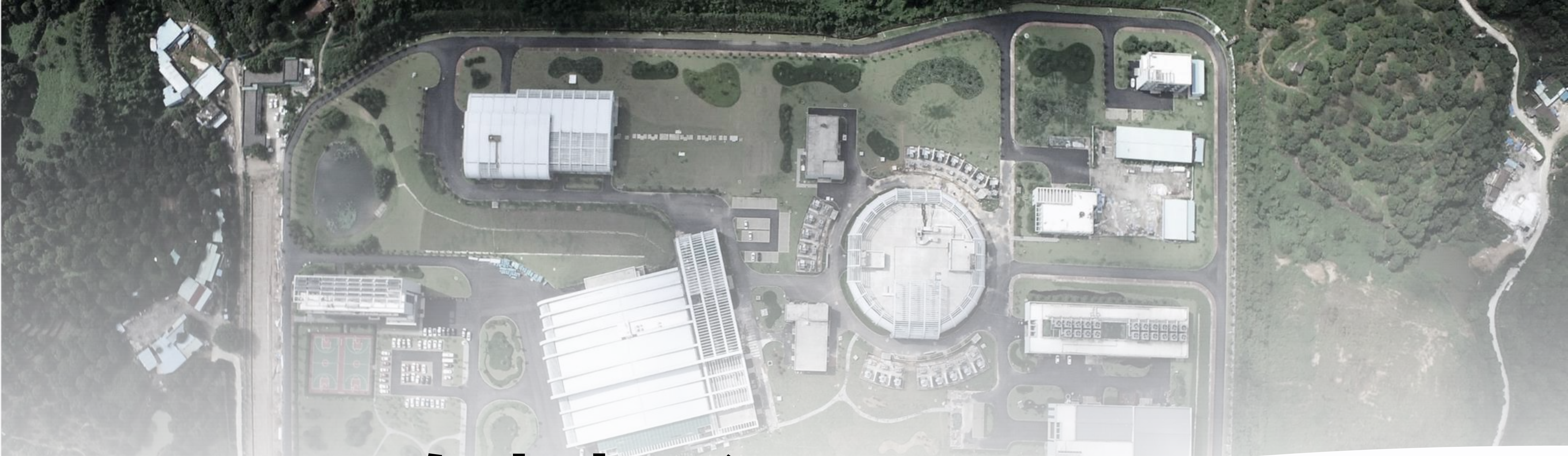


2025-2026 白光中子源 NOPTREX 宇称不守恒实验进展

张墨凡

散裂中子源科学中心

背景

为什么我们需要找寻时间反演对称性破缺?

萨哈罗夫于1967年提出了宇宙中产生**正反物质不对称**的三个基本达成条件:

1. 重子数不守恒
2. **C对称和CP对称的破坏 (即时间反演对称性破缺)**
3. 在热力学平衡之外的相互作用

需要新的标准模型以外的CP/T对称性破缺来解释现在观测到的宇宙中正反物质不对称的现象

⇒

复合核中子共振核反应是寻找对称性破缺的一个可能的渠道

NOPTREX合作组

NOPTREX
Neutron Optical Parity and Time-Reversal EXperiment

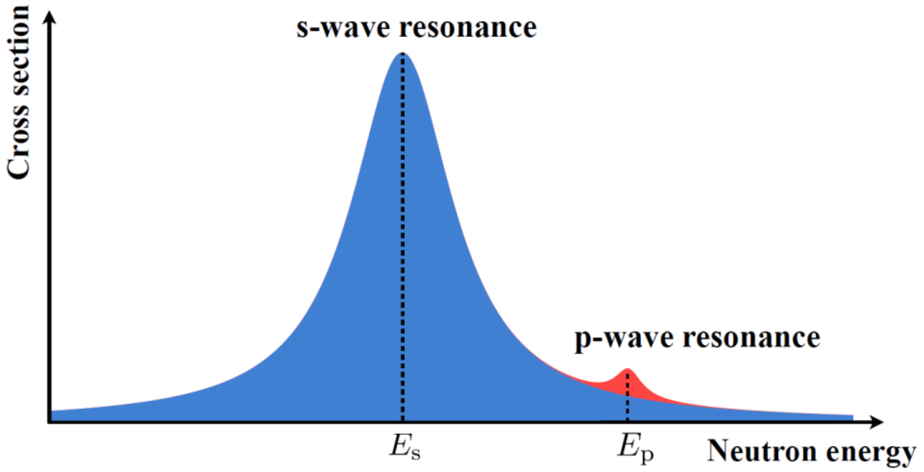
- Neutron Optics Parity and Time Reversal Experiment (NOPTREX)
- 目标：在极化中子透射核共振反应中探索宇称和时间反演对称性破缺

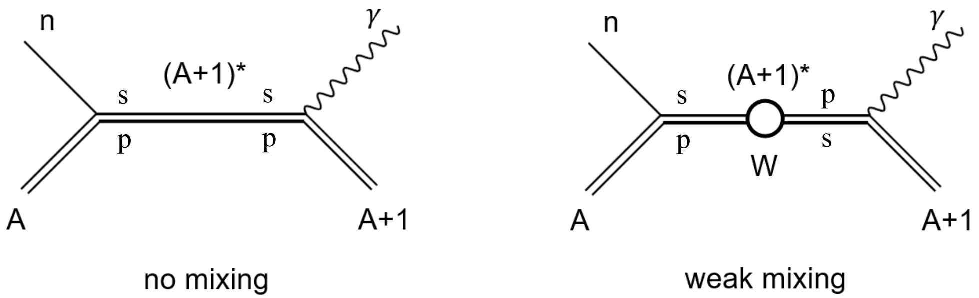
复合核中子共振核反应中对P与T对称性破缺的放大效应

T-破缺还未在中子核反应中被观测到!

⇒ 在重核中的p波共振峰对于时间反演不对称测量是此类观测中的灵敏体系[1].

⇒ P- 和 T-对称性破缺效应会通过弱相互作用力的s波p波混合放大约 $10^4 - 10^6$ [2].

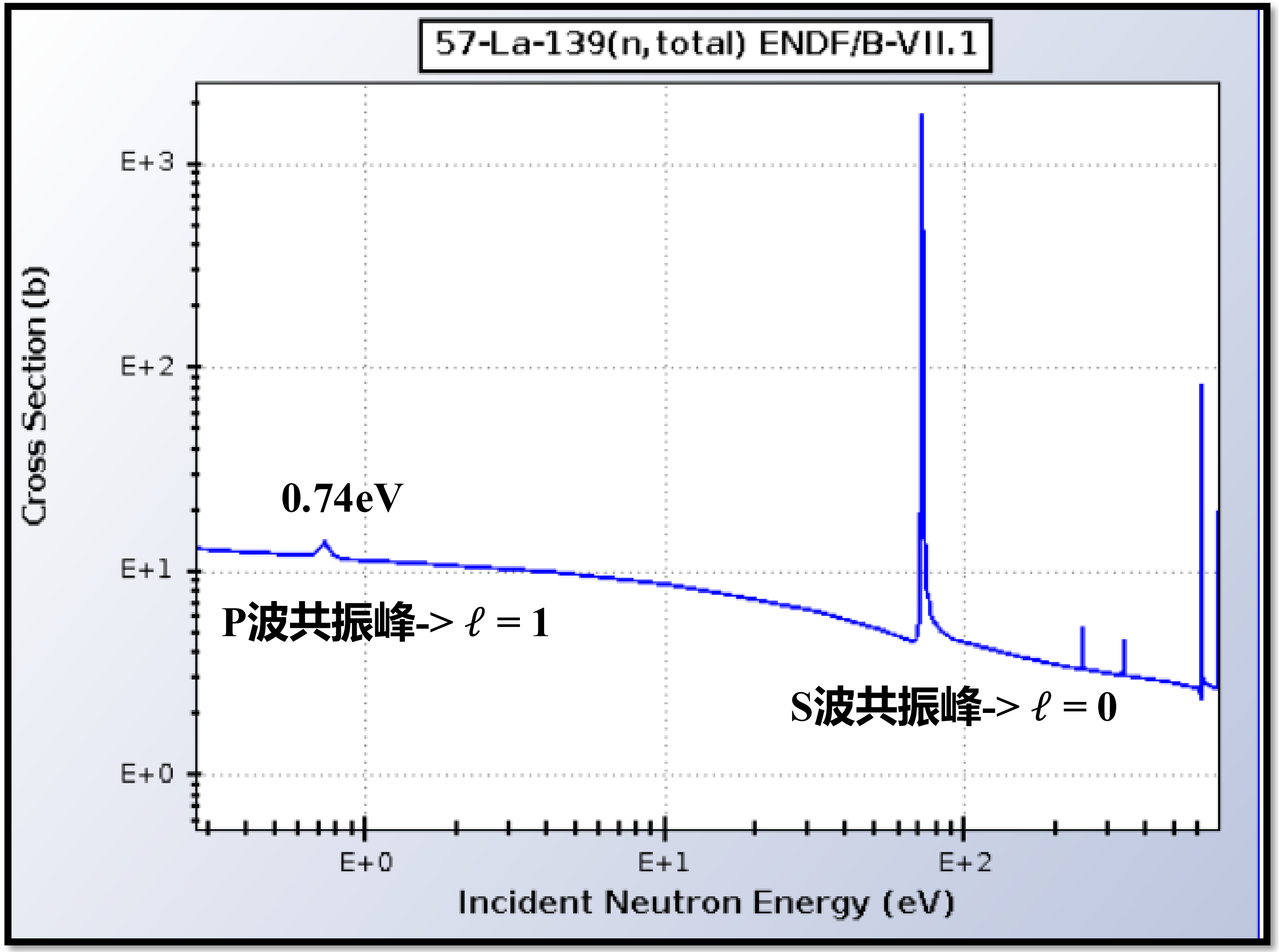


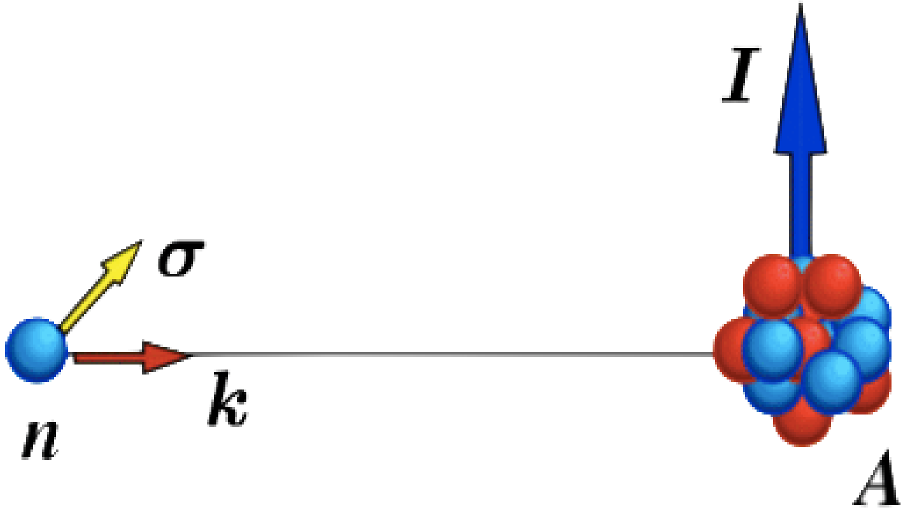


(n, γ) 反应道的sp-混合费曼图

1. Gudkov, Phys. Rep. **212** 77 (1992)
2. V.V.FLAMBAUM and G.F.GRIBAIUN, Prog. Part. Nucl. Phys., Vol. 35, pp. 423-503.1995

S波与P波共振峰





总角动量 轨道角动量 中子自旋 核自旋

$$J = \underbrace{\ell + s}_{j} + I, \quad S = s + I$$

入射中子自旋 j 　 S 反应通道自旋

正向散射振幅

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

f_0=P-even, T-even Spin Independent

f_1=P-even, T-even Spin Independent (pseudomagnetic)

f_2=P-odd, T-even P-violation

f_3=P-odd, T-odd TP-violation

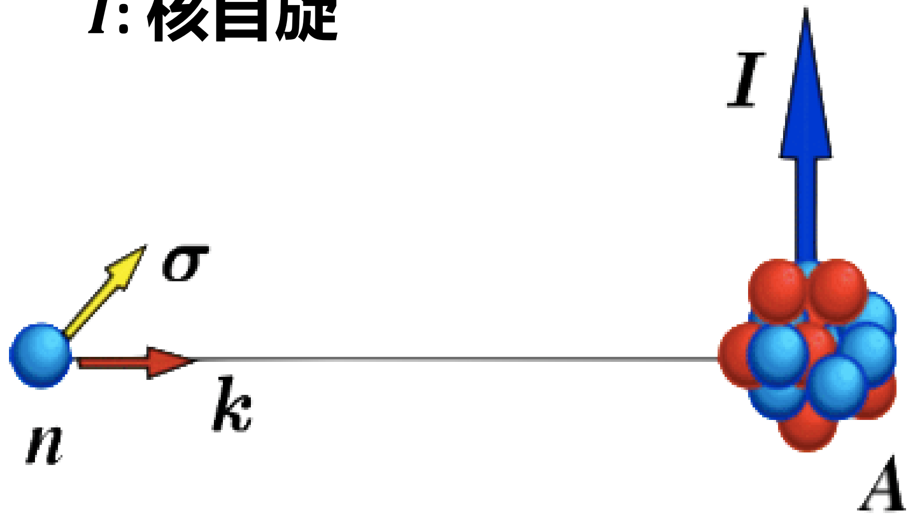
f_4=P-even, T-odd T-violation

（f_2–f_4）我们最感兴趣的项

$\vec{k}_n$: 中子动量

$\vec{\sigma}_n$: 中子自旋

$\vec{I}$: 核自旋



P-odd/T-odd 反应理论

依据中子光学理论，我们可以将前向散射振幅关联到总截面上

$$\sigma_{tot} = \frac{4\pi}{k}\mathrm{Im}[f(0)]$$

前向散射振幅描述了初态与末态如何通过弱相互作用势相互关联

$$f = \langle f|V_P + V_{PT}|i\rangle$$

其中 v 和 w 即为我们的弱混合矩阵元:

$$v + iw = \langle \phi_p|V_P + V_{PT}|\phi_s\rangle$$

于是可以将P-odd, T-odd 项与P-odd, T-even 项联系起来:

$$\frac{\Delta\sigma_{TP}}{\Delta\sigma_P} = \kappa(J)\frac{w}{v} \quad [1]$$

- TRIPLE Collaboration work: G. M. Mitchell et. Al., Phys. Rep. 354, 157 (2001).;

Works done in J-PARC
139La: https://arxiv.org/abs/1710.03065
117Sn: https://arxiv.org/abs/2202.06222
131Xe: https://arxiv.org/abs/2212.10889

1. V. Gudkov & H.Shimizu Phys. Rev. C 97, 065502 (2018)

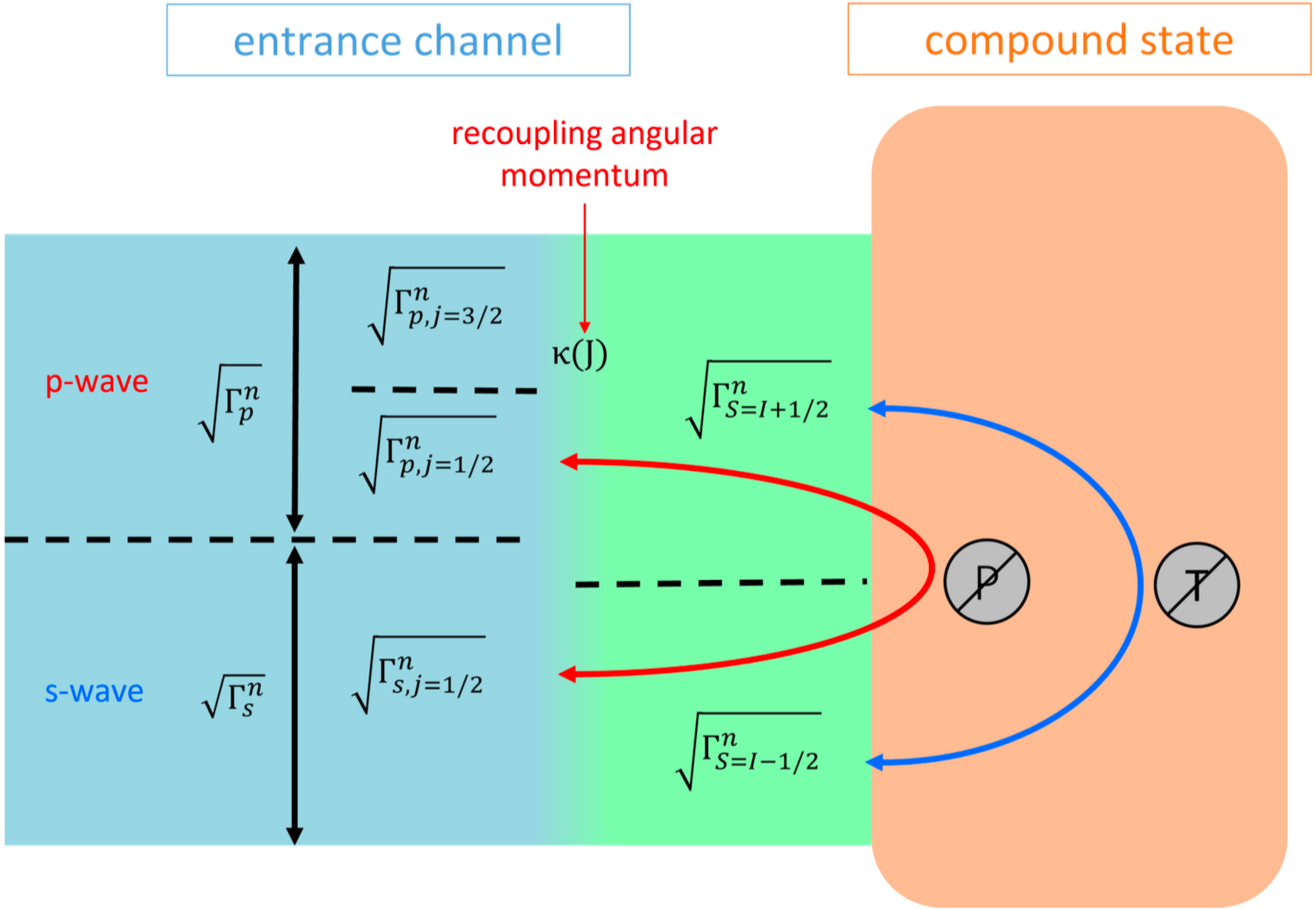


Figure 2.5: A schematic to demonstrate the connection between the neutron width of different j and S states and how they are connected through $\kappa(J)$.

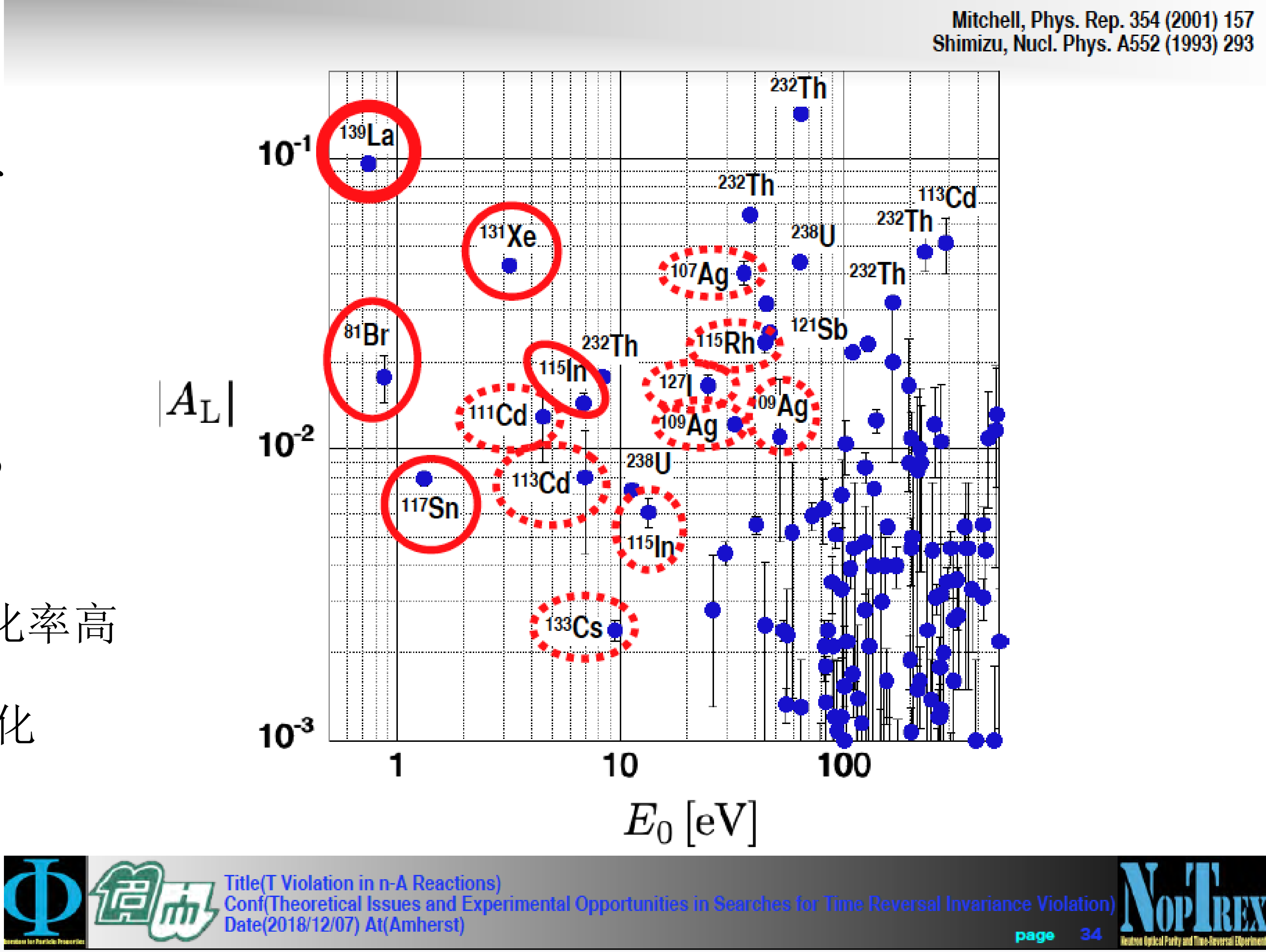
已测量的宇称不守恒

NOPTREX目标共振峰:

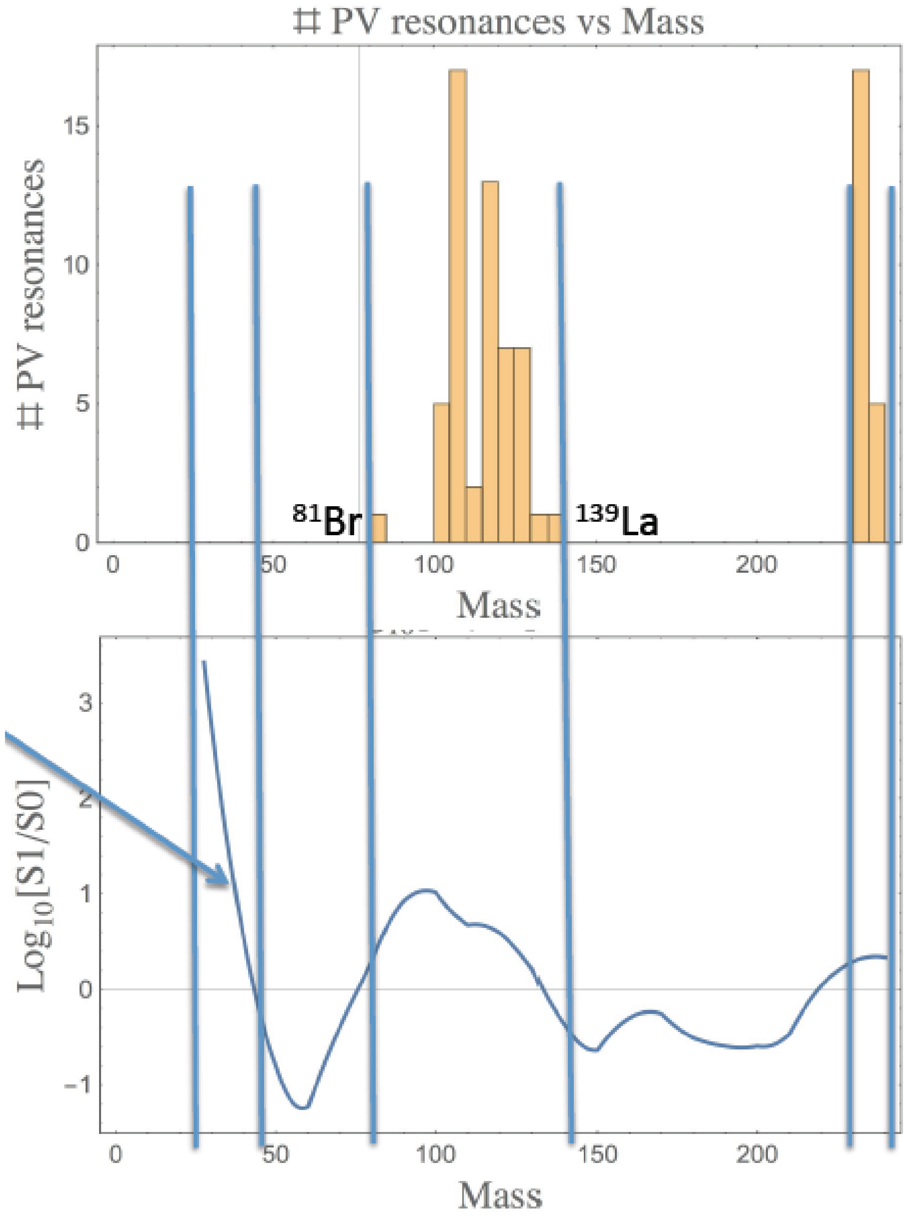
- $\Delta\sigma_P$ 大
- $\kappa(J)$ 大

} $\Delta\sigma_{TP}$大?

- 峰位能量低 -> 中子极化率高
- $I > 0$ 原子核可以被极化



PV resonances found by TRIPLE



TRIPLE:

- S1/S0在A=160处有局部极小值
- 140<A<180之间的核素无测量数据

NOPTREX:

- 该范围内有许多I>0核素：可用于T破坏实验的极化
- 需要尽可能多的p波

PV resonances occur If S1/S0 is between 1/3 and 10. The best TRIPLE resonances Have S1/S0 ~ 1

140<A<180之间呢?

S1/S0与以下核素相差不大

^{139}La, ^{81}Br, ^{131}Xe

只需一个发现

即可对NOPTREX有用

(n, γ) 微分截面(Flambaum terms)

$$\frac{d\sigma(\boldsymbol{n}_\gamma,\lambda)}{d\Omega}=\frac{1}{2}\{a_0+a_1(\boldsymbol{n}_n\cdot\boldsymbol{n}_\gamma)+\tilde{a}_2\boldsymbol{\sigma}\cdot[\boldsymbol{n}_n\times\boldsymbol{n}_\gamma]+a_3[(\boldsymbol{n}_n\cdot\boldsymbol{n}_\gamma)^2-\frac{1}{3}]$$
$$+\tilde{a}_4(\boldsymbol{n}_n\cdot\boldsymbol{n}_\gamma)\boldsymbol{\sigma}\cdot[\boldsymbol{n}_n\times\boldsymbol{n}_\gamma]+a_5\lambda(\boldsymbol{\sigma}\cdot\boldsymbol{n}_\gamma)+a_6\lambda(\boldsymbol{\sigma}\cdot\boldsymbol{n}_n)+a_7\lambda$$
$$\times[(\boldsymbol{\sigma}\cdot\boldsymbol{n}_\gamma)(\boldsymbol{n}_\gamma\cdot\boldsymbol{n}_n)-\frac{1}{3}(\boldsymbol{\sigma}\cdot\boldsymbol{n}_n)]+a_8\lambda[(\boldsymbol{\sigma}\cdot\boldsymbol{n}_n)(\boldsymbol{n}_n\cdot\boldsymbol{n}_\gamma)-\frac{1}{3}(\boldsymbol{\sigma}\cdot\boldsymbol{n}_\gamma)]$$
$$+a_9(\boldsymbol{\sigma}\cdot\boldsymbol{n}_\gamma)+a_{10}(\boldsymbol{\sigma}\cdot\boldsymbol{n}_n)+a_{11}[(\boldsymbol{\sigma}\cdot\boldsymbol{n}_\gamma)(\boldsymbol{n}_\gamma\cdot\boldsymbol{n}_n)-\frac{1}{3}(\boldsymbol{\sigma}\cdot\boldsymbol{n}_n)]$$
$$+a_{12}[(\boldsymbol{\sigma}\cdot\boldsymbol{n}_n)(\boldsymbol{n}_n\cdot\boldsymbol{n}_\gamma)-\frac{1}{3}(\boldsymbol{\sigma}\cdot\boldsymbol{n}_\gamma)]+a_{13}\lambda+a_{14}\lambda(\boldsymbol{n}_n\cdot\boldsymbol{n}_\gamma)$$
$$+\tilde{a}_{15}\lambda\boldsymbol{\sigma}\cdot[\boldsymbol{n}_n\times\boldsymbol{n}_\gamma]+a_{16}\lambda[(\boldsymbol{n}_n\cdot\boldsymbol{n}_\gamma)^2-\frac{1}{3}]$$
$$+\tilde{a}_{17}\lambda(\boldsymbol{n}_n\cdot\boldsymbol{n}_\gamma)\boldsymbol{\sigma}\cdot[\boldsymbol{n}_n\times\boldsymbol{n}_\gamma]\}.$$

$\vec{\sigma}$: 中子极化
$\vec{n}_n$: 中子动量
$\vec{n}_\gamma$: γ-动量
λ : γ-偏振

If $\vec{\sigma}=0$, and λ not measured:

$$\frac{d\sigma(n_\gamma,\lambda)}{d\Omega}\propto a_0+a_1 cos(\theta)+a_3[cos^2(\theta)-\frac{1}{3}]$$

$\kappa(J)$

If $\vec{\sigma}=\pm\vec{n}_n$, and λ not measured:

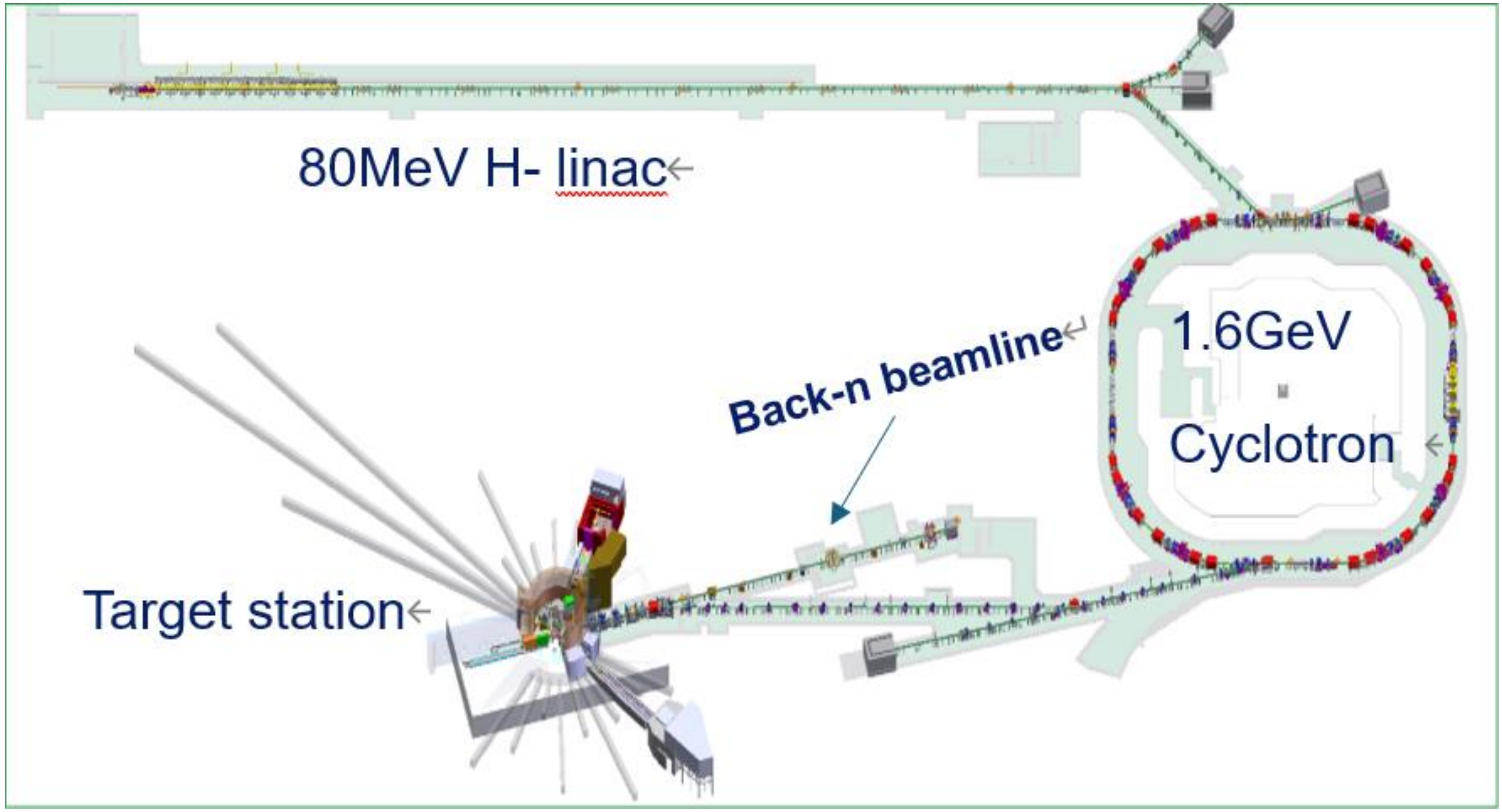
$$\frac{d\sigma(n_\gamma,\lambda)}{d\Omega}=\frac{1}{2}(a_0\pm a_{10}) \longrightarrow \frac{a_{10}}{a_0}=A_L=\frac{\sigma_+-\sigma_-}{\sigma_++\sigma_-}$$

Flambaum et. al., Prog. Part, Nncl Phys., Vol. 35, pp. 423-503.1995

装置与仪器

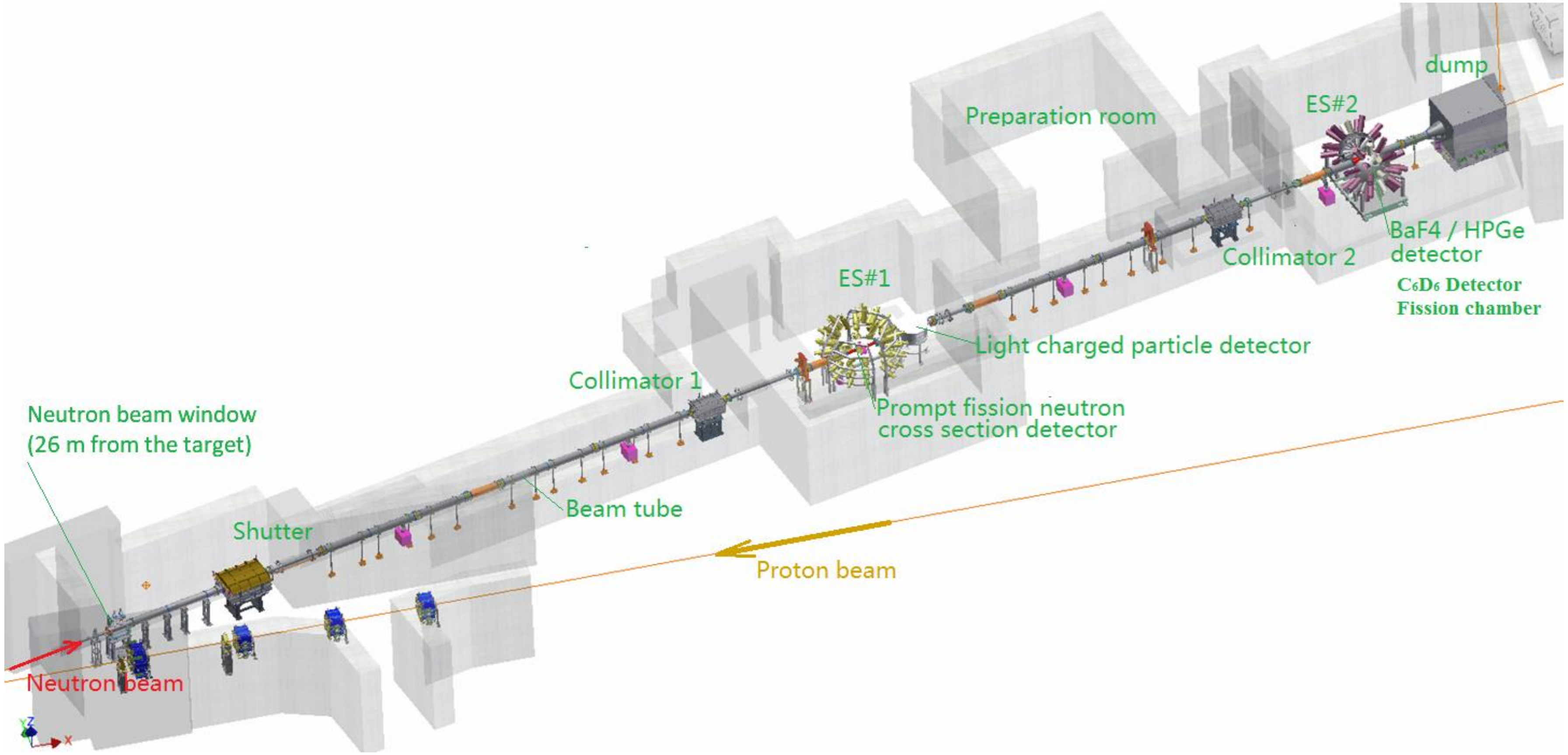
China Spallation Neutron Source

Key Parameters	Phase 1	Phase 2
Proton beam power	100 kW	500 kW
Pulse Frequency	25 Hz	25 Hz
Average beam flux	62.5 μA	312 μA
Number of spectrometers	3	9+6



Back-n White Neutron Source

Proton beam power	**100 kW**
Pulse frequency	**25 Hz**
Neutron flux	**10^4 -10^7 n/cm2**
ES #1 flight path	**54m**
ES #2 flight path	**75m**



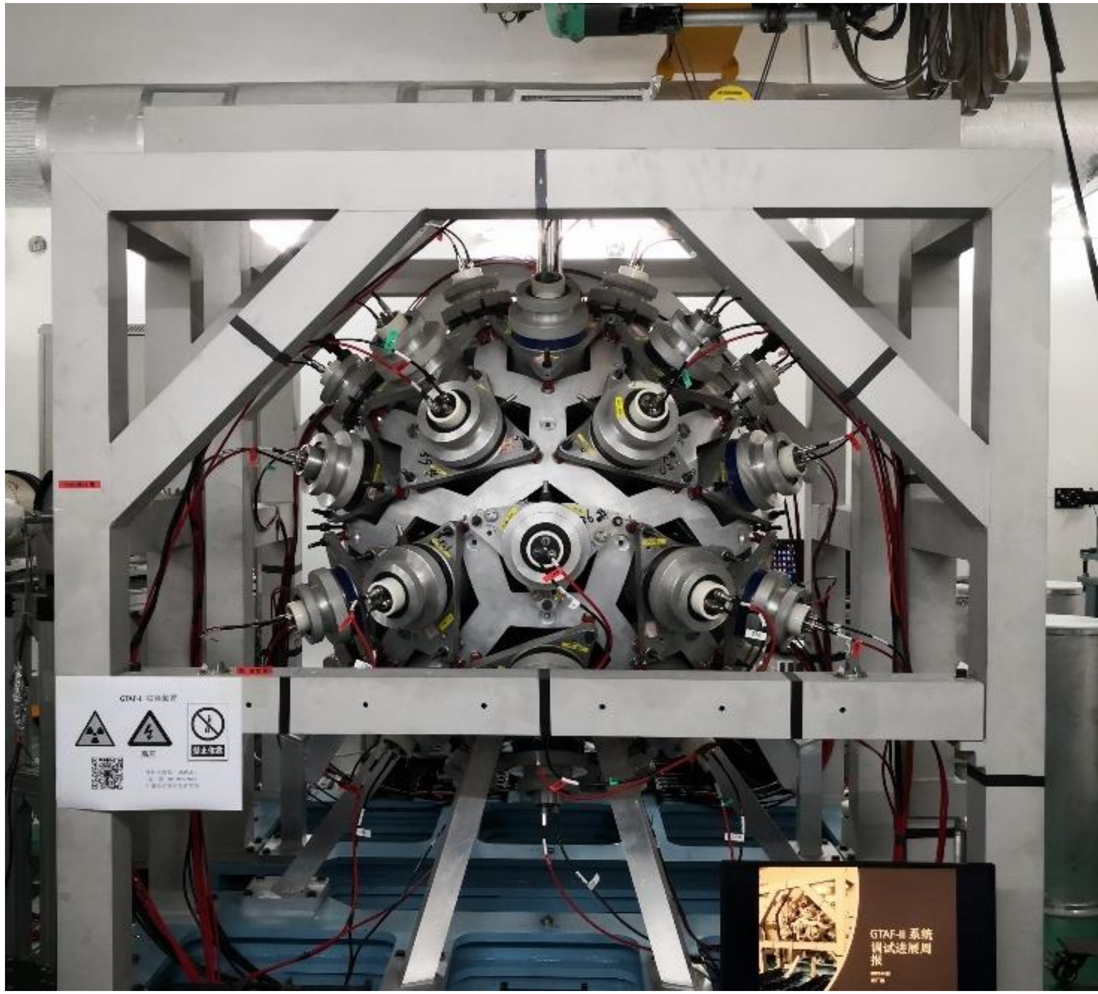
GTAF BaF_2 γ-spectrometer

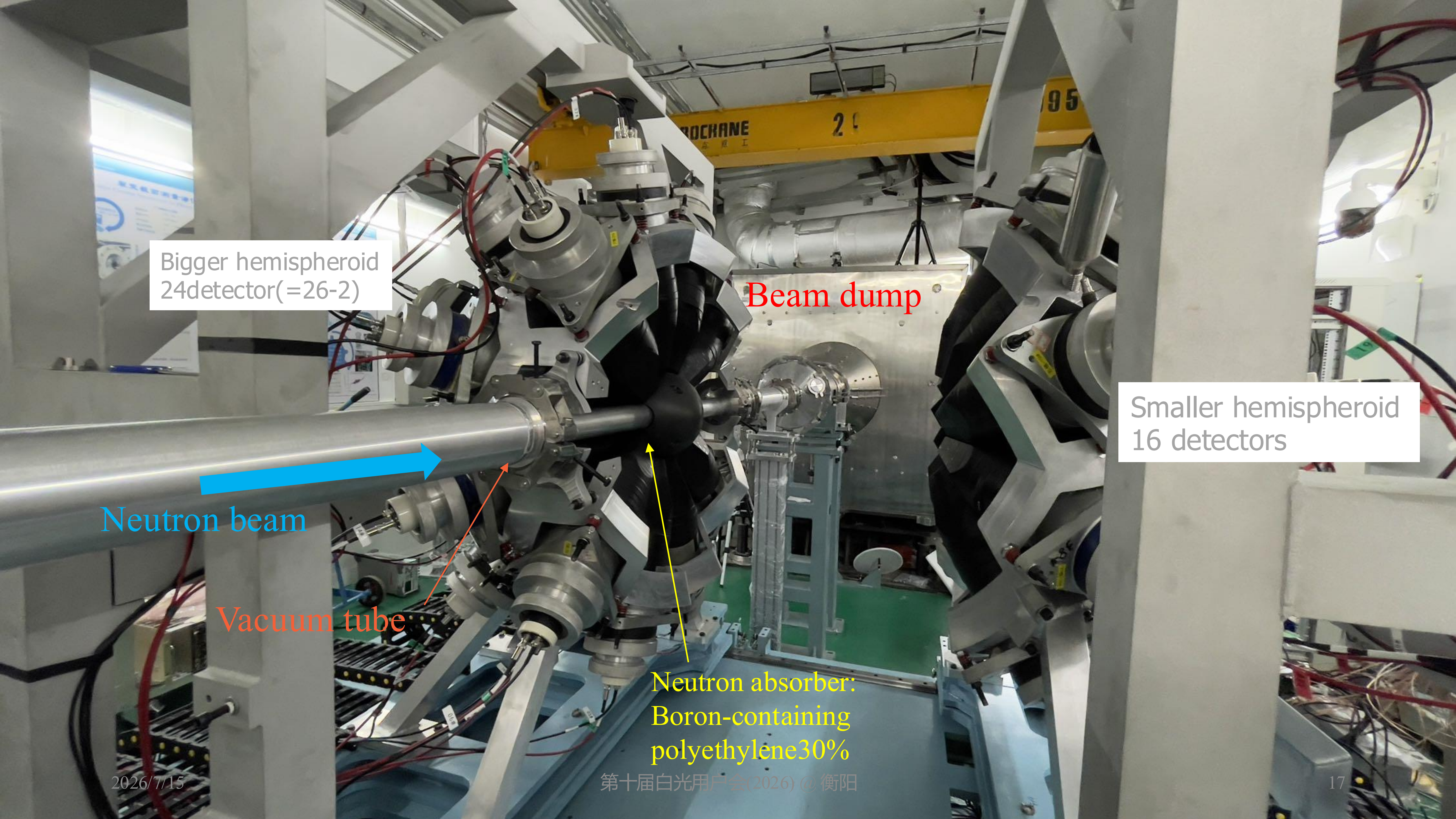
•Gamma Total Absorption Facility (GTAF)

•Prompt gamma measurement, neutron time of flight (TOF) method -> neutron energy

•Cascade gamma matches measurements——Multiplicity and Total Energy of Cascade gamma

- Locates at ES#2 ~75m flight path
- 95.2% solid angle coverage
- 42 segments (40 segments with BaF_2 crystals)
  - 2 different crystal shapes
  - Inner radius = 10cm
  - Crystal depth = 15cm




Bigger hemispheroid
24detector(=26-2)
Beam dump
Smaller hemispheroid
16 detectors
Neutron beam
Vacuum tube
Neutron absorber:
Boron-containing
polyethylene30%

3He neutron polarizer

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ELSEVIER

Full Length Article

First use of a polarized ^{3}He neutron spin filter on the Back-n White Neutron Source of CSNS

Mofan Zhang (张墨凡) [b,c], Zhou Yang (杨洲) [b], Junpei Zhang (张俊佩) [a,b,d], Chuyi Huang (黄楚怡) [a,b,d], Tianhao Wang (王天昊) [a,b,d,*], Yonghao Chen (陈永浩) [a,b], Ruirui Fan (樊瑞睿) [a,b,e,*], W. Michael Snow [c], Xin Tong (童欣) [a,b,d,*]

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Polarized nuclei
CSNS
White neutron
Fundamental physics research
Parity Violation

ABSTRACT

Polarized eV neutrons can address interesting scientific questions in nuclear physics, particle physics, and astrophysics/cosmology. We present the first experiment to polarize the neutrons on the Back-n beamline at the Chinese Spallation Neutron Source (CSNS) using an *in-situ* NSF using spin-exchange optical pumping (SEOP) of ^{3}He. A ^{3}He polarization of 68%±0.7% for this *in-situ* NSF was measured through neutron transmission method at Back-n. This is high enough to enable new experiments on the Back-n beamline.

Adiabatic spin flipper & spin transport

SCIENCE CHINA
Physics, Mechanics & Astronomy

CrossMark

• Article •
SPECIAL TOPIC:

? 2023 Vol. 66 No. 1: 000000
https://doi.org/??

Development and Application of an eV Neutron Polarization for Parity Violation Studies at CSNS Back-n Beamline

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Received ?; accepted ?

The dynamic enhancement of symmetry-breaking effects in neutron-nucleus resonances provides a sensitive testing ground for Time-Reversal Invariance Violation (TRIV). Exploiting this mechanism, the Neutron Optics Parity and Time Reversal Experiment (NOPTREX) seeks to elucidate the origin of the universe's baryon asymmetry. Critical to this effort is the precise measurement of Parity Violation (PV) asymmetries, which is essential to calibrate the nuclear parameters required for future TRIV experiments. To facilitate these studies, we developed an eV polarized neutron at the Back-n white neutron beamline of the China Spallation Neutron Source (CSNS). Neutron polarization is generated by an in-situ Spin-Exchange Optical Pumping (SEOP) ^{3}He filter. Spin manipulation is performed by an adiabatic spin flipper, while spin polarization is preserved over the flight path by a vacuum transport system equipped with a solenoidal guide field. Experiments successfully measured an asymmetry of approximately 7.8 ± 2.4 (stat.) ± 0.3 (sys.)% at the 0.747 eV p-wave resonance of ^{139}La. These results are in agreement with previous results on this resonance and validate the system's capability for PV measurements.

polarized neutron, parity violation, adiabatic spin flipper

PACS number(s): 47.55.nb, 47.20.Ky, 47.11.Fg

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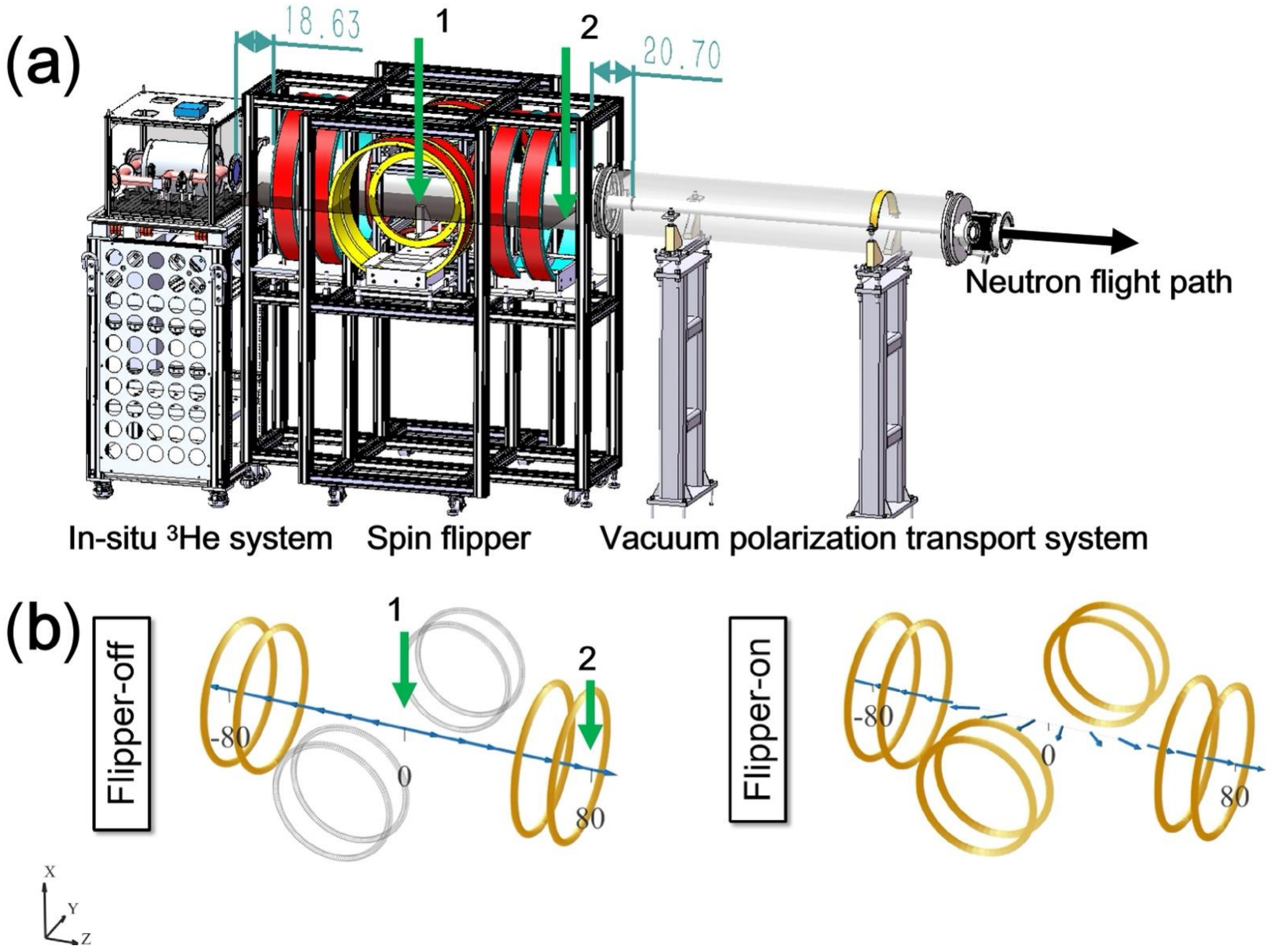
https://doi.org/10.1007/s11433-026-2979-6

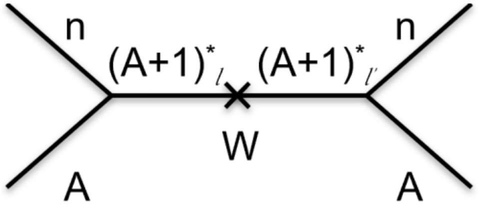


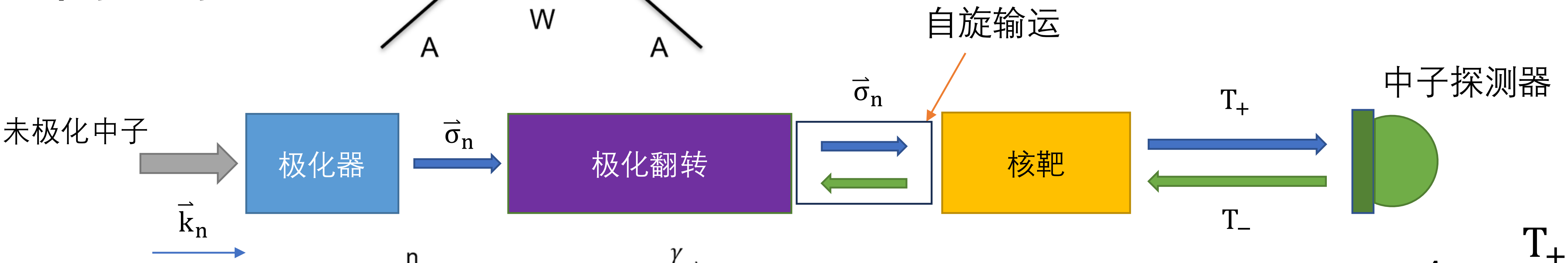
白光中子源宇称不守恒测量实验

宇称不守恒实验设置

$\vec{\sigma}_n$: 中子自旋
$\vec{k}_n$: 中子动量

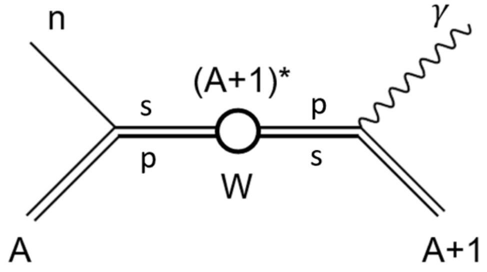
中子透射:

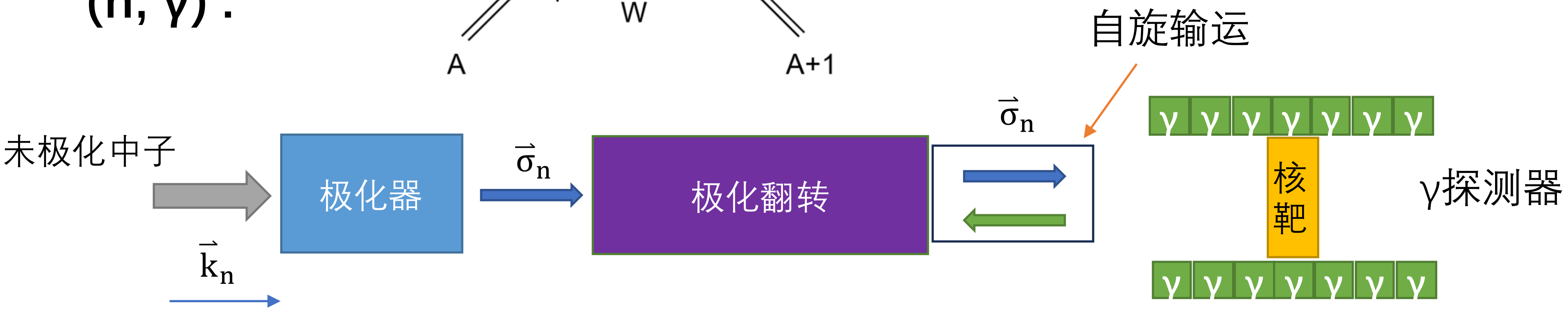




$$A_L = \frac{T_+ - T_-}{T_+ + T_-}$$

(n, γ) :





$$A_{L,\gamma} = \frac{R_+ - R_-}{R_+ + R_-}$$

白光宇称不守恒实验的优化历程

1. 2025.01 粗放实验:
   - ^{3}He极化器与GTAF探测器组合进行PV实验的可行性验证
   - 结果：散射背景过大，甚至淹没了目标共振峰（^{139}La 0.74eV p-wave)

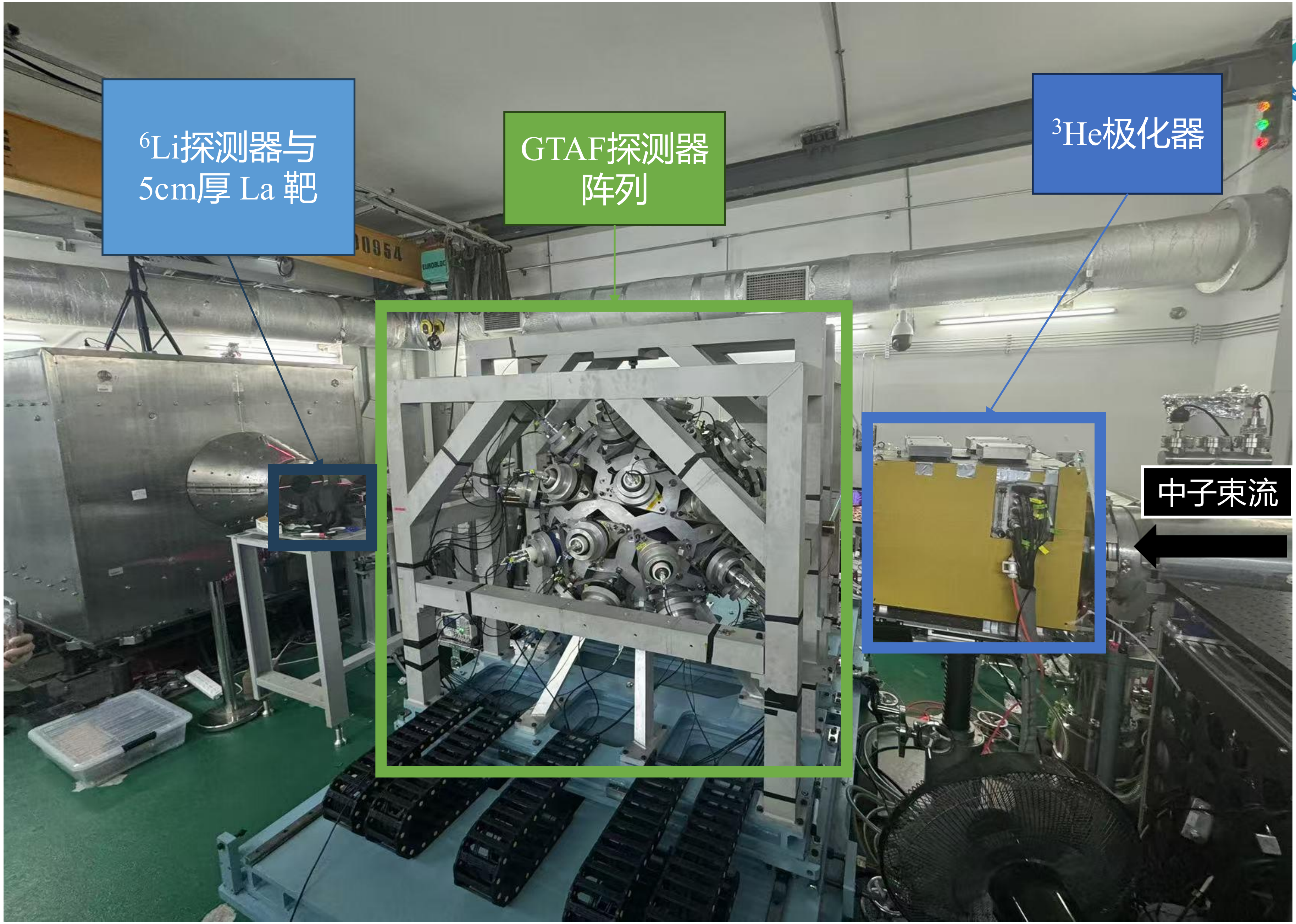
2. 2025.10 束线升级与极化翻转实验:
   - 使用已有屏蔽墙来屏蔽^{3}He极化器带来的散射本底，增加约20m极化输运螺线管，增加极化翻转器，并测量镧靶约70小时

3. 2026.06 完全体实验:
   - 中子通量提升:
     - 束斑：12-15-40 -> 50-15-30
     - 加速器运行功率：170 kW -> 185 kW
   - 靶： ϕ40mm -> ϕ45mm
   - 增加GTAF段螺线管，采集了140小时La、83小时Pd数据。并采集了前端存在^{3}He极化器情况下的空和C靶数据。

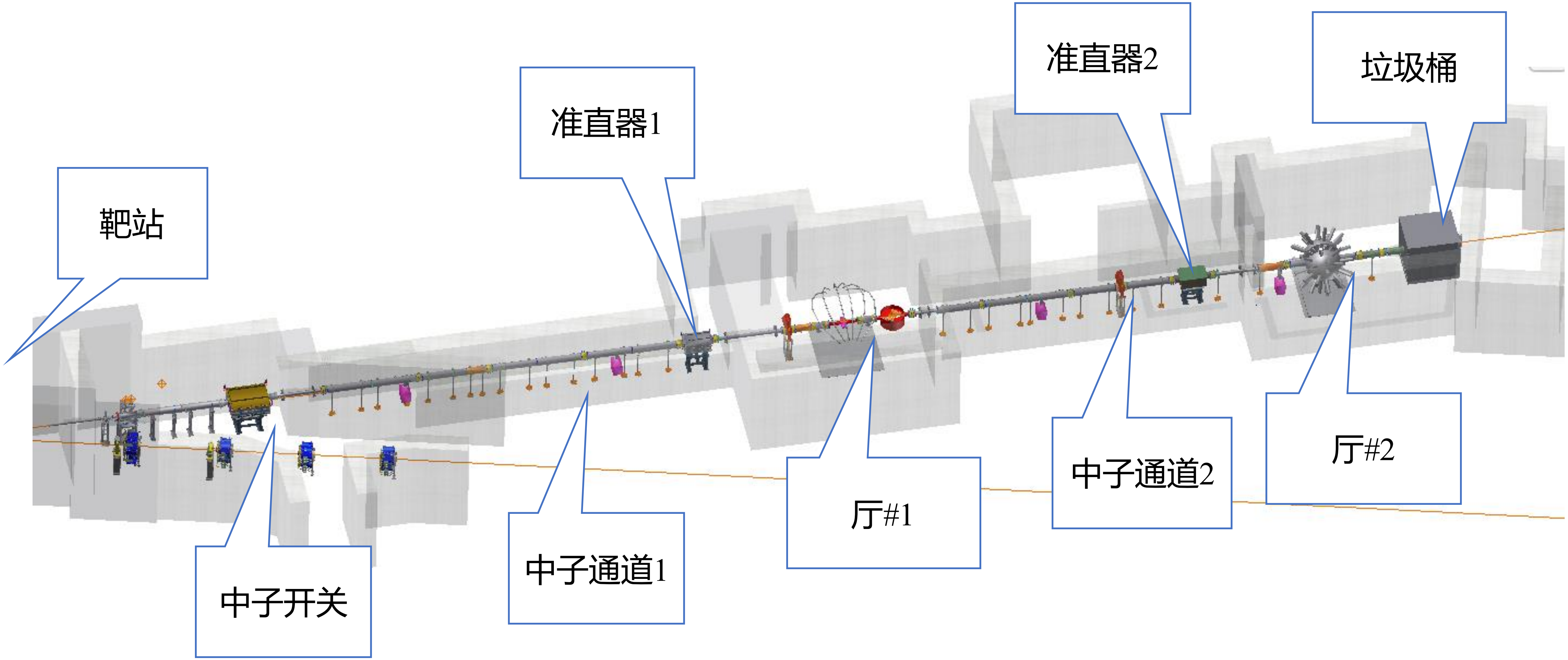
首次白光宇称不守恒实验(2024.12)

没有在^{139}La上看到宇称不守恒效应

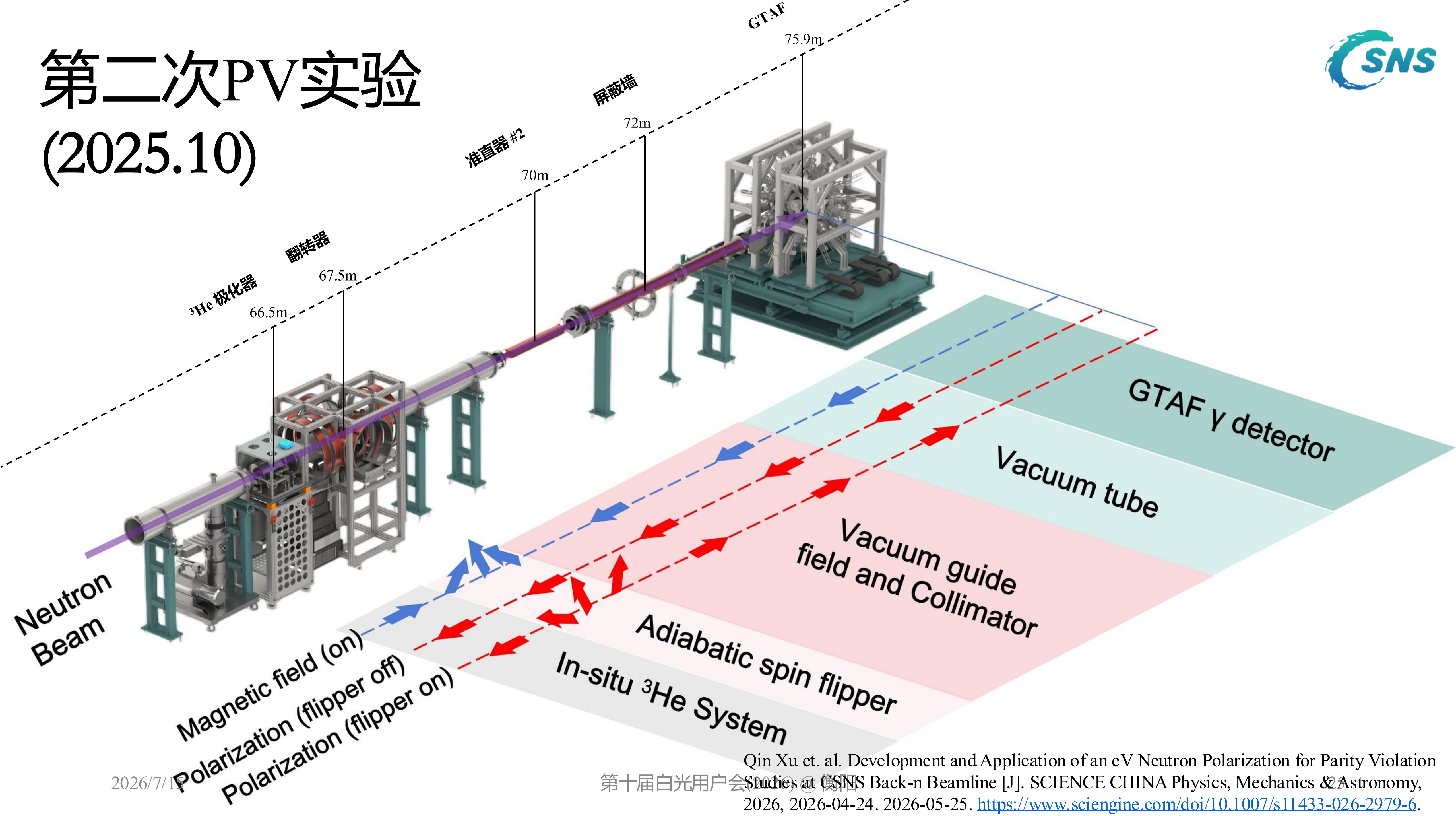
散射背景过大



白光束线示意图



第二次PV实验 (2025.10)



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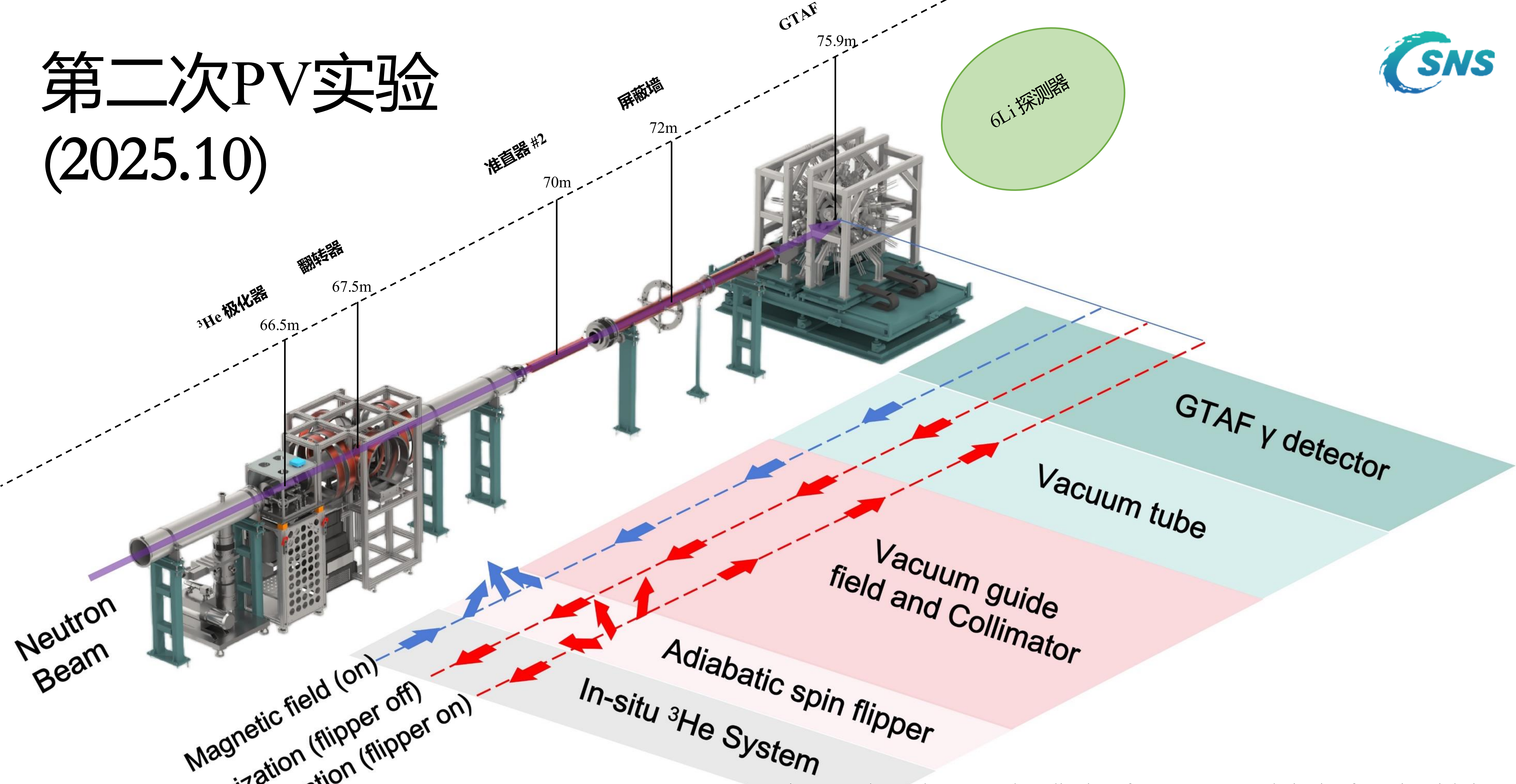
第二次PV实验
(2025.10)



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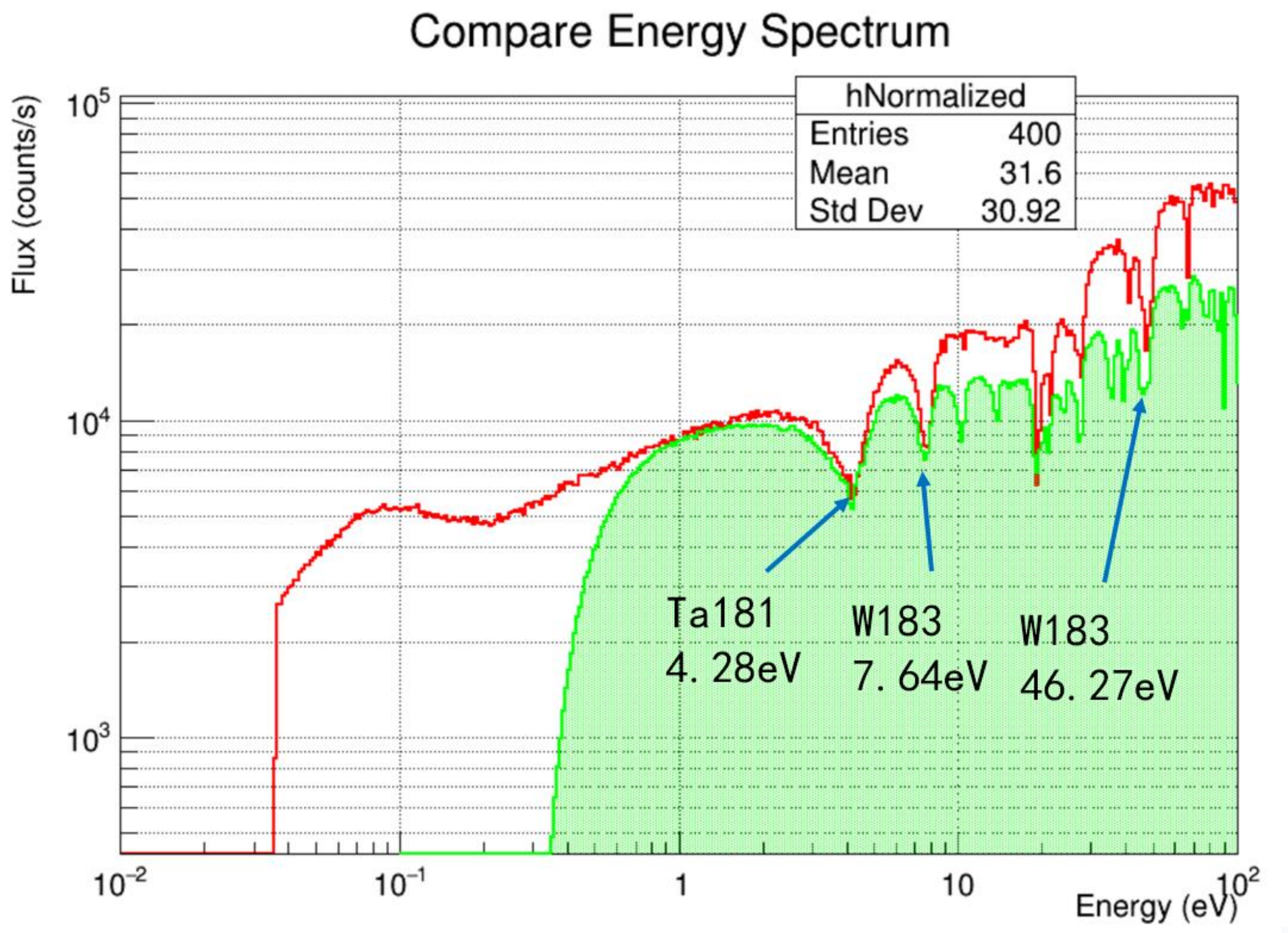
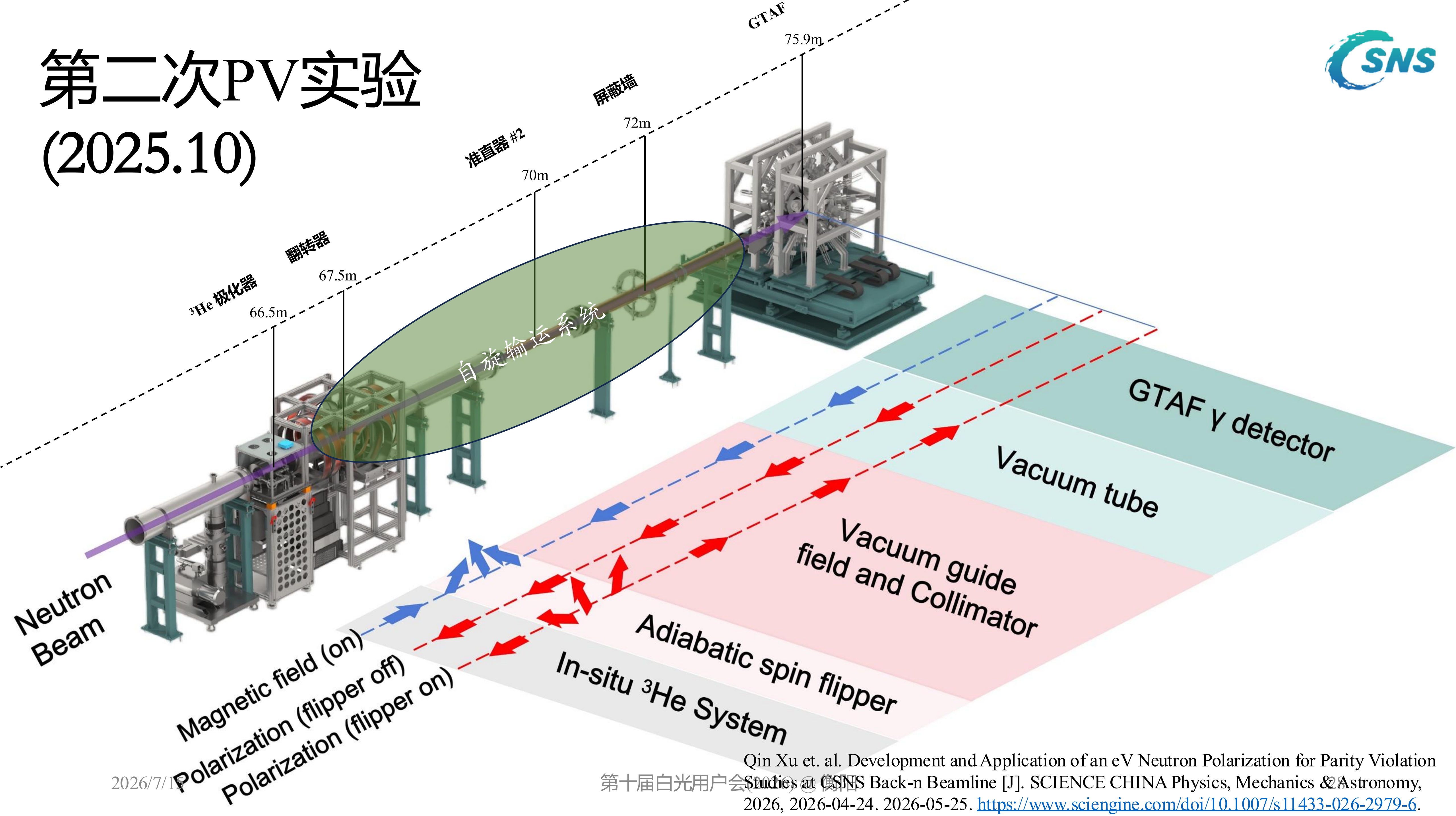
^{6}Li探测器测量到的中子通量

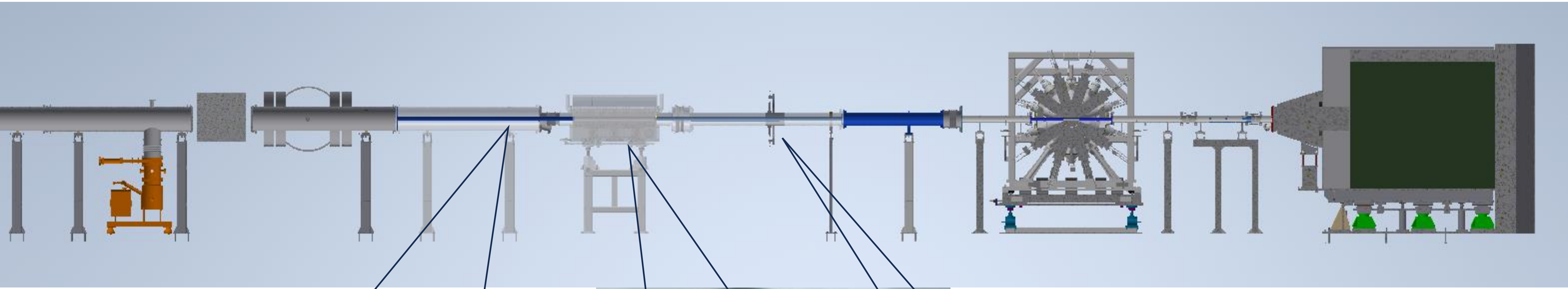


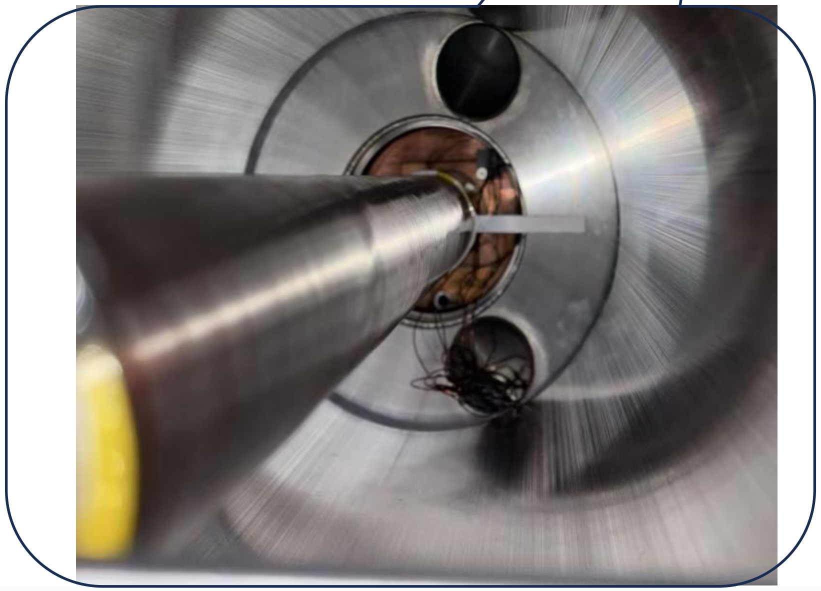
第二次PV实验 (2025.10)

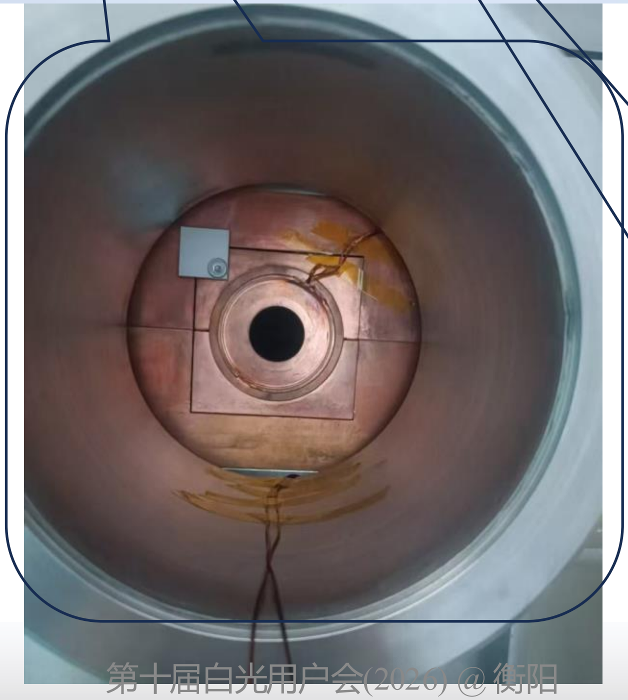


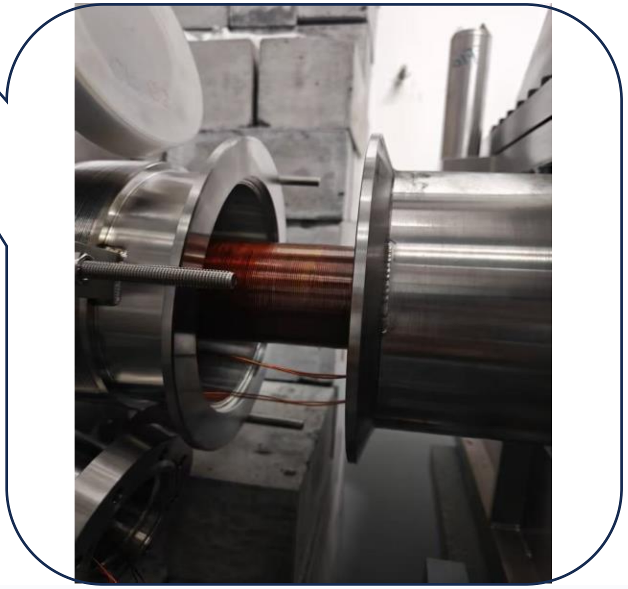
Qin Xu et. al. Development and Application of an eV Neutron Polarization for Parity Violation Studies at CSNS Back-n Beamline [J]. SCIENCE CHINA Physics, Mechanics & Astronomy, 2026, 2026-04-24. 2026-05-25. https://www.sciengine.com/doi/10.1007/s11433-026-2979-6.

自旋输运系统

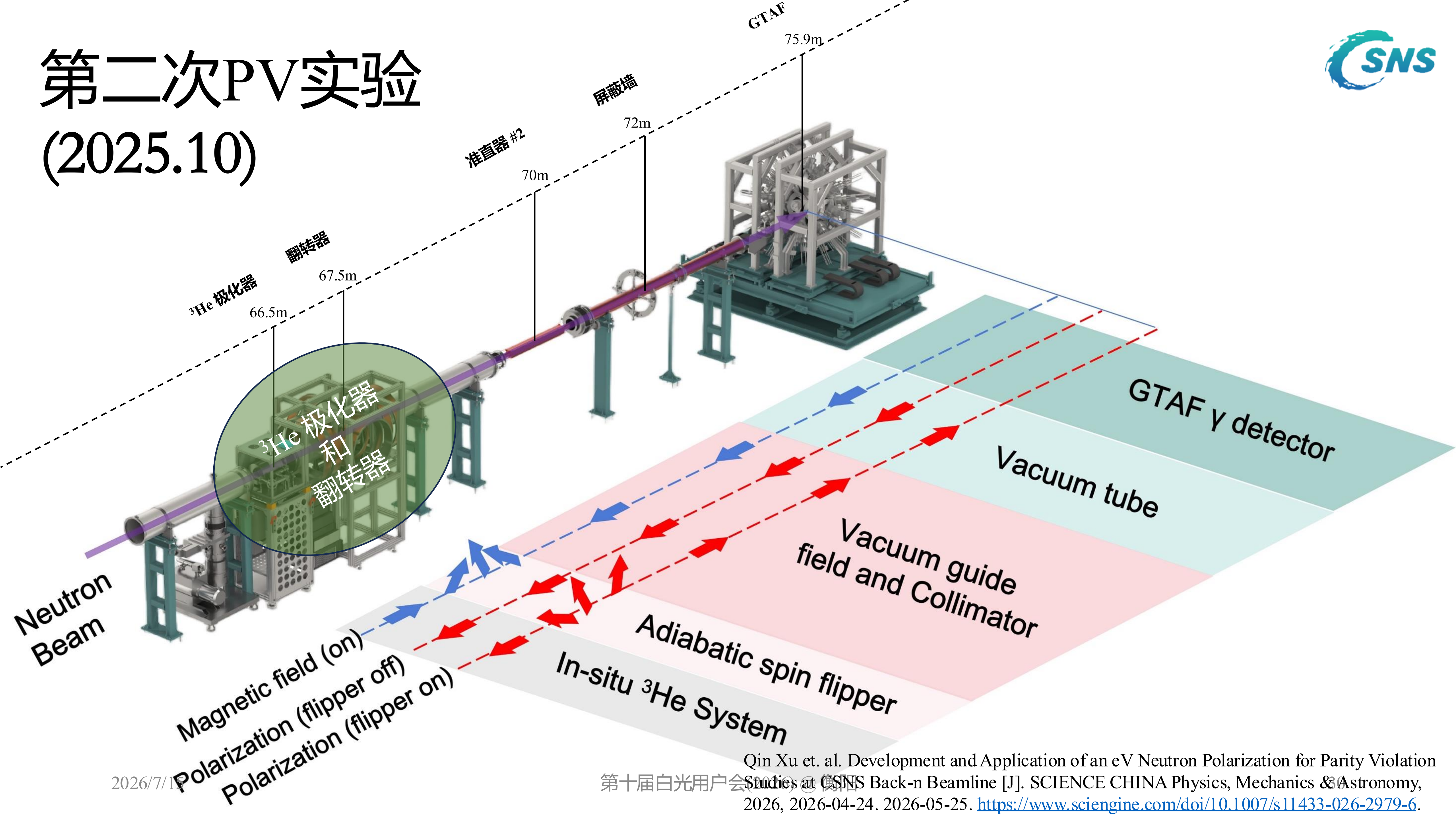






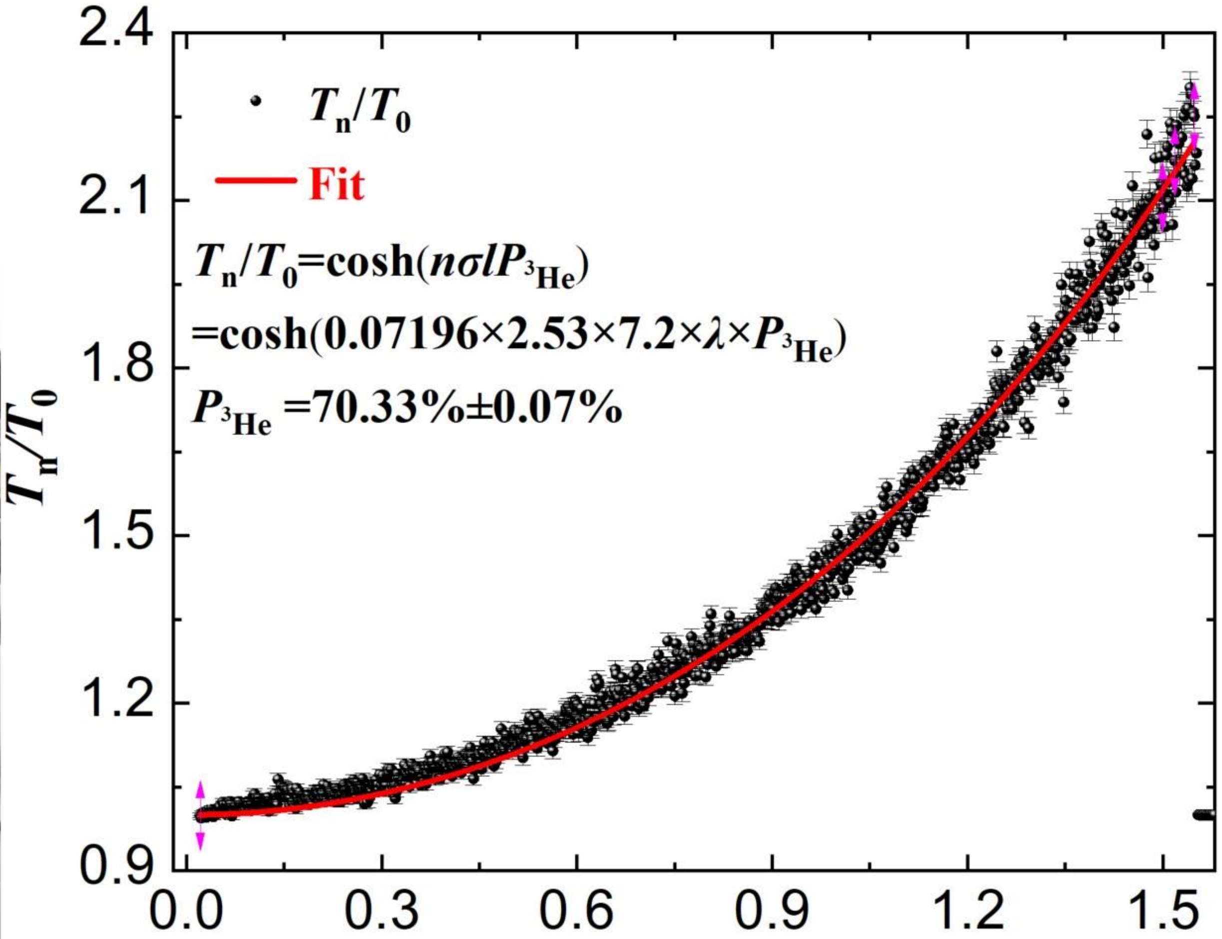


第二次PV实验
(2025.10)



Qin Xu et. al. Development and Application of an eV Neutron Polarization for Parity Violation Studies at CSNS Back-n Beamline [J]. SCIENCE CHINA Physics, Mechanics & Astronomy, 2026, 2026-04-24. 2026-05-25. https://www.sciengine.com/doi/10.1007/s11433-026-2979-6.

^{3}He 极化器



Qin Xu et. al. Development and Application of an eV Neutron Polarization for Parity Violation Studies at CSNS Back-n Beamline [J]. SCIENCE CHINA Physics, Mechanics & Astronomy, 2026, 2026-04-24. 2026-05-25. https://www.sciengine.com/doi/10.1007/s11433-026-2979-6.

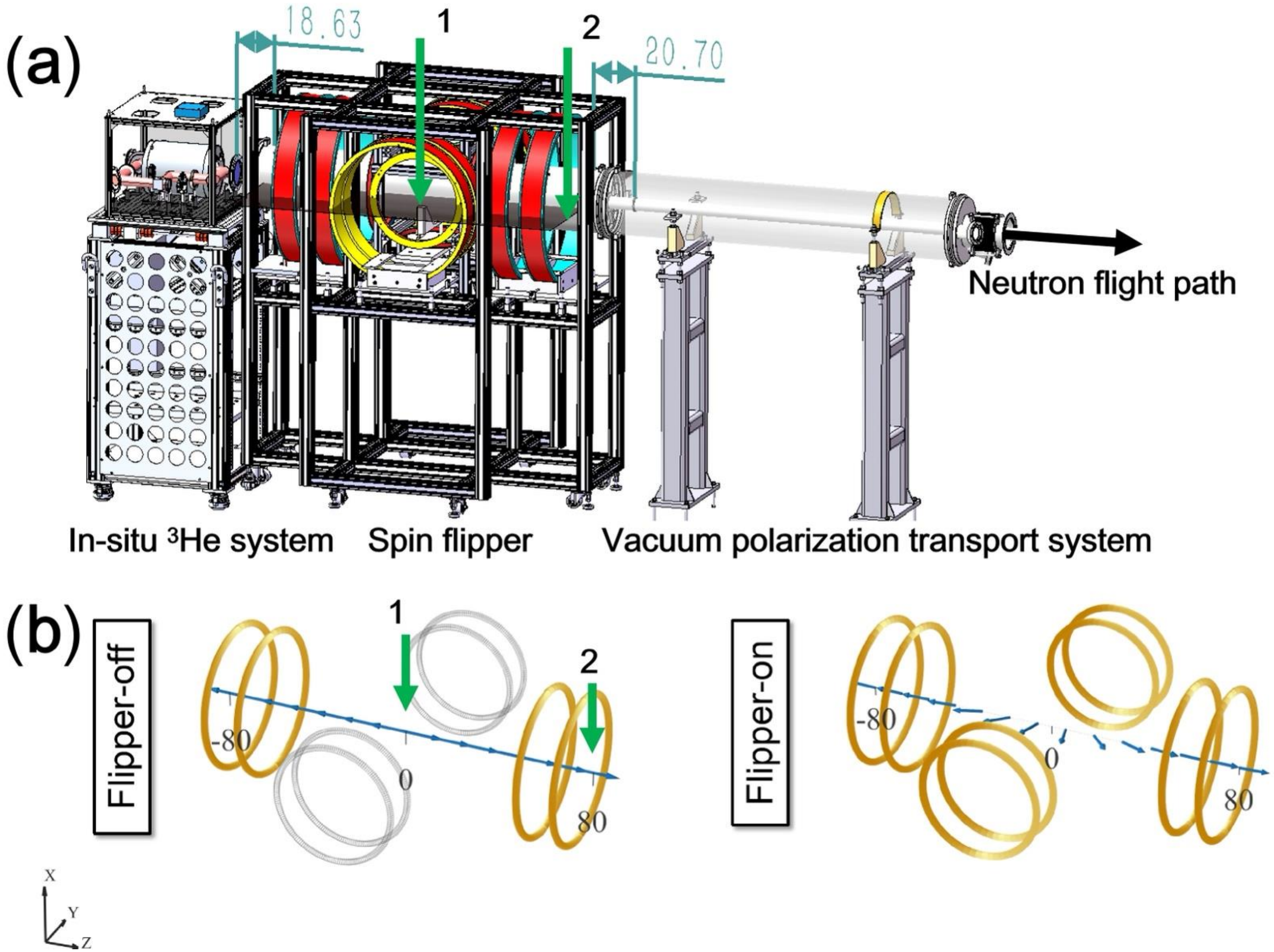
绝热翻转器

序列: [+ - - + - + + -]

脉冲长度 = 40 ms

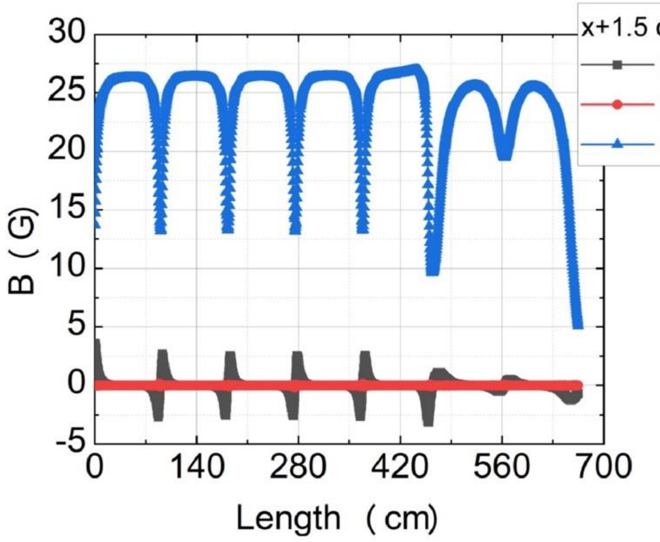
步长 = 10个脉冲

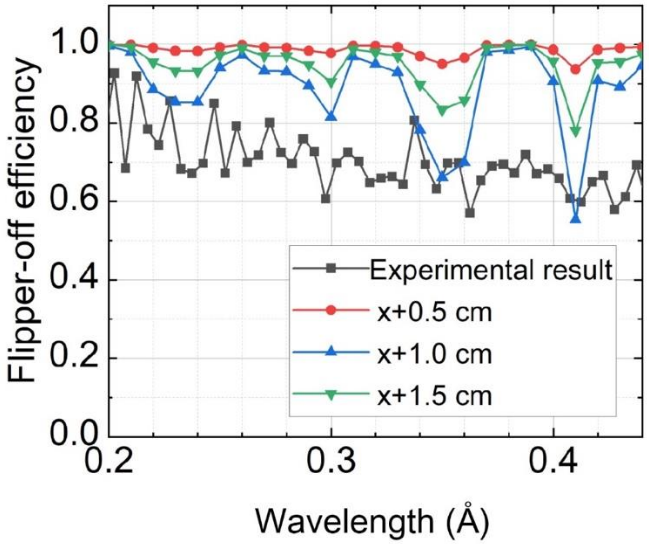
序列长度 = 80个脉冲 (不含过渡态) = 3.2 s

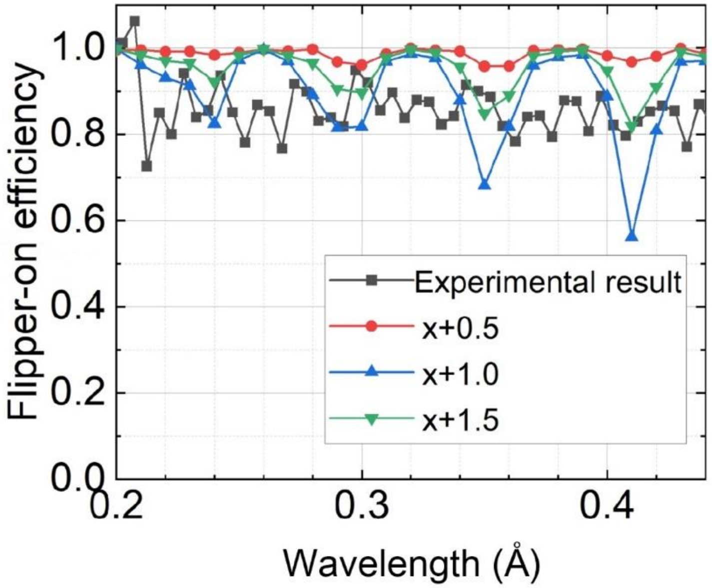


Qin Xu et. al. Development and Application of an eV Neutron Polarization for Parity Violation Studies at CSNS Back-n Beamline [J]. SCIENCE CHINA Physics, Mechanics & Astronomy, 2026, 2026-04-24. 2026-05-25. https://www.sciengine.com/doi/10.1007/s11433-026-2979-6.

中子极化传输效率







在GTAF测量：

- 翻转器关闭效率 (ε_{off}) = 70%
- 翻转器开启效率 (ε_{on}) = 90%

由分析器测量的中子极化 (f_n) = 30% @0.74eV

Qin Xu et. al. Development and Application of an eV Neutron Polarization for Parity Violation Studies at CSNS Back-n Beamline [J]. SCIENCE CHINA Physics, Mechanics & Astronomy, 2026, 2026-04-24. 2026-05-25. https://www.sciengine.com/doi/10.1007/s11433-026-2979-6.

极化传输修正后的A_L

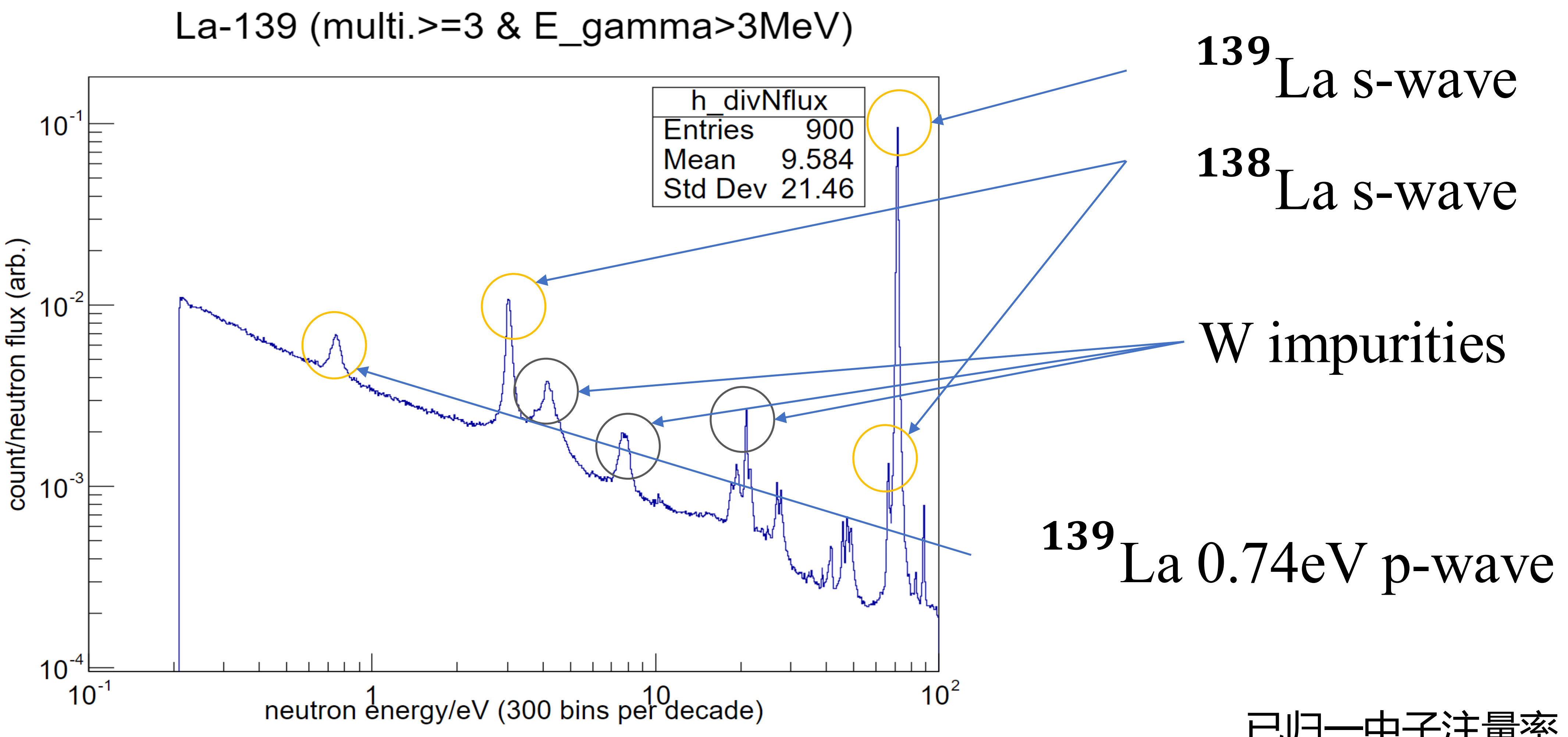
$$N(\mathcal{P}) = N_0\left[w_+(\mathcal{P})(1-e^{-\sigma_+ n}) + w_-(\mathcal{P})(1-e^{-\sigma_- n})\right]$$
$$= \frac{N_0}{2}\left[(1+\mathcal{P})(1-e^{-(\sigma n + x)}) + (1-\mathcal{P})(1-e^{-(\sigma n - x)})\right].$$

$$\mathcal{P}_{\mathrm{off}} = f_n(2\varepsilon_{\mathrm{off}} - 1)$$
$$\mathcal{P}_{\mathrm{on}} = f_n(1 - 2\varepsilon_{\mathrm{on}}).$$

$$A_{\mathrm{meas}} = \underbrace{\left[\frac{f_n e^{-\sigma n}\sinh(x)}{1-e^{-\sigma n}\cosh(x)}\right]}_{A_{\mathrm{ideal}}} \cdot \underbrace{(\varepsilon_{\mathrm{off}} + \varepsilon_{\mathrm{on}} - 1)}_{\bar{\mathrm{f}}}.$$

$$A_{measured} = \bar{\mathrm{f}}\, A_{\mathrm{ideal}}$$
$$= 0.6 \times A_{\mathrm{ideal}}$$

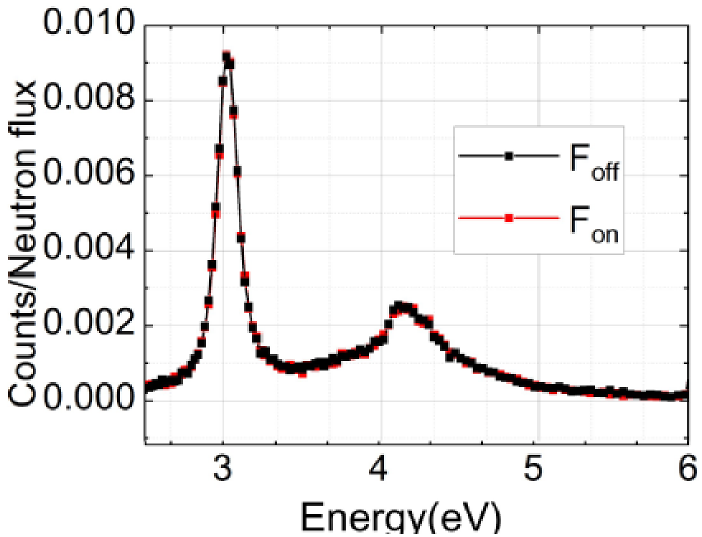
^{139}La 原始中子能谱(2025.10)



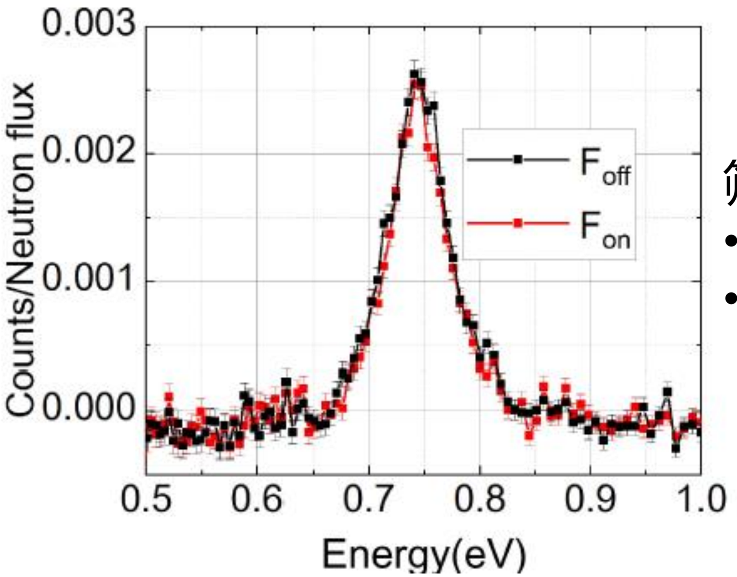
束流归一能谱

已归一中子注量率

PV计算
(合并数据)

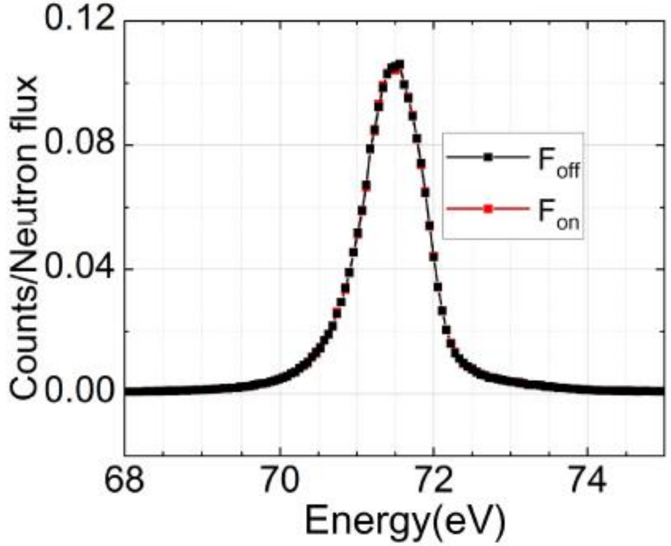


$A_{measured}(3\ to\ 4eV) = 0.37 \pm 0.31\%$



筛选条件:

- 多重性 >= 3
- 伽马加合能 > 3MeV



$A_{measured}(0.74eV) = 4.67 \pm 1.19\%$

$A_{ideal}(0.74eV) = 7.8\% \pm 2.4(stat.) \pm 0.3(sys.)\%$

$A_{measured}(72eV) = 0.05 \pm 0.34\%$

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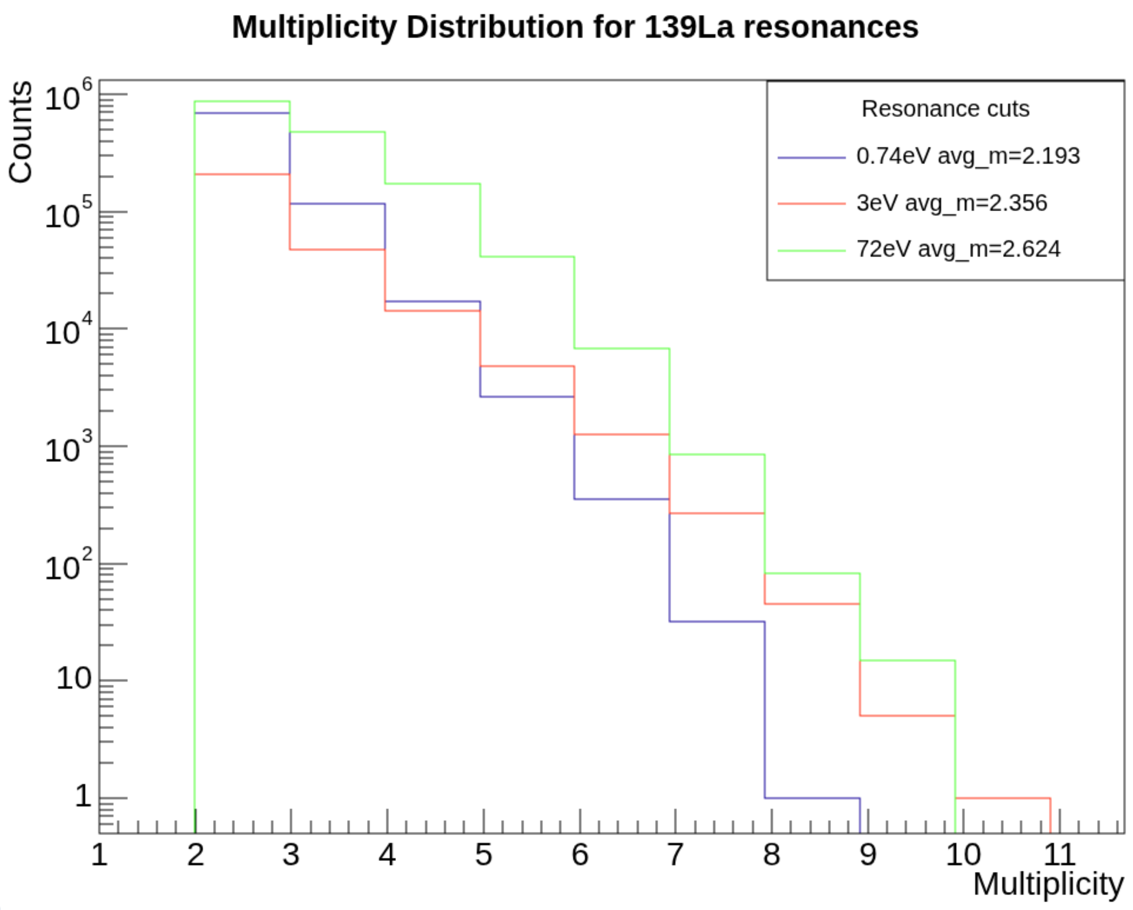
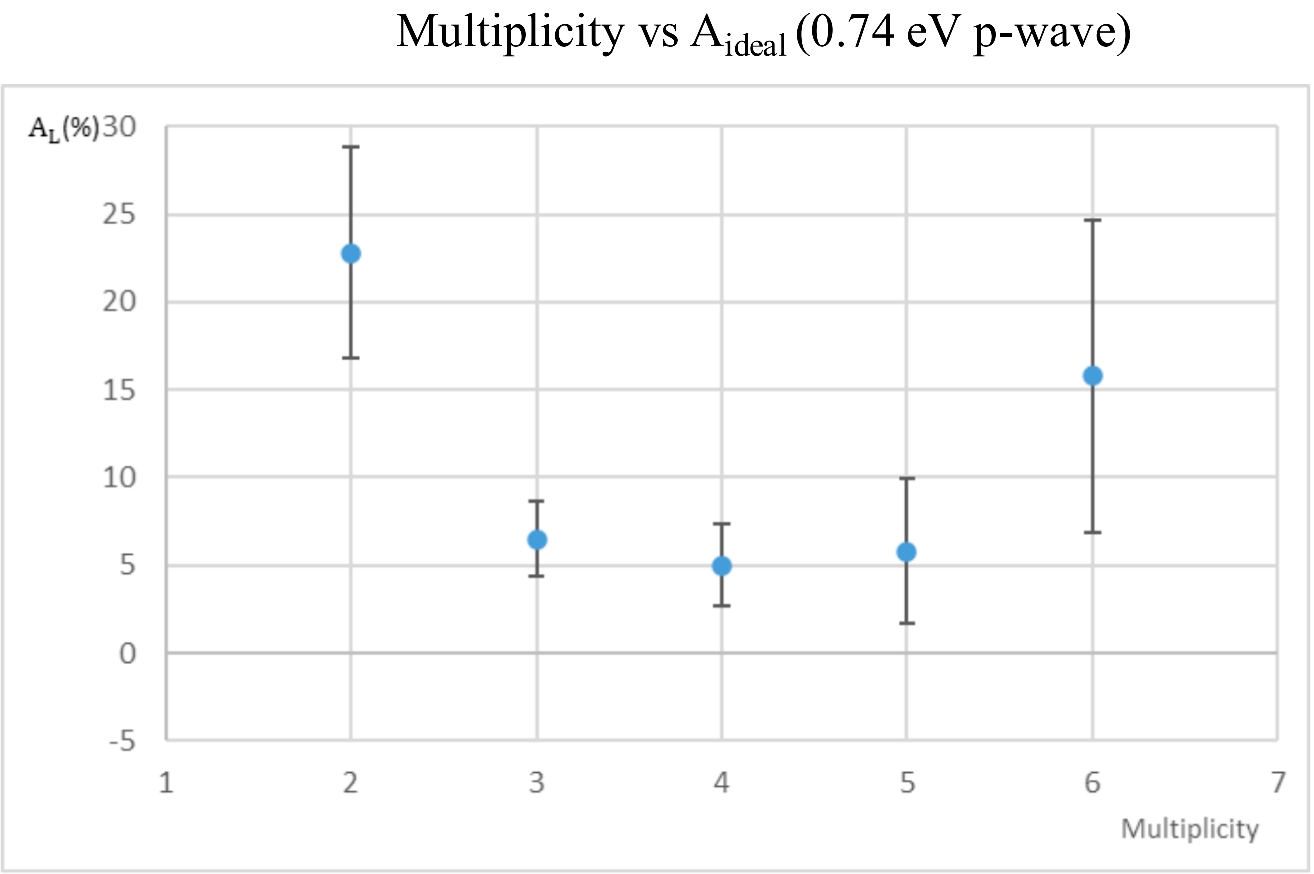
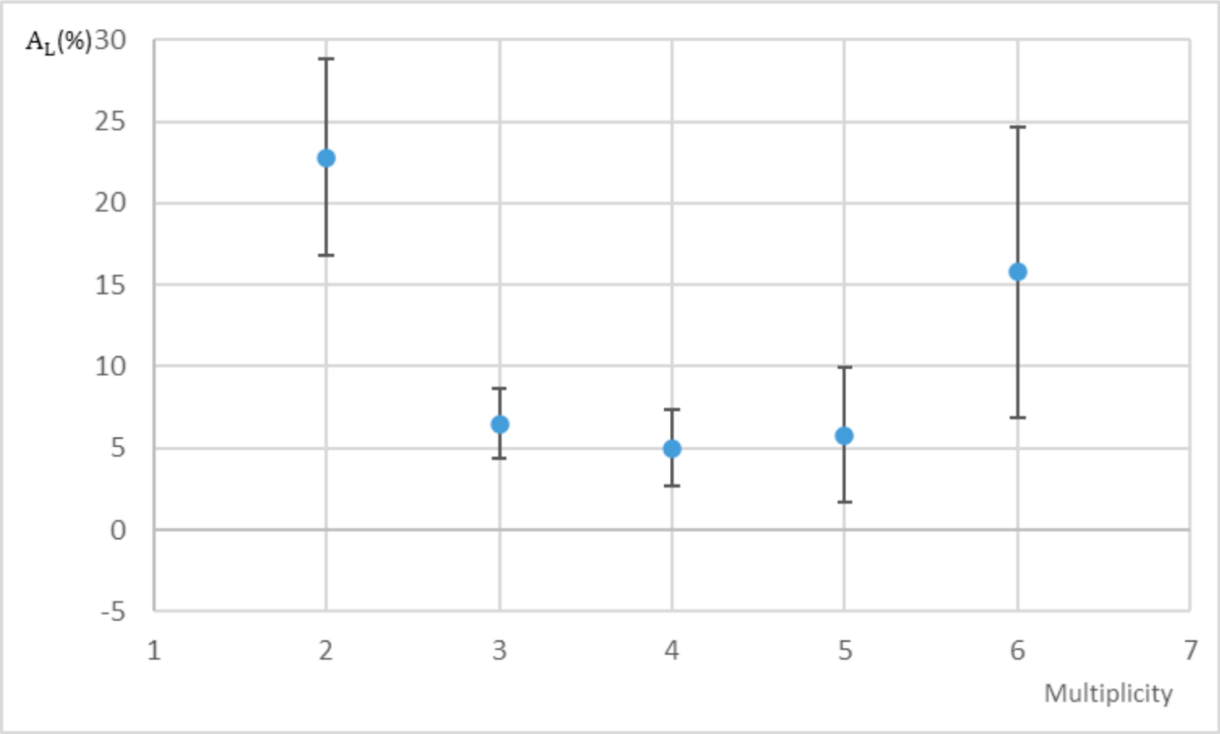
各多重性下的PV分析（合并数据）



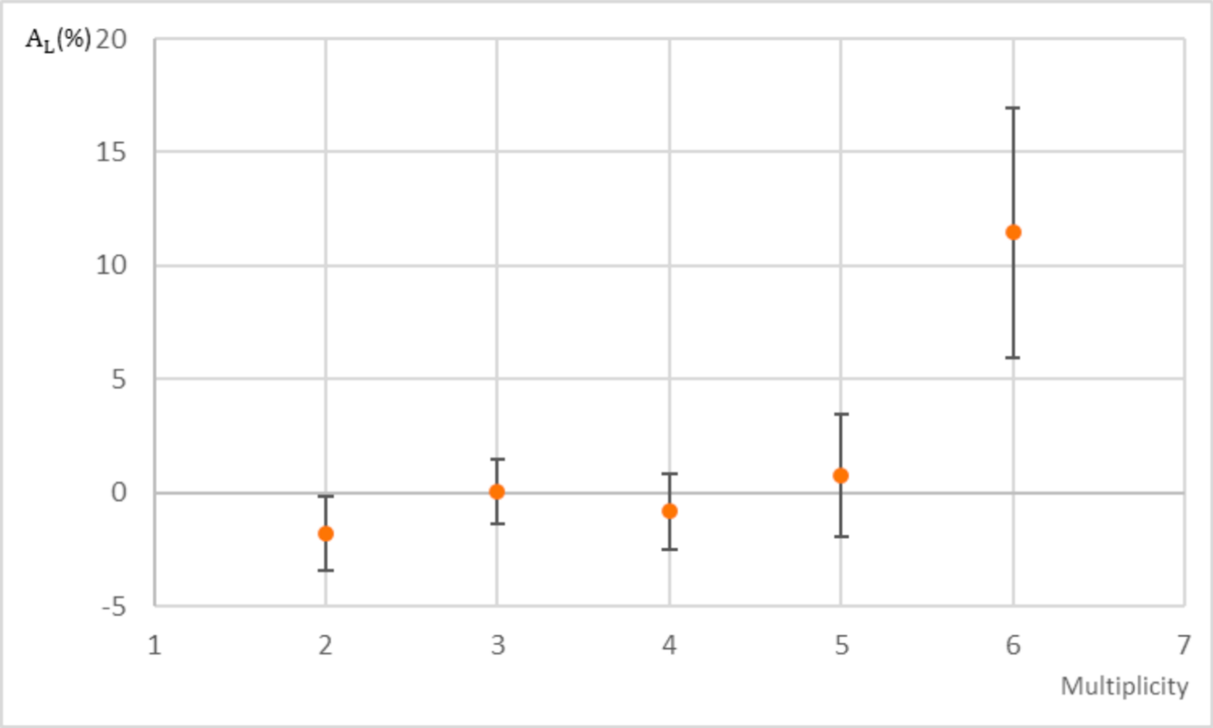


各多重性下的PV分析（合并数据）

Multiplicity vs A_{ideal} (0.74 eV p-wave)



Multiplicity vs A_{ideal} (3 eV s-wave)



8步分析法

消除所有二阶时间依赖慢漂移，包括：

- 温飘
- 瞬时束流通量变化
- 辐照损伤引起的探测器基线漂移
- 以及其他所有慢变因素

序列: [+ - - + - + + -]

步长 = 10个脉冲

脉冲长度 = 40 ms

序列长度 = 80个脉冲 (不含过渡态)
= 3.2 s

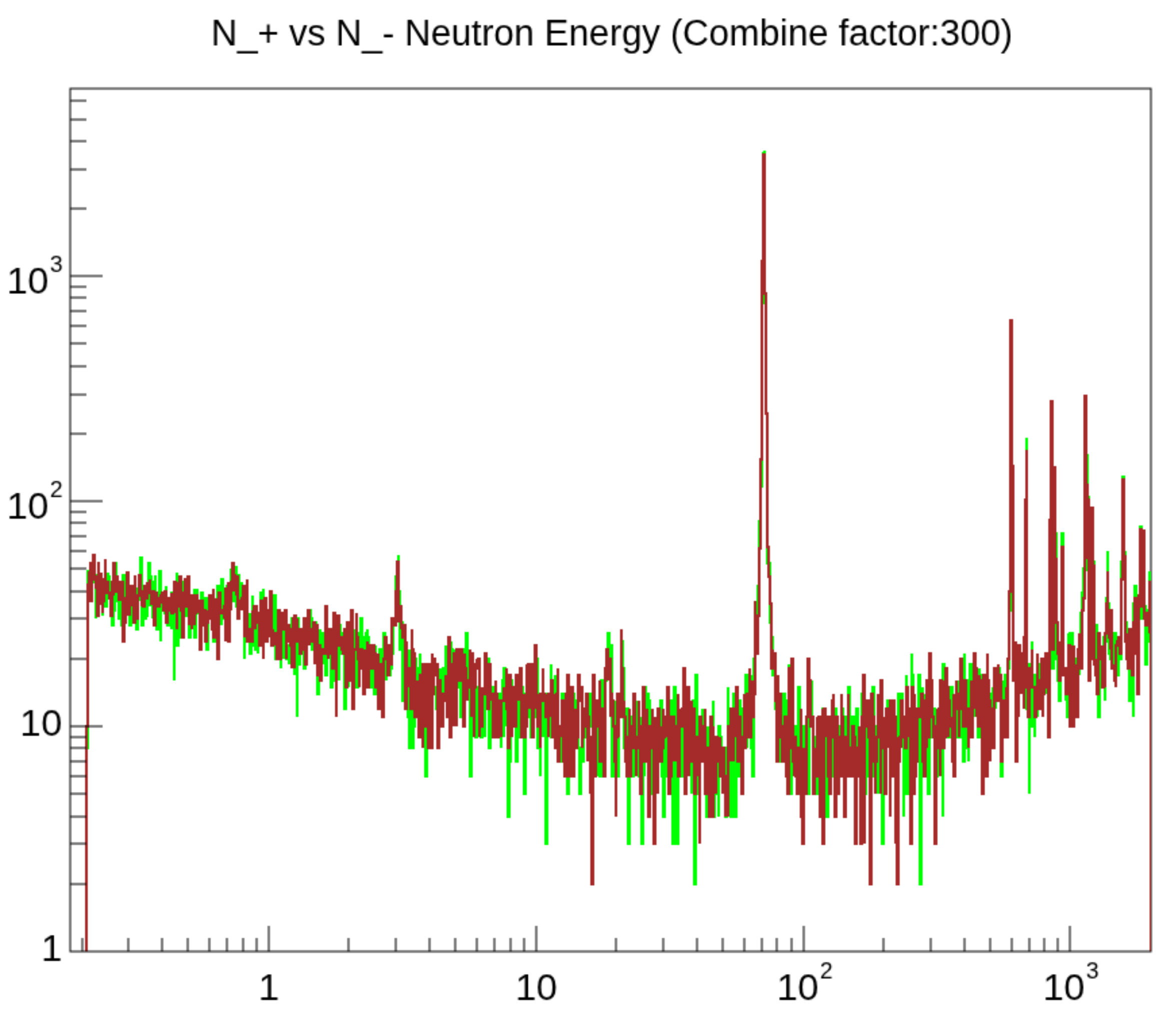
8步原始数据列表（La）

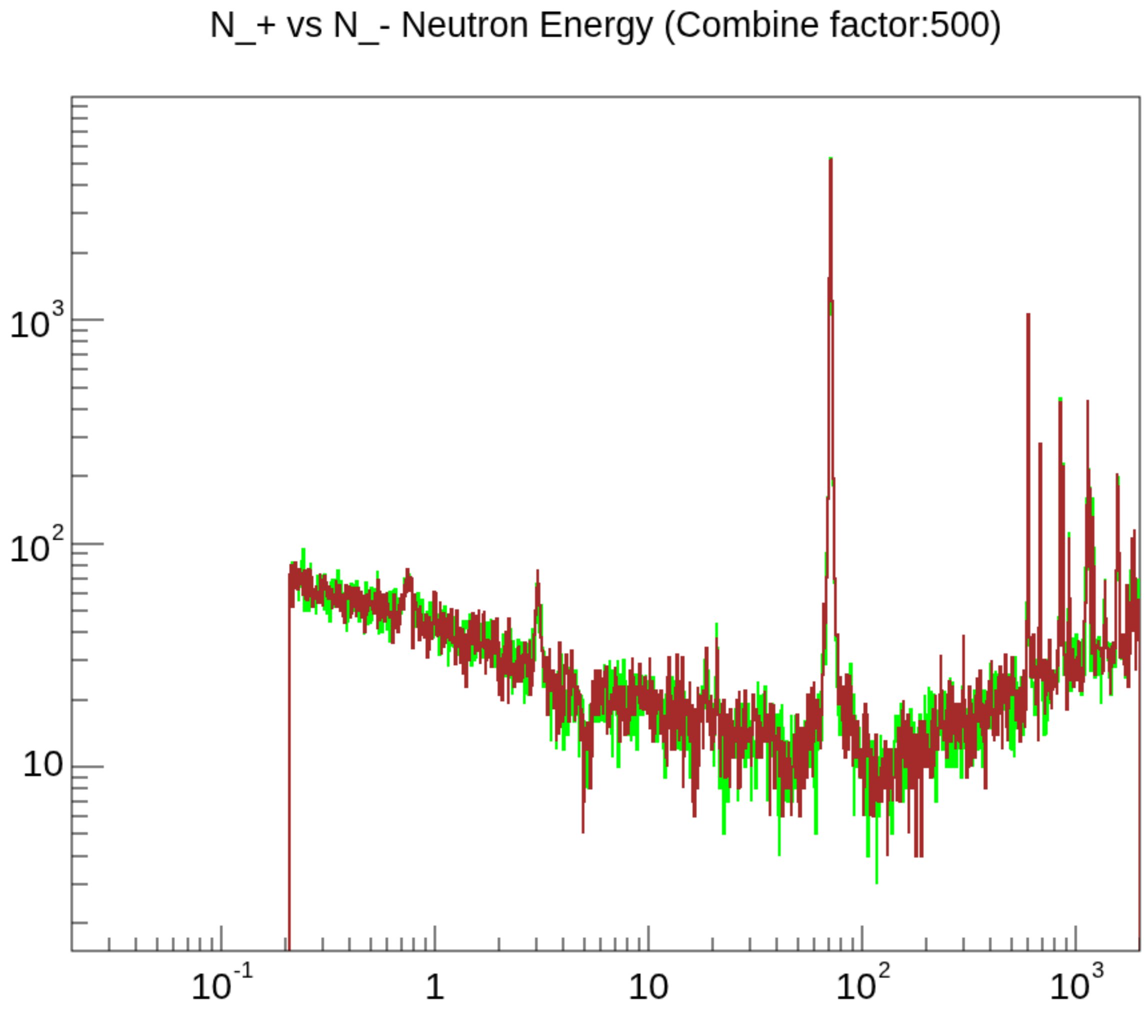
Start time	Sample	Total 8-steps	Normal 8-steps	Abnormal sequence	Insufficient pulses	Success Rate
RawData_20251030_181643	La	392	390	0	2	99.49%
RawData_20251030_191818	La	1,678	1,668	0	10	99.40%
RawData_20251031_010709	La	9,686	9,498	0	188	98.06%
RawData_20251031_124508	La	1,743	1,705	0	38	97.82%
RawData_20251031_142321	La	698	691	0	7	99.00%
RawData_20251031_152158	La	2,162	2,129	0	33	98.47%
RawData_20251031_172840	La	16,001	15,613	1	387	97.58%
RawData_20251101_101822	La	12,907	12,518	1	388	96.99%
RawData_20251101_231400	La	14,390	14,230	1	159	98.89%
Total	~65h	59,657	58,442	3	1,212	97.96%

在 0 至 2 keV 中子能区经筛选后，每个测量序列每种极化态的平均计数为 256.5。

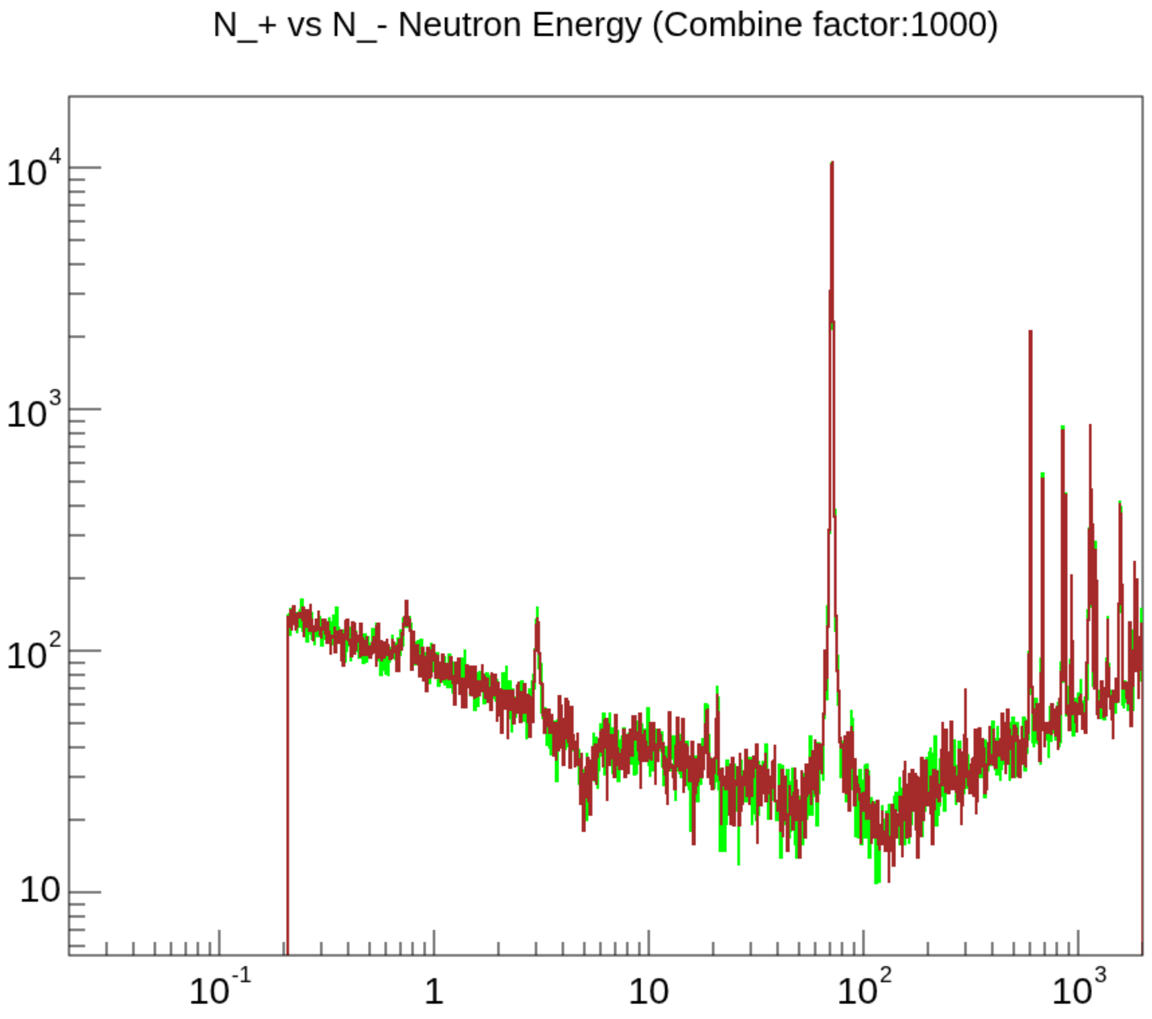
筛选条件:
- 多重性 >= 2
- 3MeV <加合能< 5.5MeV

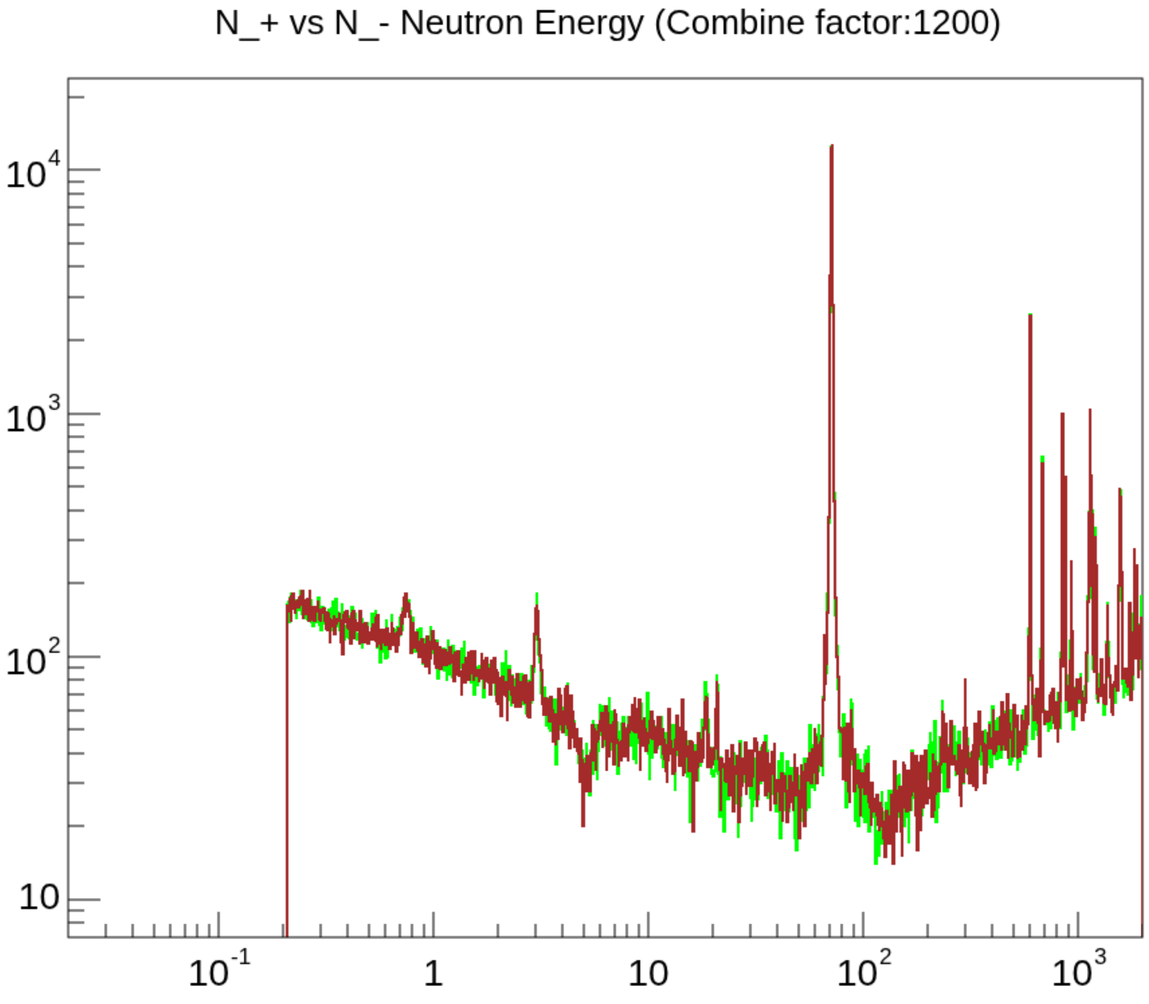
不同序列数量加合的中子能谱



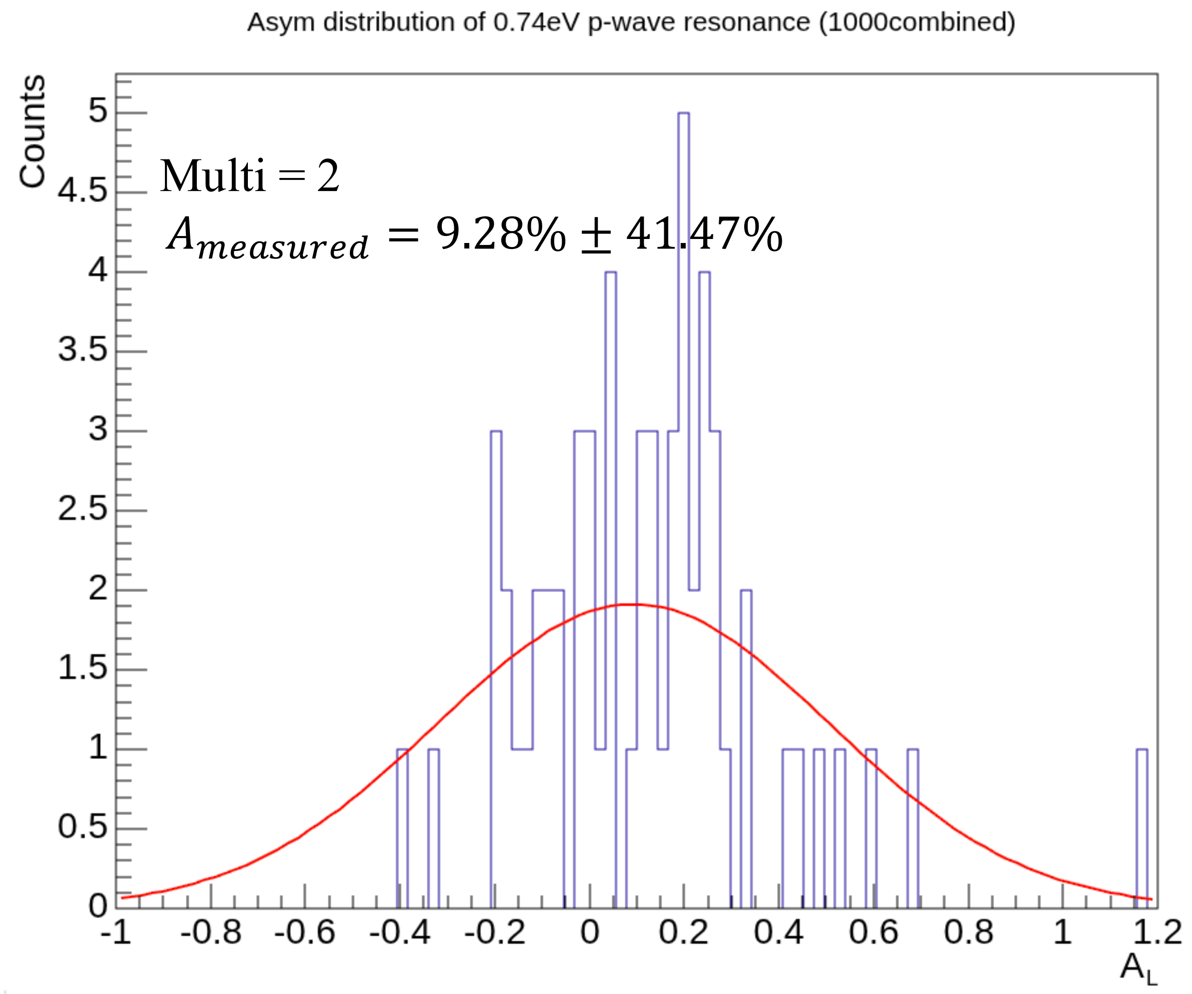


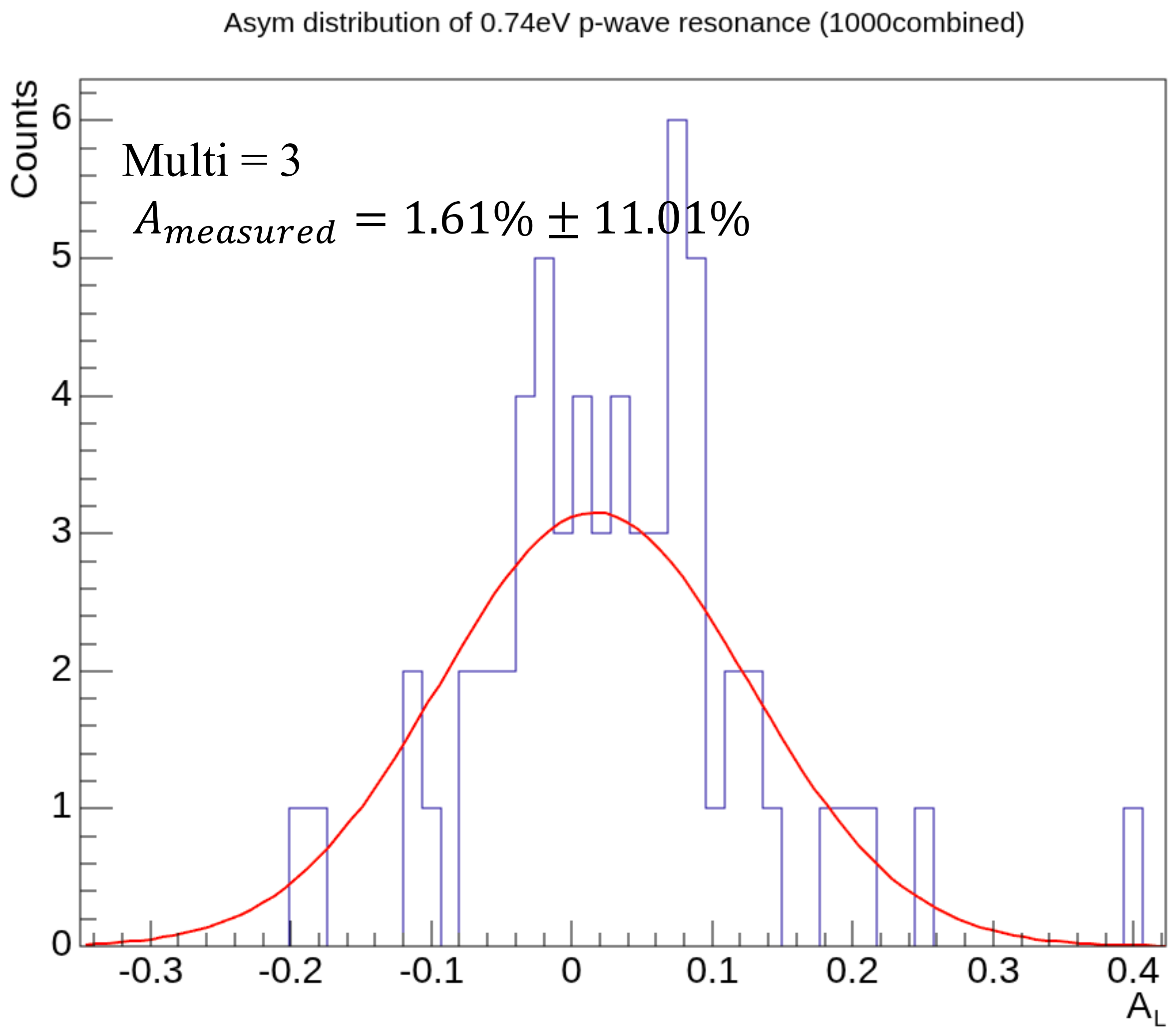
不同序列数量加合的中子能谱





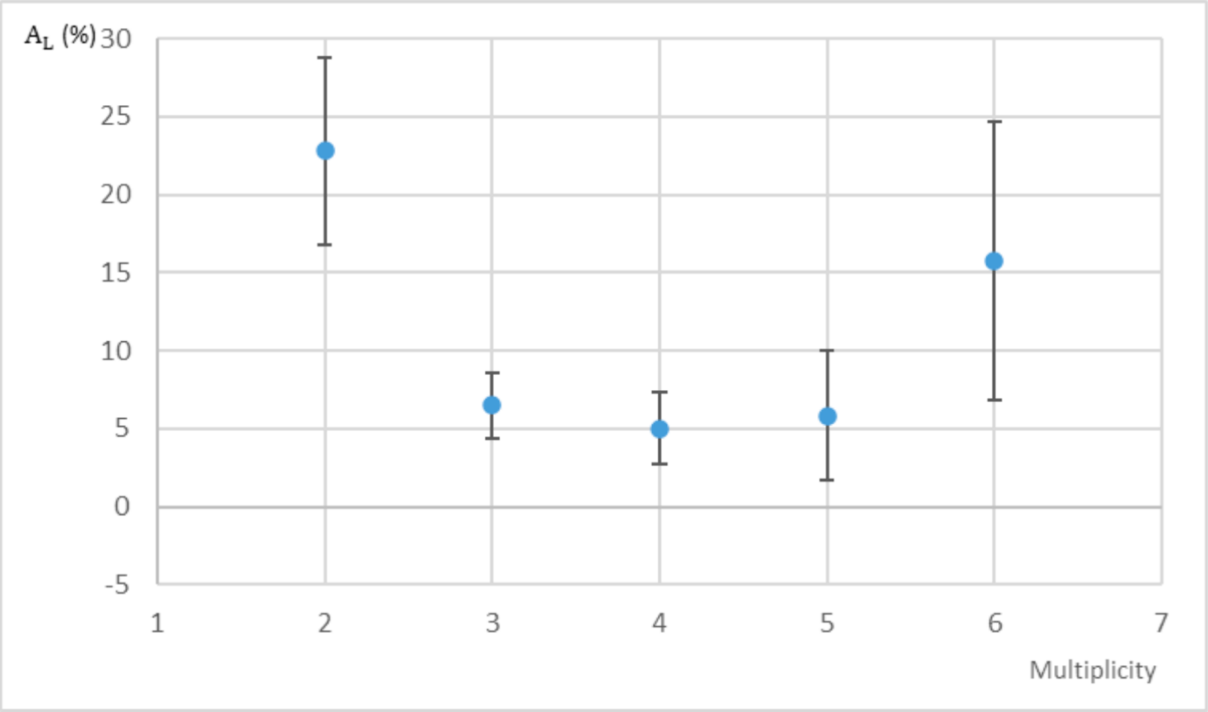
按多重性进行的8步PV分析



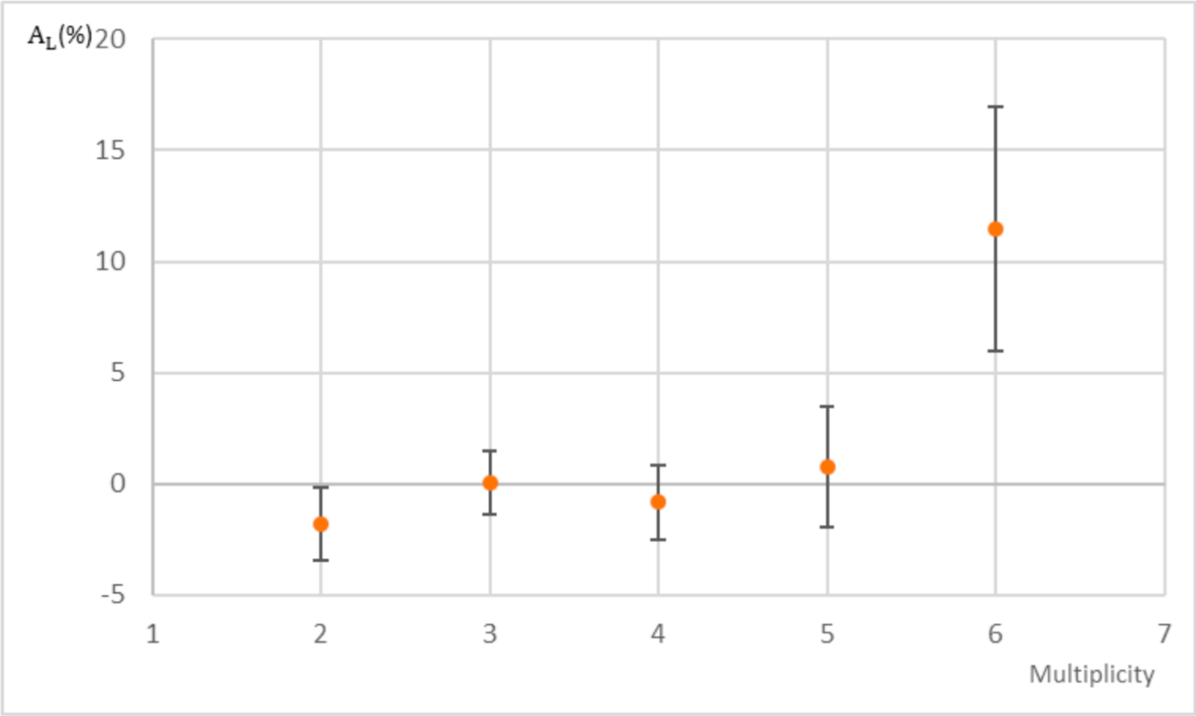


按多重性进行PV分析 (8步分析)

Multiplicity vs A_{ideal} (0.74 eV p-wave)



Multiplicity vs A_{ideal} (3 eV s-wave)



讨论：基于多重数的分析

- **脉冲模式探测器的优势：**与TRIPLE合作组先前使用的直流模式γ探测器不同，GTAF的脉冲模式运行能够保留（n,γ）反应事件信息。这为未来NOPTREX实验采用基于伽马多重性的末态选择方法奠定了基础。

- **确定共振自旋：**利用伽马多重性来确定共振峰的自旋（J），这将使我们对历史TRIPLE数据的重新分析成为可能，从而显著降低宇称破坏矩阵元（$\langle M^2\rangle$）的不确定性。

- **依赖于多重性的宇称破坏研究：** 探究宇称反常不对称性A_L是否随伽马多重性变化，这将对统计理论构成一种新颖的检验。

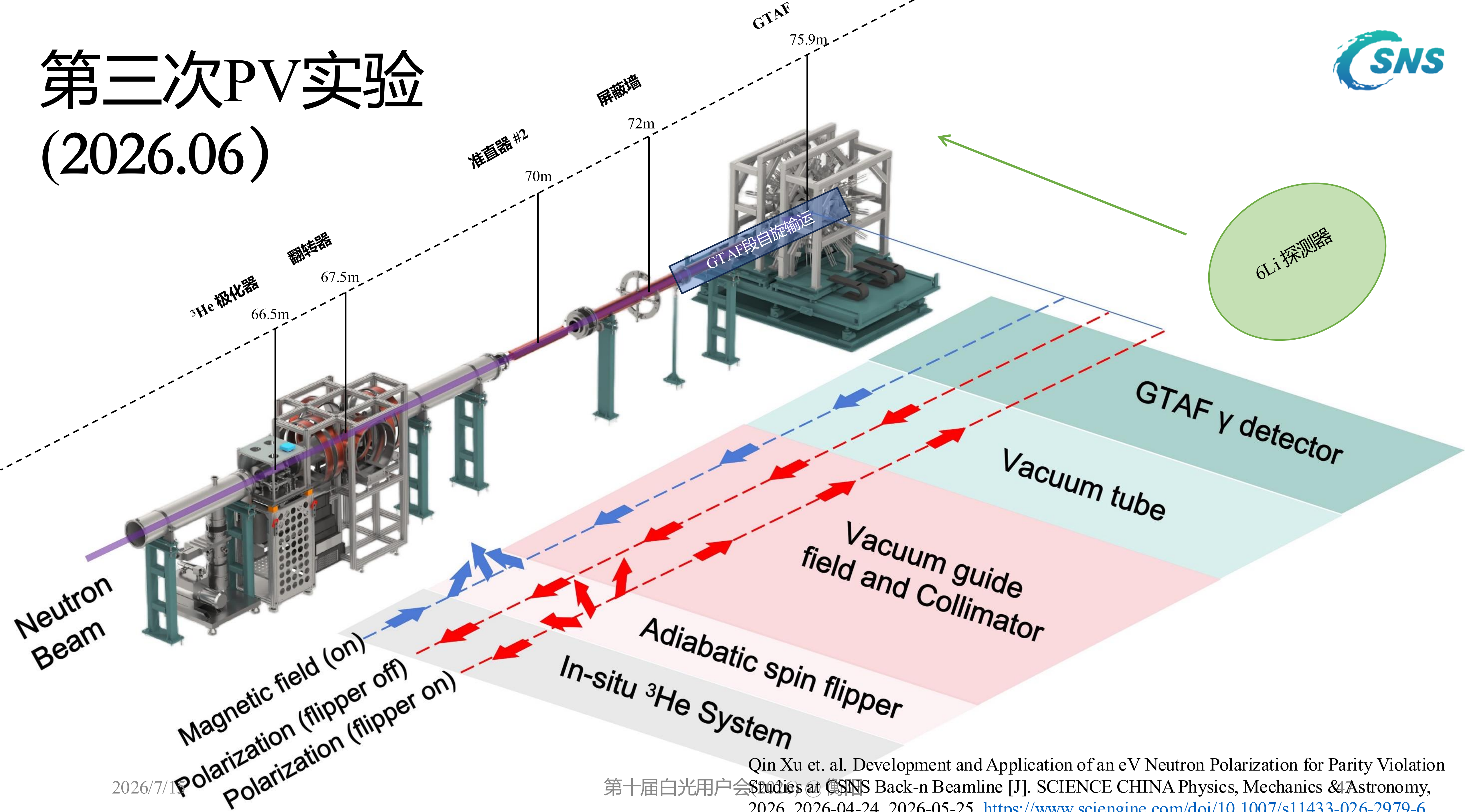
结论：改进

- 缺失约1.5m的自旋传输 -> 测量到的不对称度更低
- 58442个8步序列对应~65小时数据
- 1000个序列为0.74eV p波提供了良好的信噪比 --> 每小时有足够计数的序列。
- 无背景测量

需要更多数据：

- 更大的束流光斑
- 更多束流时间
- 更厚的靶
- 解决引导磁场不连续问题

第三次PV实验 (2026.06)



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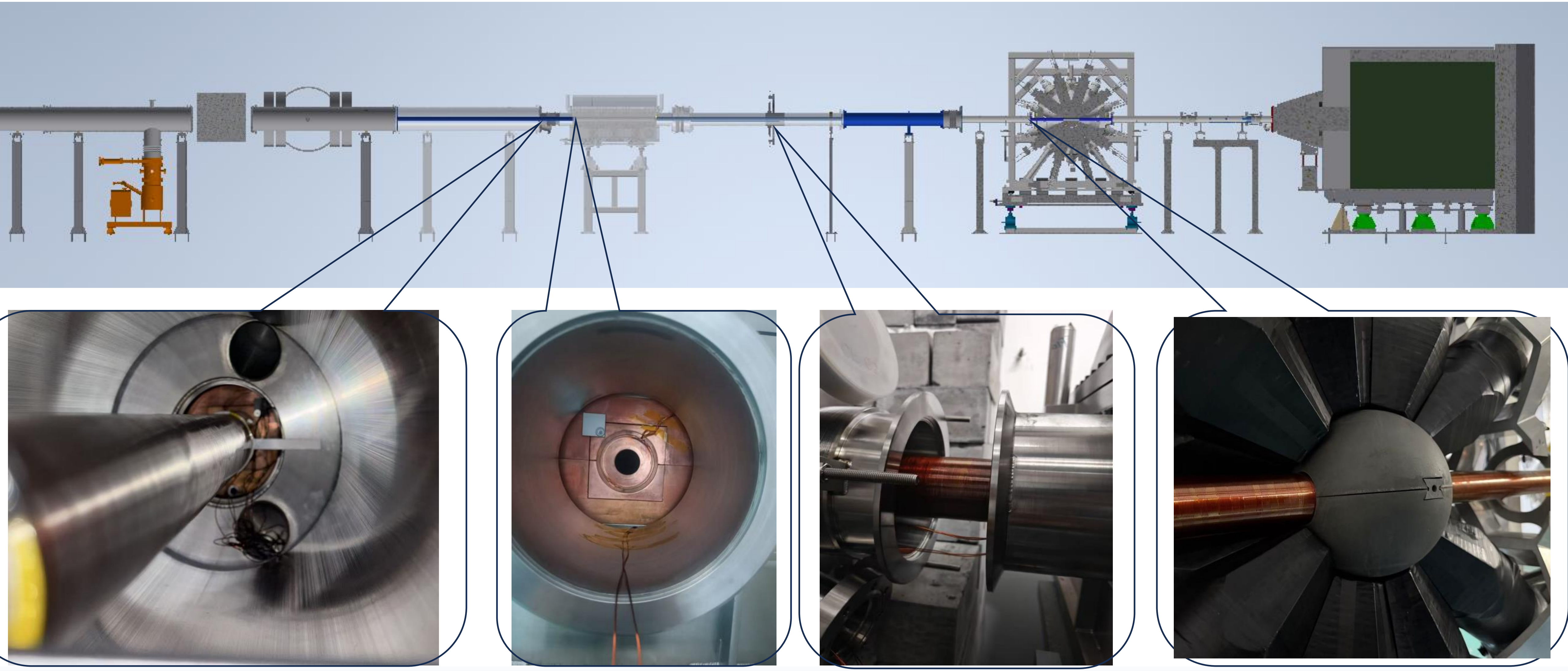
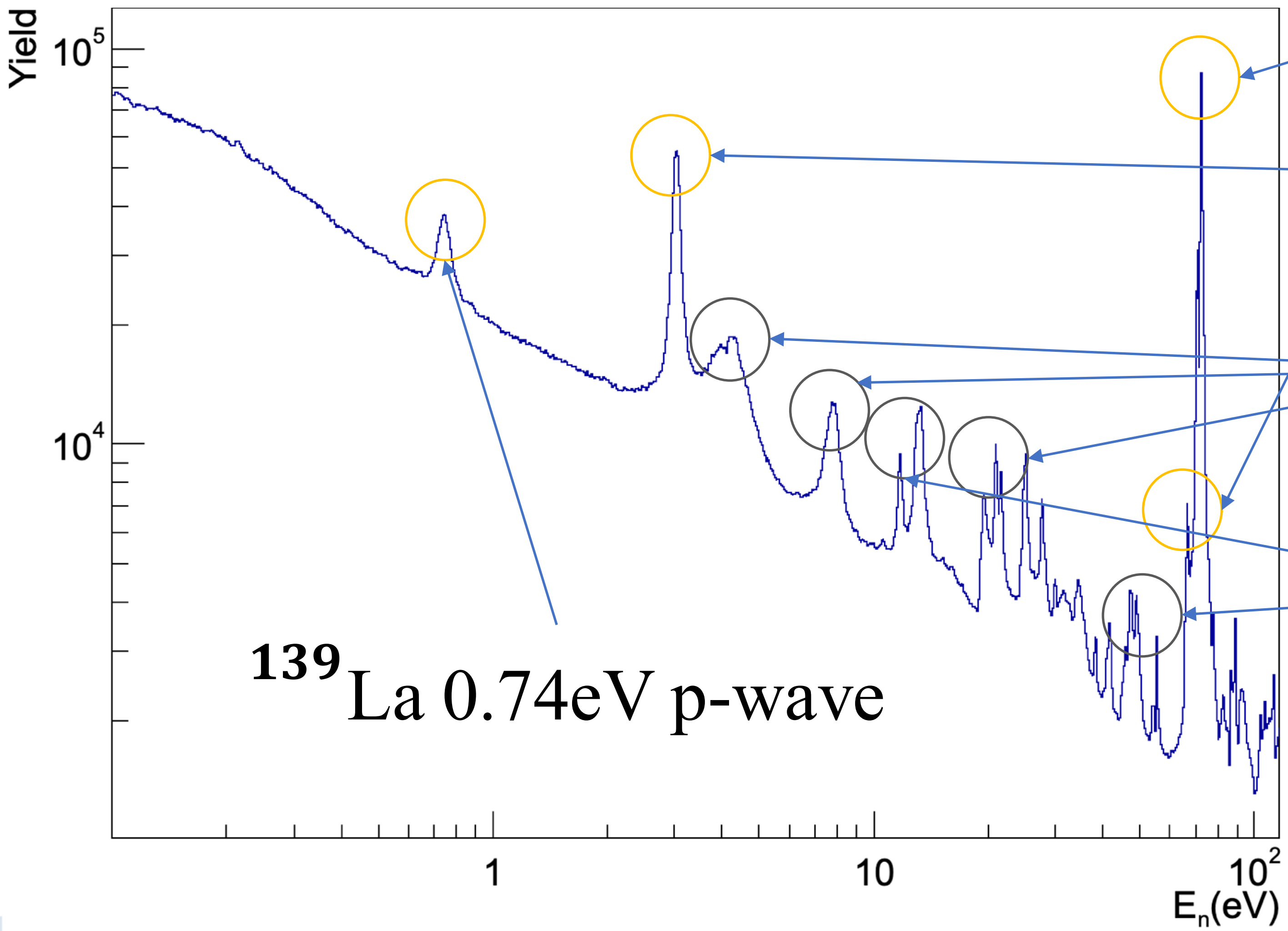
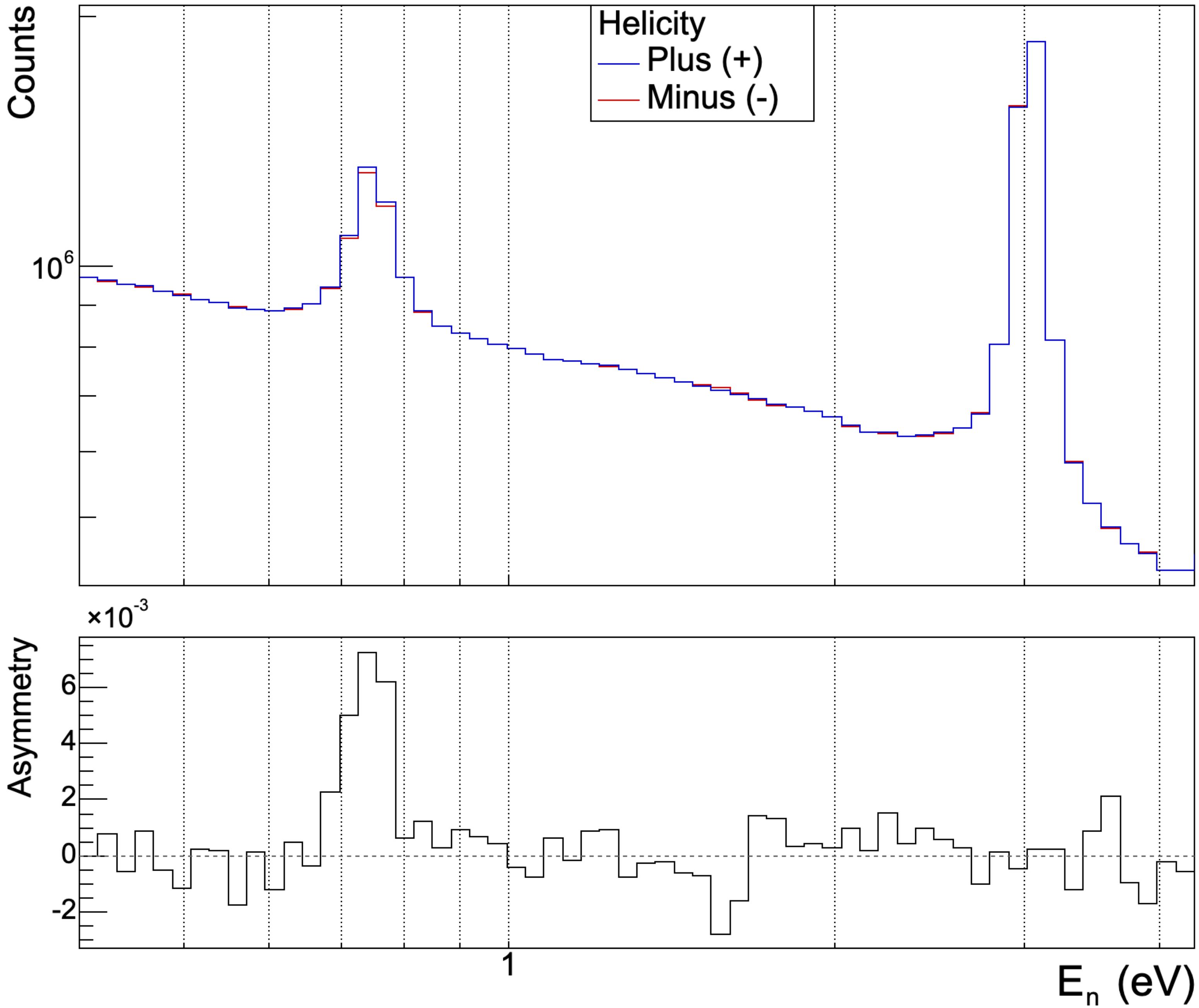
自旋输运系统（完全体）



^{139}La 中子能谱(2026.06)

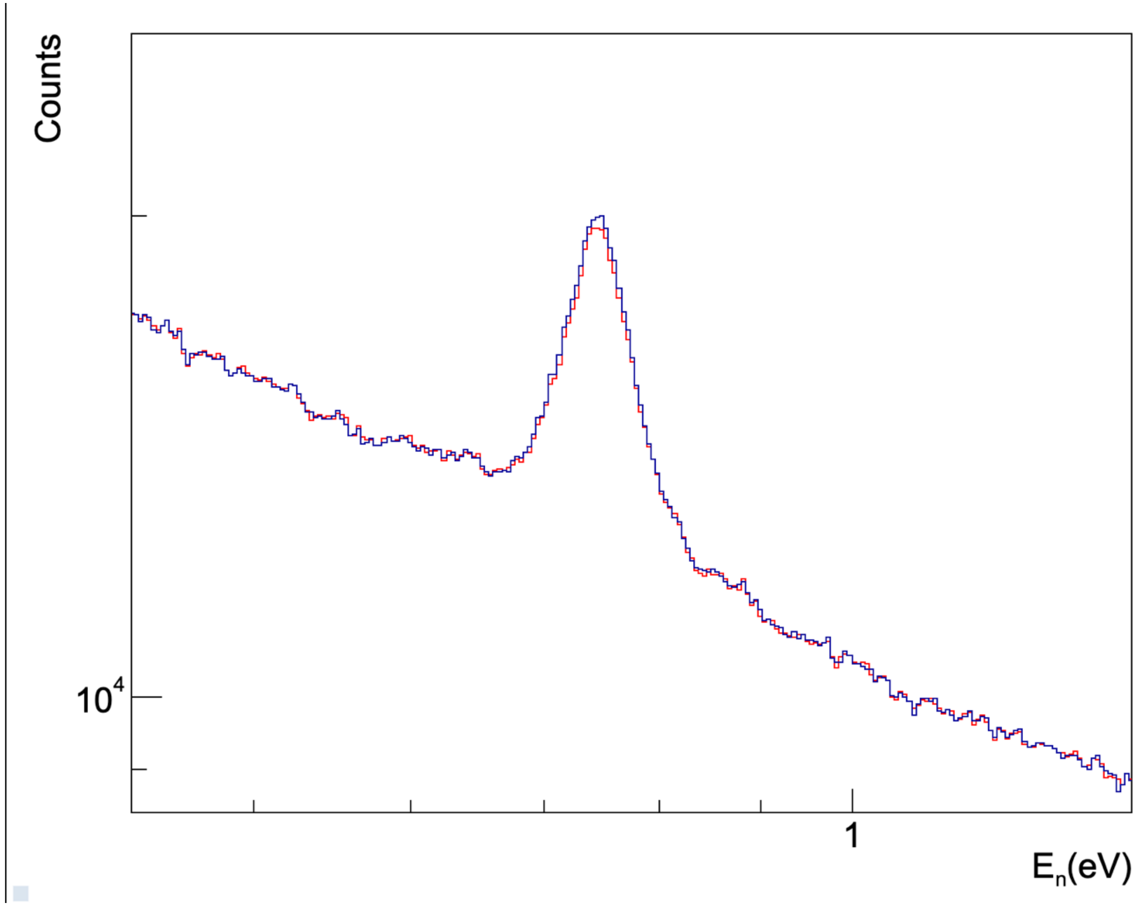


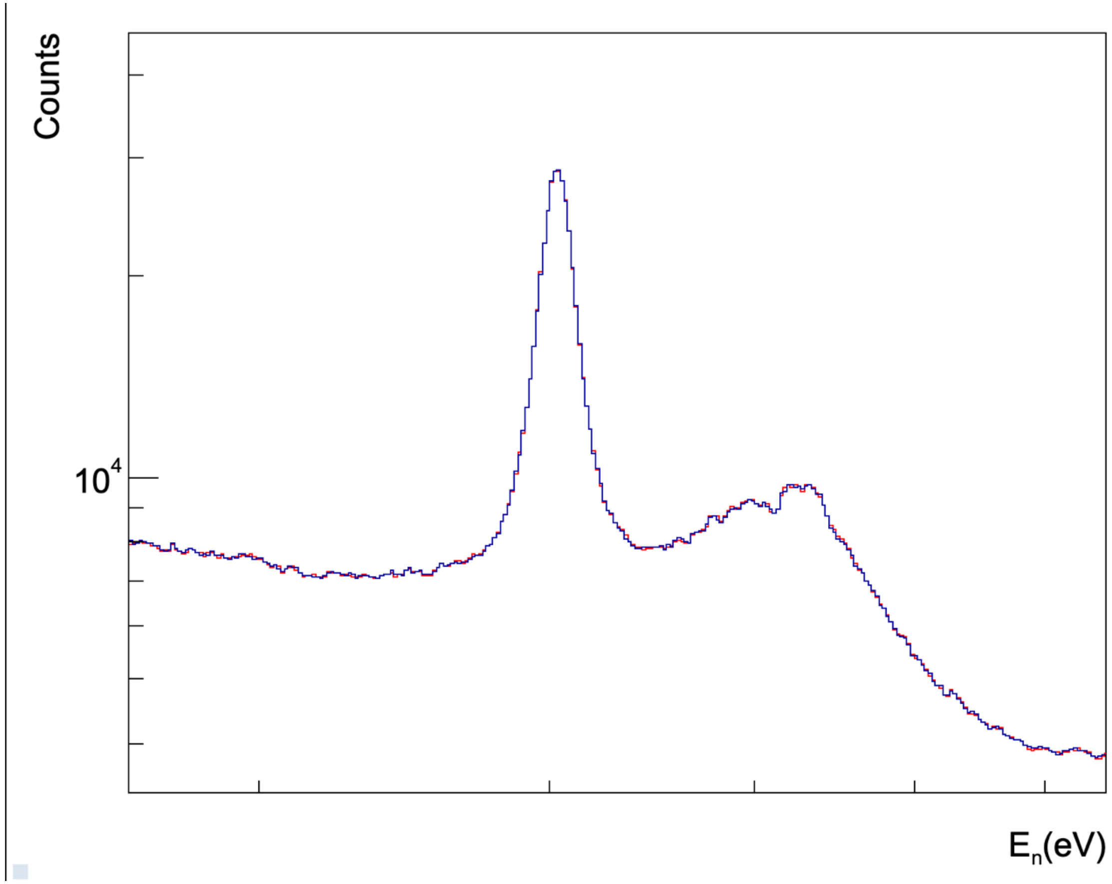
已归一中子注量率
（使用2025.10数据）


Counts
Helicity
Plus (+)
Minus (-)
10^6
×10^{-3}
Asymmetry
6
4
2
0
-2
1
E_n (eV)

PV初步分析(合并数据)

筛选条件:
- 多重性 >= 3
- 3MeV<加合能<8.5MeV





$A_{ideal}(0.74eV) = 4.3187\% \pm 3.9274\%$

$A_{ideal}(3\ to\ 4eV) = -0.0288\% \pm 0.7440\%$

2026.06 数据分析计划

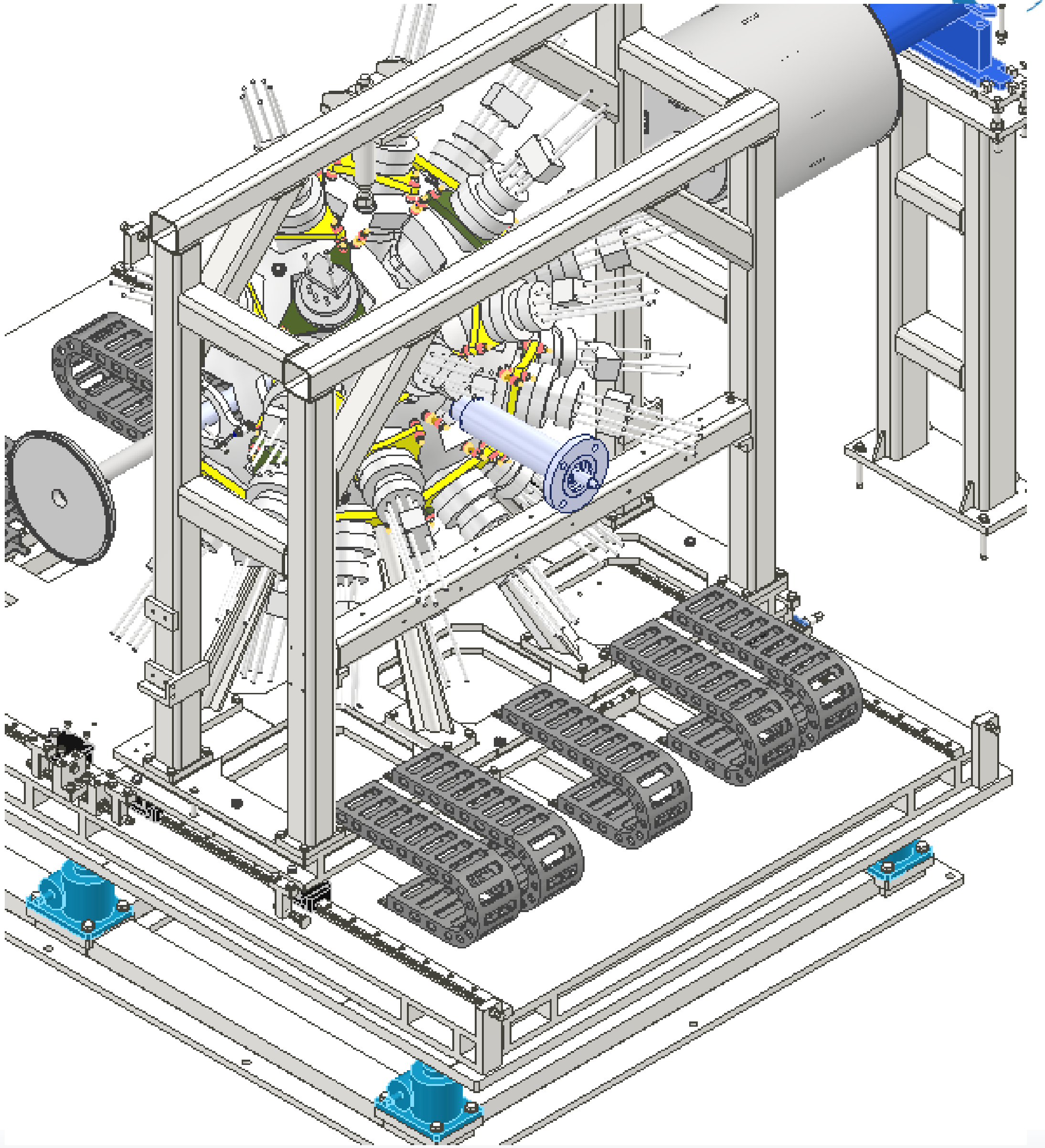
- 目标靶：140小时La、83小时Pd
- ^{6}Li 探测器数据分析->中子能谱归一
- 坪、空与C本底扣除
- 不对称性计算：
  - 合并数据：合并图、 按多重性分析
  - 8步分析：合并图、 按多重性分析

下一步：更冷一点

- 将靶降至约4K -> 降低多普勒展宽

- 第一阶段：核数据测量与装置验证。目标核素：La、Au

- 第二阶段：宇称不守恒测量+极化中子导致p-wave 峰位变化?
  - $\Delta E \sim 10^{-6}$eV [Gudkov&Bunakov1983]



合作单位

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Chinese Academy of Sciences

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山东大学
SHANDONG UNIVERSITY

SNS
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China Spallation Neutron Source

GBU
大湾区大学
Great Bay University

名古屋大学
NAGOYA UNIVERSITY

INDIANA UNIVERSITY
BLOOMINGTON

谢谢！