

基于白光中子源的准积分实验测量研究进展

第九届CSNS反角白光中子源用户研讨会 安徽六安 2025.07.23-25

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01

研究背景及意义

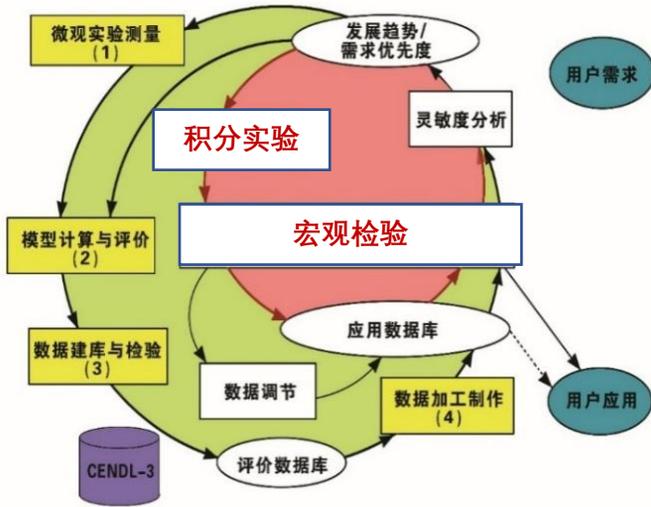
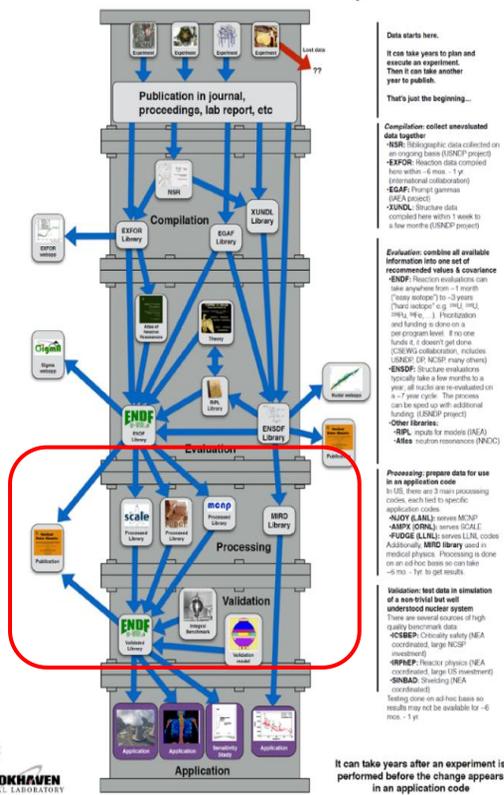


图1 核数据生产过程示意图

最后屏障：所有投入应用的核数据库，必须经过**宏观检验**验证其准确性，才能被用户所接受

重要手段：积分实验为宏观检验提供必需的实验数据

The Nuclear Data Pipeline



实验

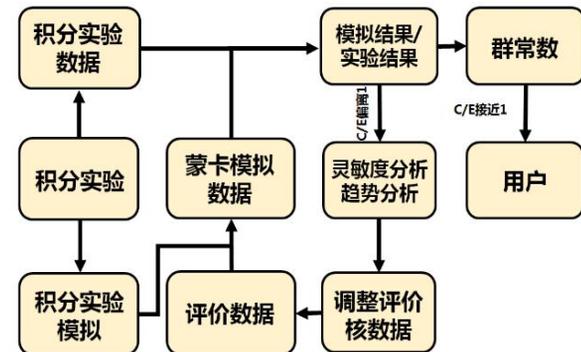
•选择或设计合适的积分/基准实验

计算

•选择可靠的计算工具，建立基准模型

分析

•利用适当的物理和数学方法追溯和发现微观评价核数据存在的不足。



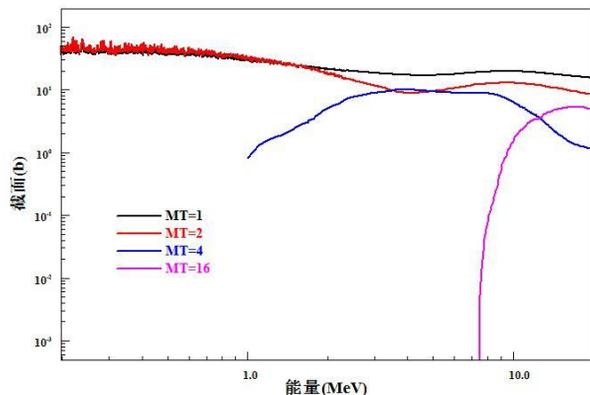


图3 中子与^{nat}Zr作用各反应道截面比较

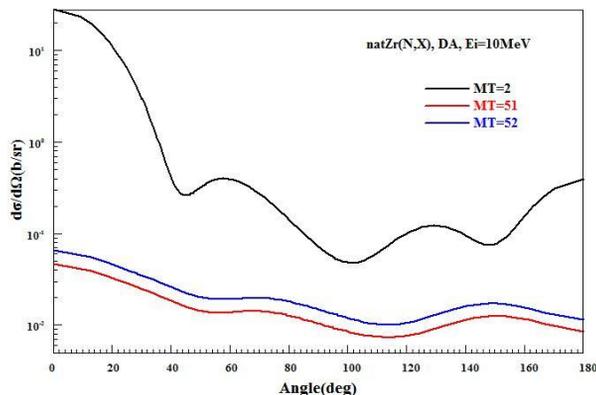
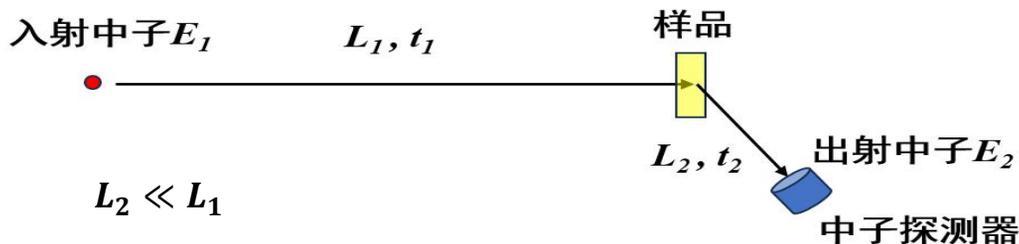


图4 中子与^{nat}Zr作用不同反应道角分布数据

- 准微分或准积分实验是国际上一种新型的检验评价数据库散射中子截面质量的方法。



- 准积分实验对弹性/非弹散射截面及其角分布非常敏感



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Nuclear Data Sheets

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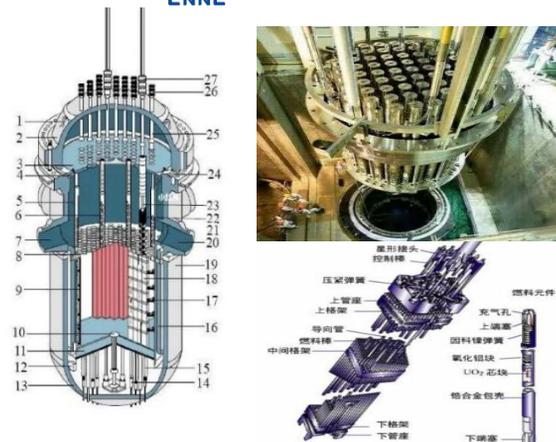
The CIELO Collaboration:
Neutron Reactions on ¹H, ¹⁶O, ⁵⁶Fe, ^{235,238}U, and ²³⁹Pu

Recent “quasi-differential” measurements from RPI that are sensitive to elastic and inelastic scattering in ²³⁸U provide useful guidance on how to improve the scattering cross sections. These data are from 0.5 up to 20 MeV incident energies. ENDF/B-VII does not in-

Ref: M.B.Chadwick et al. NUCL DATA SHEETS 118 (2014) 1–25 .

锆 (Zr) 在自然界中有⁹⁰Zr (51.45%)、⁹¹Zr (11.22%)、⁹²Zr (17.15%)、⁹⁴Zr (17.38%) 和⁹⁶Zr (2.80%) 五种稳定同位素。

- 锆 (Zr) 及其合金材料广泛应用于核工业
- 了解Zr散射中子截面数据的可靠性, 对反应堆设计研发工作具有重要指导意义



■ 现有评价核数据库中Zr的评价数据存在分歧

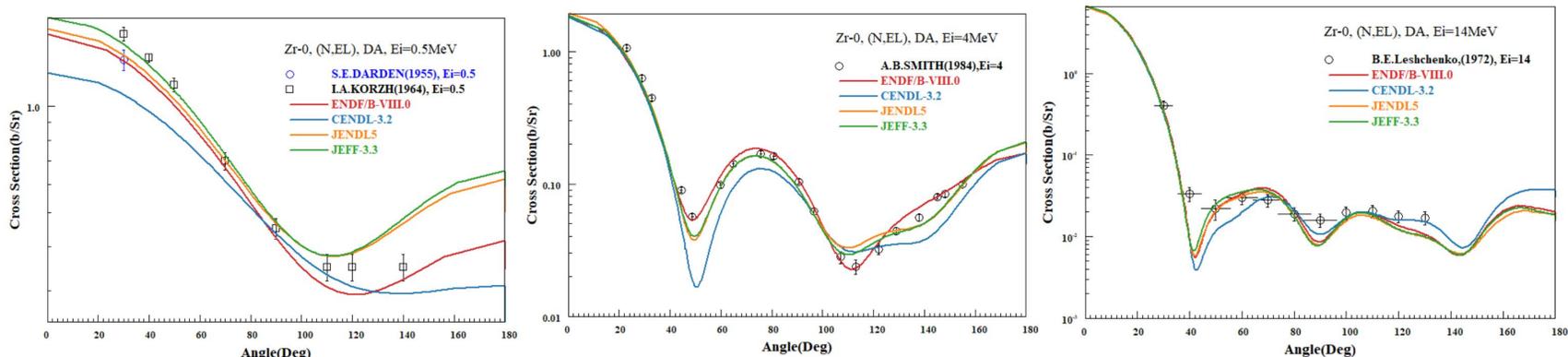


图5 不同数据库不同能量中子与^{nat}Zr作用弹性散射角分布数据

02

国内外研究进展

目前国际上开展准积分实验的主要是美国伦斯勒理工学院 (RPI)

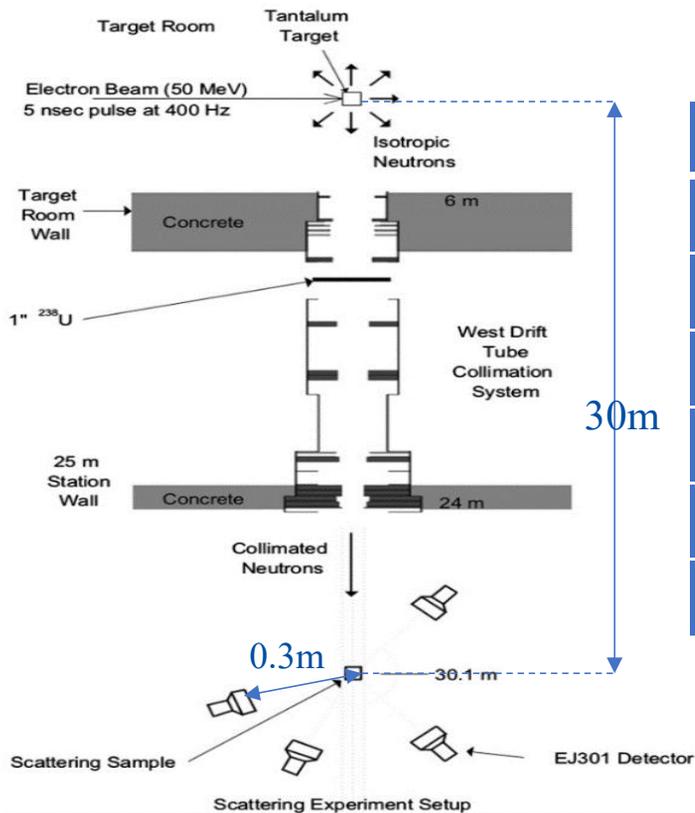


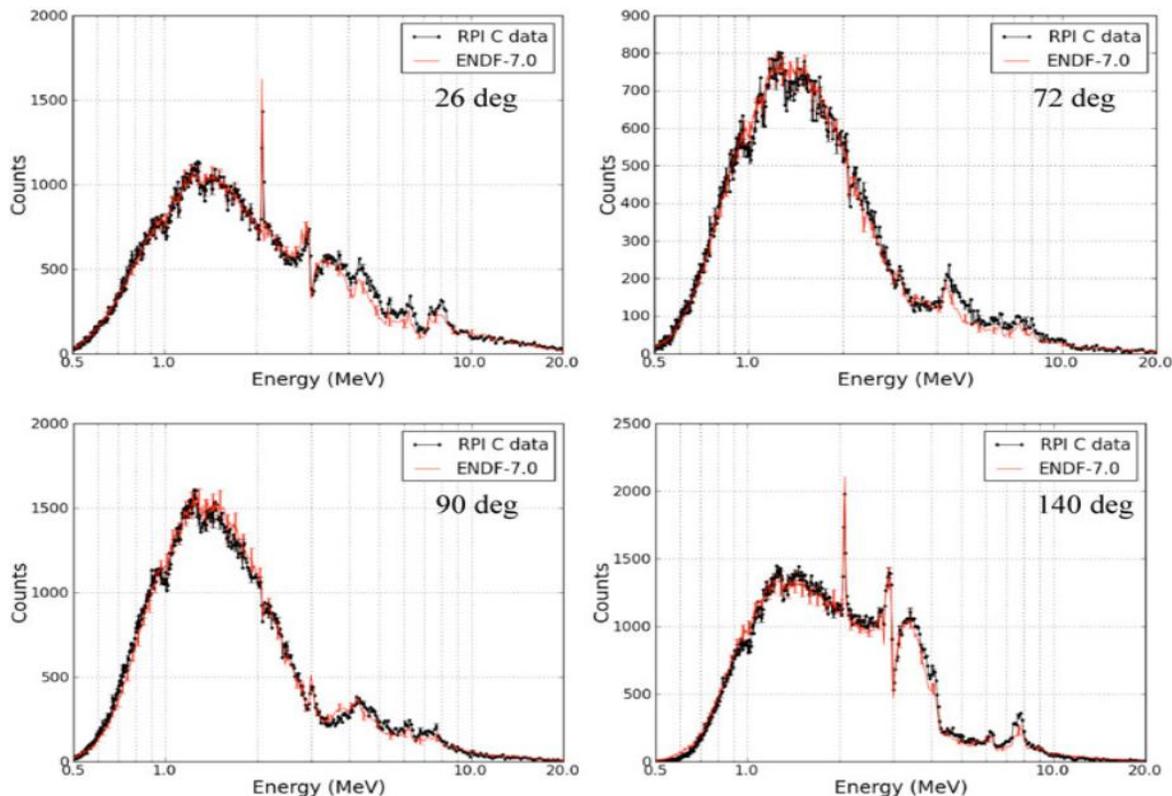
图6 RPI准积分实验布局

表1 RPI已开展的准积分实验情况

样品	直径/边长 (cm)	厚度 (cm)	距中子源距离 (m)	测量能区 (MeV)	测量角度 (°)
^{nat}Mo	7.6	5	30.07	0.5-20	26, 52, 72, 90, 107, 119, 140, 154
	7.6	8	30.07		
Be	7.5	4	30.1	0.5-20	26, 52, 73, 90, 108, 118, 140, 154
	7.5	8	30.1		
Zr	7.6	6	30.07	0.5-20	26, 52, 72, 90, 107, 119, 140, 154
	7.6	10	30.07		
^{238}U	7.6	0.98	30.07	0.5-20	27, 29, 60, 77, 112, 113, 130, 153, 156
^{nat}Fe	15.25 × 3.85	7.7	30.07	0.5-20	30, 45, 60, 77, 111, 109, 130, 153, 156
^{nat}Pb	-	3	30.07	0.5-20	30, 45, 60, 70, 100, 110, 150
	-	5	30.07		

- ^{238}U 准积分实验数据用于CIELO项目 ^{238}U 数据的评价。
Ref: **R.Capote** et al. Nuclear Data Sheets 148 (2018) 254–292.
- **Be**准积分实验数据用于美国ENDF/B-VIII.0库Be数据的评价。
Ref: **D.A.Brown** et al. Nuclear Data Sheets 148 (2018) 1–142.

■ RPI 石墨样品准积分实验结果



Ref: **F.J. Saglime** et al. NUCL INSTRUM METH A 620 (2010) 401–409.

图7 RPI石墨样品(7.5cm diam × 7cm thick) 在26°, 72°, 90°, 140° 方向散射中子谱

RPI Zr样品准积分实验结果

Ref: D. P. Barry et al. NUCL SCI ENG : 174, 188–201 ~2013.

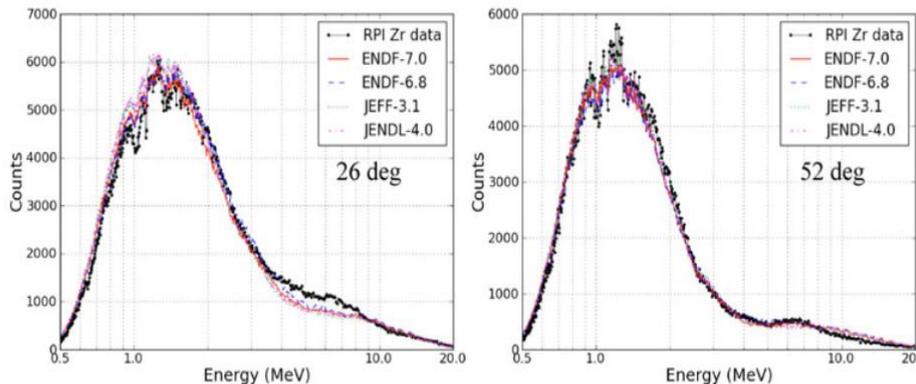


图8 RPI Zr(7.62cm diam × 6cm thick) 在26, 52度方向结果

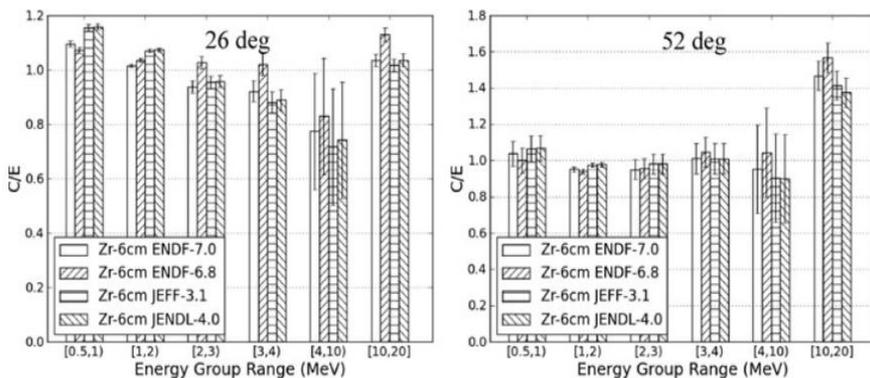


图9 RPI Zr(7.62cm diam × 6cm thick) 在26, 52度方向C/E值

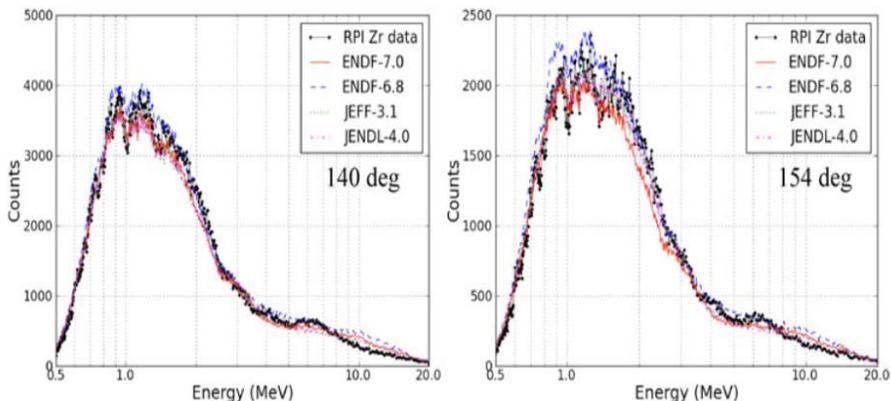


图10 RPI Zr(7.62cm diam × 6cm thick) 在140, 154度方向结果

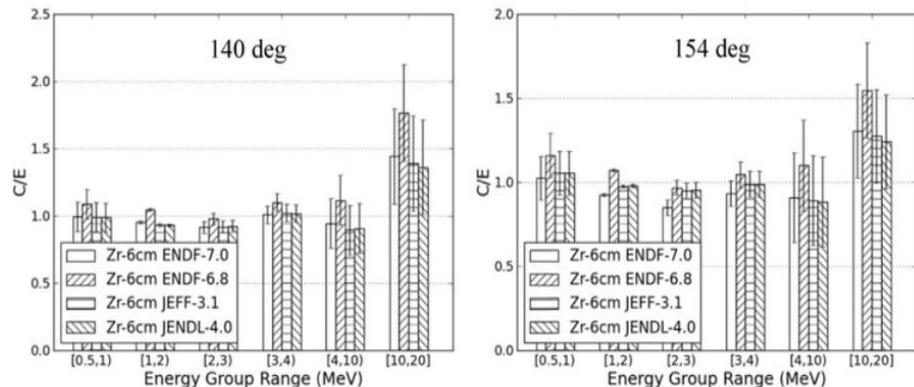
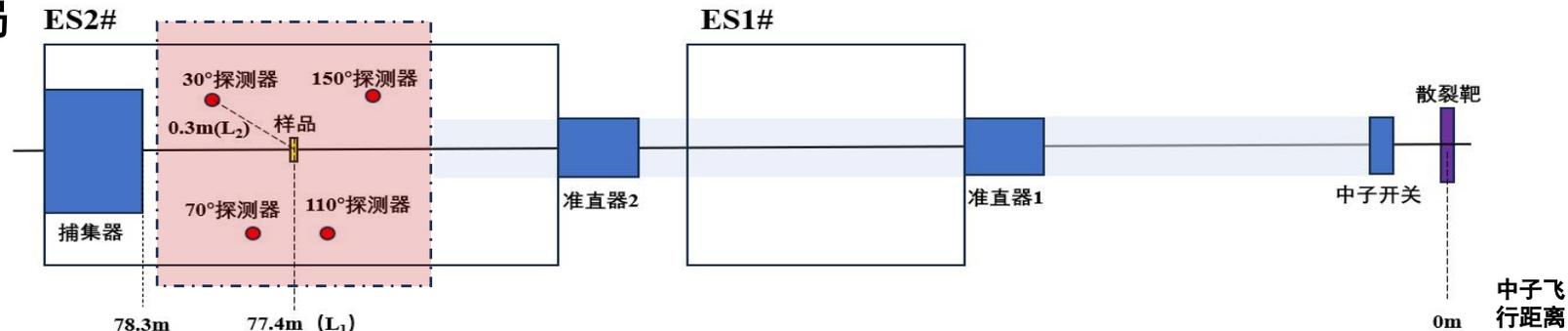


图11 RPI Zr(7.62cm diam × 6cm thick) 在140, 154度方向C/E值

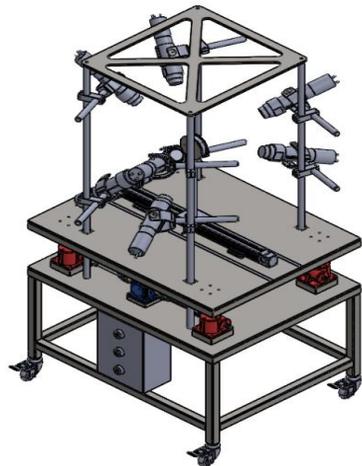
03

CI AE准积分实验

■ 实验布局



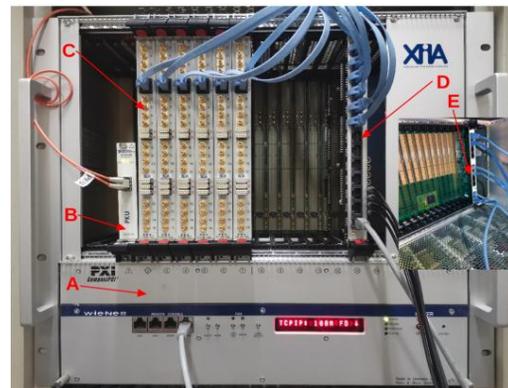
■ 测量平台设计加工



■ 探测器

	BC501A	CLYC
厂商	Saint-Gobain	RMD
晶体尺寸	2"×2"	2"×2"
数量	4	4
测量能区	0.8-20	0.2-0.8

■ 数据采集系统



- 测量位置：厅2
- 束流功率：160kW，束斑： $\phi 30\text{mm}$
- 探测器：4个BC501A+4个CLYC
- 样品：石墨、Zr
- 样品距中子源77.4m
- 样品距探测器0.3m
- 测量角度： 30° 、 70° 、 110° 、 150°
- 数据获取：XIA

表2 实验样品参数

样品	尺寸 (mm)	厚度 (mm)	中子自由程mpf	
			0.2 MeV	20 MeV
石墨	$\Phi 25$	20	0.68	0.25
锆	$\Phi 25$	5	0.2	0.07
		10	0.4	0.14
		15	0.6	0.21

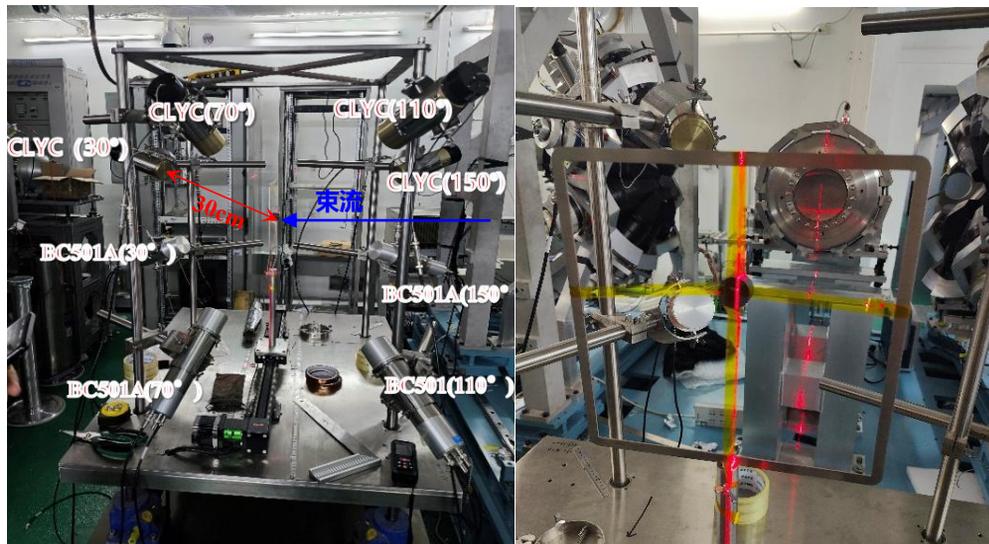


图9 石墨和Zr样品

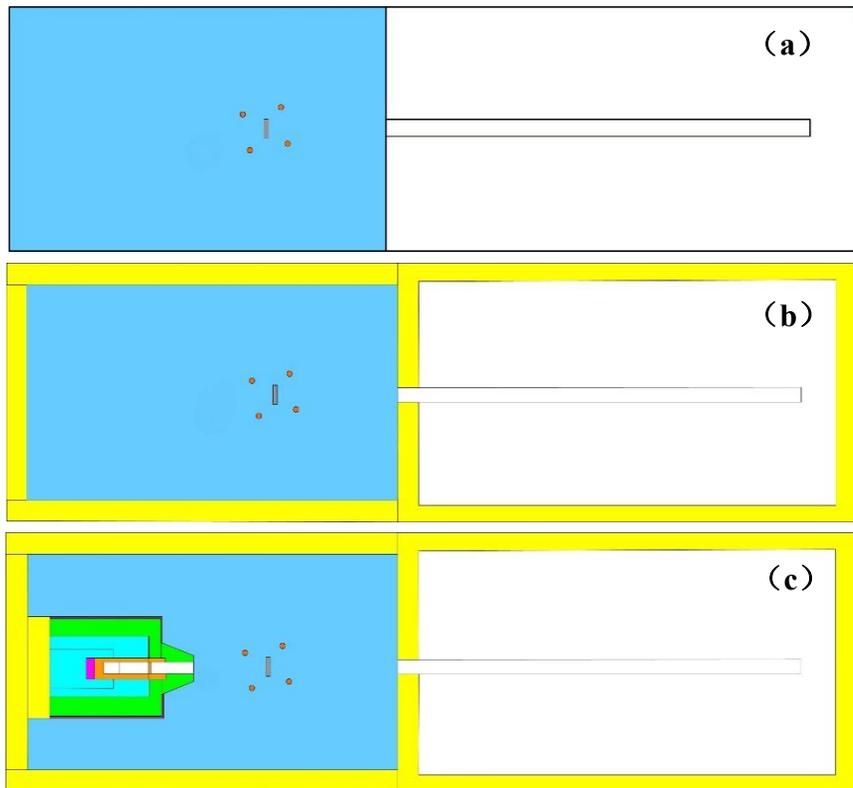
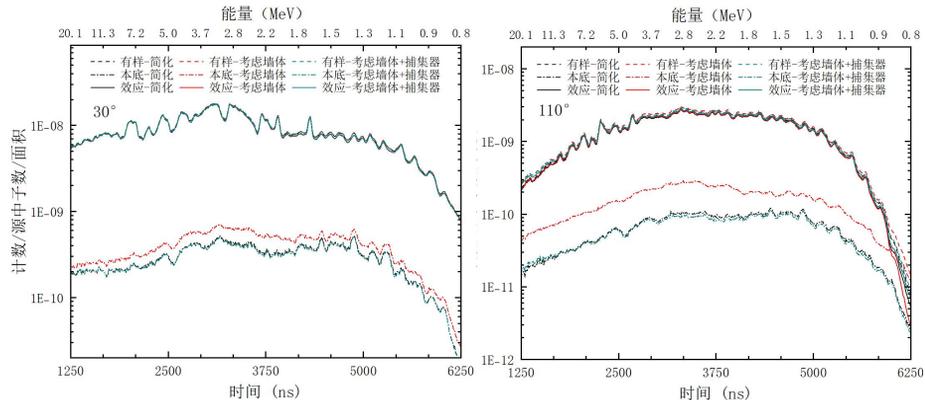


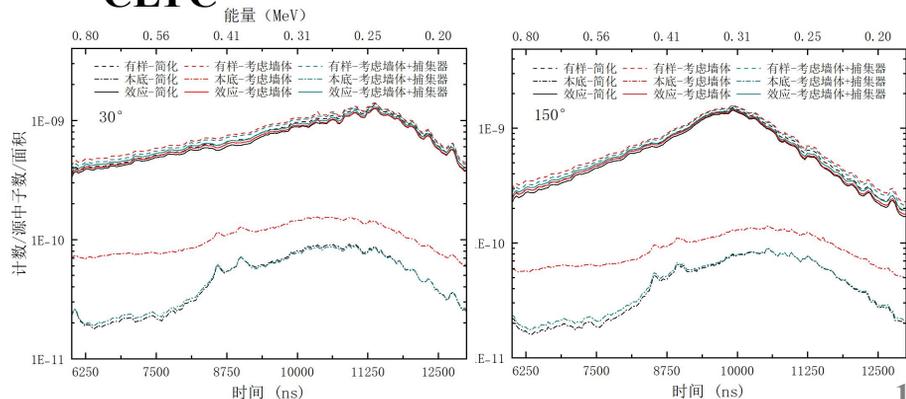
图10 MCNP模拟几何模型

(a) 简化模型；(b) 简化模型（墙体）；(c) 复杂模型（墙体+捕集器）

液闪



CLYC



04

结果分析与讨论

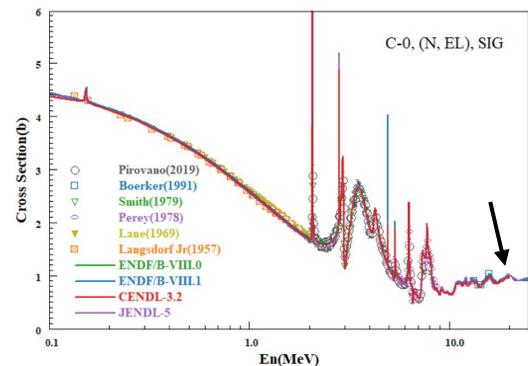
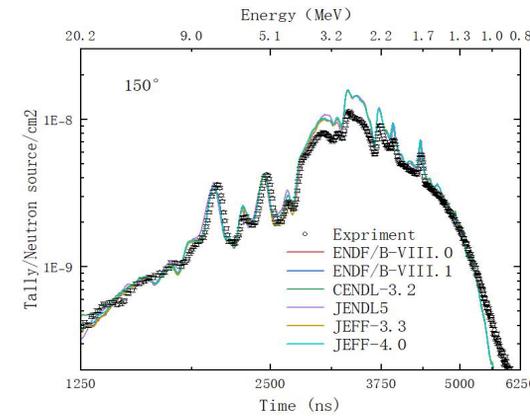
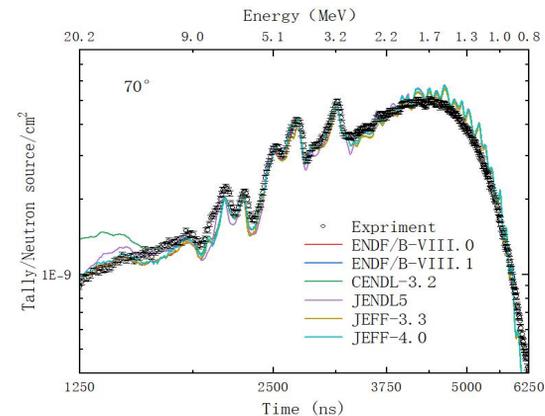
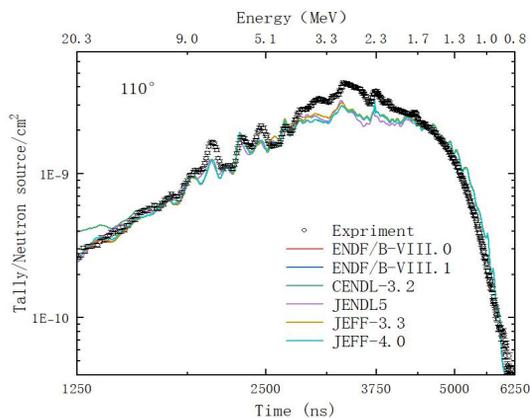
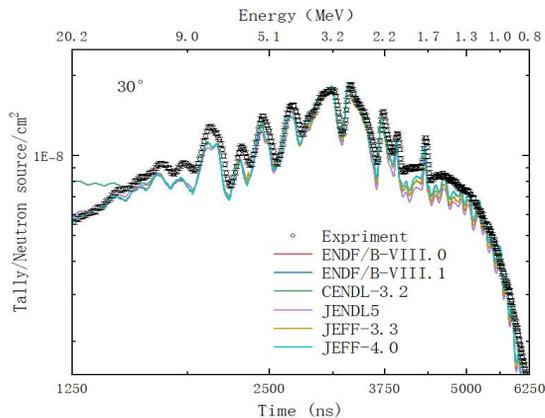


图11 中子与C作用弹性散射截面

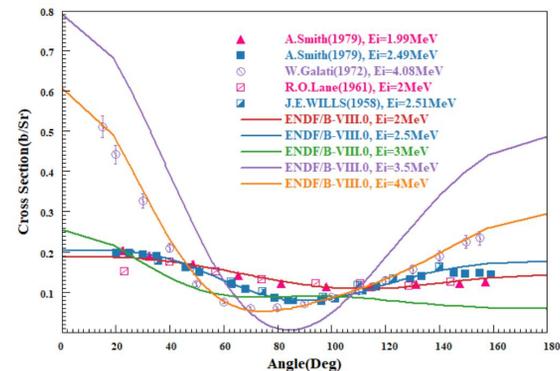
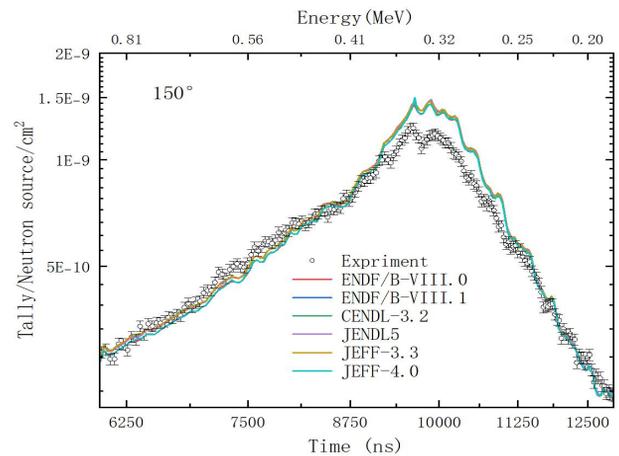
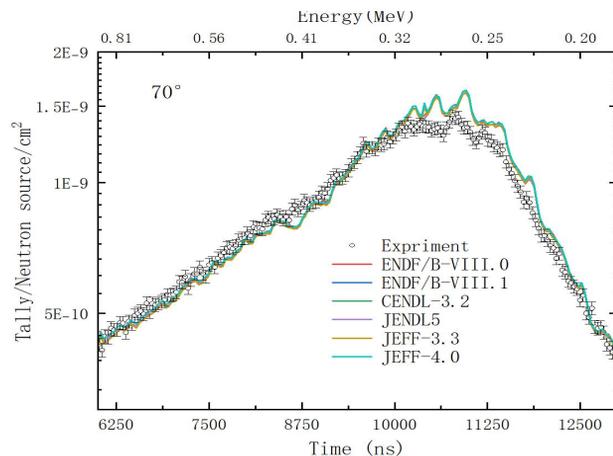
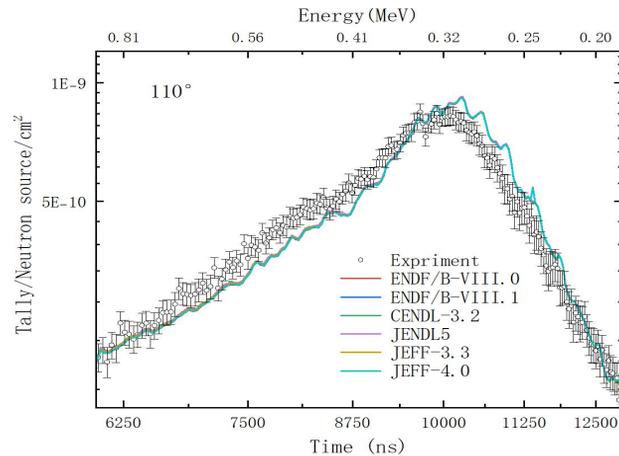
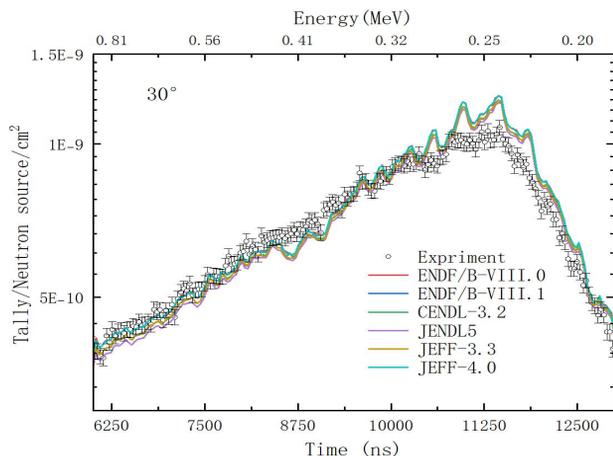
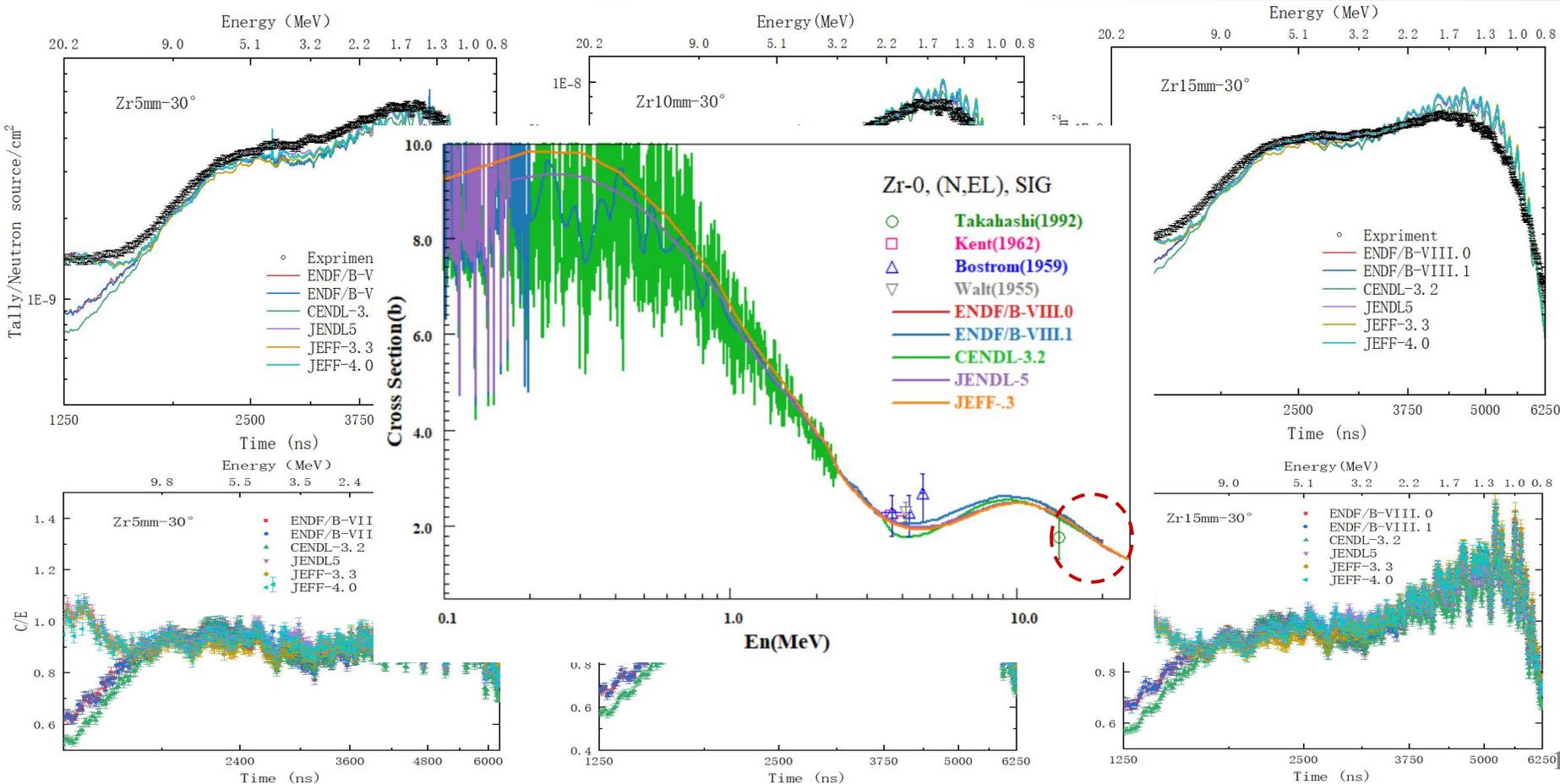


图12 不同能量中子与C作用弹性散射角分布 16

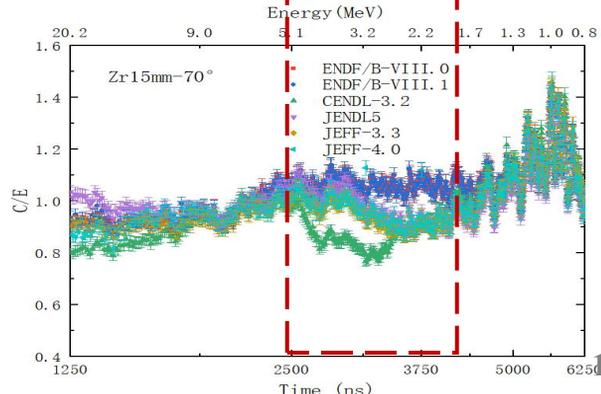
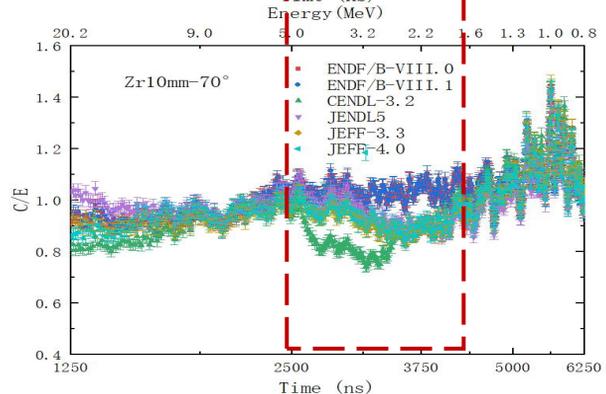
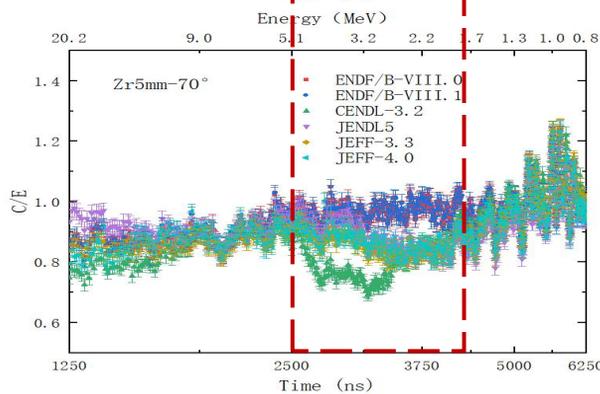
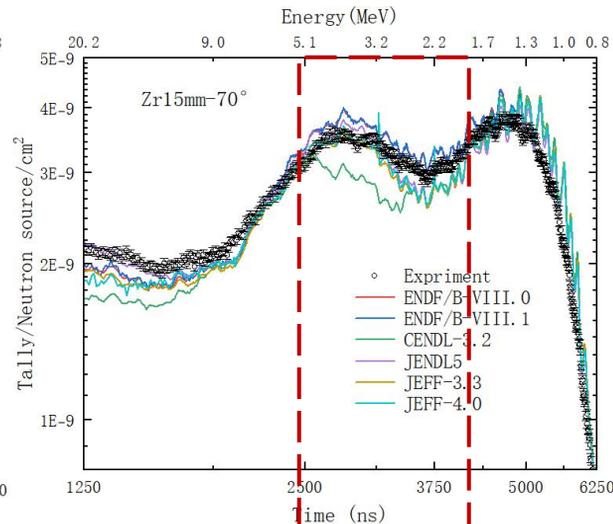
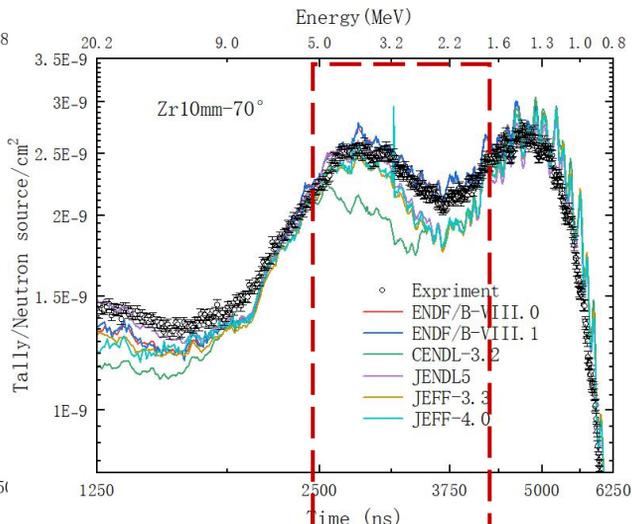
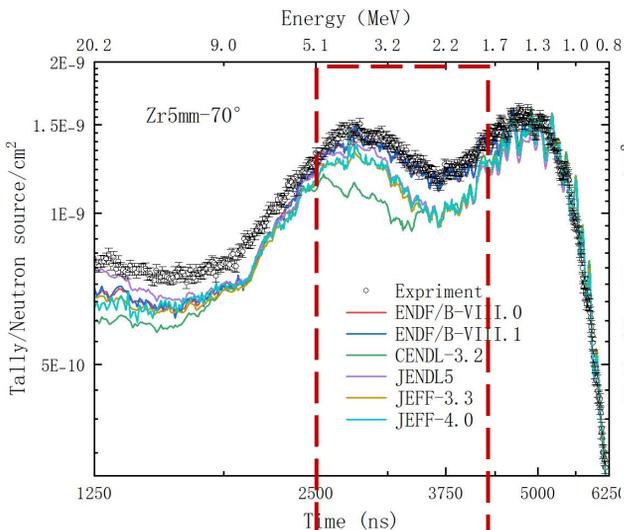
石墨-CLYC结果



Zr-BC501A-30°结果

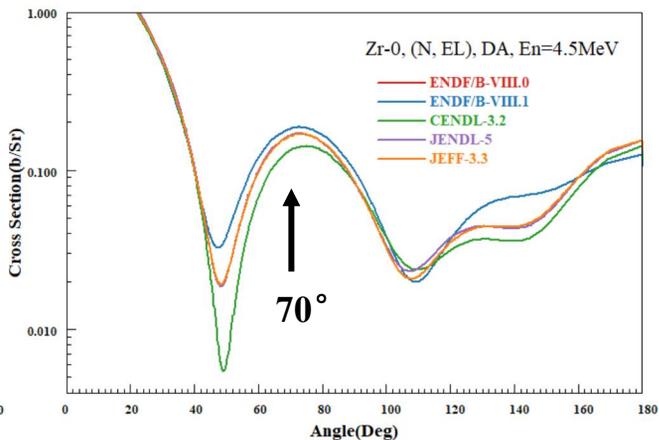
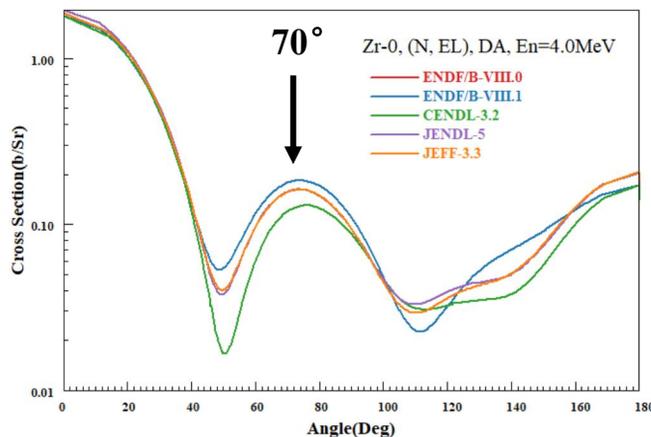
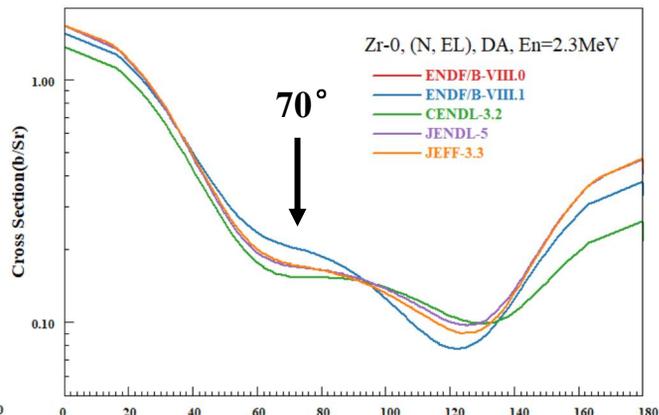
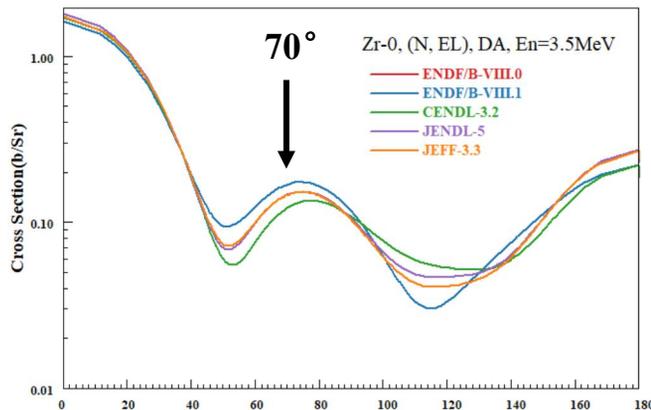


Zr-BC501A-70°结果

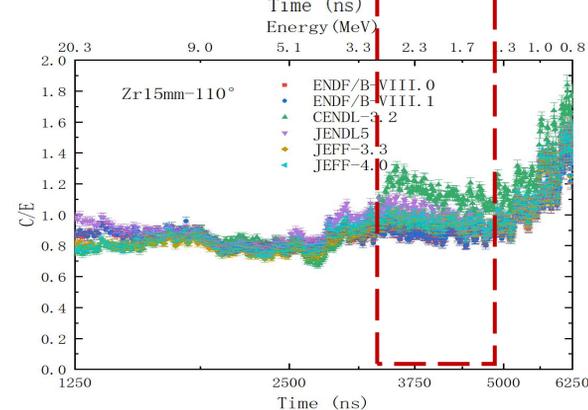
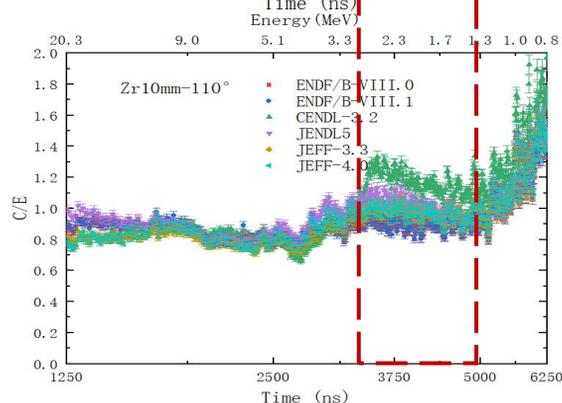
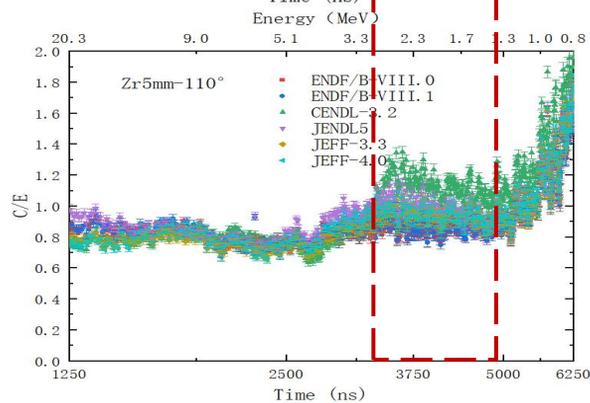
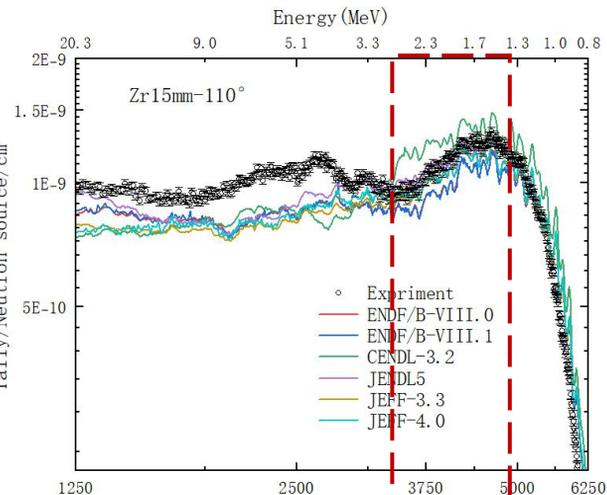
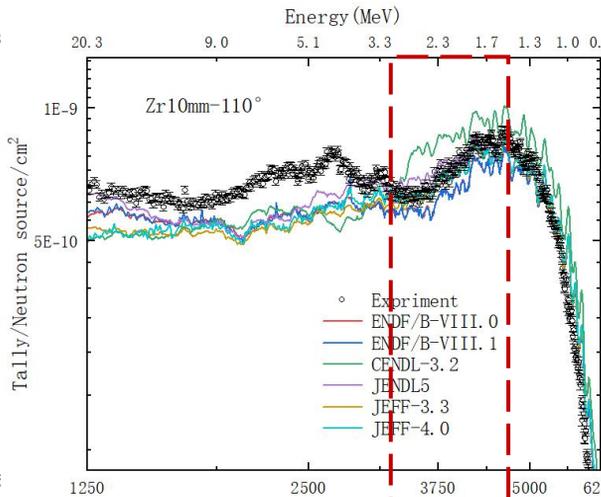
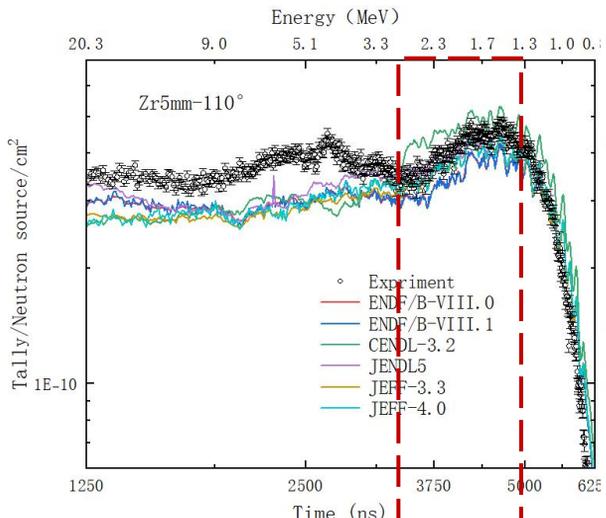


■ ^{nat}Zr 弹性散射角分布（中能区）

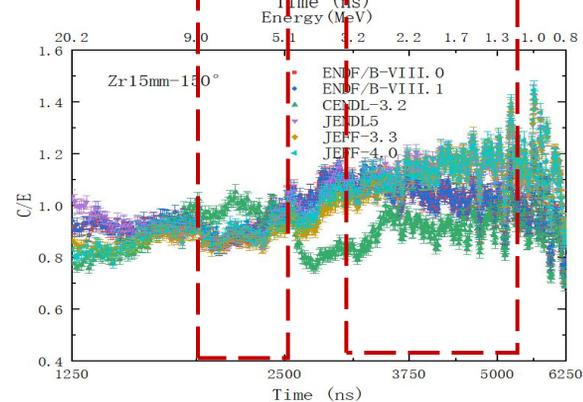
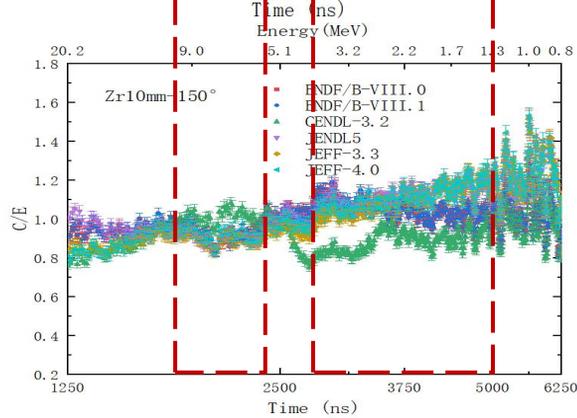
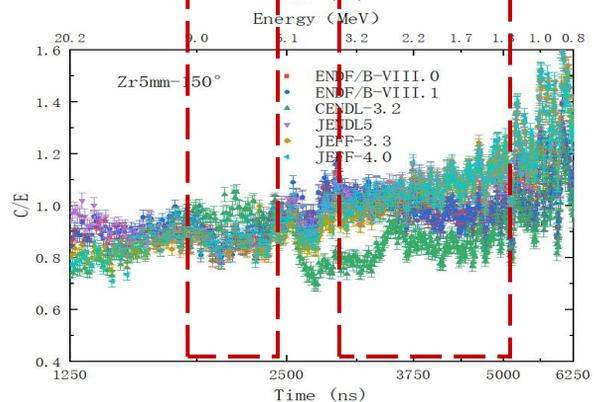
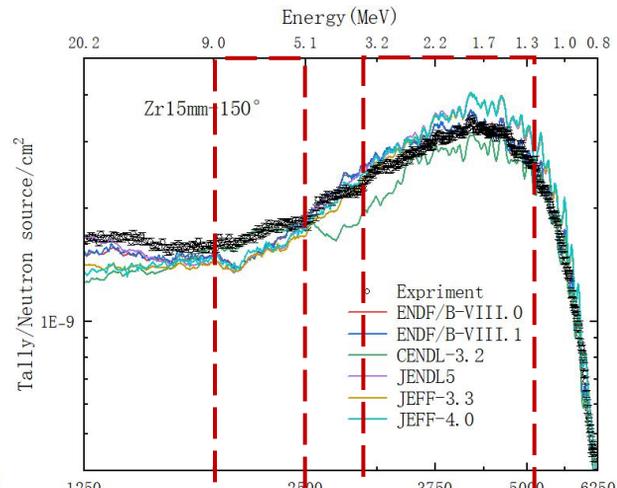
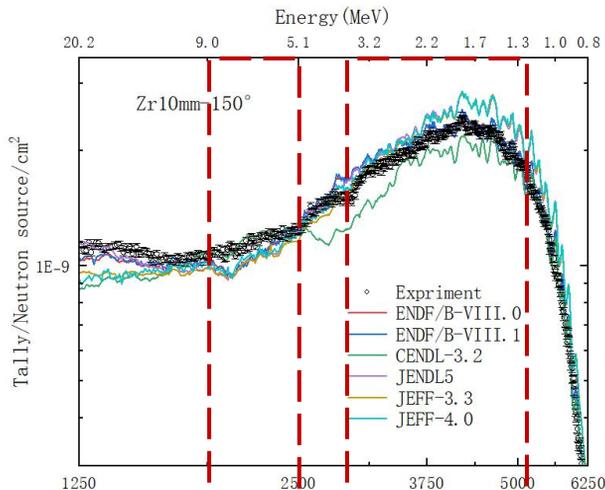
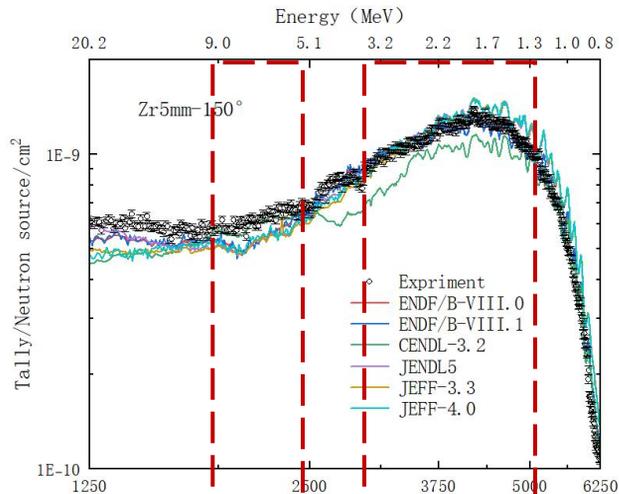
- 70° 方向，
ENDF/B-VIII.0和
ENDF/B-VIII.1库
模拟结果在2-
5MeV表现较好，
CENDL-3.2库偏低。



Zr-BC501A-110°结果

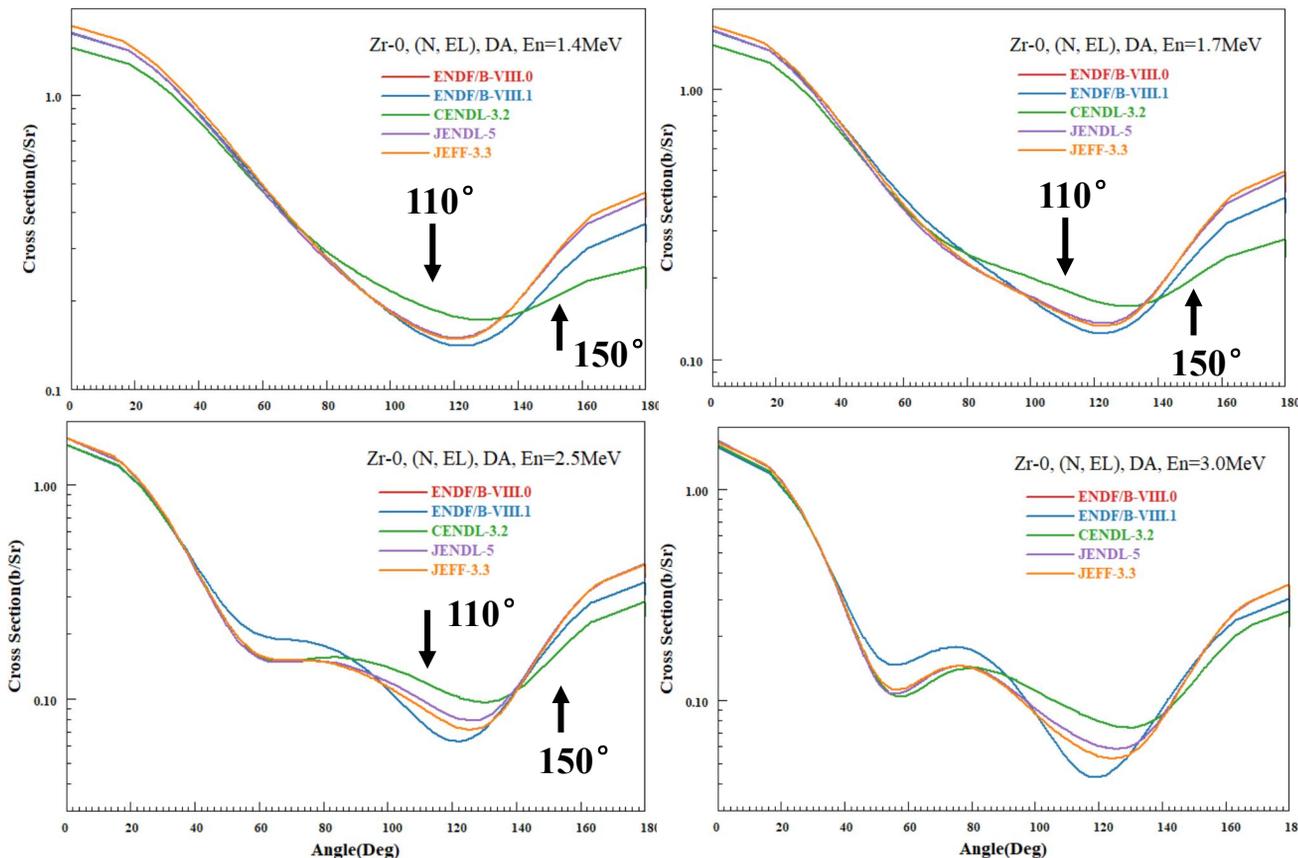


Zr-BC501A-150°结果



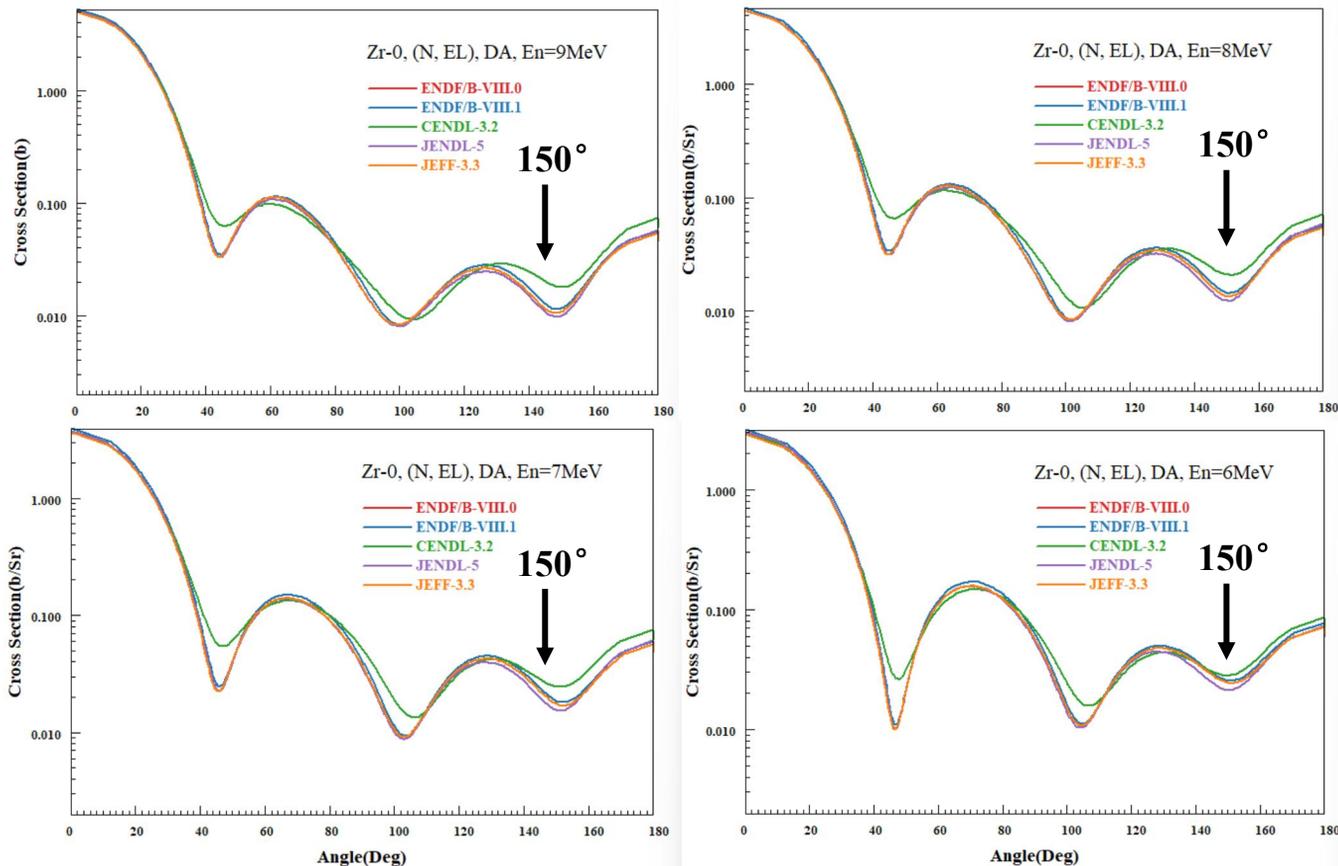
■ ^{nat}Zr 弹性散射角分布（中能/中低能区）

- 110° 方向，JENDL-5和JEFF-3.3库表现良好，CENDL-3.2偏，高，ENDF/B-VIII.0和ENDF/B-VIII.1偏低。
- 150° 方向，ENDF/B-VIII.0和ENDF/B-VIII.1表现好，CENDL-3.2偏低，JENDL-5和JEFF-3.3库偏高。

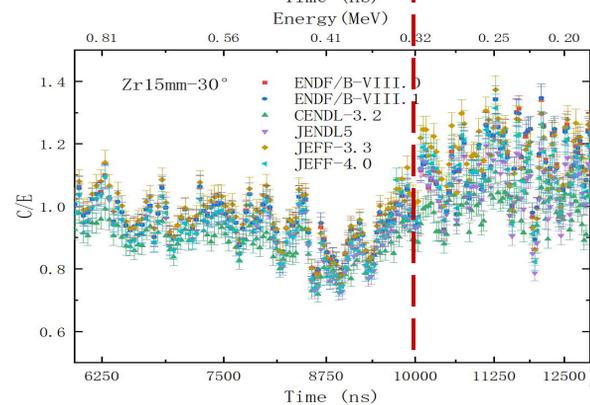
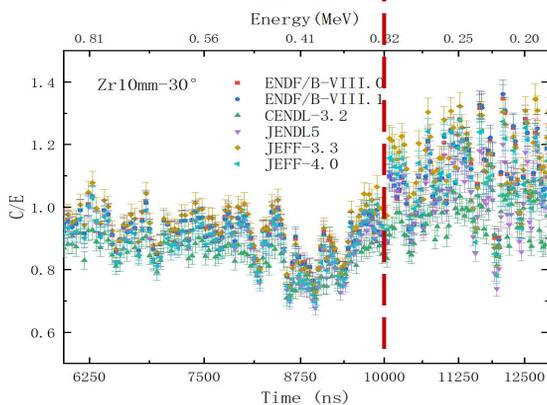
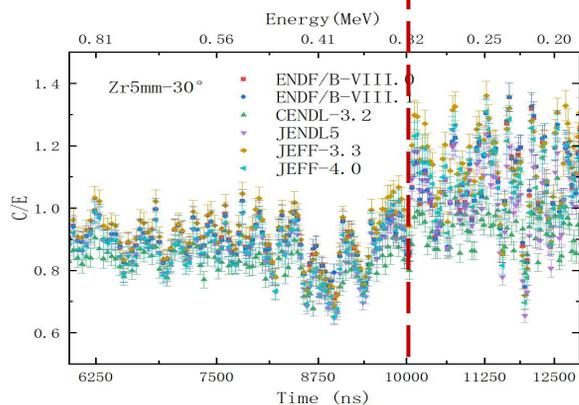
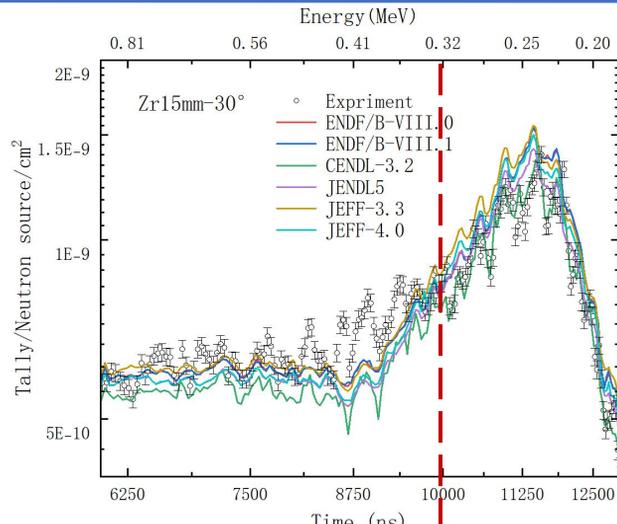
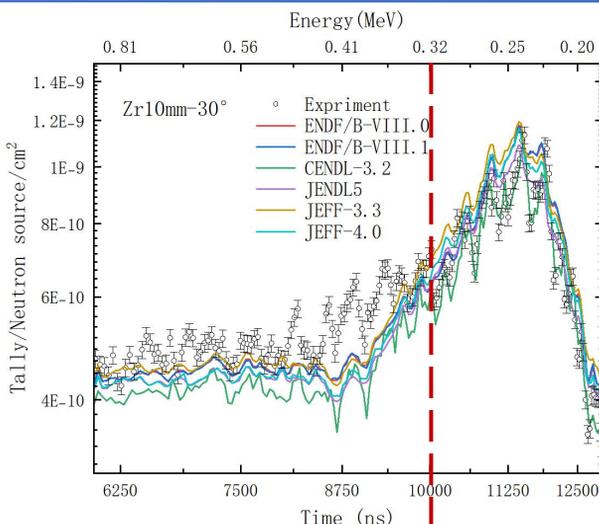
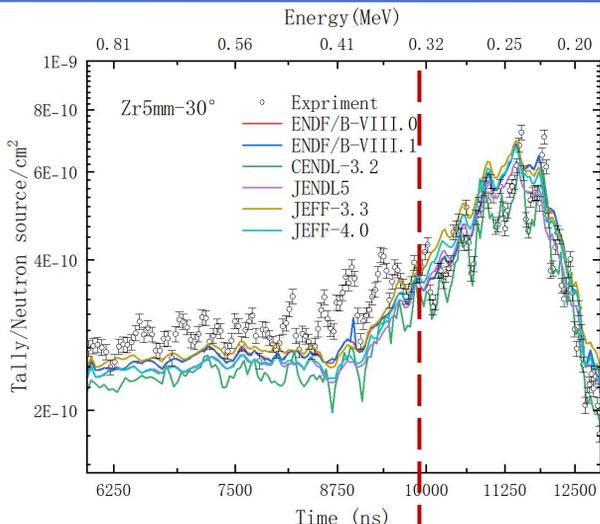


■ ^{nat}Zr 弹性散射角分布（中高能区）

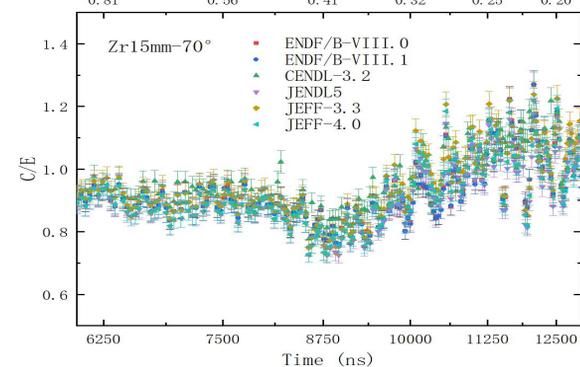
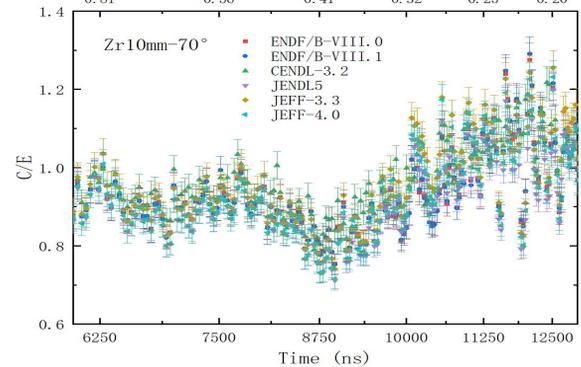
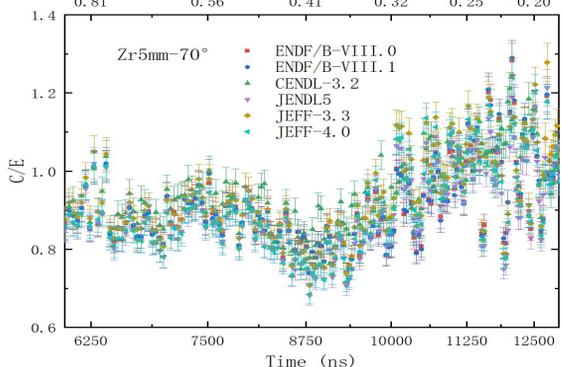
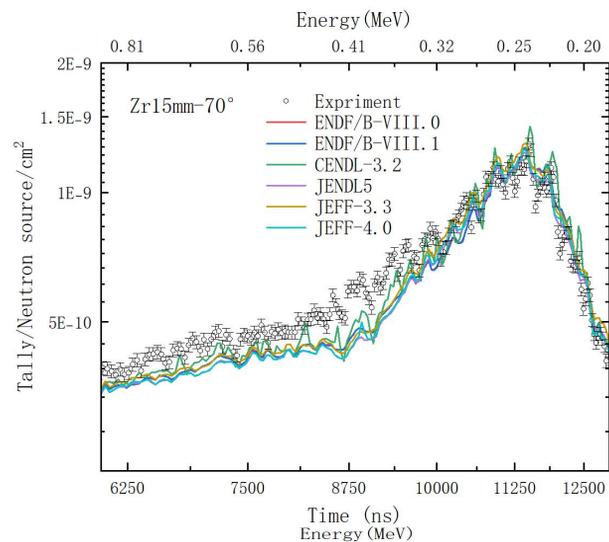
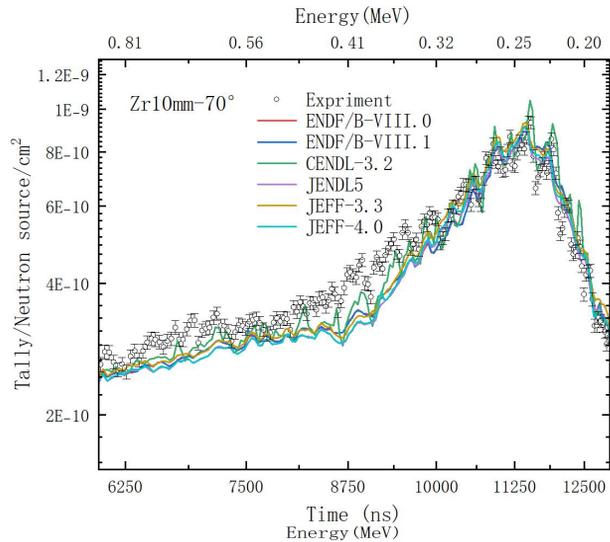
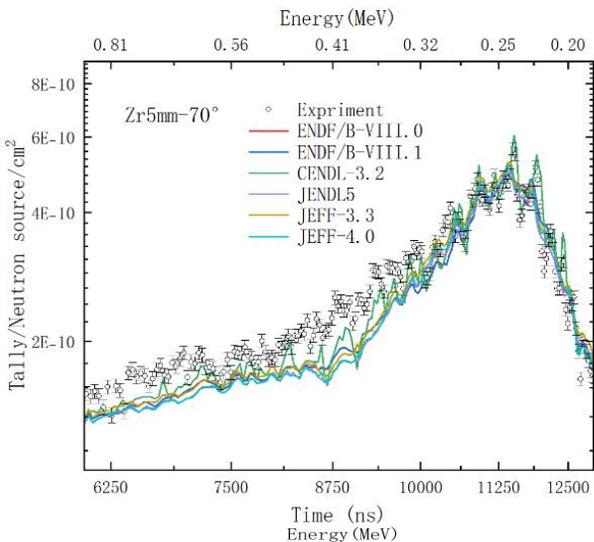
- 150° 方向，CENDL-3.2库模拟结果在5-11MeV能区表现较好，其他库偏低。



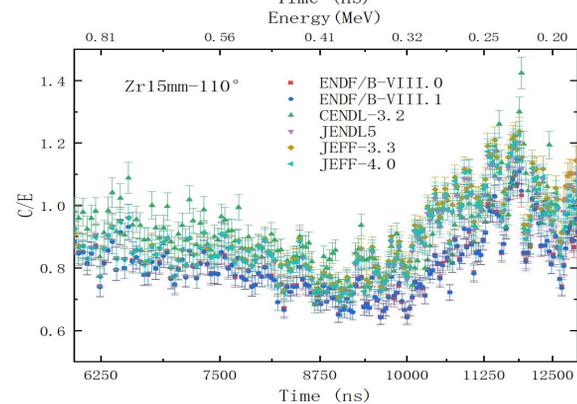
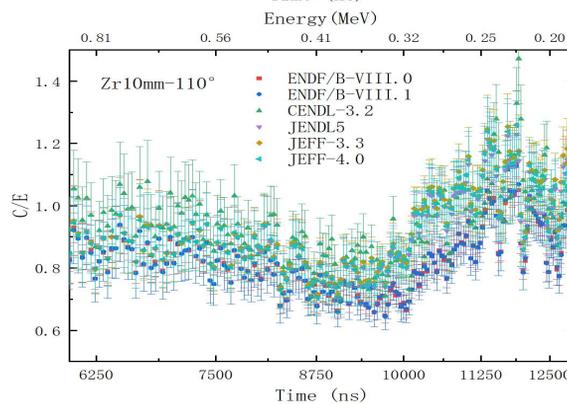
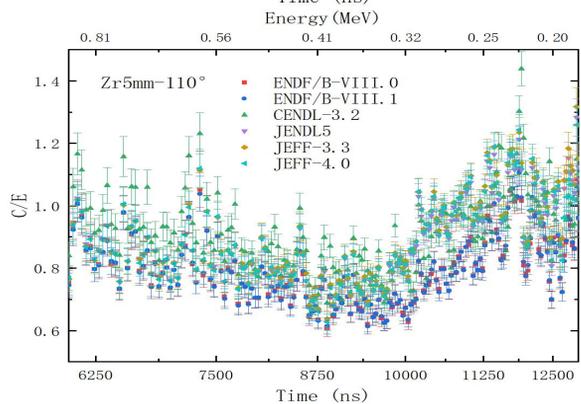
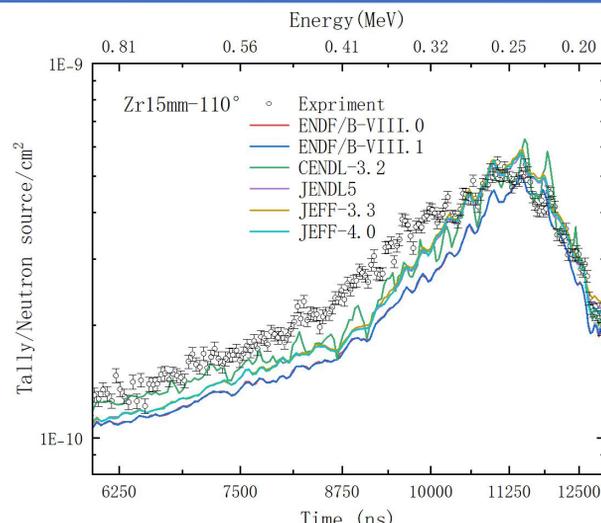
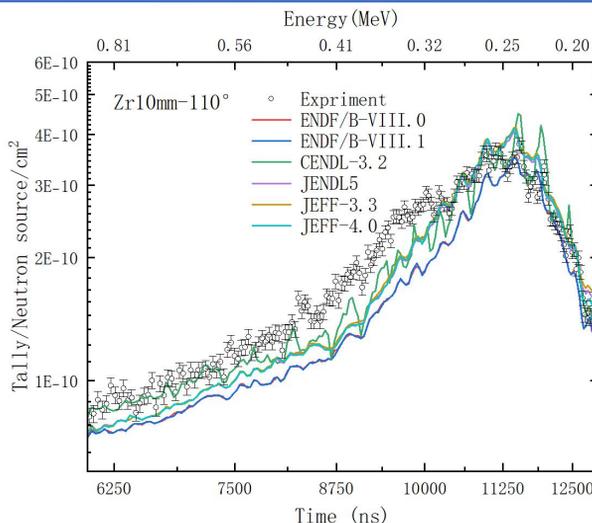
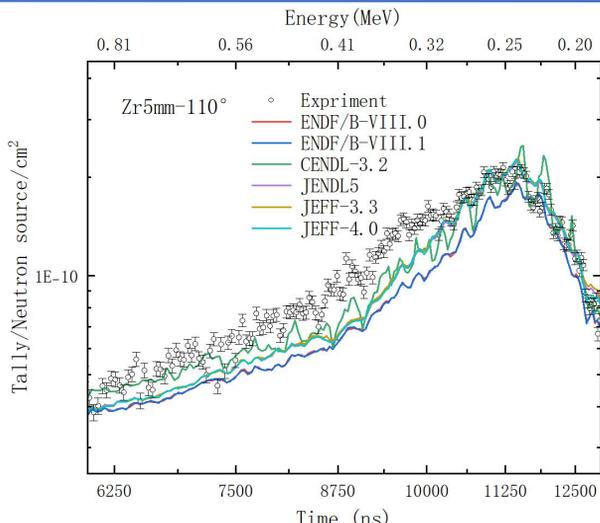
Zr-CLYC-30°结果



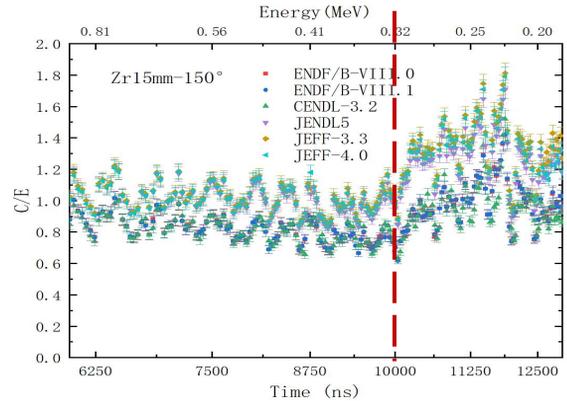
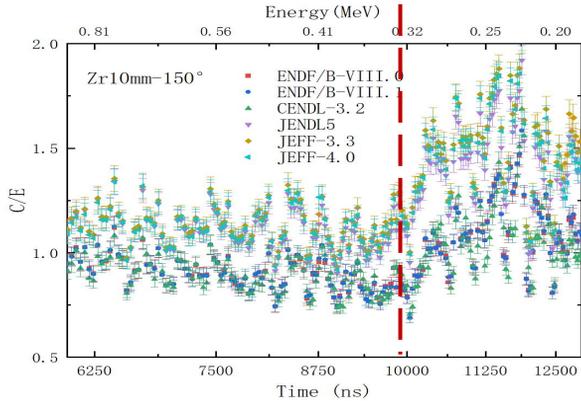
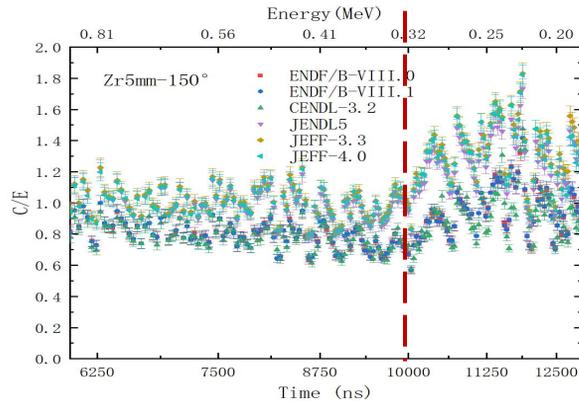
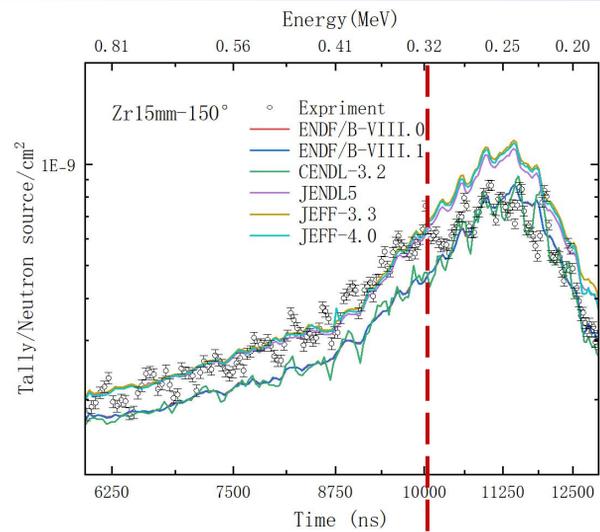
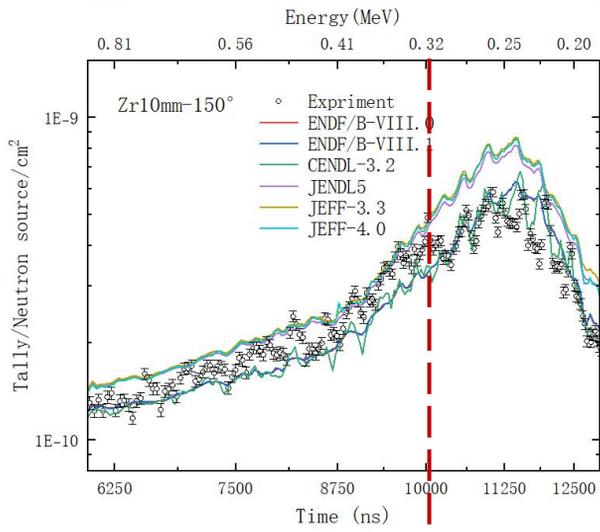
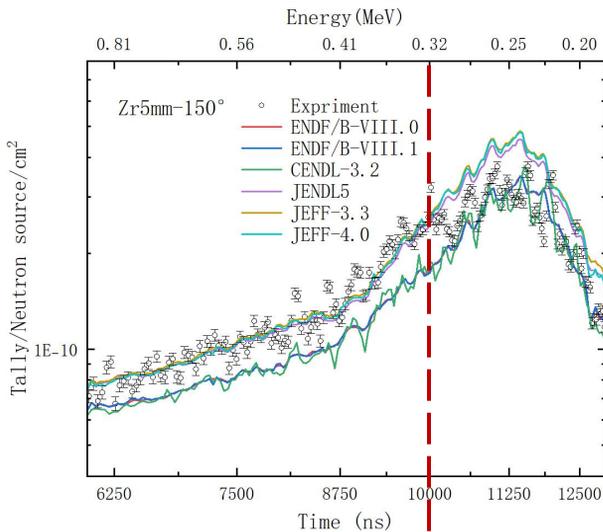
Zr-CLYC-70°结果



Zr-CLYC-110°结果

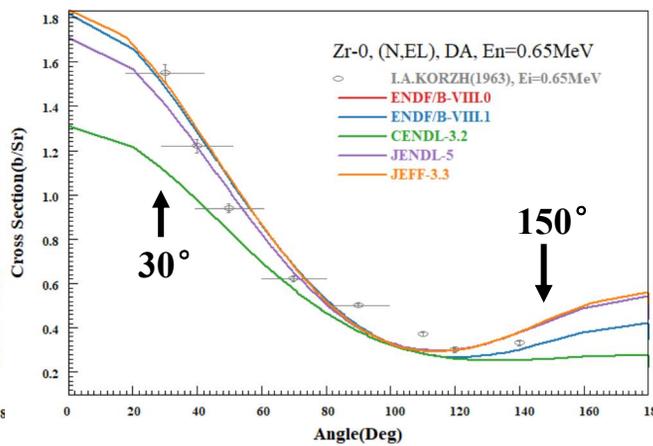
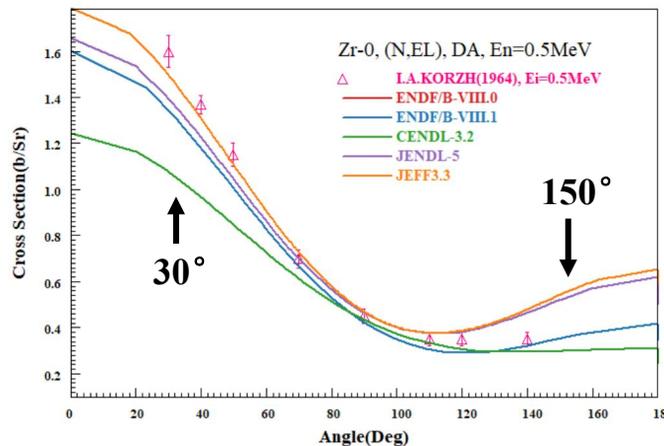
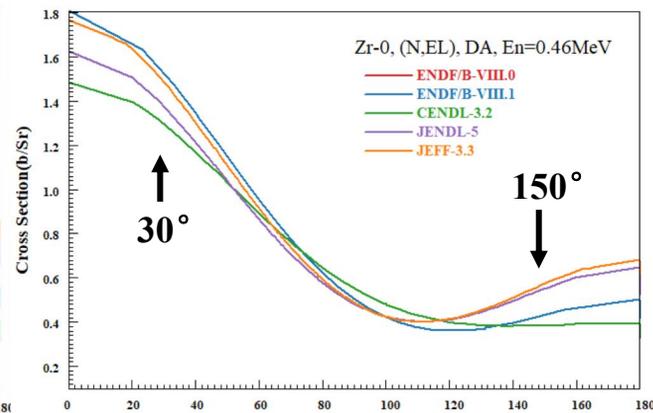
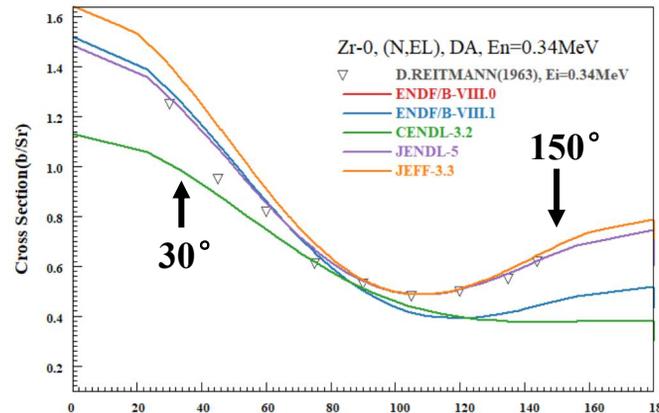


Zr-CLYC-150°结果



■ ^{nat}Zr 弹性散射角分布（低能区）

- 30° 方向，0.32MeV以上模拟结果CENDL-3.2库结果偏低。
- 150° 方向，0.32MeV以上模拟结果JENDL-5和JEFF-3.3库表现较好，CENDL-3.2、ENDF/B库结果偏低。



□ 对本次实验：

- 对双束团的影响进行评估后，对实验结果进一步分析。
- 在接近的角度和相应能区和RPI实验结果进行对比。

□ 下一步工作：

- 增加测量角度，提高探测器系统的测量能力，开展更多样品的测量。
- 期望获得可靠的源中子相关参数（ES2#- ϕ 30mm中子能谱，束斑，通量）。

感谢您的聆听与观看

