中国原子能科学研究院
中核集团 CNNC CHINA INSTITUTE OF ATOMIC ENERGY

石墨和锆样品准积分实验研究

丁琰琰，张时宇，聂阳波，潘欣怡，赵齐，徐阔之

核数据全国重点实验室，中国原子能科学研究院

2026.07.14-2026.07.16 CSNS反角白光中子实验装置（第十届）用户研讨会

目录

CONTENTS

01 研究背景及意义

准积分(微分) 实验

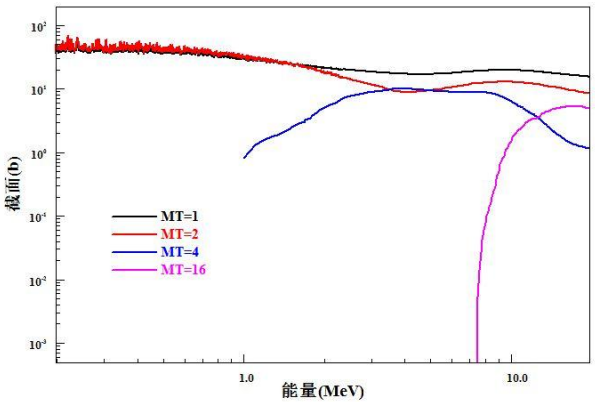


图3 中子与^{nat}Zr作用各反应道截面比较

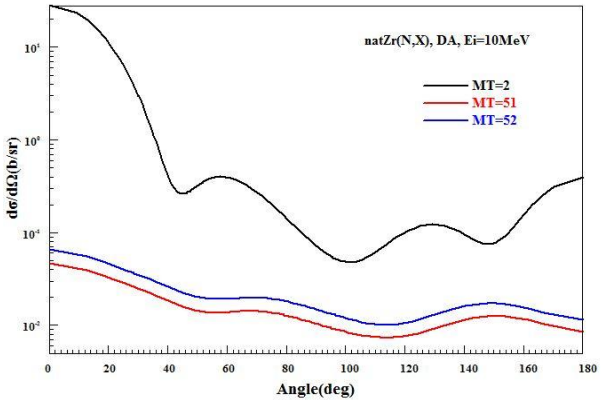
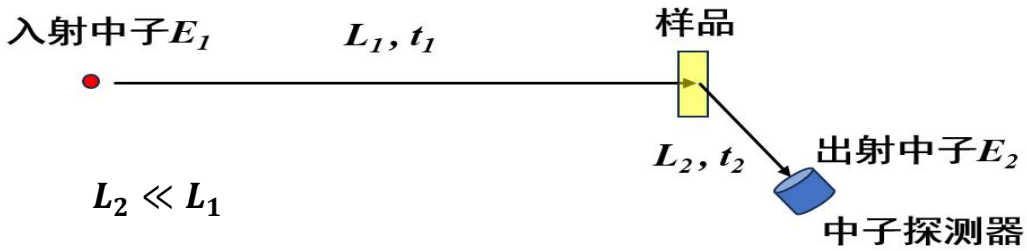


图4 中子与^{nat}Zr作用不同反应道角分布数据

■ 准积分（微分）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

Available online at www.sciencedirect.com
ScienceDirect
Nuclear Data Sheets 118 (2014) 1–25
ELSEVIER
Nuclear Data Sheets
www.elsevier.com/locate/nds

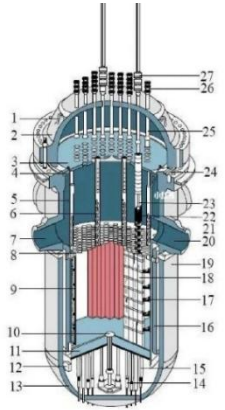
The CIELO Collaboration:
Neutron Reactions on ^{1}H, ^{16}O, ^{56}Fe, ^{235,238}U, and ^{239}Pu

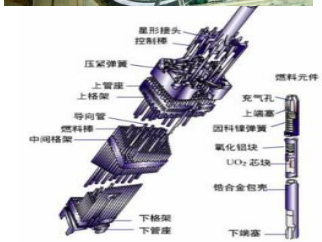
Recent "quasi-differential" measurements from RPI that are sensitive to elastic and inelastic scattering in ^{238}U provide useful guidance on how to improve the scattering cross sections. These data are from 0.5 up to 20 MeV incident energies. ENDF/B-VII does not in-

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

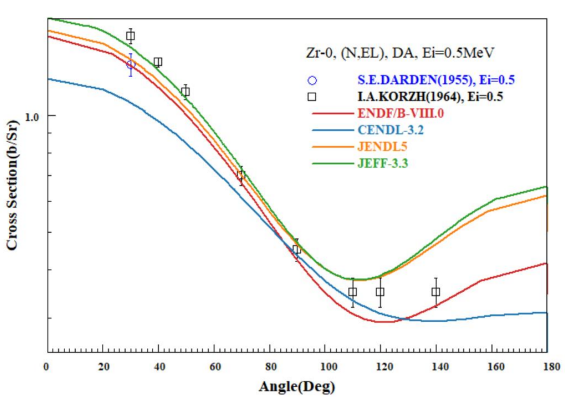
锆（Zr）在自然界中有^{90}Zr（51.45%）、^{91}Zr（11.22%）、^{92}Zr（17.15%）、^{94}Zr（17.38%）和^{96}Zr（2.80%）五种稳定同位素

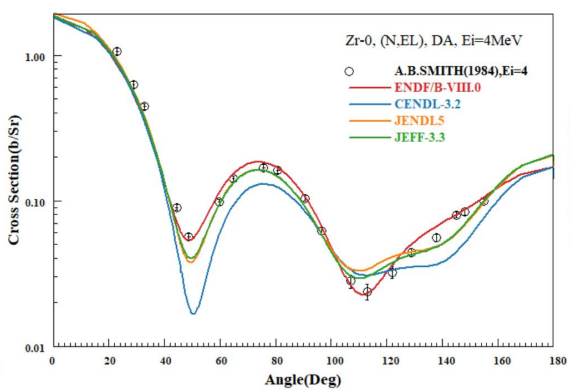
- 锆及其合金材料广泛应用于核工业
- 了解Zr散射中子截面数据的可靠性，对反应堆设计研发工作具有重要指导意义

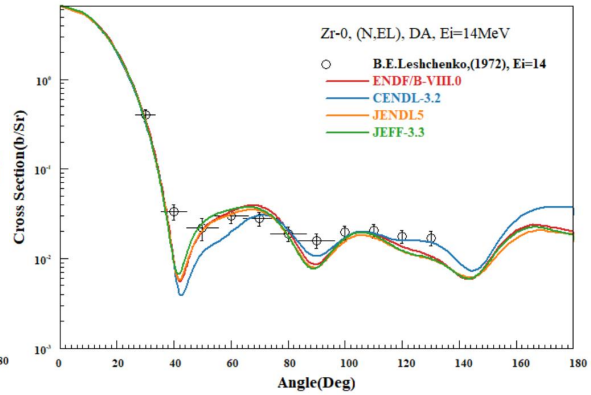




■ 现有评价核数据库中Zr的评价数据存在分歧







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）

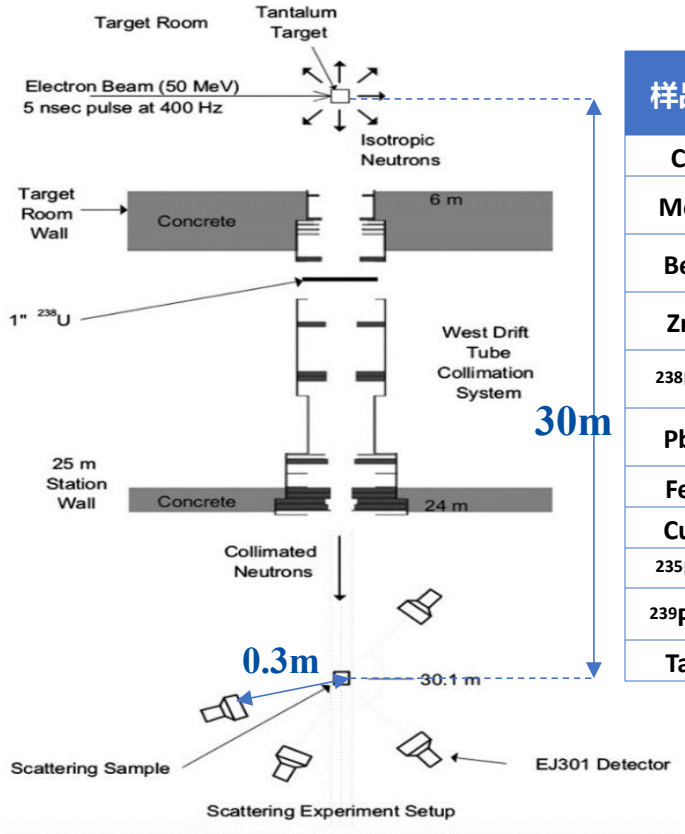


图6 RPI准积分实验布局

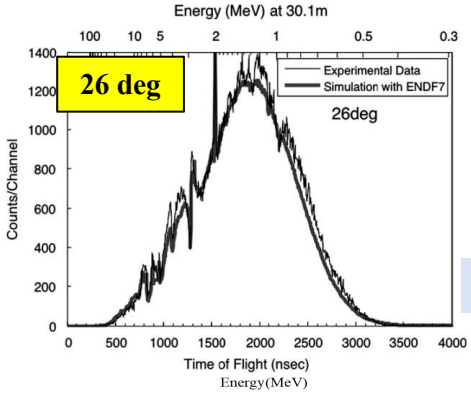
表1 RPI已开展的准积分实验情况

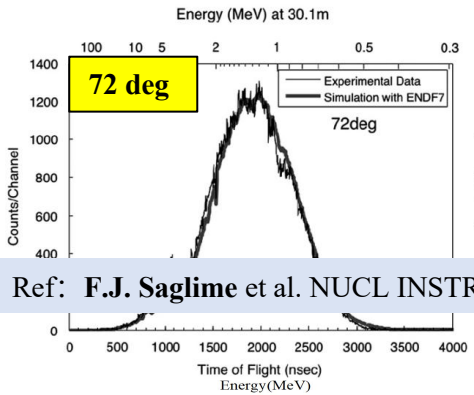
样品	直径/边长 (cm)	厚度 (cm)	距中子源距离 (m)	测量能区 (MeV)	测量角度（°）
C	7.49	7	30.1	0.5-20	26, 52, 72, 90, 107, 119, 140, 154
Mo	7.6	5, 8	30.07	0.5-20	26, 52, 72, 90, 107, 119, 140, 154
Be	7.5	4, 8	30.1	0.5-20	26,52,73,90,108,118,140,154
Zr	7.6	6	30.07	0.5-20	26, 52, 72, 90, 107, 119, 140, 154
^{238}U	7.6	0.98	30.07	0.5-20	27, 29, 60, 77, 112, 113, 130, 153,156
Pb	-	3, 5	30.07	0.5-20	30,45,60,70,100,110,150
Fe	15.25×3.85	7.7	30.07	0.5-20	30,45,60,77, 109,111, 130,153,156
Cu	7.6	2.99	30.07	0.002-20	26,31,52,73,90,119,141,154
^{235}U	2.26,1.9	0.889	21.5	0.82-20	30,75,90,150
^{239}Pu	2.55	0.307	21.5	0.82-20	30,75,90,150
Ta	7.6	5.5	30.07	0.65-20	30,45,60,95,110,125,150

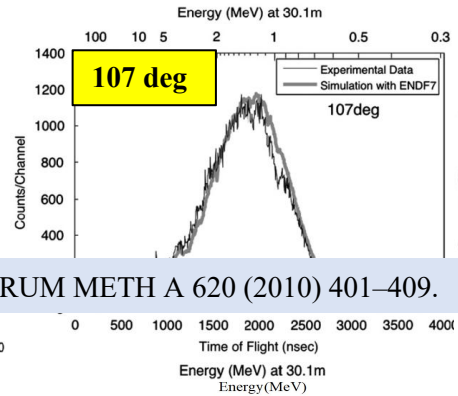
- ^{238}U准积分实验数据用于CIELO项目^{238}U数据的评价。
  Ref: **R.Capote** et al. Nuclear Data Sheets 148 (2018) 254–292.
- Be准积分实验数据用于美国ENDF/B-VIII.0库Be数据的评价。
  Ref: **D.A.Brown** et al. Nuclear Data Sheets 148 (2018) 1–142.

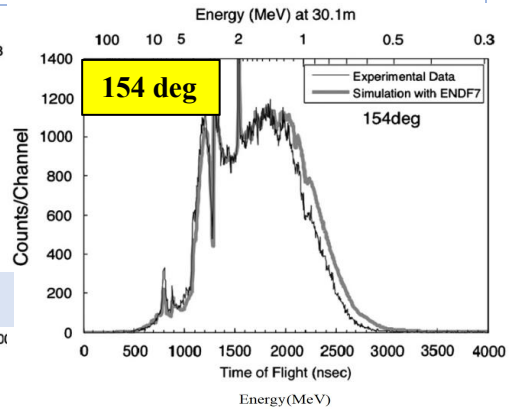
■ RPI&CIAE 石墨准积分实验结果

实验室	样品厚度/cm	测量角度	测量能区/MeV	探测器
CIAE	2	30，70，110，150	0.03-30	BC501A，CLYC
RPI	7	26, 52, 72, 90, 107, 119, 140, 154	0.5-20	EJ301

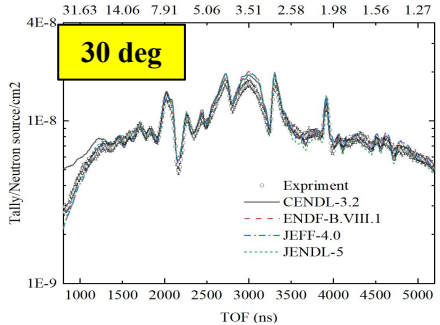


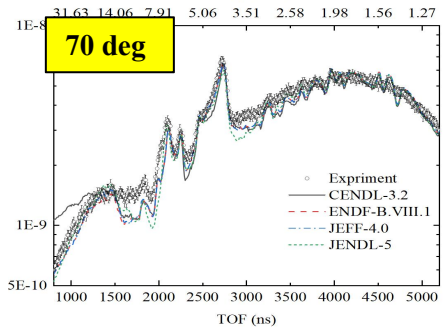


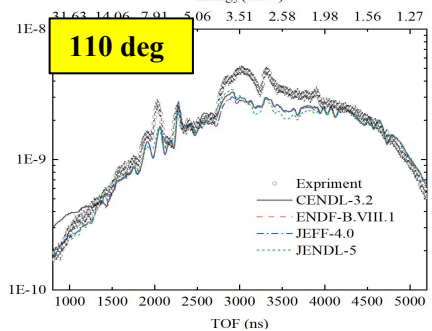


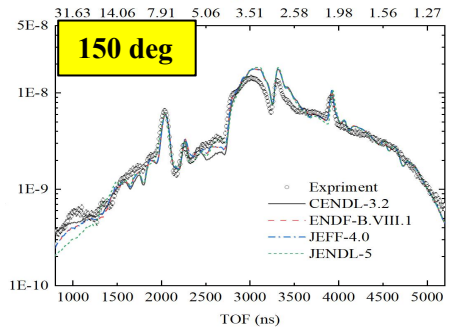


Ref：**F.J. Saglime** et al. NUCL INSTRUM METH A 620 (2010) 401–409.



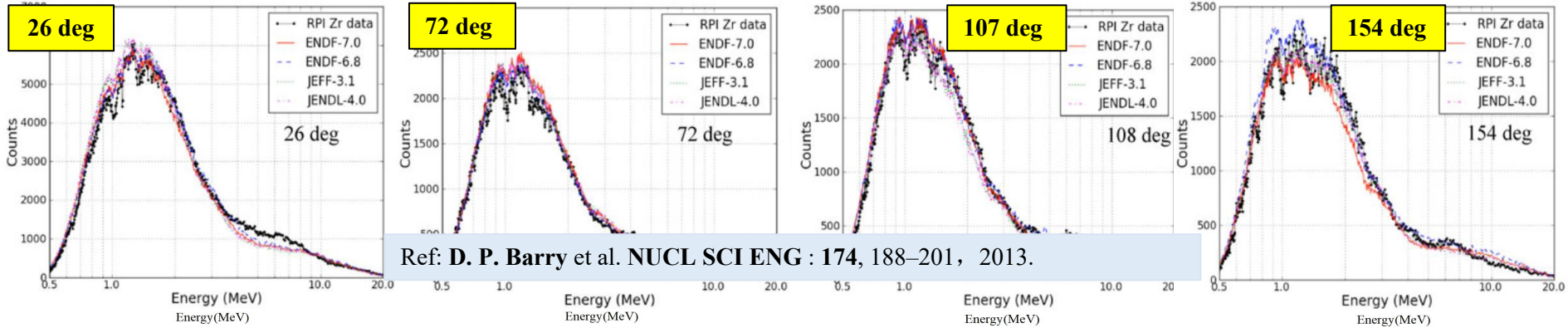




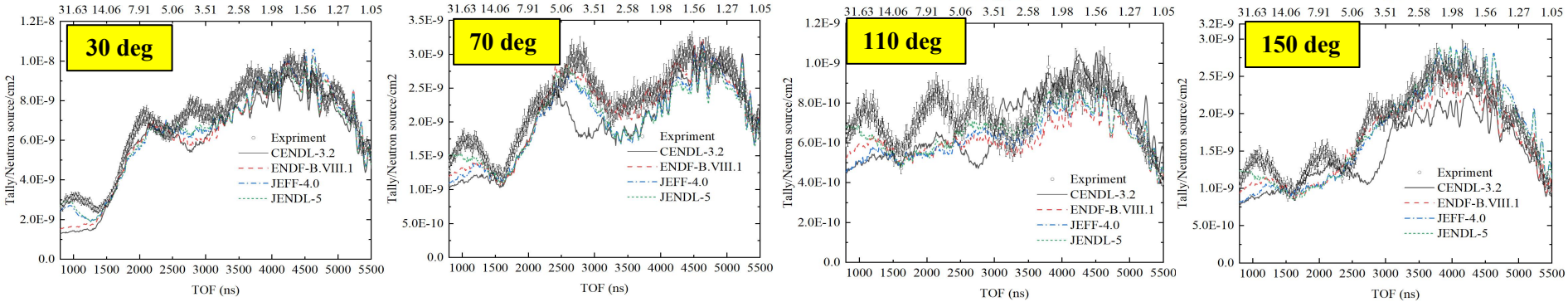


■ RPI Zr样品准积分实验结果

实验室	样品厚度/cm	测量角度	测量能区/MeV	探测器
CIAE	0.5，1，1.5	30，70，110，150	0.03-30	BC501A，CLYC
RPI	6，10	26, 52, 72, 90, 107, 119, 140, 154	0.5-20	EJ301



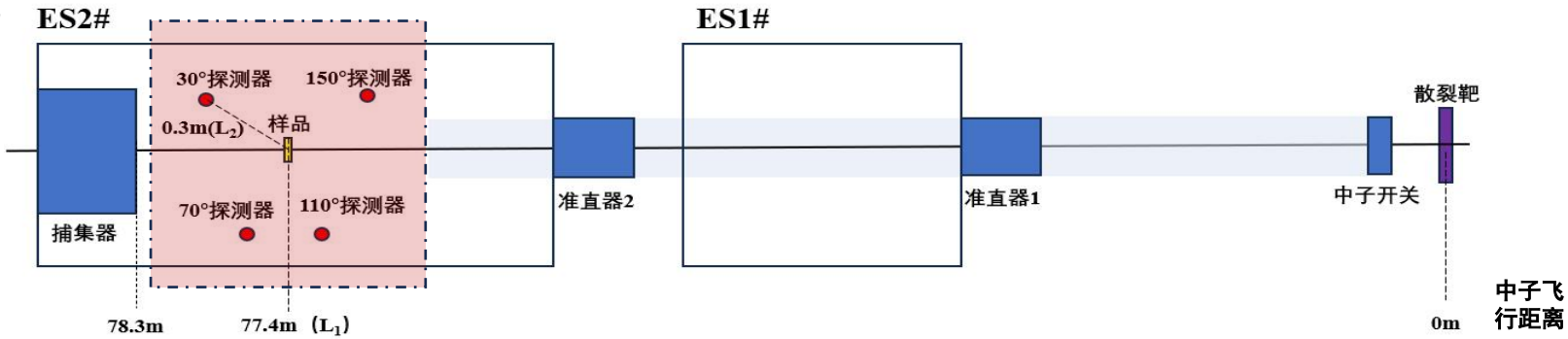
Ref: **D. P. Barry** et al. **NUCL SCI ENG** : **174**, 188–201，2013.



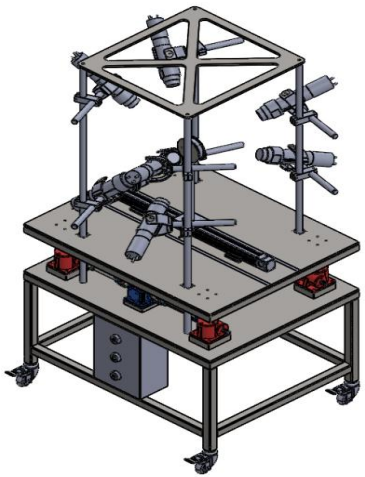
03 CIAE准积分实验

CIAE准积分实验系统

■ 实验布局



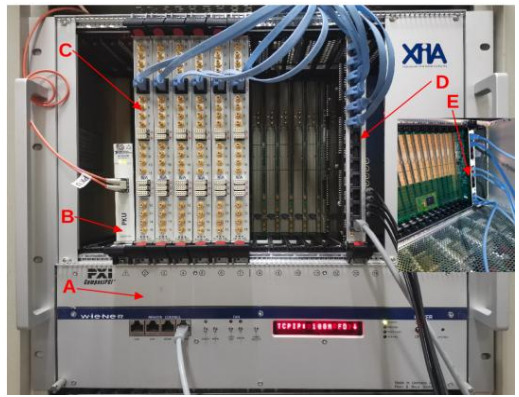
■ 测量平台设计加工



■ 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（MeV）	0.8-30	0.03-1

■ 数据采集系统



2024年实验情况

- 测量位置：厅2
- 束流功率：160kW，束斑：ϕ30mm
- 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	Φ25	20	0.68	0.25
锆	Φ25	5	0.2	0.07
		10	0.4	0.14
		15	0.6	0.21

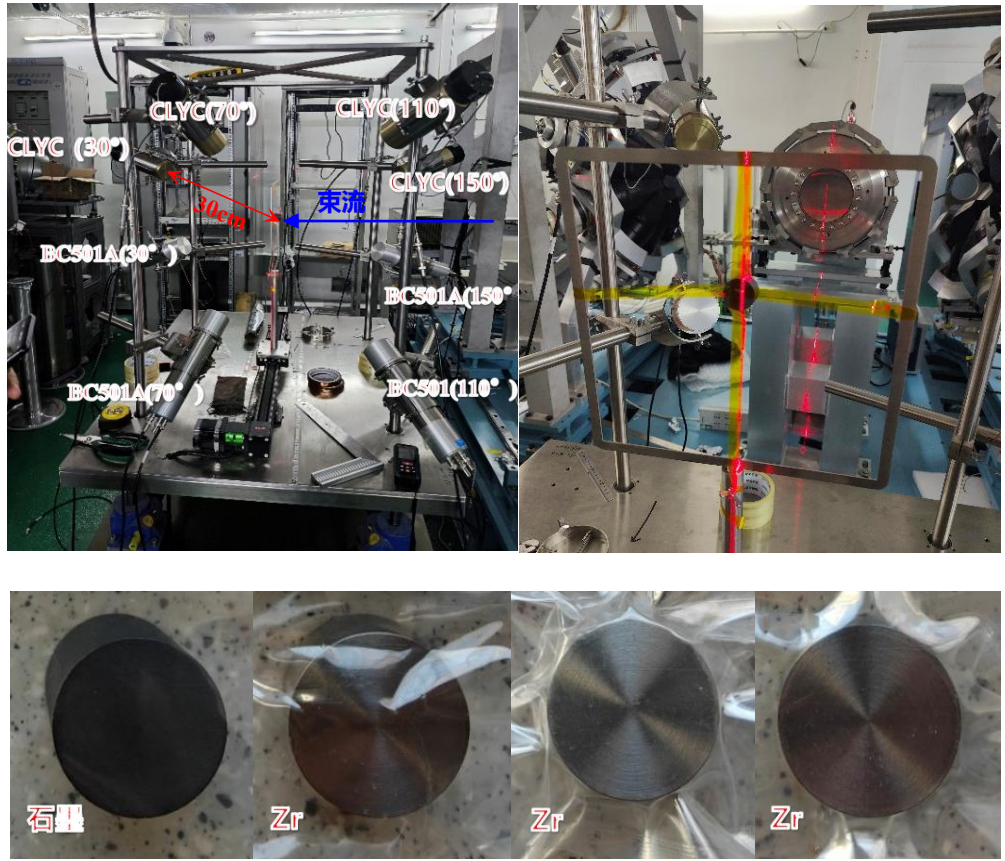


图9 石墨和Zr样品

准积分实验模拟计算

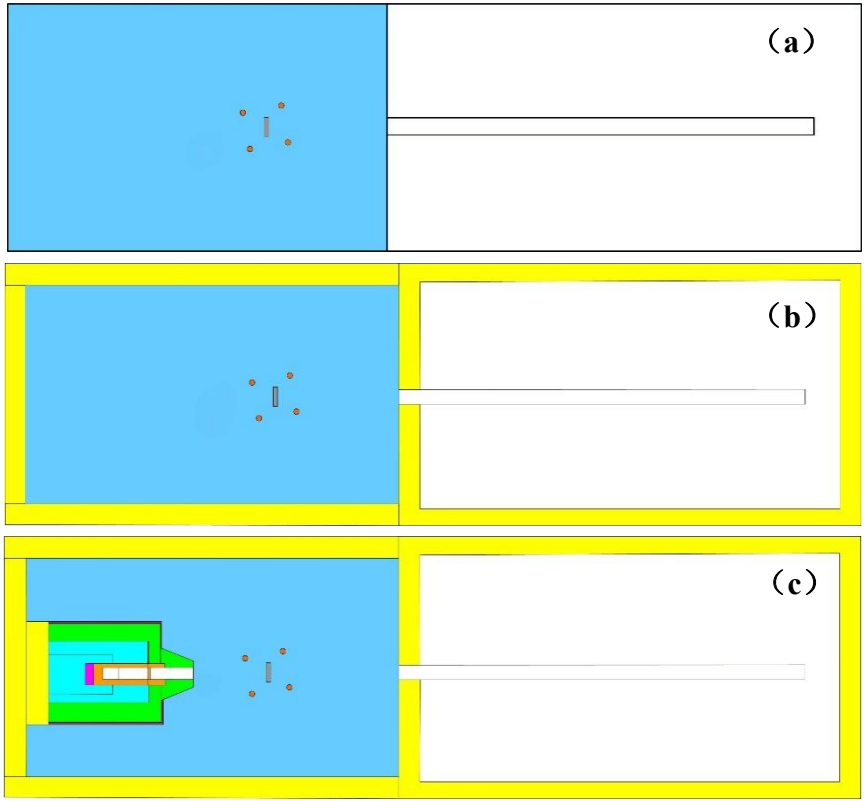
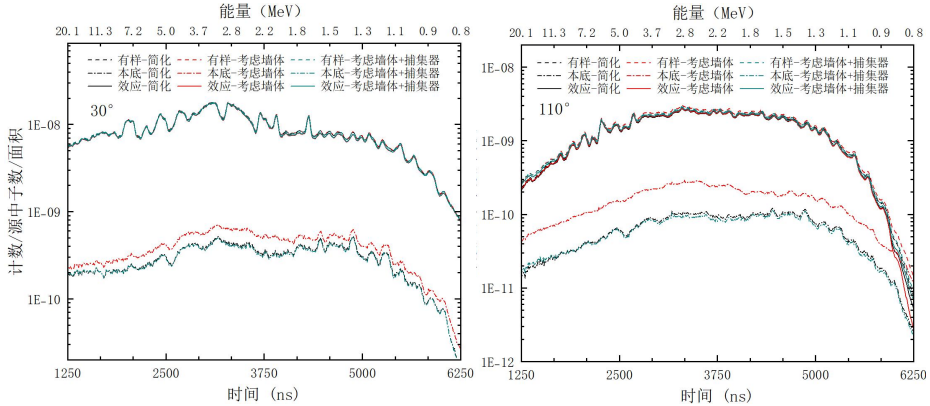


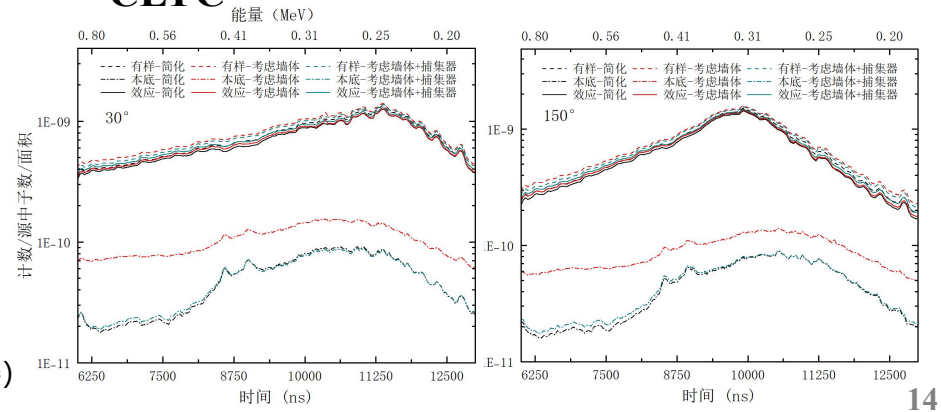
图10 MCNP模拟几何模型

（a）简化模型；（b）简化模型（墙体）；（c）复杂模型（墙体+捕集器）

- 液闪



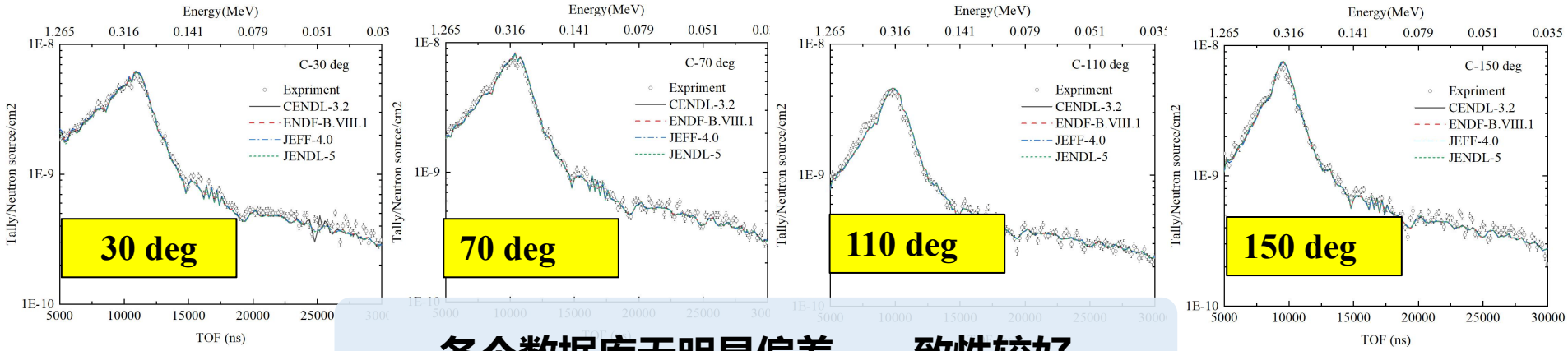
- CLYC



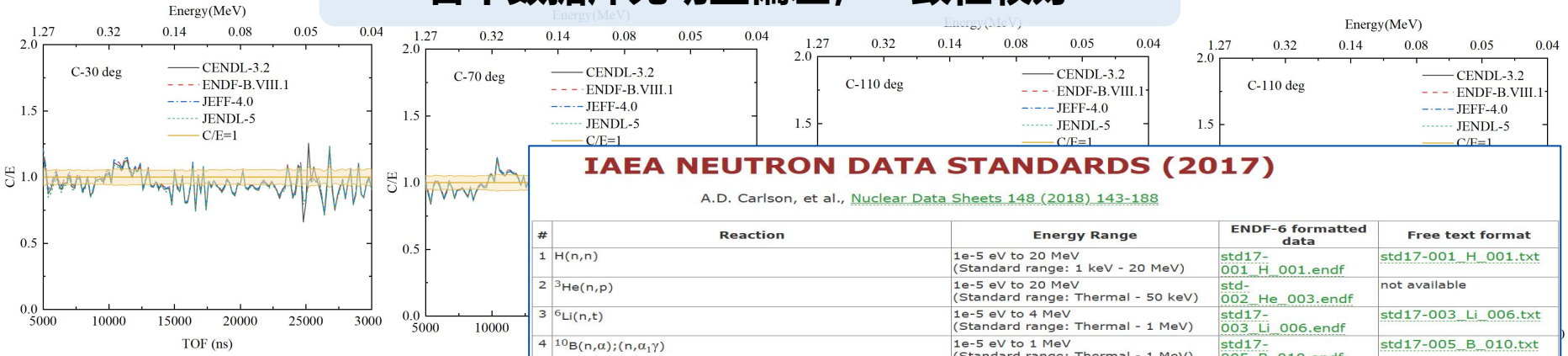
04 石墨、Zr结果分析与讨论

石墨-CLYC结果

中国原子能科学研究院
中核集团 CNNC CHINA INSTITUTE OF ATOMIC ENERGY



各个数据库无明显偏差，一致性较好



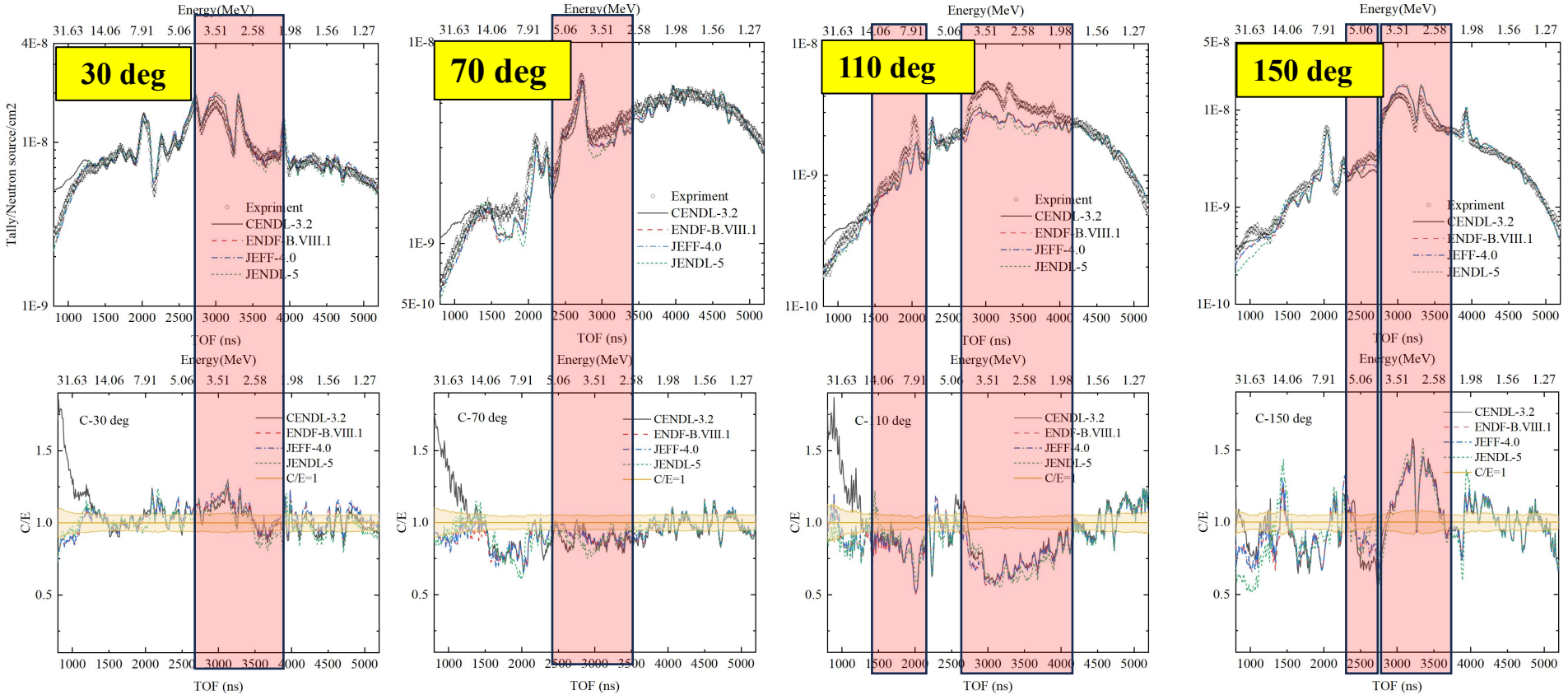
IAEA NEUTRON DATA STANDARDS (2017)

A.D. Carlson, et al., Nuclear Data Sheets 148 (2018) 143-188

#	Reaction	Energy Range	ENDF-6 formatted data	Free text format
1	H(n,n)	1e-5 eV to 20 MeV (Standard range: 1 keV - 20 MeV)	std17-001_H_001.endf	std17-001_H_001.txt
2	^{3}He(n,p)	1e-5 eV to 20 MeV (Standard range: Thermal - 50 keV)	std-002_He_003.endf	not available
3	^{6}Li(n,t)	1e-5 eV to 4 MeV (Standard range: Thermal - 1 MeV)	std17-003_Li_006.endf	std17-003_Li_006.txt
4	^{10}B(n,α);(n,α$_1$γ)	1e-5 eV to 1 MeV (Standard range: Thermal - 1 MeV)	std17-005_B_010.endf	std17-005_B_010.txt
5	^{nat}C(n,n)	up to 6.45 MeV (Standard range: 1keV - 1.8 MeV, angular distribution standard)	std17-006_C_000.endf	std17-006_C_000.txt

石墨-BC501A结果

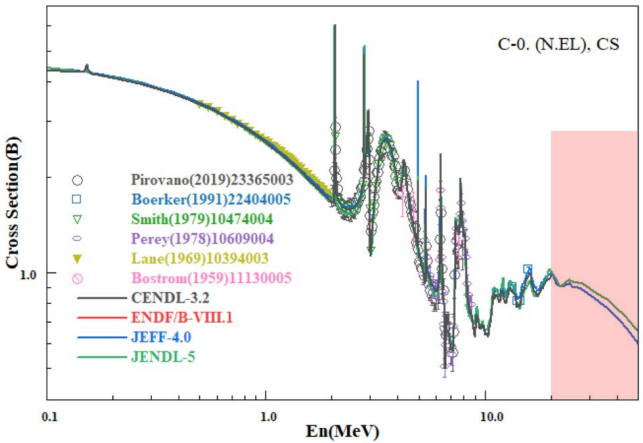
中国原子能科学研究院
中核集团 CNNC CHINA INSTITUTE OF ATOMIC ENERGY

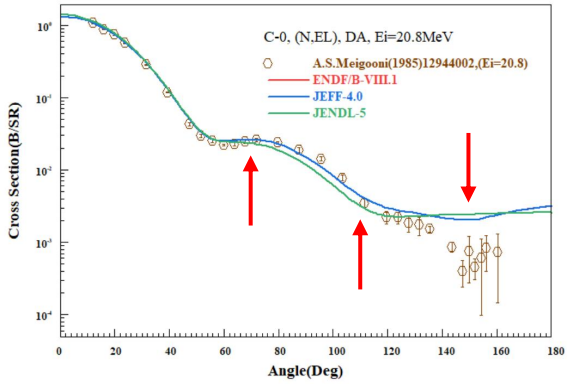


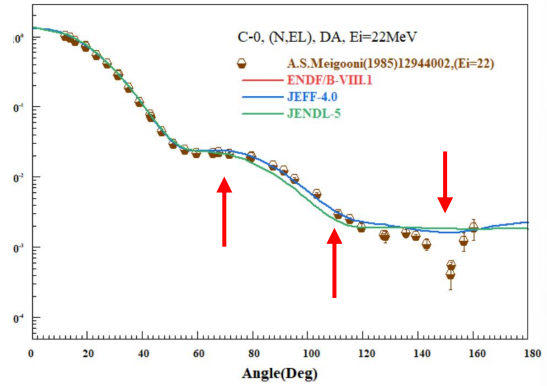
石墨-BC501A分析讨论

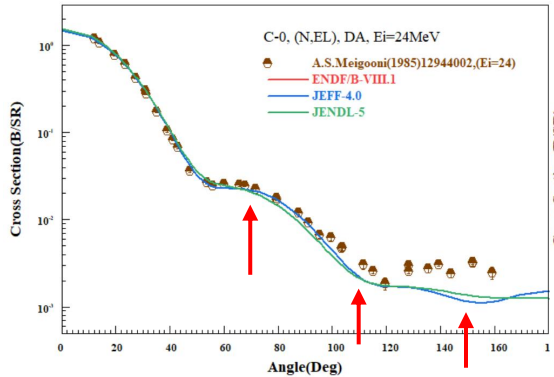
■ 石墨散射中子谱（20-30MeV）

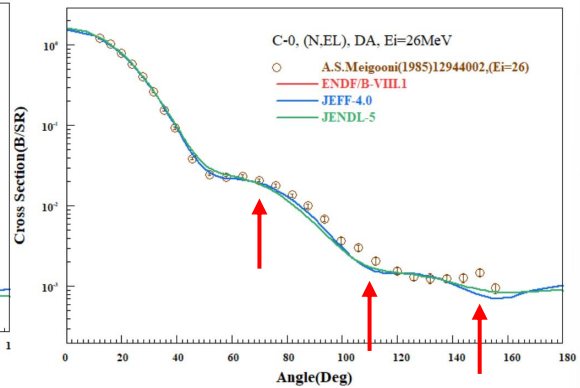
- CENDL-3.2库在30°、70°、110°方向存在明显高估情况。
- ENDF/B-VIII.1、JEFF-4.0库的计算结果在四个角度存在低估情况。





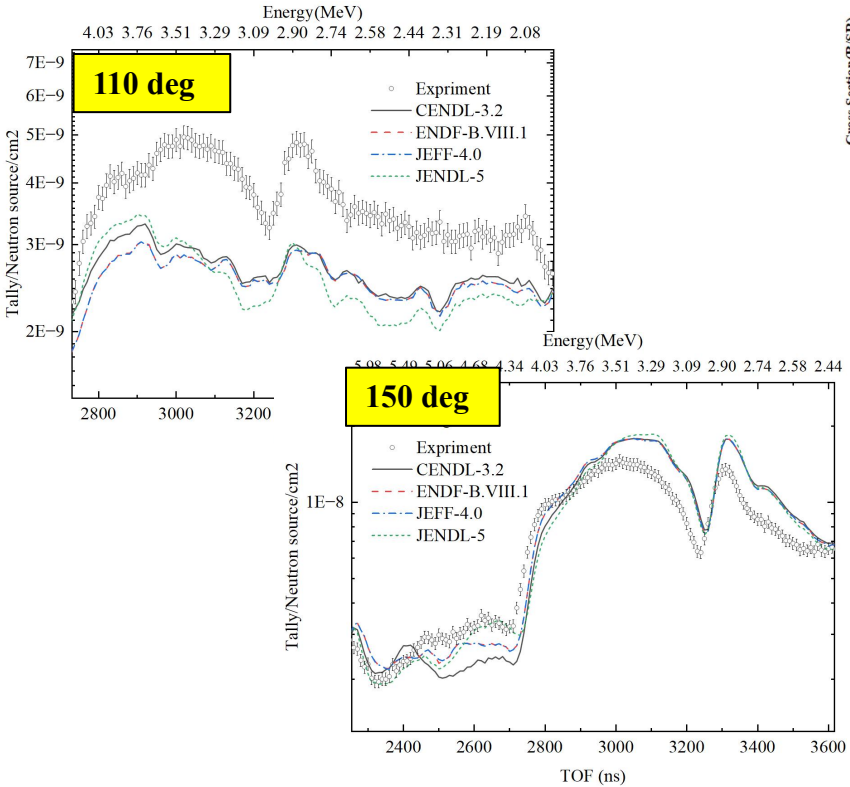


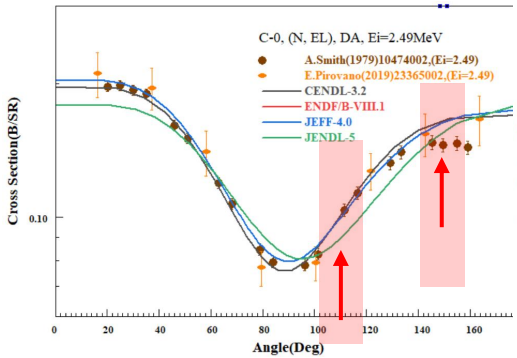


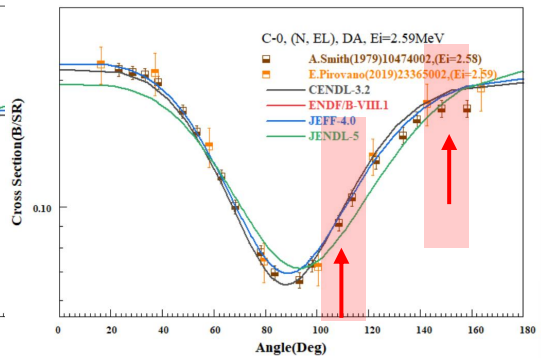


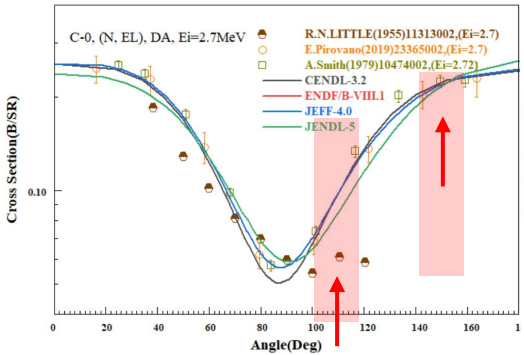
■ 石墨散射中子谱（2.0-4.0MeV）

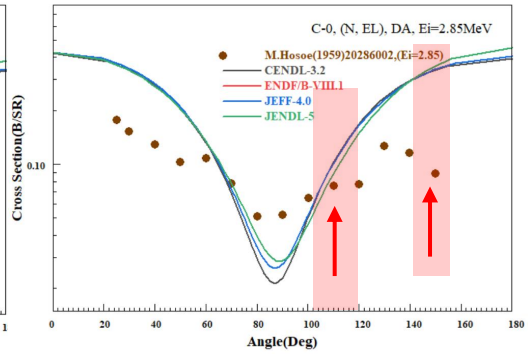
- 110°方向，不同数据库存在低估情况。
- 150°方向，不同数据库存在高估情况。





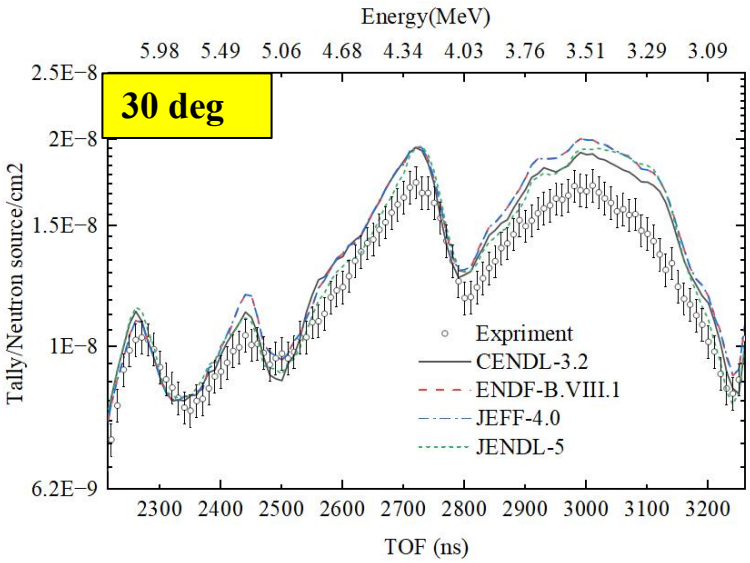


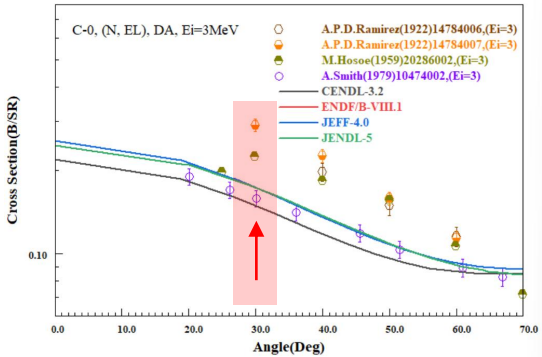


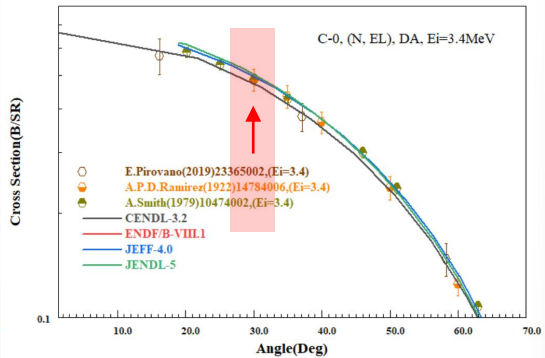


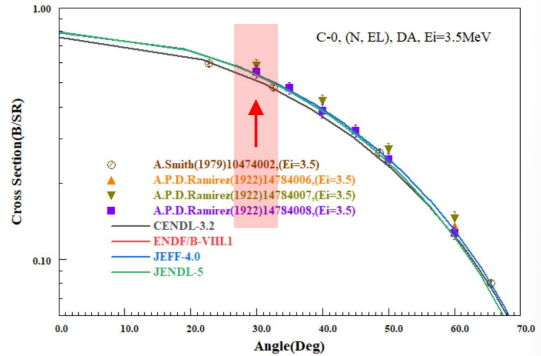
■ 石墨散射中子谱（3.0-5.0MeV）

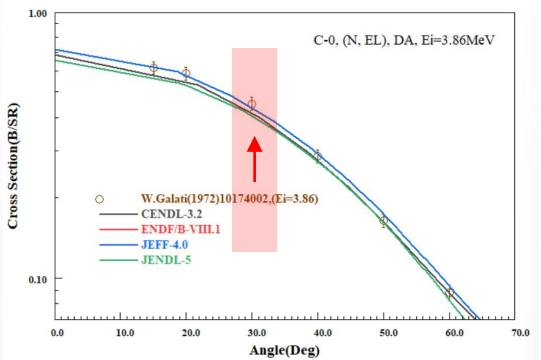
- **30°方向，**不同数据库存在高估情况，3-4MeV能区ENDF/B-VIII.1和JEFF-4.0库高估更明显。





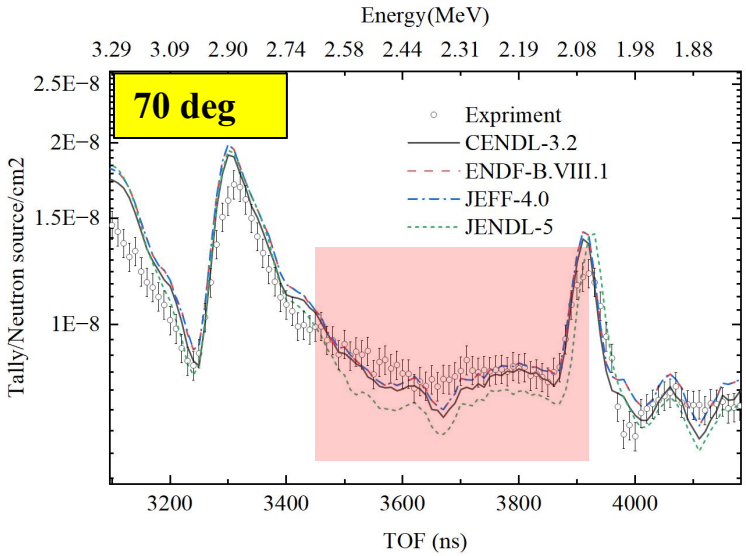


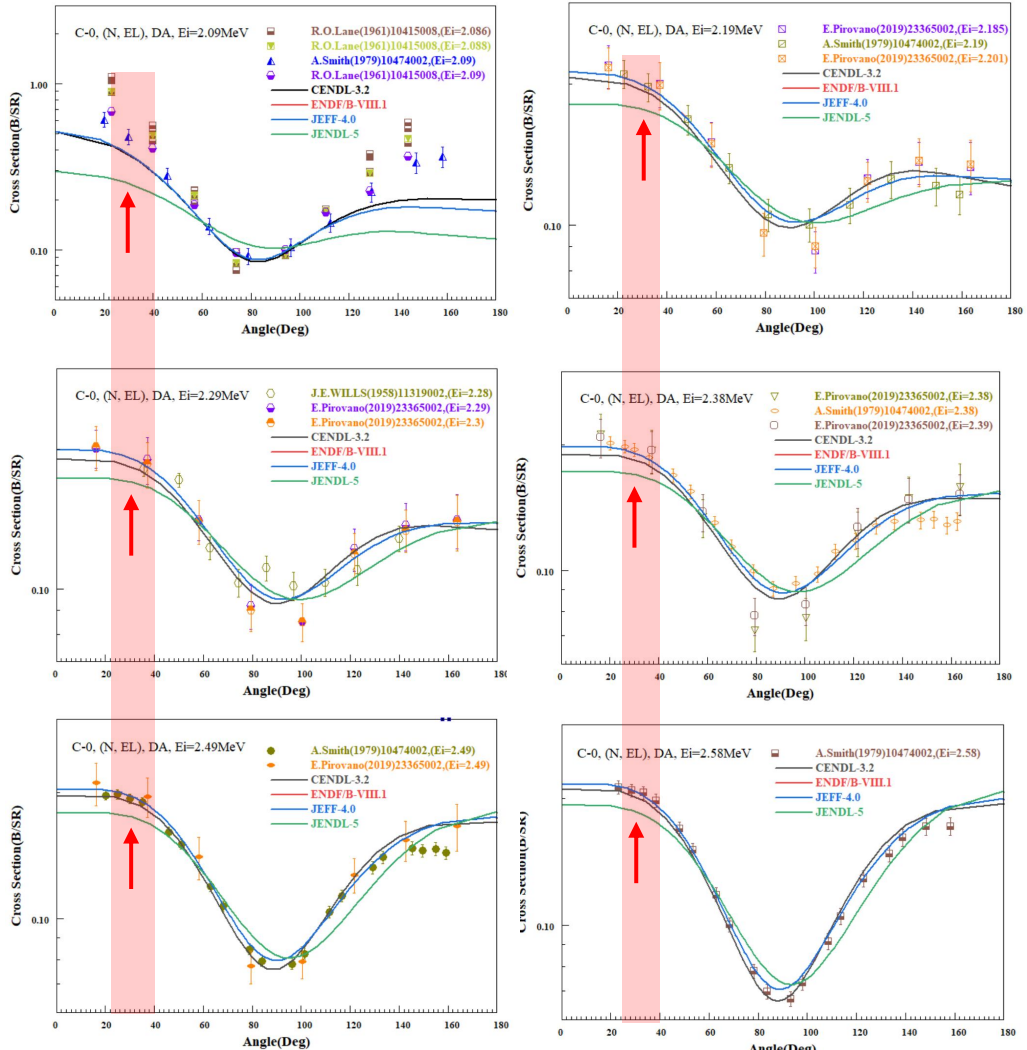




■ 30°方向石墨散射中子谱

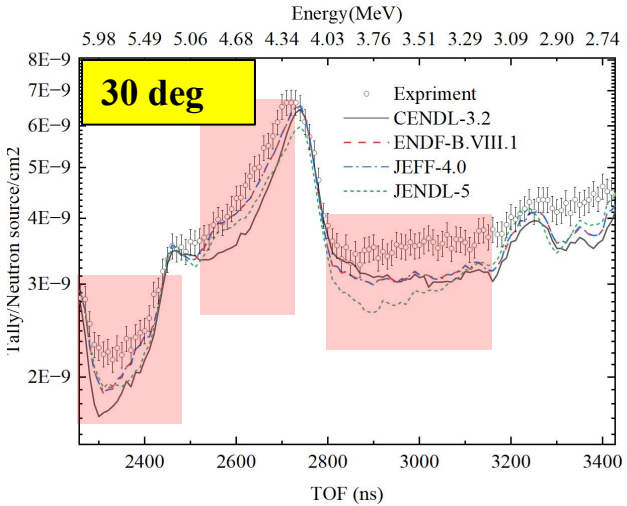
- 在2.09-2.6MeV能区，JENDL-5库模拟结果明显低于实验结果和其他数据库的模拟结果。

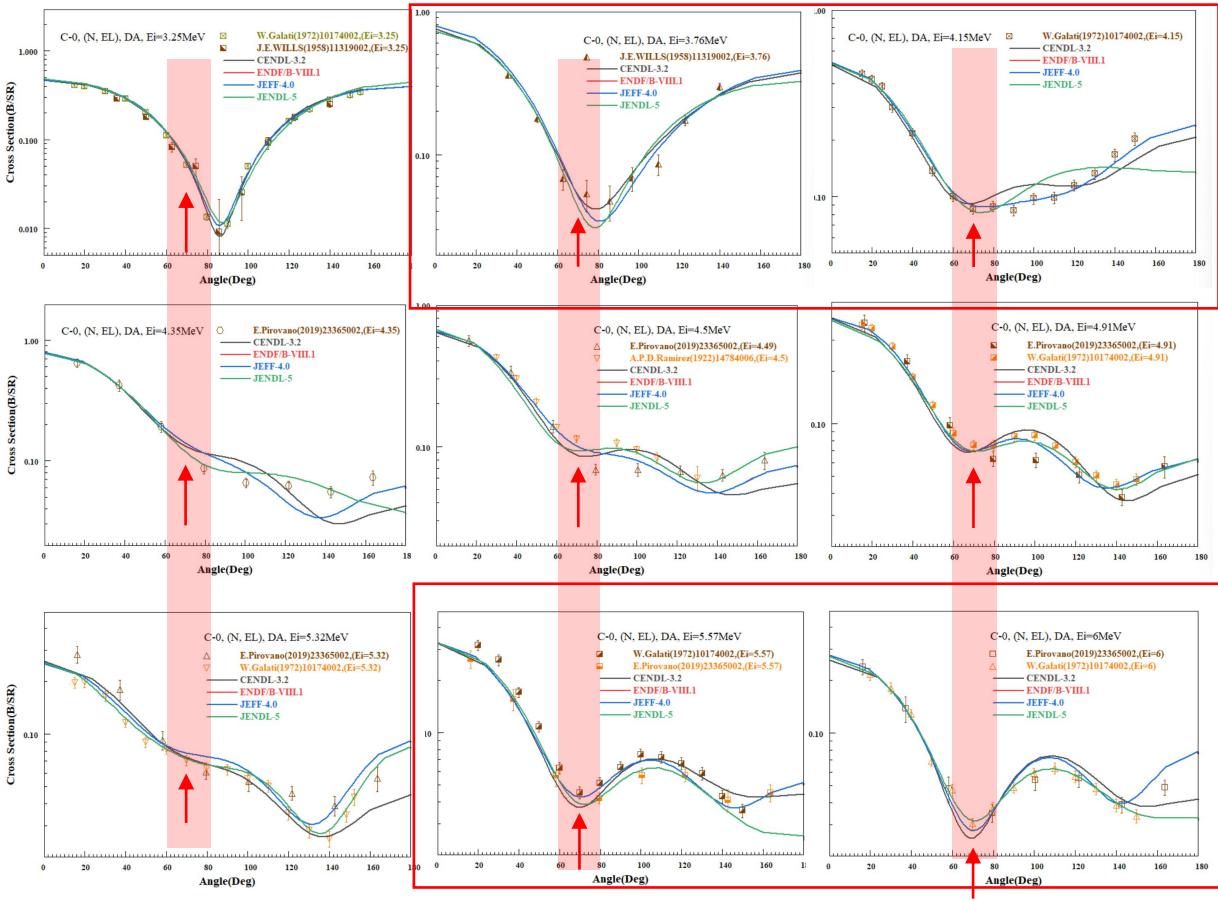




■ 70°方向石墨散射中子谱

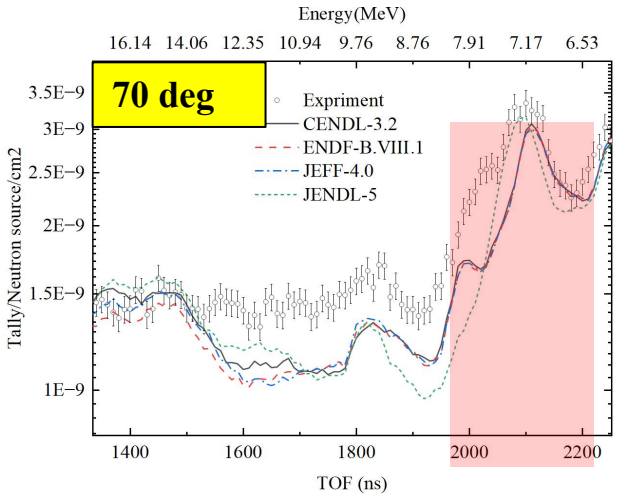
- 3.1-6.1MeV，不同数据库均存在低估情况。
- JENDL-5在3.5-4MeV能区低估尤其明显。
- CENDL-3.2库在4.5-5MeV、5.5-6.1MeV低估明显。

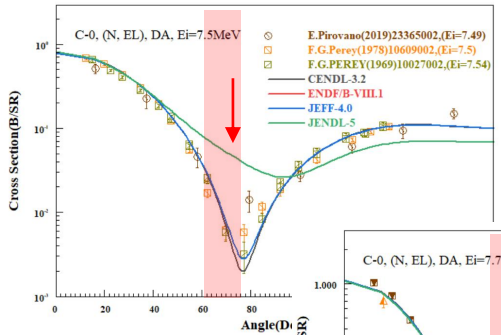


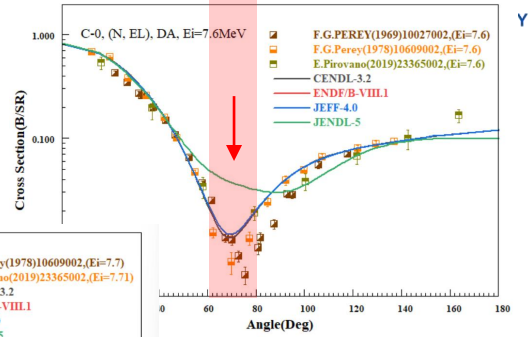


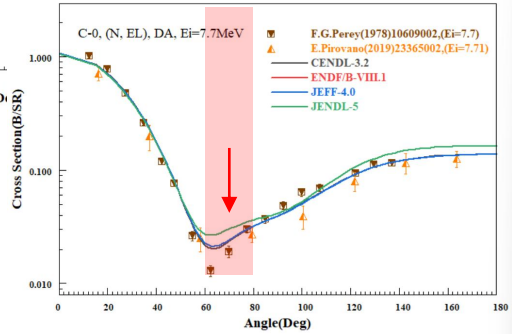
■ 70°方向石墨散射中子谱

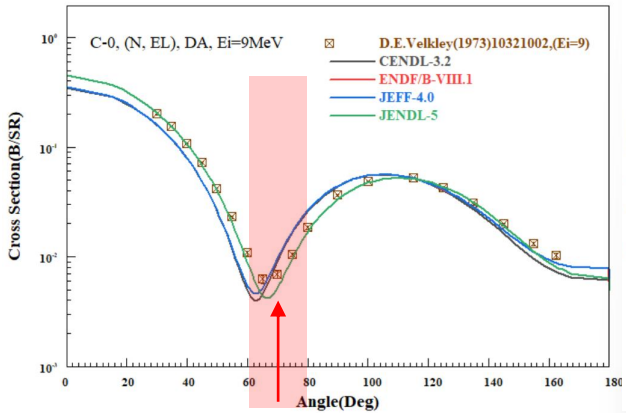
- 7.6-14MeV，不同数据库模拟结果低于实验结果，其中JENDL-5在7.7-9.8MeV能区低估尤其明显。

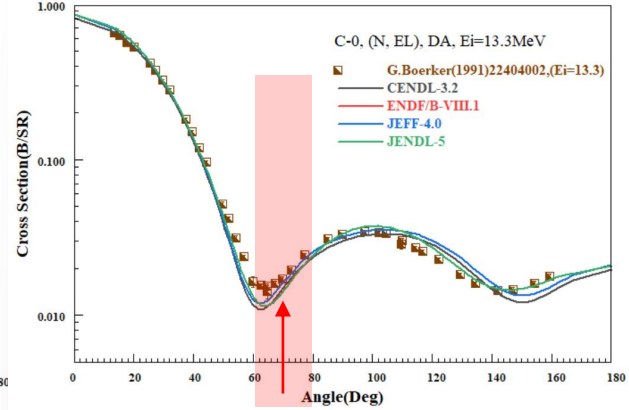






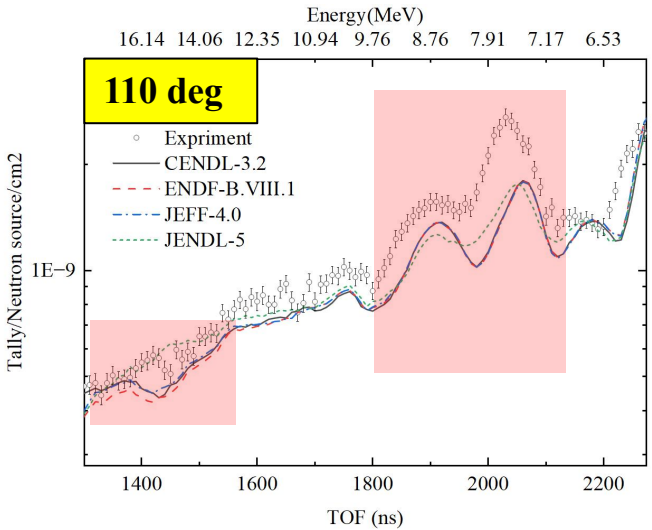


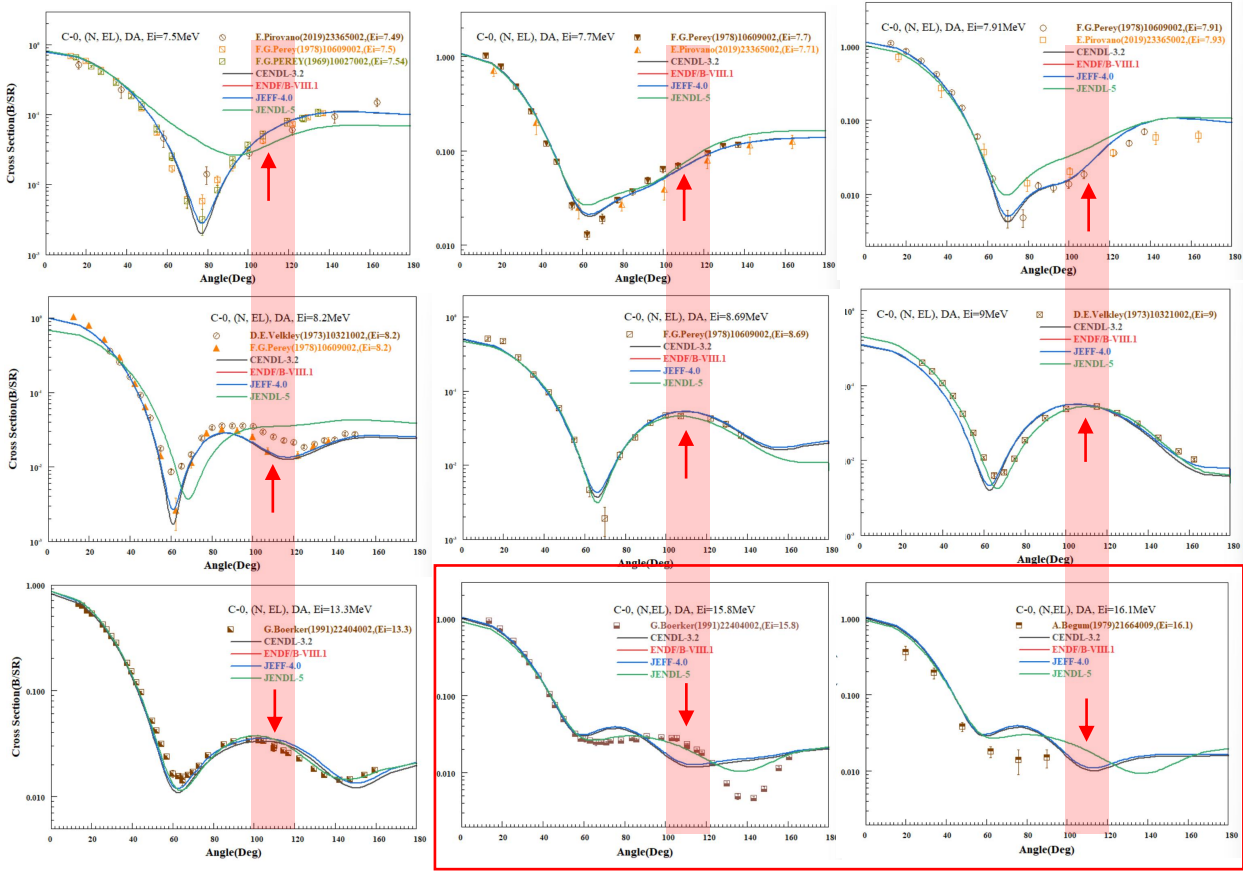




■ 110°方向石墨散射中子谱

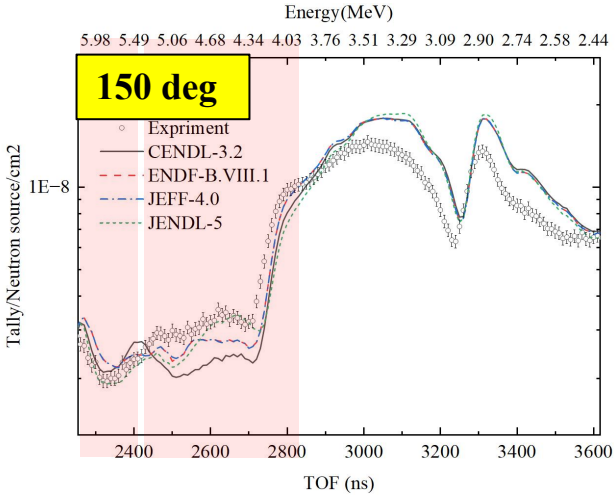
- 7.2-14MeV能区，不同数据库均存在低估情况，其中JENDL-5在7.2-9.8MeV的预测结果明显不同于其他数据库。

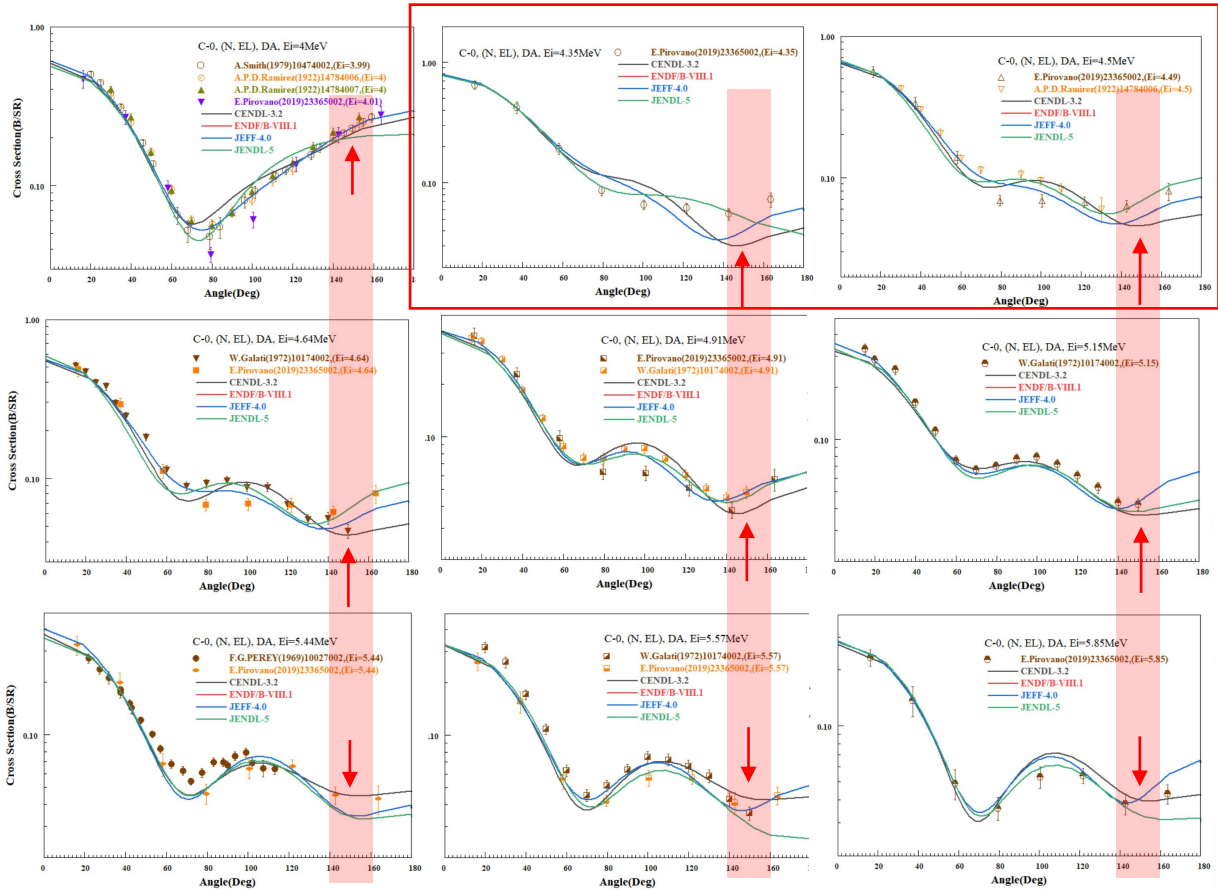




■ 150°方向石墨散射中子谱

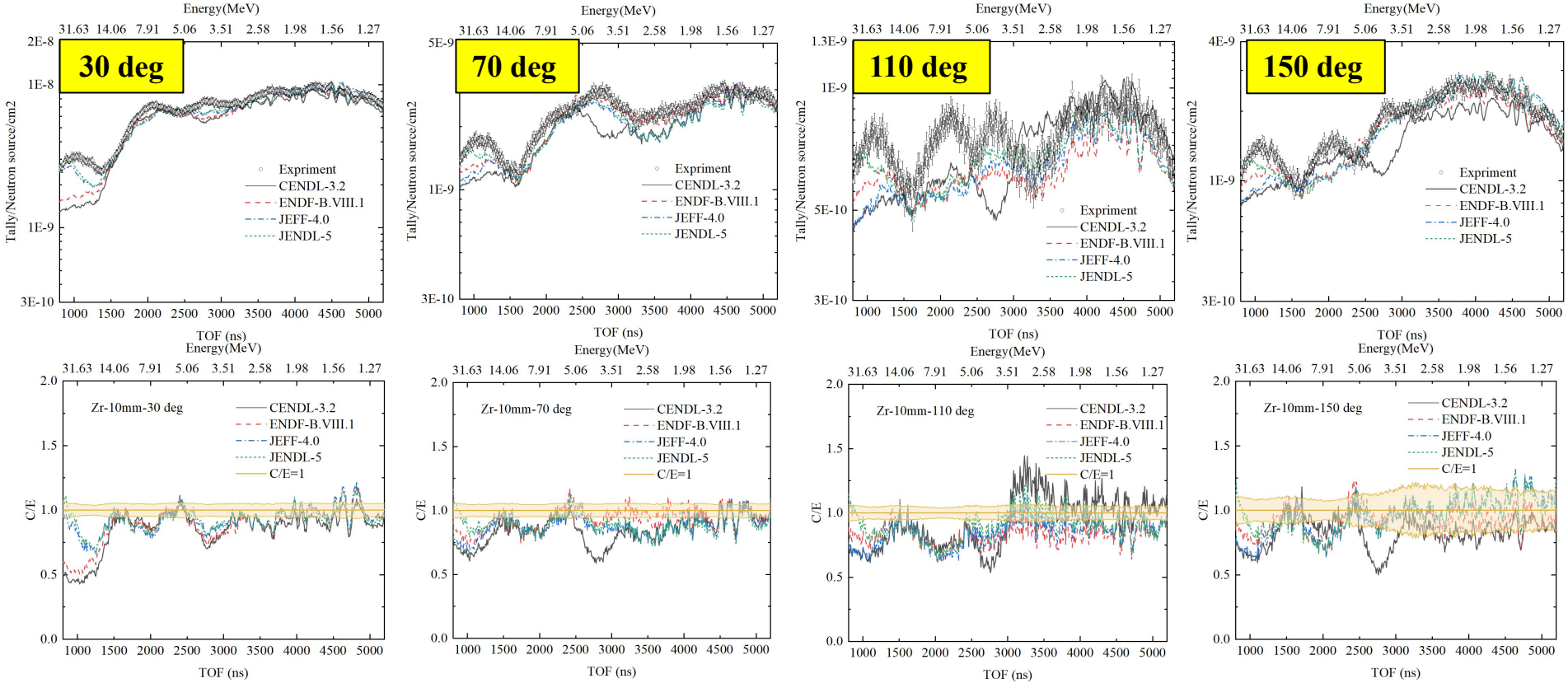
- 3.9-5.5MeV，不同数据库存在低估情况，其中CENDL-3.2库在4.3-5.3MeV低估现象更明显。
- 5.3-5.7MeV，CENDL-3.2库高估。5.7-6MeV，ENDF/B-VIII.1和JEFF-4.0库高估。



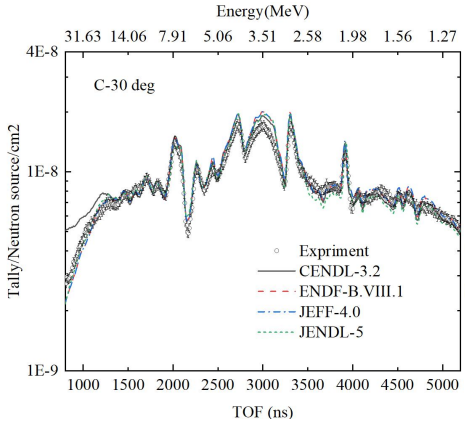


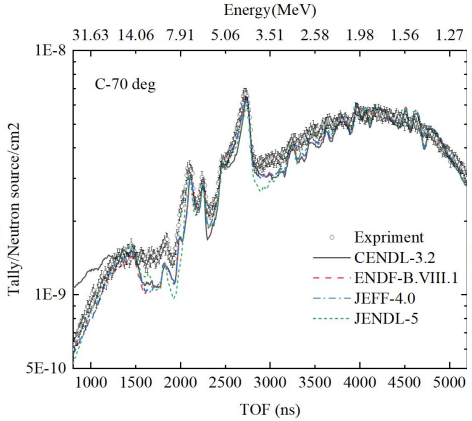
Zr-10mm-BC501A结果

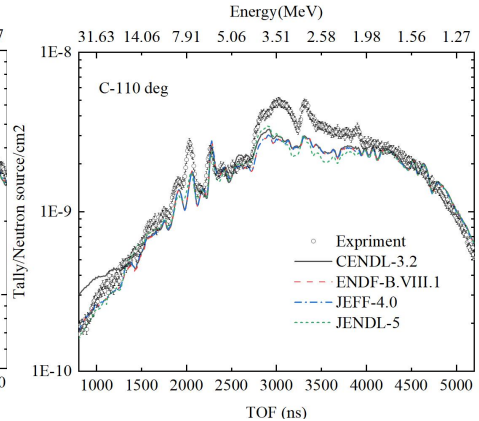
中国原子能科学研究院
中核集团 CNNC CHINA INSTITUTE OF ATOMIC ENERGY

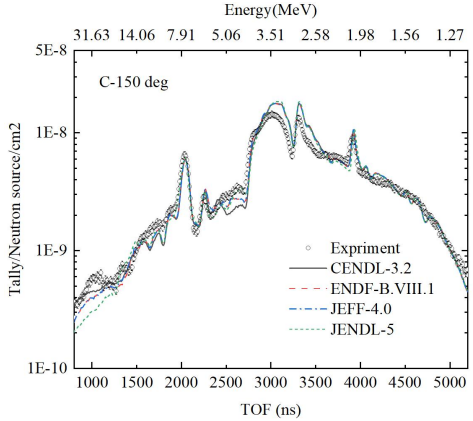


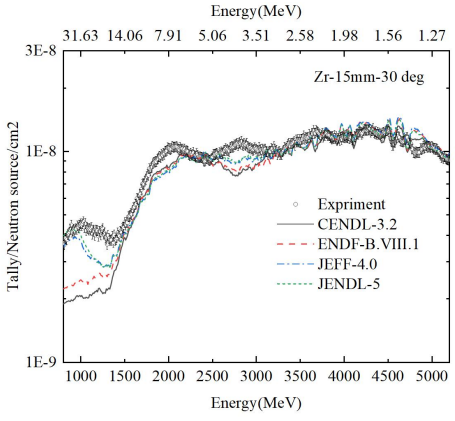
BC501A探测器系统性偏差

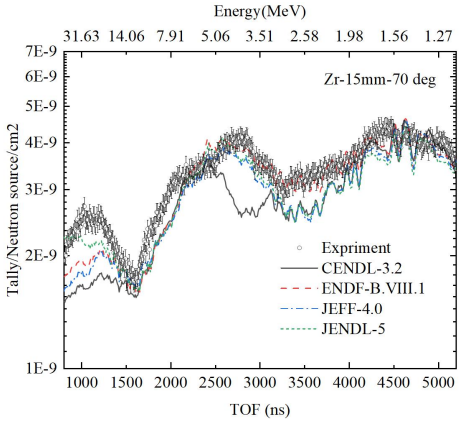


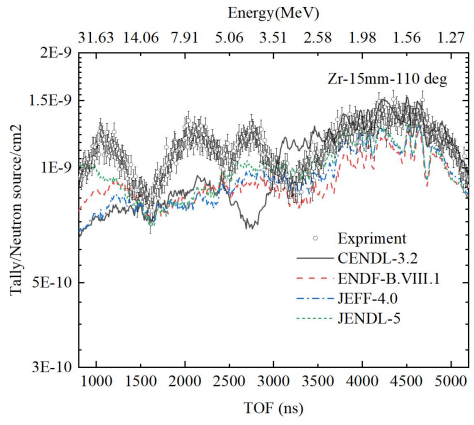


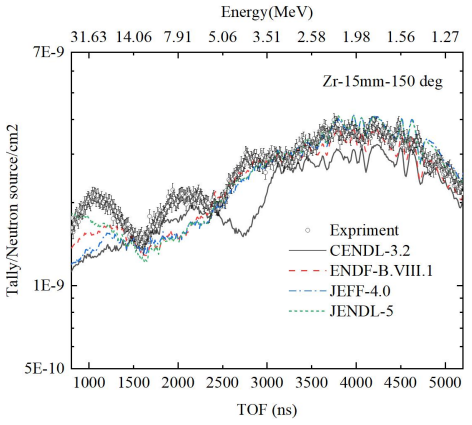








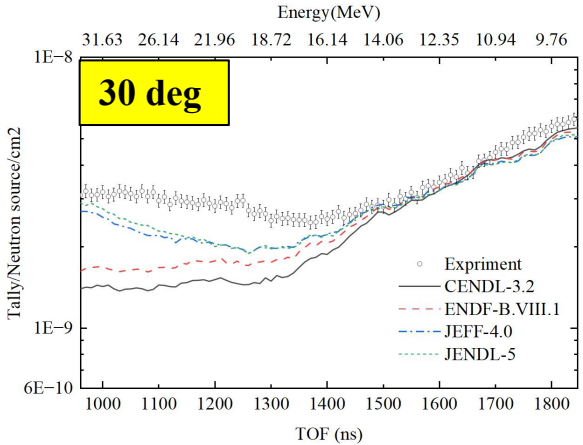




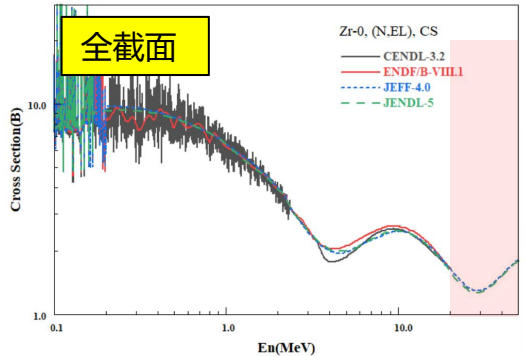
Zr-BC501A结果分析讨论

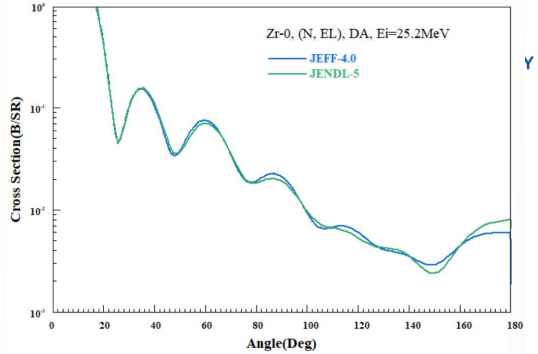
■ ^{nat}Zr散射中子谱（14-30MeV）

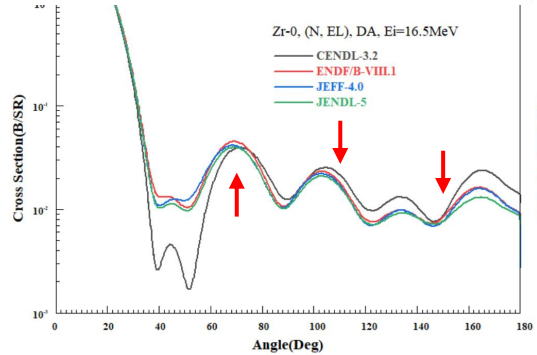
- 各数据库在四个角度模拟结果存在不同程度低估。
- CENDL-3.2库，30°低估最明显。

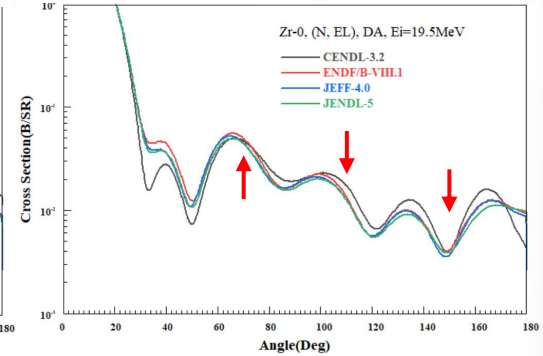


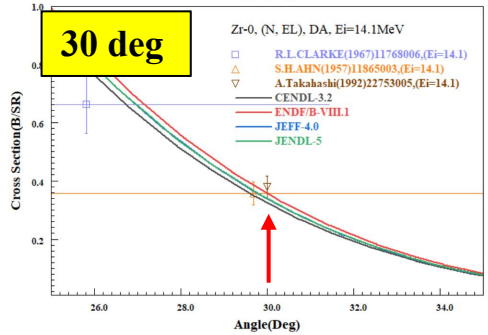
^{nat}Zr微观角分布测量数据少

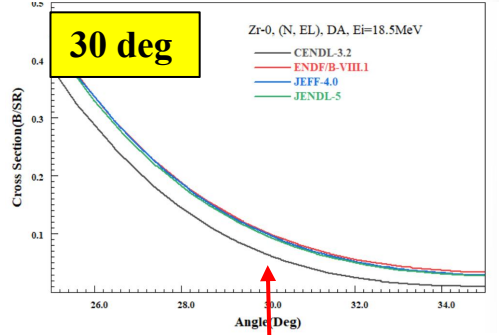






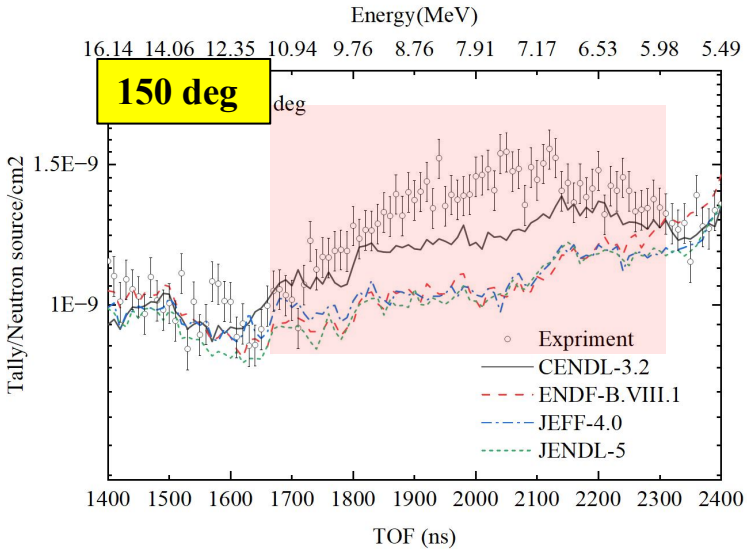


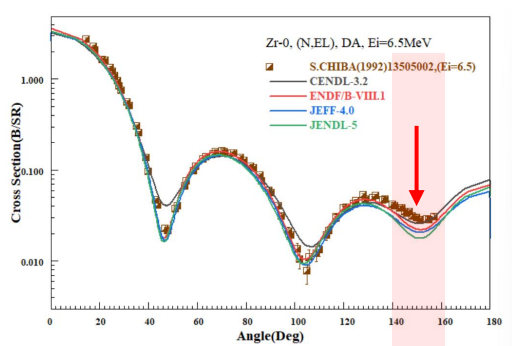


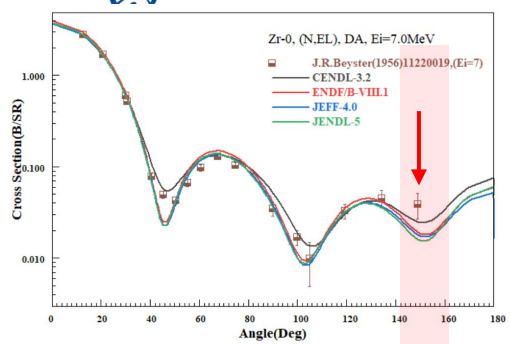


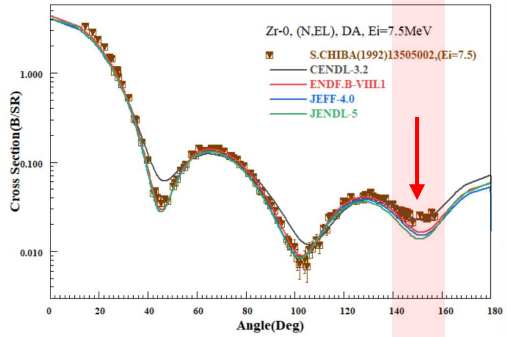
■ ^{nat}Zr散射中子谱（5.1-14MeV）

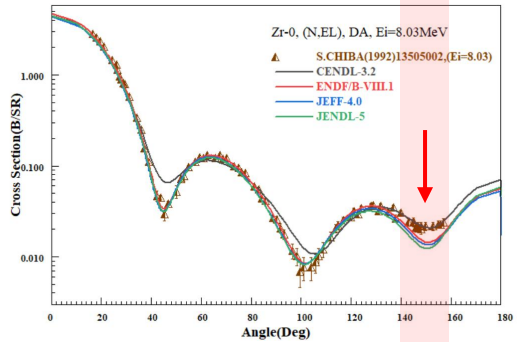
- 各数据库在四个角度均存在低估情况。
- CENDL-3.2库以外三个数据在6-11MeV，150°明显低估。

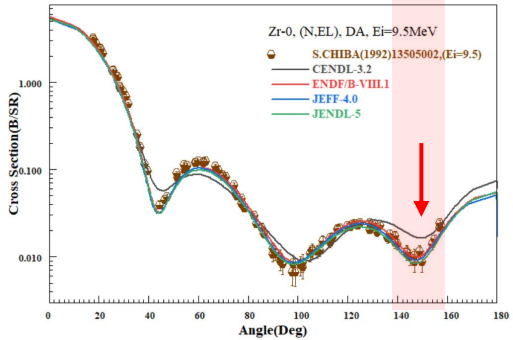


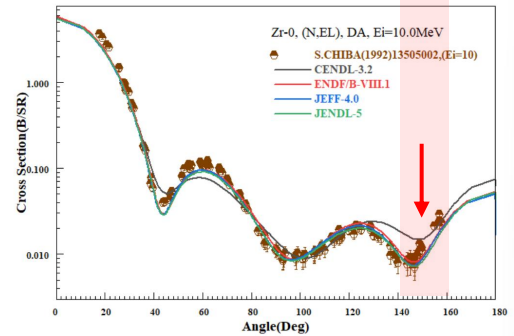






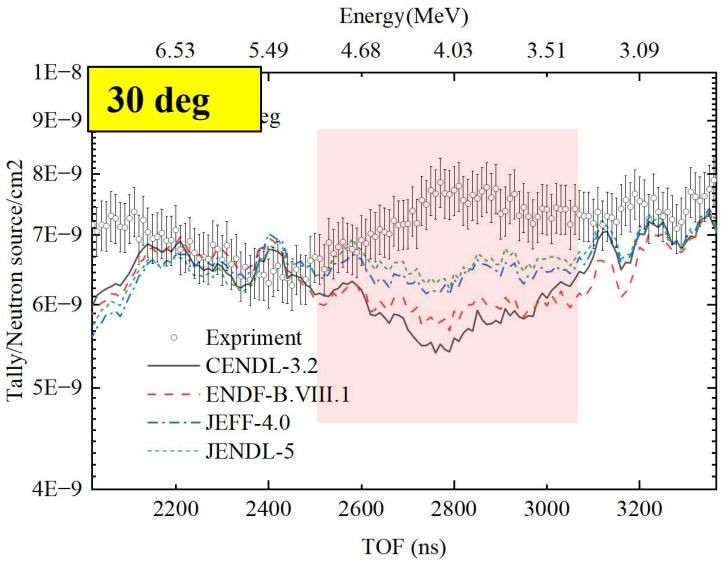


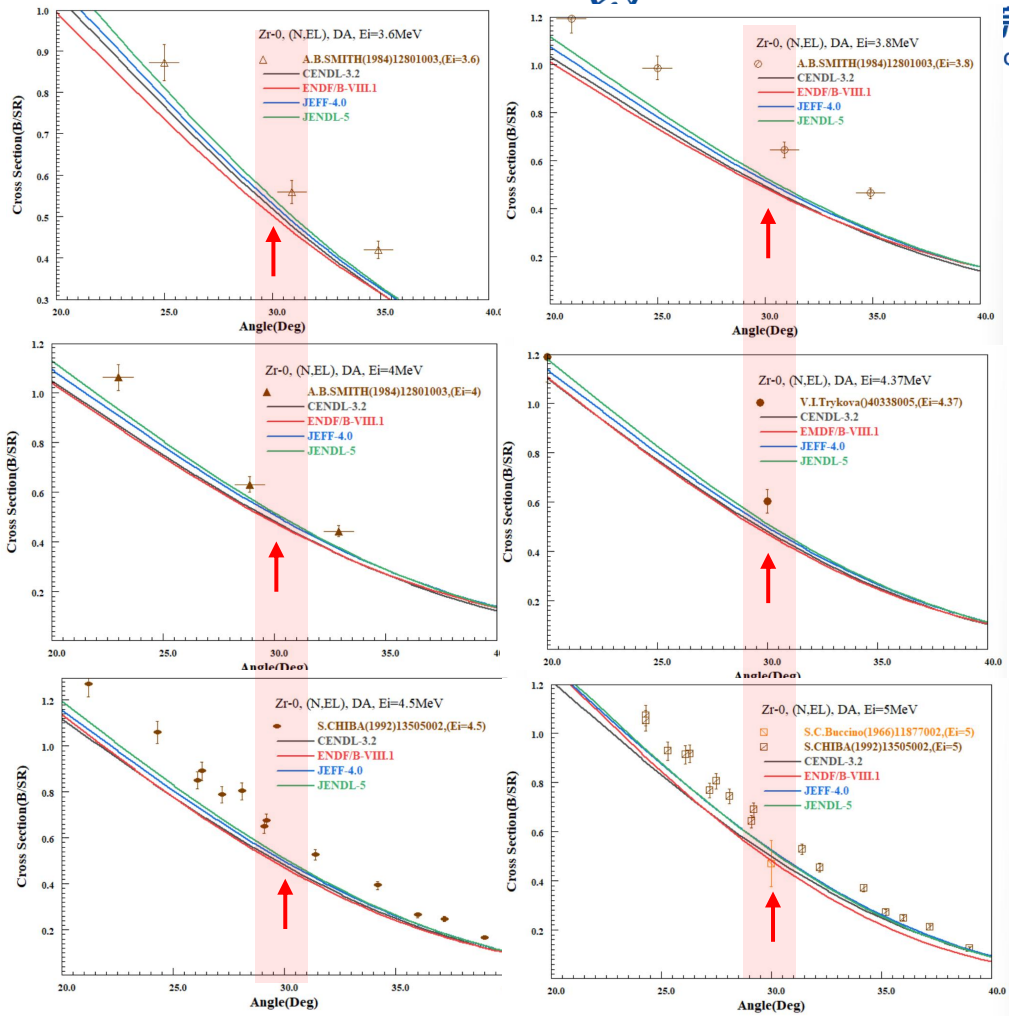




■ ^{nat}Zr散射中子谱（1.3-5.1MeV）

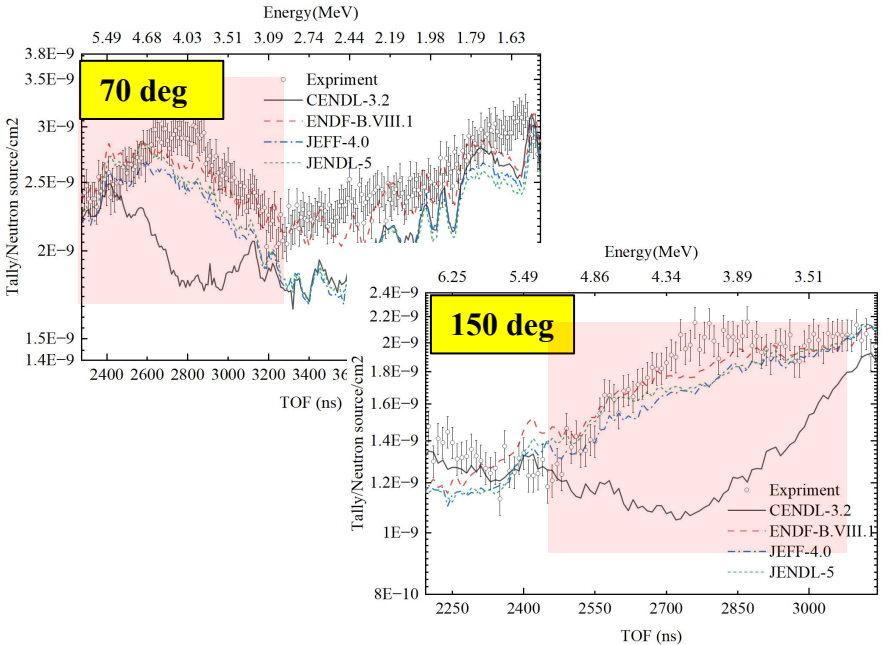
- 各数据库在四个角度存在不同程度低估情况。
- CENDL-3.2和ENDF/B-VIII.1库在3.5-5.1MeV，30°低估更加明显。

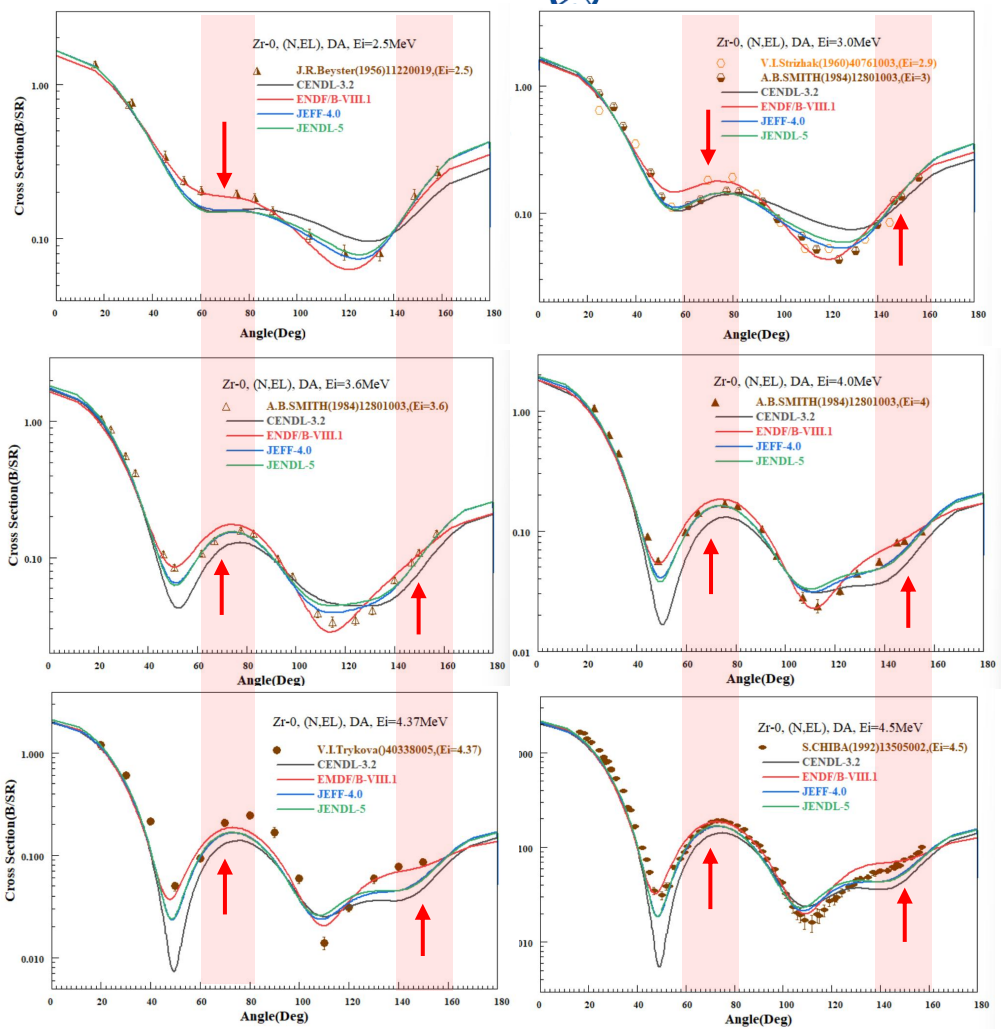




■ ^{nat}Zr散射中子谱（1.3-5.1MeV）

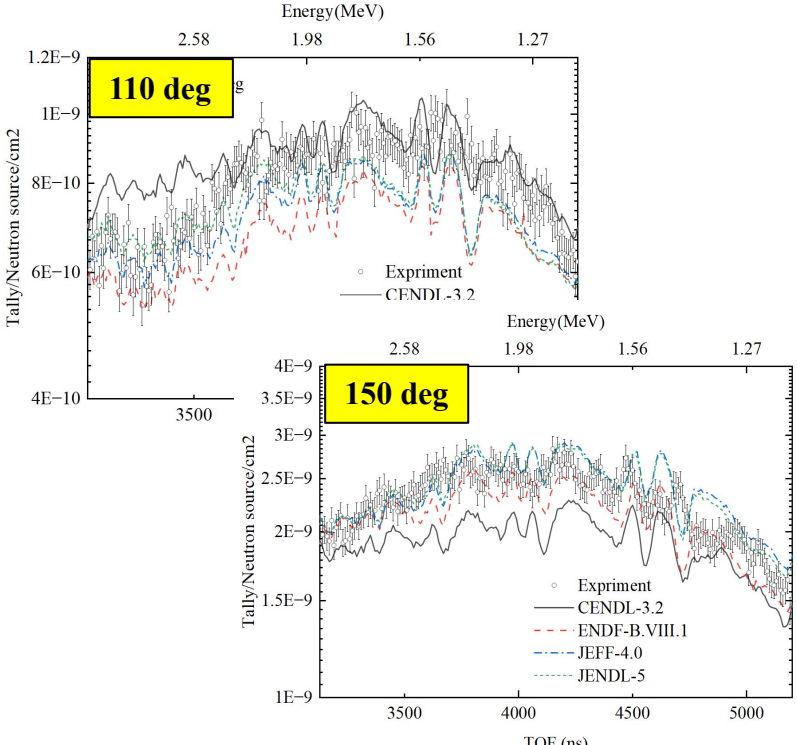
- ENDF/B-VIII.1库在1.8-5.1 MeV，70°符合更好。
- CENDL-3.2库在3-5 MeV，70°明显低估，150°明显低估。

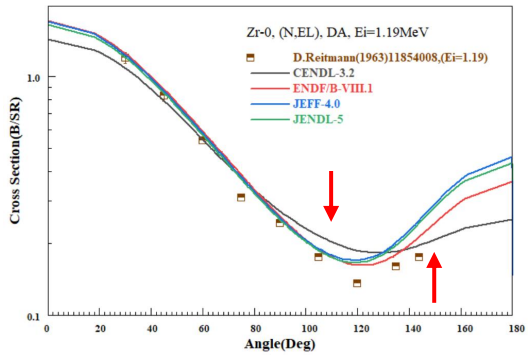


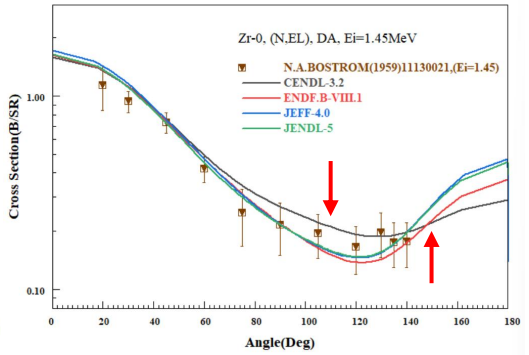


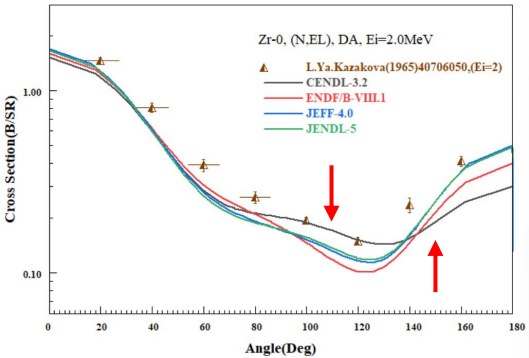
■ ^{nat}Zr散射中子谱（1.2-2.5MeV）

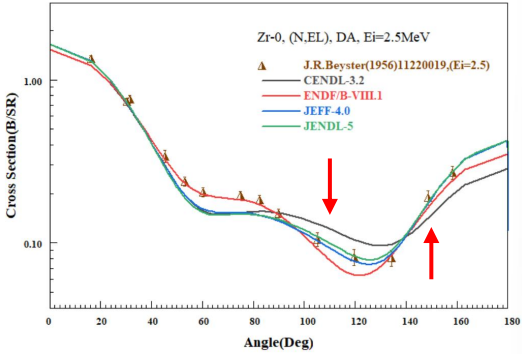
- CENDL-3.2数据库在1.2-2.5MeV能区，110°符合最好，150°存在明显低估。





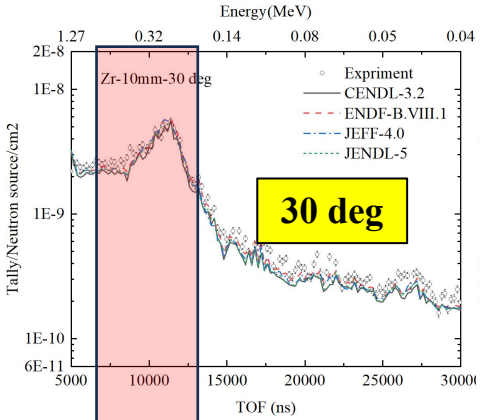


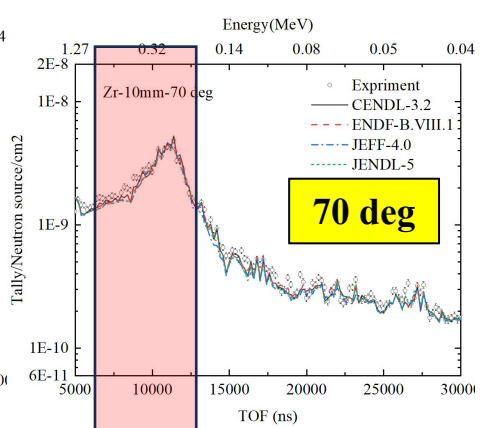


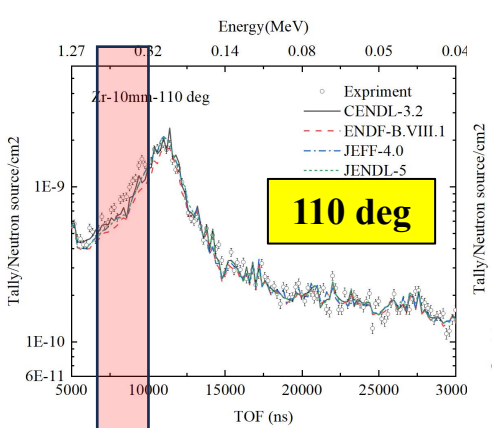


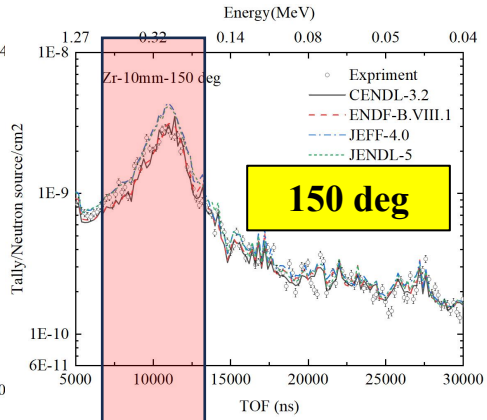
Zr的同位素多
角分布分歧较大

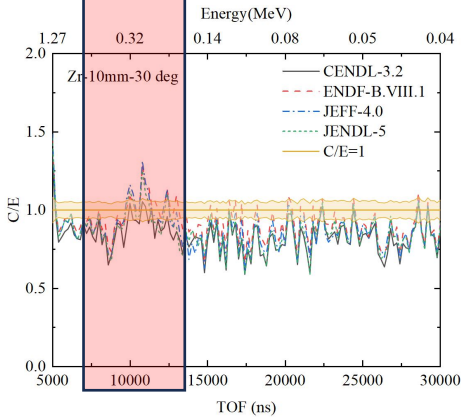
Zr-CLYC结果

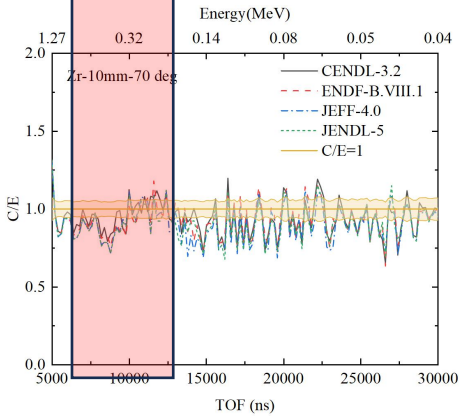

Energy(MeV)
Zr-10mm-30 deg
Expriment
CENDL-3.2
ENDF-B.VIII.1
JEFF-4.0
JENDL-5
30 deg
Tally/Neutron source/cm2
TOF (ns)

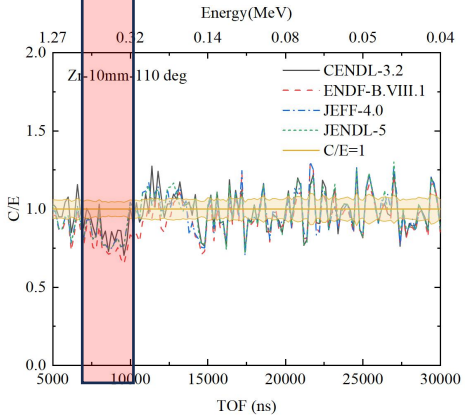

Energy(MeV)
Zr-10mm-70 deg
Expriment
CENDL-3.2
ENDF-B.VIII.1
JEFF-4.0
JENDL-5
70 deg
Tally/Neutron source/cm2
TOF (ns)

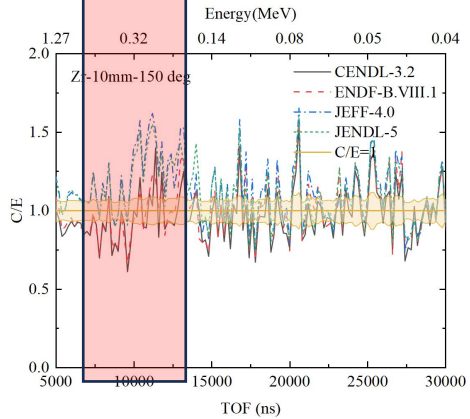

Energy(MeV)
Zr-10mm-110 deg
Expriment
CENDL-3.2
ENDF-B.VIII.1
JEFF-4.0
JENDL-5
110 deg
Tally/Neutron source/cm2
TOF (ns)


Energy(MeV)
Zr-10mm-150 deg
Expriment
CENDL-3.2
ENDF-B.VIII.1
JEFF-4.0
JENDL-5
150 deg
Tally/Neutron source/cm2
TOF (ns)


Energy(MeV)
Zr-10mm-30 deg
CENDL-3.2
ENDF-B.VIII.1
JEFF-4.0
JENDL-5
C/E=1
C/E
TOF (ns)


Energy(MeV)
Zr-10mm-70 deg
CENDL-3.2
ENDF-B.VIII.1
JEFF-4.0
JENDL-5
C/E=1
C/E
TOF (ns)

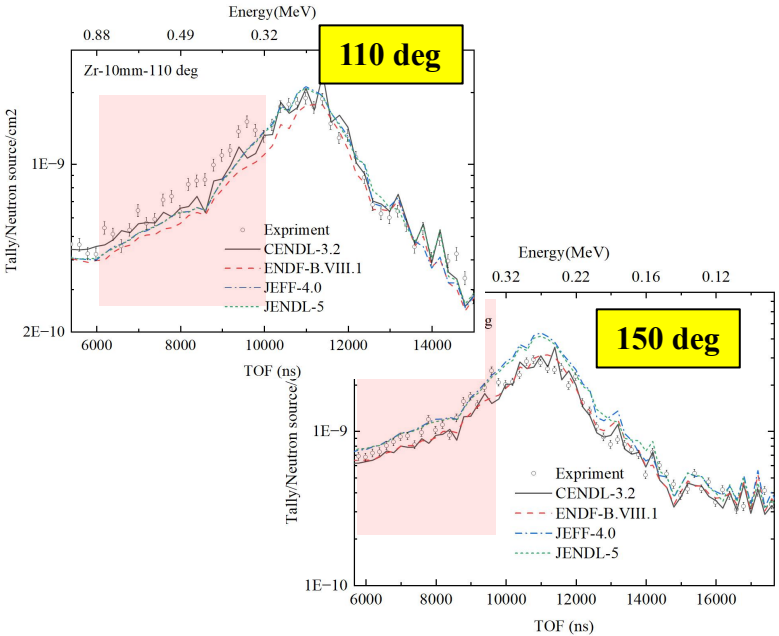

Energy(MeV)
Zr-10mm-110 deg
CENDL-3.2
ENDF-B.VIII.1
JEFF-4.0
JENDL-5
C/E=1
C/E
TOF (ns)

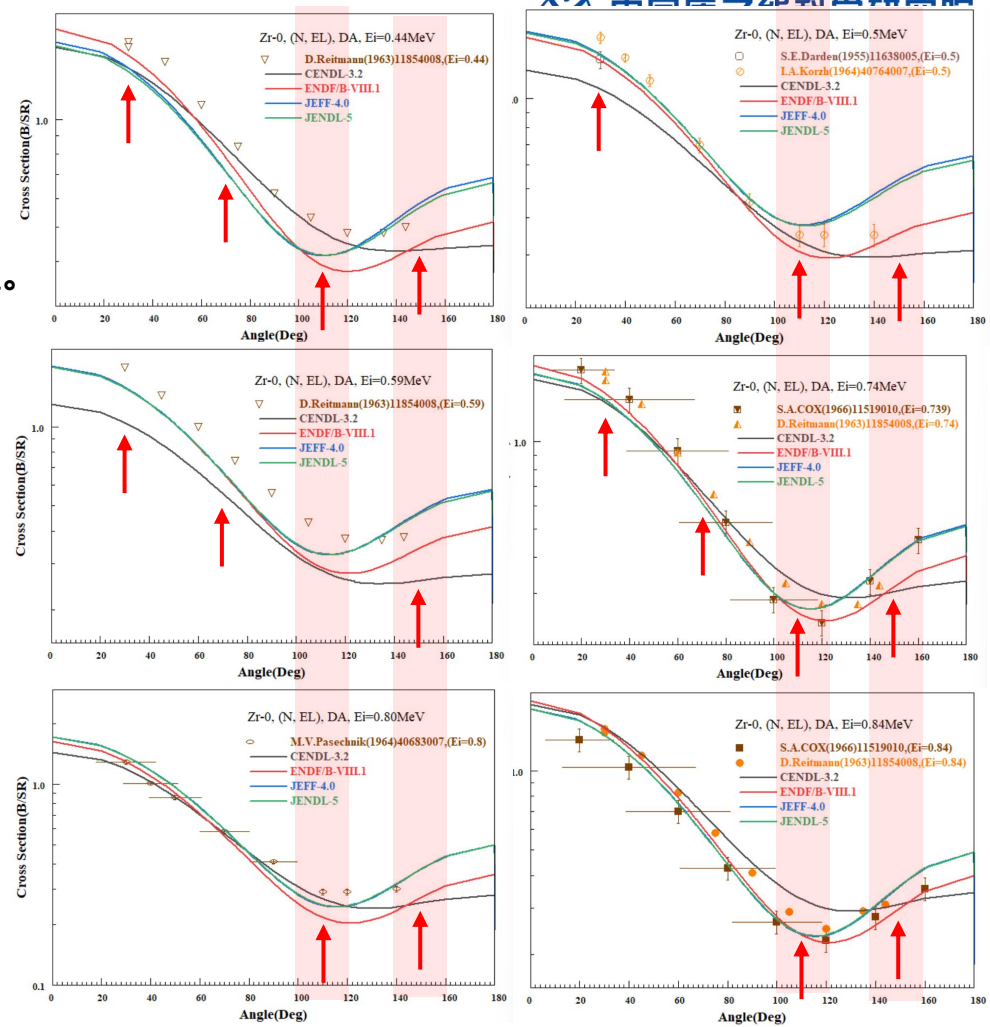

Energy(MeV)
Zr-10mm-150 deg
CENDL-3.2
ENDF-B.VIII.1
JEFF-4.0
JENDL-5
C/E=1
C/E
TOF (ns)

Zr-CLYC结果分析讨论

■ ^{nat}Zr散射中子谱（0.32-0.88MeV）

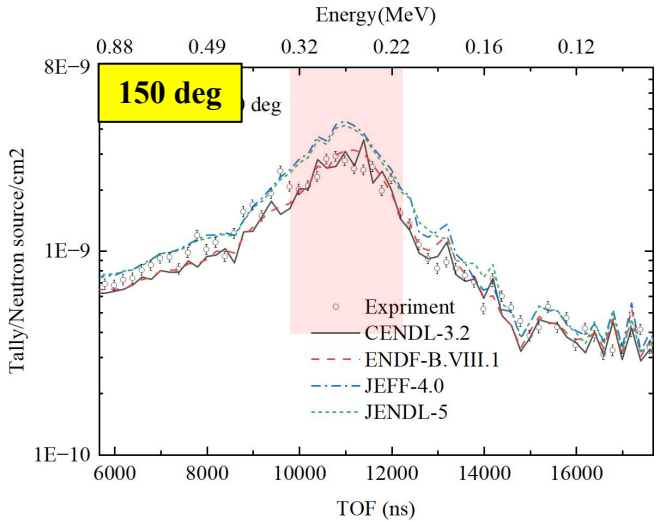
- 各库计算结果在四个角度有低估现象。
- ENDF/B-VIII.1库，在110°和150°低估最明显。
- CENDL库，在150°明显低估

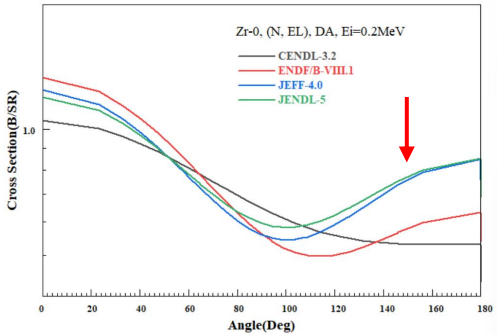


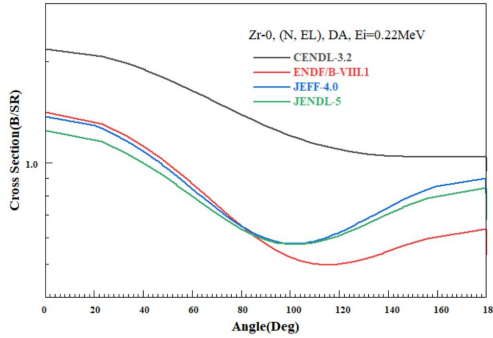


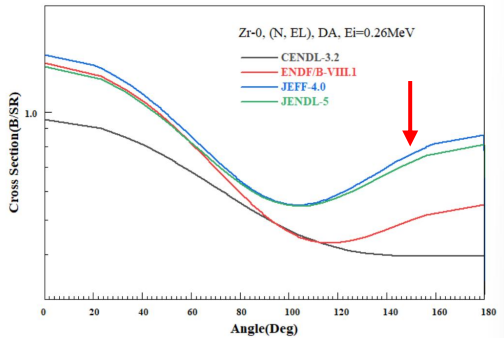
■ ^{nat}Zr散射中子谱（0.19-0.32MeV）

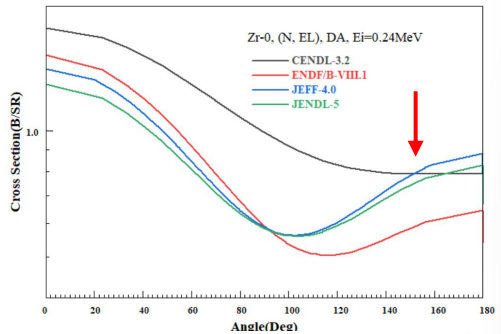
- JEFF-4.0和JENDL-5库，150°明显高估。

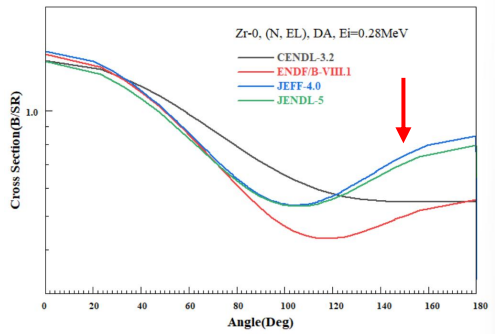


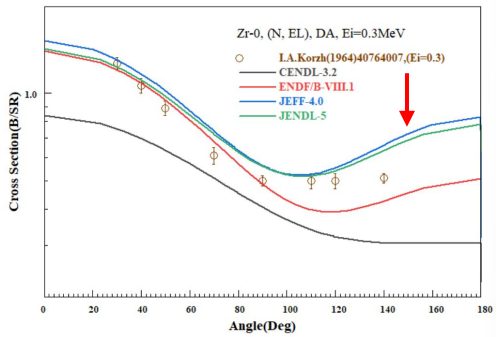












- 总结

- 基于白光中子源建立了准积分实验系统，开展了石墨和Zr样品准积分实
- 结合双束团解谱，对散射中子飞行时间谱实验结果和模拟结果进行了比较分析，为CENDL库下一步评价核数据改进与调整提供实验数据支撑。
- 研究结果表明，C和Zr数据库角分布亟需进一步完善。

- 展望

- 进一步扩充测量角度，提高探测器系统的测量能力
- 针对更多关键核素开展准积分实验
- 结合灵敏度计算对检验结果进行更深入的分析讨论

谢谢您的聆听与观看