ISINN-31

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Recent advances of the (n, cp) reaction measurements

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- **Cooperation**

PKU FLNP JINR CIAE CSNS Back-n

- **Neutron sources**

4.5MV VdG, EG-5, HI-13 tandem, CSNS Back-n

The Interaction of Neutrons with Nuclei (neutron induced nuclear reactions)

- **(*n*, *f*):** release nuclear energy and produce neutrons
- **(*n*, γ):** neutron absorption and fuel conversion(U→Pu, Th→U…)
- **(*n*, *n*), (*n*, *n'*):** neutron moderation
- **(*n*, *lcp*): Light Charged-Particle emission reaction**

  p, *d*, *t*, ^{3}He, α reactor control and neutron detection

(n, cp) reaction: (n, lcp) + (n, f) reactions

Neutron induced Charged-Particle emission reaction

QinShan Nuclear Power Station

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1. Introduction
2. From solid samples to gas samples
3. From GIC to TPC
4. From binary fissions to ternary fissions
5. Summary

1. Introduction

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Significances of the (n, cp) Reaction

- **Standard neutron cross sections:** $^{1}H(n,p)$, $^{3}He(n,p)$, $^{6}Li(n,t)$, $^{10}B(n,\alpha)$, $^{235,238}U(n,f)$
- **Nuclear engineering:** Tritium production, Reactor control, Reactor design, Material damage, Neutron detection and protection
- **Nuclear technology:** Single event effect and semiconductor doping
- **Biomedicine:** Radiation protection and cancer treatment
- **Nuclear astrophysics:** Nuclide synthesis and stellar evolution
- **Nuclear theory:** Nuclear reaction mechanism and nuclear structure

ZHANG Guohui, SCIENTIA SINICA Physica, Mechanica & Astronomica 50, 052005 (2020)

1. Introduction

(n, cp) Reaction <u>measurements</u>

Three elements

Neutron source	Sample	Detector

Two systems

Electronics and Data AcQuisition	Data processing and Simulation

1. Introduction

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Difficulties in (n, cp) reaction measurement

Facts

- Relatively small cross sections
- Strong background interferences
- Energy-loss & Self-absorption effect

Need

- High intensity neutron source
- Highly-enriched isotopic, enough thin sample
- Efficient charged particle detector

1. Introduction

~ 30 years

PKU JINR CIAE CSNS Back-n

A series of (n, cp) reactions have been measured

- **68** nuclear reactions, **128** datasets included in **Experimental Nuclear Reaction Data (EXFOR)** library, Laboratory code '**CPRBJG**'

- More than 100 publications (PRL, PLB, PRC, CPC, NIMA, EPJA, …)

Light nuclei — Medium mass nuclei — Heavy Nuclei

^{1}H ^{2}H ^{6}Li ^{10}B ^{12}C ^{14}N ^{16}O ^{19}F ^{20}Ne

^{25}Mg ^{35}Cl ^{39}K ^{40}Ca $^{54,56,57}Fe$ $^{58,60,61}Ni$ ^{63}Cu $^{64,66,67}Zn$

^{91}Zr ^{95}Mo $^{143,144}Nd$ $^{147,149}Sm$ $^{232}\underline{Th}$ $^{235}\underline{U}$

(n, p), (n, d), (n, t), (n, α), (n, <u>f</u>) reactions

1. Introduction

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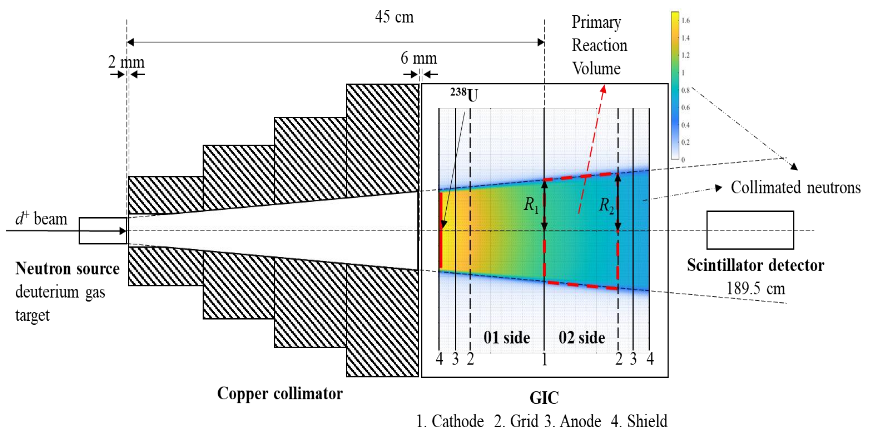
Recent advances

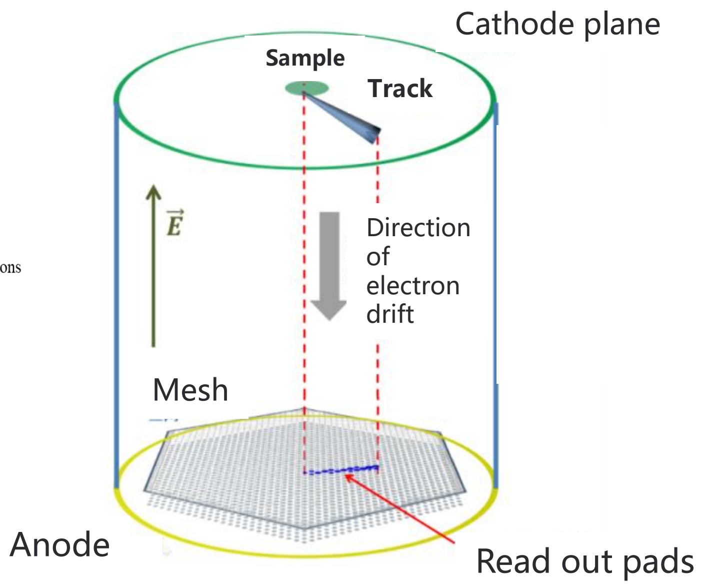
1st From solid samples to gas samples

2nd From GIC to TPC

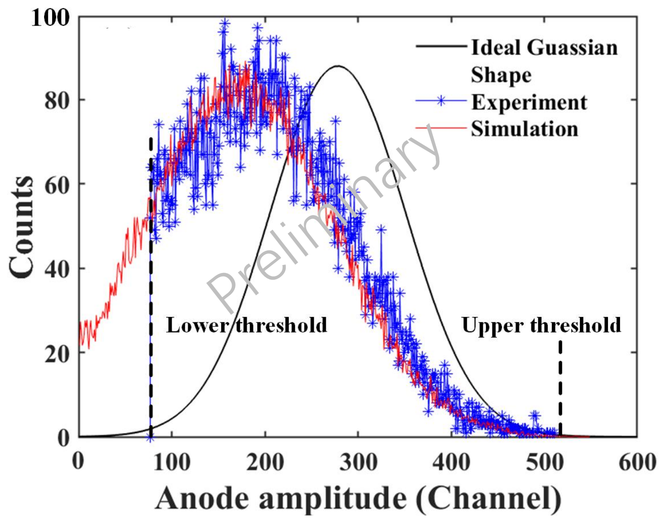
3rd From binary fissions to ternary fissions



Neutron flux distribution in the gas sample



Structure of the TPC



LRA measured from the ternary fission of the ^{252}Cf

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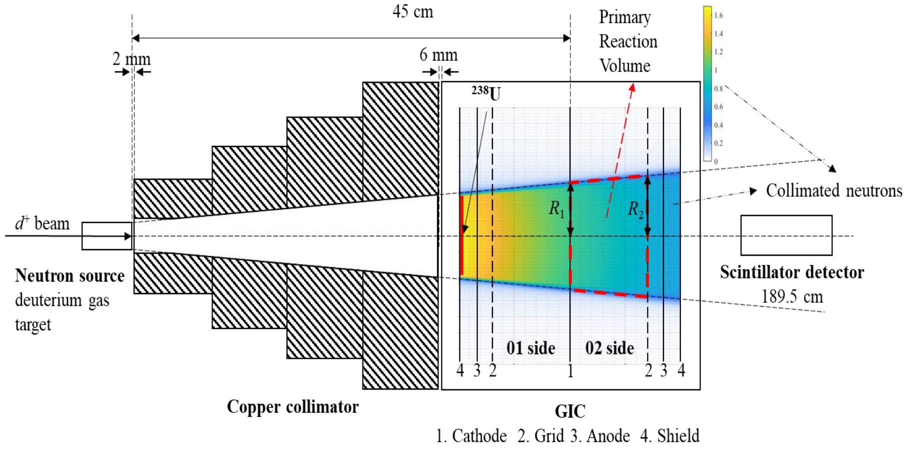
4. From binary fissions to ternary fissions

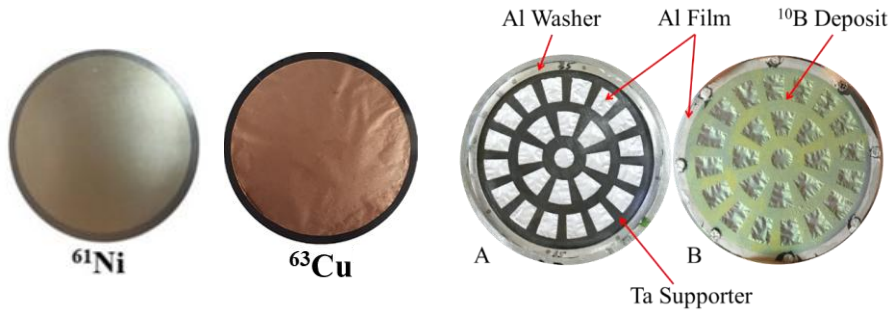
5. Summary

2. From solid samples to gas samples

Advantages of using gas samples

- ✓ **Nuclei number:** compared to solid sample, > 2 orders of magnitudes
- ✓ **Sample:** easy preparation (Working gas + Sample gas)
- ✓ **Detection:** no self-absorption, high detection efficiency



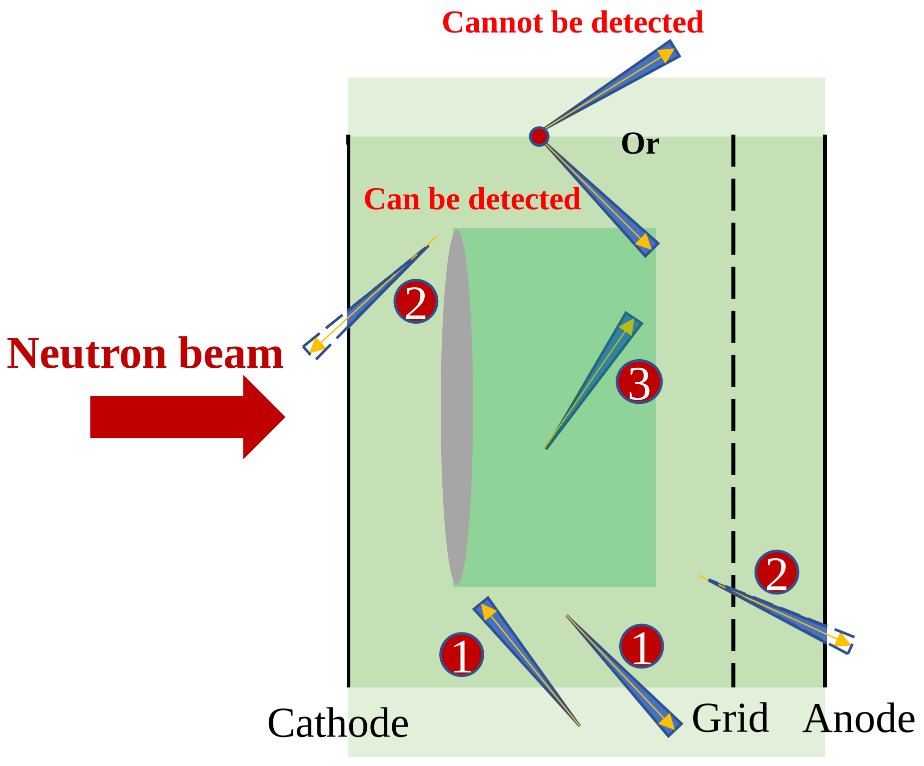


Gas sample vs Solid samples

2. From solid samples to gas samples

Difficulty: The Wall Effect

Part of the particle energy cannot be deposited in the sensitive volume



Grid ionization Chamber

(1) Radial wall effect

part of the energy deposit in areas with low electric field

(2) Axial wall effect

part of the energy deposit in the plates or between the grid and the anode

(3) No wall effect

2. From solid samples to gas samples

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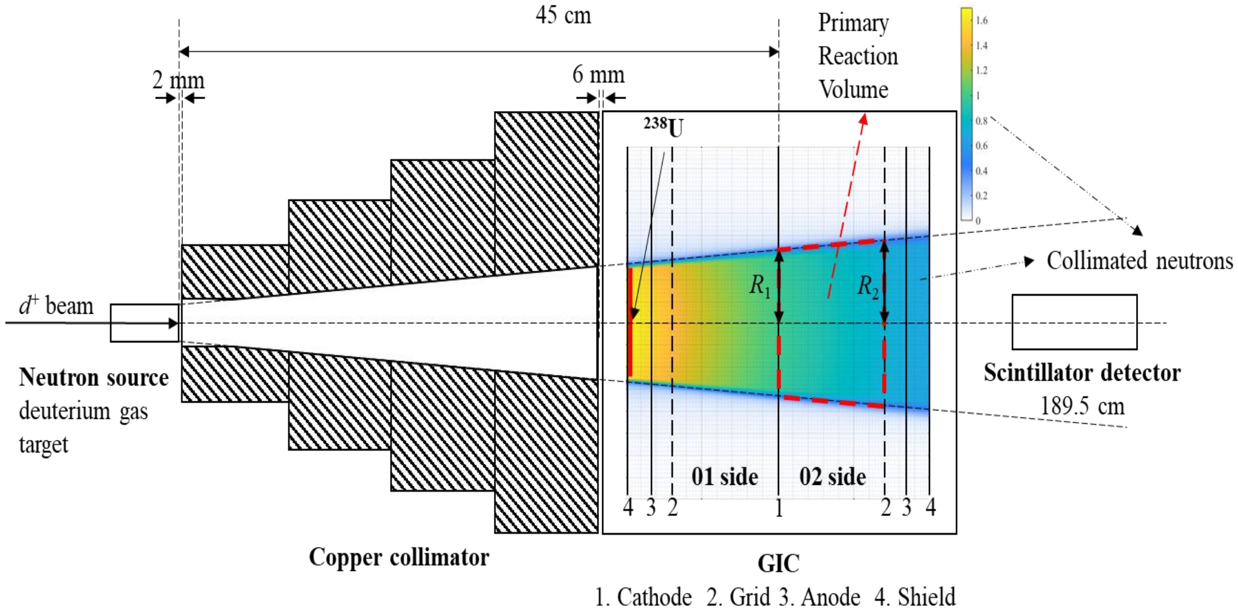
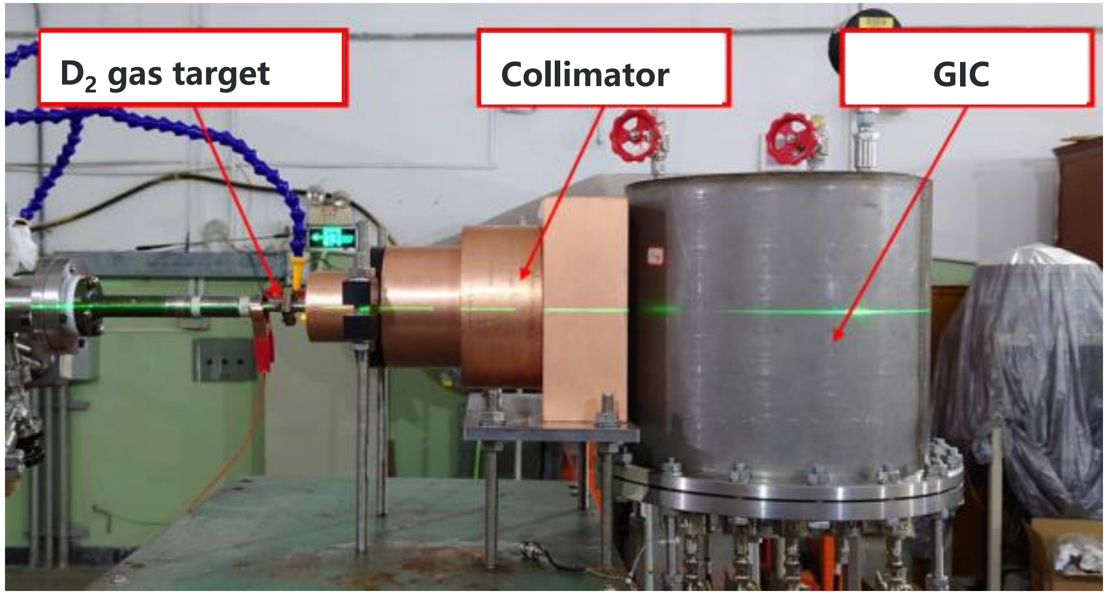
Experimental setup

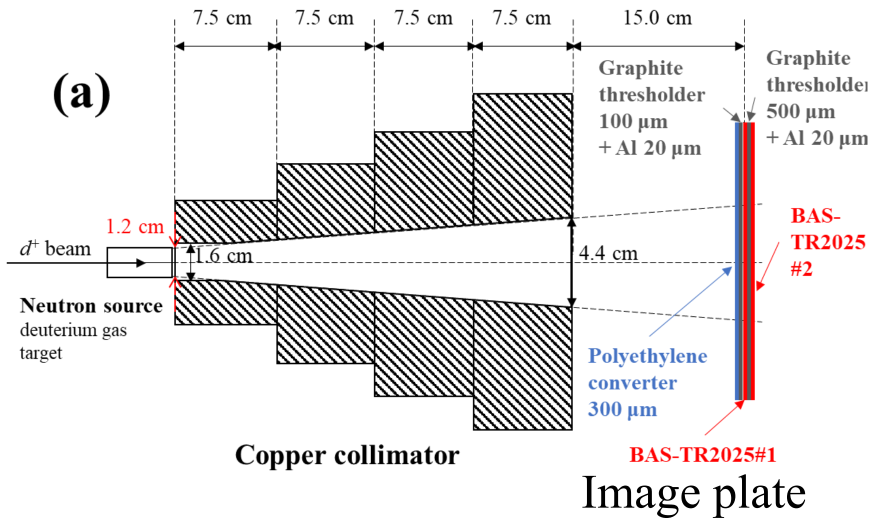


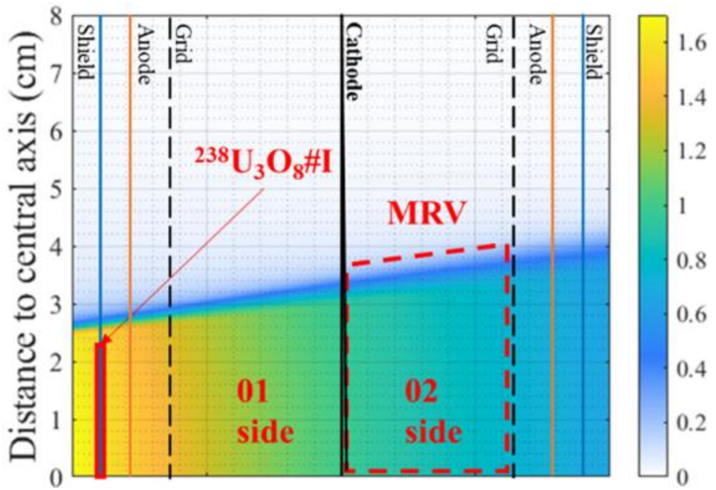


- Neutron **Collimator** to reduce the radial wall effect
- Using **Rise Time** information of cathode and anode signals
- Detained **Simulations** for corrections

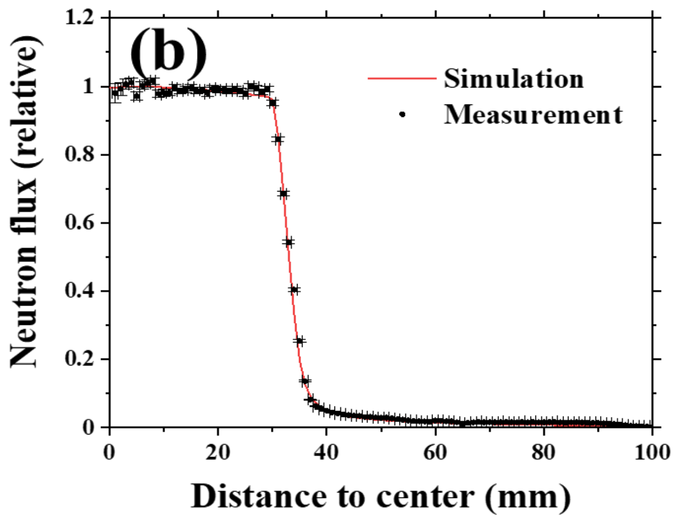
2. From solid samples to gas samples

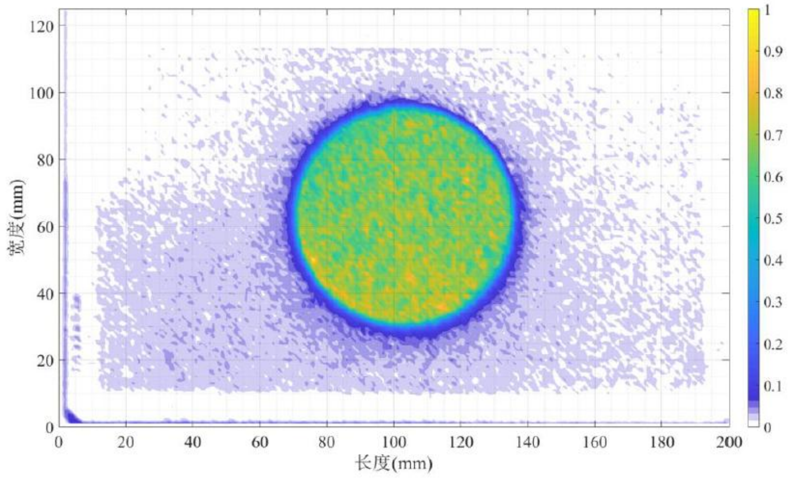
➢ Test of the neutron collimation effect





Neutron fluence distribution from simulation



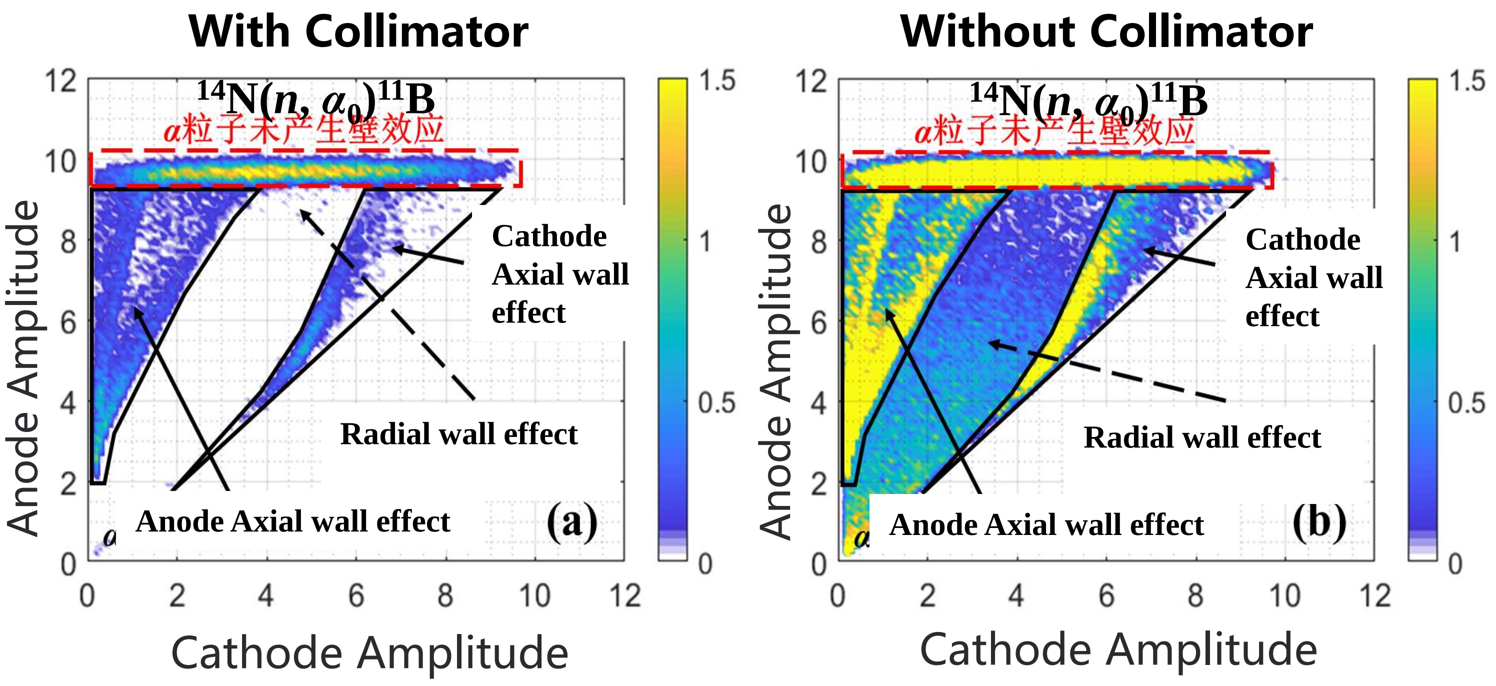


Neutron beam profile from measurement

2. From solid samples to gas samples

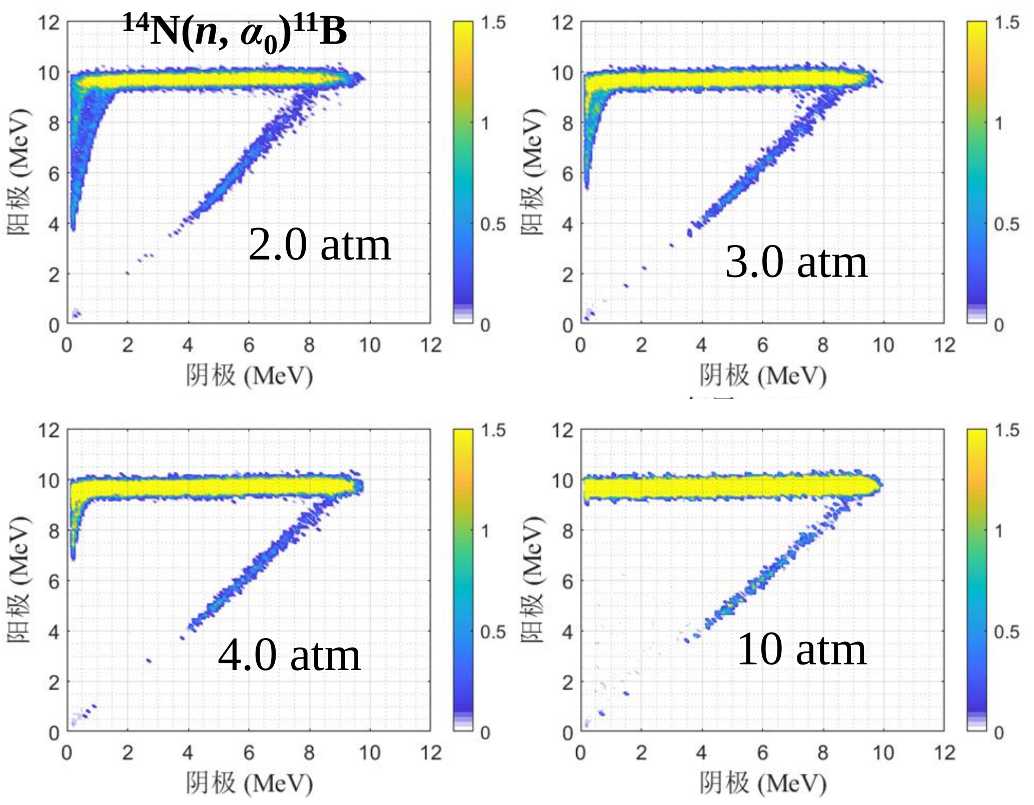
- **Detailed Simulations were performed**

$^{14}N(n, \alpha_0)^{11}B$



1 atm Kr + 8% N_2, $^{14}N(n, \alpha_0)^{11}B$ reaction simulation, E_n=10.0 MeV

Different gas pressures

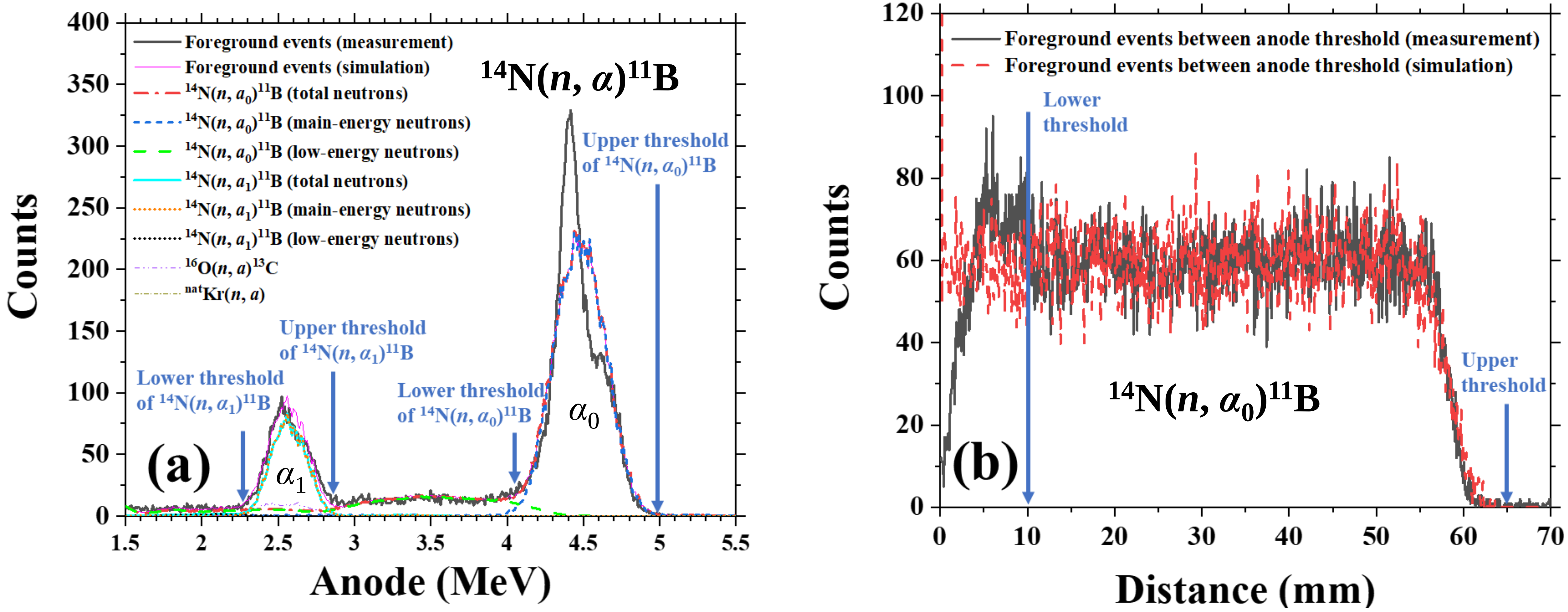


Kr + 8% N_2, $^{14}N(n, \alpha_0)^{11}B$ reaction simulation, E_n=10.0 MeV

2. From solid samples to gas samples

➢ Combined with Simulation results to correct the axial wall effect

- Gas Sample: 3.8 atm Kr + 5.00% N_2 + 0.35% CO_2



The measured and simulated anode spectrum of the ^{14}N(n, $\alpha_{0,1}$)^{11}B reactions (a), the measured and simulated distance projection spectrum of the ^{14}N(n, α_0)^{11}B reaction (b) at E_n = 5.15 MeV

2. From solid samples to gas samples

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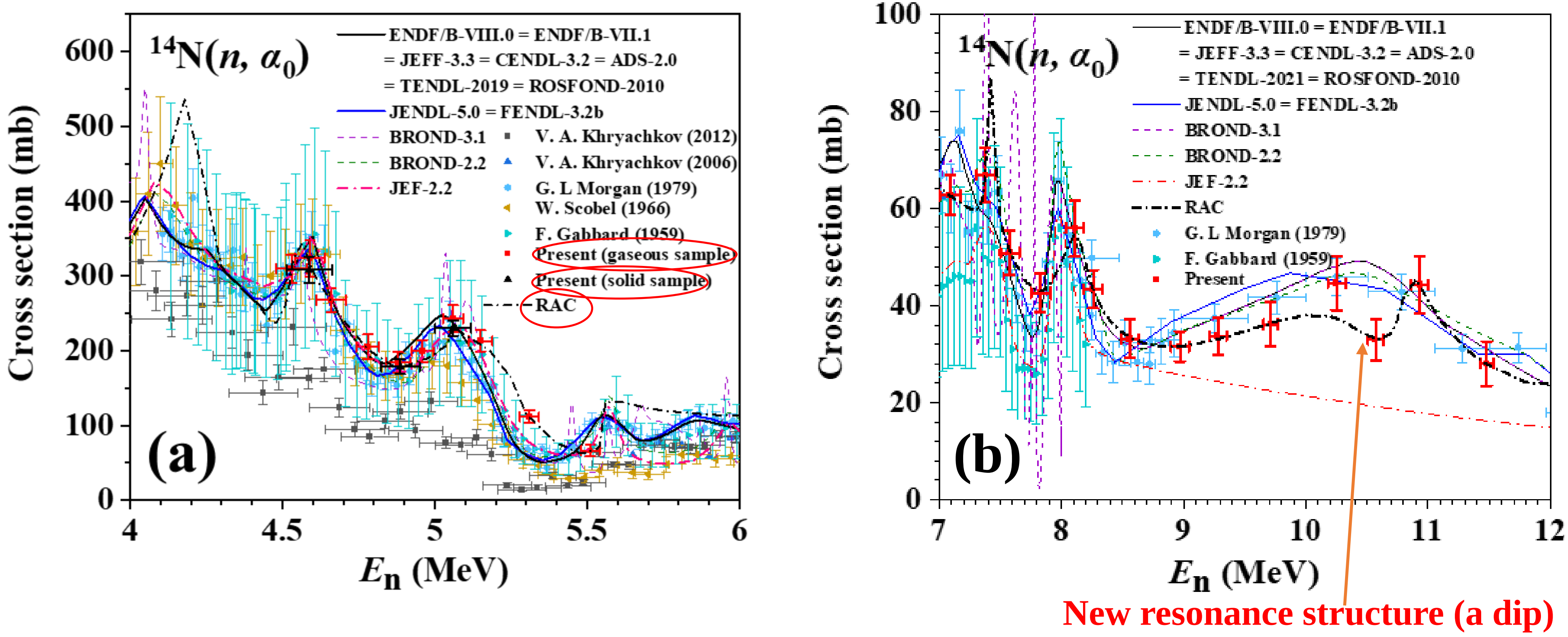
❑ Measured $^{14}N(n, \alpha_0)^{11}B$ cross sections @PKU and CIAE

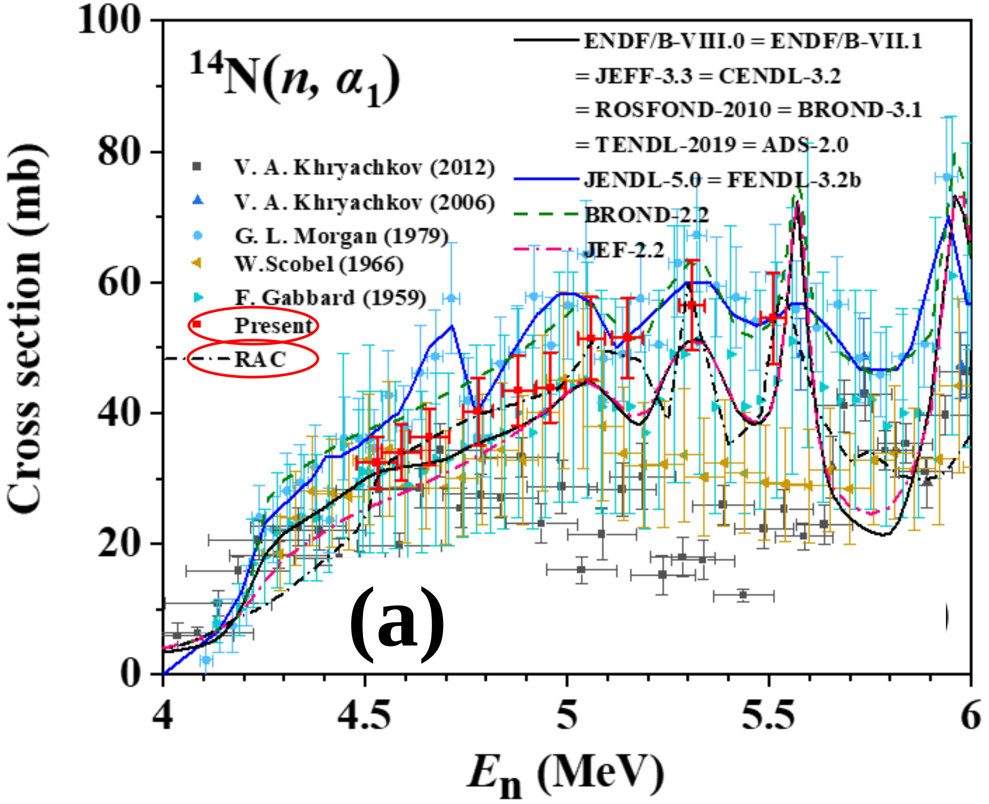


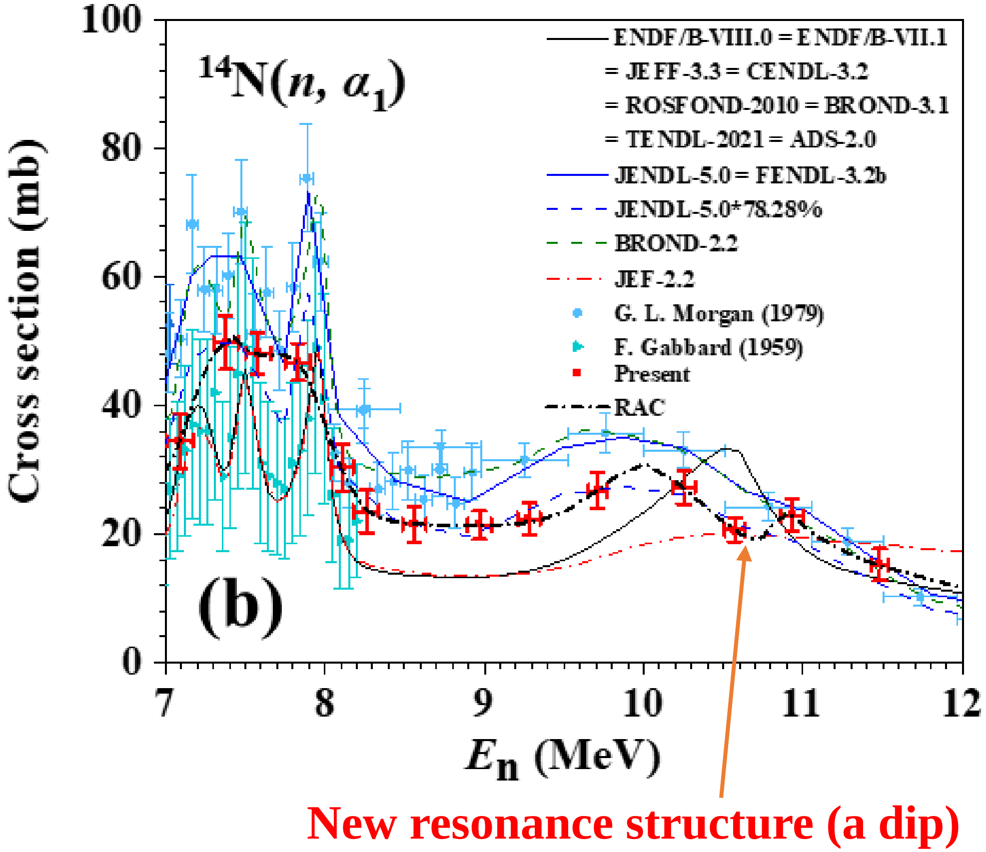
Present cross sections of the $^{14}N(n, \alpha_0)^{11}B$ reaction compared with existing measurement, evaluation and R-matrix calculation results.

Yiwei Hu et al., EPJA, 60, 51 (2024)

2. From solid samples to gas samples

❑ **Measured $^{14}N(n, \alpha_1)^{11}B$ cross sections @PKU and CIAE**





Present cross sections of the $^{14}N(n, \alpha_1)^{11}B$ reaction compared with existing measurement, evaluation and R-matrix calculation results.

Yiwei Hu et al., EPJA, 60, 51 (2024)

2. From solid samples to gas samples

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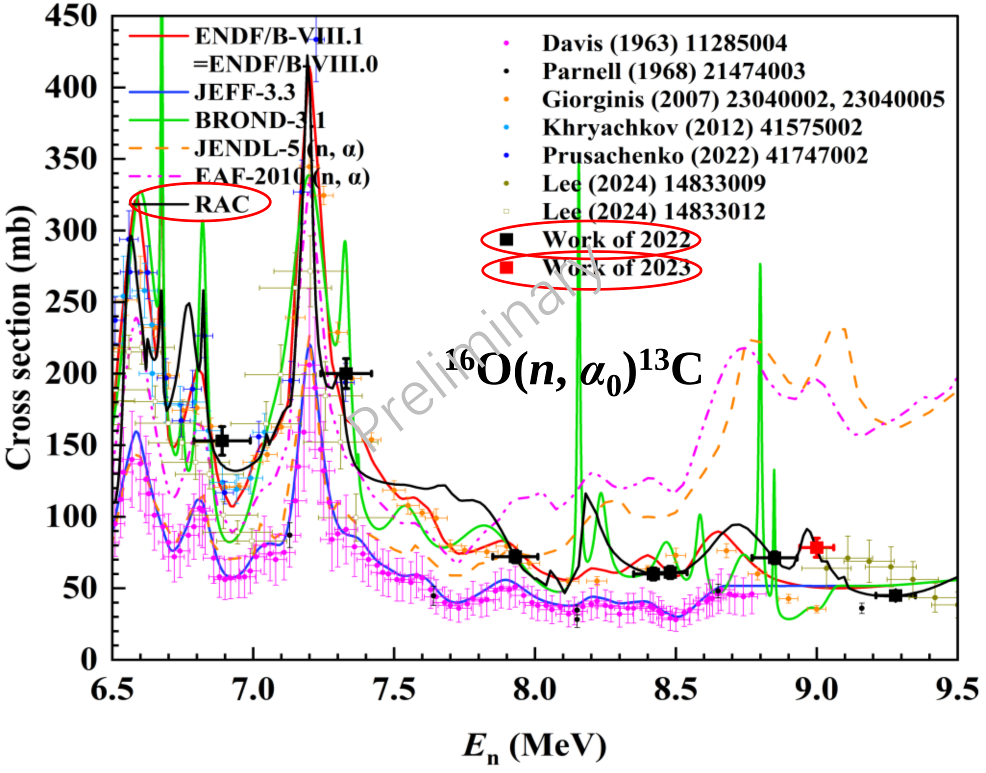
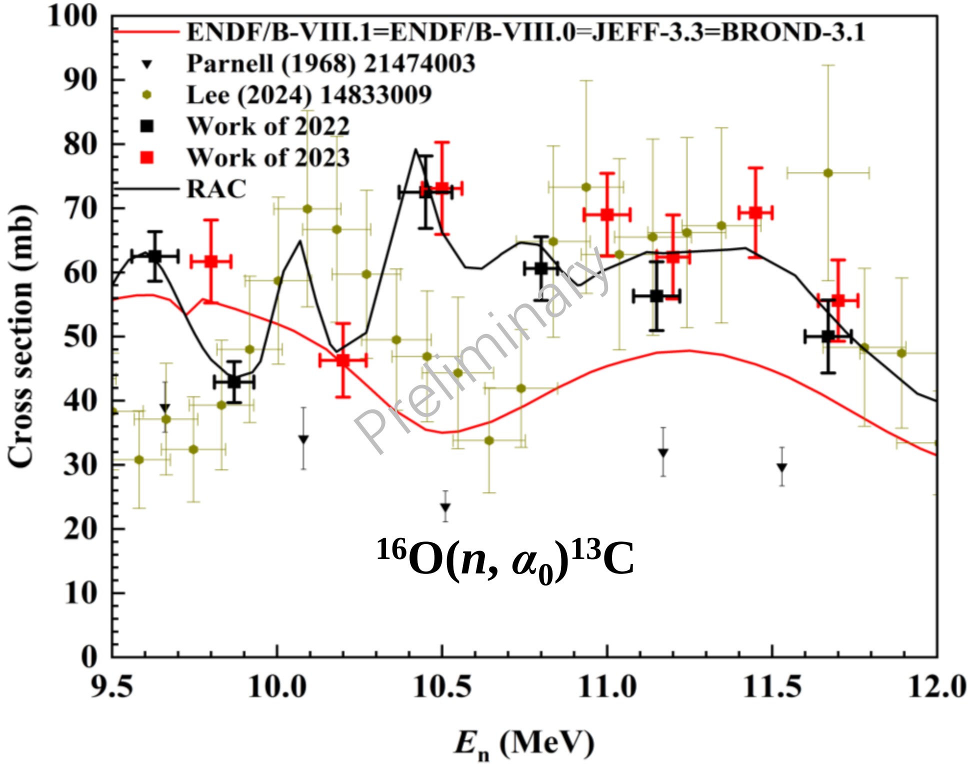
- **Measured $^{16}O(n, \alpha_0)^{13}C$ cross sections @CIAE**
  - Woking Gas: 3.0 atm Kr+4.0%CO_2 in 2022, 4.0 atm Kr+3.0%CO_2 in 2023





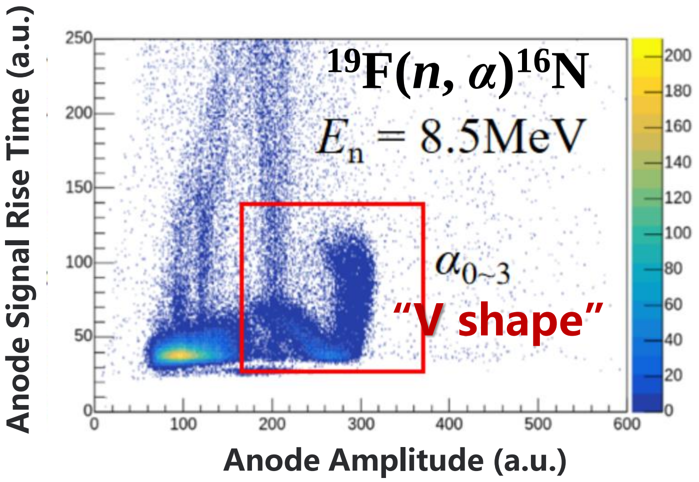
Present cross sections of the $^{16}O(n, \alpha_0)^{13}C$ reaction compared with existing measurement, evaluation and R-matrix calculation results.

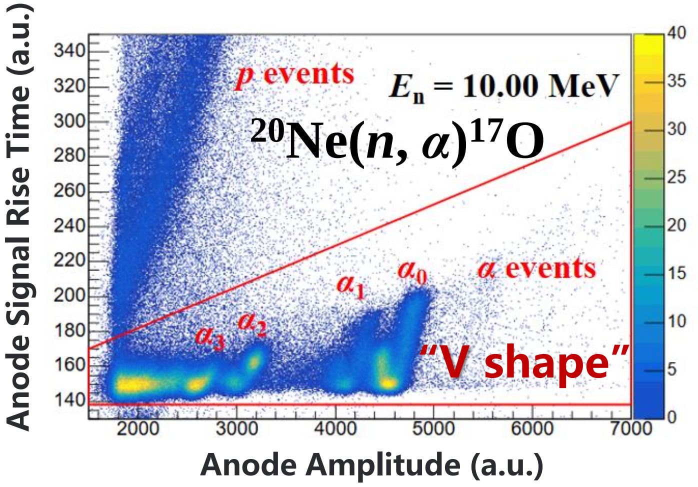
Cong Xia et al., EPJA, under review

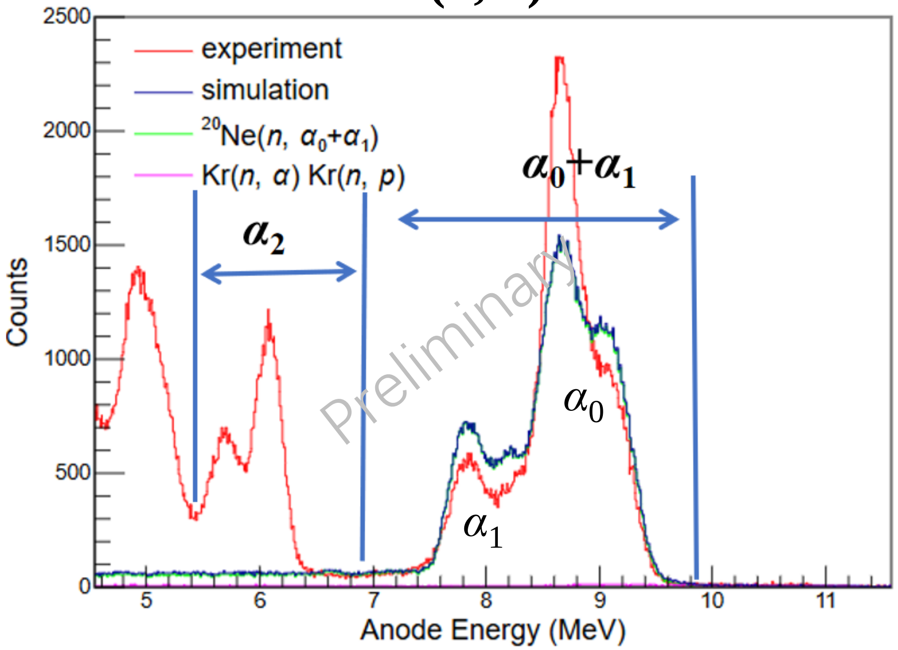
2. From solid samples to gas samples

- **Measured ^{19}F(n, α)^{16}N and ^{20}Ne(n, α)^{17}O cross sections @CIAE**
  - Working Gas: **Data measured @Dubna in July 2024 are in processing**

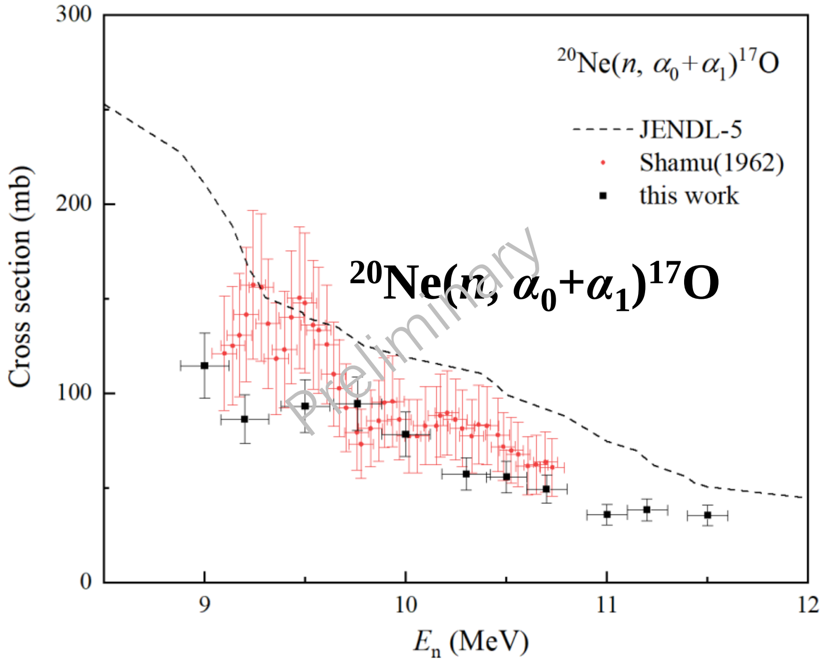
    For **^{19}F(n, α)^{16}N**, 3.96bar 97.0%Kr + 3.0%CF_4. For **^{20}Ne(n, α)^{17}O**, 4.5bar 78.9%Kr + 20.0%Ne + 1.1%CH_4







Anode spectrum

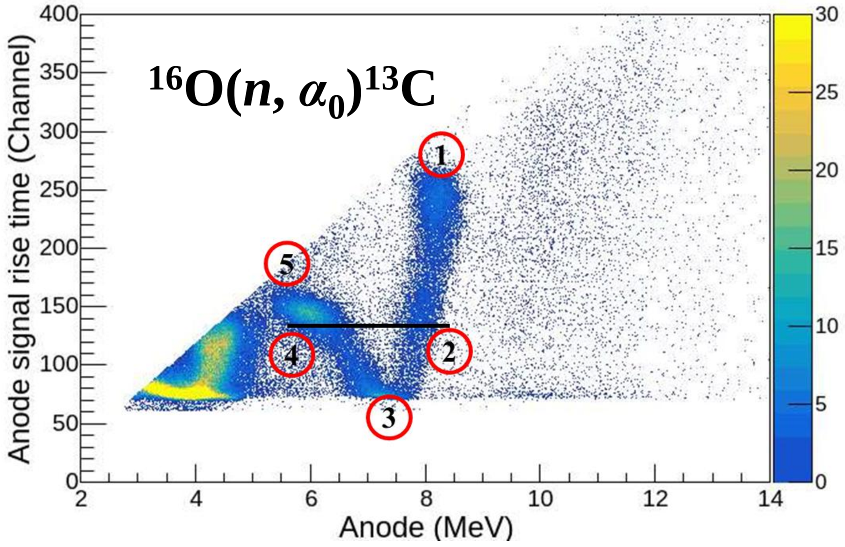


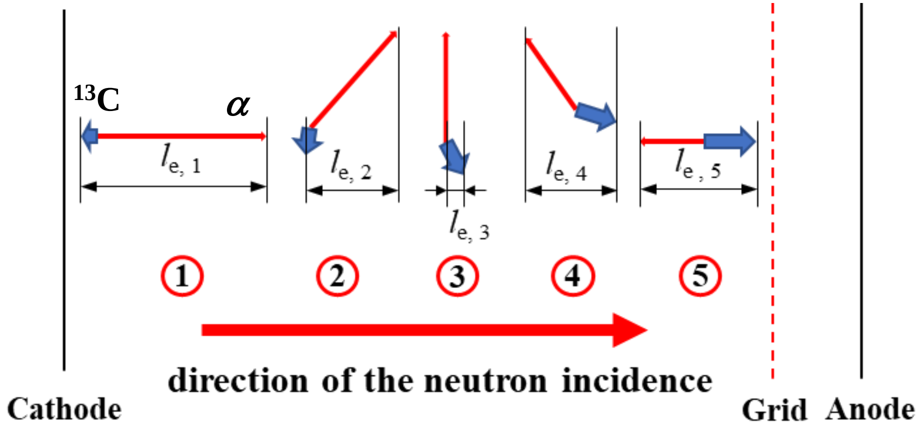
^{20}Ne(n, α_0+α_1)^{17}O cross sections

Wenkai Ren et al., to be submitted

2. From solid samples to gas samples

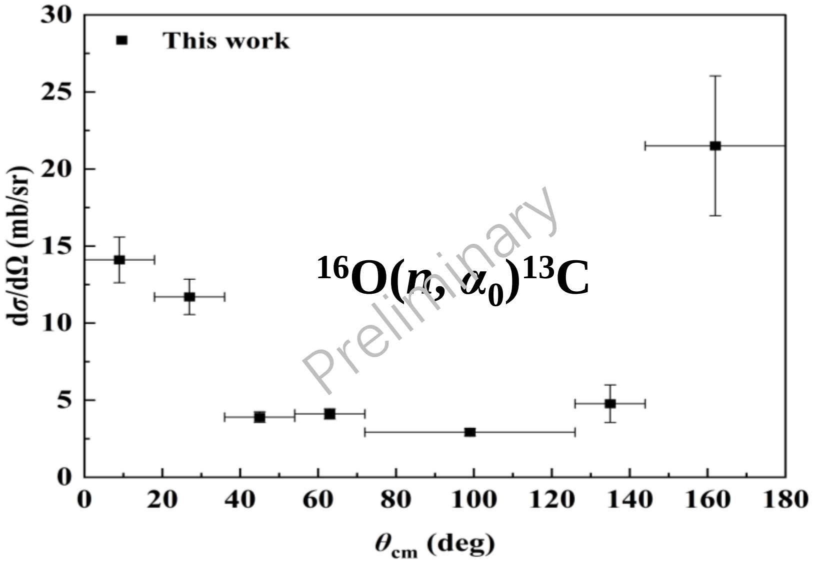
❑Measurement of angular differential cross sections using gas sample @CIAE





Pulse Height Defect (^{13}C residual nuclei)
Kinematic effect

"V shape" in the two-dimensional spectrum of the anode rise time vs anode amplitude



Angular differential cross sections of the $^{16}O(n, \alpha_0)^{13}C$ reaction at E_n = 10.45 MeV

Cong Xia et al., to be submitted

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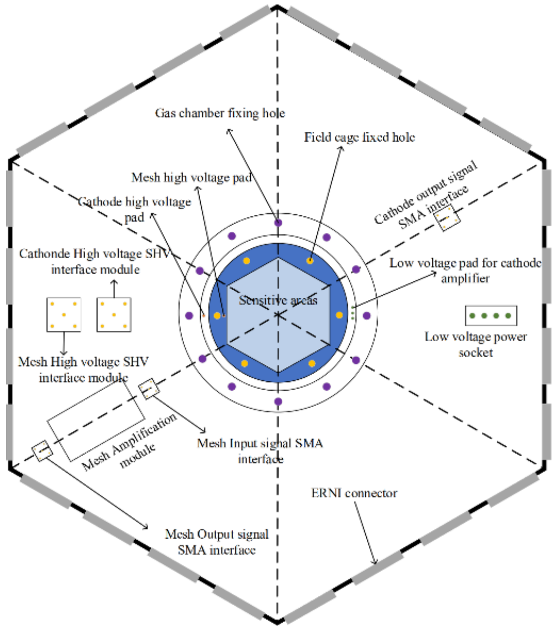
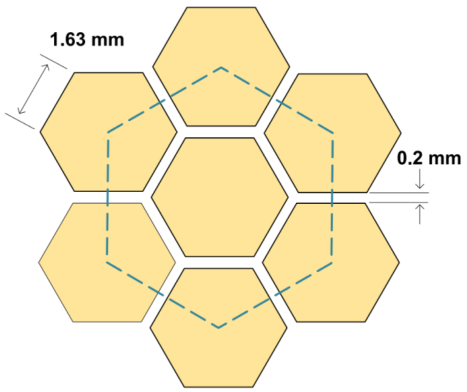
3. From GIC to TPC

Multi-purpose Time Projection Chamber (MTPC) @CSNS Back-n





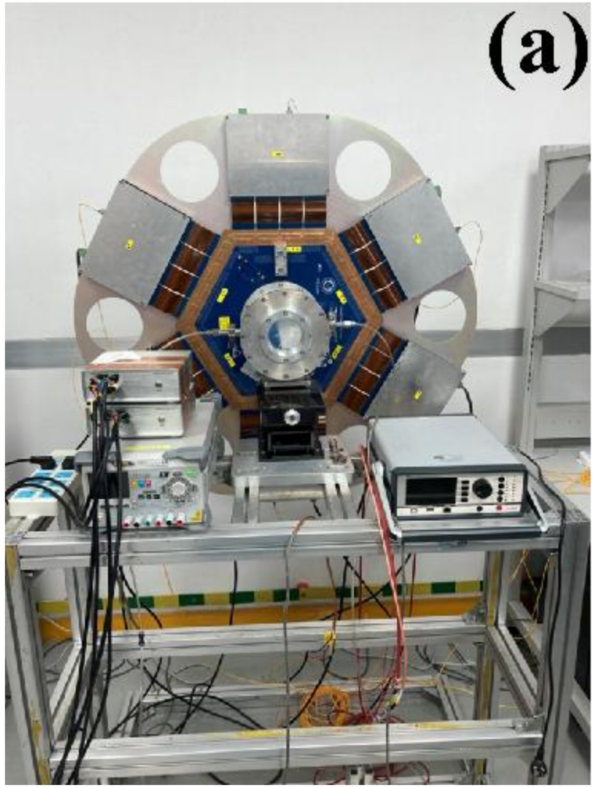
- Developed by **CSNS Back-n** team and **USTC**
- Gain structure: Micromegas
- Signal: **1519 readout pads** + cathode + mesh
- Code: BLUET

TPC (**T**ime **P**rojection **C**hamber)

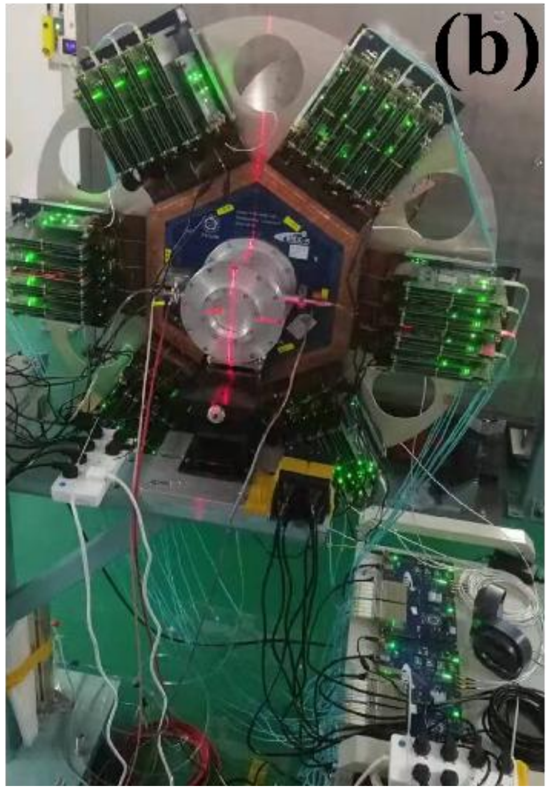
- **Particle track reconstruction**
- **Particle type identification**
- **Nuclear reaction event location**

3. From GIC to TPC

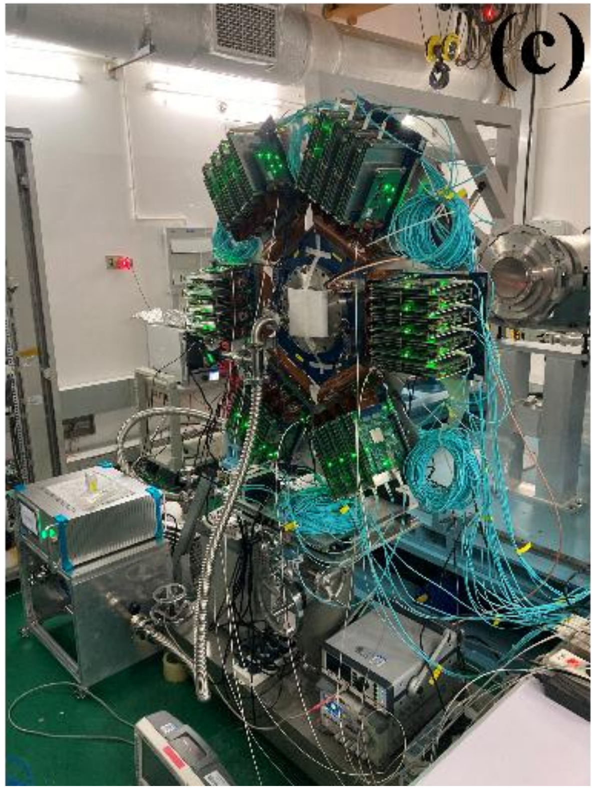
Three versions of the MTPC



MTPC-v0



MTPC-v1



MTPC-v2

Haofan Bai and **Guohui Zhang**, Radiation Detection Technology and Methods, online published

3. From GIC to TPC

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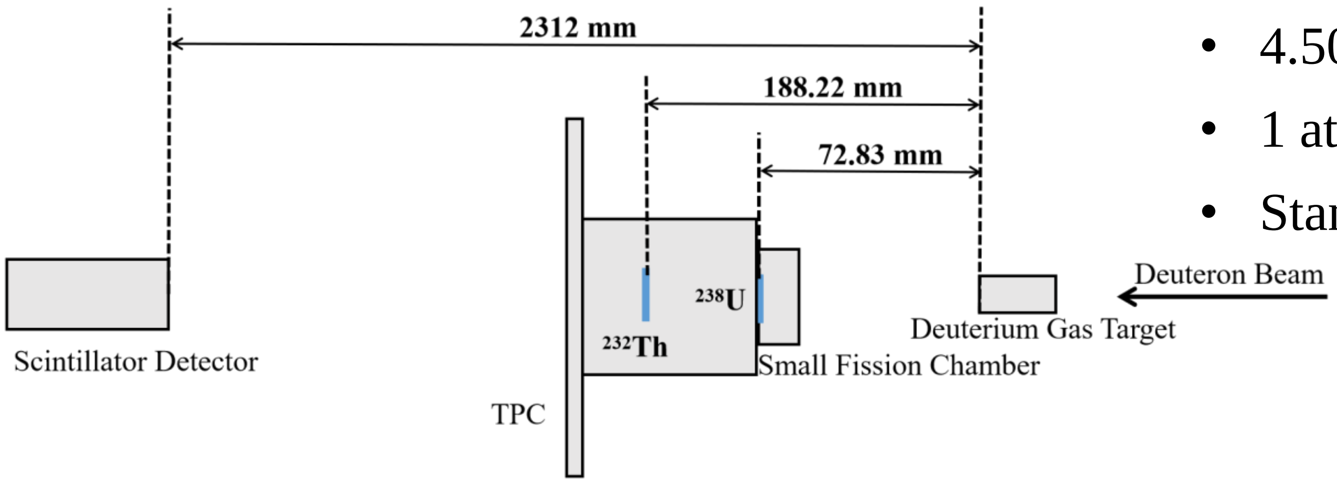
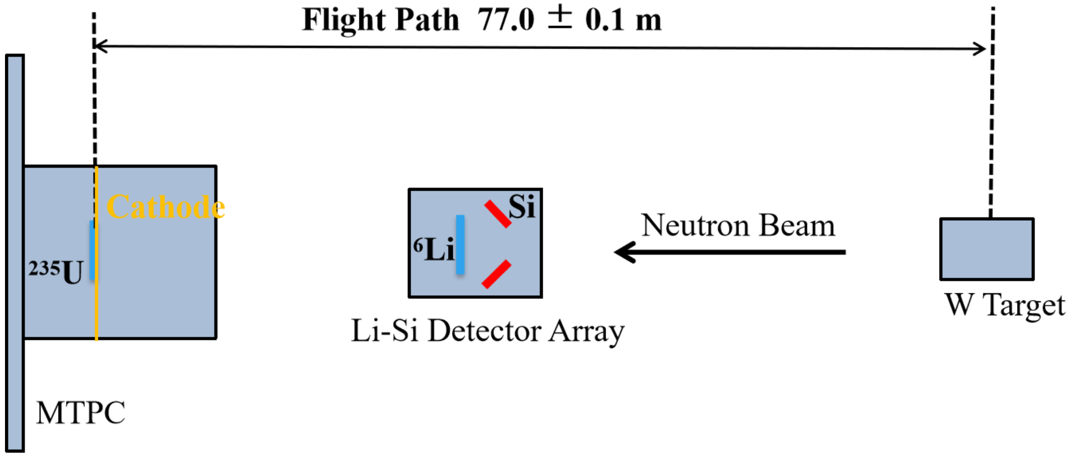
^{232}Th(n, f) cross section measurement:



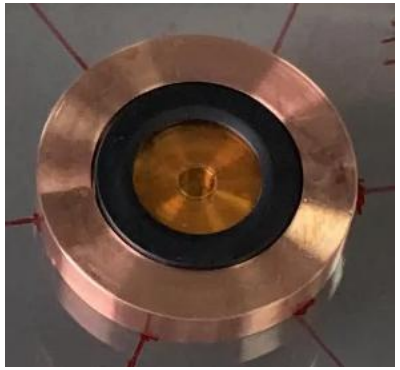
- Based on 4.5 MV VdG @PKU
- 4.50 ~ 5.40 MeV, 5 neutron energies
- 1 atm P10 working gas
- Standard reaction: ^{238}U(n, f)

^{235}U(n, f) cross section measurement:



- Based on white neutron source @CSNS Back-n
- 0.5 eV ~ 10 keV, 43 neutron energies
- 0.6 atm 75% Ar + 25% CH_4
- Standard reaction: ^{6}Li(n, t) ^{4}He

Sources and samples

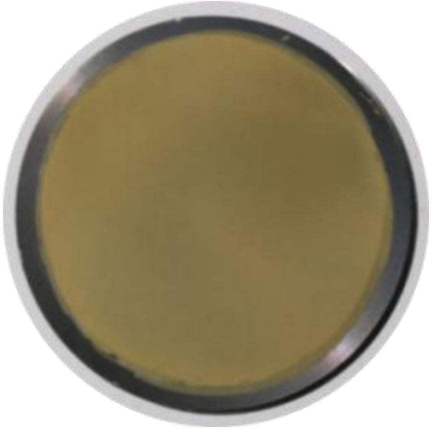


^{55}Fe X-ray source

(CSNS Back-n)

α source

(PKU)



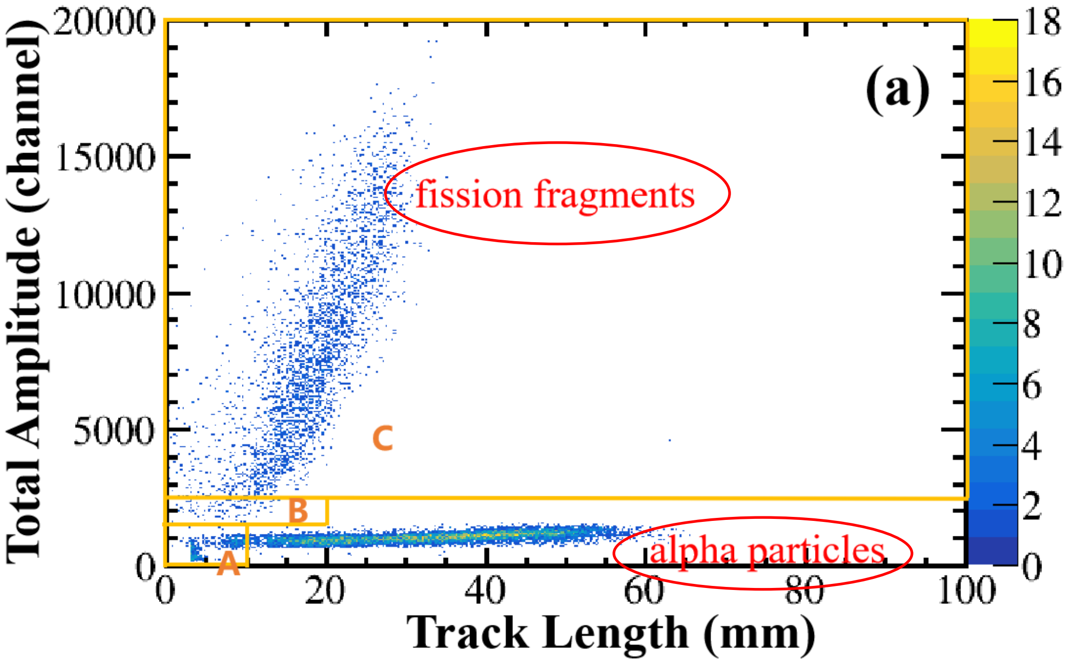
^{232}Th sample

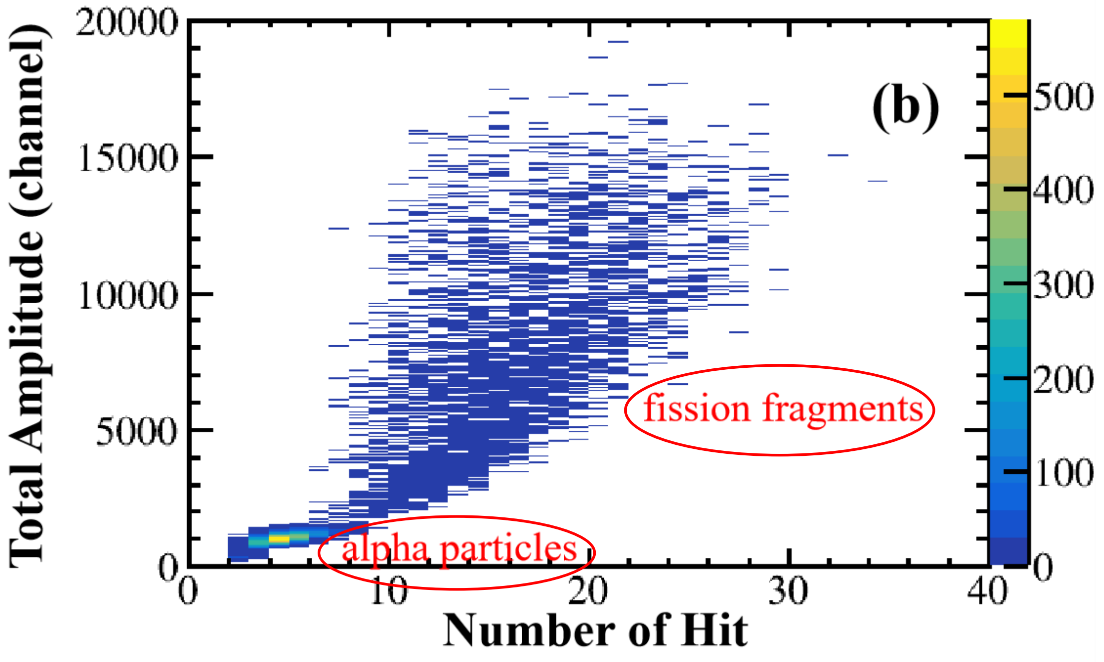
(FLNP, JINR)

^{235}U sample

(NINT)
Northwest Institute of Nuclear Technology

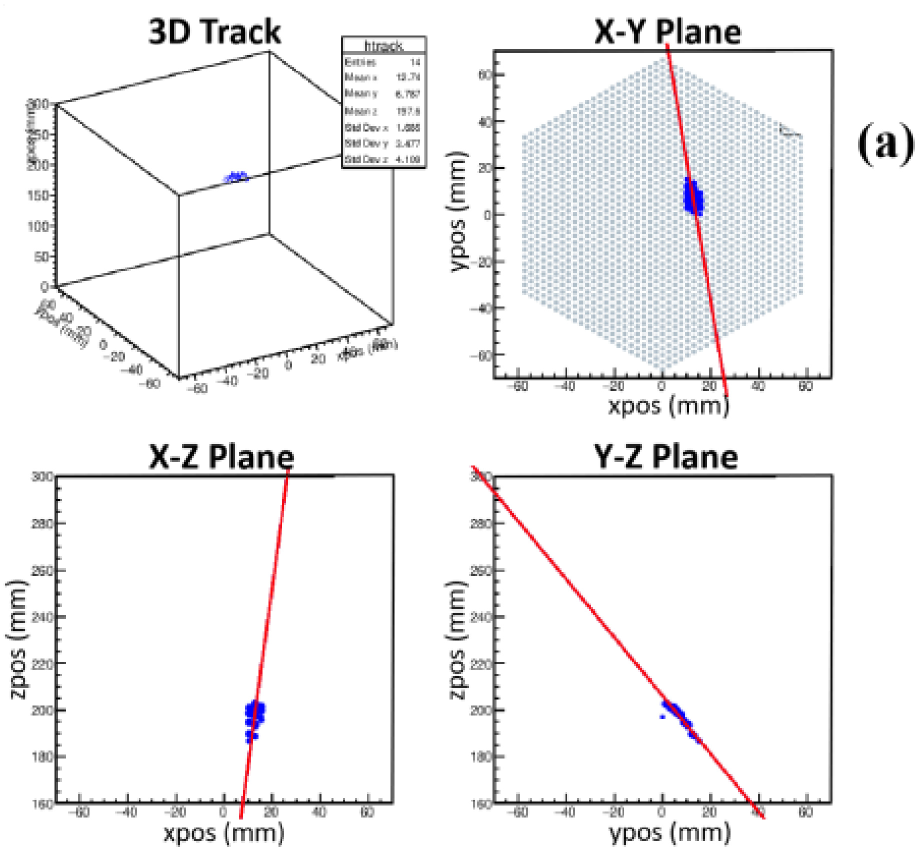
3. From GIC to TPC

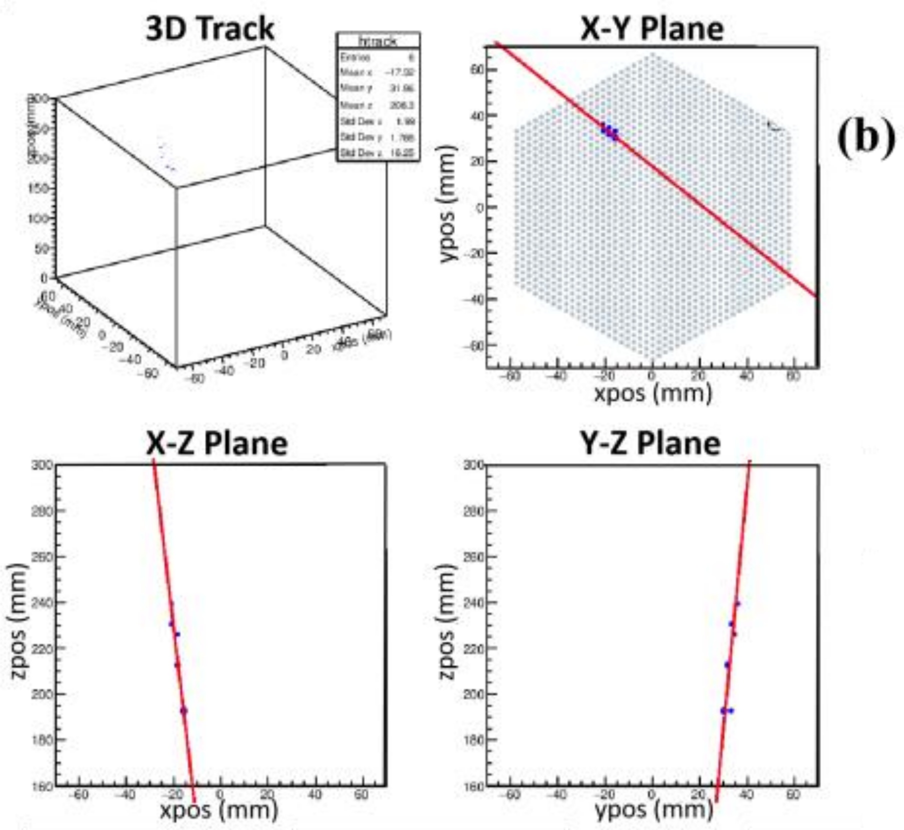




- In Track Length-Total Amplitude 2D spectrum, the fission event region can be divided into three areas
- All events in area C are fission events
- Fission events in area A and B can be identified based on the reconstructed track plots

3. From GIC to TPC

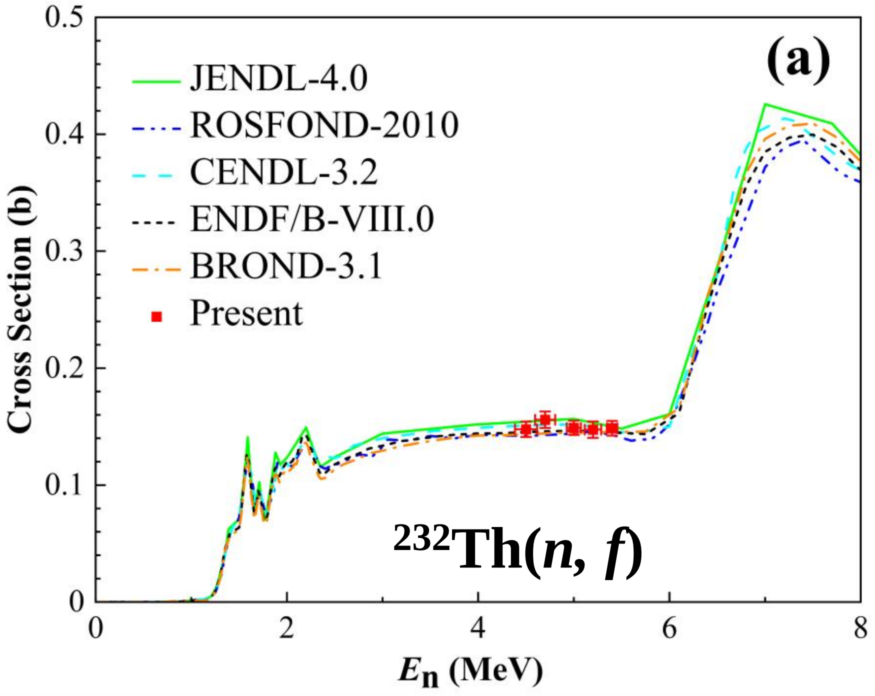


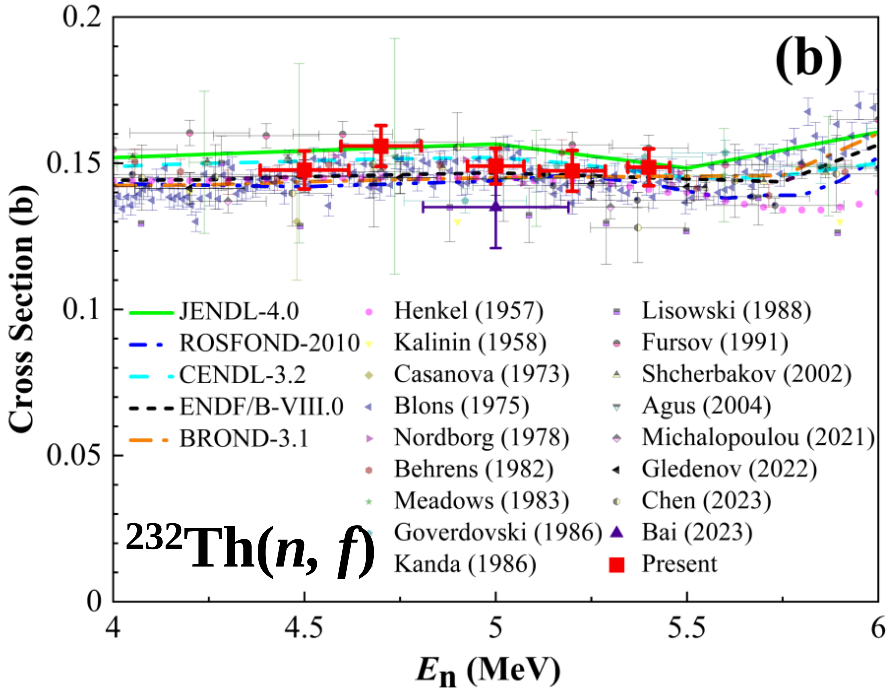


Track of Fission Fragment **Track of α Particle**

Obvious difference exist

□ Measurement results of the ^{232}Th(n, f) cross sections @PKU





-Uncertainties < 5.0 %

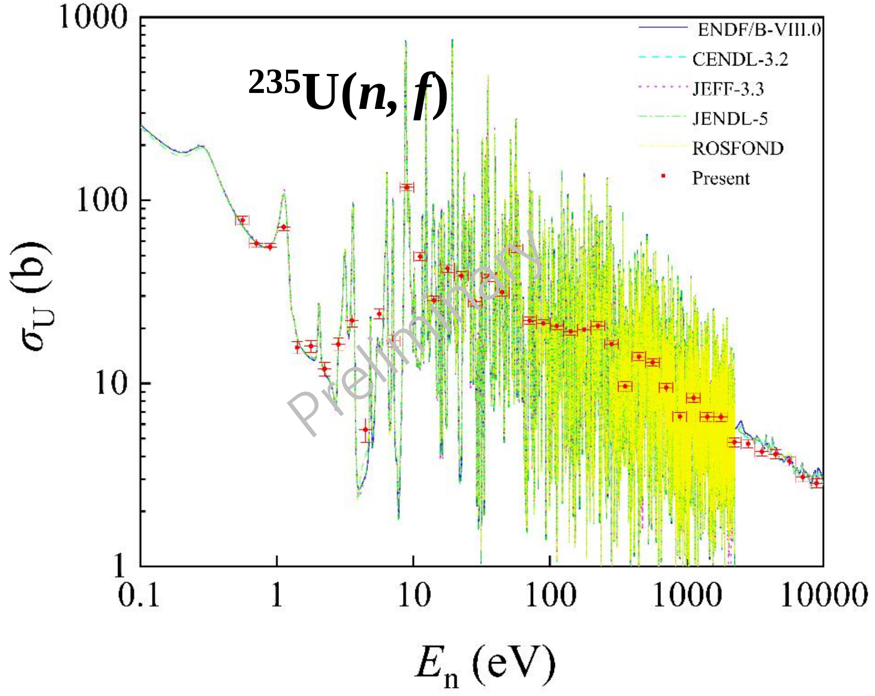
-First ^{232}Th(n, f) cross section measurement using TPC

Haofan Bai et al., NIMA 1058, 168912 (2024)

Haofan Bai et al., CPC 48 (10), 104001 (2024)

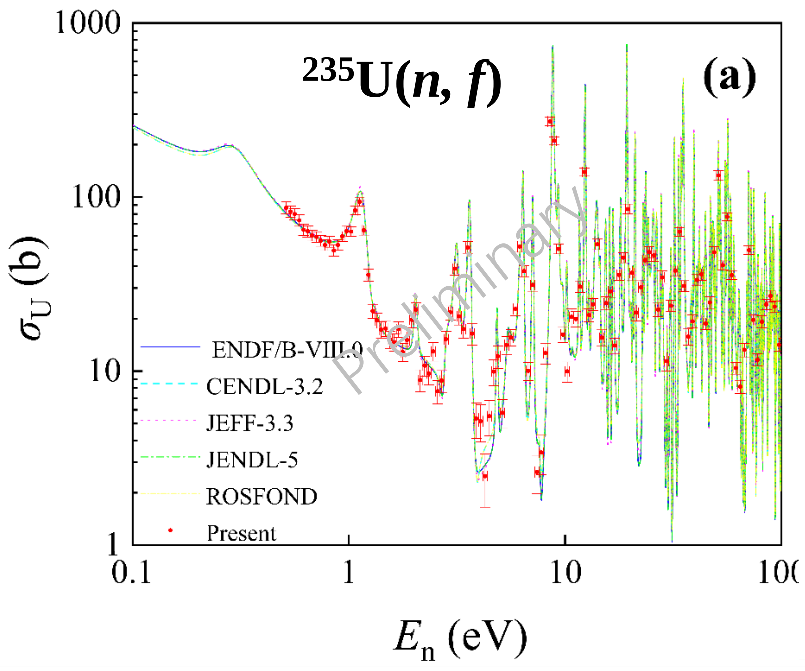
3. From GIC to TPC

☐ Measurement results of ^{235}U(*n*, *f*) cross section @CSNS Back-n

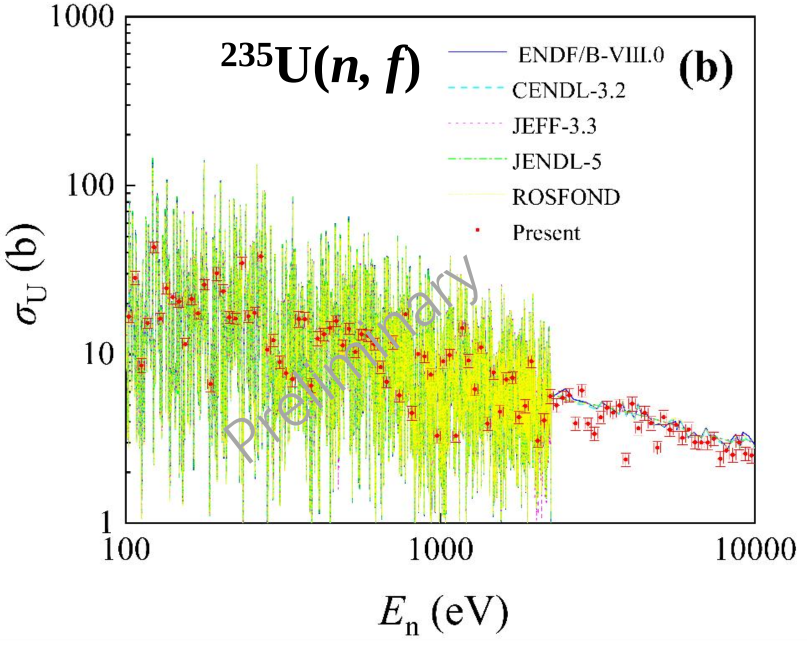


0.5 eV ~ 10 keV

10 bins per E_n magnitude



0.5 ~ 100 eV



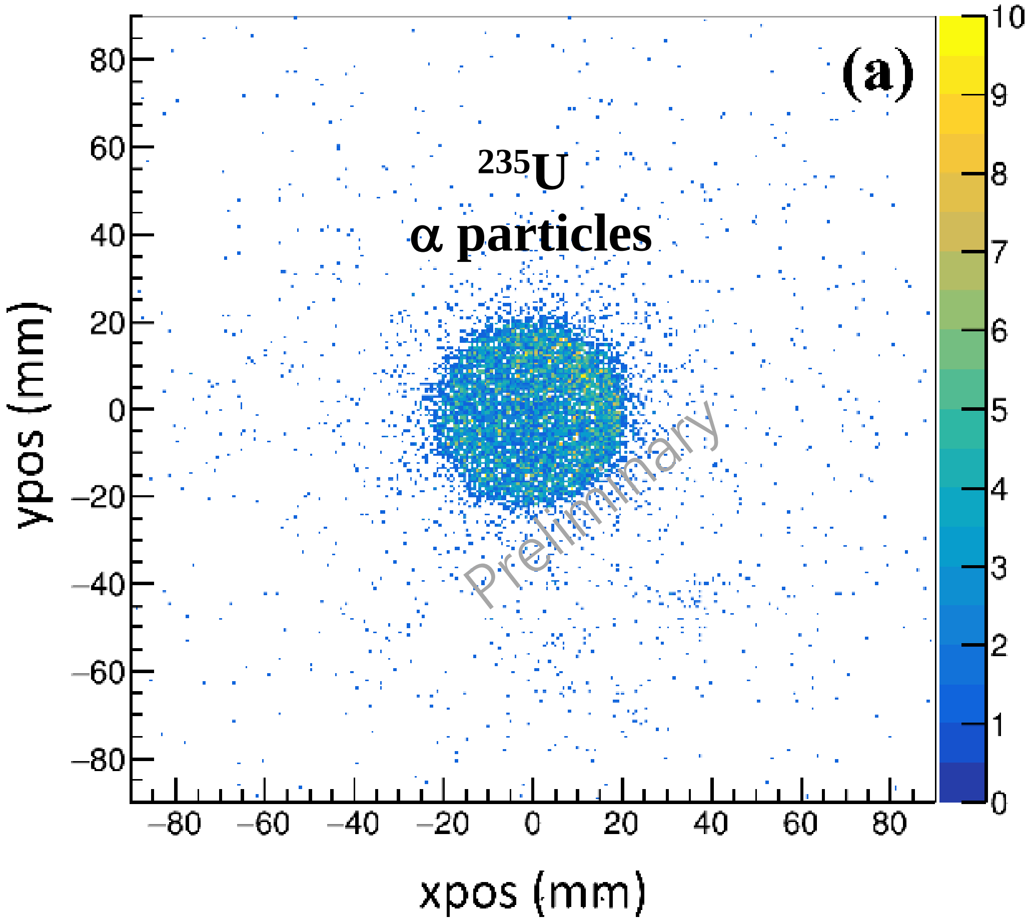
100 eV ~ 10 keV

50 bins per E_n magnitude

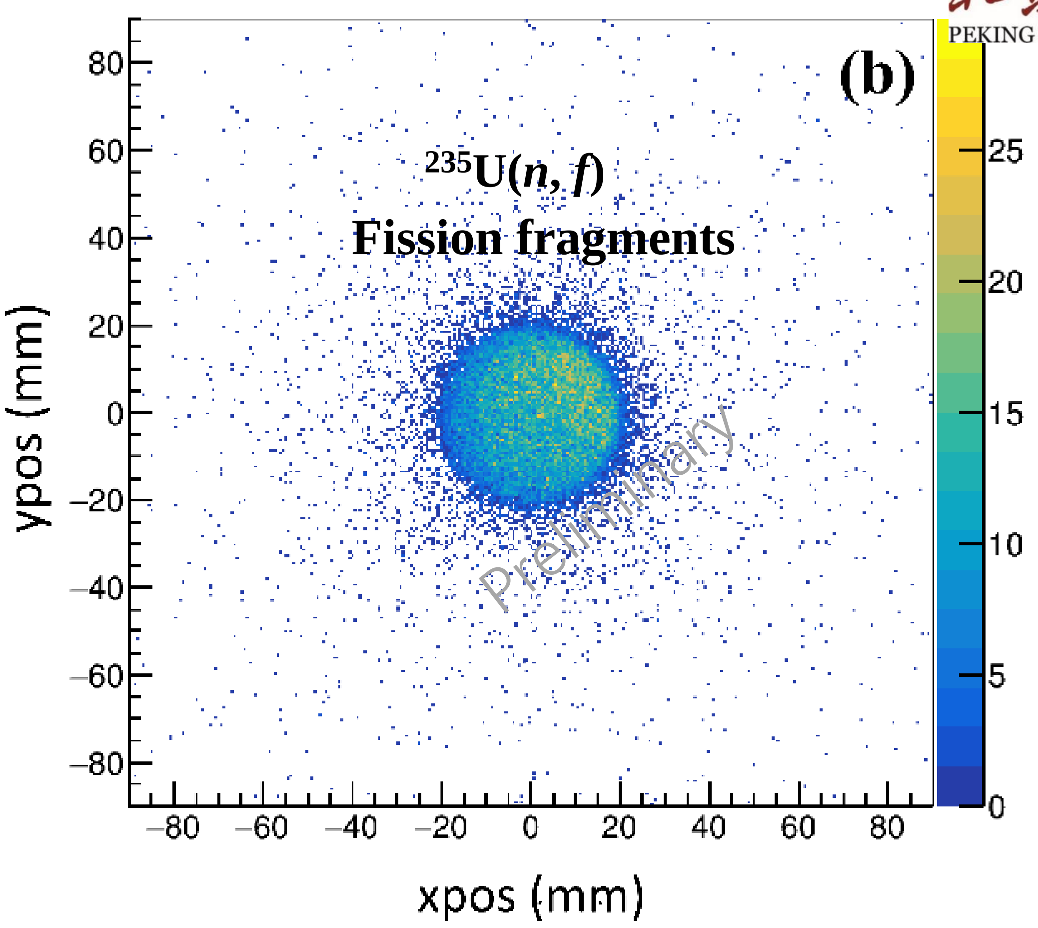
- Consistent with the data from evaluation libraries
- Longer measurement duration needed

Han Yi, Haofan Bai, et al., to be submitted

3. From GIC to TPC



Distribution of starting points of the tracks of the α particles from the ^{235}U sample



Distribution of starting points of the tracks of the Fission Fragments from ^{235}U(n, f) reaction

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北京大學
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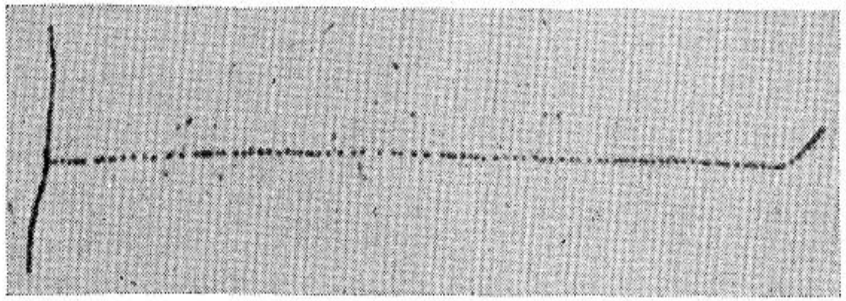
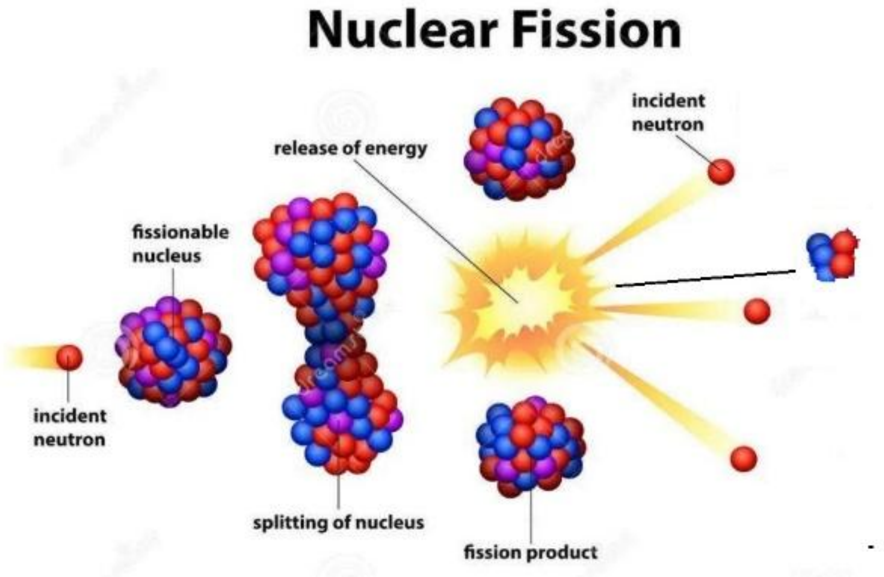
4. From binary fissions to ternary fissions

1947 Tsien San-Tsiang(钱三强) Ho Zah-Wei(何泽慧) discovered tracks of ternary fission and quaternary fission



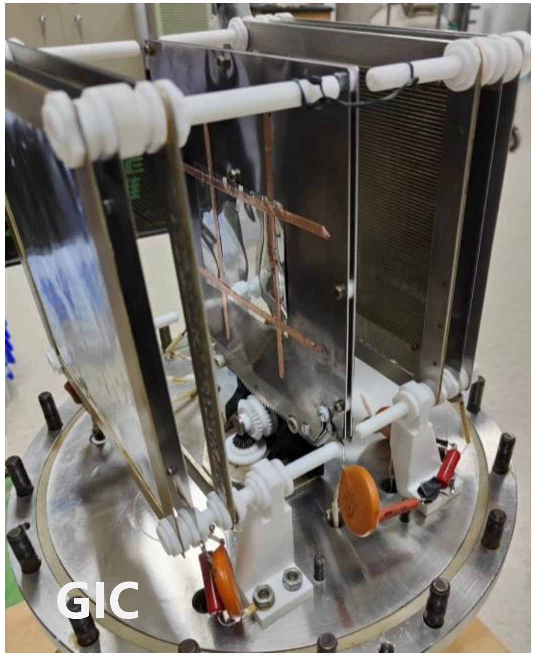


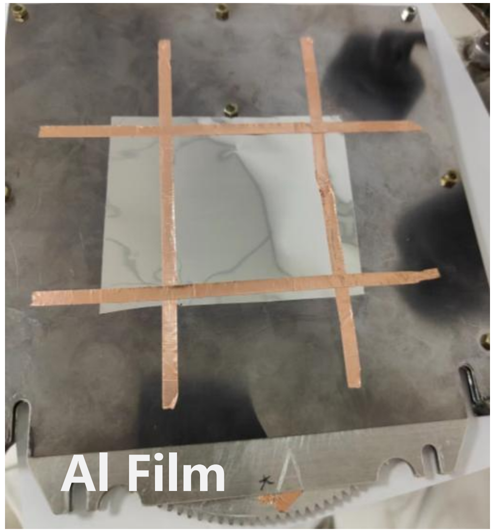
- Most of the third charged particles emitted in ternary fissions are **α particles (LRA)**, there are also **^{3}H,** ^{1}H, ^{2}H, ^{6}He, ^{7}Li, ^{8}Li, ^{9}Li, ^{9}Be and ^{10}Be in addition
- The absolute yield of these light charged particles emitted in ternary fission are **important nuclear reaction data**

4. From binary fissions to ternary fissions

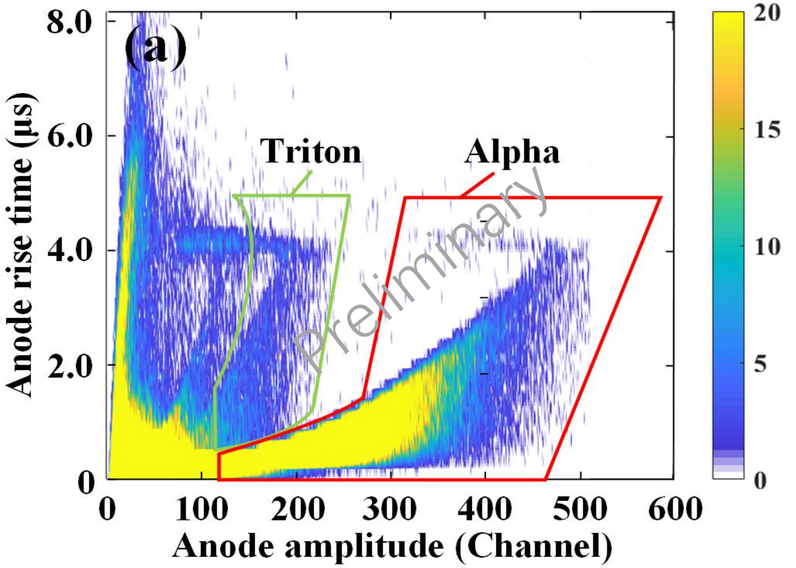
4.1 Measurement of the ^{252}Cf ternary fission

Using GIC @NINT

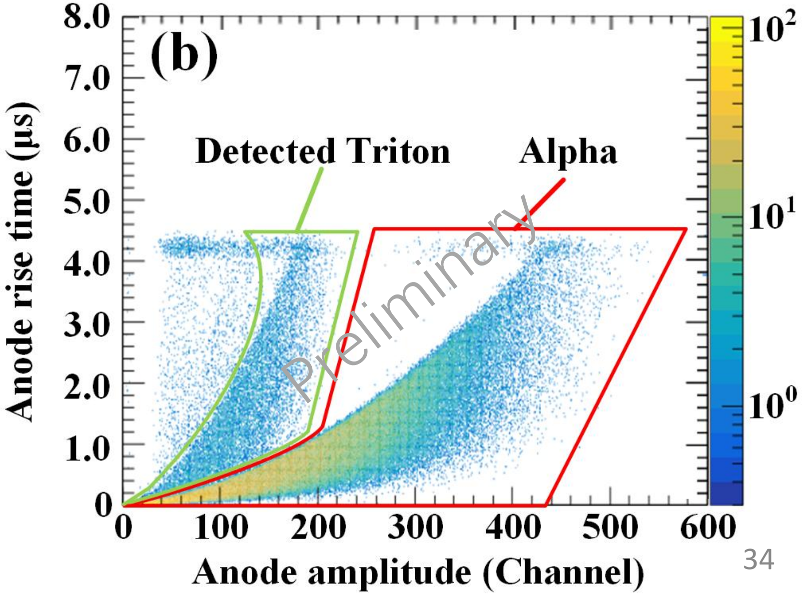




Experiment



Simulation



Radioactive source: ^{252}Cf (30 μm Al film covered)

Working gas: 90%Ar+10%CH_4 (7.0 atm)

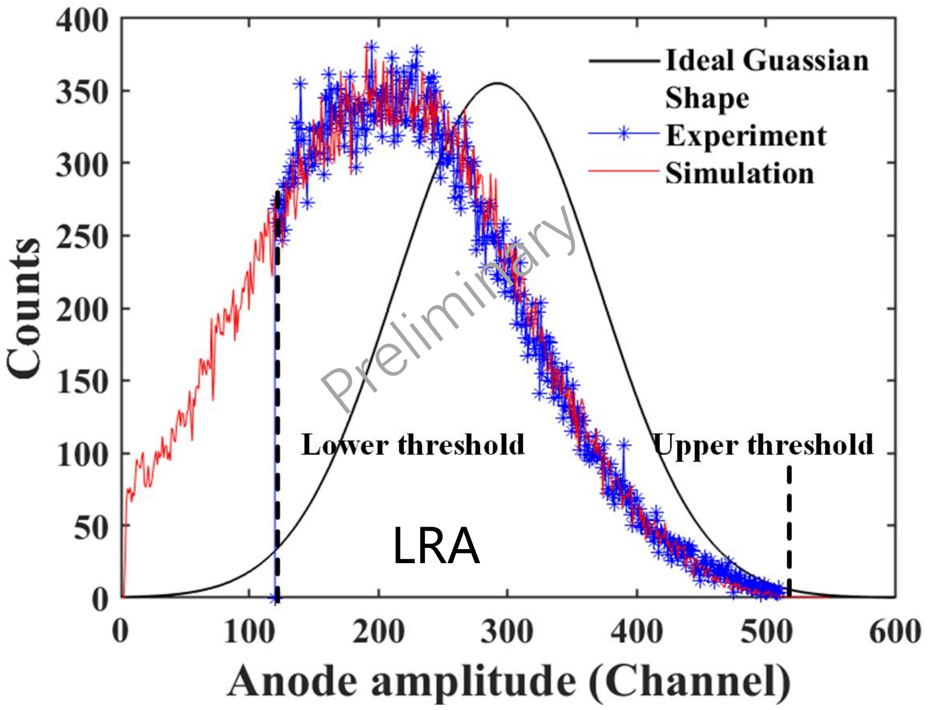
Voltage: +1400 V/ - 2800 V

Distance between cathode and grid: 74 mm

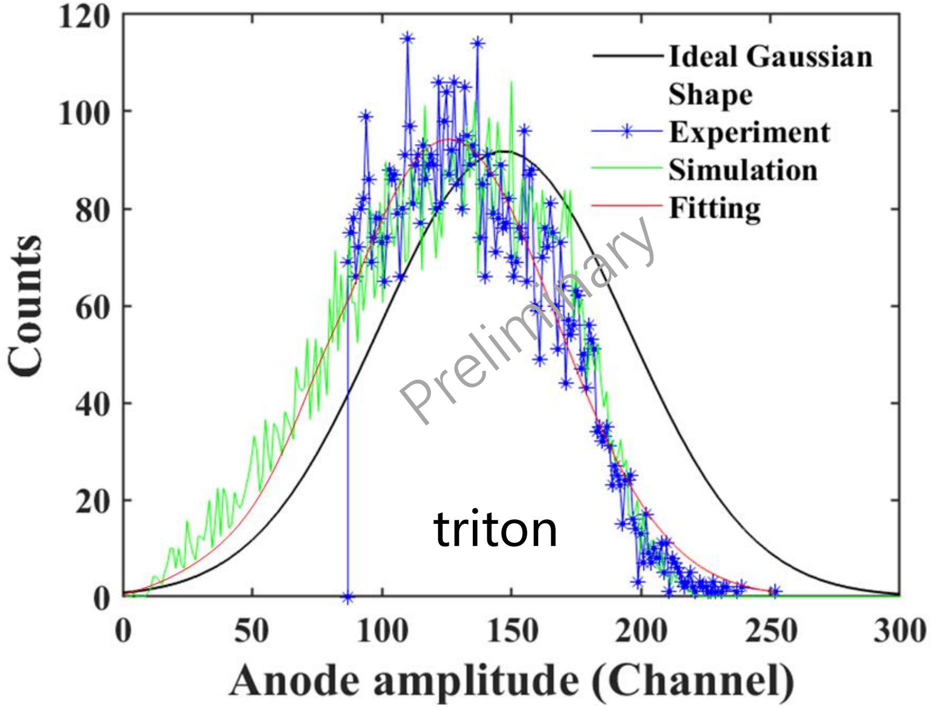
4. From binary fissions to ternary fissions

Measurement of the ^{252}Cf ternary fissions @NINT

- ✓ By selecting the event region, the anode projection spectra of the long-range α particles and the tritons are obtained, and the mean energy and FWHM are determined from simulations.



Anode spectrum of the long-range α particles



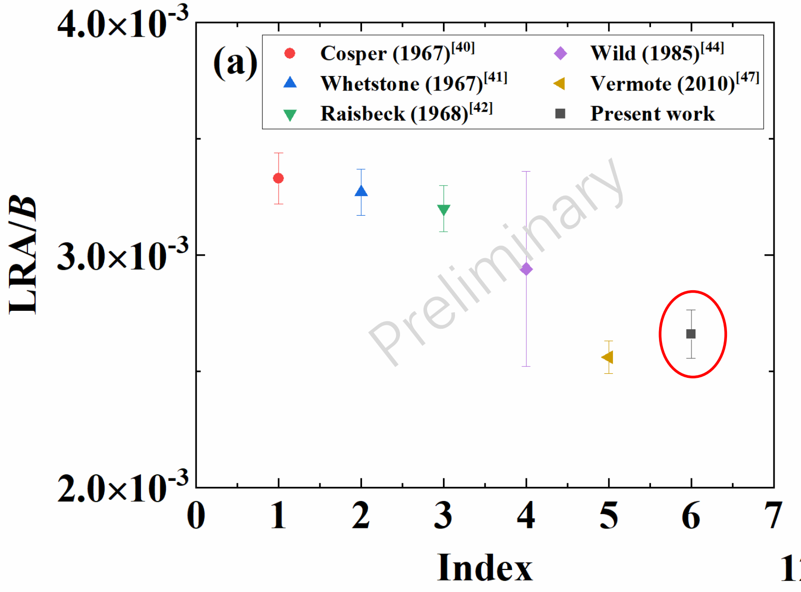
Anode spectrum of the tritons

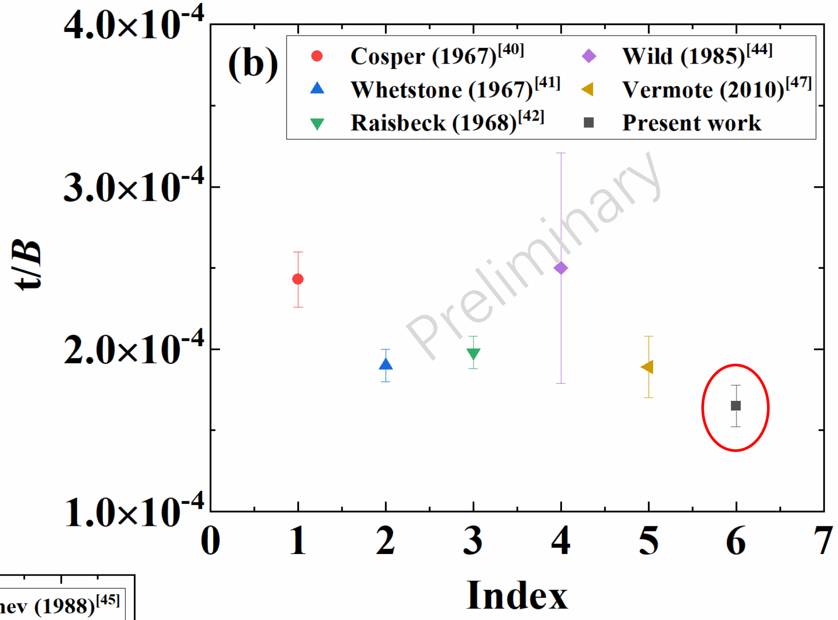
Zepeng Wu et al., to be submitted

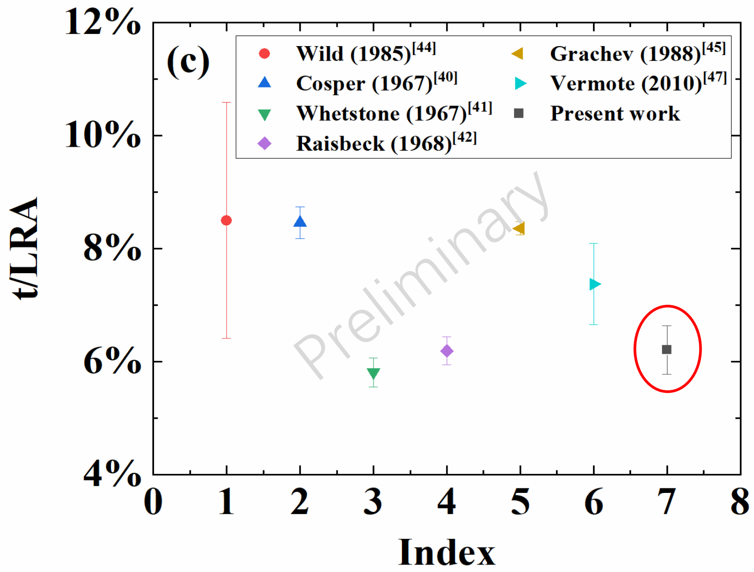
4. From binary fissions to ternary fissions

Measurement of the ^{252}Cf ternary fissions @NINT

Ternary fission yield







4. From binary fissions to ternary fissions

4.2 Measurement of thermal neutron induced ^{235}U ternary fissions @NINT

Radioactive source：^{235}U (30 μm Al film covered)

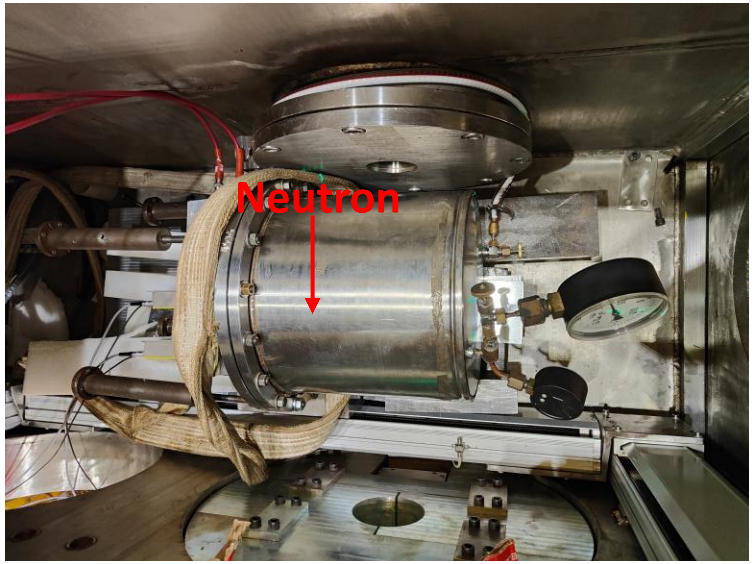
Working gas：90%Ar+10%CH_4 (8.0 atm)

Voltage：+1450 V/ - 2900 V

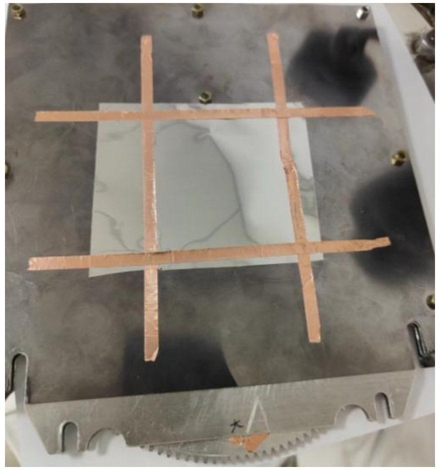
Distance between cathode and grid：74 mm

Measuring time： 144346 s

Neutron flux monitor: ^{197}Au

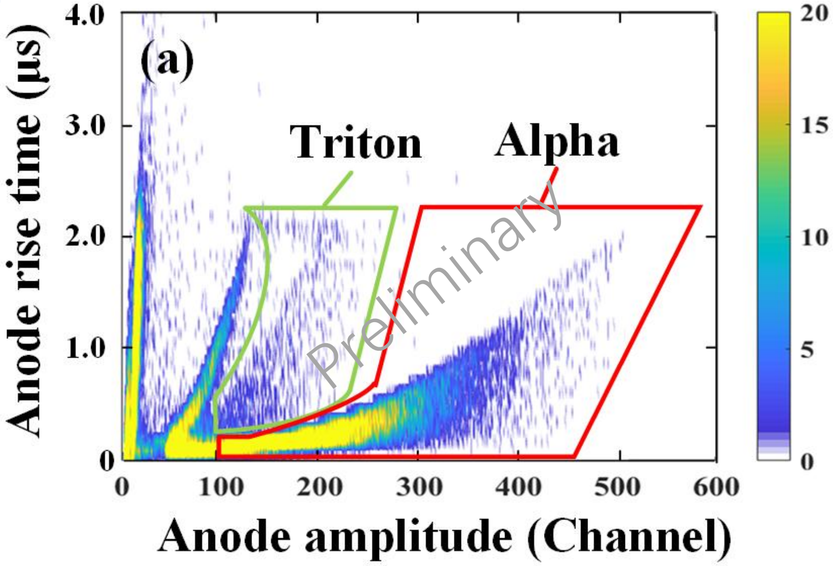


GIC+ NINT Reactor

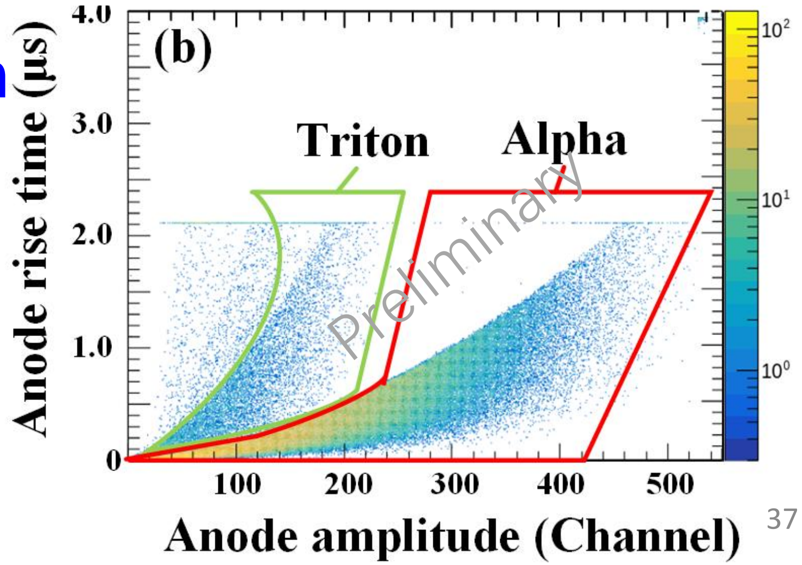


Al Film

Experiment



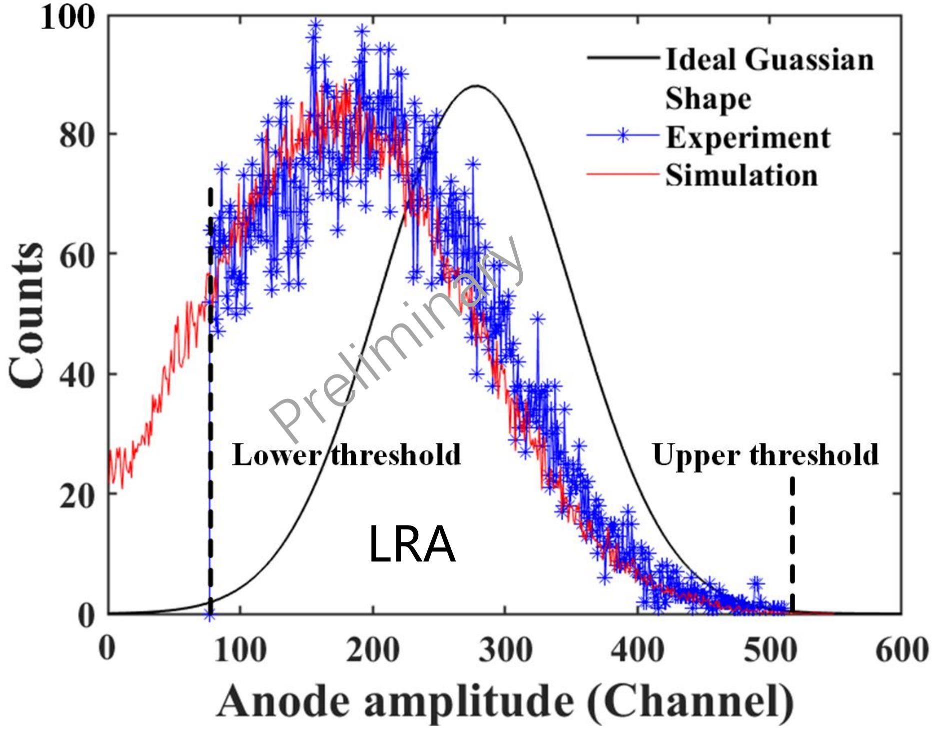
Simulation



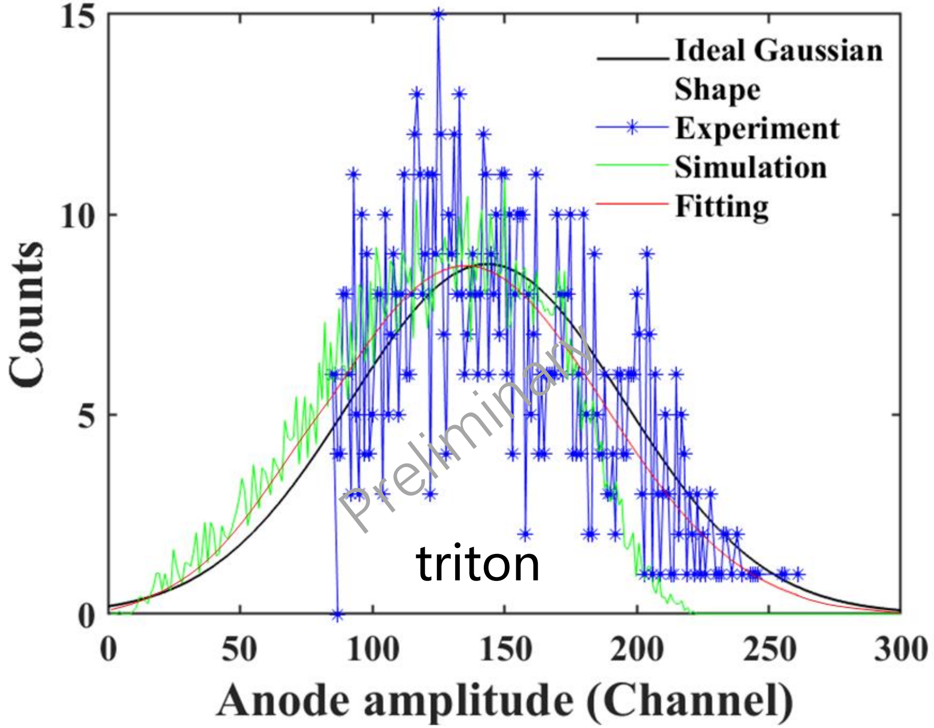
4. From binary fissions to ternary fissions

Measurement of thermal neutron induced ^{235}U ternary fissions @NINT

✓ By selecting the event region, the anode projection spectra of the long-range α particles and the tritons are obtained, and the mean energy and FWHM are determined from simulations.



Anode spectrum of the long-range α particles



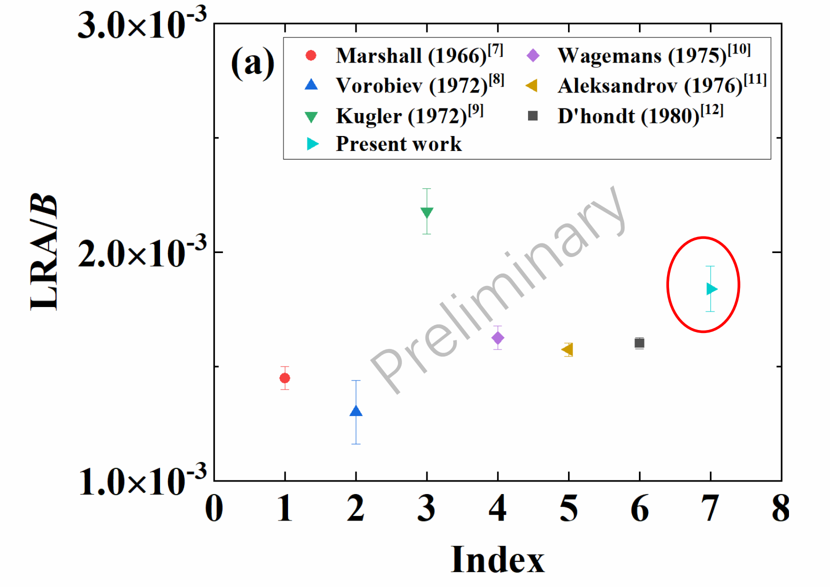
Anode spectrum of the tritons

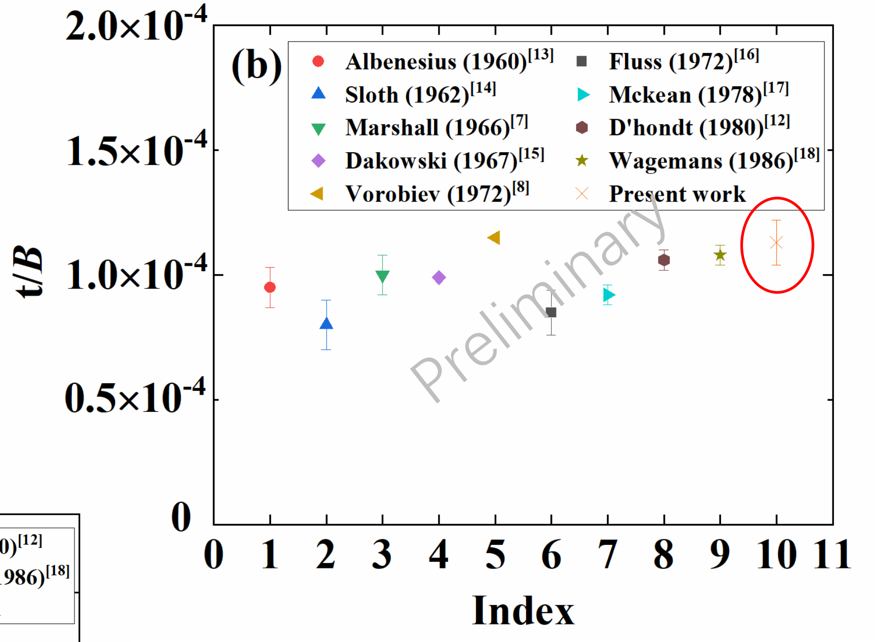
Zepeng Wu et al., to be submitted

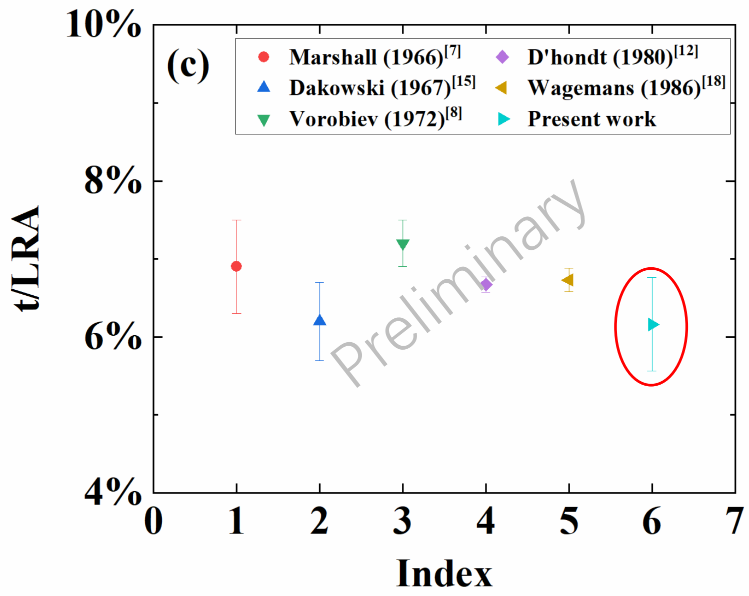
4. From binary fissions to ternary fissions

Measurement of the thermal neutron induced ^{235}U ternary fission @NINT

Ternary fission yield







May 29, 12:50, Room V6

Zepeng Wu, Presentation#65

E_n=3.2 MeV fast neutron induced

^{235}U ternary fission measured @CIAE

Data are in processing...

4. From binary fissions to ternary fissions

4.3 Measurement of the ternary fissions using MTPC

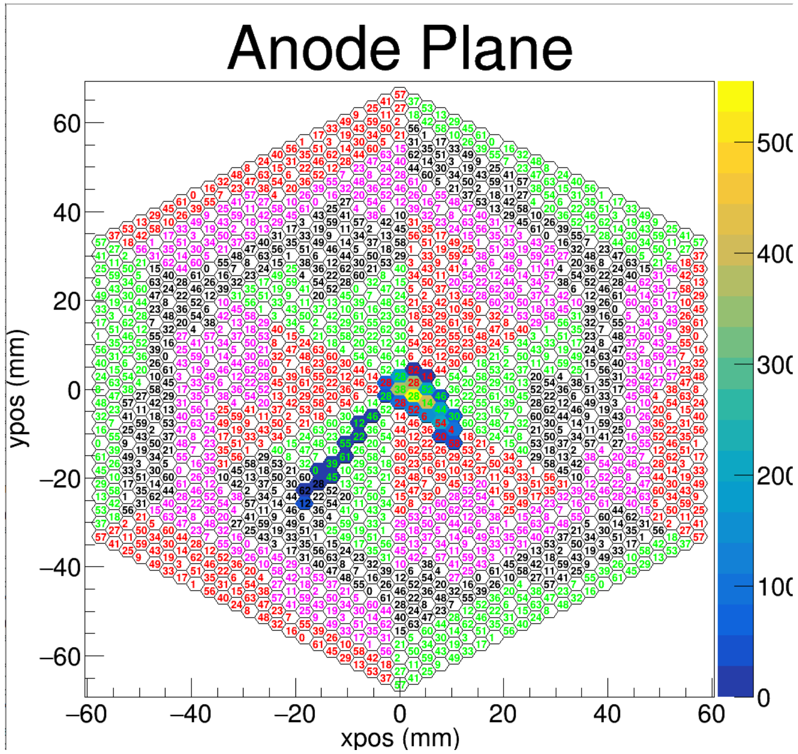
^{252}Cf Spontaneous Fission

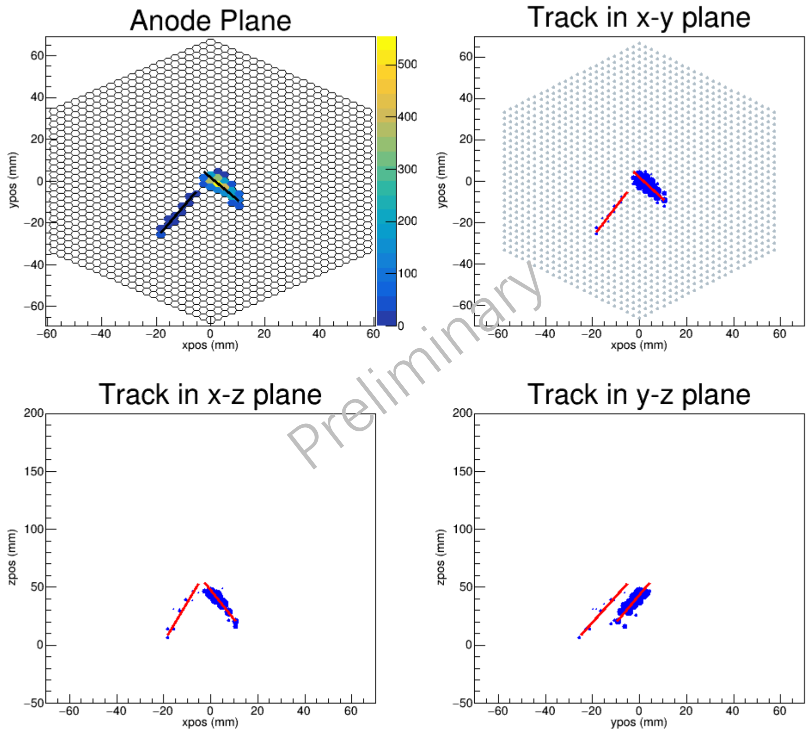
Radioactive source: ^{252}Cf (no Al film covered)

Working gas: 75%Ar+25%CH_4 (0.6 atm)

Voltage: - 270 V/ - 1215 V

More measurements will be performed





Ternary fission event (?)

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5. Summary

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- Recent advances on measurements of **(n, cp) reactions** are outlined
- Cooperation among PKU, JINR, CIAE and CSNS Back-n is fruitful
- TPC will be an important tool for future (n, cp) reaction measurements
- Theoretical analysis are needed
- More and Further Cooperations are expected!

Future...

- **Theoretical analysis:** Isotopic effect, α-cluster effect, ...
- **High-precision** measurements
- **Many-body** reactions
- **Polarized neutron** induced reactions

Thank you!