



华中师范大学
CENTRAL CHINA NORMAL UNIVERSITY

六氟化硒高压气体TPC无中微子双贝塔衰变 中的太阳中微子本底

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第三届地下和空间粒子物理与宇宙物理前沿问题研讨会

2024年5月8-12日，西昌

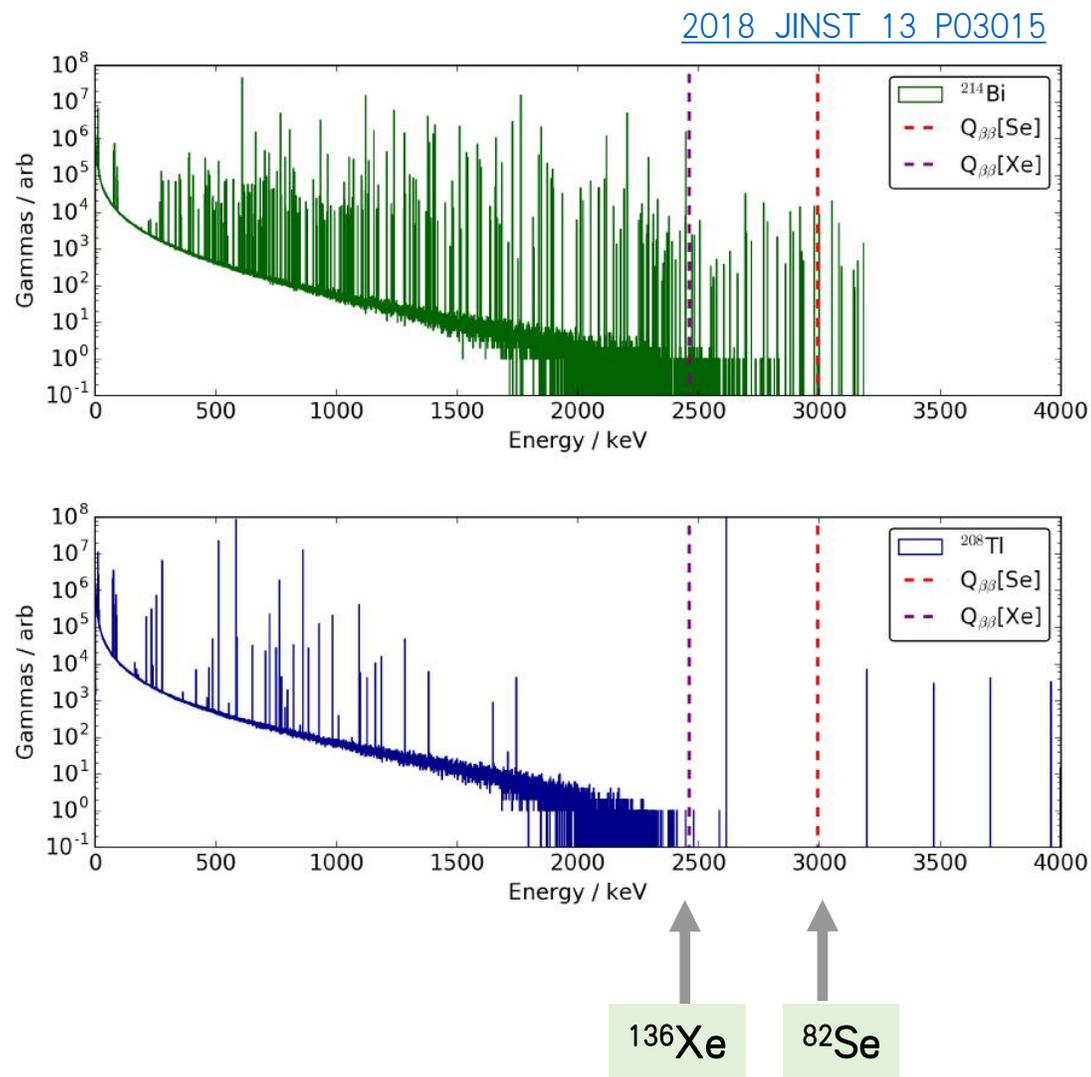
NvDEx实验

- 主要优势
 - ^{82}Se 的高 $Q_{\beta\beta}$ 值 (2.998 MeV)
 - Topmetal-S高能量分辨率
 - TPC径迹重建, 离子漂移低扩散
 - 锦屏地下实验室
- 本底
 - 环境、材料中自然放射性本底
 - 宇宙线相关本底
 - $2\nu\beta\beta$ 本底
 - 中微子本底

陈凯: [NvDEx-100实验预研进展](#) (周三下午)

梁天宇: [NvDEx实验 \$\text{SeF}_6/\text{SF}_6\$ 气体中离子漂移性质研究](#) (周三下午)

陈龙: [NvDEx读出ASIC研究进展](#) (周四下午)



太阳中微子本底

- 随着其他本底的减少变得重要
- 对⁸²Se核素影响更大
 - 低 Q_ν

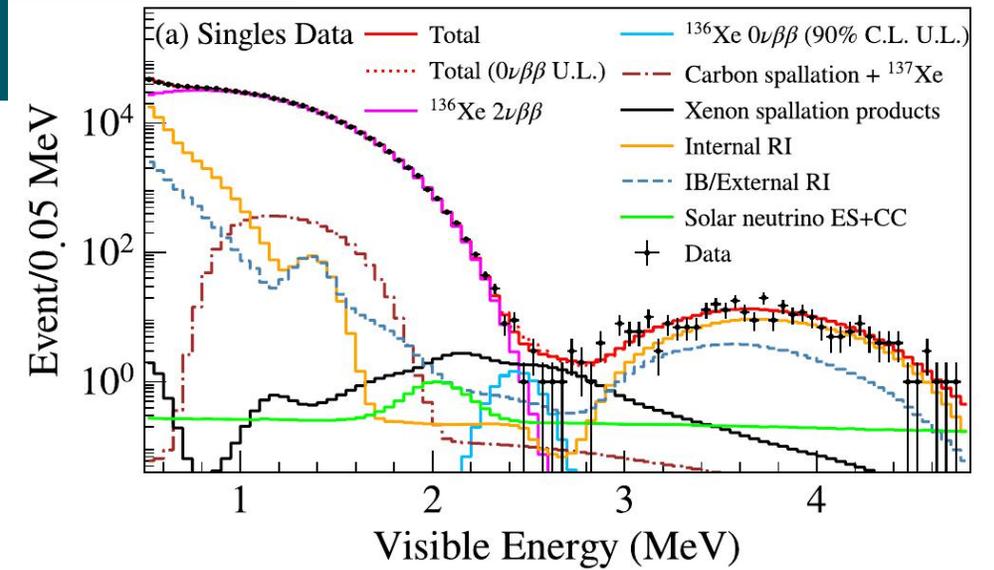
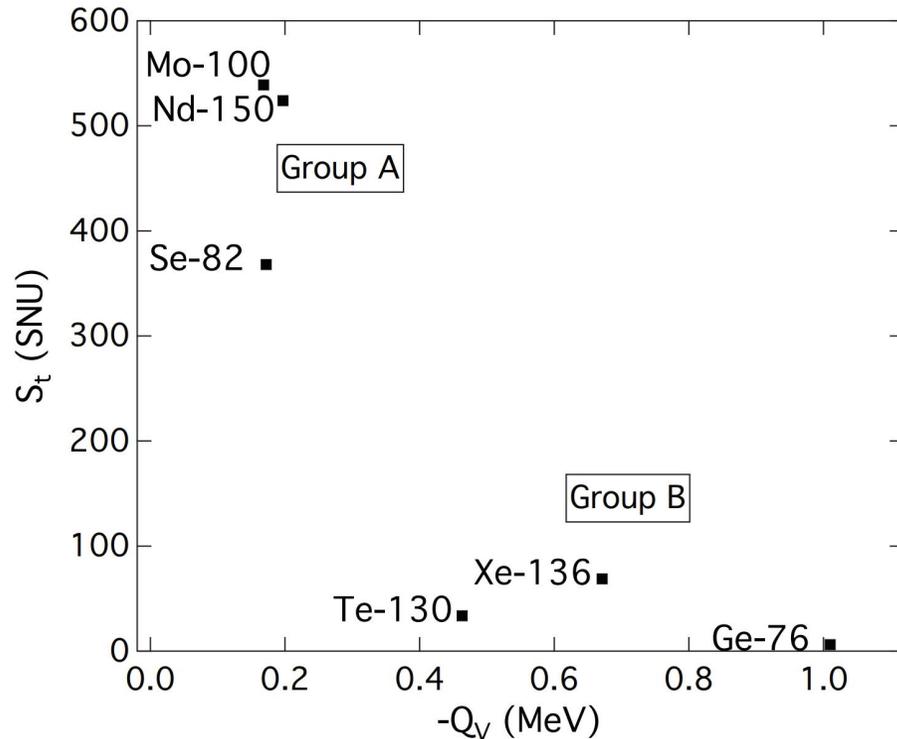
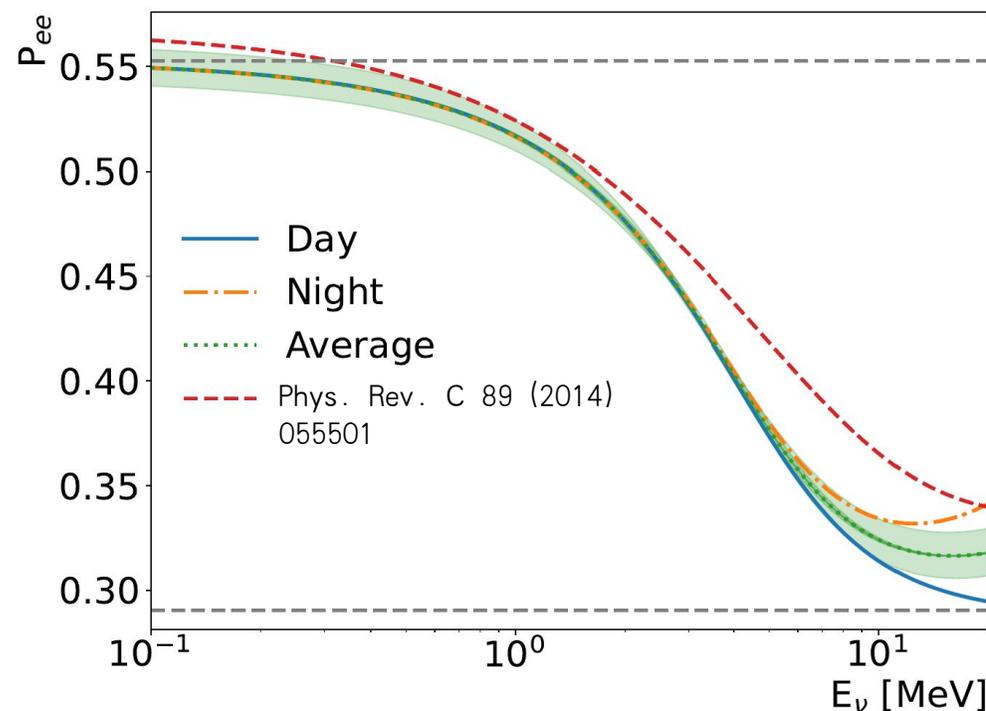
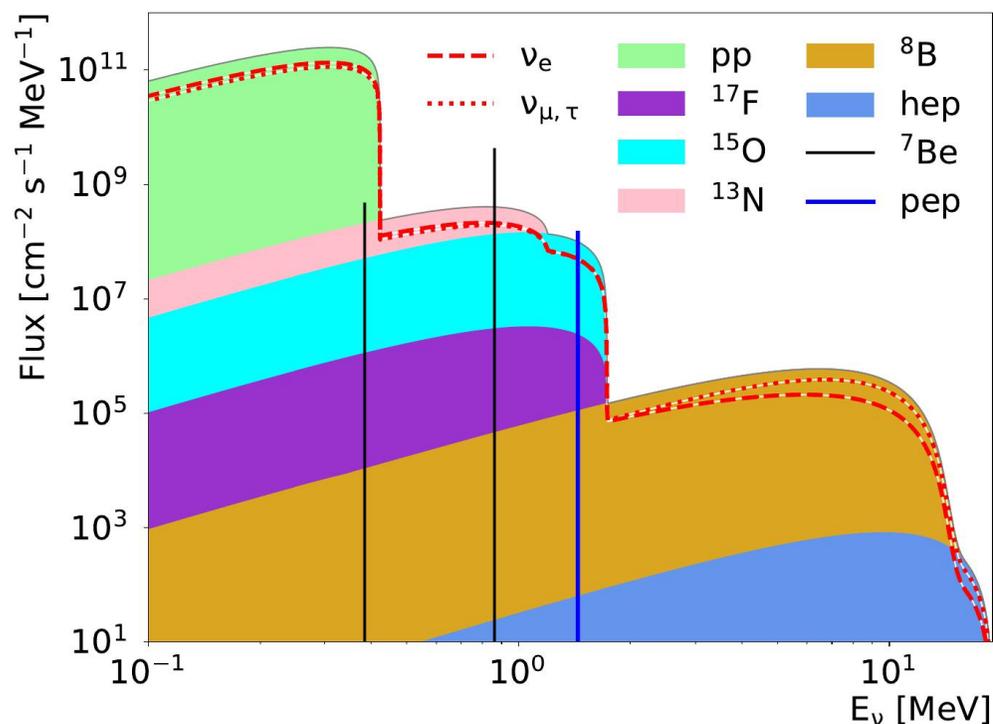


TABLE 2. $\beta\beta$, CC, and SB Q values in units of MeV and solar- ν capture rates in units of SNU for selected $\beta\beta$ nuclei including the effect of oscillations. Column 3 gives S_t for no oscillations, S_B is the ^8B - ν capture rate, and S_t is the total solar- ν capture rate. The background rates for β decay (B_{SB}) and $\beta\beta(2\nu)$ ($B_{2\nu}$) are calculated for $\delta = 0.02$.

Isotope	S_{pp} (SNU)	S_B (SNU)	S_t no osc. (SNU)	S_t (SNU)	B_{SB} events/ t y	$B_{2\nu}$ events/ t y
⁷⁶ Ge	0	5.0	15.7	6.3	0.03	0.005
⁸² Se	257	10.0	672	368	4.42	0.15
¹⁰⁰ Mo	391	6.0	975	539	0.11	1.56
¹³⁰ Te	0	6.1	67.7	33.7	0.48	0.01
¹³⁶ Xe	0	9.8	136	68.8	0.55	0.003
¹⁵⁰ Nd	352	15.5	961	524	0.12	1.00

太阳中微子

- 标准太阳模型
 - B16-AGSS09
- 中微子振荡
- 物质效应



中微子相关物理过程

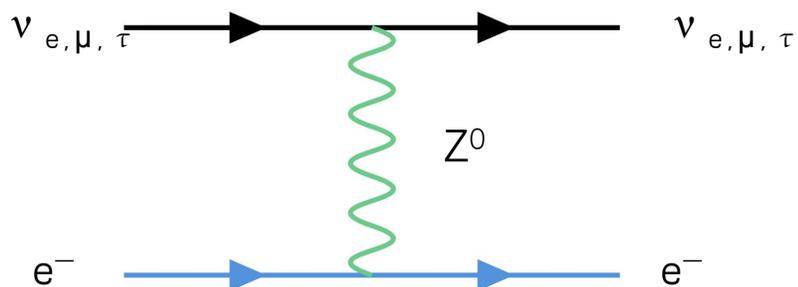
• 中微子-电子散射

$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi} \left[g_L^2 + g_R^2 \left(1 - \frac{T}{E_\nu}\right)^2 - g_L g_R \frac{m_e T}{E_\nu^2} \right]$$

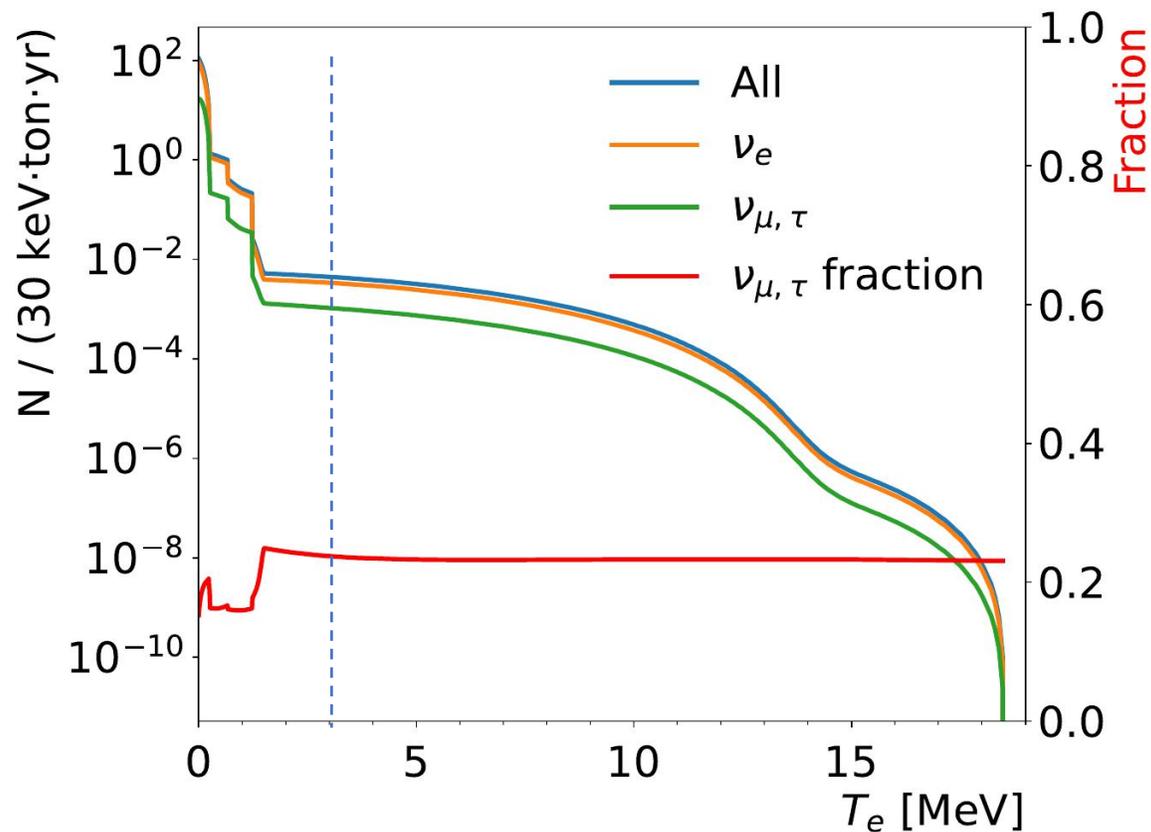
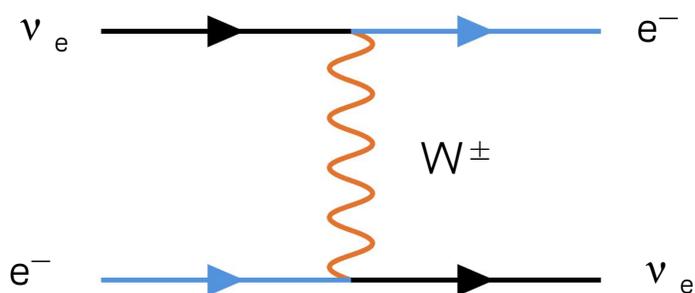
事例率 [events/(ton · yr)]

无振荡	有振荡	ROI
738.6	487.5	0.00445

NC



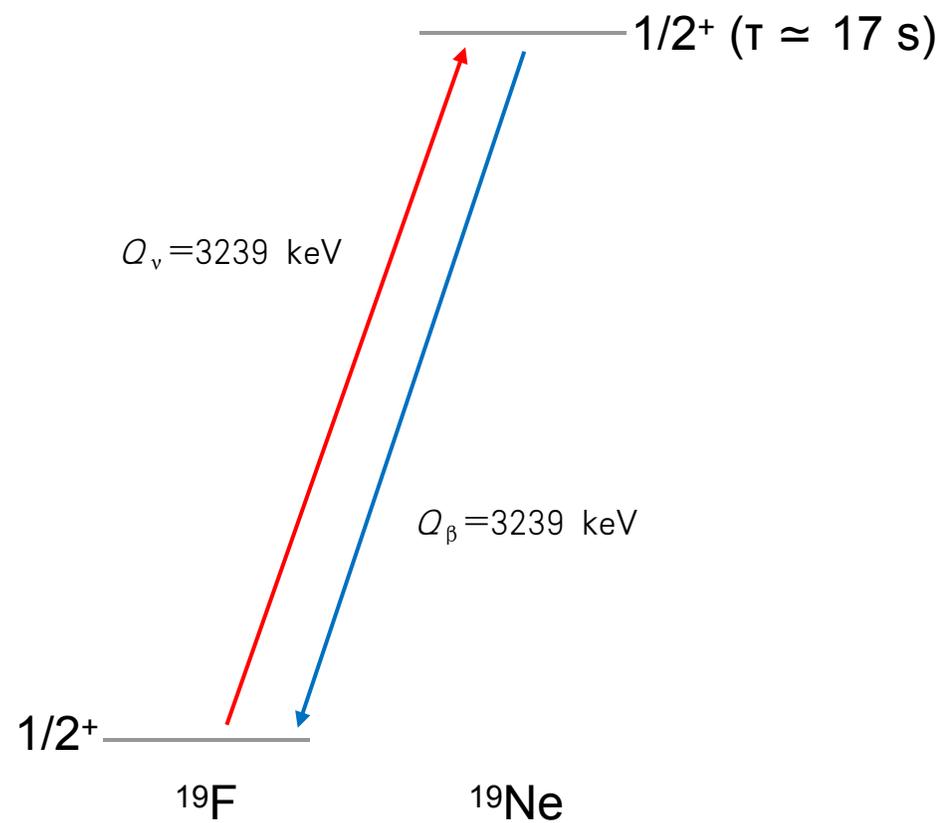
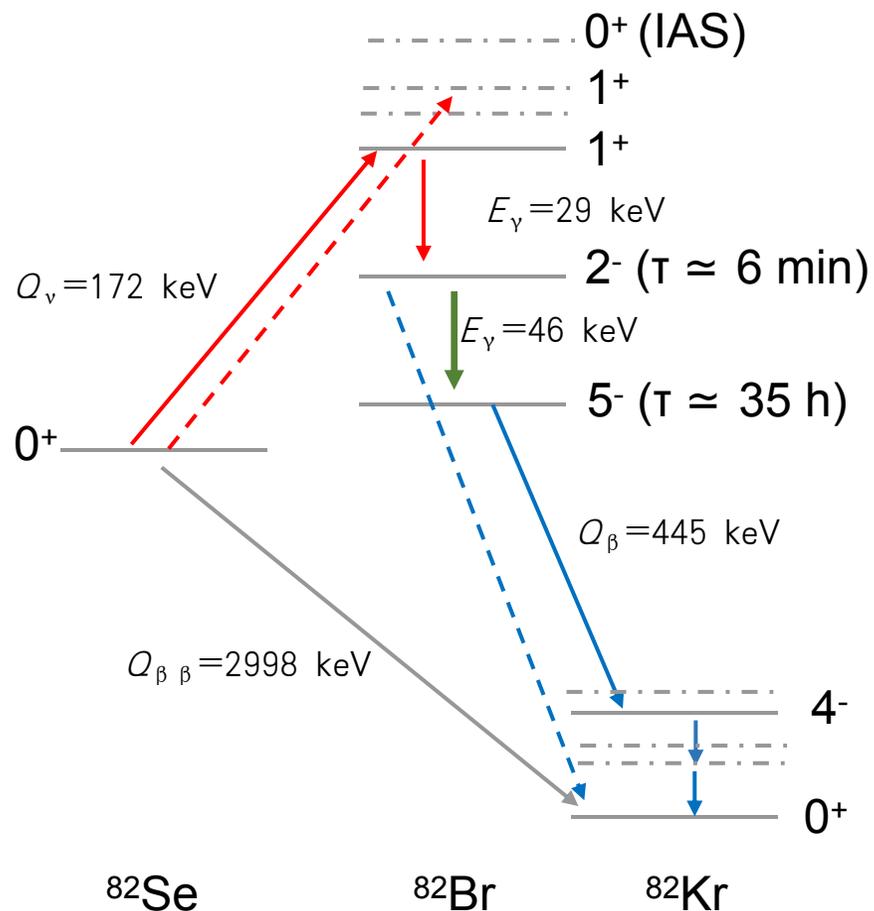
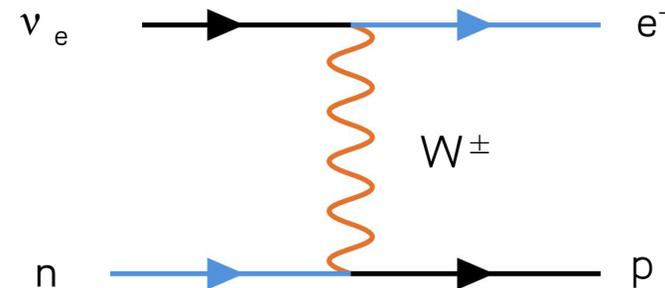
CC



中微子相关物理过程

- 中微子-核子散射

CC



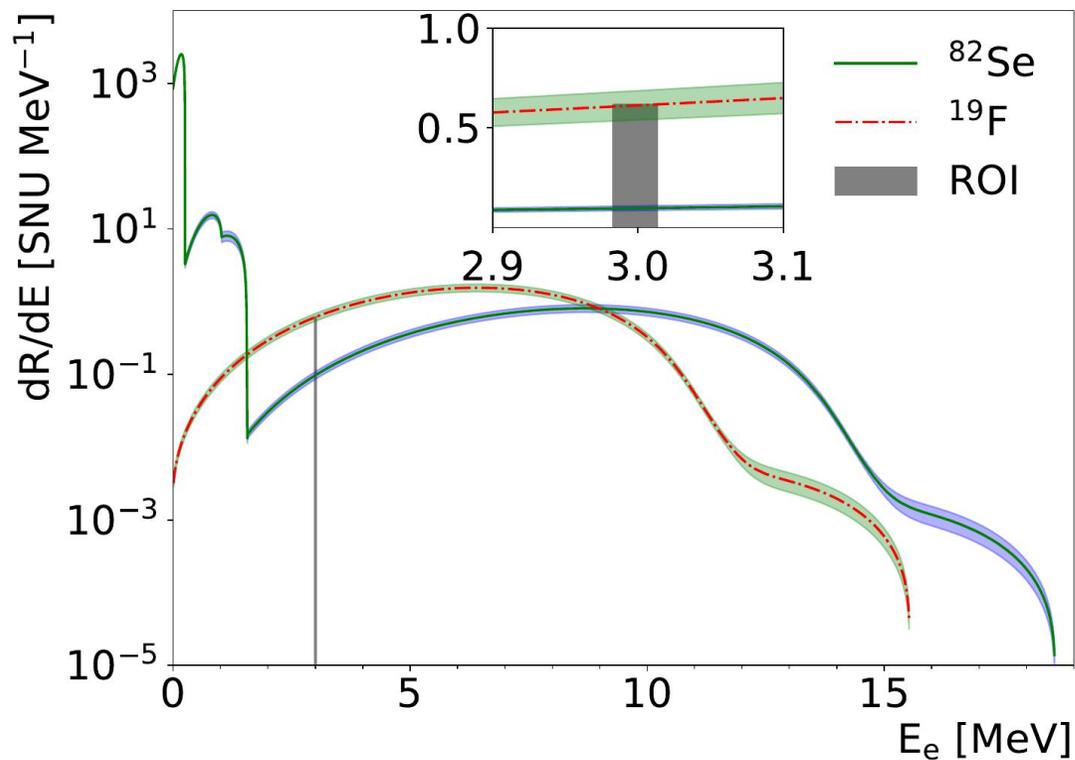
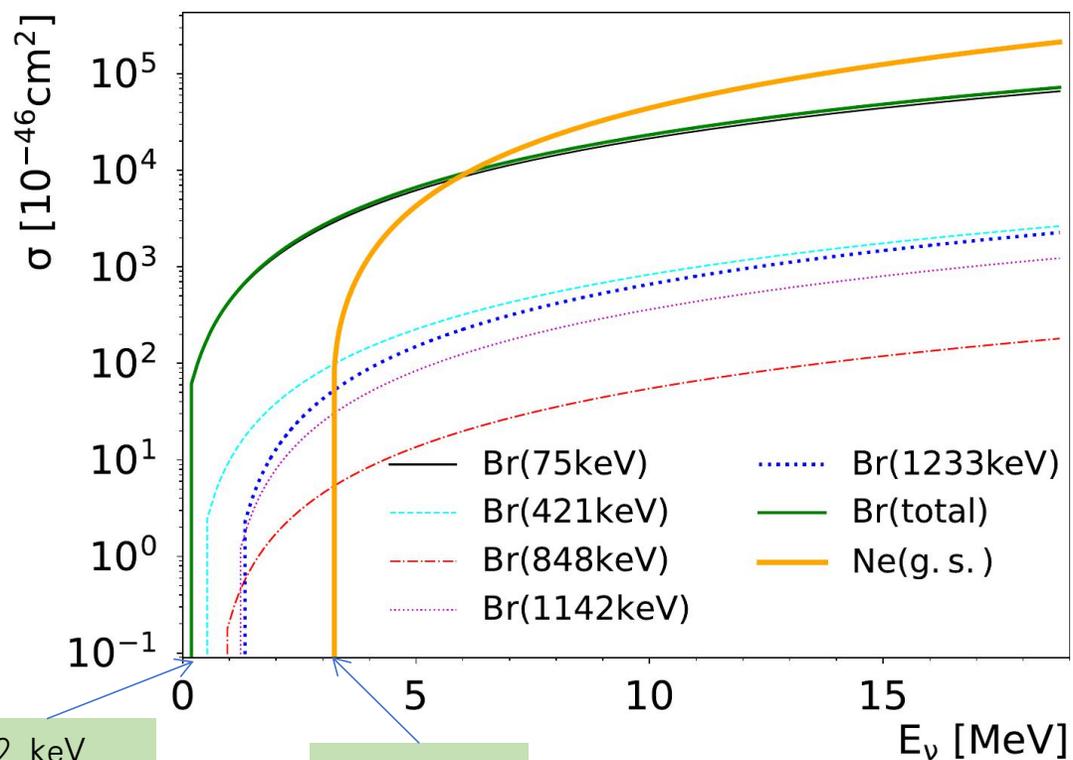
带电流反应截面和事例率

$$\sigma_k = \frac{G_F^2 \cos^2 \theta_c}{\pi} p_e E_e F(Z, E_e) \left[B(F)_k + \left(\frac{g_A}{g_V} \right)^2 B(GT)_k \right]$$

$$= (1.597 \times 10^{-44} \text{ cm}^2) p_e E_e F(Z, E_e) \left[B(F)_k + \left(\frac{g_A}{g_V} \right)^2 B(GT)_k \right]$$

事例率 [events/(ton · yr)]

核素	无振荡	有振荡	ROI
^{82}Se	65.55	34.64	0.00025
^{19}F	6.13	2.03	0.0043



172 keV

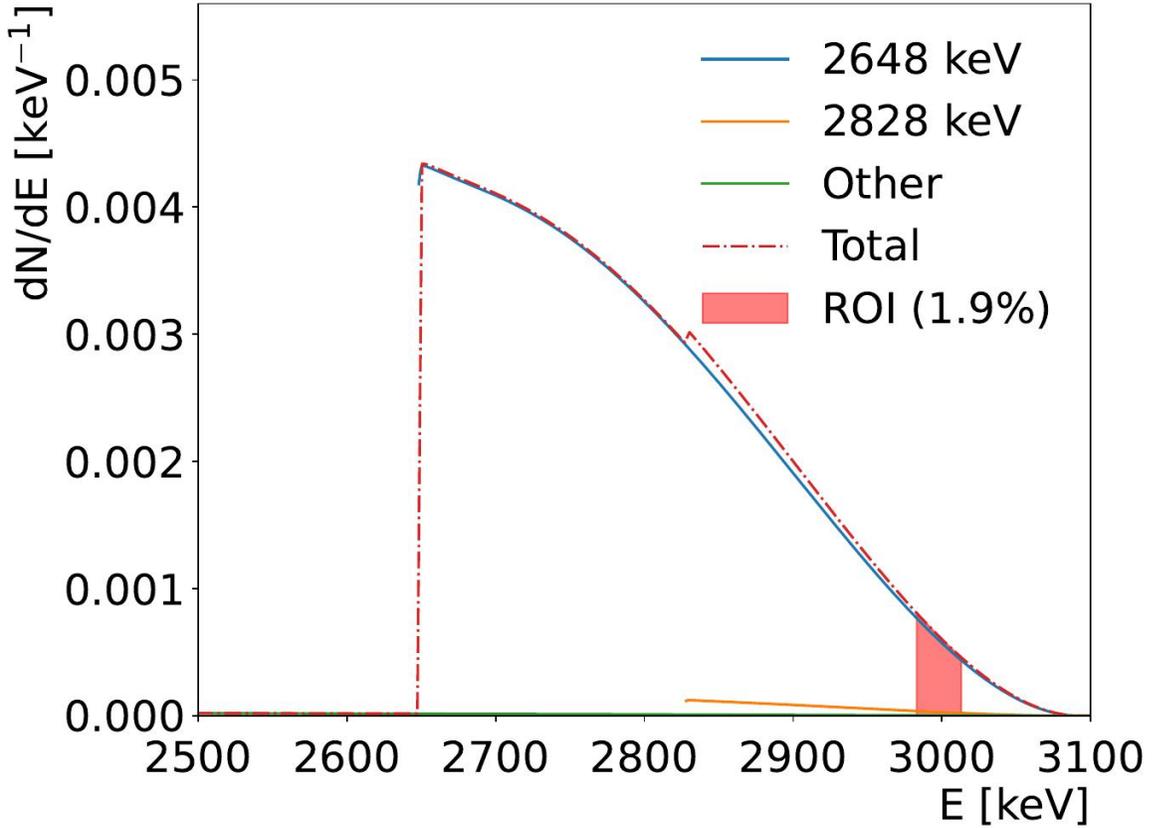
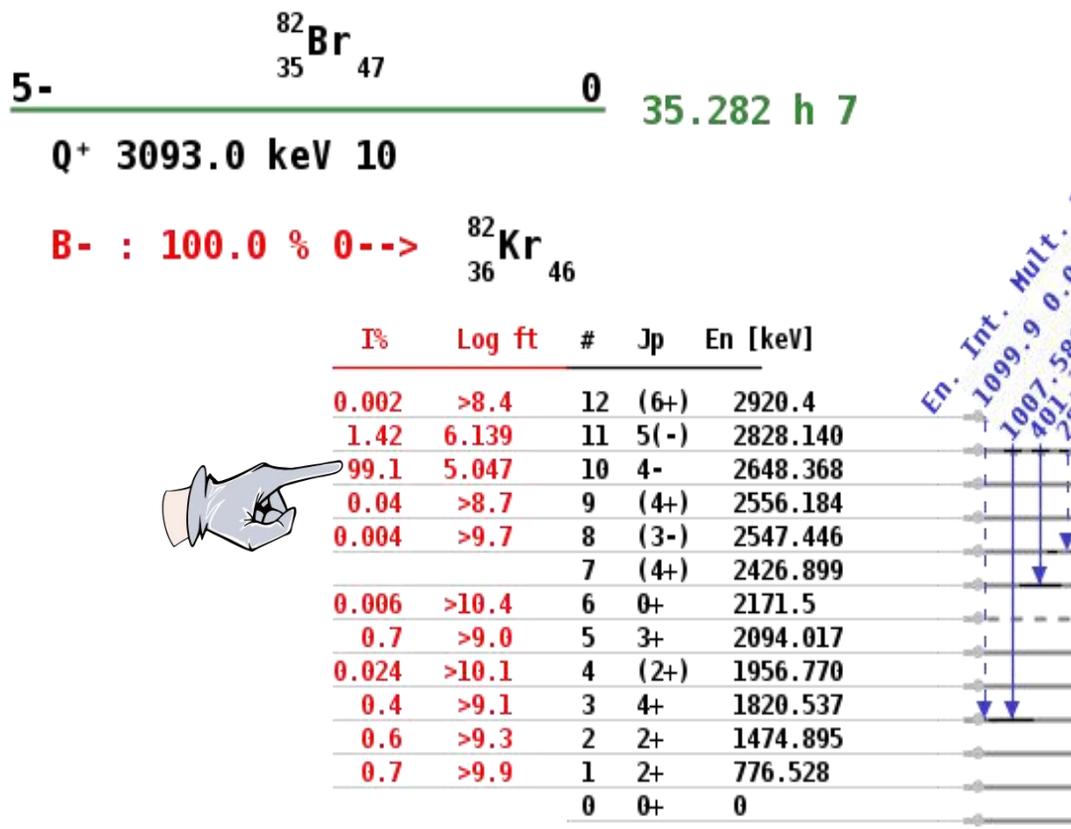
3.24 MeV

^{82}Br 衰变

事例率 [events/(ton · yr)]

- 基态

核素	无振荡	有振荡	ROI
^{82}Br	63.98	33.80	0.64



^{82}Kr STABLE

82mBr衰变

- 2- 激发态

事例率 [events/(ton · yr)]

核素	无振荡	有振荡	ROI
82mBr	1.57	0.83	0.00052

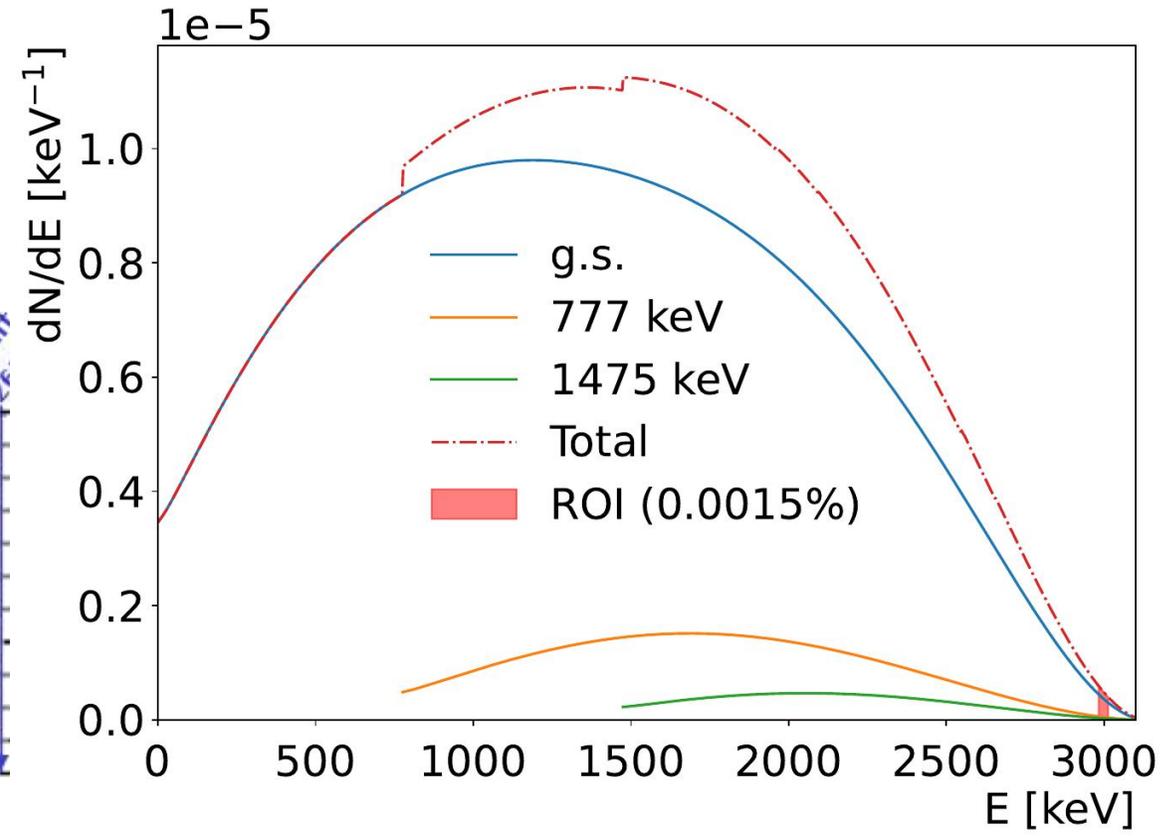
^{82m}Br₃₅⁴⁷ **45.9492** **6.13 m** 5
 2- Q+ 3093.1 keV 10

B- : 2.4 % 3--> ⁸²Kr₃₆⁴⁶

I%	Log ft	#	Jp	En [keV]
0.00111	7.58	11	2+	2655.865
0.00047	8.42	10	(4+)	2556.20
0.0021	7.61	9	(3-)	2547.88
0.00053	8.37	8	2+	2479.71
0.00005	10.5	7	0+	2171.64
0.003	8.4	6	3+	2093.98
0.0056	8.29	5	(2+)	1956.801
		4	4+	1820.6
0.00140	10.40	3	0+	1487.56
0.049	7.93	2	2+	1474.901
0.22	7.91	1	2+	776.524
2.1	8.88	0	0+	0



⁸²Kr₃₆⁴⁶ **STABLE**



^{19}Ne 的衰变

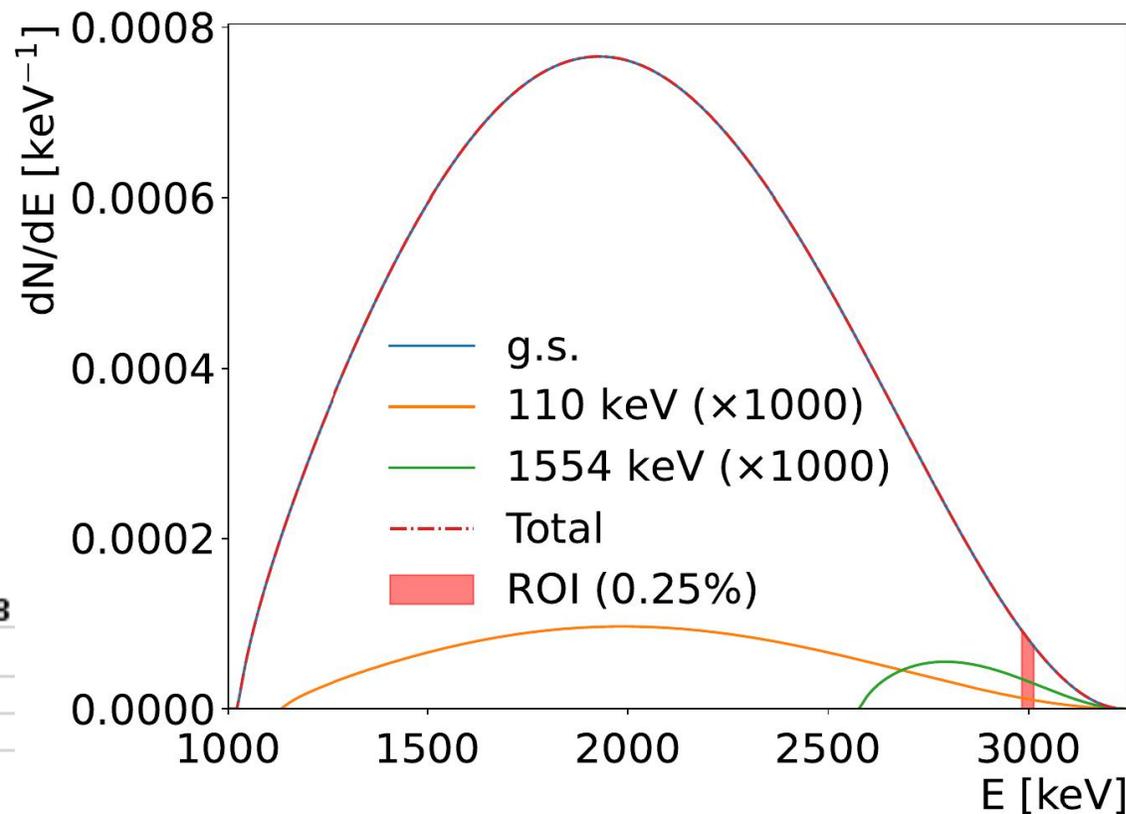
- 正电子能量
- 正负电子湮灭能量

事例率 [events/(ton · yr)]

核素	无振荡	有振荡	ROI
^{19}Ne	6.13	2.03	0.0049



I%	I β %	Log ft	#	Jp	En [keV]
0.00222	0.00213	5.71	3	3/2+	1554.038
			2	5/2+	197.143
0.012	0.012	7.06	1	1/2-	109.894
99.988	99.888	3.2329	0	1/2+	0



$^{19}\text{F}_{10}$ STABLE

Geant4模拟

- 事例产生

- 信号: BxDecay0
- 本底: particle gun

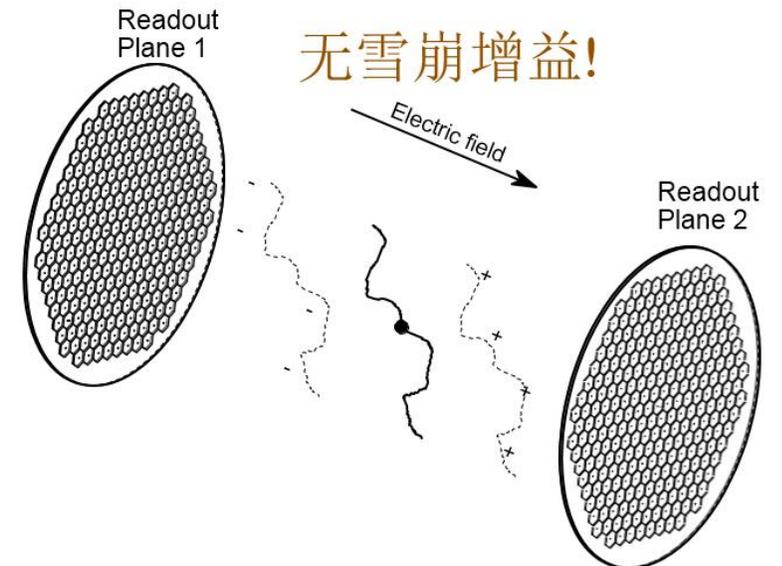
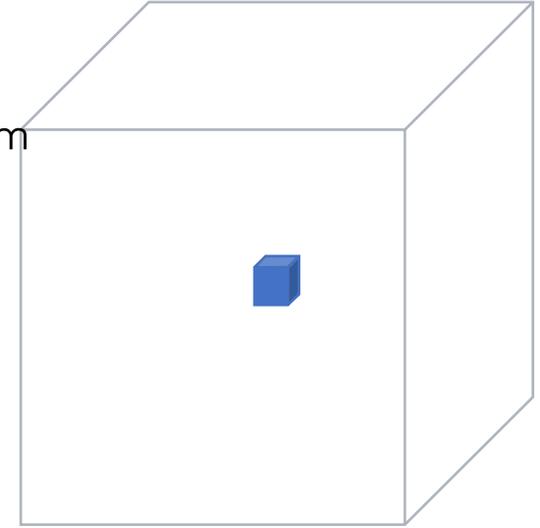
- 探测器模拟

- 10 bar气压
- 记录在路径上损失的能量 E
- 六边形像素阵列读出
 - 像素距离8 mm
 - $N_e = E / W \oplus 0.34\%$ FWHM涨落
 - xy平面的位置信息: 1 mm扩散

产生区域: $0.5 \text{ m} \times 0.5 \text{ m} \times 0.5 \text{ m}$

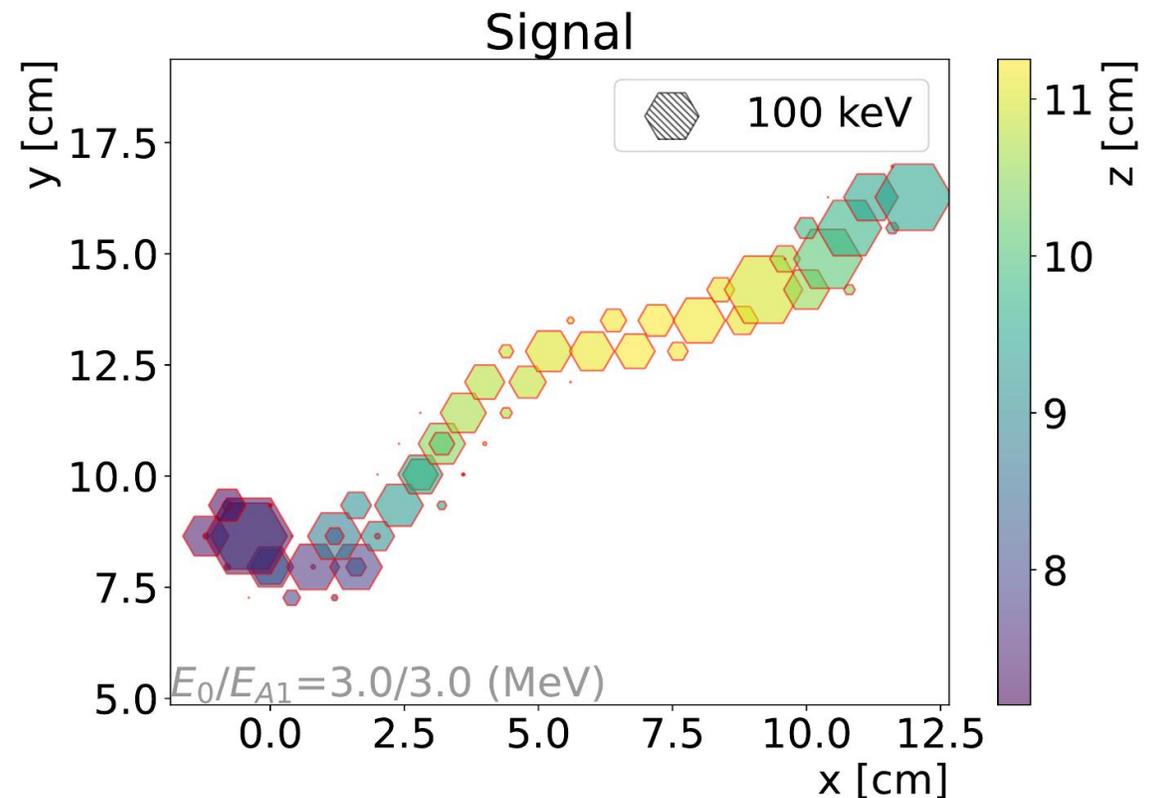
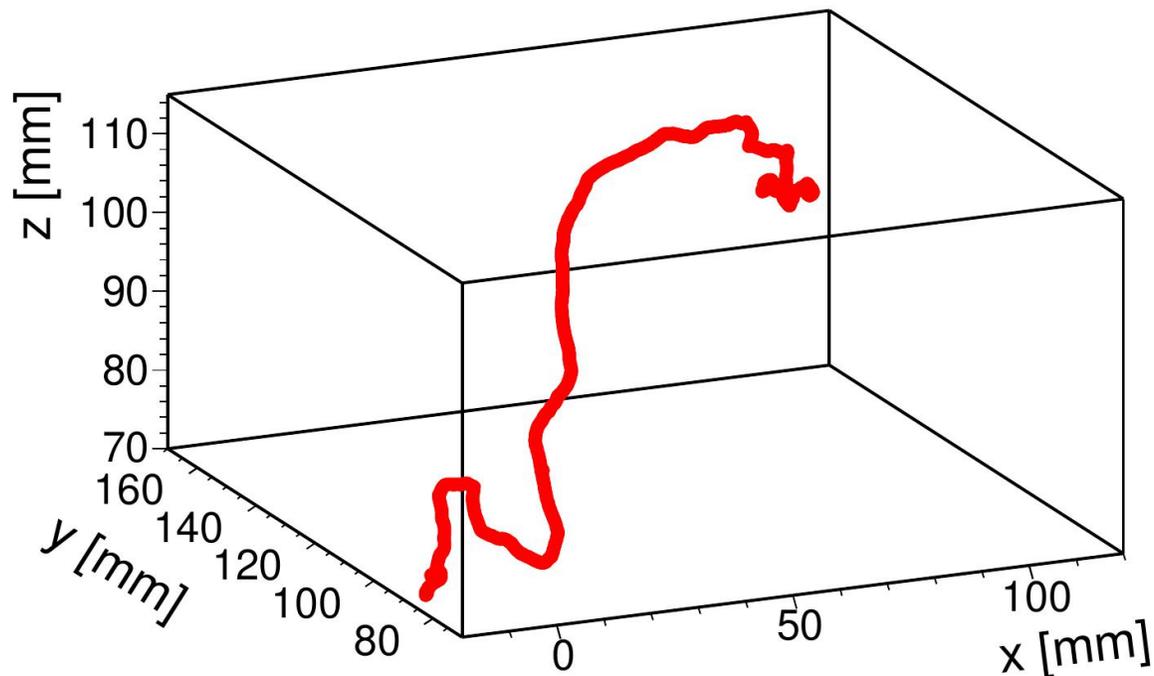
探测区域: $40 \text{ m} \times 40 \text{ m} \times 40 \text{ m}$

重建区域: $7 \text{ m} \times 7 \text{ m} \times 40 \text{ m}$



重建

- 每个像素提取“raw block”
- 将“raw block”分割成小的“block”
 - 对“block”的能量加入40 e-电子学噪声(\rightarrow 信号能量分辨率1% FWHM)
- 将临近的“block”组成“cluster”



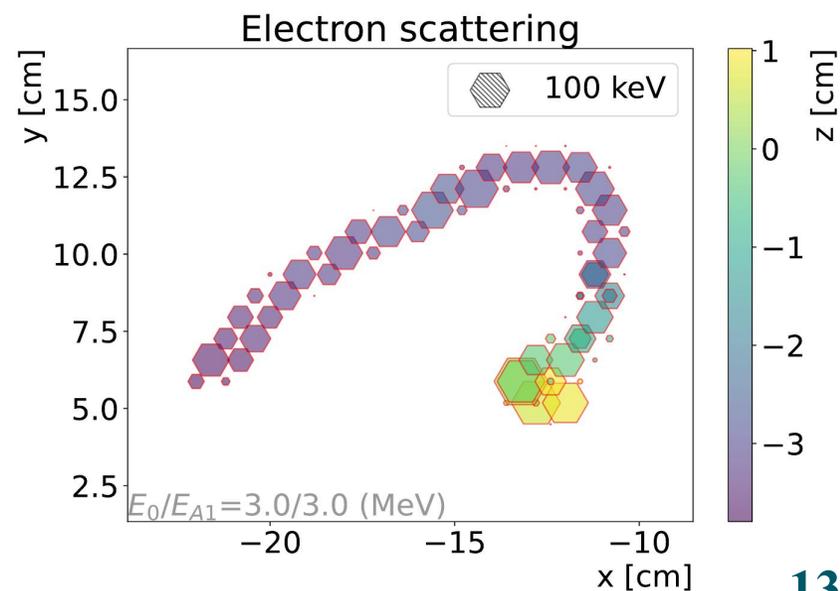
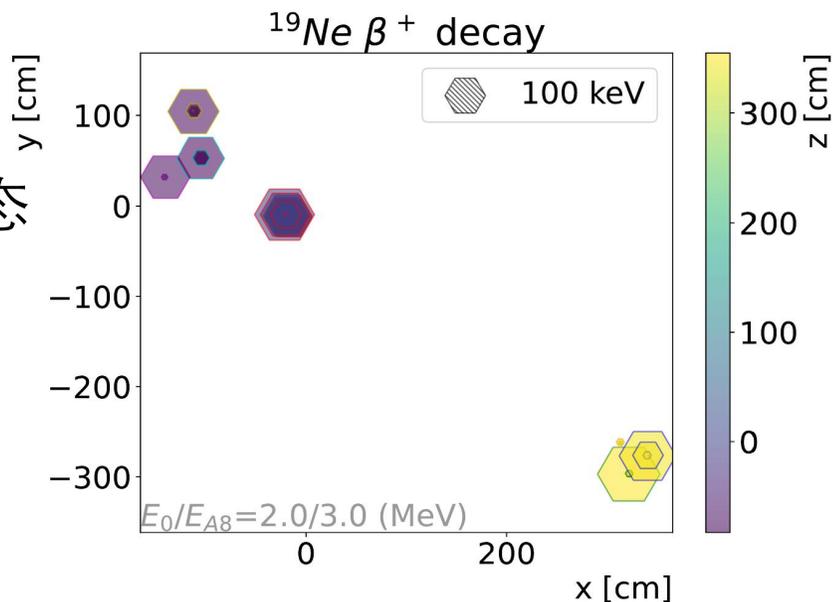
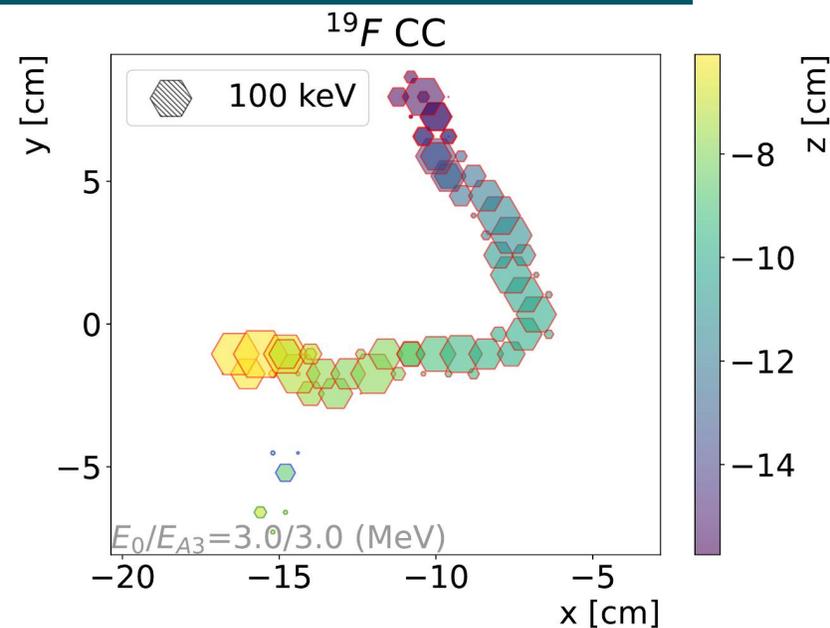
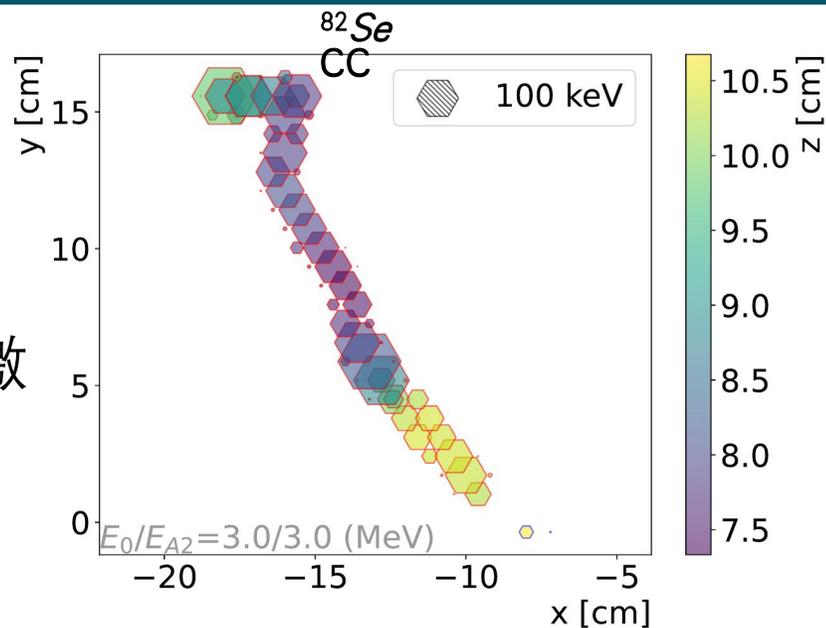
本底过程

- 末态有单个电子

- 电子散射
- ^{19}F CC
- ^{82}Se CC到 ^{82}Br (75 keV)激发态有一个29 keV光子

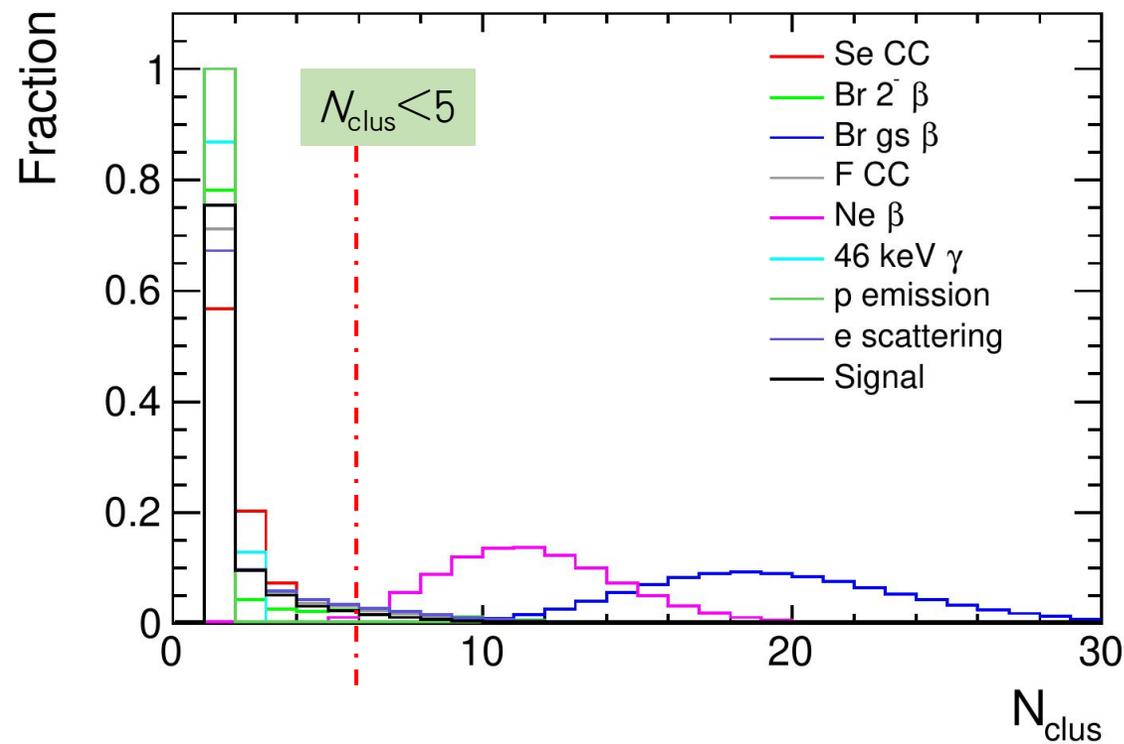
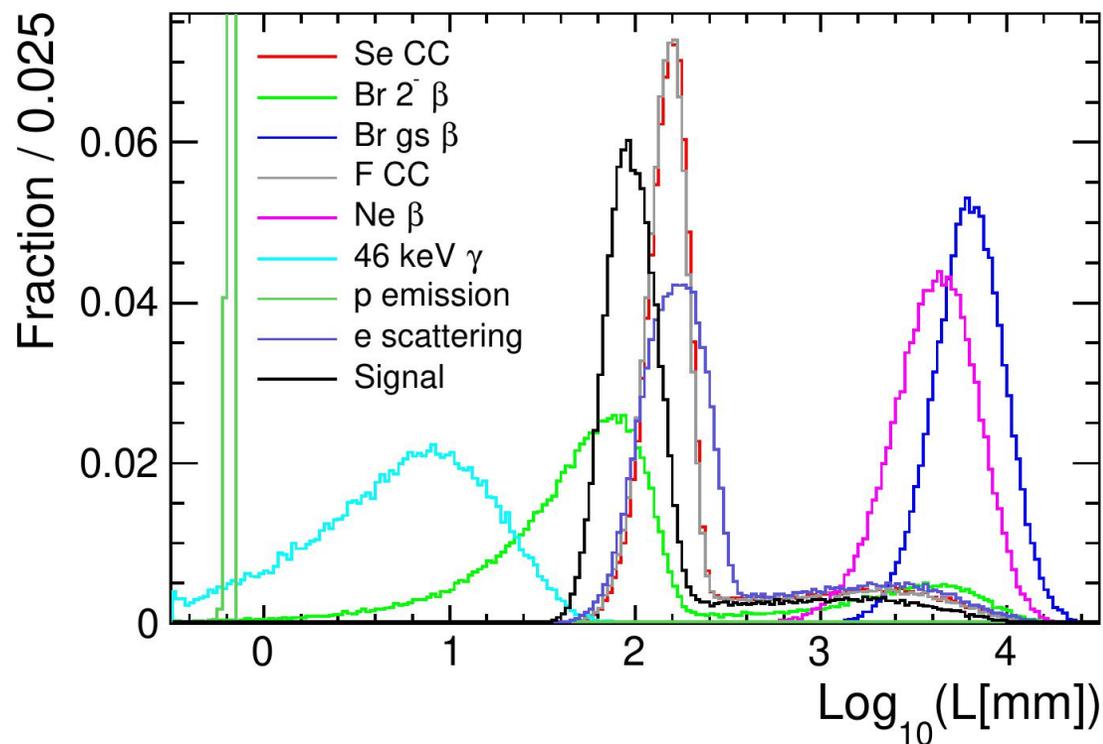
- 末态有多个高能光子

- ^{19}Ne 衰变
- ^{82}Br 基态衰变
- ^{82}Se CC到 ^{82}Br 高能激发态



Cluster

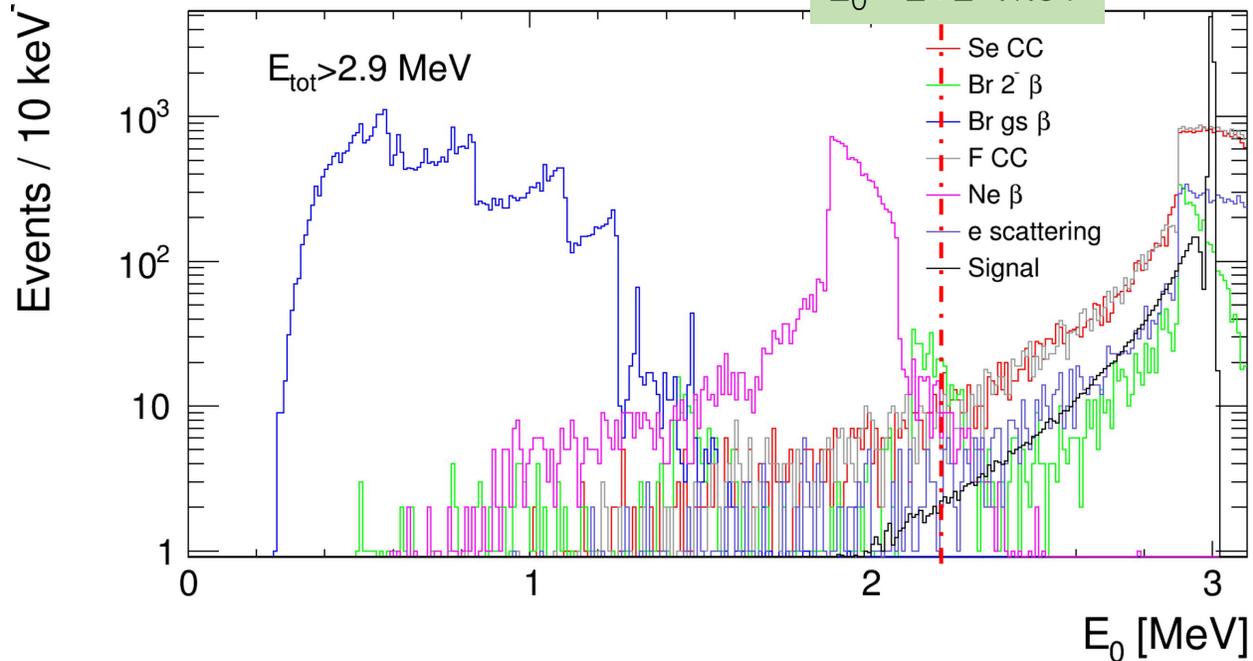
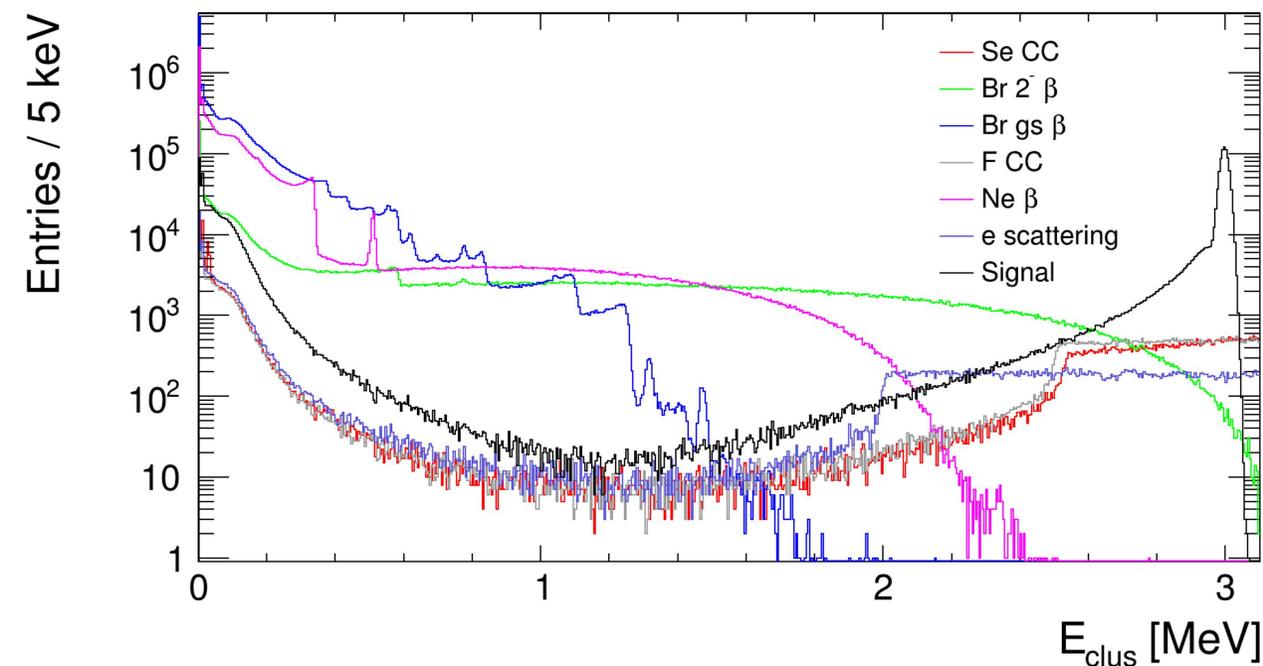
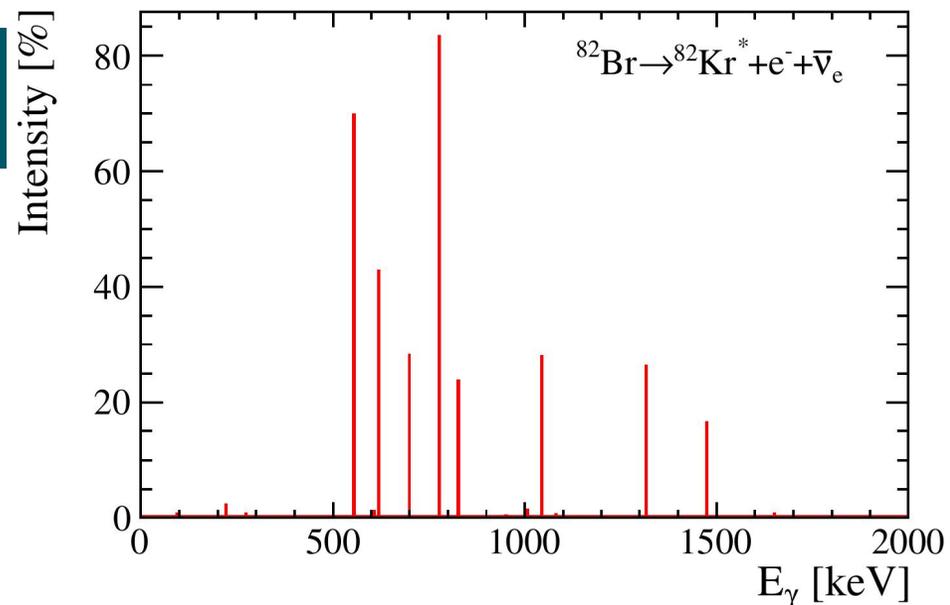
- ^{82}Br 基态的 β^- 衰变、 ^{19}Ne 的 β^+ 衰变
 - 大量cluster
 - 分布范围大



L : 能量沉积与反应点的最大距离

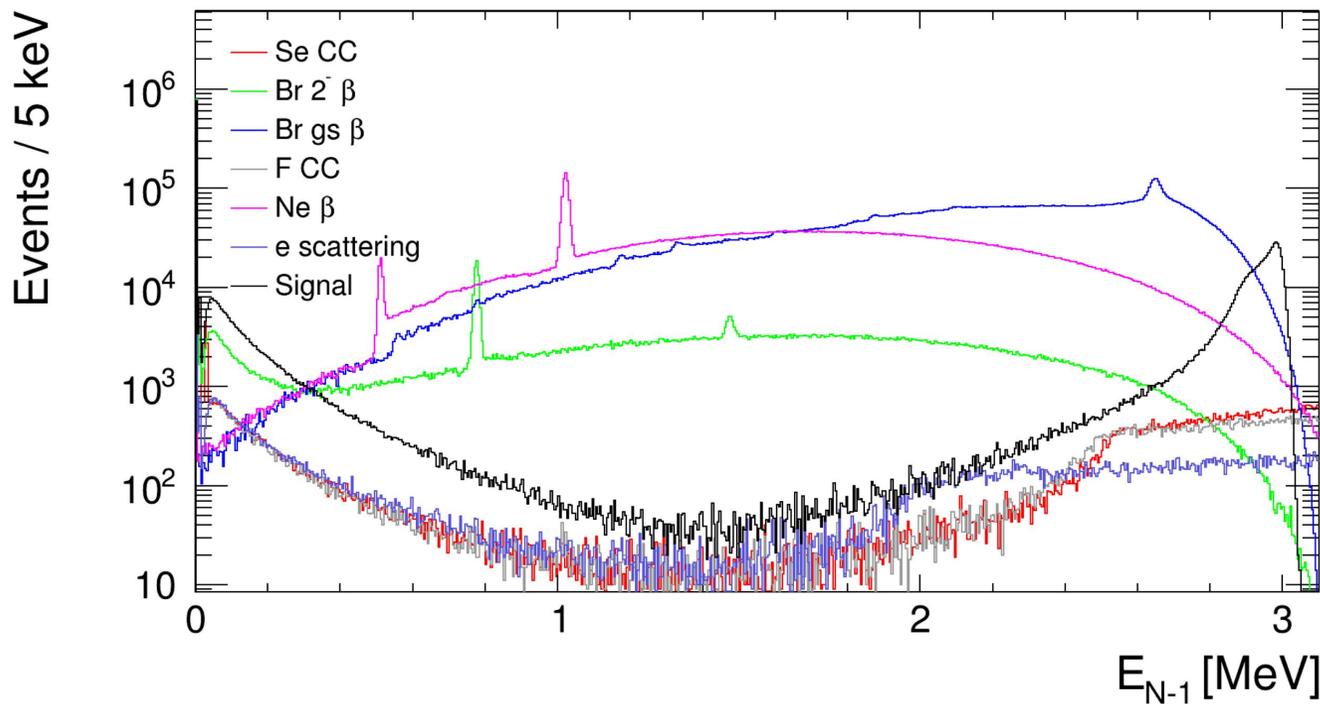
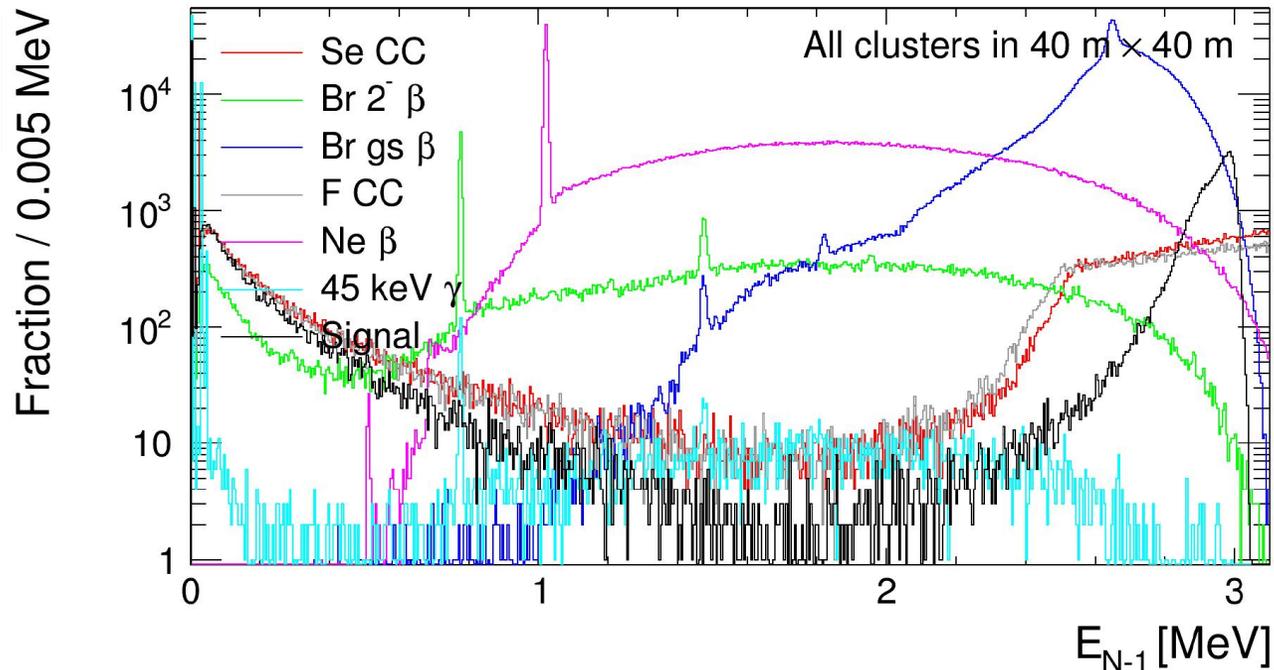
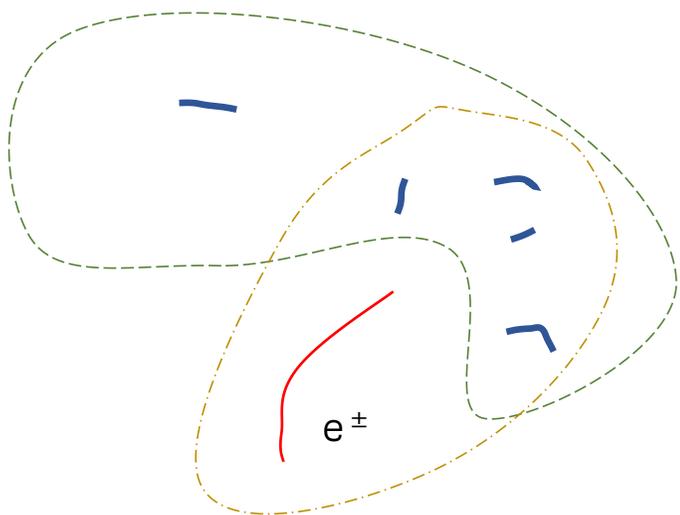
Cluster能量

- 明显的不同能量的 γ 的特征峰
- $N_{\text{clus}} < 5, E_0 > 2.2 \text{ MeV}$
 - Br CC本底: $0.64 \rightarrow < 0.0001 \text{ events}/(\text{ton}\cdot\text{yr})$



E_{N-1}

- 事例中所有cluster总能量减掉其中某个cluster的能量
- 当被去掉的cluster是 β 衰变中产生的 e^\pm 时, E_{N-1} 是末态核素激发态的能量



结果

- ^{82}Br 的 β 衰变
 - 只考虑能量时是主要本底
 - 可以通过 E_0 、 N_{clus} 减少
- 单电子本底需要其他方法来减少
 - 与自然放射性 γ 本底相似

$$N_{\text{clus}} < 5$$

$$E_0 > 2.2 \text{ MeV}$$

Source	All energy	With oscillation	ROI	Selection
Electron scattering	728.6	481.0	0.00445	0.00395(13)*
^{82}Se CC	63.95	33.88	0.00021	0.000185(4)*
^{82}Br β decay	62.41	33.07	0.63	< 0.0001 (95% C.L.)
^{82m}Br β decay	1.54	0.81	0.00052	0.00037(2)*
^{19}F CC	5.11	1.69	0.0036	0.00318(7)*
^{19}Ne β decay			0.0042	0.000003(3)
Proton emission	0.292	0.093	0	0
Total single-electron events			0.00878	0.00769(15)
Total multi-site events			0.63	< 0.0001 (95% C.L.)

未来

- 一个大型的多用途的 SeF_6 探测器?
 - 中微子物理、暗物质.....

AAAS
Research
Volume 2022, Article ID 9798721, 9 pages
<https://doi.org/10.34133/2022/9798721>

Research
A SCIENCE PARTNER JOURNAL

Research Article

Determination of Double Beta Decay Half-Life of ^{136}Xe with the PandaX-4T Natural Xenon Detector

PHYSICAL REVIEW LETTERS **130**, 021802 (2023)

Search for Solar ^8B Neutrinos in the PandaX-4T Experiment Using Neutrino-Nucleus Coherent Scattering

arXiv > hep-ex > arXiv:2401.07045

High Energy Physics - Experiment

[Submitted on 13 Jan 2024]

A Measurement of Solar pp Neutrino Flux using PandaX-4T Electron Recoil Data

2024-5-10

OPEN ACCESS

IOP Publishing

Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **50** (2023) 013001 (115pp)

<https://doi.org/10.1088/1361-6471/ac841a>

Topical Review

A next-generation liquid xenon observatory for dark matter and neutrino physics

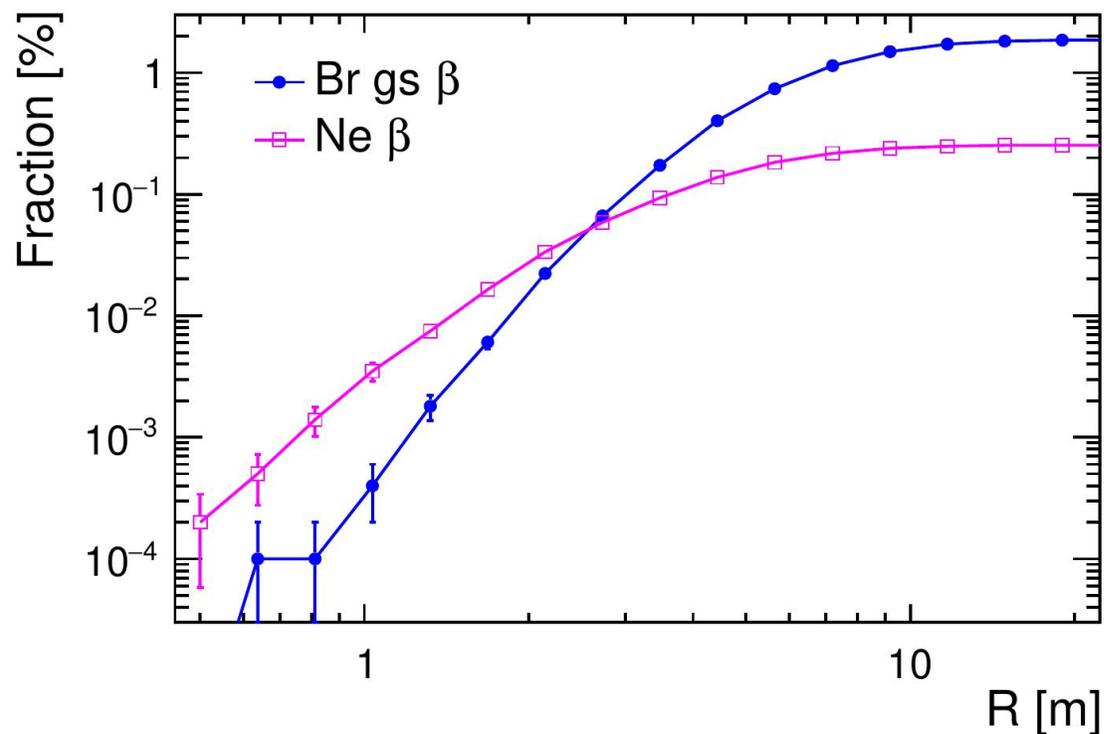
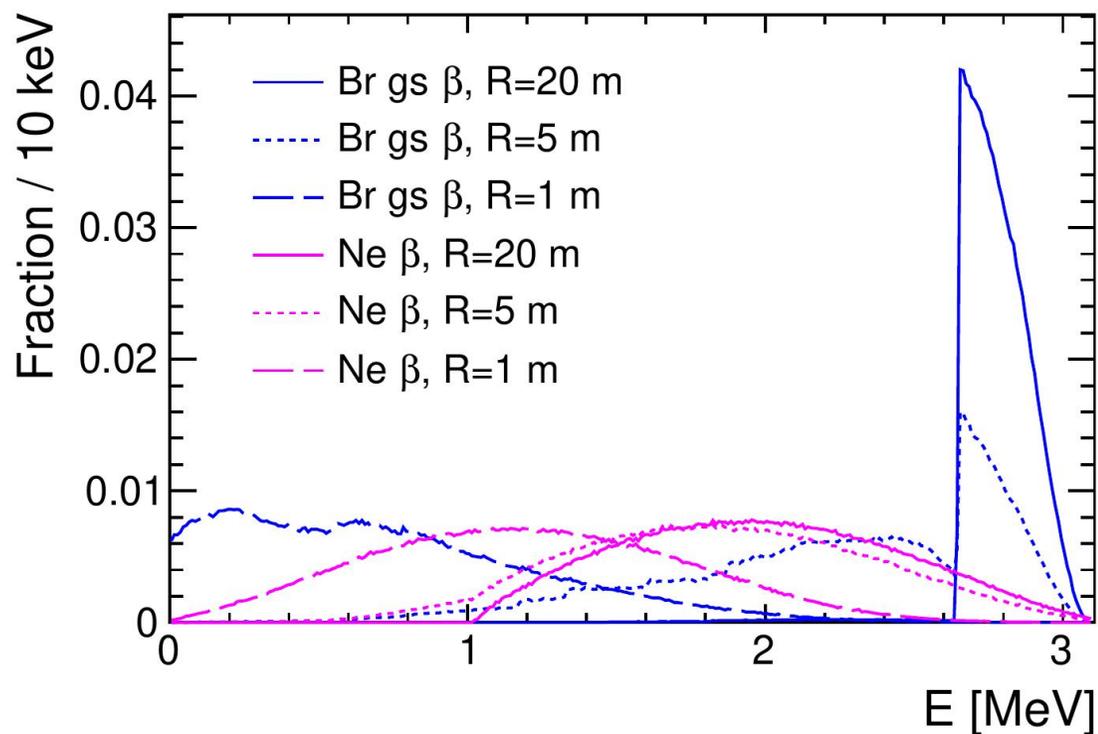
总结

- 太阳中微子与 ^{82}Se 发生带电流过程，在 $0\nu\beta\beta$ 的ROI区域事例率较高
 - 在将来可能成为重要本底
- 太阳中微子在 $^{82}\text{SeF}_6$ 中产生的本底可分为两类
 - 单电子 (+低能光子) \rightarrow 与自然放射性 γ 本底类似
 - 电子+多个高能光子 \rightarrow 通过一些基于cluster数目、能量的简单筛选将本底有效减少
- 太阳中微子本底事件的一些特征可用于本底鉴别
- 将进一步研究 $^{82}\text{SeF}_6$ 高压气体探测器对太阳中微子研究、暗物质寻找的灵敏度

Backup

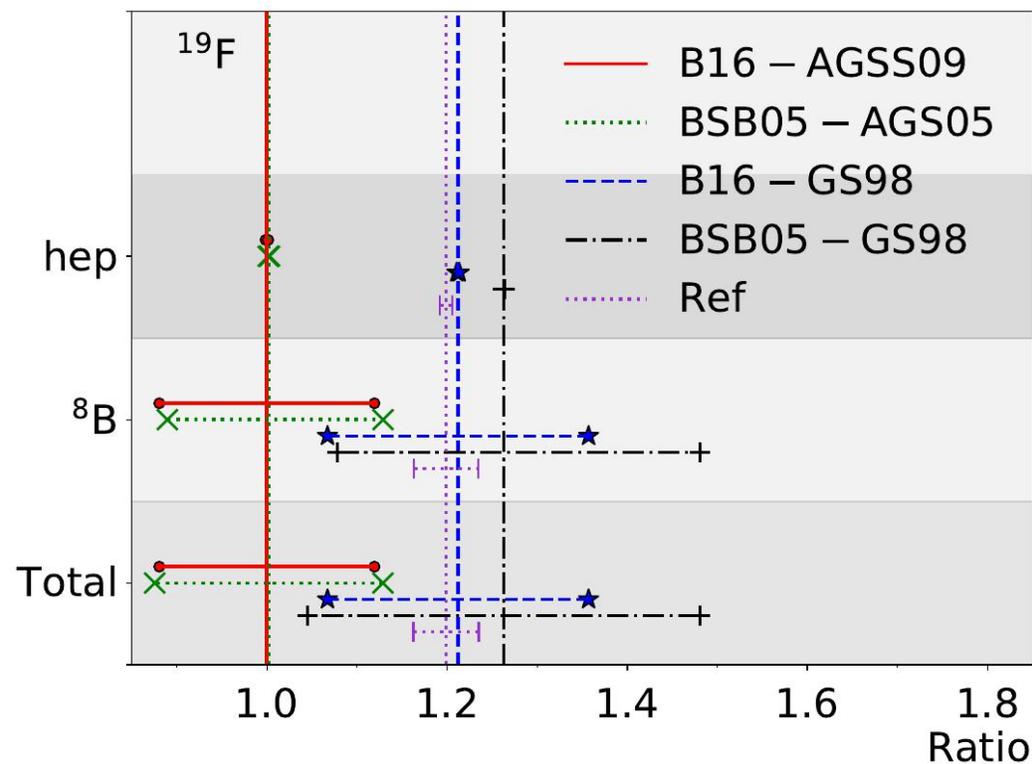
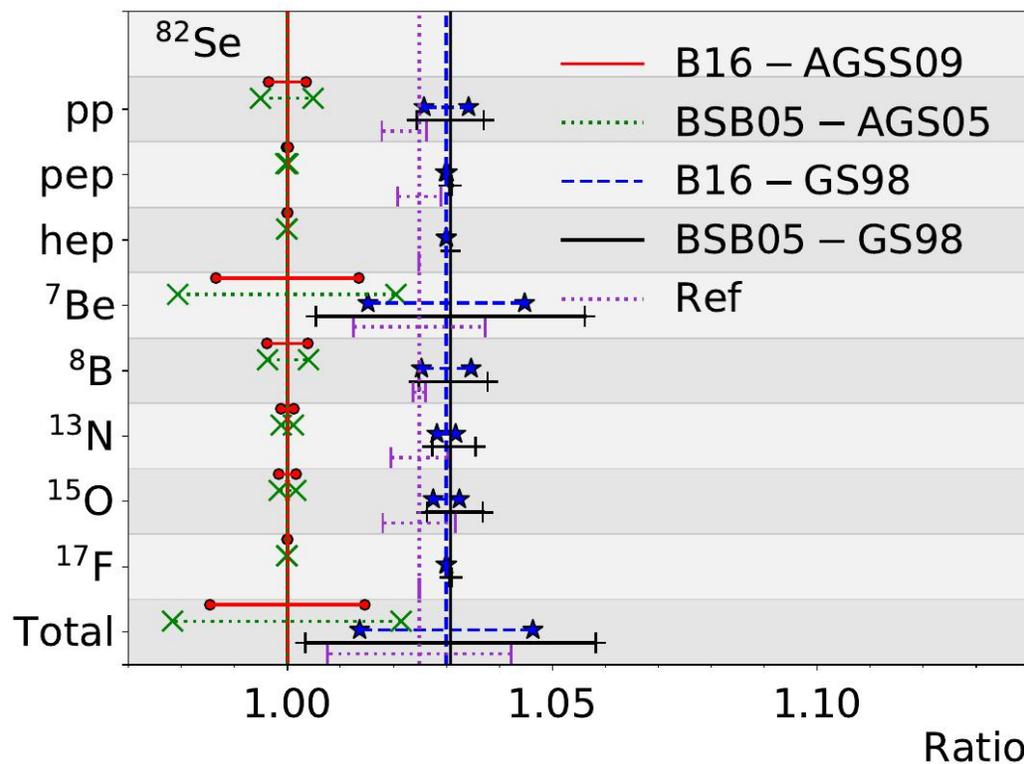
探测器大小

- 能量不完全收集
- 边缘影响信号效率



太阳中微子通量不确定度

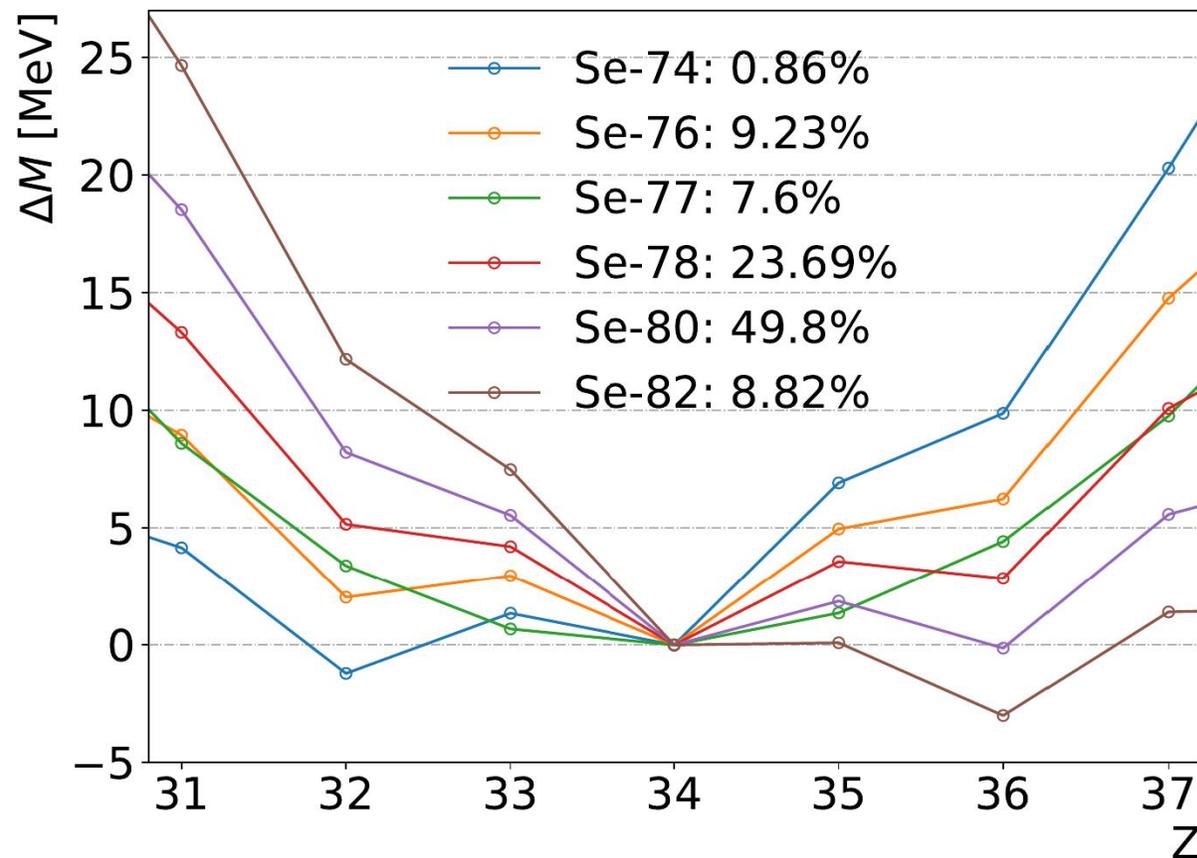
- ^{82}Se CC相关本底主要受pp、 ^7Be 中微子影响, $\sim 3\%$
- ^{19}F CC相关本底受 ^8B 中微子影响, (10-20)%
 - 对电子散射本底也适用

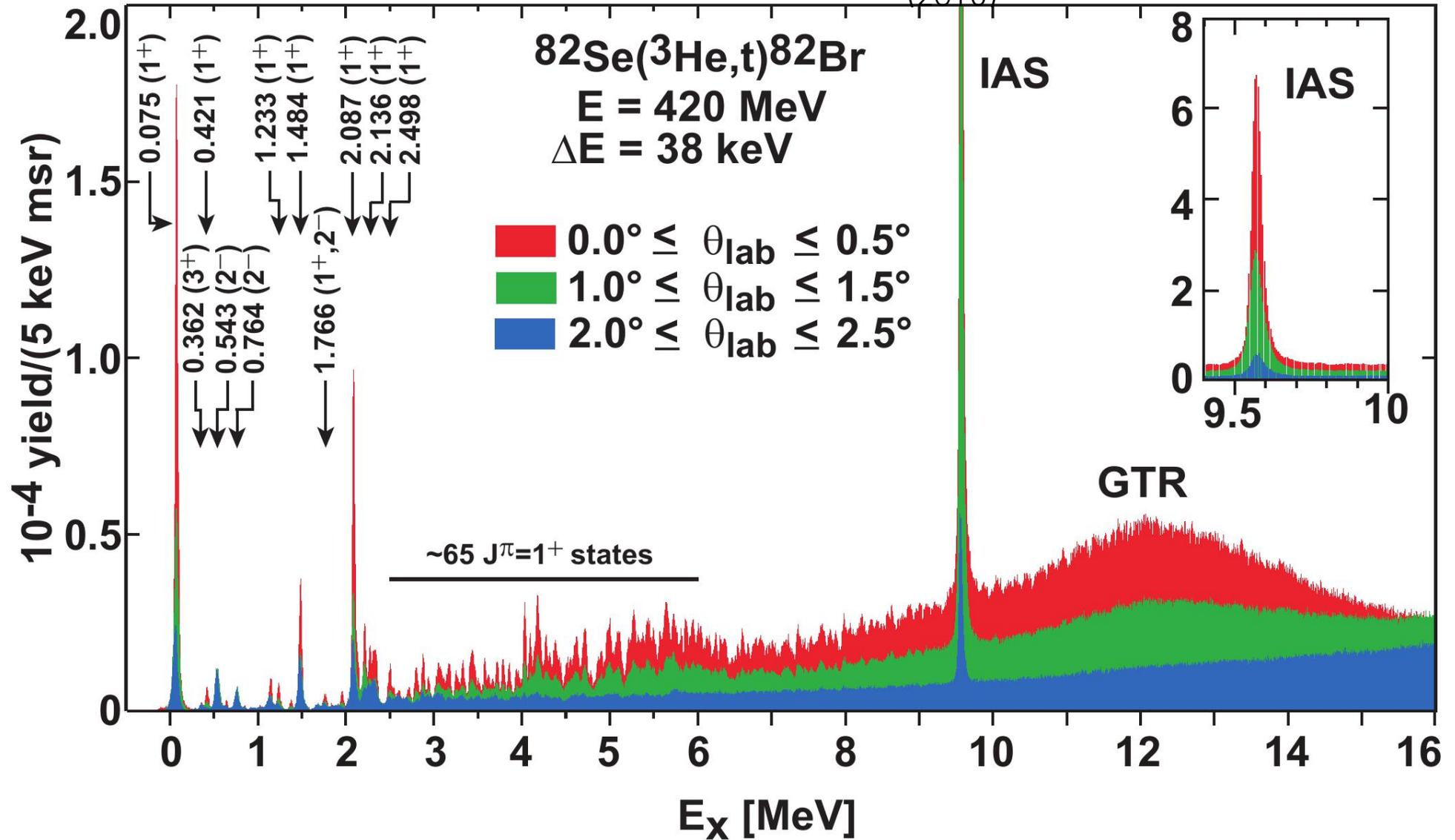


其他同位素

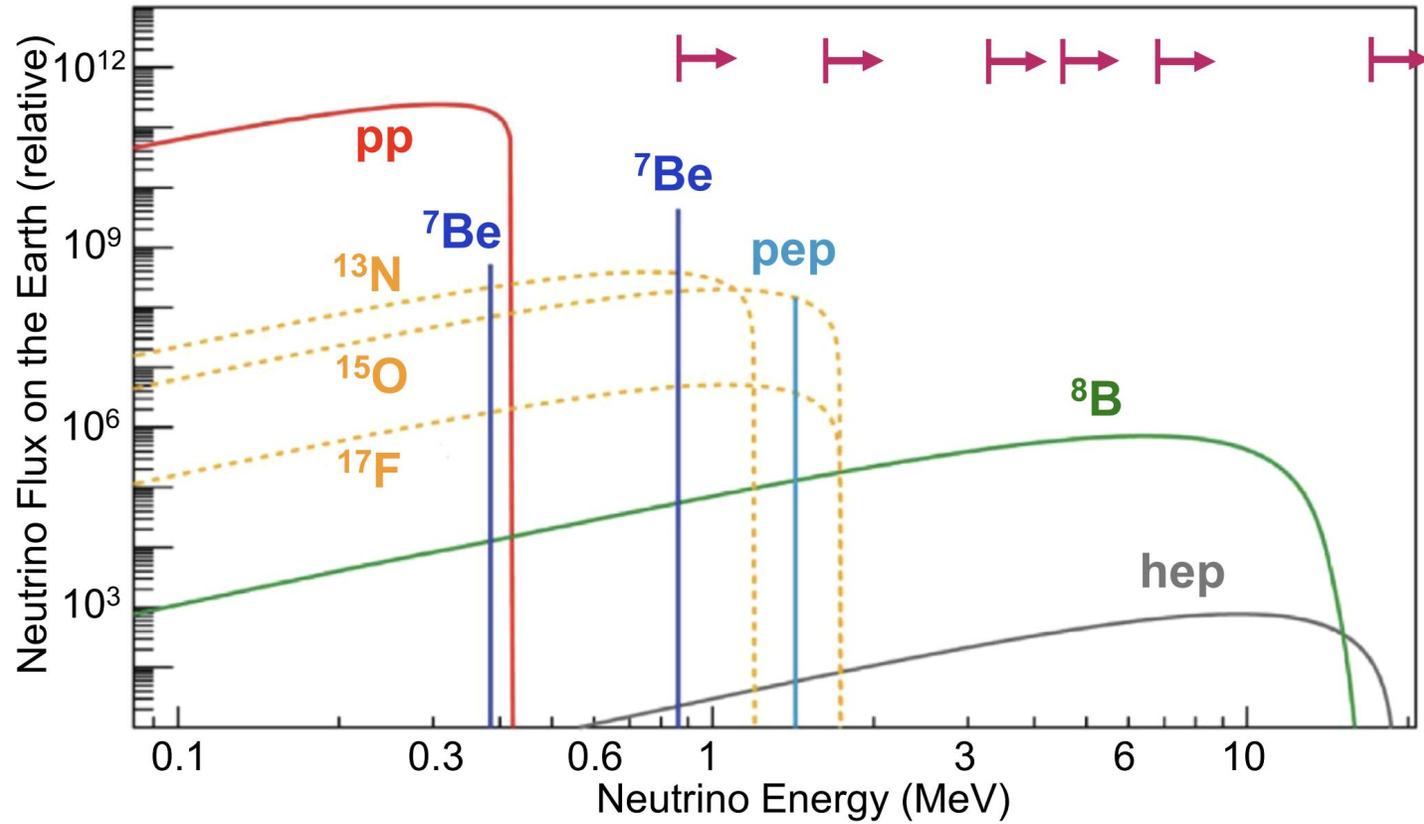
- ^{19}F 丰度几乎100%
- Se有多种同位素
 - 阈值高
 - $Q_{\beta\beta}$ 低, 或 β^+ 衰变

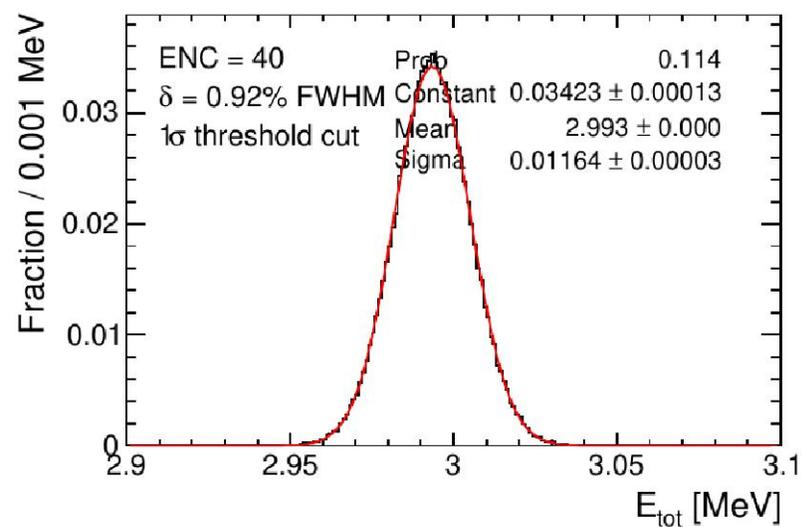
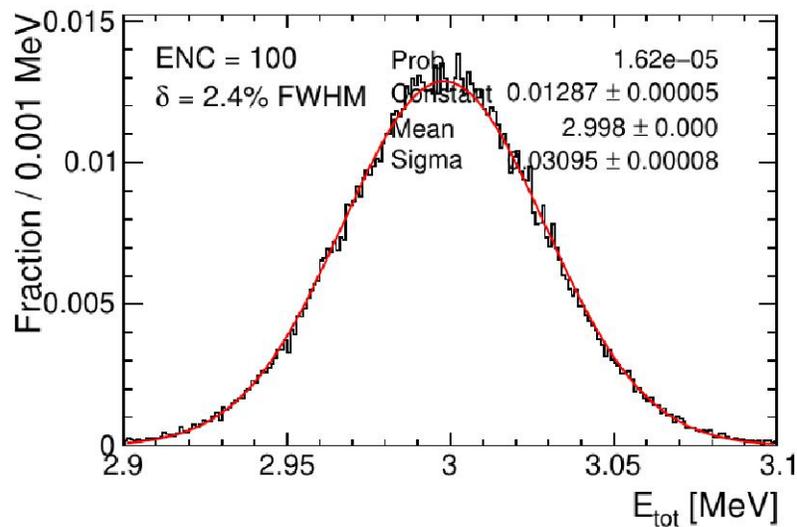
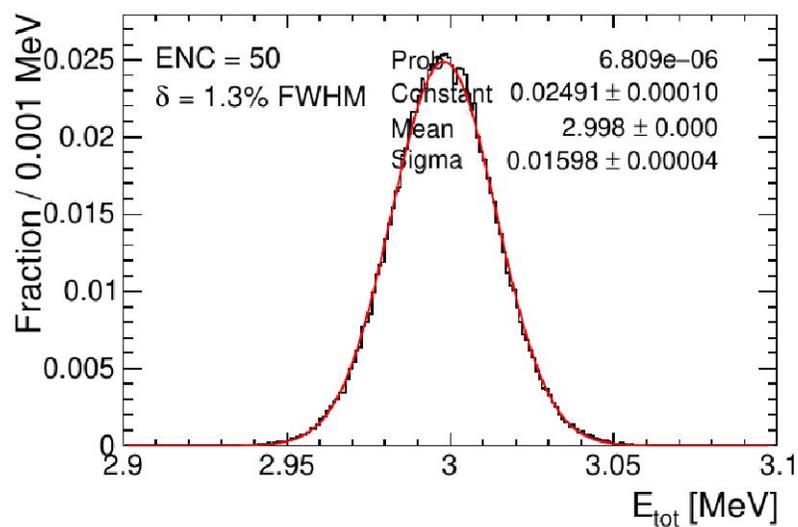
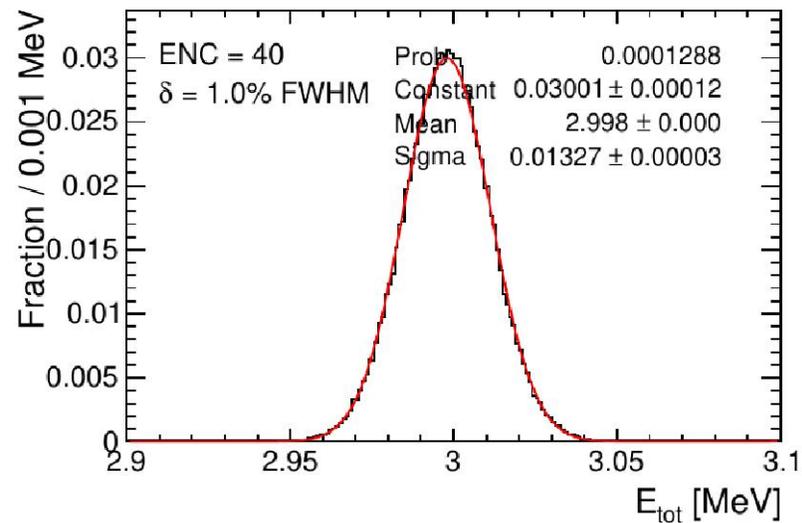
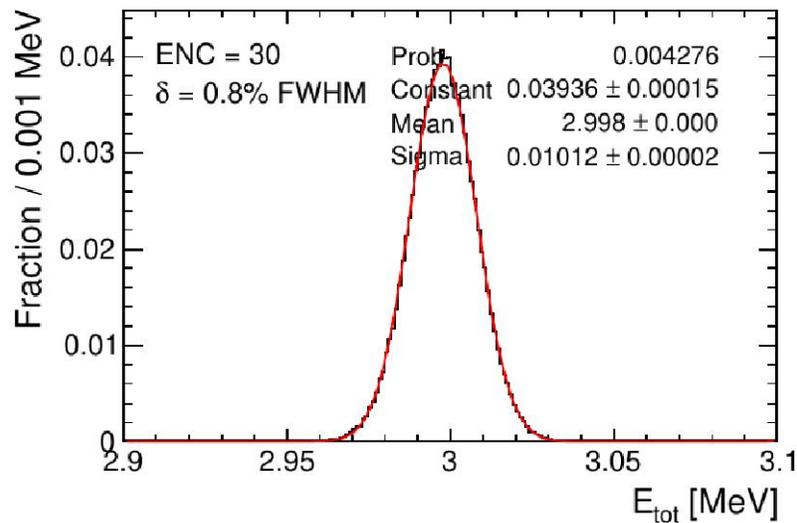
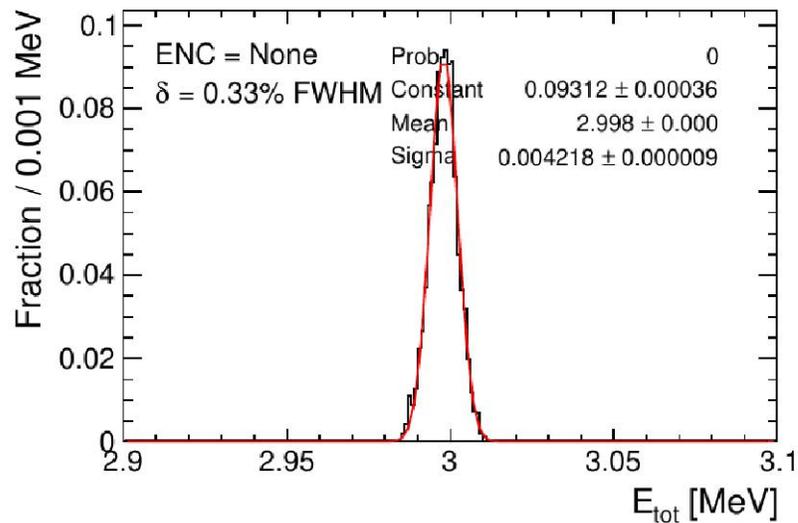
Isotope	Abundance(%)	Q_{β}/MeV	$Q_{\beta\beta}/\text{MeV}$	Br lifetime	Br decay
^{74}Se	0.86	6.925	1.209	25.4 min	β^+
^{76}Se	9.23	4.963	—	16.2 h	β^+
^{77}Se	7.6	1.365	—	57 h	β^+
^{78}Se	23.7	3.574	—	6.45 min	β^-, β^+
^{80}Se	49.8	1.870	0.134	17 min	β^-, β^+
^{82}Se	8.82	0.095	2.998	35 h	β^-





Target Nuclei :	⁷ Li	¹⁸ O	¹⁹ F	⁶ Li	⁴² Ca	¹² C
Q_EC (MeV) :	0.86	1.66	3.24	4.29	6.43	17.3





电子散射

- 方向性

$$\cos^2 \theta = \frac{T(m_e + E_\nu)^2}{(T + 2m_e)E_\nu^2}$$

