中國科學院
CHINESE ACADEMY OF SCIENCES

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New uranium isotope discovered at SHANS and CAFE2 project in Lanzhou

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REC SEP @ SHE CHEM
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18th Workshop on
Recoil Separator for Superheavy Element Chemistry

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Heavy Ion Research Facility in Lanzhou (HIRFL)

Terminal Right-2

SHANS

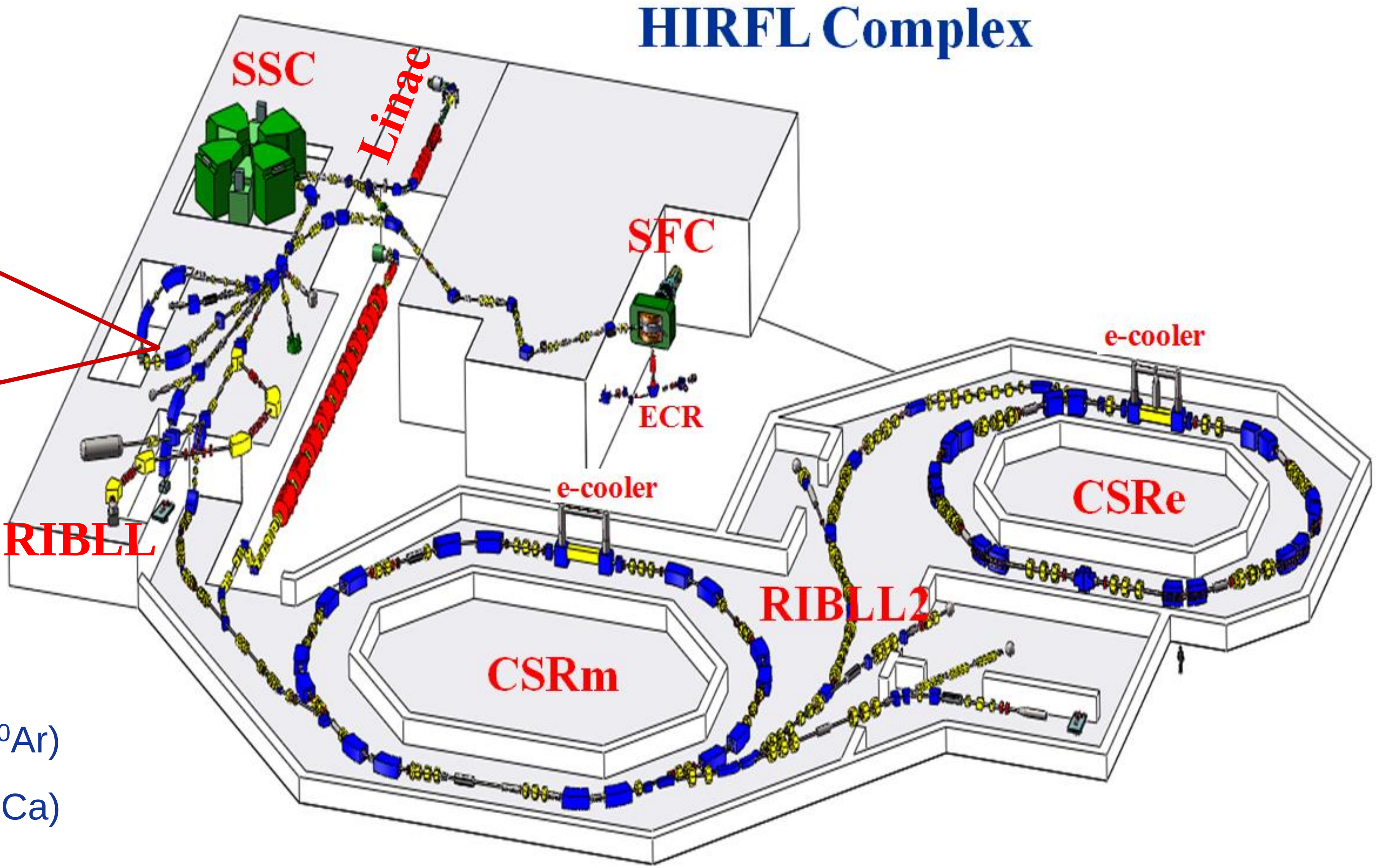
Mode: ECR/SECR + SFC

Ions: Ar, Ca, Ne, Mg, Ni, Kr, …

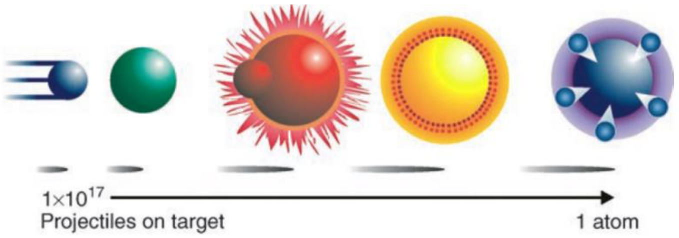
Energy: ~ 5 MeV/u

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

200~500 pnA (^{40}Ca)



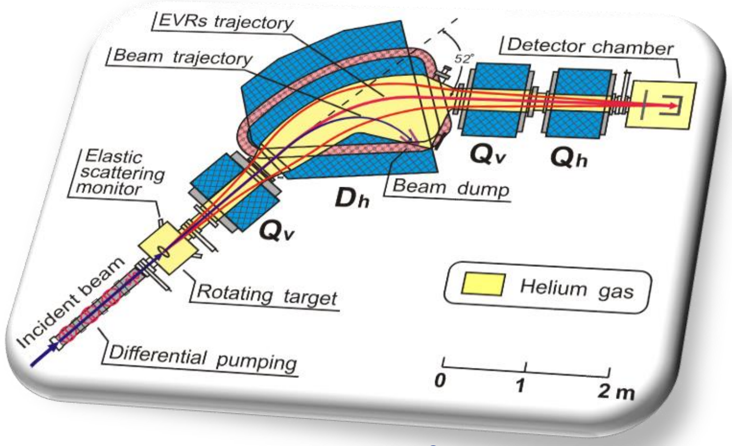
Status of SHANS



Production

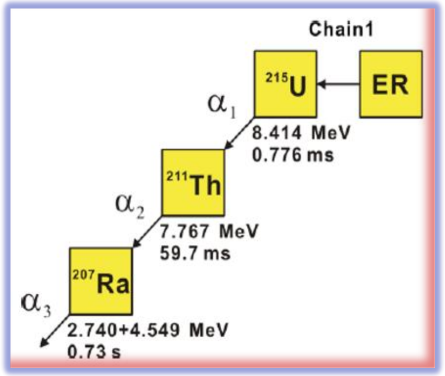
Fusion-evaporation reaction
- Beam energy: ~5 MeV/u
- Exc. Energy of CN: 20~50 MeV
- Deexcitation: 3~5 *n* or *p* evaporation

Experimental Method

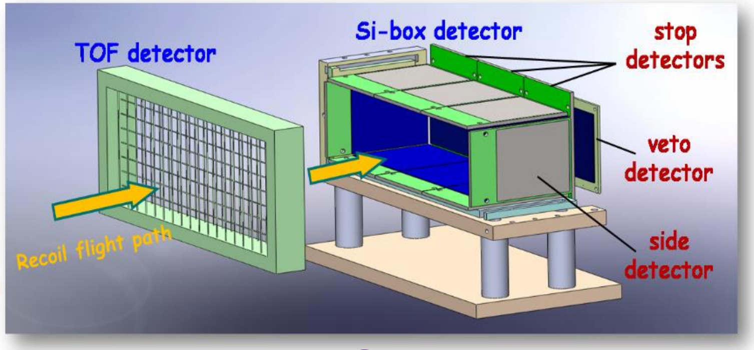


Separation

Gas-filled recoil separator:
- Flight time: ~1 us
- Transmission: >10%
- Filling gas: Helium (~100 Pa)

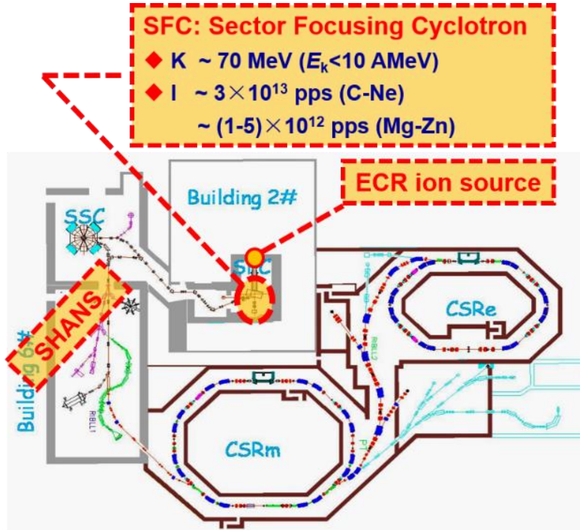


ER-α-α correlation

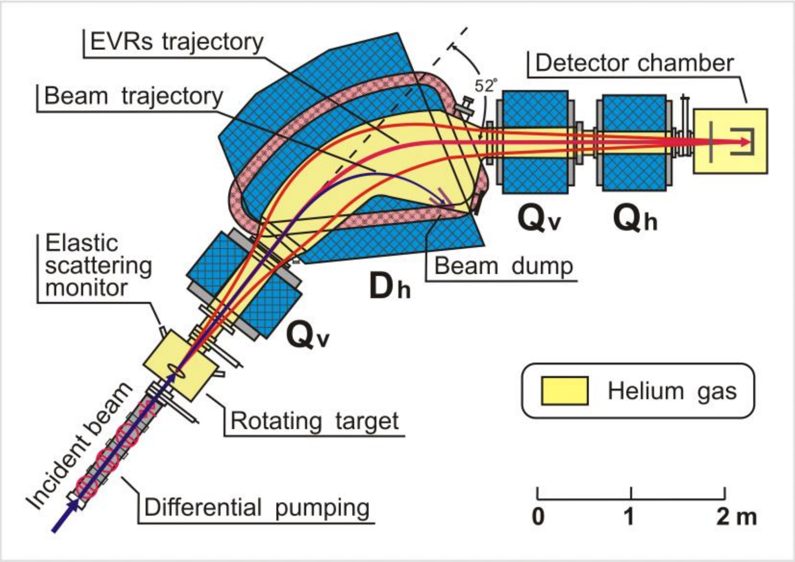


Identification

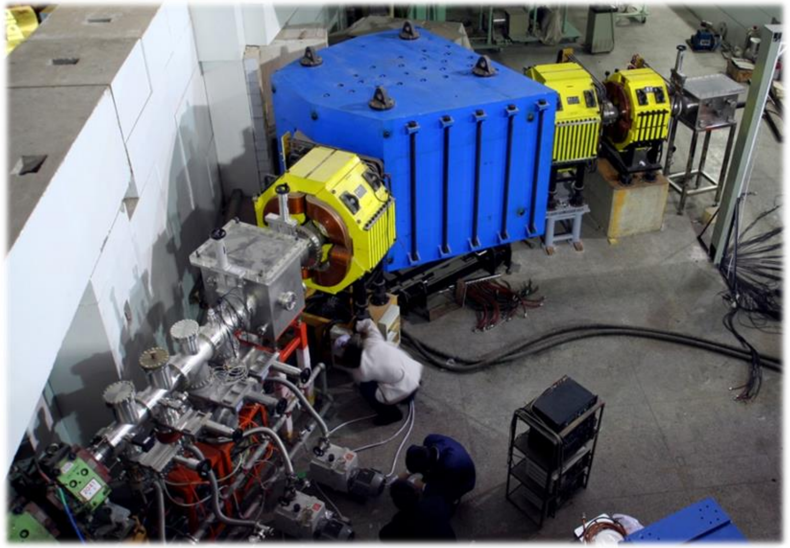
Gas-filled recoil separator - SHANS



HIRFL @ Lanzhou



SHANS



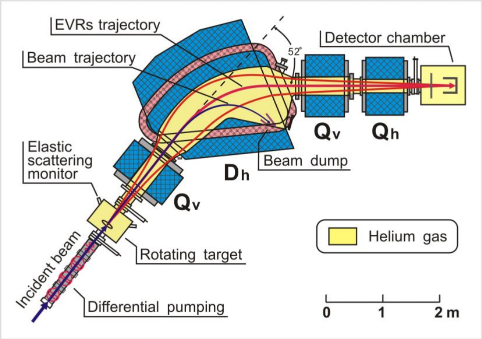
Technical parameters of the gas-filled separator.

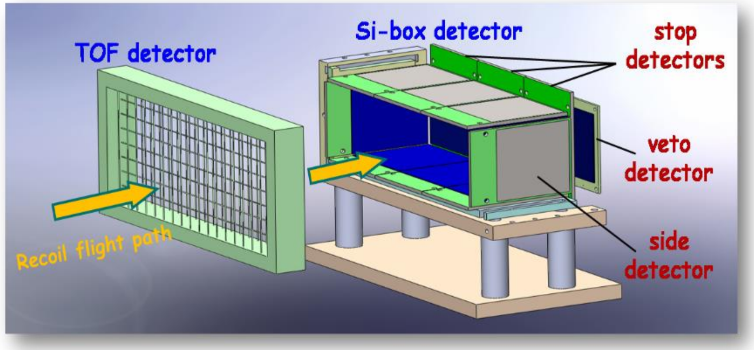
Parameters	Values
Configuration	$Q_v D_h Q_v Q_h$
Total length	6.5 m
Angular acceptance	25 msr
Dispersion	7.3 mm/%$B\rho$
D_h magnet	
Bending radius	1.8 m
Central trajectory length	1.6 m
Bending angle	52°
Maximum magnetic rigidity	2.9 Tm
Entrance angle	−45°
Exit angle	22°
Q_v magnets	
Effective length	667 mm
Aperture radius	120 mm
Maximum field gradient	6.8 T/m
Q_h magnet	
Effective length	500 mm
Aperture radius	85 mm
Maximum field gradient	8.9 T/m

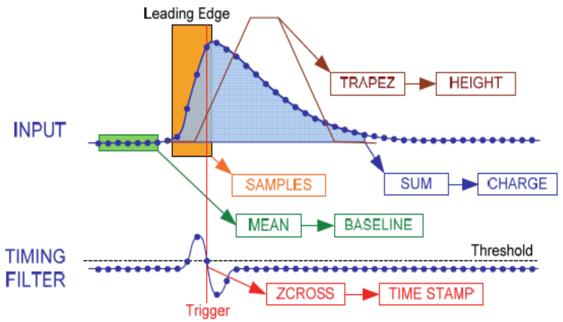
Spectrometer for Heavy Atoms and Nuclear Structure (SHANS)

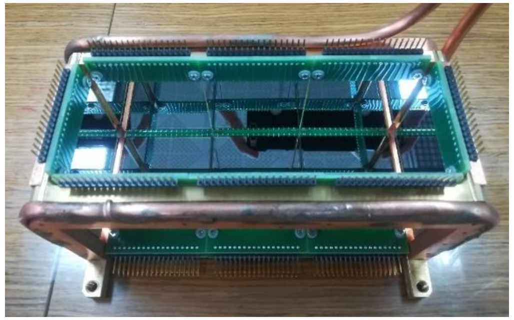
Z. Y. Zhang, *et al.*, Nucl. Instrum. Methods Phys. Res., B 317, 315 (2013).

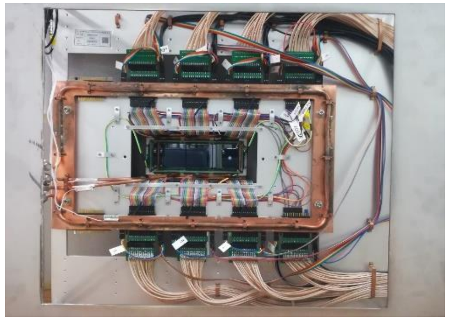
Detection System and Digital Electronics











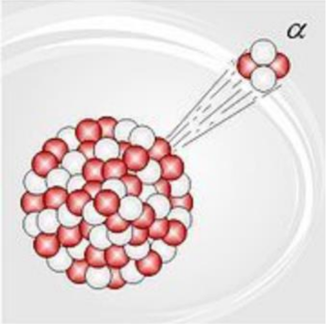
- Energy-time-position correlation measurement (ER-α-α decay chain)
  - **MWPC, Si-box detector (15 x 5 cm^2, 72% eff. and 35-keV FWHM for α's)**
- Digital data acquisition electronics
  - **100 MHz sampling rate, 14 bit digital res., max. 80 MB/s data rate**
- Digital pulse processing technique
  -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

Contents

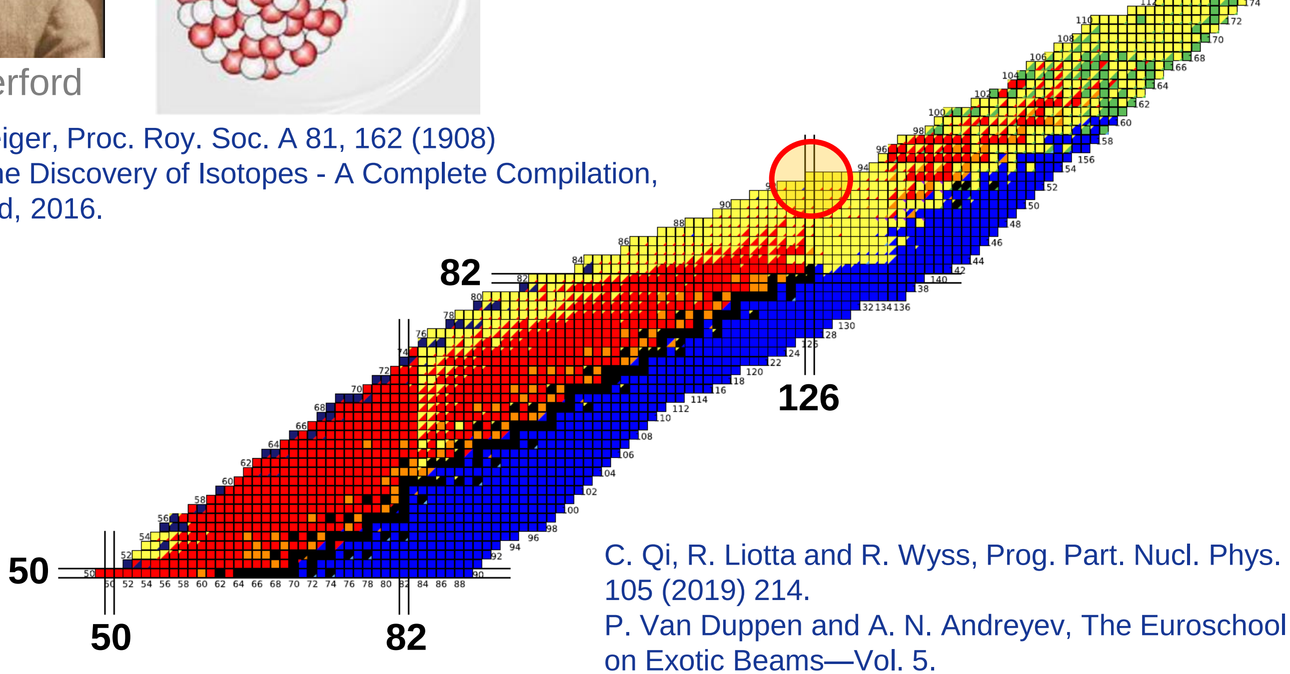
Motivation – α decay

- Search for new U and Np isotopes near the heaviest proton drip line
- Study the α-decay properties for unknown nuclides far from stability
- Investigate the structure evolution near the *N*=126 shell closure

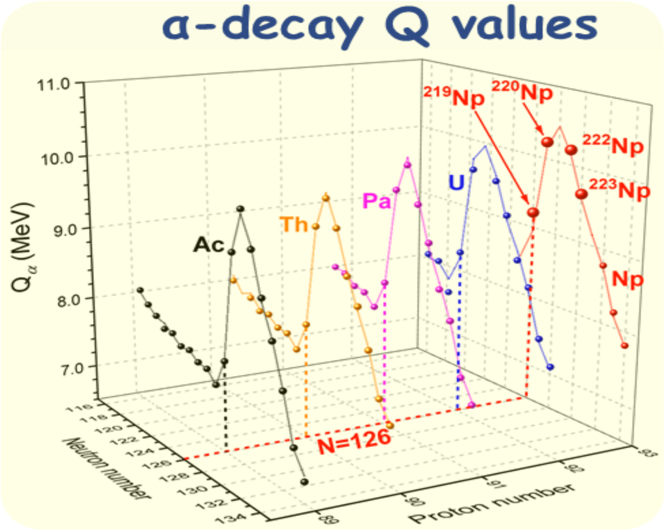
Ernest Rutherford

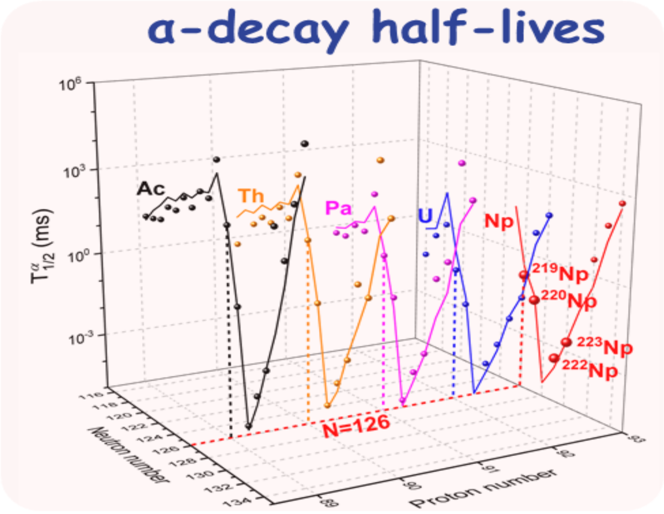


E. Rutherford, H. Geiger, Proc. Roy. Soc. A 81, 162 (1908)
M. Thoennessen, The Discovery of Isotopes - A Complete Compilation, Springer, Switzerland, 2016.



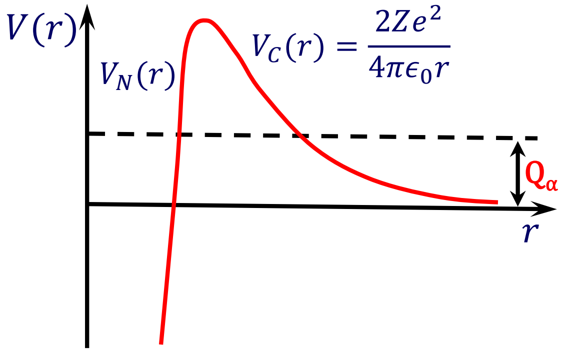
C. Qi, R. Liotta and R. Wyss, Prog. Part. Nucl. Phys. 105 (2019) 214.
P. Van Duppen and A. N. Andreyev, The Euroschool on Exotic Beams—Vol. 5.



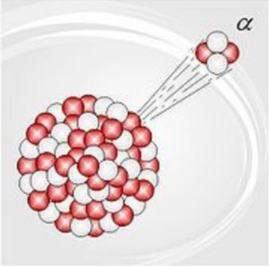


Z. Y. Zhang, *et al.*, Phys. Rev. Lett. 122, 192503 (2019)
L. Ma, *et al.*, Phys. Rev. Lett. 125, 032502 (2020).

Motivation – α-decay reduced width (δ^2)



G. Gamow, Z. Phys. 51 (1928) 204.

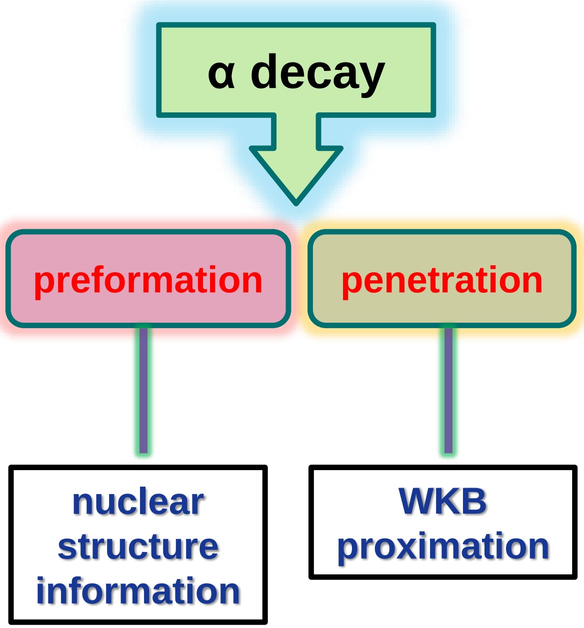


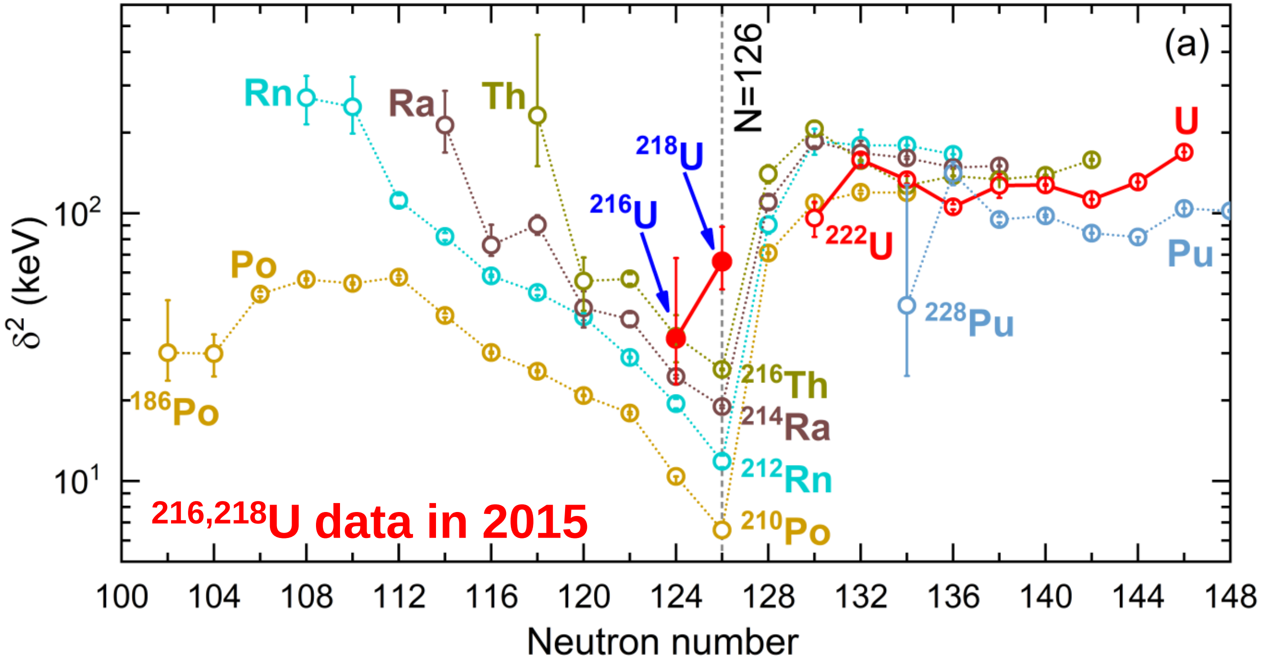
$$\lambda = \delta^2 \cdot P/h$$

decay constant — reduced decay width (preformation probability) — penetrability

$$P = \exp\left[-2 \cdot \int_{R_i}^{R_0} \frac{\sqrt{2M}}{\hbar} \sqrt{V_N(r) + V_c(r) + V_{cent}(r) - E}\, dr\right]$$ (WKB proximation)

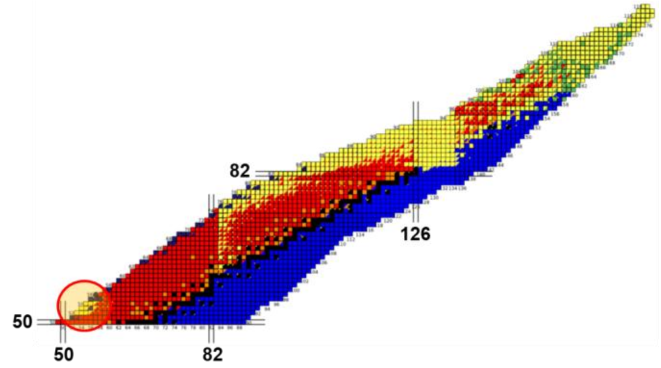
J. O. Rasmussen, Phys. Rev. 113, 1593 (1959).





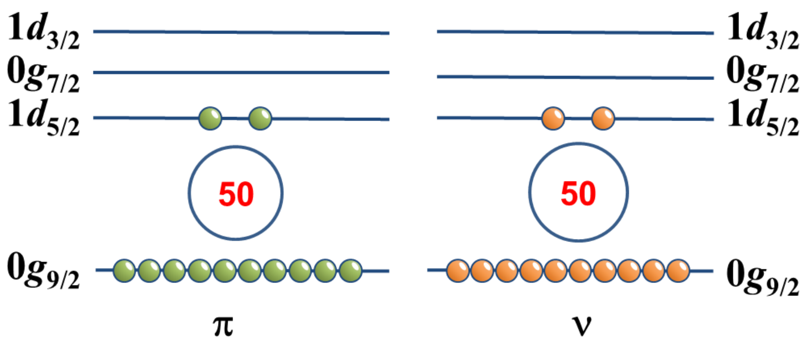
L. Ma, Z. Zhang, et al, Phys. Rev. C 91, 051302 (2015)

Motivation – superallowed α decay



C. Qi, R. Liotta and R. Wyss, Progress in Particle and Nuclear Physics 105 (2019) 214–251

$^{104}_{52}\mathrm{Te}_{52}$



Near ^{100}Sn, valence protons and neutrons occupy same orbitals, resulting in stronger proton-neutron interactions

^{104}Te → ^{100}Sn decay is of particular interest because enhanced proton-neutron interactions could result in an unusually large preformation factor.

Chain	Nuclide	E_α (keV)	$T_{1/2}$	b_α (%)	W_α
$N = Z$	^{108}Xe	4400(200)	58^{+106}_{-23} μs	100[a]	~3.7[b]
$N = Z$	^{104}Te	4900(200)	<18 ns	100[a]	$\gtrsim$13.1[c]
$N = Z + 2$	^{114}Ba	3480(20) [17]	380^{+190}_{-110} ms [17]	0.9(3) [35]	6^{+4}_{-3} [17]
$N = Z + 2$	^{110}Xe	3720(20) [17]	95^{+25}_{-20} ms [17]	64(35) [35]	$2.4^{+1.5}_{-1.6}$ [16]
$N = Z + 2$	^{106}Te	4128(9) [36]	70^{+20}_{-15} μs [17]	100 [35]	$4.4^{+1.2}_{-0.9}$ [17]
$N = Z + 4$	^{112}Xe	3216(7) [36]	2.7(8) s [37]	$0.8^{+1.1}_{-0.5}$ [36]	$3.4^{+4.7}_{-2.5}$ [36]
$N = Z + 4$	^{108}Te	3314(4) [20]	2.1(1) s [37]	49(4) [36]	2.7(3) [36]

$$W_\alpha = \delta^2/\delta^2(^{212}\mathrm{Po})$$

^{108}Xe and ^{104}Te, at least for one of them Wα $\gtrsim$ 5, indicating superallowed character.

K. Auranen, *et al.*, Phys. Rev. Lett. 121, 182501 (2018).

Valence	Nuclide	W_α	Nuclide	W_α	$W_\alpha^{\mathrm{Te}}/W_\alpha^{\mathrm{Po}}$
α	^{104}Te	3[a]	^{212}Po	1.0	3[a]
$\alpha + n$	^{105}Te	2.0 ± 0.3	^{213}Po	0.73 ± 0.14	2.7 ± 0.7
$\alpha + 2n$	^{106}Te	4.63 ± 0.56	^{214}Po	1.53 ± 0.02	3.02 ± 0.37
$\alpha + 3n$	^{107}Te	1.45 ± 0.63	^{215}Po	1.16 ± 0.01	1.25 ± 0.54
$\alpha + 4n$	^{108}Te	2.19 ± 0.27	^{216}Po	1.59 ± 0.01	1.38 ± 0.17

[a]Lower limit; see text for details.

S. N. Liddick, et al., Phys. Rev. Lett. 97, 082501 (2006).

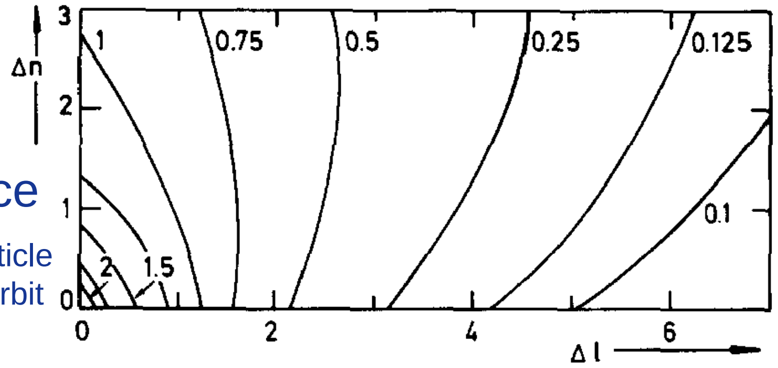
R. D. Macfarlane, et al., Phys. Rev. Lett. 14, 114 (1965).
D. Seweryniak, et al., Phys. Rev. C 73, 061301(R) (2006).
I. G. Darby, et al., Phys. Rev. Lett. 105, 162502 (2010).

Motivation – proton-neutron interaction

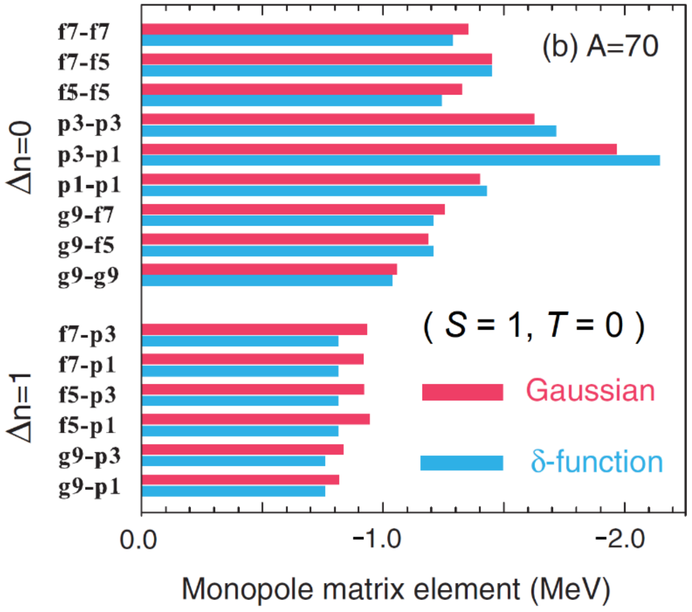
Relative proton and neutron interactions

δ force

One particle in $1s_{1/2}$ orbit



K. Heyde, *et al.*, Nucl. Phys. A 466, 189 (1987).



T. Otsuka, *et al.*, Rev. Mod. Phys. 92, 015002 (2020).

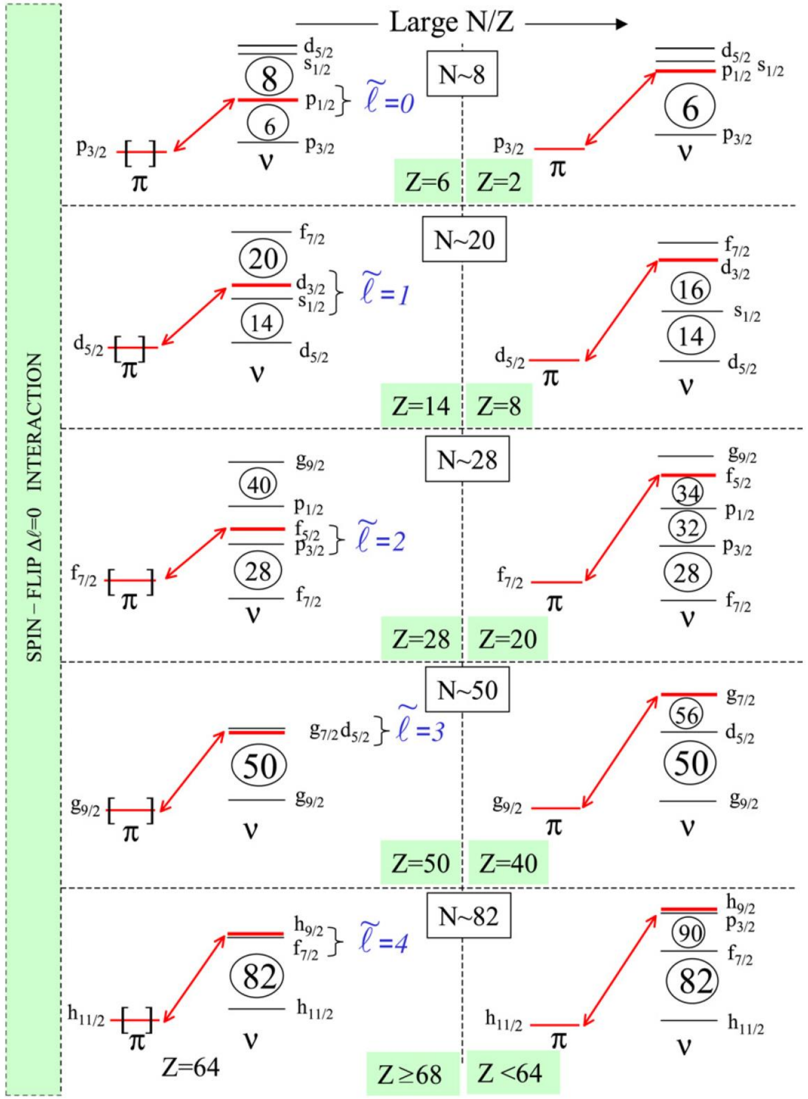
Spin-obit partners ($\Delta n = \Delta l = 0$)

↓

Larger spatial overlap

↓

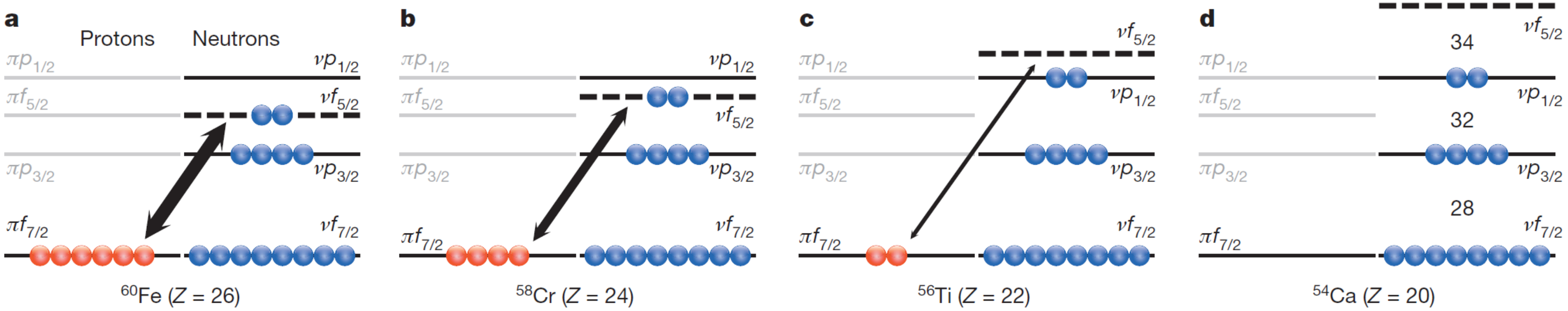
Stronger attractive p-n interaction



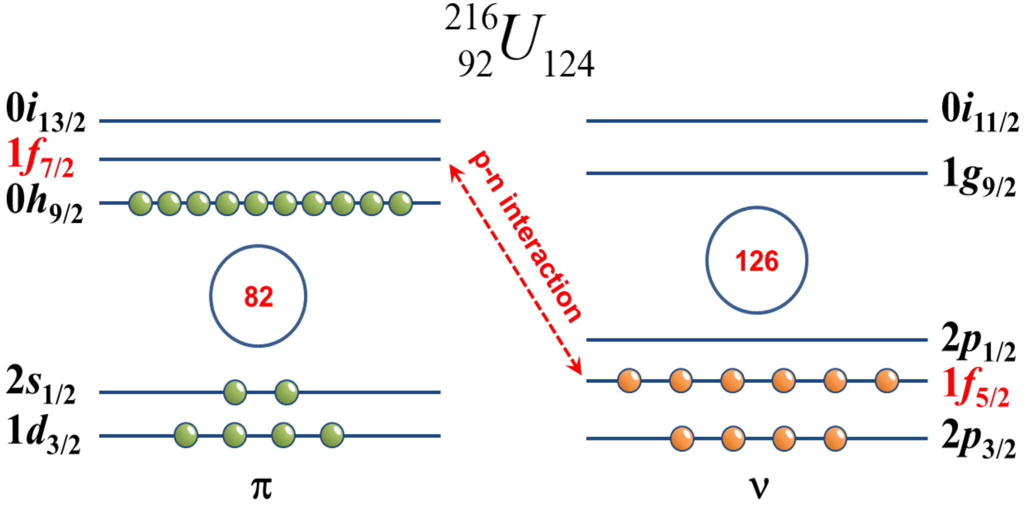
O. Sorlin and M. G. Porquet, Prog. Part. Nucl. Phys. 61, 602 (2008).

Motivation – proton-neutron interaction

^{54}Ca provides evidence for the onset of a new subshell at N=34

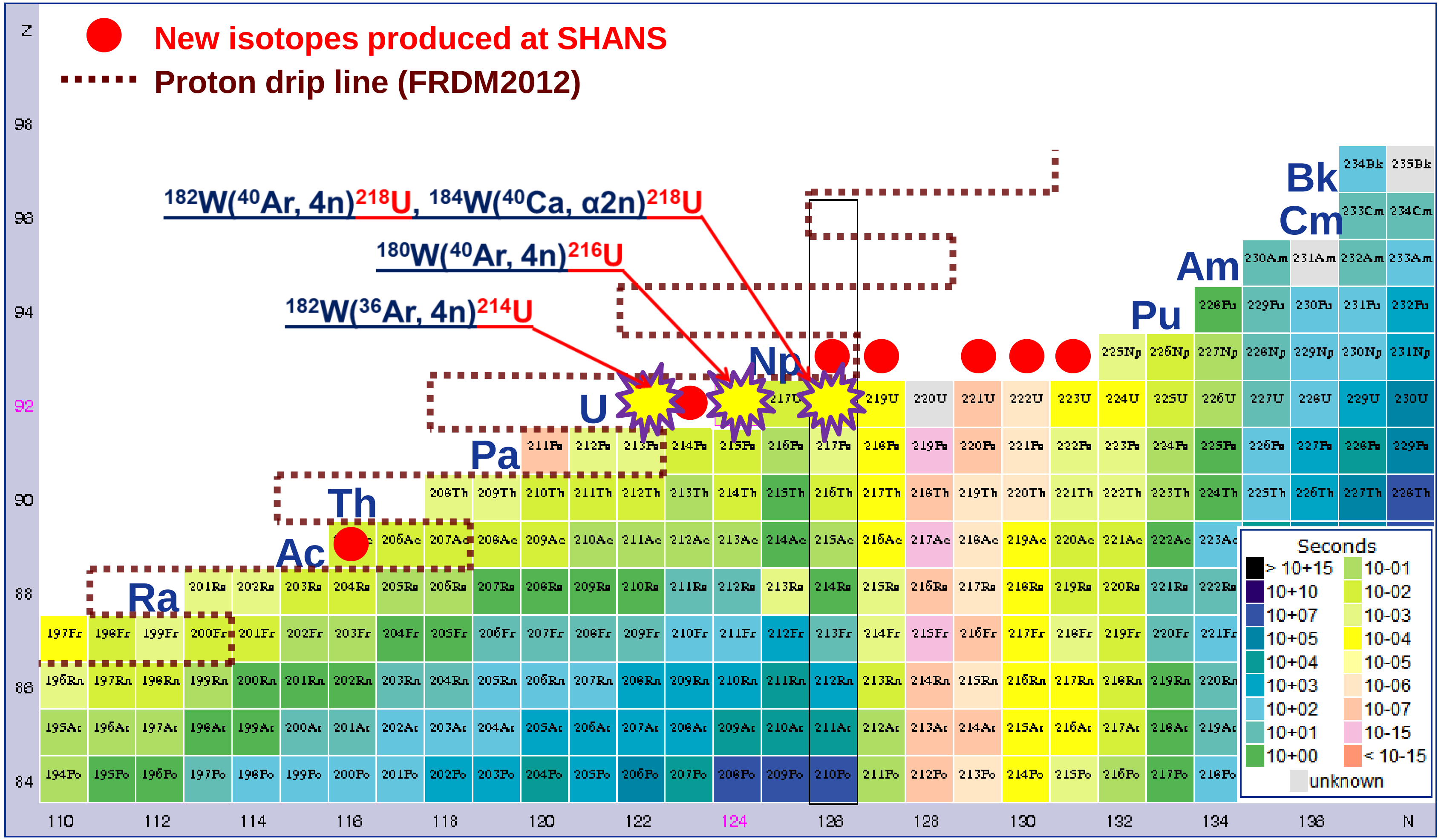


D. Steppenbeck, *et al.*, Nature 502, 207 (2013).
F. Wienholtz, et al., Nature 498, 346 (2013).



Does the p-n interaction between $\pi 1f_{7/2}$ and $\nu 1f_{5/2}$ orbits have a significant impact on nuclear structure evolution or α decay in uranium region?

Lightest uranium isotopes $^{214,216,218}U$



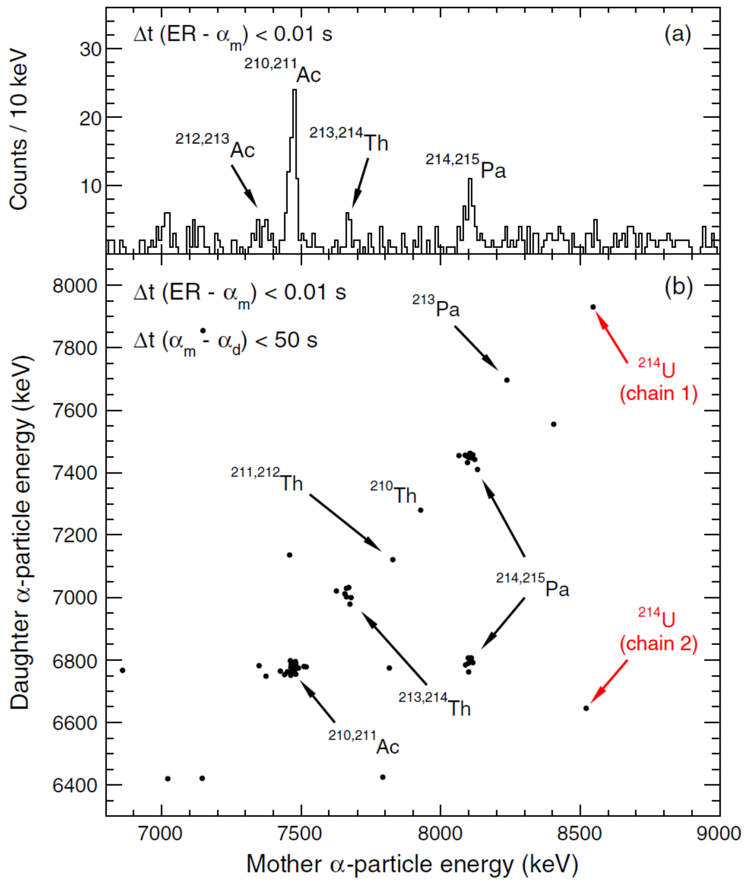
^{205}Ac: PRC 89, 014308 (2014)
^{216}U: PRC 91, 051302 (2015)
^{215}U: EPJA 51, 88 (2015)

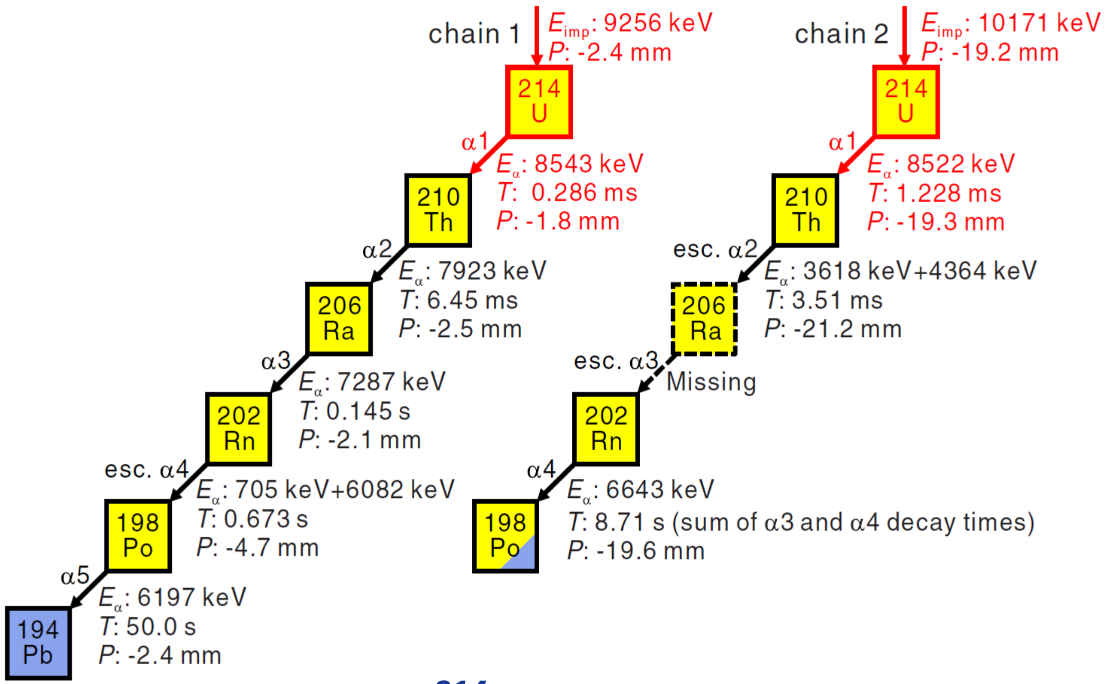
^{223}Np: PLB 771, 303 (2017)
^{219}Np: PLB 777, 212 (2018)
^{224}Np: PRC 98, 044302 (2018)

^{220}Np: PRL 122, 192503 (2019)
^{222}Np: PRL 125, 032502 (2020)
^{214}U: PRL 126, 152502 (2021)

New isotope ^{214}U

^{36}Ar+^{182}W -> ^{214}U+4n @ SHANS – 2 events for ^{214}U (10 pb@184 MeV)





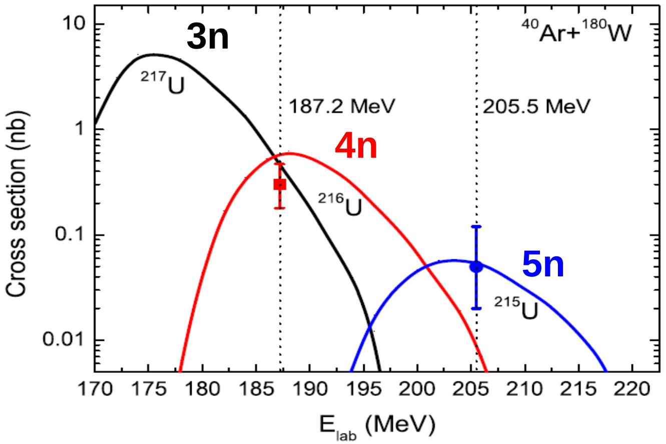
^{214}U:

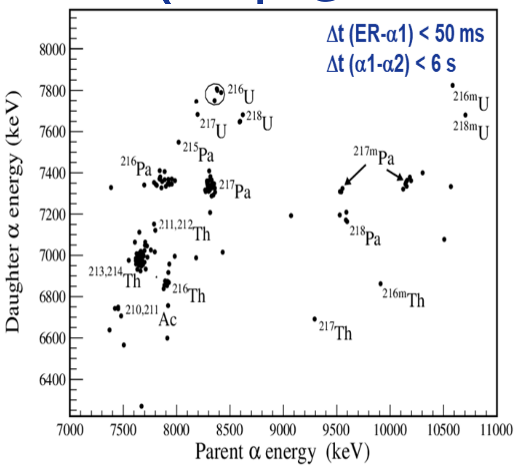
E_α **= 8533(18) keV**

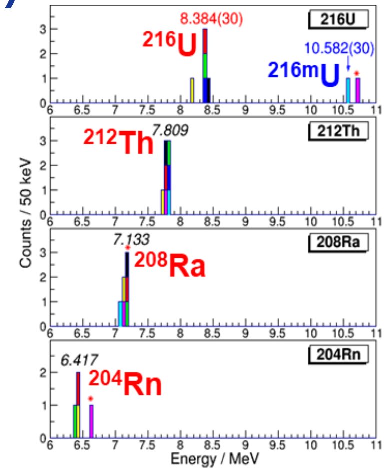
$T_{1/2} = 0.52^{+0.95}_{-0.21}$ **ms**

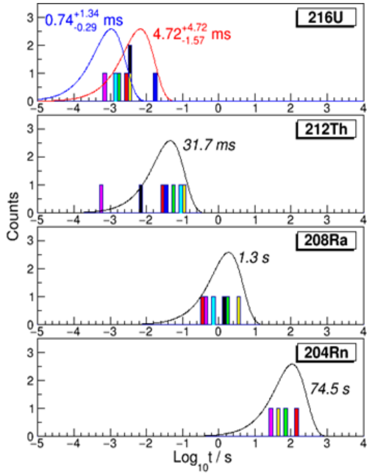
Previous studies on ^{216}U

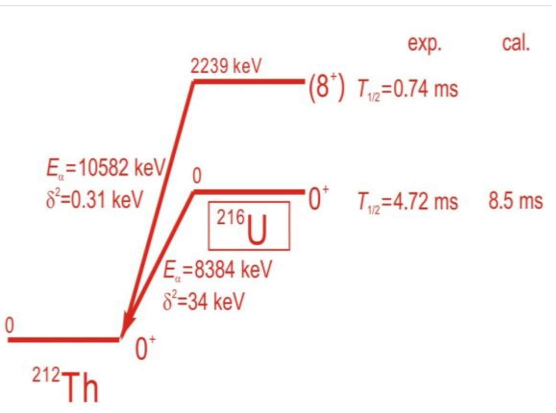
^{40}Ar+^{180}W @ SHANS – 4 events for ^{216g}U (300 pb@190 MeV)





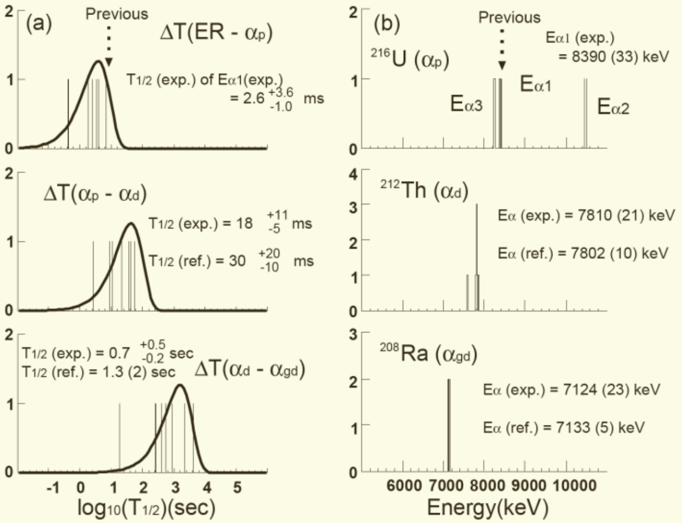






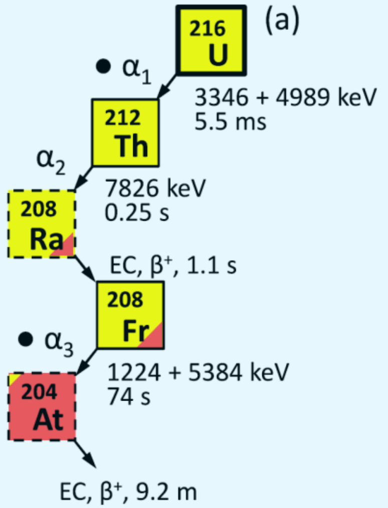
L. Ma, Z. Zhang, et al, Phys. Rev. C 91, 051302 (2015)

^{82}Kr+^{136,137}Ba @ GARIS – 3 events for ^{216g}U



Y. Wakabayashi, et al. RIKEN Accel. Prog. Rep. 48, 70 (2015)

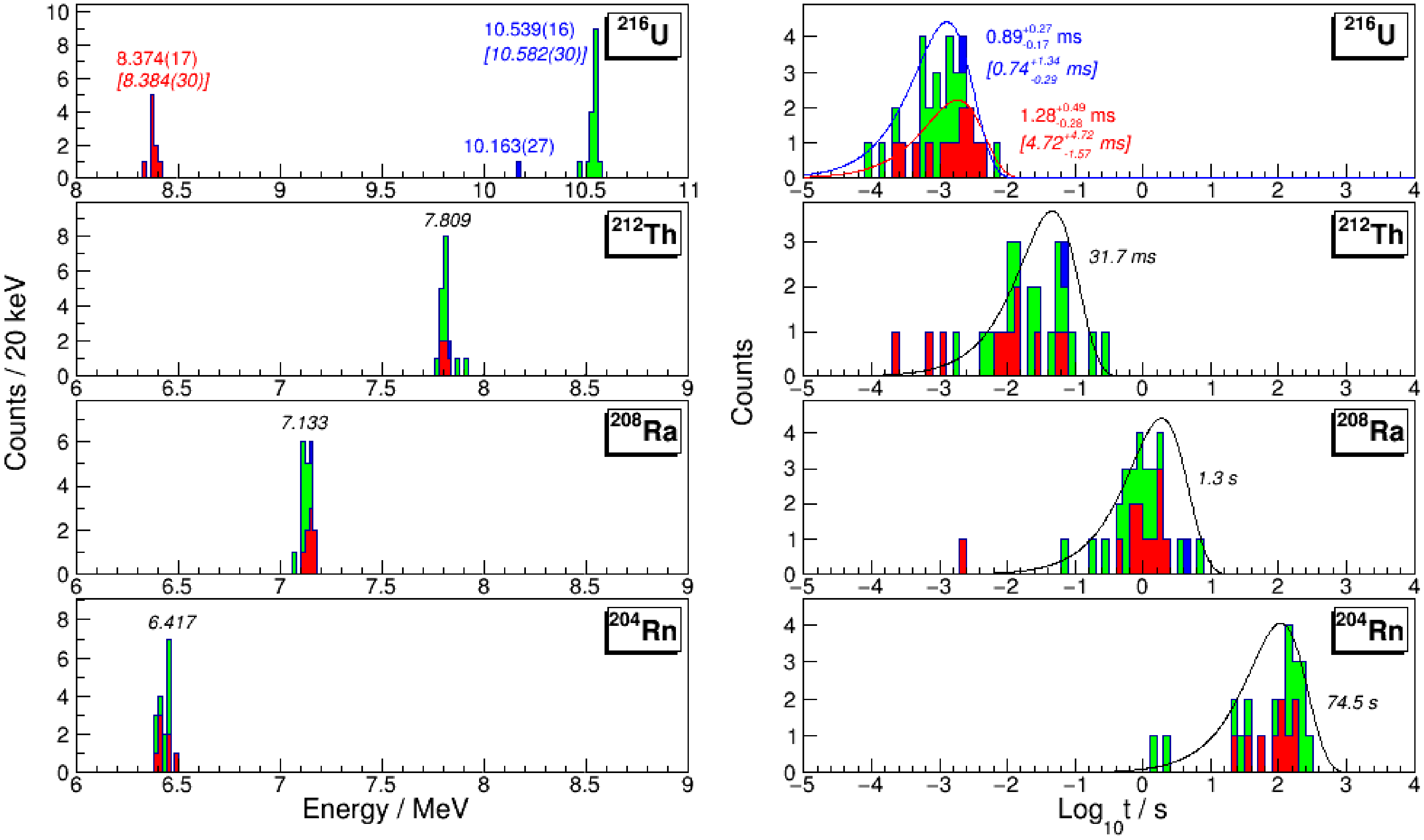
^{48}Ca+^{248}Cm (DIT) @ SHIP – 1 events for ^{216g}U



H. M. Devaraja, S. Heinz, et al. Phys. Lett. B 748, 199 (2015)

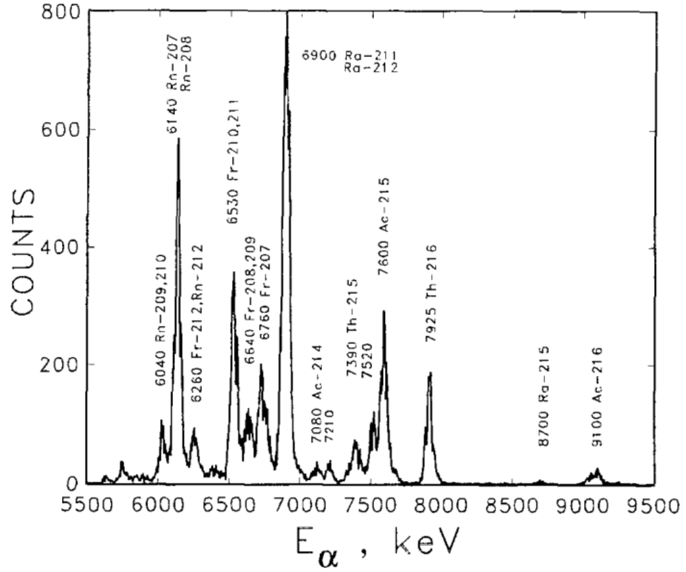
^{216}U in this work

$^{40}Ar+^{180}W \rightarrow ^{216}U+4n$ @ SHANS – 13 events for ^{216g}U (300 pb@191 MeV)



Previous studies on ^{218g}U

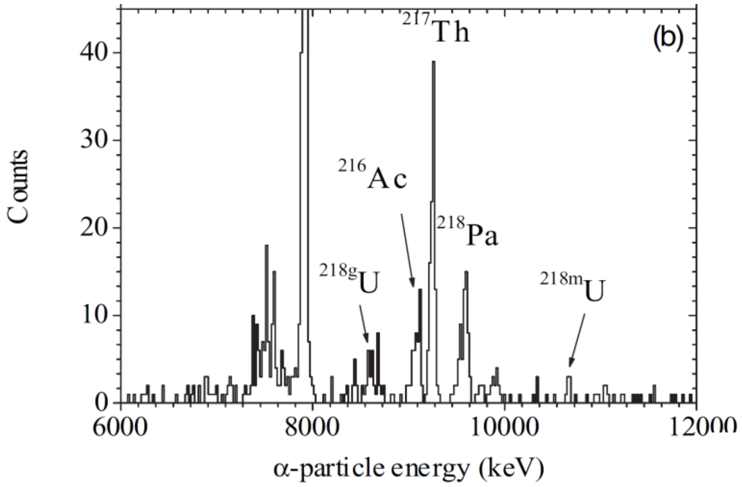
$^{27}Al + ^{197}Au$ @ VASSILISSA – 4 events for ^{218g}U

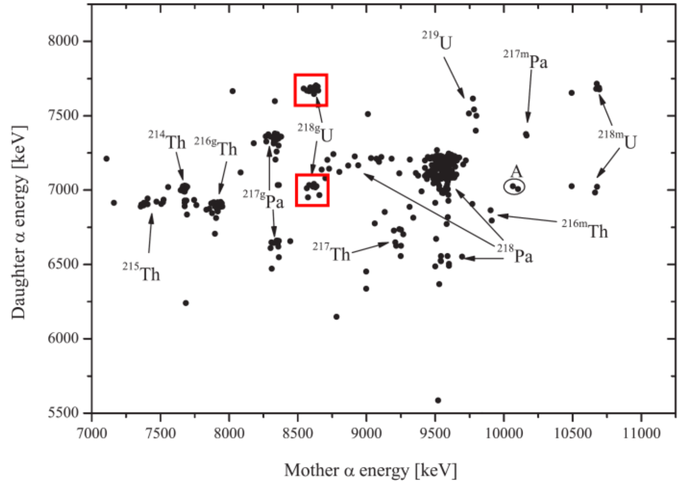


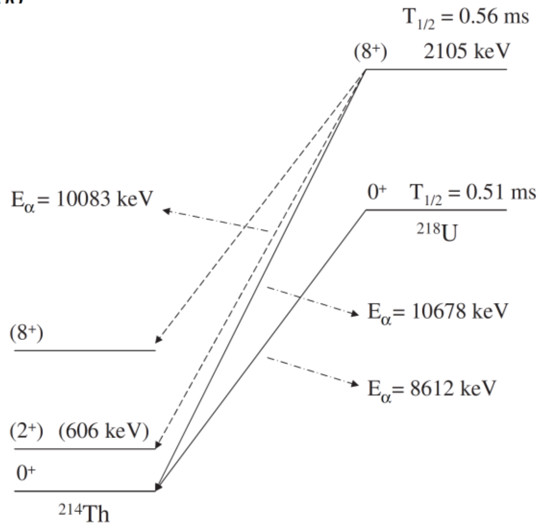
^{218}U			^{214}Th			^{210}Ra		
E_α keV	ΔT ms	Δx mm	E_α keV	ΔT ms	Δx mm	E_α keV	ΔT sec	Δx mm
8631			7694	13	0.4	7030	2.57	0.0
8610			7677	12	0.3			
8653						7025	4.45	0.4
8610	2.2	0.0				6960	0.47	0.9

A. N. Andreyev, et al., Z. Phys. A 342, 123 (1992).

$^{40}Ar + ^{182}W$ @ RITU – 20 events for ^{218g}U





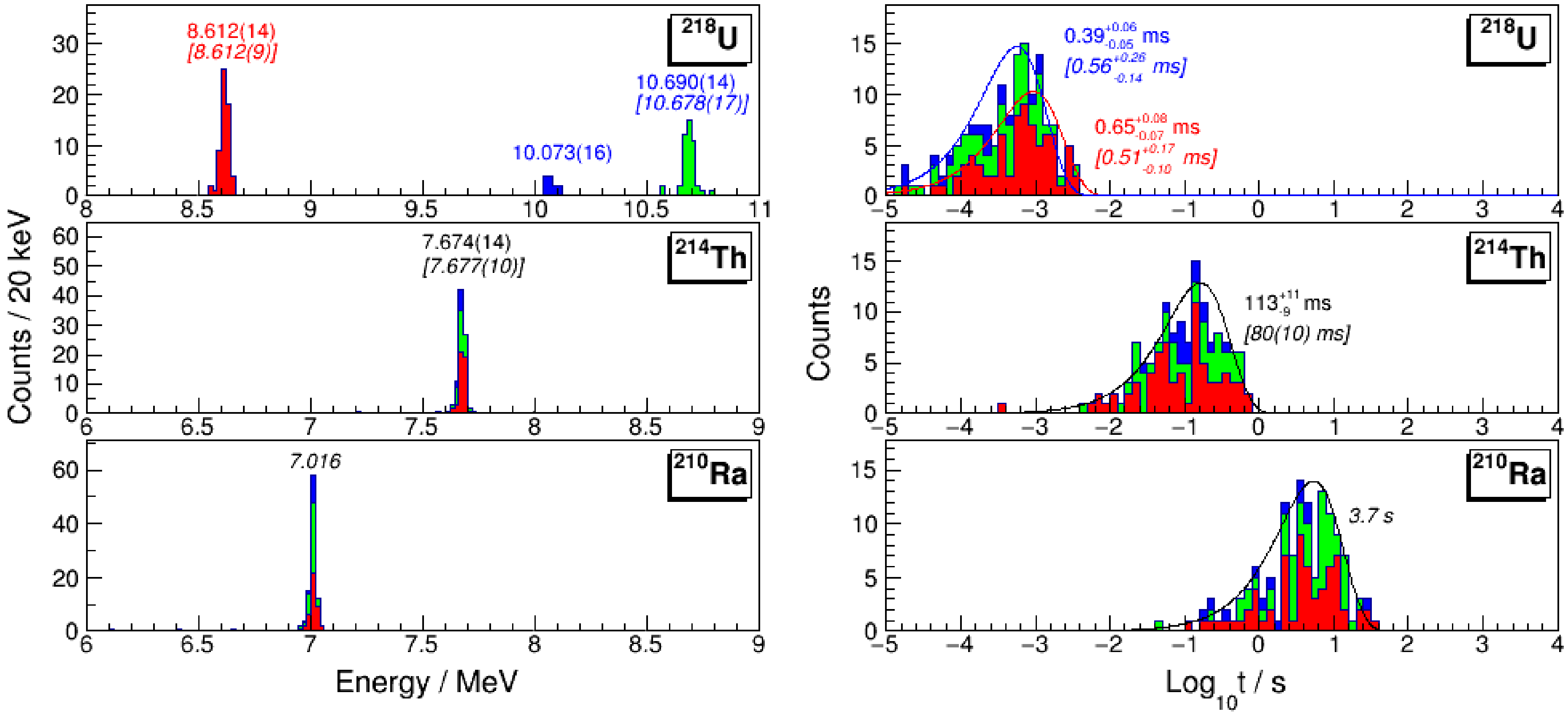


A. P. Leppänen, et al., Phys. Rev. C 75, 054307 (2007).
A. P. Leppänen, et al., Eur. Phys. J. A 25, 183 (2005).

^{218}U in this work

^{40}Ar+^{182}W -> ^{218}U+4n @ SHANS – 41 events for ^{218g}U (768 pb@190 MeV)

^{40}Ca+^{184}W -> ^{218}U+α2n @ SHANS – 35 events for ^{218g}U (325 pb@206 MeV)



Ground-state-to-ground-state α-decay of $^{214,216,218}U$

Isotope	This work			Literature data			Ref.
	E_α/keV	$T_{1/2}$/ms	δ^2/keV	E_α/keV	$T_{1/2}$/ms	events	
^{214}U (2 events)	8533(18)	$0.52^{+0.95}_{-0.21}$	128^{+233}_{-52}	-	-	-	
^{216}U (13 events)	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*
				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 (76 events)	8612(14)	$0.65^{+0.08}_{-0.07}$	53^{+7}_{-6}	8600(30)	$1.15^{+1.58}_{-0.42}$	3	Ma, *et al.* @ *SHANS*
				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.

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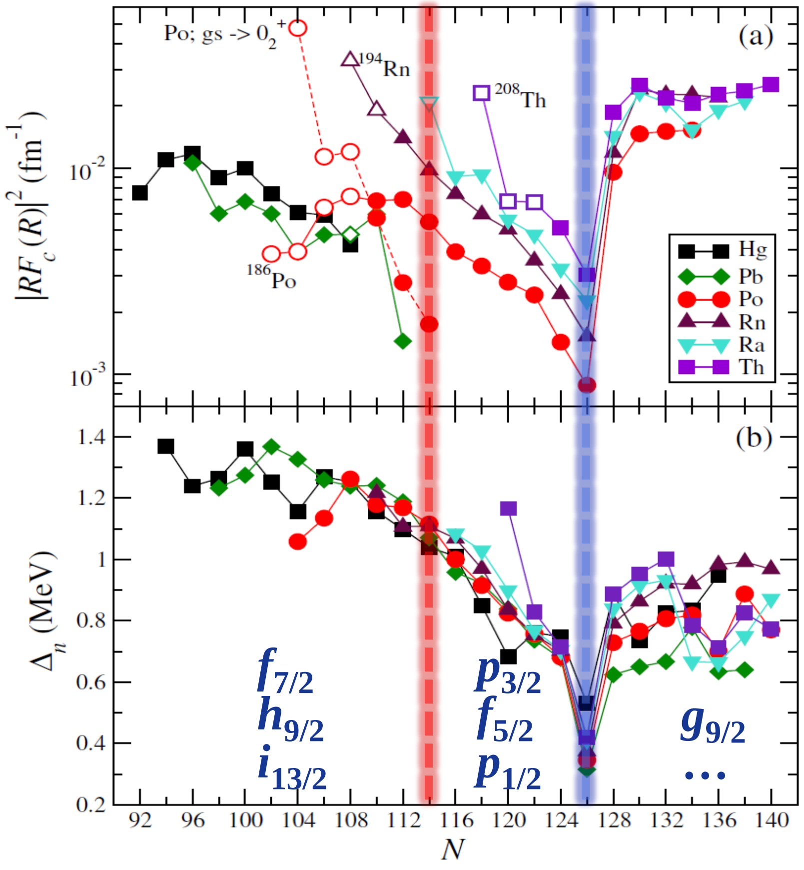
Enhanced α-particle clustering



Neutron pairing gap:

$$\Delta_n(Z,N)=\frac{1}{2}[B(Z,N)+B(Z,N-2)-2B(Z,N-1)]$$

A. N. Andreyev, *et al.*, Phys. Rev. Lett. 110, 242502 (2013).
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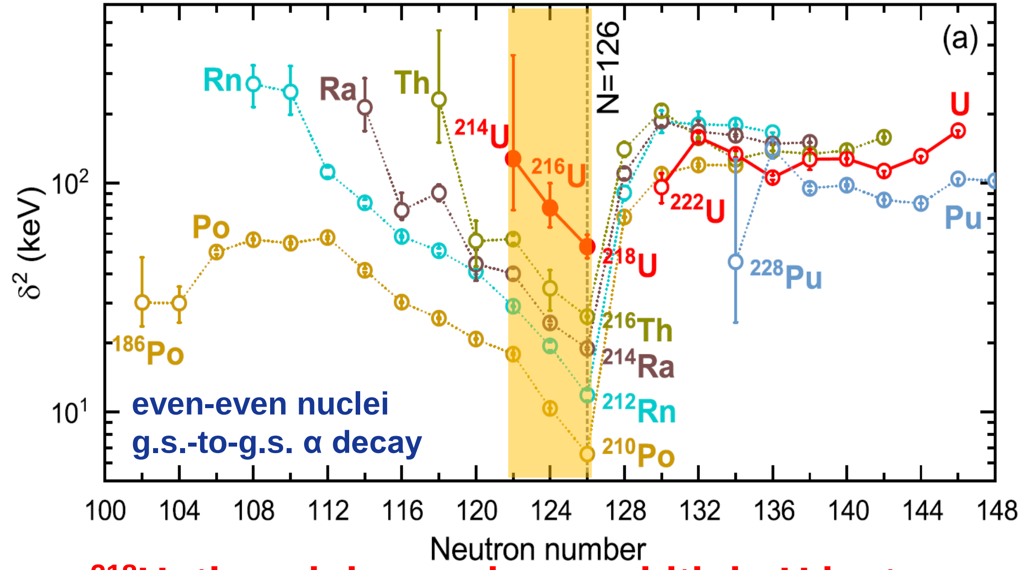
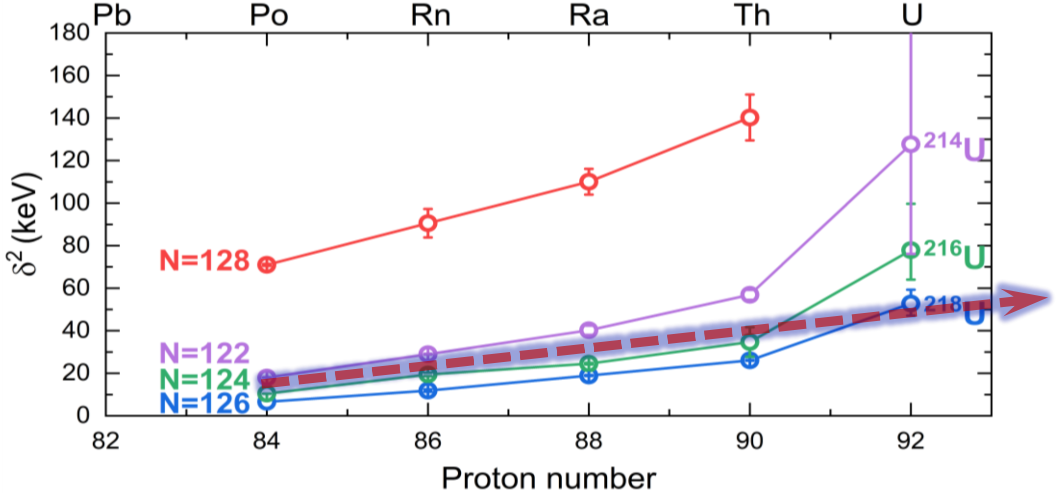
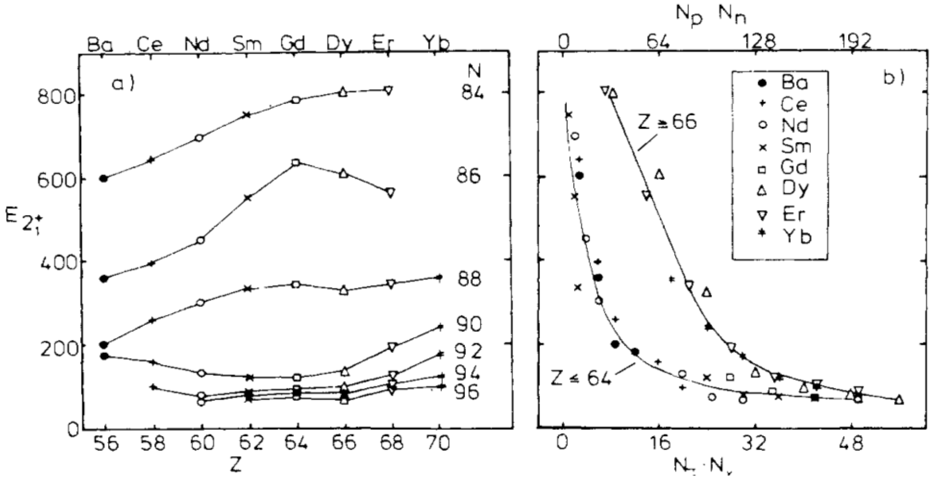


^{218}U: the minimum decay width in U isotopes



Enhanced α-particle formation probability in U

Enhanced decay width in N_pN_n scheme



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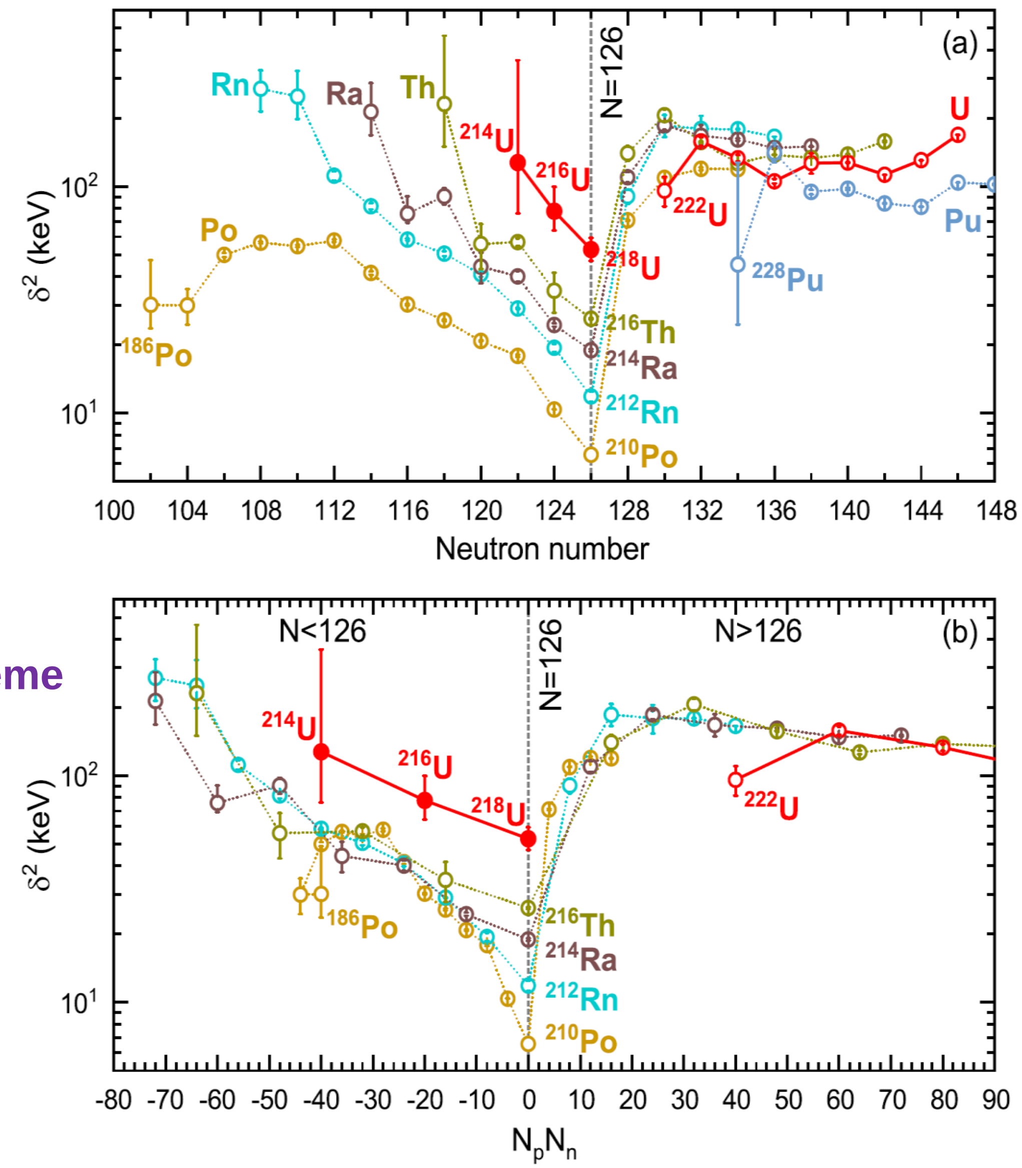
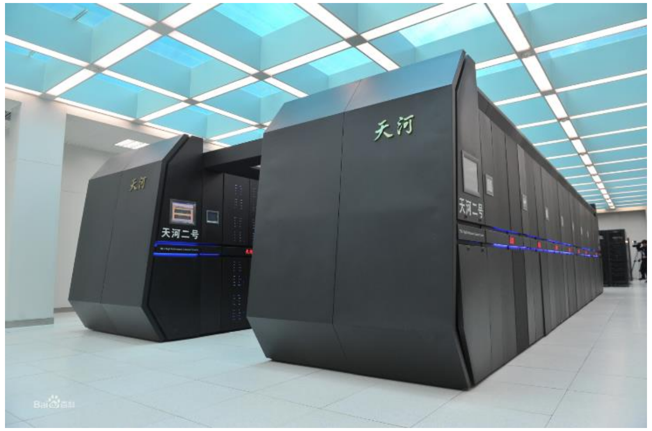


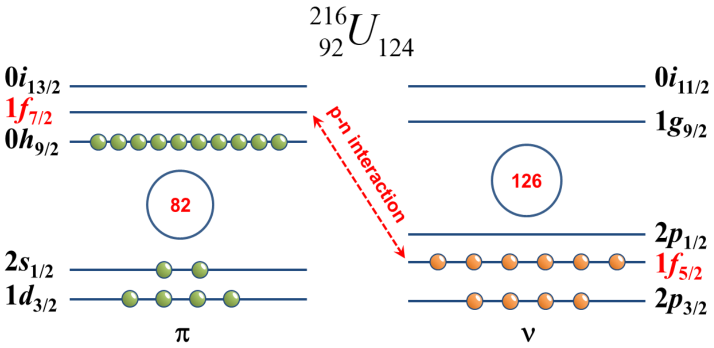
- **Remarkable simplification of the δ^2 systematics in N_pN_n scheme**
- **N>126: dominated by p-p and n-n pairing**
- **N<126: p-n interaction plays a key role**

^{214}U: $N_pN_n = (Z-82)\cdot(N-126) = -40$
^{216}U: $N_pN_n = (Z-82)\cdot(N-126) = -20$
^{218}U: $N_pN_n = (Z-82)\cdot(N-126) = 0$

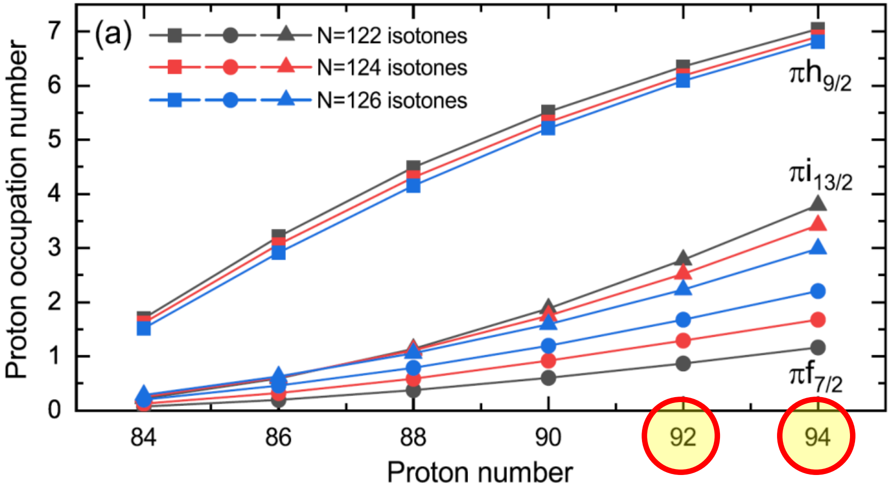
- **^{214,216}U: δ^2 values are significantly enhanced by a factor of two as compared with Po-Th N_pN_n systematics with N<126**

Large-scale shell model calculations



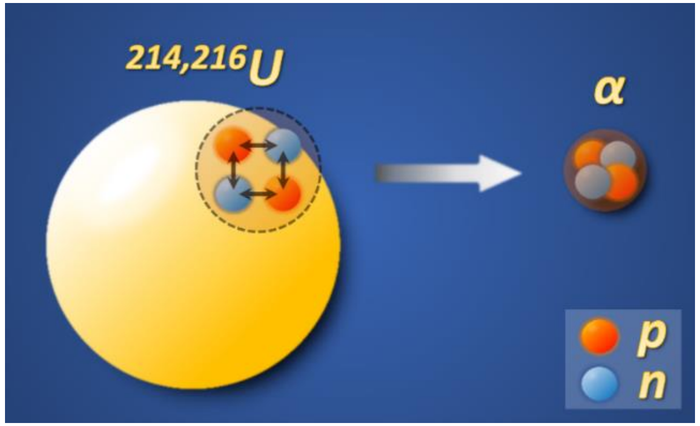


Supporting the increased occupancy of $\pi 1f_{7/2}$ orbit

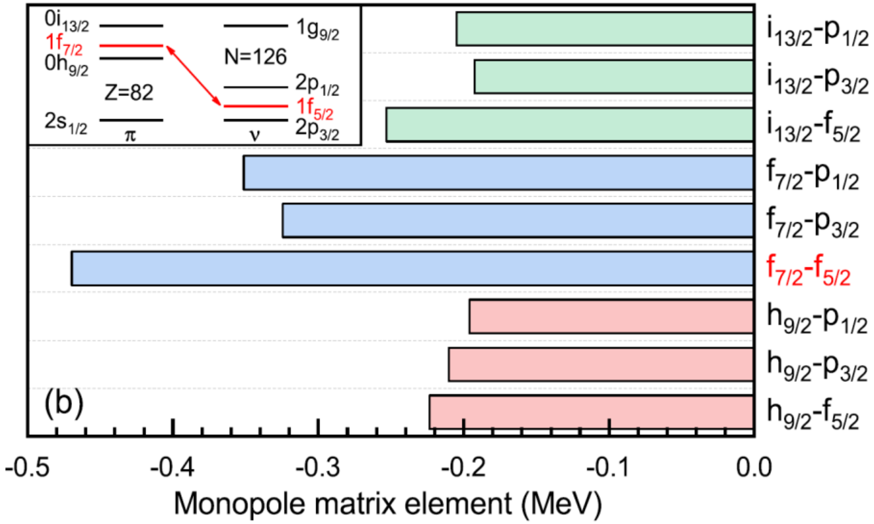


Model space:
Proton: $0h_{9/2}$, $1f_{7/2}$, $0i_{13/2}$
Neutron: $2p_{1/2}$, $1f_{5/2}$, $2p_{3/2}$

Two-body interactions:
p-p: Kuo-Herling particle interaction
n-n: Kuo-Herling hole interaction
p-n: V_{MU} + M3Y spin-obit interaction



Supporting the strong $\pi 1f_{7/2}$ and $\nu 1f_{5/2}$ interaction



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Achievements

PHYSICAL REVIEW LETTERS **126,** 152502 (2021)

Editors' Suggestion **Featured in Physics**

New α-Emitting Isotope ^{214}U and Abnormal Enhancement of α-Particle Clustering in Lightest Uranium Isotopes

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Physics — SYNOPSIS

A Lightweight Among Heavyweights

Researchers have observed the lightest uranium isotope to date, offering insight into models of nuclear structure.

By Katherine Wright

Discovering new isotopes is like the stamp collecting of physics, but the consequences of adding to the set are much further reaching. A team of researchers using the Heavy Ion Research Facility in Lanzhou, China, has now expanded the collection with the discovery of the lightest uranium isotope to date [1]. The finding could have implications for our understanding of a particular type of radioactive decay that is still mysterious despite more than a century of work.

Uranium is an inherently unstable element. All of its isotopes are radioactive, with the most abundant ones having half-lives ranging from 150,000 to 4.5 billion years (roughly the age of Earth). Naturally occurring uranium contains between 140 and 146 neutrons. The newly discovered isotope has just 122, one fewer than the previous record for the element.

The team created the isotope in a "fusion-evaporation" reaction, which involved firing a beam of argon at a tungsten target and monitoring the fusion products. They identified two previously discovered light uranium isotopes—uranium-216 and uranium-218—as well as the new one, uranium-214, which has a blink-and-you'll-miss-it half-life of 0.5 ms.

Credit: APS/Carin Cain

The number of neutrons in this isotope sits near a so-called magic neutron number, specifically 126, which makes it interesting for studying nuclear stability. Magic isotopes are unusually stable, and observing their near neighbors provides opportunities to probe how nuclear structure influences radioactive decay processes. In this case, measurements from the three observed uranium isotopes suggest that they experience an enhanced proton-neutron interaction compared with isotopes of other elements. This stronger interaction affects the formation of alpha particles in the nucleus, a complex quantum many-body problem whose details are still unknown.

Katherine Wright is the Deputy Editor of *Physics*.

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1. Z. Y. Zhang *et al.*, "New α-emitting isotope ^{214}U and abnormal enhancement of α-particle clustering in lightest uranium isotopes," Phys. Rev. Lett. 126, 152502 (2021).

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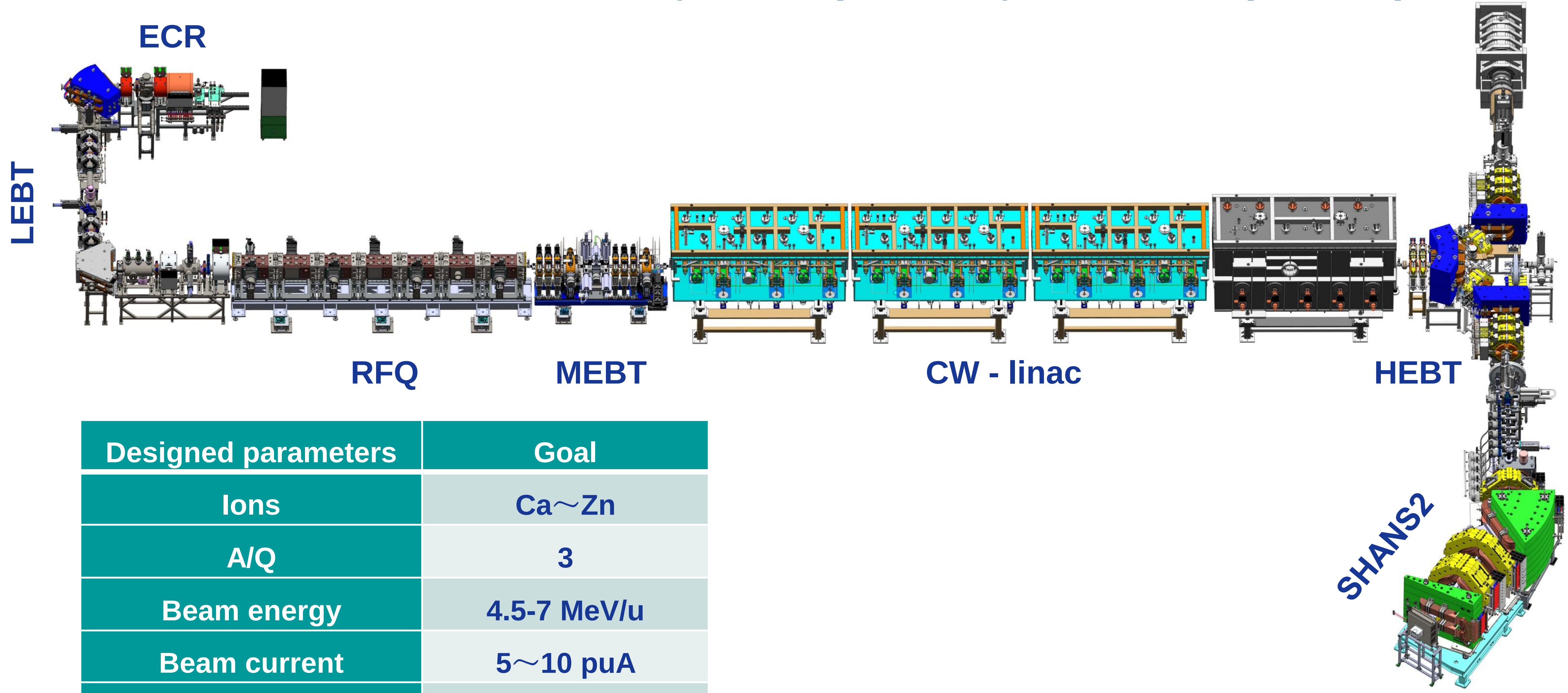
Contents

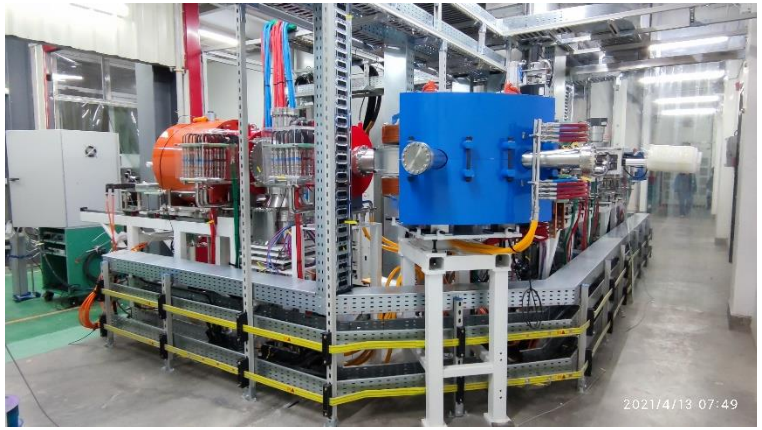
CAFE2 Project in Lanzhou

China Accelerator Facility for Superheavy Elements (CAFE2)



Designed parameters	Goal
Ions	Ca～Zn
A/Q	3
Beam energy	4.5-7 MeV/u
Beam current	5～10 puA
Running mode	CW

Status of CAFE2



ECR + LEBT

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

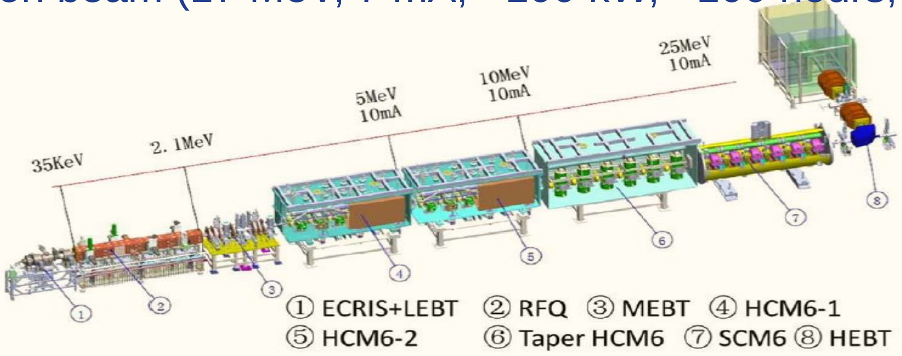


Fig. 2. Schematic layout of the 25 MeV demo facility.

Chinese ADS Front-end superconducting demo linac (CAFe)

Y. He, Z. Wang, Z. Qin, *et al.*, 10th Int. Particle Accelerator Conf. (IPAC2019), Melbourne, Australia (2019).
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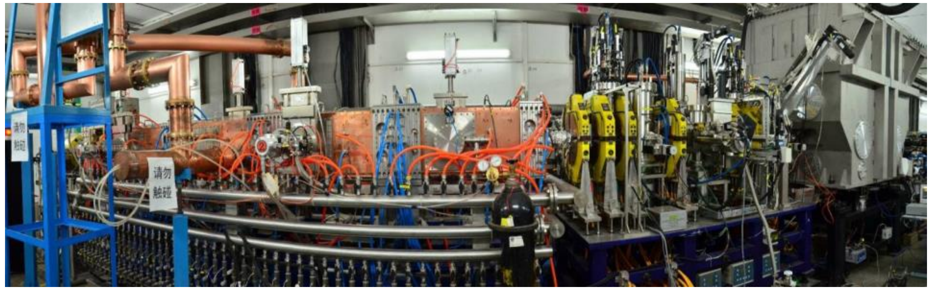
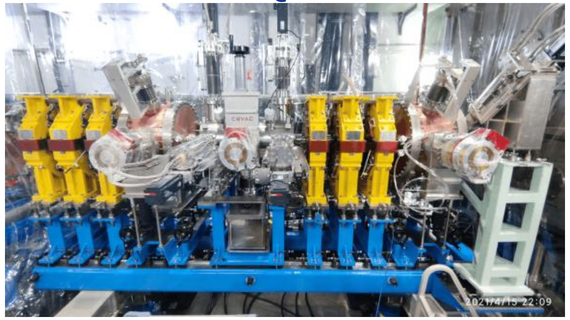
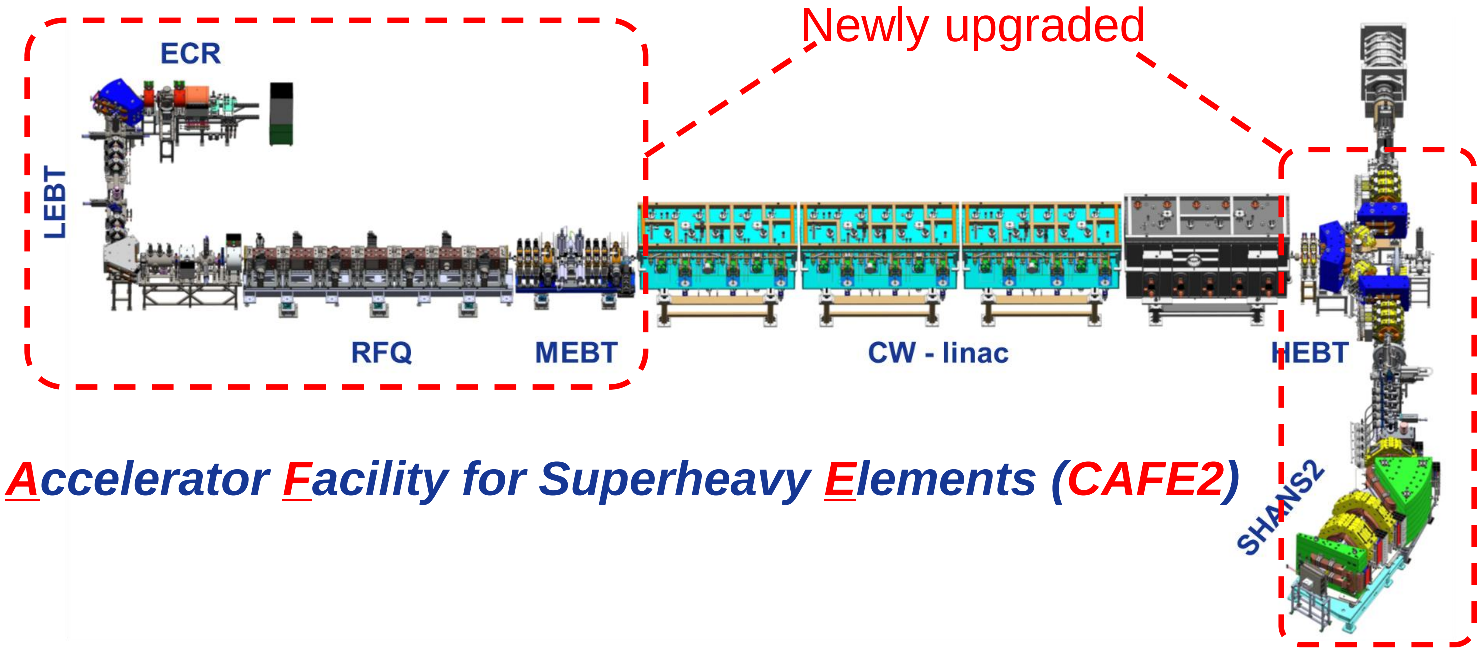


RFQ

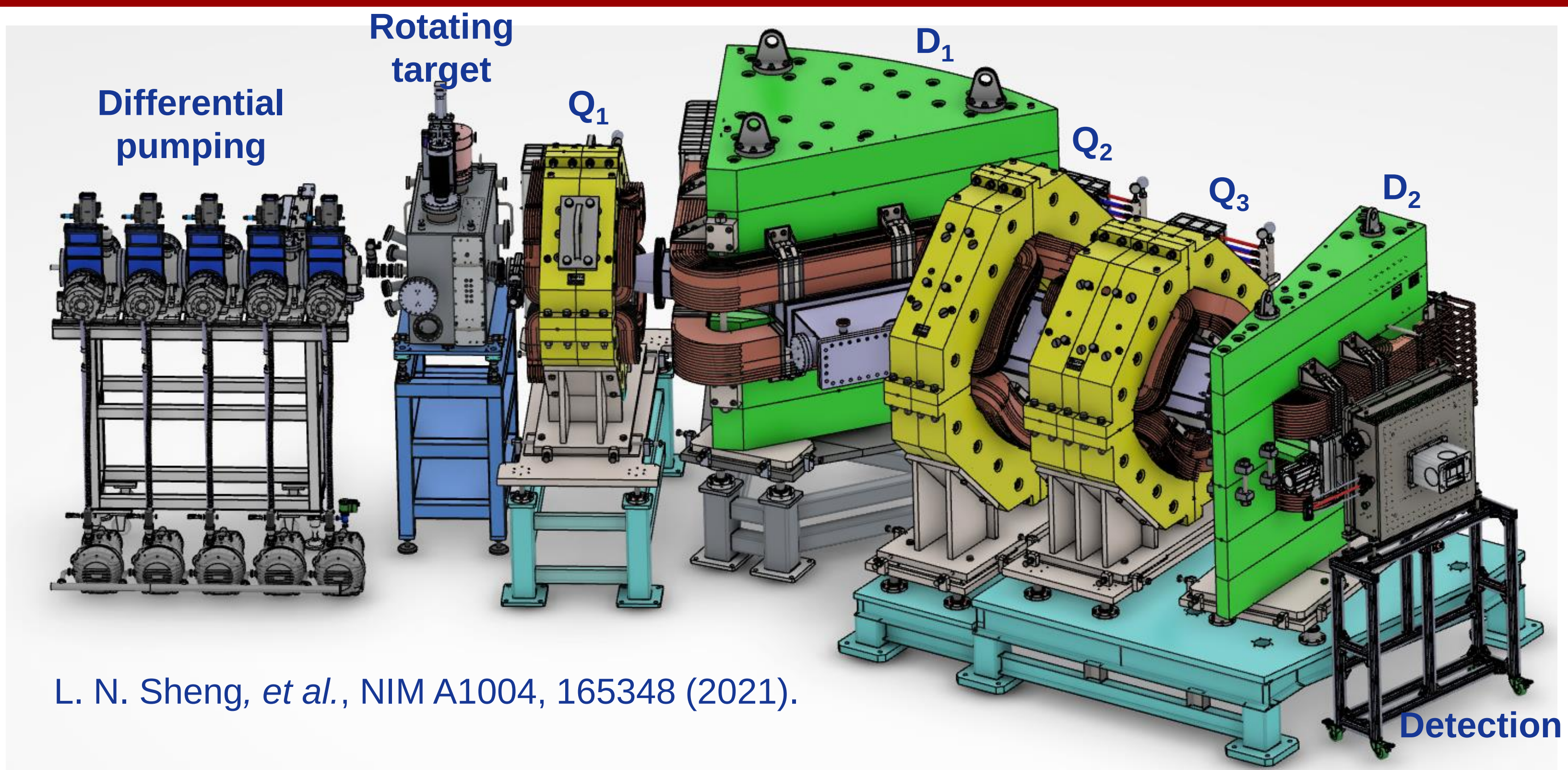


MEBT



***C**hina **A**ccelerator **F**acility for Superheavy **E**lements (CAFE2)*

SHANS2

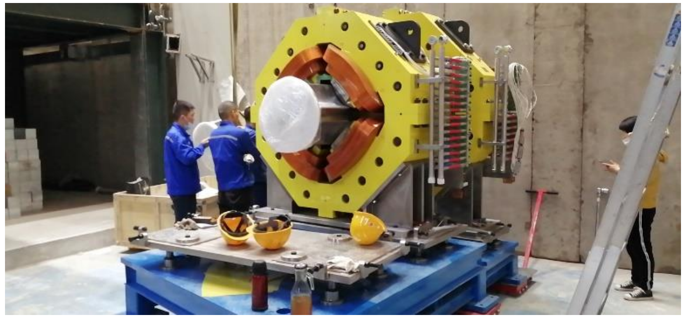


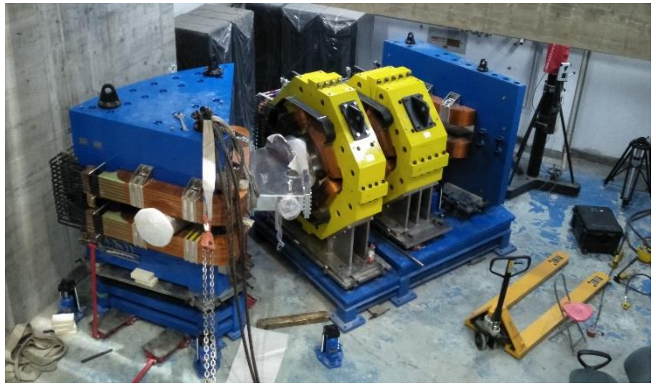
L. N. Sheng, *et al.*, NIM A1004, 165348 (2021).

Separator	DGFRS	DGFRS-II	Garis	Garis-II	RITU	BGS	TASCA	SHANS	SHANS2
Location	FLNR Dubna Russia	FLNR Dubna Russia	RIKEN Wako Japan	RIKEN Wako Japan	JYFL Jyväskylä Finland	LBNL Berkeley USA	GSI Darmstadt Germany	IMP Lanzhou China	IMP Lanzhou China
Configuration	DQ_hQ_v	$Q_vD_hQ_vQ_hD$	DQ_hQ_vD	$Q_vDQ_hQ_vD$	$Q_vDQ_hQ_v$	Q_vQ_hD	DQ_hQ_v	$Q_vDQ_vQ_h$	$Q_vDQ_vQ_hD$
Deflection angle	23°	(30+10)°	(45+10)°	(30+7)°	25°	(25+45)°	30°	52°	(30+10)°
max. B×ρ (Tm)	3.1	3.2	2.16	2.43	2.2	2.5	2.35	2.88	2.56
Length(m)	4	7.1	5.76	5.06	4.8	4.6	3.5	6.5	5.85
Dispersion (mm/%B×ρ)	7.5		9.7	19.3	10	20	9	7.3	(22)
solid angle(msr)	10		12.2	18.5	10	45	13.3	25	25

D_1 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**
D_2 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**
Q_1 quadrupole magnet	
Length, aperture, max. gradient	**0.46 m, Φ162 mm, 11.85 T/m**
Q_2 quadrupole magnet	
Length, aperture, max. gradient	**0.45 m, Φ324 mm, 4.2 T/m**
Q_3 quadrupole magnet	
Length, aperture, max. gradient	**0.63 m, Φ314 mm, 5.03 T/m**

SHANS2

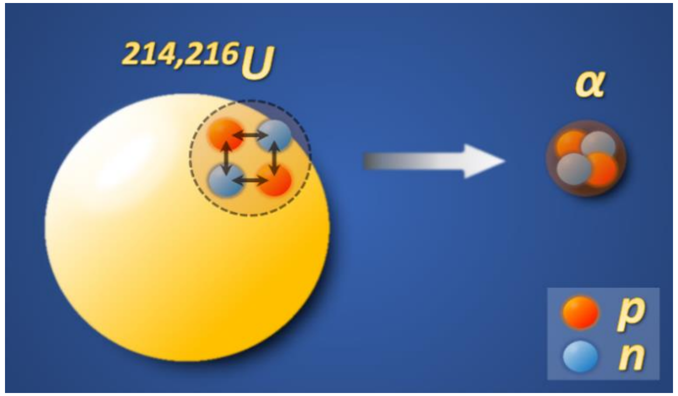


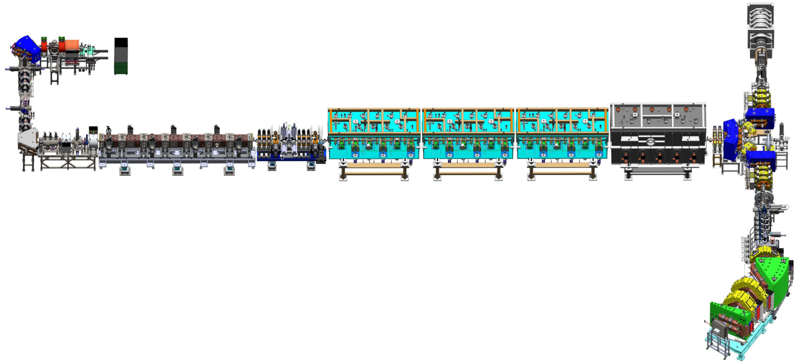


Contents

Summary and outlook

- New uranium isotope ^{214}U was studied at SHANS, and more precise α-decay data for $^{216,218}U$ were measured.
- Significant enhancement of δ^2 for $^{214,216}U$ is found by comparing with Po-Th N_pN_n systematics.
- The new feature can be attributed to the strong monopole interaction between the valence $\pi 1f_{7/2}$ protons and $\nu 1f_{5/2}$ neutrons.
- CAFE2 project is carrying out at IMP involving a new gas-filled recoil separator SHANS2.
- The verification experiment for element 115 with $^{48}Ca+^{243}Am$ is planning.





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Thank you for all your attention!