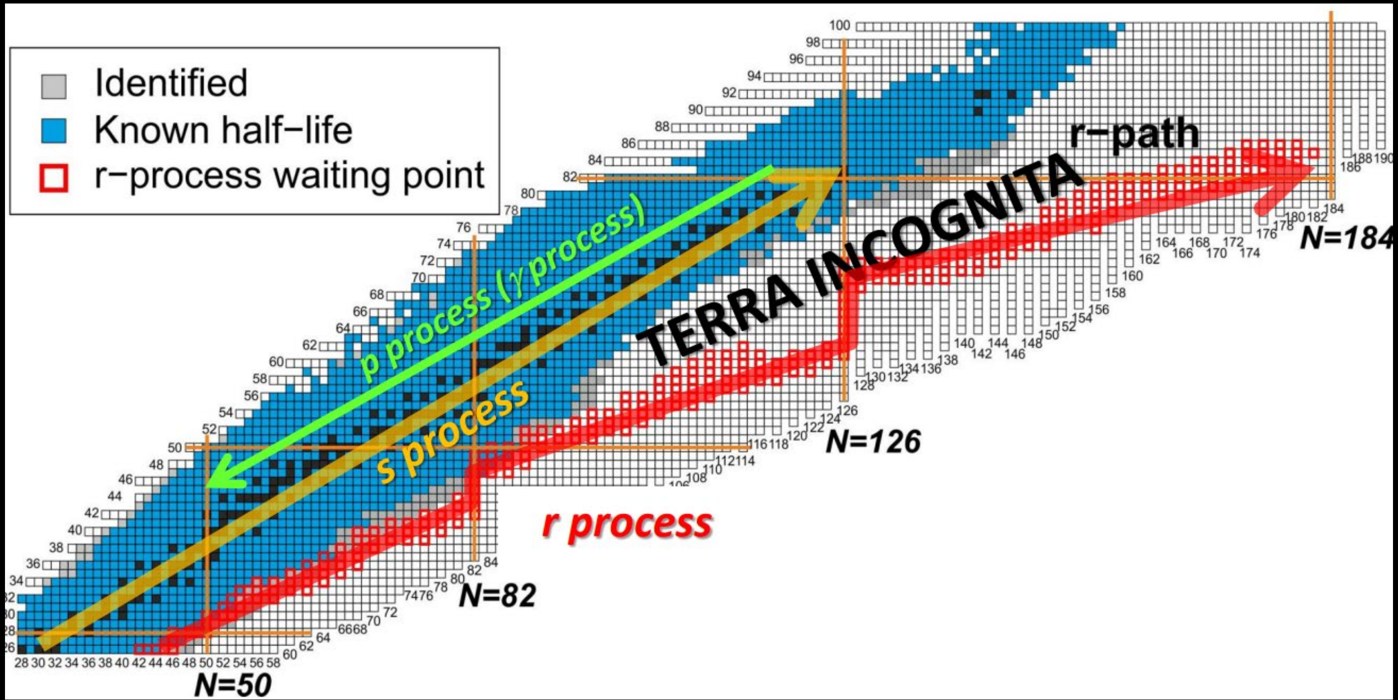
大湾区大学物质科学学院
SCHOOL OF PHYSICAL SCIENCES
GREAT BAY UNIVERSITY

Novel Neutron Detector Design for Accurate Measurement in Ultra-iron Nucleosynthesis Study

Jianqi Chen(陈建琪),
Junsheng Jing(景俊升), Yongce Gong(贡庸策)

chenjianqi@gbu.edu.cn
2025.5.29

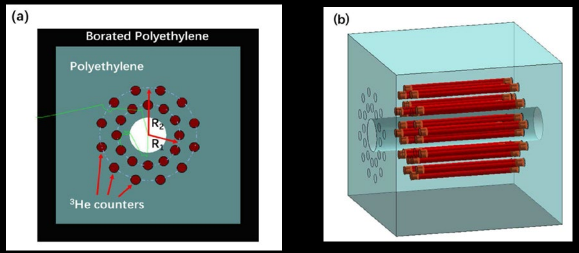
Polyethylene Moderated ^{3}He Neutron Detector for Ultra-iron Synthesis



- Three neutron emission reaction in nuclear astrophysics: (α,n), (γ,n) and $\beta-delayed$ neutron emission.

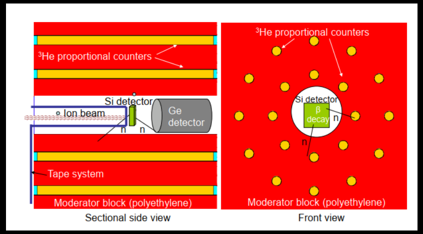
- Many data scarce($^{13}C(\alpha,n)^{16}O$, et al), and measured data ($\sigma_{(r,n)}^{Saclay} > \sigma_{(r,n)}^{Livermore}$, $\sigma_{(r,2n)}^{Saclay} < \sigma_{(r,2n)}^{Livermore}$ et al) exists great discrepancy.

- s-process (α,n) cross section



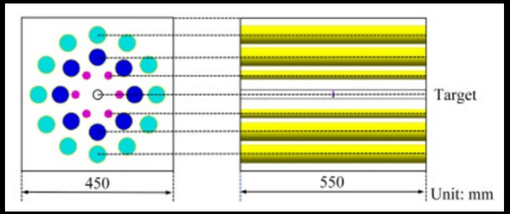
[Nuclear Science and Techniques, 2022, 33(4)]

- r-process $\beta-delayed$ neutron emission probability



[NIM-A, 422.1-3, 1999: 43-46]

- p-process (γ,n) cross section

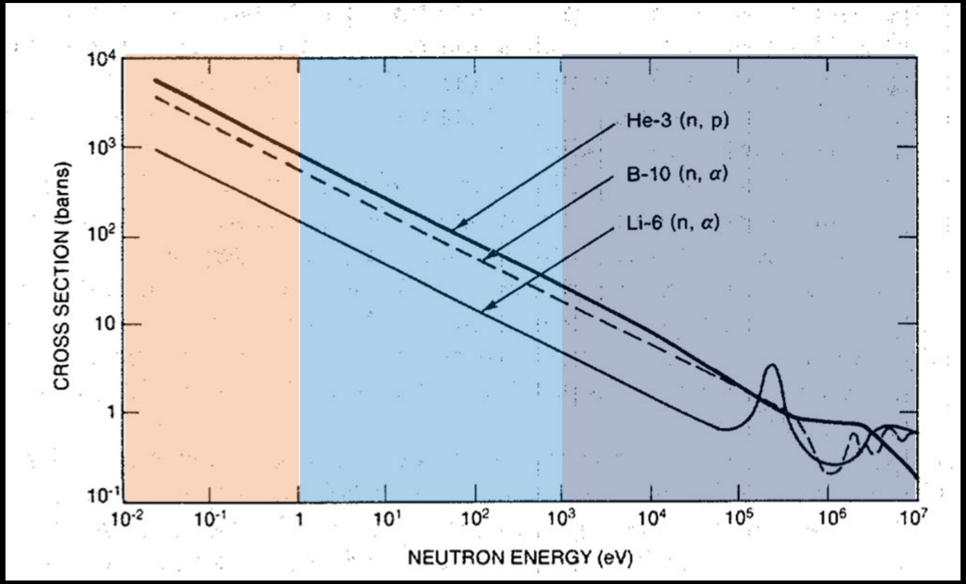


[核技术,2020,43(11):9]

Characteristic of Polyethylene Moderated ^{3}He Neutron Detector

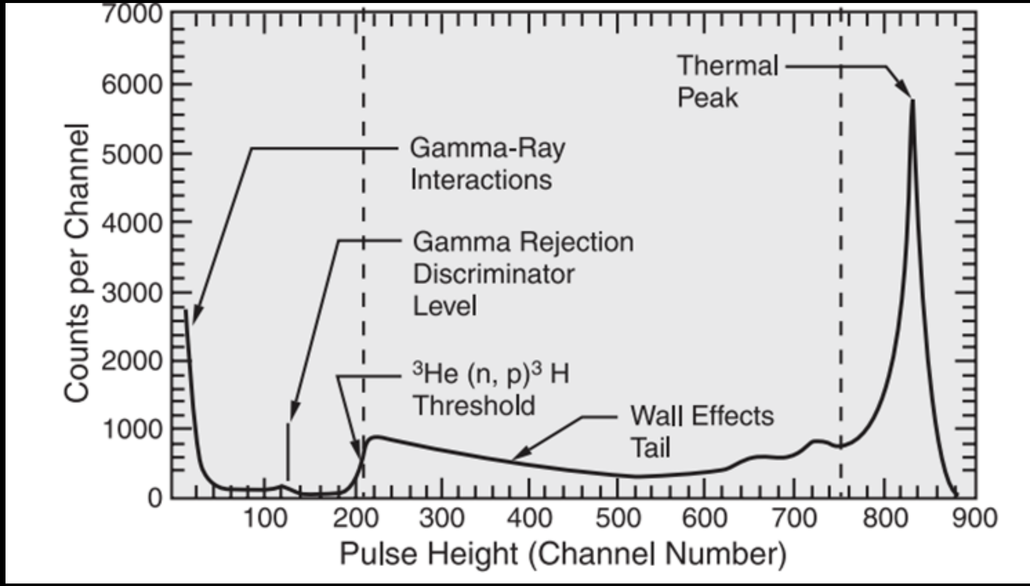
- Detection principle

$n+^3He \rightarrow p+^3H$ +765 KeV



- High detection efficiency
- Good n/gamma discrimination
- Free from cross-talks
- Polyethylene: cheap, compact, easy assembly, and shaping

- Pulse amplitude spectrum

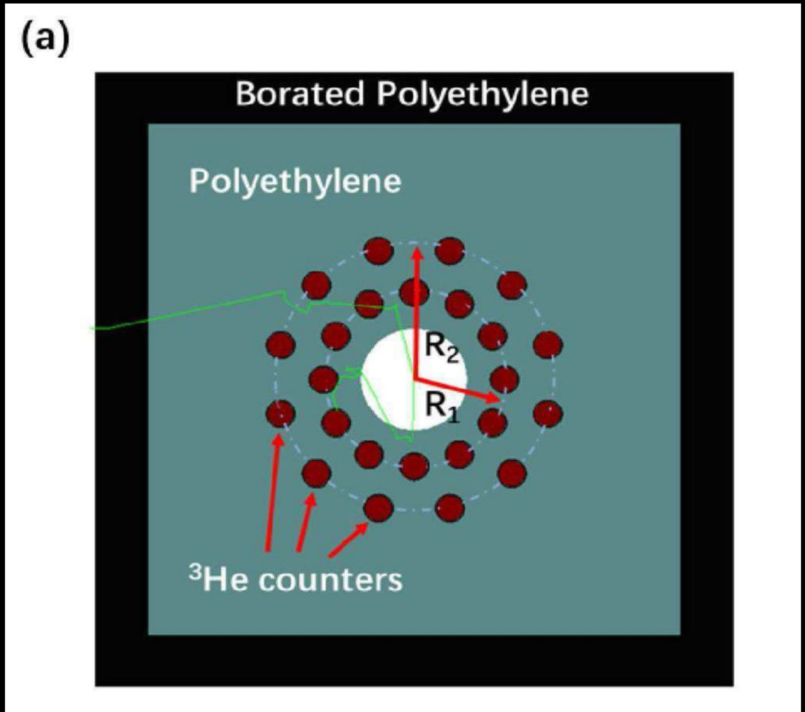


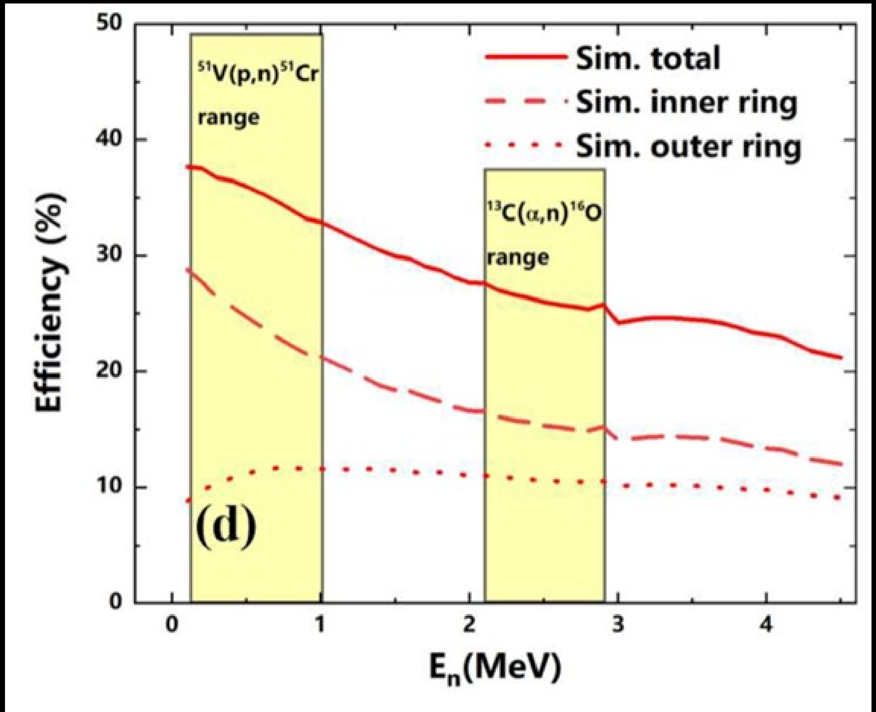
https://www.mirion.com/discover/knowledge hub/articles/education/nuclear-measurement-fundamental-principle-neutron-detection-and-counting

http://large.stanford.edu/courses/2012/ph241/lam1/images/f1big.png

Challenge of Neutron Energy above 1 MeV

- Efficiency energy dependency(example: ^{13}C(alpha, n)^{16}O at JUNA)





- Detection efficiency gradually drops with neutron energy when $E_n > 1\ MeV$.

[Nuclear Science and Techniques, 2022, 33(4)]

Challenge of Multiple Neutron Detection

- P_{xn} and $\sigma_{(\gamma,xn)}$ measurements($\mathrm{x} \geq 2$)

For $n = 3$, single, double, and triple neutron events (N_s, N_s, and N_t), respectively, are expressed explicitly by

$$N_s = N_1 \cdot \varepsilon(E_1) + N_2 \cdot {}_2C_1 \cdot \varepsilon(E_2) \cdot (1 - \varepsilon(E_2)) + N_3 \cdot {}_3C_1 \cdot \varepsilon(E_3) \cdot (1 - \varepsilon(E_3))^2, \quad (3)$$

$$N_d = N_2 \cdot \varepsilon(E_2)^2 + N_3 \cdot {}_3C_2 \cdot \varepsilon(E_3)^2 \cdot (1 - \varepsilon(E_3)), \quad (4)$$

and

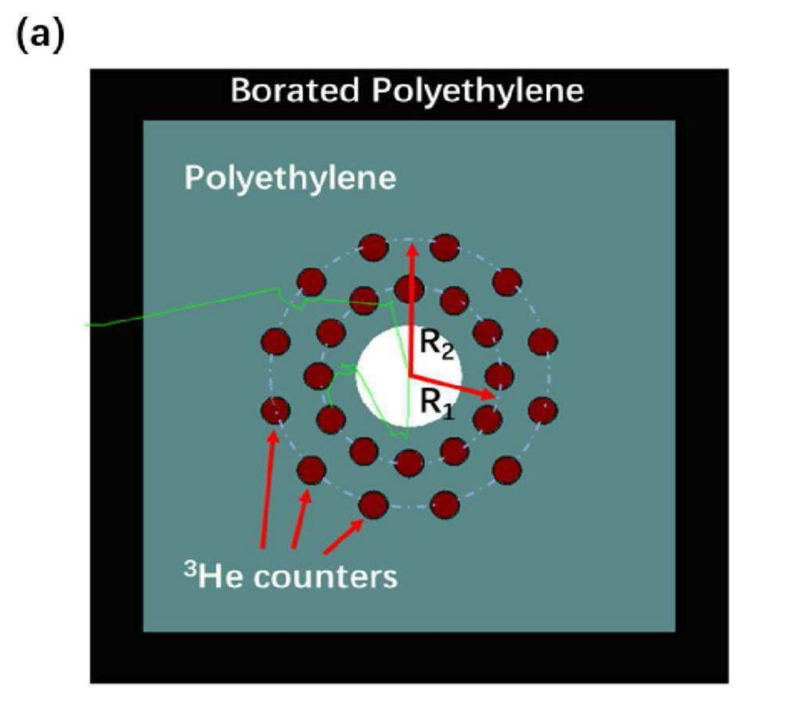
$$N_t = N_3 \cdot \varepsilon(E_3)^3. \quad (5)$$

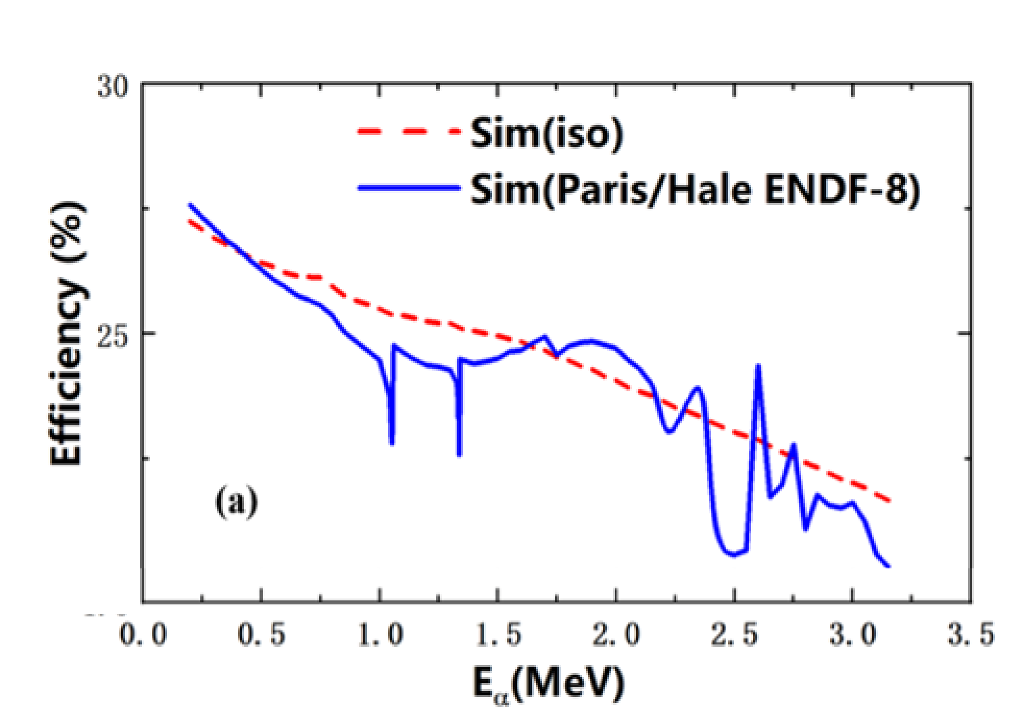
- **Hard to infer the number of P_{xn} and (γ, xn) reaction with a energy dependent efficiency.**

[NIM-A, A 871(2017), 135-141]

Challenge of Neutron Emission Angle

- Neutron emission angle dependency(example: $^{13}C(alpha, n)^{16}O$ at JUNA)



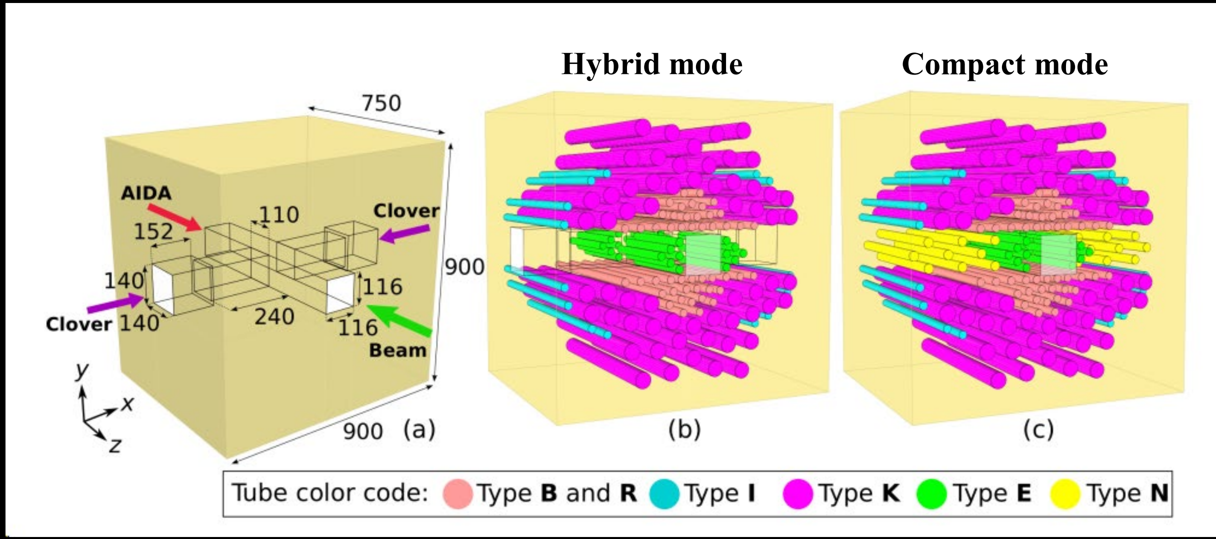


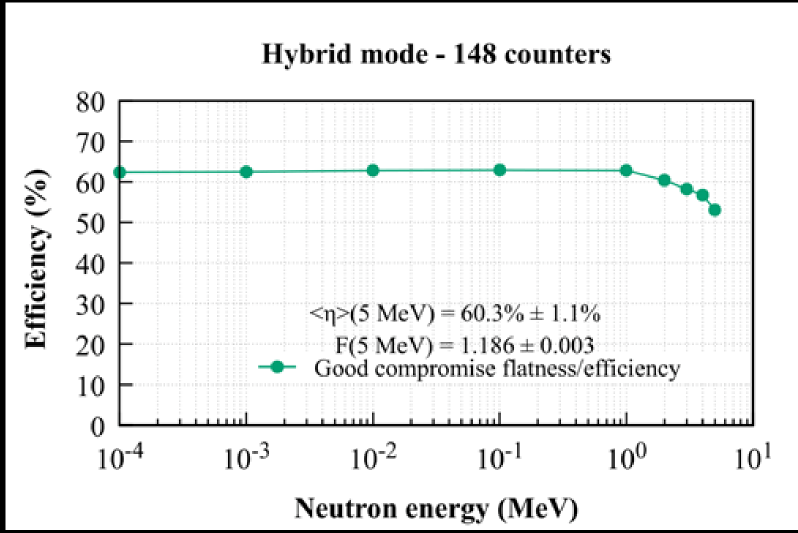
- Detection efficiency strongly depends on neutron emission angle distribution for some experiments.

[Nuclear Science and Techniques, 2022, 33(4)]

Challenge of Detection Efficiency

- Detection efficiency saturation(example: P_n experiment using BRIKEN)





^{3}He Volume 119801.6 cm^3 (~120 L)@1 atm

- Detection efficiency get saturated with the increasing number of ^{3}He tubes.

[The BRIKEN collaboration, Jinst, 2017, 12]

Reason Analysis behind Challenges

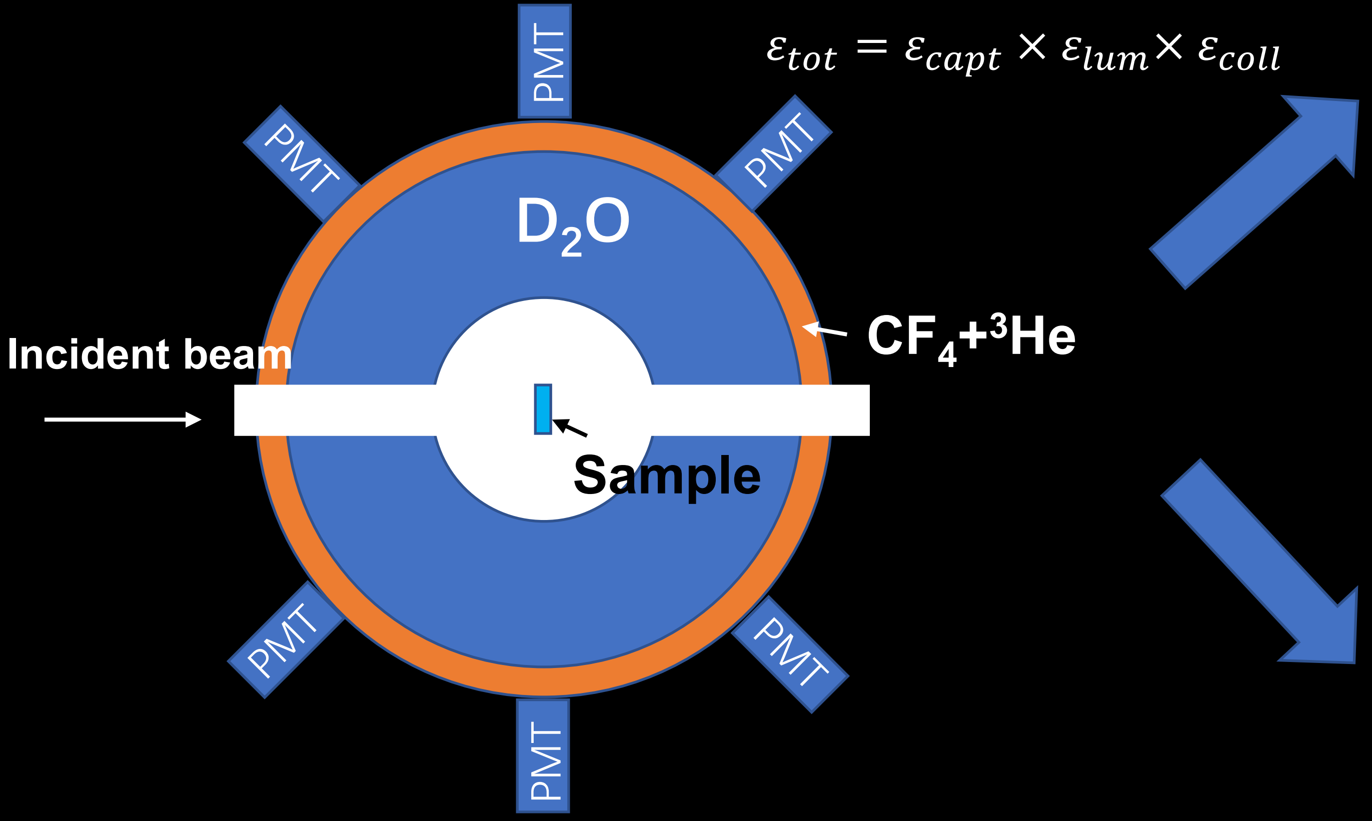
- Challenge summary
  - Efficiency energy dependency when E_n>1 MeV, especially for P_{xn} and (γ, xn) measurements.
  - Efficiency neutron emission angular dependency.
  - Hard to lift detection efficiency when number of ^{3}He tubes reaches to a certain number.
- Reason analysis
  - Neutron-proton(H of Polyethylene) elastic cross section rely on neutron energy (energy dependency).
  - ^{3}He tube can't fully cover 4π, partial neutron may emitted through the wide gap of ^{3}He tubes(angle dependency and low efficiency).
  - A substantial fraction of thermal neutrons would be absorbed by polyethylene (low efficiency).

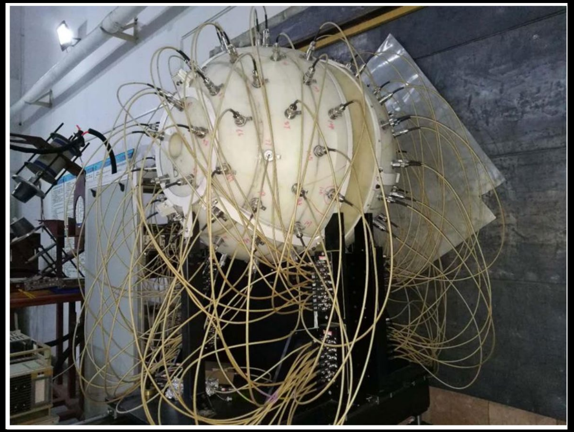
New detector with high detection efficiency as well as less sensitivity to neutron energy and angular distribution is required!

Inspiration of new detector design

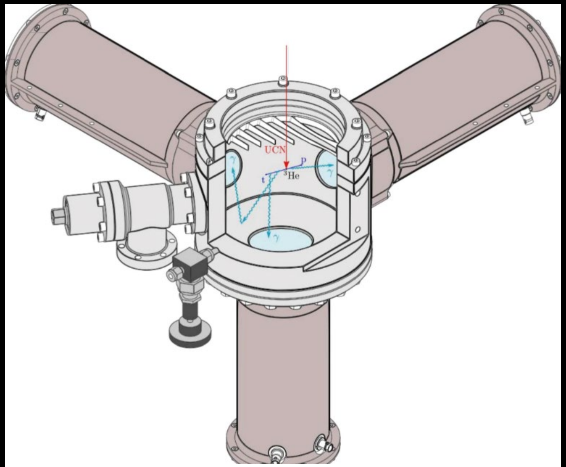
- **Heavy water moderated neutron detector**

$$\varepsilon_{tot} = \varepsilon_{capt} \times \varepsilon_{lum} \times \varepsilon_{coll}$$





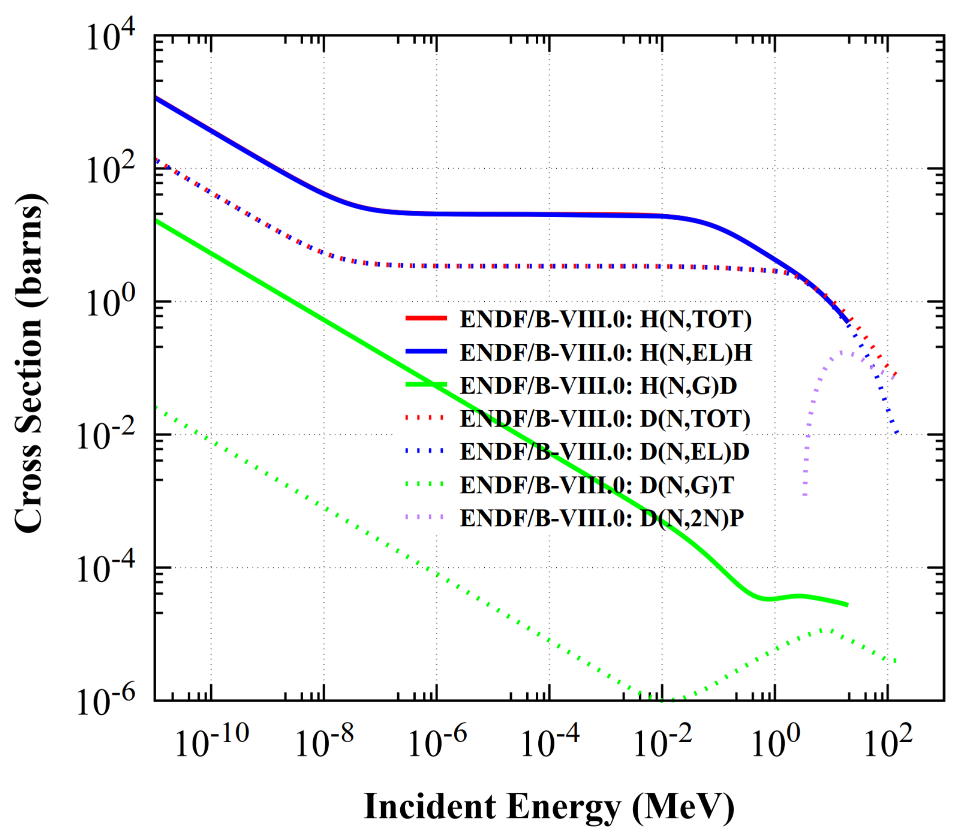
[陈建琪,博士论文,基于直接中子法测量^{93}Nb(n,2n)$^{92g+m}$Nb反应截面的实验研究]



[William PhD thesis neutron to hidden neutron oscillation in ultracold neutron beam]

Why using Heavy Water?

- **Excitation function of H and D**



[ENDF/B-VIII]

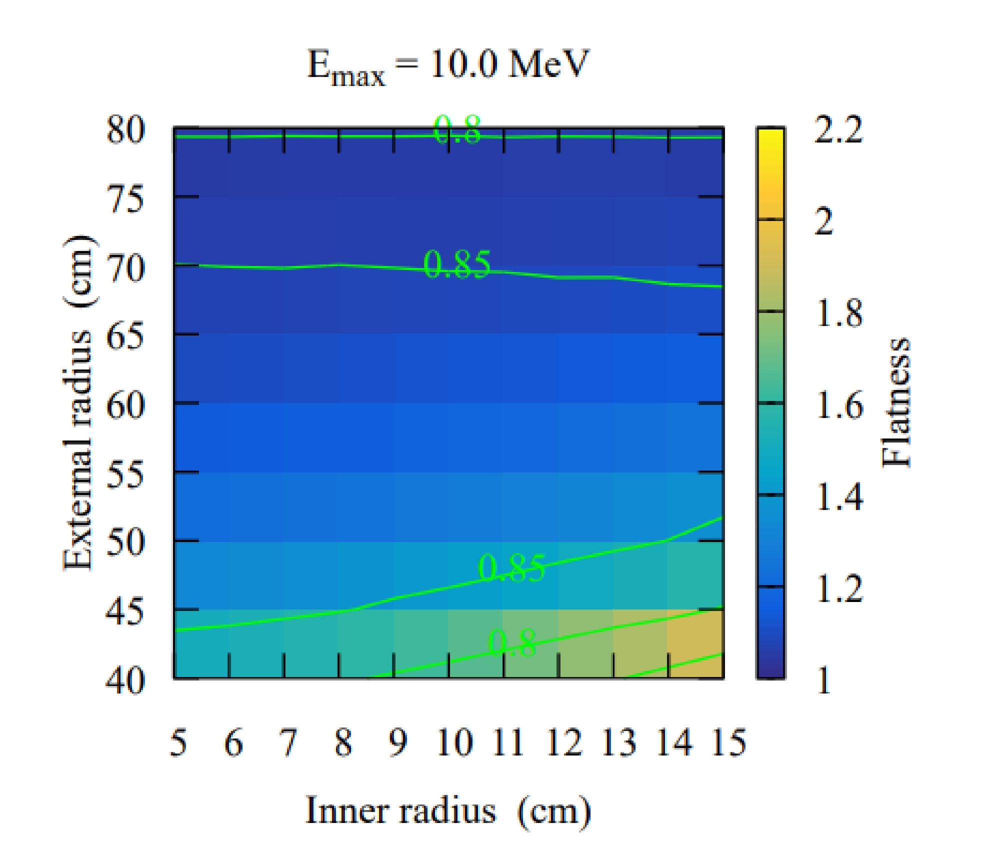
- D has a longer flatness region than H for excitation function curve of elastic scatter.

- The (n, gamma) cross-section of D is 2-3 orders of magnitude lower than that of H, greatly reducing neutron absorption.

- When E_n >3 MeV, it can open the (n, 2n) channel of D, which can effectively increase neutron number to balance the neutron number decrease trend caused by the fall of elastic scatter cross section.

Find the optimal configuration

- **Efficiency and Flatness as a function of inner and outer raidus**



[Courtesy: Junsheng]

Software: MCNPX

Emission angle: isotropic distribution

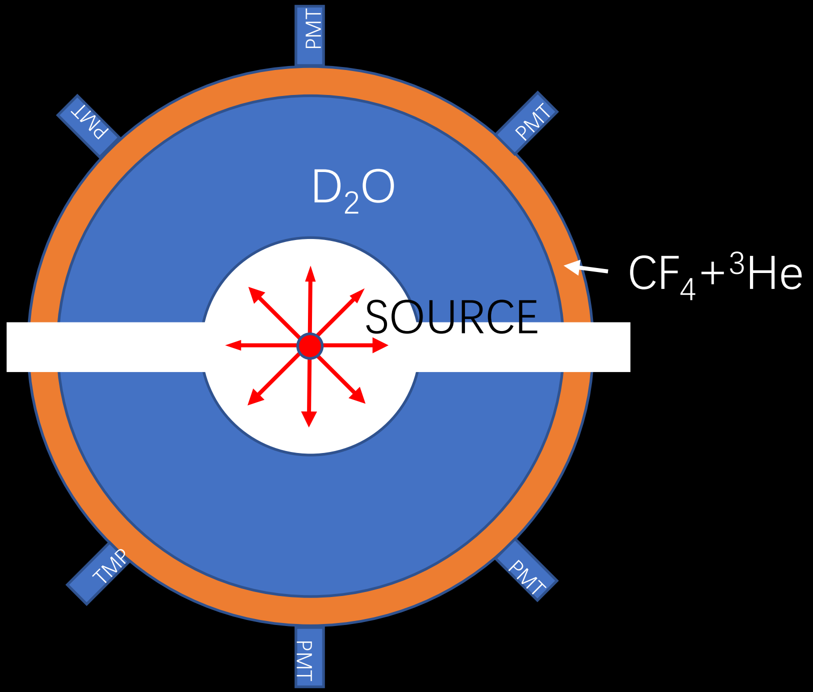
$$E_n = \{0.01, 0.1, 1.0, \ldots, 10.0\}\, MeV$$

- average detection efficiency $\varepsilon_{av}(E_{max}) = \frac{1}{Num(E_i)} \sum_{E_i \le E_{max}} \varepsilon(E_i)$

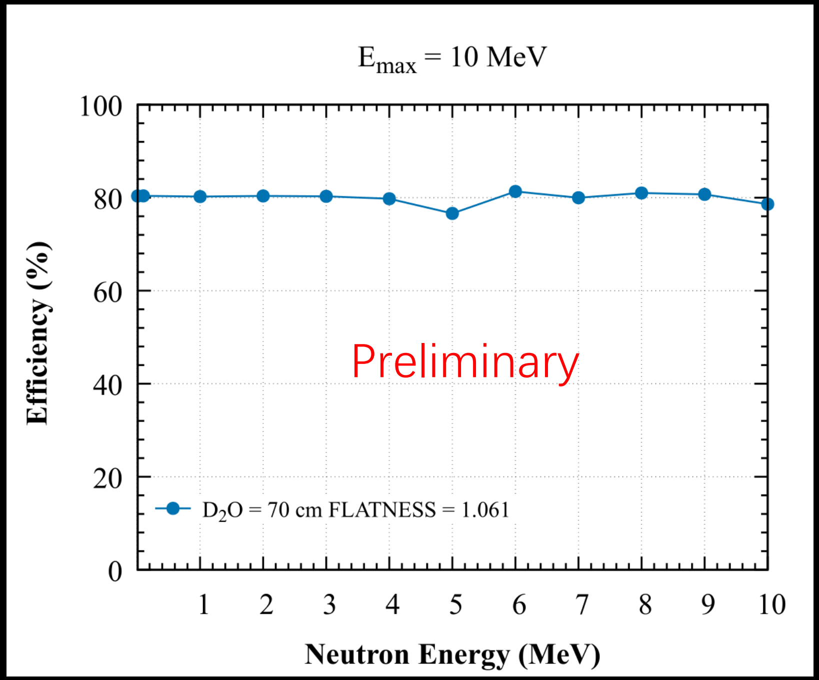
- flatness factor $F(E_{max}) = \frac{Max(\varepsilon(E_i))}{Min(\varepsilon(E_j))}$

Detection efficiency @ D_2O_{th} = 70 cm

- **Configuration**



- **Efficiency vs Neutron Energy**

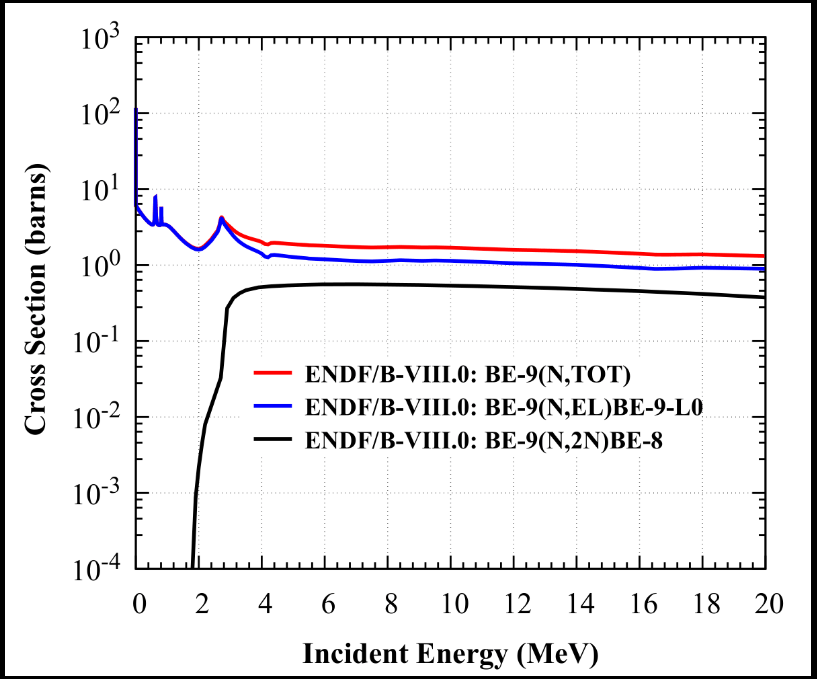


[Courtesy: Junsheng]

- $E_n = \{0.01, 0.1, 1.0, \ldots, 10.0\}\ MeV$
- Neutron emitted isotropically
- optimal configuration: $\emptyset_{in} = 20$ cm, $\emptyset_{out} = 160$ cm, $\emptyset_{ch} = 8$ cm, ^{3}He thickness 3.2 cm

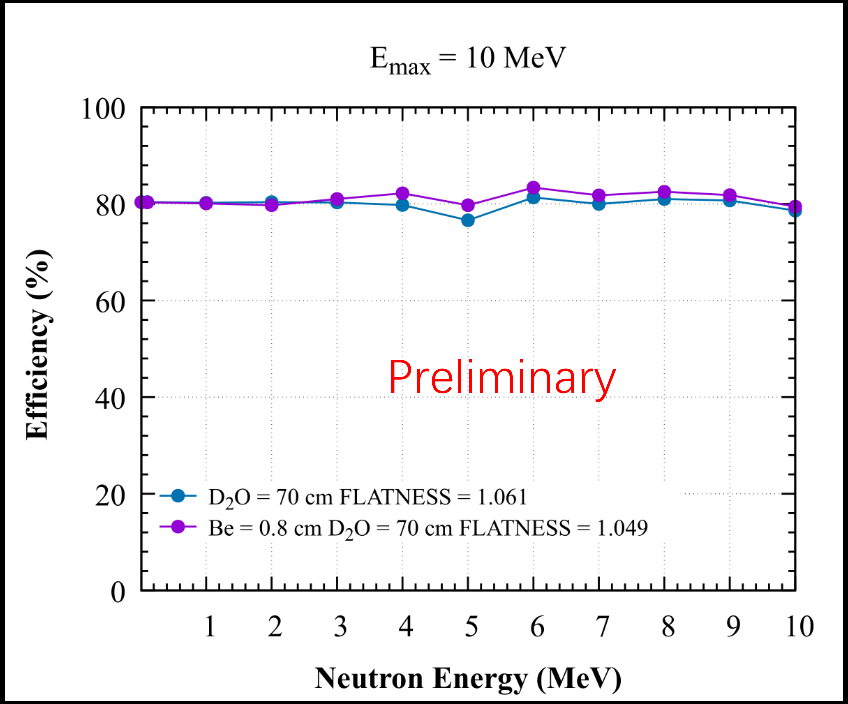
Detection efficiency @ 0.8 cm Be + 70 cm D_2O

- 9Be excitation function



[ENDF]

- Efficiency vs Neutron Energy

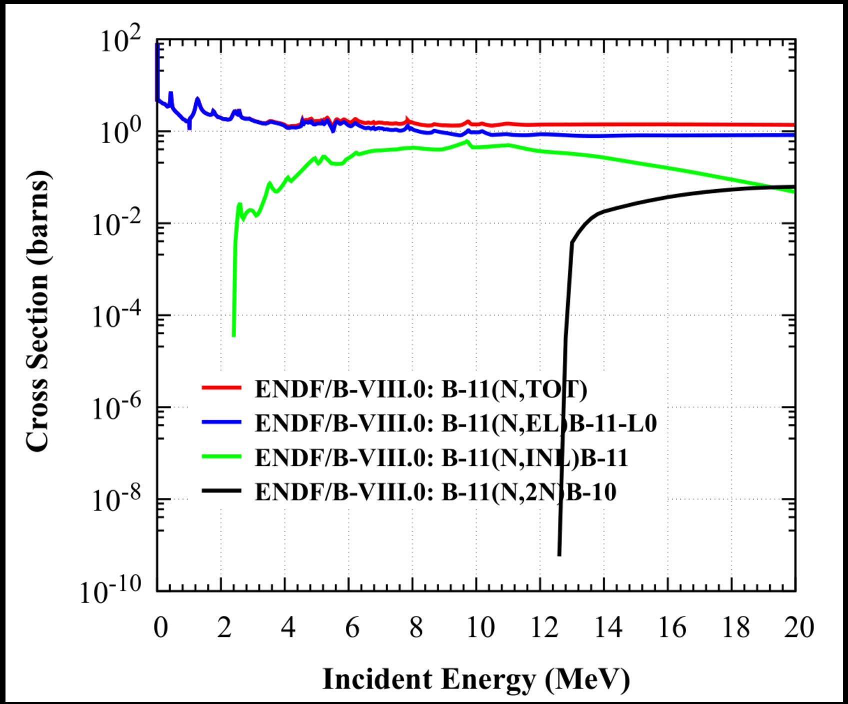


[Courtesy： Junsheng]

- After adding 0.8 cm Be, efficiency curve lift a bit, but the valley around 5 MeV still exists.

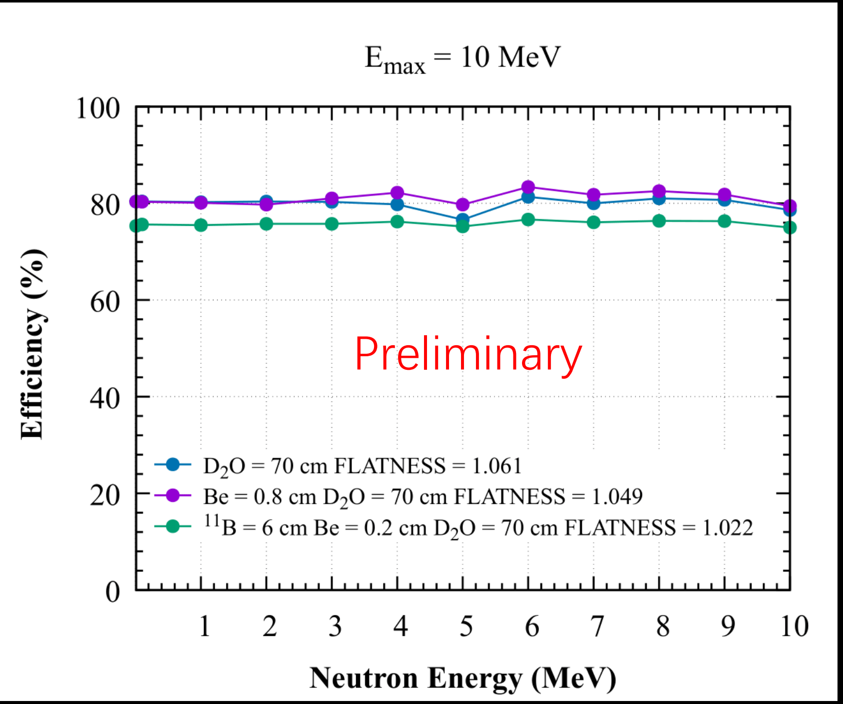
Detection efficiency @ 6 cm B + 0.8 cm Be + 70 cm D_2O

- ^{11}B excitation function



[ENDF]

- Efficiency vs Neutron Energy

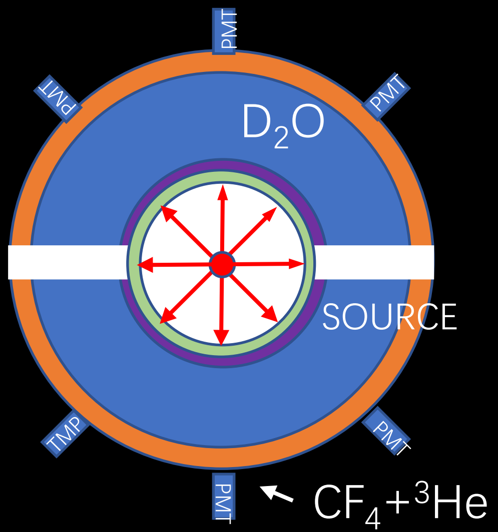


[Courtesy: Junsheng]

- After adding 6 cm ^{11}B, efficiency drops to 75%, flatness has significant improvement, reaching to 1.02.

Efficiency Angular Dependency

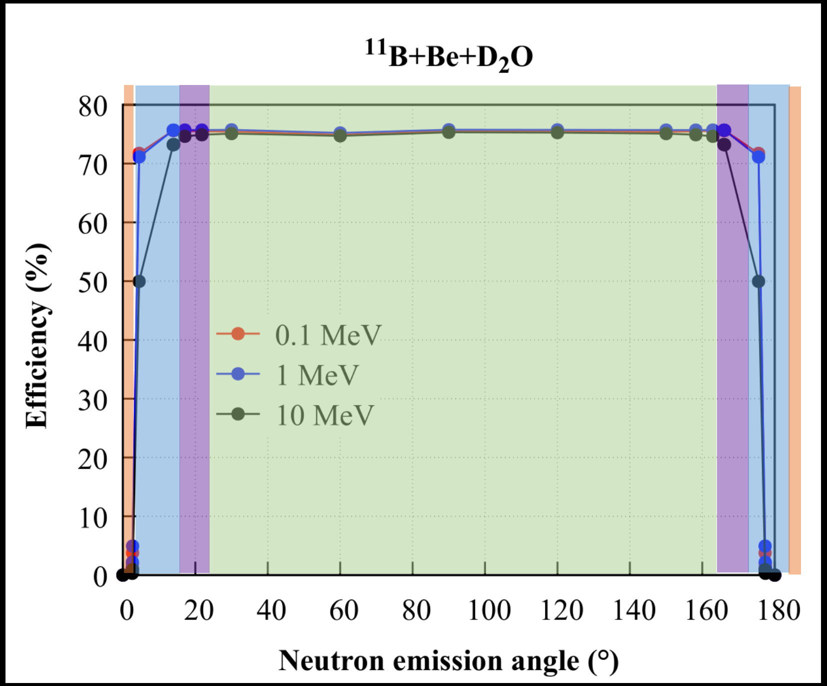
- **Optimal Configuration**



Neutron energy: $\{0.1, 1, 10\}$ MeV
Neutron emission angle: $\{30^\circ, 60^\circ, 90^\circ, 120^\circ, 150^\circ\}$ and angle with respect to different materials
Run number： 10^7

^3He	$^3He+D_2O$
$^3He+D_2O+Be$	
$^3He+D_2O+Be+B$	

- **Efficiency vs Neutron Emission Angle**

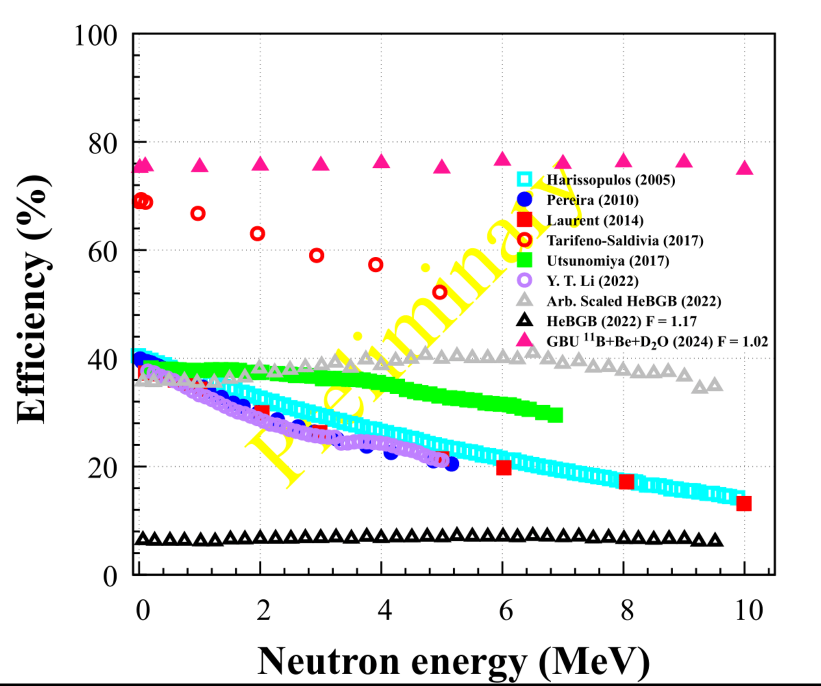


[Courtesy： Junsheng]

- Efficiency independency angle region: $[16^\circ, 164^\circ]$.
- Flatness region independent with neutron energy.

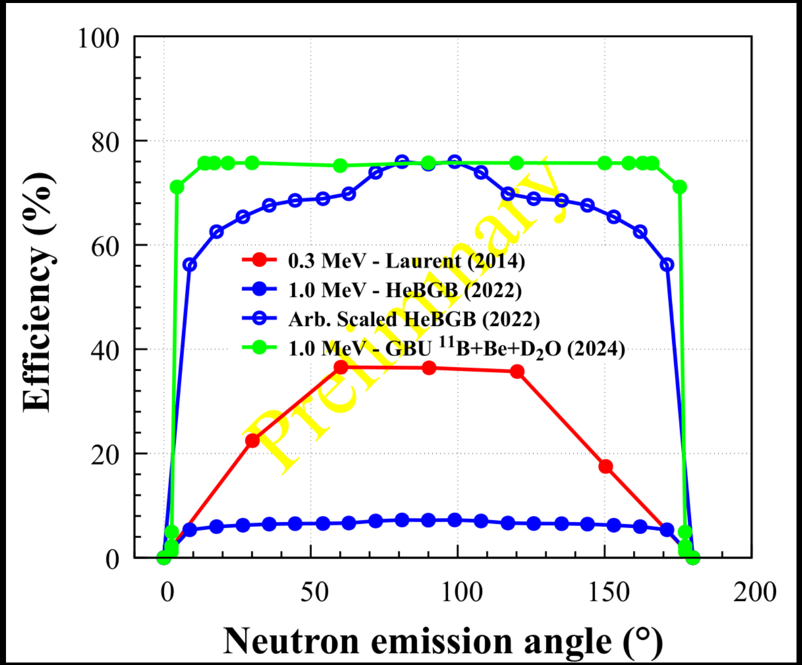
Performance comparison

- **Efficiency vs Neutron Energy**



[Courtesy： Junsheng]

- **Efficiency vs Neutron emission angle**

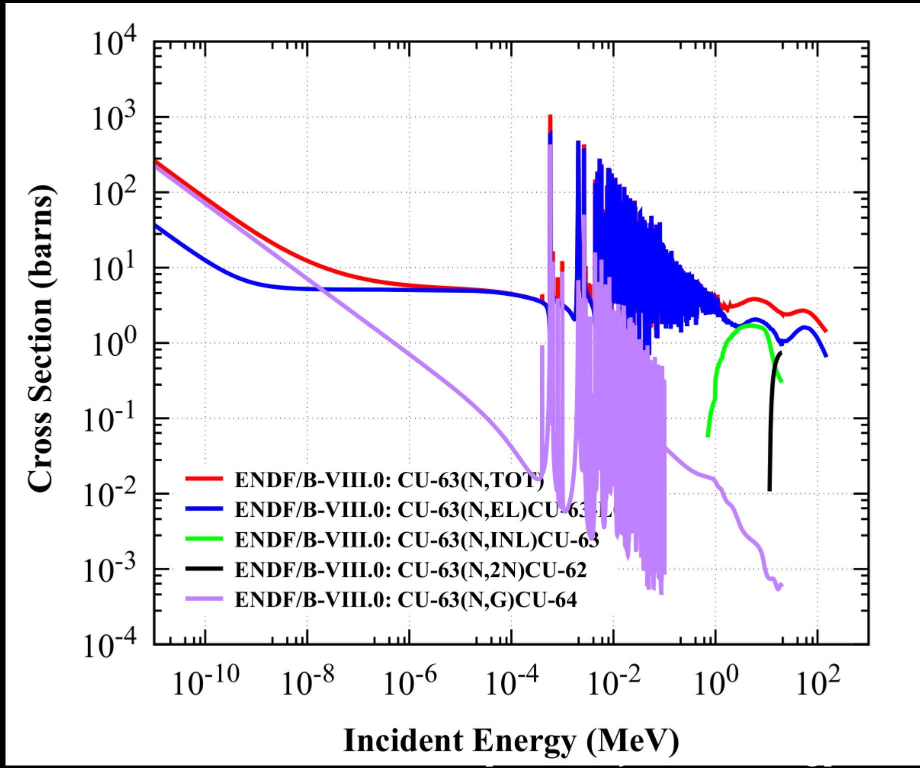


[Courtesy： Junsheng]

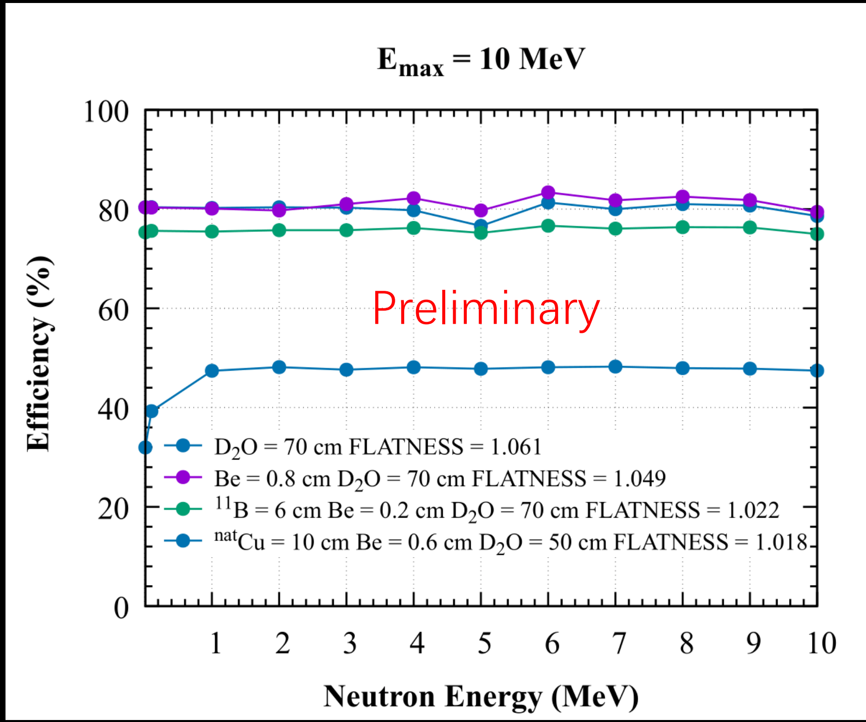
- "CF_4+^{3}He" gas scintillation detector(6 cm ^{11}B+0.2 cm Be+70 cm+2.8 cm ^{3}He) has a better flatness of 1.02, and detection efficiency as high as 75%.
- "CF_4+^{3}He" gas scintillation detector has a wider insensitive angle region.

Alternative configuration 1 $^{11}B \rightarrow {}^{nat}Cu$

- **^{63}Cu excitation function**



- **Efficiency vs Neutron Energy**

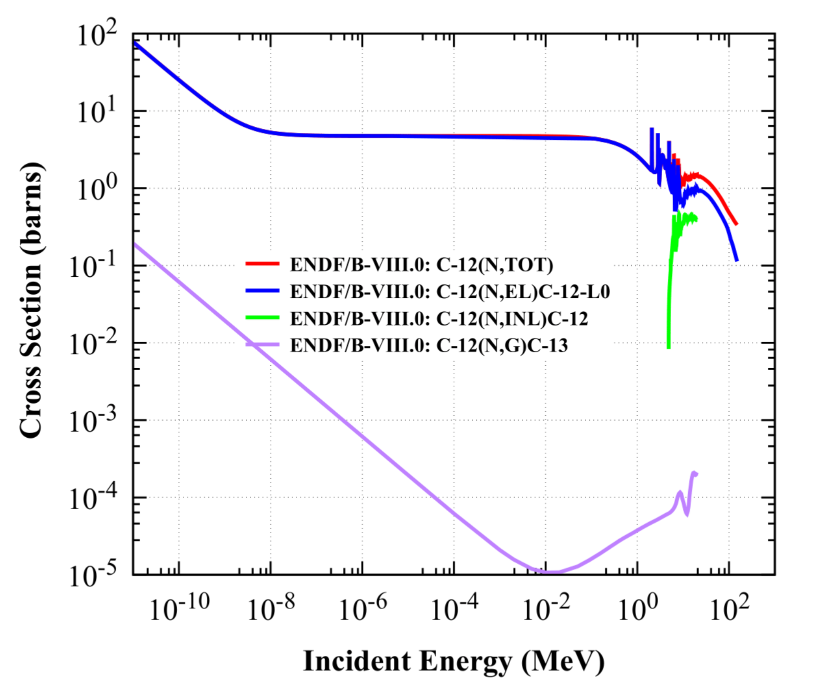


[Courtesy: Junsheng]

- After substituting 10 cm ^{nat}Cu by 6 cm ^{11}B, detection efficiency drops to 50%, and flatness curve get worse when $E_n < 1\ MeV$.

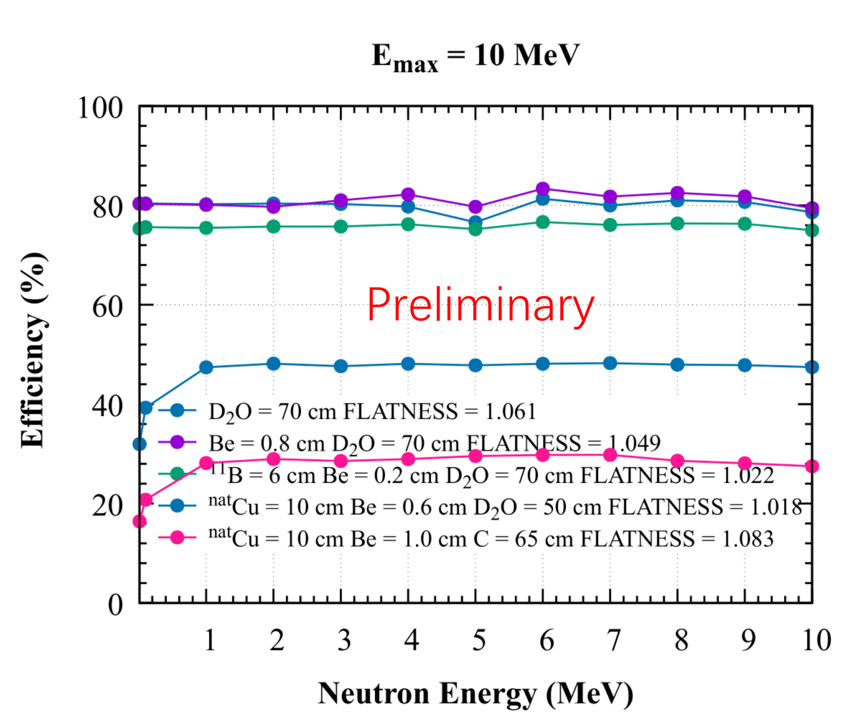
Alternative configuration 2 $D_2O \rightarrow C$

- C excitation function



[Courtesy：Junsheng]

- Efficiency vs Neutron Energy



[Courtesy：Junsheng]

- Besides replacing ^{11}B by ^{nat}Cu, also substitute D_2O by C(Graphite), detection efficiency drops to 30% and flatness curve still is bad when $E_n < 1\ MeV$.

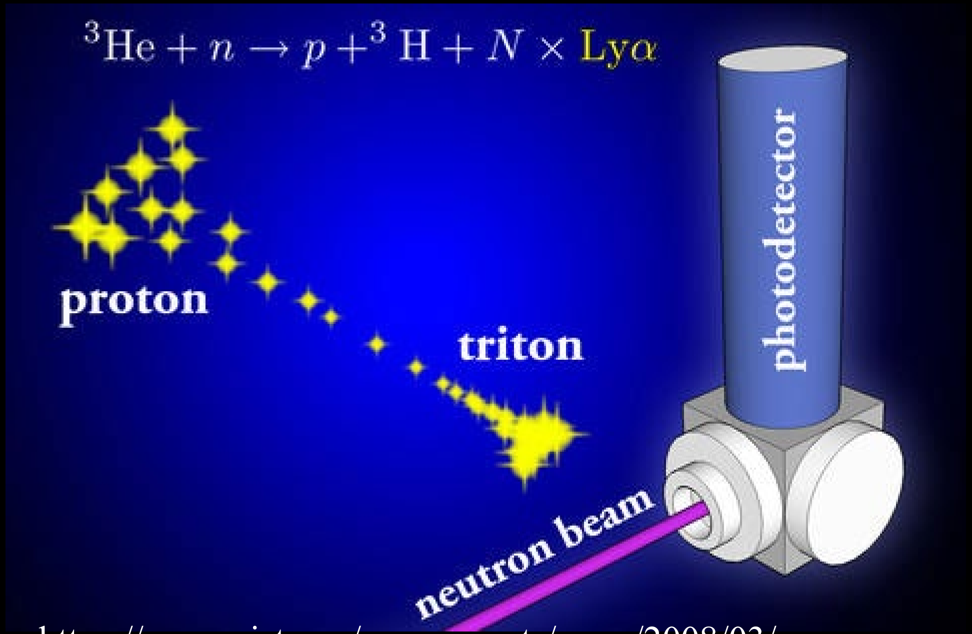
Summary

- Pros
  - high detection efficiency of 75% and less sensitivity to neutron energy and emission angle.
  - less sensitivity to neutron energy, flatness: 1.02.
  - less sensitivity to neutron emission angle: independency region: $[16^\circ, 164^\circ]$ with respect to the incident beam.

- Cons
  - Volume is big and Cost is high(6 cm ^{11}B + 0.2 cm Be +70 cm D_2O, ~275 L ^3He at 4 atm)
  - Two alternative configurations(^{nat}Cu+Be+D_2O and ^{nat}Cu+Be+C) have relativly low detection efficiency and a bad flatness when $E_n < 1$ MeV.
  - Not considering the contribution of light generation probability and light collection efficiency yet, more simulation and experimental work need to do.

Next plan: A demo detector

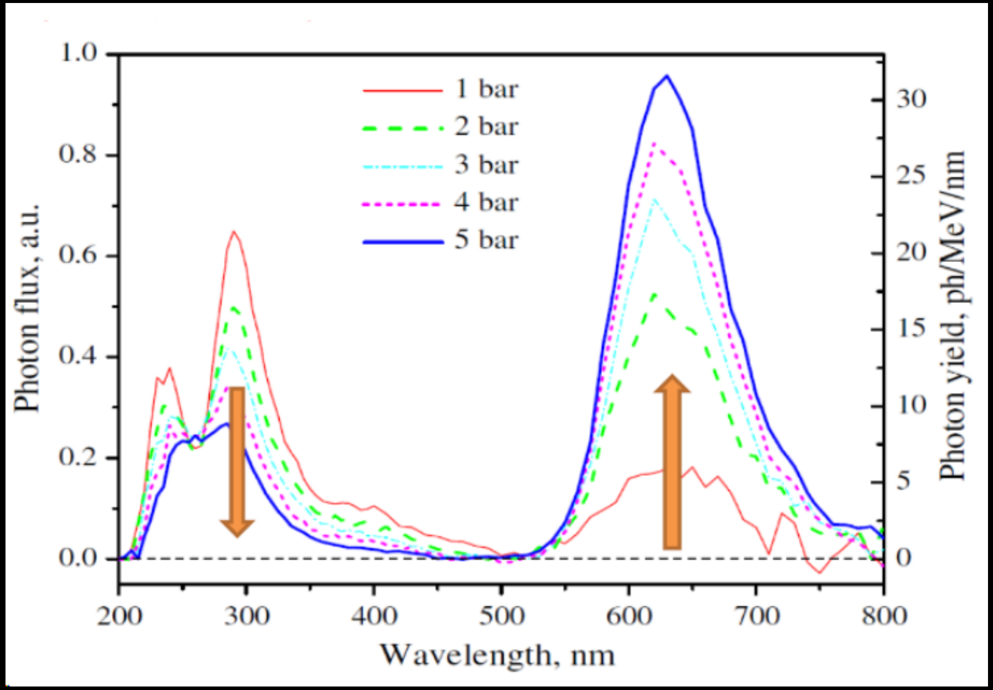
- **Detection principle**



https://www.nist.gov/news-events/news/2008/03/new-nist-detector-can-see-single-neutrons-over-broad-range

- About 40 photons per ultracold neutron.
- UV light with wavelength of 122 nm.
- Pressure: ~0.4 atm.

- **CF4 light spectrum**

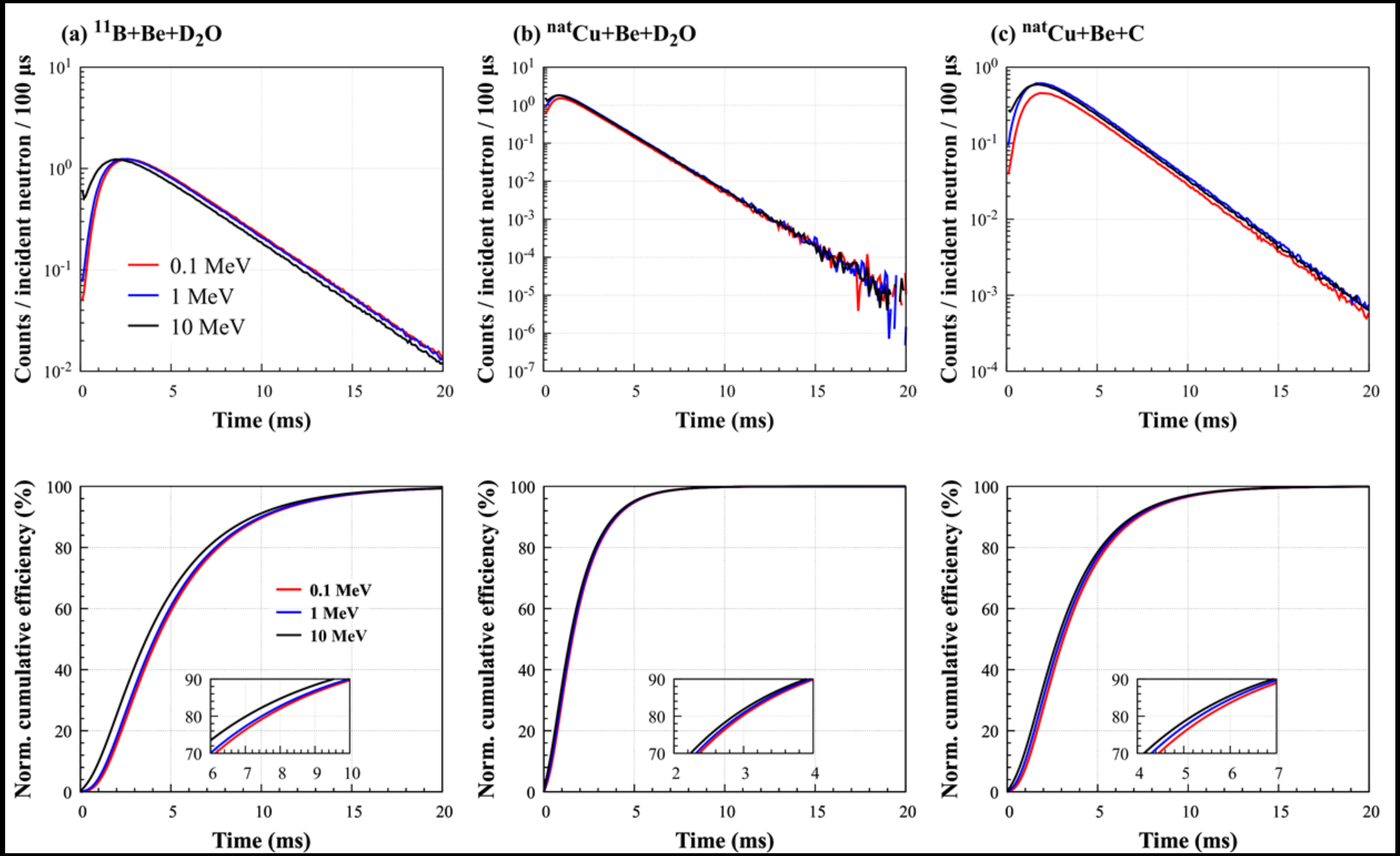


Light Yield : 1000 photon/MeV
[祁辉荣，COUSP2024 CONFERENCE]

Thank you!
欢迎批评指正！

Back-up slides

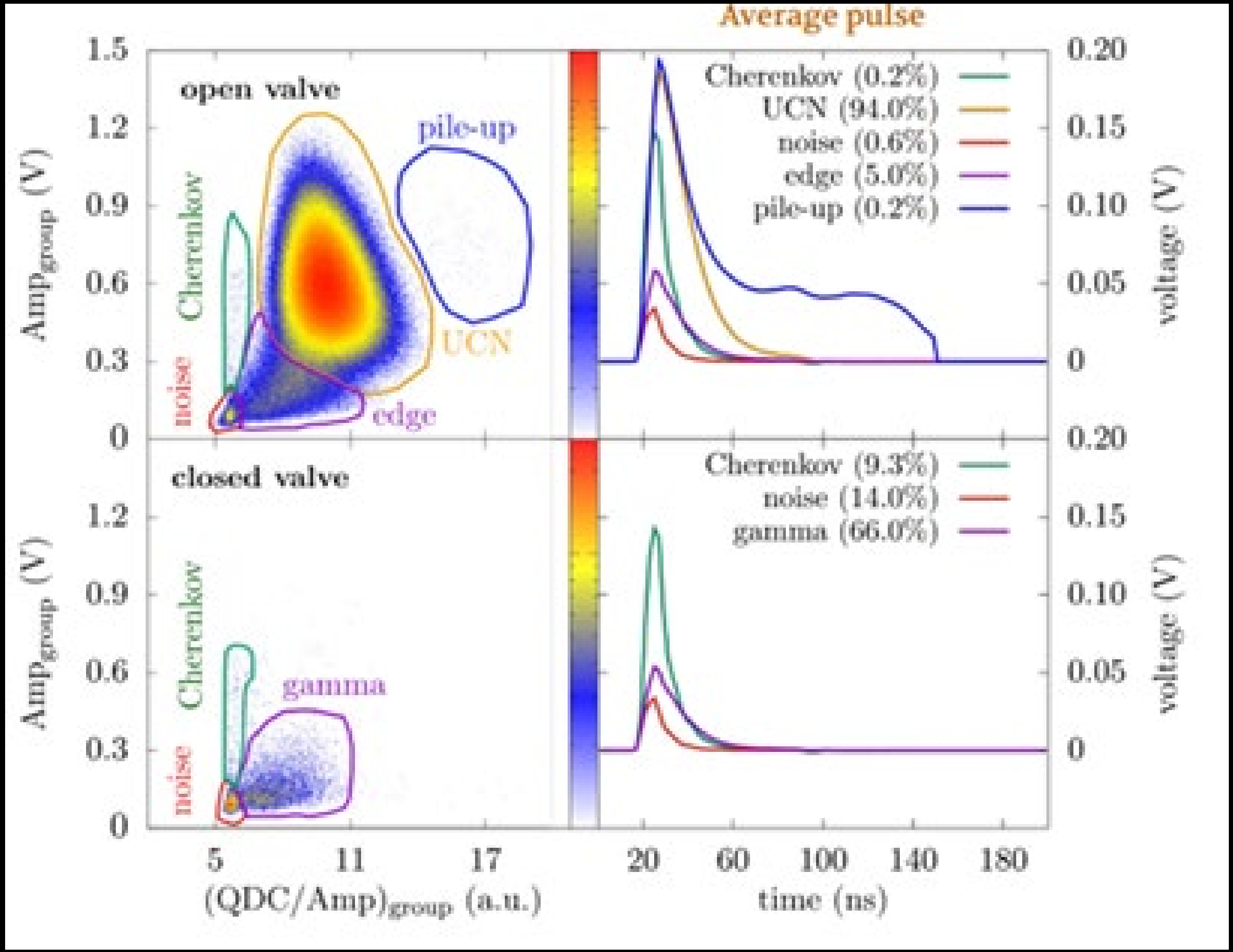
Moderation time



[Courtesy: Junsheng]

- moderation time doesn't depend on neutron energy and time after 10 ms.

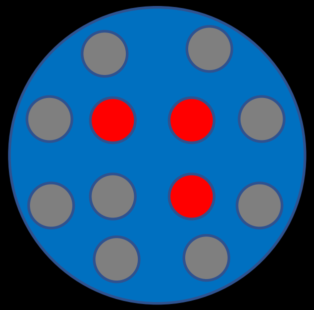
UCN detector PSA analysis



[William Master Thesis]

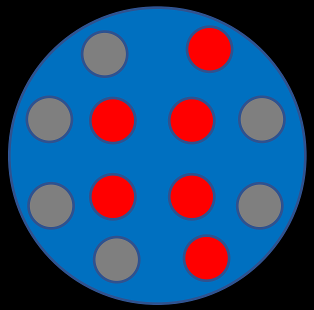
Coincidence mode

- Four coincidence modes
  - Maj 3



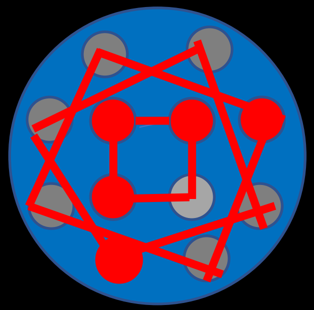
three signals at least

  - Maj 6



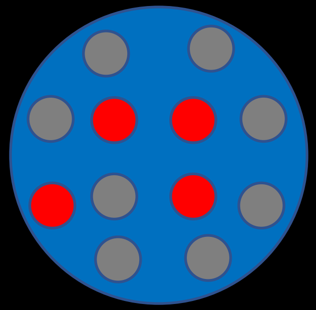
six signals at least

  - The 3 fold mode



One signal at least in each group
A coincidence between three subgroups

  - The 4 fold mode



One signal at least in each group
A coincidence between four subgroups

[Ledoux, X. , et al. "The 4π neutron detector CARMEN." Nuclear Instruments & Methods in Physics Research 844.FEB.1(2017):24-31]