



海纳百川 有容乃大



四川大学
SICHUAN UNIVERSITY

第三届地下和空间粒子物理与宇宙物理前沿问题研讨会，西昌，2024

基于CLYC和机器学习 的快中子能谱测量研究

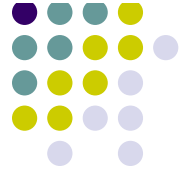
韩纪锋

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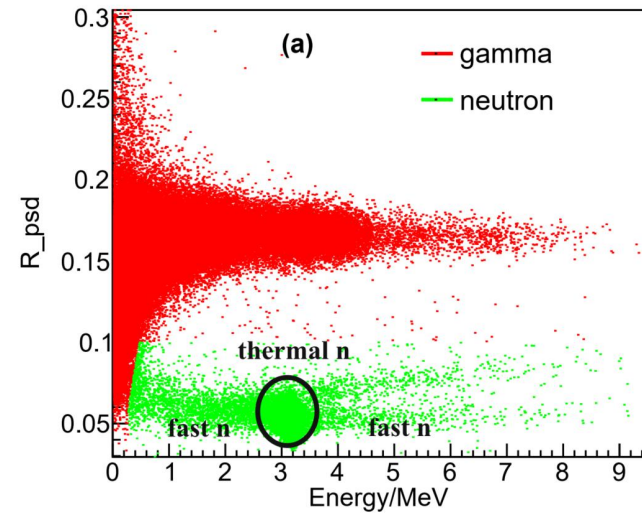
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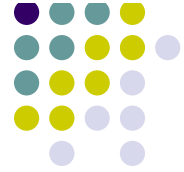




主要内容

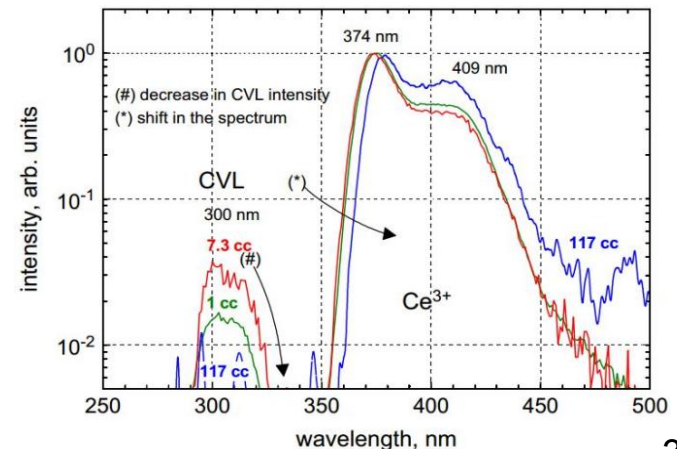
- 研究背景
- 中子、伽马甄别
- 快中子能谱探测
- 小结





研究背景

- 中子伽马多模探测器
 - 混合辐射场监测、辐射剂量与防护...
 - CLYC晶体: CapeSym、北玻院
 - 高速波形采样
- 特点
 - 热中子高效探测, ${}^6\text{Li}$ 富集度95%
 - 良好能量分辨, $\sim 5\% @ 662 \text{ keV}$
 - 良好PSD能力
 - 实现快中子探测, Cl、H



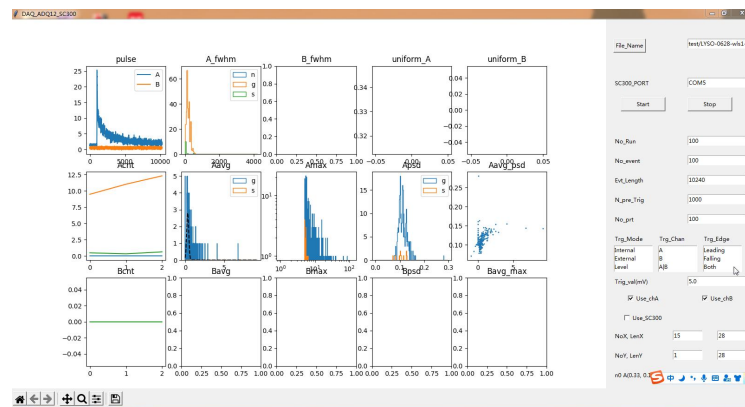
测试方法

- 基于高速采样卡

- TELEDYNE, ADQ12, 1Gbps
- 自制基于python的DAQ程序

- DAQ主要功能

- 高速数据采集
- 实时ng甄别
- n、g计数率
- n、g能谱
- 符合

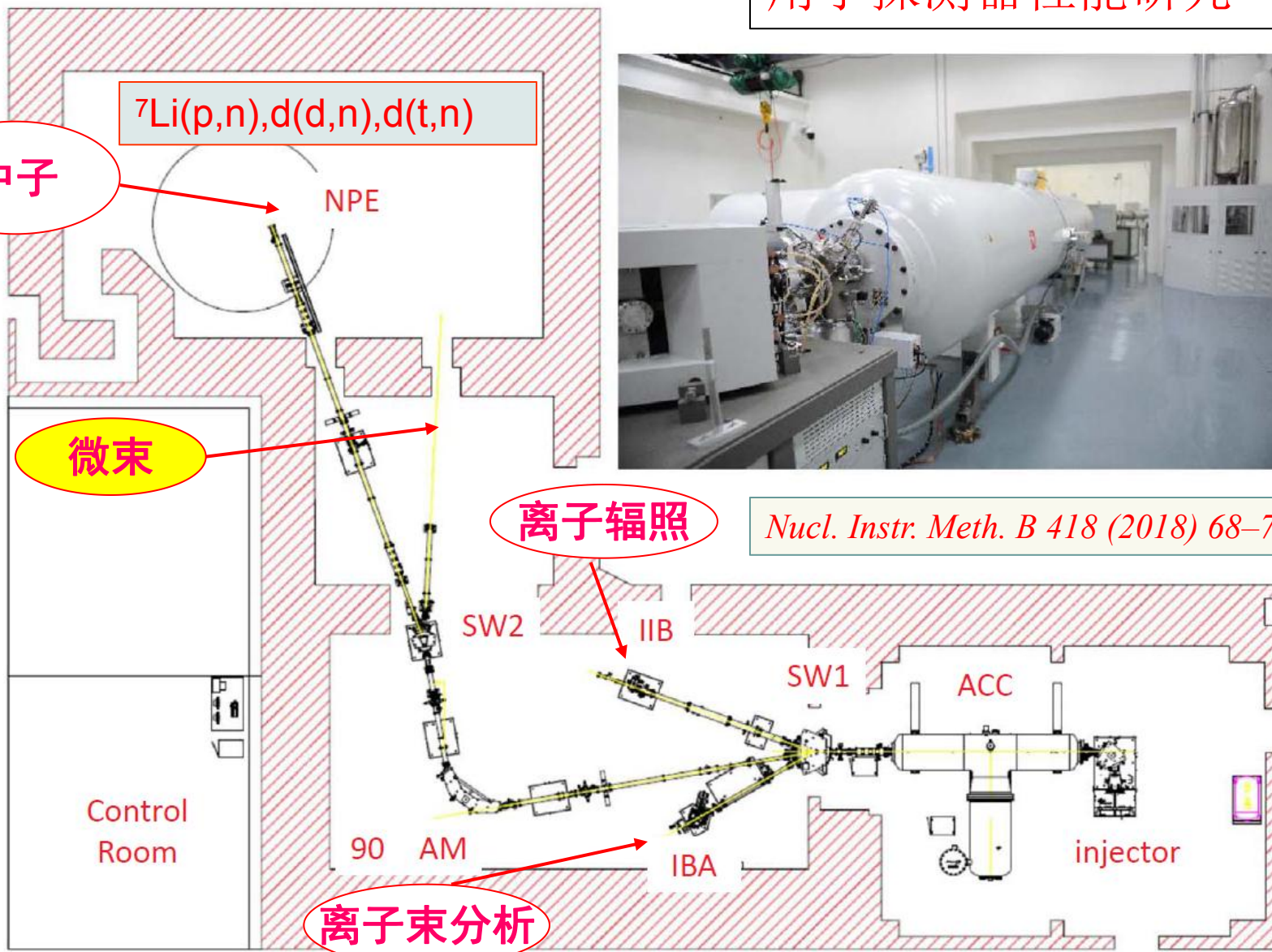


快中子探测研究平台

基于加速器产生单能中子，
用于探测器性能研究



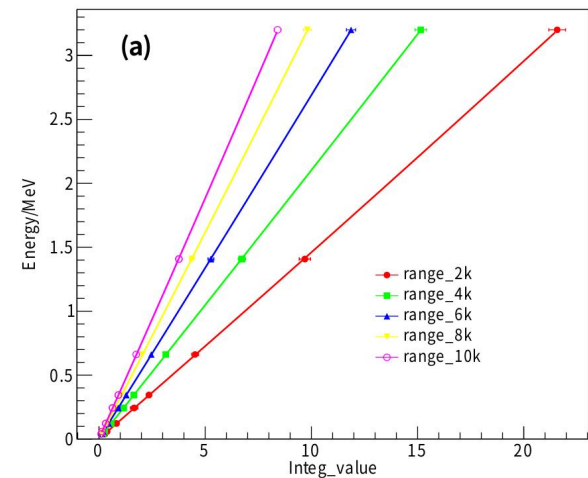
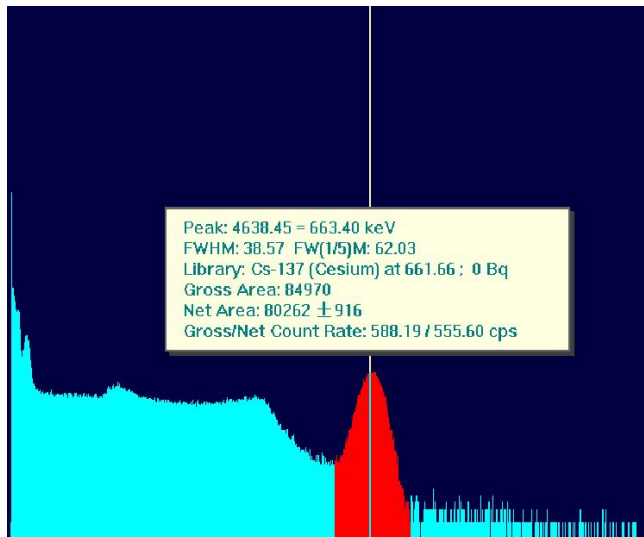
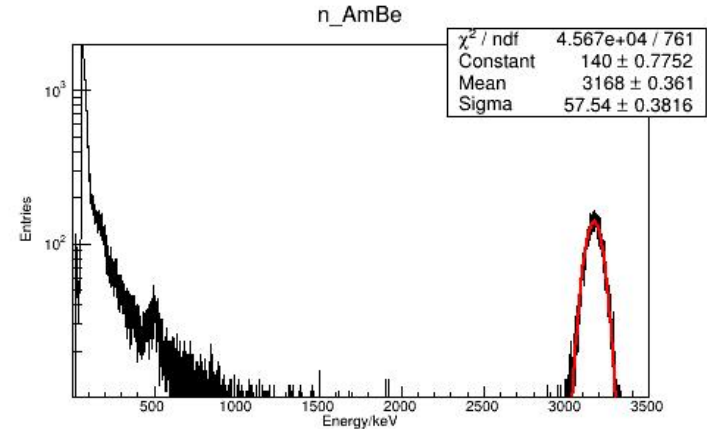
Nucl. Instr. Meth. B 418 (2018) 68–73



产生从
H到U的
几乎所有
离子

CLYC晶体的能量分辨

- 热中子相对宽度约1.8%
- 伽马能量分辨
 - 4.62%@662keV
 - 具有良好的线性0.06–3 MeV

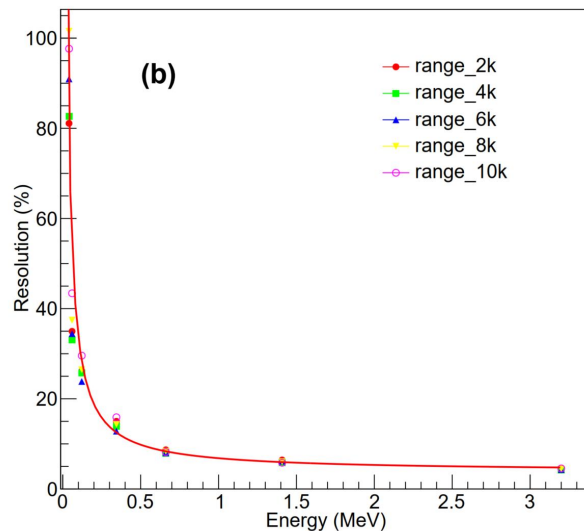
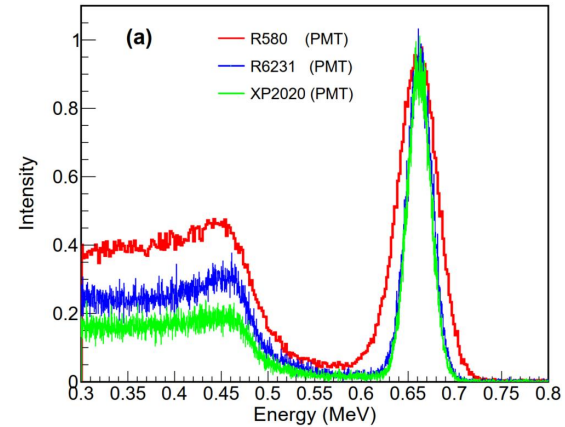




耦合不同PMT

● 测试3个PMT

- XP2020的分辨率最好
- R580的能量分辨最好
- R6231综合最好



PMT	Int_T /ns	Reso (%) @662keV	FOM
R580	6000	7.90	2.58
R6231	4000	5.03	2.10
XP2020	6000	4.62	1.70



CLYC晶体信号特征

● 3类典型信号

1. 超慢信号, us
2. 慢信号, 百ns
3. 快信号, 10ns (PMT噪声)

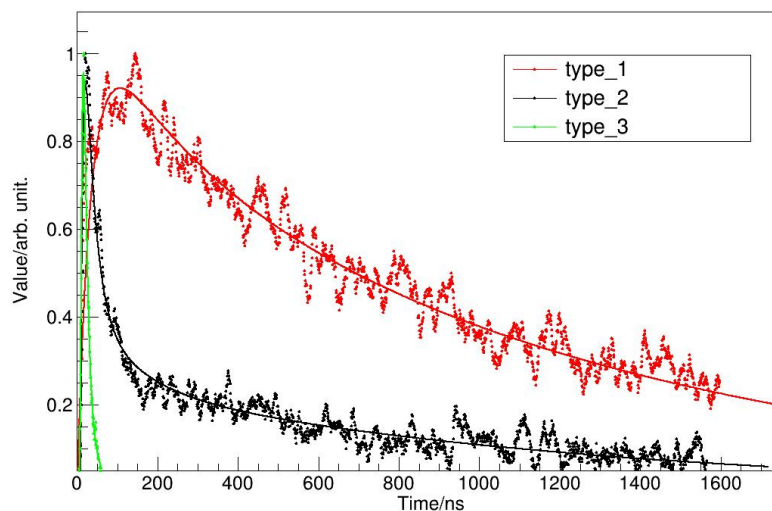
● 中子

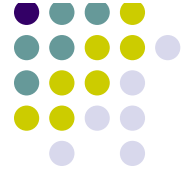
- 以T1 (超慢信号) 为主

● 伽马

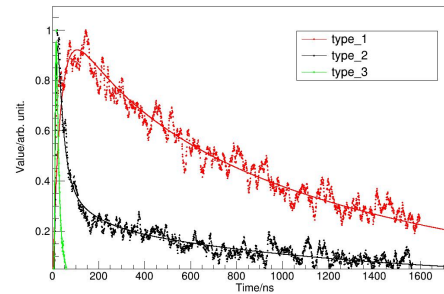
- 以T2 (快信号) 为主
- 约2%超慢信号干扰

Am-Be源结果





CLYC信号拟合



- 多指数拟合4种成分
 - 平均信号扣除噪声干扰

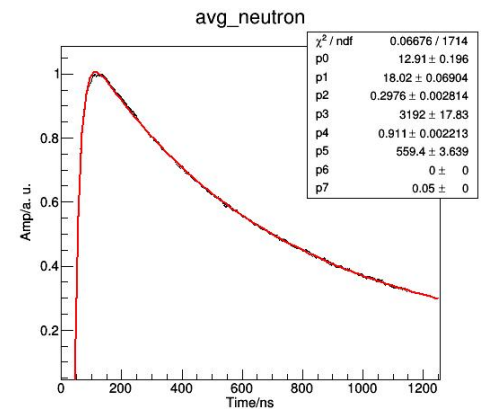
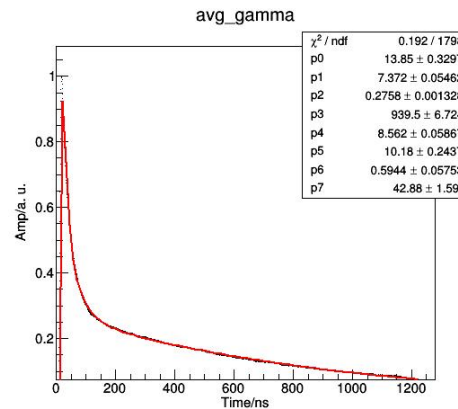
● 中子信号特征

- 信号很宽
- 上升沿较慢、下降沿很慢
- 下降沿缺少10、43ns成分, n-g甄别依据

● 问题

- 拟合自由度大, 结果不唯一
- 用2000个脉冲的平均值进行拟合, 降低噪声
- 初值选择很重要

$$Y = -A_1 e^{-\frac{t}{\tau_1}} + A_2 e^{-\frac{t}{\tau_2}} + A_3 e^{-\frac{t}{\tau_3}} + A_4 e^{-\frac{t}{\tau_4}}$$



	Tau_1	Tau_2	Tau_3	Tau_4
Gamma	7.35	918	10.2	43
Neutron	17.8	3193	570	-

n-γ 甄別

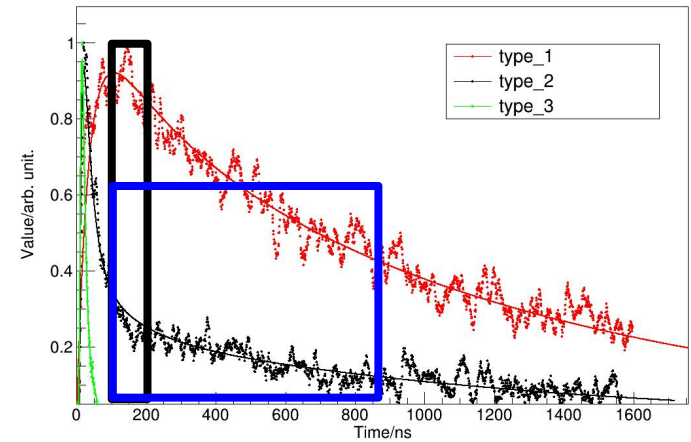
● CLYC晶体的PSD方法

- n下降沿无10-43ns成分
- 用下降沿快速下降部分占比
- 占比较小为n
- 占比较大为γ

● 结果

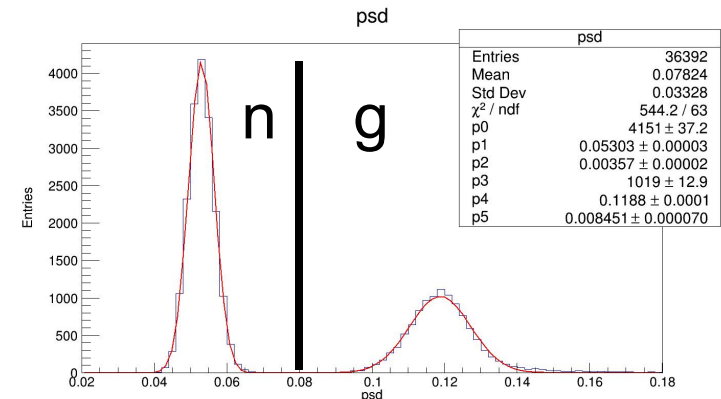
- 甄別优度FOM值2.3 (>500keV)
- CLYC晶体具有极好的n-γ 甄別能力

$$FOM = \frac{|\mu_n - \mu_g|}{(\sigma_n + \sigma_g) * 2.355}$$

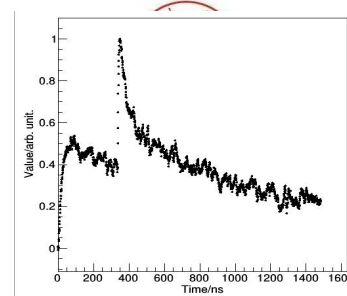


$$psd = \frac{\sum (0,24ns)}{\sum (0,500ns)}$$

psd分母区间变化影响较小

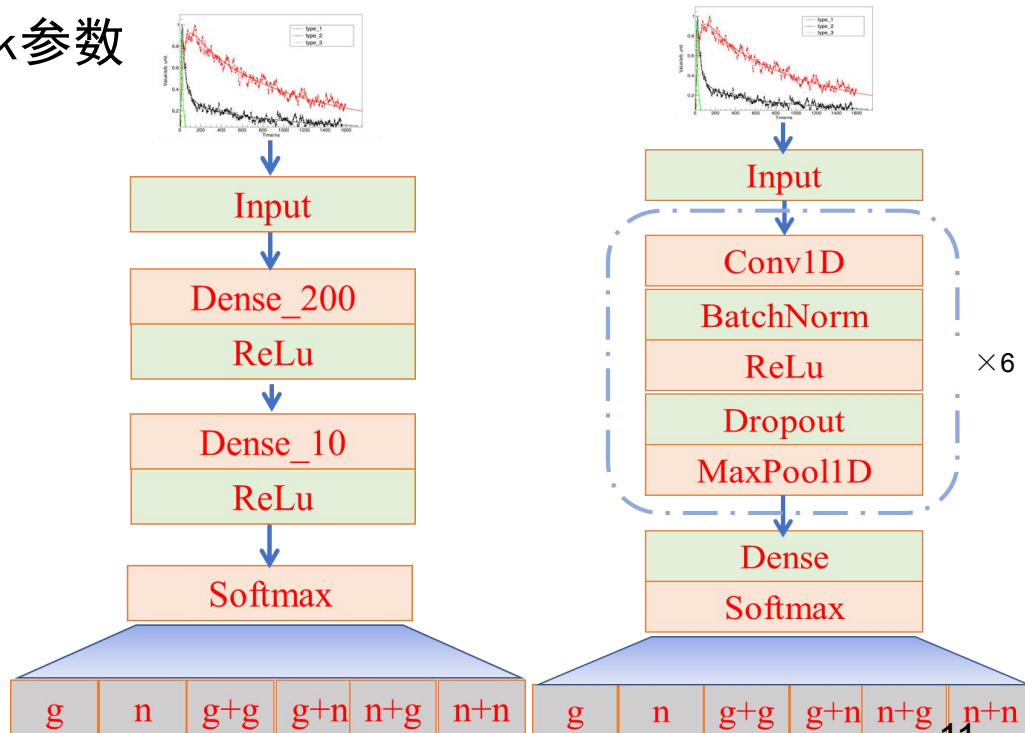


基于CNN的堆积甄别-模拟信号



直接将不堆积脉冲叠加生成堆积脉冲
标签容易获得

- 计数率较高，存在信号堆积
 - 全谱数据输入（归一化）
 - 6种信号类型：n, g, n+g, n+n, g+g, g+n
- 构建了2个网络
 - 全连接网络FCNN，约400k参数
 - 卷积网络CNN，约4k参数
- 数据
 - 相同数据源
 - 训练集64%
 - 验证集16%
 - 测试集20%



堆积脉冲甄别-结果

● 总体识别准确率

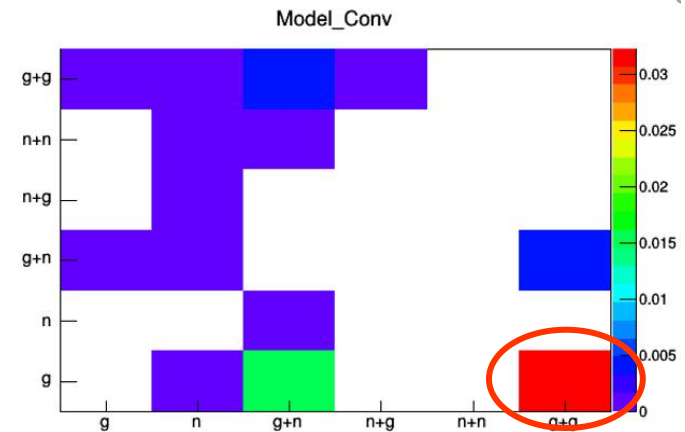
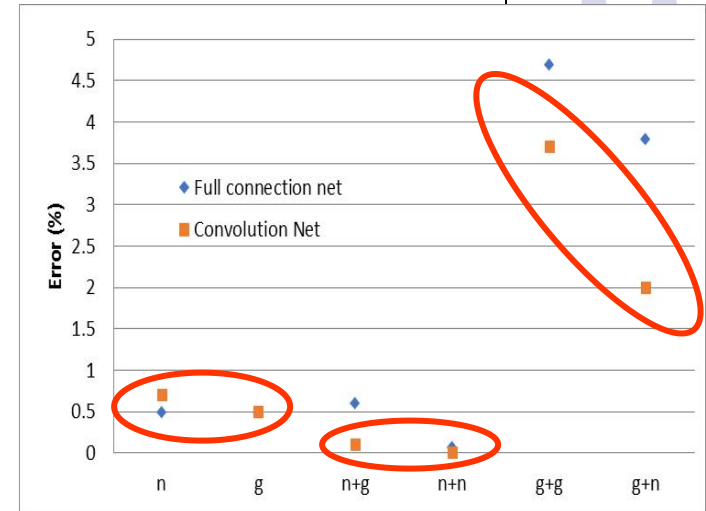
- FCNN网络：98.7%；CNN网络：99.2%
- 各类波形的误判率均小于5%
- CNN网络性能更好，参数更少，更适合

● 误判率

- n+n、n+g误判率几乎0%；
- n、g误判率小于1%；
- g+n误判率2%；
- g+g误判率3.6%；

● 误判原因

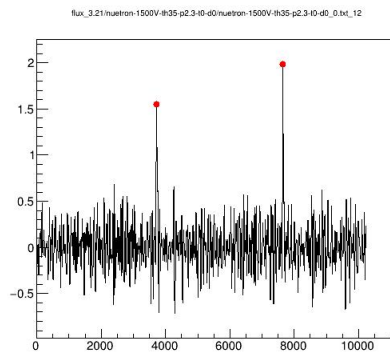
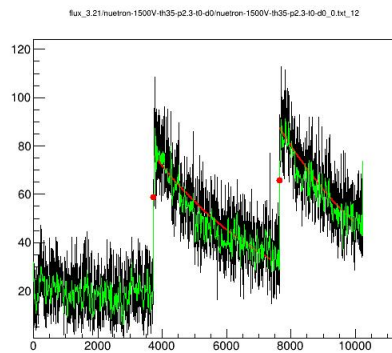
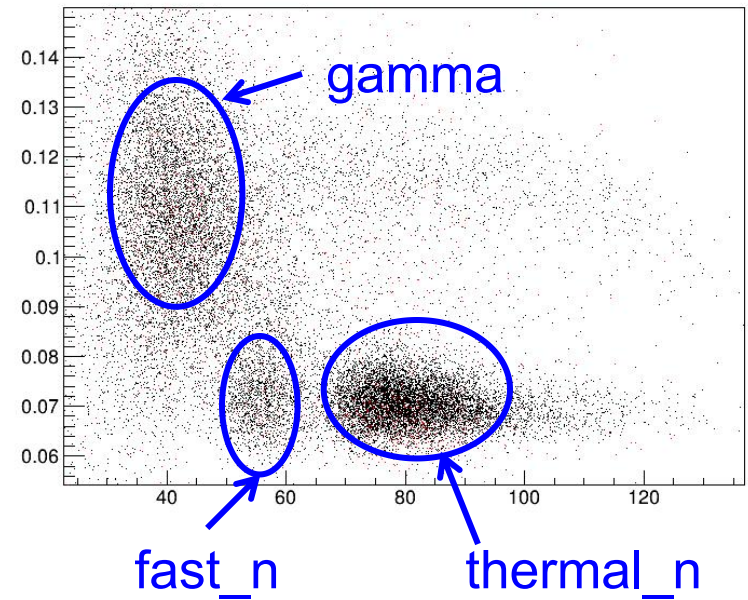
- g、n幅度较小时，易被噪声干扰



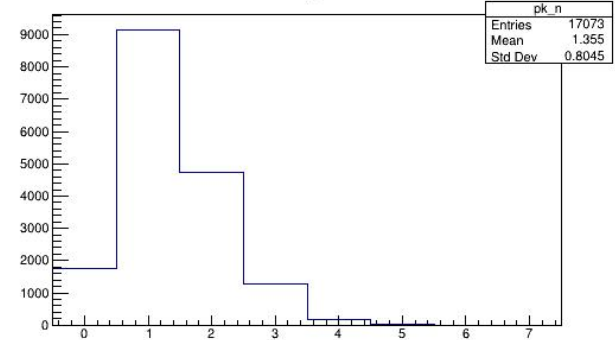
堆积脉冲实验数据

- 基于加速器单能中子源
 - 中子能量1.5MeV，产额约1E9
 - 实现了堆积脉冲psd甄别
 - 黑色：长堆积， $>500\text{ns}$
 - 红色：短堆积， $\leq 500\text{ns}$
- 特征
 - 基线无法回0，涨落提升约10倍

mg_avg_psd



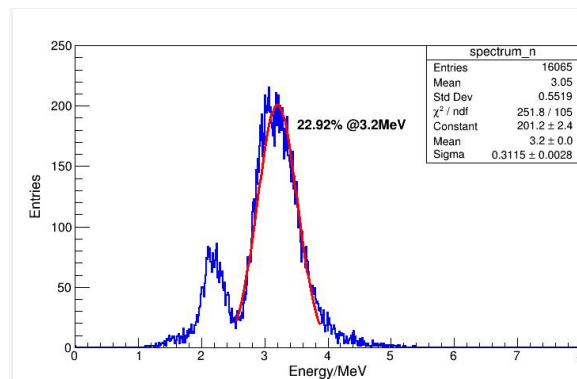
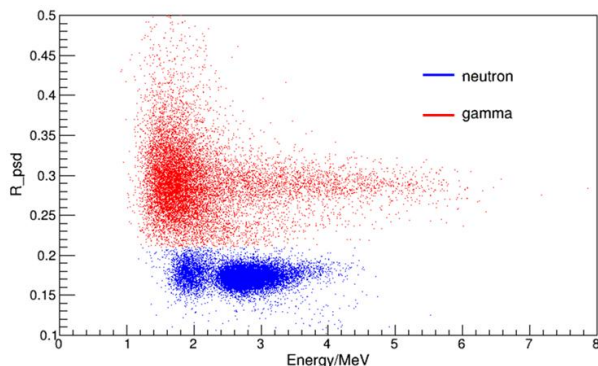
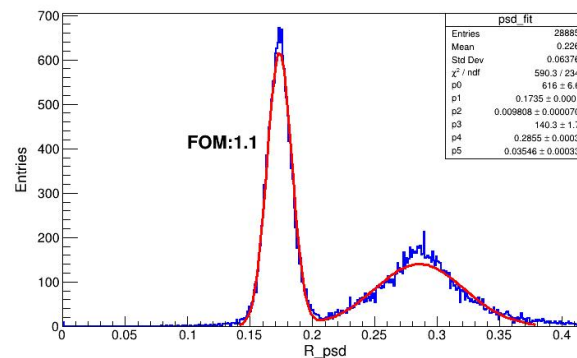
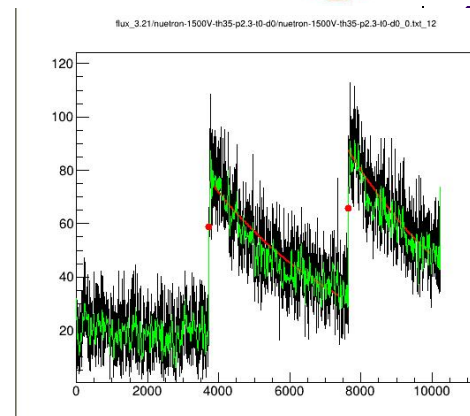
PK_N



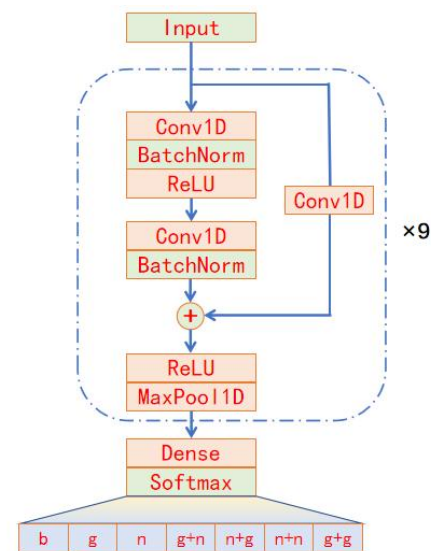
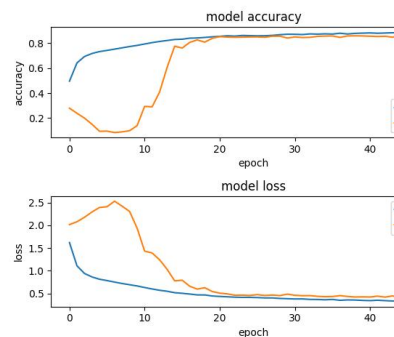
实现基于上升沿的寻峰算法、堆积脉冲ng甄别

堆积脉冲-能量和FOM值

- 提取单个脉冲的种类、能量
 - 仅能利用一部分脉冲波形
 - 热中子峰相对宽度为22%，差于未堆积的2%
 - FOM值1.1，差于未堆积的2.0
 - 基线rms约12mV，远大于未堆积1mV
- 拓展CLYC至高计数率场景
 - CLYC实测脉冲计数率3E6 cps
 - 实际粒子通量约1E8-1E9 cps



堆积脉冲甄别-ANN

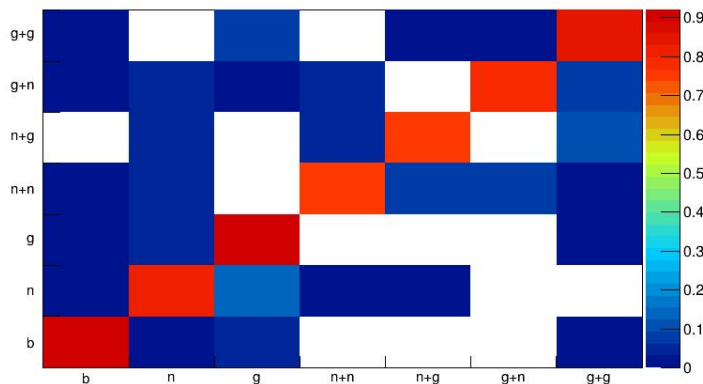


● 监督学习

- 标签：基于滤波寻峰算法结果
- 训练FNN、CNN、ResNet网络
- 残差网络（ResNet）准确率更好

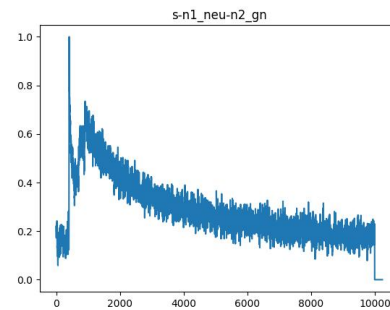
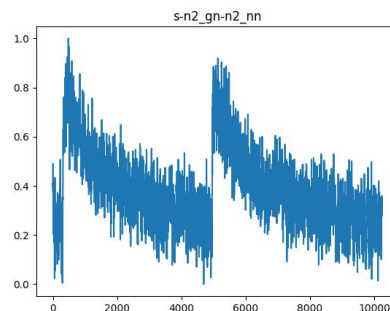
● 结果

- 94.5%准确度
- ResNet准确度更优



● 识别错误原因

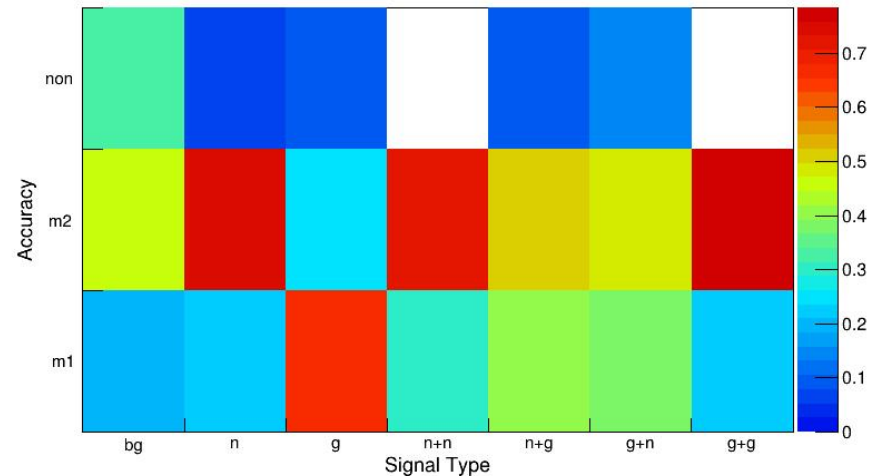
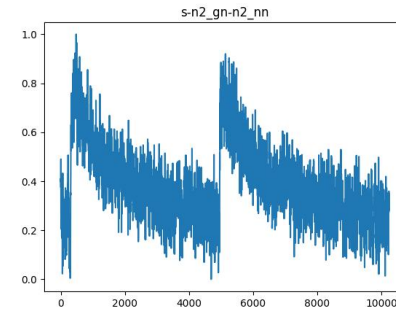
- 脉冲幅度小、本底噪声大
- 脉冲间距太短





识别错误事例的进一步分析

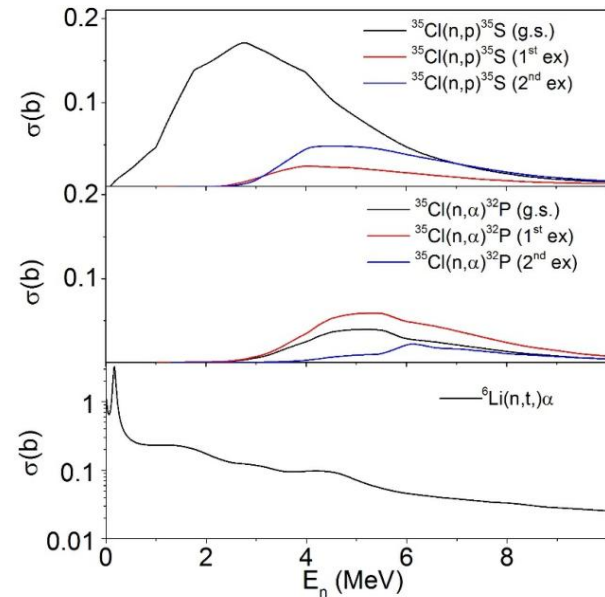
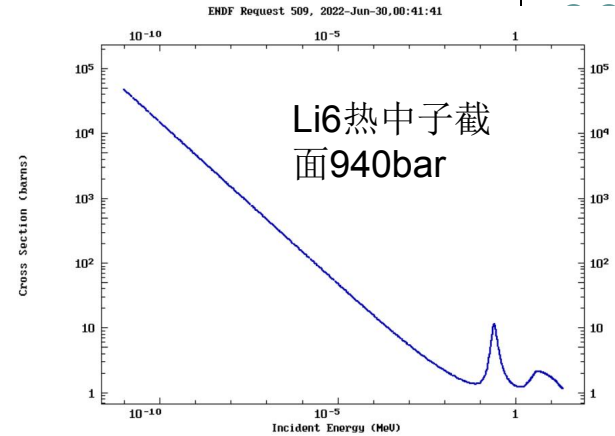
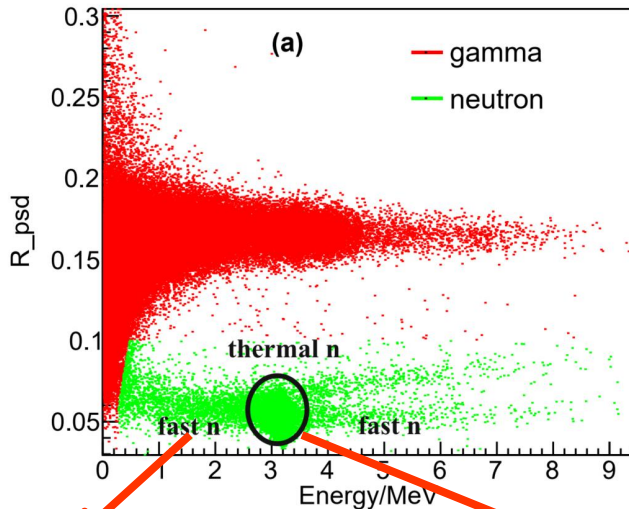
- 对于2种算法预测不一致的脉冲
 - 手工给出标签
 - 约96%事例可通过人眼识别获得标签
 - 约4%事例无法给出标签
- 错误事例的识别
 - ANN准确率60%
 - 电荷积分法准确率30%
 - 全部错误10%
 - 神经网络算法更准确

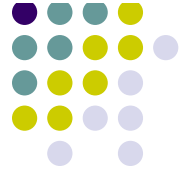


CLYC用于快中子探测

● 探测原理

- CLYC的 ${}^6\text{Li}$, ${}^{35}\text{Cl}$ 具有相对较大快中子反应截面
- Li6 的热中子截面极大, 存在很高的热中子峰 (3.2MeVee), 该区域的快、热中子难以区分

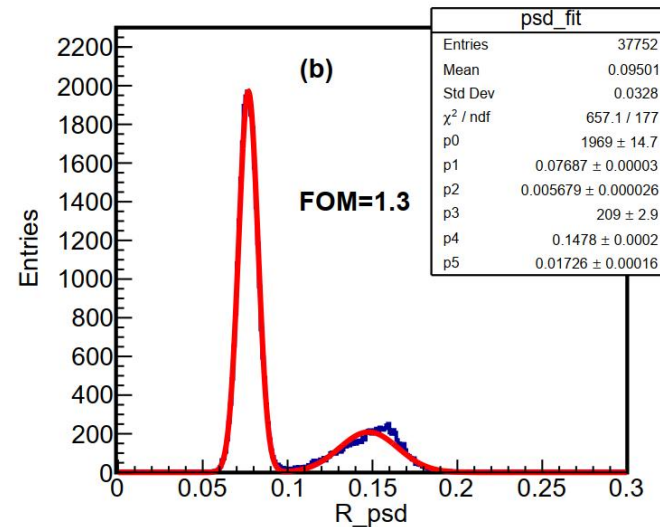
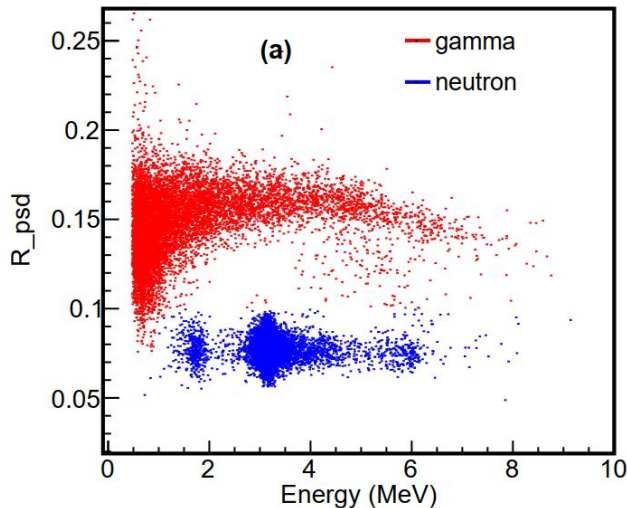
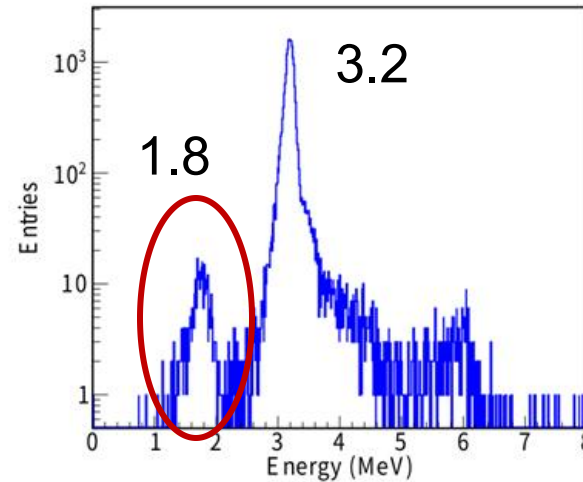


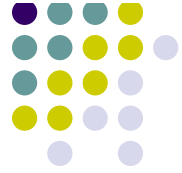


CLYC快中子探测 ($E_n=1.4 \text{ MeV}$)

● 快中子峰

- 3.2MeV, 热中子
- 1.8MeV, $^{35}\text{Cl} (n, p) ^{35}\text{S}$
- 6.1MeV, 热中子叠峰
- FOM值约1.3

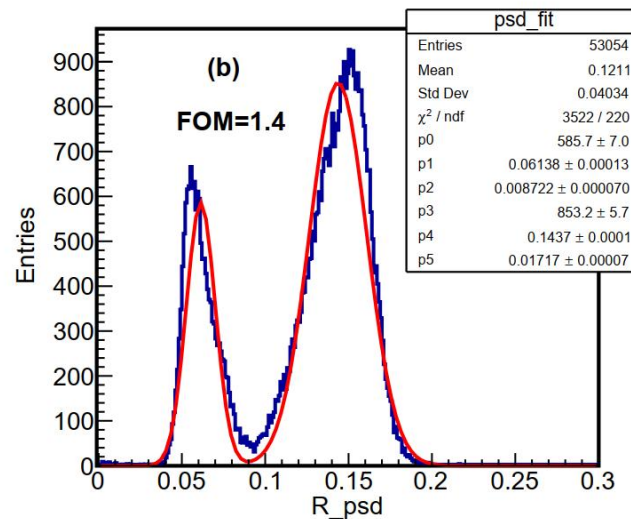
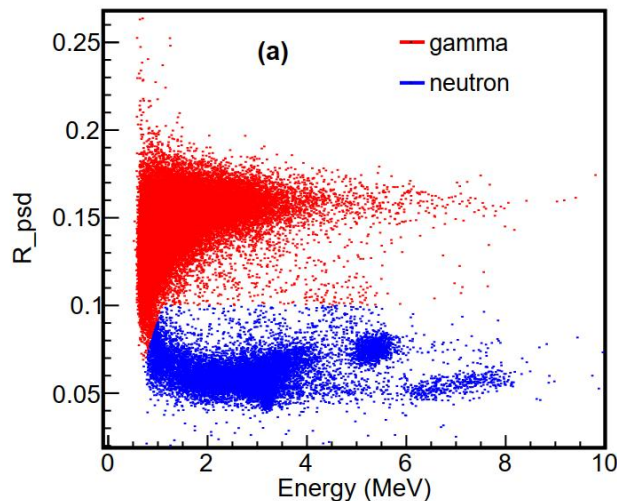
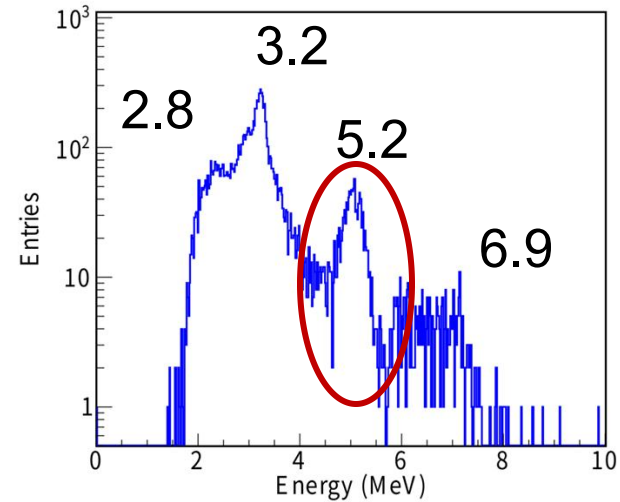




CLYC快中子探测 ($E_n=5.2$ MeV)

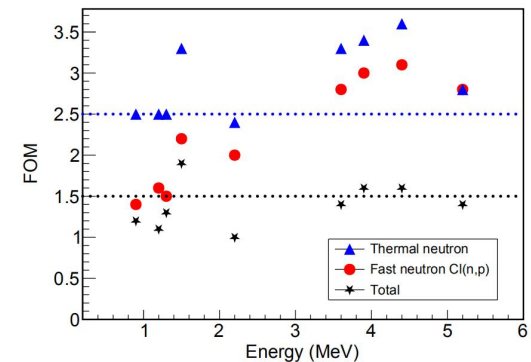
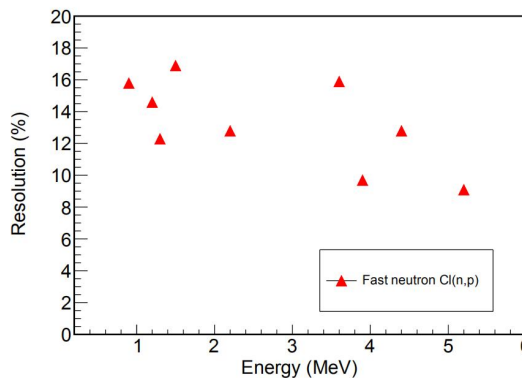
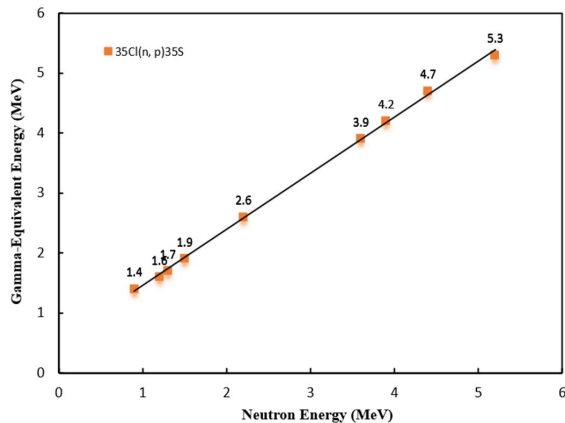
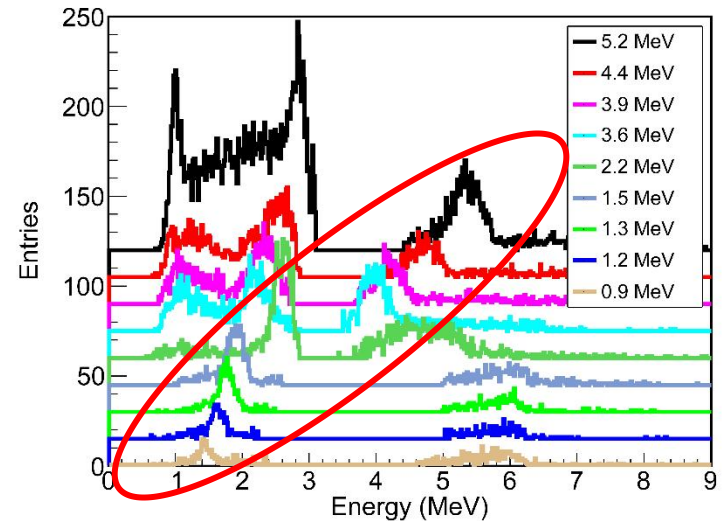
● 观测到多个峰

- 3.2MeV, 热中子
- 5.2MeV, $^{35}\text{Cl}(n, p)^{35}\text{S}$
- 6.9MeV, $^6\text{Li}(n, t)^4\text{He}$
- 2.8MeV, $^{35}\text{Cl}(n, \alpha)^{35}\text{P}^*$
- FOM值约1.4



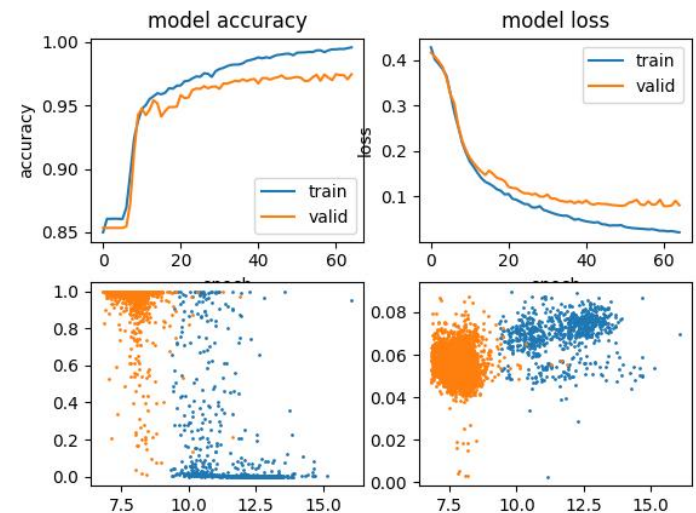
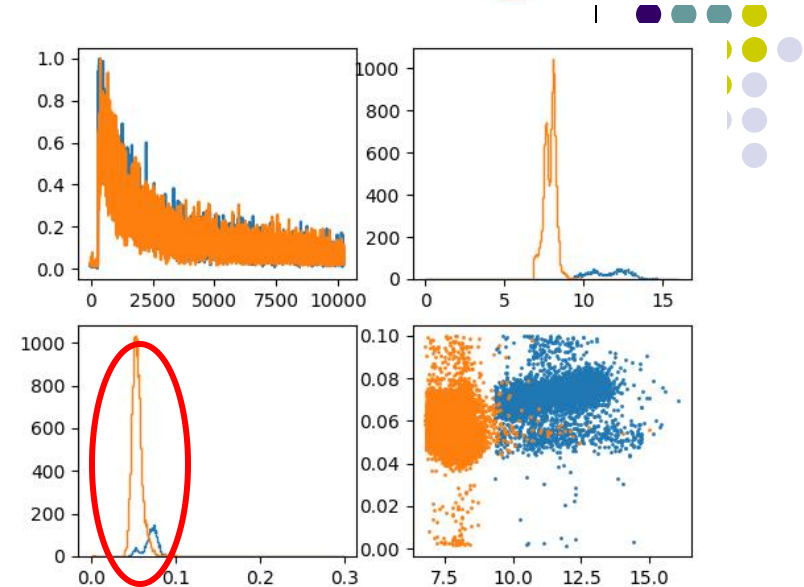
CLYC快中子能谱探测

- $Cl(n, p)S$ 反应探测快中子
 - 线性良好，可用于快中子能谱探测
 - 能量分辨率约15%，淬灭因子约0.9
 - 快中子FOM值稍差于热中子
 - 在3MeV存在热中子干扰



核反应通道甄别

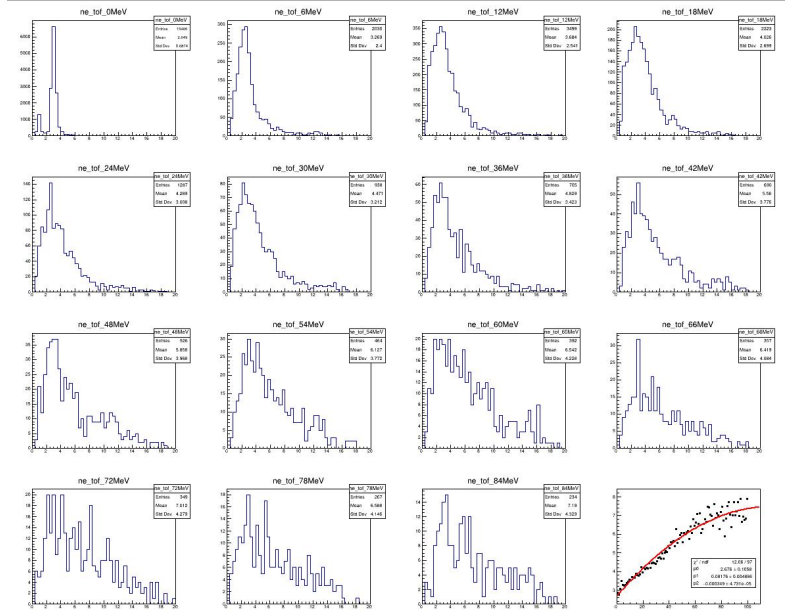
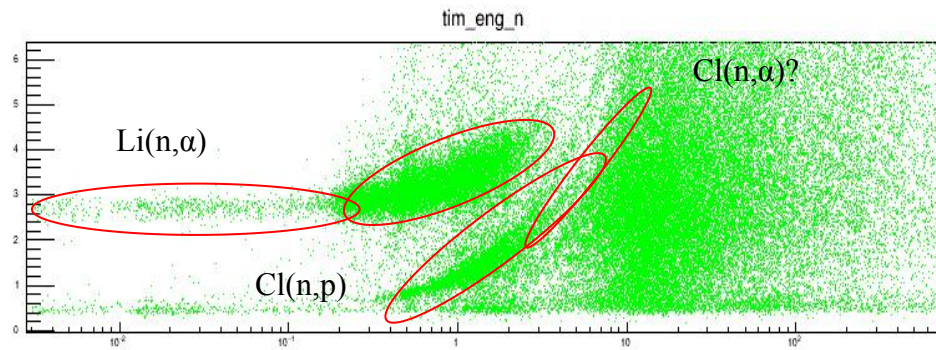
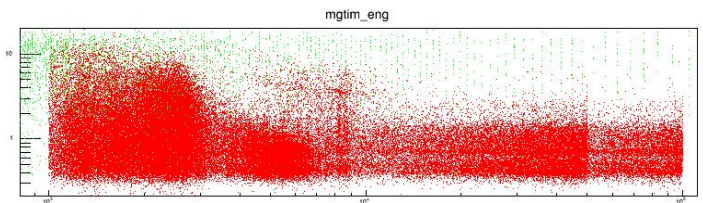
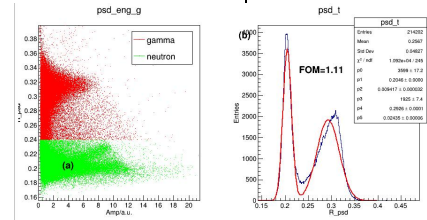
- 各核反应通道波形存在差异
 - $\text{Li6}, {}^6\text{Li} (n, t) {}^4\text{He}$
 - $\text{Cl35}, {}^{35}\text{Cl} (n, p) {}^{35}\text{S}$
- 传统电荷积分法无法区分
 - FOM值约0.3
- 神经网络算法
 - 利用能量差异给出标签
 - 准确率97%
- 结论
 - 通过ANN可有效识别核反应通道
 - 用C6LYC同时探测热中子和快中子

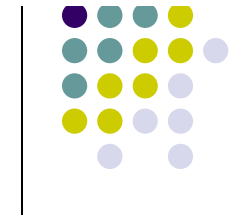


基于散裂白光源的多模探测

● CLYC进行白光测试

- 中子伽马存在显著差异
- 伽马持续存在
- 0-10MeV, 可分辨反应通道, $\text{Li}(n,\alpha), \text{Cl}(n,p)$
- 10MeV以上能区复杂, 中子能量和沉积能量正相关。铅砖慢化影响

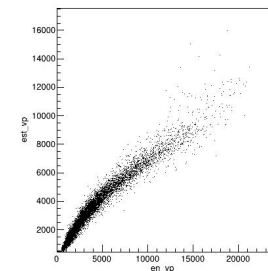
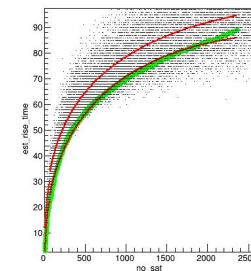
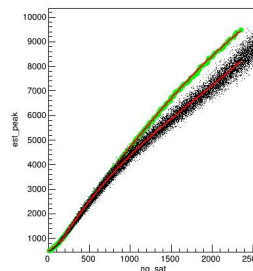
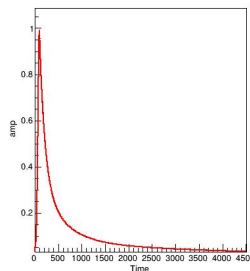




基于散裂白光源的多模探测

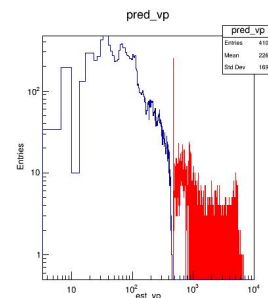
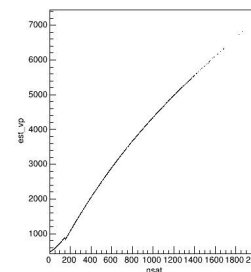
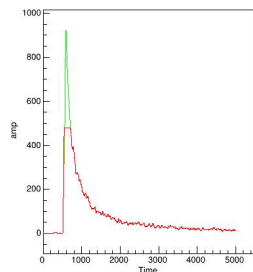
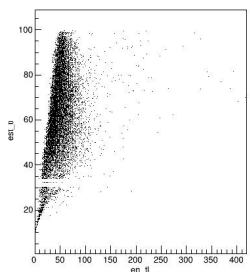
■ 动态范围提升算法

- 采集卡动态范围有限
- 信号幅度差异很大
- 出现大量饱和信号



■ 饱和信号的重建

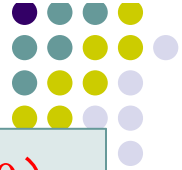
- 拟合不饱和信号特征
- 根据饱和平台长度→实际峰位、峰值
- 补齐饱和信号
- 动态范围提升9倍





小结

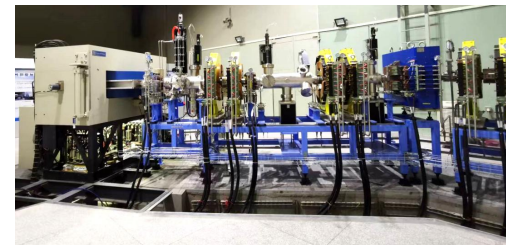
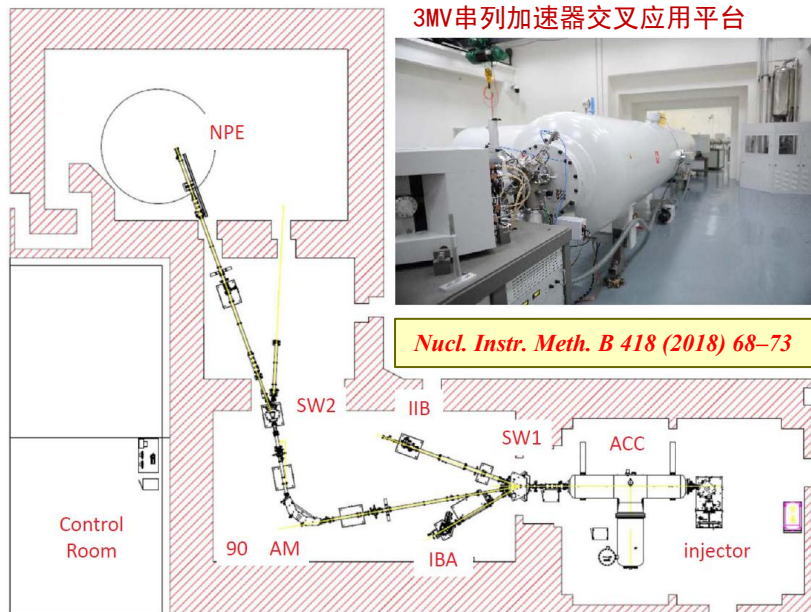
- 研究了CLYC中子伽马多模探测器的性能
 - 实现堆积脉冲的psd甄别和能量提取
 - 实现快中子能谱探测, $^{35}\text{Cl} (n, p) ^{35}\text{S}$
 - 用ANN网络实现核反应通道的甄别 $^{35}\text{Cl} (n, p) ^{35}\text{S}$, $^6\text{Li} (n, \alpha)\text{T}$
 - C6LYC同时探测快中子、热中子、伽马



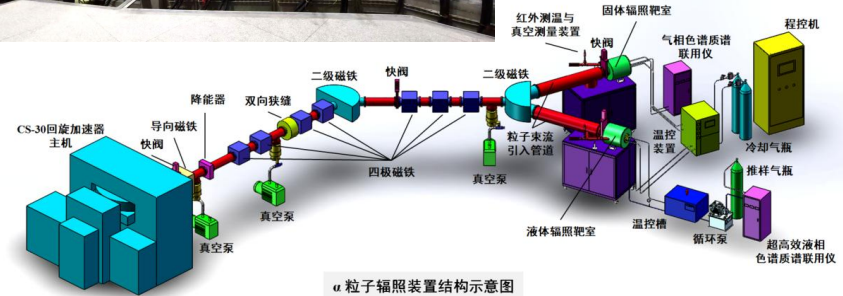
致谢

- 感谢基金委、科技部、四川省科技厅、川大资助
- 感谢合作者（闪烁玻璃合作组）

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