A gaseous time projection chamber with Micromegas readout for low-radioactive material screening

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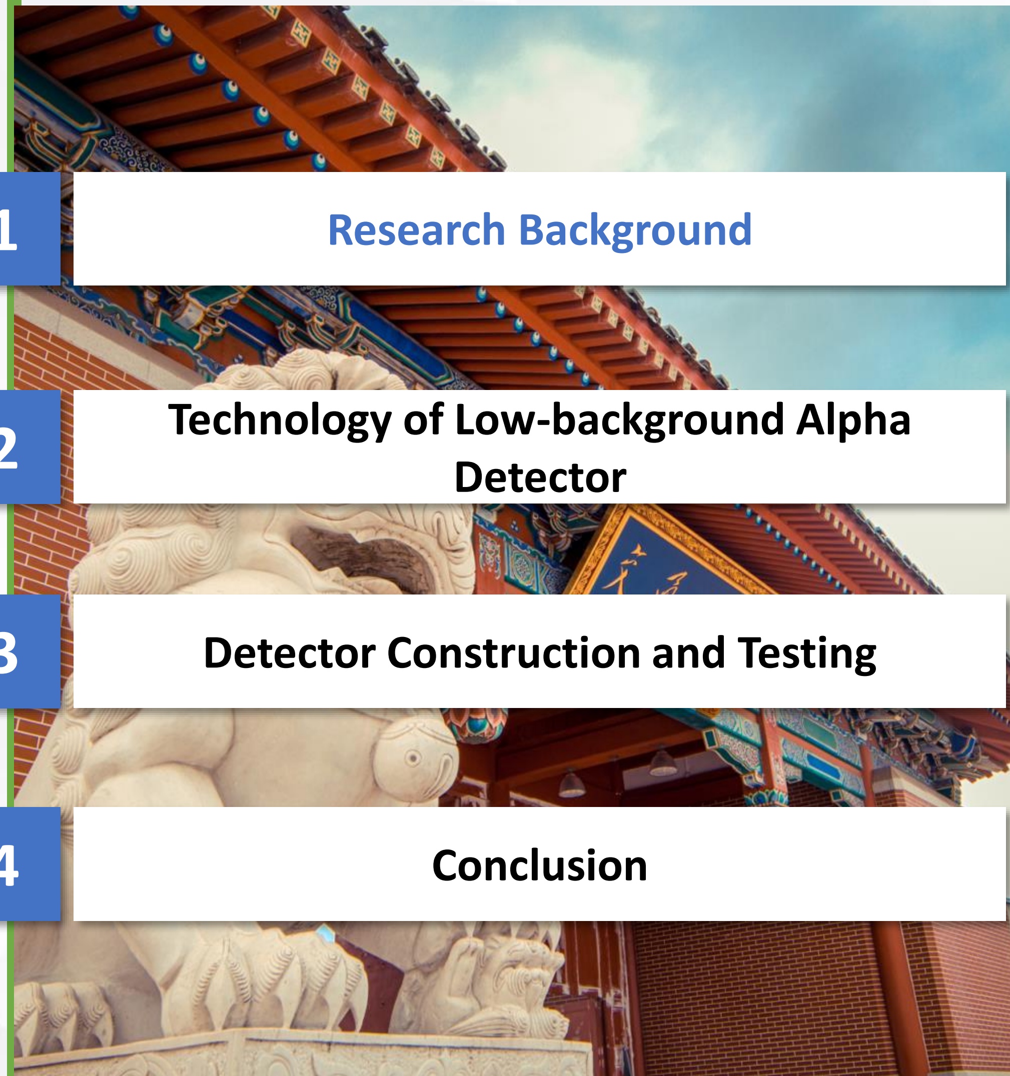
Low Radioactivity Techniques (LRT2024)

Outline

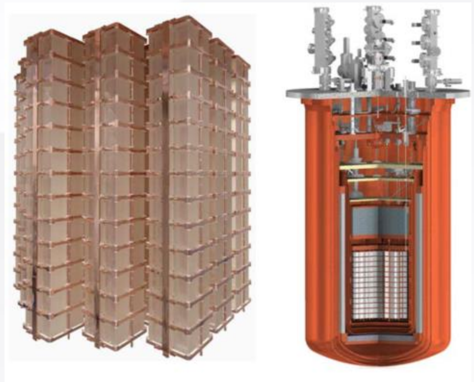


1. Research Background
2. Technology of Low-background Alpha Detector
3. Detector Construction and Testing
4. Conclusion

Underground rare event detection and background

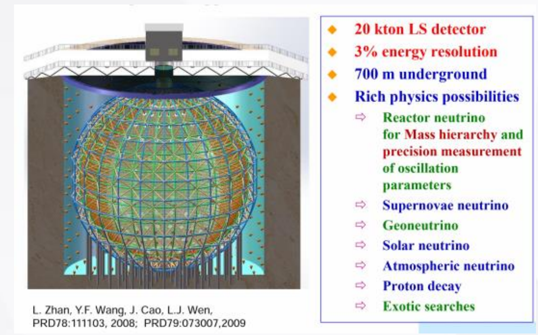
Neutrinoless double beta decay detection

- CUORE
- 200 kg ^{130}Te
- $\bar{\nu}_e == \nu_e$
- Crystal and copper surface contamination



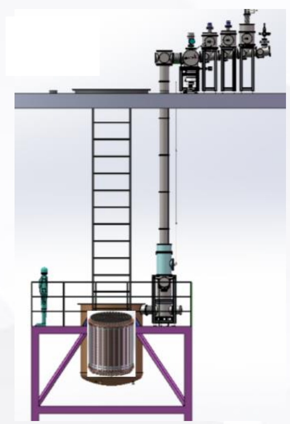
Neutrino detection

- JUNO
- 20 kt Liquid Scintillator
- Radon on organic glass sphere surface bring contamination



Dark matter detection

- PandaX-4T
- 4 t liquid xenon (TPC)
- WIMP
- Copper and Teflon surface contamination
- Radon from detector and pipeline surfaces



Radioactivity background

- Cosmic rays and their derivatives
- Lab environment (high-energy gamma, neutron)
- Internal and surface radioactivity of detector materials introduce background (radon exhalation)

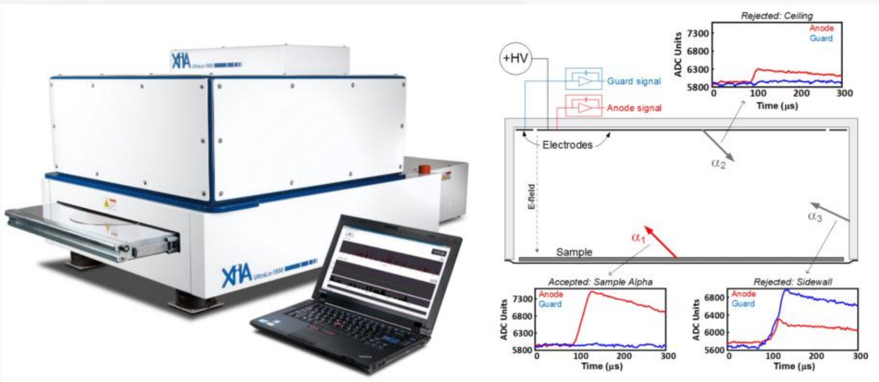
- The background is crucial as the signals are rare and determines the experiment sensitivity.

Status of Low-Background Measurement Techniques

Detection Technology	Measurement Object	Sensitivity	Remarks
Inductively Coupled Plasma Mass Spectrometry	Heavy elements in high-purity oxygen-free copper	ppt	Complex chemical pretreatment
Neutron Activation Analysis (NAA)	^{238}U and ^{232}Th in Teflon	sub-ppt, ppt	Utilizes neutron irradiation
High-Purity Germanium Gamma Detector	^{238}U and ^{232}Th in high-purity oxygen-free copper	1-10 uBq/kg sub-ppb, ppb	Non-destructive testing, high energy resolution
betaCage	Radioactivity on the surface of large-area materials	-	Proposed by the CDMS collaboration
SuperNEMO BiPo-3 detector	^{208}Tl and ^{214}Bi Inside thin film materials	Background ^{208}Tl : 0.9±0.2 uBq/m^2 ^{214}Bi : 1.0±0.3 uBq/m^2	Developed by the SuperNEMO collaboration
UltraLo-1800	Radioactivity on the surface of large-area materials	Background 1.4 uBq/cm^2	XIA commercial detector

XIA: UltraLo-1800

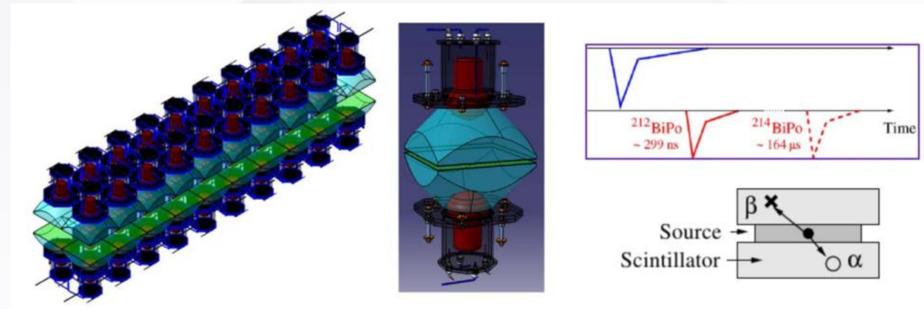
- Ionization Chamber

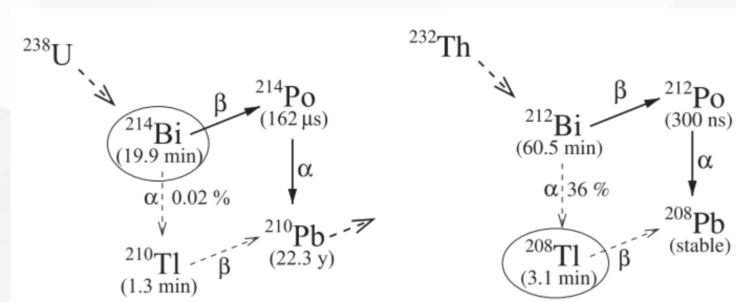


- Identify the alpha signals using pulse waveforms (rise time, amplitude, and shape).
- Background 0.14 uBq/cm^2 , for alpha measurement of semiconductor.
- Measurement area: 1800 cm^2

SuperNEMO: BiPo-3 detector

- Scintillator





- Background ^{214}Bi: 1.0±0.3 μBq/m^2
- Background ^{208}Tl: 0.9±0.2 μBq/m^2
- Measurement Area: 3.6 m^2

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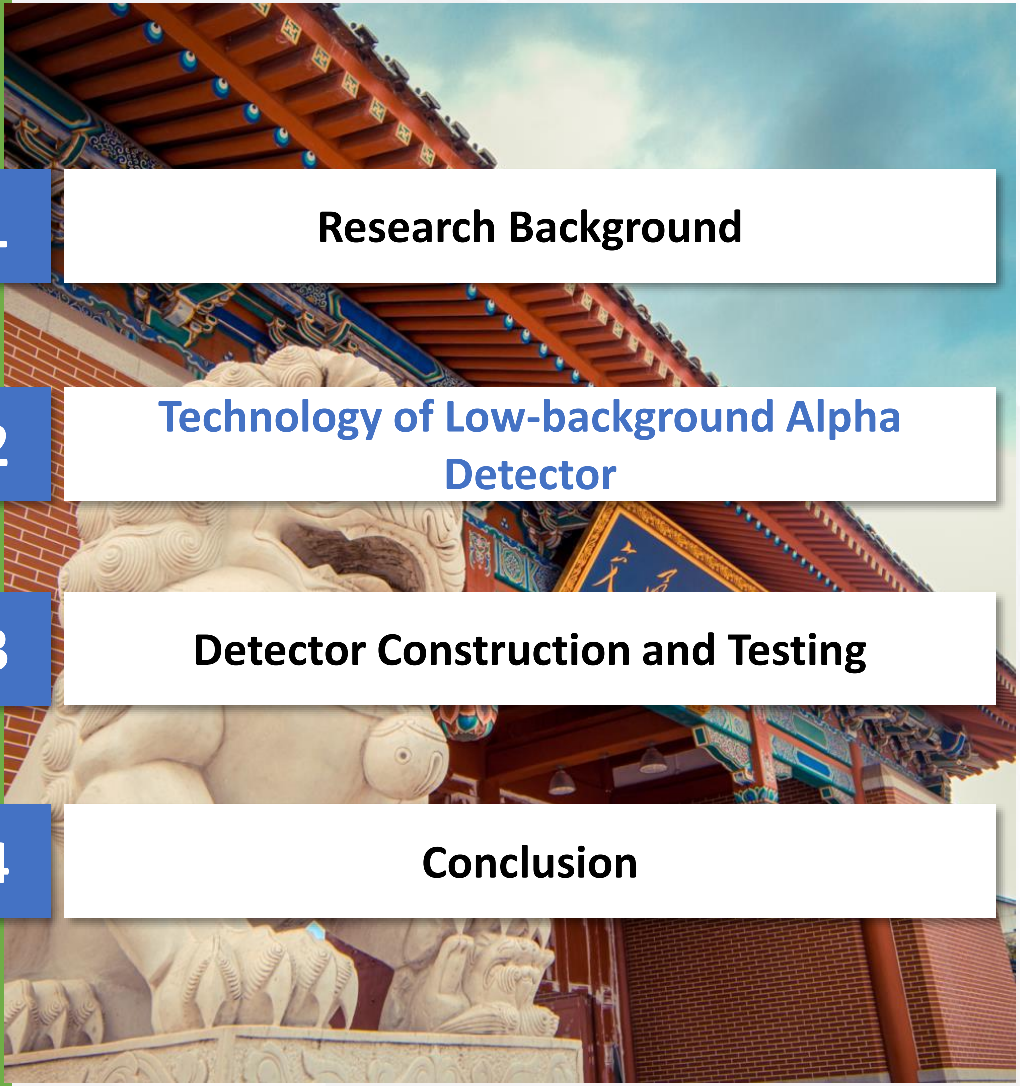
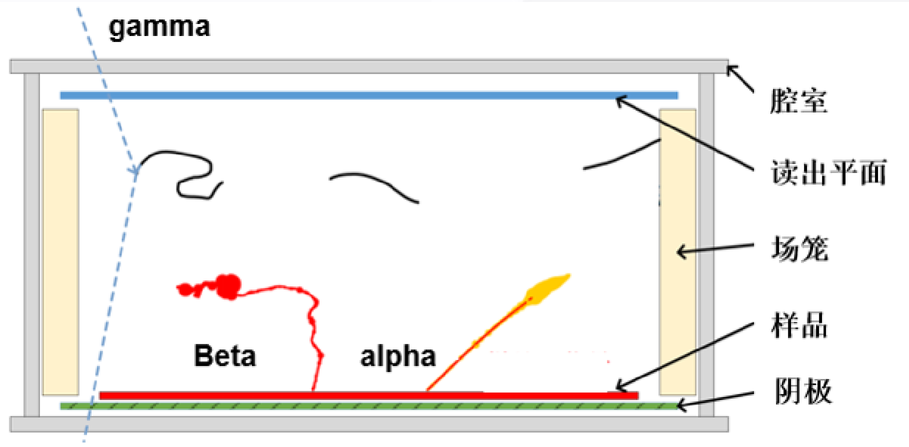
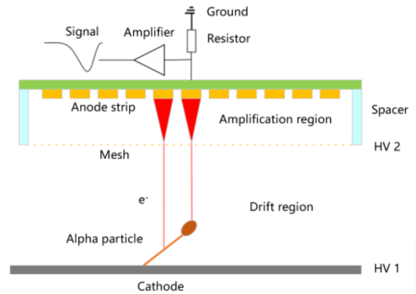


Technology of Gas TPC and Micromegas

- Gas Time Projection Chamber (TPC)

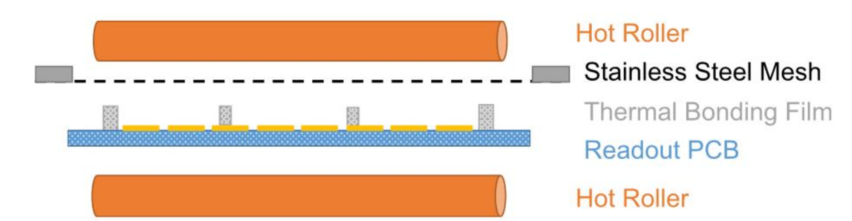




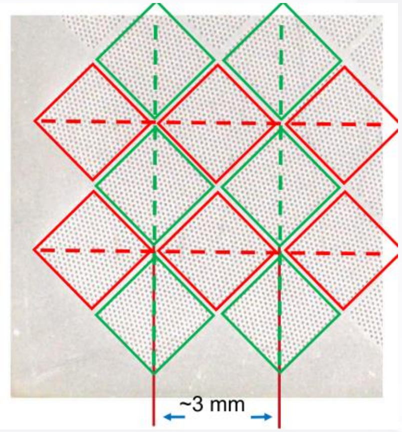
➢ Samples placed inside, record particle energy, track information

- Micromegas

➢ Readout: 20×20 cm^2



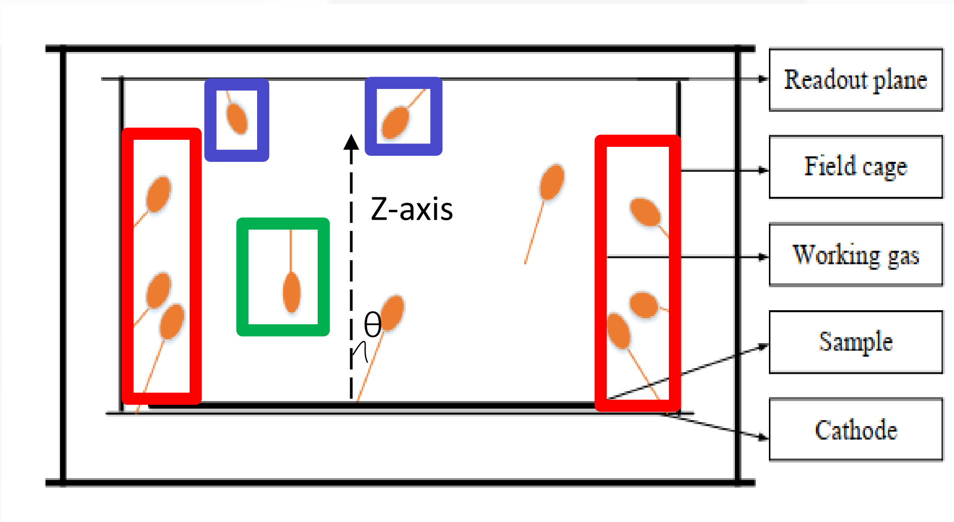
FENG J, ZHANG Z, LIU J, et al. A thermal bonding method for manufacturing Micromegas detectors[J]. 2021, 989: 164958.

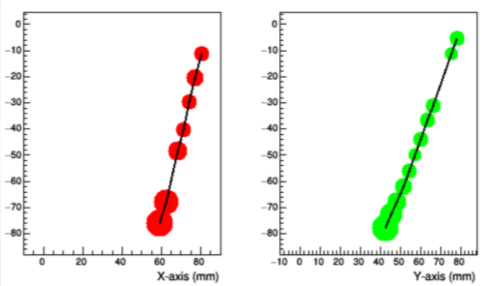


➢ Thermal bonding Micromegas, strip readout

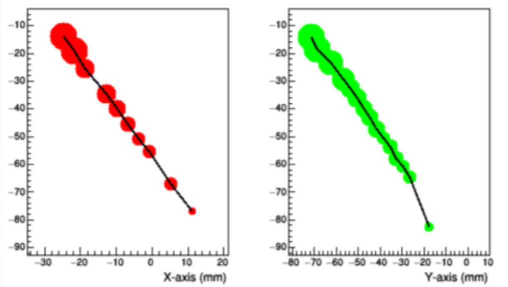
Trajectory Reconstruction and S-B Discrimination

Signal-Background Discrimination Method - Track-related





Alpha tracks from top to bottom



Alpha tracks from bottom to top

- α particle tracks are almost straight, with a **Bragg** peak at the track end.

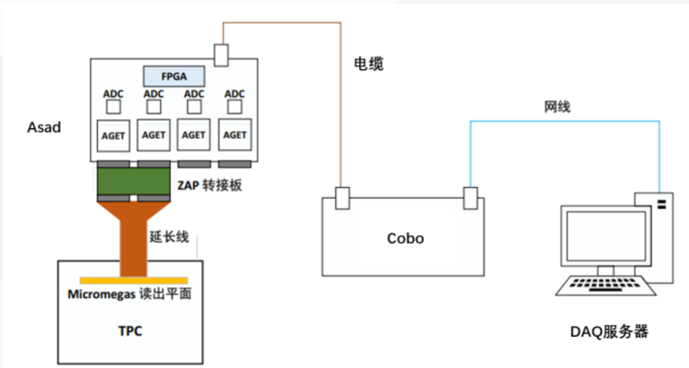
a. The starting position of the track --- Identify the background near the **field cage**.

b. The track direction --- Identify the background of the **readout plane** and half of the **gas** background.

c. The number of triggered strips --- Identify short tracks of particles, which are likely from the **gas** and **readout plane**.

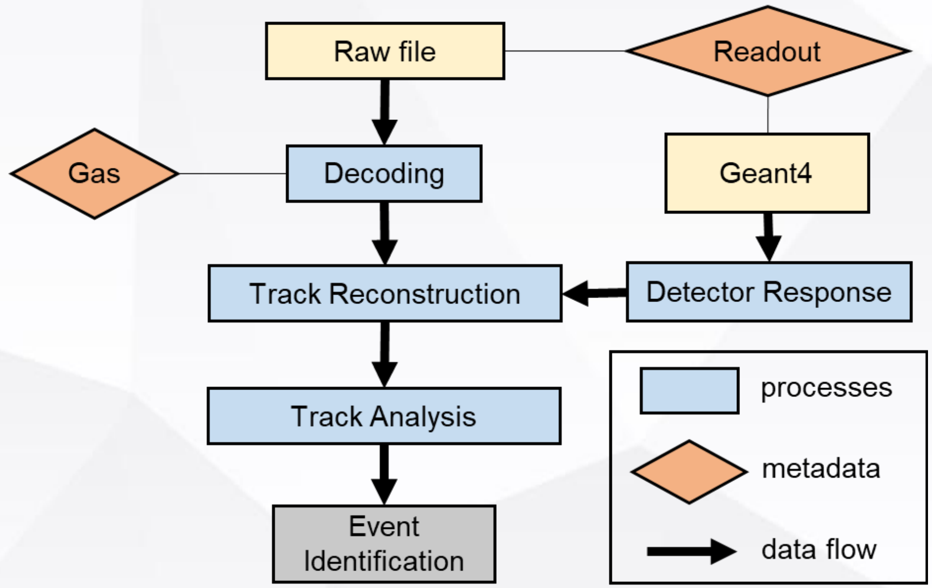
Subsystems of the Detector

Data Acquisition System
(Cobo-Asad, Concentration Board , ASIC Support and Analog-Digital conversion)



Slow Control Monitoring System
(voltage, current, and pressure)

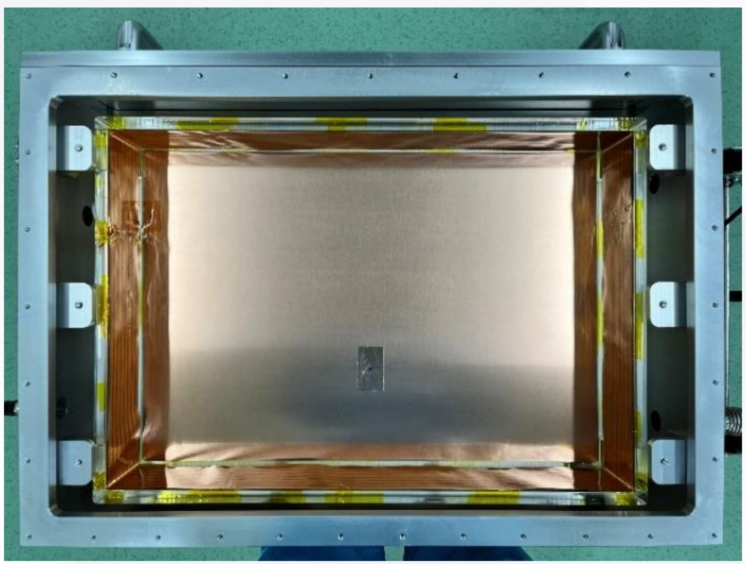
Data Analysis Framework
(REST, Rare Event Search Toolkit)



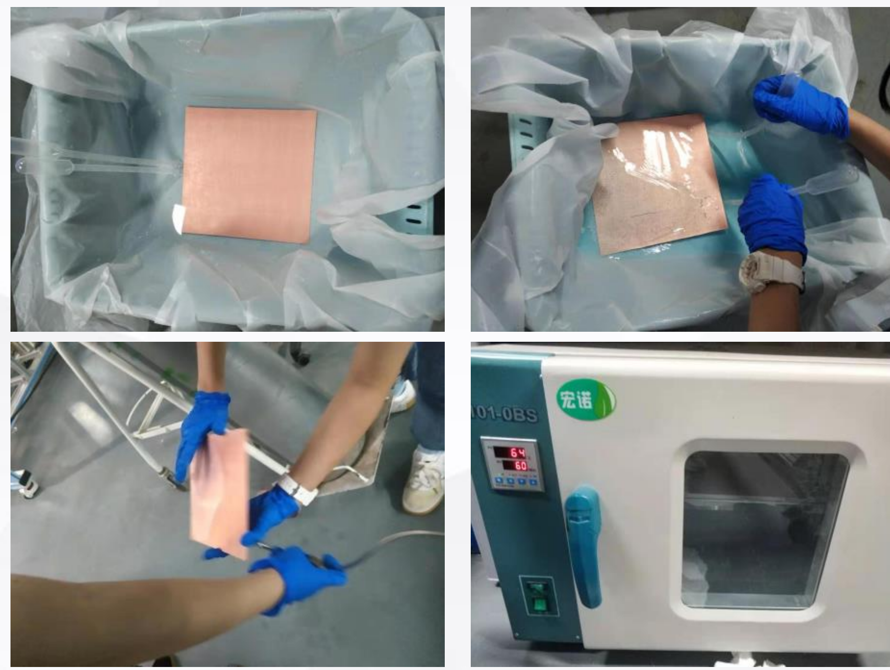
Low-Background Treatment of Detector Materials

Treatment of low-background detector material components

- Oxygen-free copper cathode: Degrease (Alconox) -> Acid wash -> Rinse with ultrapure water -> Dry with nitrogen gas -> Dry in the oven
- Acrylic + Flexible PCB field cage: Wipe with Alconox -> Clean with ultrapure water -> Dry with nitrogen
- Aluminum inner wall: Wipe with Alconox -> Clean with ultrapure water -> Dry with nitrogen gas
- Gas: Getter purification



- Detector internal structure



- Copper cathode treatment process

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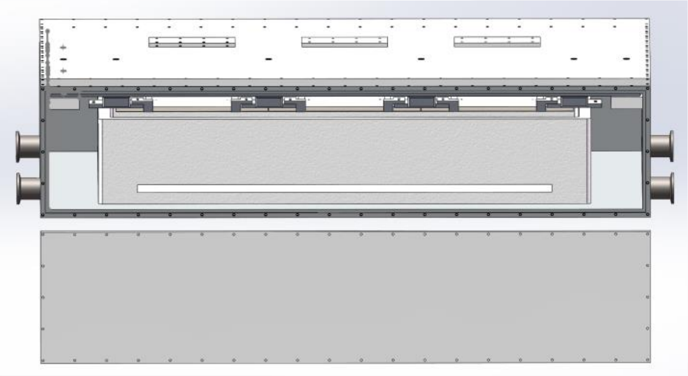
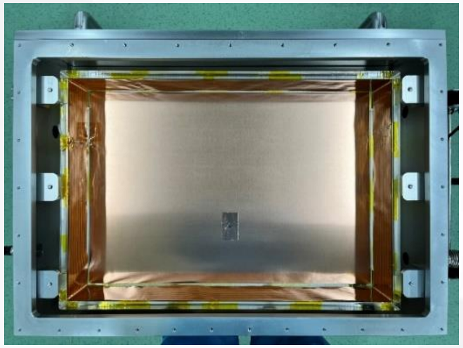
Outline

Construction of the Charge Particle Detector

Charged Particle detector

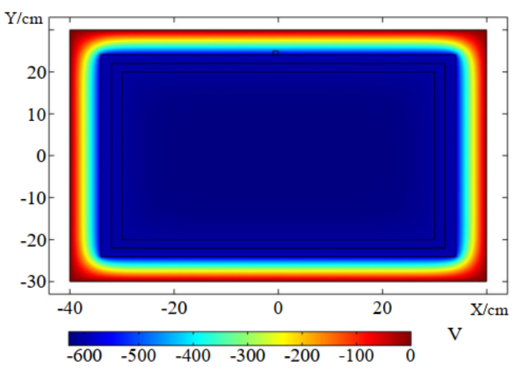


Readout plane - Micromegas



Internal detector photo

- Time Projection Chamber (0.5-1.5 bar Argon/Xenon)
- Readout plane： 2400 cm^2 （2×3 Micromegas）
- Drift distance： 10 cm (Volume: 24 L)
- Flexible PCB field cage
- Samples are placed directly on the cathode to ensure complete deposition of alpha energy.

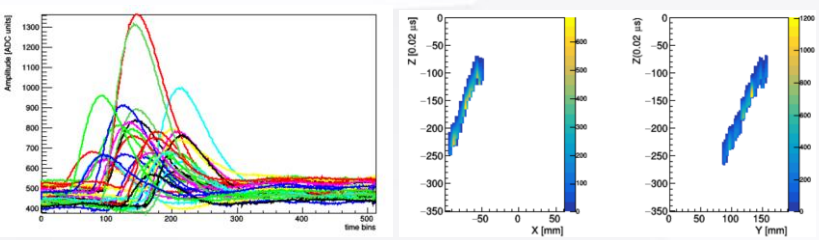


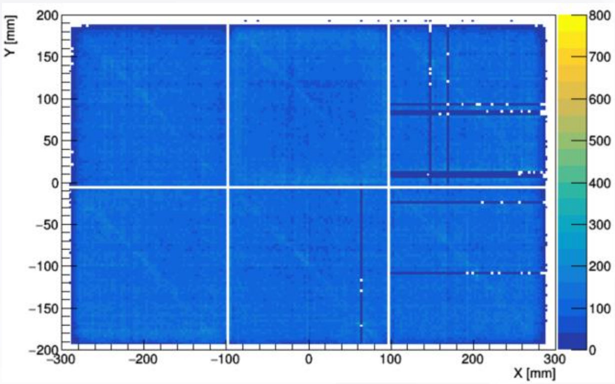
E-field distribution in the X-Y plane

External detector photo

Testing of the Charge Particle Detector

Cosmic ray Muon test

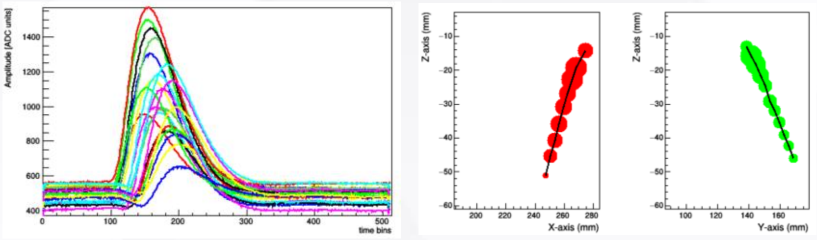


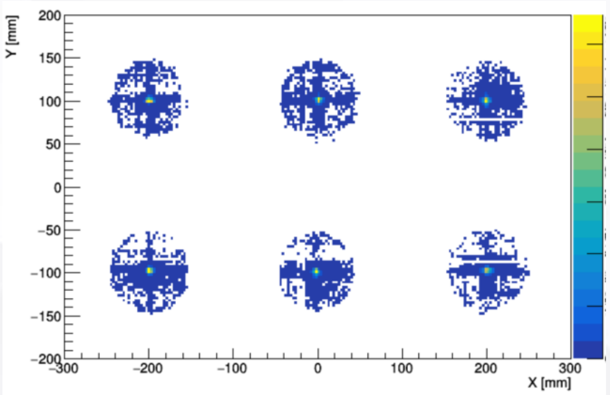


Muon track starting point distribution map

➢ Check the detector and monitor its long-term stable operation.

Alpha calibration (Am-241 source)





Alpha track starting point distribution map

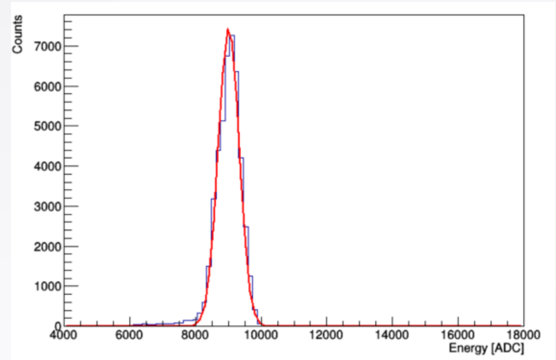
➢ Calibrate each Micromegas module with the Am-241 source.

Testing of the Charge Particle Detector

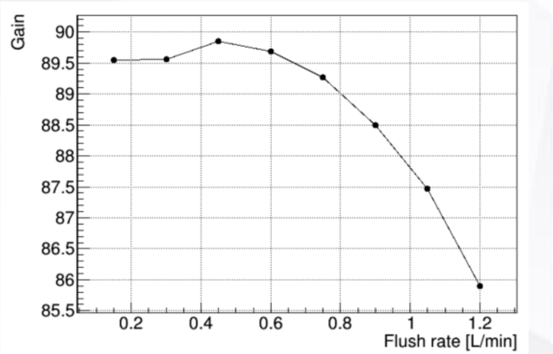
Gas--- 1bar Ar-7%CO_2 （0.1 L/min）

- Alpha calibration (Am-241 source)

➢ Calibrate the detector with the 5.485 MeV energy peak of the Am-241 to optimize the working conditions of the detector.

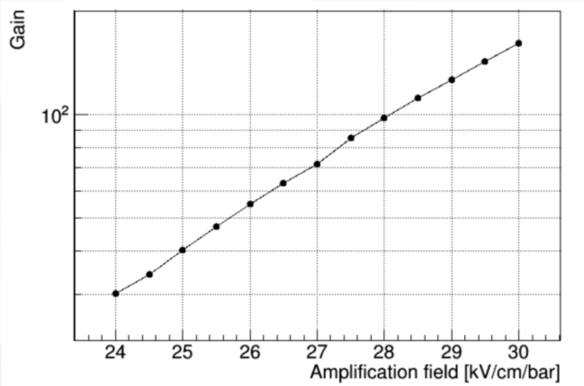


Spectrum of Am-241
9.5% FWHM at 5.485 MeV

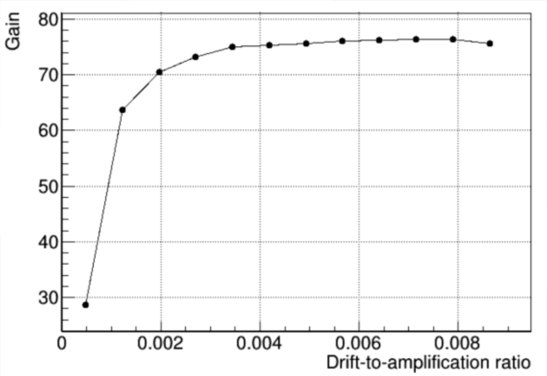


Gain evolves with flow rates

➢ Cleanroom



Gain evolves with amplification fields

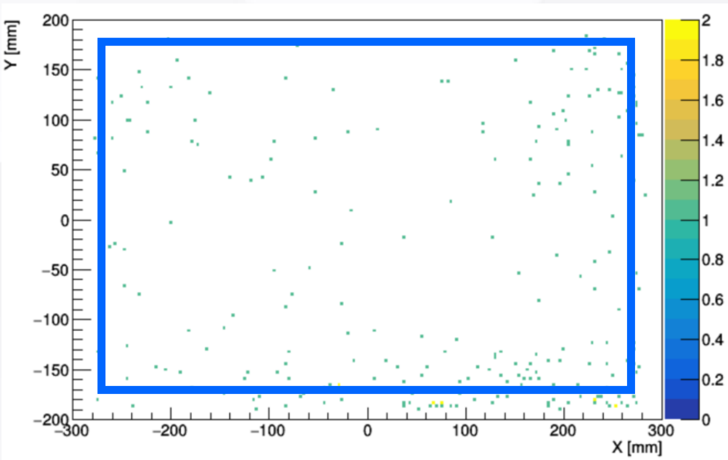


Gain evolves with drift fields

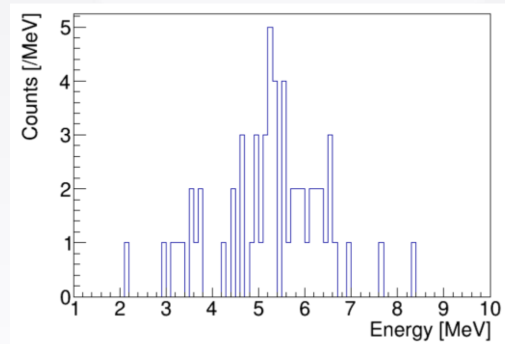
Background Measurement of the Detector

- Intrinsic alpha background of the detector

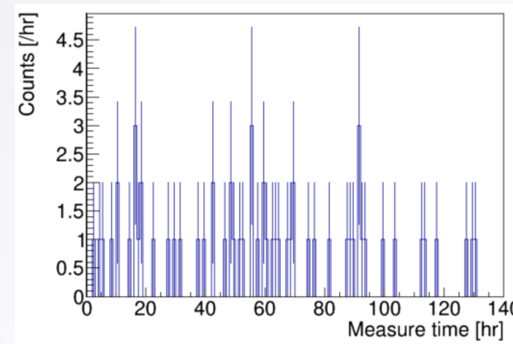
Gas--- 1bar Ar-7%CO_2 (0.1 L/min)



Alpha track starting point distribution map



Background spectrum



Background counting rate

- Alpha background (Copper cathode + Gas): $(0.14 \pm 0.02)\times10^{-6}$ Bq/cm^2

- Multiple rounds of alpha background test of the detector (uBq/cm^2)

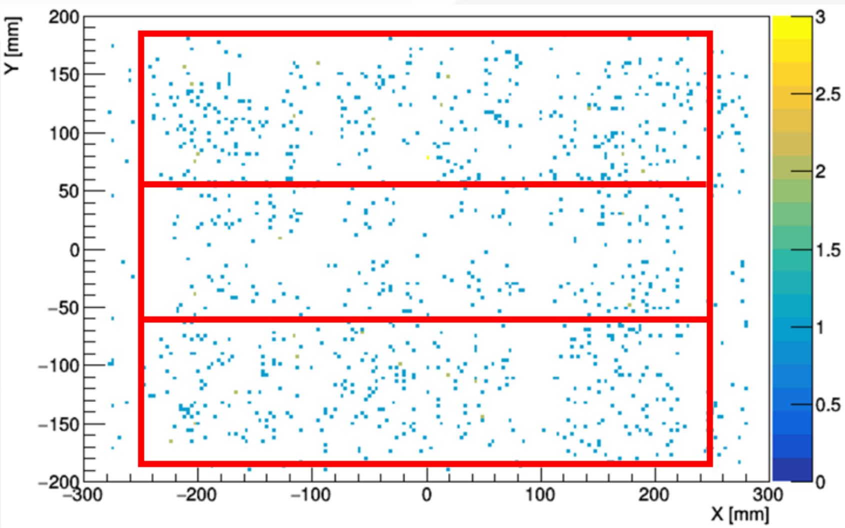
	Argon gas filled for a month		Pickling copper cathode		Replace field cage with less acrylic	
1.29 ± 0.06	→	0.82 ± 0.06	→	0.47 ± 0.03	→	0.14 ± 0.02

- (Track-related cut for α signals： Energy cut 1-10 MeV, track direction upwards, FV cut 2.7 cm to exclude backgrounds from the field cage)

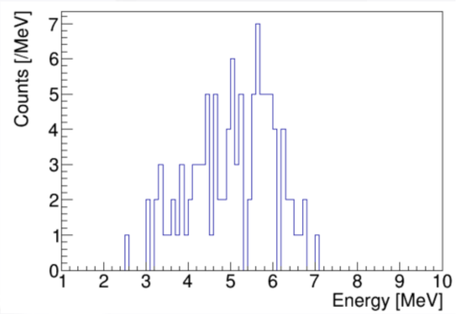
Measurement of Acrylic Surface Radioactivity

- Acrylic sample test (JUNO production)

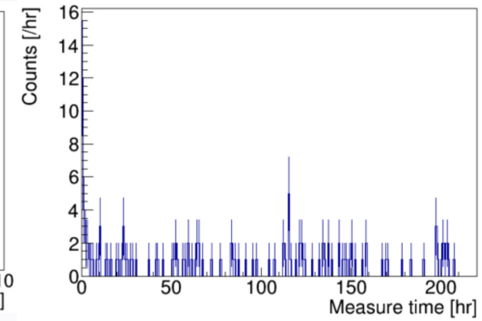
Gas--- 1bar Ar-7%CO_2 （0.1 L/min）



Alpha track starting point distribution map



Sample spectrum



Sample counting rate

- 3 pieces of Acrylic samples: 1730 cm^2, exposed in the underground lab, Rn~180 Bq/m^3
- Gas --- 1bar Ar-7%CO_2 （0.1 L/min）

- α contamination (Acrylic+ Gas): 0.91 ±0.03 uBq/cm^2
- α background (Cathode + Gas): 0.14 ± 0.02 uBq/cm^2
- Estimated α background of Acrylic sample: 0.77 ~ 0.91 uBq/cm^2

- Assuming the gas background is 0.14 ± 0.02 $\mu Bq/cm^2$
- Assuming the gas background is 0

Measurement of Acrylic Surface Radioactivity

- Acrylic sample α test (JUNO production)

	No sample	Acrylic 1 (Exposed in the underground lab - Rn~250Bq/m^3)	Acrylic 2 (Wiped with dust-free paper)	Acrylic 3 (Cleaned with alcohol)	Acrylic 4 (Rinsed with pure water + nitrogen gas)
Measure area [cm^2]	1889	1730	1730	1270	1270
Measure time [hr]	187	160	170	185	252
Contamination (Acrylic + Gas) [uBq/cm^2]	-	0.91 ± 0.03	0.45 ± 0.03	**0.18 ± 0.03**	0.25 ± 0.03
Background (Copper cathode + Gas) [uBq/cm^2]	**0.14 ± 0.02**	-	-	-	-
Estimated contamination of Acrylic [uBq/cm^2]	-	0.77 ~ 0.91	0.31 ~ 0.45	0.04 ~ 0.18	0.11 ~ 0.25

- （Track-related cut for α signals： Energy cut 1-10 MeV, track direction upwards, FV cut 2.7 cm to exclude backgrounds from the field cage）

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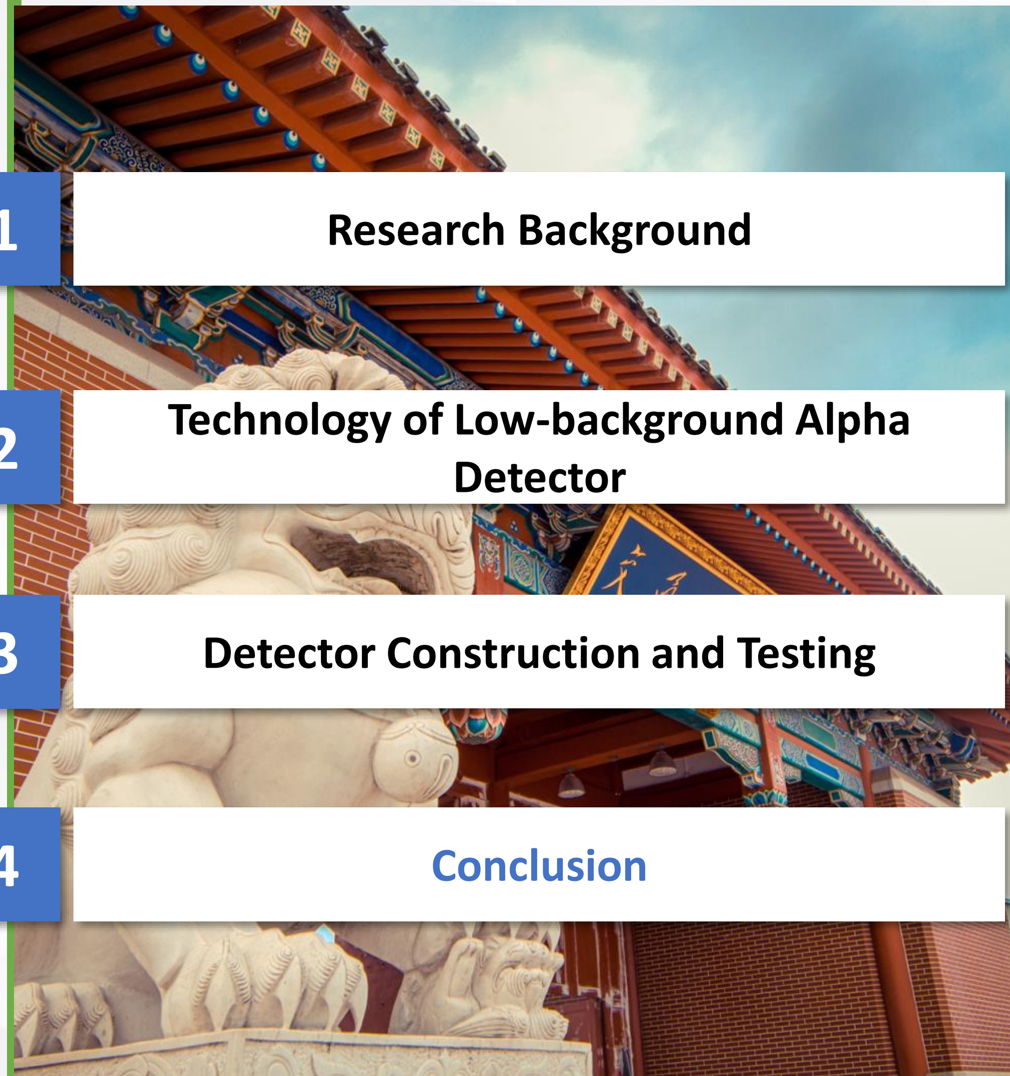

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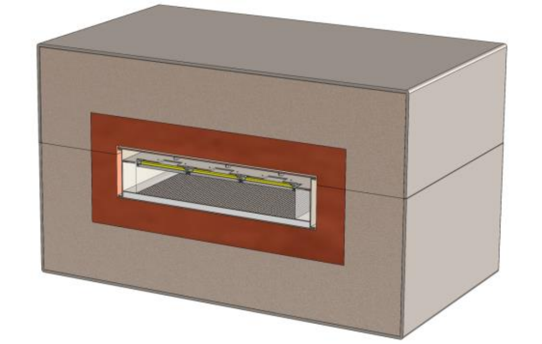
Conclusion

- Ultra-Low Background Charged Particle Detector
  - Combining gas TPC and thermal-bonding Micromegas.
  - Particle track discrimination to reduce backgrounds.
  - Large area, high detection efficiency, high sensitivity.



Detector and shield

- Next Steps
  - Further reduce the intrinsic background of the detector to enhance the its sensitivity. Optimize the design and simplify the operation process.
  - Install shielding, and conduct low background material surface radioactivity measurement at the Jinping Underground Laboratory.

Thank you for attention

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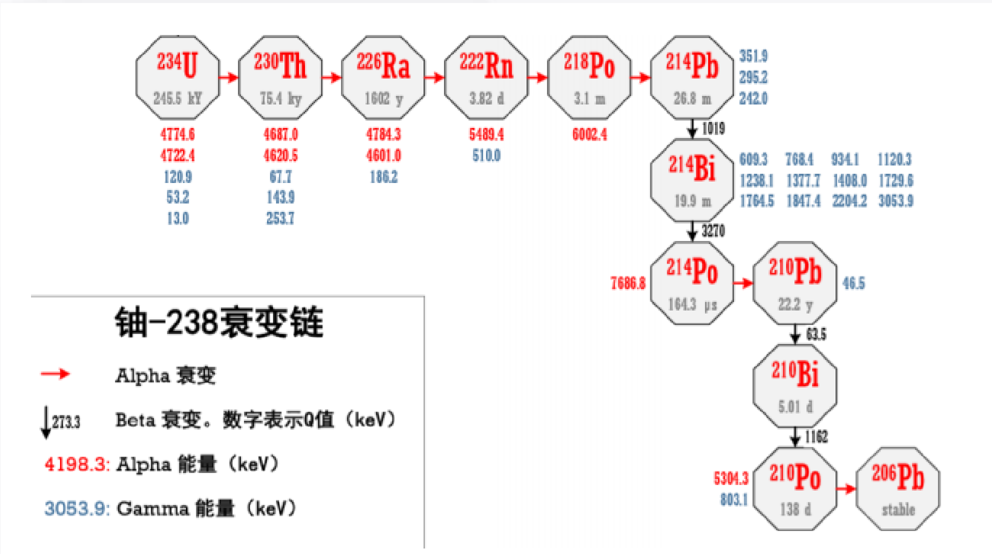
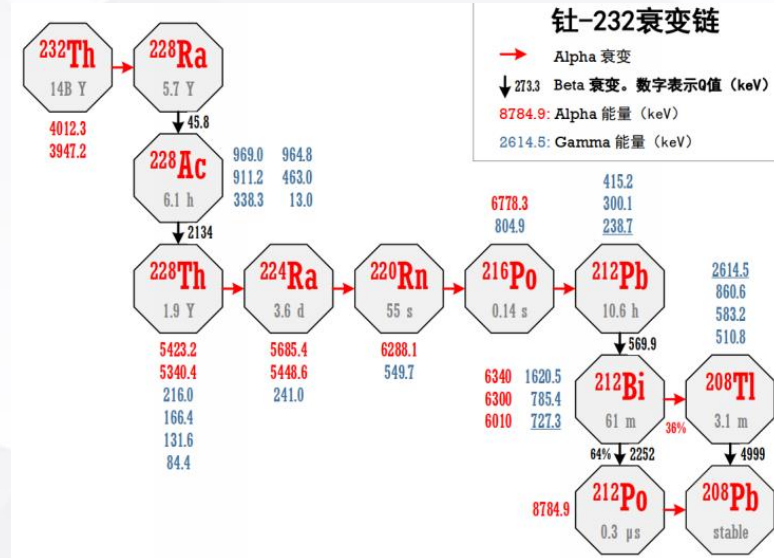
Backup



铀-238衰变链
Alpha 衰变
273.3 Beta 衰变。数字表示Q值（keV）
4198.3: Alpha 能量（keV）
3053.9: Gamma 能量（keV）
234U 245.5 kY
4774.6
4722.4
120.9
53.2
13.0
230Th 75.4 ky
4687.0
4620.5
67.7
143.9
253.7
226Ra 1602 y
4784.3
4601.0
186.2
222Rn 3.82 d
5489.4
510.0
218Po 3.1 m
6002.4
214Pb 26.8 m
351.9
295.2
242.0
1019
214Bi 19.9 m
609.3 768.4 934.1 1120.3
1238.1 1377.7 1408.0 1729.6
1764.5 1847.4 2204.2 3053.9
3270
214Po 164.3 μs
7686.8
210Pb 22.2 y
46.5
63.5
210Bi 5.01 d
1162
210Po 138 d
5304.3
803.1
206Pb stable



钍-232衰变链
Alpha 衰变
273.3 Beta 衰变。数字表示Q值（keV）
8784.9: Alpha 能量（keV）
2614.5: Gamma 能量（keV）
232Th 14B Y
4012.3
3947.2
228Ra 5.7 Y
45.8
228Ac 6.1 h
969.0 964.8
911.2 463.0
338.3 13.0
2134
228Th 1.9 Y
5423.2
5340.4
216.0
166.4
131.6
84.4
224Ra 3.6 d
5685.4
5448.6
241.0
220Rn 55 s
6288.1
549.7
216Po 0.14 s
6778.3
804.9
212Pb 10.6 h
415.2
300.1
238.7
569.9
212Bi 61 m
6340 1620.5
6300 785.4
6010 727.3
36%
64% 2252
208Tl 3.1 m
2614.5
860.6
583.2
510.8
4999
212Po 0.3 μs
8784.9
208Pb stable