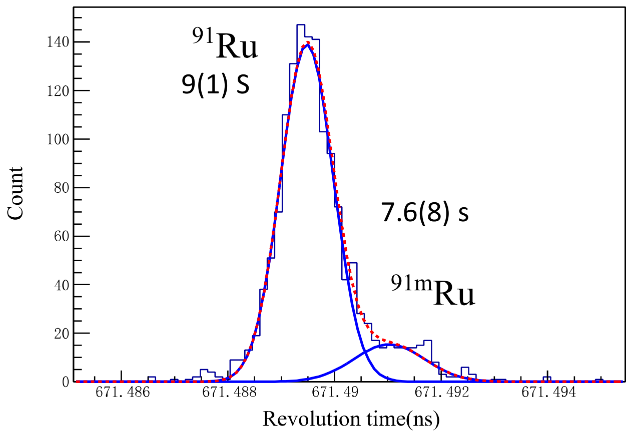
$R \approx 8(2) \times 10^5 (FWHM)$

$R < 1.1\text{~}1.9 \times 10^5 (FWHM)$

Mass resolving power

2016

E*~ 363keV



IMS@CSRe

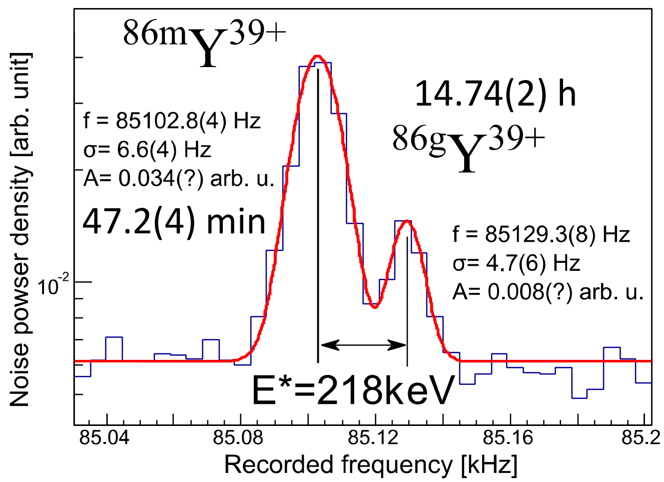
$$\frac{m}{\Delta m} \sim 2.3 \times 10^5$$

$$R = \frac{1}{\gamma^2} \frac{T}{2.355\sigma(T)} \sim 3.3 \times 10^5$$

New isomer mass!

2005

E*=218.3(2)keV



SMS@ESR

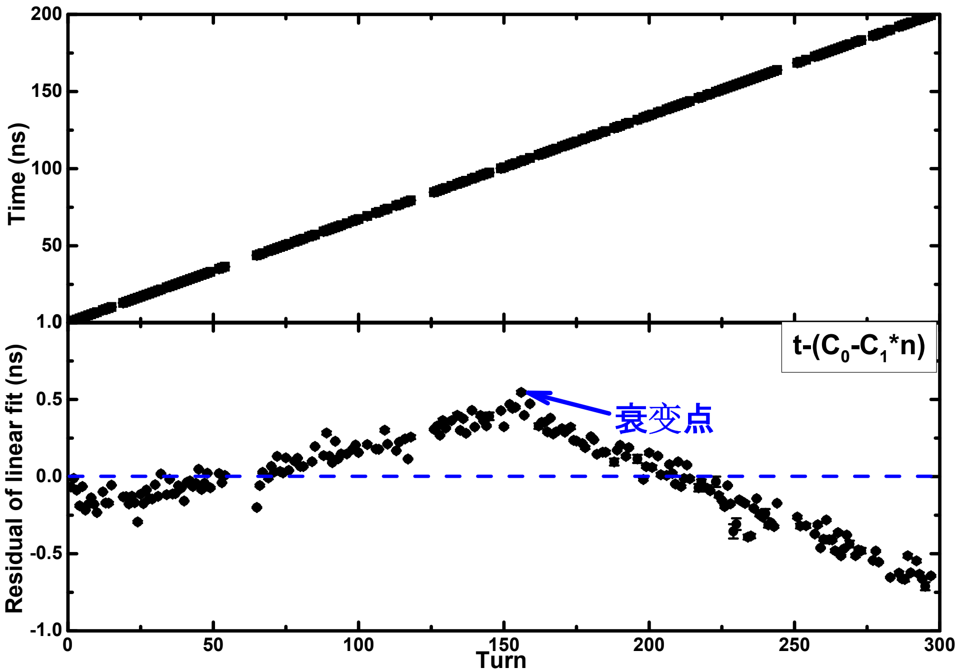
$$\frac{m}{\Delta m} = 3.6 \times 10^5$$

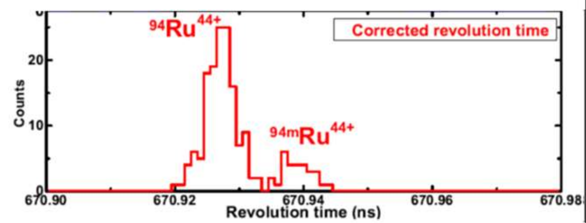
$$R = \frac{1}{\gamma_t^2} \frac{f}{2.355\sigma(f)} \sim 7 \times 10^5$$

Decay studies using IMS @ CSRe

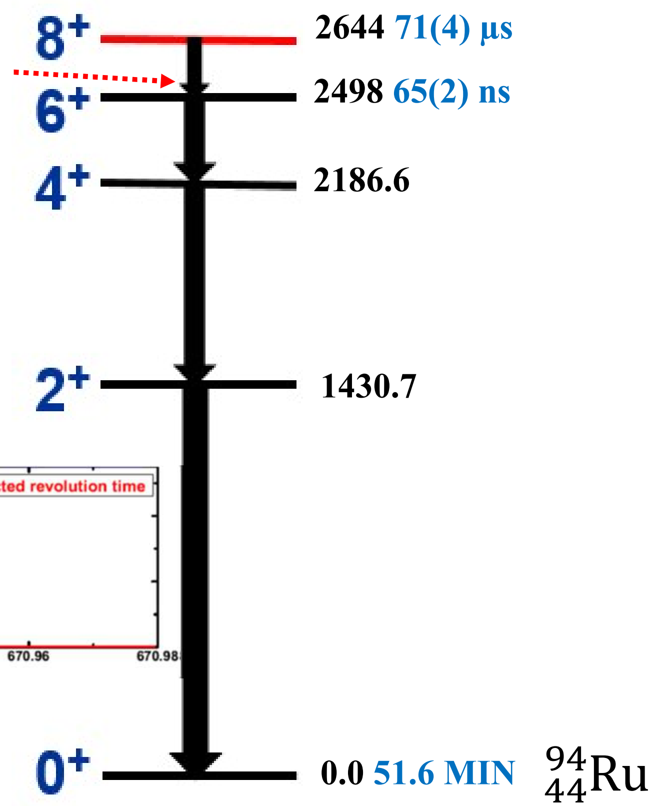
Revolution time in CSRe ~ 0.6 μs;

($^{94m}Ru^{44+}$, $T_{1/2}$: 71(4) → 131(7)μs, exp:102(17) μs)



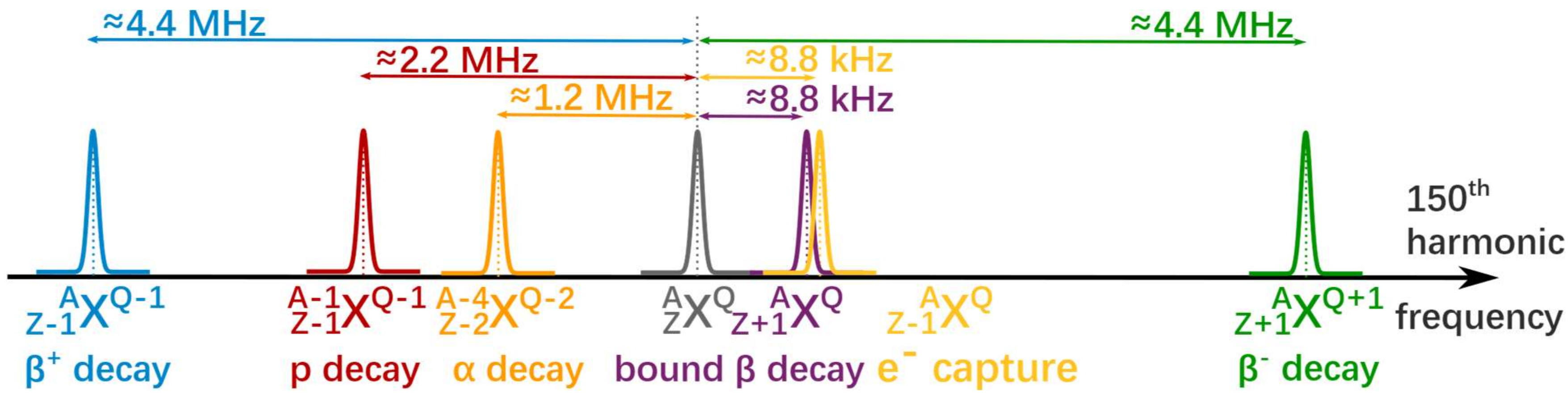


51.8(6) min 71(4) μs



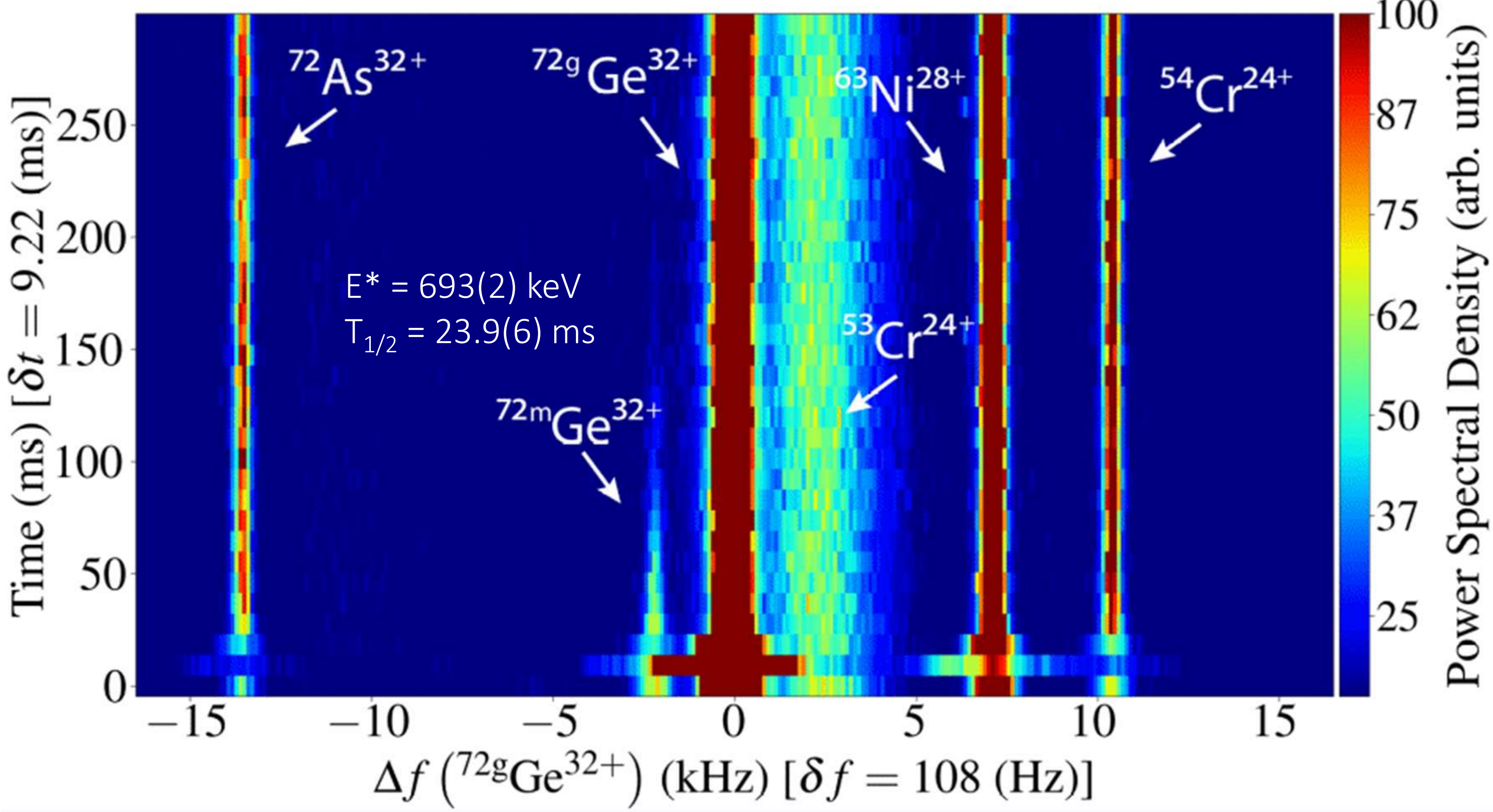
Q. Zeng et al., Physical Review C **96**, (2017).

Schottky Mass Spectrometry



Decay studies using Schottky+IMS @ ESR

Double gamma-decay of 72mGe at ESR:



D. Freire-Fernández et al., Phys. Rev. Lett. **133**, 022502 (2024).

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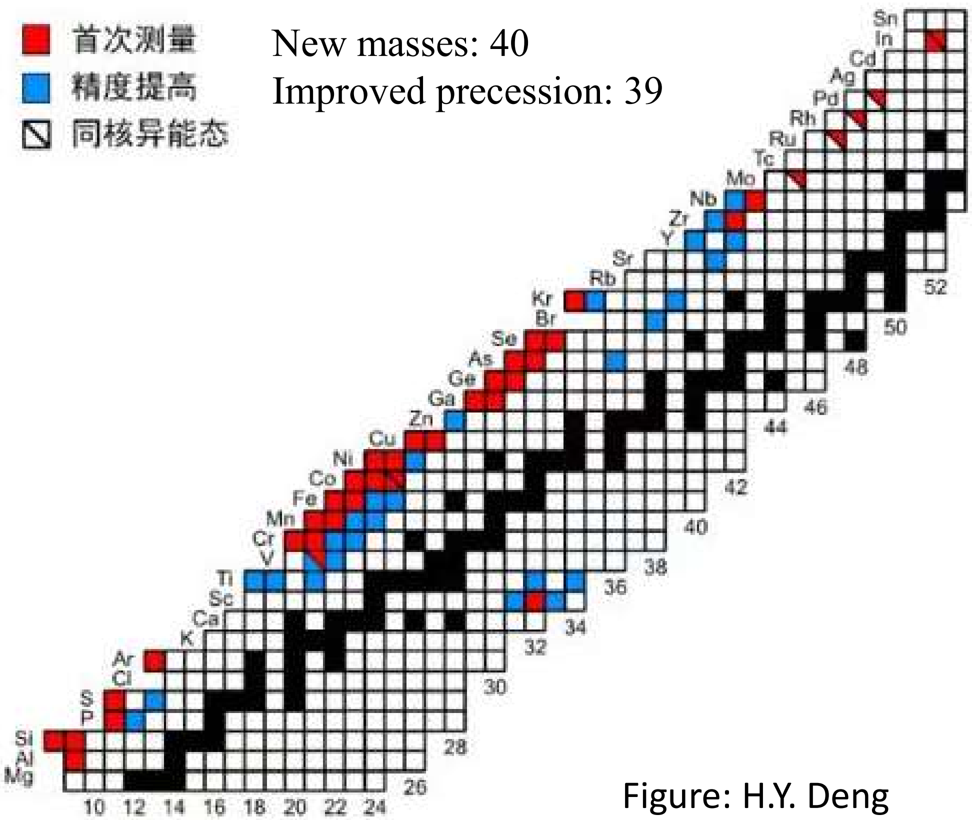
03 Current status of M & $T_{1/2}$ experiments

04 Thoughts for Day One experiments

Current status of mass measurements at CSRe



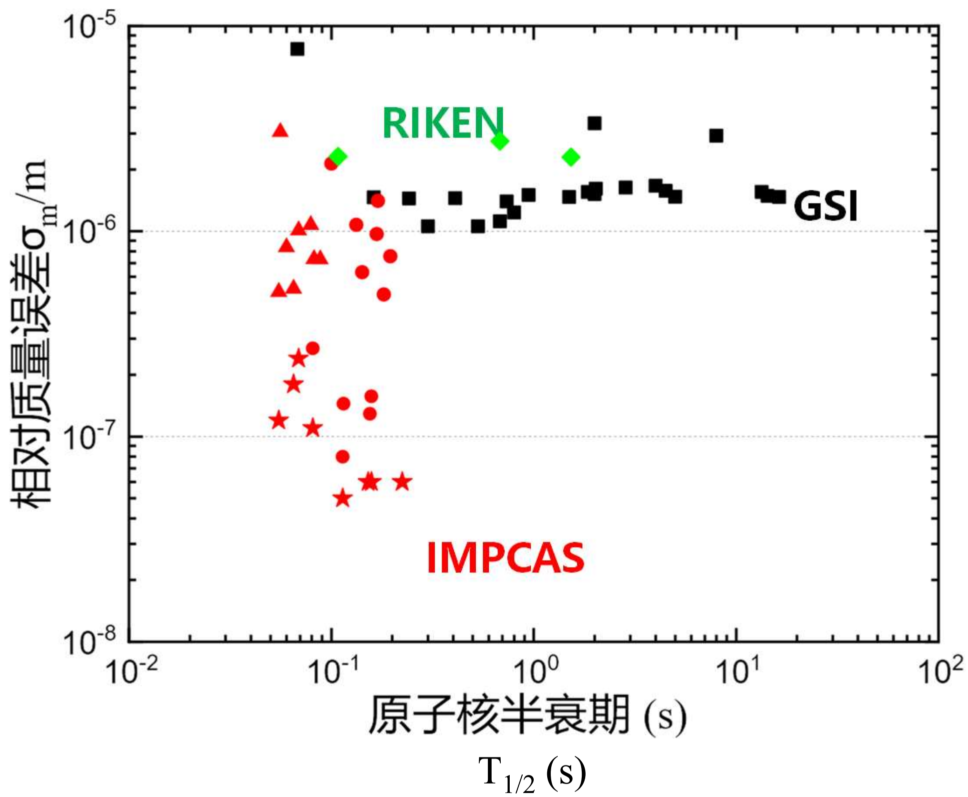
New masses: 40
Improved precession: 39

Figure: H.Y. Deng

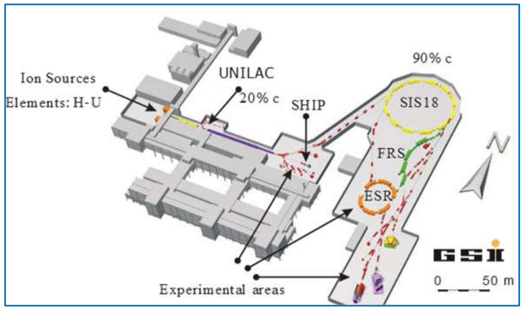
Precision
10^{-5}~10^{-7}
(5~200 keV)

1. B. Mei et al., NIM A 624, 109 (2010)
2. X. L. Tu et al., PRL 106, 112501 (2011)
3. X. L. Tu et al., NIM A 654, 213 (2011)
4. Y. H. Zhang et al., PRL 109, 102501 (2012)
5. X. L. Yan et al. ApJL 766, L8 (2013)
6. H. S. Xu et al., IJMS 349, 162 (2013)
7. X. L. Tu et al., JPG 41, 025104 (2014)
8. W. Zhang et al., NIM A 755, 38 (2014)
9. W. Zhang et al., NIM A 756, 1 (2014)
10. B. Mei et al., PRC 89, 054612 (2014)
11. P. Shuai et al., PLB 735,327 (2014)
12. J.J. He et al., PRC 89, 035802 (2014)
13. Y.H. Zhang et al., Phys. Scr. 91, 073002 (2016)
14. Y.H. Lam et al., APJ 818, 78 (2016)
15. P. Shuai et al., NIM B 376, 311 (2016)
16. X.L. Tu et al., NPA 945, 89 (2016)
17. B. Mei et al., PRC 94,044615 (2016)
18. X. Xu et al., PRL 117, 182503 (2016)
19. P. Zhang et al., PLB 767, 20 (2017)
20. X.L. Tu et al., PRC 95, 014610 (2017)

The storage ring mass spectrometer club



GSI



IMPCAS

RIKEN

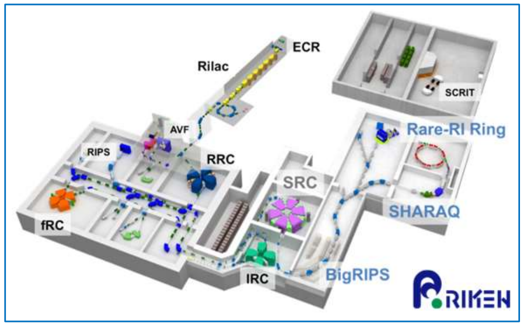
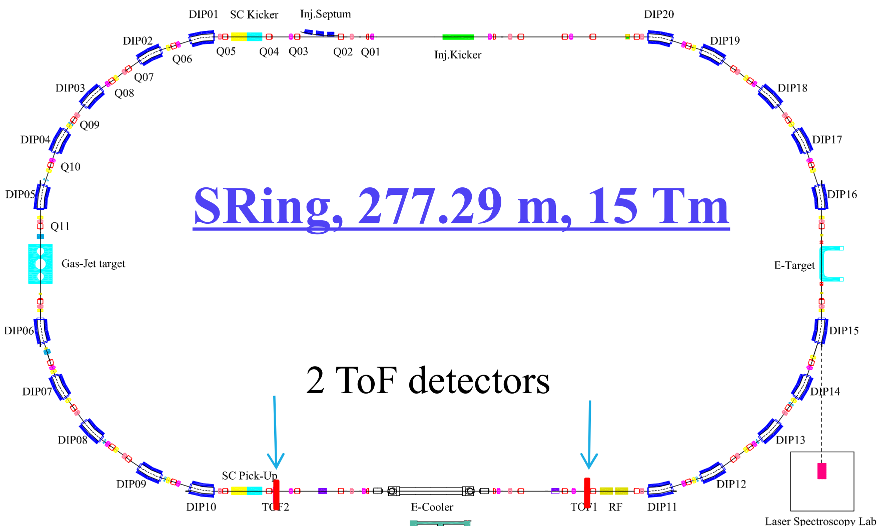
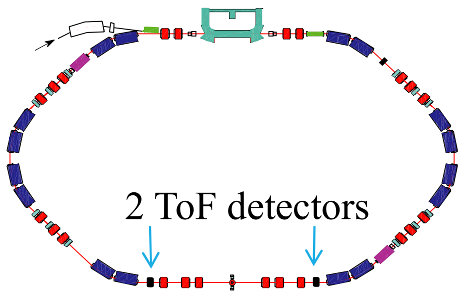


Figure: M. Zhang

A new storage ring SRing @ HIAF

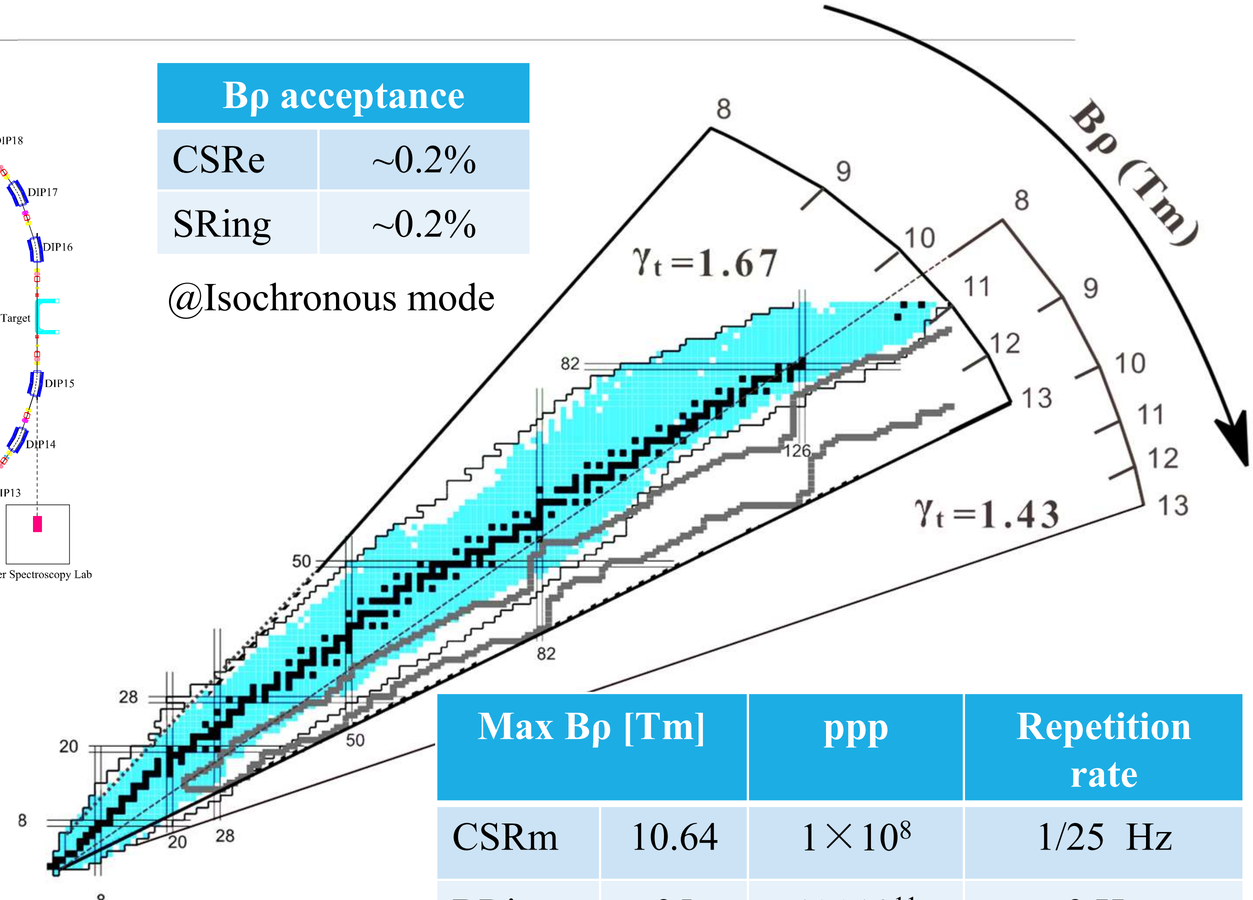




CSRe, 128.8 m, 8.4Tm

Bρ acceptance	
CSRe	~0.2%
SRing	~0.2%

@Isochronous mode

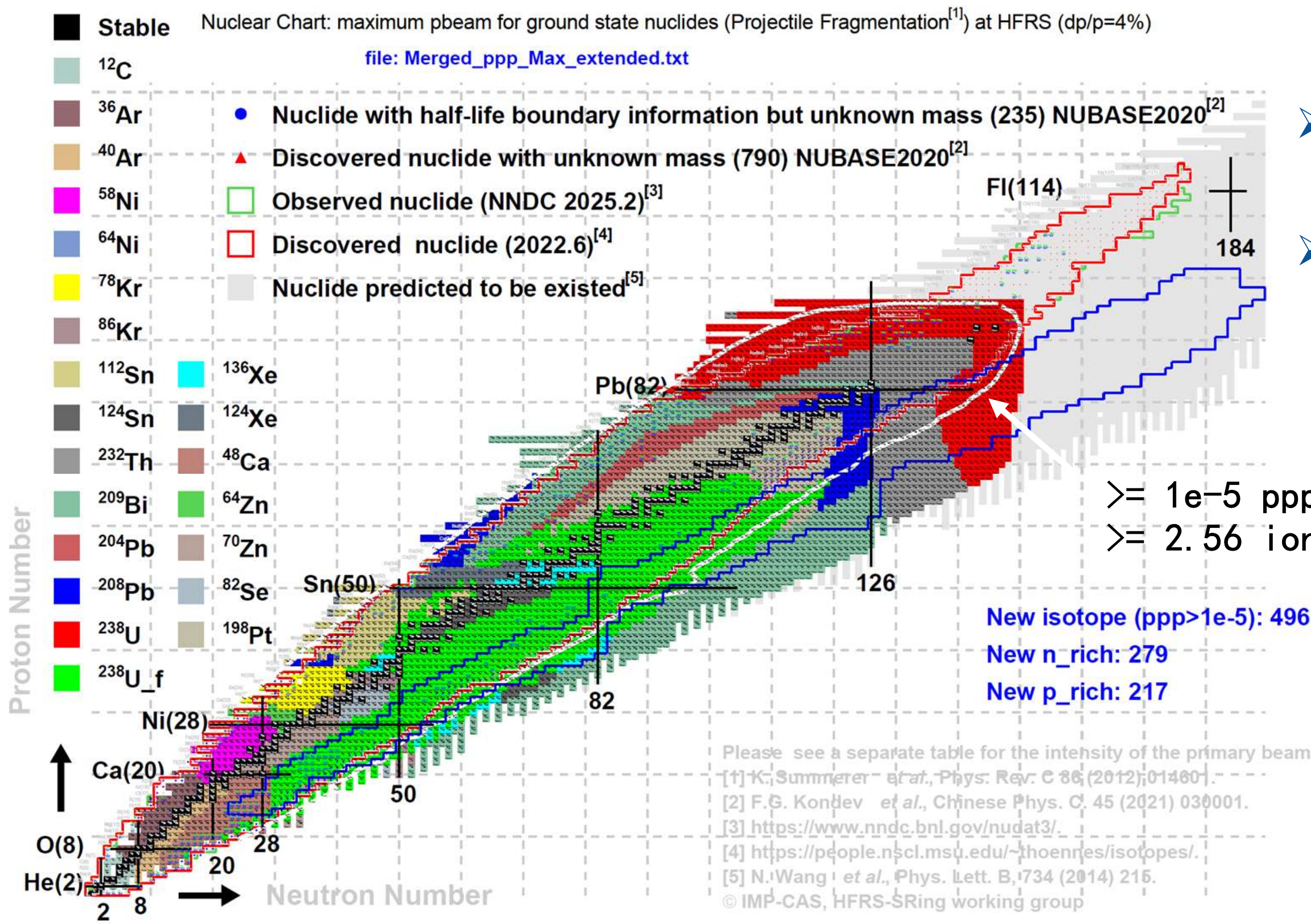


Max Bρ [Tm]		ppp	Repetition rate
CSRm	10.64	1×10^8	1/25 Hz
BRing	35	1×10^{11}	3 Hz

B. Wu et al., NIM. A 881,27 (**2018**)

Outline

Production of nuclei of unknown mass

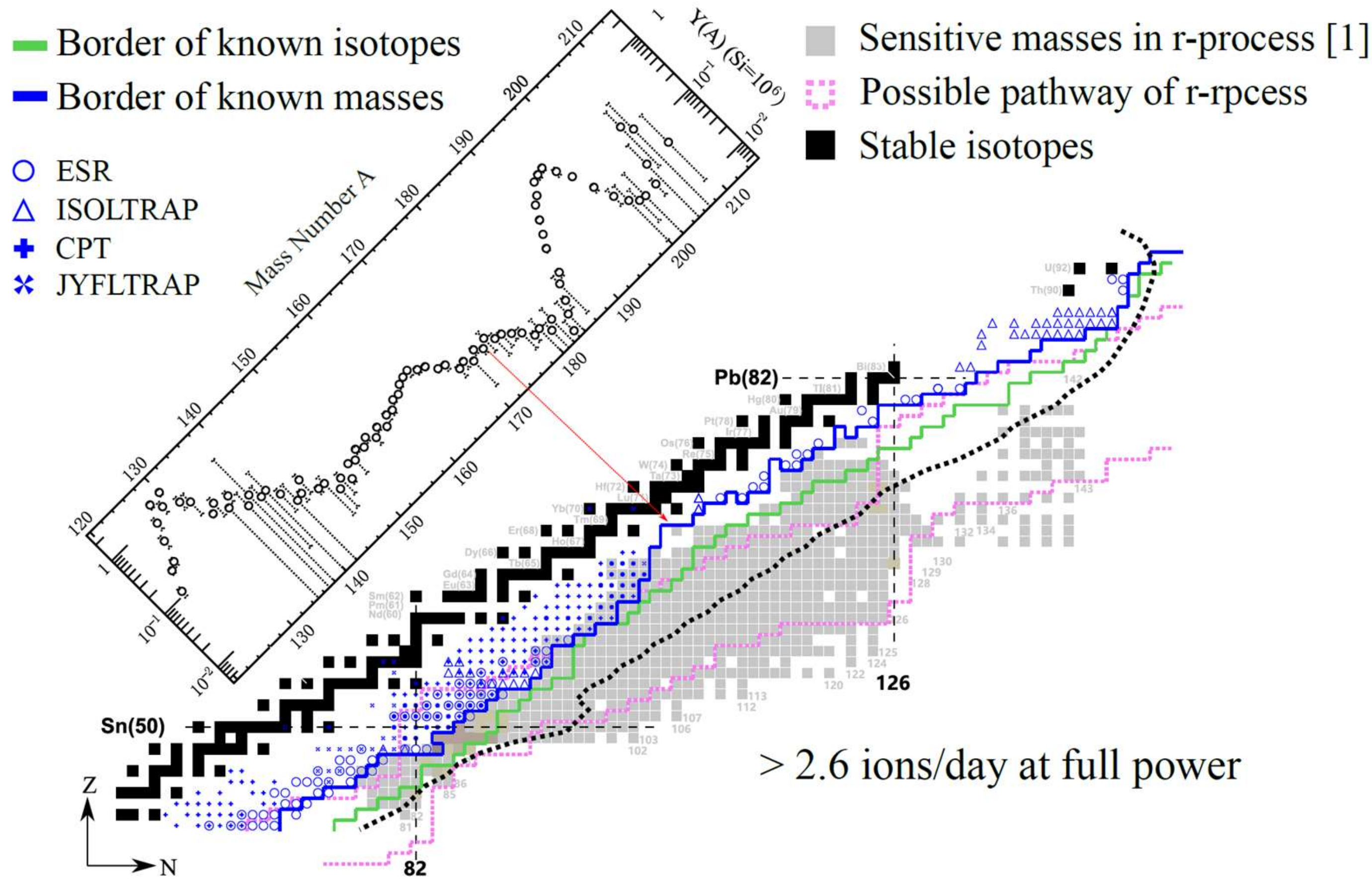


>= 1e-5 ppp
>= 2.56 ions/day

- **Projectile fragmentation**
- **^{238}U in flight fission**

H.Y. Jiao *et al.*
in preparation

Production of nuclei of unknown mass



> 2.6 ions/day at full power

Production of nuclei of unknown mass

Primary beam: ^{232}Th, ^{208}Pb, ^{198}Pt. Intensity: 1e11 ppp, 3 Hz extraction rate. RI beam: 5 ~ 10000 ppp

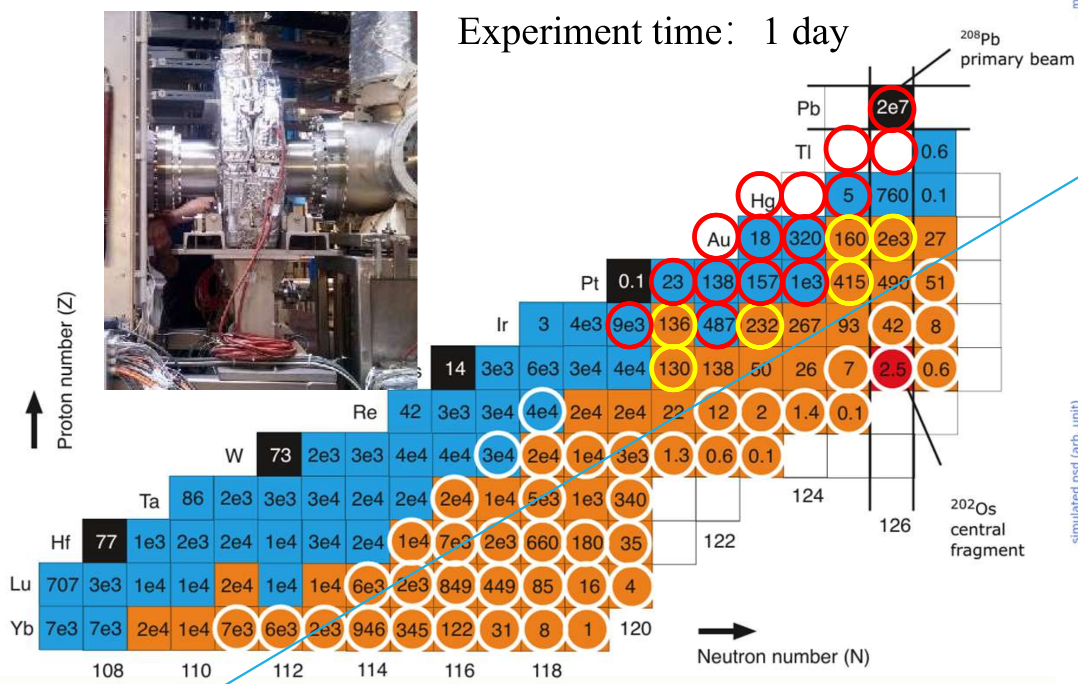
						^{204}Pb	^{204}Pb	^{205}Pb	^{206}Pb	^{207}Pb	^{208}Pb	^{209}Pb	^{210}Pb	^{212}Pb	^{213}Pb	^{214}Pb	^{215}Pb	^{216}Pb (^{232}Th 1e+1)
						^{202}Tl	^{203}Tl	^{204}Tl	^{205}Tl	^{206}Tl	^{207}Tl	^{208}Tl	^{209}Tl	^{210}Tl	^{211}Tl	^{212}Tl (^{232}Th 3e+1)		
	^{196}Hg	^{197}Hg	^{198}Hg	^{199}Hg	^{200}Hg	^{201}Hg	^{202}Hg	^{203}Hg	^{204}Hg	^{205}Hg	^{206}Hg	^{207}Hg	^{208}Hg	^{209}Hg (^{232}Th 2e+1)	^{210}Hg (^{232}Th 7)	^{211}Hg (^{232}Th 3)		
	^{195}Au	^{196}Au	^{197}Au	^{198}Au	^{199}Au	^{200}Au	^{201}Au	^{202}Au	^{203}Au	^{204}Au (^{208}Pb 2e+4)	^{205}Au (^{208}Pb 6e+3)	^{206}Au (^{208}Pb 5e+1)						
	^{194}Pt	^{195}Pt	^{196}Pt	^{197}Pt	^{198}Pt	^{199}Pt	^{200}Pt	^{201}Pt	^{202}Pt	^{203}Pt (^{208}Pb 7e+2)	^{204}Pt (^{208}Pb 2e+2)							
	^{193}Ir	^{194}Ir	^{195}Ir	^{196}Ir	^{197}Ir	^{198}Ir (^{198}Pt 5e+4)	^{199}Ir	^{200}Ir (^{208}Pb 6e+2)	^{201}Ir (^{208}Pb 1e+2)	^{202}Ir (^{208}Pb 2e+1)								
	^{192}Os	^{193}Os	^{194}Os	^{195}Os	^{196}Os	^{197}Os (^{208}Pb 5e+2)	^{198}Os (^{208}Pb 1e+2)	^{199}Os (^{208}Pb 3e+1)	^{200}Os (^{208}Pb 5)									
	^{191}Re	^{192}Re	^{193}Re	^{194}Re (^{198}Pt 7e+3)	^{195}Re (^{198}Pt 2e+3)													
^{189}W (^{198}Pt 3e+4)	^{190}W	^{191}W	^{192}W (^{198}Pt 1e+3)															

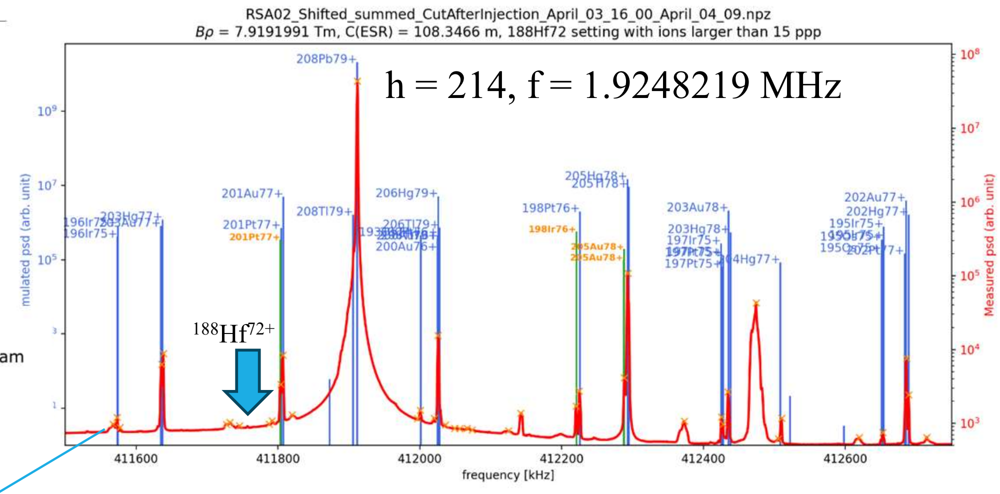
SLIDE FROM YUHU ZHANG

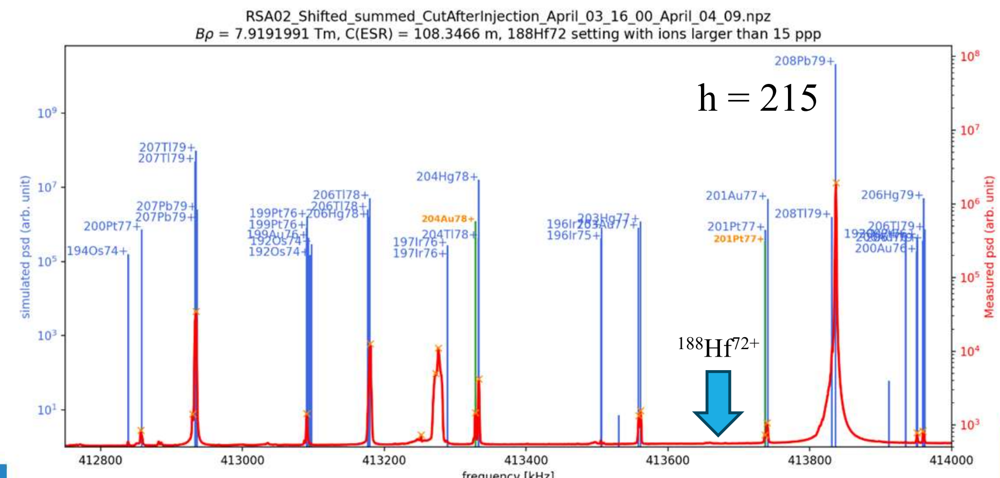
2025-4 ESR beam time

1. Intense peaks： $^{208}Pb^{79+}$, $^{200}Pt^{76+}$, $^{197,198}Ir^{75+}$, $^{205}Hg^{78+}$, $^{204}Hg^{77+}$, $^{202}Au^{77+}$, $^{201}Au^{77+}$, $^{195}Os^{75+}$, $^{207}Tl^{79+}$, $^{199}Pt/Ir^{76+}$, $^{206}Tl^{78+}$, $^{204}Au^{78+}$, $^{203}Au/Hg^{77+}$, $^{201}Pt^{77+}$
2. New masses： $^{200}Ir^{76+}$, $^{198}Ir^{76+}$, **$^{205}Au^{78+}$**, $^{197}Os^{76+,75+}$, **$^{204}Au^{78+,77+}$**, $^{203}Pt^{77+}$, **$^{198}Ir^{76+}$**

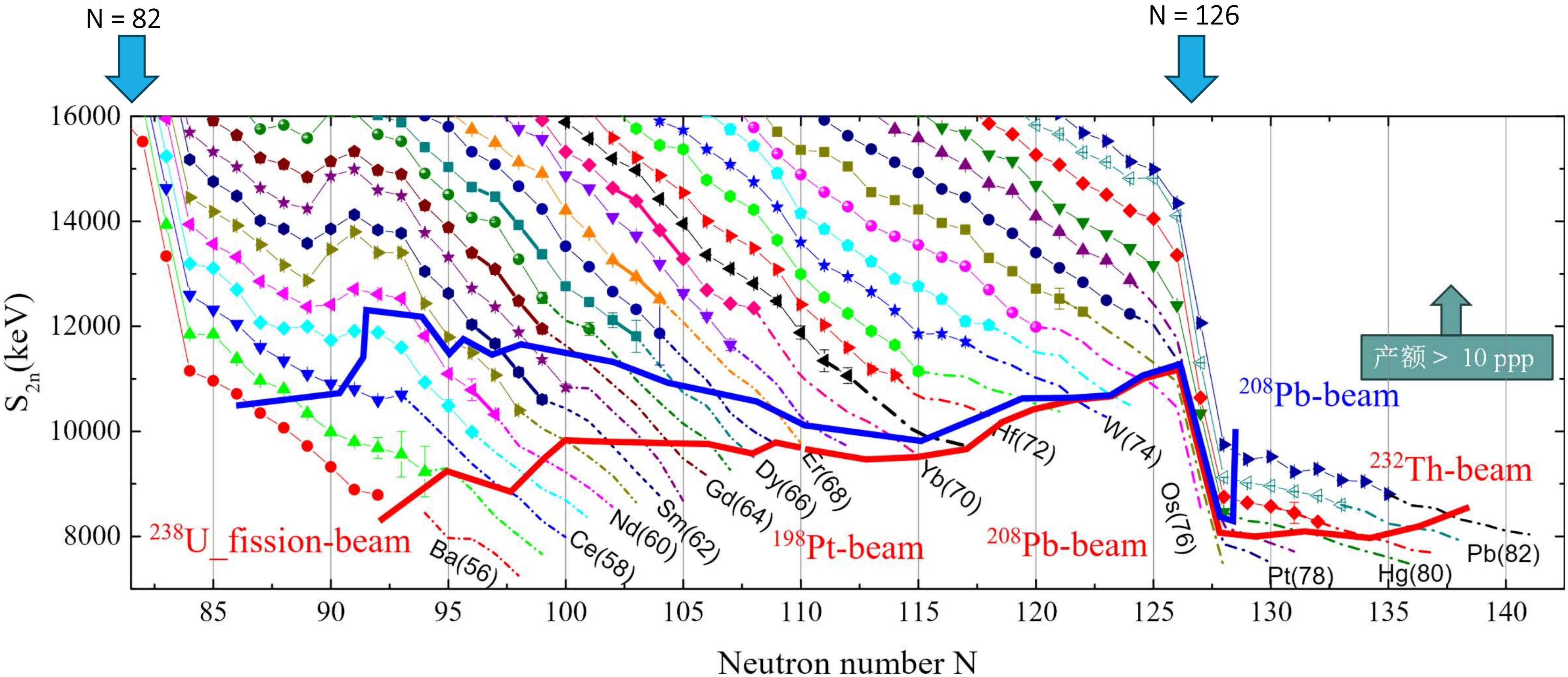
Experiment time： 1 day







Production of nuclei of unknown mass



Mass measurements at SRing

① Intensity reach1e8 ppp

- ^{176}Yb projectile fragments（new masses）
- ^{208}Pb projectile fragments（new masses）
- Isomer decay measurements（decay $T_{1/2}$）

② Intensity reach 1e9 ppp

- ^{238}U in-flight fission（new masses）

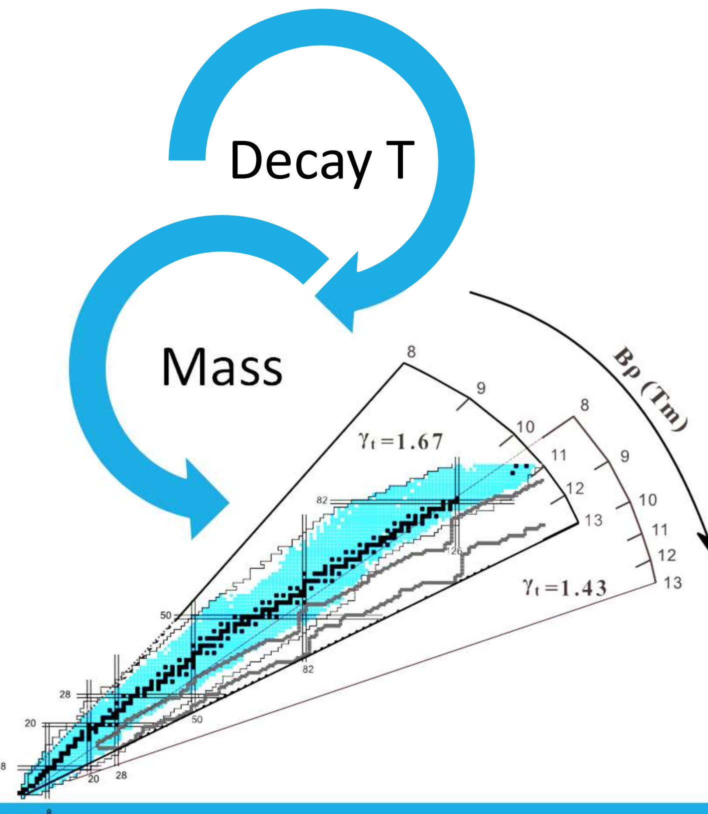
③ Intensity reach 1e10 ppp

- ^{209}Bi projectile fragments（new masses）
- ^{134}Sn projectile fragments （new masses）

④ Intensity reach 1e11 ppp

- ^{209}Bi projectile fragments （new masses ）
- ^{112}Sn projectile fragments （new masses）

◆Fast extraction of RI-beam @ 3Hz



B. Wu, J.C. Yang, J.W. Xia, X.L. Yan, X.J. Hu, L.J. Mao *et al*, Nucl. Instr. Meth. Phys. Res. A 881 (2018) 27–35.

Decay half-life measurements at SRing

1. Orbital Electron Capture Experiments

Electron capture decay of ^{111}Sn experiment

Electron capture decay of **^{64}Cu and ^{7}Be**

3. Two-Photon Decay Experiments

Measurement of the 0^+ isomeric state of $^{72}Kr^{36+}$ and $^{68}Se^{34+}$

4. Bound-State β-Decay Experiments

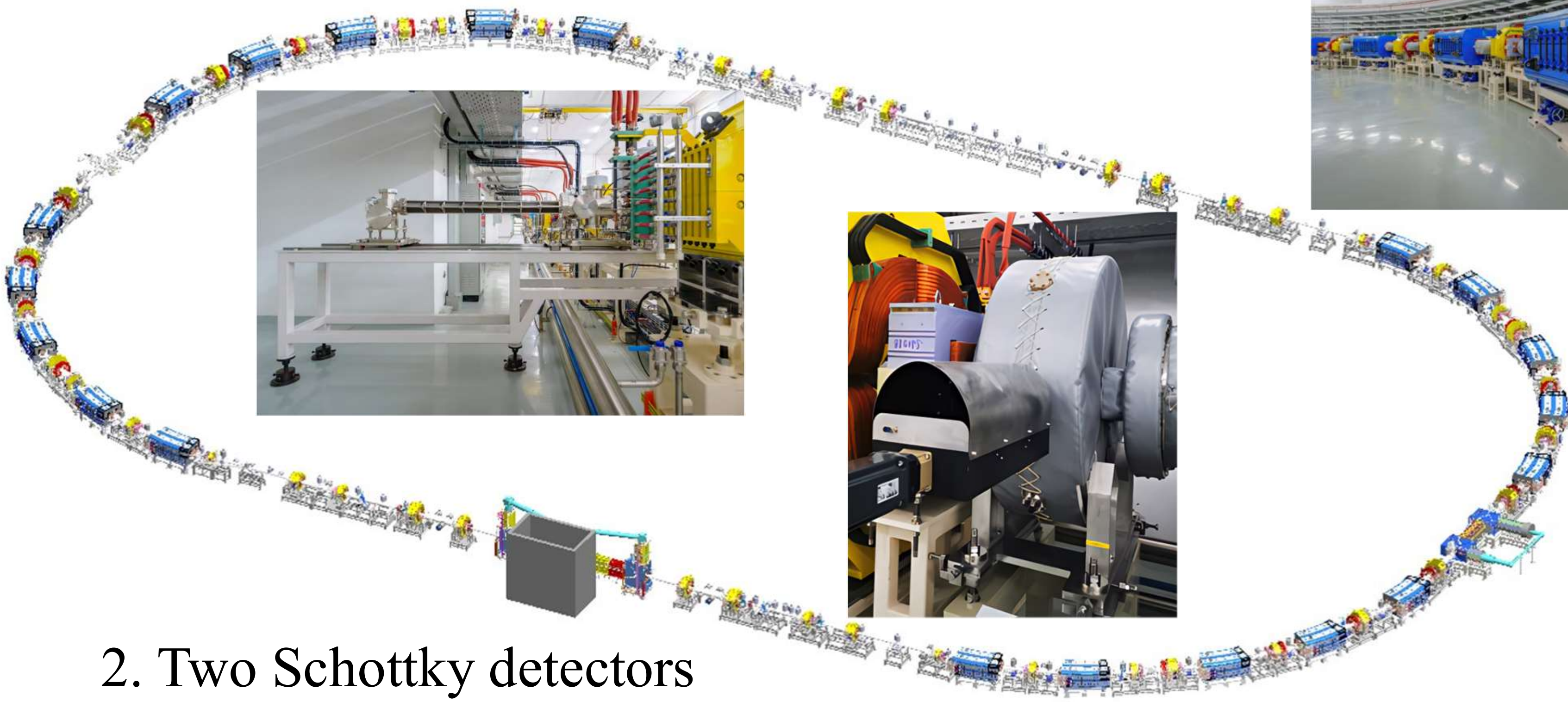
Measurement of the bound-state β-decay lifetime of **$^{205}Tl^{81+}$**

High Intensity Accelerator Facility (HIAF)

2025年3月23日 Huang

The Spectrometer Ring (SRing)

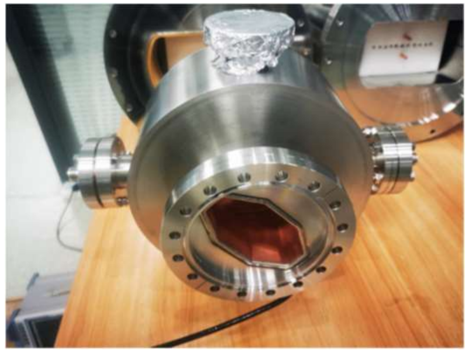
1. Two TOF-detectors (under construction)



2. Two Schottky detectors

R&D of the SRing-Schottky Cavities








Improved sensitivity of the Cavity

New Schottky cavities installed at SRing

	Cylinder cavity without copper coat	Cylinder cavity with copper coat
Resonant frequency	308.65 MHz	308.35 MHz
Loaded Q	2572	10278

Current Schottky cavity installed at CSRe

Resonant frequency	254 MHz
Loaded Q	500

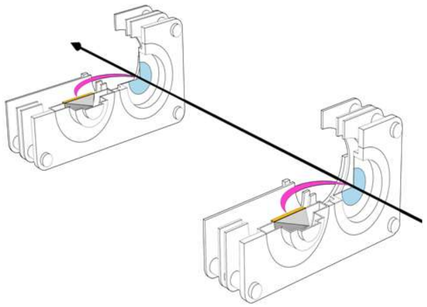
Summary

Isochronous Mass Spectrometry（IMS）

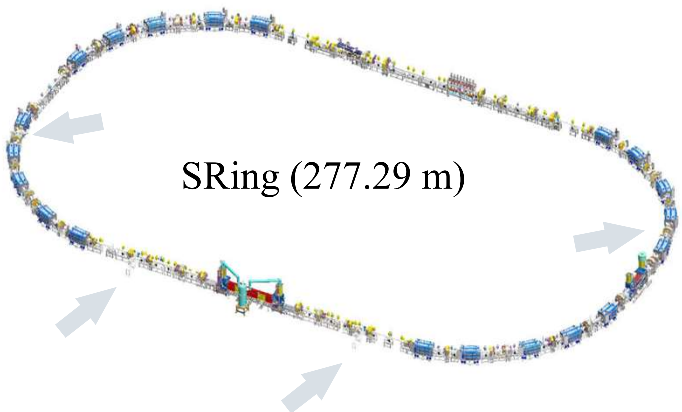
- Pros：Fast (~ 200 μs)
  Bρ determination
  Moderate m-resolving power (> 3e5)
- Cons：limited by C-foil of the TOF (< 1 ms)

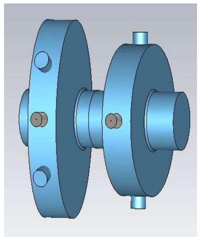
Schottky Mass Spectrometry（SMS）

- Pros：High m-resolving power (~ 8e5)
  Simultaneous M & T measurement
  Capable of any beam intensity
- Cons：limited by beam cooling (> 1s)



TOF detectors





Position-sensitive Schottky detectors

SRing M & $T_{1/2}$ experiment team

TOF MS

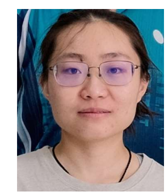
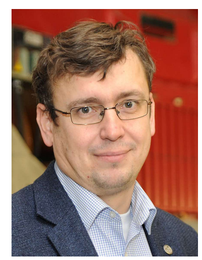
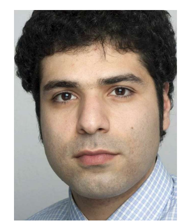
- TOF detector R& D：付超义、焦红扬、颜鑫亮、张敏、李宏福、邢元明；
- Data Acquisition System：颜鑫亮、邢元明、史金阳、周旭、孙铭泽；徐星、卢子伟；
- Online Analysis: 邢元明、史金阳、周旭、张敏
- Beam optics：葛文文、王耿、Sergey Litvinov

- Secretary：张佳
- Supervisor team：王猛、张玉虎、原有进、武军霞、周小红

Schottky MS（collaboration）

- Schottky cavities：朱光宇、王永恒、杜泽、何佩琳
- Data Acquisition system：王茜、陈瑞九、于越、
- On-line Data Analysis：陈瑞九、王轩、颜鑫亮
- Scientific Advisor： Yury Litvinov




Thank you