The development of (70 ~ 100) MeV Mono-energetic neutron reference fields based on the 100 MeV Cyclotron

Jiaoting Yu, Wei Li, Shiyao Li, XI Qin, Xinqi Luo, Xueying Deng, An Du, Hailiang Qin, Yujun Mo, Yuyang He, Bin Shi, Shufeng Zhang, Yuntao Liu

Neutron metrology laboratory

Department of application of nuclear technology

China institute of atomic energy

12.9.2022, Beijing Cyclotron

中国原子能科学研究院
CHINA INSTITUTE OF ATOMIC ENERGY
CNNC

CONTENT

Main fields of Neutron metrology Laboratory

Neutron Metrology and Measurement Laboratory

Neutron Metrology

- Thermal neutron
  Mono-energetic neutron (from 8 keV ~ 20 MeV)
- Quasi-monoenergetic neutron
  Now: 70 ~ 100 MeV
  Future: 500MeV or 2GeV
- White neutron field
  Base on spallation neutron source

Neutron measurement in workplace

- Cosmic ray measurement
- Spectrum and dosimetry measurement on the workplace
- Development of instruments for commerce

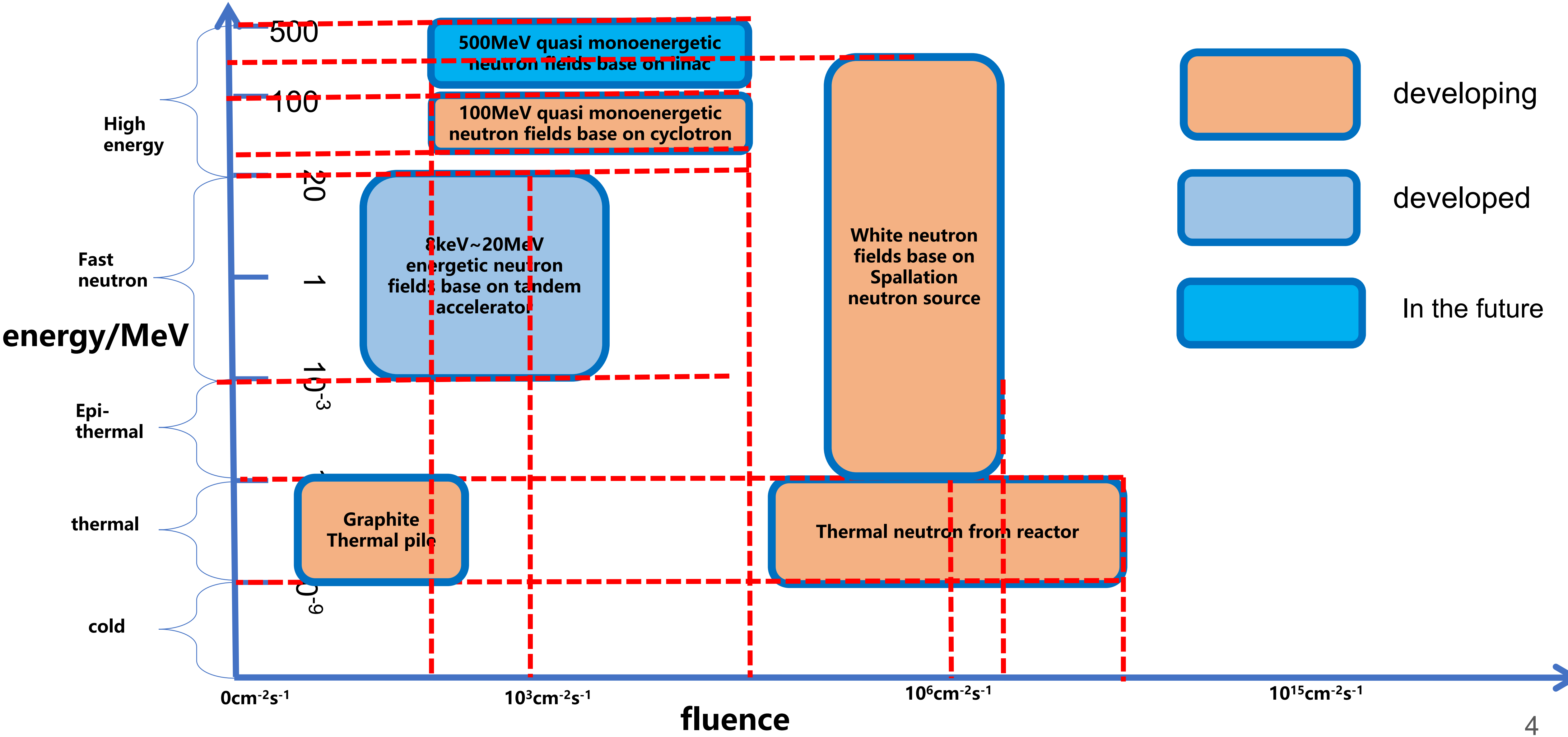
Particle beam Analyzing for materials

- PIXE and PIGE
- Positron annihilation
- Neutron induced gamma ray analyze

Neutron nuclear medicine

- Neutron dosimetry for BNCT
- Development of target for BNCT
- micro /nano dosimetry

Neutron reference fields

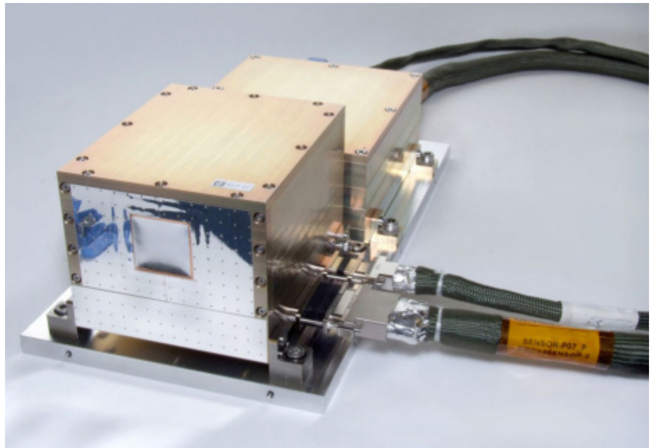


中国原子能科学研究院
CHINA INSTITUTE OF ATOMIC ENERGY

CONTENT

Why we need high energy neutron fields

- Neutron will be produced by primary cosmic ray which is reacted with atmosphere, lunar soil, space station materials, astronaut…
- For many purposes: such as astronauts healthy monitor, space environment monitor …;
- all kinds of detectors were send to space: neutron personal dosimetry, TEPC, neutron spectrometer …;

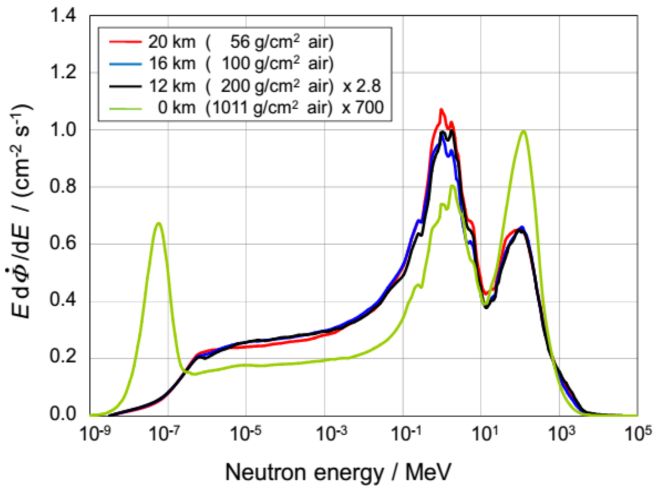


Space Sci Rev (2020) 216:104
https://doi.org/10.1007/s11214-020-00725-3

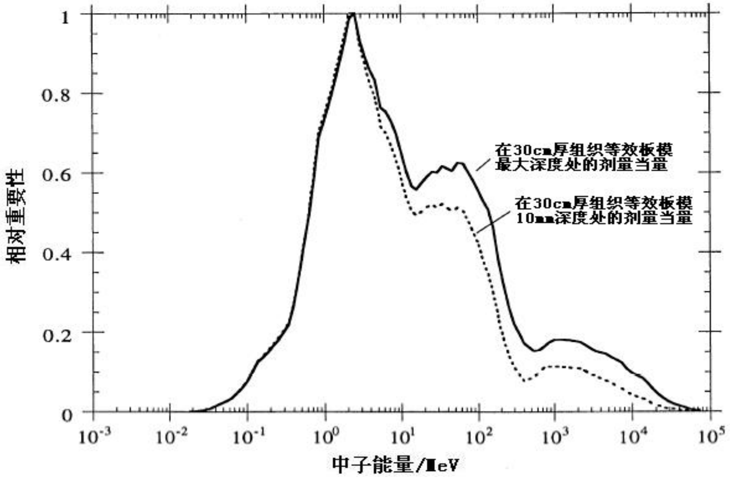
SPECIAL COMMUNICATION

The Lunar Lander Neutron and Dosimetry (LND) Experiment on Chang'E 4

Tens of MeV neutron plays an important role!



Neutron energy distribution at different heights from the ground



Relative weights with neutron energy for dose equivalent

Why we need high energy neutron fields

- The key experiments for launching neutron detectors are: get fluence response, dosimetry response and energy calibration at interested neutron energy region.

Launching neutron detector in China

↓ **Status for now**

< 20 MeV， MC simulation + monoenergetic calibration
> 20 MeV， MC simulation (only)

↓ **problem**

> 20 MeV， lack of cross-section data, depend on the theoretical model

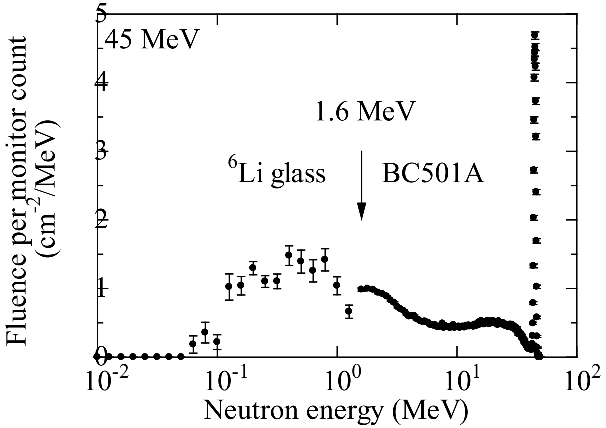
↓ **result**

above 20 MeV, measurement results quality is poor

- Secondary neutrons in proton/hadron therapy
  - Patient radiation protection (En max ~250 MeV / 800 MeV) ⇨ secondary cancer risk
- Shielding benchmark experiments for high energy accelerator facilities
- Cross section studies
  - Accelerator-driven reactors, spallation sources
- Study of neutron-induced single–event effect (SEE)
  - Test of semiconductors

Why we need high energy neutron fields

- NMIJ (Japan)
  - development of QMN fields at TIARA facility from JAEA
    - ✓ calibration services at 45 MeV started in 2015
  - Medium/long term : up to 400 MeV using RCNP facility



- i-Themba Labs (South Africa)
  - Development of QMN fields between up to 200 MeV
  - Collaboration between

    i-Themba Labs, NMISA, PTB and IRSN

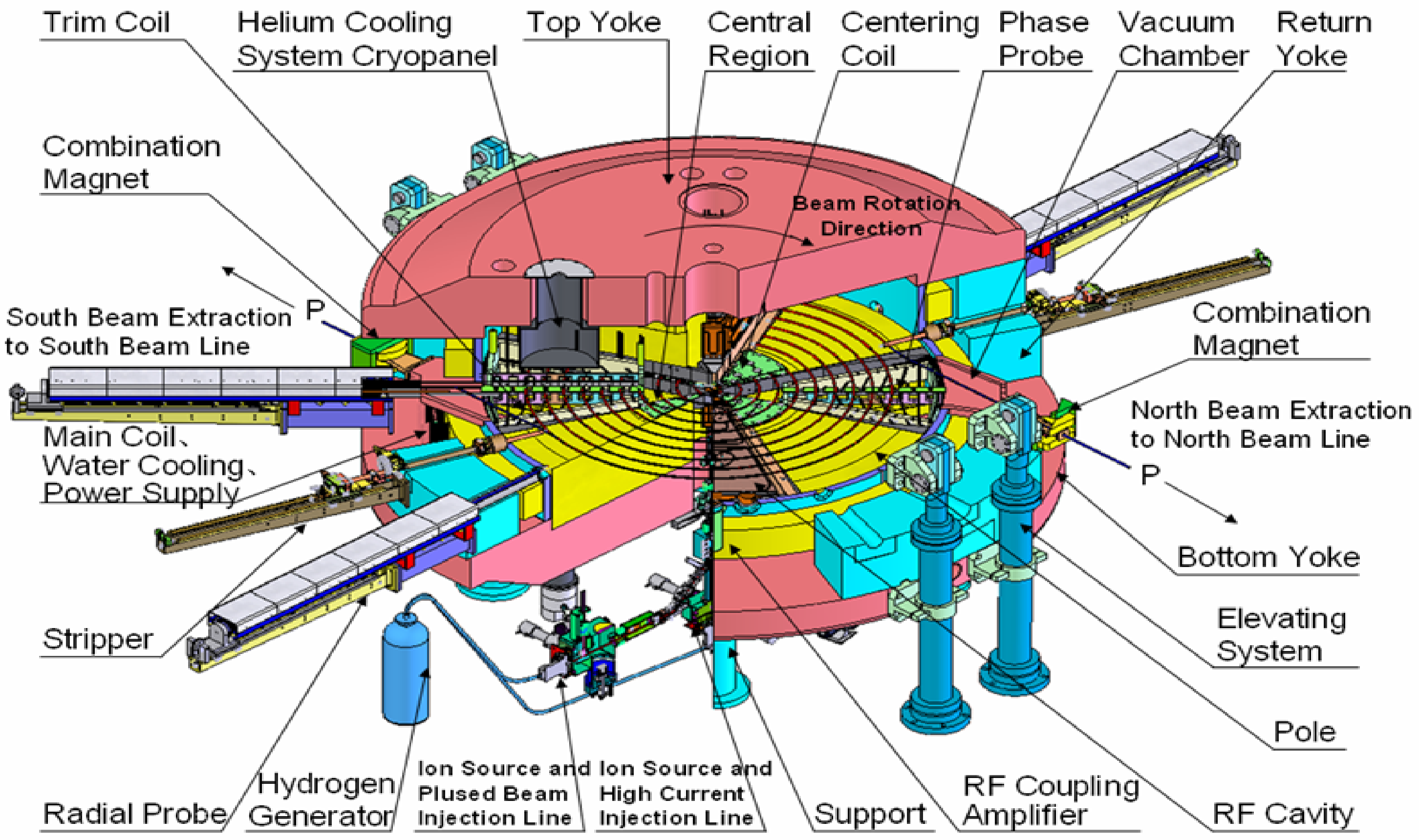
- CIAE (China)
  - QMN fields in development from 70 MeV to 100 MeV

CONTENT

Layout of QMN in CIAE

中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY
中核集团 CNNC

General View of the 100 MeV Cyclotron

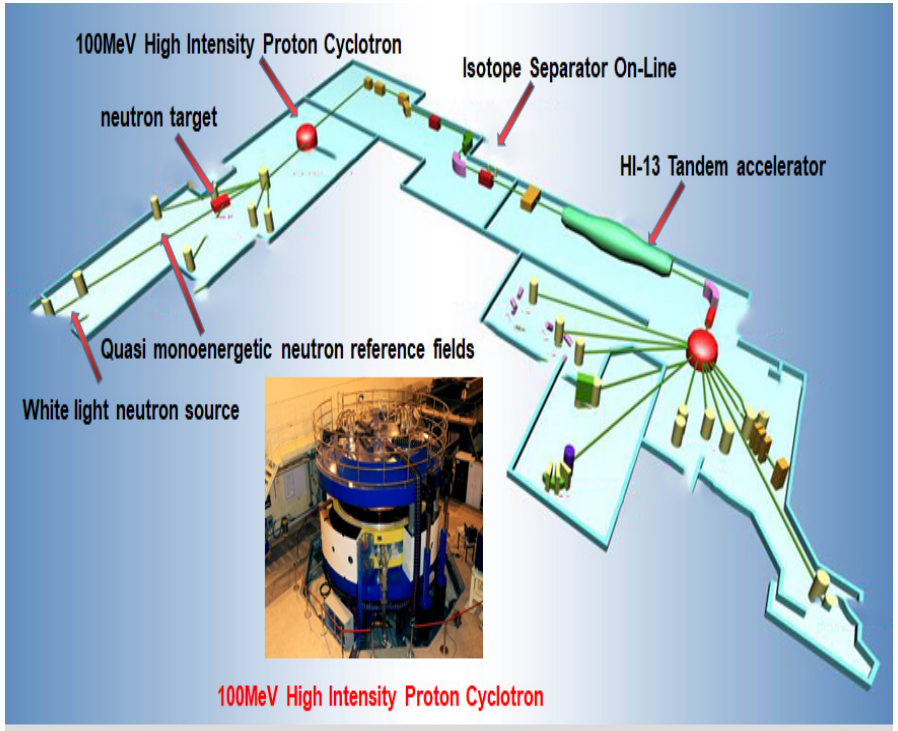


- **the current at ion source : more than 10 mA**
- **Proton energy: （70 ~ 100） MeV**

Layout of QMN in CIAE

中国原子能科学研究院
CHINA INSTITUTE OF ATOMIC ENERGY
中核集团 CNNC

- Proton extracted and transported in two common lines simultaneously (north and south lines)
- 6 beam lines
  - ✓ North hall
    - ➢ N1 beam dump/ beam line testing
    - ➢ N2: radioactive ion-beam, inject into 13 MV tandem accelerator
    - ➢ N3: produce isotope for medicine
  - ✓ South hall
    - ➢ S1: quasi monoenergetic neutron source



- ✓ South hall
  - ➢ S2: white light spectrum neutron source
  - ➢ S3: proton radiation beam for radio-biological and single event effect testing of electronic device

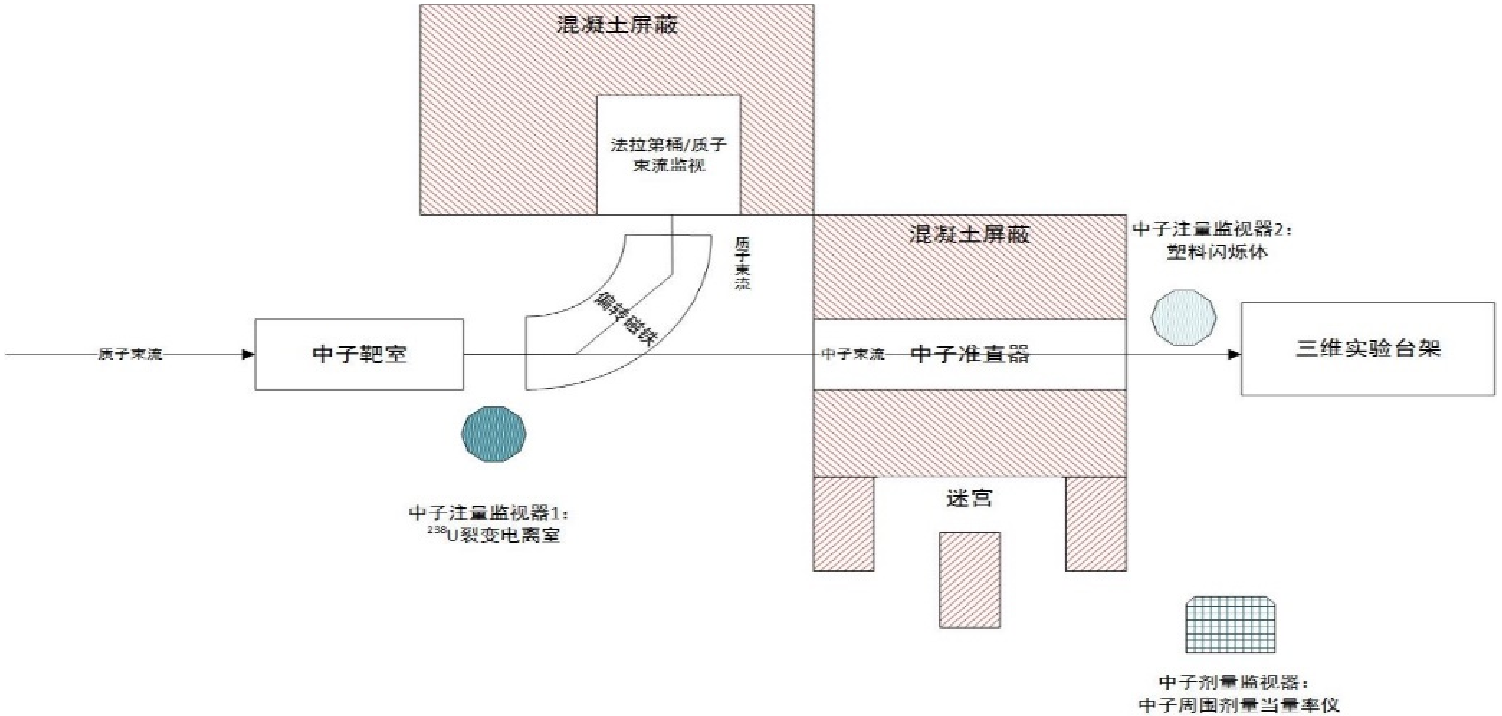
Layout of QMN in CIAE

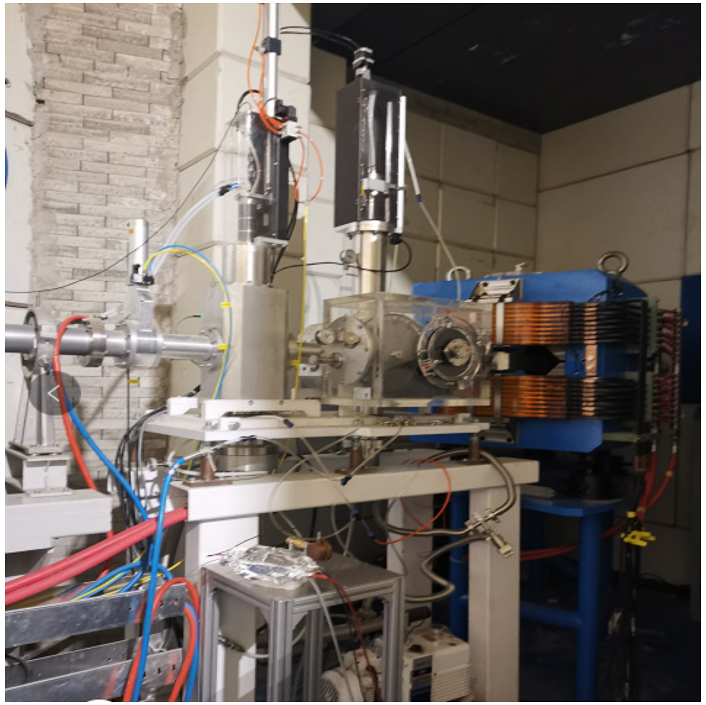
中国原子能科学研究院
CHINA INSTITUTE OF ATOMIC ENERGY
中核集团 CNNC

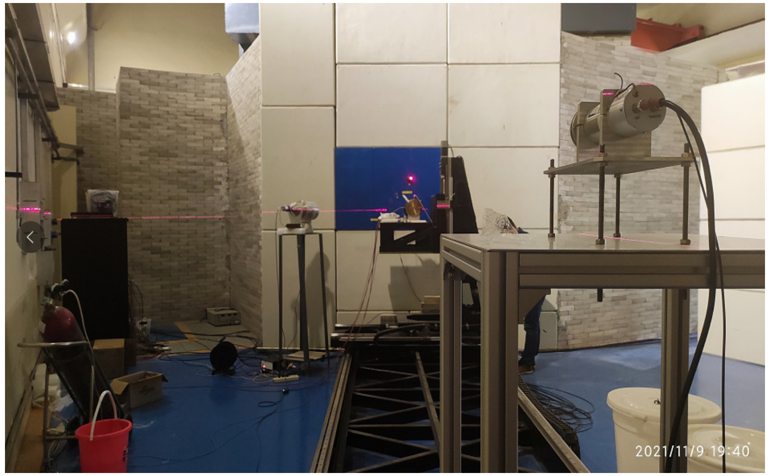
Key points of QMN designing:

- **fluence**
  - The higher the neutron fluence rate, the better; (related to the aperture of collimator, thickness of target)
- **energy monochromaticity (sometimes has contradiction with fluence)**
  - The more monochromatic the energy, the better; (related to target materials, thickness, the aperture of collimator)
- **Background proton** (related to the bending magnet designing)
- **Background neutron**
  - **contamination neutron** (proton react with magnet, beam pipe, beam stop foil (Ti), Ar gas in target chamber, air and etc.)
  - **Low energy neutron:** $^{7}Li(p,n)^{7}Be$ Isotropic vaporized neutrons
  - **Room scattering neutron;**
- **Background photon**
  - Prompt gamma produced by proton reaction; (related to the aperture of collimator)
  - Delayed gamma; (materials of collimator, shielding materials)
- **Neutron and proton monitor** (fission chamber, scintillation detector, faraday cup)

Layout of QMN in CIAE







- Proton from two quadrupole magnets， faraday cup transports into target chamber, bending into beam dump (embedded in concrete shielding wall) by bending magnet.
- Collimators: two layers, inside: iron 1m ×1m×3m , 15 cm diameter aperture, outside concrete;
- Proton beam spot on target: 2 cm
- Distance from target to collimator: 2 m
- Distance from target to wall: 12 m

Layout of QMN in CIAE

☐ How to determine the thickness of the target

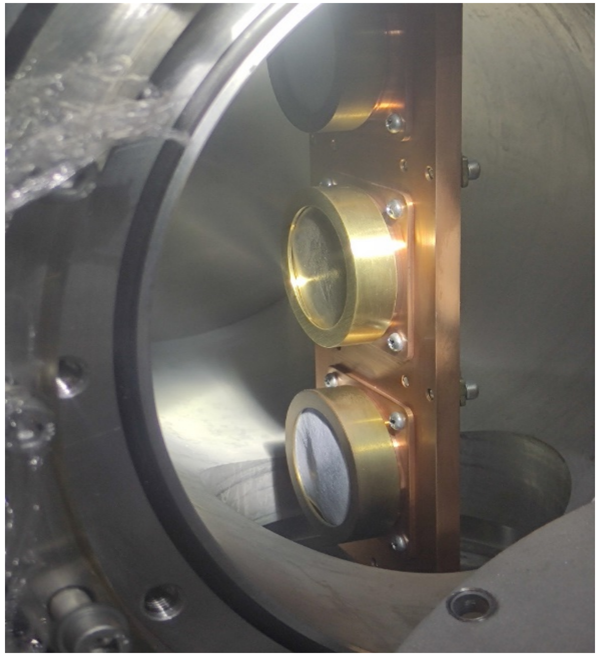
Simulate the thickness of target by SRIM

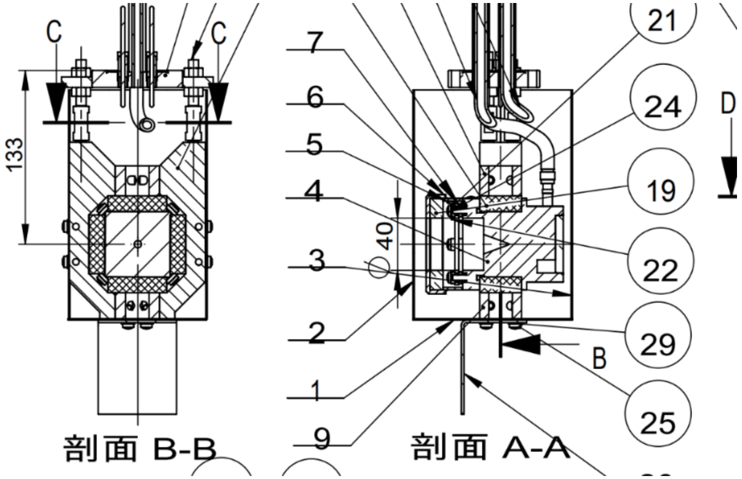
Proton energy /MeV	Lithium thickness/ mm	Energy deposition on the target/MeV	Select thickness/ mm
70	3	1.32	4
	4	**1.76**	
	5	2.21	
	6	2.66	
	7	3.11	
	8	3.56	
	9	4.02	
80	3	1.18	5
	4	1.58	
	5	**1.98**	
	6	2.38	
	7	2.79	
	8	3.19	

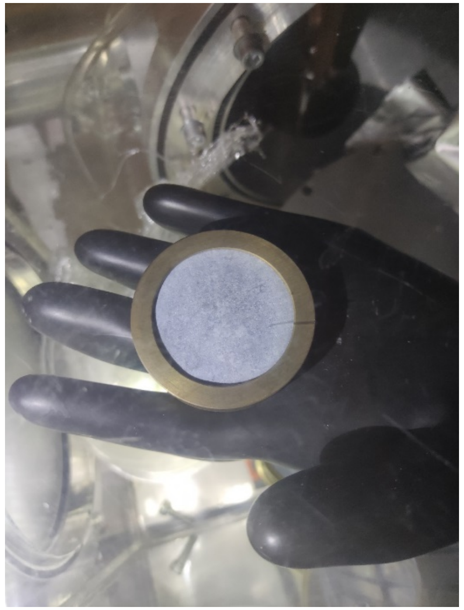
Proton energy /MeV	Lithium thickness/mm	Energy deposition on the target/MeV	Select thickness/ mm
90	3	1.08	6
	4	1.44	
	5	1.81	
	6	**2.18**	
	7	2.55	
	8	2.92	
	9	3.29	
100	3	0.99	6
	4	1.33	
	5	1.66	
	6	**2.00**	
	7	2.34	
	8	2.68	

Layout of QMN in CIAE

- Target chamber
  - Consists of Faraday cup, and target plate filled with Argon gas with 1.1 atm;
  - five targets on the plate
    - 4, 5, 6 mm metal ^{7}Li
    - Fluorescent target
    - Blank target

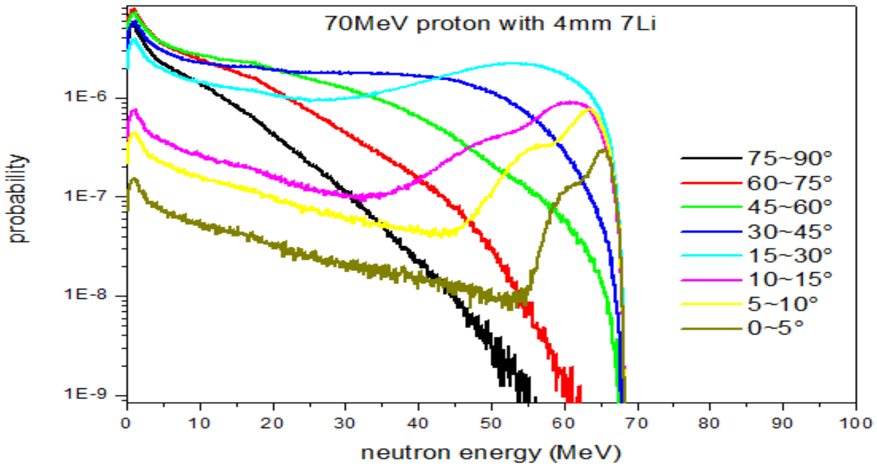


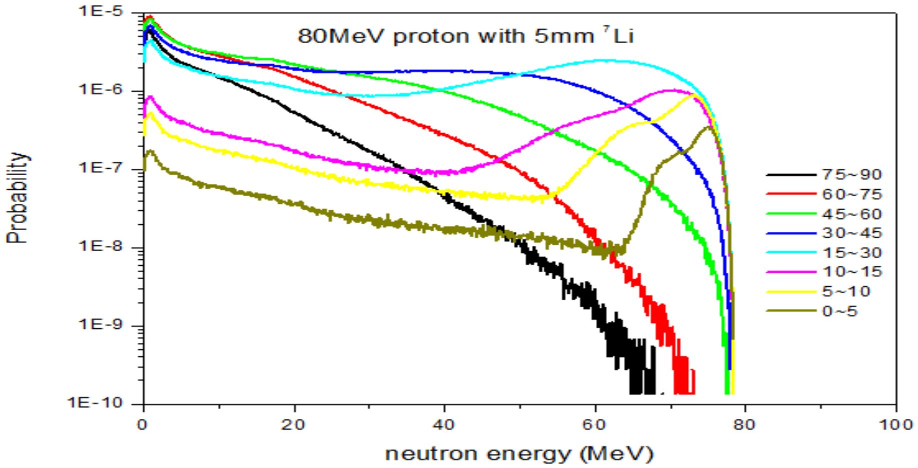


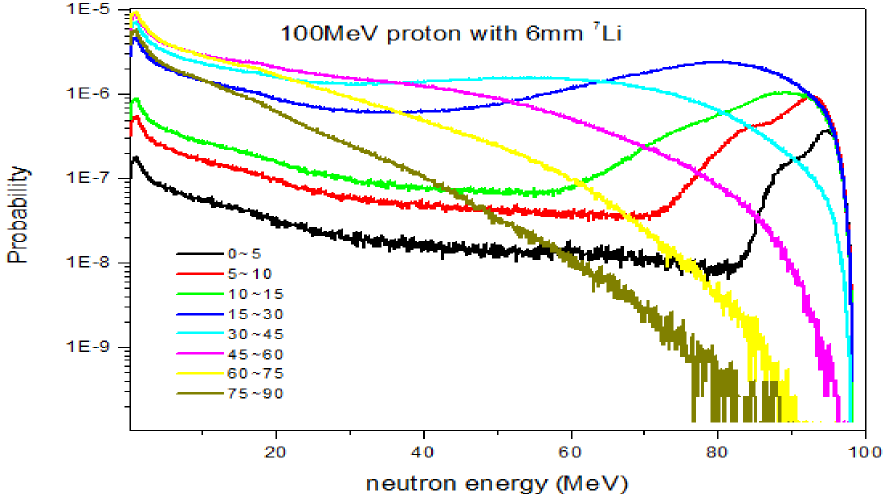


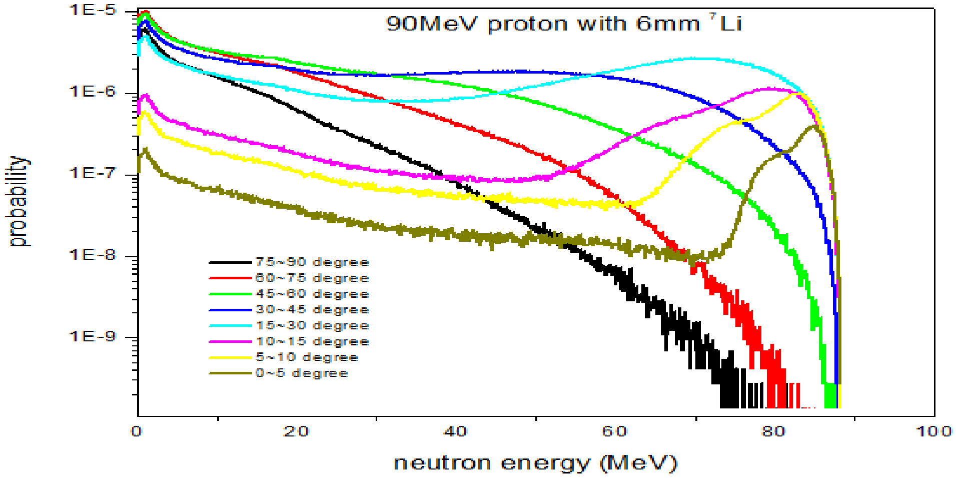
Layout of QMN in CIAE

Simulation result (MCNPX, with CEM03.03 model which is combined the preequilibrium emission and evaporation model)



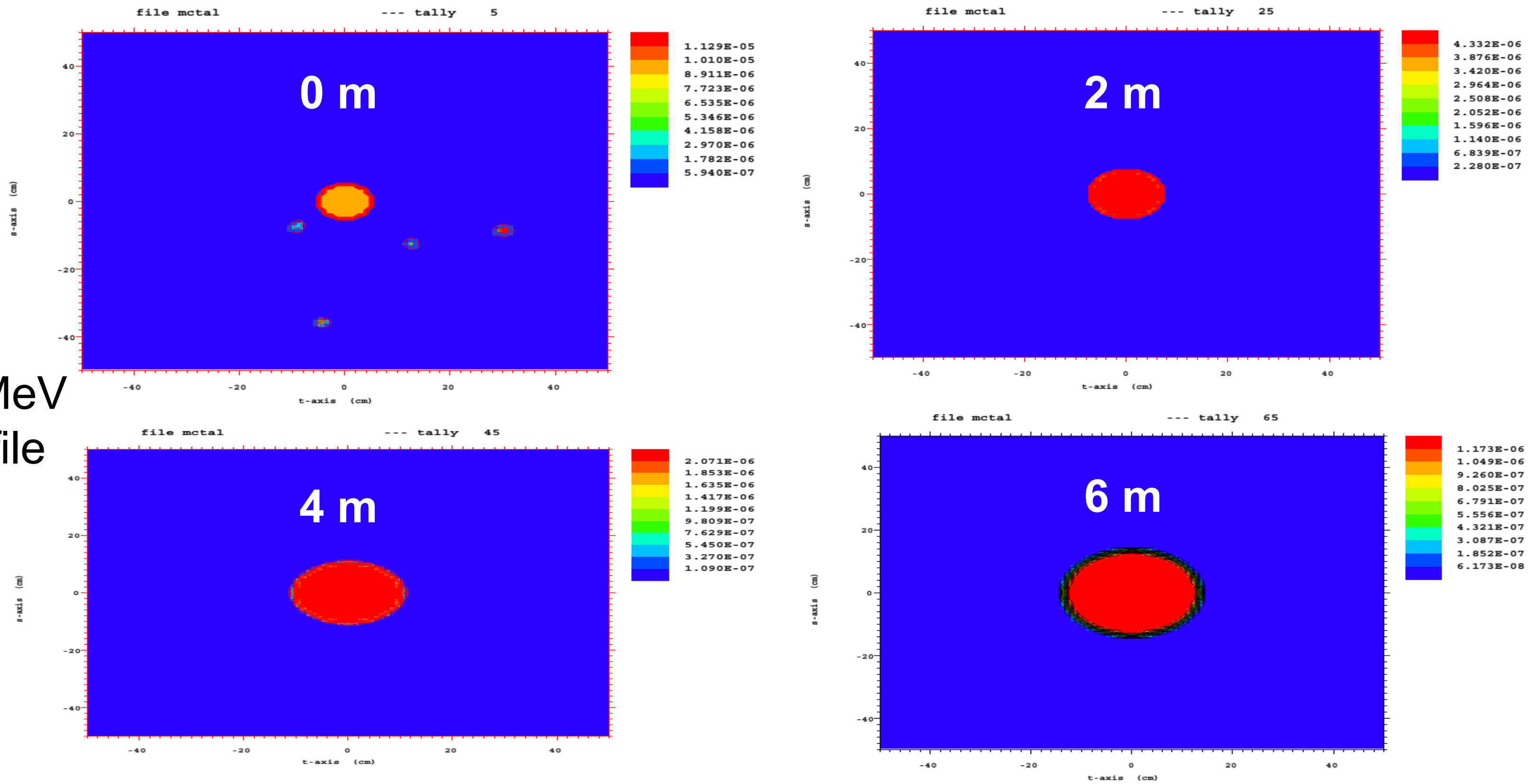






Layout of QMN in CIAE

Simulation for 100MeV neutron beam profile

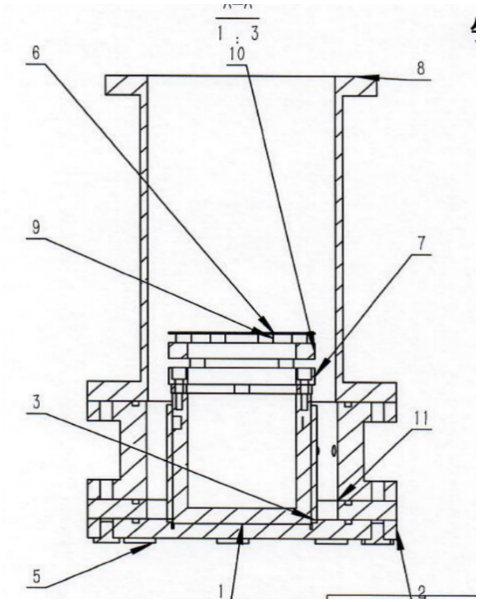


Simulation results for 100MeV neutron beam

Neutron Fluence cm-2s-1/uA	Neutron ambient dose equivalent mSv/h/uA	Peak energy /MeV	Peak neutron ratio	Photon fluence cm-2s-1/uA	photon ambient dose equivalent mSv/h/uA	Photon/neutron fluence
5.47E+04	**7.19E+01**	**9.26E+01**	**50.29%**	4.79E+03	9.83E+01	**8.77%**

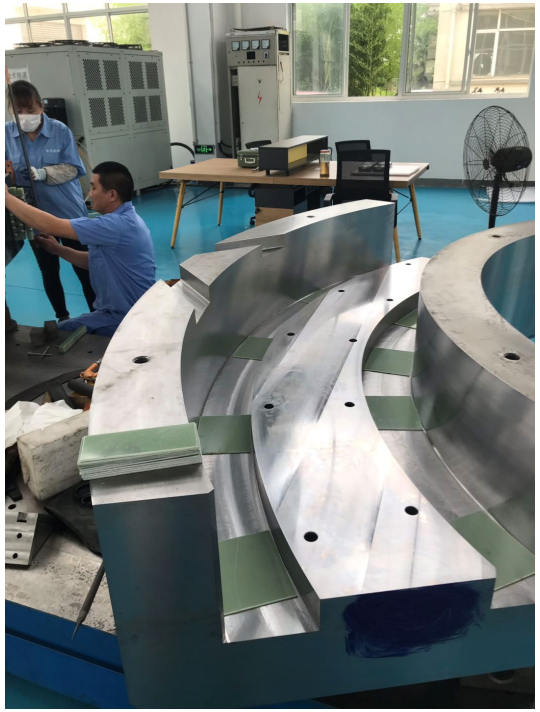
Layout of QMN in CIAE

◻ Beam dump and bending magnet

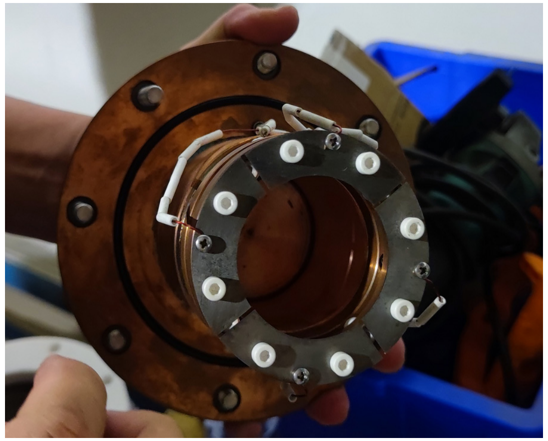


项目号	名称	零件号	数量
1	法拉第桶杯	CJFLD-21-09-01	1
2	内焊法兰100-副本	CJFLD-21-09-02	1
3	法拉第通套	CJFLD-21-09-03	1
4	绝缘法-副本	CJFLD-21-09-04	1
5	绝缘套	CJFLD-21-09-05	8
6	四分钼片	CJFLD-21-09-06	1
7	负压环	CJFLD-21-09-07	2
8	法拉第通外壳	CJFLD-21-09-08	1
9	陶瓷环	CJFLD-21-09-09	8
10	法拉第通外壳-副本	CJFLD-21-09-10	1

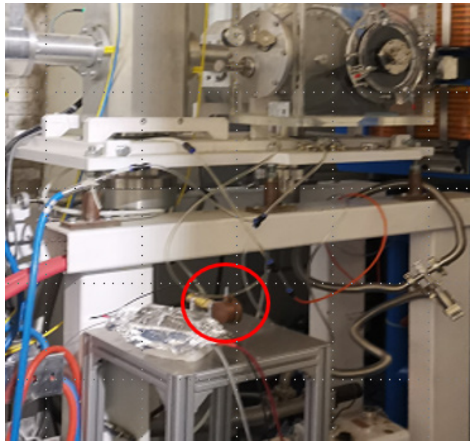
Proton energy/MeV	Range in graphite / mm	Range in Copper / mm
70	20.13	7.09
80	25.57	8.95
100	38.08	13.21



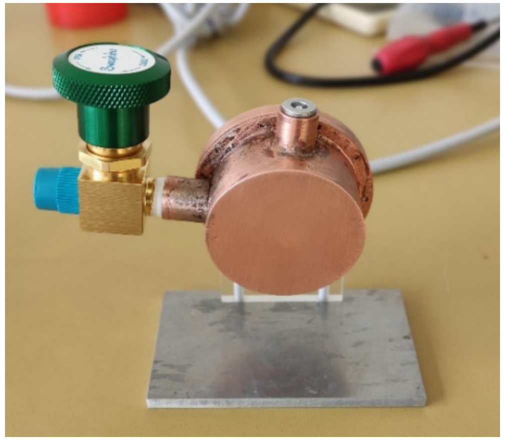
Layout of QMN in CIAE



Faraday cup as proton beam monitor



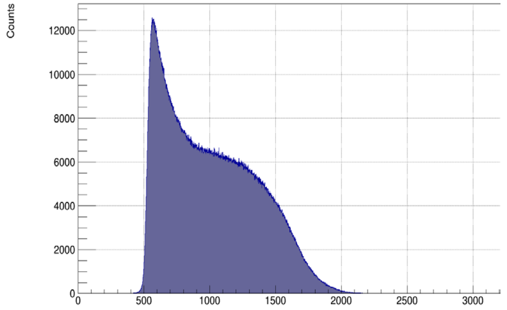
Neutron monitor 1, U-8 fission chamber



Assembly of fission chamber assembly
The effective zone diameter of the coating is 25mm, and the mass thickness is about 200μg/cm2.

Proton vacuum beam pipe

Neutron monitor 2, thin 5mm plastic scintillation detector



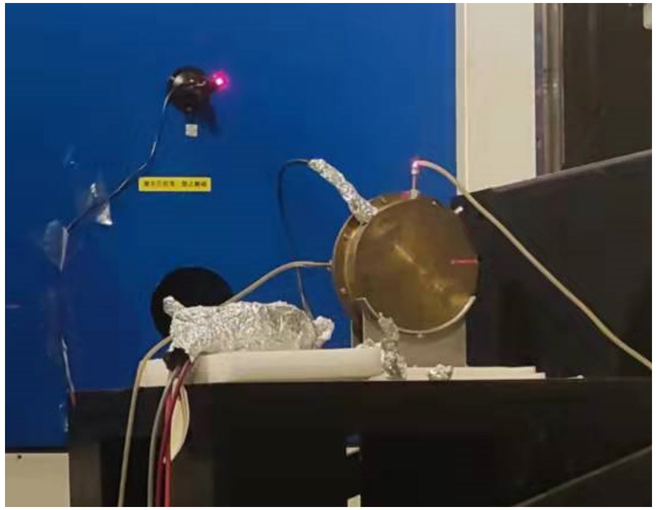
Pulse height spectrum of plastic scintillator

CONTENT

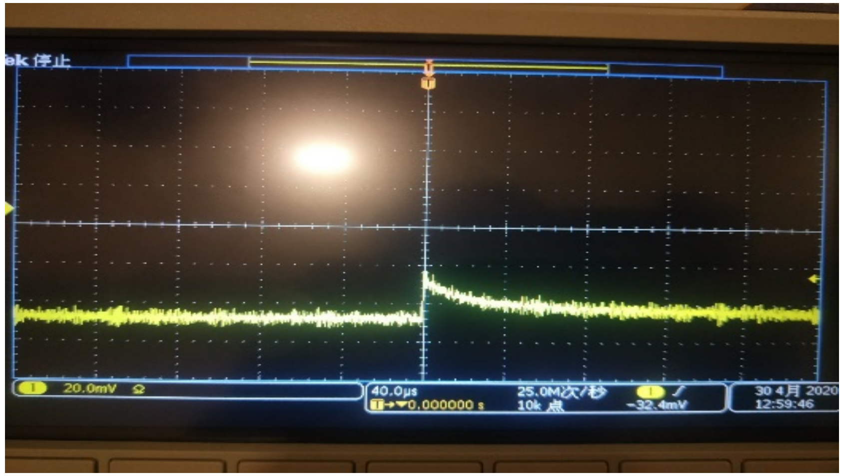
Experiment results

☐ 238U fission chamber confirms that we get the neutrons---the first neutron experiment

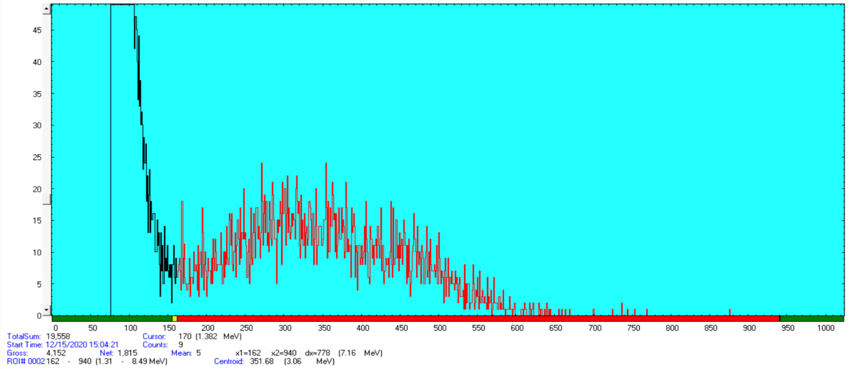
238U FC



238U FC experiment



Signals from the preamplifier by U-8 FC



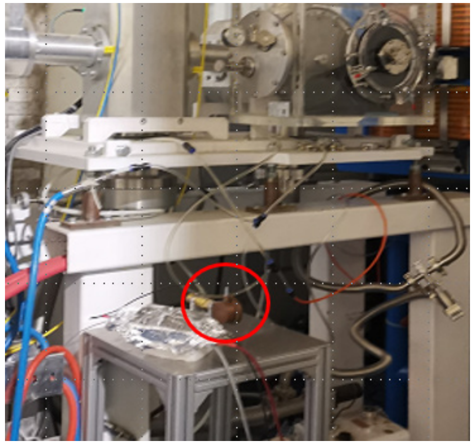
Pulse height spectrum from U-8 FC

- The main target material is natural U, the diameter of the target area is 100 mm, and the active aera is 78.54 cm^2

Experiment results

☐ Neutron monitors and proton monitor repeatability

- Fission Chamber around target: NM1
- Plastic scintillator in experiment room: NM2
- Faraday cup as the proton monitor: PM
- Neutron detector: N



Repeatability of neutron and proton monitor

Neutron energy/MeV	With/without target	Repeatability of N/NM1	Repeatability of N/NM2	Repeatability of N/PM
100	With T	1.86%	1.48%	3.45%
	Without T	1.67%	1.01%	1.09%
70	With T	1.04%	0.77%	1.41%
	Without T	6.67%	5.11%	4.02%

Experiment results

Background

- neutron Background
  - contamination neutron; ratio: N (with target) / N' (without target), on beam
  - Room scattering neutron; ratio: N_s (on beam) / N'_s (out of beam), with target;

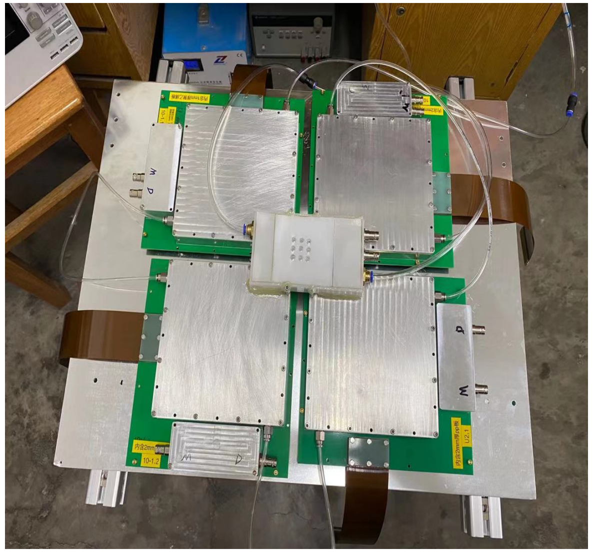
N / N' \ distance (cm)	23.1	53	100	300	500
70	3.27	/	2.01	1.82	2.29
100	/	2.63	2.60	2.48	2.27

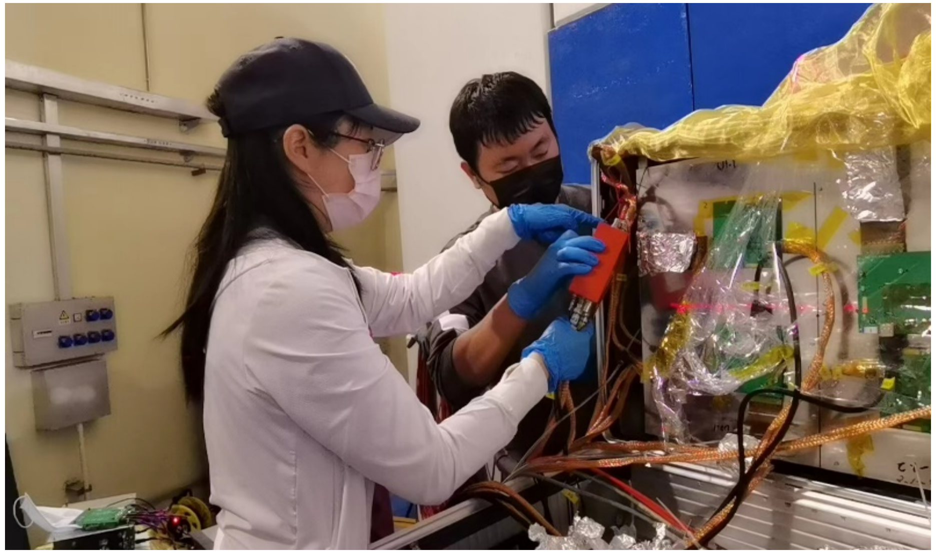
N_s / N'_s \ distance (cm)	23.1	53	100	300	500
70	16.9	/	11.0	7.4	4.5
100	/	18.5	12.3	6.8	5.0

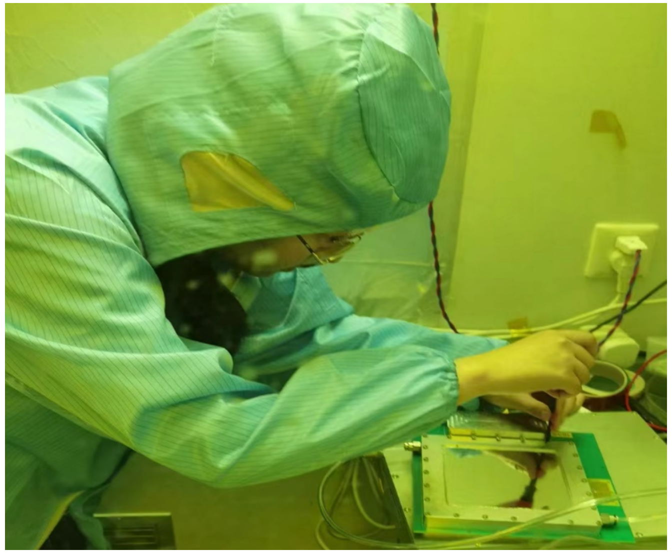
Experiment results

◻ Neutron beam profile

- ➢ Micromegas detectors, 512 channels, 64 + 64 strips (orthogonality) for readout , 10 cm × 10cm area per detector, 4 detectors for measurements.
- ➢ at 0.5 m, 1 m, 1.5 m, 2 m, 2.5 m, 3 m, 4 m positions.

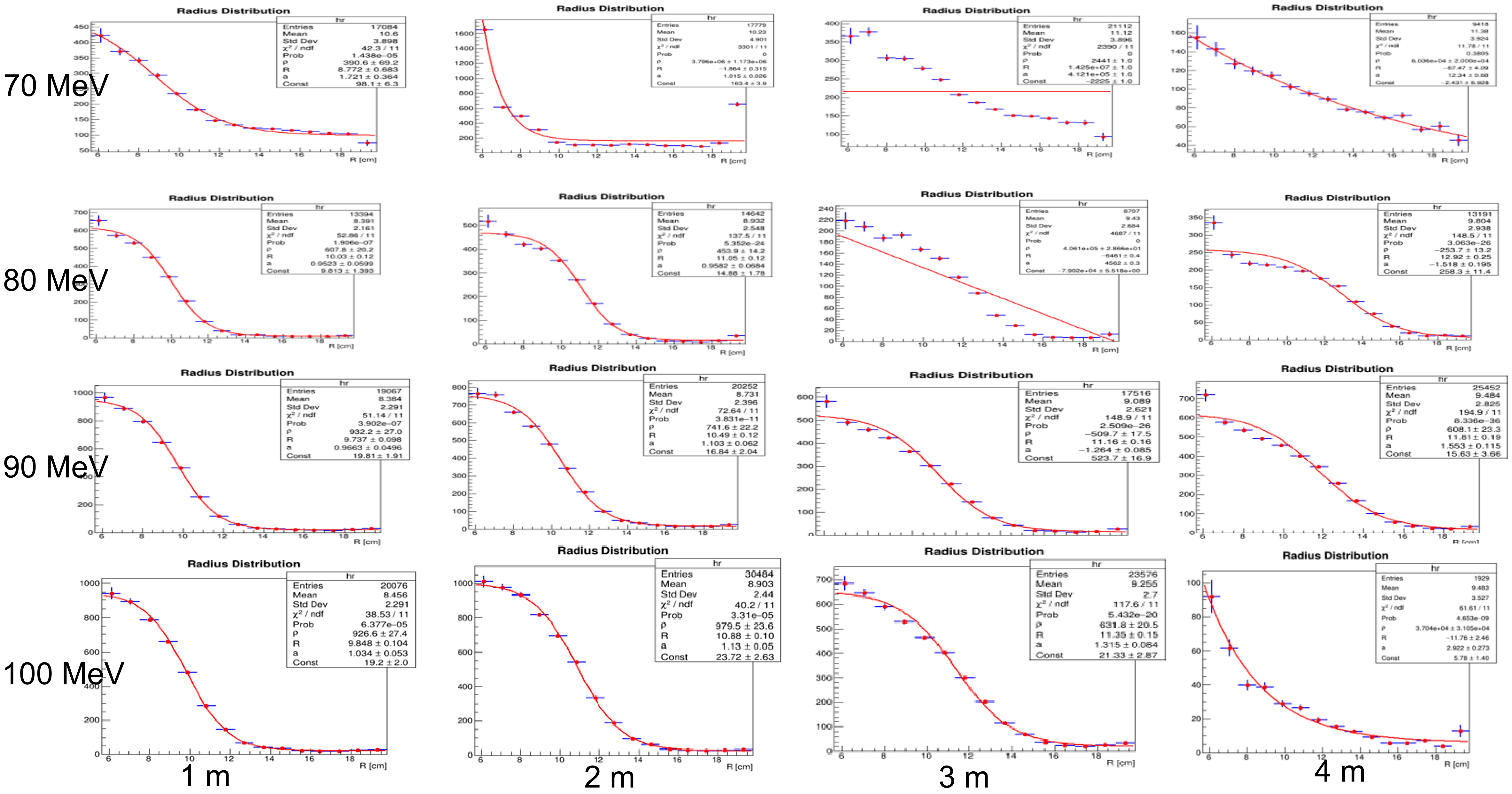






Experiment results

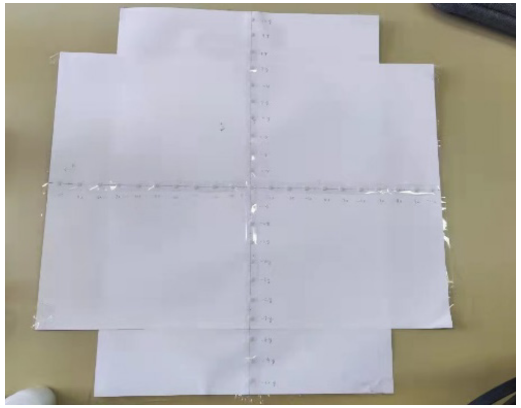
中国原子能科学研究院
CHINA INSTITUTE OF ATOMIC ENERGY

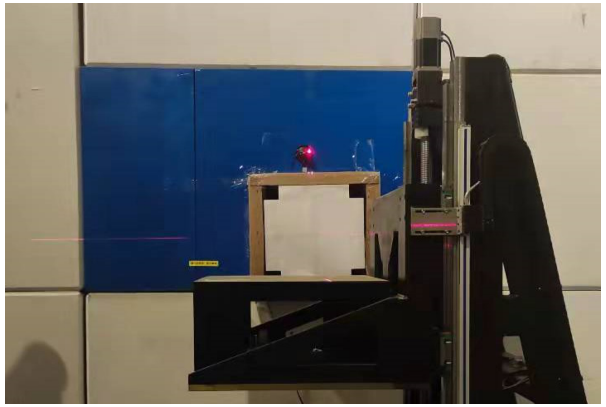


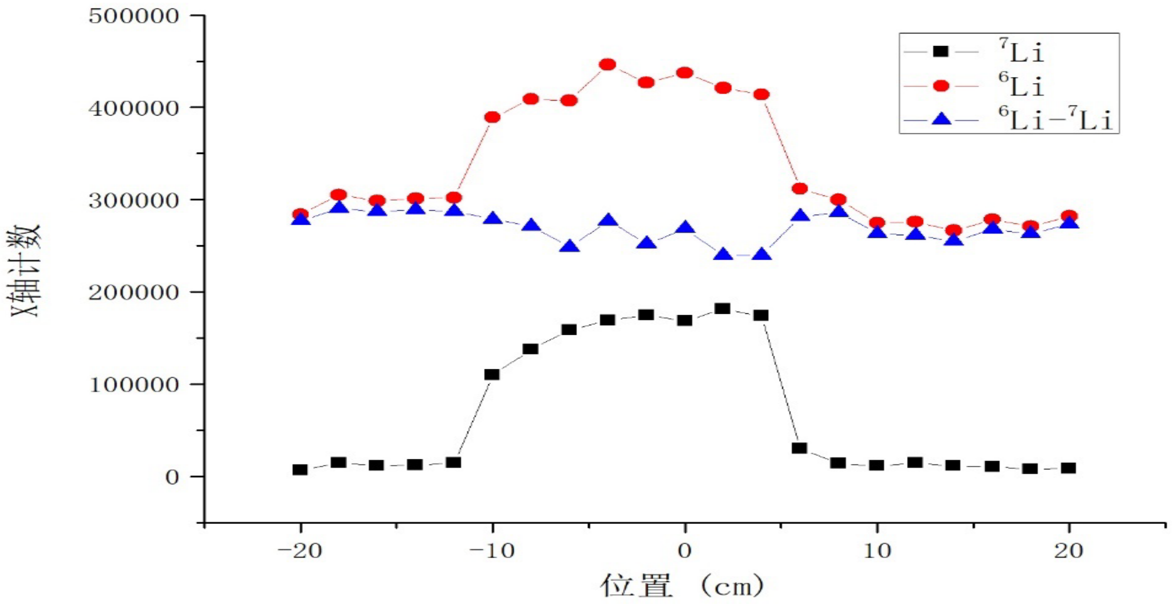
Experiment results

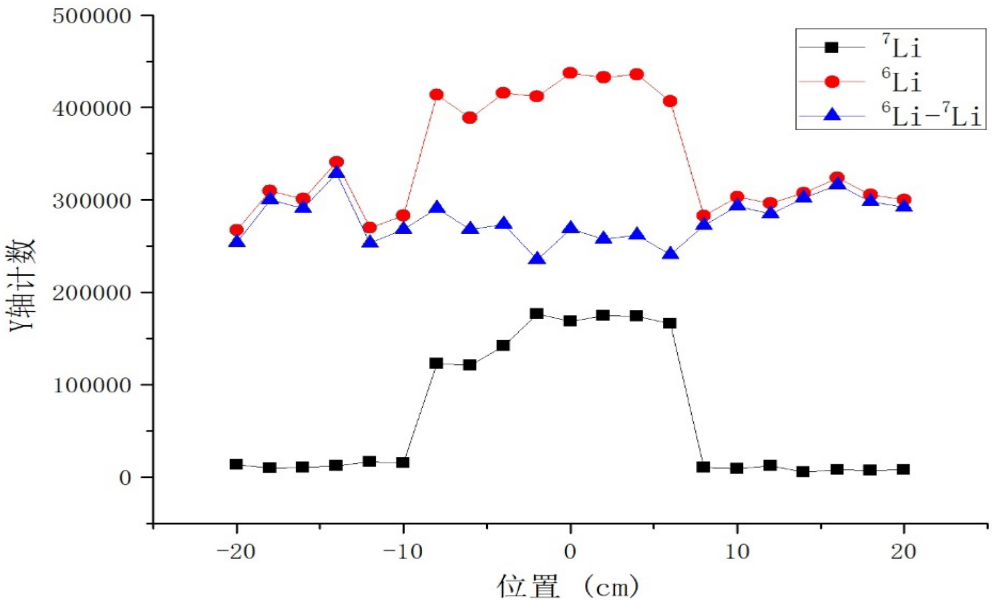
◻ gamma beam profile

- 7Li – 6Li pairs of thermoluminescence detectors
- was placed 30 cm away from the outlet of the collimator
- The XY plane was perpendicular to the direction of the beam.







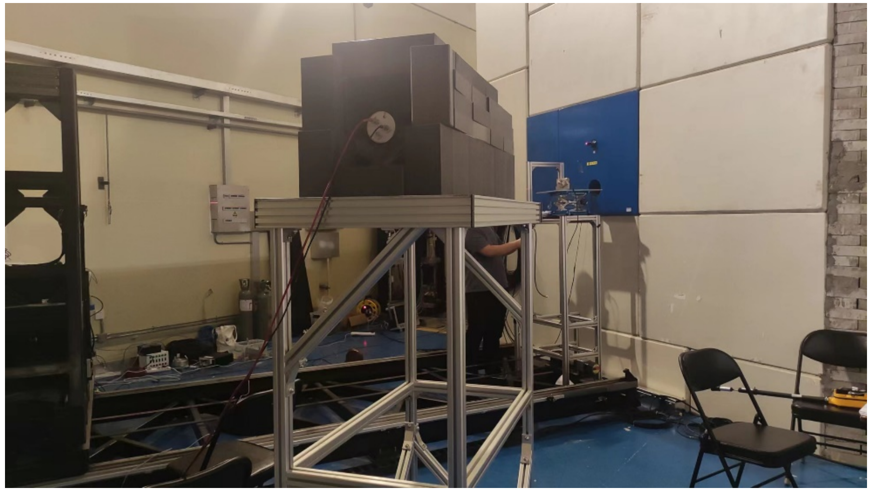


Experiment results

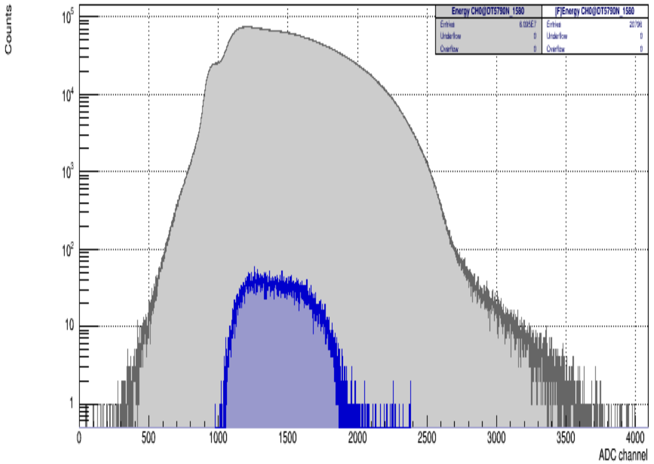
中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY

Neutron spectrum measurement

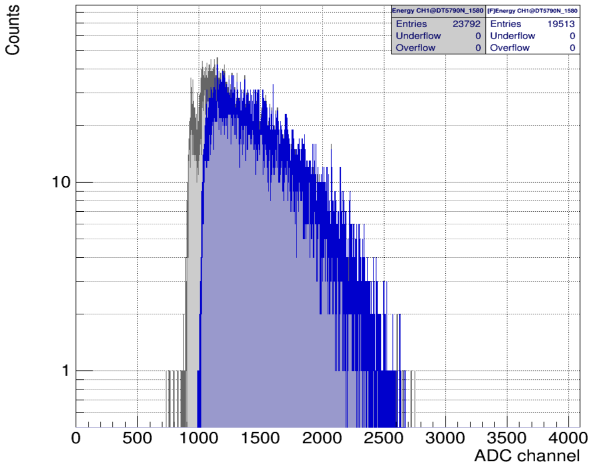
- DC beam mode, TOF method with two liquid scintillation detector, one for start, one for stop gate signal
- TOF detector1: EJ301, 2” diameter, detector2: EJ309, 5” diameter; coincidence electronic: CAEN 5790;
- Angles between secondary neutron and neutron beam line are 57°, 57°, 59° at 70 MeV, 90 MeV, 100 MeV
- Secondary neutron flight lengths are 3.46 m, 3.00 m, 3.00m at 70 MeV, 90 MeV, 100 MeV
- Detector2 use shielding B-PE to reduce the background of coincidence event.



Picture of two scintillation TOF experiment

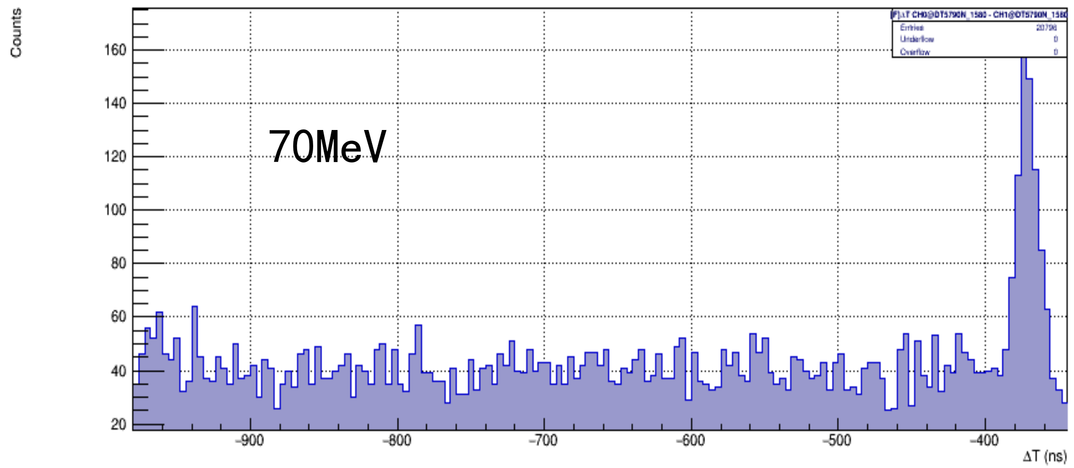


Pulse height spectrum of detector1

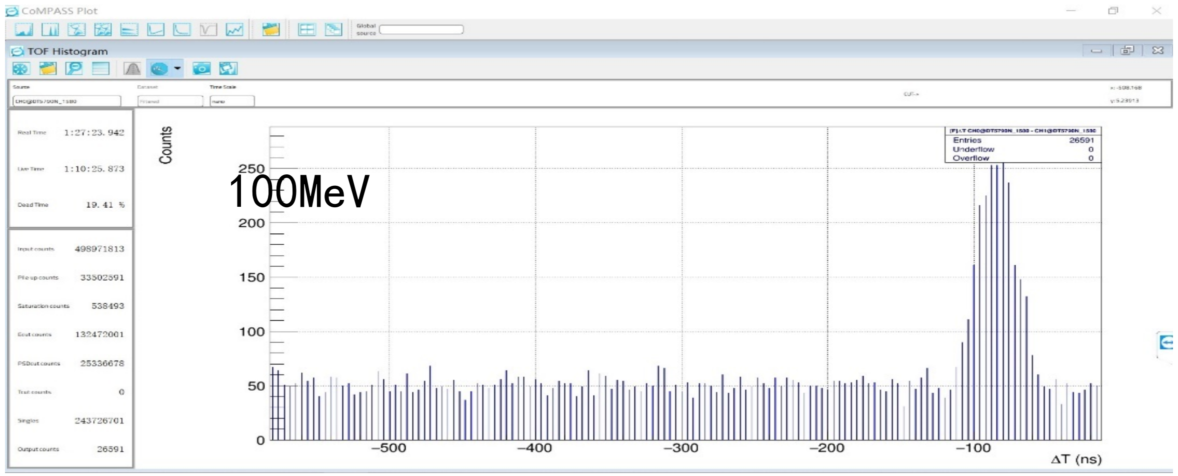


Pulse height spectrum of detector2

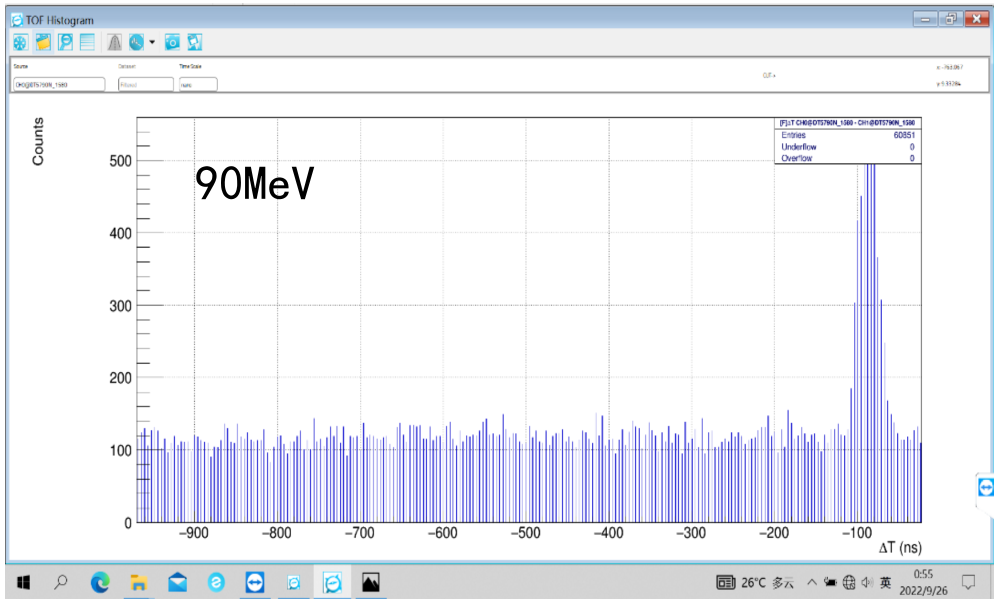
Experiment results



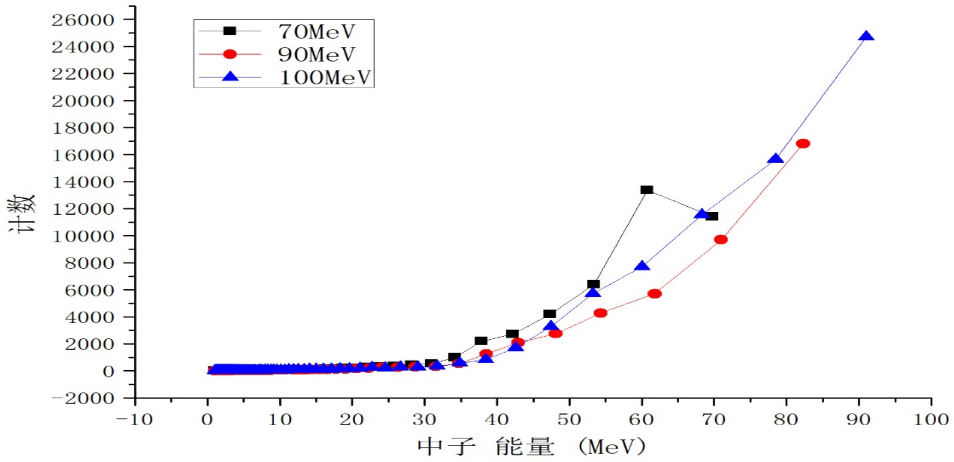
TOF Spectrum



TOF Spectrum



TOF Spectrum

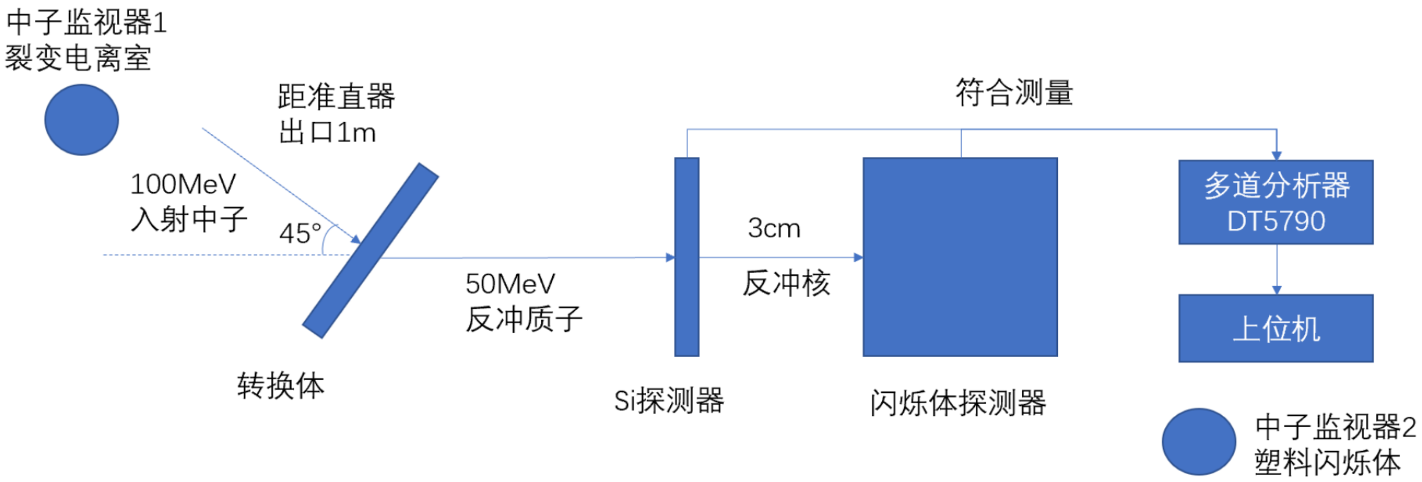


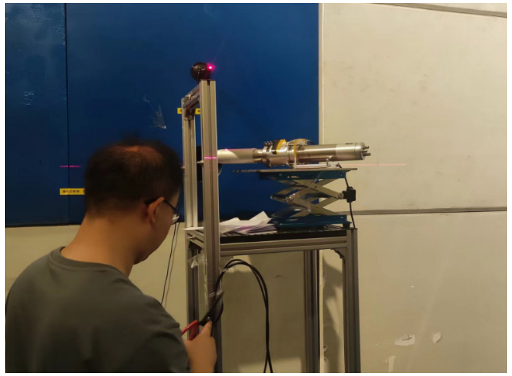
Neutron energy distribution

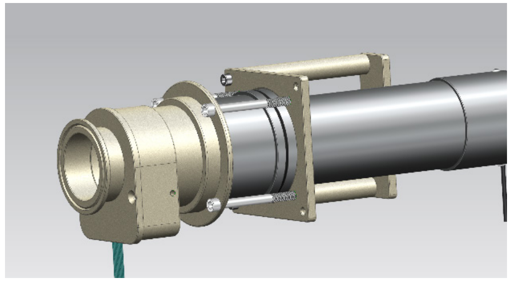
中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY 中核集团 CNNC

☐ Neutron fluence absolute measurement

- ΔE-E telescope, polyethylene convertor Φ38 mm×1 mm； ΔE detector: silicon, Φ40 mm×1.5 mm; E detector: BC501A Φ2'' × 2''; with two apertures to define the solid angle.
- Telescope is located outside the neutron beam to reduce the background events for ΔE-E detectors
- CAEN DT5790 is used for coincidence electronic box.





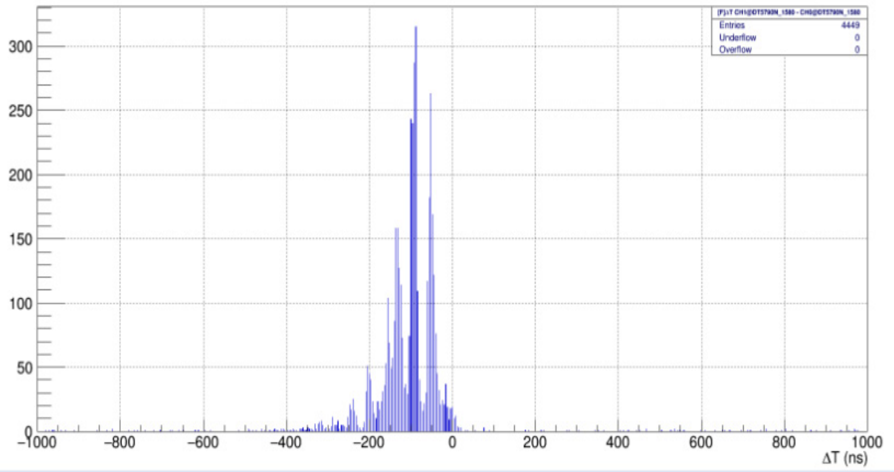


Experiment results

中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY

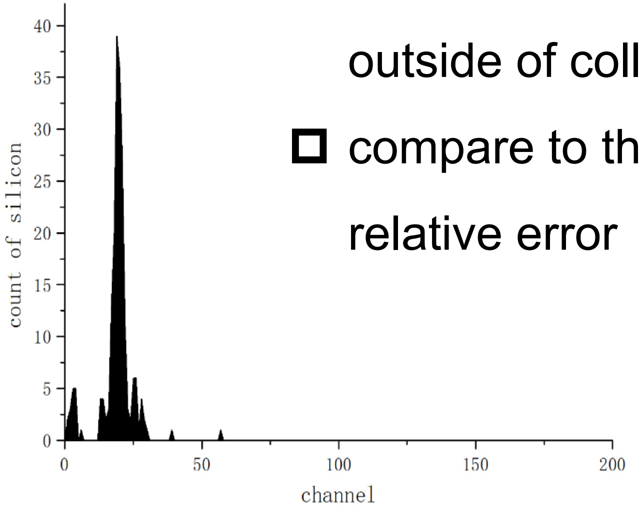
- Fluence response is calculated by Geant4

Energy/ MeV	70	80	90	100
Response/ cm^2	1.03E-05	1.51E-05	2.02E-05	2.92E-05
Fluence /cm^{-2} s^{-1}μA^{-1}	8.55E+04	7.12E+04	6.42E+04	5.04E+04

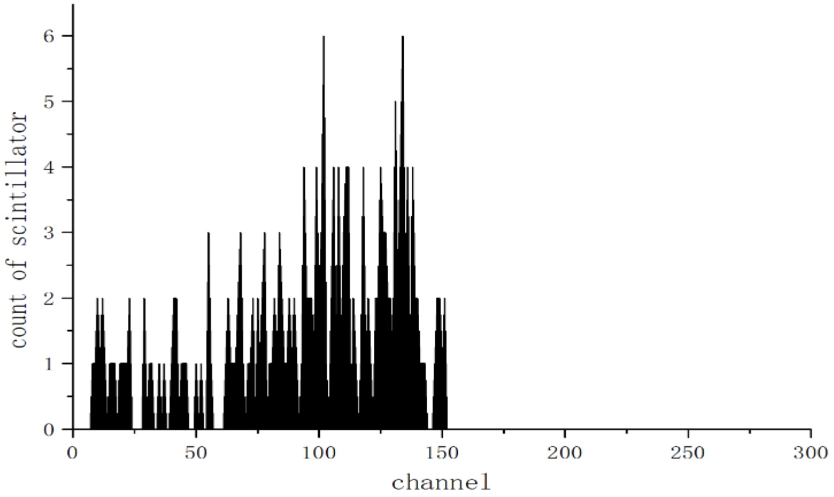


Coincidence events TOF spectrum

- Measurement point: 80 cm from outside of collimator
- compare to the simulation result, 24% relative error



Coincidence events pulse height spectrum for silicon



Coincidence events pulse height spectrum for silicon

CONTENT

Summary

- QMN is important for detector calibration, SEE, proton therapy, shielding materials benchmark, cross-section measurement;
- 70 MeV ~ 100 MeV QMN is established in CIAE for the first time in China
- Get the information of QMN
  - Neutron monitors: FC, thin plastic scintillation;
  - Proton monitor: faraday cup;
  - Neutron beam profile: micromegas detector;
  - Energy: two scintillation TOF method;
  - Fluence: ΔE-E telescope
- Next plan: reduce the neutron background
  - Reduce the contamination neutrons
  - Fully close the neutron target Chamber by concrete shielding materials
  - Add the neutron beam dump to reduce the scattering neutron.

Thanks for your attention