第二十届全国中高能核物理大会

在电子散射实验中研究丰中子氢同位素^{6}H

Study of the neutron-rich hydrogen isotope ^{6}H in an electron scattering experiment at MAMI-A1

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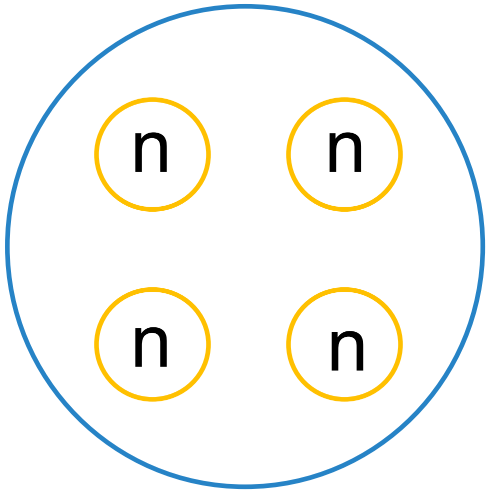
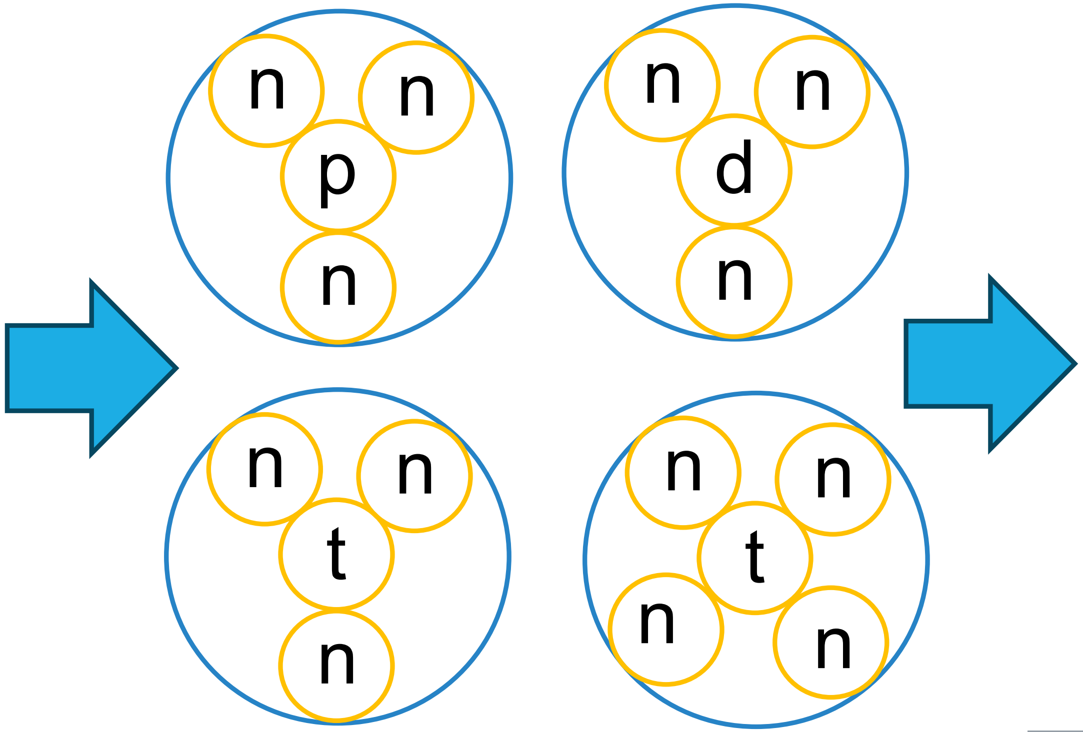
Based on PhysRevLett.134.162501

研究背景

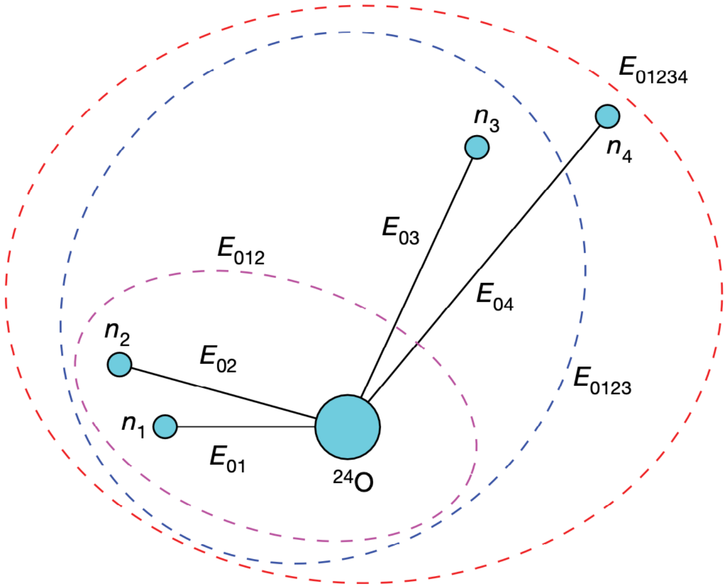
- 核子能够离开中子滴线多远？
- 丰中子环境下的核子间相互作用？
- 四中子态 ^4n，$^{27}O/^{28}O$ 等丰中子态在实验中被发现，如何理解它们的结构和其中的相互作用？

Nature 606, 678–682 (2022)





Nature 620, 965–970 (2023)



研究背景

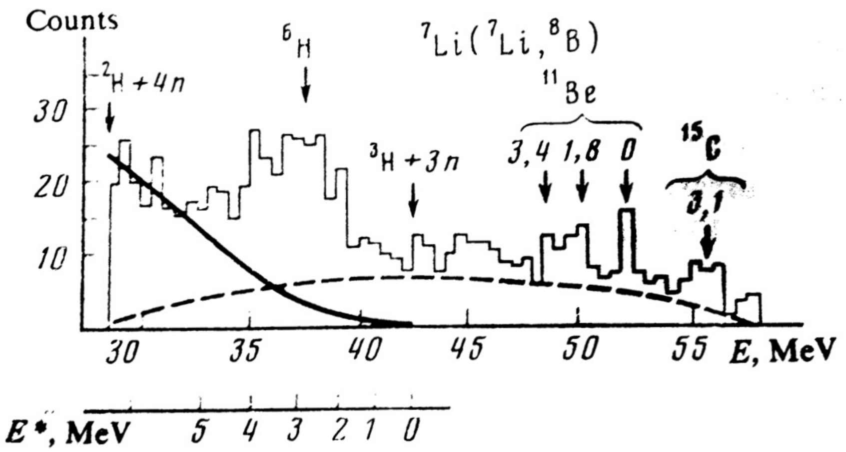
^{3}He z: 2 n: 1 Jπ 1/2+ $T_{1/2}$:stable	^{4}He z: 2 n: 2 Jπ 0+ $T_{1/2}$:stable	^{5}He z: 2 n: 3 Jπ 3/2- $T_{1/2}$:0.648 meV decay n ?%	^{6}He z: 2 n: 4 Jπ 0+ $T_{1/2}$:806.7 ms 1.5 decay β- 100%	^{7}He z: 2 n: 5 Jπ (3/2)- $T_{1/2}$:150 keV 20 decay n ?%	^{8}He z: 2 n: 6 Jπ 0+ $T_{1/2}$:119.1 ms 1.2 decay β- 100% β- n 16%
^{2}H z: 1 n: 1 Jπ 1+ $T_{1/2}$:stable	^{3}H z: 1 n: 2 Jπ 1/2+ $T_{1/2}$:12.32 y 0.02 decay β- 100%	^{4}H z: 1 n: 3 Jπ 2- $T_{1/2}$: decay n 100%	^{5}H z: 1 n: 4 Jπ (1/2+) $T_{1/2}$:5.3 meV 0.4 decay ec SF 100%	^{6}H z: 1 n: 5 Jπ ? $T_{1/2}$:1.55 meV 0.44 ?	^{7}H z: 1 n: 6 Jπ (1/2+) $T_{1/2}$:0.09 meV +94-6 ?

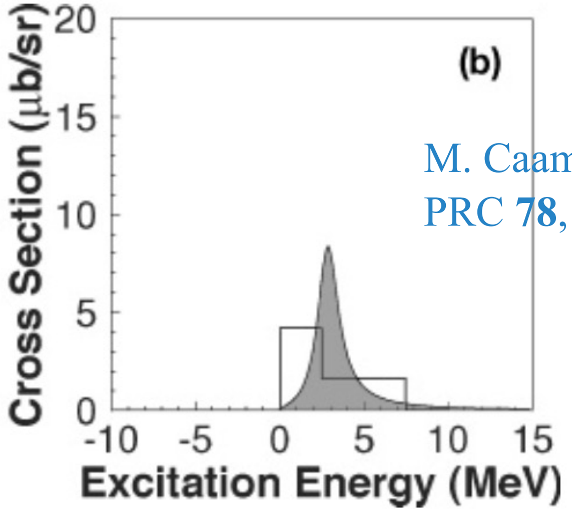
- ^{4}H, ^{5}H：研究较多，信号明显
- ^{6}H, ^{7}H：研究较少，信号模糊，结果相互冲突
- ^{6}H 和 ^{7}H 有着已知最大的中子数和质子数之比，是研究丰中子条件下的核子之间相互作用的理想平台。

研究背景

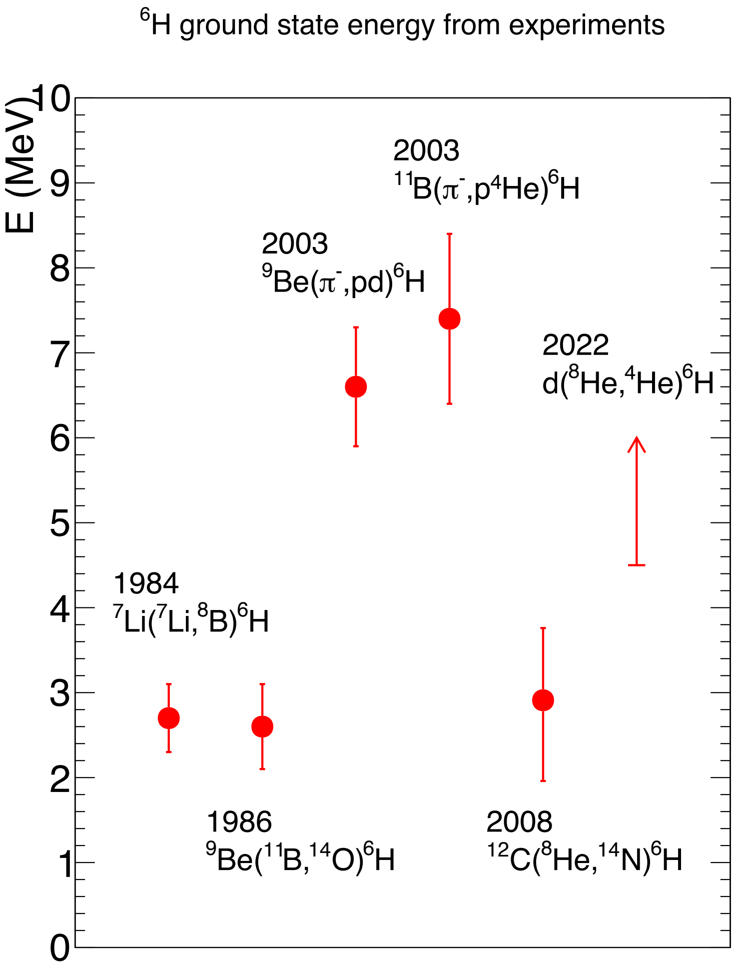
■ 历史上对 ^{6}H 的实验研究

D. Aleksandrov et al. , YF 39 (1984), pp. 513–517

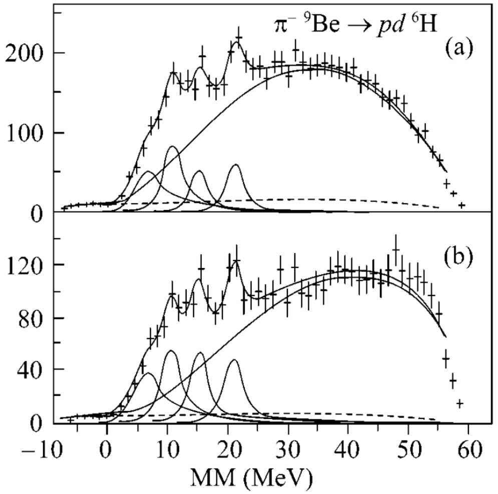




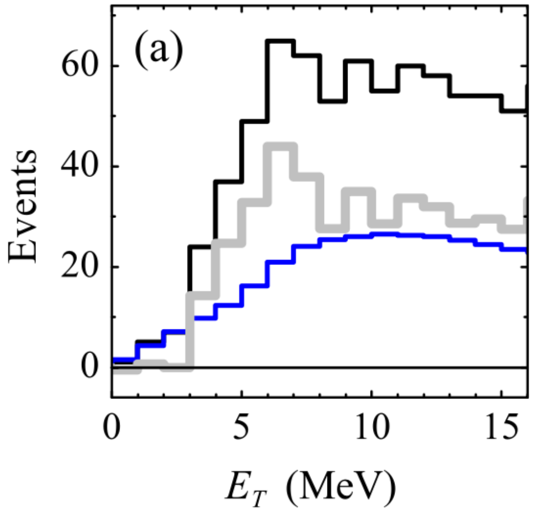
M. Caamaño et al. , PRC **78**, 044001 (2008)



Yu.B.Gurov et. al., JETP Letters, Vol.78, No.4, 2003, pp. 183-187

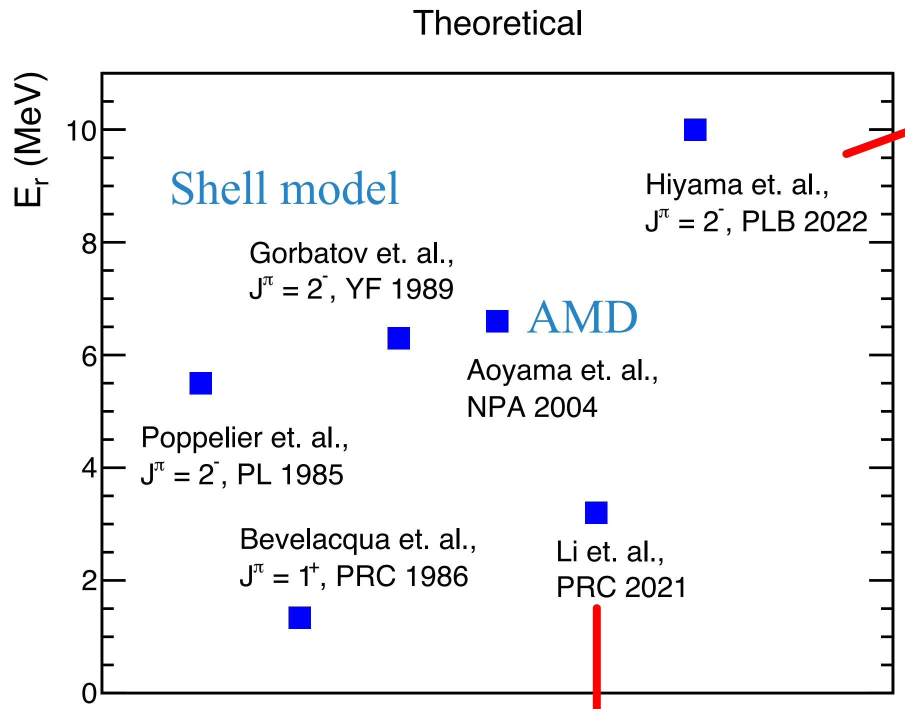


E. Yu. Nikolskii et al. , PRC 105, 064605 (2022)



研究背景

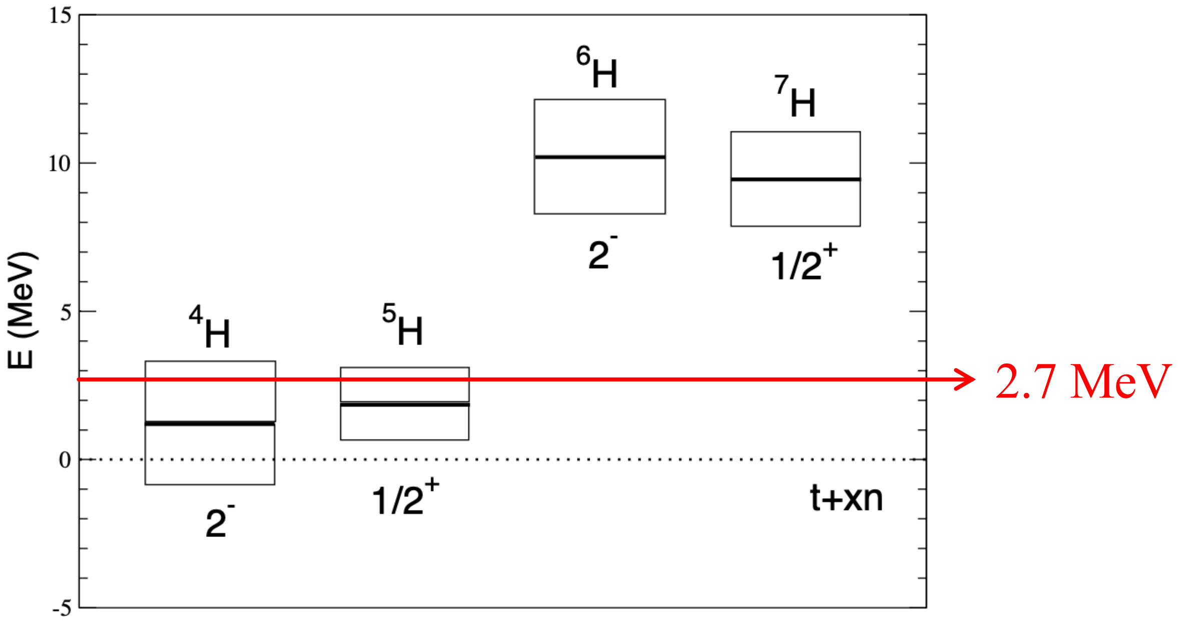
- 对 ^{6}H 的理论计算



IMP group, Physical Review C104 (2021) 6,
Gamow shell model

E. Hiyama et. al., Physics Letters B 833 (2022) 137367

With an effective n-t potential

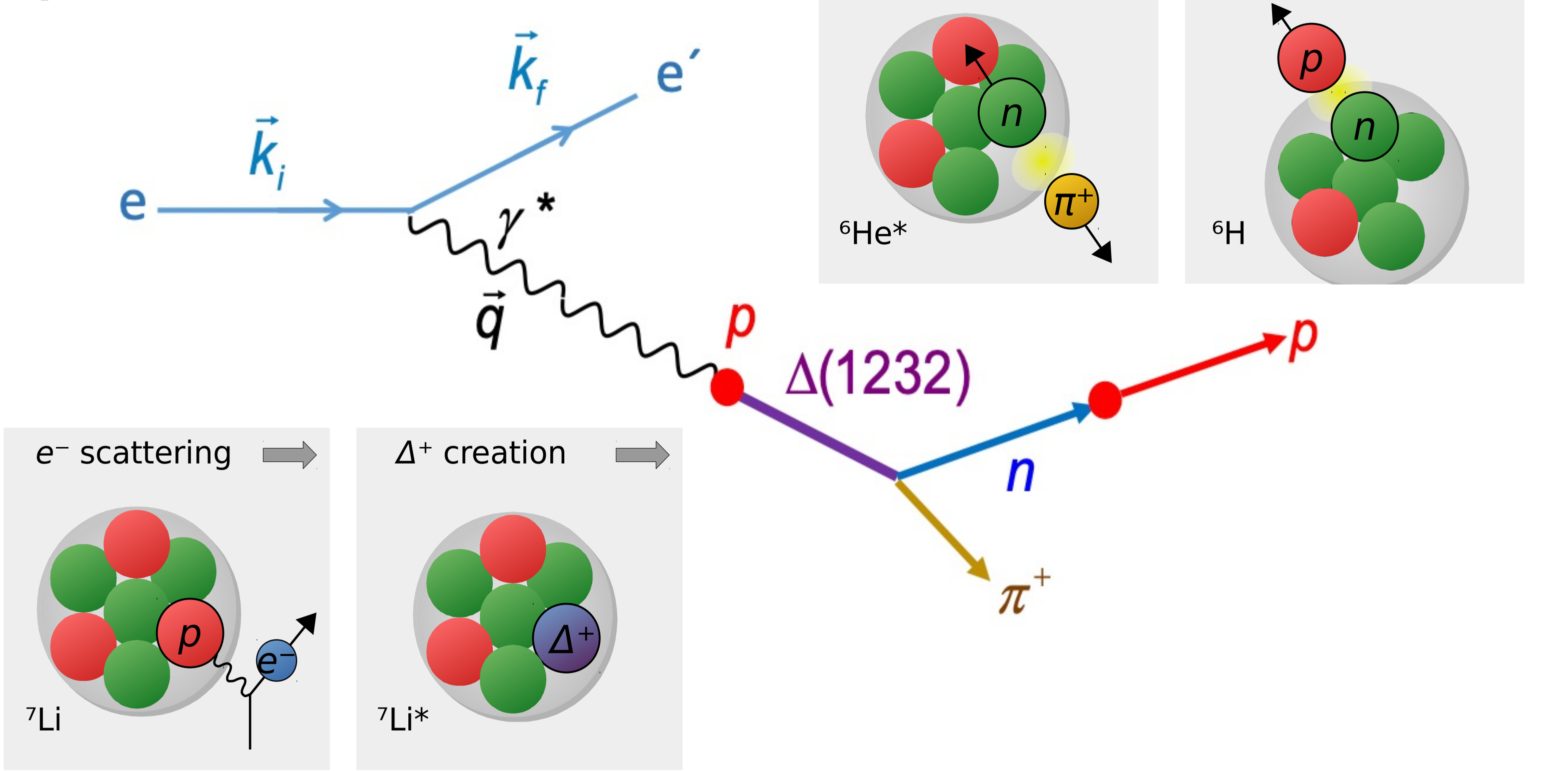


我们需要对^{6}H的精确测量

实验原理

- 核反应： $^{7}\mathrm{Li}(\mathrm{e},\mathrm{e}'\mathrm{p}\pi^{+})^{6}\mathrm{H}$
- 测量散射电子、反应中产生的质子和π^{+}的动量。重建该反应的丢失质量谱（miss-mass spectrum）。
- 预期产生率：在目标区间内约每天1个事例。
- 预期信号解析度：约1.2 MeV。

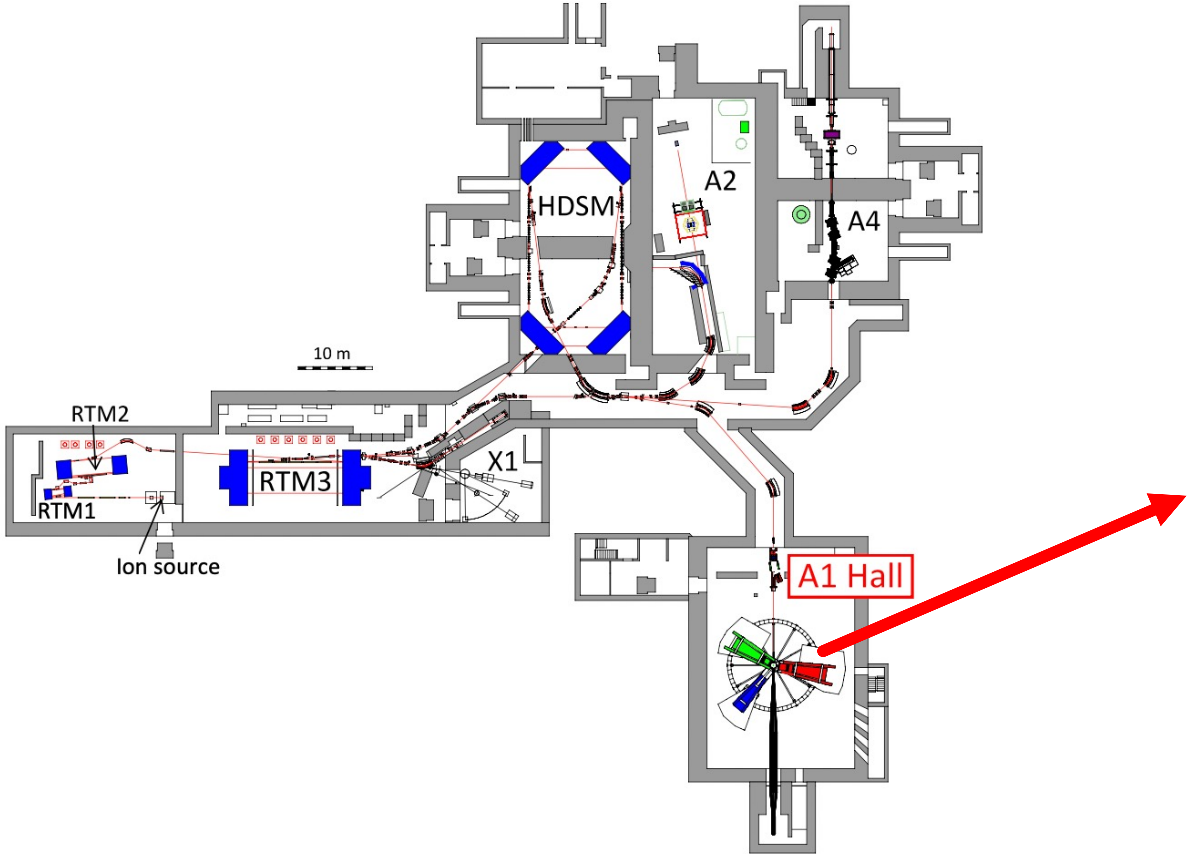
$$p + \gamma^{*} \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$

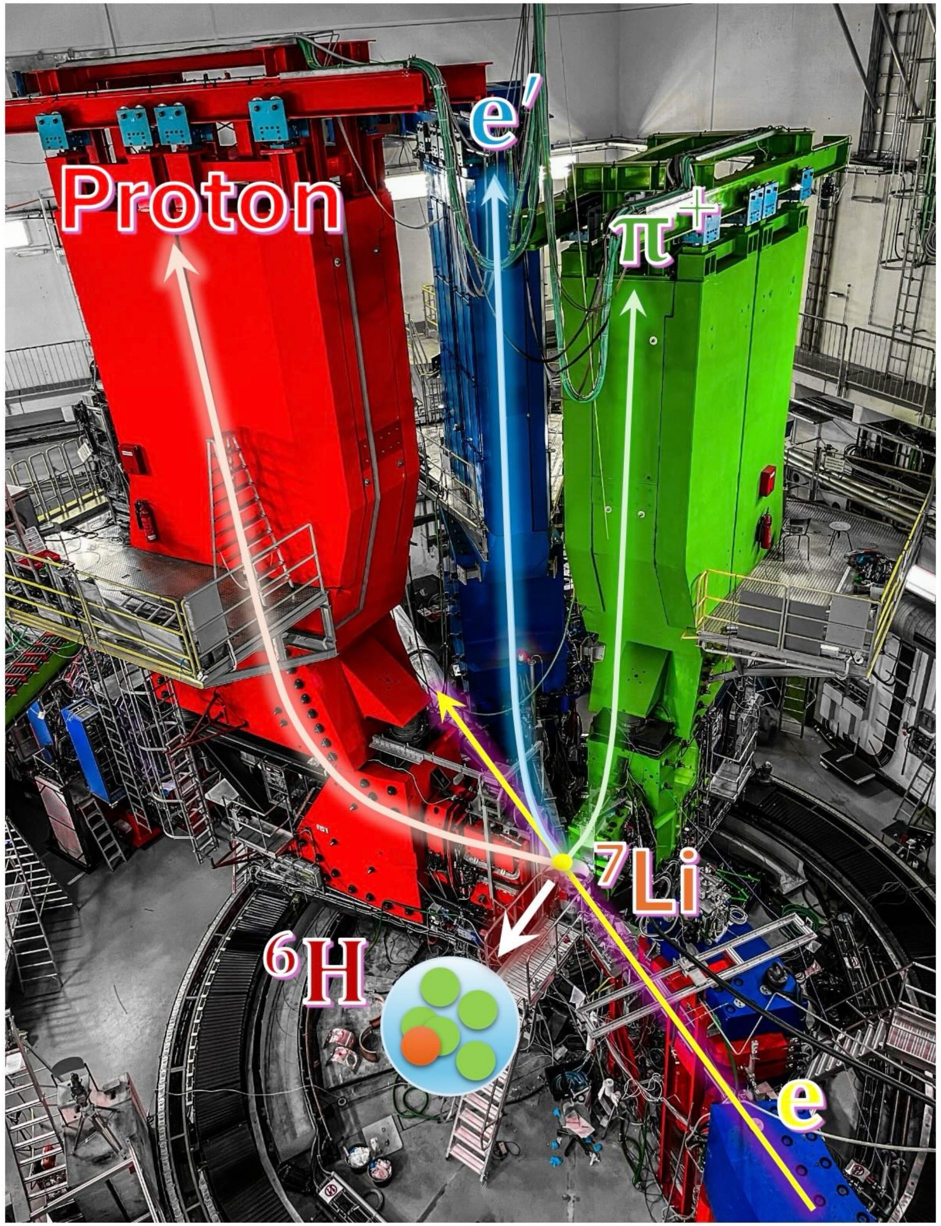


实验装置

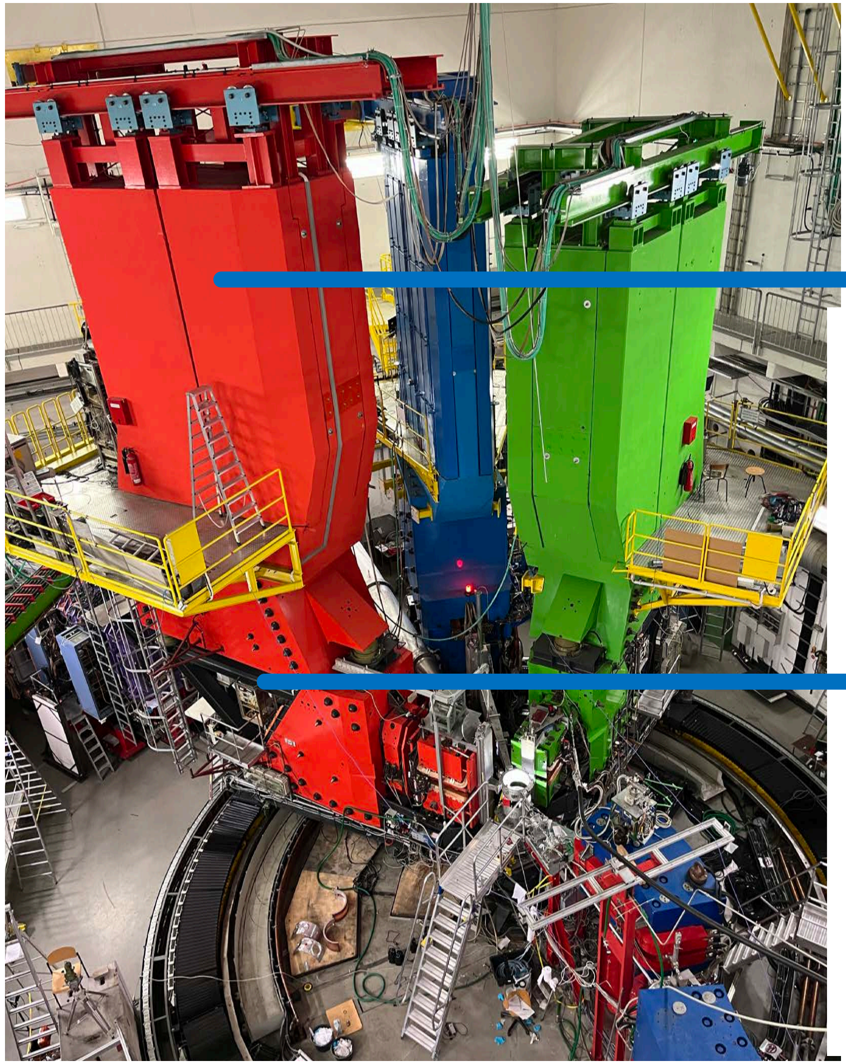
- 美因茨大学核物理研究所

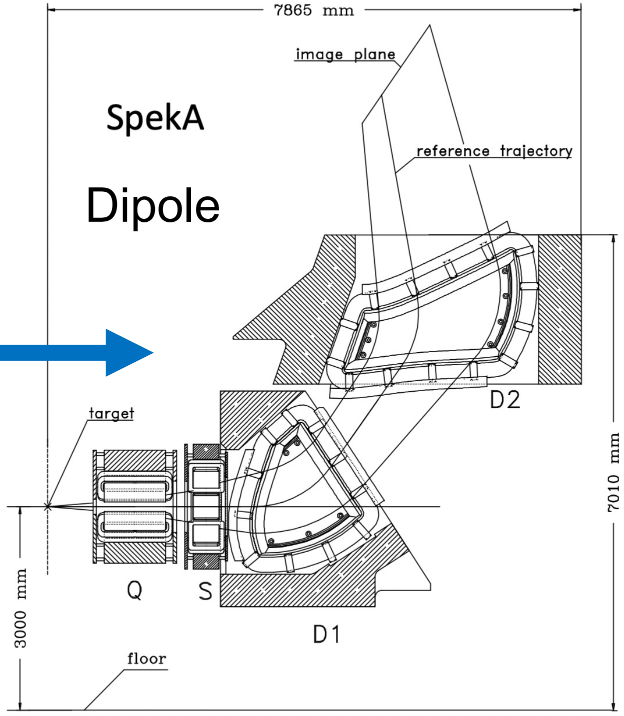
  美因茨加速器（MAMI）：855 MeV电子束流

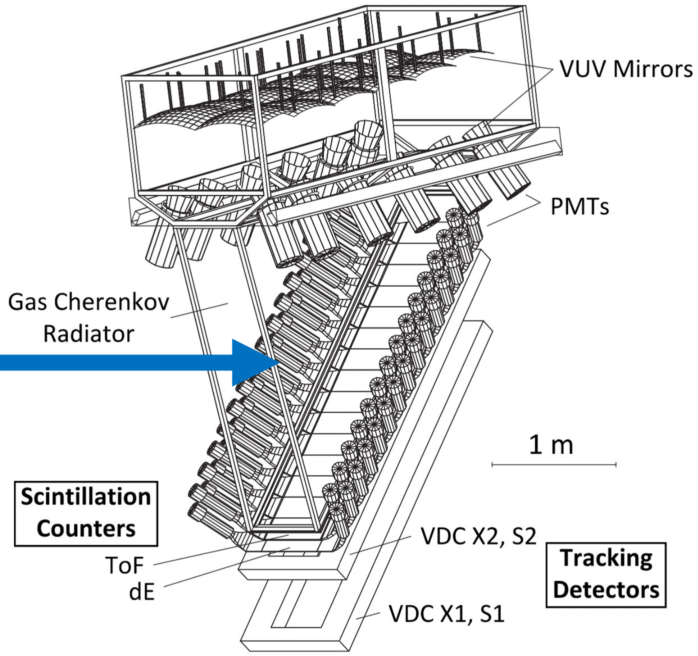




实验装置





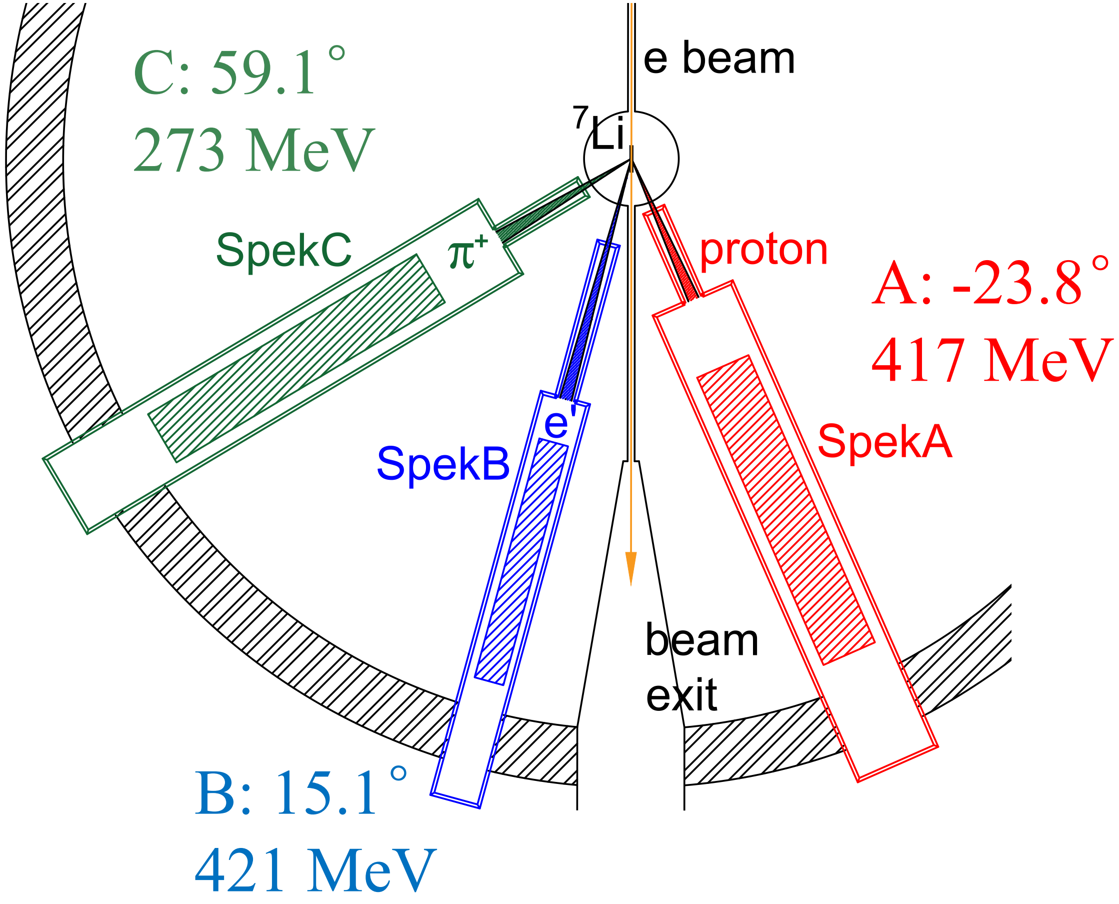


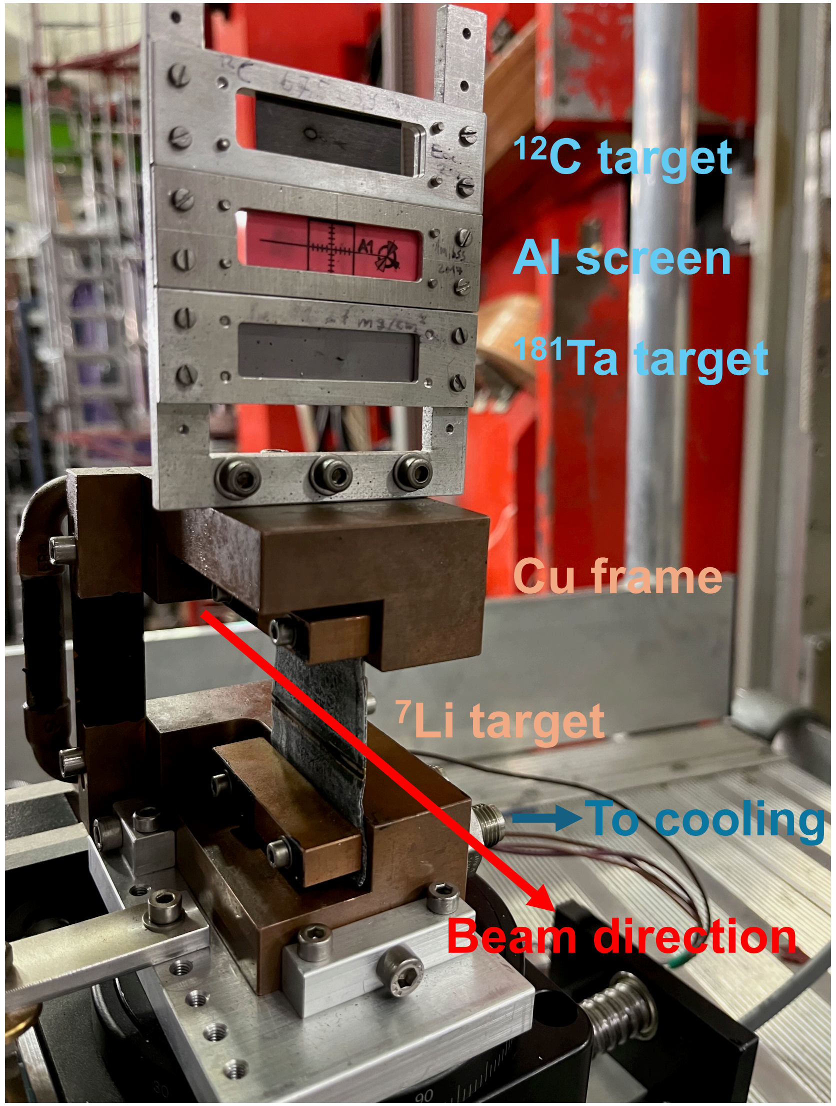
探测器系统：

- VDC：粒子径迹重建
- dE：能量损失测量
- TOF：能量损失、飞行时间测量
- Cherenkov：pion/电子鉴别

实验装置

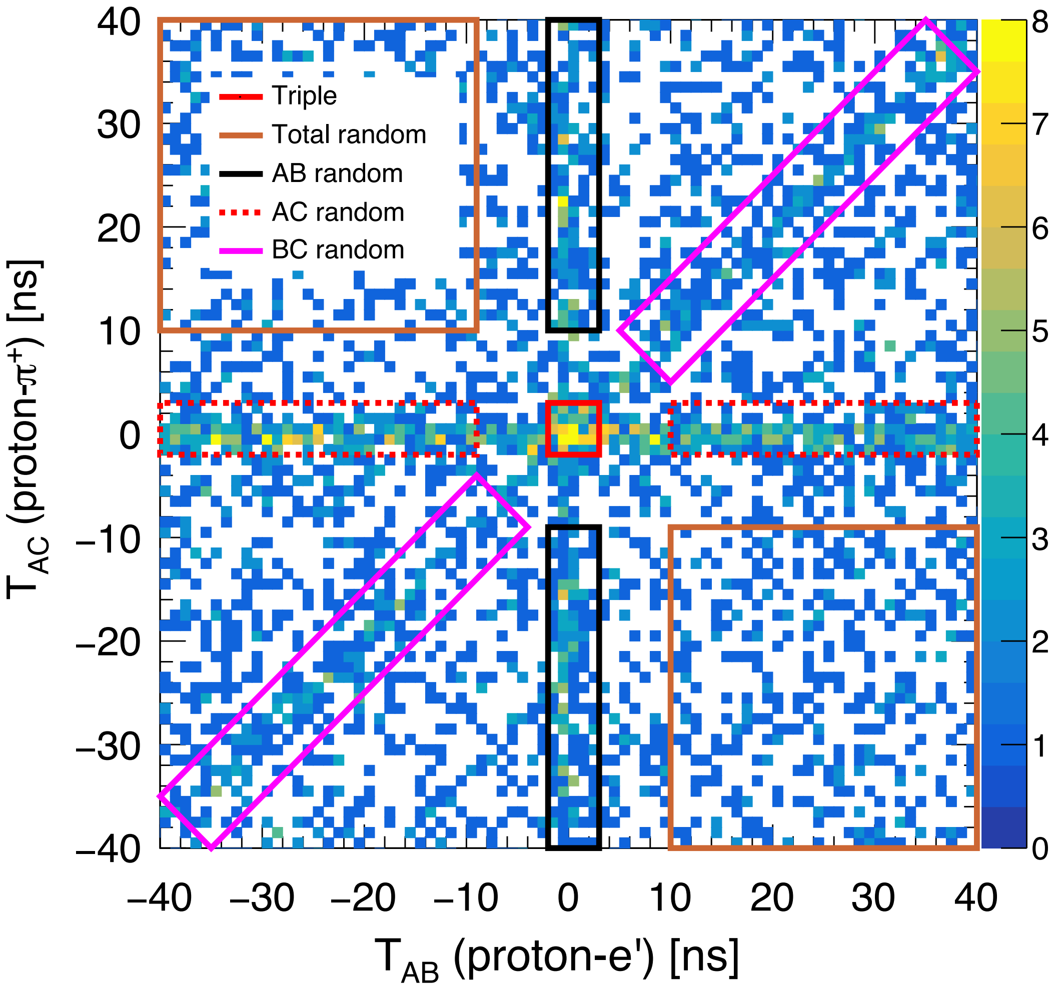
- run_2023: 92.7% natural Lithium,
- run_2024: 99.99% enriched Lithium-7

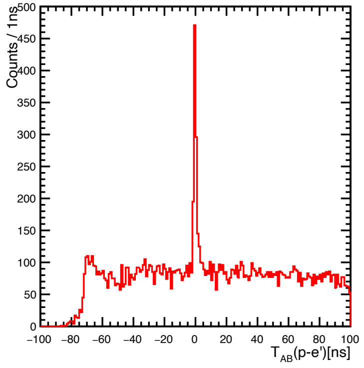


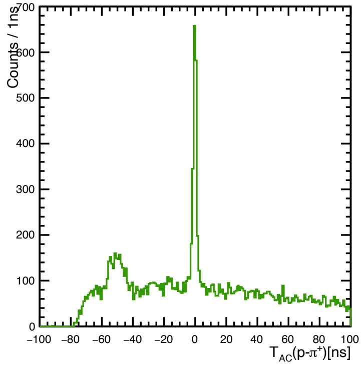


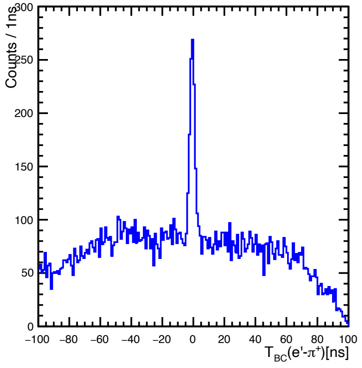
数据分析

- 选择位于三重符合区间的事例







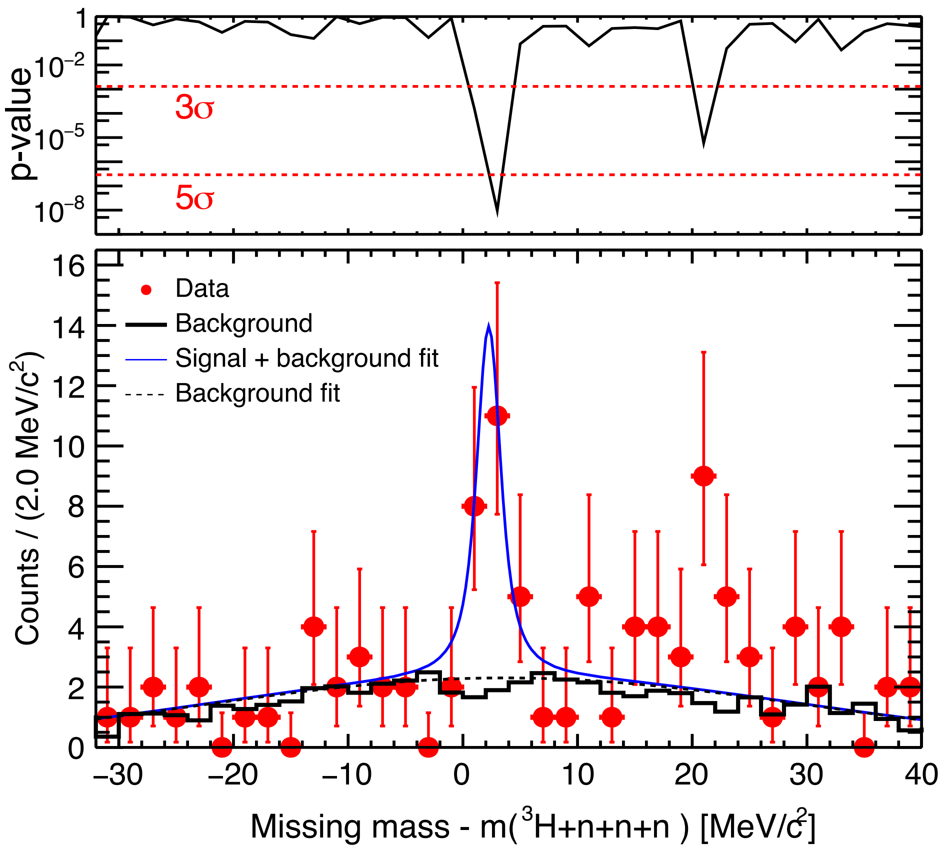


随机背景 = AB随机 + AC随机 + BC随机 – 2 × 完全随机

（根据选取区域的面积，缩放到三重符合区域）

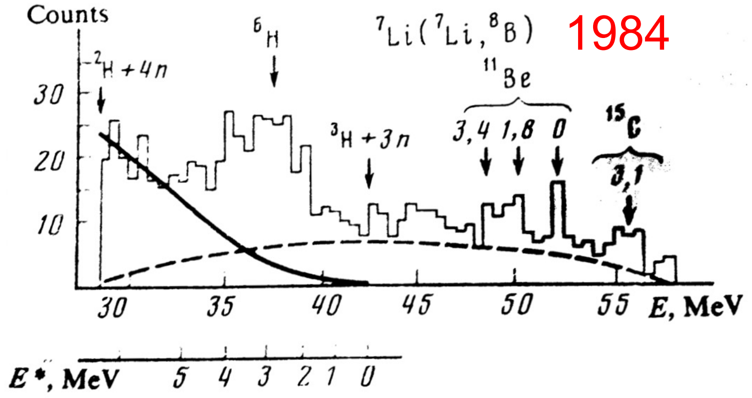
实验结果

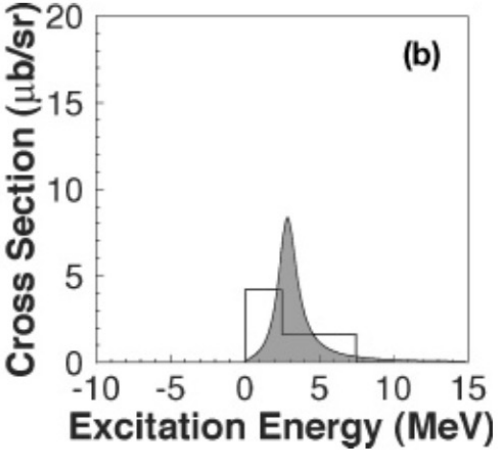
- ^{6}H能量分布：丢失质量信号 – 3H+n+n+n阈值。支持^{6}H基态能量较小。



$$E = 2.3 \pm 0.5\ (\text{stat.}) \pm 0.4\ (\text{syst.})\ \text{MeV},$$

$$\Gamma = 1.9 \pm 1.0\ (\text{stat.}) \pm 0.4\ (\text{syst.})\ \text{MeV}$$



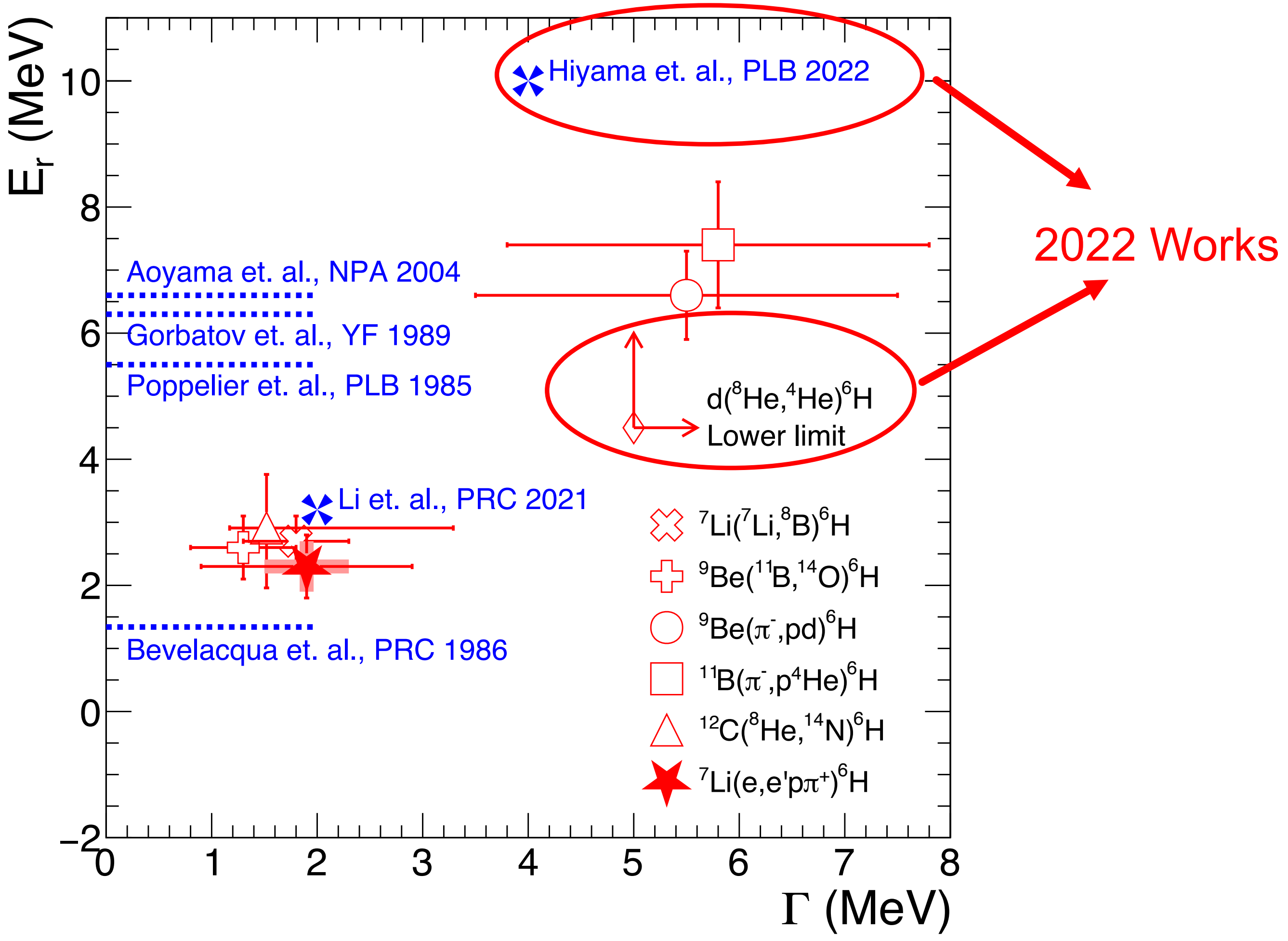


实验结果

- 首次在电子散射实验中观测到^{6}H信号。
- 测量得到的^{6}H基态能量和宽度远小于2022年最新的实验测量和理论计算结果，支持^{6}H基态能量较小，其中可能存在比预期中更强的中子之间相互作用。
- 期待更多的理论解释。
- 验证了电子散射产生丰中子核的可能性，可以推广到其它丰中子核实验。

$^6\mathrm{Li}(e,e'p\pi^+)^5\mathrm{H}$, $^4\mathrm{He}(e,e'p\pi^+)^3\mathrm{n}$,

$^7\mathrm{Li}(e,e'\pi^+\pi^+)^7\mathrm{H}$, $^4\mathrm{He}(e,e'\pi^+\pi^+)^4\mathrm{n}$



总结

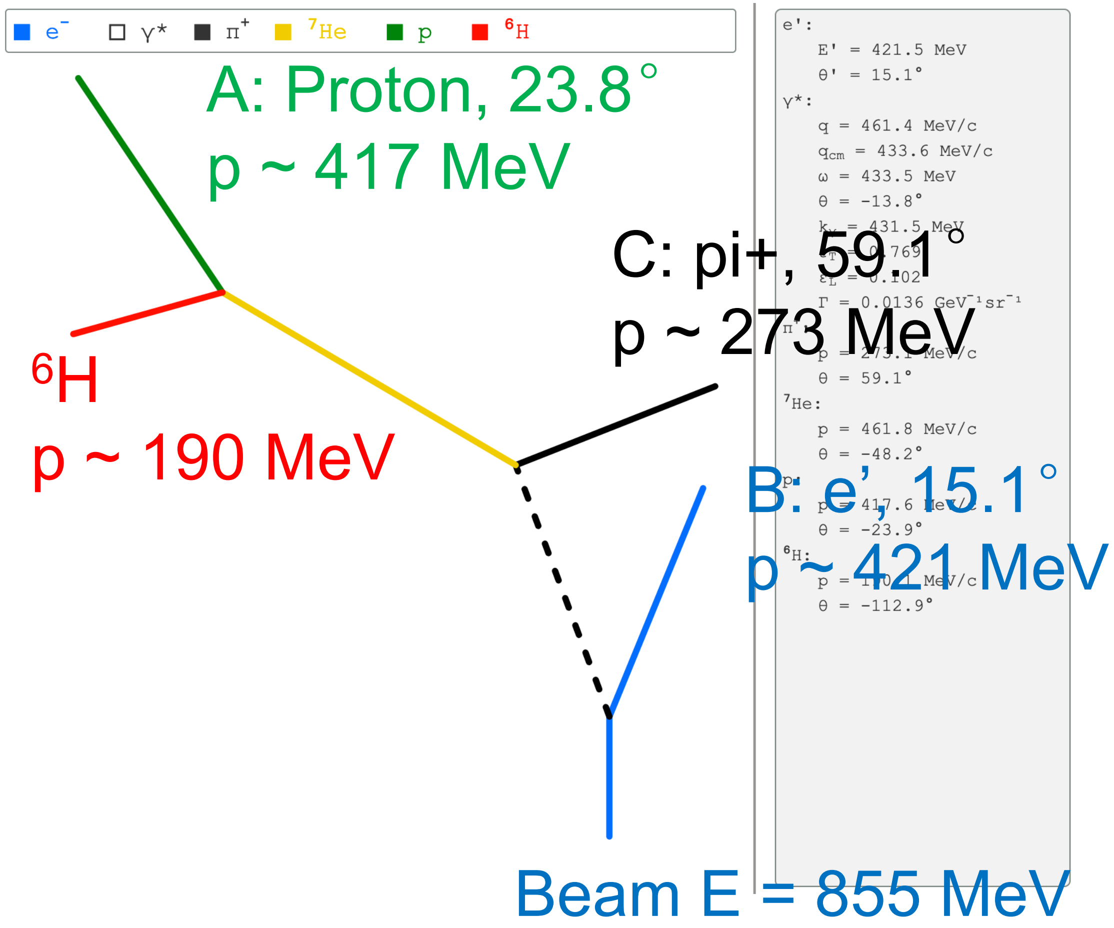
- 为了研究^{6}H基态能量上存在的难题，我们首次在电子散射实验MAMI-A1上产生了^{6}H。
- 测量得到的^{6}H基态能量和宽度远小于最新的实验测量和理论计算结果，其中可能存在比预期中更强的中子之间相互作用。
- 该电子散射实验方法有望推广到其它对丰中子核的研究中。

感谢合作组成员： Jinhui Chen, Josef Pochodzalla, Patrick Achenbach, Mirco Christmann, Michael O. Distler, Luca Doria, Anselm Esser, Julian Geratz, Christian Helmel, Matthias Hoek, Ryoko Kino, Pascal Klag, Yu-Gang Ma, David Markus, Harald Merkel, Miha Mihovilović, Ulrich Muller, Sho Nagao, Satoshi N. Nakamura, Kotaro Nishi, Fumiya Oura, Jonas Pätschke, Bj¨orn S¨oren Schlimme, Concettina Sfienti, Marcell Steinen, Michaela Thiel, Andrzej Wilczek, and Luca Wilhelm

Backups

MAMI-A1 setup

- Choice of kinematics: 1. W ~ 1200 MeV for proton to produce Delta$^+$(1232); 2. low momentum transfer to ^{6}H; 3. feasible with the setups of three spectrometers.



Optical properties of the A1 spectrometers

	units	A	B	C
Configuration	-	QSDD	D	QSDD
dispersive plane	-	point-ponit	point-ponit	point-ponit
non dispersive plane	-	parallel-ponit	point-ponit	parallel-ponit
Maximum momentum	[MeV/c]	735	870	551
Reference momentum	[MeV/c]	630	810	459
Central Momentum	[MeV/c]	665	810	490
Solid Angle	[msr]	28	5.6	28
Scattering Angle	-	-	-	-
minimum angle	-	18°	7°	8°
maximum angle	-	160°	62°	160°
Momentum acceptance	-	20%	15%	25%

Beam time summary

Date	July 2023	July 2023	Sep 2023	April 2024
Beam energy (MeV)	855	855	855	855
Beam current (nA)	400	400	400	700
Kinematic	1	2	2	2
Target	Natural Li	Natural Li	Natural Li	Enriched ^{7}Li
Target length (cm)	4.5	4.5	4.5	2.5
Target width (mm)	0.75	0.75	0.75	1.0
Effective time	~ 120 h	~ 120 h	~ 160 h	~ 160 h

Kinematics 1

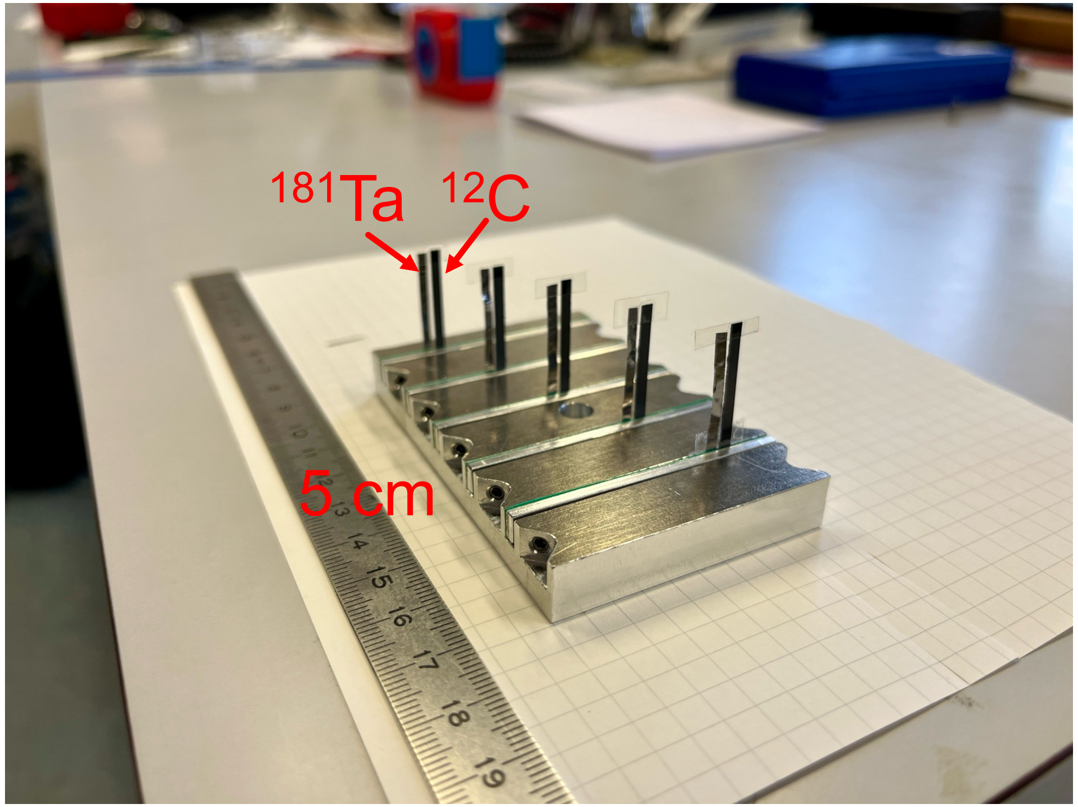
Spectrometer	Degree (°)	Momentum (MeV/c)
A (proton)	-23.8	379
B (e’)	15.1	531
C (π^+)	59.1	162

Kinematics 2

Spectrometer	Degree (°)	Momentum (MeV/c)
A (proton)	-23.8	417
B (e’)	15.1	421
C (π^+)	59.1	273

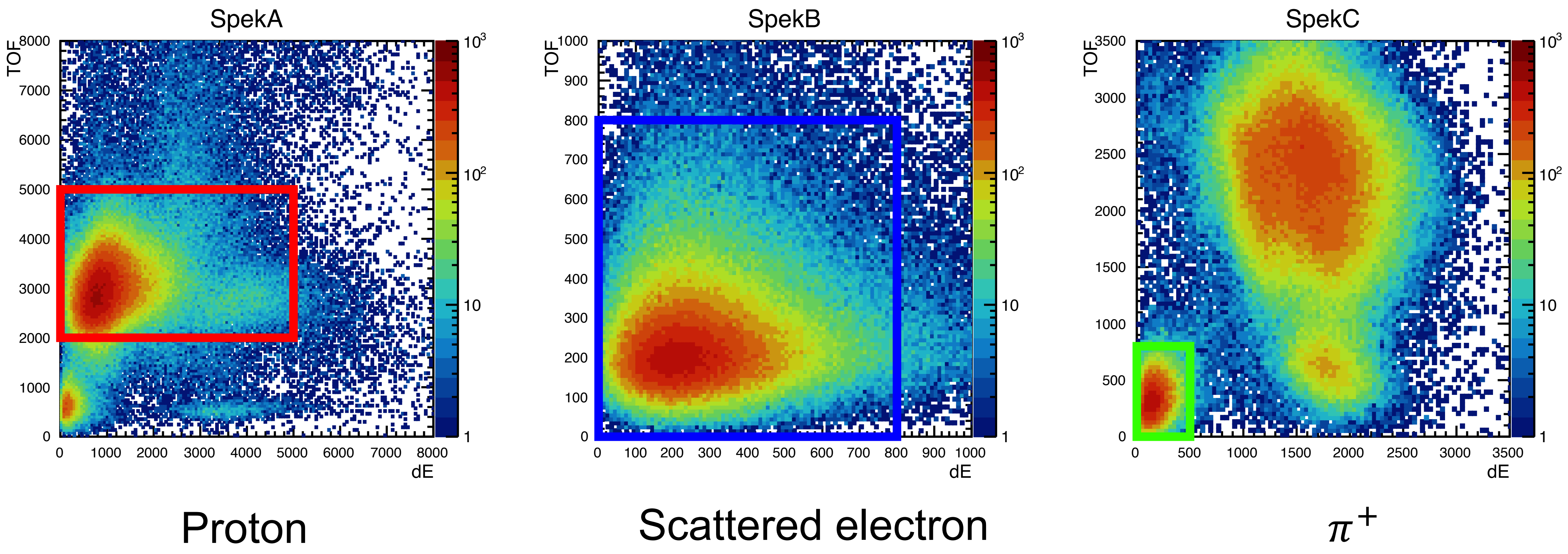
Momentum calibration

- Principle： Electron scattering with ^{181}Ta and ^{12}C target. Compare with the certain input momentum the correction factors can be obtained.
- Ebeam (MeV) = 180, 195, 210 with undulator (~10keV uncertainty); 225, 420 without undulator (~160 keV uncertainty)
- Electron scattering with several target positions and momentum settings.
- Calibration beam time has been done in May 2024.



Data analysis

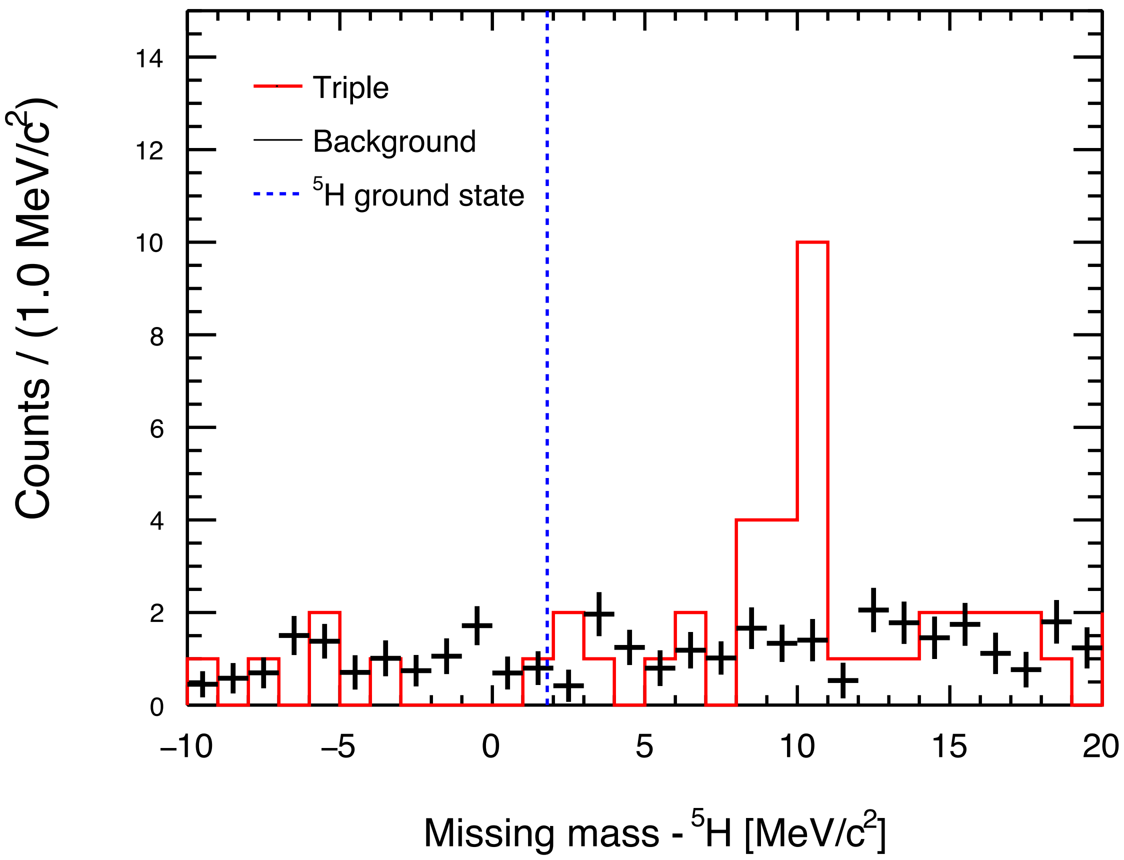
- Particle identification: according to the energy loss in scintillators.



Data analysis

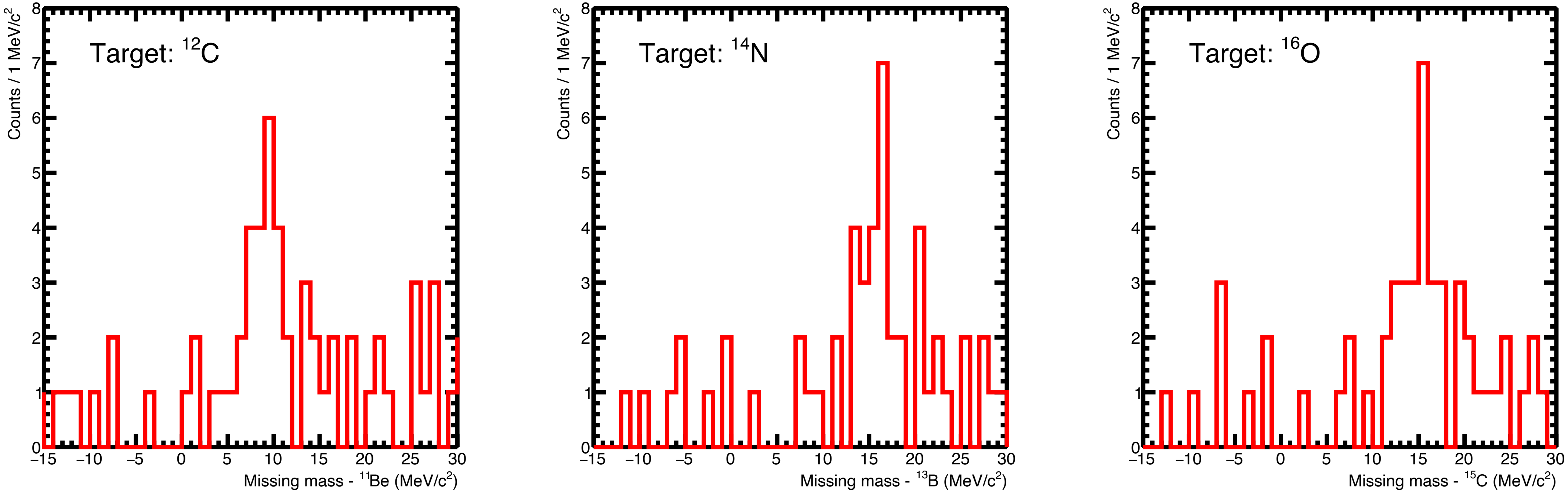
- Can the signal come from ^6Li which can produce ^5H? About 7.3% ^6Li in natural lithium.
- The peak near 3 MeV can also be seen with enriched ^7Li target.
- Replace ^7Li with ^6Li in analysis. The energy is about 10 MeV, which is much large than ^5H ground state ~ 1.8 MeV.

Reaction: $^6Li(e, e'p\pi^+)$



Backup

- Can the signal come from the C, N, and O in air?
- Replace the target with C, N, or O. The obtained energies are also much larger than ground states.



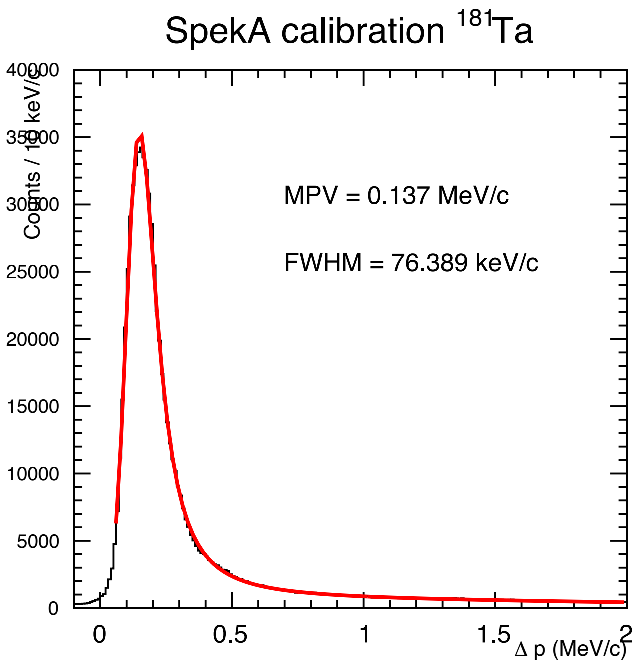
Backup: Momentum calibration

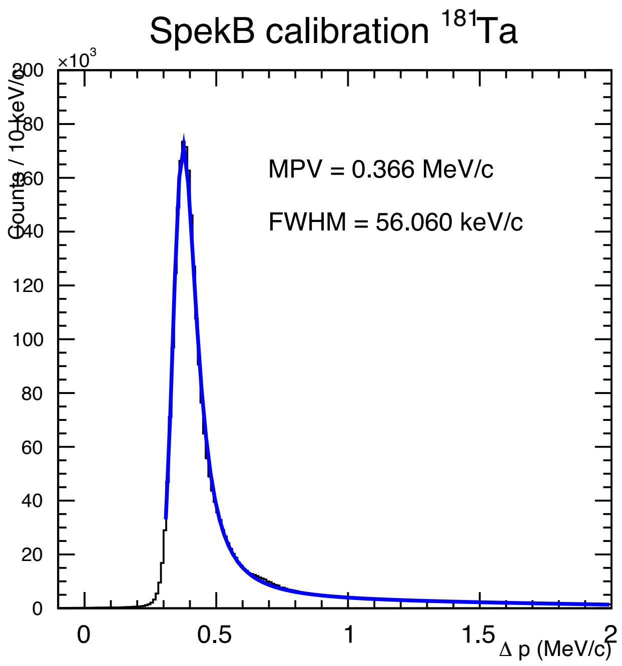
- Scattering electron on ^{181}Ta target
- $\Delta p = p_{in} - p_{measured}$, energy losses in target and detector system are considered.
- Fit function: Landau (energy loss) and Gaussian (detector resolution) convolution.

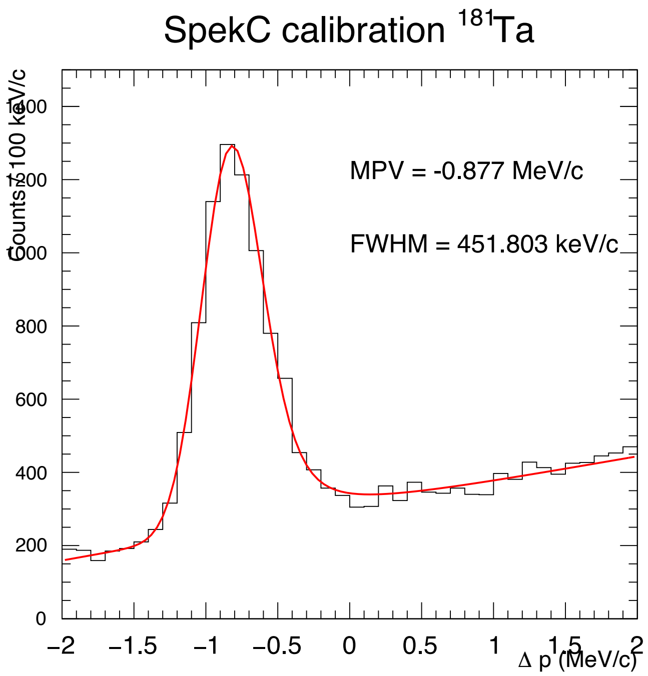
Spectrometer	Δp (MeV/c)	Correction factor
A	0.136821	1.00032587
B	0.36578	1.00087166
C	-0.87746	0.99791517

Momentum calibration

- Scattering electron on ^{181}Ta target
- $\Delta p = p_{in} - p_{measured}$, energy losses in target and detector system are considered.
- Fit function: Landau (energy loss) and Gaussian (detector resolution) convolution.







Momentum calibration

- Correction factor check: missing mass spectrum of ^{12}C ground and excited states.