

Status of the gas-filled separator SHANS2

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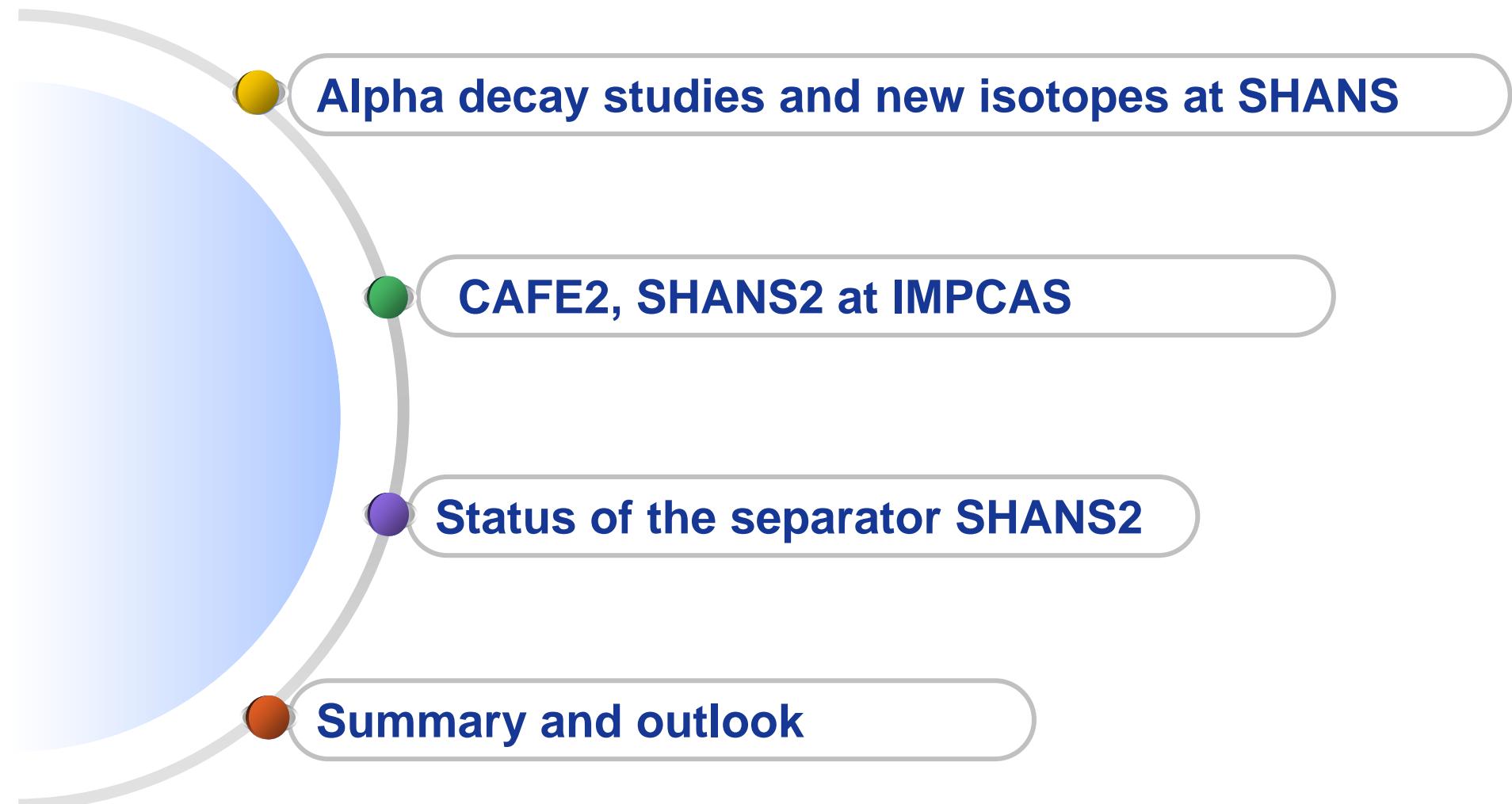


TASCA 23

April 25 - 27, 2023

20th Workshop on Recoil Separator for
Superheavy Element Chemistry & Physics

Outline



HIRFL layout



SHANS

Spectrometer for Heavy Atoms and Nuclear Structure (SHANS)

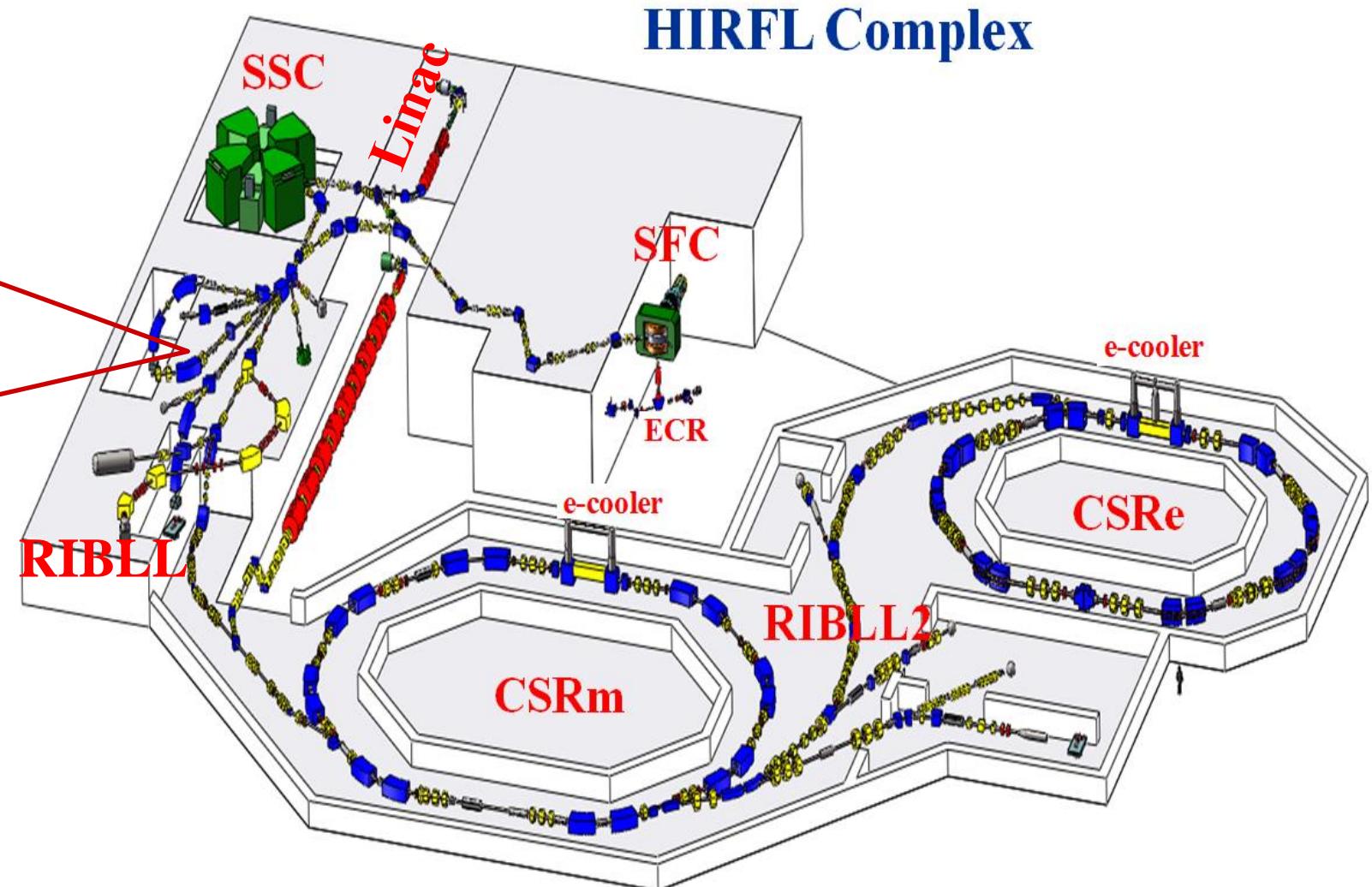
Mode: ECR/SECR + SFC

Ions: Ar, Ca, Ne, Mg, Ni, Kr, ...

Energy: ~ 5 MeV/u

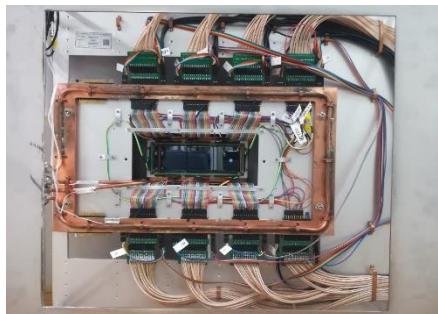
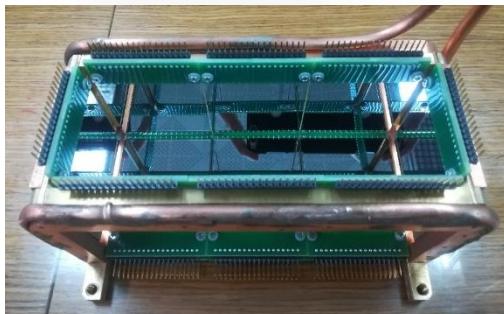
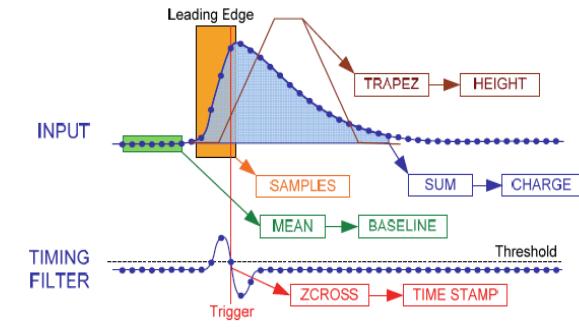
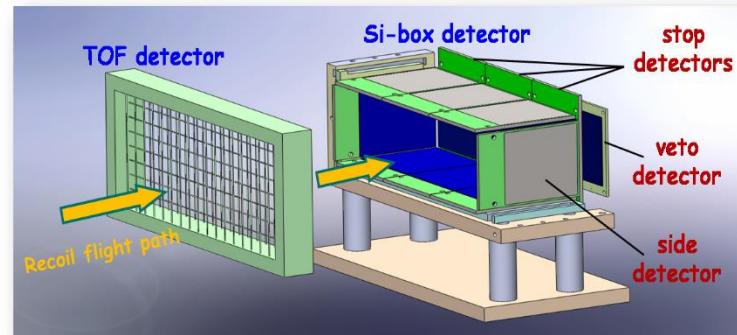
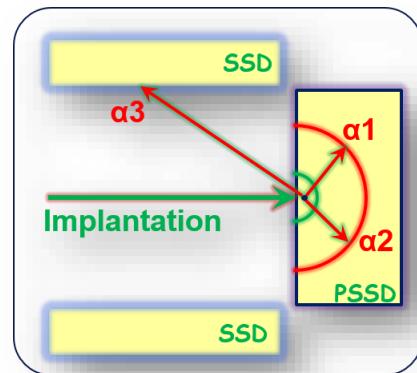
Typical Intensity: ~500 pnA ($^{36,40}\text{Ar}$)

200~500 pnA (^{40}Ca)



Heavy Ion Research Facility in Lanzhou (HIRFL), China

Detection System and Digital Electronics

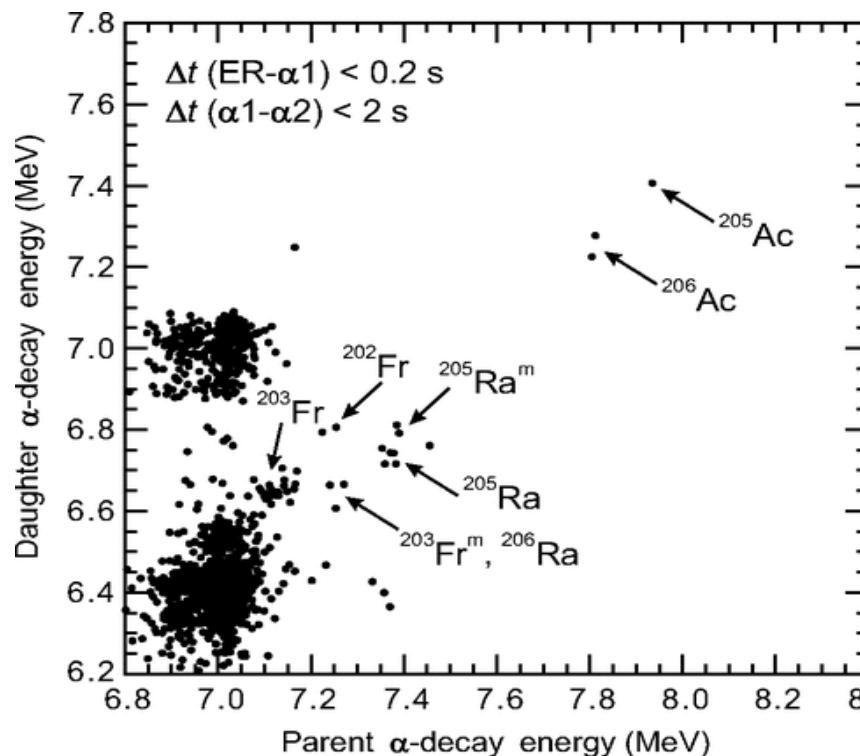


- Energy-time-position correlation measurement (ER- α - α decay chain)
 - MWPC, Si-box detector ($15 \times 5 \text{ cm}^2$, 72% eff. and 35-keV FWHM for α 's)
- Digital data acquisition electronics
 - 100 MHz sampling rate, 14 bit digital res., max. 80 MB/s data rate
- Digital pulse processing technique
 - trapezoidal filter, pulse shape fitting method, RC-CR² filter

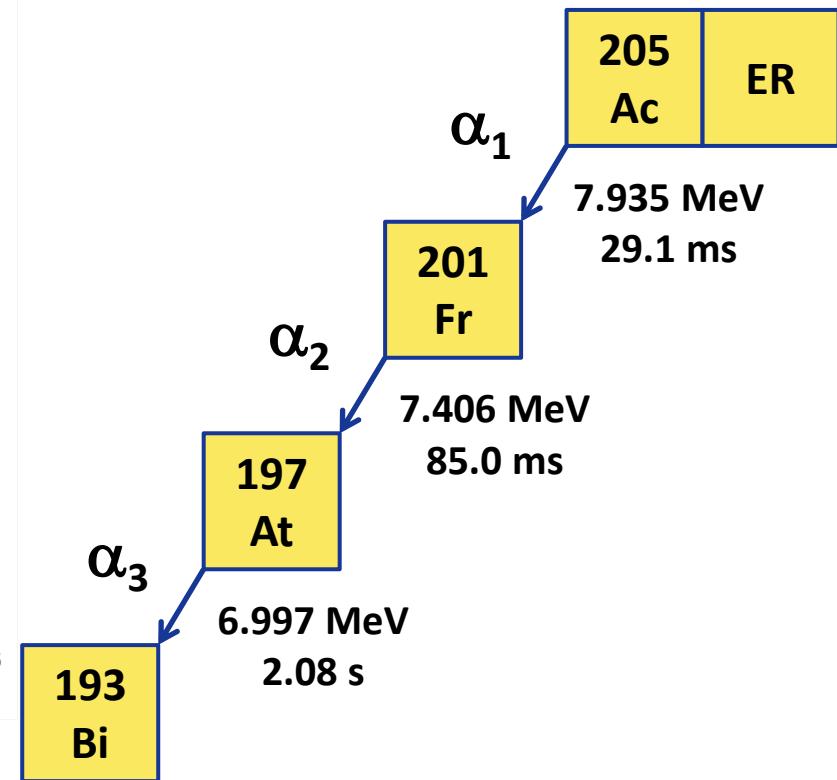
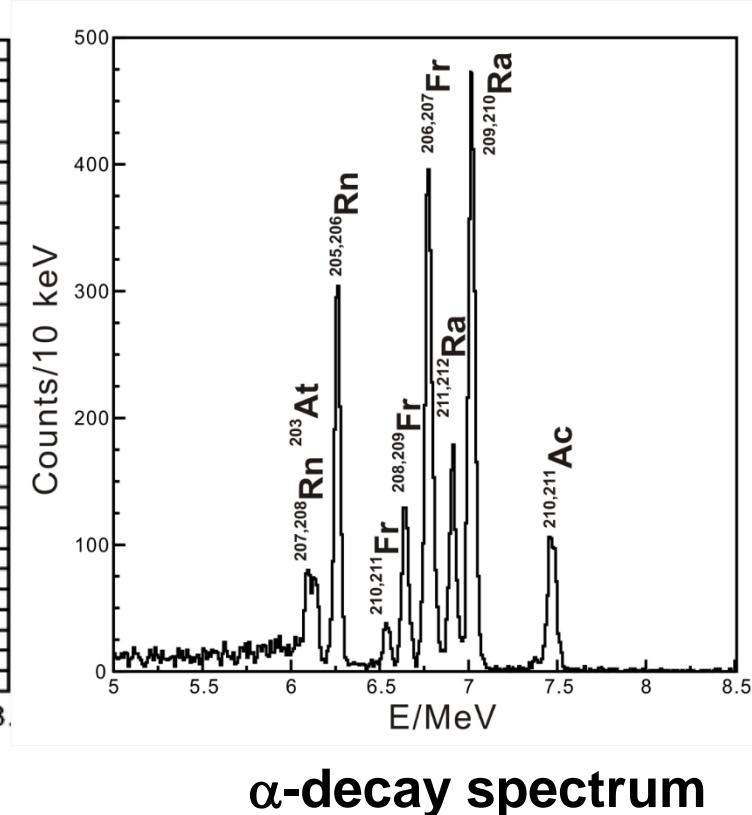


New isotope ^{205}Ac

$^{40}\text{Ca} + ^{169}\text{Tm}$ ($E_{\text{lab}}=198$ MeV)



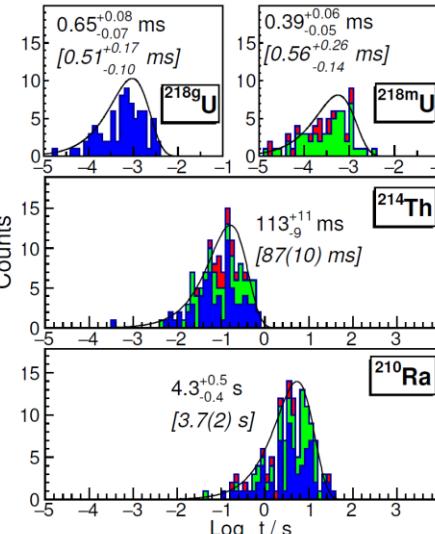
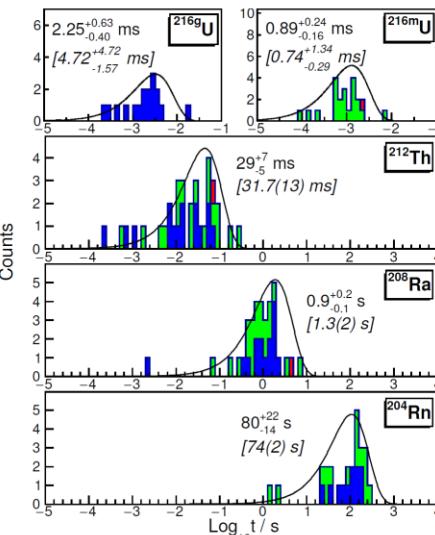
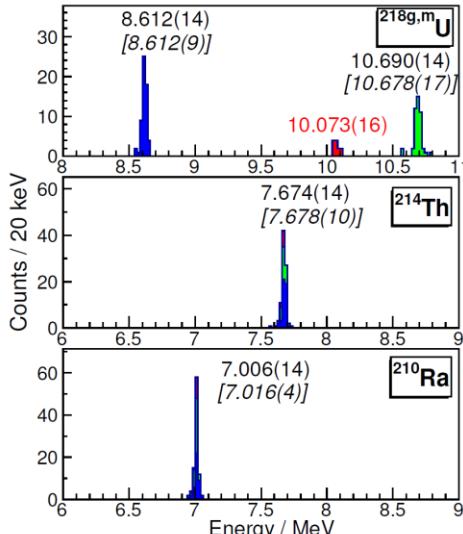
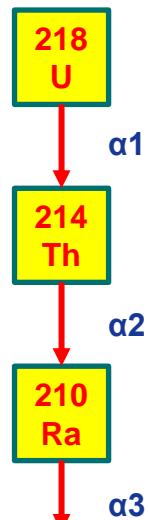
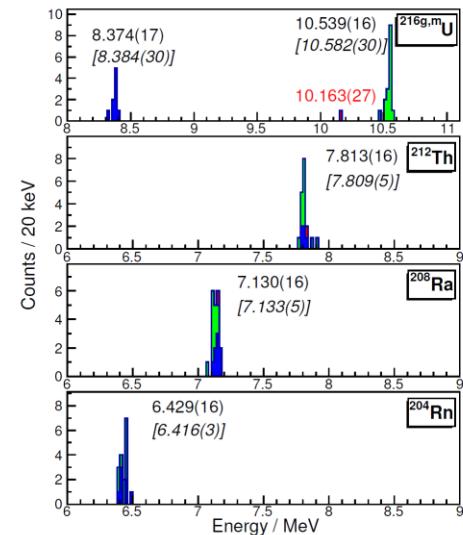
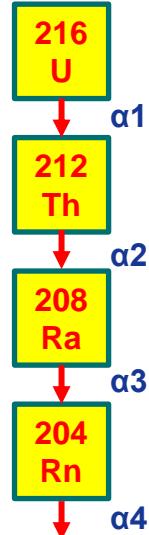
Z.Y. Zhang *et al.*, Phys. Rev. C 89, 014308 (2014)



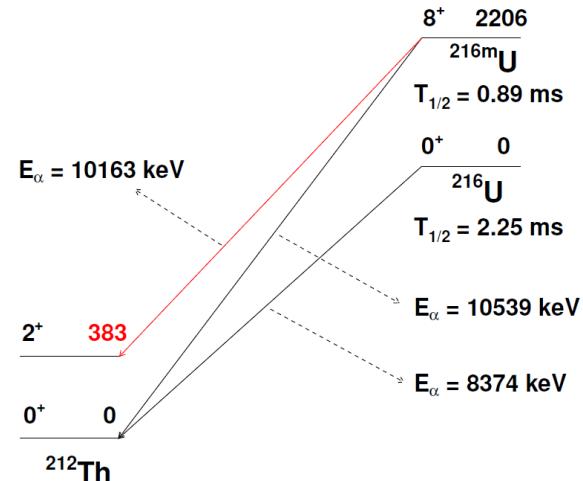
The probability of accidental coincidences for ER- α_1 - α_2 events during a time interval of 2 s is estimated to be 1.7×10^{-8}

$$E_\alpha = 7.935(30) \text{ MeV}, T_{1/2} = 20^{+97}_{-9} \text{ ms}$$

α -decay fine structure of $^{216,218}\text{U}$

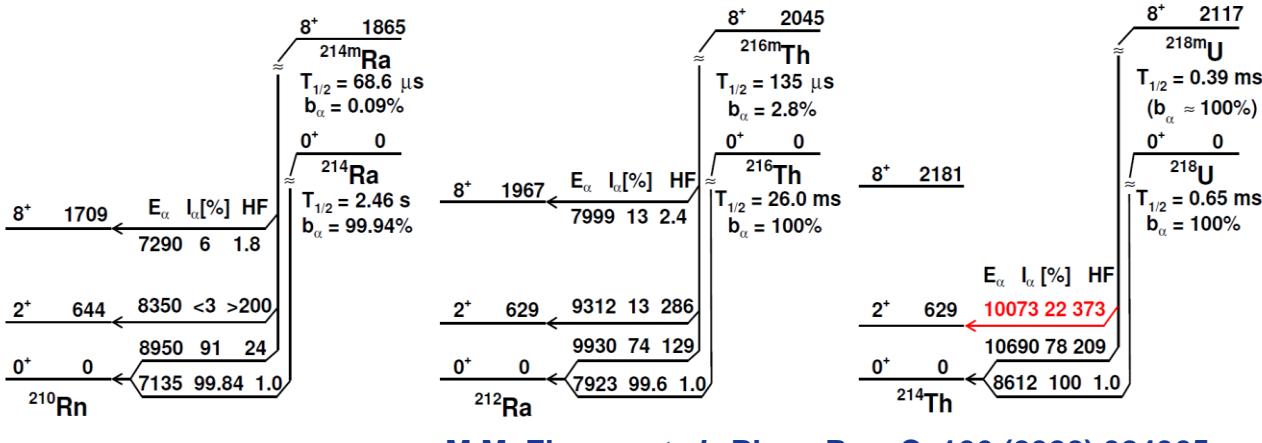


$^{40}\text{Ar} + ^{180}\text{W} \rightarrow ^{216}\text{U} + 4\text{n} - ^{216}\text{gU}$ (13 evts) and ^{216}mU (19+1 evts) (300 pb@191 MeV)



$^{40}\text{Ar} + ^{182}\text{W} \rightarrow ^{218}\text{U} + 4\text{n} - ^{218}\text{gU}$ (41) and ^{218}mU (38+9) (768 pb@190 MeV)

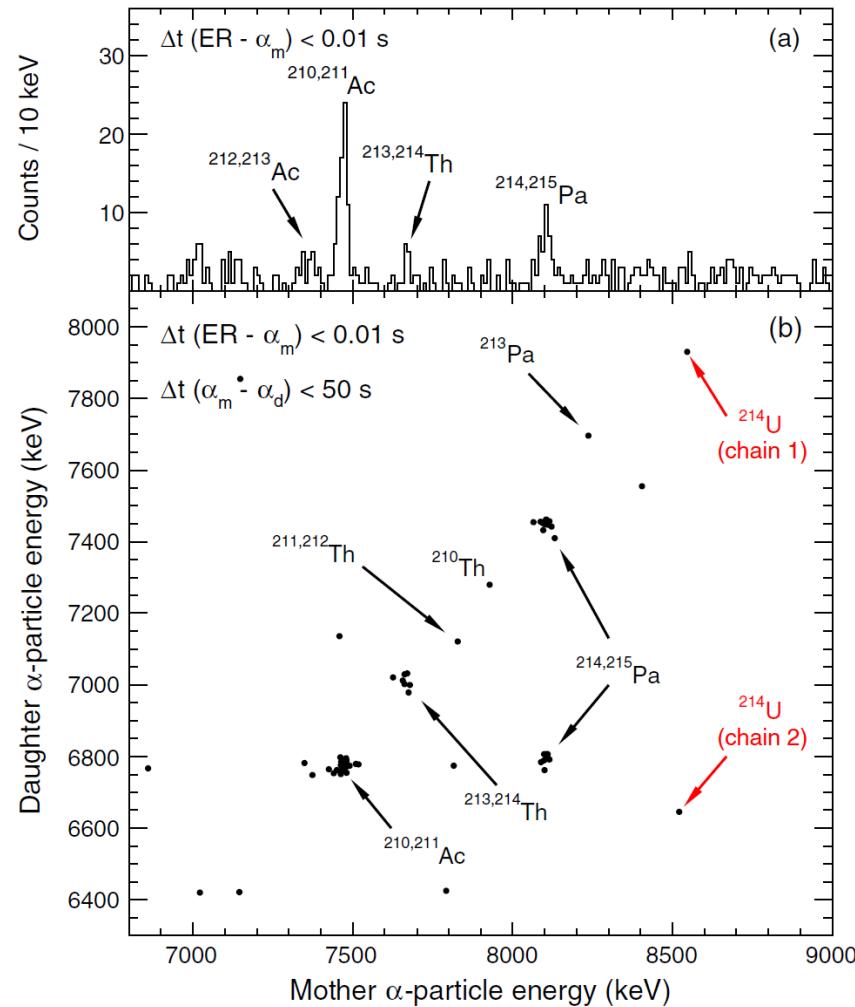
$^{40}\text{Ca} + ^{184}\text{W} \rightarrow ^{218}\text{U} + \alpha 2\text{n} - ^{218}\text{gU}$ (35) and ^{218}mU (19+7) (325 pb@206 MeV)



M.M. Zhang, et al., Phys. Rev. C, 106 (2022) 024305

New isotope ^{214}U

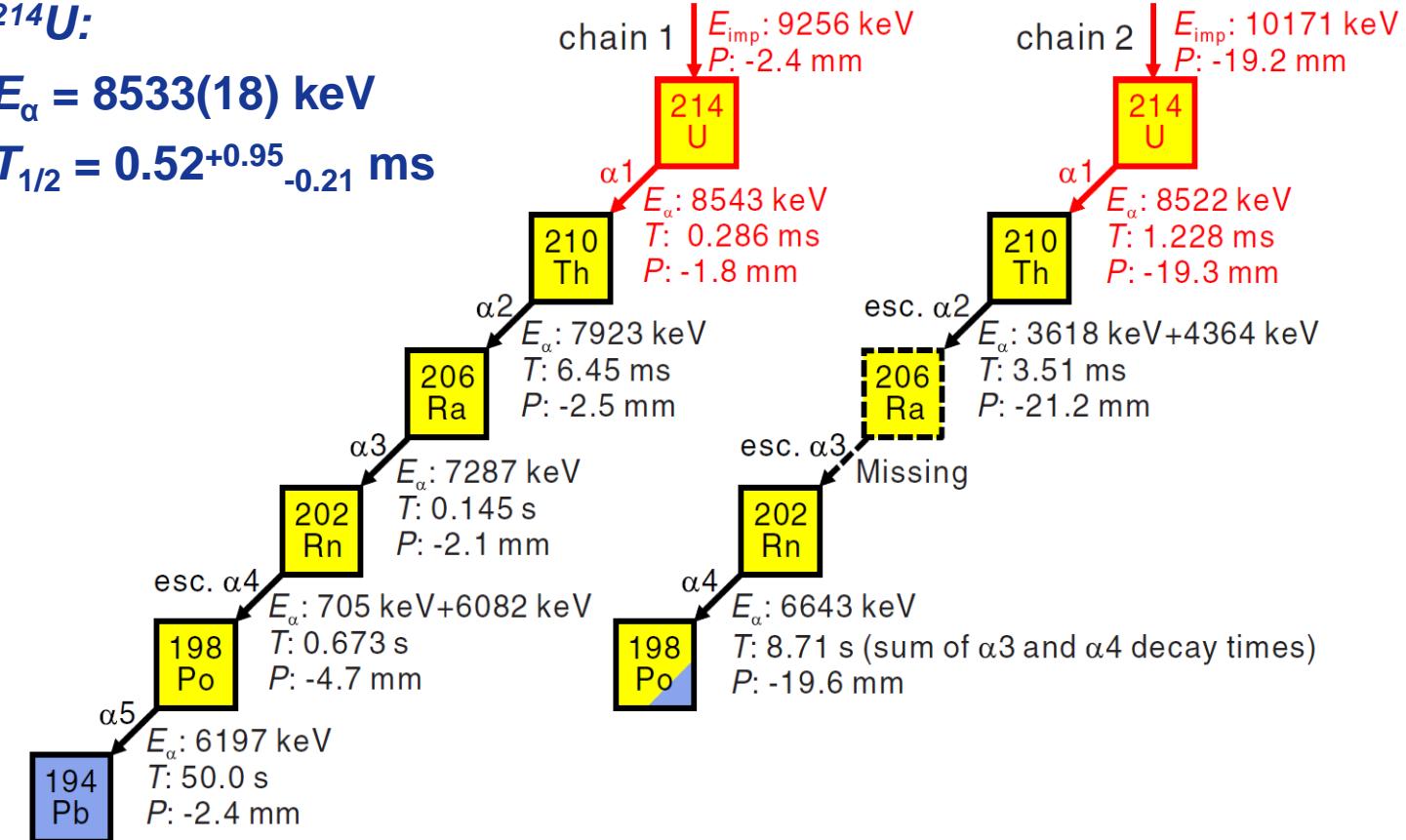
$^{36}\text{Ar} + ^{182}\text{W} \rightarrow ^{214}\text{U} + 4\text{n}$ @ SHANS – ^{214}U (2 events) (10 pb@184 MeV)



^{214}U :

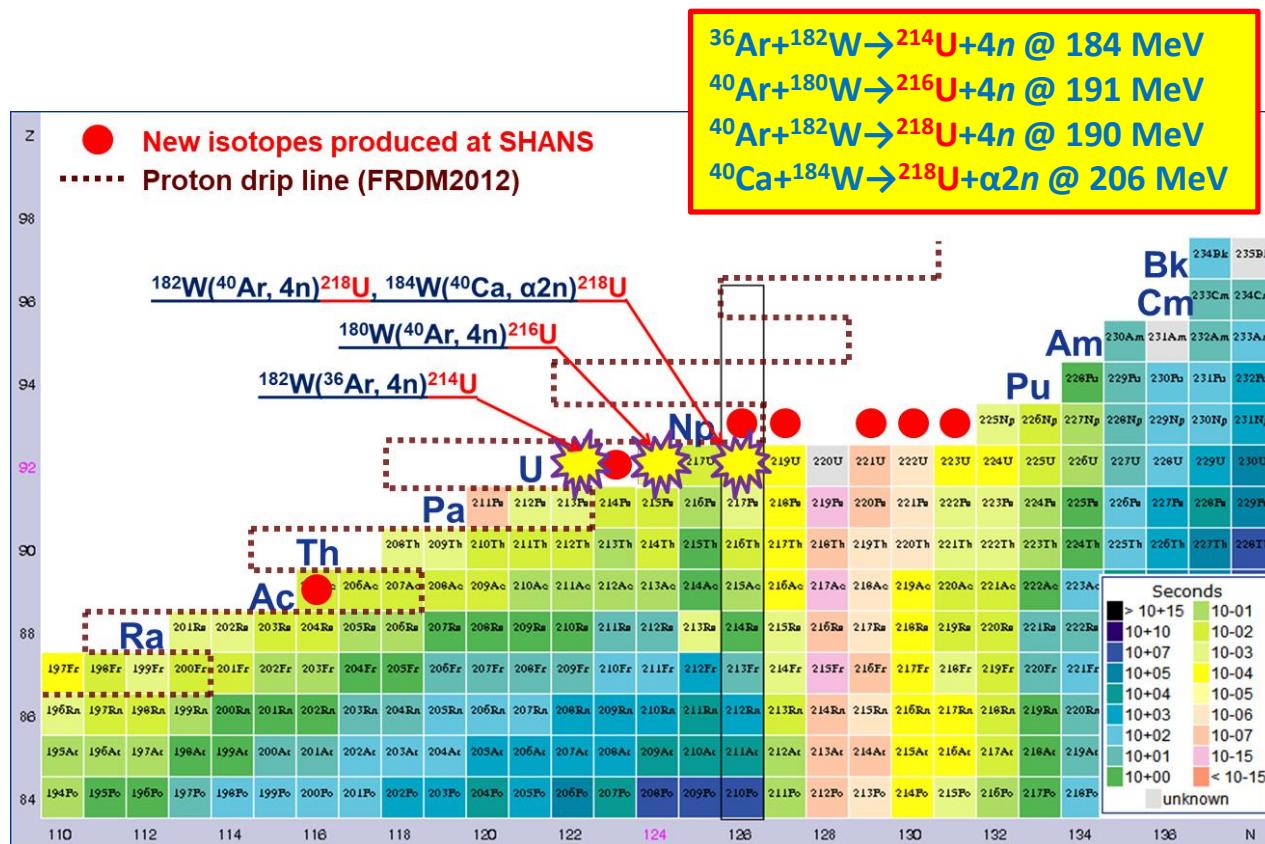
$$E_\alpha = 8533(18) \text{ keV}$$

$$T_{1/2} = 0.52^{+0.95}_{-0.21} \text{ ms}$$



New isotope ^{214}U and measurements for $^{216,218}\text{U}$

- ✓ The lightest U isotope ^{214}U was synthesized at SHANS
- ✓ More precise α -decay properties of $^{216,218}\text{U}$ were measured

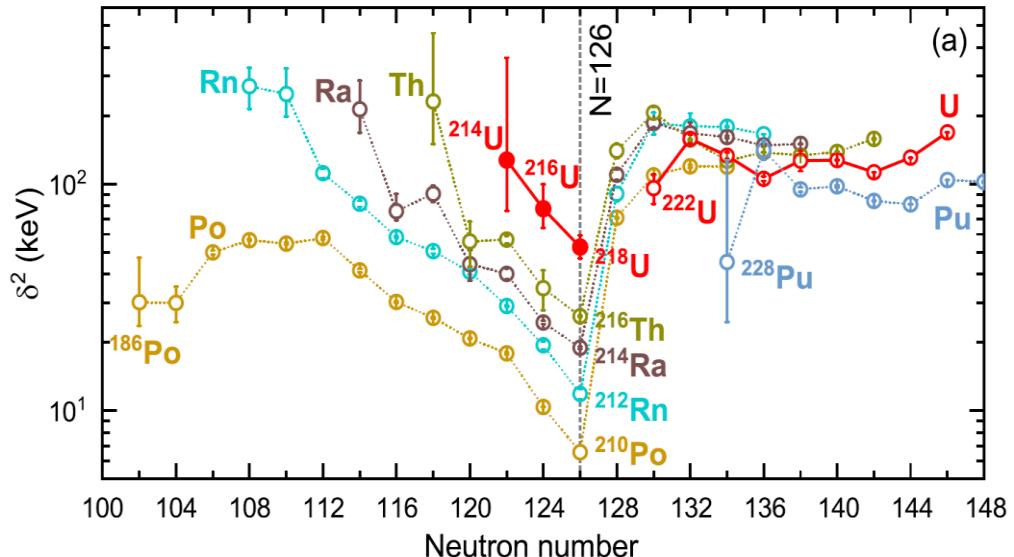


Isotope	This work			Literature data			Ref.
	E_α/keV	$T_{1/2}/\text{ms}$	δ^2/keV	E_α/keV	$T_{1/2}/\text{ms}$	events	
^{214}U	8533(18)	$0.52^{+0.95}_{-0.21}$	128^{+233}_{-52}	-	-	-	-
	2 events						
^{216}U	8374(17)	$2.25^{+0.63}_{-0.40}$ ^a	78^{+22}_{-14}	8384(30)	$4.72^{+4.72}_{-1.57}$	4	Ma, et al. @ SHANS
	13 events			8340(50)	$3.8^{+8.8}_{-3.2}$	3	Devaraja, et al. @ SHIP
				8390(33)	$2.6^{+3.6}_{-1.0}$	1	Wakabayashi, et al. @ GARIS
^{218}U	8612(14)	$0.65^{+0.08}_{-0.07}$	53^{+7}_{-6}	8600(30)	$1.15^{+1.58}_{-0.42}$	3	Ma, et al. @ SHANS
	76 events			8612(9)	$0.51^{+0.17}_{-0.10}$	20	Leppänen, et al. @ RITU
				8625(25)	$1.5^{+7.3}_{-0.7}$	4	Andreyev, et al. @ VASSILISSA

a) The value is deduced by combining all **21 decay events** from this work and Refs., and is also used for the decay width calculation for ^{216}U .

L. Ma, et al., Phys. Rev. C 91, 051302(R) (2015).
H. M. Devaraja, et al., Phys. Lett. B 748, 199 (2015).
Y. Wakabayashi, et al., RIKEN Accel. Prog. Rep. 48, 70 (2015).
A. P. Leppänen, et al., Phys. Rev. C 75, 054307 (2007).
A. P. Leppänen, et al., Eur. Phys. J. A 25, 183 (2005).
A. N. Andreyev,, Z. Phys. A 342, 123 (1992).

Enhanced α -particle clustering



- Remarkable simplification of the δ^2 systematics in $N_p N_n$ scheme

- N>126: dominated by p-p and n-n pairing

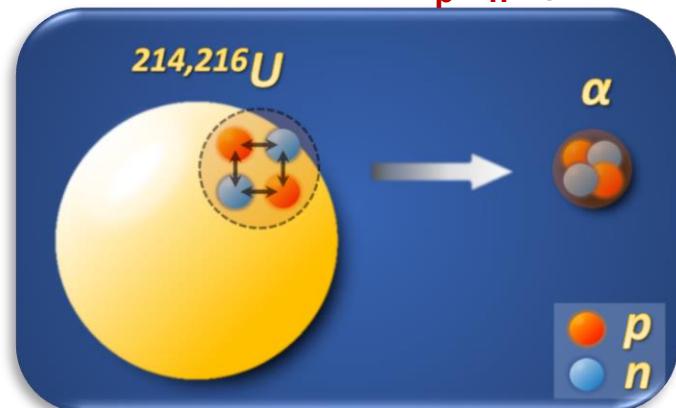
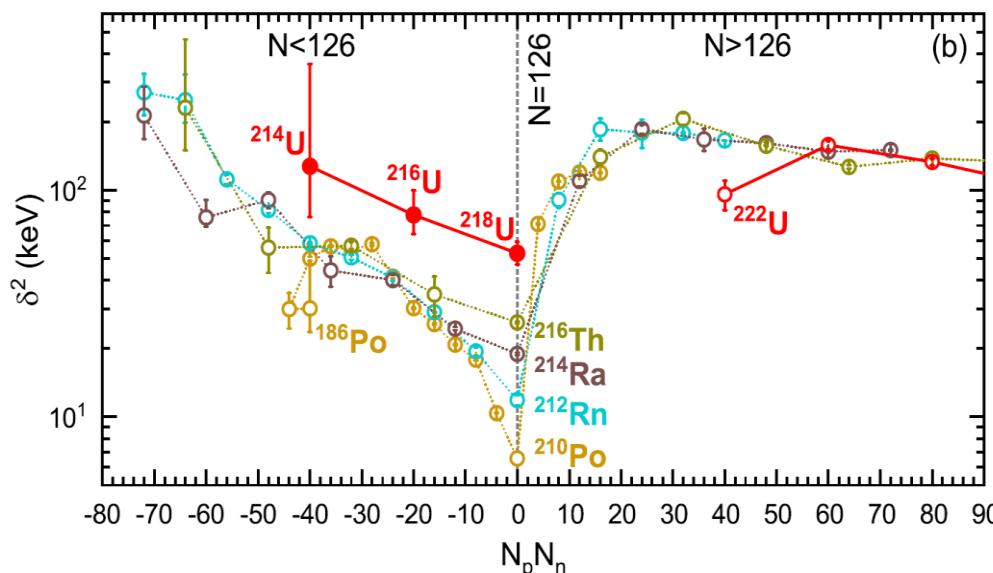
- N<126: p-n interaction plays a key role

$$^{214}\text{U}: N_p N_n = (Z-82) \cdot (N-126) = -40$$

$$^{216}\text{U}: N_p N_n = (Z-82) \cdot (N-126) = -20$$

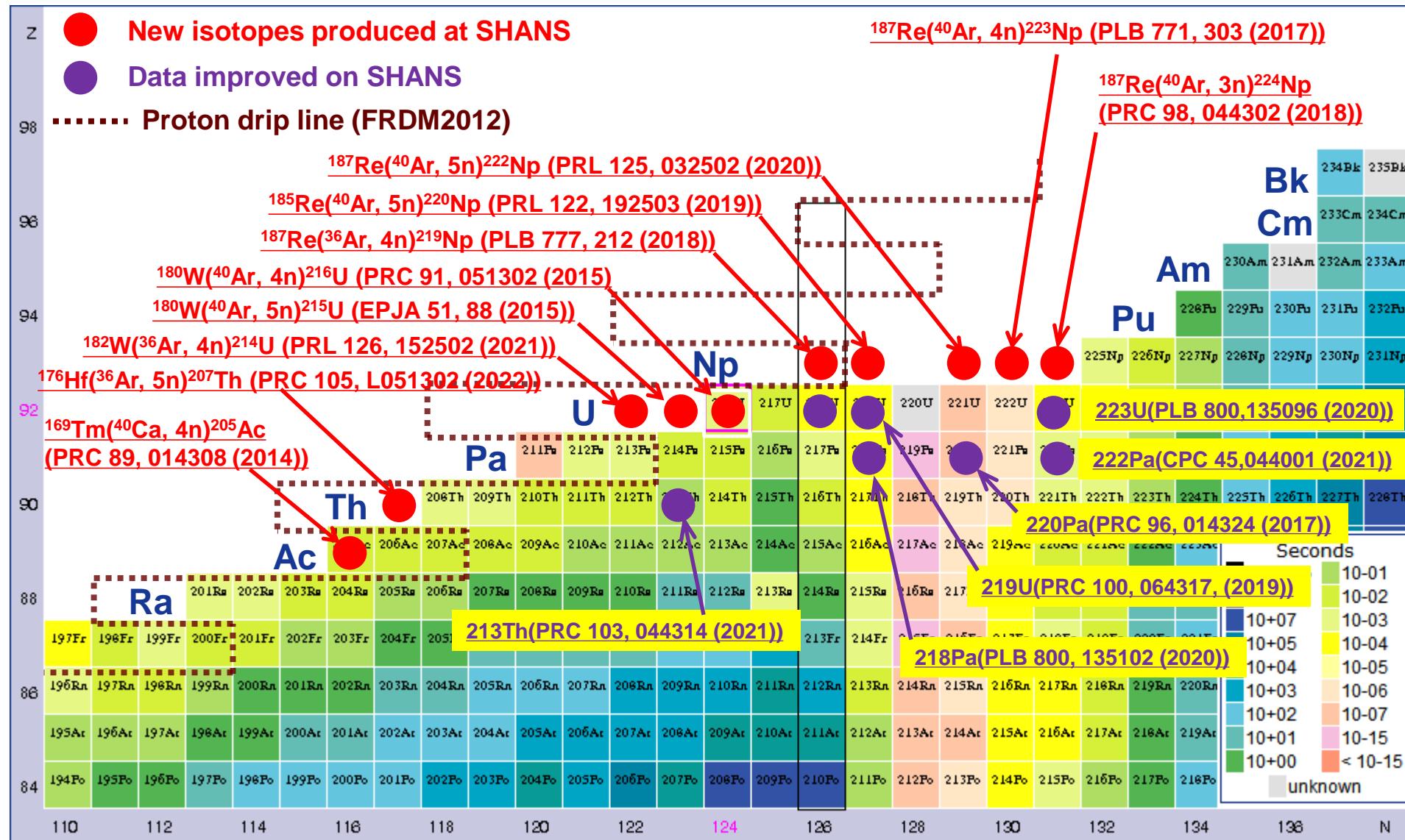
$$^{218}\text{U}: N_p N_n = (Z-82) \cdot (N-126) = 0$$

- ^{214,216}U: δ^2 values are enhanced by a factor of two as compared with Po-Th $N_p N_n$ systematics with N<126



Z. Y. Zhang, et al., Phys. Rev. Lett. 126, 152502 (2021).

New isotopes and nuclear structure study at SHANS

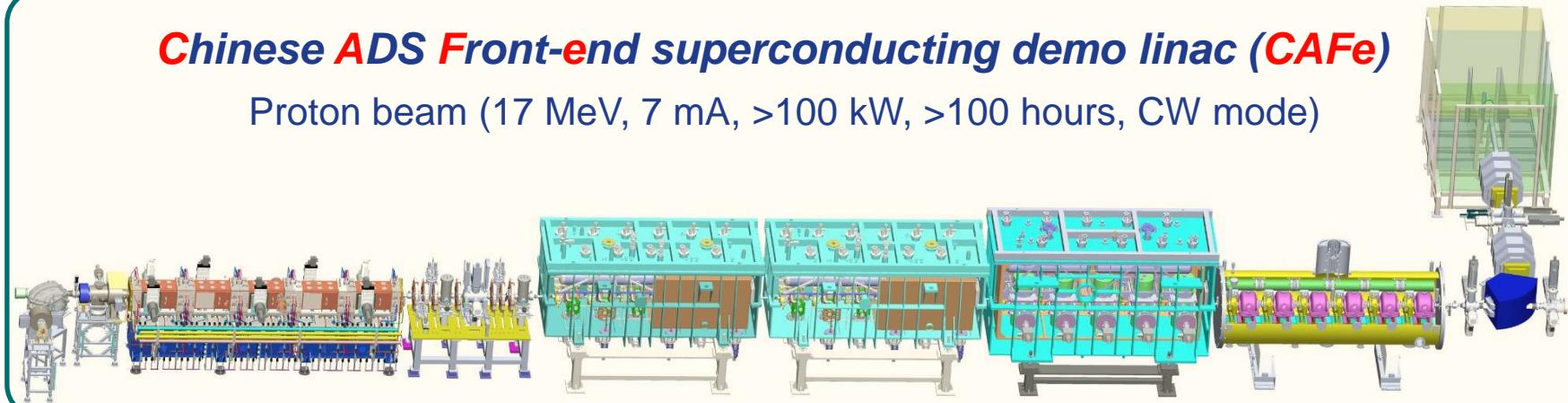


CAFe and CAFE2

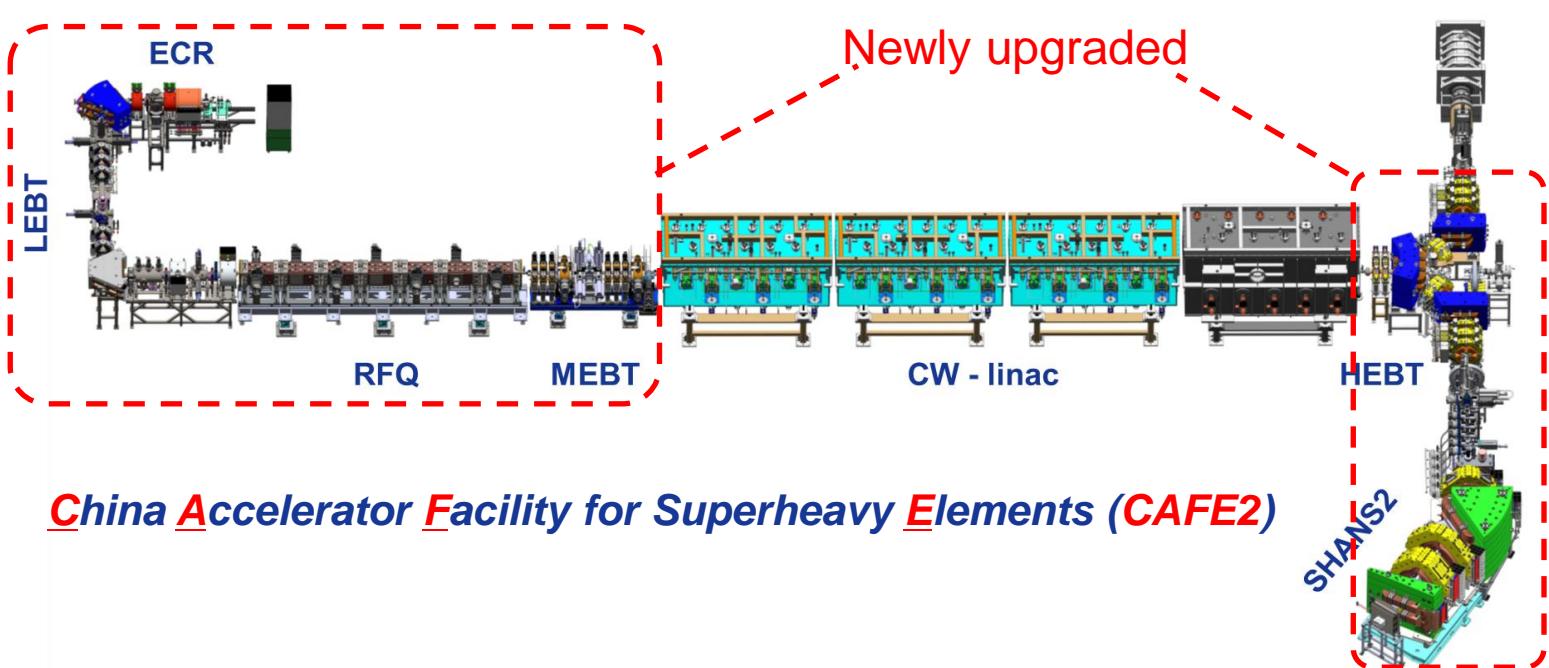


Chinese ADS Front-end superconducting demo linac (CAFe)

Proton beam (17 MeV, 7 mA, >100 kW, >100 hours, CW mode)



- Y. He, Z. Wang, Z. Qin, et al., 10th Int. Particle Accelerator Conf. (IPAC2019), Melbourne, Australia (2019).
- S.-H. Liu, Z.-J. Wang, H. Jia, et al., Nucl. Instru. Meth. A **843**, 11-17 (2017).
- Z.-J. Wang, Y. He, H. Jia, et al., Phys. Rev. Accel. Beams **19**, 120101 (2016).



China Accelerator Facility for Superheavy Elements (CAFE2)

➤ **Accelerator:**

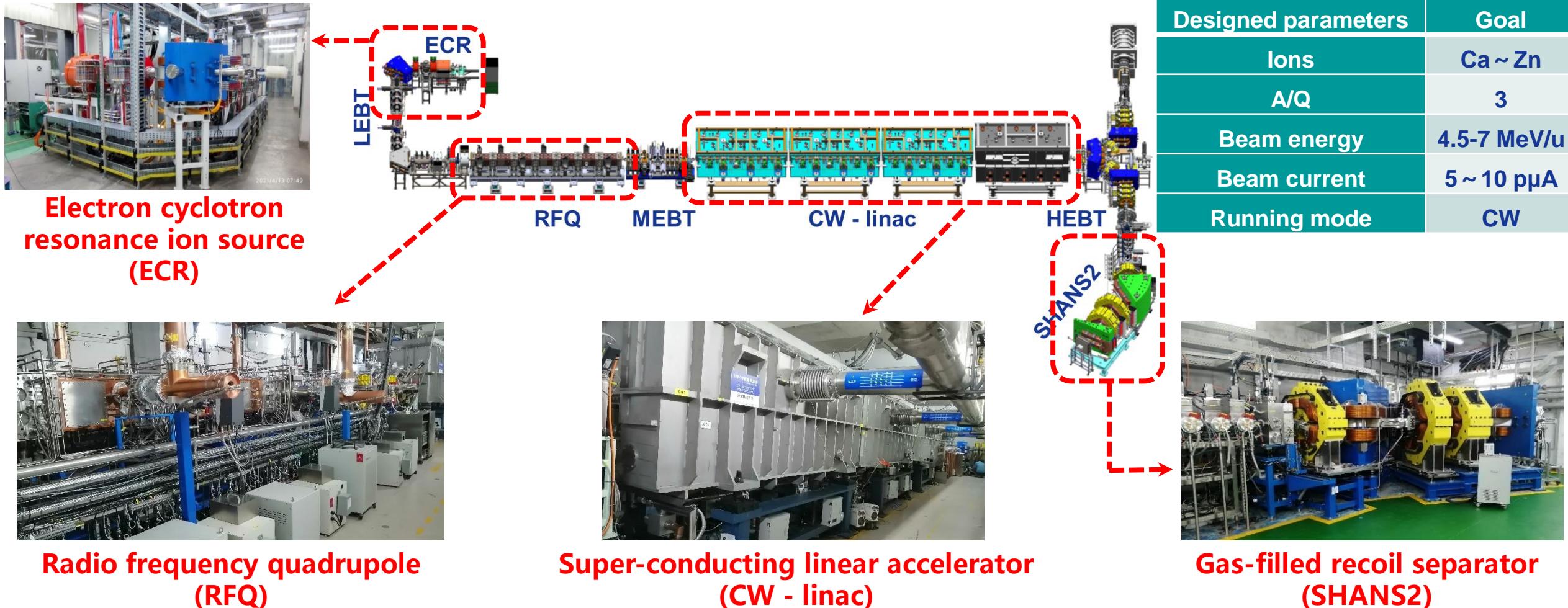
- ECR ion source
- Low energy beam transfer (LEBT)
- Radio frequency quadrupole (RFQ)
- Medium energy beam transfer (MEBT)
- High energy beam transfer (HEBT)

➤ **Terminal:**

- Differential pumping system
- Rotating target with actinide material
- Gas-filled recoil separator (SHANS2)
- Detection system and DAQ

CAFE2 project at IMPCAS

China Accelerator Facility for Superheavy Elements (CAFE2)
 (started in May 2019 – commissioned in Feb. 2022)



Magnet system

Parameters of magnets

D₁ dipole magnet

Deflection angle	30°
Entrance and exit edge angles	0, -34°
Deflection radius	1.6 m
Max. magnetic field	1.563 T
Vertical gap	±79 mm

D₂ dipole magnet

Deflection angle	10°
Entrance and exit edge angles	-10, 10°
Deflection radius	2.5 m
Max. magnetic field	1.1 T
Vertical gap	±93 mm

Q₁ quadrupole magnet

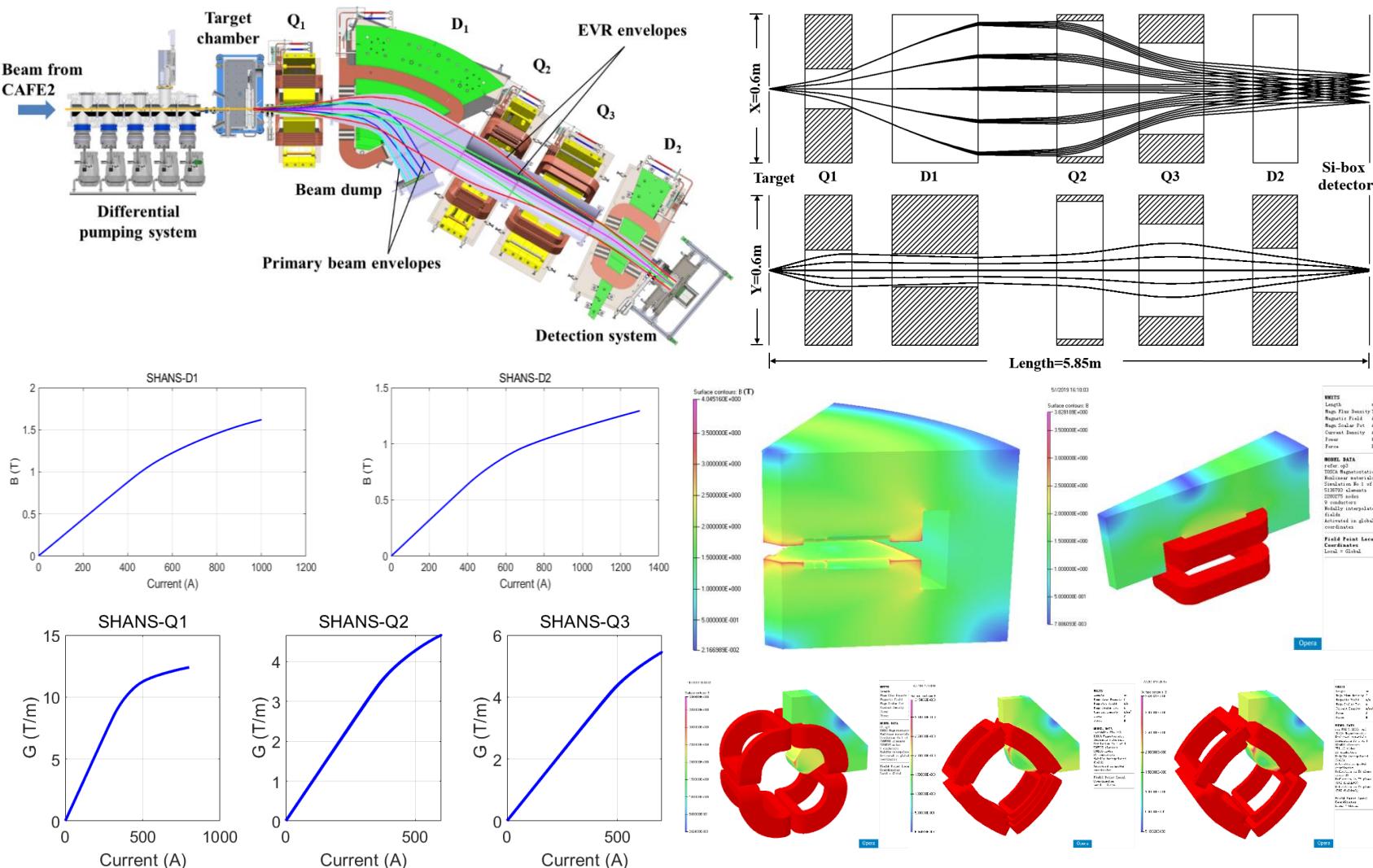
Length, aperture, max. gradient	0.46 m, Φ162 mm, 11.85 T/m
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Q₂ quadrupole magnet

Length, aperture, max. gradient	0.45 m, Φ324 mm, 4.2 T/m
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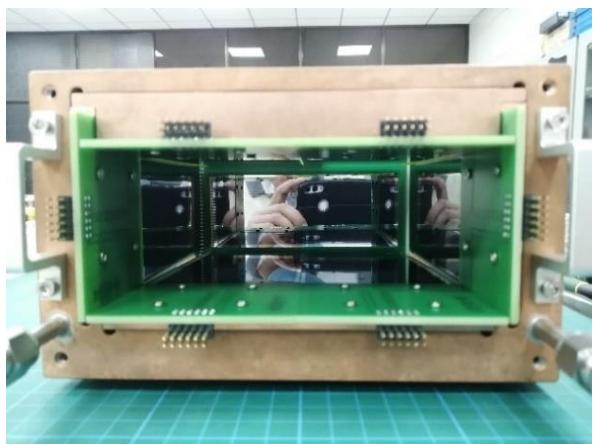
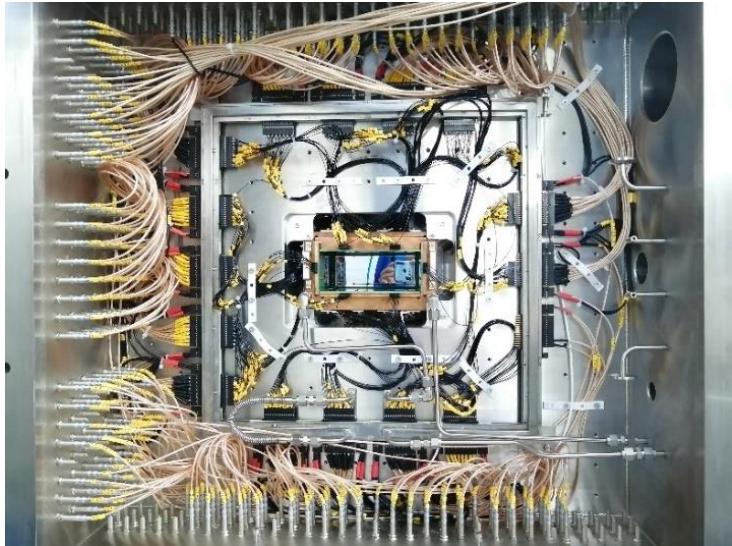
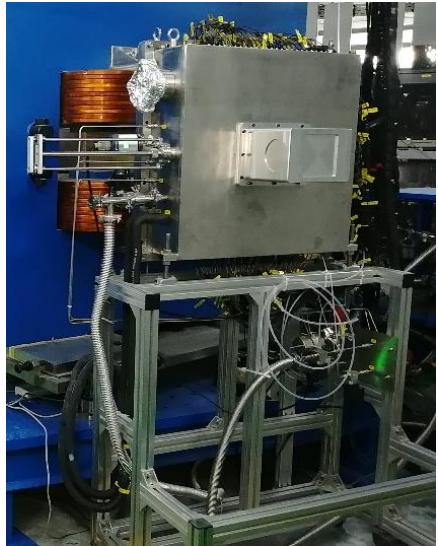
Q₃ quadrupole magnet

Length, aperture, max. gradient	0.63 m, Φ314 mm, 5.03 T/m
---------------------------------	---------------------------



L. N. Sheng, et al., Nucl. Instrum. Methods, A 1004, 165348 (2021).

Detection system



Si-box detection array

	DSSD (BB17)	SSD (W4)	VETO (MSX25)
Sensitive area	128×48 mm ²	65×120 mm ²	50×50 mm ²
Junction side	48 strips	8 strips	No strips
Ohmic side	128 strips	No strips	No strips
Strip width	1 mm	15 mm	
Thickness	300±20 µm	500±10 µm	300 µm
Thickness of dead layer	100 nm	100 nm	100 nm
Depletion bias voltage	40 V	30 V	30 V
Energy resolution (FWHM)	20~30 keV	~50 keV	

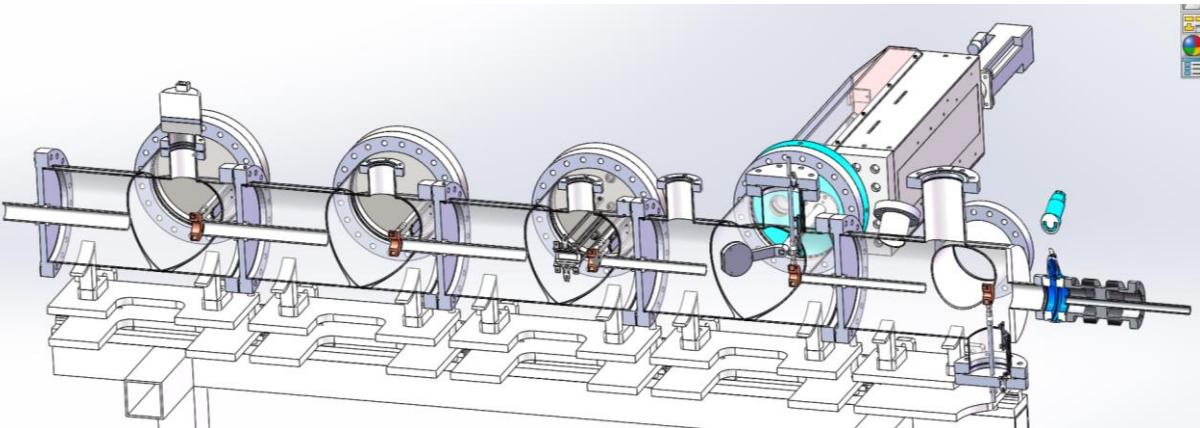
Multi-Wire Proportional Counter (MWPC)

Sensitive area	180×80 mm ²
Working gas	Isobutane
Pressure	~370 Pa
Wire material	Tungsten plated with gold
Diameter of wires	Cathode: 20µm Anode: 15µm
Distance between wires	Cathode: 1 mm Anode: 2 mm
Voltage of anode	+500 V
Voltage of cathode	-150 V

Differential pumping & Rotating target

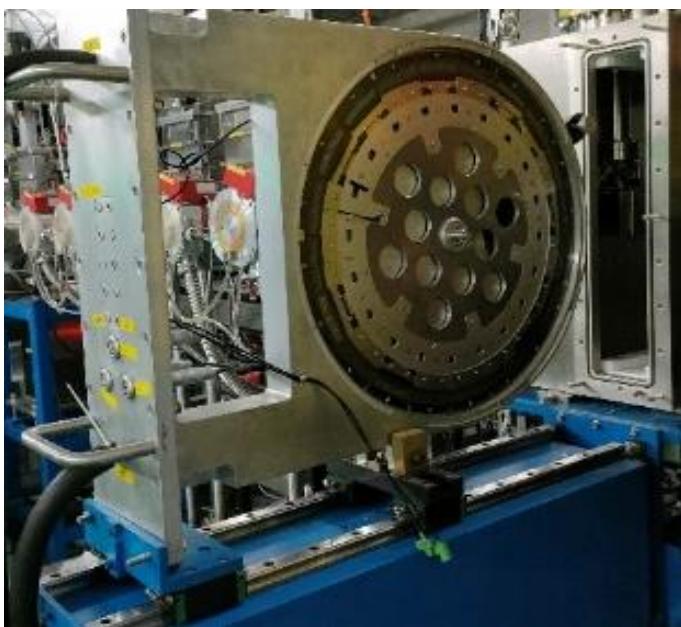
Differential pumping:

- Helium gas filled in separator ($P < 300 \text{ Pa}$)
- High vacuum pressure before differential pumping ($P < 5 \times 10^{-6} \text{ Pa}$)
- Beam diagnosis (HR, BPM, FC, ACCT, BD ...)

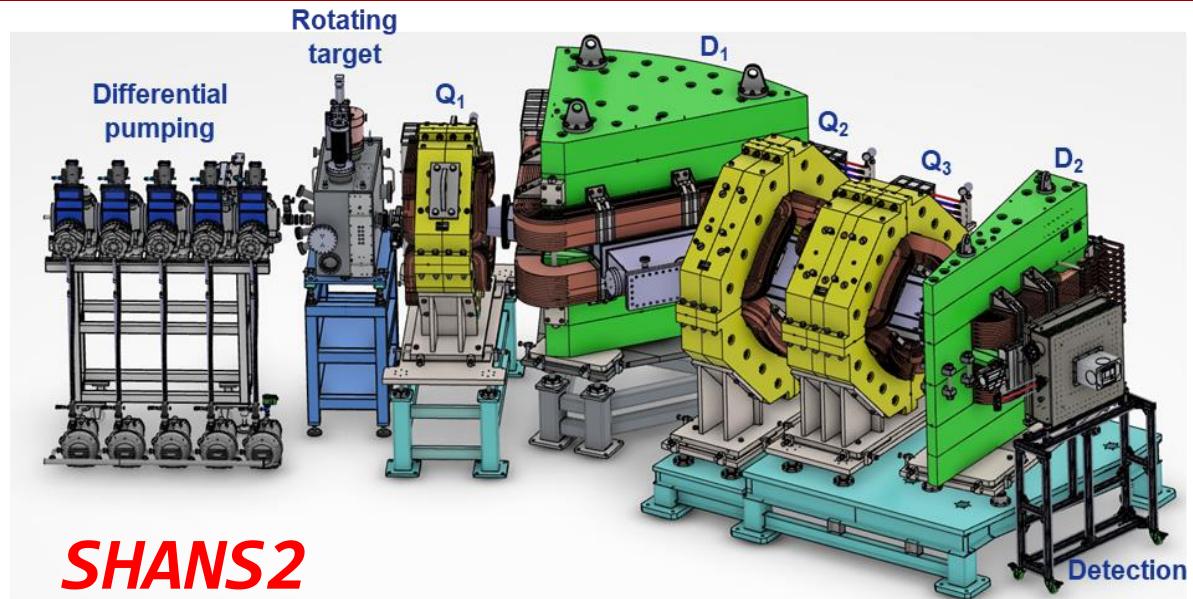


Rotating target:

- Target wheel with a diameter of 50 cm for 20 segments
- ^{175}Lu and ^{169}Tm targets have been used under beams with the intensity up to 3 p μA



New gas-filled separator SHANS2



Nuclear Inst. and Methods in Physics Research, A 1050 (2023) 168113

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

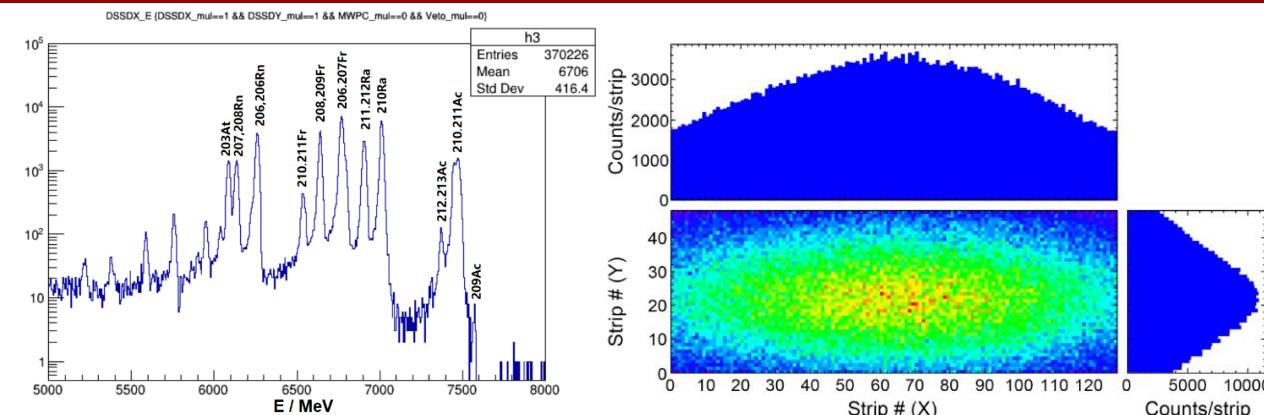
Full Length Article

A gas-filled recoil separator, SHANS2, at the China Accelerator Facility for Superheavy Elements

S.Y. Xu ^{a,b}, Z.Y. Zhang ^{a,b,*}, Z.G. Gan ^{a,b,c}, M.H. Huang ^{a,b}, L. Ma ^a, J.G. Wang ^a, M.M. Zhang ^a, H.B. Yang ^a, C.L. Yang ^a, Z. Zhao ^{a,b}, X.Y. Huang ^{a,b}, L.X. Chen ^{a,d}, X.J. Wen ^{a,d}, H. Zhou ^{a,b}, H. Jia ^a, L.N. Sheng ^a, J.Q. Wu ^a, X.L. Peng ^a, Q. Hu ^a, J. Yang ^a, Q.G. Yao ^{a,b}, Y.S. Qin ^a, H.H. Yan ^a, Z. Chai ^{a,b}, J.C. Zhang ^a, Y. Zhang ^a, Z. Du ^a, H.M. Xie ^a, B. Zhao ^a, G.Z. Sun ^a, F.F. Wang ^a, C.Z. Yuan ^a, X.L. Wu ^a, R.F. Chen ^a, H.B. Zhang ^a, Z.W. Lu ^a, H.R. Yang ^a, X.X. Xu ^a, Y.X. Chen ^a, A.H. Feng ^a, P. Sun ^a, J.K. Xu ^a, Y. He ^{a,b,c}, L.T. Sun ^{a,b}, X.H. Zhou ^{a,b}, H.S. Xu ^{a,b,c}, V.K. Utyonkov ^e, A.A. Voinov ^e, Yu.S. Tsyganov ^e, A.N. Polyakov ^e, D.I. Solovyev ^e



Preliminary test experiments

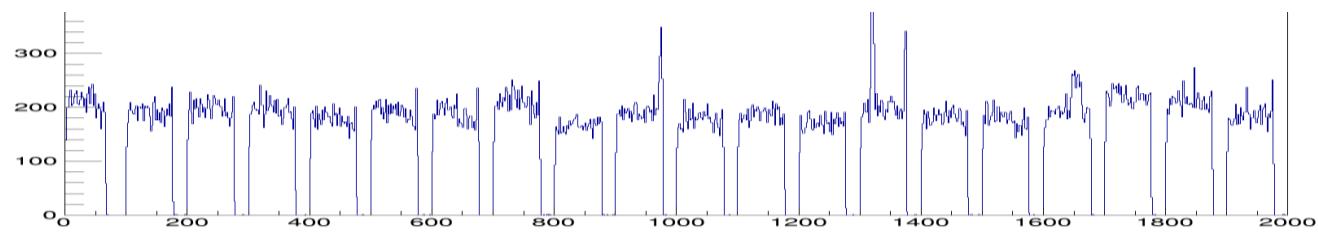
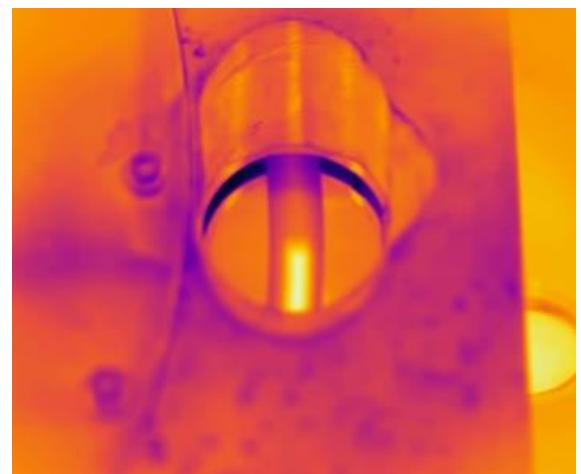


- Tests by combining the accelerator and the separator
- Tests for the performance of the separator, the detectors, and DAQ
- A few experiments for Ac and Pa new isotopes were performed

Experiments with beams (^{40}Ar , ^{40}Ca , ^{55}Mn) have been performed with the maximum intensity of 3 p μ A

- SS003: $^{40}\text{Ar} + ^{175}\text{Lu}$ @193 MeV
- SS004: $^{40}\text{Ar} + ^{169}\text{Tm}$ @179 / 193 MeV
- SS005: $^{40}\text{Ca} + ^{169}\text{Tm}$ @200 / 217 MeV
- SS006: $^{55}\text{Mn} + ^{159}\text{Tb}$ @257 MeV, $^{55}\text{Mn} + ^{209}\text{Bi}$ @270 MeV
- SS007: $^{40}\text{Ca} + ^{169}\text{Tm}$ @200 / 227 / 212 MeV, $^{40}\text{Ca} + ^{175}\text{Lu}$ @228 MeV

2022.01-2022.07



New isotope ^{204}Ac at SHANS and SHANS2

Physics Letters B 834 (2022) 137484



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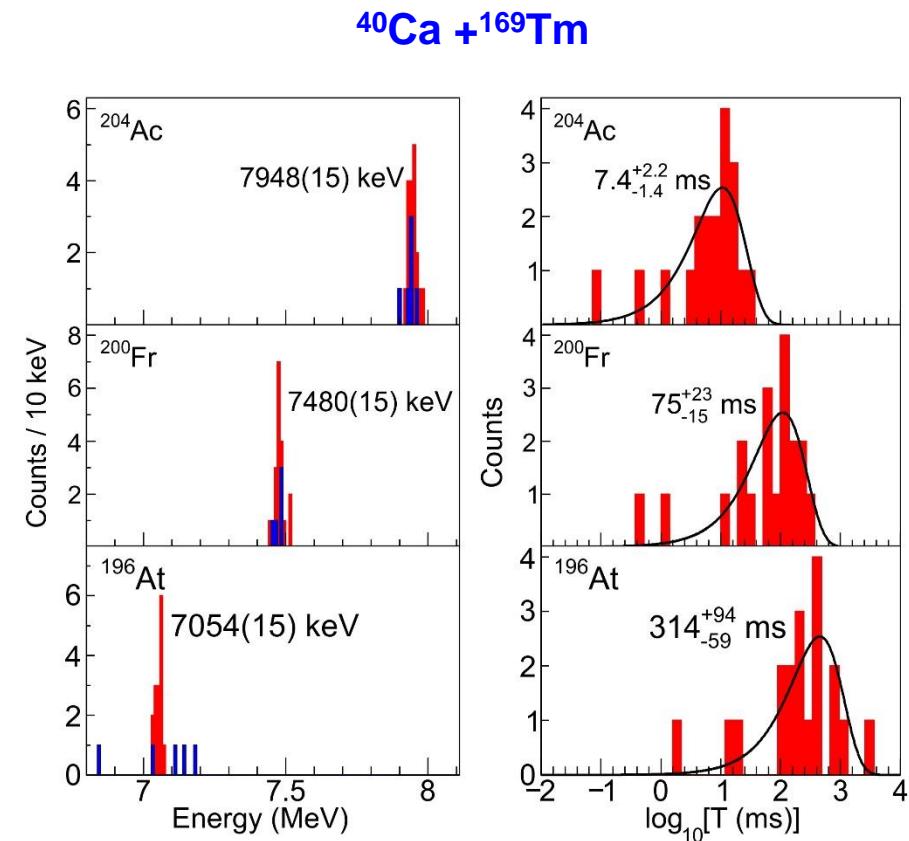
α decay of the new isotope ^{204}Ac

M.H. Huang ^{a,b}, Z.G. Gan ^{a,b,c,*}, Z.Y. Zhang ^{a,b}, L. Ma ^a, J.G. Wang ^a, M.M. Zhang ^a, H.B. Yang ^a, C.L. Yang ^a, X.Y. Huang ^{a,b}, Z. Zhao ^{a,b}, S.Y. Xu ^{a,b}, L.X. Chen ^{d,a}, X.J. Wen ^d, Y.F. Niu ^e, C.X. Yuan ^f, Y.L. Tian ^{a,c}, Y.S. Wang ^{a,b}, J.Y. Wang ^a, M.L. Liu ^a, Y.H. Qiang ^a, W.Q. Yang ^a, H.B. Zhang ^a, Z.W. Lu ^a, S. Guo ^{a,b}, W.X. Huang ^{a,b}, Y. He ^a, Z.Z. Ren ^g, S.G. Zhou ^{h,i}, X.H. Zhou ^{a,b}, H.S. Xu ^{a,b}, V.K. Utyonkov ^j, A.A. Voinov ^j, Yu.S. Tsyganov ^j, A.N. Polyakov ^j

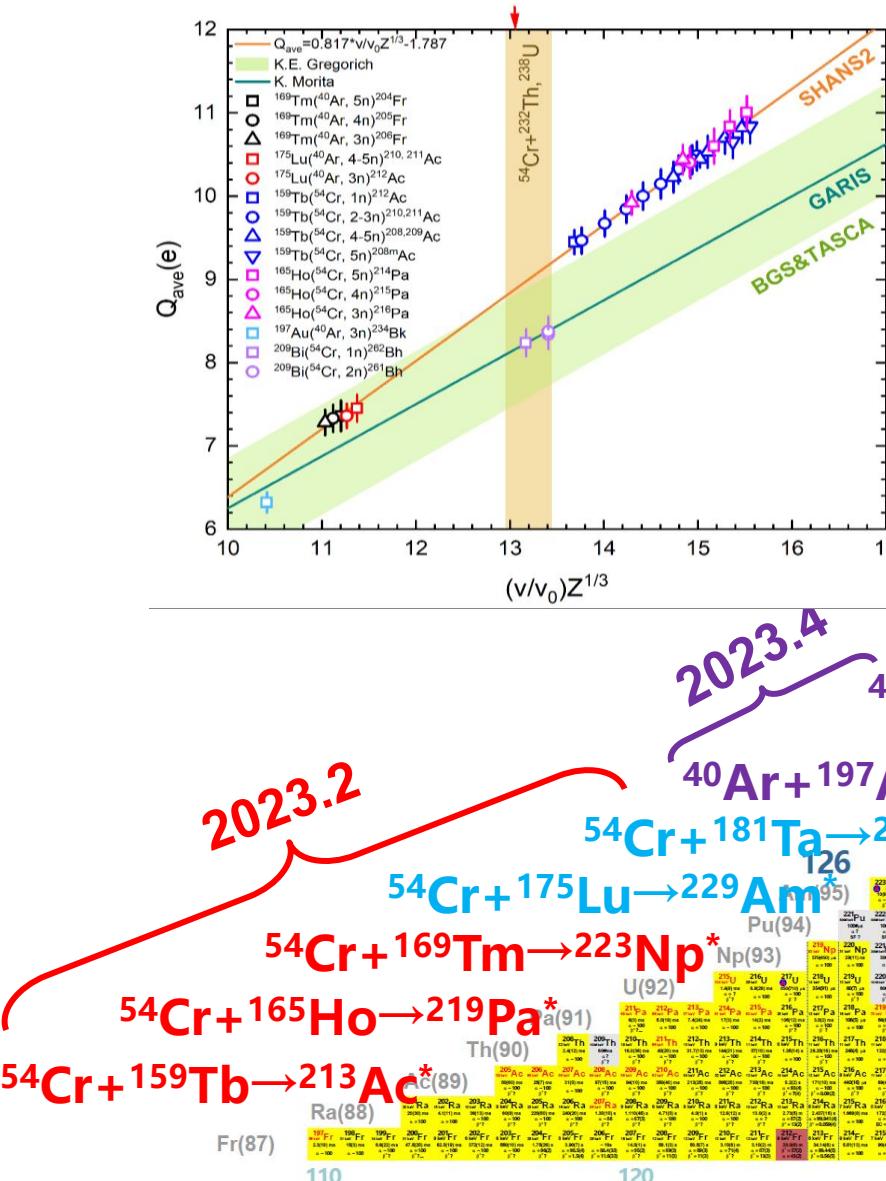


E_b^{Lab} (MeV)	I_b (μA)	t (h)	d_{Tm}/d_C ($\mu\text{g/cm}^2$)	GFRS	Acc.	n	σ_{ER} (pb)
200	1.98	111	450/60	SHANS2	CAFE2	11	$6.5^{+2.9}_{-2.0}$
210	0.18	321	400/40	SHANS	HIRFL	3	24^{+23}_{-16}
212	0.21	145	450/60	SHANS	HIRFL	4	61^{+50}_{-37}
214	0.21	112	450/60	SHANS	HIRFL	1	20^{+47}_{-18}

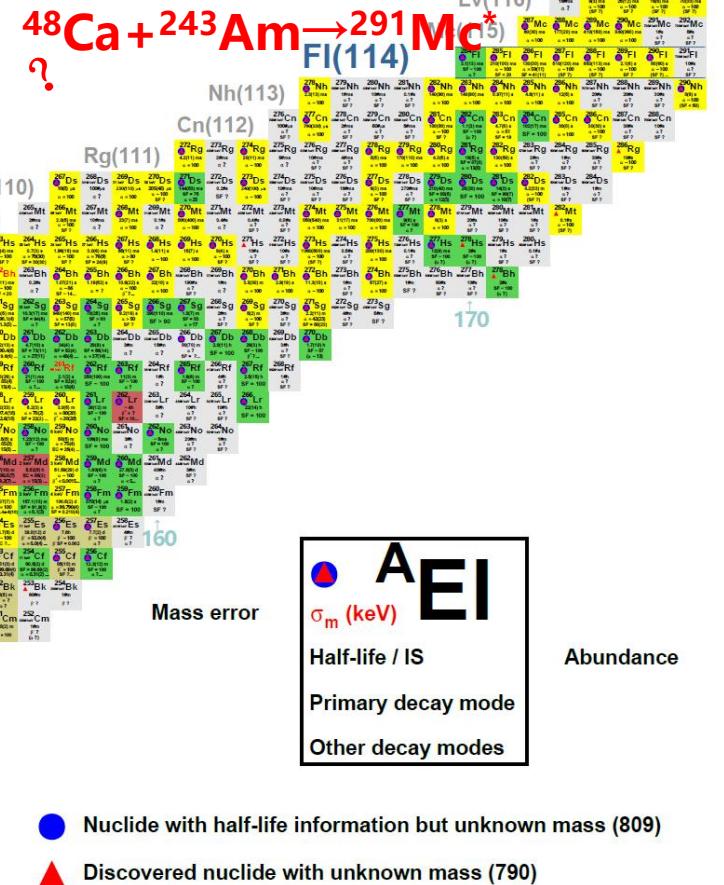
- One order of increase for beam intensity
- 2~3 times higher for transmission
- Better energy and position resolution



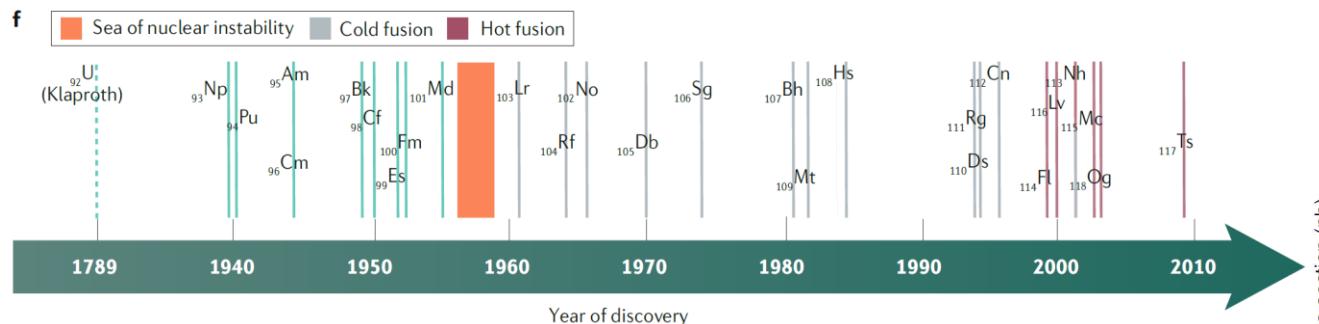
Experiments in 2023



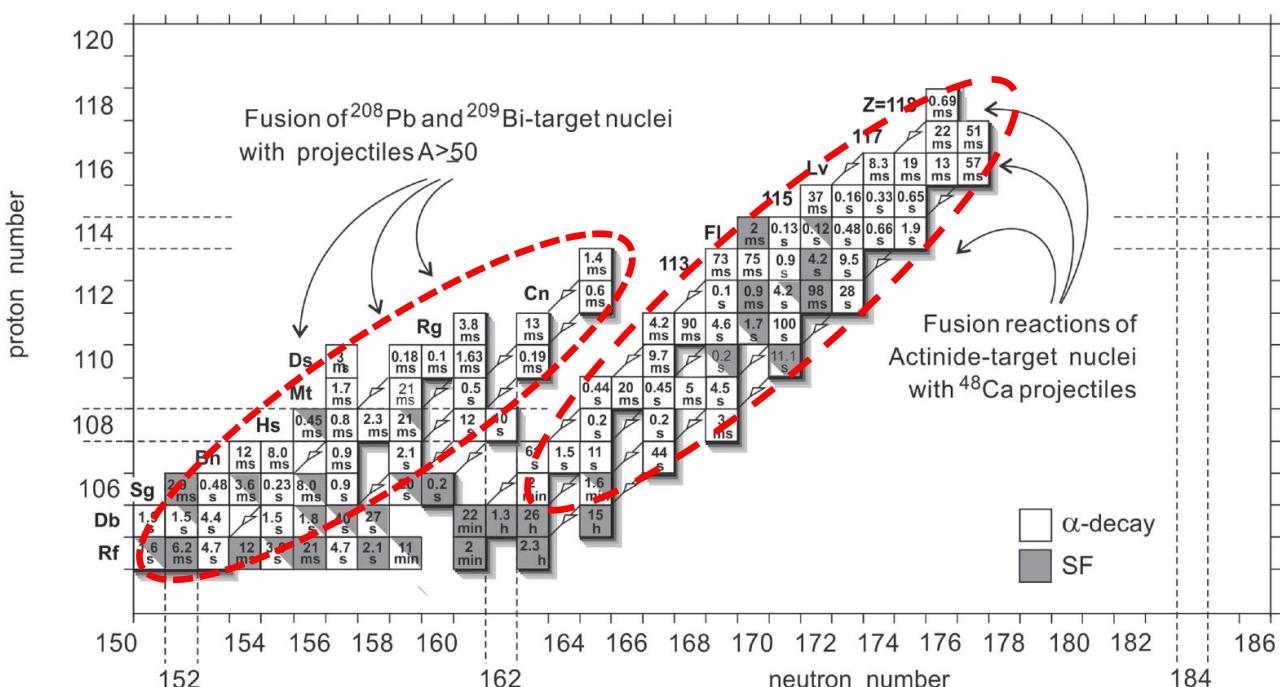
Equilibrium charge state
magnetic rigidity
Cross section



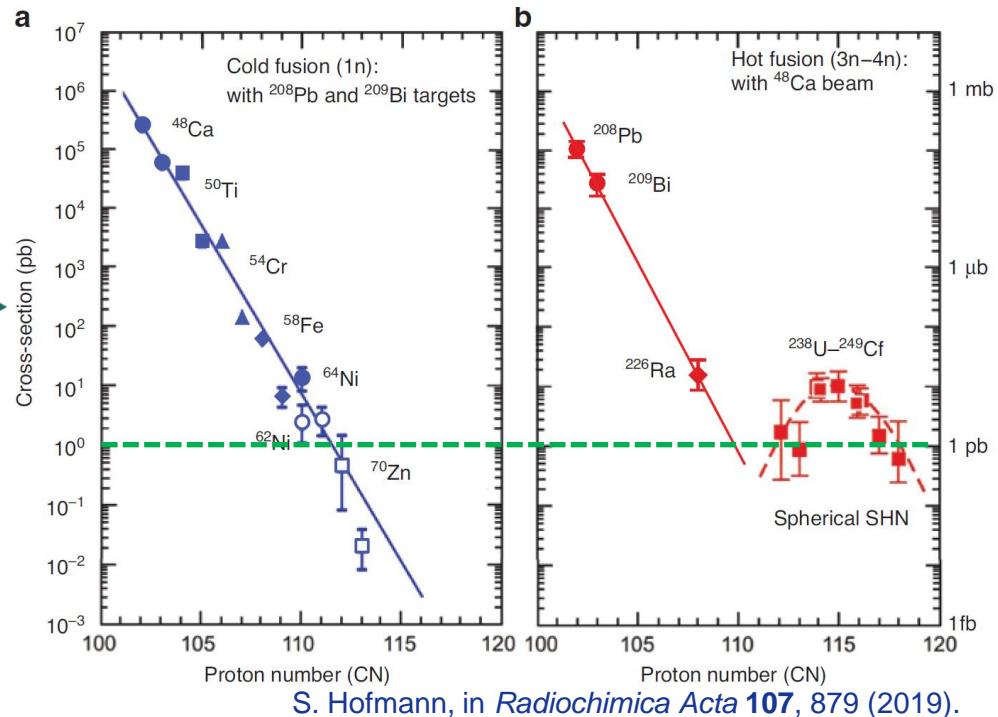
SHE (future) ?



P. Schwerdtfeger, et al., *Nature Reviews Chemistry* **4**, 359 (2020).



Y. T. Oganessian, et al., *Physica Scripta* **92**, 023003 (2017).



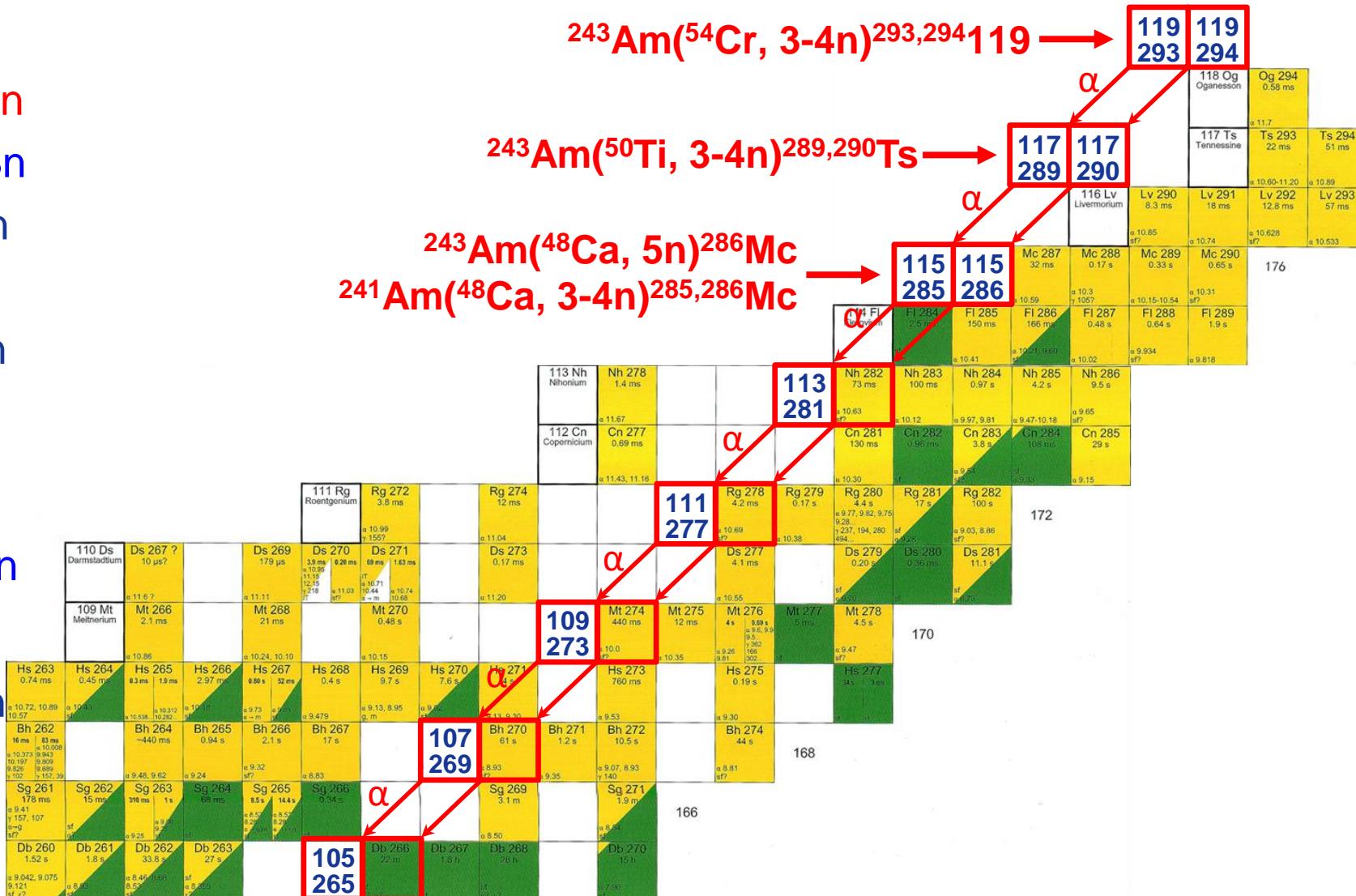
➤ Challenges:

- High beam intensity with Ca~Fe ions (5~10 pμA)
- Long beam time (a few months or years expt.)
- Actinide target material (U, Am, Cm, Cf ...)
- Rotating target withstanding high power beams
- High efficiency separator
- Atom-at-a-time detection and DAQ

SHE (future) ?

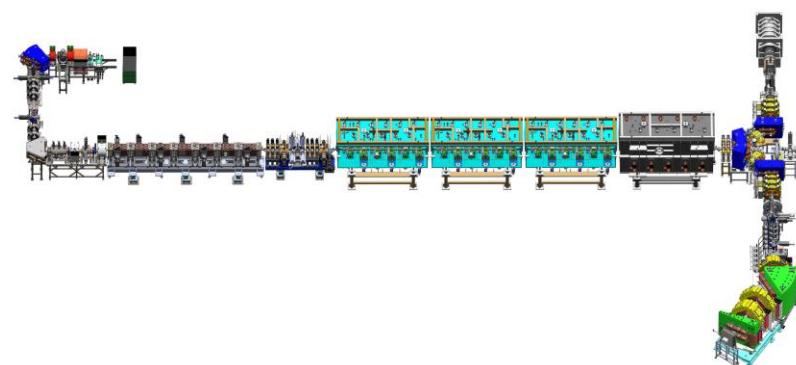
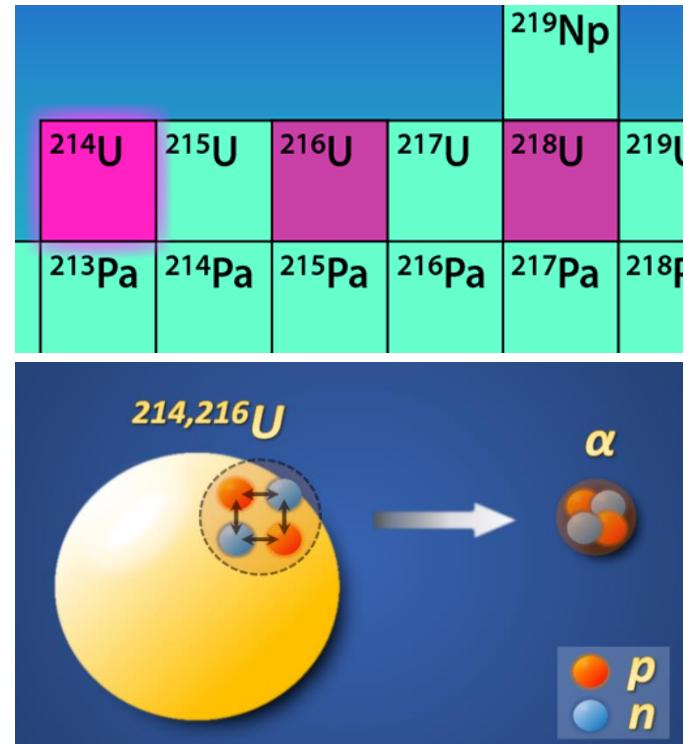
- ❖ 119
- ❖ $^{54}\text{Cr} + ^{243}\text{Am} \rightarrow ^{297}\text{119}^* \rightarrow ^{294}\text{119} + 3\text{n}$
- ❖ $^{55}\text{Mn} + ^{244}\text{Pu} \rightarrow ^{299}\text{119}^* \rightarrow ^{296}\text{119} + 3\text{n}$
- ❖ $^{51}\text{V} + ^{248}\text{Cm} \rightarrow ^{299}\text{119}^* \rightarrow ^{296}\text{119} + 3\text{n}$
- ❖ $^{50}\text{Ti} + ^{249}\text{Bk} \rightarrow ^{299}\text{119}^* \rightarrow ^{296}\text{119} + 3\text{n}$
- ❖ $^{45}\text{Sc} + ^{249}\text{Cf} \rightarrow ^{294}\text{119}^* \rightarrow ^{291}\text{119} + 3\text{n}$

- 120
- $^{55}\text{Mn} + ^{243}\text{Am} \rightarrow ^{298}\text{120}^* \rightarrow ^{295}\text{120} + 3\text{n}$
- $^{58}\text{Fe} + ^{244}\text{Pu} \rightarrow ^{302}\text{120}^* \rightarrow ^{299}\text{120} + 3\text{n}$
- $^{54}\text{Cr} + ^{248}\text{Cm} \rightarrow ^{302}\text{120}^* \rightarrow ^{299}\text{120} + 3\text{n}$
- $^{50}\text{Ti} + ^{249}\text{Cf} \rightarrow ^{299}\text{120}^* \rightarrow ^{296}\text{120} + 3\text{n}$



Summary

- ❖ More than ten new isotopes near the heaviest proton drip line were synthesized successfully at SHANS
- ❖ CAFE2 project with a new gas-filled recoil separator SHANS2 is carrying out at IMP for the study of SHE.
- ❖ The experiment for element 115 with $^{48}\text{Ca} + ^{243}\text{Am}$ reaction will be performed in next year.





Collaboration



**7TH INTERNATIONAL CONFERENCE
ON THE CHEMISTRY AND PHYSICS
OF THE TRANSACTINIDE ELEMENTS**

Huizhou, China
November 12-17, 2023

Topics

- Theories and experiments of heaviest-element synthesis
- Nuclear reaction studies
- Nuclear structure and spectroscopy
- Atomic physics studies
- Chemical properties of transactinide elements
- Technical developments
- Large-scale facilities in the field of superheavy element research

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Thank you for all your attention!