基于TOF-PGAA方法
的核结构研究展望

汇报人：张广鑫
中山大学
Email: zhanggx37@mail.sysu.edu.cn

中山大學 中法核工程与技术学院
Institut franco-chinois de l'énergie nucléaire Université Sun Yat-sen

T-PGAA：Time-resolved prompt-gamma activation analysis

- PGAA方法：瞬发gamma活化分析技术，鉴别待测样品中（被中子活化后）特定核素的种类和数量；

- 鉴于PGAA方法在核素复杂时，渐变能力较弱，ISIS散裂中子源在2019年首次发展了带时间分辨的PGAA方法--中子飞行时间！

- 通过中子飞行时间（TOF，对应中子共振峰位置）和退激射线能量的（HPGe）关联测量，精确的鉴定待测物品中各种核素的种类和含量。

- 注意：用PGAA方法判断的往往都是稳定核（或附近核素），默认能级纲图信息较为全面。

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Time-resolved prompt-gamma activation analysis at spallation neutron sources and applications to cultural heritage, security, and radiation protection

Giovanni Romanelli [a], Giulia Festa [b,*], Dalila Onorati [c], Enrico Preziosi [c], Pierfrancesco Ulpiani [d], Carla Andreani [c], Roberto Senesi [c,e]

[a] ISIS Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, OX11 0QX, UK

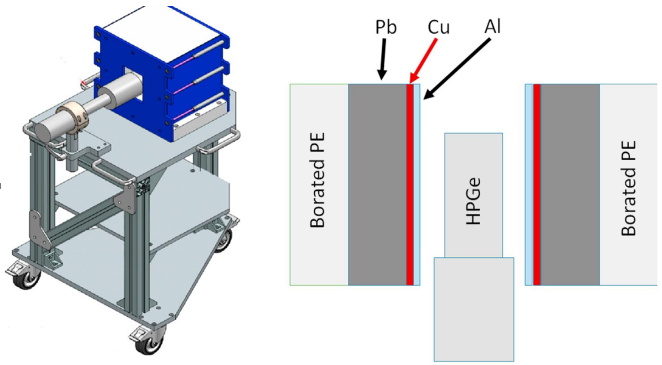
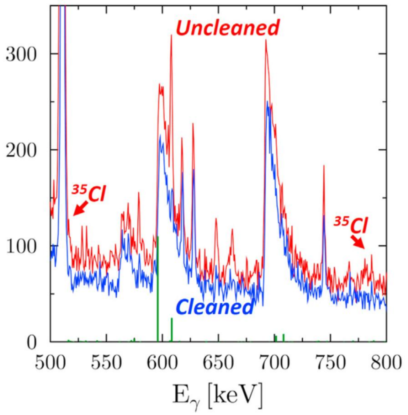
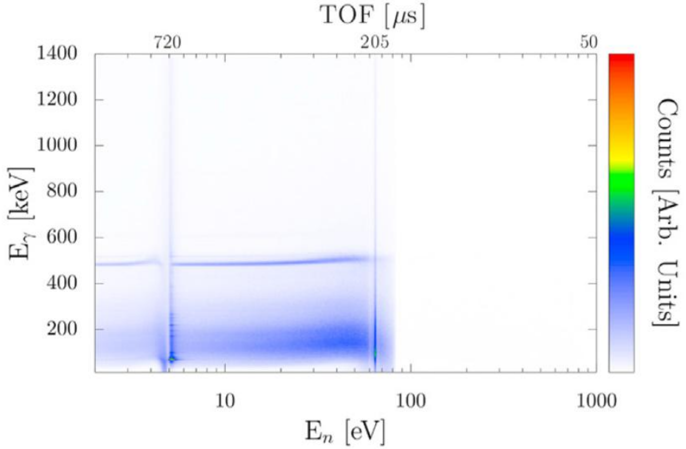


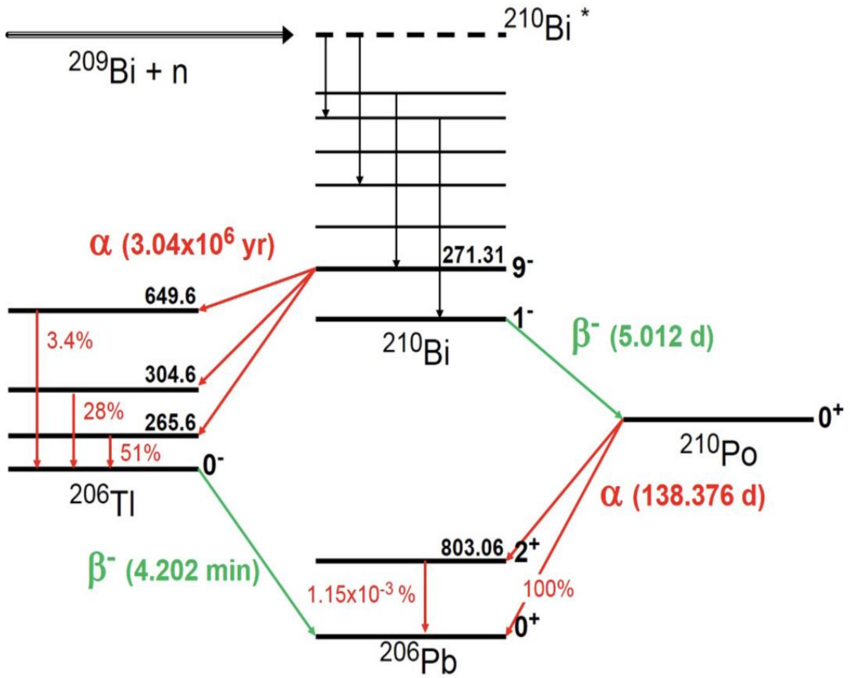
Fig. 6. A schematic drawing of the PGAA shielding being assembled at the VESUVIO spectrometer.

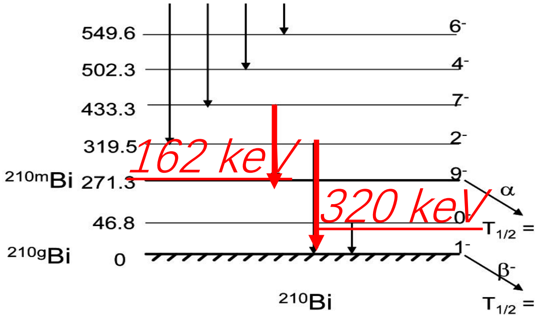


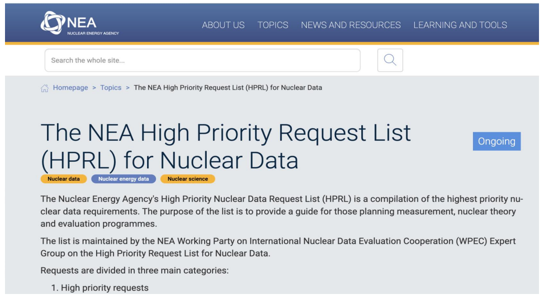


T-PGAA的应用：中子俘获退激过程的isomer ratio

- n + ^{A}X -> $^{A+1}$X*, Ex ~ S(n)+TKE(n),
- 其中复合核自旋 = 靶核自旋+-1/2（s波俘获）
- 中子俘获后退激过程一般被假设为统计过程（复合核处于高激发态，无单粒子核结构效应？），*NLD+PSF*
- *但是先进核能对isomer ratio提出了更高的要求！*
- 铅铋快堆中，^{209}Bi俘获中子形成^{210}Bi的4^{-}，5^{-}共振态；
- 既可以退激到210Bi的基态(1^{-})，半衰期短，产生剧毒的^{210}Po，
- 也可以产生isomer(9^{-})，半衰期超过百万年，不产生^{210}Po，

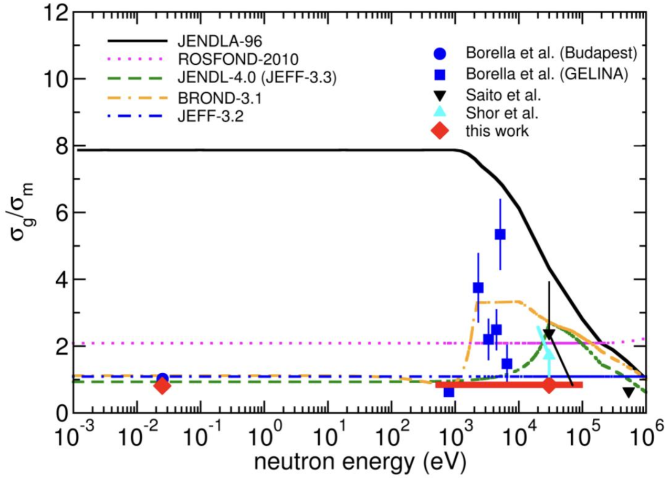






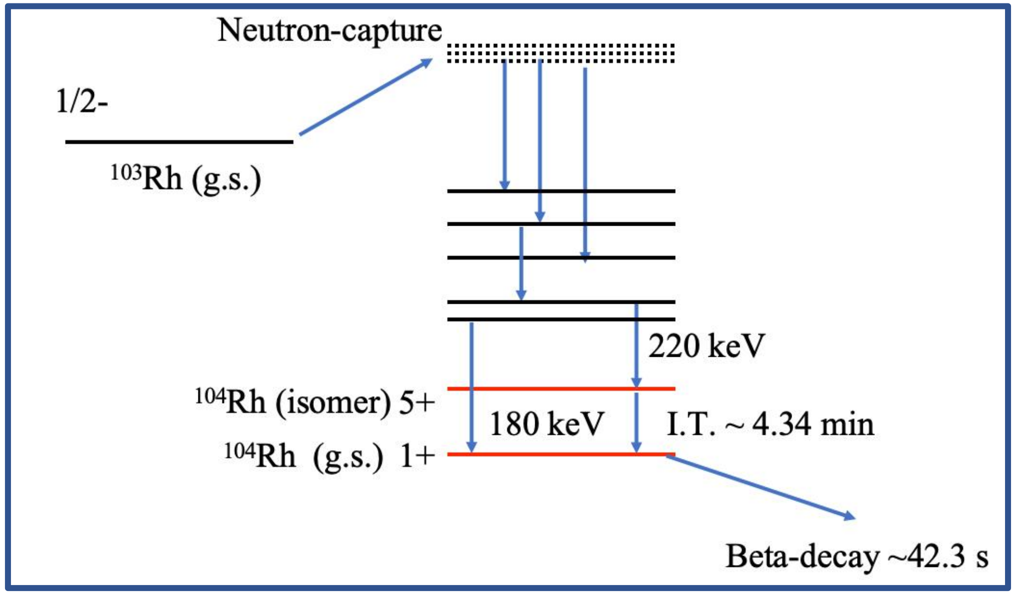
83-Bi-209(n,g)Bi-210g,m

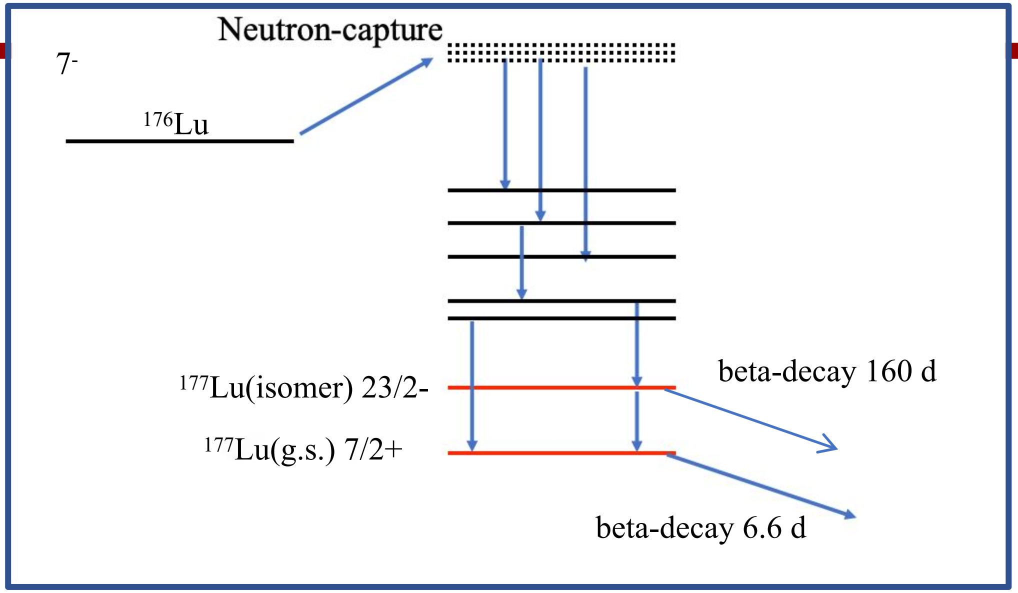
ID	114
Type	H - High priority request
Target	83-Bi-209
Reaction	(n,g)Bi-210g,m
Quantity	BR - Branching ratio for isomeric states of residuals
Incident energy	500 eV - 300 keV
Accuracy	10 %
Field(s)	ADS, Fission
Accepted date	09-Nov-2018
Status	Work in progress
Latest review date	28-Apr-2022

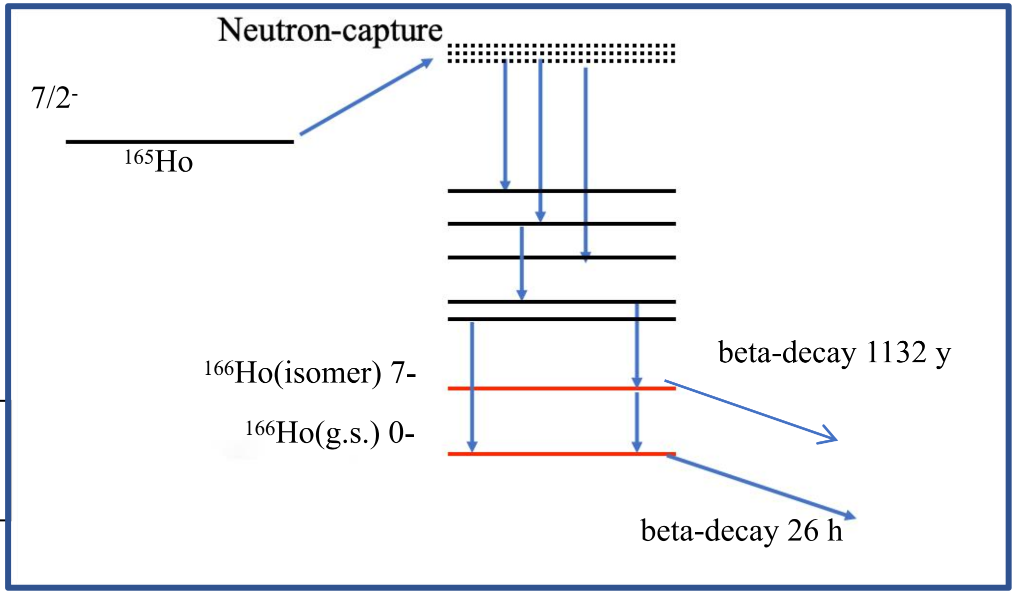


T-PGAA的潜在应用：大量isomer ratio需要测量！

✓ 自给能探测器 ^{103}Rh， isomer ratio 是研究快中子响应的关键!



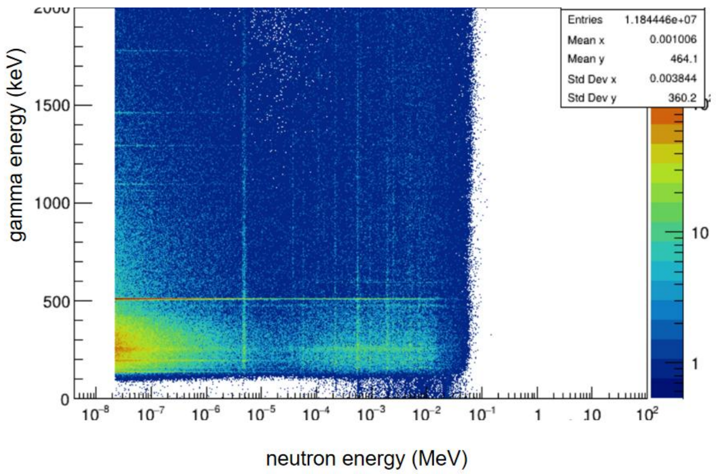


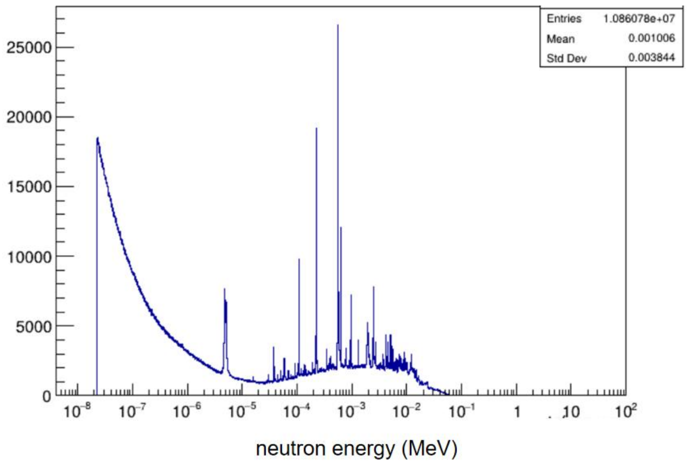


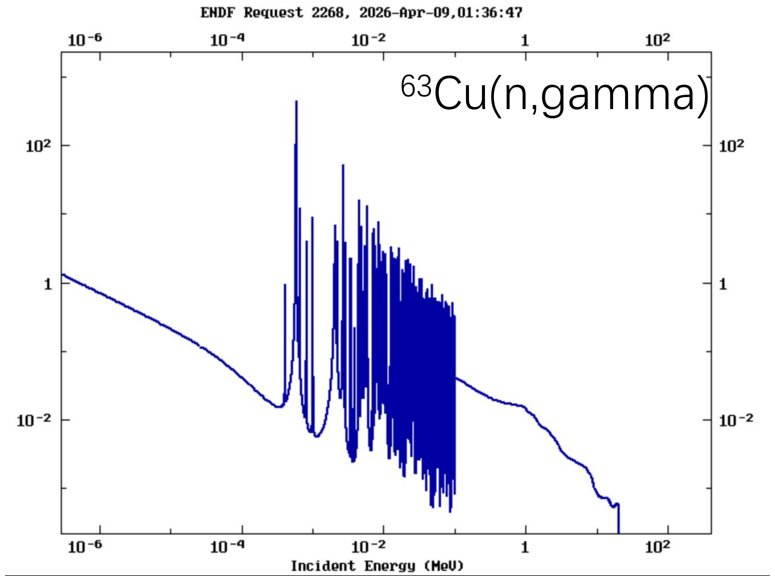
✓ 核药生产 ^{177}Lu, ^{166}Ho, isomer ratio 是控制产品质量的重要信息!

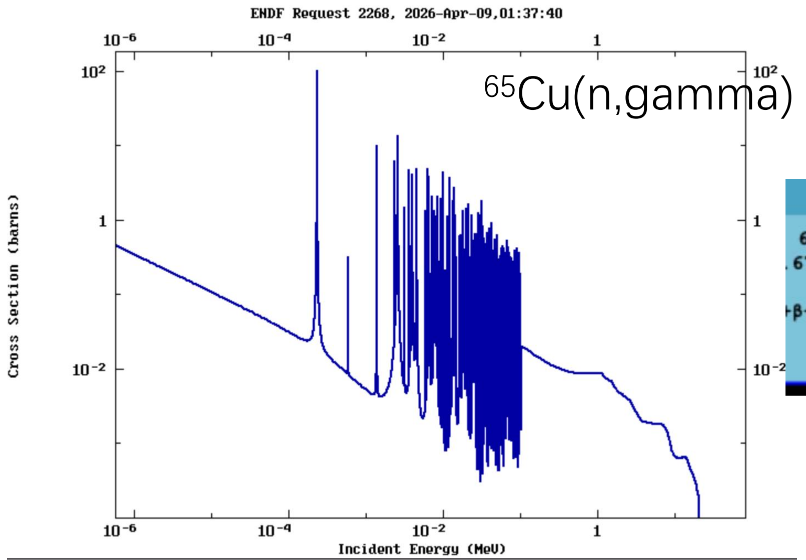
T-PGAA在CSNS的实测案例（Cu靶）

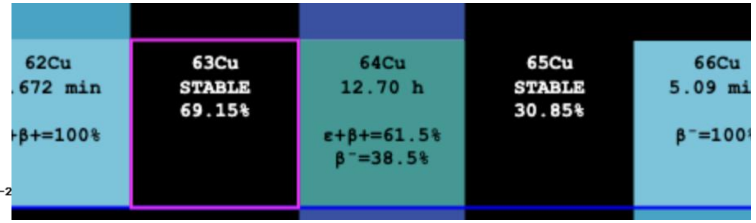
- 2026上半年，复合Cu靶 1.5 mm厚，2天束流时间，30 mm束斑，1 HPGe



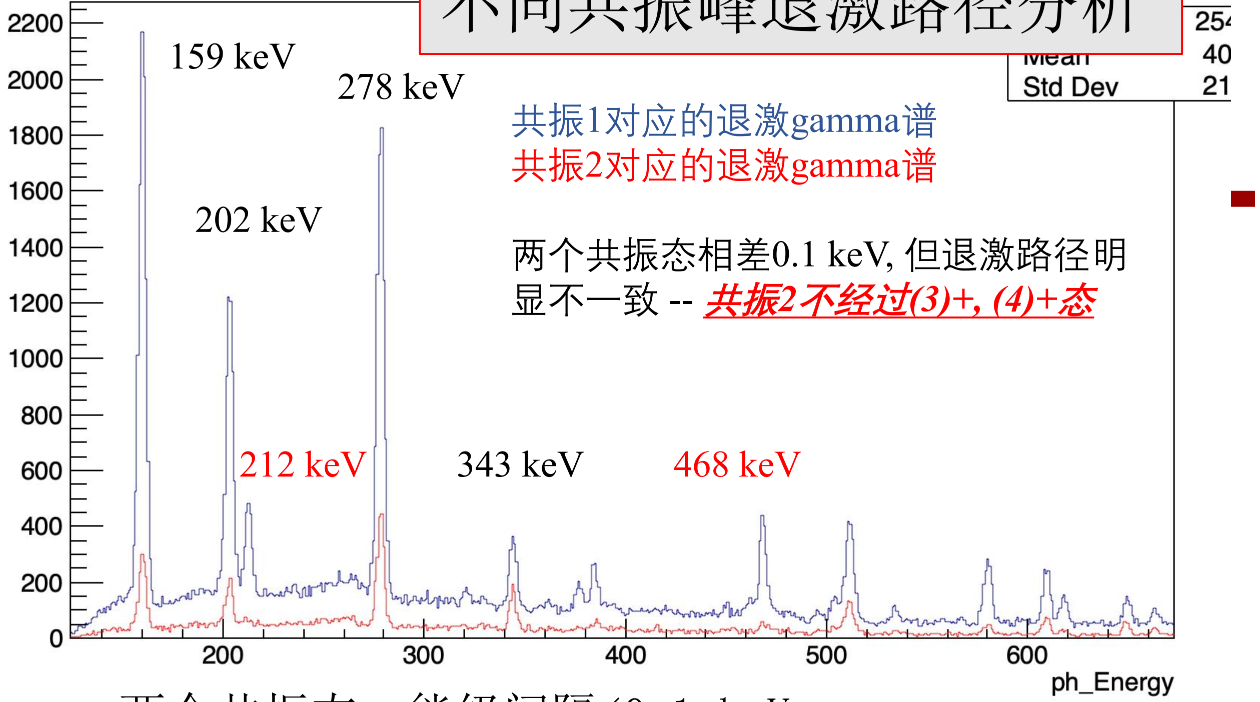


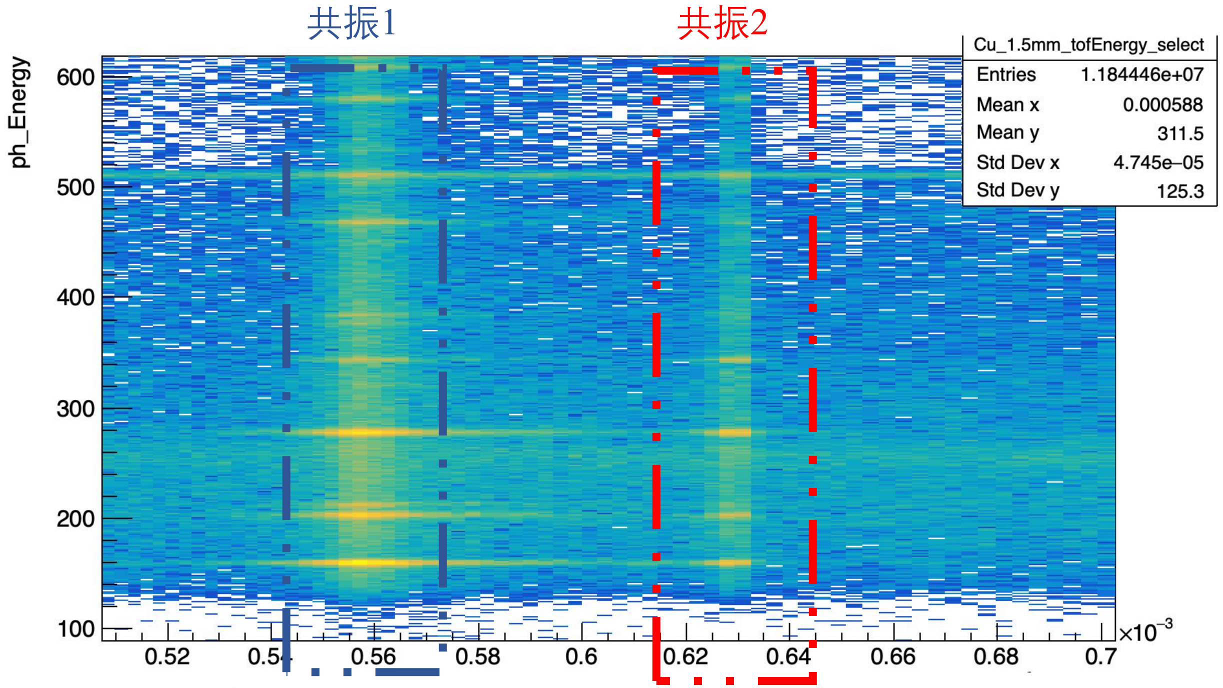




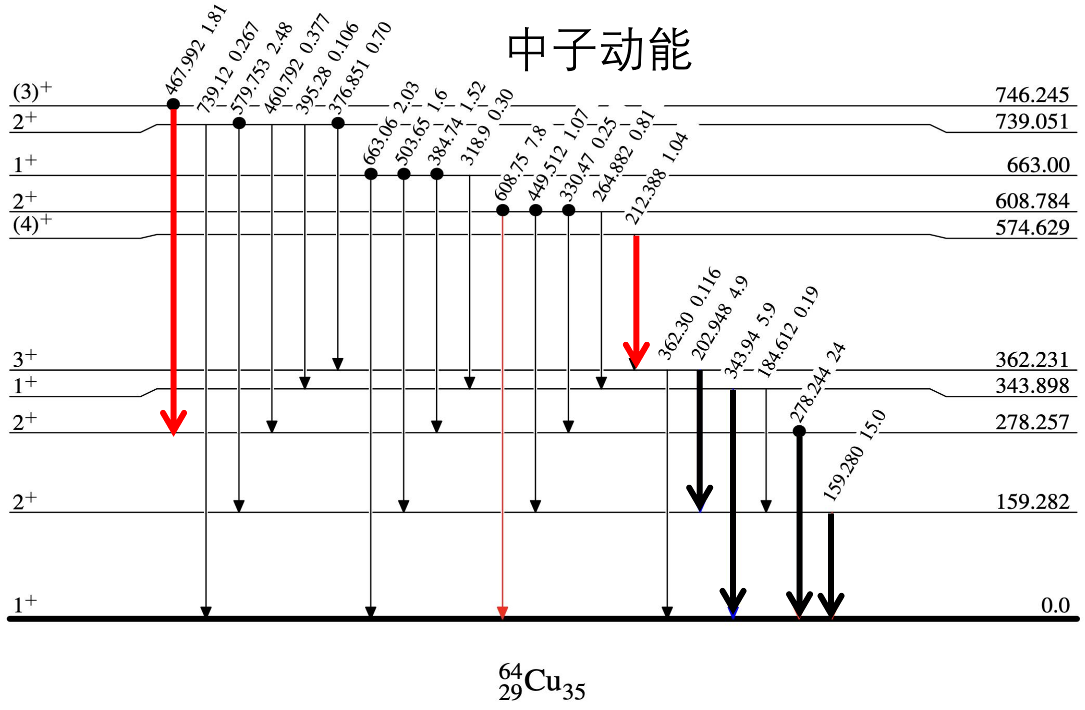


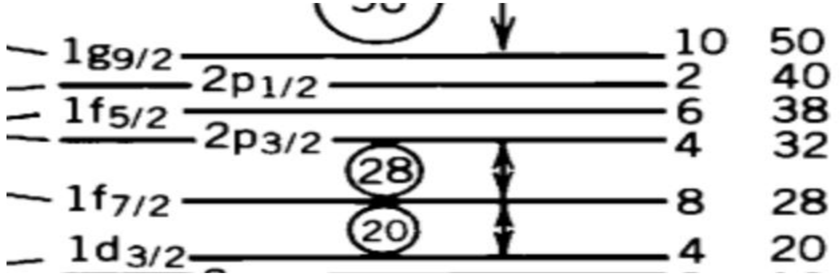
不同共振峰退激路径分析





- 两个共振态，能级间隔<0.1 keV
- ^{63}Cu基态3/2−，^{64}Cu共振态可能是2$^-$或者3$^-$态，但退激路径有明显差异！
- 中子组态不一样？
- 质子$p_{3/2}$*<u>中子$p_{3/2}$</u> 只能形成0+--- 3+的多重态，质子$p_{3/2}$*<u>中子$f_{5/2}$</u>才能形成 4+？

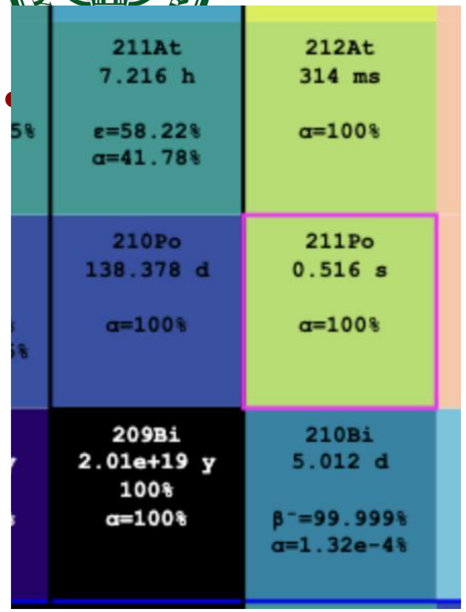




如果gamma退激是统计过程？

In PRC 74, 064615 (2006), *Isomer ratio measurements as a probe of the dynamics of breakup and incomplete fusion;*

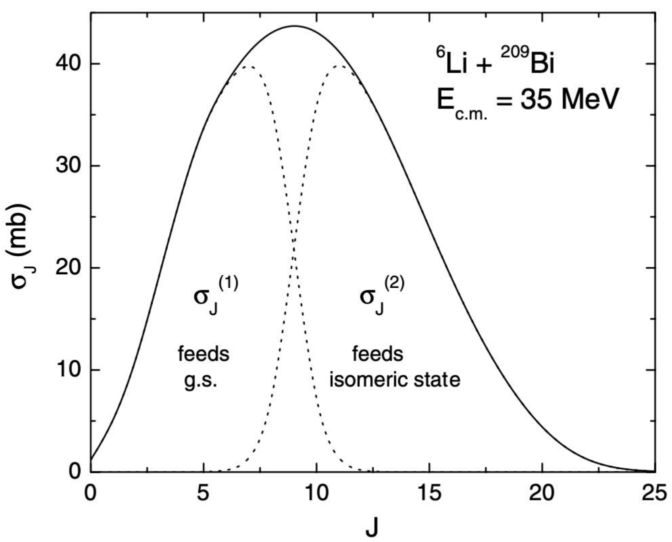
- J_{eff} can be set to be different value for ^{212}At and ^{211}Po;
- Assume $\delta = 0.5$;

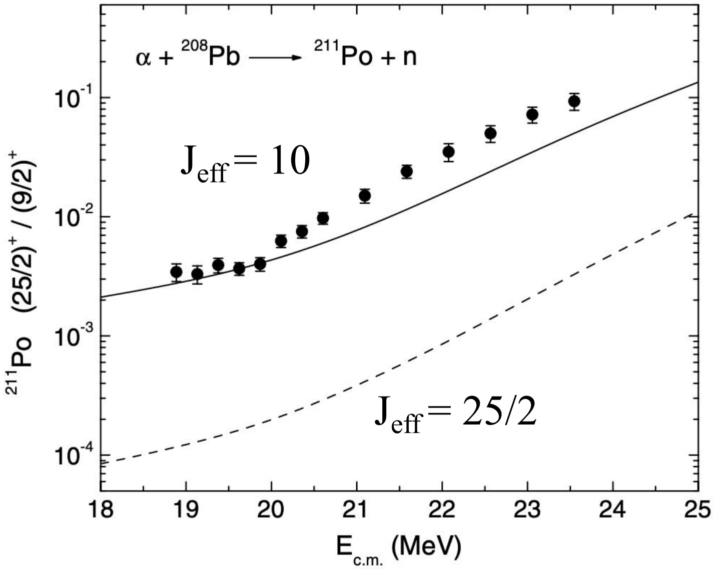


$$R = \frac{\sum_J \sigma_J^{(2)}}{\sum_J \sigma_J^{(1)}},$$

$$\sigma_J^{(1)} = \frac{\sigma_J}{1+\exp\left(\frac{J_{\rm eff}-J}{\delta}\right)},$$

$$\sigma_J^{(2)} = \frac{\sigma_J}{1+\exp\left(\frac{J-J_{\rm eff}}{\delta}\right)},$$





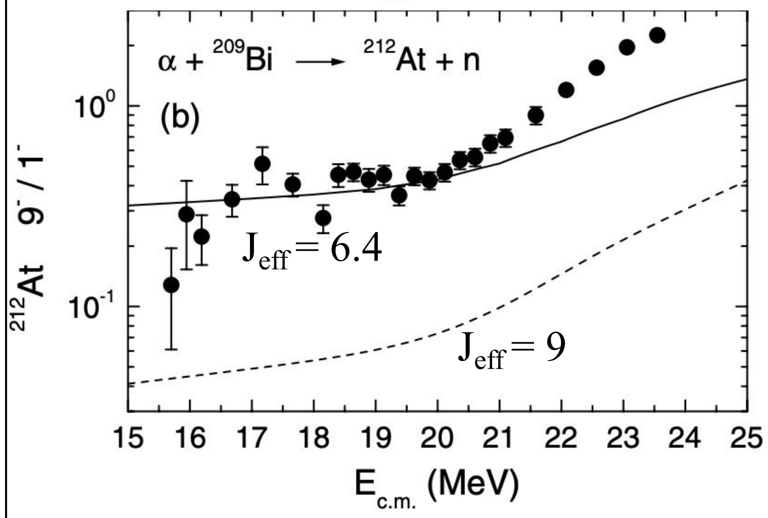
Ground and isomeric state information for $^{211}_{84}$Po

E(level) (MeV)	Jπ	Mass Excess (keV)	$T_{1/2}$	Decay Modes
0.0	9/2+	-12432.5 *13*	0.516 s *3*	α = 100%
1.462	(25/2+)	-10970.5 *13*	25.3 s *4*	α = 99.984% IT = 0.016%

Ground and isomeric state information for $^{212}_{85}$At

E(level) (MeV)	Jπ	Mass Excess (keV)	$T_{1/2}$	Decay Modes
0.0	(1-)	-8628.1 *24*	314.0 ms *20*	α = 100%
0.2229	(9-)	-8405.2 *24*	121.0 ms *20*	α = 99.5% IT = 0.5%

- 实验中，可以测量isomer和g.s.发射的alpha，进而推导熔合蒸发布局isomer分支比；
- 用J_{eff}和 δ从统计上区分不同分波截面退激到isomer和g.s的概率；
- 因此，此模型中复合核的自旋一致（或接近），布局isomer的分支比应类似！



T-PGAA在CSNS的测量初步结论

- (n,gamma)共振能区，核结构因素会影响退激路径（即分支比），值得进一步研究！
- 现有实验条件下，209Bi(n,gamma)想达到63Cu(n,gamma)数据量，需要200天束流时间：需要大规模阵列！
- 至少两个探测器、纯的Cu靶、更多的统计，能够让上面的分析推广到所有明显的已知共振态。

- 相比于熔合蒸发、多核子转移、弹核碎裂反应，中子俘获反应是产生高激发、低自旋态的关键技术手段！
- Odd-Odd核低激发态能级密度高 -> 对应不同质子-中子形成的多重态-> 可形成大量不同的退激路径;
- 研究中子共振态 - 不同退激路径直接的关联 >> 共振态的谱因子?

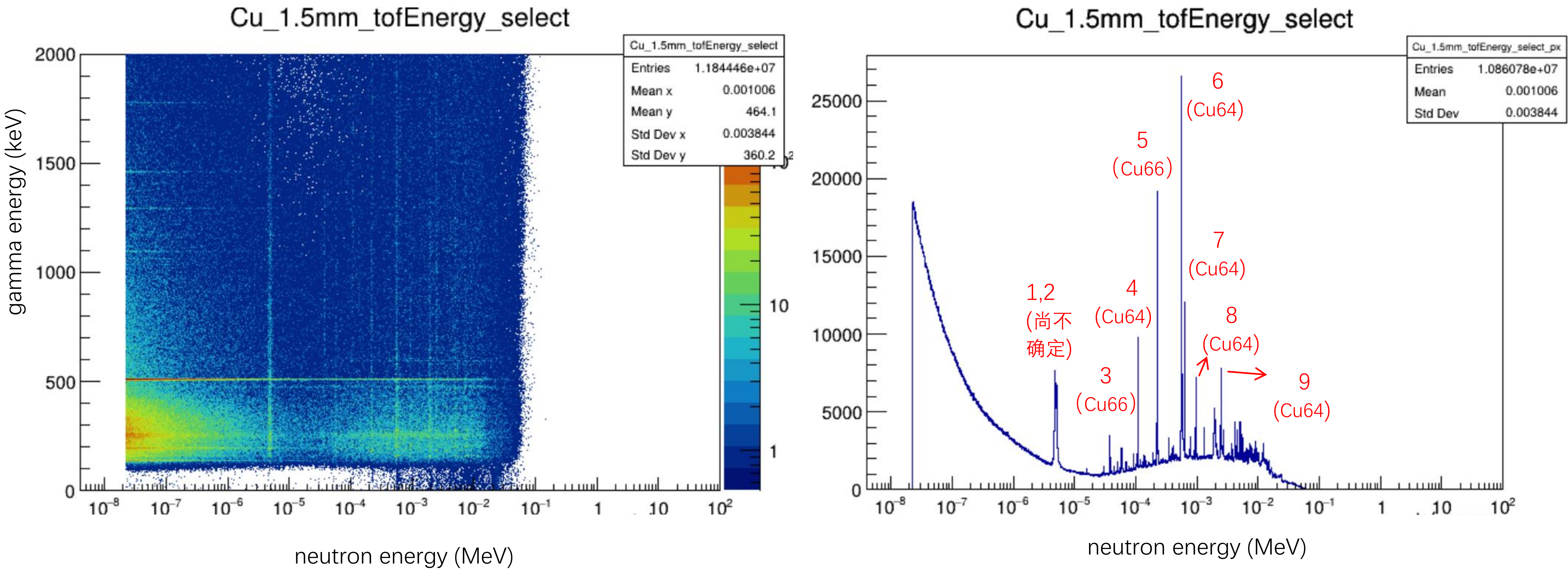
Thank you for your attention

—— 散裂中子+T-PGAA不仅是研究isomer ratio关键核数据的理想平台，

新的核结构研究？高激发、低自旋？形状共存、跨壳激发......

汇报人：张广鑫
中山大学
Email: zhanggx37@mail.sysu.edu.cn

中山大學中法核工程与技术学院
Institut franco-chinois de l'énergie nucléaire université Sun Yat-sen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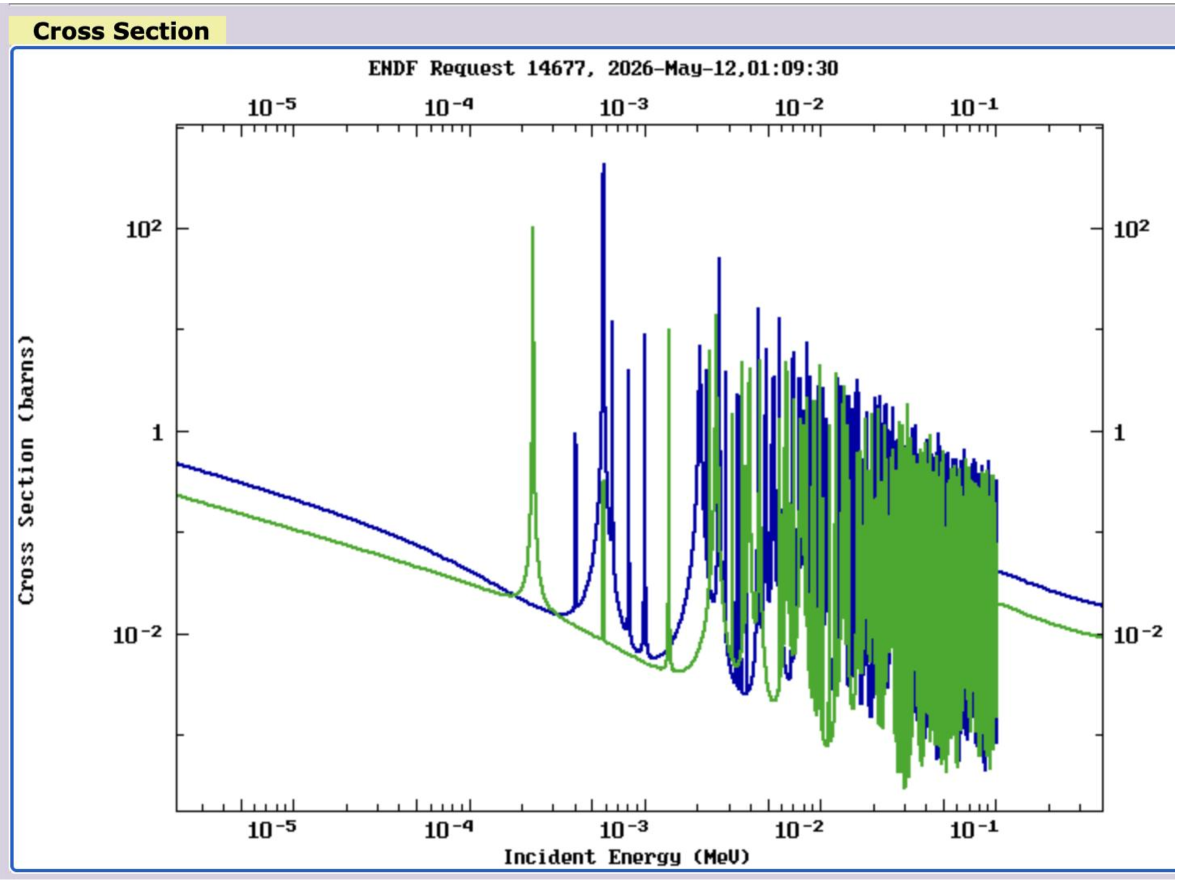
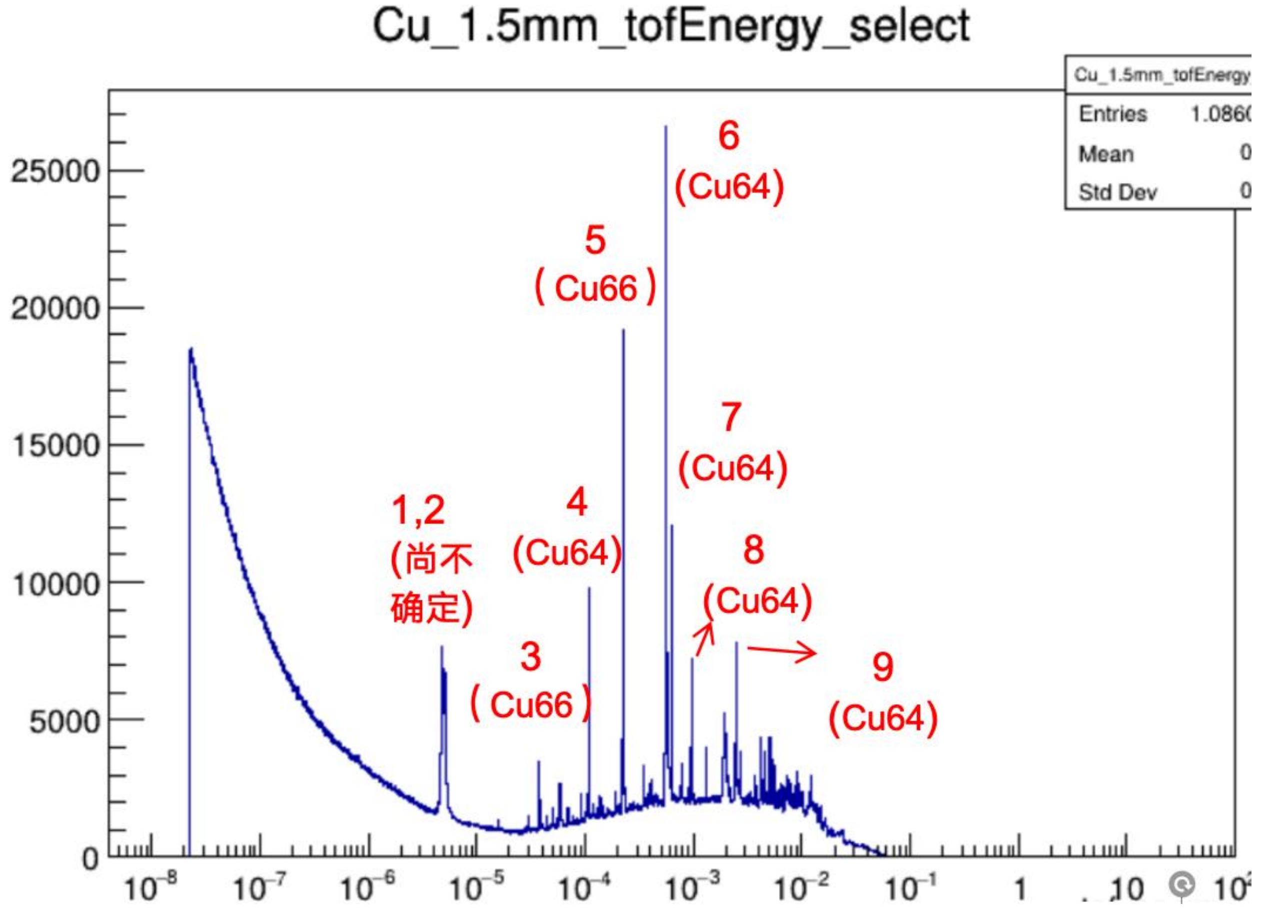
Cu_1.5mm_tofEnergy_select
Entries 1.184446e+07
Mean x 0.001006
Mean y 464.1
Std Dev x 0.003844
Std Dev y 360.2
gamma energy (keV)
neutron energy (MeV)
Cu_1.5mm_tofEnergy_select
Cu_1.5mm_tofEnergy_select_px
Entries 1.086078e+07
Mean 0.001006
Std Dev 0.003844
1,2
(尚不确定)
3
(Cu66)
4
(Cu64)
5
(Cu66)
6
(Cu64)
7
(Cu64)
8
(Cu64)
9
(Cu64)
neutron energy (MeV)

ENDF/B-VIII.0

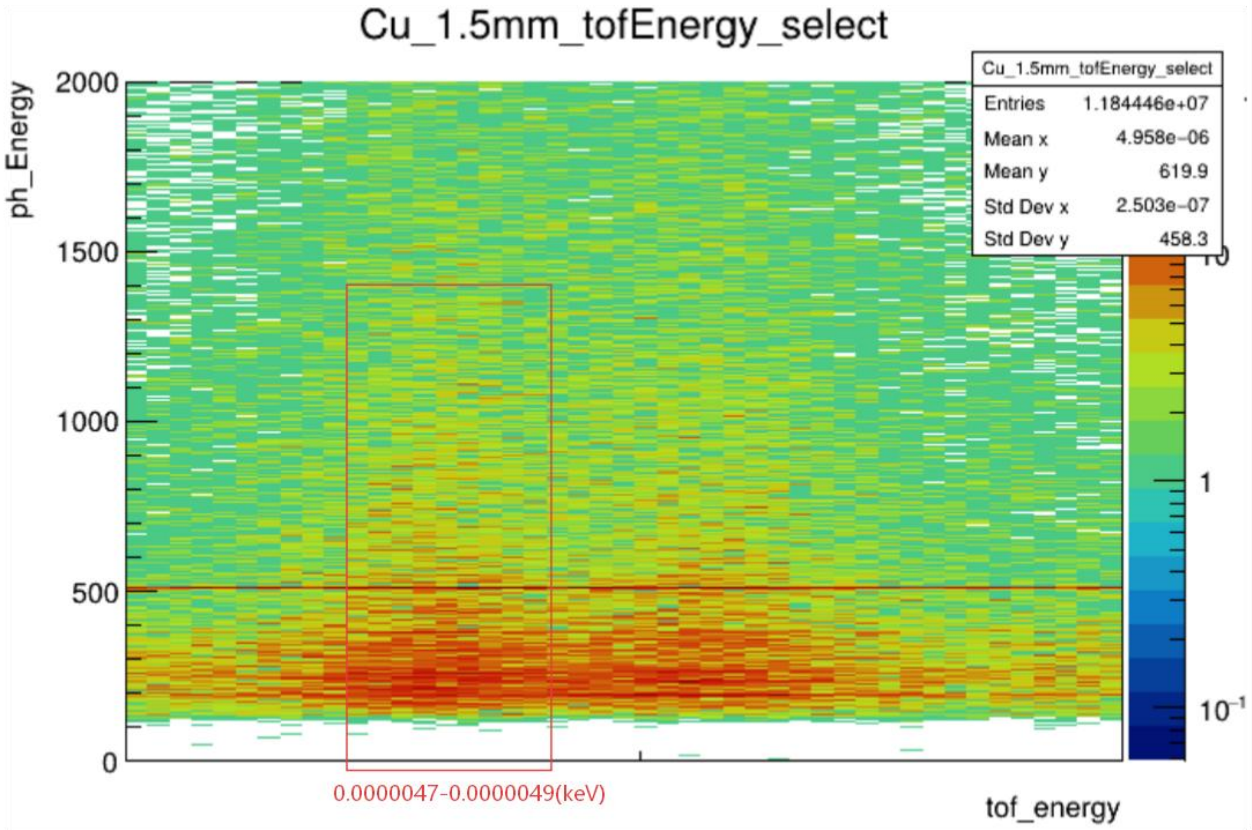
63Cu(n,gamma)64Cu

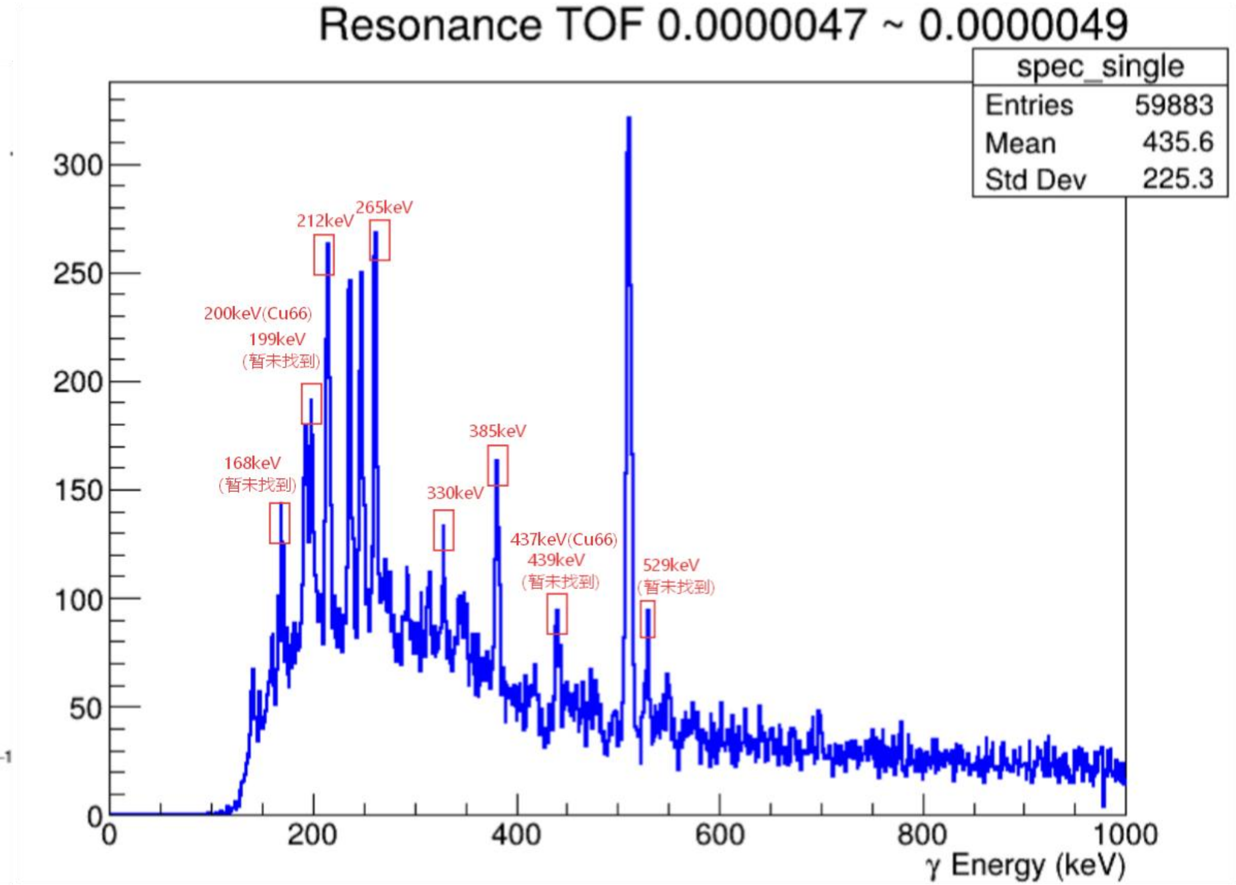
65Cu(n,gamma)66Cu





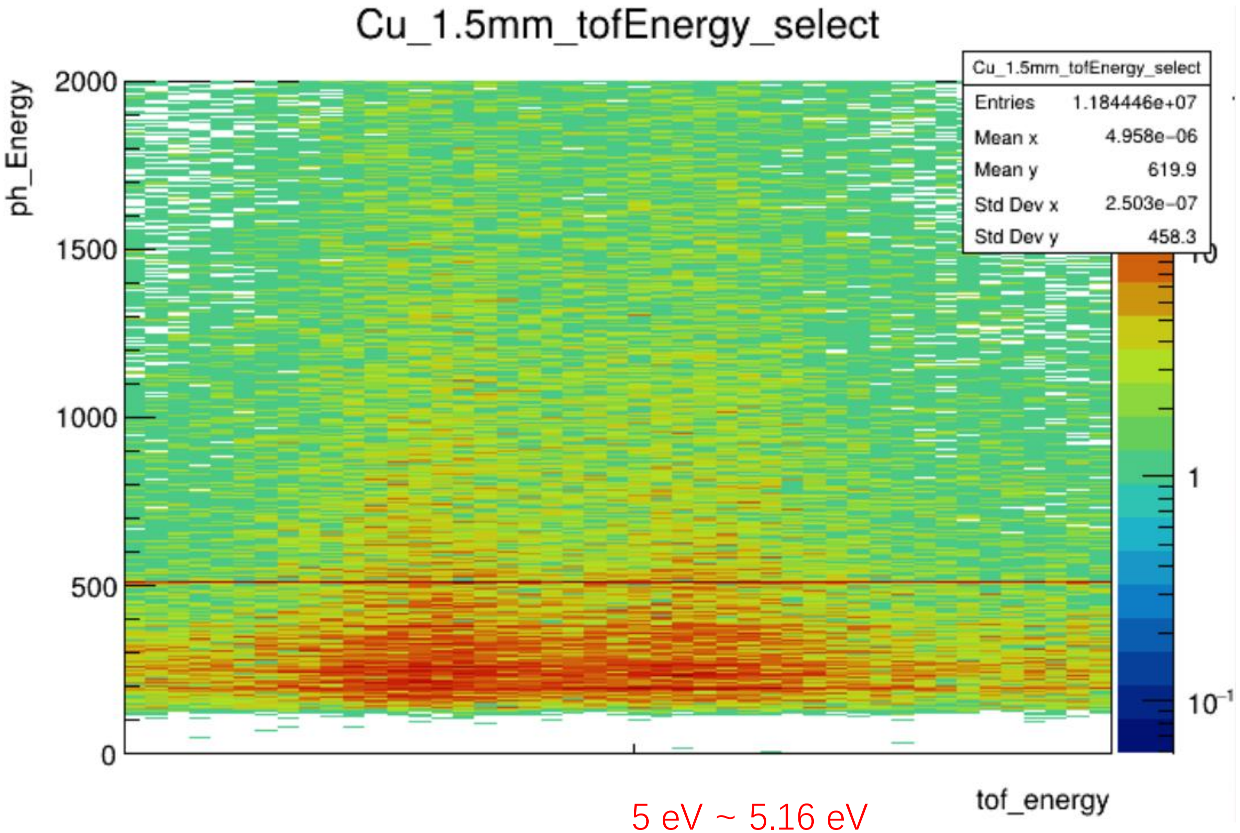
1

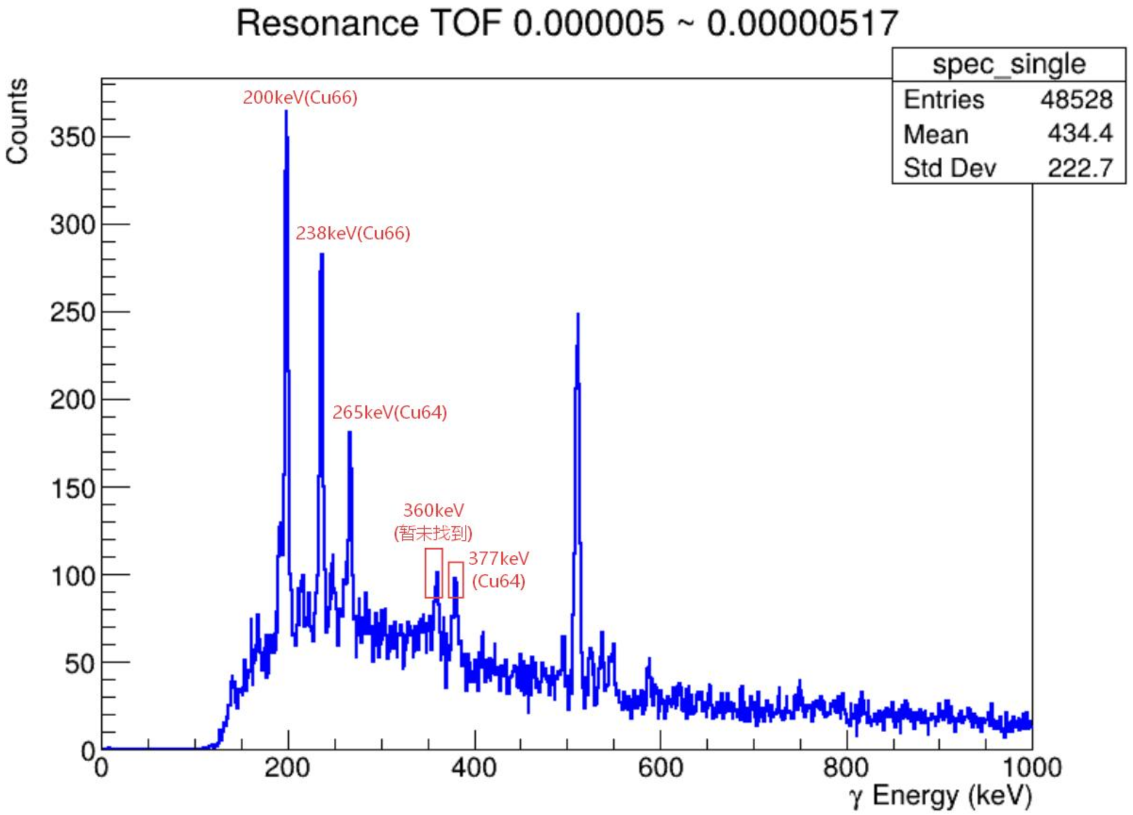




4.72 eV ~ 4.88 eV
特征峰中心值 : 4.8 eV
展宽 : 0.16 eV

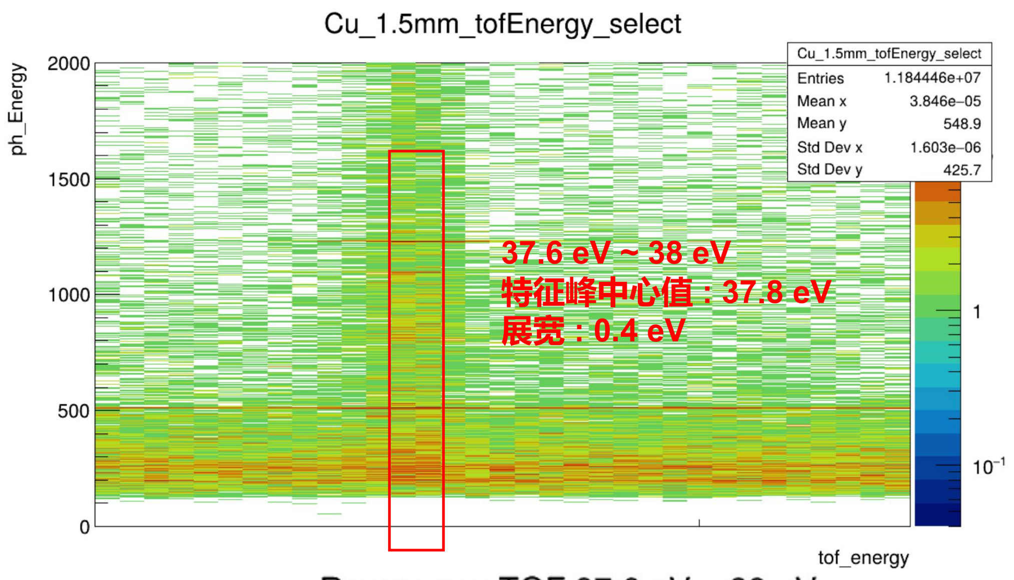
2

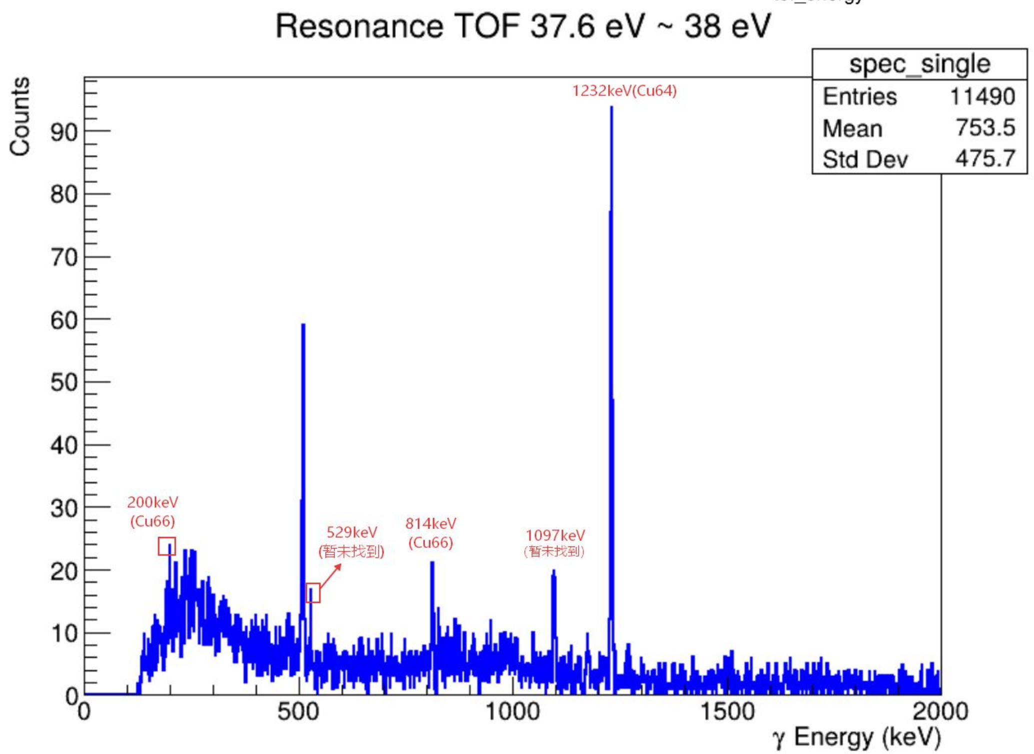


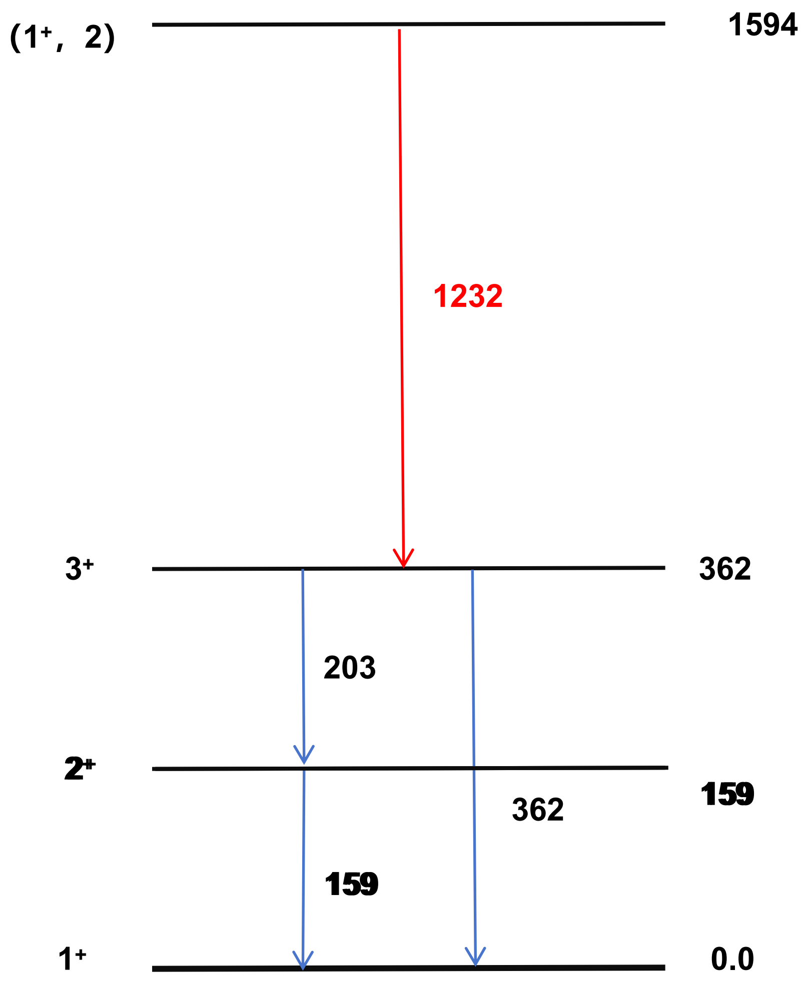


5 eV ~ 5.16 eV
特征峰中心值 : 5.08 eV
展宽 : 0.16 eV

3 Cu64



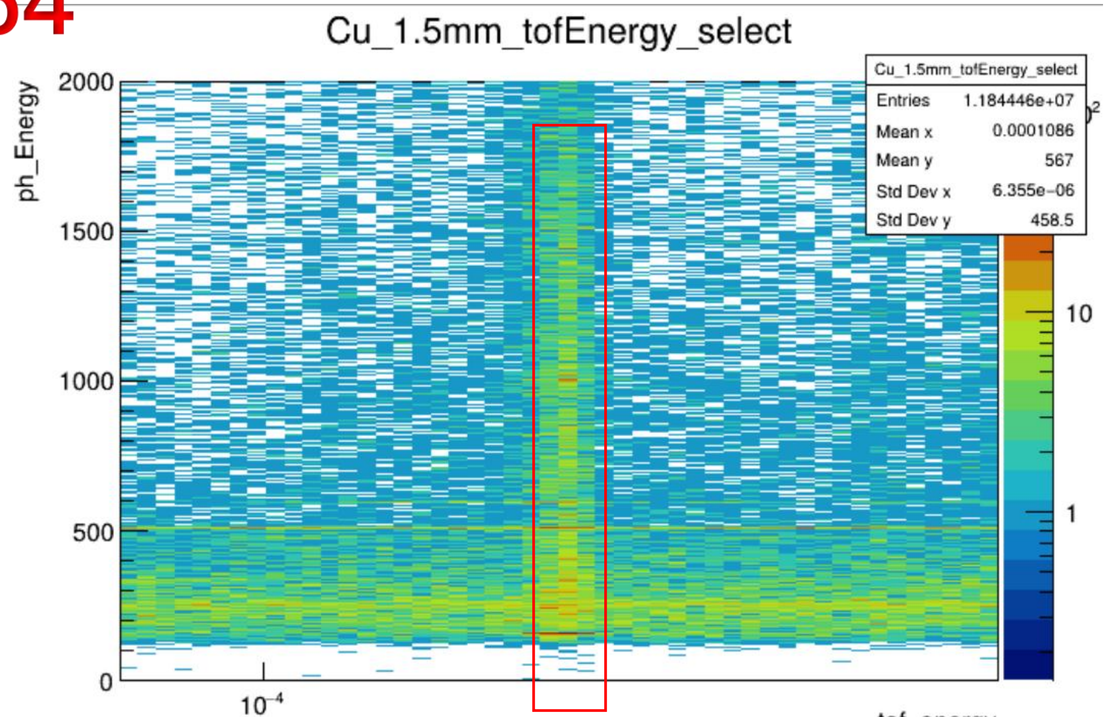




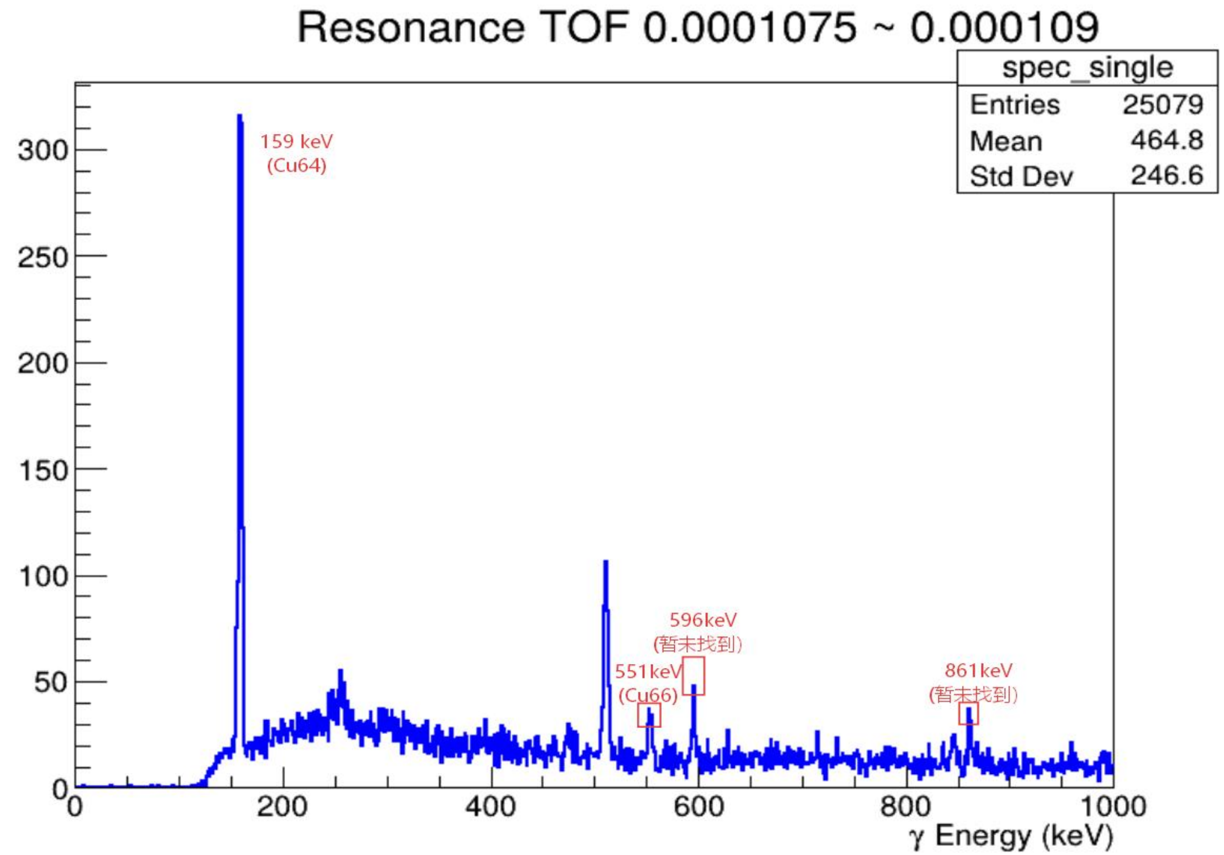
在37.6–38 eV共振区间的γ能谱中，仅观测到与能级1232 keV对应的特征γ射线峰，而362 keV能级退激至低能级的其余特征γ射线（如362 keV、202 keV、159 keV）未被观测到。

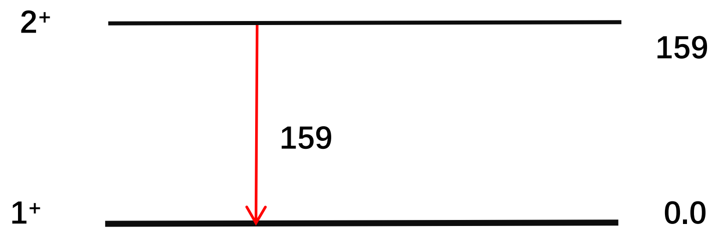
4

Cu64



0.1075 keV ~ 0.1091 keV
特征峰中心值 : 0.1083 keV
展宽 : 1.6 eV

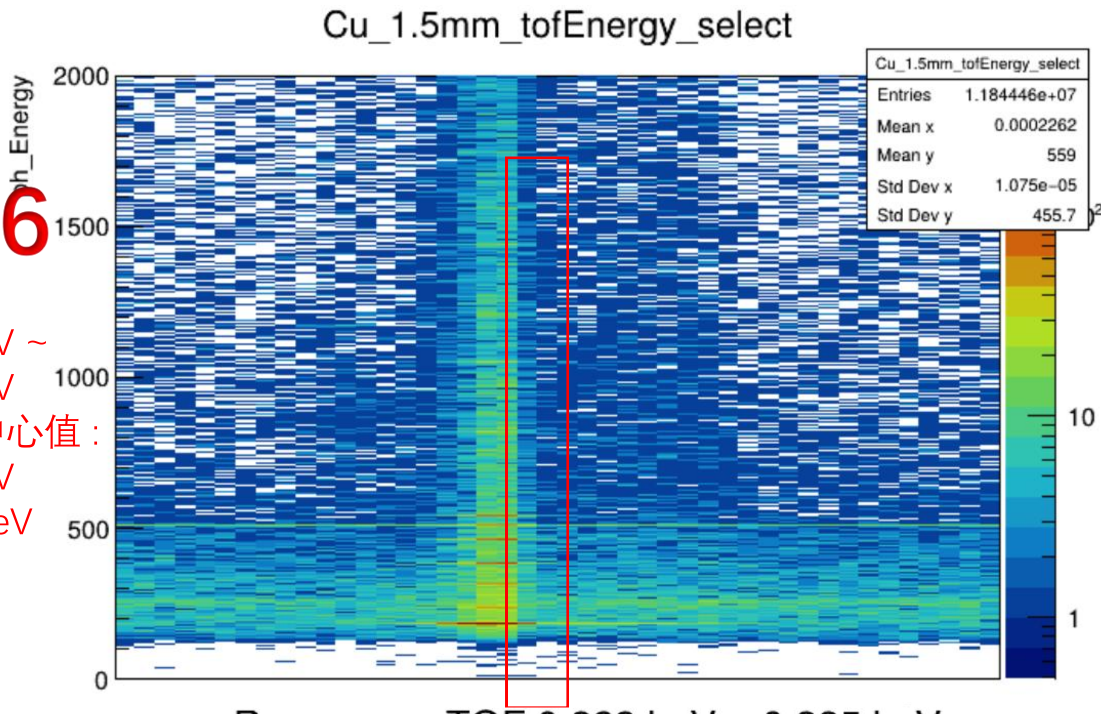




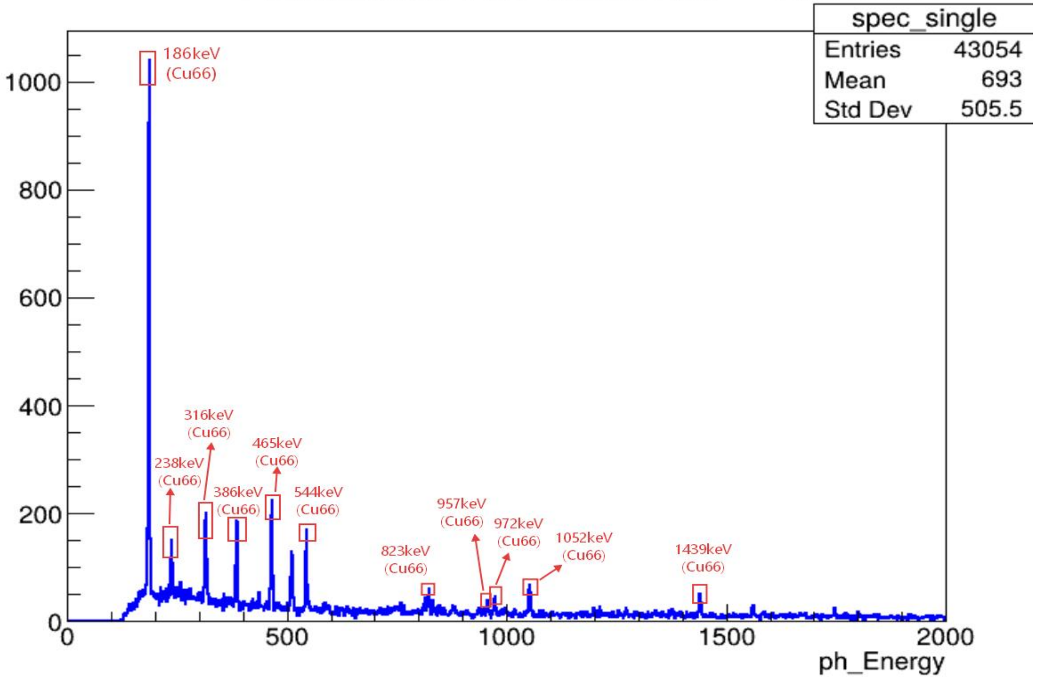
5

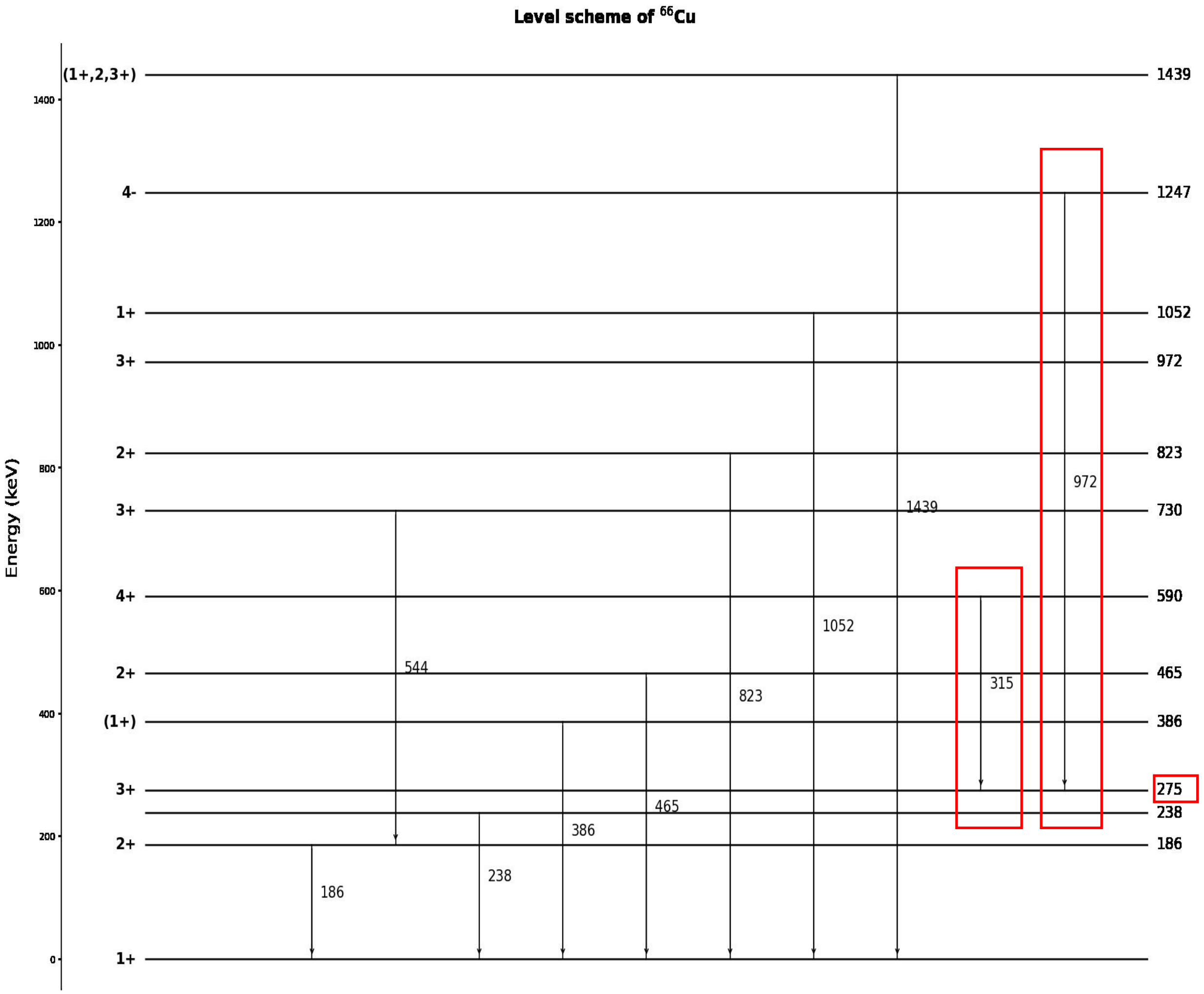
Cu66

0.223 keV ~
0.225 keV
特征峰中心值：
0.224 keV
展宽：2 eV



Resonance TOF 0.223 keV ~ 0.225 keV





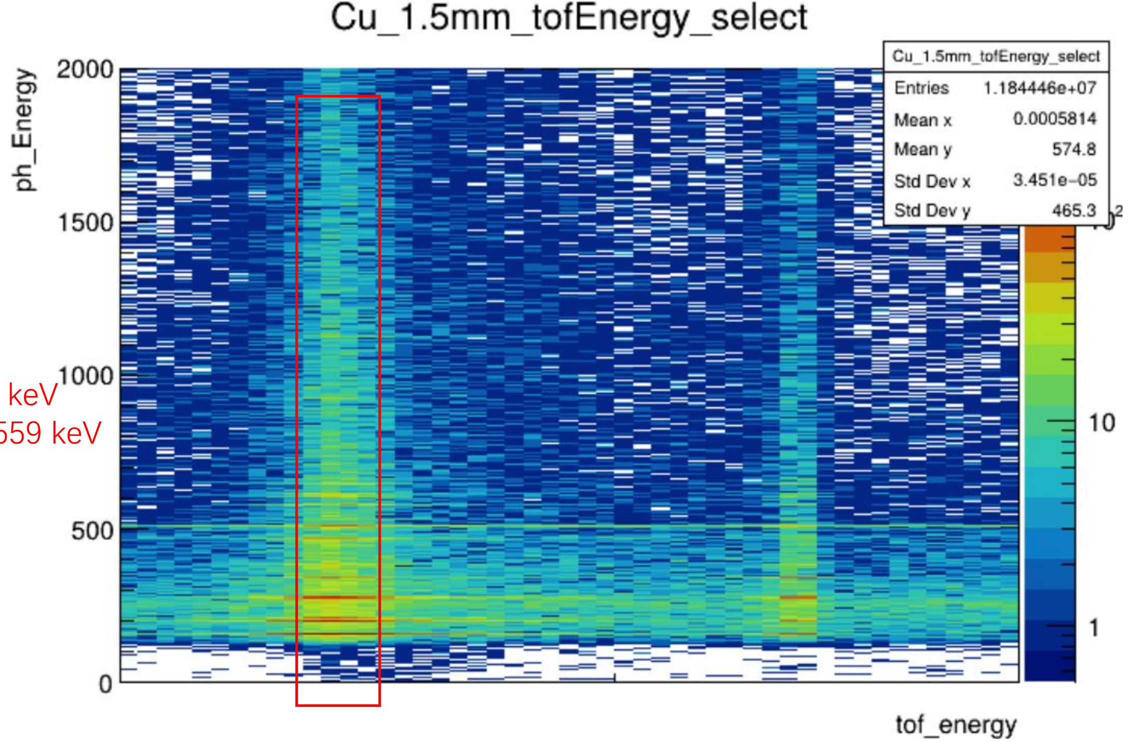
➢ **275 keV能级无向下γ跃迁的原因探究**

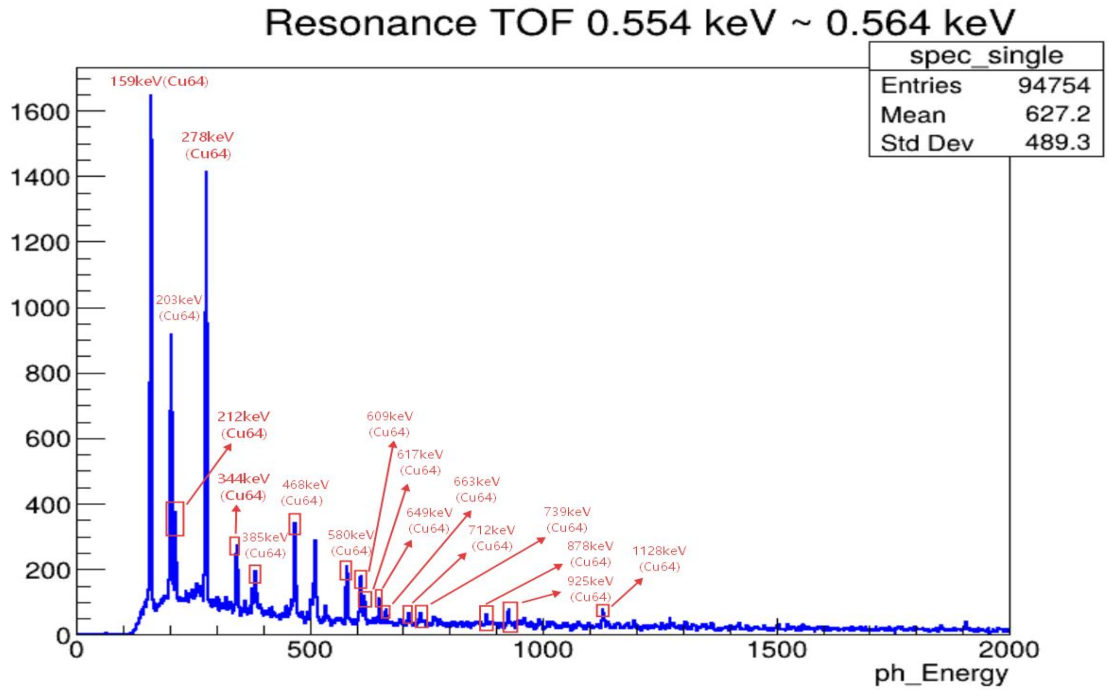
1. 低能区（0–100 keV）γ射线能量过低，被探测器屏蔽/自吸收，完全无法有效探测；

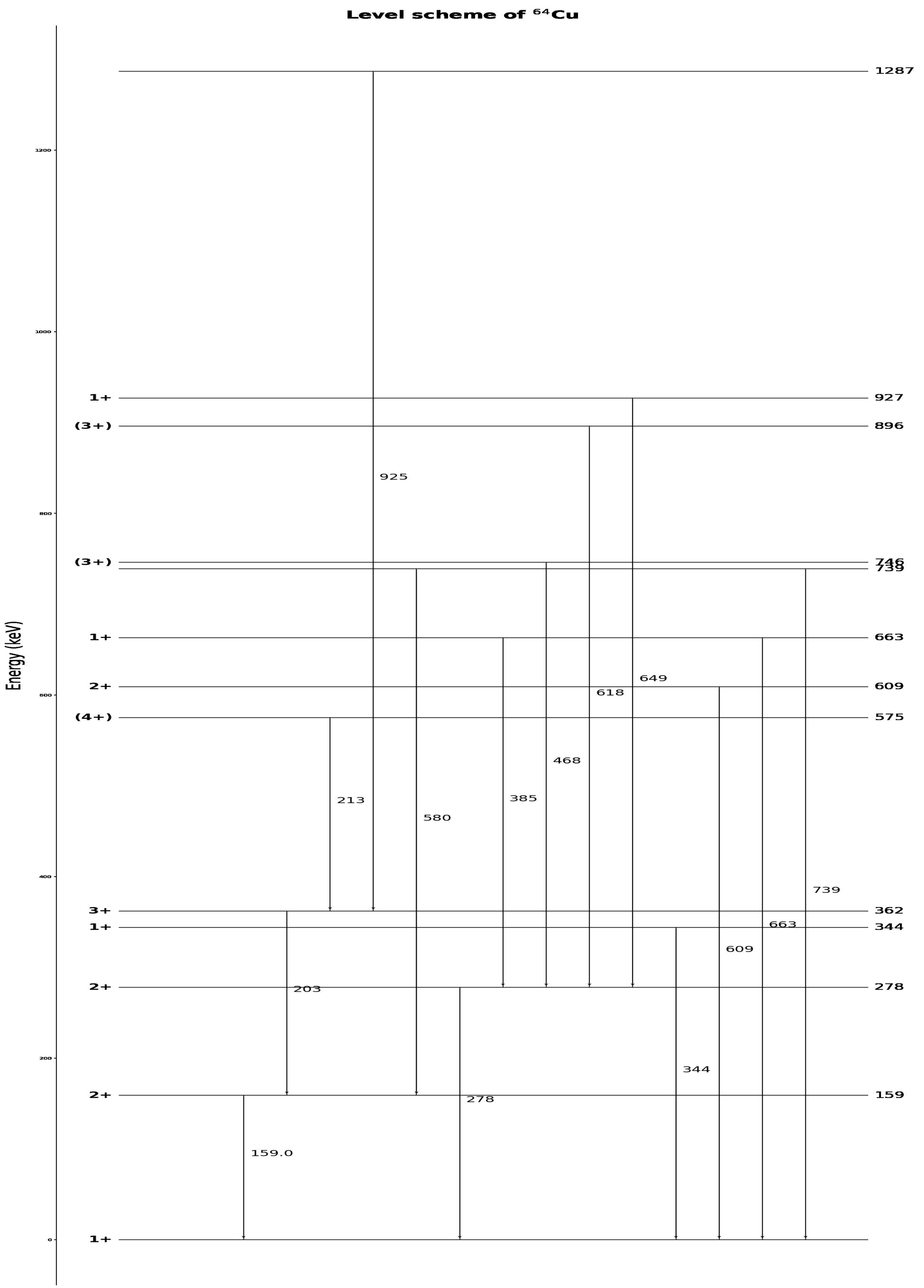
2. 275 keV跃迁的内转换占主导，γ光子产额极低，进一步加剧了低能区信号缺失。

6
Cu64

0.554 keV ~ 0.564 keV
特征峰中心值：0.559 keV
展宽：10 eV

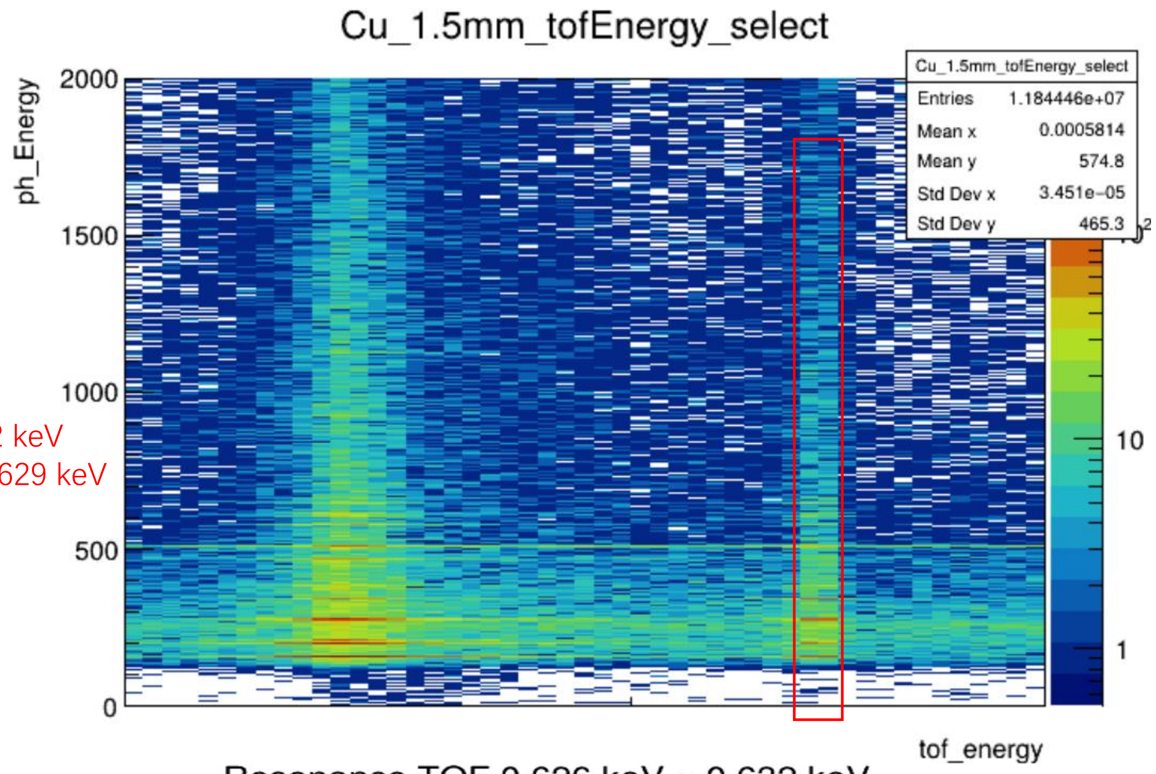


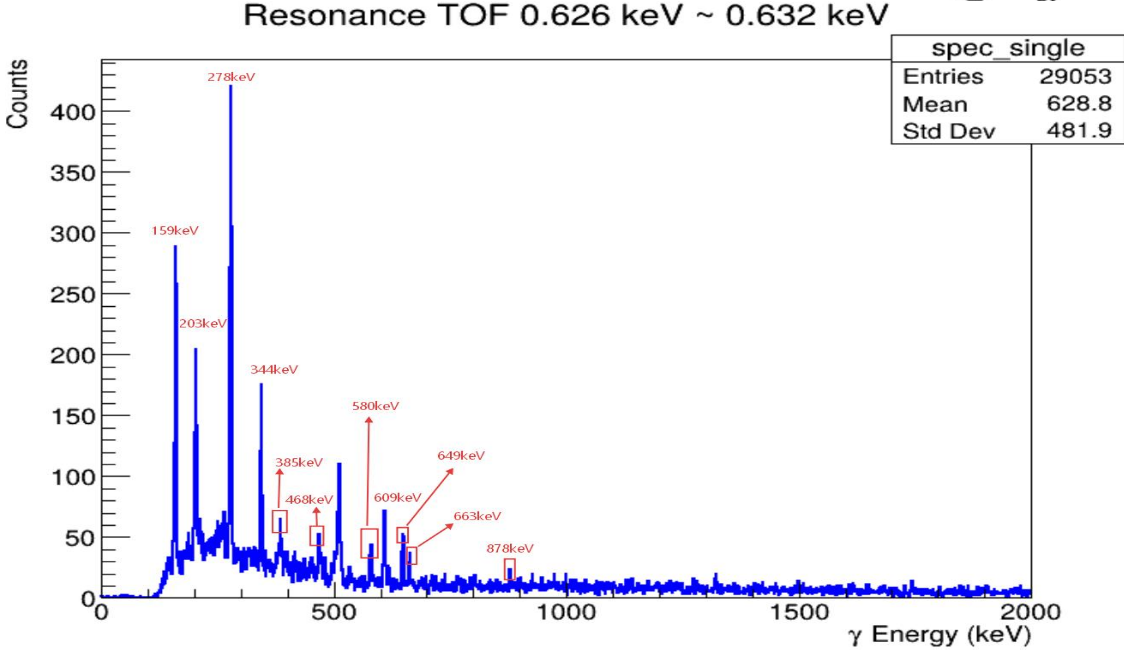


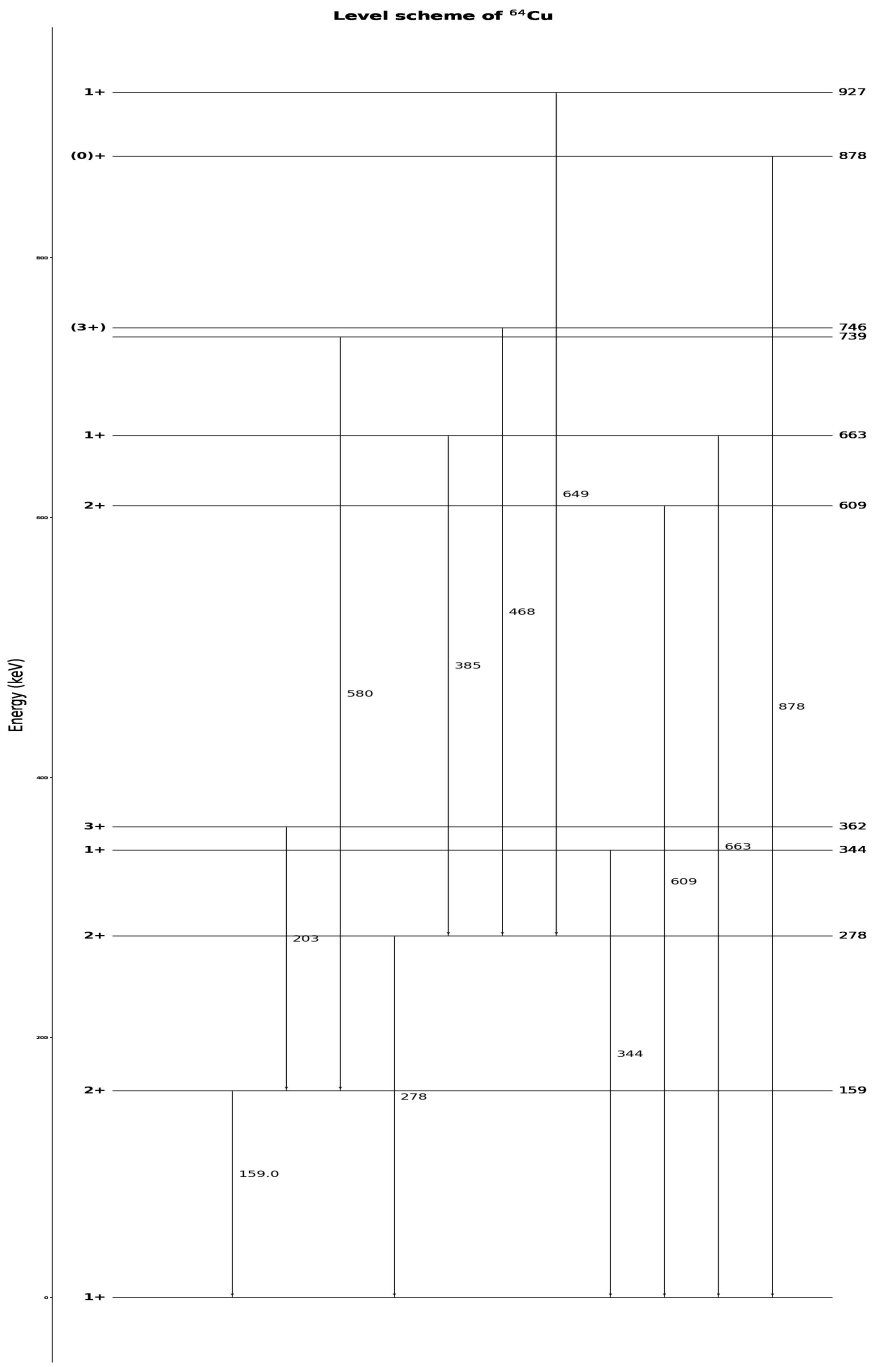


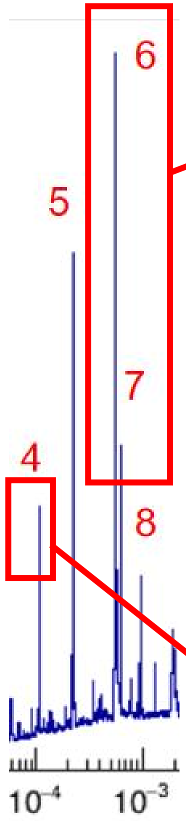
7
Cu64

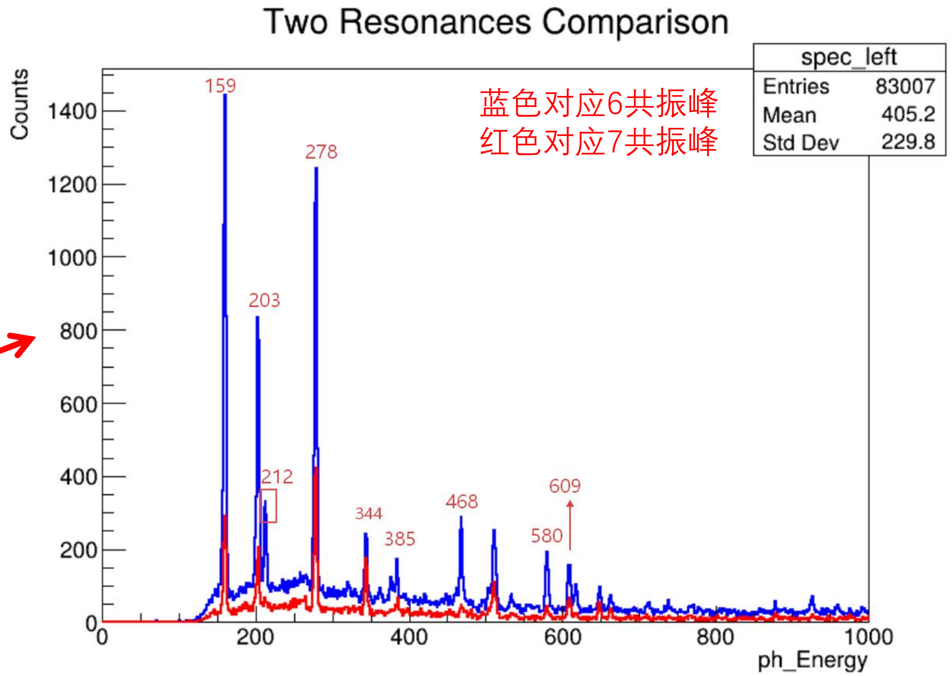
0.626 keV ~ 0.632 keV
特征峰中心值 : 0.629 keV
展宽 : 6 eV

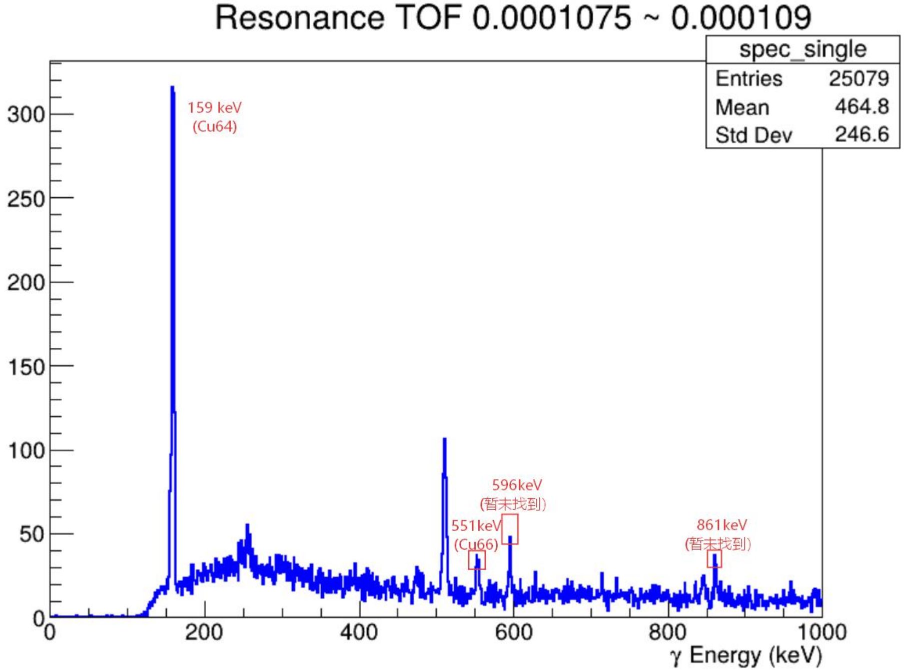


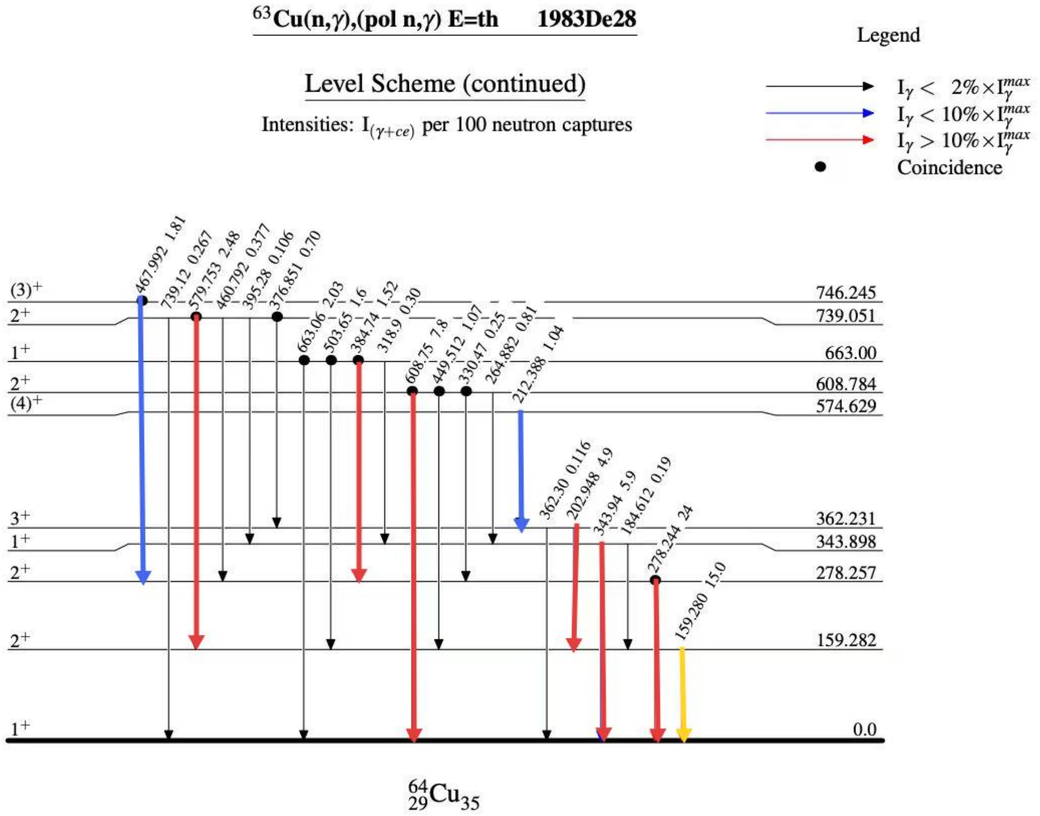












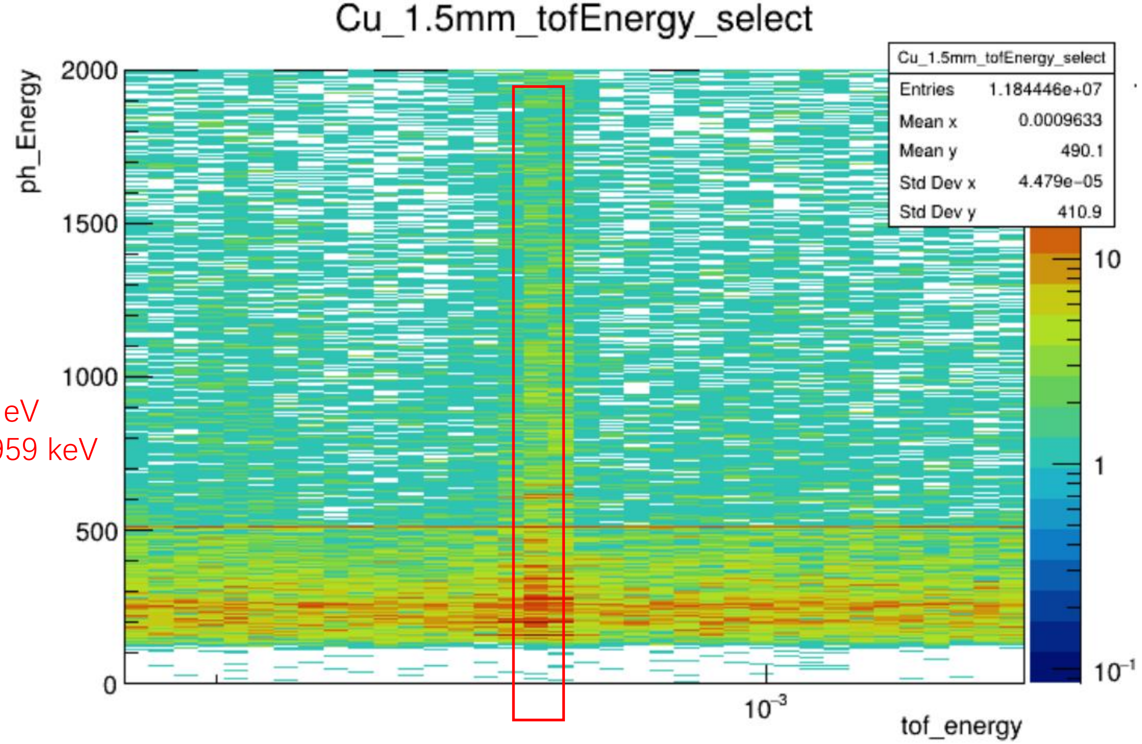
特点总结

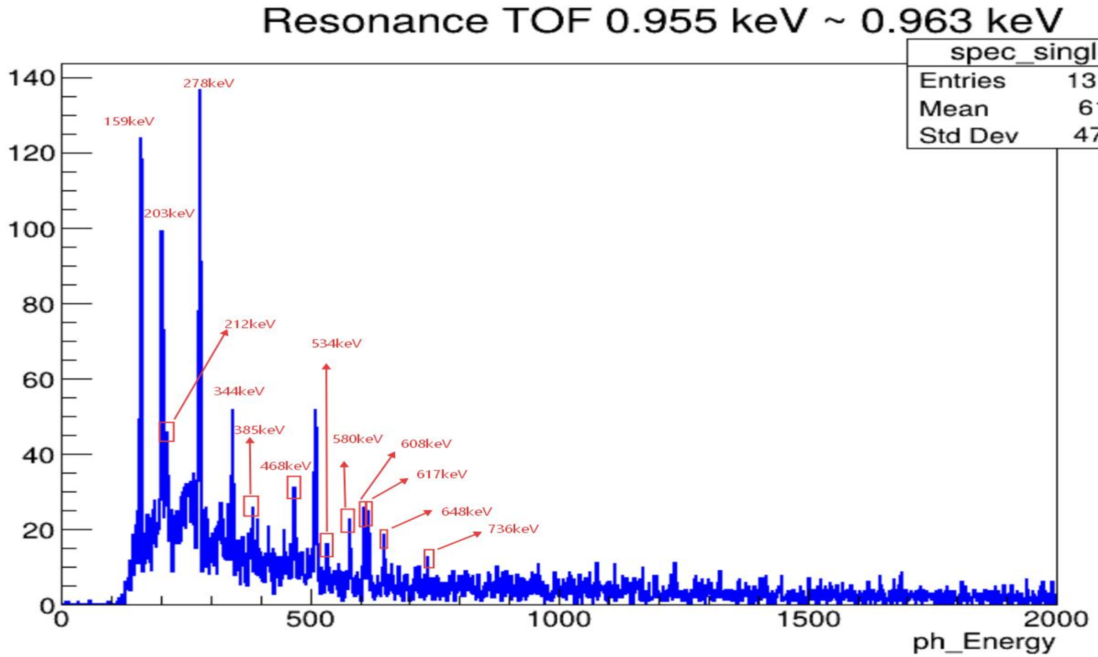
1. 共振峰4：其俘获γ谱中仅观测到159 keV特征峰，其他特征峰均未被观测到。

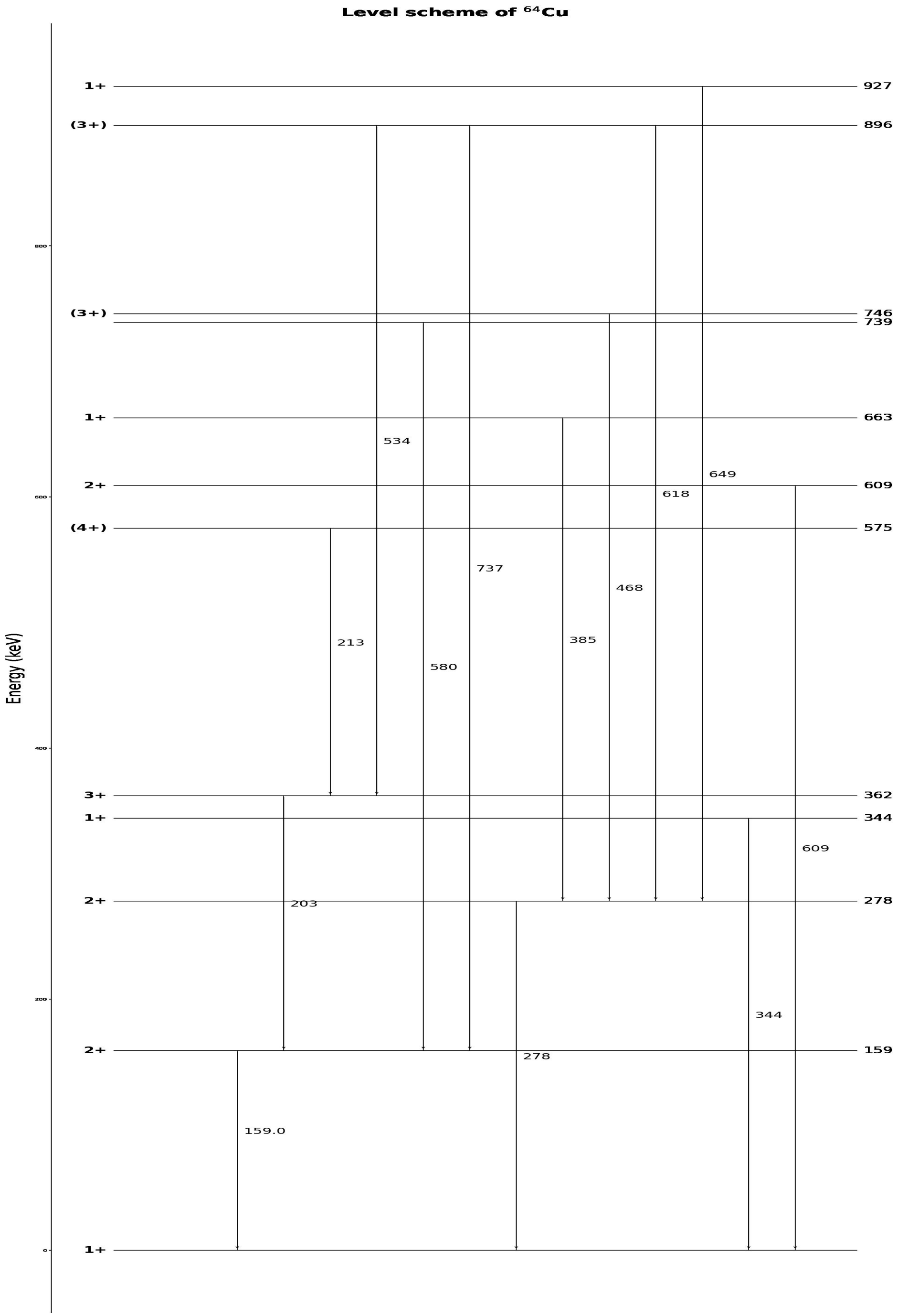
2. 共振峰6 vs 峰7：相较于共振峰7的γ谱，共振峰6的γ谱额外出现了212 keV和468 keV两个特征峰，二者的能谱结构存在明显差异。

8
Cu64

0.955 keV ~ 0.963 eV
特征峰中心值 : 0.959 keV
展宽 : 8 eV

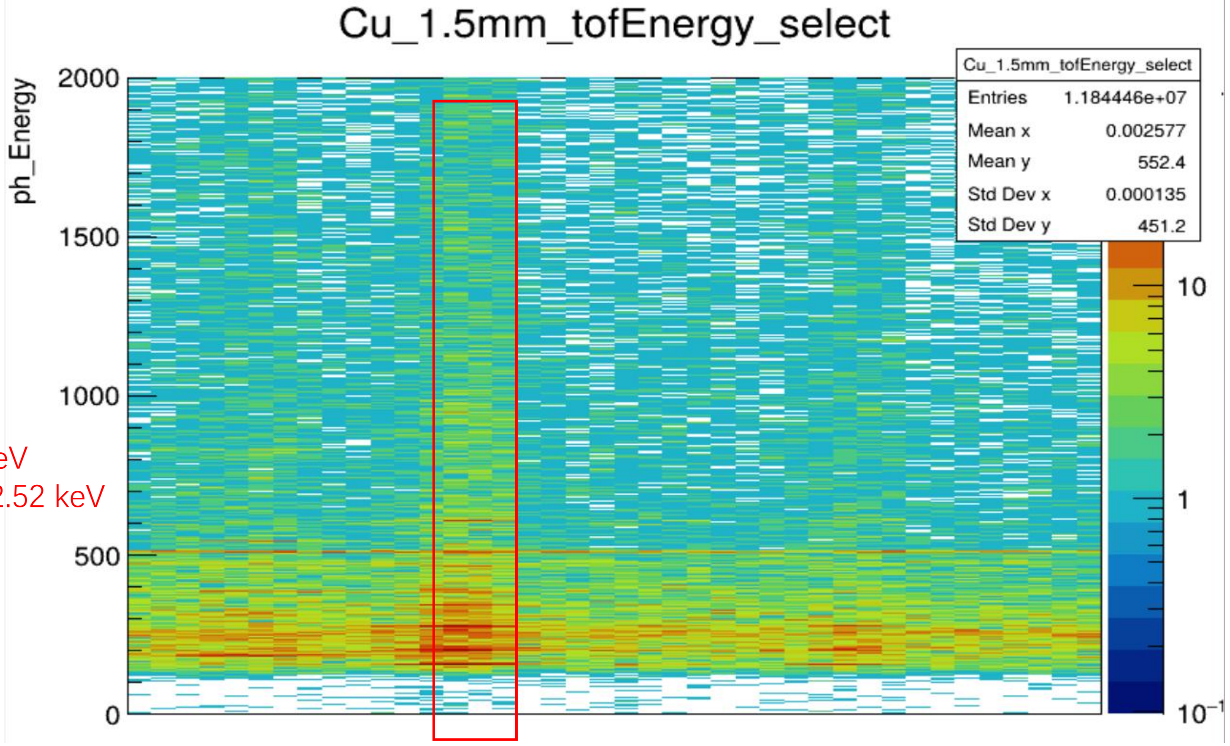


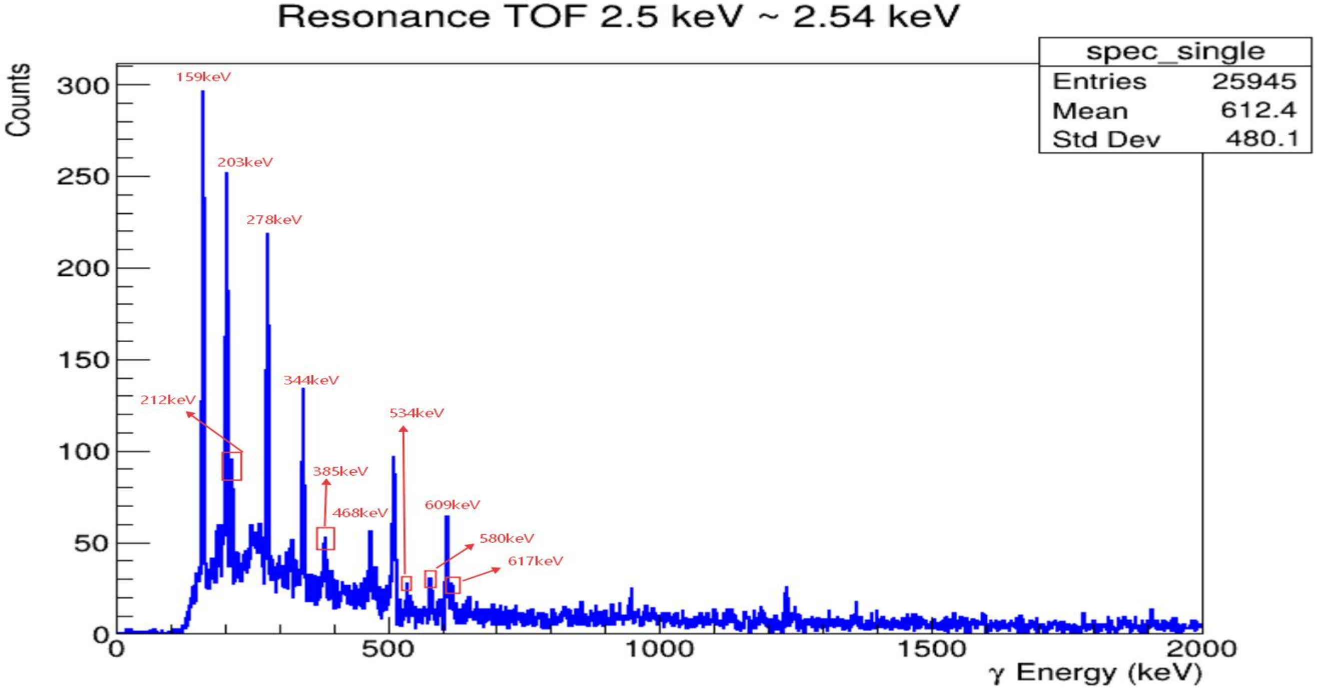


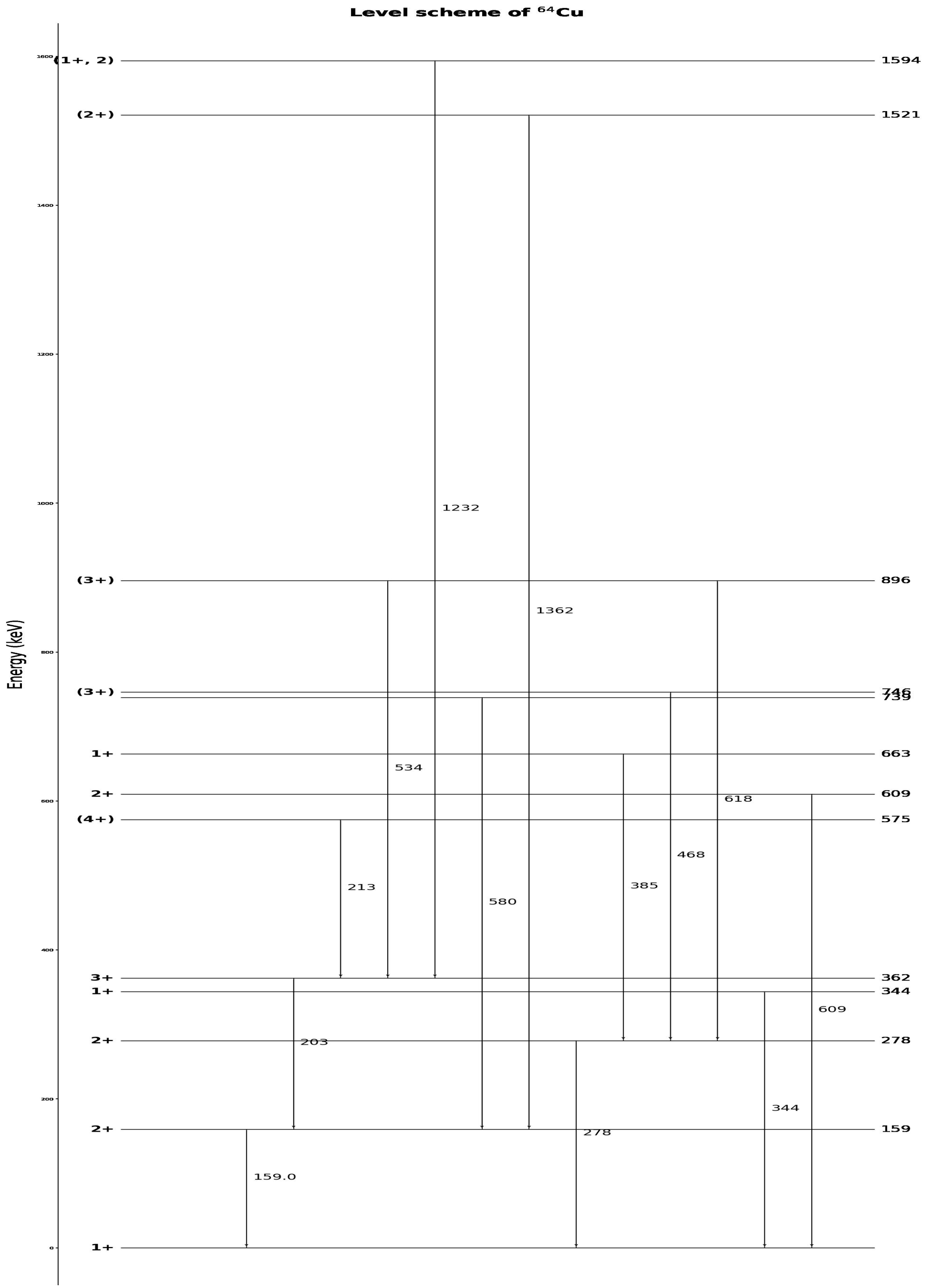


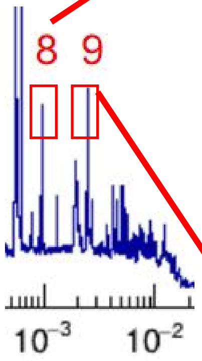
9
Cu64

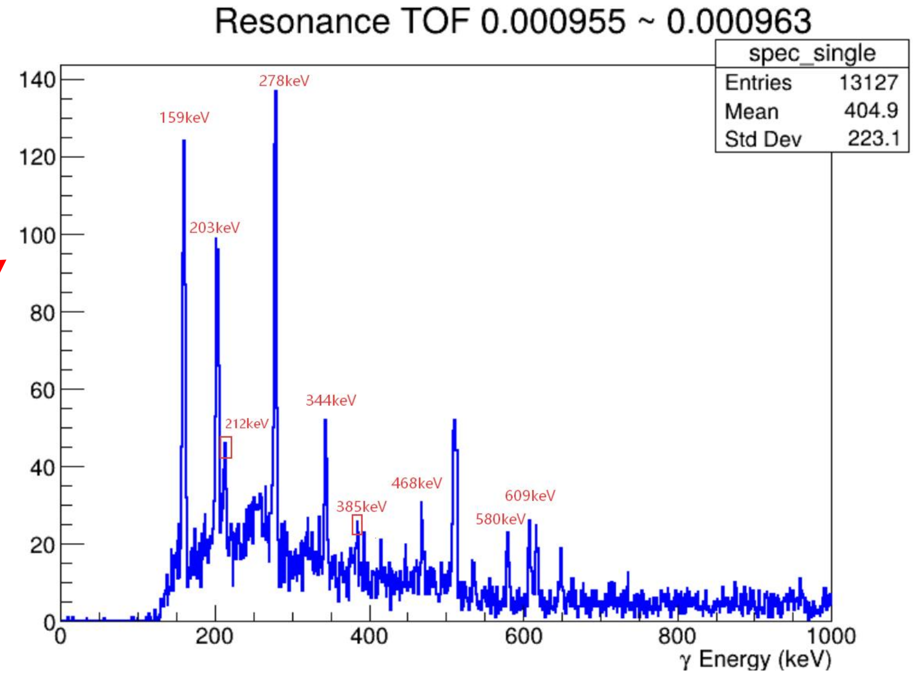
2.5 keV ~ 2.54 keV
特征峰中心值 : 2.52 keV
展宽 : 40 eV

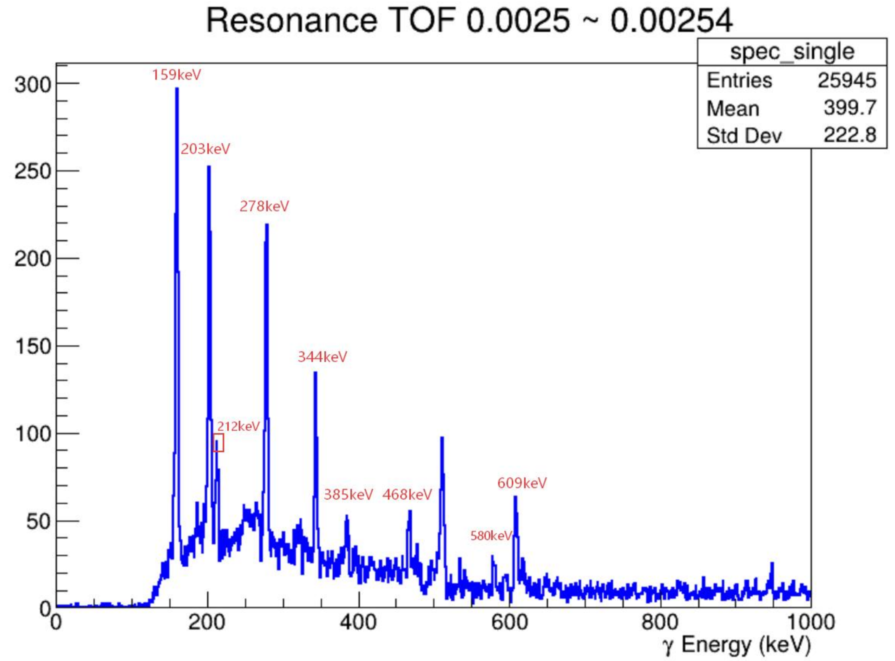


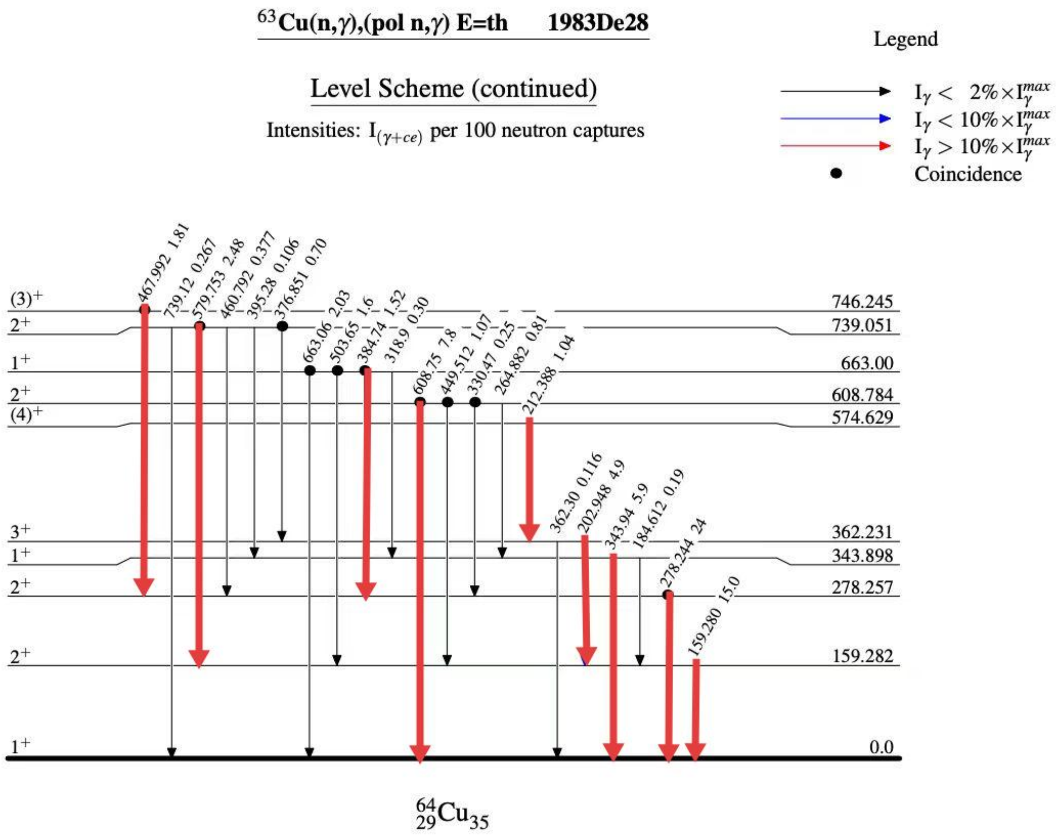












二者虽然都包含159、203、278、344、385、468、580、609 keV等特征峰，但峰强度的相对比例明显不同，这种差异源于两个共振能级不同的γ衰变分支比，这是区分这两个共振的关键特征。