

POLARIZED EV NEUTRON FOR T-REVERSAL SYMMETRY BREAKING EXPERIMENT

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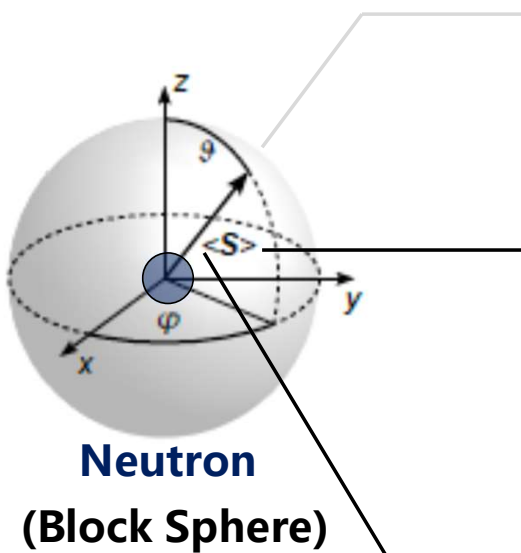
China Spallation Neutron Source

2nd Workshop on Polarized Beam and Target – Physics and Applications, 2026.04.02, Huizhou



- I. CSNS polarized neutron overview**
- II. Polarized neutron on Back-n beamline**
- III. NOPTREX collaboration**
- IV. Summary**

Neutron basics



$q < 10^{-22}e$
Electrical Neutral

$$\vec{s} = \frac{\hbar}{2} \vec{\sigma}$$

Neutron spin

$$\vec{\mu}_n = \frac{2}{\hbar} \gamma_n \mu_N \vec{s} = -9.66 \times 10^{-17} \text{ J.T}^{-1}$$

Neutron magnetic moment

$$\vec{P} = (\langle \sigma_x \rangle, \langle \sigma_y \rangle, \langle \sigma_z \rangle)$$

Neutron polarization

- Baryons
- Electrical Neutral ($<10^{-22}e$)
- Spin = $\frac{1}{2}$
- Magnetic moment: $-1.913 \mu_N$
- Mass = 939.566 MeV
- Lifetime $\sim 880s$
- Electrical dipole moment: $< 1.3 \times 10^{-26} e \cdot \text{cm}$

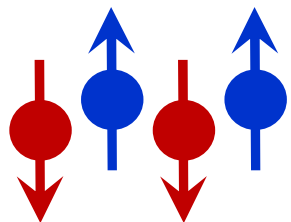
- Respond to all four forces, and possibly “fifth” force
- Simpler compare to nucleus
- Polarization is a unique feature

- Difficult to handle, can’t accelerate/ guide/ focus
- Destruction to detect
- Low flux

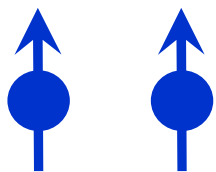
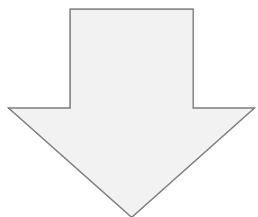
CSNS Polarized Neutron Overview



❑ Polarized neutrons have applications in material and nuclear research

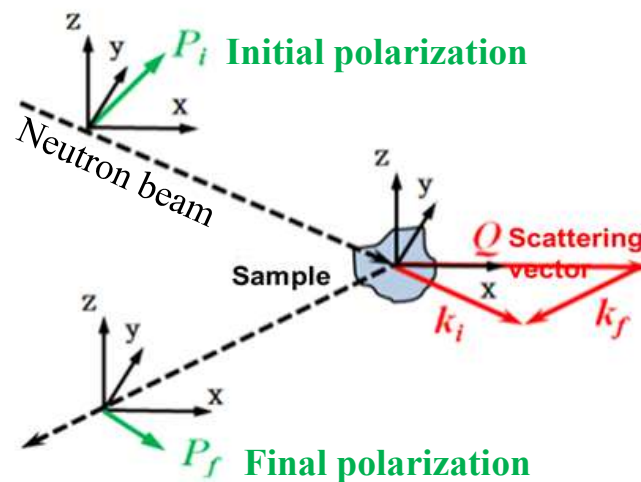


Regular neutrons



Polarized neutrons

Polarized neutron scattering



Momentum shift

$$Q = k_f - k_i$$

$$k_f = (k_{fx}, k_{fy}, k_{fz})$$

$$k_i = (k_{ix}, k_{iy}, k_{iz})$$

Energy shift

$$\Delta E = E_f - E_i$$

Polarization Shift

$$P_i \rightarrow P_f$$

$$P_f = (P_{fx}, P_{fy}, P_{fz})$$

$$P_i = (P_{ix}, P_{iy}, P_{iz})$$

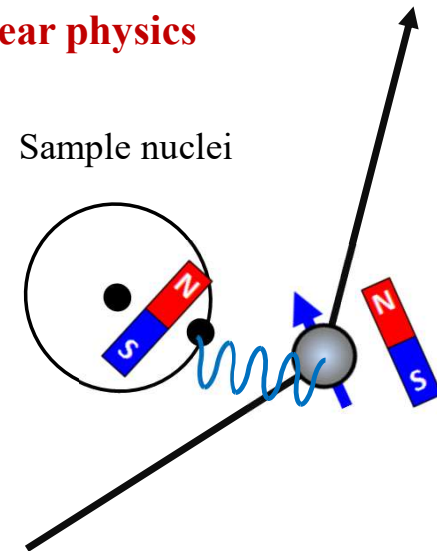
E: meV - eV

- ❖ Study of magnetic materials
- ❖ Separation of incoherent scattering
- ❖ Neutron Spin manipulation

E: eV - MeV

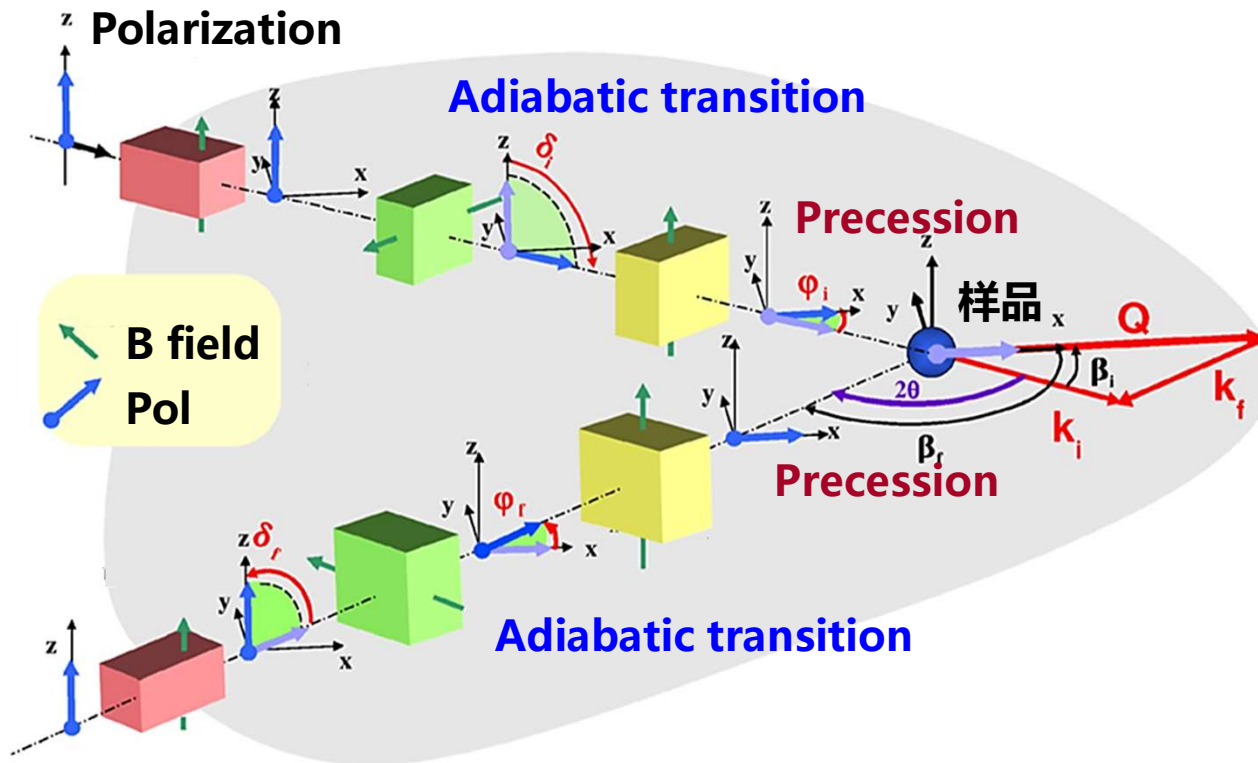
- ❖ Nuclear physics

Sample nuclei

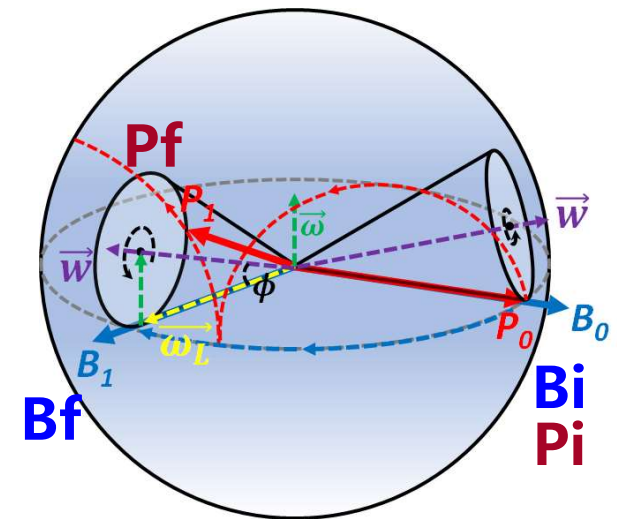


Control of neutron polarization

◆ Control of neutron polarization through B field



Larmor precession



Bloch Equation

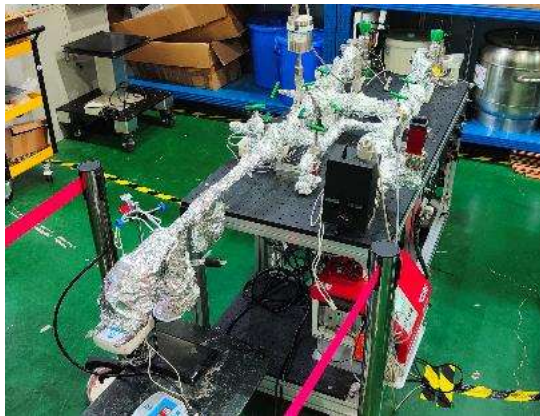
$$\frac{d\vec{P}}{dt} = -\gamma_L \vec{P} \times \vec{B}$$

Current polarized instrument capability

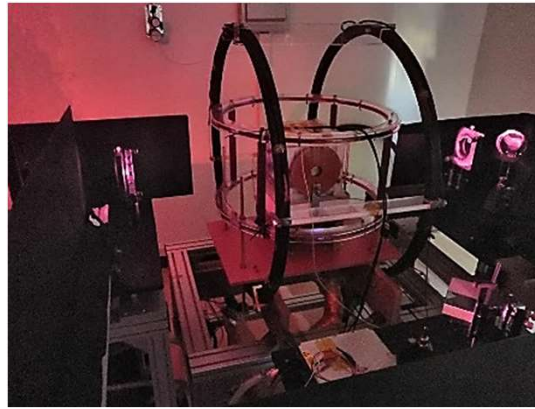


- CSNS established in-house development capability for SEOP ^3He system

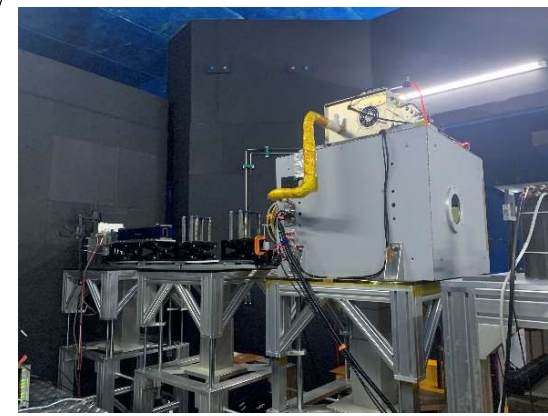
1. In-house ^3He cell fabrication and filling



2. Off-situ and in-situ SEOP ^3He spin filter



3. Beamline commission and scientific application

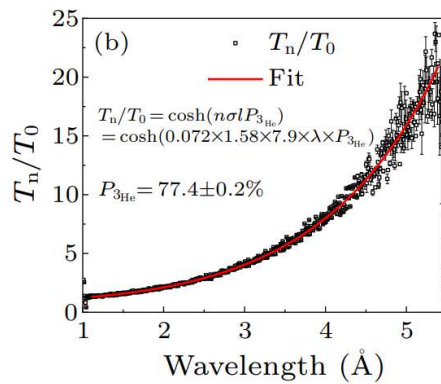
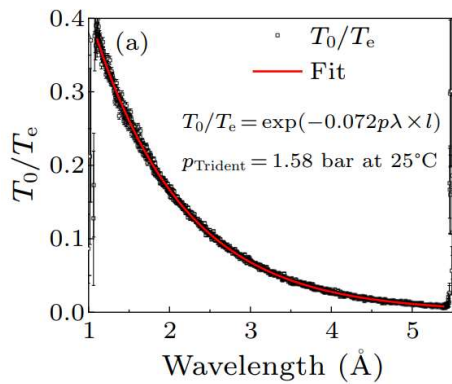


Current polarized instrument capability



- Cell quality assessment using TOF neutron and NMR method

Online benchmarking: Neutron transmission measurement at CSNS



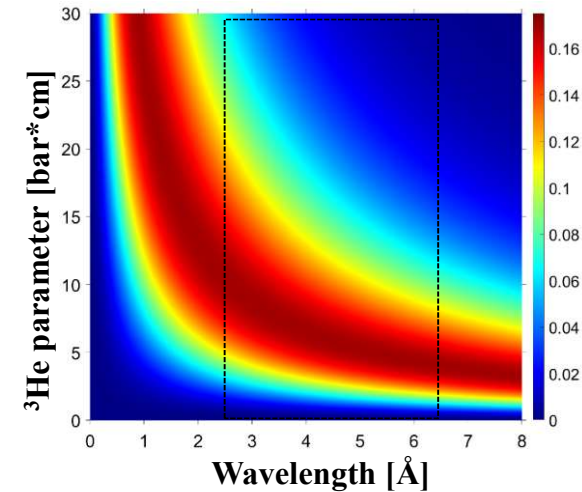
³He gas pressure calibration

$$T_{depol}(\lambda)/T_0 = \exp(-0.072 P_{3He} \cdot l \cdot \lambda)$$

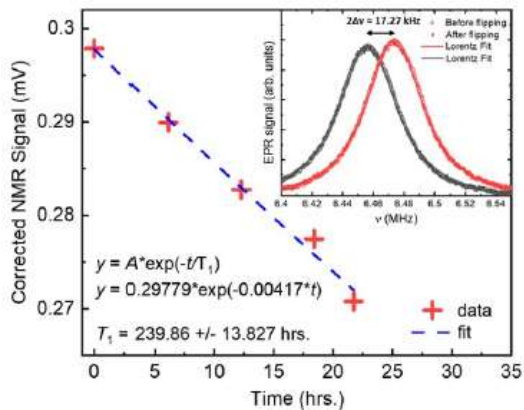
³He polarization calibration

$$T_{pol}(\lambda)/T_{depol}(\lambda) = \cosh(0.072 P_{3He} \cdot l \cdot \lambda \cdot P_{3He})$$

³He filter parameter



Offline benchmarking: FID and EPR measurement



$$P_{3He} = \frac{\Delta\nu}{kHz} \cdot \frac{Amagat}{1.13 \times \kappa_{eff}[He]}$$

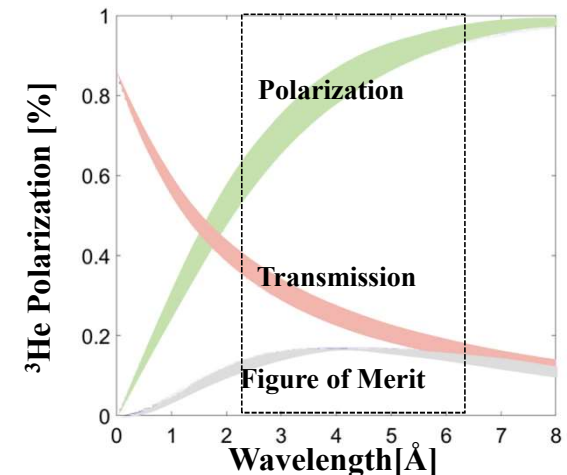
Amagat: gas density unit ($2.686 \times 10^{25}m^{-3}$)

κ_{eff} : frequency shift coefficient (6.2)

[He]: ³He gas density

❖ Chuyi Huang *et al*; *Chinese Phys. Lett.* 38 092801 (2021)

❖ J.P. Zhang, *et al.*; *Sci China Phys Mech*, 65 (2022).

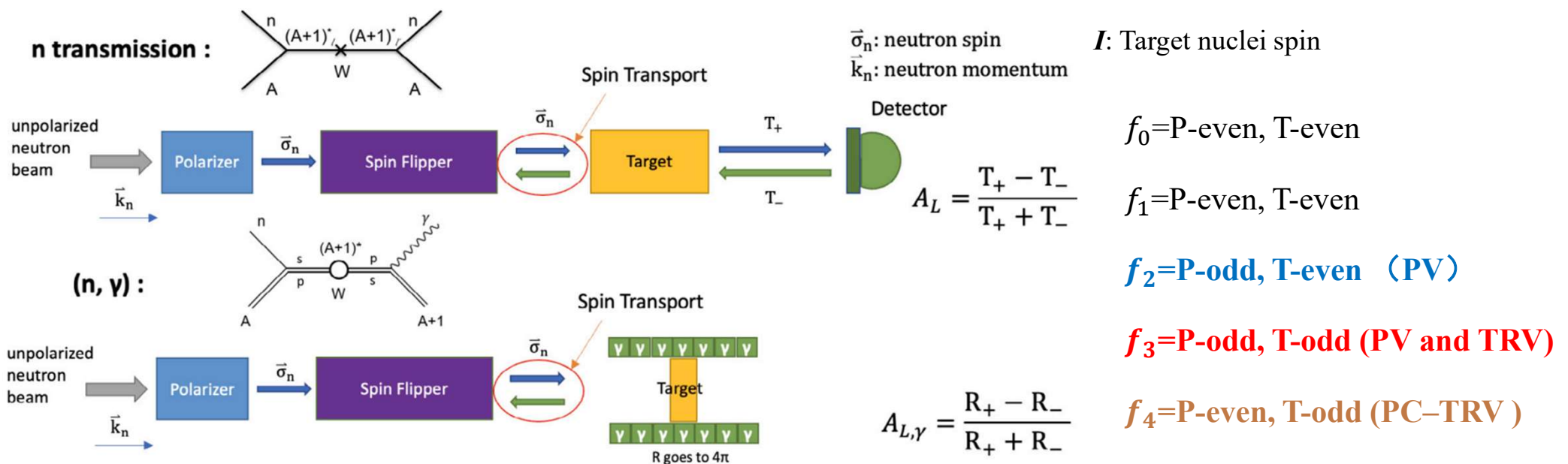


The NOPTREX Measurement



- The NOPTREX experiment aims to investigate parity violation(PV) and time reversal violation(TRV) in neutron-nucleus interactions.

$$f = f_0 + f_1(\vec{\sigma}_n \cdot \vec{I}) + f_2(\vec{\sigma}_n \cdot \vec{k}_n) + f_3(\vec{\sigma}_n \cdot [\vec{k}_n \times \vec{I}]) + f_4(\vec{\sigma}_n \cdot (\vec{I} \times \vec{k}_n)(\vec{I} \cdot \vec{k}_n))$$



By decomposing the interaction terms according to symmetries, PV and TRV can be measured using polarized neutrons.

The NOPTREX Collaboration



NOPTREX: A Neutron Optics Time-Reversal Violation Experiment

NOPTREX Collaboration

Nagoya U.: H.M. Shimizu, M. Kitaguchi, K. Hirota, T. Yamamoto, K. Ishizaki, S. Endoh, Y. Niinomi, I. Ide, H. Tada, T. Morishima, Y. Kiyonagi, J. Hisano, N. Wada, T. Matshshita

Kyushu U.: T. Yoshioka, S. Takada, J. Koga, S. Makise

JAEA: T. Okudaira, K. Sakai, A. Kimura, H. Harada

KEK: T. Ino, S. Ishimoto, K. Taketani, K. Mishima

U. British Columbia: T. Momose

Hiroshima U.: M. Iinuma

Tokyo Inst. Tech.: H. Fujioka, Y. Tani

Osaka U.: K. Ogata, H. Kohri, M. Yosoi, T. Shima, H. Yoshikawa

Yamagata U.: T. Iwata, Y. Miyachi

RIKEN: Y. Yamagata, T. Uesaka, K. Tateishi, H. Ikegami

Kyoto U.: Y. I. Takahashi, M. Hino

Ashikaga U.: D. Takahashi

Japan Women's U.: R. Ishiguro



Indiana U.: W. M. Snow, C. Auton, J. Carini, J. Curole, K. Dickerson, J. Doskow, H. Lu, G. Otero, K. Steffen, J. Vanderwerp, G. Visser

U. South Carolina: V. Gudkov

ORNL: J.D. Bowman, P. Jiang, S. Penttila

U. Kentucky: C. Crawford, B. Plaster, L. Cole, H. Dhahri

LANL: D. Schaper

NIST: C. Haddock

Southern Illinois U.: B.M. Goodson

Ohio U.: P. King

Middle Tennessee State U.: R. Maruhin

Eastern Kentucky U.: J. Fry

Western Kentucky U.: I. Novikov

Berea College: M. Veillette, D. Olivera-Verlade

UNAM: L. Barron-Palos, A. Perez-Martin

PSI: P. Hautle

One experiment:
Five neutron sources



Schaper et al., NIM A969 (2020) 163961

- J. Bowman, C. Bowman, J. Bush, P. Delheij, C. Frankle, C. Gould, D. Haase, J. Knudson, G. Mitchell, S. Penttila et al., Phys. Rev. Lett. 65, 1192 (1990).
- T. Okudaira, S. Takada, K. Hirota, A. Kimura, M. Kitaguchi, J. Koga, K. Nagamoto, T. Nakao, A. Okada, K. Sakai et al., Phys. Rev. C 97, 034622 (2018).
- A. Adhikary and P. Das, Phys. Part. Nucl. 56, 1059 (2025).

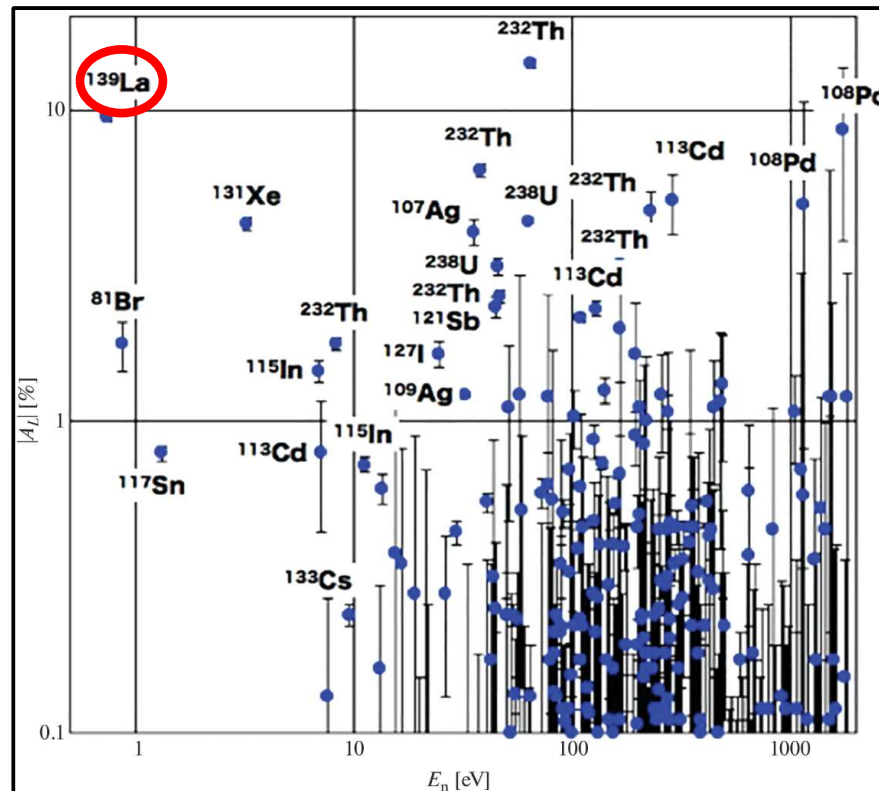
The NOPTREX Collaboration



NOPTREX: A Neutron Optics Time-Reversal Violation Experiment

- Mixing of s-wave and p-wave resonances through weak interaction enhances parity-violating amplitudes by factors of 10^4 to 10^6 in the vicinity of p-wave resonances

Series measurement of P-odd/T-odd and P-Odd term



- Polarize Neutron at resonance energy (734meV)
- Transfer calibrated and polarized neutron to gamma detector
- (Expend to other resonance energy)
....
- Measurement of f_2 (P-odd/T-even) term
- Introduce polarized nuclear target
- Integrate of polarized target with neutron beamline
- Measurement of f_3 (P-odd/T-odd)

Setting up polarized neutron at Back-n



• Polarized Neutron at CSNS back-n beamline

First Use of a Polarized ^3He Neutron Spin Filter on the Back-n
White Neutron Source of CSNS

Mofan Zhang (张墨凡)^{2,3}, Zhou Yang (杨洲)², Junpei Zhang (张俊佩)^{1,2,4}, Chuyi Huang (黄楚怡)^{1,2,4}, Tianhao Wang (王天昊)^{*1,2,4}, Yonghao Chen (陈永浩)^{1,2}, Ruirui Fan (樊睿睿)^{†1,2,5}, W. Michael Snow³ and Xin Tong (童欣)^{‡1,2,4}

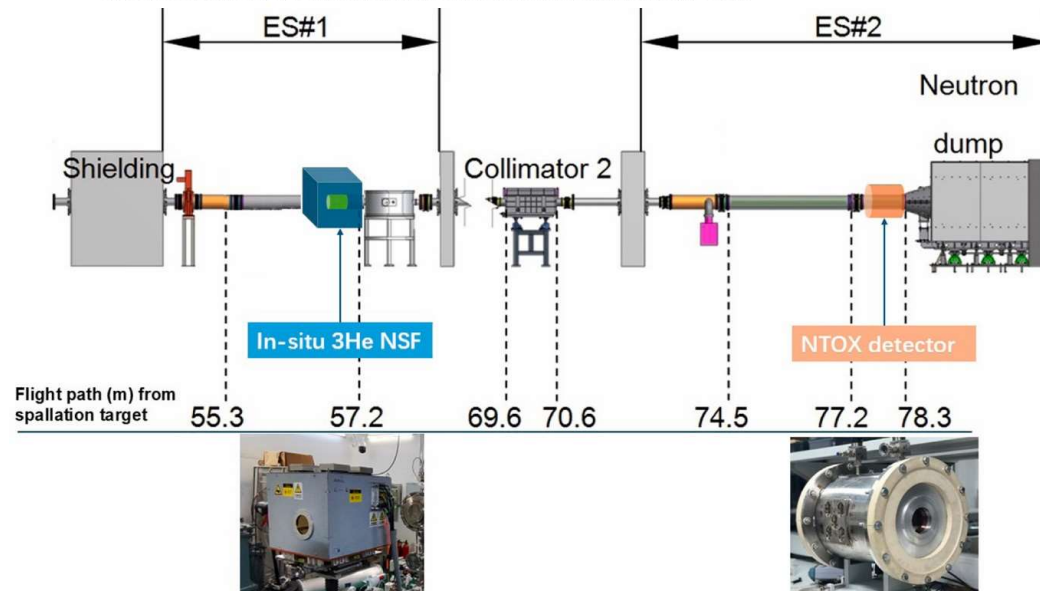
¹Institute of High Energy Physics, Chinese Academy of Sciences, 19B Yuquan Road, Shijingshan District, Beijing, 100049, China

²China Spallation Neutron Source, 1 Zhongziyuan Road, Dalang, Dongguan, Guangdong, 523803, China

³Indiana University, Bloomington, IN 47405, USA

⁴Guangdong Provincial Key Laboratory of Extreme Conditions, Dongguan, 523803, China

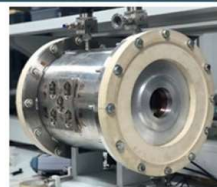
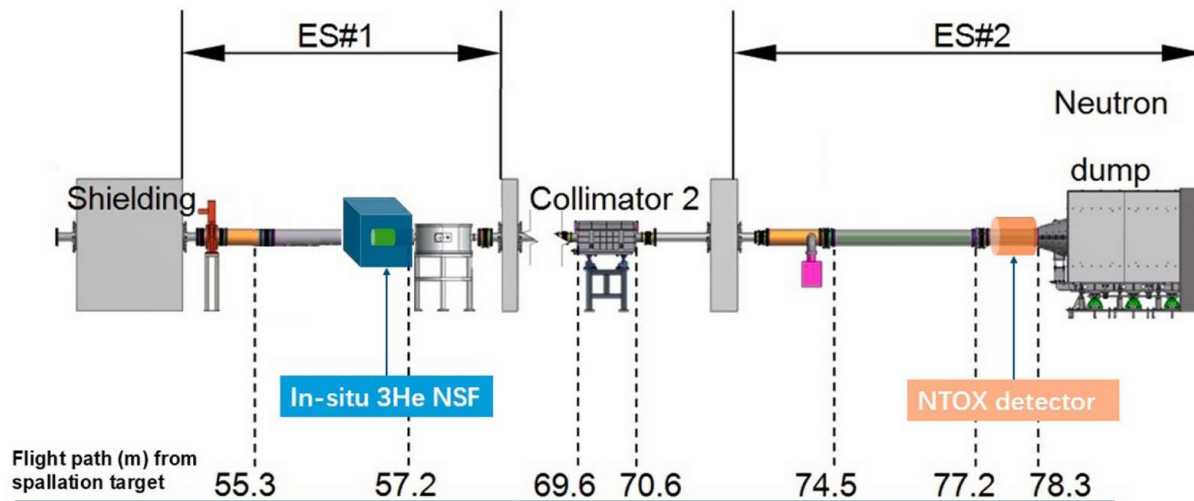
⁵State Key Laboratory of Particle Detection and Electronics, Beijing, 100049, China



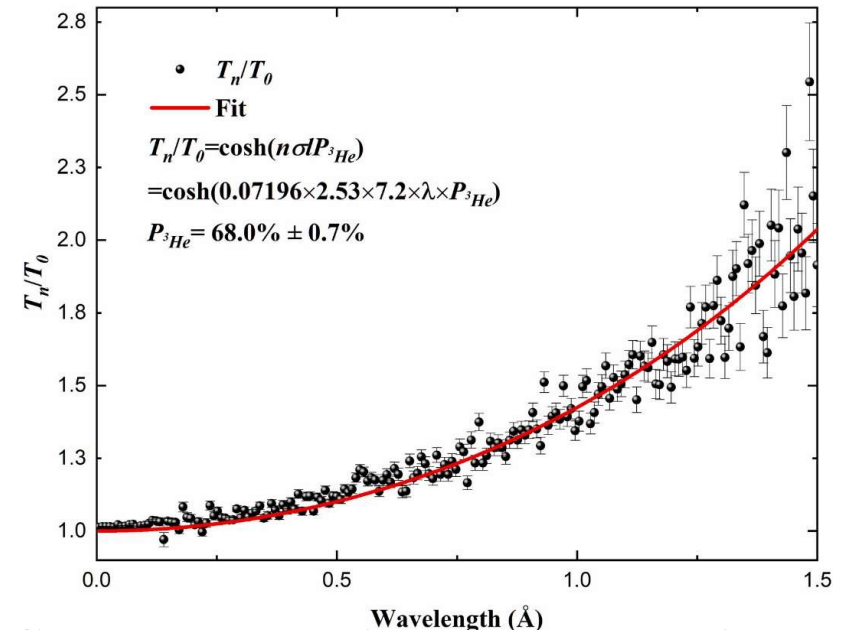
Setting up polarized neutron at Back-n



- Polarized Neutron at CSNS back-n beamline



Neutron detector
(Radiation chamber)



Good news: polarized neutron acquired
Question: how to use it?

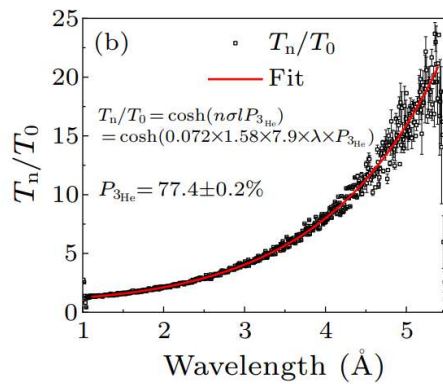
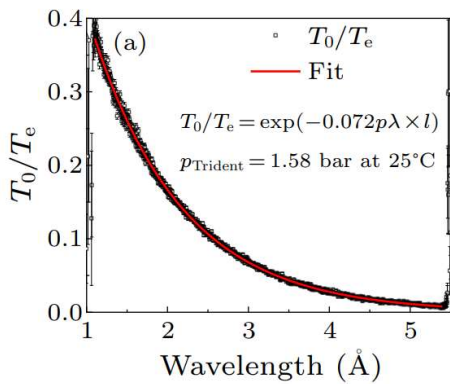
Flipping and Transfer polarized neutron
Reduce background

Calibration of polarization



- Cell quality assessment using TOF neutron and NMR method

Online benchmarking: Neutron transmission measurement at CSNS



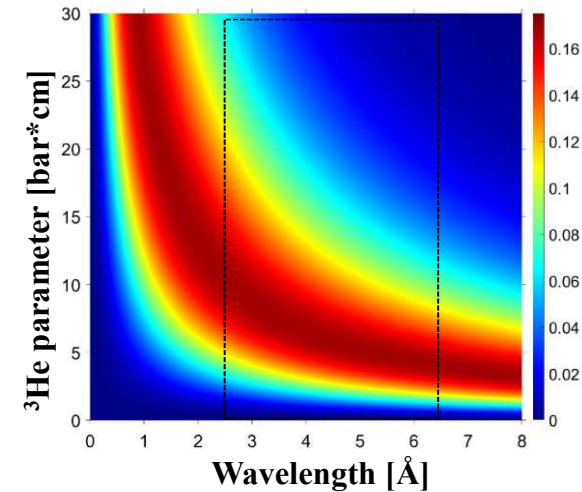
^3He gas pressure calibration

$$T_{\text{depol}}(\lambda)/T_0 = \exp(-0.072 P_{3\text{He}} \cdot l \cdot \lambda)$$

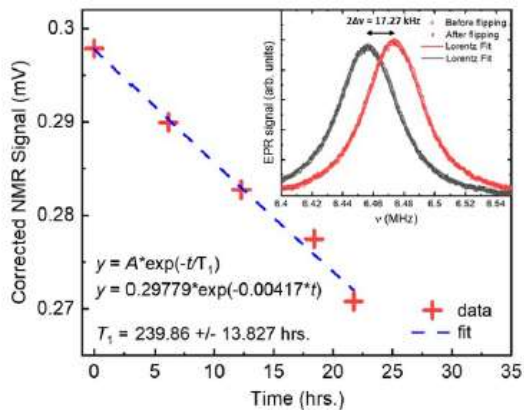
^3He polarization calibration

$$T_{\text{pol}}(\lambda)/T_{\text{depol}}(\lambda) = \cosh(0.072 P_{3\text{He}} \cdot l \cdot \lambda \cdot P_{3\text{He}})$$

^3He filter parameter



Offline benchmarking: FID and EPR measurement



$$P_{3\text{He}} = \frac{\Delta\nu}{\text{kHz}} \cdot \frac{\text{Amagat}}{1.13 \times \kappa_{\text{eff}}[\text{He}]}$$

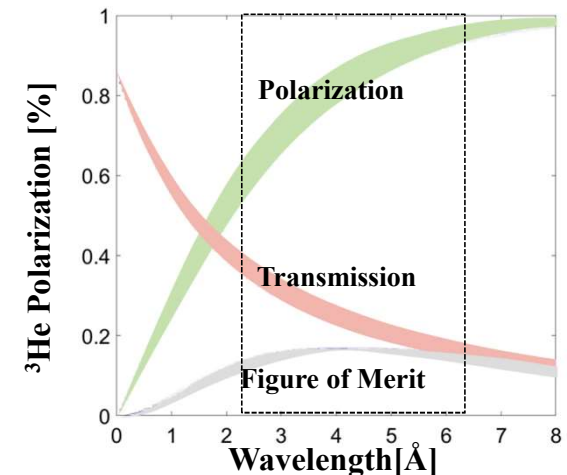
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κ_{eff} : frequency shift coefficient (6.2)

[He]: ^3He gas density

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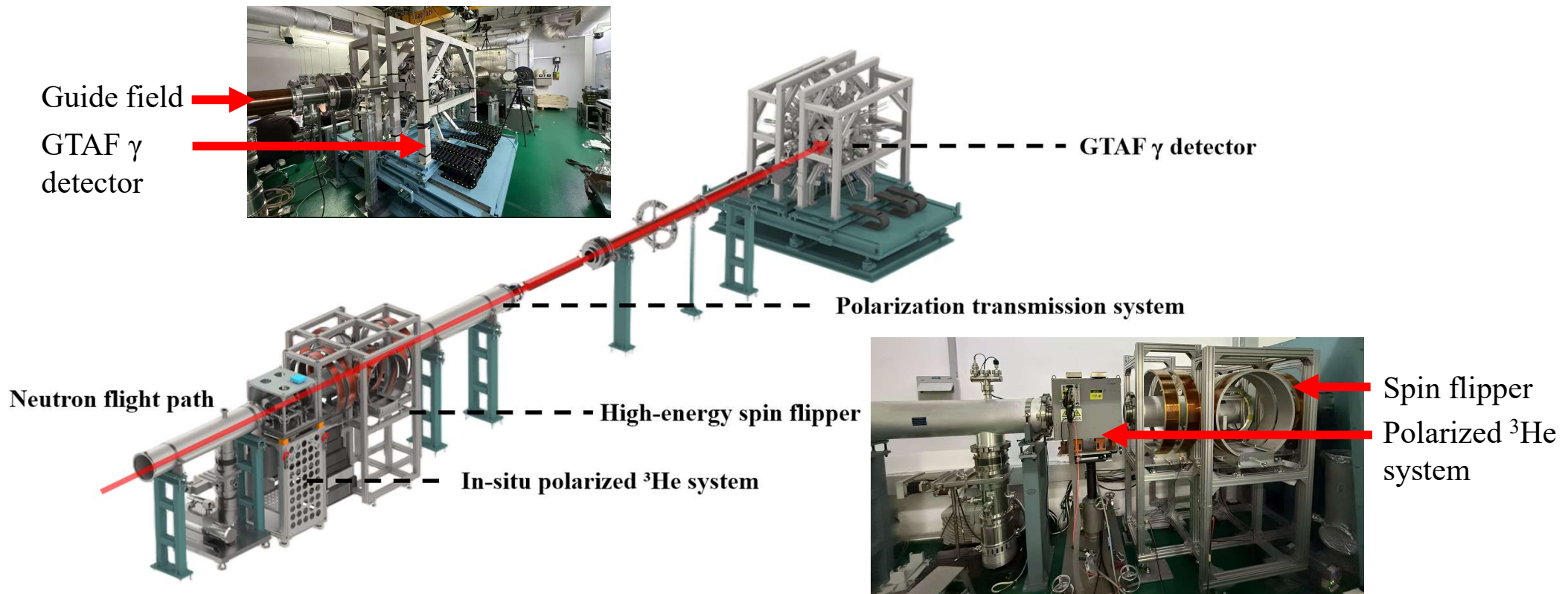
❖ J.P. Zhang, *et al.*; *Sci China Phys Mech*, 65 (2022).



Making NOPTREX f_2 measurement



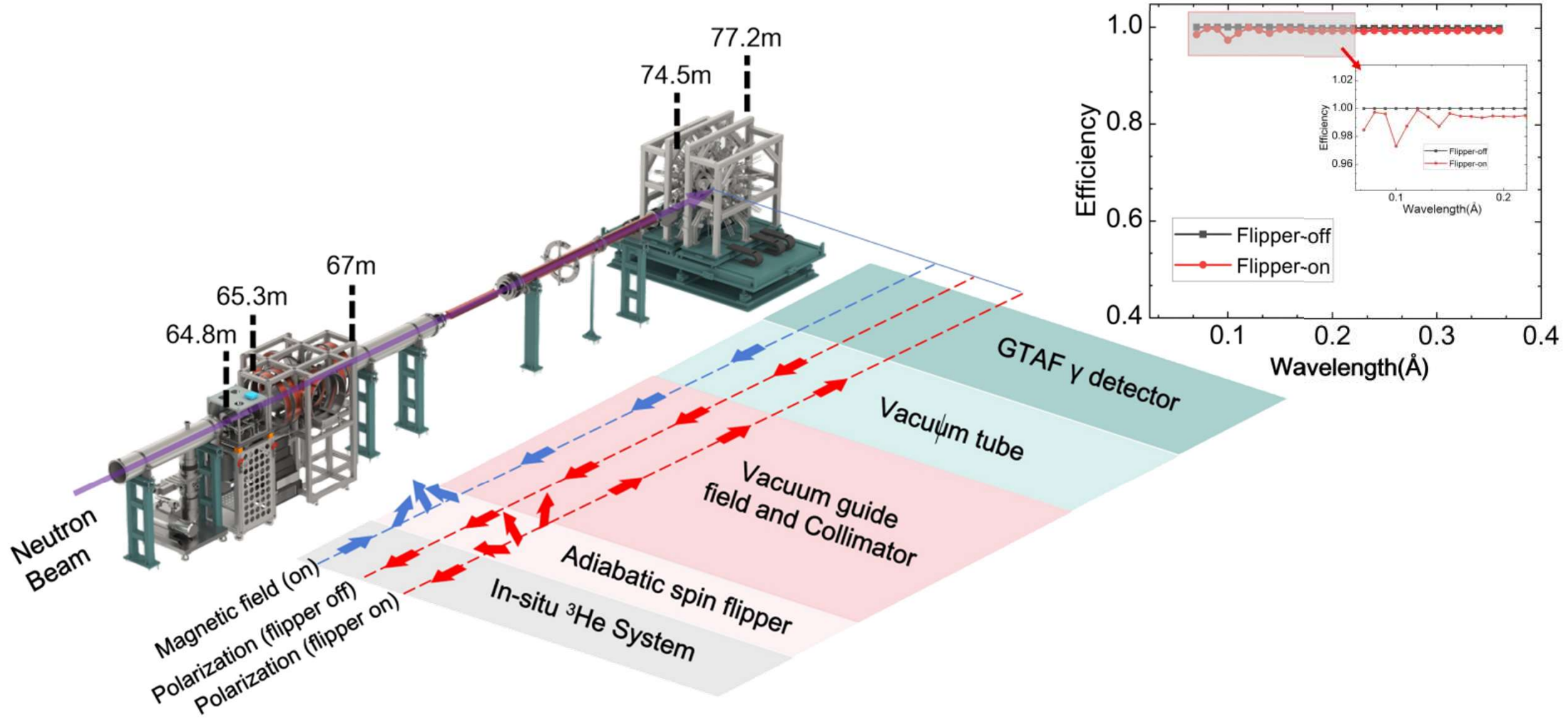
- The high-energy polarized neutron control system consists of in-situ ^3He , a high-energy neutron spin flipper, and a guide field.



Polarization Transfer design



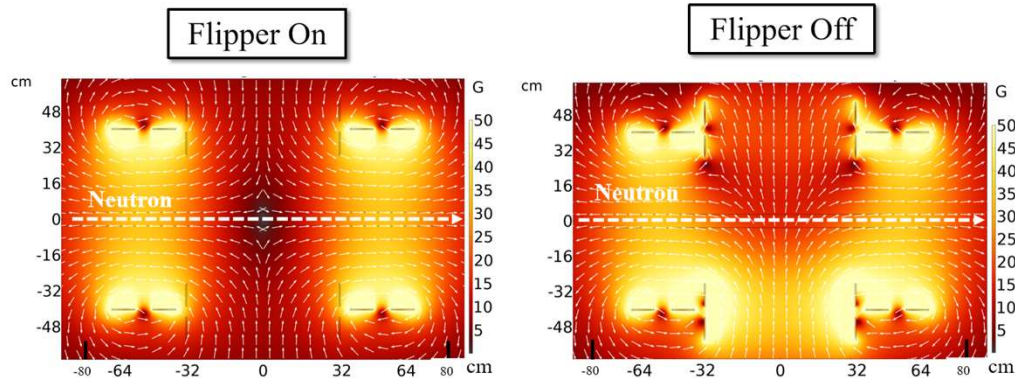
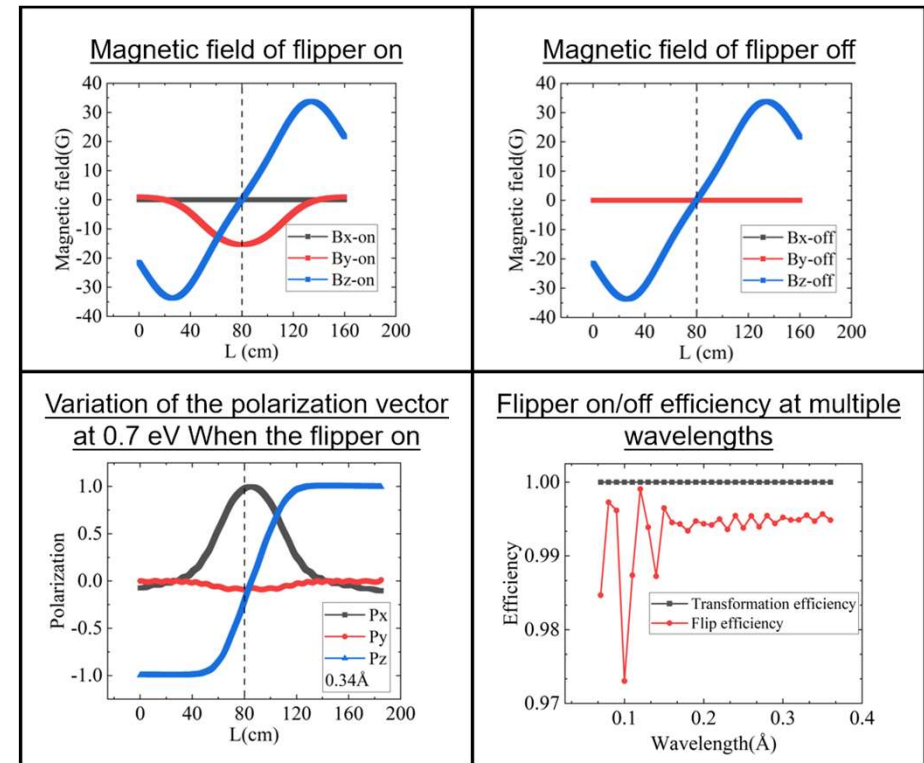
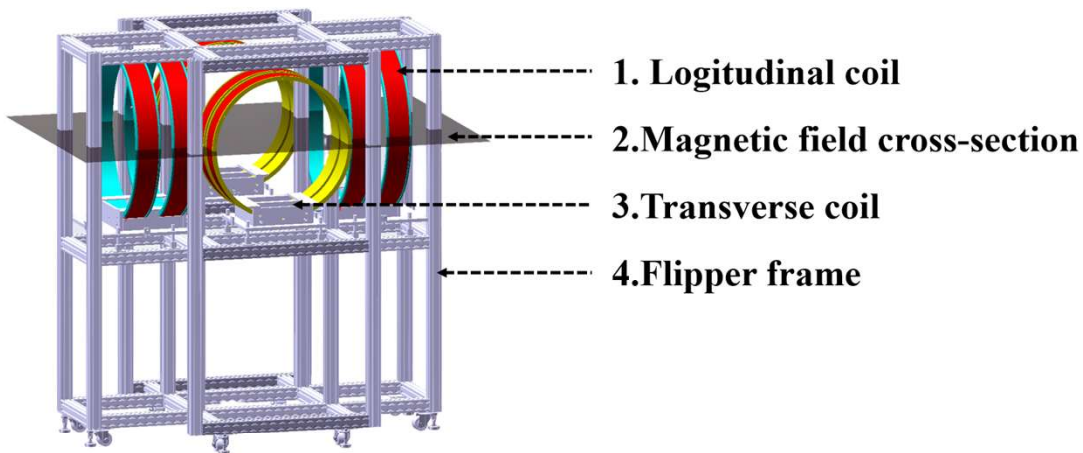
Flipping and Transfer polarized neutron in a controlled manner



Flipper Magnetic Field Design



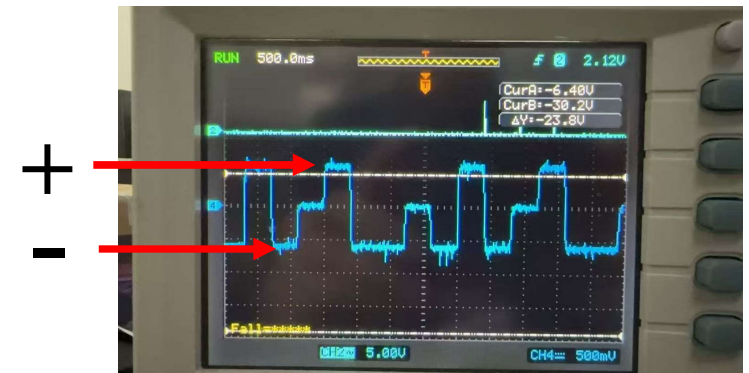
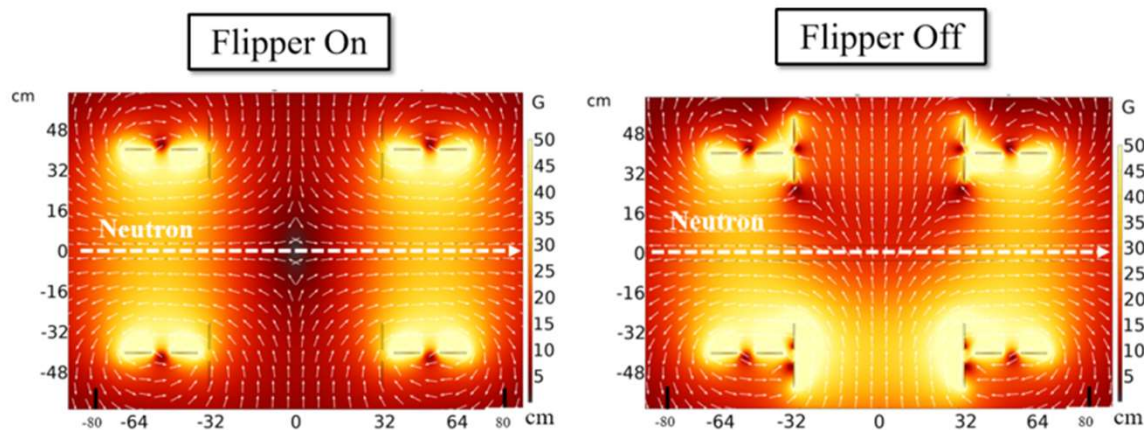
- Main Structure and Magnetic Field Distribution of the Spin Flipper
- Precise zero magnetic field control required (0.1mm for 3mm beamsize)



Spin flipper circuit design



- A special cycle is used to eliminate magnetic field asymmetry effects and detector thermal drift errors.
- Optimized circuit design changes the spin flipper operating state every 10 pulses (0.4 s).



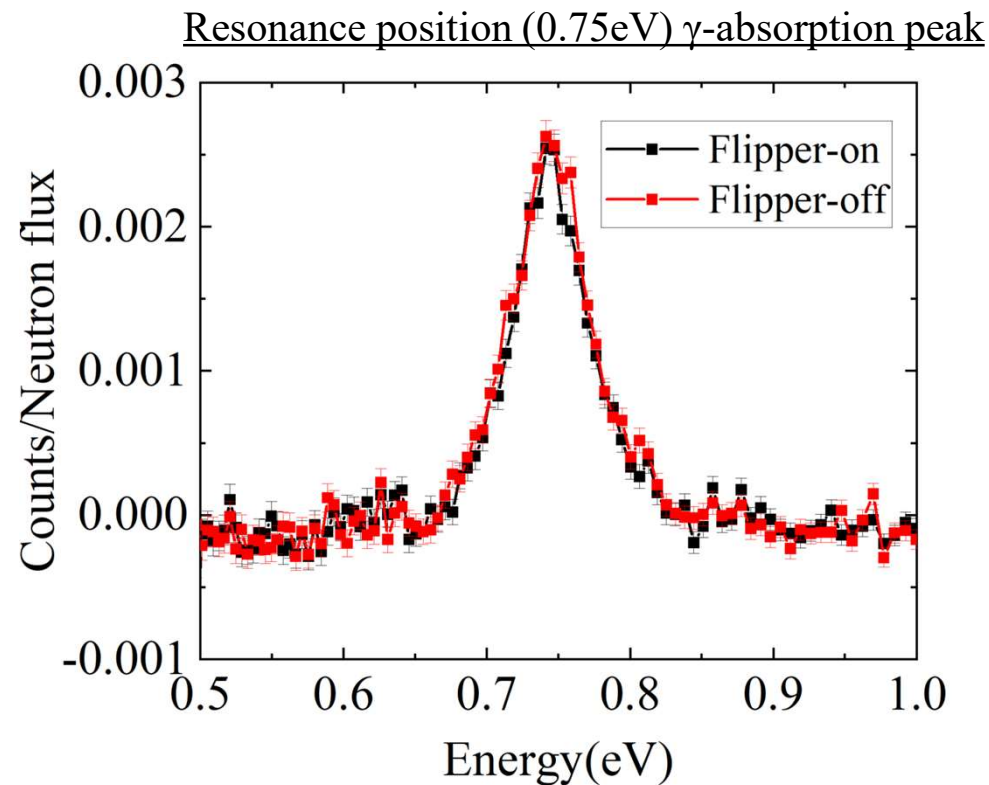
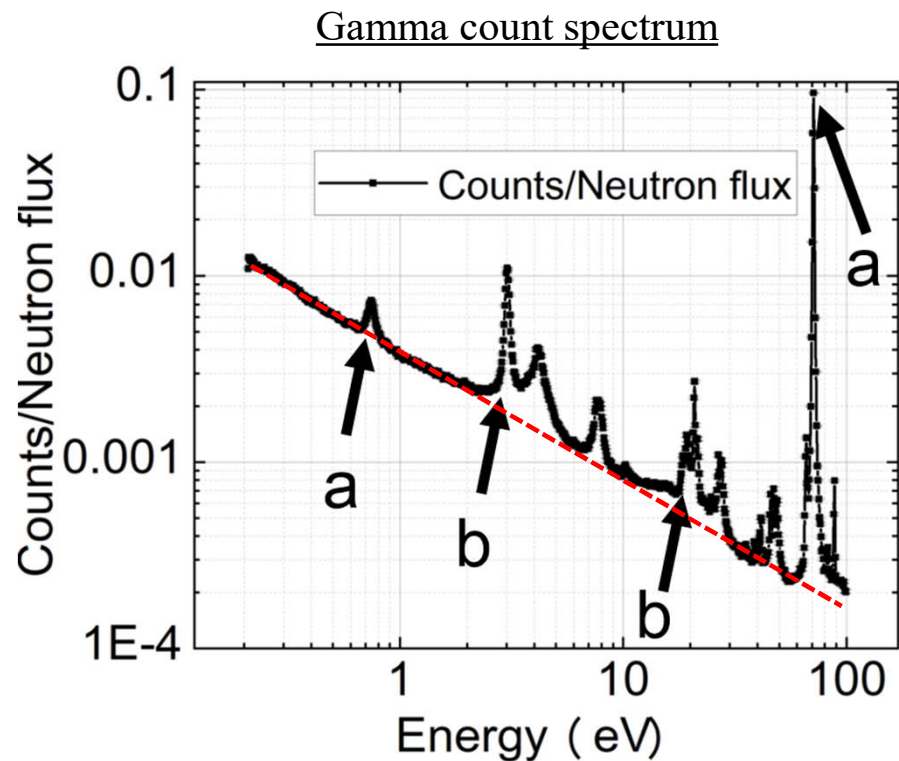
feedback signal for the operating status of the flipper

Experiment results



NOPTREX f_2 term measurement

- Clean $1/v$ dependence background with easy to identify resonating peak
- Stable and repeatable Asymmetry acquired along with

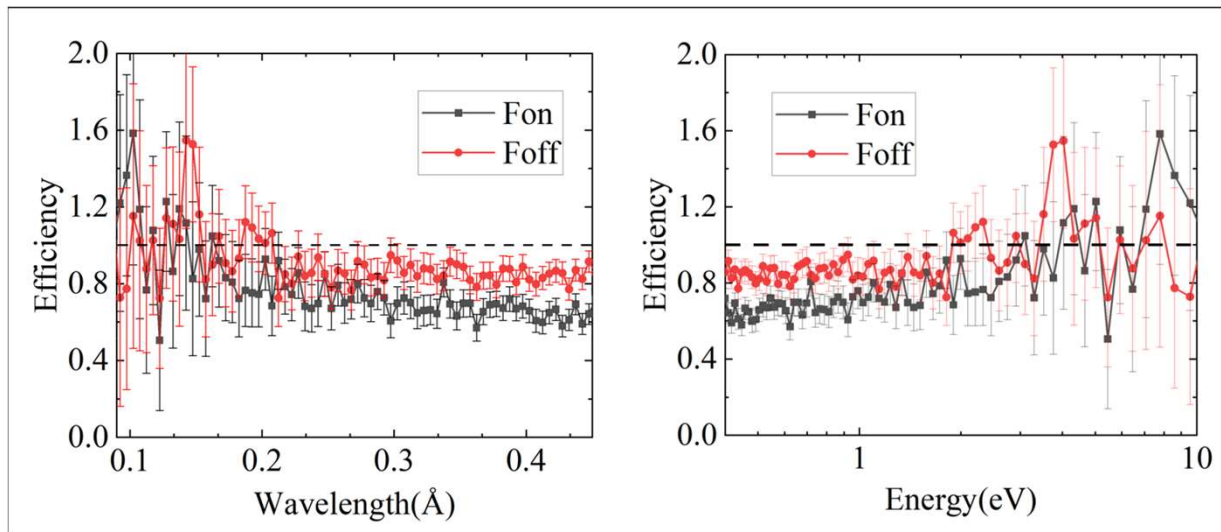


(a) La^{139} resonance at 0.75eV and 71eV; (b) La^{138} resonance at 3eV and 21eV

Experiment results



- Calibration of Spin Flipper Transmission and Efficiency at Different Energies Enables Measurement of Additional Elements



Calibration through 4 Spin flip measurements

$$M_{1,2} = \frac{1}{4}(1 \pm a\epsilon p)T_0T_aT_{\text{trans},\epsilon}T_p,$$

$$M_{3,4} = \frac{1}{4}(1 \mp a\epsilon p)T_0T_aT_{\text{trans},\epsilon}T_p.$$

Extract exact polarization transfer efficiency

$$\epsilon_{\text{off}} = \frac{(M_1 - M_2)/(M_1 + M_2)}{AP},$$

$$\epsilon_{\text{on}} = \frac{(M_4 - M_3)/(M_4 + M_3)}{AP}.$$

Neutron transmission and spin flipping efficiency at different energies of the flipper

Summary and Acknowledgement



- ❑ **NOPTREX provides an alternative and effective way to measure time-reversal asymmetry through polarized neutron and polarized nuclei.**
- ❑ **First step of NOPTREX at CSNS done, still much to be developed and learned.**
- ❑ **NOPTREX China collaboration**
 - ❑ Polarized Neutron: Xin Tong, Tianhao Wang, Junpei Zhang, Xu Qin
 - ❑ Back-n Beamline: Ruirui Fan, Yongjia Lv, You Lv, Wei Jiang, Kang Sun, Mofan Zhang
 - ❑ CIAE GTAF team: Guangyuan Luan, Qiwei Zhang, Xichao Ruan, Hongyi Wu
 - ❑ Indiana University: M. W. Snow, Sepehr Samineei

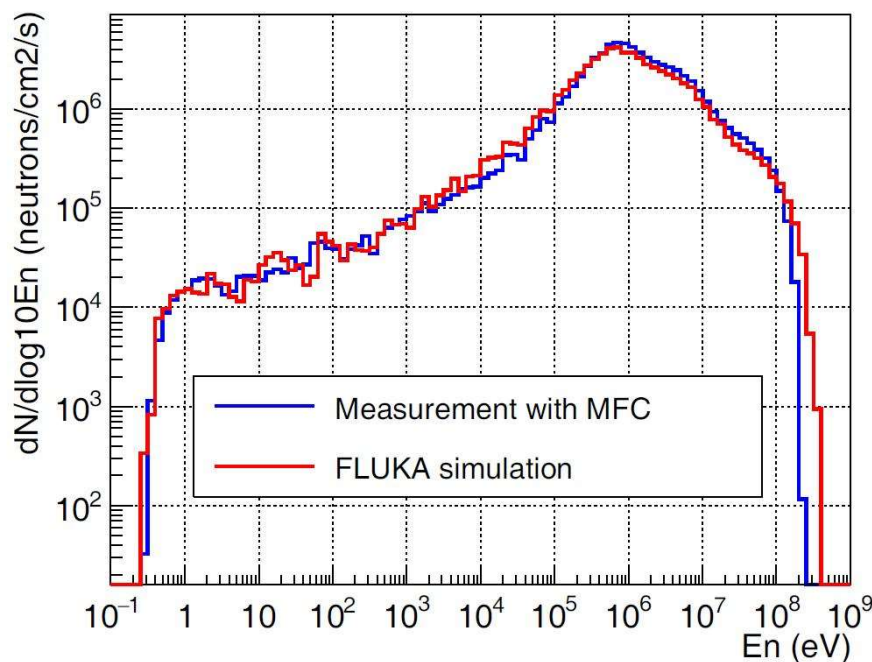
• *Thankyou for your attention*

Backup: Back-n and GTAF



- 与J-PARC束流相比在高中能中子注量有着明显优势，在全球范围内稀少的超长中子飞行距离束线
- CSNS 1.6 GeV质子与钨靶散裂反应，180° 方向出射的中子

• 能量



10⁷ n/cm²/s (100kW 实验厅 中子能量范围) 通量 (neutrons/cm²/s)

0.1-1 eV	4.08×10^3
1-10 eV	1.79×10^4
10-100 eV	3.01×10^4
0.1-1 keV	5.01×10^4
1-10 keV	1.23×10^5
10-100 keV	4.30×10^5
0.1-1 MeV	2.98×10^6
1-10 MeV	2.77×10^6
10-200 MeV	6.21×10^5
Total	7.03×10^6

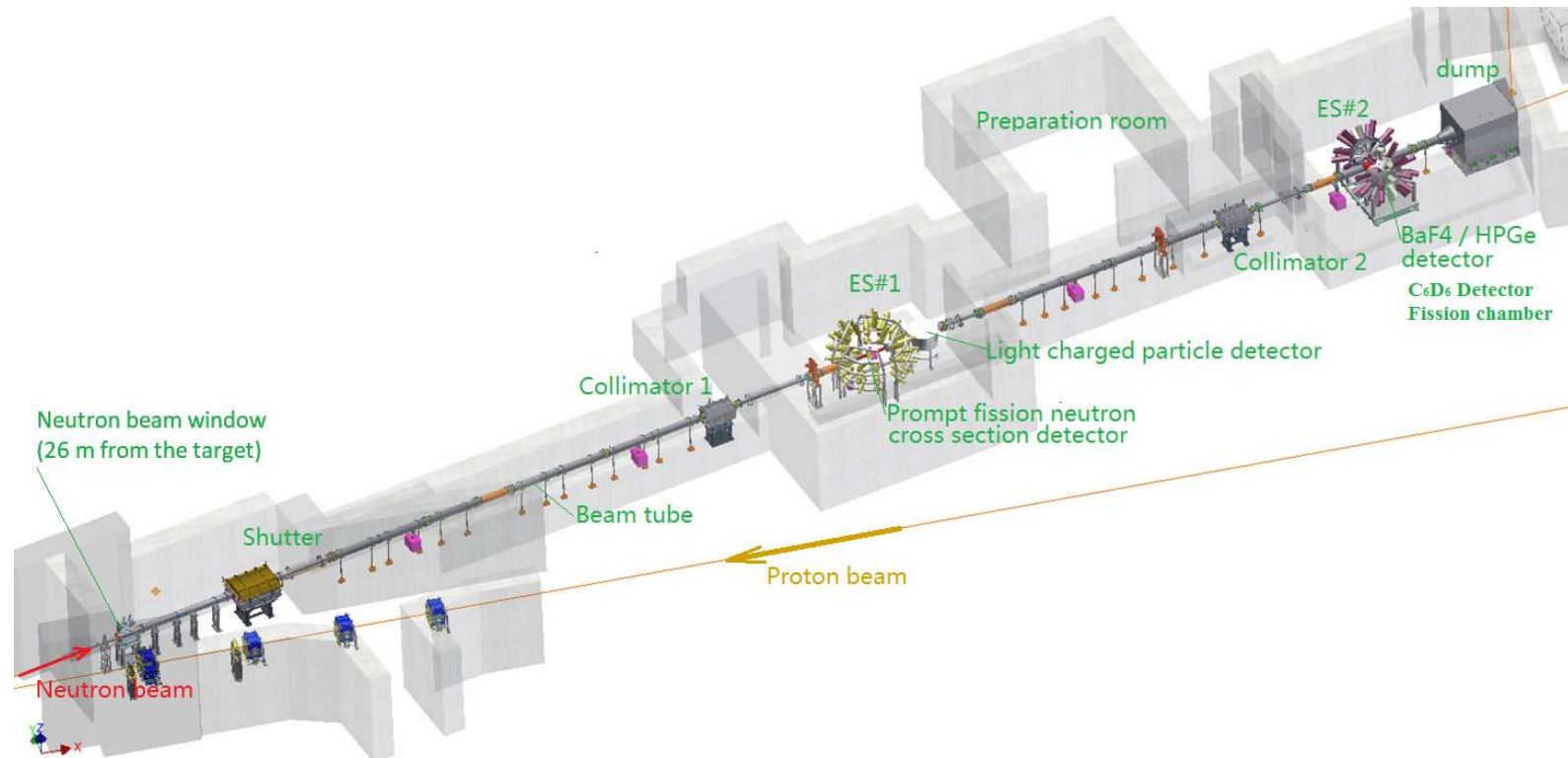
Back-n厅2(#ES2) 注量

Backup: Back-n and GTAF

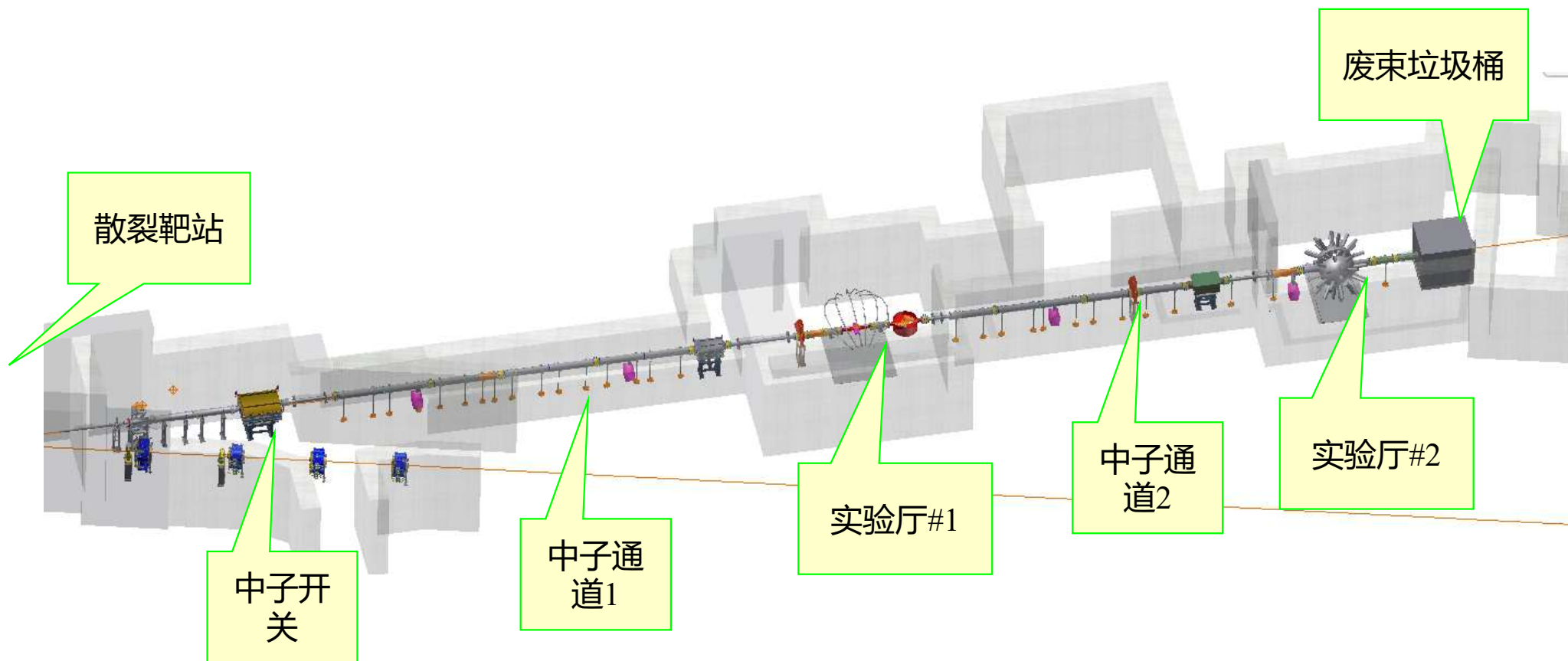


Back-n White Neutron Source

质子打靶能量	100 kW
脉冲频率	25 Hz
中子通量	$10^4 - 10^7$ n/cm ²
ES #1 中子飞行距离	54m
ES #2中子飞行距离	75m



Backup: Back-n and GTAF

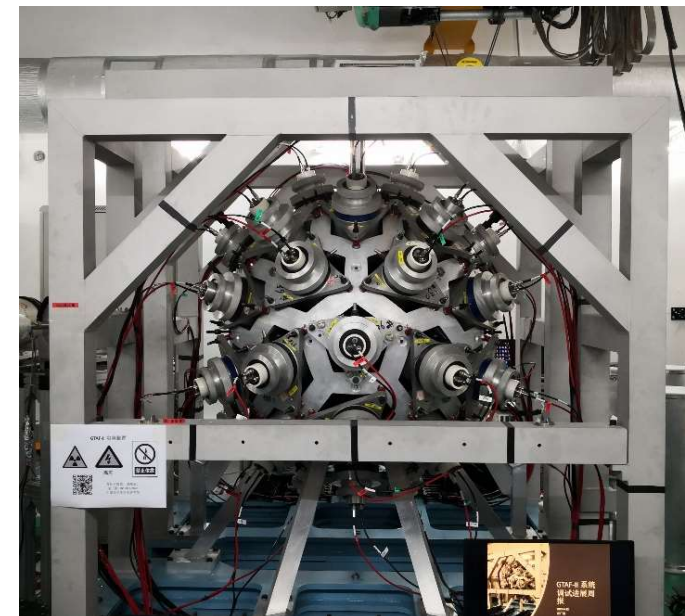
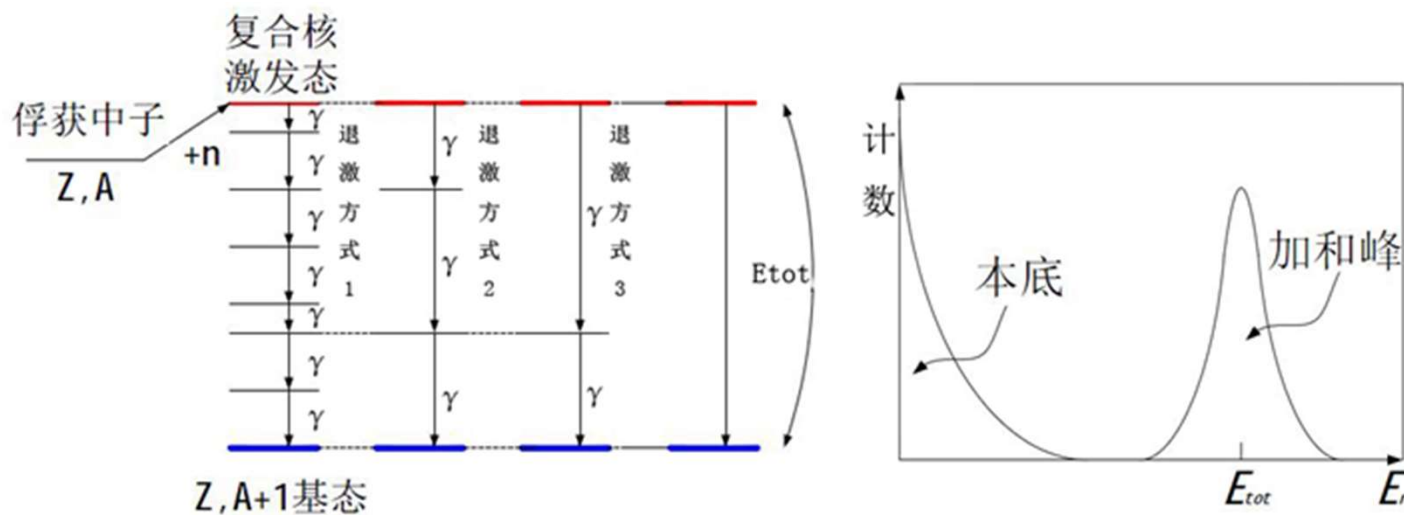


Backup: Back-n and GTAF



全吸收型 γ 射线探测系统

Gamma Total Absorption Facility, 是一种能够接近 4π 全立体角方向伽玛全收集的测量装置。利用瞬发 γ 射线法测量 (n,γ) 反应截面数据。

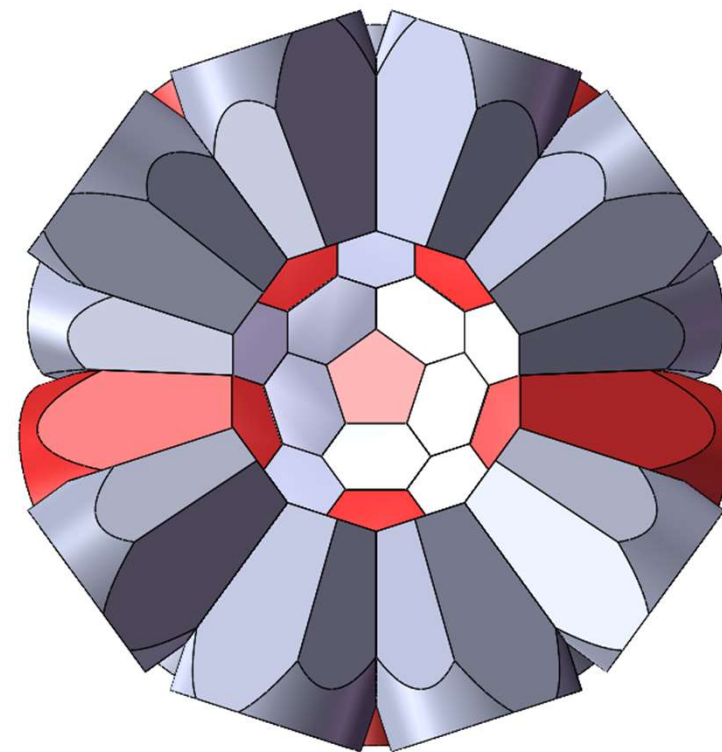
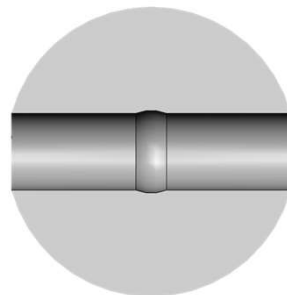


- 相对于缓发 γ 测量法, 瞬发 γ 射线法可以测量终态核半衰期较短的俘获反应;
- 在针对稀有样品、放射性样品及小反应截面样品的测量中具有突出优势。

BaF₂晶体探测器:
较高的能量分辨;
较好的时间分辨;
较低的中子灵敏度;
接近100%的 γ 探测效率。

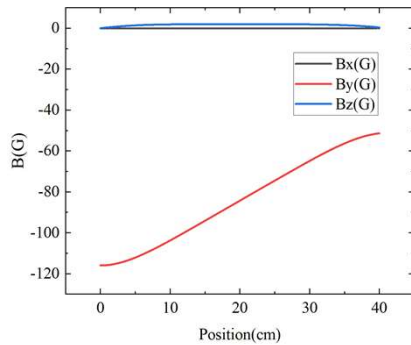
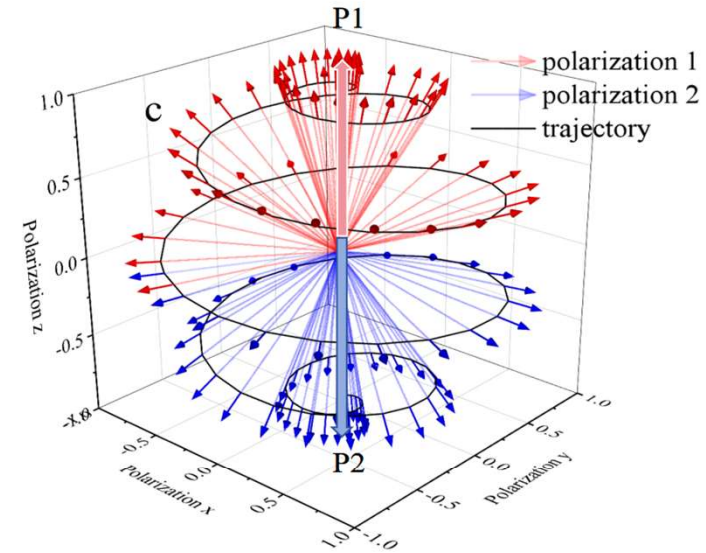
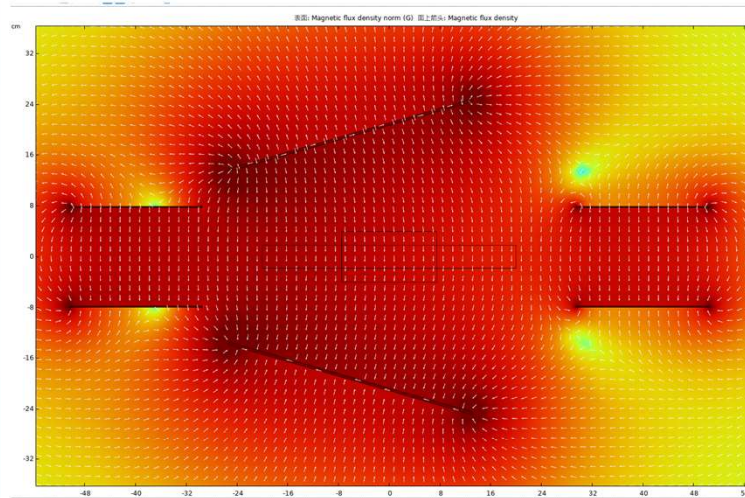
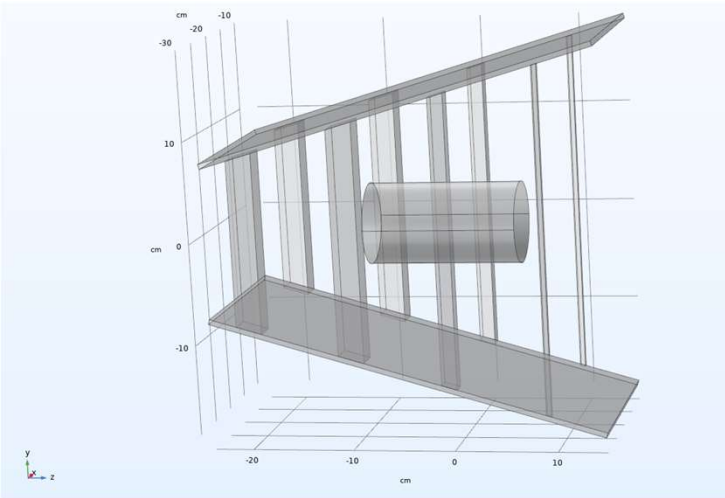
GTAF-II BaF₂探测器阵列

- 42 部分 (其中40个有晶体探测器)
 - 2种不同的晶体形状
 - 内径 = 10cm
 - 晶体深度 = 15cm
- 含硼聚乙烯中子吸收体
 - 最大厚度 \approx 7cm
- 类比装置:
 - LANL DANCE
 - CERN n_TOF TAC
 - Karlsruhe 4π BaF₂

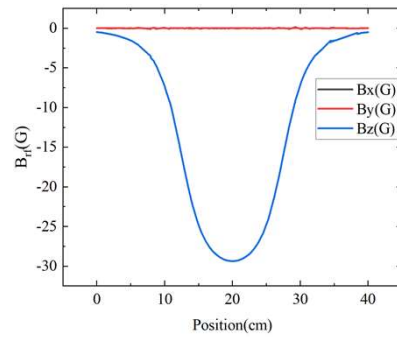


Other Choice: RF flipping

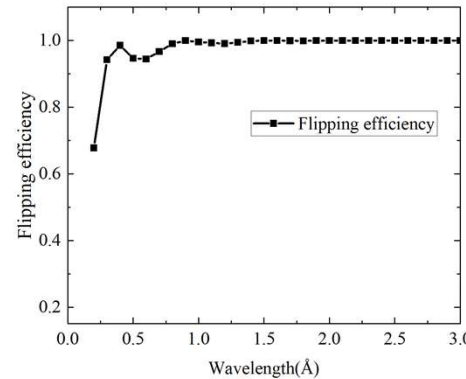
- Pushing the boundary for RF-flipper to eV neutron



One-dimensional gradient magnetic field distribution



One-dimensional RF magnetic field distribution



Simulation results of flipping efficiency at different wavelengths

2 meter long with 200W of RF magnetic field

Too much interference

Not enough space