

Screeener3D: 大幅面低本底 带电粒子谱仪研制

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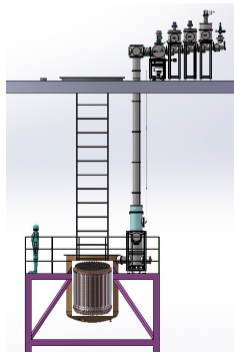
稀有事件实验中的材料表面放射性问题

- 稀有事件实验：探测器本底水平直接决定物理灵敏度
- 放射性洁净度要求=块材洁净+表面洁净
 - 零件机械加工、组装调试、氦气及其子核→表面二次污染
- 表面污染直接、间接引入本底
 - 表面污染释放的 α 、 β 粒子→本底事件（CUORE、CDMS等）
 - 表面污染源→转移到灵敏体积→本底事件（PandaX、JUNO等）

Summary of ER and NR backgrounds		
Source	ER in mDRU	NR in mDRU
Materials	0.0210 ± 0.0042	$2.0 \pm 0.3 \cdot 10^{-4}$
^{222}Rn	0.0114 ± 0.0012	-
^{85}Kr	0.0053 ± 0.0011	-
^{136}Xe	0.0023 ± 0.0003	-
Neutrino	0.0090 ± 0.0002	$0.8 \pm 0.4 \cdot 10^{-4}$
Sum	0.049 ± 0.005	$2.8 \pm 0.5 \cdot 10^{-4}$
2-year yield (evts)	1001.6 ± 102.2	5.7 ± 1.0
after selection (evts)	2.5 ± 0.3	2.3 ± 0.4

PandaX-4T实验

氦气贡献电子反冲（ER）本底，氦气主要来源于探测器和相关管路材料表面的氦释气。



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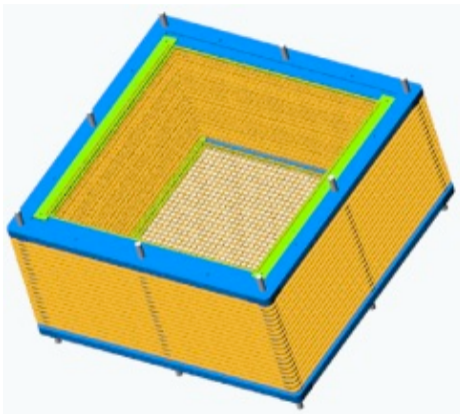
JUNO 实验

- 2万吨液体闪烁体，巨型亚克力球形容器
- 亚克力表面Rn放射性是关键问题
- 亚克力拼接前的放置、拼接后的清洗效果等，都需要定性测量表面放射性

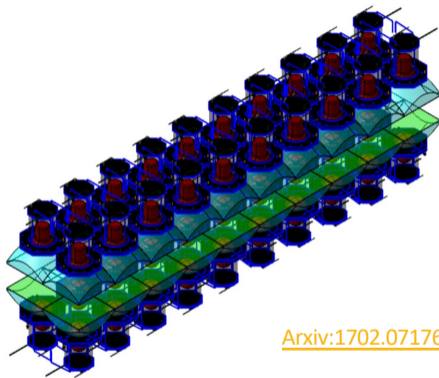


仪器与方法	典型对象	典型精度	设备举例	备注
高纯锗 (HPGe) γ 谱线分析	高纯无氧铜内的 ²³⁸ U和 ²³² Th	1-10 μ Bq/kg (10 ⁻⁸ -10 ⁻⁹ g/g)	清华GeTHU; 意大利GeMPI	无损检测, 对样品没有任何影响
中子活化分析 (NAA)	特氟龙内的 ²³⁸ U和 ²³² Th	10 ⁻¹⁰ -10 ⁻¹¹ g/g	美国MIT, UC Davis 中子活化设施	需要利用中子辐照; 测量窗口短
电感耦合等离子体质谱仪 (ICP-MS)	高纯无氧铜内的重元素	10 ⁻¹² g/g	美国PNNL实验室; 国内多家单位	克量级取样; 复杂化学预处理
带电粒子谱仪 (CPS)	大面积材料表面放射性	10 ⁻⁴ -10 ⁻² Bq/m ²	法国BiPo-3; XIA公司 Ultralo 1800	对材料表面的 α 粒子, 电子放射性灵敏

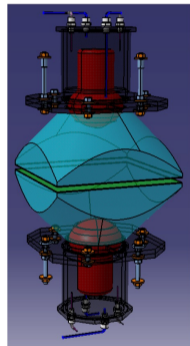
国际研究现状



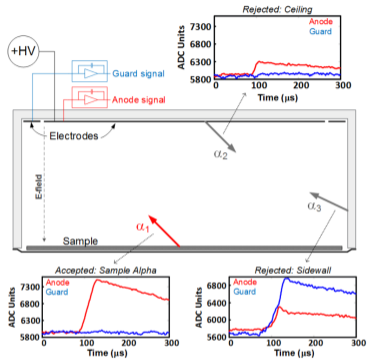
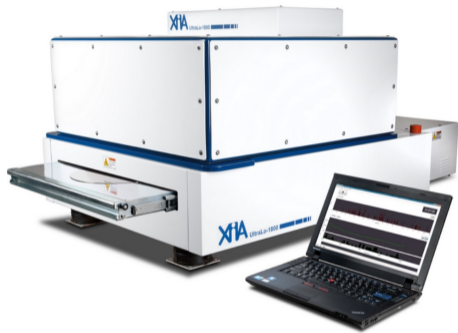
BetaCage: CDMS实验组提出的低本底MWPC设计, 未能实现



[Arxiv:1702.07176](https://arxiv.org/abs/1702.07176)



BiPo-3: SuperNEMO实验组设计建造PMT阵列, 测量Bi-Po耦合

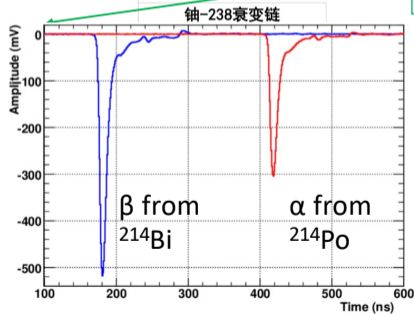
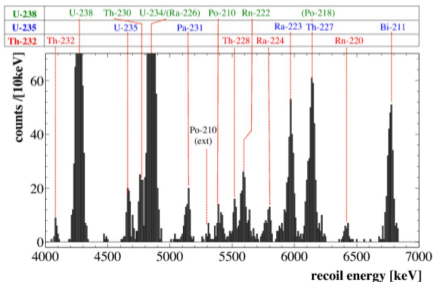
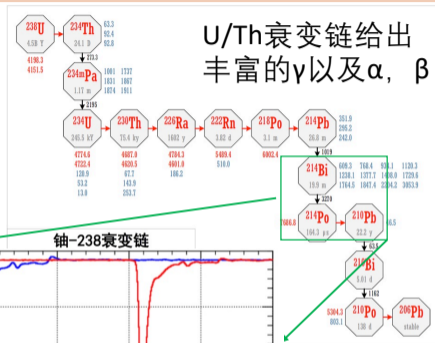


XIA Ultralo-1800: 主要针对半导体硅片测量;
9%FWHM@4.6MeV; 5×10^{-4} c/cm²/hr, 满足硅片 5α 每天的要求

Canberra LB4200: 最大5寸硅片; 约 10^{-2} c/cm²/hr

利用其放出的 α/β 粒子, 测量材料表面放射性

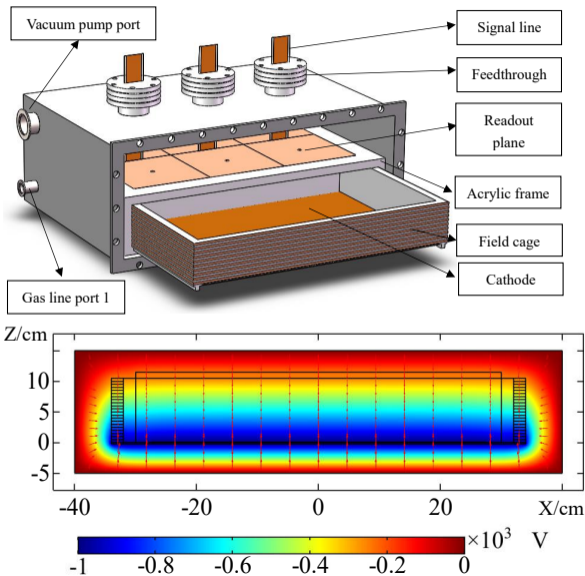
- 高能 α 粒子的特征谱线可用于分辨不同表面污染
- β 测量针对无 γ 释放 (如 ^{209}Pb) 或者 γ 强度很小 (如 ^{210}Pb) 的同位素
- 同时测量 α, β 的Bi-Po耦合技术



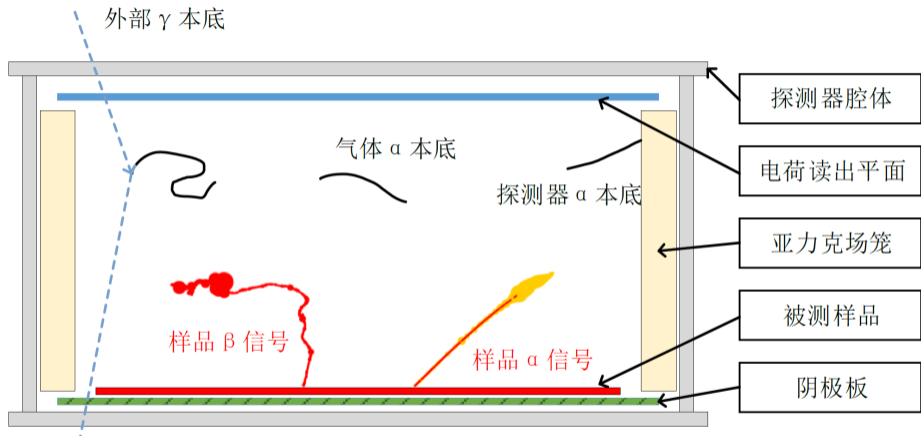
CRESST 实验测量的 α 粒子谱线

探测器概念设计

- 常压氙气、氙气 (0.5-1.5 bar)
时间投影室探测器 (TPC)
- $40 \times 60 \text{ cm}^2$ 电荷读出平面; 10cm
漂移距离
- 基于Micromegas + AGET的多通道读出
- 平板型样品直接放置于阴极板上方, 保证 α 能量完全沉积到TPC中

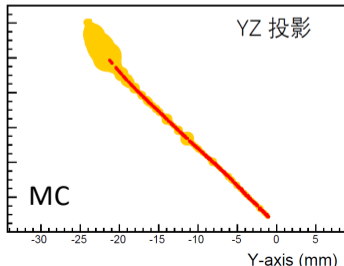
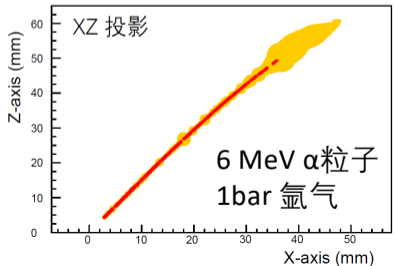
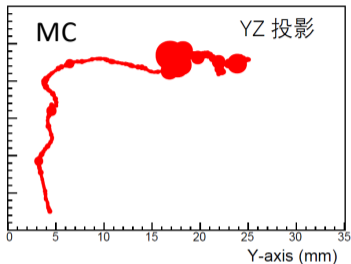
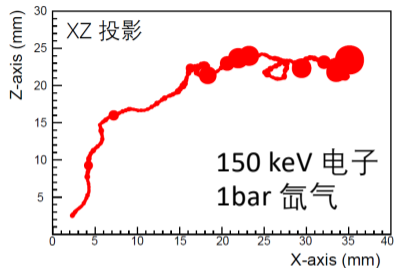


用于极低放射性材料筛选的时间投影室技术: 能量+径迹



- 粒子鉴别
- 高位置分辨率
- 本底去除
- 高效率 (>90%)
- 大幅面 ($\sim 2000\text{cm}^2$)
- 可调工作气体、气压

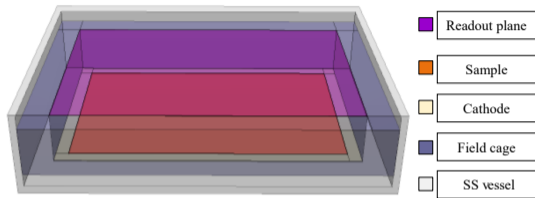
气体TPC核心优势：径迹+能量测量 → 鉴别与定位



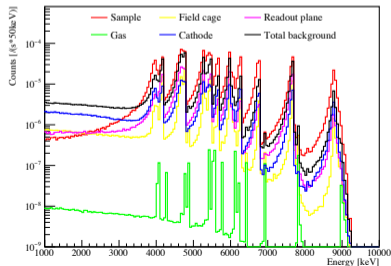
- 粒子鉴别：利用径迹的弯曲程度和 dE/dx 可以明确区分 α/β
- 利用 dE/dx 与布拉格峰确定 α/β 径迹起点，明确放射性来源
 - 去除探测器材料对于 α 测量的影响
 - 大大抑制 β 测量中环境和探测器本底的影响

- 利用GEANT4 + REST 模拟分析框架重建了探测器几何。
- 对于alpha 区间, 开展探测灵敏度研究, 预期灵敏度可达 $100 \mu\text{Bq}/\text{m}^2$ 以下

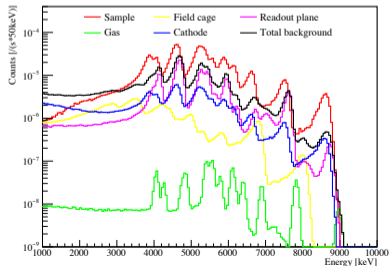
Sensitive Gaseous Volume: $60 \times 40 \times 10 \text{ cm}$, 1 bar Ar



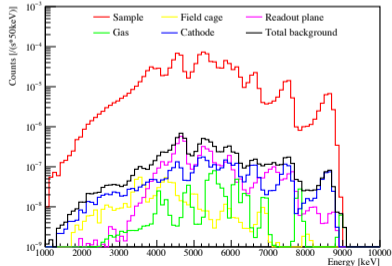
GEANT4 spectrum



+ Energy smearing



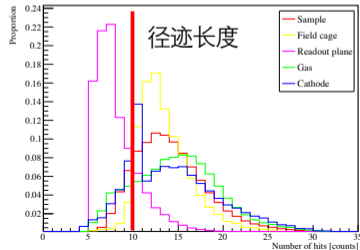
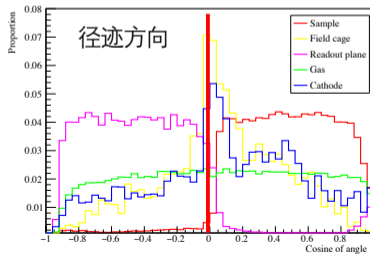
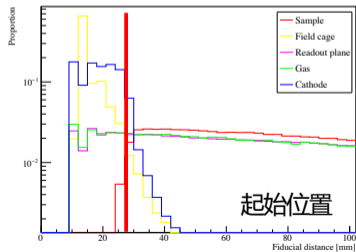
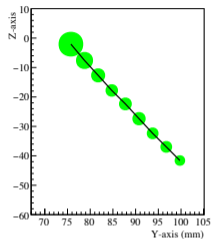
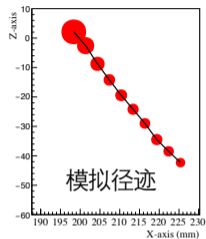
+ Topological cuts



径迹相关cuts (Topological cuts)

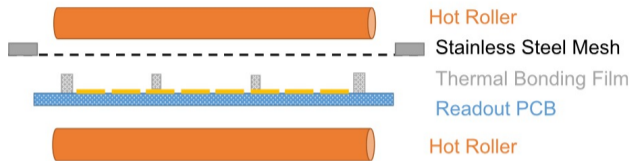
NST 32, 142 (2021)

- 利用径迹起始位置, 方向, 长度逐步对事件进行筛选, 压低本底的情况下尽可能的保留信号
- 最终在1-10MeV的区间, 本底事件率小于1个每天

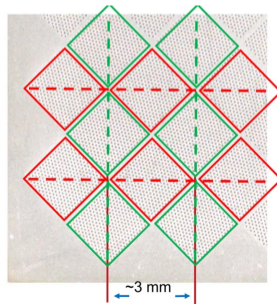


TPC建设: 热压接Micromegas

- 3mm 条读出
- 读出面积: $20 \times 20 \text{ cm}^2$
- 128通道
- 柔性Kapton PCB读出+高纯无氧铜背板
 - 依托PandaX-III实验发展的低本底Micromegas技术

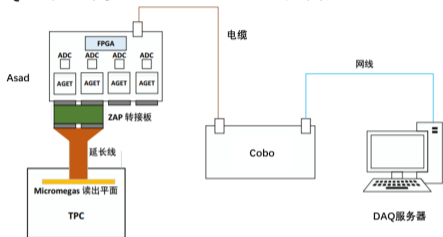


FENG J, ZHANG Z, LIU J, et al. A thermal bonding method for manufacturing Micromegas detectors[J]. NIMA 2021, 989: 164958.

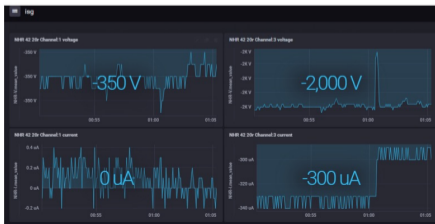


TPC建设：子系统

DAQ系统：商业ASAD+COBO 与 科大FEC+DCM两套解决方案

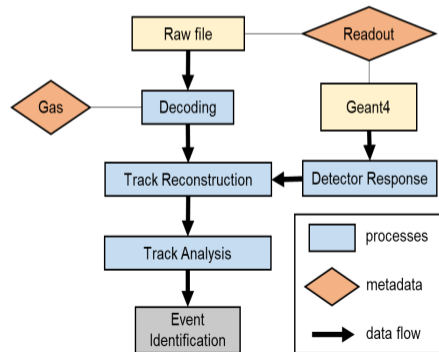


网页端慢控制系统：监测电压、电流、压强、环境温度等

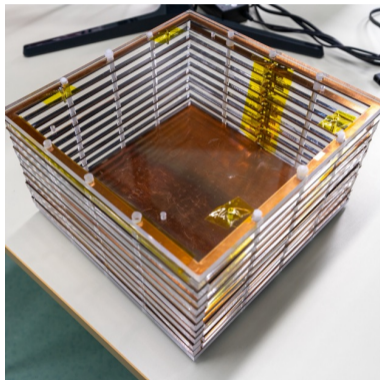


蒙特卡洛仿真与数据分析系统：

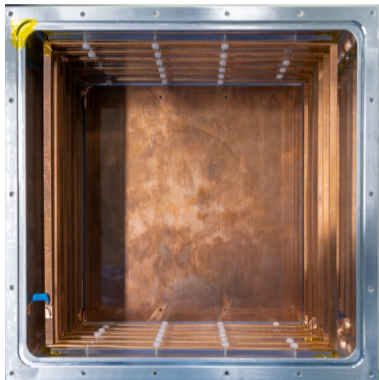
PandaX-III实验研发的REST分析框架



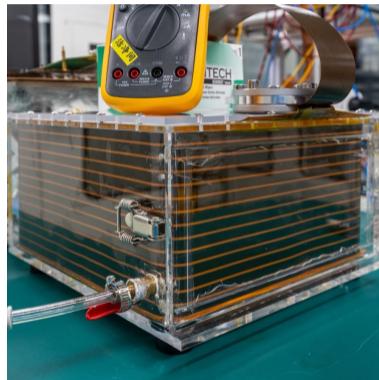
多轮原型探测器迭代 (单块 Micromegas)



亚克力+铜条场笼
@圆桶腔体

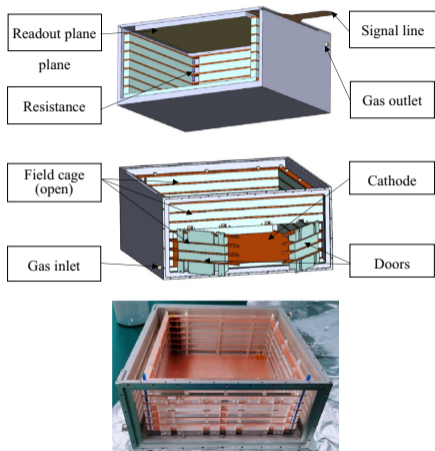


场笼 + 适配铝合金腔体

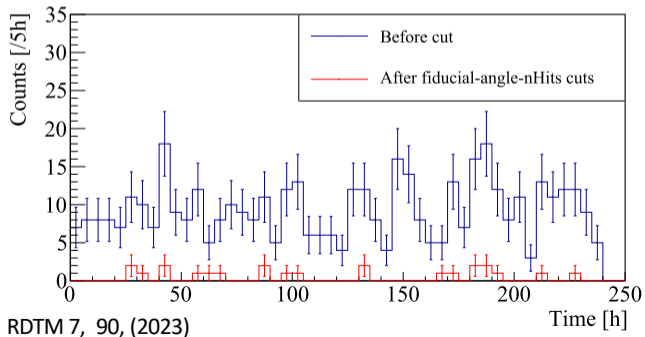


柔性PCB场笼 + 适配亚克力腔体

多轮原型探测器迭代 (单块 Micromegas)

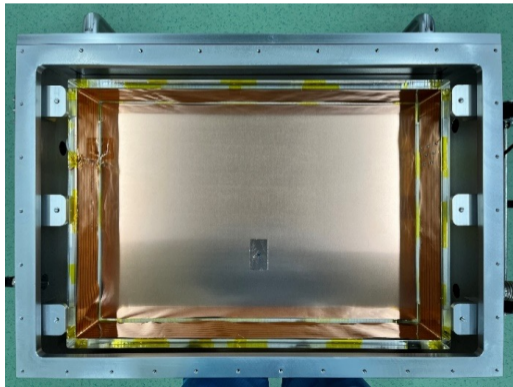
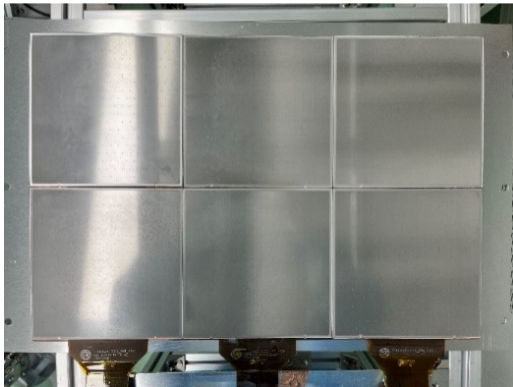


- 长时间稳定运行
- 本底计数率达到 $(0.13 \pm 0.03) \times 10^{-6} \text{ Bq/cm}^2$
 $(4.7 \pm 0.9) \times 10^{-4} \text{ counts/cm}^2/\text{h}$
- Ultralo-1800: $5 \times 10^{-4} \text{ counts/cm}^2/\text{h}$

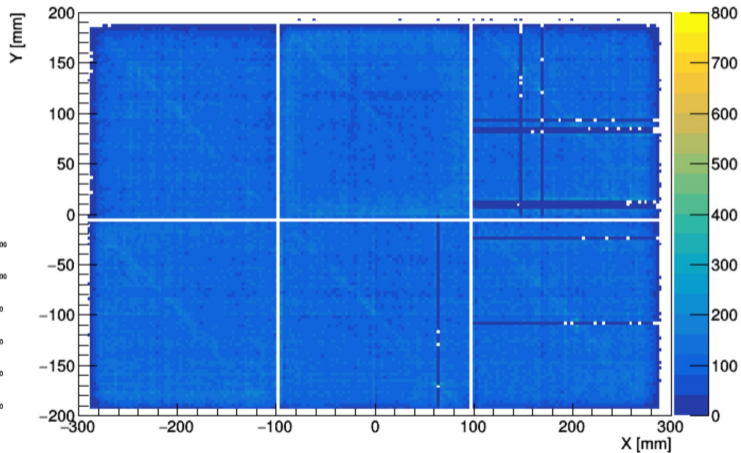
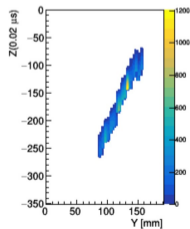
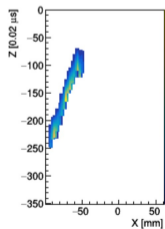
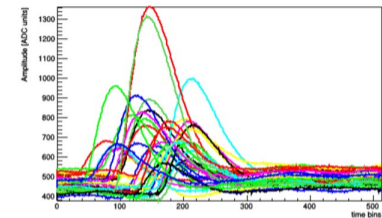


大幅面探测器建设

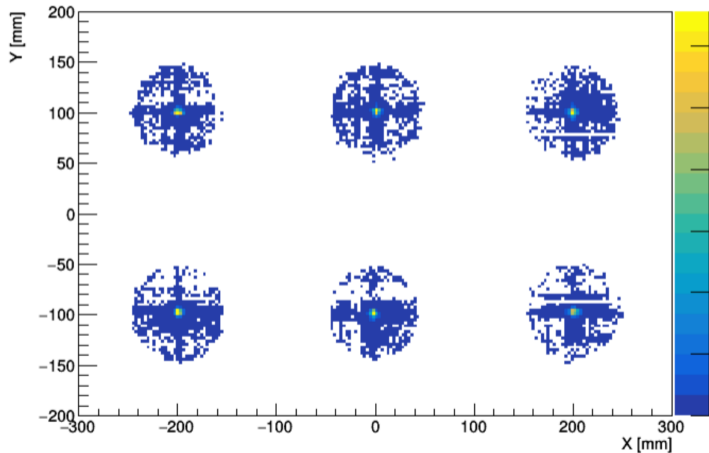
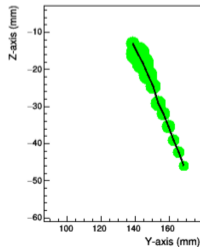
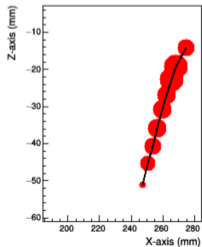
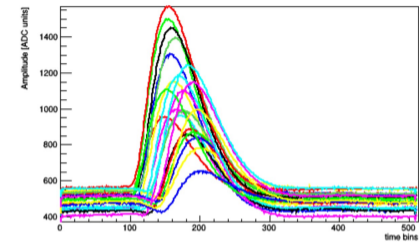
- 6块Micromegas作为读出平面，总面积2400 cm²
- 高纯无氧铜阴极板
- 所有场笼材料根据PandaX低本底要求清洗



宇宙射线事例



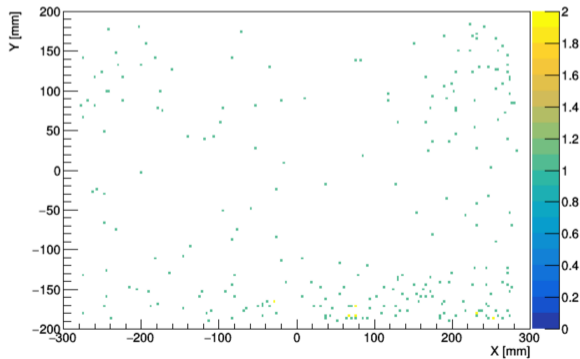
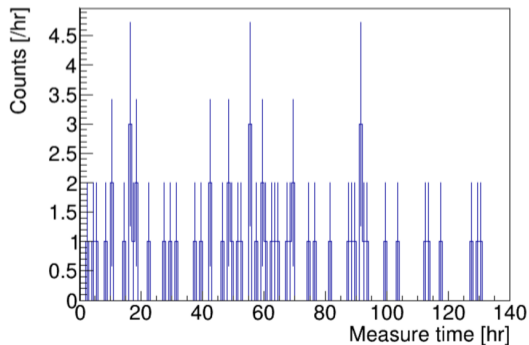
Alpha标定事例



探测器本底

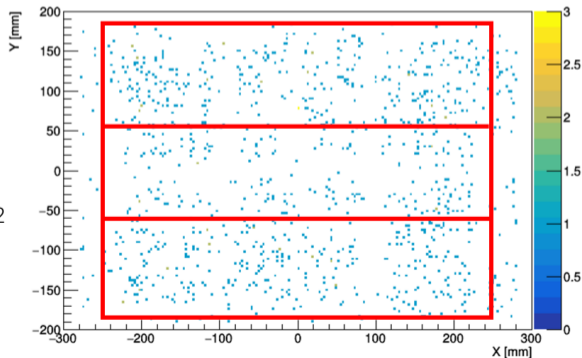
- 多轮探测器迭代, 达到本底要求 ($\mu\text{Bq}/\text{cm}^2$)

1.29 ± 0.06 $\xrightarrow{\text{氩气保压}}$ 0.82 ± 0.06 $\xrightarrow{\text{铜板酸洗}}$ 0.47 ± 0.03 $\xrightarrow{\text{替换亚克力场笼}}$ 0.14 ± 0.02



测量 JUNO 亚克力样品

- 3块样品: 1730 cm^2 , 长期暴露在JUNO地下实验室高氡环境 ($Rn \sim 180 \text{ Bq/m}^3$)
- α 计数率 (Acrylic+ Gas): $0.91 \pm 0.03 \text{ } \mu\text{Bq/cm}^2$
- 对比本底 $0.14 \pm 0.02 \text{ } \mu\text{Bq/cm}^2$
- 亚克力样品 α 本底: $0.77 \sim 0.91 \text{ } \mu\text{Bq/cm}^2$



亚克力表面处理对表面放射性的影响

	No sample	Acrylic 1 (Exposed in the underground lab)	Acrylic 2 (Wiped with dust-free paper)	Acrylic 3 (Cleaned with alcohol)	Acrylic 4 (pure water rinse + N2 gas)
Measure area [cm ²]	1889	1730	1730	1270	1270
Measure time [hr]	187	160	170	185	252
Contamination (Acrylic + Gas) [$\mu\text{Bq}/\text{cm}^2$]	-	0.91 ± 0.03	0.45 ± 0.03	0.18 ± 0.03	0.25 ± 0.03
Background (Copper cathode + Gas) [$\mu\text{Bq}/\text{cm}^2$]	0.14 ± 0.02	-	-	-	-
Estimated contamination of Acrylic [$\mu\text{Bq}/\text{cm}^2$]	-	0.77 ~ 0.91	0.31 ~ 0.45	0.04 ~ 0.18	0.11 ~ 0.25

结论与展望

- 利用气体探测器的能量+径迹特性测量样品表面污染

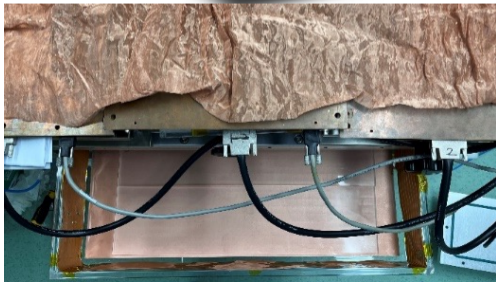
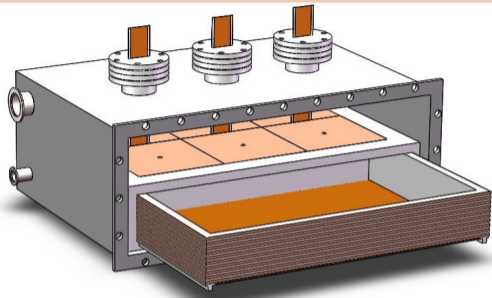
- 粒子鉴别去除本底
- 大幅面、高灵敏度、高效率

- 探测器进展

- 成功建设400cm²原型探测器和2400cm²探测器探测器
- 本底计数率均达到商业化产品水平

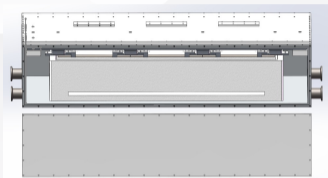
- 低本底材料测量

- 测量JUNO亚克力样品
- 对于亚克力表面处理方法给出了指导性意见

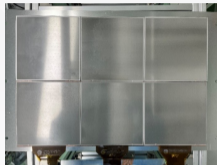


谢谢各位关注

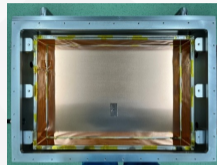
⊕ Charged Particle detector



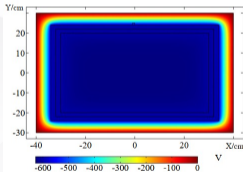
- Time Projection Chamber (0.5-1.5 bar Argon/Xenon)
- Readout plane: 2400 cm² (2×3 Micromegas)
- Drift distance: 10 cm (Volume: 24 L)
- Flexible PCB field cage
- Samples are placed directly on the cathode to ensure complete deposition of alpha energy.



Readout plane - Micromegas



Internal detector photo



E-field distribution in the X-Y plane



External detector photo

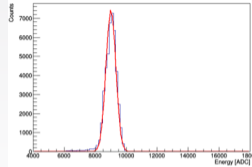
⊕ Alpha calibration (Am-241 source)

- Calibrate the detector with the 5.485 MeV energy peak of the Am-241 to optimize the working conditions of the detector.

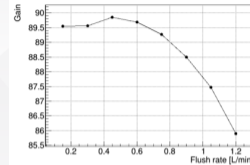


➤ Cleanroom

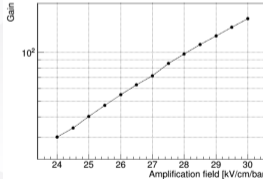
Gas--- 1bar Ar-7%CO₂ (0.1 L/min)



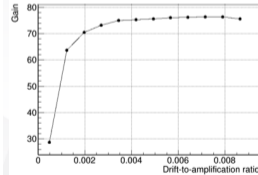
Spectrum of Am-241
9.5% FWHM at 5.485 MeV



Gain evolves with flow rates



Gain evolves with amplification fields



Gain evolves with drift fields