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

Nuclear Data Measurement activities at CIAE

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China Institute of Atomic Energy (CIAE)

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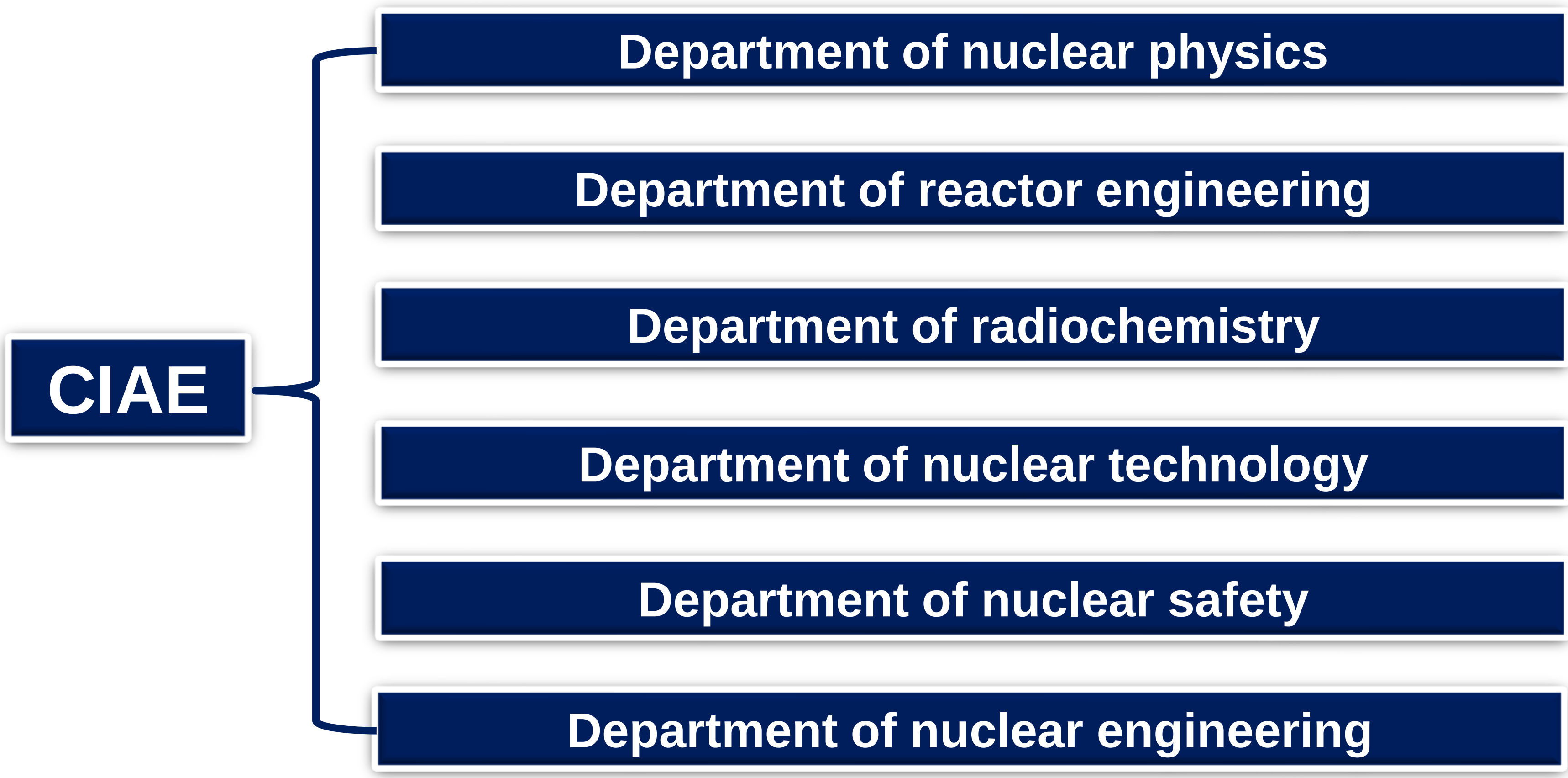
CNDC
CHINA NUCLEAR DATA CENTER

Contents

Introduction

CIAE was founded in 1950, is the birthplace of China's nuclear science and technology, and the "cradle" and "old hen" of China's nuclear industry.

- 6 departments, 12 National and ministerial level laboratories;
- More than 3000 staffs.



DNP has 9 labs, about 210 staffs.

DNP

- Radiation effect lab
- Basic nuclear physics lab
- Neutron physics lab
- China nuclear data centre
- HI-13 tandem accelerator lab
- Neutron scattering lab
- Nuclear technology lab
- Laser physics lab
- Accelerator R&D lab

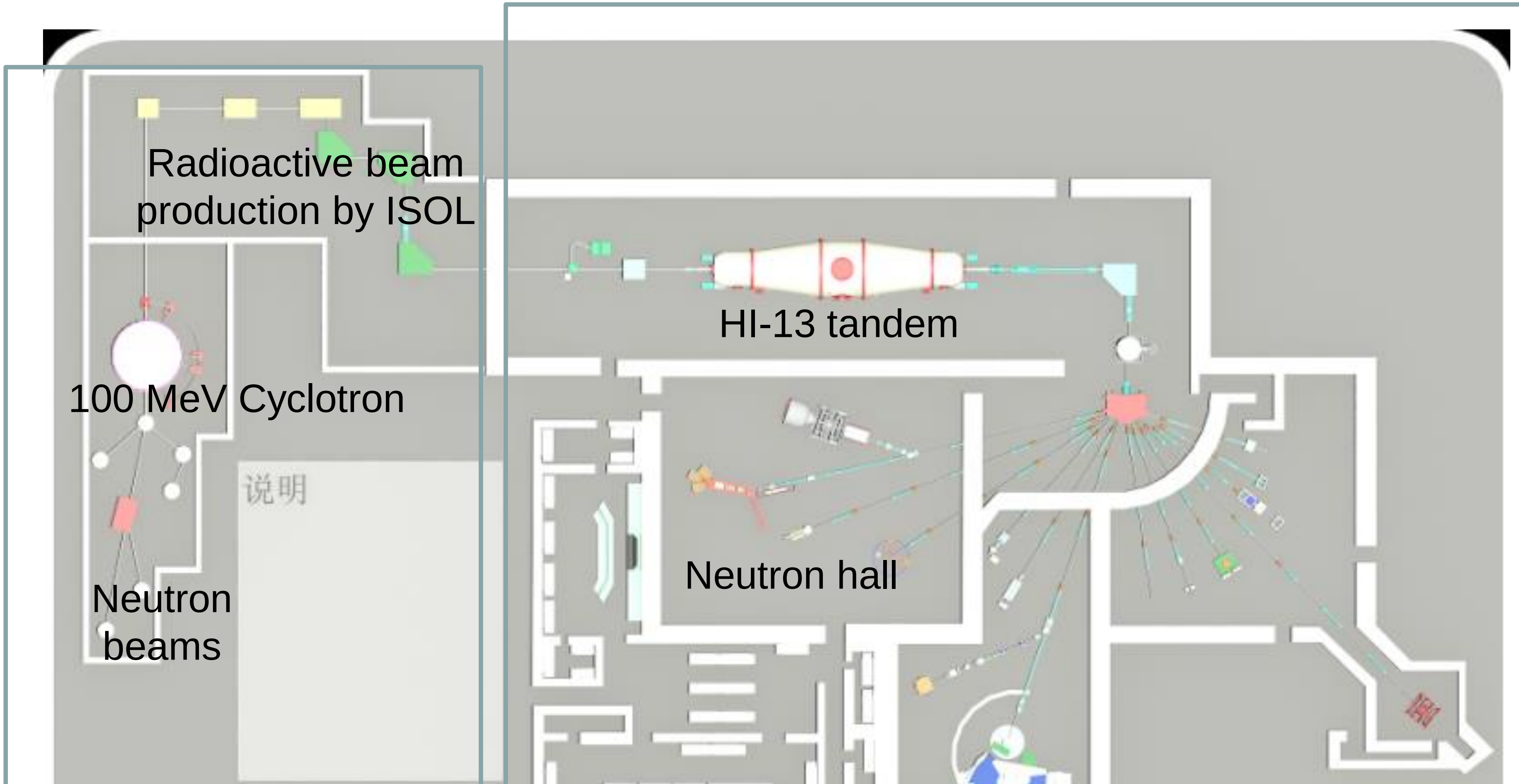
Main purpose of ND production in China

- Nuclear energy system development
  - Generation IV reactors R&D
  - CiADS(Chinese Initiative Accelerator Driven System)
  - TMSR(Thorium Molten Salt Reactor)
  - Fusion reactor
- Nuclear science study
- Nuclear technology applications

Neutron sources used for ND measurement at CIAE

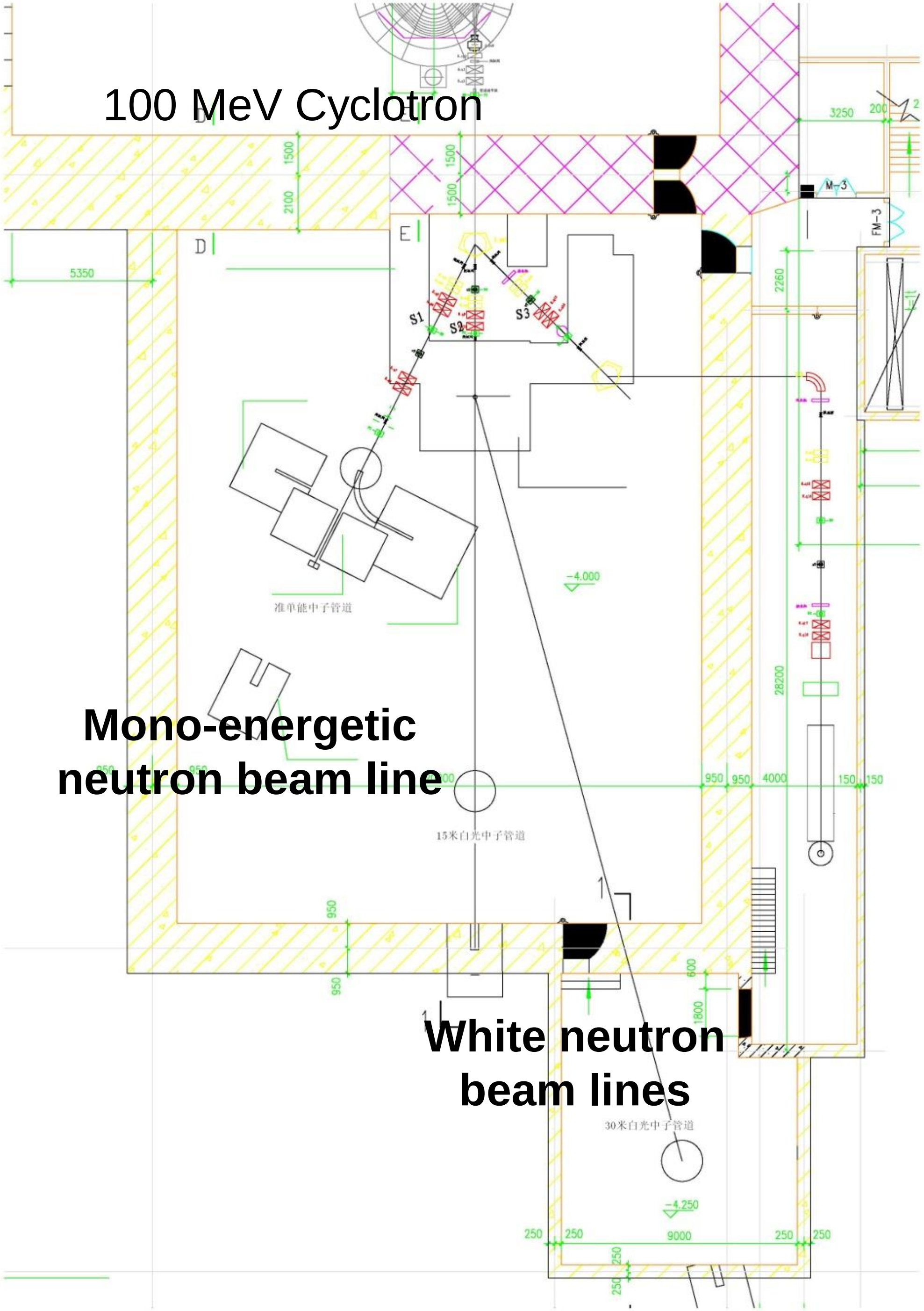
1. **HI-13 2×13 MV tandem accelerator: 5-40 MeV (DC and pulsed)**
2. **Reactor: High flux thermal neutrons**
3. **Neutron generator: 14 MeV and 2.5 MeV (DC and pulsed)**
4. **2×1.7 MV tandem: 10 keV-5 MeV and 14-20 MeV (DC and pulsed)**
5. **100 MeV proton Cyclotron**
6. **China Spallation Neutron Source at IHEP (CSNS)**

HI-13 tandem accelerator



70-100 MeV (p+7Li)	10^{10} n/s/sr
WNS	10^{12} n/s/sr

8-26 MeV (d+D)	10^8
4-23 MeV (p+T)	10^7 n/s/sr
22-42 MeV (d+T)	10^6



Three neutron beam lines designed:

1. **Mono-energetic neutrons (70-100 MeV)**
2. **White neutrons with 15 and 30 meters FP.**

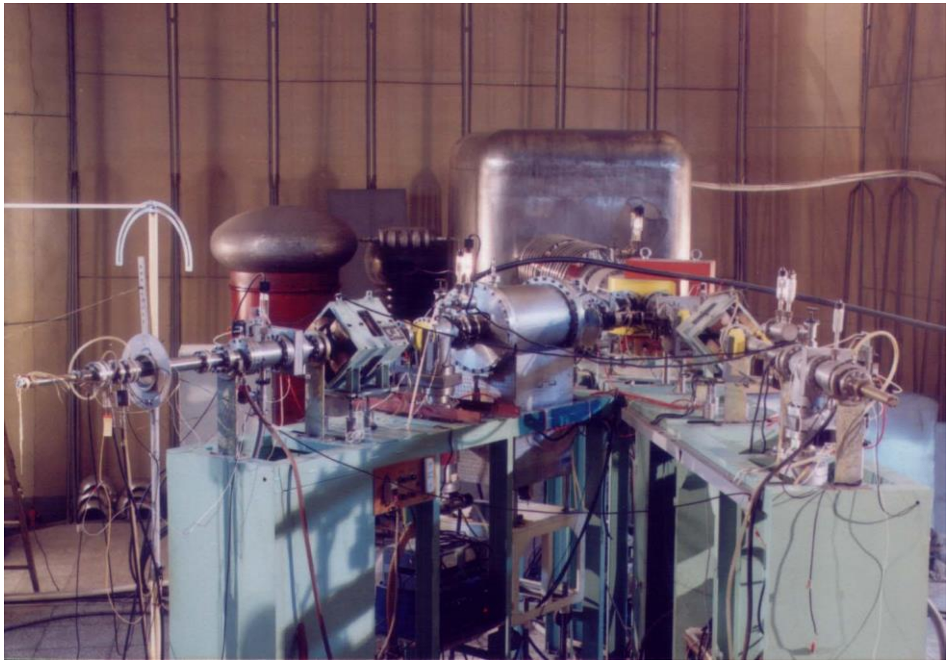
Various ND measurements are planed with these neutron beam lines

600 kV Cockcroft-Walton neutron generator

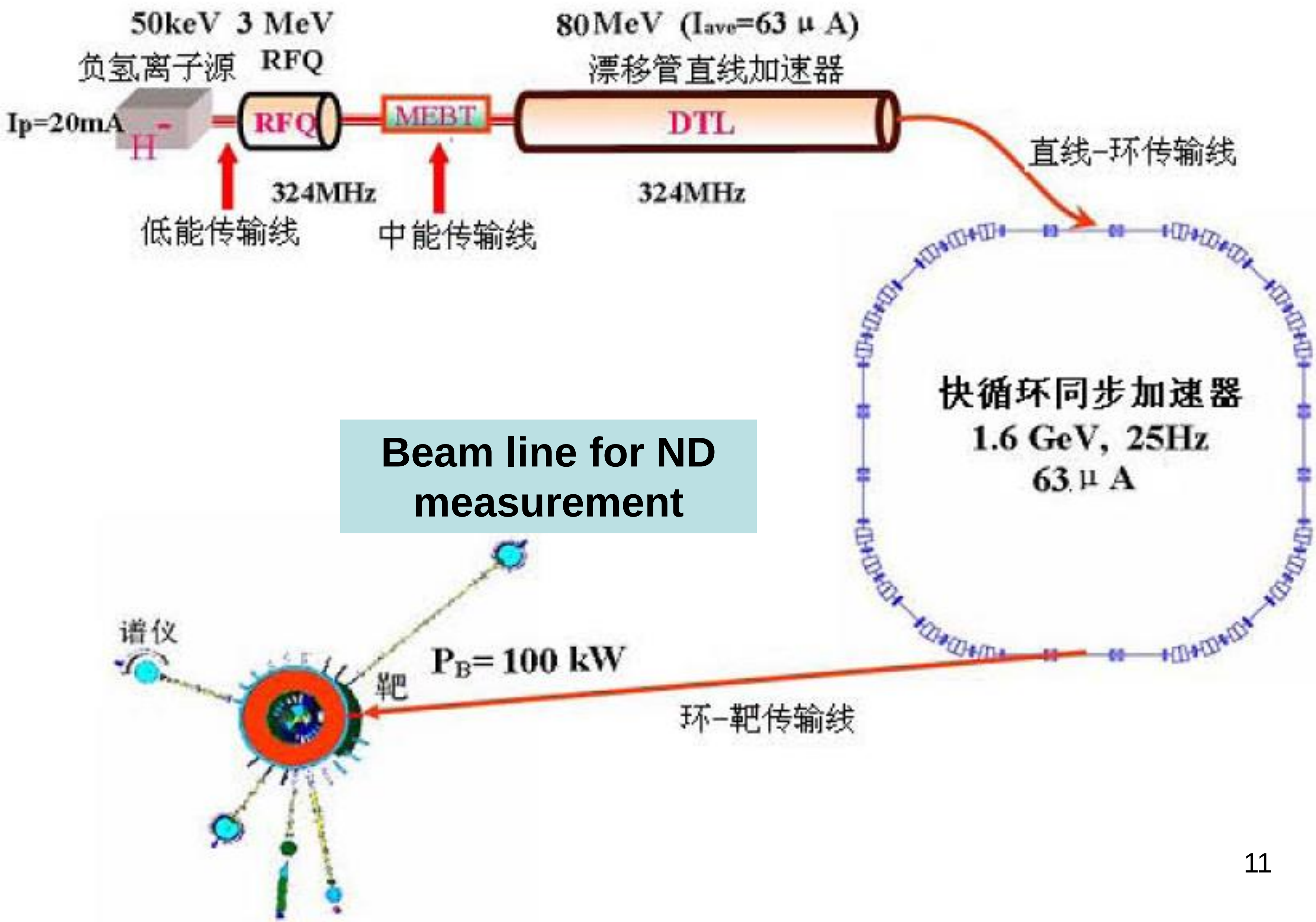
- **Provide 14 and 2.5 MeV neutrons for ND measurement, detector calibration and other applications**
- **Provide 6.13 MeV gammas for detector calibration**

- **> 1000 hours beam time every year for different users**

Ions	p and d
Current	Maximum 1 mA (DC) ~30 μA (pulsed)
Pulse width	~2 ns
Neutron yield	10^{11} n/s for DC 10^{9} n/s for pulsed 14 MeV 10^{9} n/s for DC 10^{8} n/s for pulsed 2.5 MeV



The back-streaming neutron beam of CSNS



Summary of neutron sources for ND measurement

facility	energy	intensity (1/s/sr)
Reactors	thermal	10^{14} n/cm^2/s
HI-13	8-26 MeV (d+D) 4-23 MeV (p+T) 22-42 MeV (d+T)	10^8 [illegible] [illegible]
2×1.7MV	3-6 MeV [illegible] [illegible] [illegible]) [illegible]eV (p+Li)	[illegible] 10^8 10^9 10^8
[illegible]	2.5, 14 MeV	10^8， 10^{10}
CSNS	0.5 eV-100 MeV	10^7 n/cm^2/s
Cyclotron	0.1-20 MeV	10^{12}

From thermal to hundred MeV, mono-energetic, quasi-monoenergetic, white neutron source

Spectrometers and recent progress of ND measurement

HPGe detector for gamma spectroscopy

- **Well calibrated**
- **Excitation function measurement**
- **Fission yield measurement**
- **Decay data measurement**

Excitation function (94 neutron reactions, 18 charged particle reactions)

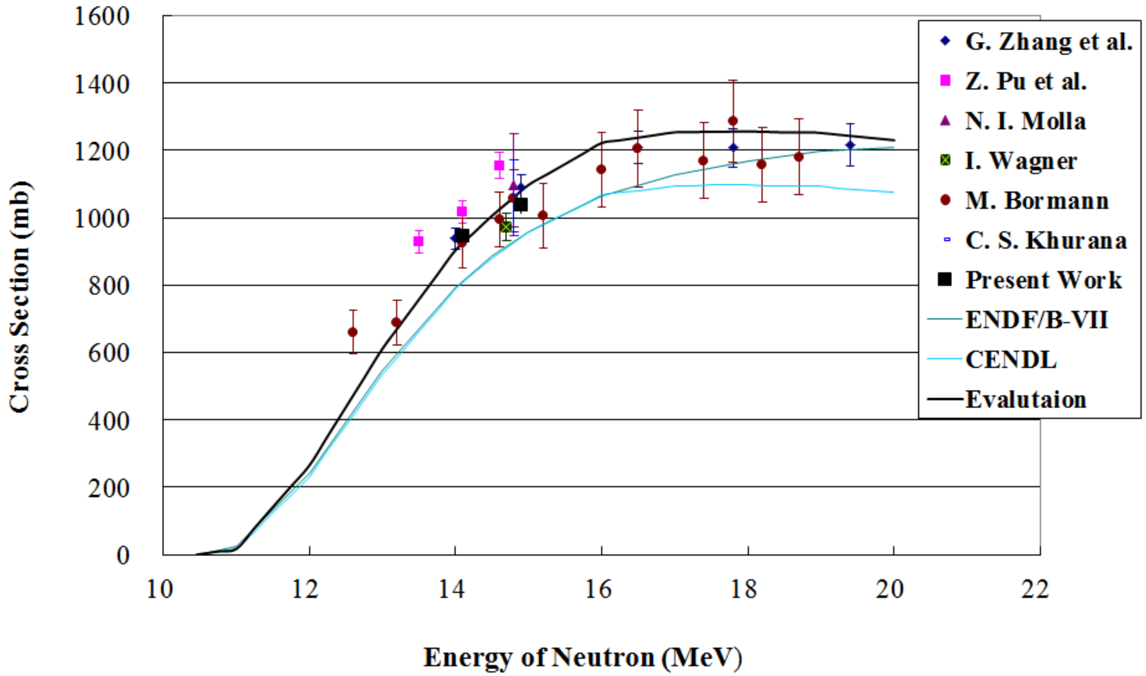
^{23}Na(n,2n)^{22}Na	^{24}Mg(n,p)^{24}Na	^{27}Al(n, a)^{24}Na	^{45}Sc(n,2n)^{44g,}Sc	^{45}Sc(n,2n)^{44m}Sc	^{45}Sc(n,2n)$^{44m+g}$Sc
^{46}Ti(n,p)^{46}Sc	^{47}Ti(n,p)^{47}Sc	^{48}Ti(n,p)^{46}Sc	^{51}V(n,a)^{48}Sc	^{55}Mn(n,2n)^{54}Mn	^{54}Fe(n,p)^{54}Mn
^{54}Fe(n,a)^{51}Cr	^{56}Fe(n,p)^{55}Mn	^{59}Co(n,2n)^{58}Co	^{59}Co(n,p)^{59}Fe	^{59}Co(n,a)^{56}Mn	^{58}Ni(n,2n)^{57}Ni
^{58}Ni(n,p)^{58}Co	^{58}Ni(n,x)^{57}Co	^{60}Ni(n,p)^{60}Co	^{62}Ni(n,a)^{59}Co	^{62}Ni(n, a)^{59}Fe	^{63}Cu(n,a)^{60}Co
^{66}Zn(n,2n)^{65}Zn	^{67}Zn(n,p)^{67}Cu	^{70}Zn(n,2n)^{69m}Zn	^{71}Ga(n,r)^{72}Ga	^{85}Rb(n,2n)^{84m}Rb	^{85}Rb(n,2n)$^{84m+g}$Rb
^{85}Rb(n,p)^{85m}Kr	^{85}Rb(n, a)^{82}Br	^{87}Rb(n,2n)^{86}Rb	^{87}Rb(n,p)^{87}Kr	^{89}Y(n,2n)^{88}Y	^{90}Zr(n,2n)^{89}Zr
^{89}Zr(n,2n)^{88}Zr	^{96}Zr(n,2n)^{95}Zr	^{92}Mo(n,p)^{92}Nb	^{98}Mo(n,r)^{99}Mo	^{93}Nb(n,2n)^{92m}Nb	^{93}Nb(n,a)^{90m} Y
^{109}Ag(n,2n)^{108m}Ag	^{113}In(n,2n)^{112m}In	^{113}In(n,n')^{113m}In	^{115}In(n,2n)^{114m}In	^{115}In(n,n’)^{115m}In	^{115}In(n,r)^{116m}In
^{115}In(n,p)^{115}Cd	^{115}In(n,a)^{112}Ag	^{127}I(n,2n)^{126}I	^{124}Xe(n,2n)^{123}Xe	^{132}Ba(n,2n)^{131}Ba	^{134}Ba(n,2n)^{133m}Ba
^{134}Ba(n,2n)1^{33m+g}Ba	^{134}Ba(n,p)$^{134m+g}$Cs	^{134}Ba(n,a)^{131m}Xe	^{137}Ba(n,p)^{137}Cs	^{136}Ba(n,p)^{136}Cs	^{138}Ba(n,a)^{135}Xe
^{136}Ce(n,2n)^{135}Ce	^{138}Ce(n,2n)^{137m}Ce	^{140}Ce(n,2n)^{139}Ce	^{140}Ce(n,p)^{140}La	^{142}Ce(n,2n)^{141}Ce	^{151}Eu(n,2n)^{150m}Eu
^{151}Eu(n,r)^{152m}Eu	^{151}Eu(n,r)^{152g}Eu	^{153}Eu(n,2n)^{152g}Eu	^{153}Eu(n,r)^{154}Eu	^{159}Tb(n,2n)^{158}Tb	^{159}Tb(n,r)^{160}Tb
^{165}Ho(n,r)^{166m}Ho	^{169}Tm(n,2n)^{168m}Tm	^{169}Tm(n,3n)^{167}Tm	^{169}Tm(n,r)^{170}Tm	^{175}Lu(n,2n)$^{174m+g}$Lu	^{176}Hf(n,2n)^{175}Hf
^{180}Hf(n,r)^{181}Hf	^{179}Hf(n,2n)^{178m2}Hf	^{180}Hf(n,2n)^{179m2}Hf	^{181}Ta(n,2n)^{180m}Ta	^{181}Ta(n,p)^{181}Hf	^{182}W(n,n’a)^{178m2}Hf
^{185}Re(n,2n)^{184m}Re	^{185}Re(n,2n)$^{184m+g}$Re	^{187}Re(n,2n)^{186g}Re	^{187}Re(n,2n)^{186m}Re	^{193}Ir(n,2n)^{192m2}Ir	Pt(n,x)^{195m}Pt
^{198}Pt(n,2n)^{197}Pt	^{197}Au(n.2n)^{196}Au	^{197}Au(n,3n)^{195}Au	^{204}Pb(n,2n)^{203}Pb		

^{51}V(d,2n)^{51}Cr	^{89}Y(p,n)^{89}Zr	^{89}Y(p,2n)^{88}Zr	^{89}Y(p,pn)^{88}Y	^{51}V(p,n)^{51}Cr	Fe(p,x)^{57}Co
Fe(p,x)^{54}Mn	Fe(p,x)^{55}Co	Fe(p,x)^{56}Co	^{27}Al(d,pa)^{24}Na	Ti(p,x)^{48}V	Ti(d,x)^{48}V
Mo(p,x)^{95m,g}Tc	Mo(p,x)^{96g}Tc	Mo(p,x)^{99}Mo	Mo(d,x)^{95m,g}Tc	Mo(d,x)^{96g}Tc	Mo(d,x)^{99}Mo

Excitation function measurement

69Ga(n,2n)68Ga cross section measurement

Method: activation
Neutron source: d-T reaction, 14.1 and 14.9 MeV
Measurement: HPGe detector
Findings: the 511 keV gammas can't be used, the branching ratio of 68Ga decay should be re-evaluated
Evaluation: New evaluation has been proposed

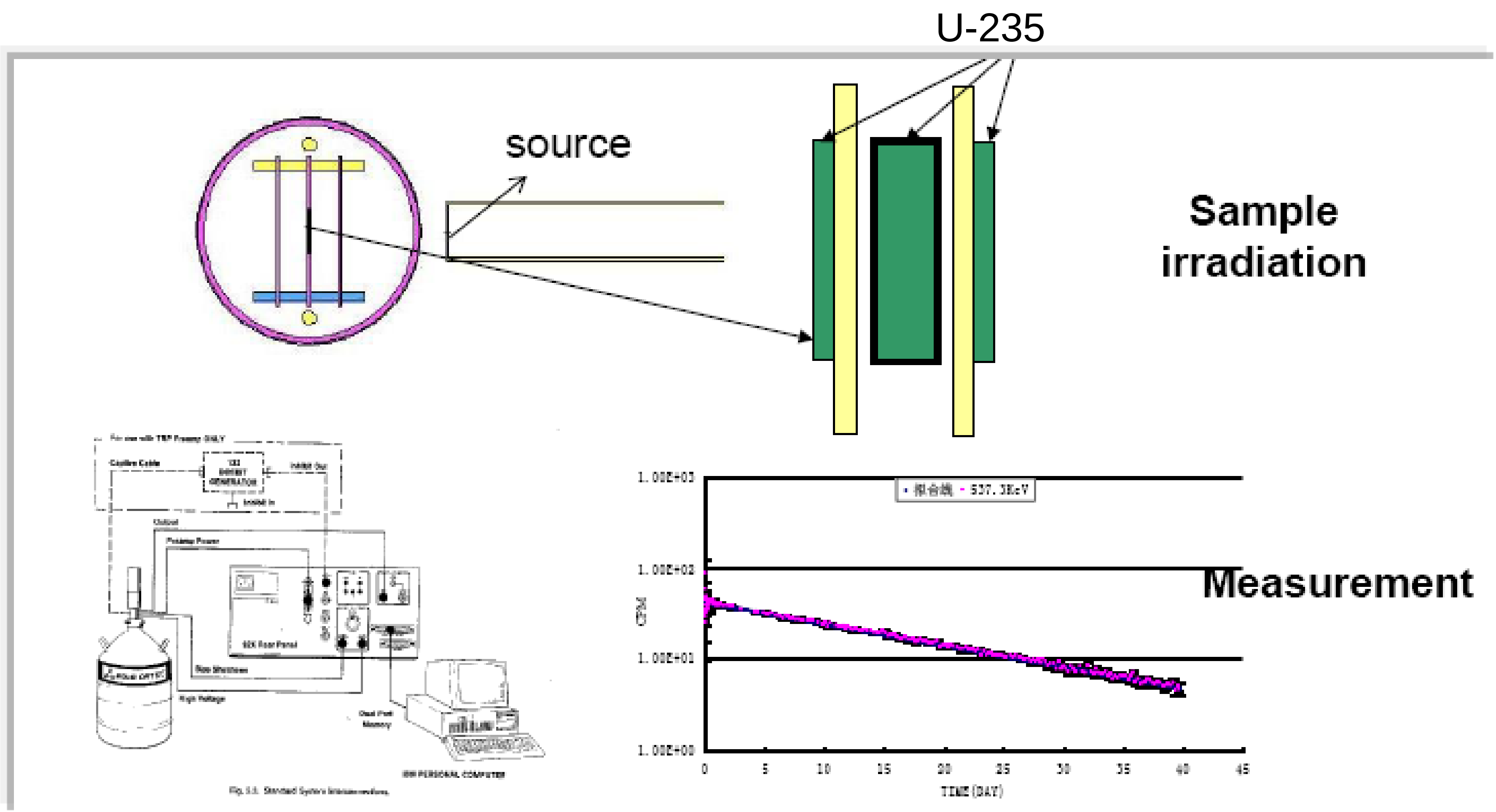


Fission yields

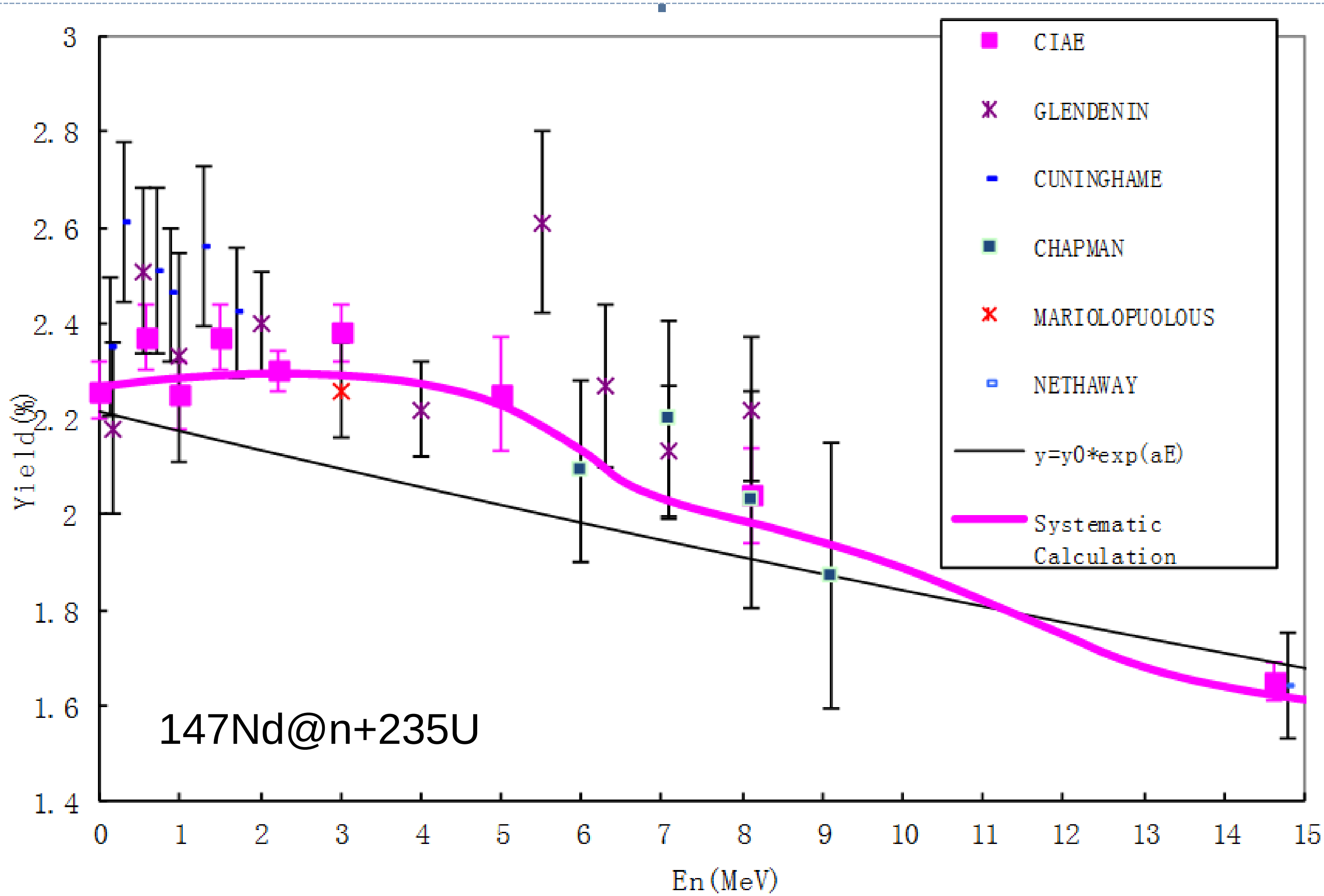
Nuclei	En	FY	Method
U-238	Fission spectrum, 3, 5, 8, 14MeV	^{95}Zr, ^{99}Mo, ^{140}Ba, ^{147}Nd etc.	RC, γ
U-235	Thermal, 0.5, 1, 1.5, 3, 5, 8, 14MeV	^{95}Zr, ^{99}Mo, ^{140}Ba, ^{147}Nd etc.	Γ
U-235、238	Thermal, 3, 14MeV	^{85m,87,88}Kr, ^{135,138}Xe etc. (gas yield)	γ
Th-232	14 MeV	^{95}Zr, ^{99}Mo, ^{140}Ba, ^{147}Nd etc.	γ
U-235,Pu-239	Thermal	^{95}Y, ^{138}Cs, ^{101}Mo, ^{142}La etc. (short life nuclei)	RC, γ

Fission yields measurement

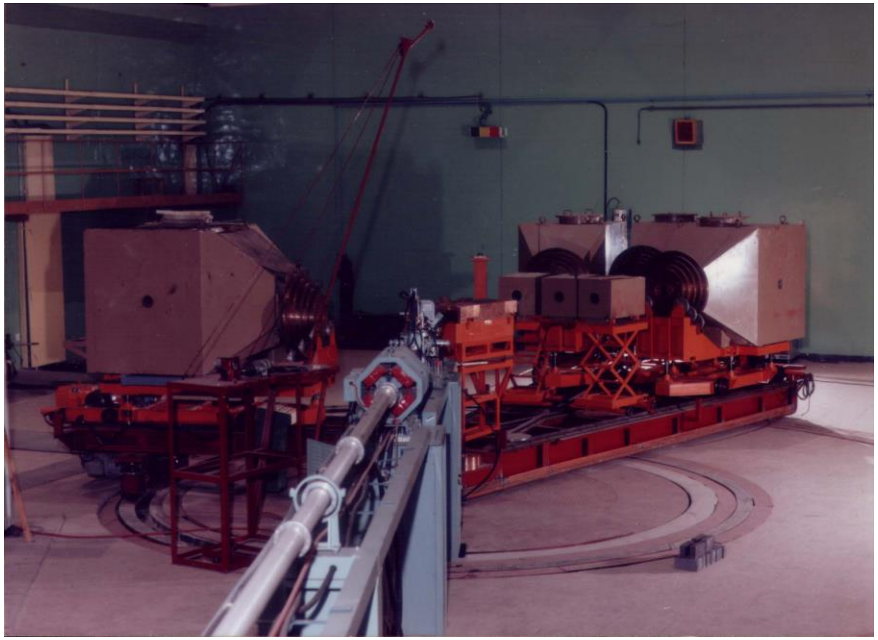
The fission yields of ^{235}U at 3 MeV, 14 MeV and ^{252}Cf spontaneous fission neutrons, ^{232}Th at 14 MeV neutrons were measured.

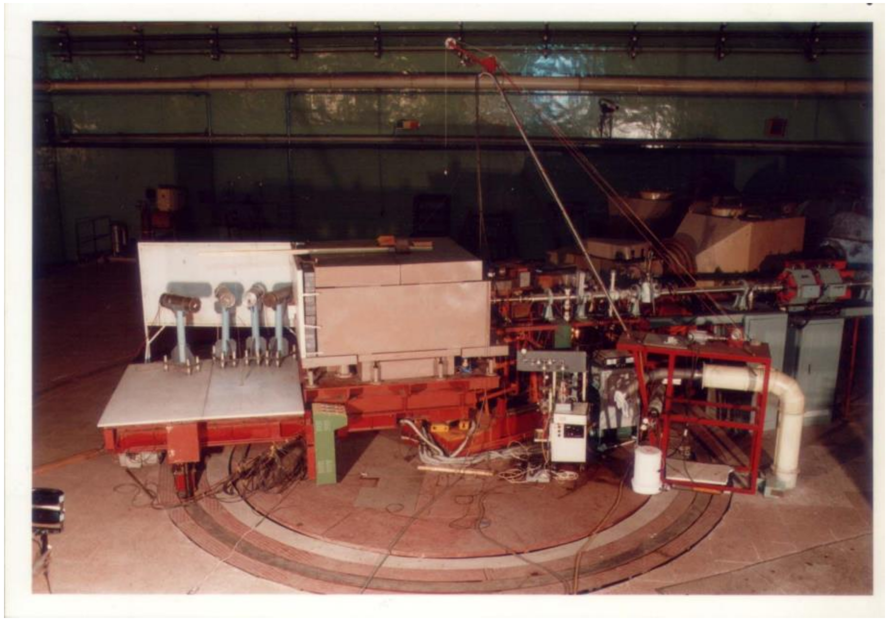


Combined with our previous measurements, the energy dependent fission yields were studied with a systematic method.
The fission yields for some products deviate from a linear function more than 10%.



Fast neutron Time-of-Flight spectrometers (HI-13 Tandem)



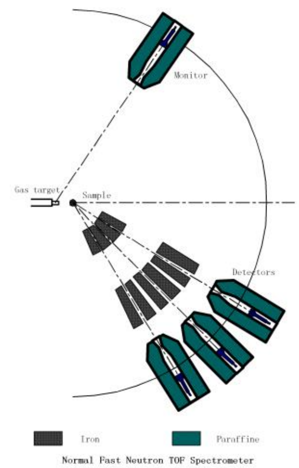


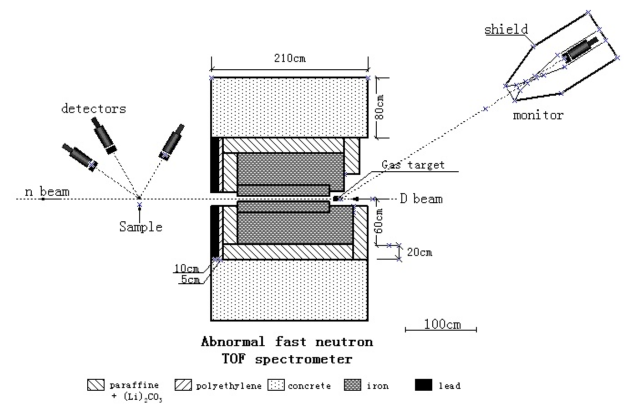
- **Composed of Normal and Abnormal fast neutron TOF spectrometers**
- **Mainly for fast neutron spectrum measurement, ND measurement(DX and DDX), basic science research, detector calibration and other applications**
- **Combined with the 5-40 MeV neutrons produced by the HI-13 Tandem accelerator.**

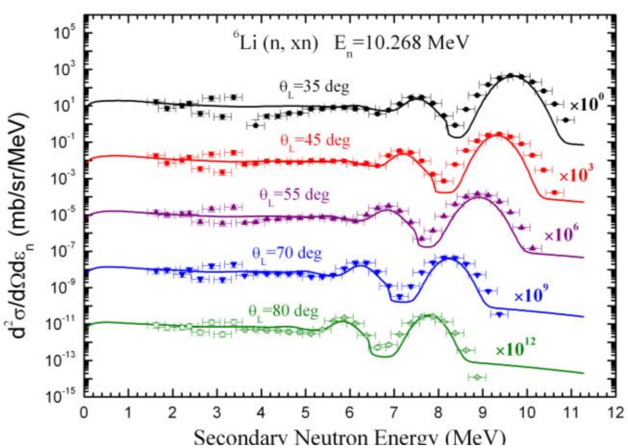
Secondary neutron DX and DDX measurement

With the Normal and Abnormal fast neutron TOF spectrometer and the deuterium and tritium gas target. Many of the secondary neutron DX and DDX data were measured.

En	Samples
14 MeV	C、^{238}U、D、^{209}Bi、^{6,7}Li、Zr、Al
6 MeV	Be
8 MeV	^{6,7}Li、Fe、Be、D
10 MeV	^{6,7}Li、Be、V、^{238}U、^{209}Bi、Fe、C
20-40	Be、C、^{209}Bi



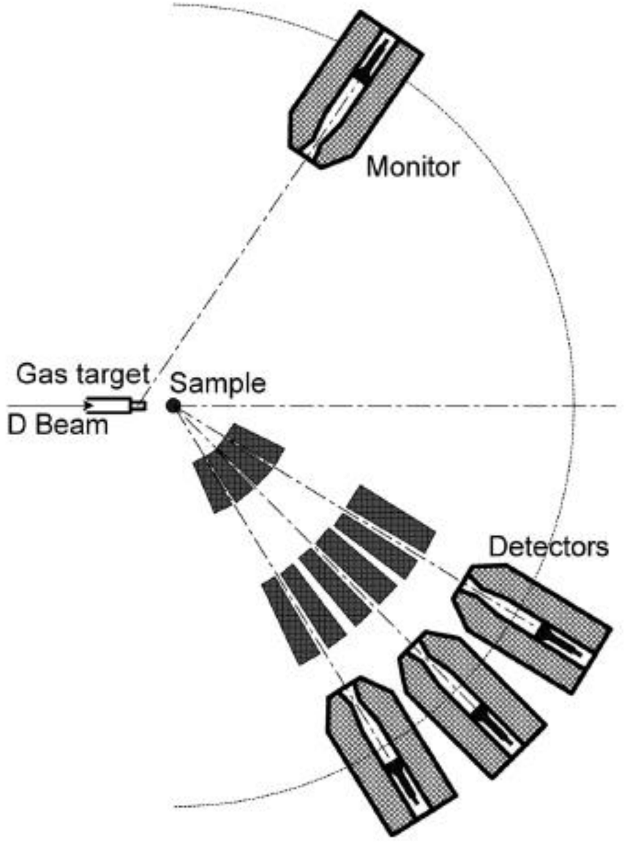




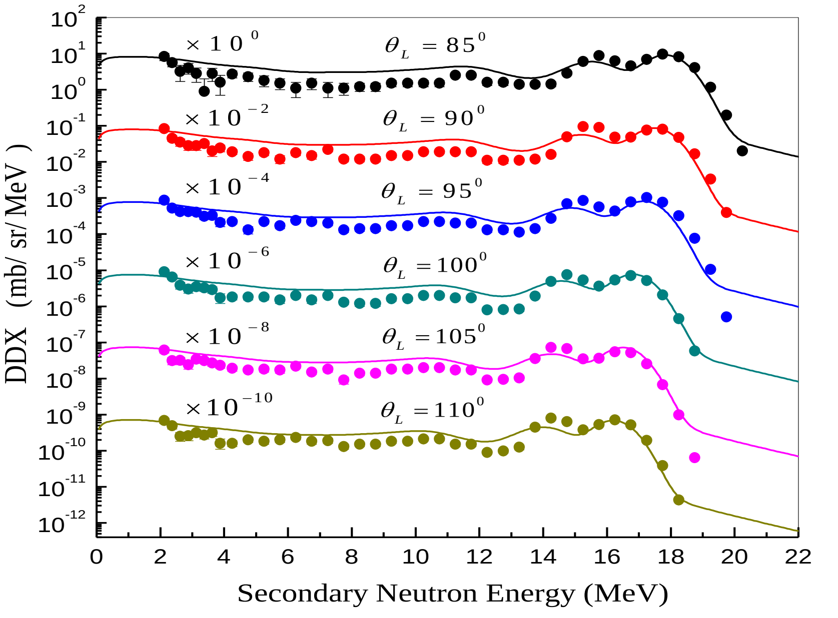
The abnormal TOF spectrometer was used to eliminate the influence from the breakup source neutrons between 8 and 14 MeV

Secondary neutron DX and DDX measurement

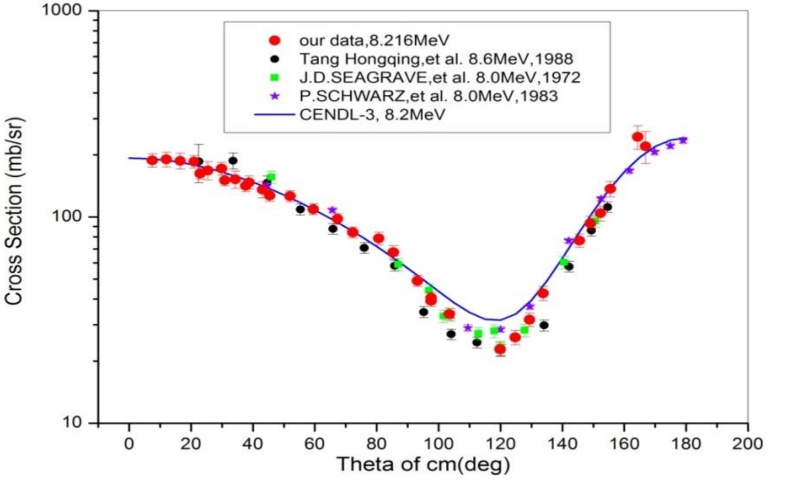
^{9}Be at 22 and 25 MeV
D at 8.2 MeV have been finished



The TOF spectrometer

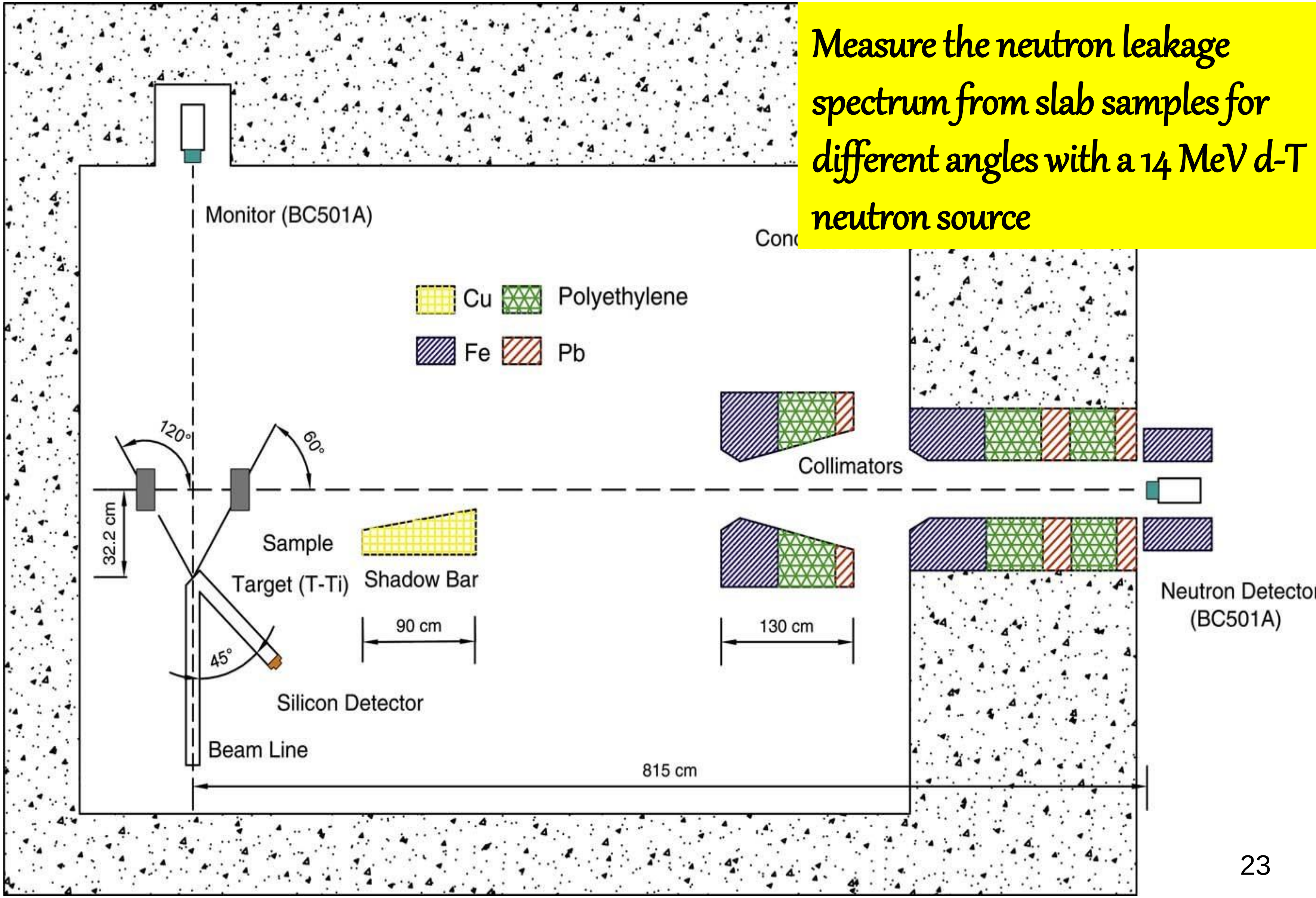


DDX for Be at 22 MeV

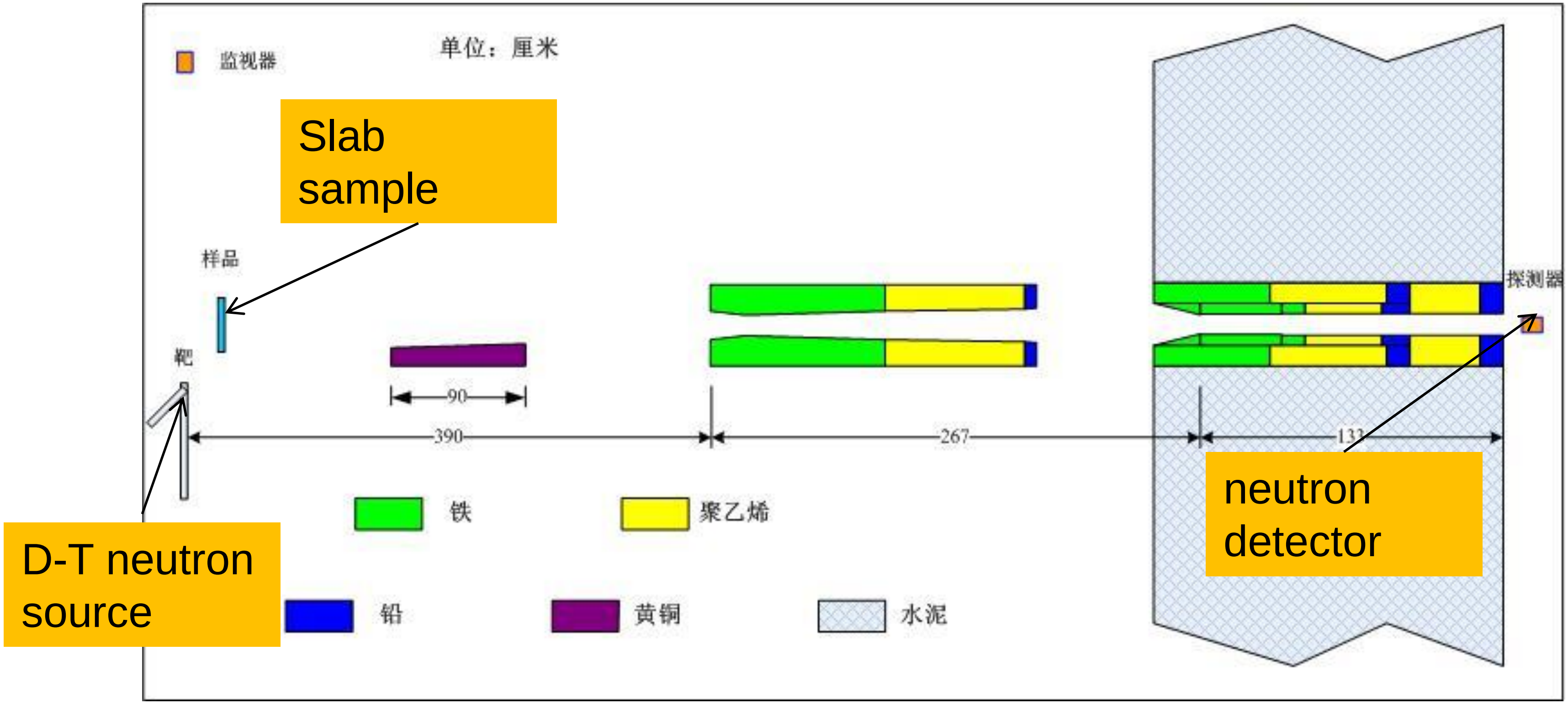


DX for D at 8.2 MeV

Nuclear data integral experimental setup at CIAE



Measure the neutron leakage spectrum from slab samples for different angles with a 14 MeV d-T neutron source



The collimator system

List of measured samples

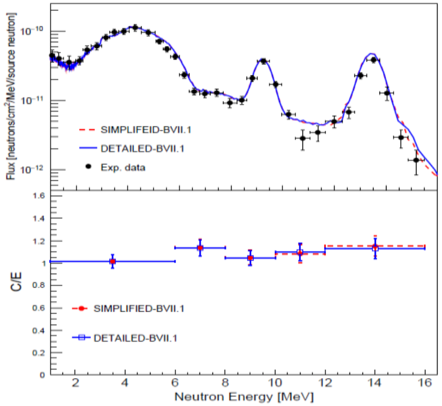
Sample	Sample size/cm	Sample thickness/cm	Angle/°	Institute
^{238}U	10×10	5	45、135	CIAE
Be	10×10	5、11	60、120	
^{nat}Fe	10×10	5、10	60、120	
Nb	10×10	5、10	60、120	
H_2O	Φ13	5.2	60	
PE	Φ13 10×10	6 5	60 45	
Pb	Φ13	5	60	CIAE-INEST
Pb-Bi	Φ13	5	60	
ThO_2	Φ13	5.4、10.8	60、120	CIAE-SINAP

Collaboration between CIAE-IMP for ADS purpose

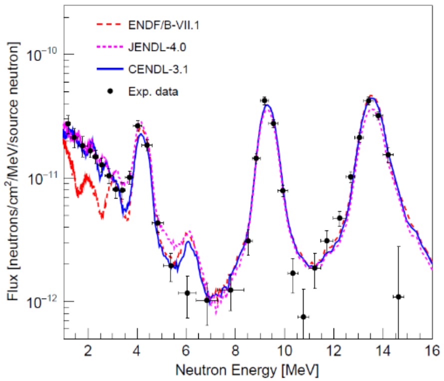
sample	dimension	Angle
Polyethylene	10cm*10cm*5cm	60
Gallium	10cm*10cm*5cm, 10cm*10cm*10cm, Ø13cm*3.2cm, Ø13cm*6.4cm	60,120
Tungsten(block)	10cm×10cm×3.6cm, 10cm×10cm×7.2cm	60,120
Tungsten(Granular)	9.8*9.9*7.2cm ,（granular diameter:1mm）	60
Graphite	Φ13*2cm, Φ13*20cm	60,120
SiC	Φ13*2cm, Φ13*20cm	60,120
238U	10cm*10cm*2cm,	60
238U	10cm*10cm*5cm, 10cm*10cm*11cm	60, 120
W+U	W:10cm*10cm*3.5cm , U: 10cm*10cm*2cm	60
W+U+C	W:10cm*10cm*3.5cm, U: 10cm*10cm*2cm C: 10cm*10cm*2cm	60
W+U+C+CH2	W:10cm*10cm*3.5cm , U: 10cm*10cm*2cm C: 10cm*10cm*2cm, CH2: 10cm*10cm*2cm	60
U+C	U: 10cm*10cm*5cm , C: 10cm*10cm*10cm	60
U+C+CH2	U: 10cm*10cm*5cm , C: 10cm*10cm*10cm CH2: 10cm*10cm*10 cm	60

14MeV n + Polyethylene, Graphite, SiC

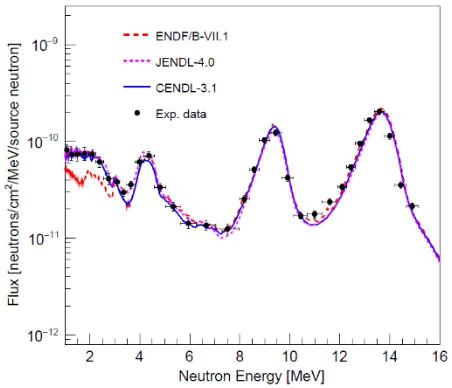
Polyethylene: 60°



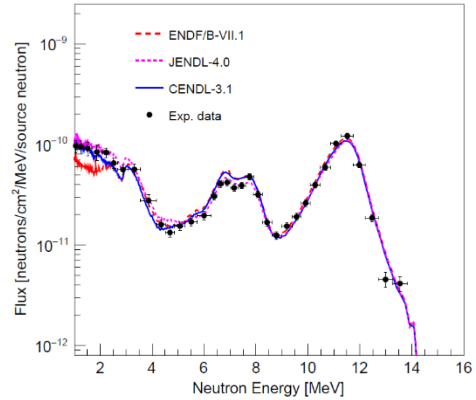
Graphite: 2cm, 60°



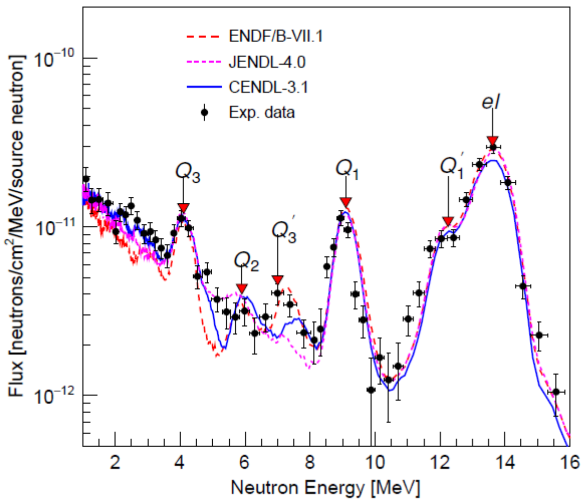
Graphite:20cm, 60°



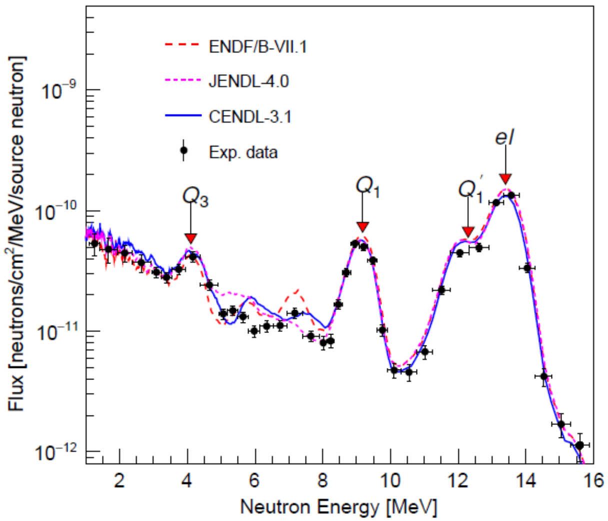
Graphite: 20cm,120°



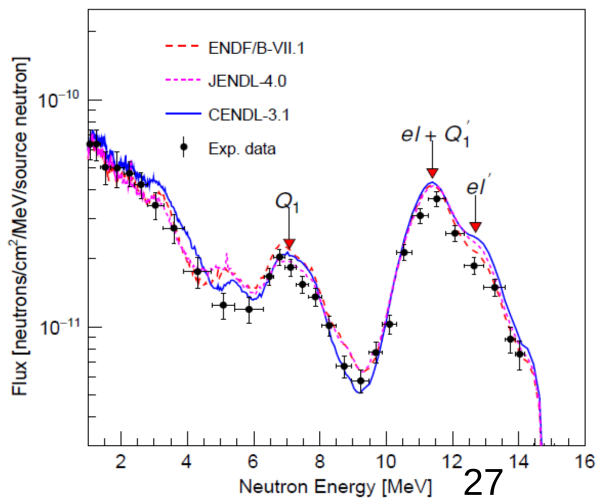
SiC: 2cm, 60°



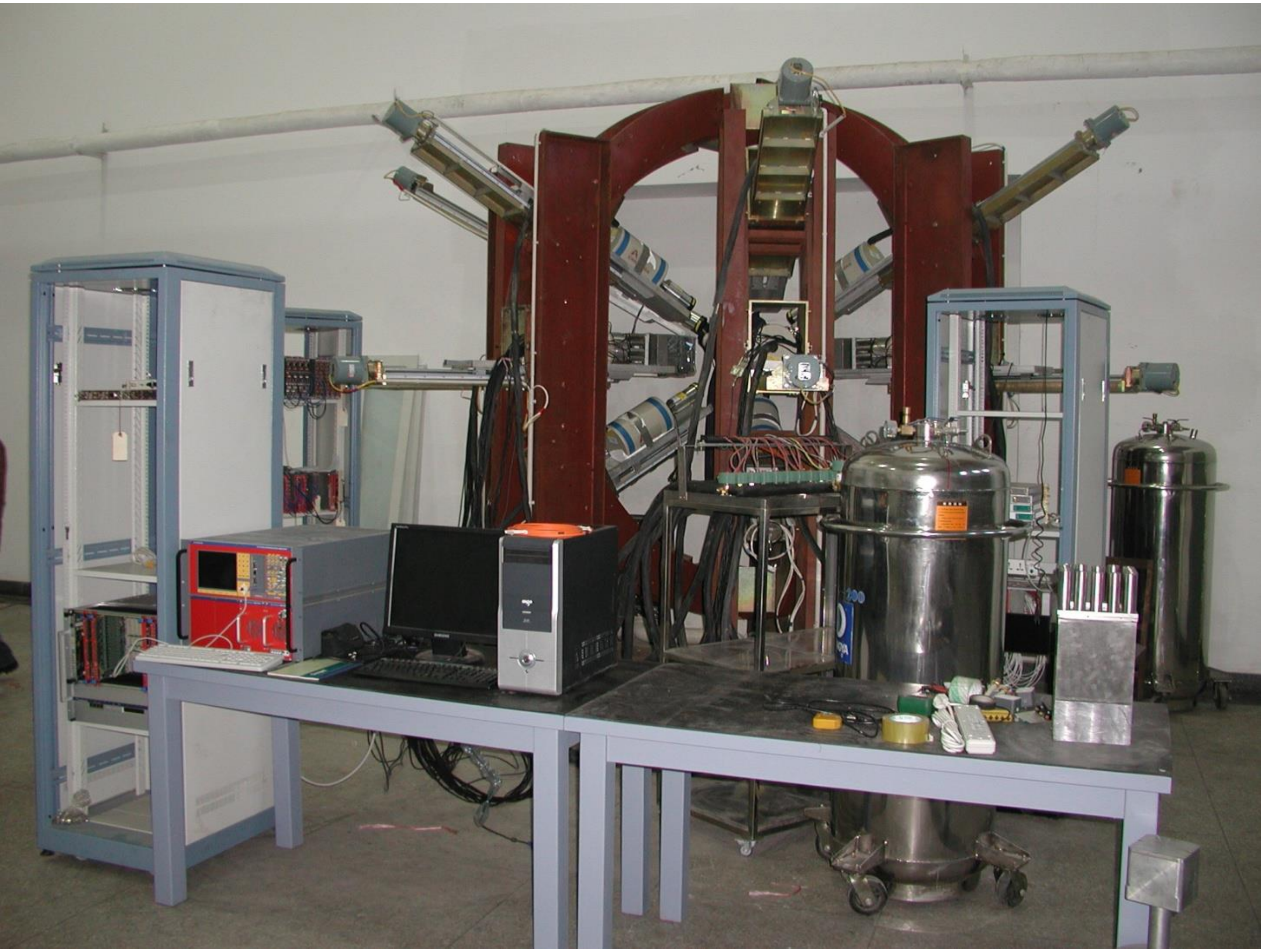
SiC: 20cm, 60°



SiC: 20cm, 120°



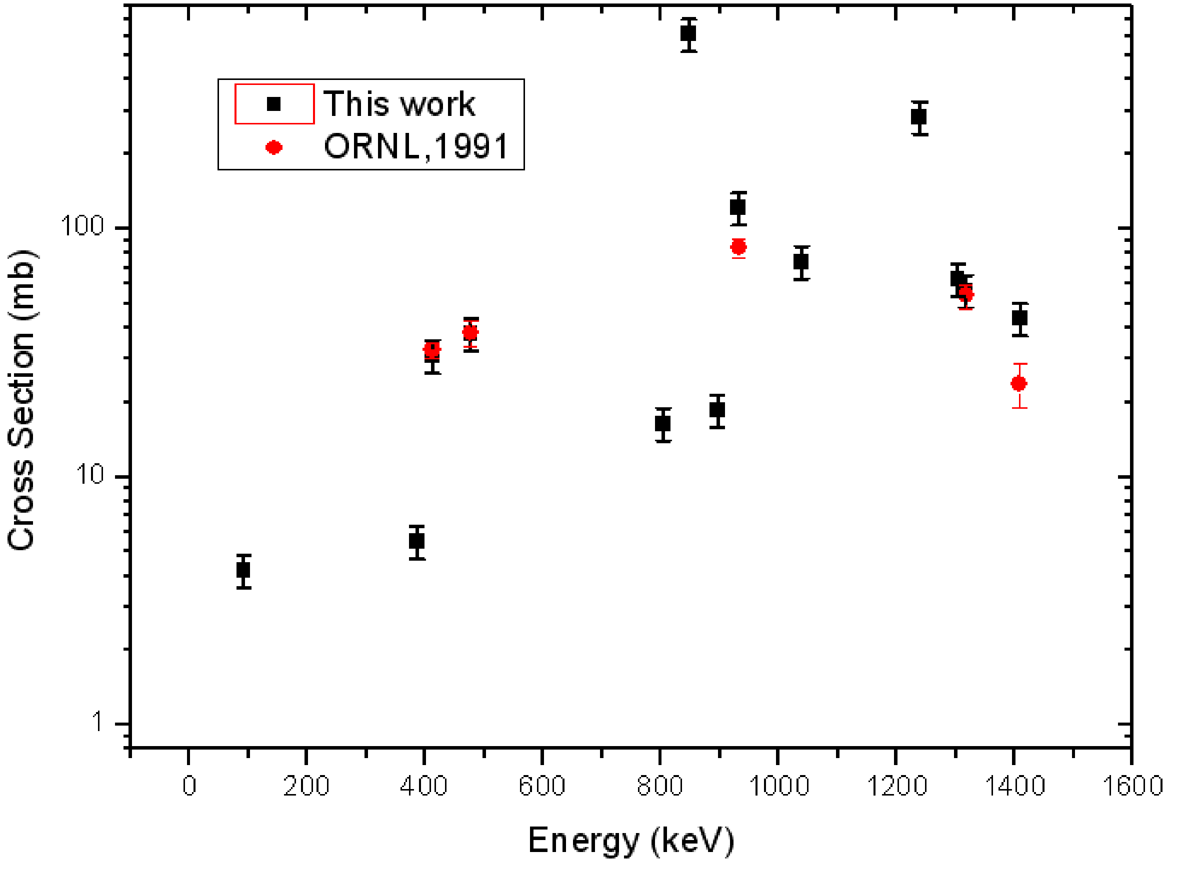
HPGe detector array for high resolution gamma spectroscopy



- **6 Clover and 6 HPGe detectors**
- **Mainly used for (n,2nγ) and (n,n'γ) measurement**

Gamma production CS measurement

$^{nat}Fe(n,n'\gamma)$ and $^{235,238}U(n,2n\gamma)$ have been carried out

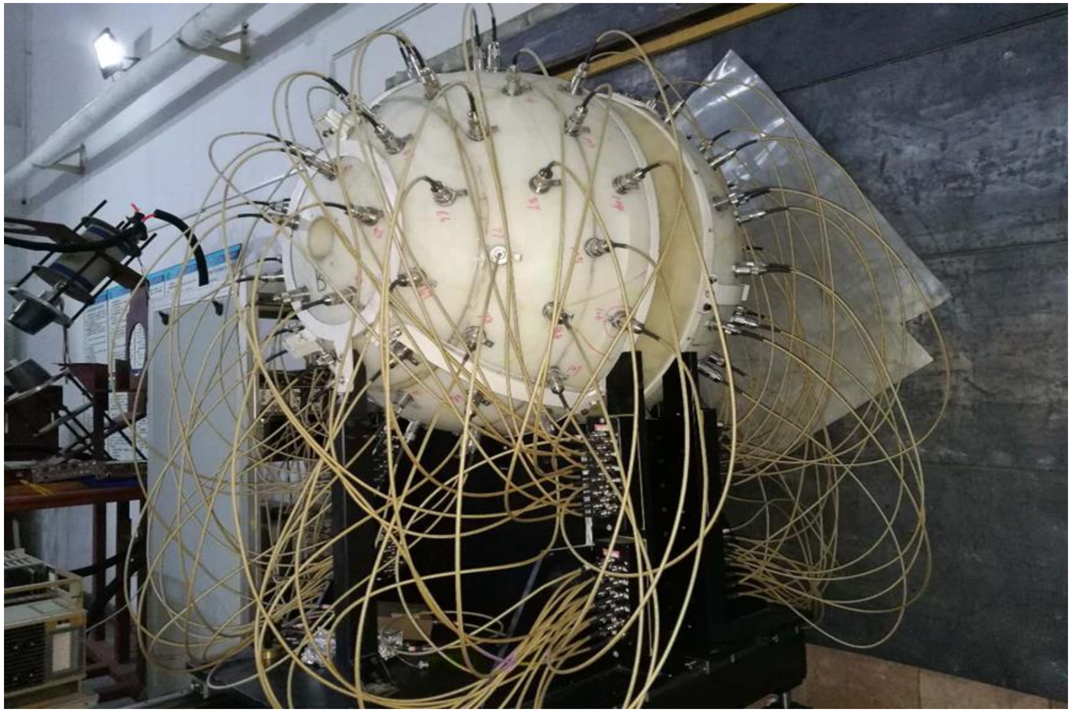


The measured results for $^{238}U(n,n'\gamma)$

(n,2n) measurement with HeSAN

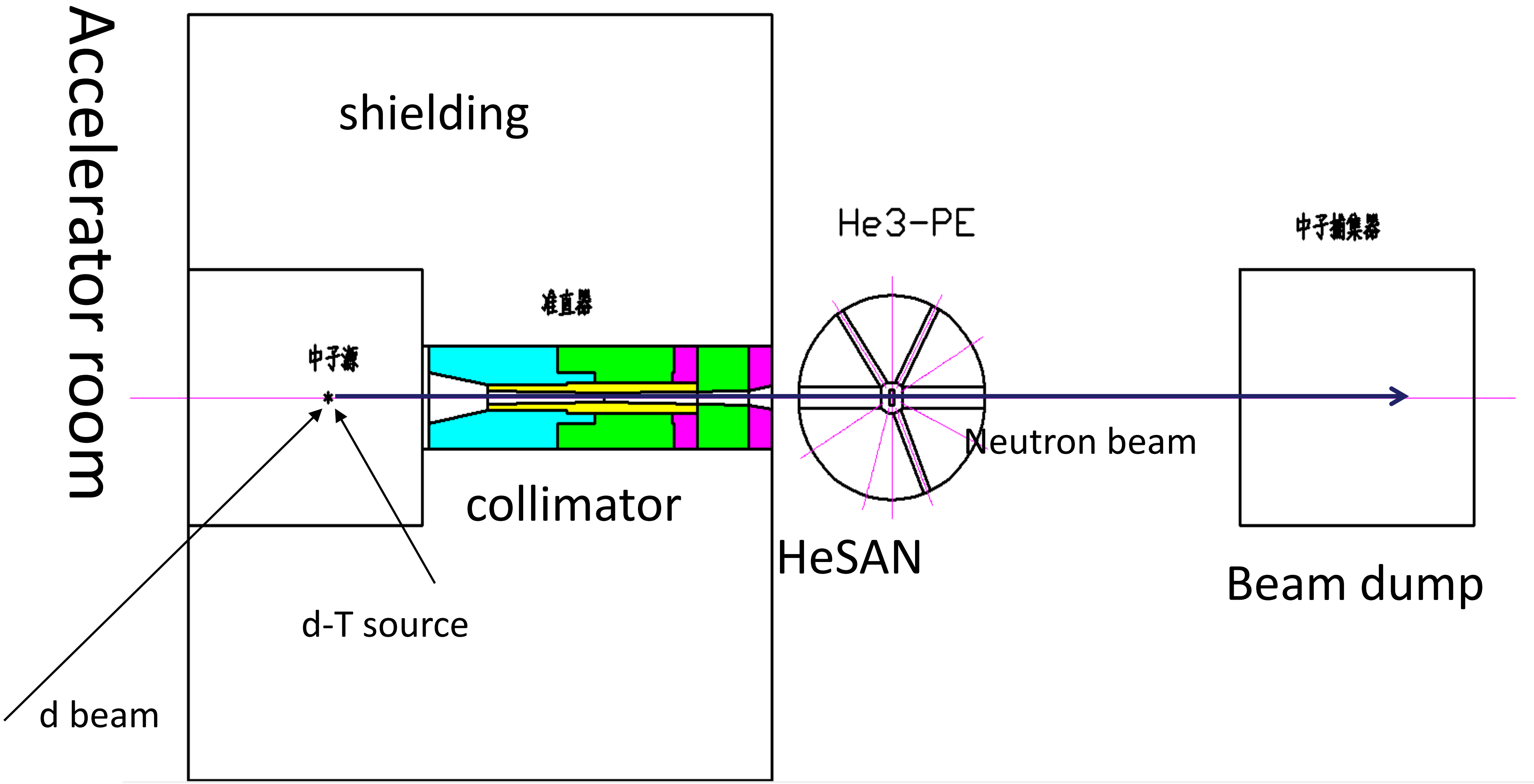
HeSAN (氦-3): He-3 SphericAl Neutron Detector Array

110 He-3 counters uniformly distributed in a spherical PE moderator

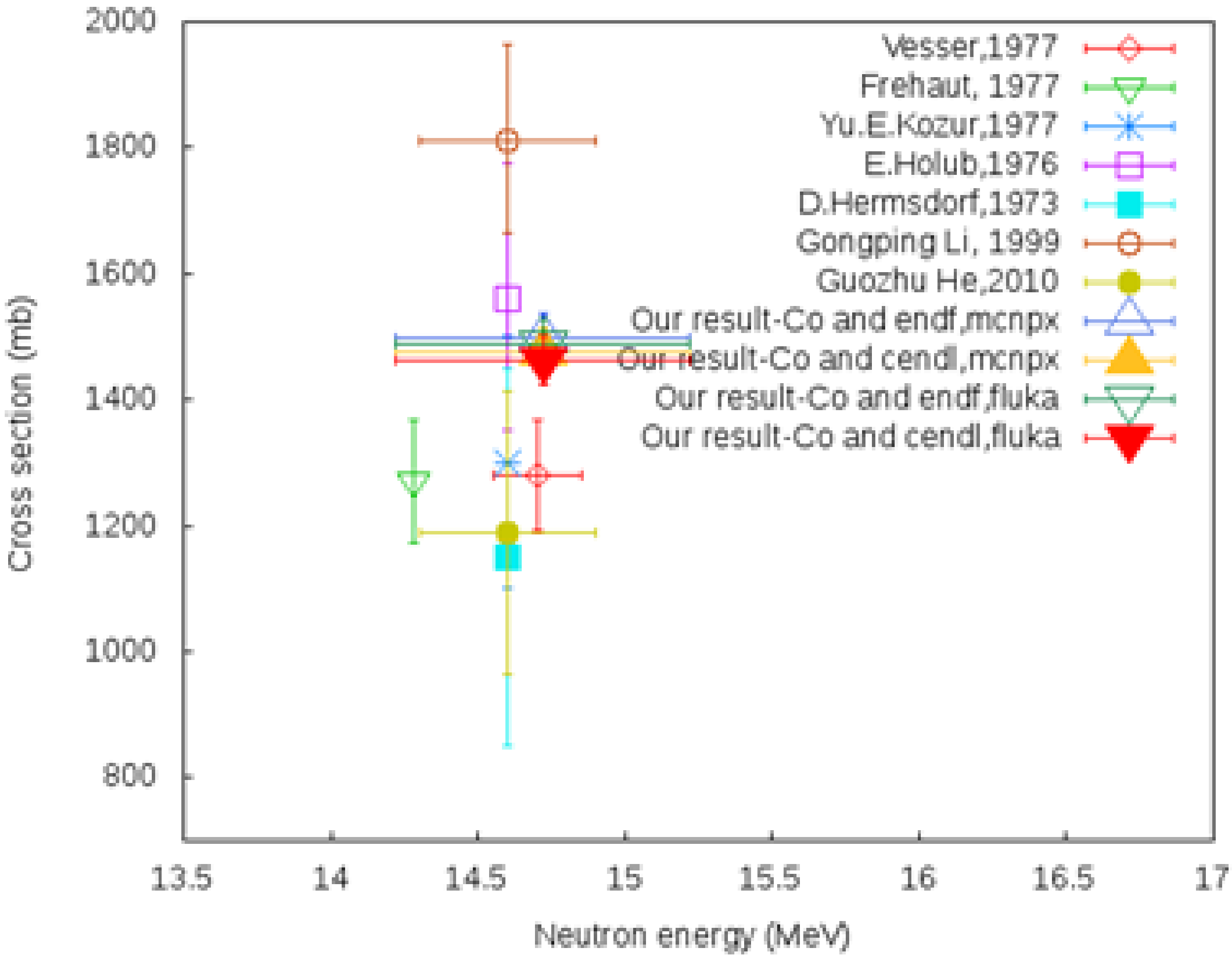


- Insensitive to gamma rays
- Detection efficiency acceptable (~33% for 252Cf source)
- Spherical design makes the efficiency more independent on energy

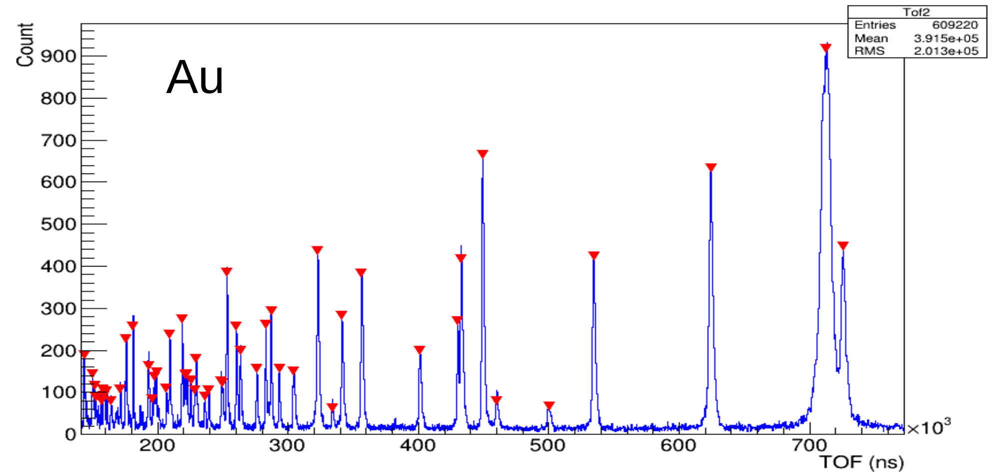
Experimental setup:

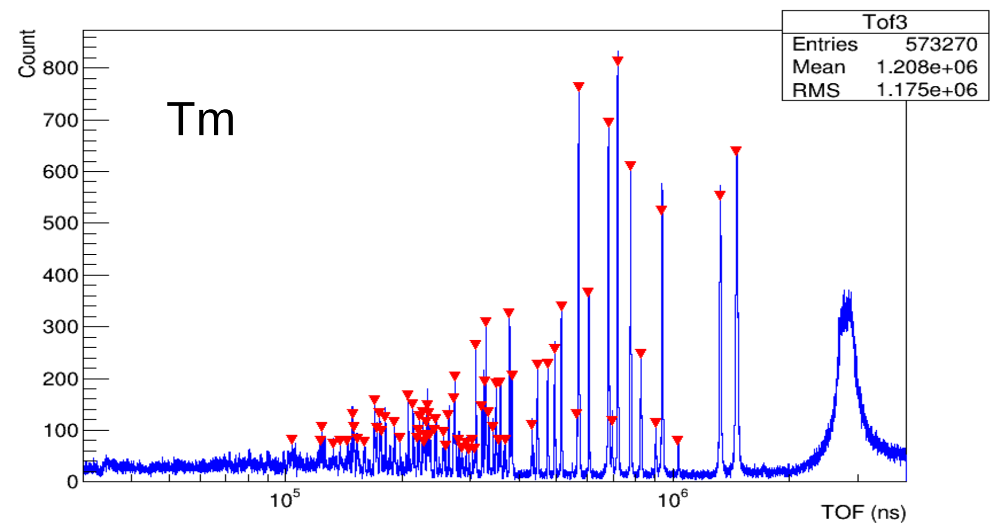


First measurement on 93Nb(n,2n) shows HeSAN work well

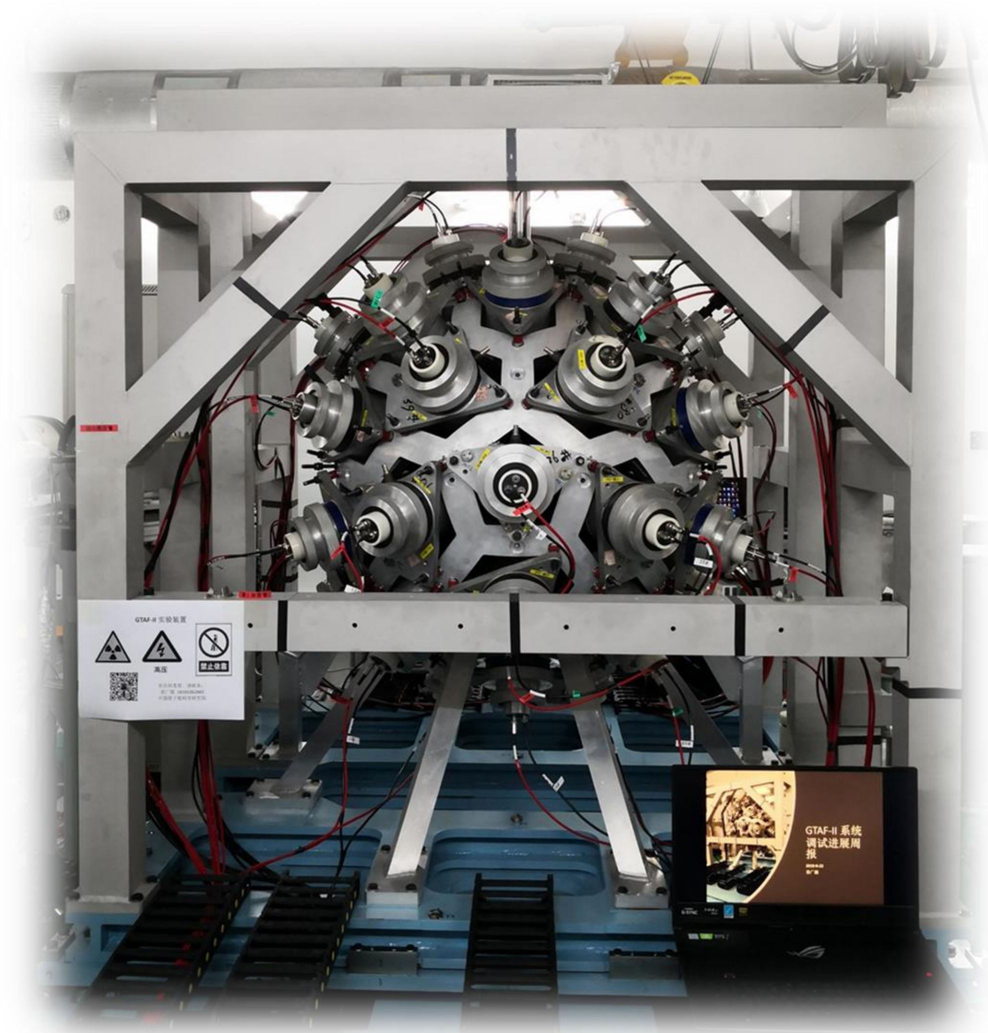


(n,g) reaction cross section measurement with C6D6 system at CSNS Back-n





Gamma Total Absorption Facility(GTAF) for neutron capture cross section measurement



- **Composed of 42 BaF_2 detectors**
- **Readout by FADC**
- **Will be installed at CSNS for (n,g) measurement in 2019**

Measurements performed at Back-n

- Neutron capture
  - C_6D_6: ^{169}Tm, ^{197}Au, ^{57}Fe, ^{nat}Se, ^{89}Y, ^{nat}Er/^{162}Er, ^{232}Th, ^{238}U, ^{93}Nb，^{nat}Cu， ^{nat}Lu, $^{113\&115}$In, $^{185\&187}$Re , ^{181}Ta, $^{107\&109}$Ag, ^{165}Ho
  - GTAF-II: ^{169}Tm, ^{93}Nb
- Total cross-section
  - ^{12}C, ^{27}Al， ^{9}Be， ^{7}Li， ^{nat}Fe
- Fission cross-section
  - ^{235}U, ^{238}U, ^{236}U, ^{239}Pu, ^{232}Th， ^{239}Pu
- Light charged particle emission
  - LPDA: ^{6}Li(n, x), ^{10}B(n, x), ^{63}Ni，(n-d)， ^{17}O, (n-p)弹散
  - TPC样机: ^{12}C， ^{14}N， ^{12}C (^{13}C集团结构)
- Inelastic cross-section (in-beam gamma)
  - ^{56}Fe (n, n’), ^{nat}Mo， ^{16}O， ^{nat}Ru， ^{nat}Lu， ^{nat}Mo， ^{nat}Ti, ^{209}Bi, ^{90}Zr, ^{55}Cr, ^{155}Eu, ^{178}Hf, ^{232}Th

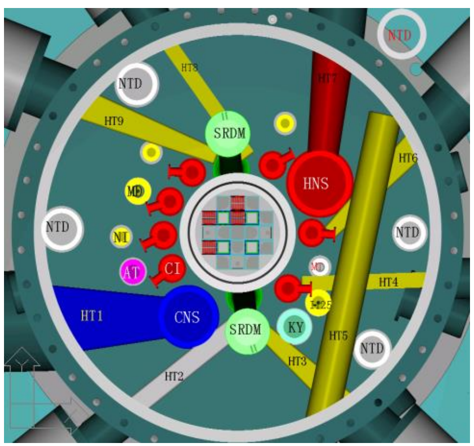
CARR ISOL for decay data measurement

- Mass resolution > 400
- For short life decay data measurement

Brief introduction of CARR

China Advaned Research Reactor(CARR)

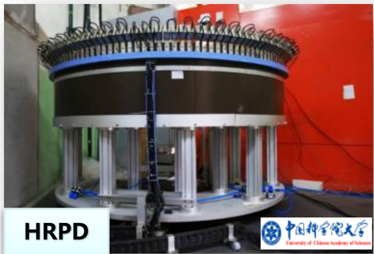
- 60 MW, reach full power in 2012
- Max flux: 1.0×10^{15} n/s/cm^2
- 19.75 wt% U^{235}
- Horizontal tube 9
- Veritical tube 25

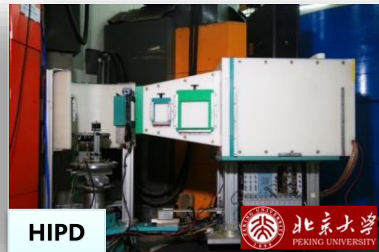


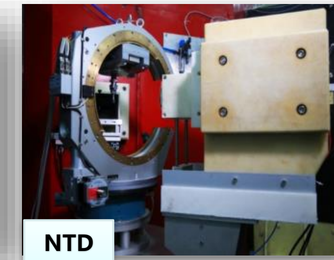
Multipurpose:
- Neutron scattering & imaging
- Neutron activation analysis
- Silicon doping
- Radio-isotope production
- Irradiation test of materials
- Nuclear data

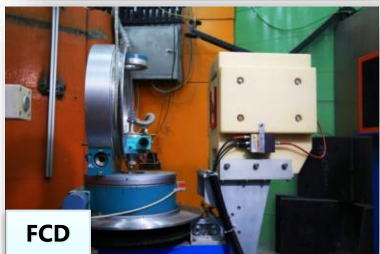
CARR Neutron Facilities

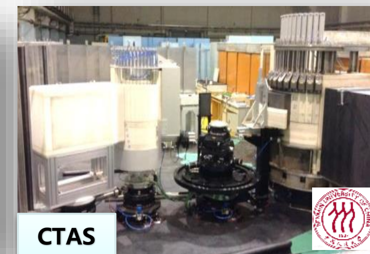
Neutron Instruments at CARR





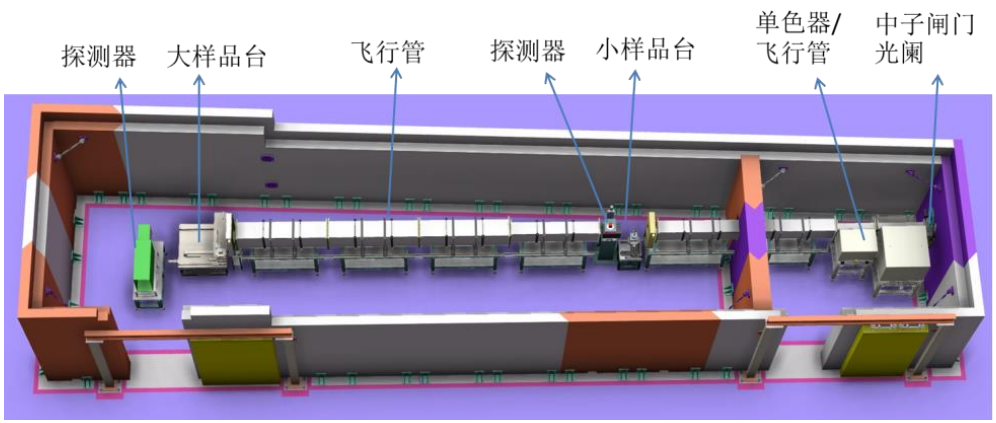






6 Diffractometer
4 Spectrometer
2 Large scale
1 Imaging
1 Activation

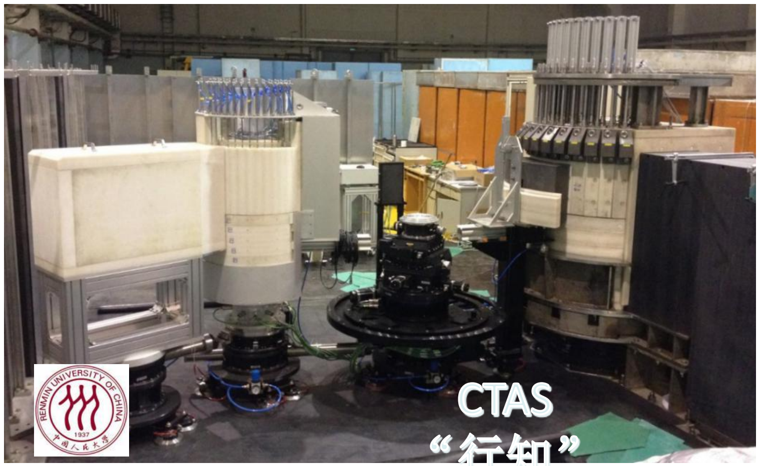
Cold Neutron Imaging



	Thermal	Cold
Aperture -object distance (L)	800cm, 1050cm	800cm,1600cm
Aperture D (cm)	4, 3, 2, 1 and 0.5	5, 4, 2, 1 and 0.5
L/D	**58~2000**	160～1600
Neutron flux at sample position (max.)	4.6×10^{9} n•cm^{-2}s^{-1}	7.9×10^{7} n•cm^{-2}s^{-1}
Beam size at sample position	17cm×32cm	30cm×30cm
Detector system	IP and CCD	
Design resolution	0.15mm	0.12mm

✓ **Flexible-variable collimation**
✓ **Potential-large sample area**

Cold Neutron Spectrometers

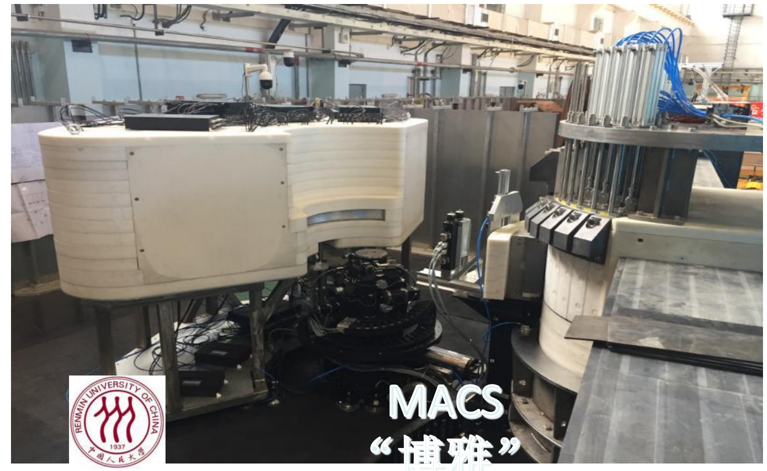


Incident Neutron Energy: 2.4 meV< Ei < 19meV

Polarizer：S-bender supermirror polarizer & 3D guide-field magnet

Sample Environment：

CCR (4K)，^{3}He refrigerator （300mK)，dilution refrigerator （30mK)，magnet (9T & 12T)



Incident Neutron Energy: 2.4 meV< Ei < 19meV

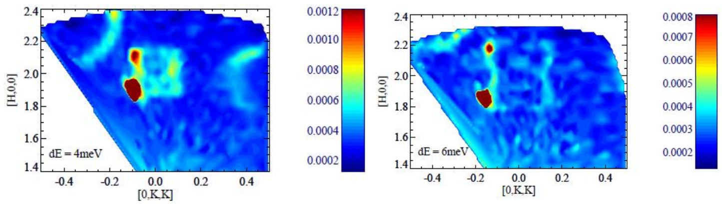
Multi Channel Analyzer：85-170 E-Q scanning channel，high efficiency

Sample Environment:

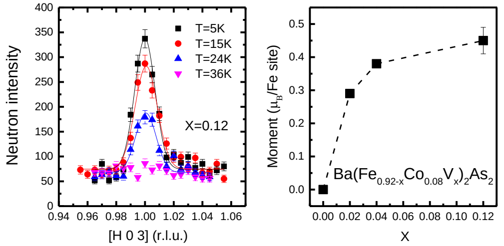
CCR (4K)，^{3}He refrigerator （300mK)，dilution refrigerator （30mK)，magnet (9T & 12T)

Cold Neutron Spectrometers

Const-E Map of Cu Single Crystal



Magnetic ordering in Superconductor



Evolution of superconductivity and antiferromagnetic order in $Ba(Fe_{0.92-x}Co_{0.08}V_x)_2As_2$ *Phys. Rev. B 101,174516(2020)*

Extreme Suppression of Antiferromagnetic Order and Critical Scaling in a Two-Dimensional Random Quantum Magnet *Phys. Rev. Lett. 126,037201(2021)*

Frustrated magnetism of the triangular-lattice antiferromagnets α-CrOOH and α-CrOOD *New J. Phys. 23,033040 (2021)*

DyOCl: a rare-earth based two-dimensional van der waals material with strong magnetic anisotropy *Phys. Rev. B 104,214410(2021)*

Antiferromagnetic structure and magnetic properties of Dy_2O_2Te: an isostructural analog of the rare-earth superconductors Re_2O_2Bi *Phys. Rev. B 105,134419(2022)*

Summary

- Nuclear data needs increase in China in recent years, particularly driven by some large new nuclear energy system projects.
- Substantial progress on nuclear data measurement has been made in recent years.
- Some new facilities such as CSNS are put into operation, these facilities greatly improved the capability of the nuclear data measurement in China.

Thank you for your attention