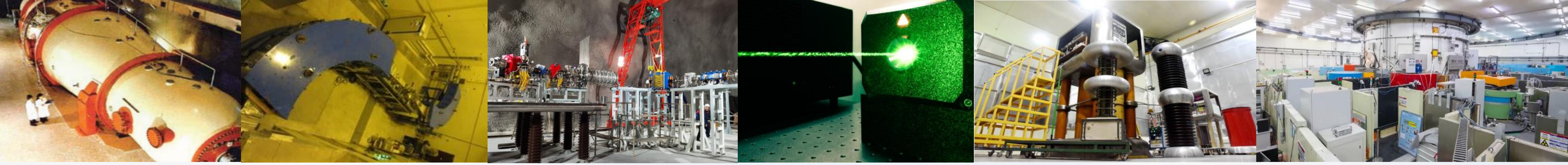


The 7th international workshop on Compound-Nuclear Reactions and Related Topics (CNR*24) 8 - 12 July, 2024

Progress on Nuclear Reaction Study in CENDL

XU Ruirui

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

Outlines

Introduction

Nuclear Reaction

Perspective

Nuclear Reaction Data

Platform for Chinese Experiments

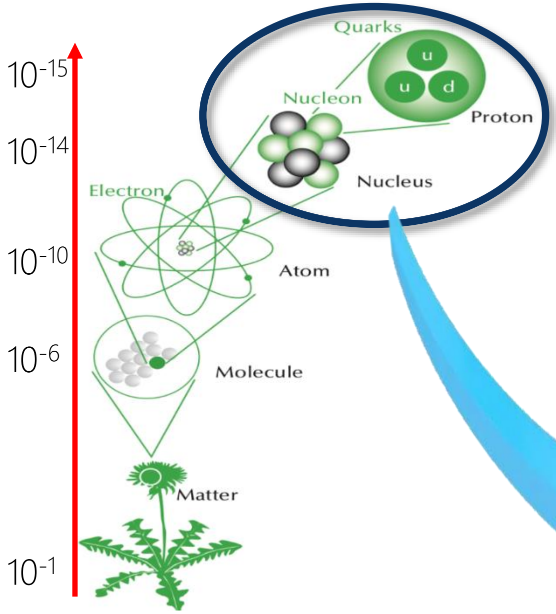
Platform for Theoretical Models

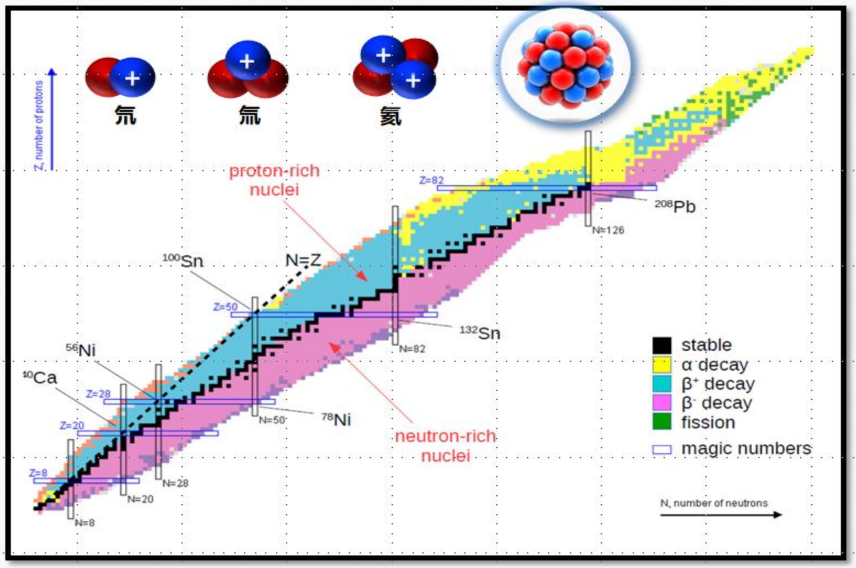
Nuclear Data Improvement

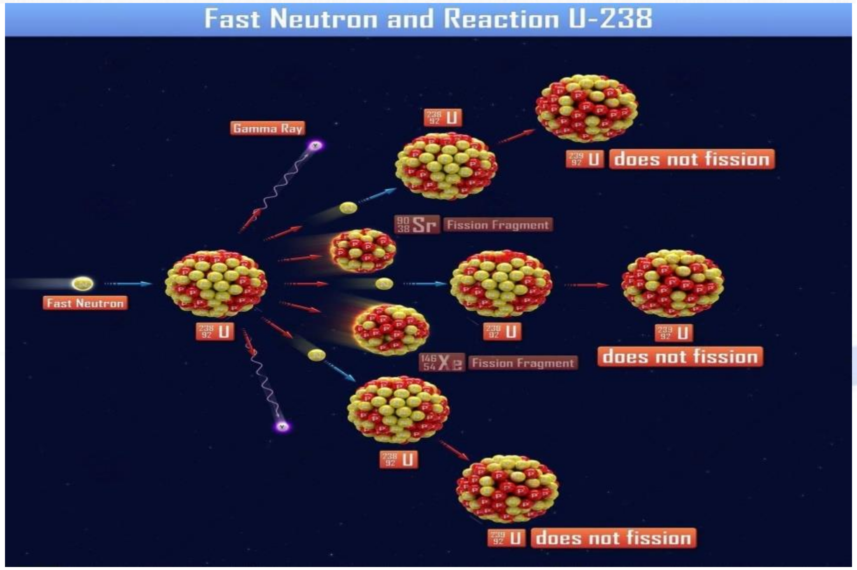
Treatment for Experimental data

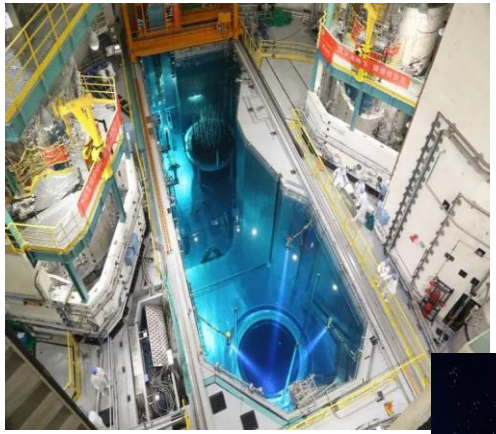
Processing and V&V for PD

From fundamental particles to applications



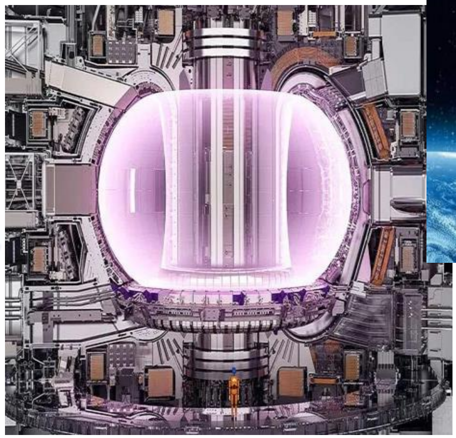






Pressurized Water Reactor(PWR)

Space Reactor



Fusion

I. General Information of CNDC

1.1 About CNDC

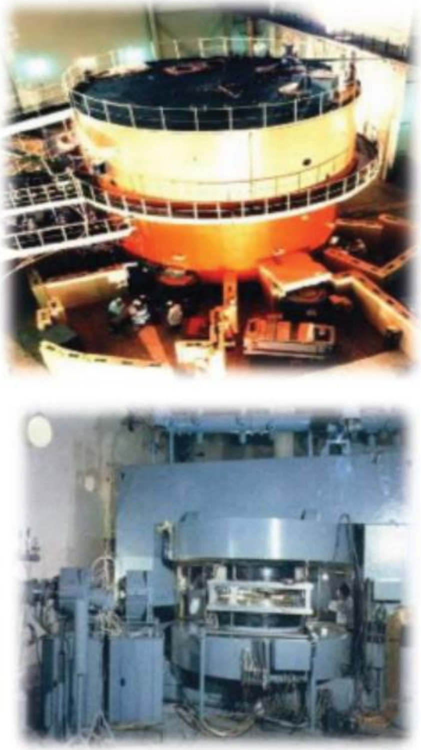
Nuclear data study started in 60's last century by measurements with the first reactor and cyclotron in CIAE, China Nuclear Data Center (CNDC) was established in 1975 and joined the nuclear data activities of IAEA as the national nuclear data center of China since 1984. As a window, CNDC has been open to the world since 1978. and CNDC has established a good cooperative relationship with the IAEA, OECD/NEA, and major nuclear data centers and institutions in the world.

The main task of CNDC:

- ✓ The management of domestic nuclear data activities.
- ✓ The nuclear data evaluations, libraries and relevant methodology studies.
- ✓ Nuclear data measurements and methodology studies
- ✓ The exchange of nuclear data activities with IAEA, foreign nuclear data centers and agencies.
- ✓ The services for domestic and foreign nuclear data application users.

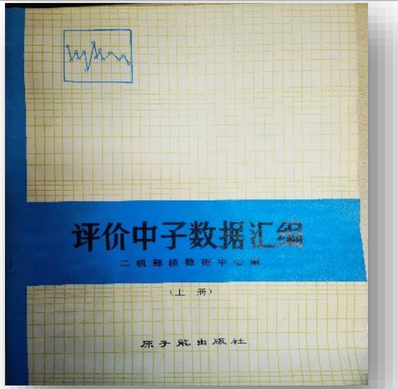
1.2 Mainly tasks of CNDC in 2023/2024:

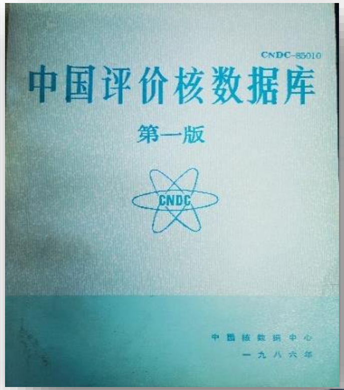
- ✓ New Five Years Plan (2021-2025) for nuclear data (CENDL Project).
- ✓ Data evaluation for next CENDL version and sub-libraries
- ✓ Methodological studies of nuclear data evaluation(incl. theoretical and experimental for fission process…).
- ✓ Nuclear data measurements and related methodological studies.(Mr.Ruan)
- ✓ The compilations for EXFOR.
- ✓ Nuclear data services.

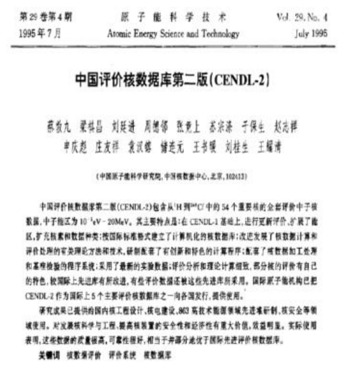


The 1st reactor and cyclotron in China

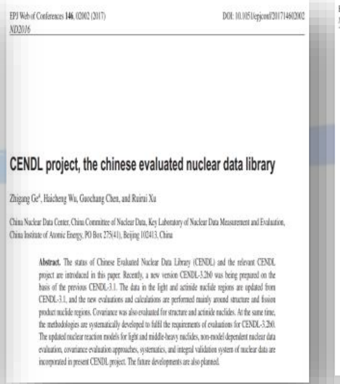
Nuclei	Edited ~ 1979, 16	CENDL-1, 1986, 36	CENDL-2 1991, 66	CENDL-3.1 2010, 240	CENDL-3.2 2020, 272
Few body	^{1,2,3}H,^{3,4}He	^{1,2,3}H,^{3,4}He	^{1,2,3}H,^{3,4}He	^{1,2,3}H,^{3,4}He	nn-1, ^{1,2,3}H,^{3,4}He
Light	^{6}, ^{7}Li, ^{9}Be	^{6,7}Li,^{9}Be,^{10,11}B,^{14}N,^{16}O,^{19}F	^{6,7}Li,^{9}Be,^{10,11}B,^{14}N,^{16}O,^{19}F	^{6,7}Li,^{9}Be,^{10,11}B,^{12}C, ^{14}N,^{16}O,^{19}F	Same
Medium heavy	^{0}Pb, ^{0}W, ^{0}Al, ^{0}Fe	19 nuclei ^{23}Na, ^{0}Mg, ^{27}Al, ^{0}Si, ^{0}V, ^{0}Cr, ^{0}Fe, ^{0}Ni, ^{0}Cu, ^{0}Zn, ^{0}Zr,^{93}Nb, ^{0}Mo,^{0}Sn, ^{0}Hf, ^{181}Ta, ^{0}W, ^{197}Au, ^{0}Pb	45 nuclei ^{23}Na, ^{0}Mg, ^{27}Al, ^{0}Si, ^{31}P, ^{0}S, ^{0}K, ^{0}Ca,^{0}Ti ^{0}V, ^{0,50,52,53,54,55}Cr, ^{55}Mn ^{0,54,56,57,58}Fe, ^{59}Co, ^{0}Ni, ^{0,63,65}Cu, ^{0}Zn, ^{0}Zr,^{93}Nb, ^{0}Mo,^{0,107,109}Ag, ^{0}Cd, ^{0}In, ^{0}Sn, ^{0}Sb, ^{0}Lu, ^{0}Hf, ^{181}Ta, ^{0}W, ^{197}Au, ^{0}Hg, ^{0}Tl, ^{0}Pb	192 nuclei ^{23}Na~^{208}Pb	223 nuclei ^{23}Na~^{208}Pb
Actinides	^{235,238}U,^{239,240}P	^{235}, ^{238}U, ^{239,240}Pu	8 nuclei ^{235}, ^{238}U, ^{237}Np, ^{239,240}Pu, ^{241}Am, ^{249}Bk, ^{249}Cf	34 nuclei ^{232}Th~^{249}Cf	34 nuclei ^{232}Th~^{249}C



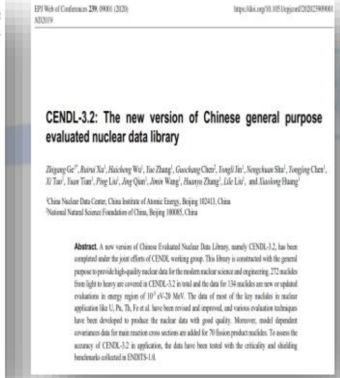


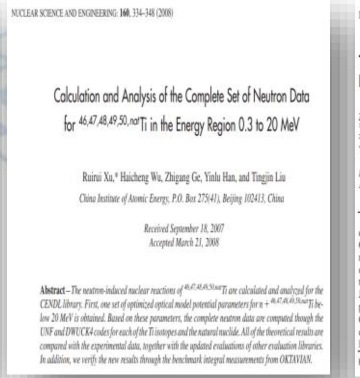

第29卷第4期 原子能科学技术 Vol. 29, No. 4
1995年7月 Atomic Energy Science and Technology July 1995

中国评价核数据库第二版(CENDL-2)


CENDL project, the chinese evaluated nuclear data library

Zhigang Ge, Haicheng Wu, Guochang Chen, and Ruirui Xu

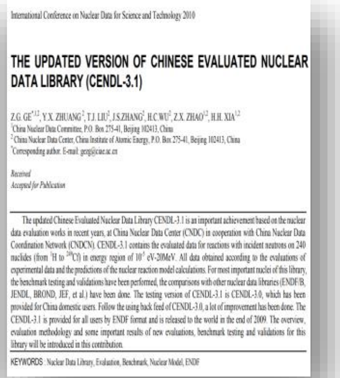

CENDL-3.2: The new version of Chinese general purpose evaluated nuclear data library


NUCLEAR SCIENCE AND ENGINEERING: 160, 334–348 (2008)

Calculation and Analysis of the Complete Set of Neutron Data for ^{46,47,48,49,50,nat}Ti in the Energy Region 0.3 to 20 MeV

Ruirui Xu, Haicheng Wu, Zhigang Ge, Yinlu Han, and Tingjin Liu

China Institute of Atomic Energy, P.O. Box 275(41), Beijing 102413, China


International Conference on Nuclear Data for Science and Technology 2010

THE UPDATED VERSION OF CHINESE EVALUATED NUCLEAR DATA LIBRARY (CENDL-3.1)

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Platform for Theoretical Models

Nuclear Data Improvement

Treatment for Experimental data

Processing and V&V for PD

The New Evaluation Project & Data in CENDL-4.0

Nuclear	CENDL-4.0-v1 共 A=410, Z=86
Light Elements (A=17) (Z=10)	^{1}n, ^{1,2,3}H, ^{3,4}He, ^{6,7}Li, ^{9}Be, ^{10,11}B, ^{12,13}C, ^{14,15}N, ^{16}O, ^{19}F
Fission Products & Medium Elements (A=359) (Z=69)	^{22,23}Na, ^{24,25,26}Mg, ^{27}Al, ^{28,29,30}Si, ^{31}P, ^{32,33,34,36}S, ^{35,37}Cl, ^{39,40,41}K, ^{40,42,43,44,46,48}Ca, ^{46,47,48,49,50}Ti, ^{50,51}V, ^{50,52,53,54}Cr, ^{55}Mn, ^{54,56,57,58}Fe, ^{59}Co, ^{58,59,60,61,62,64}Ni, ^{63,65}Cu, ^{64,65,66,67,68,70}Zn, ^{69,71}Ga, ^{70,71,72,73,74,75,76,77,78}Ge, ^{74,75}As, ^{74,76,77,78,79,80,82}Se, ^{79,81}Br, ^{78,80,81,82,83,84,85,86,87,88}Kr, ^{85,86,87}Rb, ^{84,86,87,88,89,90}Sr, ^{89,90,91}Y, ^{90,91,92,93,94,95,96}Zr, ^{93,94,95,96}Nb, ^{92,93,94,95,96,97,98,99,100}Mo, ^{99,104}Tc, ^{96,98,99,100,101,102,103,104,105,106}Ru, ^{103,105}Rh, ^{102,104,105,106,107,108,110}Pd, ^{107,109,111}Ag, ^{106,108,109,110,111,112,113,114,115,116}Cd, ^{113,115}In, ^{112,113,114,115,116,117,118,119,120,122,123,124,125,126,128}Sn, ^{121,122,123,124,125,126,127}Sb, ^{120,122,123,124,125,126,127,128,130,132}Te, ^{127,129,130,131,133,135}I, ^{123,124,126,128,129,130,131,132,133,134,135,136}Xe, ^{133,134,135,136,137}Cs, ^{130,132,133,134,135,136,137,138,139,140}Ba, ^{138,139,140}La, ^{136,138,139,140,141,142,143,144}Ce, ^{141,142,143,145}Pr, ^{142,143,144,145,146,147,148,149,150}Nd, ^{147,148,148m,149,150,151}Pm, ^{144,145,146,147,148,149,150,151,152,153,154}Sm, ^{151,152,153,154,155,156,157}Eu, ^{152,153,154,155,156,157,158,159,160,161}Gd, ^{157,158,159,160,161}Tb, ^{156,157,158,159,160,161,162,163,164,165}Dy, ^{163,165,166}Ho, ^{162,164,166,167,168,169,170}Er, ^{168,169,170,171}Tm, ^{168,169,170,171,172,173,174,175,176}Yb, ^{175,176,177}Lu, ^{174,176,177,178,179,180,181}Hf, ^{180,181,182}Ta, ^{180,182,183,184,186,187,188}W, ^{185,187}Re, ^{191,193}Ir, ^{197}Au, ^{196,198,199,200,201,202,204}Hg, ^{203,205}Tl, ^{204,206,207,208}Pb, ^{209}Bi
Actinides (A=34) (Z=7)	^{232}Th, ^{232,233,234,235,236,237,238,239,240,241}U, ^{236,237,238,239}Np, ^{236,237,238,239,240,241,242,243,244,245,246}Pu, ^{240,241,242,242m,243,244}Am, ^{249}Bk, ^{249}Cf

~ neutron data of 30 nuclei are being improved based on the new experimental data

light elements: ^{4}He, ^{6}Li, ^{9,10,11}B, ^{12,13,14,15}C, ^{14,15}N

Medium elements: ^{27}Al, ^{50,51}V, ^{52}Cr, $^{54, 56-58}$Fe, $^{69, 71}$Ga, ^{95}Mo, $^{204, 206-208}$Pb

Actinides: $^{235, 238}$U, $^{239, 240, 241}$Pu

1. Platform of Chinese Experimental Facilities（partly)

For Nuclear Data — Neutron, Photon, proton beams

中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences
ADS related data (proton induced)

兰州大学
LANZHOU UNIVERSITY
Excitation function around 14 MeV

西北核技术研究院
Decay data

四川大学
SICHUAN UNIVERSITY
Excitation function

中国工程物理研究院
CHINA ACADEMY OF ENGINEERING PHYSICS
Integral experiments, other data measurement

中国原子能科学研究院
CHINA INSTITUTE OF ATOMIC ENERGY
Excitation function, FY, γ production yields, DX and DDX, benchmark experiments, etc

北京大学
PEKING UNIVERSITY
Charged reaction measurement (n,LCP)

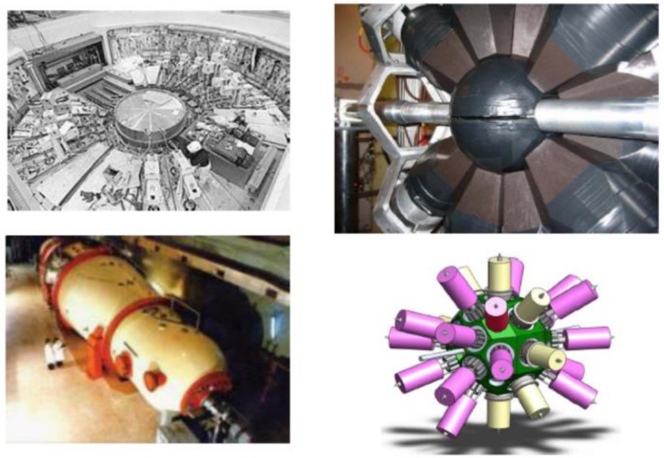
中国科学院上海应用物理研究所
SINAP
Shanghai Institute of Applied Physics, Chinese Academy of Sciences
Th-U cycle related data

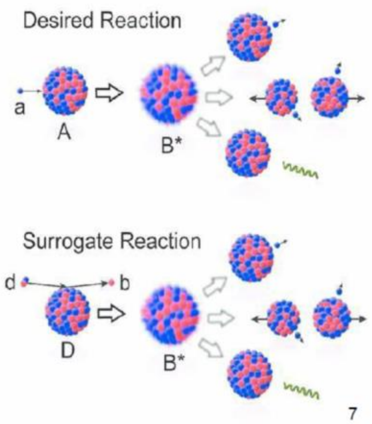
CSNS
中国散裂中子源
CHINA SPALLATION NEUTRON SOURCE
CS measurement for wide energy

1. The platform of Chinese Experimental Facilities

For Nuclear Data — Neutron beams

- 中子核数据测量的三要素：
  中子源、探测器与实验方法

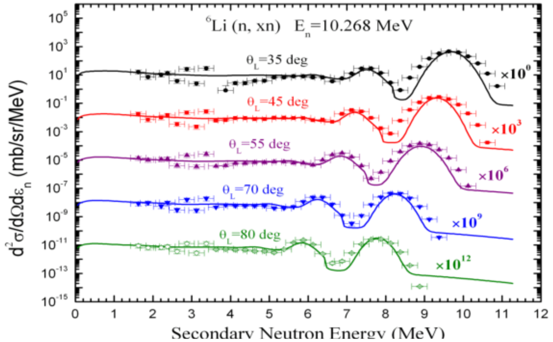




设备	中子能量	强度
中国原子能科学研究院，中国工程物理研究院等，反应堆	热中子	10^{14} n/cm²/s
中国原子能科学研究院，HI-13 串列加速器	4~42 MeV	10^{6}-10^{8} n/sr/s
中国原子能科学研究院，2×1.7 MV 小串列	0.03~6，14~20 MeV	10^{8}-10^{9} n/sr/s
中国原子能科学研究院、兰州大学、中国工程物理研究院等，高压倍加器	2.5, 14 MeV	10^{8}，10^{10} n/sr/s
北京大学，4.5 MV 静电加速器	0.03~7 MeV	10^{7}-10^{8} n/sr/s
四川大学，2×3 MV 串列加速器	0.03~9，15~22 MeV	10^{8}-10^{9} n/sr/s
中科院上海应用物理研究所，TMSR-PNS	热中子~keV	10^{4} n/cm²/s
中科院高能物理研究所，CSNS Back-n	热中子~300 MeV	10^{7} n/cm²/s

@ 8-14MeV Double differential Cross Sections

能量	样品
14 MeV附近	C、^{238}U、D、^{209}Bi、^{6,7}Li、Zr、Al
6 MeV附近	Be
8 MeV附近	^{6,7}Li、Fe、Be、D、Ga
10 MeV附近	^{6,7}Li、Be、V、^{238}U、^{209}Bi、Fe、C
20-40 MeV	Be、C、^{209}Bi



@ (n,2n), (n,p) reaction cross sections

^{23}Na(n,2n)^{22}Na	^{24}Mg(n,p)^{24}Na	^{27}Al(n, a)^{24}Na	^{45}Sc(n,2n)^{44g}Sc	^{45}Sc(n,2n)^{44m}Sc	^{45}Sc(n,2n)$^{44m+g}$Sc
^{46}Ti(n,p)^{46}Sc	^{47}Ti(n,p)^{47}Sc	^{48}Ti(n,p)^{46}Sc	^{51}V(n,a)^{48}Sc	^{55}Mn(n,2n)^{54}Mn	^{54}Fe(n,p)^{54}Mn
^{54}Fe(n,a)^{51}Cr	^{56}Fe(n,p)^{55}Mn	^{59}Co(n,2n)^{58}Co	^{59}Co(n,p)^{59}Fe	^{59}Co(n,a)^{56}Mn	^{58}Ni(n,2n)^{57}Ni
^{58}Ni(n,p)^{58}Co	^{58}Ni(n,x)^{57}Co	^{60}Ni(n,p)^{60}Co	^{62}Ni(n,a)^{59}Co	^{62}Ni(n, a)^{59}Fe	^{63}Cu(n,a)^{60}Co
^{66}Zn(n,2n)^{65}Zn	^{67}Zn(n,p)^{67}Cu	^{70}Zn(n,2n)^{69m}Zn	^{71}Ga(n,r)^{72}Ga	^{85}Rb(n,2n)^{84m}Rb	^{85}Rb(n,2n)$^{84m+g}$Rb
^{85}Rb(n,p)^{85m}Kr	^{85}Rb(n, a)^{82}Br	^{87}Rb(n,2n)^{86}Rb	^{87}Rb(n,p)^{87}Kr	^{89}Y(n,2n)^{88}Y	^{90}Zr(n,2n)^{89}Zr
^{89}Zr(n,2n)^{88}Zr	^{96}Zr(n,2n)^{95}Zr	^{92}Mo(n,p)^{92}Nb	^{98}Mo(n,r)^{99}Mo	^{93}Nb(n,2n)^{92m}Nb	^{93}Nb(n,a)^{90m}Y
^{109}Ag(n,2n)^{108m}Ag	^{113}In(n,2n)^{112m}In	^{113}In(n,n')^{113m}In	^{115}In(n,2n)^{114m}In	^{115}In(n,n')^{115m}In	^{115}In(n,r)^{116m}In
^{115}In(n,p)^{115}Cd	^{115}In(n,a)^{112}Ag	^{127}I(n,2n)^{126}I	^{124}Xe(n,2n)^{123}Xe	^{132}Ba(n,2n)^{131}Ba	^{134}Ba(n,2n)^{133m}Ba
^{134}Ba(n,2n)1^{33m+g}Ba	^{134}Ba(n,p)$^{134m+g}$Cs	^{134}Ba(n,a)^{131m}Xe	^{137}Ba(n,p)^{137}Cs	^{136}Ba(n,p)^{136}Cs	^{138}Ba(n,a)^{135}Xe
^{136}Ce(n,2n)^{135}Ce	^{138}Ce(n,2n)^{137m}Ce	^{140}Ce(n,2n)^{139}Ce	^{140}Ce(n,p)^{140}La	^{142}Ce(n,2n)^{141}Ce	^{151}Eu(n,2n)^{150m}Eu
^{151}Eu(n,r)^{152m}Eu	^{151}Eu(n,r)^{152g}Eu	^{153}Eu(n,2n)^{152g}Eu	^{153}Eu(n,r)^{154}Eu	^{159}Tb(n,2n)^{158}Tb	^{159}Tb(n,r)^{160}Tb
^{165}Ho(n,r)^{166m}Ho	^{169}Tm(n,2n)^{168m}Tm	^{169}Tm(n,3n)^{167}Tm	^{169}Tm(n,r)^{170}Tm	^{175}Lu(n,2n)$^{174m+g}$Lu	^{176}Hf(n,2n)^{175}Hf
^{180}Hf(n,r)^{181}Hf	^{179}Hf(n,2n)^{178m2}Hf	^{180}Hf(n,2n)^{179m2}Hf	^{181}Ta(n,2n)^{180m}Ta	^{181}Ta(n,p)^{181}Hf	^{182}W(n,n'a)^{178m2}Hf
^{185}Re(n,2n)^{184m}Re	^{185}Re(n,2n)$^{184m+g}$Re	^{187}Re(n,2n)^{186g}Re	^{187}Re(n,2n)^{186m}Re	^{193}Ir(n,2n)^{192m2}Ir	Pt(n,x)^{195m}Pt
^{198}Pt(n,2n)^{197}Pt	^{197}Au(n.2n)^{196}Au	^{197}Au(n,3n)^{195}Au	^{204}Pb(n,2n)^{203}Pb	69Ga(n,2n)68Ga	241Am(n,γ)240Am
239Pu(n,2n)238Pu					

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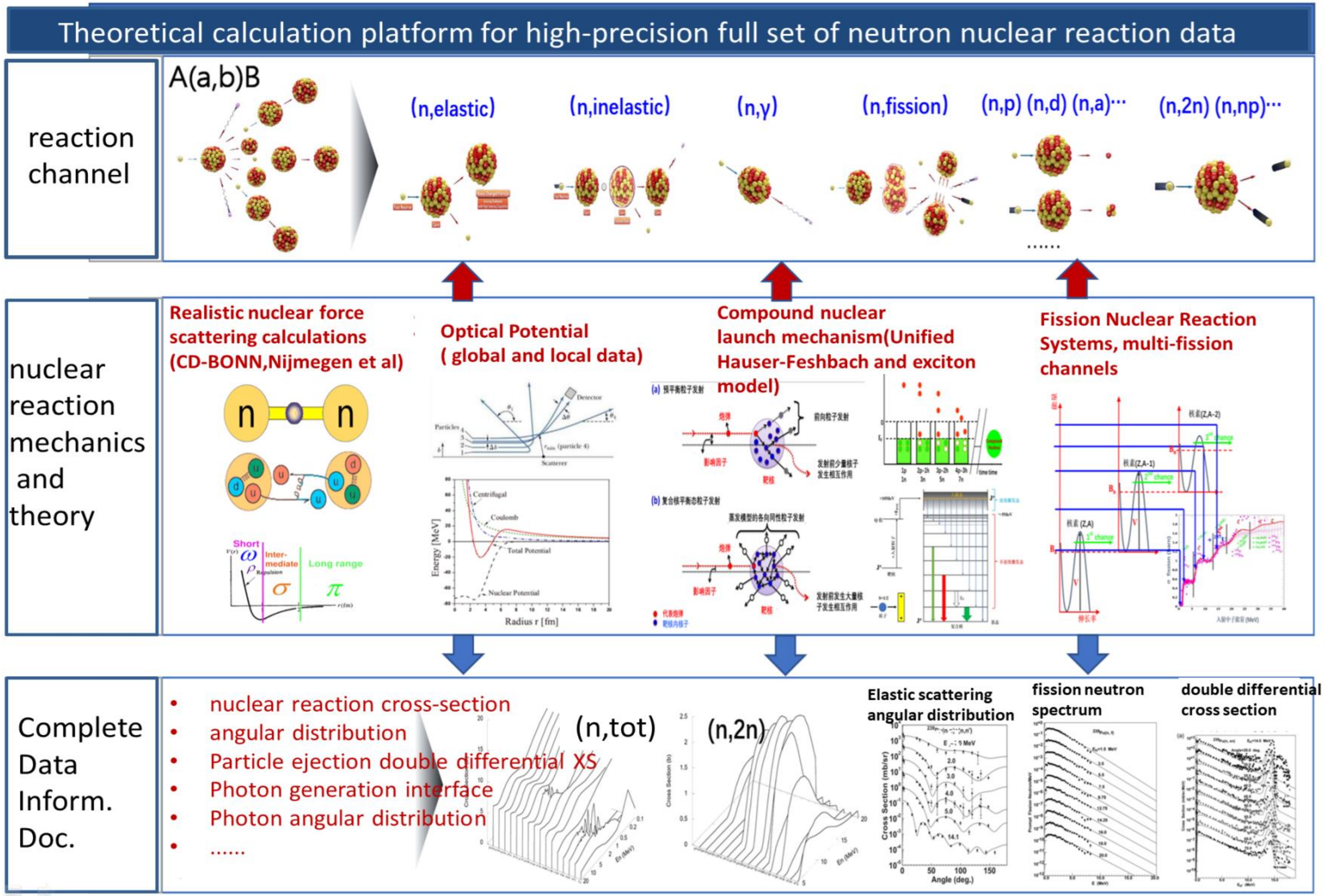
Processing and V&V for PD

2. Platform of Chinese Theoretical Model for nuclear reaction

For Nuclear Data — Neutron and Photon beams



Chinese Nuclear Reaction Codes：

1. UNF: UNiFed function

- Incident: Neutron, proton, photon
- Target: light, medium heavy, actinides
- Energy: ~ 20MeV

J.S. Zhang, Nucl. Sci. Eng. 142, 207, 2002

J.S. Zhang, Nucl. Sci. Eng. 114, 55, 1993

2. MEND: Medium Energy Nuclear Data

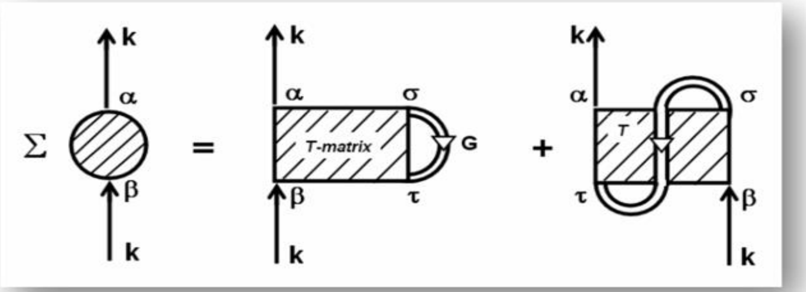
- Incident: neutron, proton, deuteron, triton, alpha, photon
- Target: medium heavy, actinides
- Energy: ~ 200MeV

C.H. Cai, Nucl. Sci. Eng. 153, 93, 2006

C.H. Cai, Chin. J. Comp. Phys. 20, 279, 2003

2.1 Nuclear optical potentials: bridge the nuclear structure and nuclear reactions

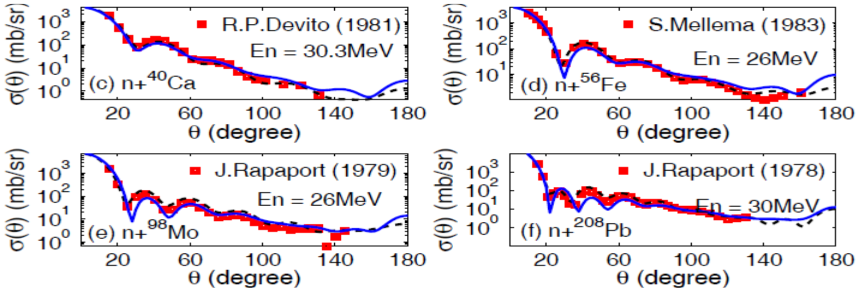
DBHF approach in nuclear matter with Bonn A



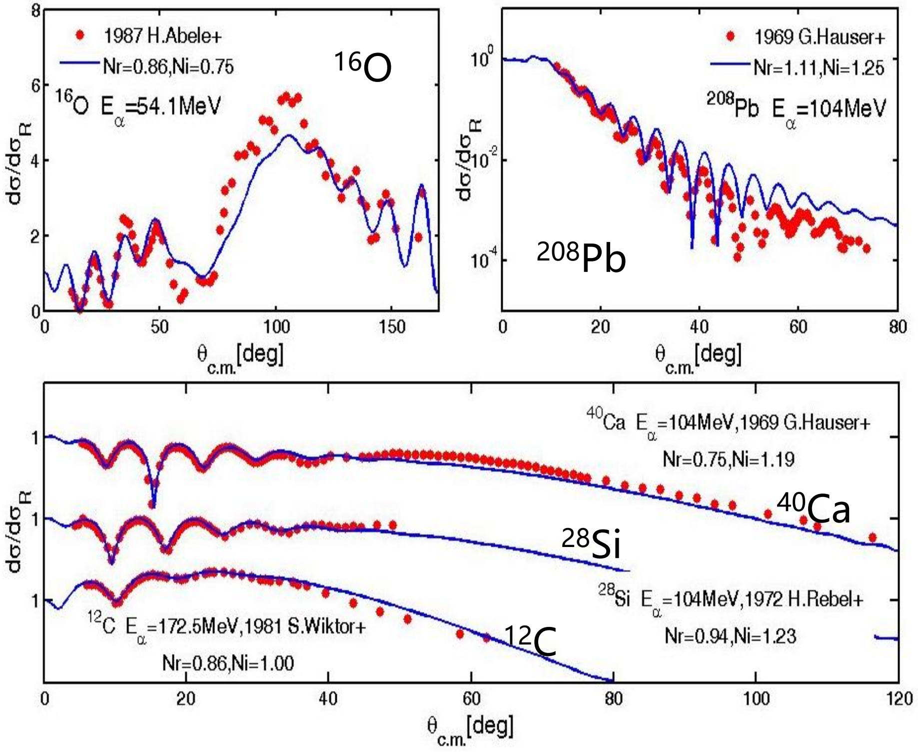
CHINA NUCLEAR DATA CENTER

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

- Nucleon-nucleus scattering
- Nucleon distributions base on D1S
- Local density approximation
- Low density expansion



Double folding approach for alpha potential



CTOM potential

1. ***R. Xu****, *Z.Y. Ma, et al., Phys. Rev. C, 2012;*
2. ***R. Xu****, *Z.Y. Ma, et al., Phys. Rev. C, 2016;*
3. ***R. Xu****, *Z.Y. Ma, et al., EPJ Woc, 2017;*
4. *Z. Zhang,* ***R. Xu****, *et al., Nucl. Phys. A, 2019;*
5. *X.D. Sun,* ***R. Xu****, *et al., Phys. Rev. C, 2020;*

2.2 Improving nuclear data library of light nucleus

The n+d systems are calculated by solving the following Faddeev-AGS equation:

$$U = Pv_1 + Pv_1G_1U,$$

where U, P, v_1 and G_1 are the transition operator, the permutation operator, the channel interaction, and the channel resolvent, respectively. The Faddeev equation is solved with the wave-packet method described in *O.A. Rubtsova et al., Ann. Phys. 360, 613 (2015).*

NN interactions used: For elastic scattering and total reaction cross sections: Nijmegen potential: nijmI. For breakup double-differential cross sections: MT I-III s-wave separable potential

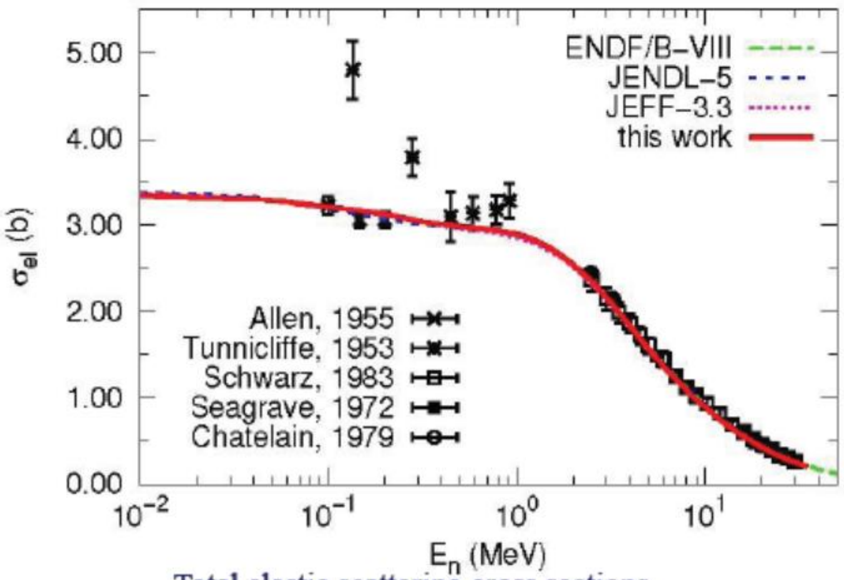
The elastic scattering amplitude:

$$A_{el}^{\Gamma\alpha\beta}(q_0) \approx \frac{2m}{3q_0}\frac{\left\langle Z_{1j0}^{\Gamma\alpha\beta}\middle|\mathfrak{U}^{\Gamma}\middle|Z_{1j0}^{\Gamma\alpha\beta}\right\rangle}{d_{j0}}$$

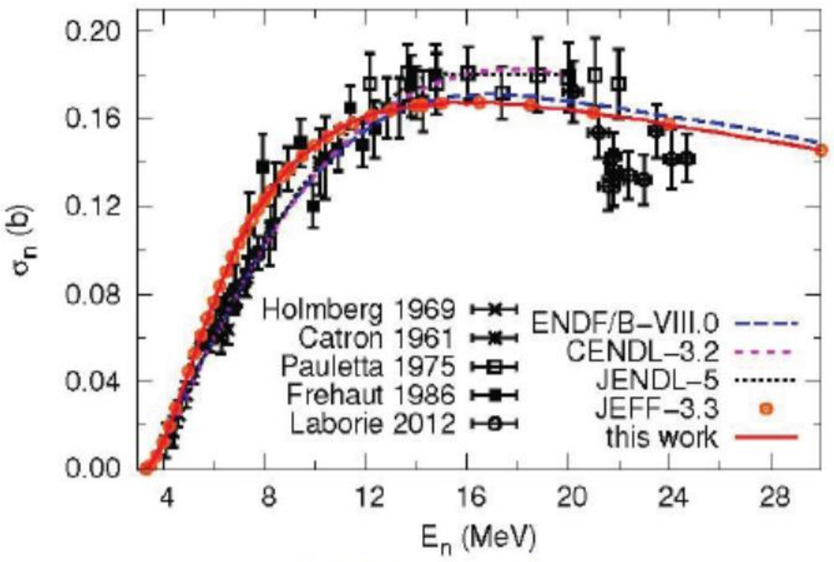
The breakup amplitude:

$$A_{bu}^{\Gamma\alpha\beta}(\theta) = \frac{4\pi m}{3\sqrt{3}} q_0 K^4 e^{\frac{i\pi}{4}} T^{\Gamma\alpha\beta}(p,q), \quad \theta = \tan^{-1}\left(\frac{\sqrt{3}q}{2p}\right)$$

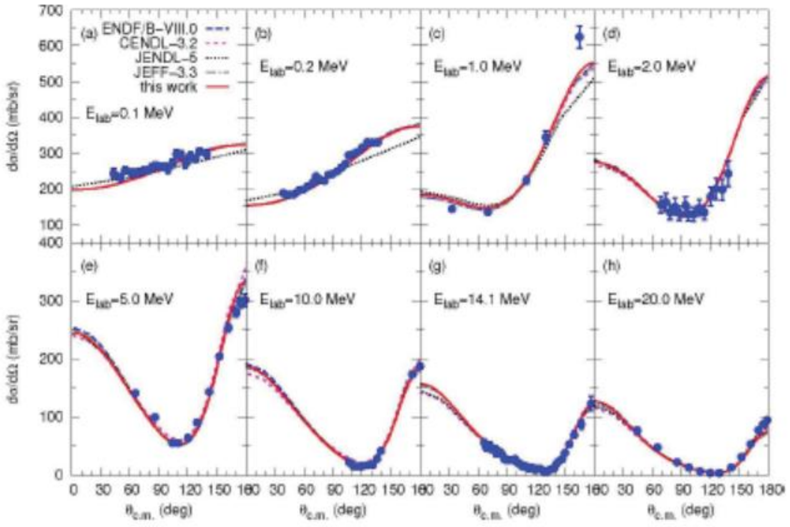
$$T^{\Gamma\alpha\beta}(p,q) \approx e^{i\delta(p_k)}\frac{\mathbb{T}_{1j0,kj}^{\Gamma\alpha\beta}}{p_k q_j q_0} \qquad \mathbb{T}_{1j0,kj}^{\Gamma\alpha\beta} \equiv \frac{\left\langle Z_{1j0}^{\Gamma\alpha\beta}\middle|\mathfrak{U}^{\Gamma}\middle|Z_{kj}^{\Gamma\alpha\beta}\right\rangle}{\sqrt{d_{j_0}d_k d_j}}, \quad \begin{cases} q_0 \in \mathfrak{D}_{j_0} \\ q \in \mathfrak{D}_j \\ p \in \Delta_k^s \end{cases}$$



Total elastic scattering cross sections



d(n,2n)p cross sections

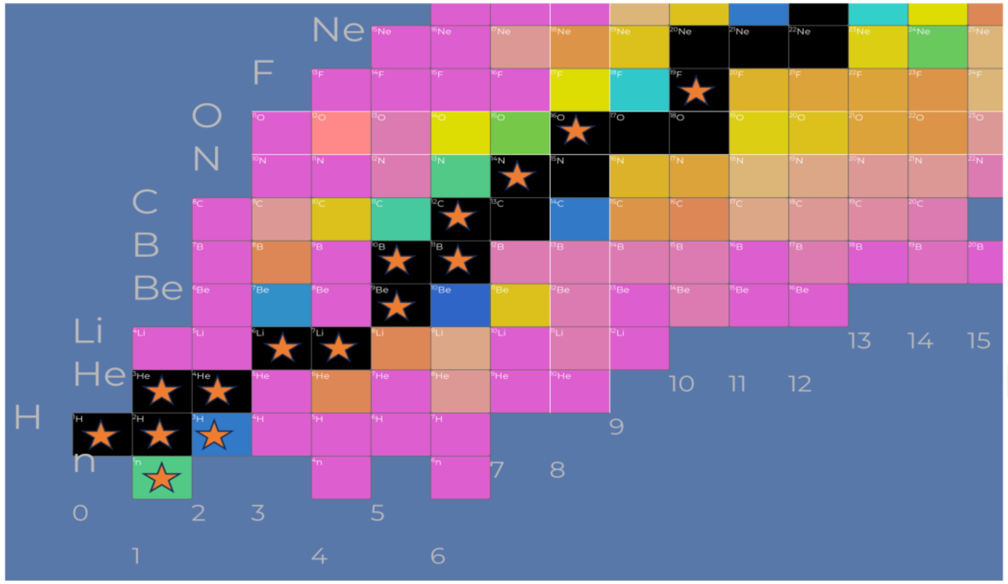


Elastic scattering angular distributions

Atomic Energy Science and Tech.. Vol.56,No5(2022).

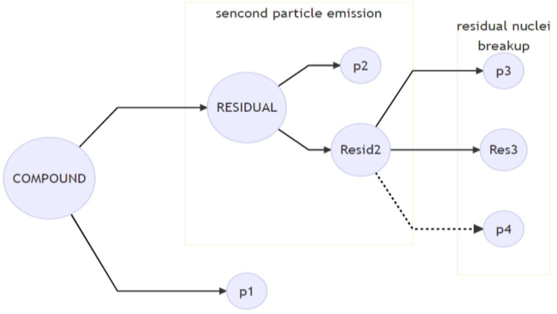
2.2 Improving nuclear data library of light nucleus

- **Neutron induced nuclear reaction dataset for light nucleus are incomplete, only including ^{3,4}He, ^{6,7}Li, ^{9}Be, ^{10,11}B, ^{12}C, ^{14}N, ^{16}O, ^{19}F in CENDL-3.2.**
- **Key steps and technologies:**
  - **Theoretical models beyond R matrix**
  - **Consistent evaluation both experimental and theoretical results for the fast neutron energy**
  - **Nuclear data processing research**



Applying **S**tatistical **T**heory of **L**ight **N**ucleus reactions to predict complete nuclear reaction data, key considerations:

- Must include special but not negligible channels, for example ^{6}Li(n, ddt) with tens of mb cross section
- The number of open levels increase significantly when induced neutron energy as large as 30 MeV
- Providing both cross-sections and energy-angular double differential spectra data
- Understanding reaction mechanism of pre-equilibrium emission and complex particle formation process



1. Dynamics of Compound nuclei
2. Kinematics of emission

$$\sigma_{m_1,k_1}(E_L)=\sum_{j\pi}\sigma_a^{j\pi}(E_L)\left\{\sum_{n=3}^{n_{max}}P^{j\pi}(n)\frac{W^{j\pi}_{m_1,k_1}(n,E^*,\varepsilon_{m_1})}{W^{j\pi}_T(n,E^*)}+Q^{j\pi}(n)\frac{W^{j\pi}_{m_1,k_1}(E^*,\varepsilon_{m_1})}{W^{j\pi}_T(E^*)}\right\}$$

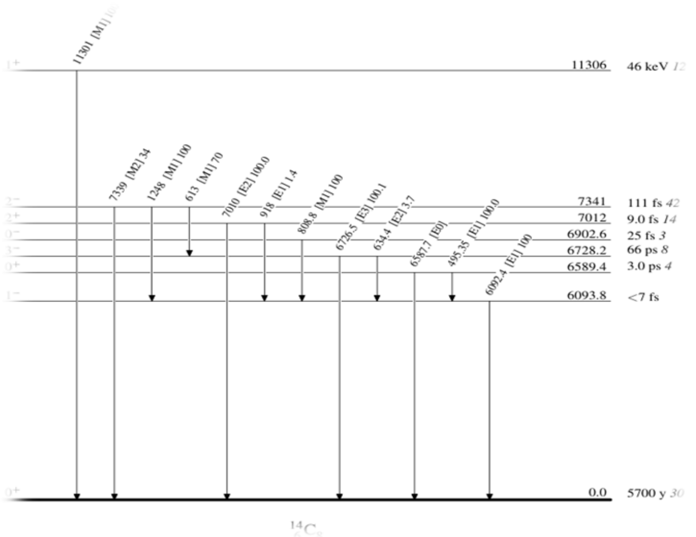
Absorb XS

pre-equilibrium emission

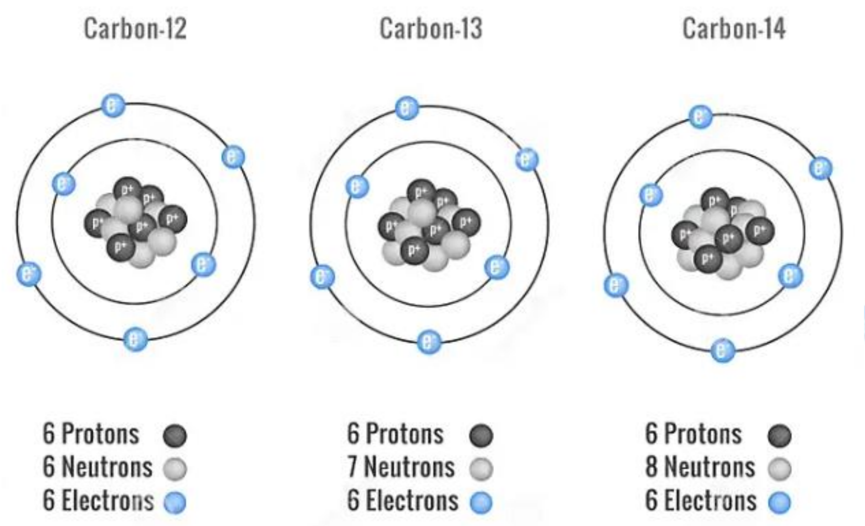
equilibrium emission

Open channels

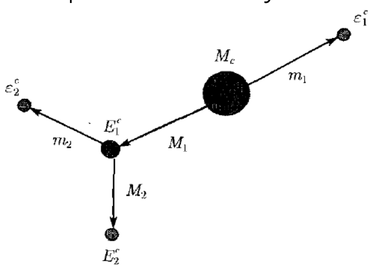
$$
n + {}^{13}C \to {}^{14}C^{*} \to
\begin{cases}
\gamma + {}^{14}C, & E_{th} = 0 \\
n + {}^{13}C \begin{cases} \gamma + {}^{13}C, & k \le 6 \\ 2n + {}^{12}C, & k > 6 \end{cases} & E_{th} = 0 \\
p + {}^{13}B, & E_{th} = 13.6MeV \\
d + {}^{12}B, & E_{th} = 16.5MeV \\
t + {}^{11}B, & E_{th} = 13.4MeV \\
\alpha + {}^{10}Be, & E_{th} = 4.13MeV \\
{}^{5}He + {}^{9}Be \begin{cases} {}^{9}Be, & k = 1 \\ n + 2\alpha, & k > 1 \end{cases} & E_{th} = 12.3MeV \\
2n + {}^{12}C, & E_{th} = 5.33MeV \\
n + p + {}^{12}B, & E_{th} = 18.9MeV \\
n + \alpha + {}^{9}Be, & E_{th} = 11.5MeV \\
2\alpha + {}^{6}He, & E_{th} = 12.1MeV
\end{cases}
$$



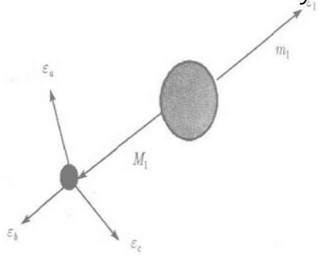
Mass、half life、level width、binding energy…



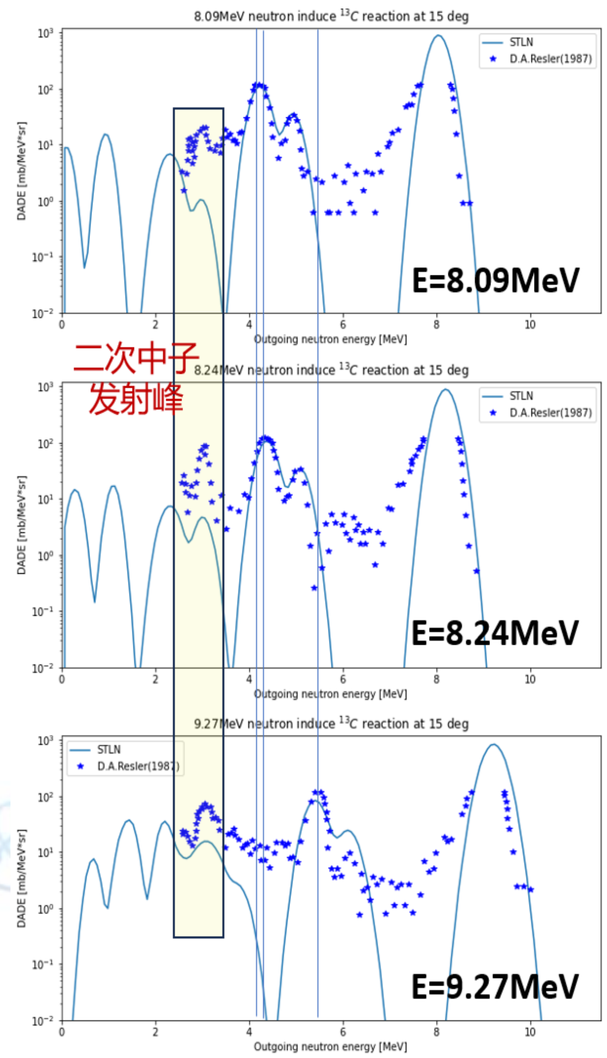
Sequential decay



Simultaneous decay



- Good coincidence to exp. Data of Ohio Unv. for elastic and inelastic peaks at three incident energies.
- The second underestimated to the yellows



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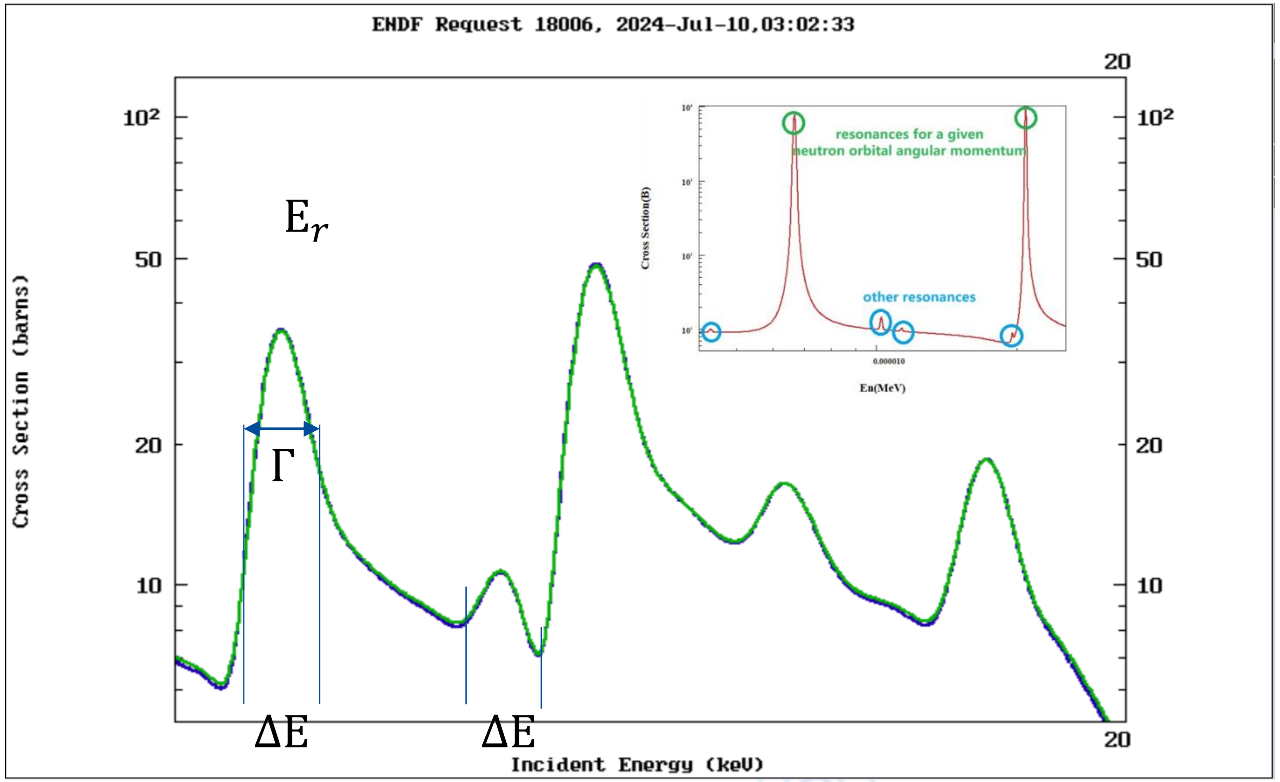
3.1. Resolved Resonance Energy Region – ResIntegralPeak.py

How to quickly evaluate and identify the resonance peak of different libs ?

How to get the integral interval ΔE:

1. For those peaks that are sufficiently high, ΔE= $(E_r + \frac{\Gamma}{2}, E_r - \frac{\Gamma}{2})$, where E_r is the resonance energy and Γ is the FWHM of each peak.
2. For smaller peaks, where the minimum cross-section is greater than half of the maximum value, take the area between two minima points as ΔE.



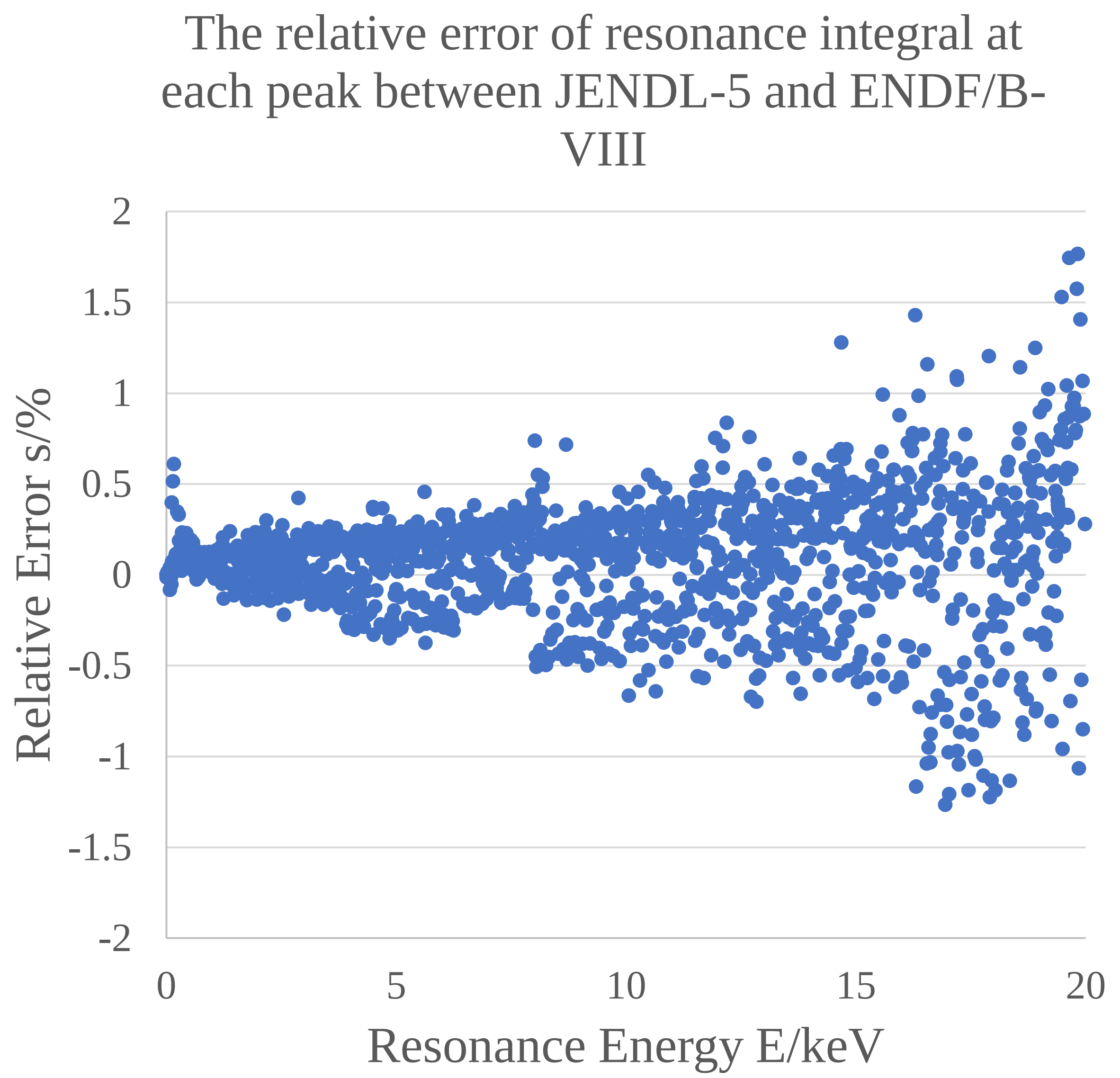
The resonance integral is defined as

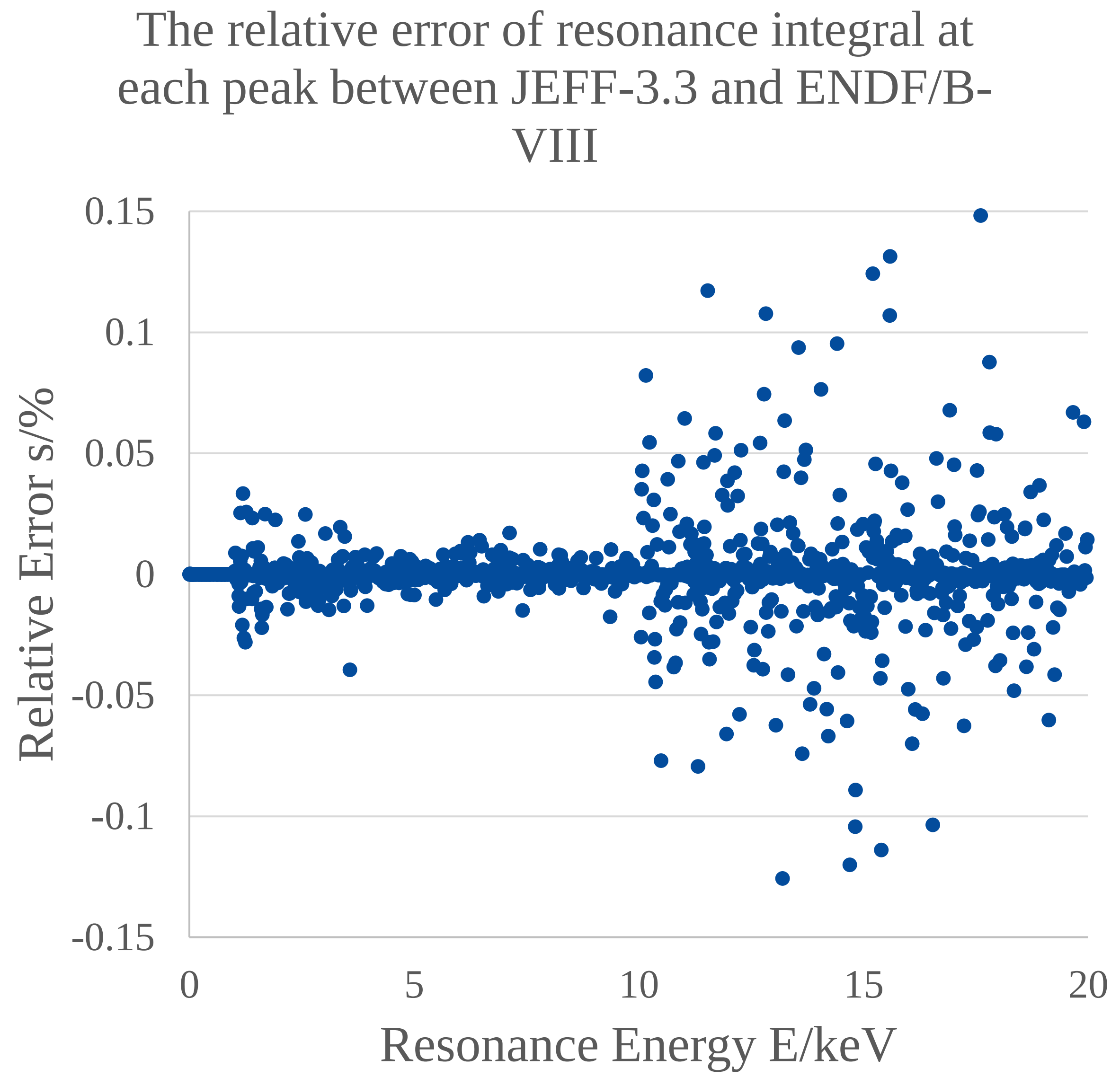
$$RI = \int_{\Delta E} \frac{\sigma_{TOT}(E)}{E} d(E) \text{ (b)}$$

The relative error is calculated as

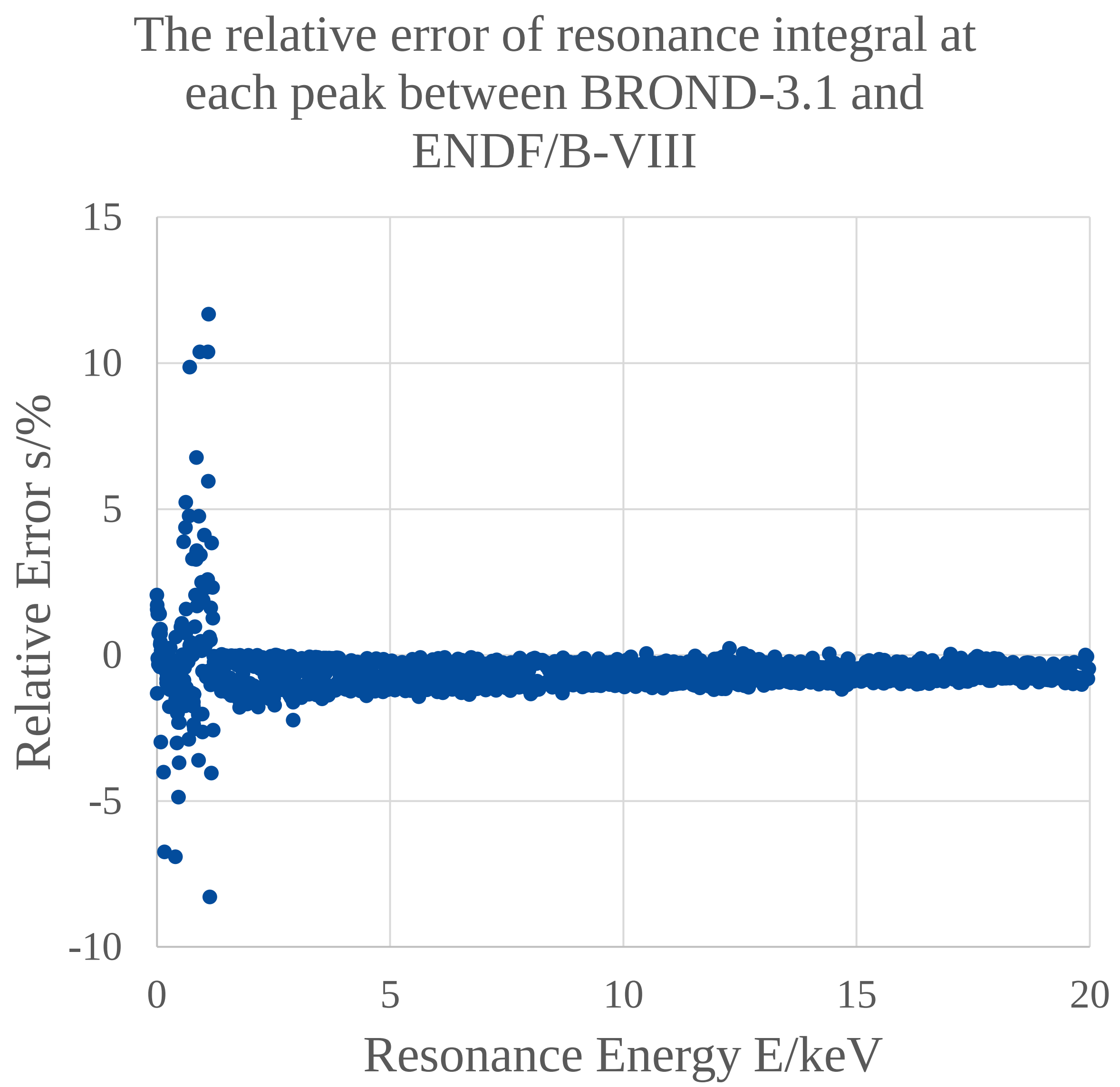
$$s = \frac{RI_{other\ Eval.} - RI_{ENDF/B-VIII}}{RI_{ENDF/B-VIII}} * 100(\%)$$

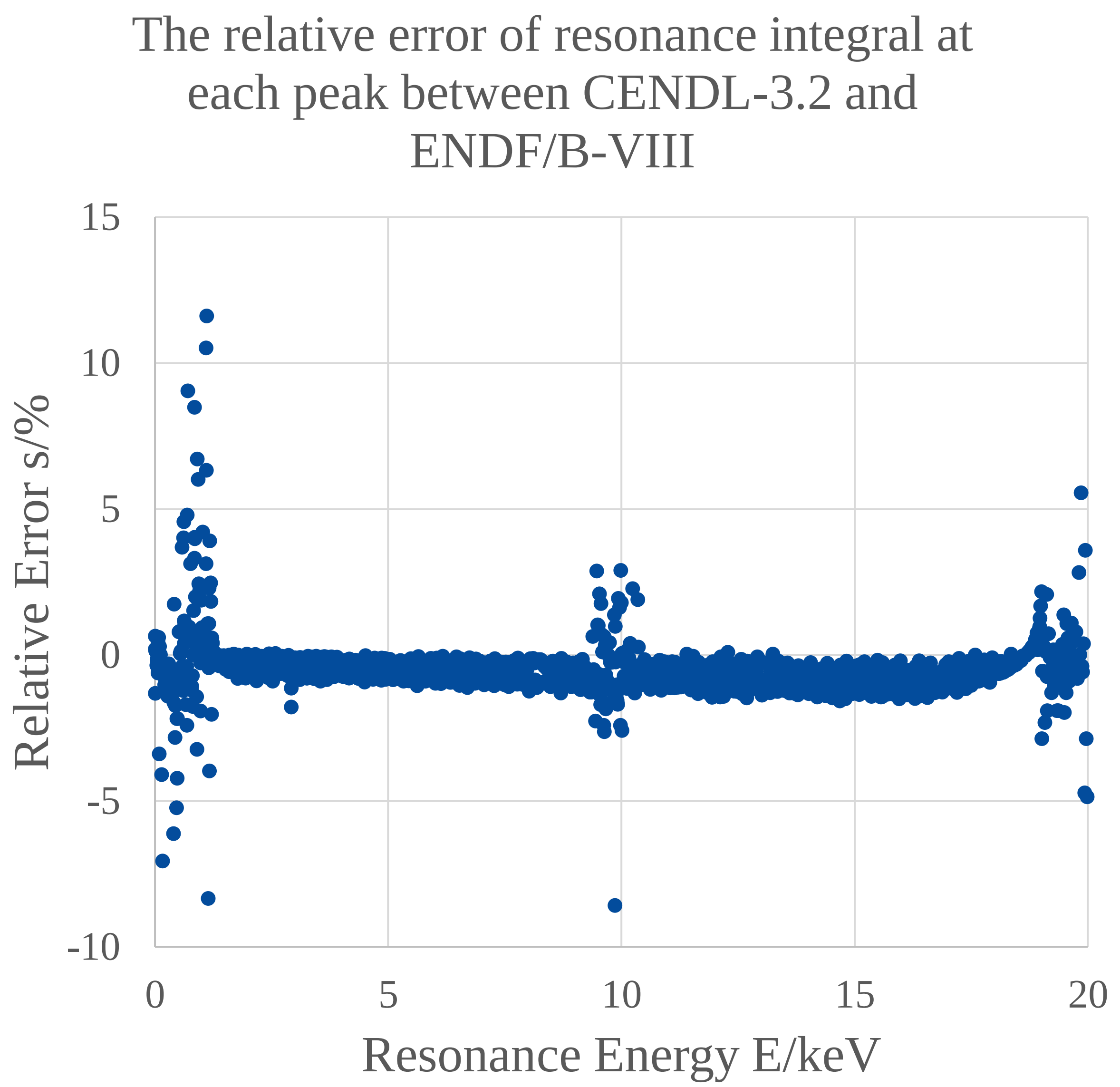
In the resolved resonance region of ^{238}U in ENDF/B-VIII, there are 926 resolved resonances for a given neutron orbital angular momentum. More than 3k resonance energies in (2,151). According to the total cross-section data from IAEA ENDF database, 1650 peaks are found automatically in this region. Some of them are “false peaks” due to calculation, which has been removed from the comparisons.





For JENDL-5 and JEFF-3.3, the relative error of resonance integral in each peak is small, and the resonance peak positions have no significant deviations. However, as energy increases, the deviation between JENDL-5 and ENDF/B-VIII gradually increases, peaked at around 1%.



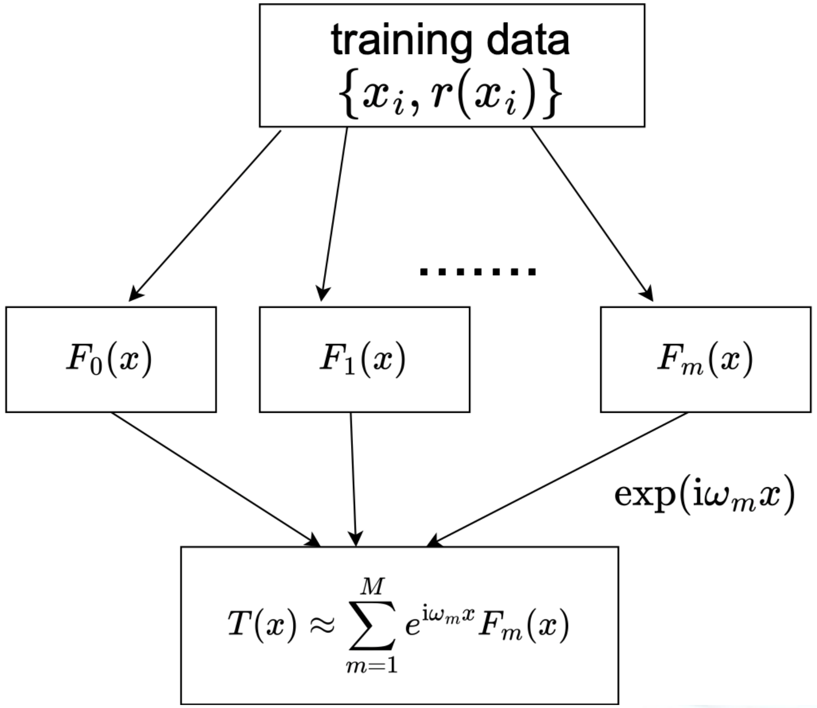


BROND-3.1 and CENDL-3.2 exhibit significant deviations from ENDF/B-VIII below 1.2 keV. These deviations come from both peak values and peak positions. For CENDL-3.2, the deviations near 10 keV and in 19~20 keV are primarily due to peak values, where the peak positions are almost the same.

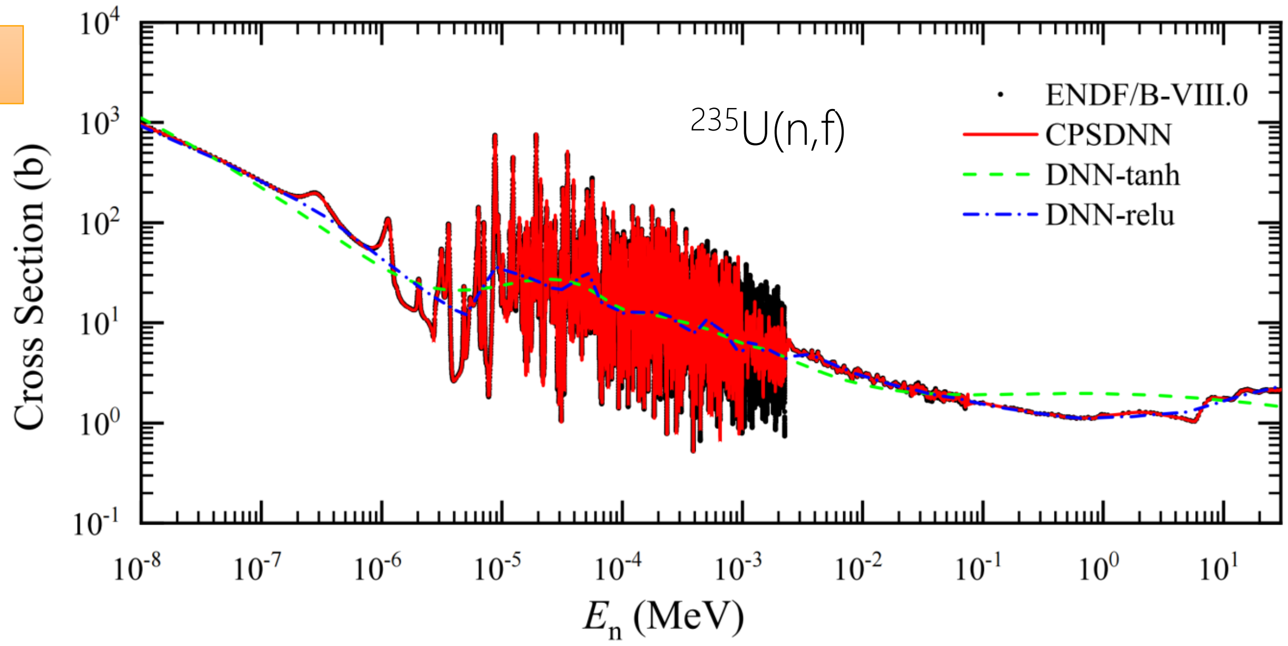
3.2. Resonance Energy Region - AI

- Coupled Phase Shift Deep Neural Network(CPSDNN) Approach for Studying Resonance Cross Sections of ^{235}U(n,f) Reaction

CPSDNN to deal with high-frequency oscillating data



The neural network structure diagram of CPSDNN. Each $F_m(x)$ (m = 0, 1, ..., M) represents a neural network. The T(x) represents the training process of neural network.



The comparison of the raw cross sections, the predicted results of DNNs and CPSDNN for ^{235}U(n,f) reaction.

The black points are the evaluated data derived from ENDF/B-VIII.0. The green and the blue lines are the predicted results of DNNs with the tanh and relu activation functions, respectively.

The red line is the predicted results of CPSDNN.

K. Xu, X.J. Sun*, R.R. Xu*, et al. Phys. Lett. B 855 (2024) 138825

3.3. Real application of Unified Monte Carlo (UMC-B) for n+48Ti

$$p(\sigma) = C\, L(y_E, V_E|\sigma)\, p_0(\sigma|\sigma_C, V_C)$$

$$\langle \sigma_i \rangle = \int_S \sigma_i p(\sigma) d\sigma$$

$$(V)_{ij} = \langle \sigma_i \sigma_j \rangle - \langle \sigma_i \rangle \langle \sigma_j \rangle$$

$$L(y_E, V_E|\sigma) \sim \exp\left\{-\frac{1}{2}[(y - y_E)^T \bullet V_E^{-1} \bullet (y - y_E)]\right\}$$

$$p_0(\sigma|\sigma_C, V_C) \sim \exp\left\{-\frac{1}{2}[(\sigma - \sigma_C)^T \bullet V_C^{-1} \bullet (\sigma - \sigma_C)]\right\}$$

y_e, v_e : measured quantities with "n" elements
σ_C, v_C : calculated using nuclear models with "m" elements

UMC-B：

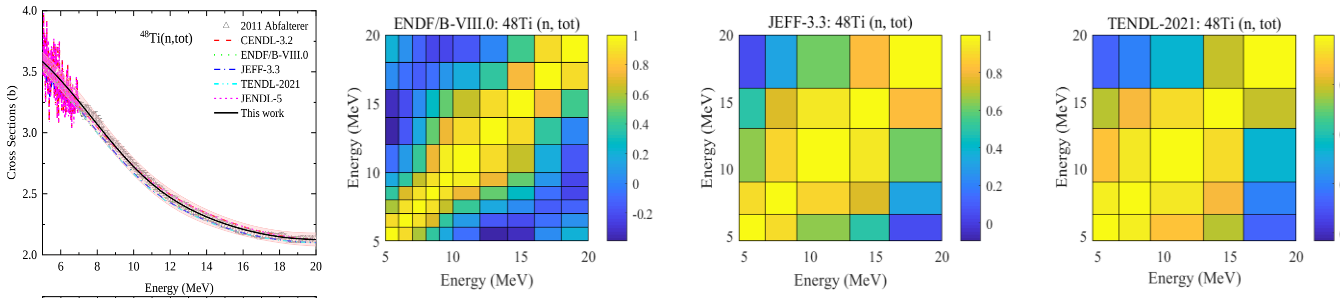
For each random set $\{\sigma_i\}$ we calculate

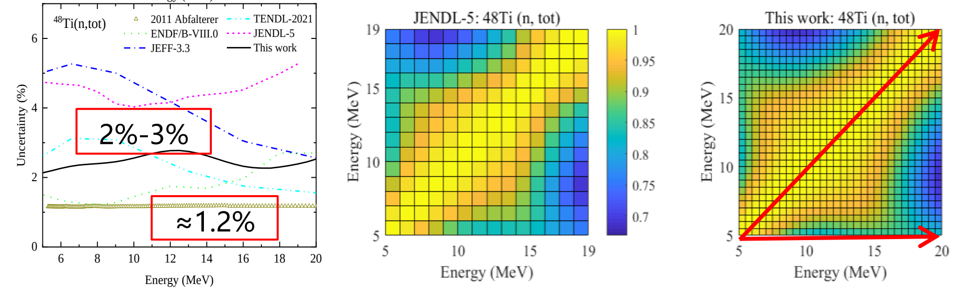
$$\omega_k = \exp\left\{-\frac{1}{2}\left[(y_k - y_E)^T \bullet V_E^{-1} \bullet (y_k - y_E)\right]\right\}$$

$$\sigma_i = \left[\sum_{k=1,K} \omega_k \sigma_{Cik}\right] \Big/ \left[\sum_{k=1,K} \omega_k\right]$$

$$(V_\sigma)_{ij} = \left[\sum_{k=1,K} \omega_k \sigma_{Cik} \sigma_{Cjk}\right] \Big/ \left[\sum_{k=1,K} \omega_k\right] - \sigma_i \sigma_j$$

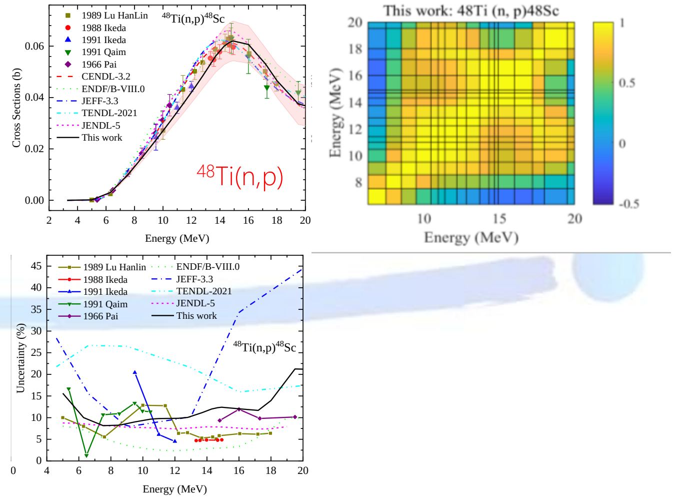
total cross section:



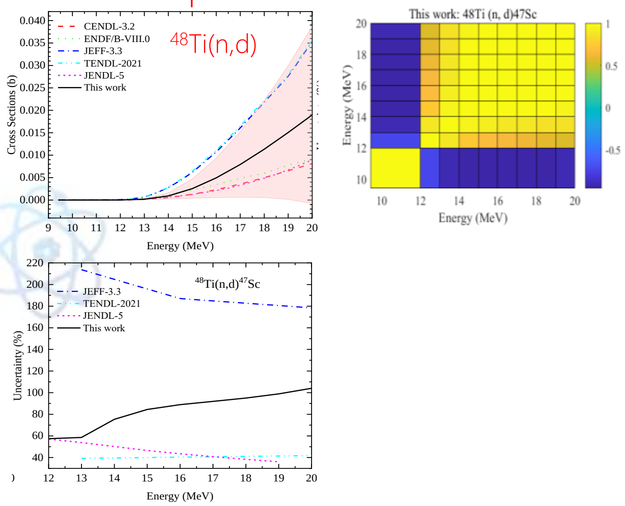


Simultaneously possessing the rationality of mathematics and nuclear reaction physics

rich experimental data:



lack of experimental data:



This work was in collaboration with R. Capote(IAEA),
Chinese Physics C Vol. 48, No. 7 (2024) 074101; doi: 10.1088/1674-1137/ad432c

中国原子能科学研究院 China Institute of Atomic Energy

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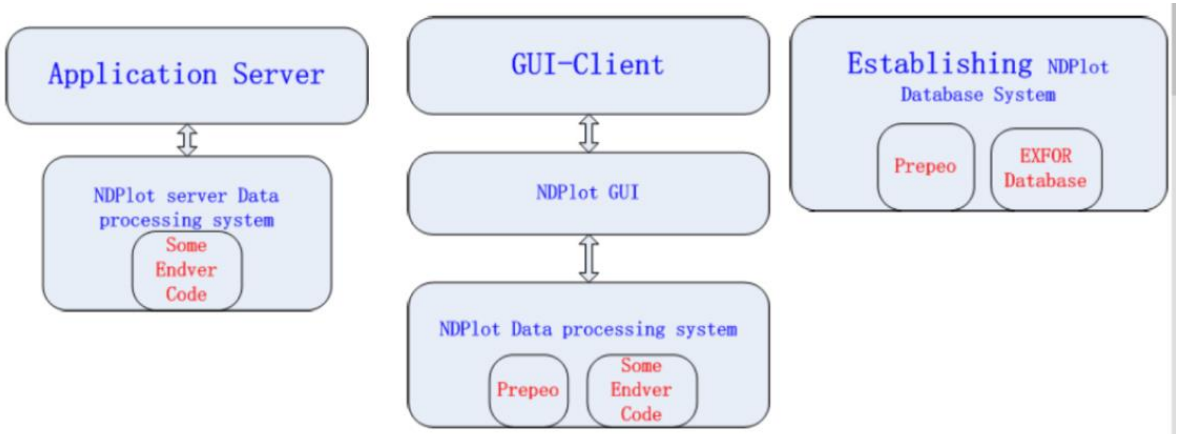
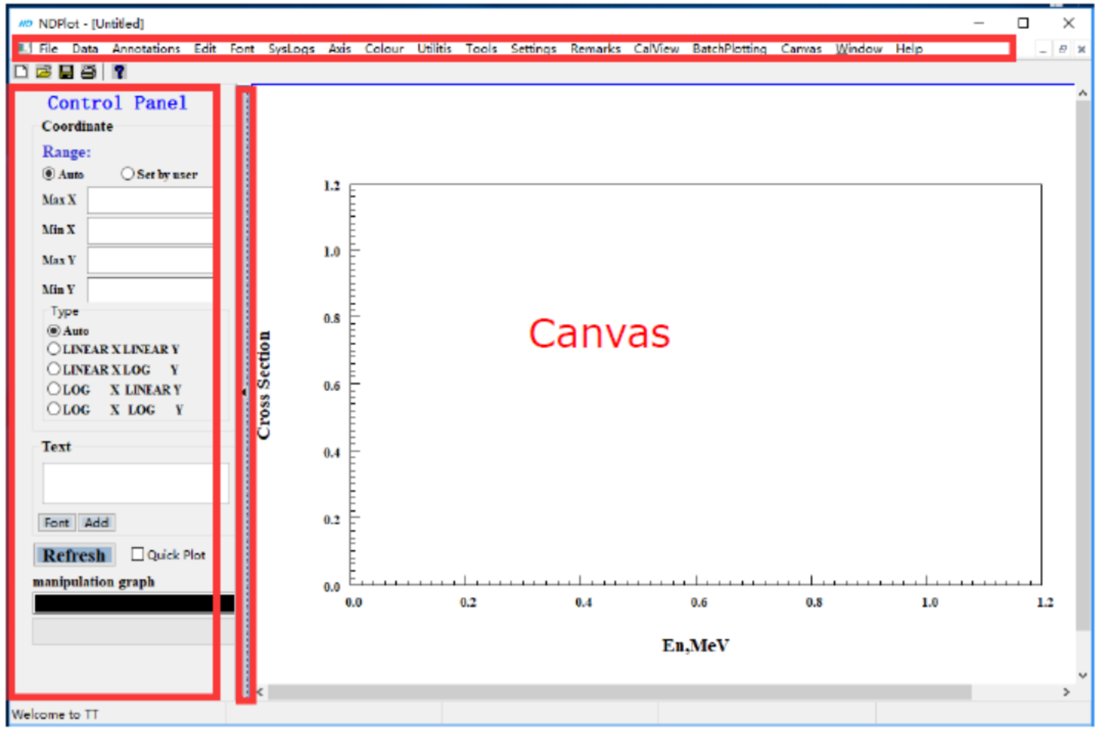
NDPlot by Prof. Jin Yongli is an efficient nuclear data evaluation tool, not only for plotting, but also Integrated application software.

Powerful Batch Plotting
Quick Choice Menu
Ratios of cross sections
Fission yield, covariance... ...

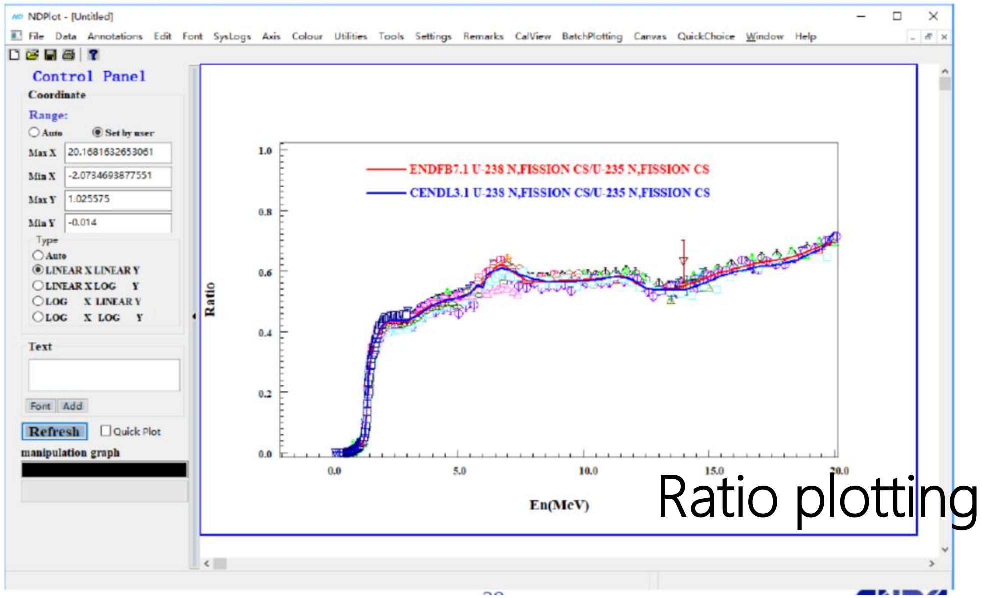


1 Endver : **LSTTAB,X4TOC4.** Prepro: **Convert** ENDF to PENDF

Screenshot



((92-U-238(N,F),,SIG)/(92-U-235(N,F),,SIG))



X4table: A software for extracting key information from original EXFOR documents

GETTABLE0.8

文件 保存 编辑 帮助

X4文件路径 E:/2023/word/x4table/get/n_13-Al-27_p.txt

ENTRY	YEAR	AUTHOR	INSTITUTE	REFERENCE	FACILITY	SOURCE	METHOD	DETECTOR	MONITOR	ENERGY	POINTS
10088	1970	L.Husain	1USAARK	J,PR/C,1,1233,1970	CCW	D-T	ACTIV	GELI	26-FE-56(N,P)25-MN-56,,SIG|13	14.8	1
10186	1971	G.N.Salaita	1USASMU	J,NP/A,170,193,1971	VDG	D-T	ACTIV	GELI	-	14.8	1
10238	1975	D.L.Smith	1USAANL	J,NSE,58,314,197511	DYNAM	P-LI7,P-LI	ACTIV	GELI,NAICR	92-U-235(N,F),,SIG|92-U-238(N,	2.805~9.96	82
10417	1967	J.A.Grundl	1USALAS	J,NSE,30,39,196710	VDG	-	ACTIV	PROPC	13-AL-27(N,P)12-MG-27,,SIG|92	2.44~14.1	12
10431	1971	A.Bari	1USAARK	T,BARI,1971	CCW	D-T	ACTIV	GELI	-	-	0
10776	1976	R.A.Sigg	1USAARK	T,SIGG,1976	CCW	D-T	ACTIV	GELI	13-AL-27(N,A)11-NA-24,,SIG	14.6	1
11196	1962	J.Kantele	1USAARK	J,NP,35,353,62	CCW	D-T	ACTIV	-	29-CU-63(N,2N)29-CU-62,,SIG|2	13.4~14.7	4
11274	1953	E.B.Paul	1CANCRC	J,CJP,31,267,1953	-	D-T	ACTIV	-	-	14.5	1
11453	1959	O.M.Hudson Jr	1USATNC	J,BAP,4,97(G2),5903	-	-	ACTIV	-	13-AL-27(N,P)12-MG-27,,SIG|13	13.03~17.06	32
11474	1952	S.G.Forbes	1USALAS	J,PR,88,1309,1952	ACCEL	D-T	ACTIV	PROPC	-	14.1	1
11484	1959	A.Poularikas	1USAARK	J,PR,115,989,59	CCW	D-T	ACTIV	-	29-CU-63(N,2N)29-CU-62,,SIG	14.8	1
11492	1962	F.L.Hassler	1USABRN	J,PR,125,1011,62	CCW	D-T	-	TELES	1-H-1(N,EL)1-H-1,,DA	14.4	1
11494	1962	F.Gabbard	1USAKTY	J,PR,128,1276,1962	VDG	D-T	ACTIV	NAICR	13-AL-27(N,P)12-MG-27,,SIG	12.4~17.7	14
11512	1967	J.M.Ferguson	1USANRD	J,NP/A,98,65,6705	-	-	ACTIV	NAICR	13-AL-27(N,P)12-MG-27,,SIG,,A\	12.35~13.89	40
11515	1968	N.Ranakumar	1USAGIT	J,NP/A,122,679,1968	-	-	ACTIV	GELI	26-FE-56(N,P)25-MN-56,,SIG	14.4	1
11524	1954	R.L.Henkel	1USALAS	W,HENKEL,54	-	-	-	-	-	2.63~5.18	38
12730	1982	R.C.Harper	1USAAUB	J,JP/G,8,153,8201	DYNAM	D-T	ACTIV,ASSOP	GELI	-	14.2	1
12912	1981	P.Welch	1USAOHO	J,BAP,26,708(G3),198105	VDGT	D-T	ACTIV	GELI	-	20.~23.	2
12969	1987	J.W.Meadows	1USAANL	J,ANE,14,489,1987	CCW	D-T	ACTIV	GELI,FISCH	92-U-235(N,F),,SIG|92-U-238(N,	14.74	1
20280	1957	S.Yasumi	2JPNKON	J,JPJ,12,443,5705	CCW	D-T	ACTIV	PROPC	-	14.1	1
20329	1961	M.Sakisaka	2JPNKON	J,JPJ,16,1869,6110	CCW	D-T	ACTIV	-	-	14.1	1
20799	1973	J.C.Robertson	2UK NPL	J,JNE,27,531,197308	VDG	D-T	ACTIV,COINC	COIN,PROPC,NAICR	26-FE-56(N,P)25-MN-56,,SIG	14.78	1
20822	1972	J.C.Robertson	2UK NPL	J,JNE,26,(1),1,1972	VDG	D-D	TOF,ACTIV	SOLST	-	4.3~5.27	18
20842	1978	P.Andersson	2SWDLND	R,LUNF-D6-3021,7811	VDG	D-T	ACTIV	GELI,LONGC	1-H-1(N,EL)1-H-1,,SIG	14.9	1
20867	1978	T.B.Ryves	2UK NPL	J,JP/G,4,(11),1783,78	VDG	D-T	ACTIV	COIN,PROPC,NAICR,SOLST	26-FE-56(N,P)25-MN-56,,SIG	14.65~19.	6

- •Python language
- •Tkinter package
- •Exfor X4 file was downloaded from IAEA website, X4 CD, etc.
- •Keywords: Entry, Year, Author, Institute, Reference, Facility, Source, Method, Detector, Monitor, Energy, Points
- •Output: Text, Excel.

By Tao Xi et al.

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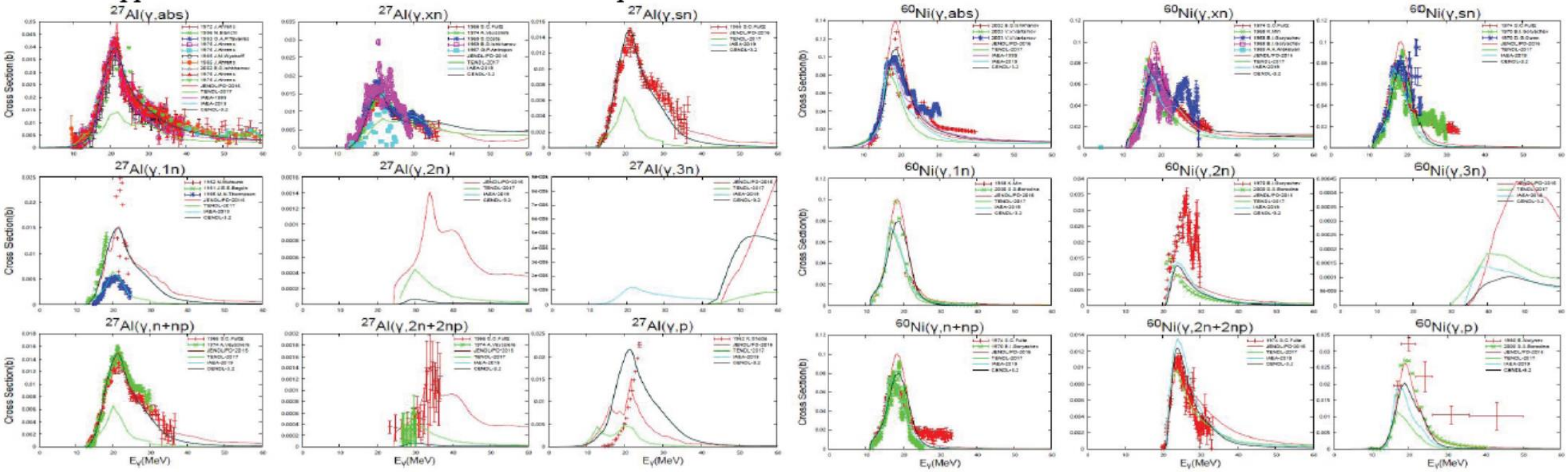
Photonuclear data library

- ✓ All of the photonuclear data are mainly evaluated based on the theoretical calculations with the Chinese photonuclear reaction codes **GLUNF** for the light 6 nuclei and **MEND-G** for the medium-heavy **264** nuclei with the standard ENDF-6 format.
- ✓ The incident photon energies for the medium-heavy nuclei are up to **200MeV**and the n, p, d, t, He-3, α are considered to totally 18th particle emission reactions in the MEND-G code. Moreover, the new measurements.
- ✓ To ensure the availability and reliability of the PD file, nuclear data processing code system NJOY2016 and MCNP6 are used to verify and validate the PD library. The testing results show that the data structure of each nuclide is complete, the data content is reasonable, and can be applied to the simulation of Monte Carlo transport.



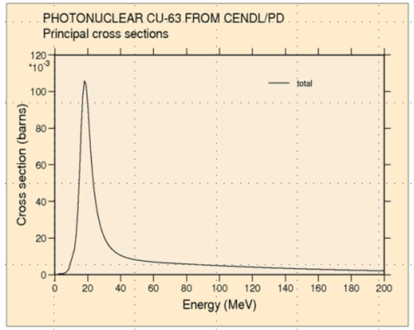
The comparisons the photonuclear data of CENDL-PD, JENDL/PD-2016, TENDL-2017, IAEA/PD-2019 and the experimental data for ^{27}Al and ^{60}Ni.

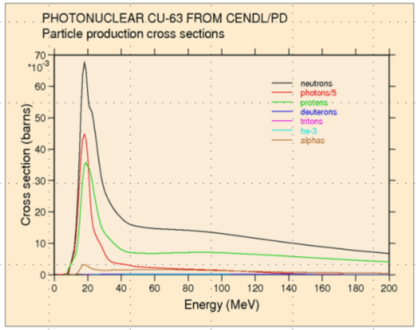
Supported by IAEA CRP contract No. 20466

Process 1: ACE-file generation
Process 2: ACE-file verification
Benchmarking 3: ACE-file V&V

Ping Liu, et al., Ann. Nucl. Ene. 2024

ENDF → NJOY → ACE

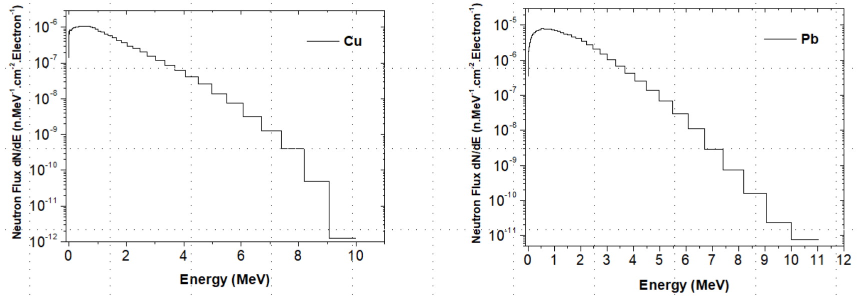




266 materials from CENDL/PD-b can be generated the ACE files.

ACE file → Simple problem M-C simulation → V&V

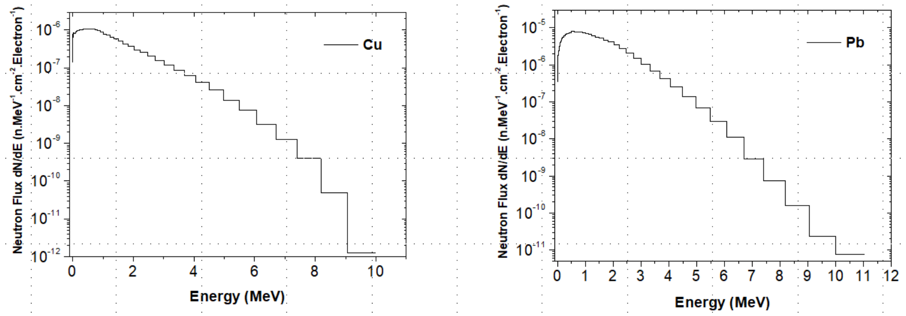
Simple problem: 20 MeV electrons on a cylindrical target, tallies neutron flux



ACE files of CENDL/PD-b can perform the Monte Carlo simulation and give reasonable results.

ACE file → Simple problem M-C simulation → V&V

Simple problem: 20 MeV electrons on a cylindrical target, tallies neutron flux



ACE files of CENDL/PD-b can perform the Monte Carlo simulation and give reasonable results.

Benchmark (Barber and George experiment) + **M-C simulation**

W. C. BARBER and W. D. GEORGE, "Neutron Yields from Targets Bombarded by Electrons," Phys. Rev., 116, 1551 (1959). http://dx.doi.org/10.1103/ Phys Rev.116.1551.

Tallies the neutron yields per incident electron for a variety of primary electron energies, target materials, and thicknesses.

Testing material：C、Al、Cu、Ta、Pb

Conclusion:

1. The results of C, Cu, Ta from CENDL/PD-b are in good agreement with the experimental values, all within the uncertainty of the experimental data.
2. the results of Al and Pb for all photonuclear libraries are lower than experimental values, and preliminary analysis for the reason of underestimation was performed.
3. More experimental validation for photonuclear libraries is still needed.

New Evaluation Project and Data in CENDL-4.0

Motivation: Precision, Total number, Types

the coming 2025

ID	Reaction	JENDL-5 2021	ENDF/B-VIII.0 2018	JEFF-3.3 2017	CENDL-3.2 2020	CENDL-4.0 2025	BROND-3.1 2016	TENDL 2021
1	Photo-Nuclear Data (G)	2684	163	0	0	266	0	2804
2	Photo-Atomic Interaction Data (PHOTO)	100	100	0	0	0	0	0
3	Radioactive Decay Data (DECAY)	4071	3821	3852	0	2354 (A=66~172)	0	0
4	Spontaneous Fission Product Yields (S/FPY)	10	9	3	0	9	0	0
5	Atomic Relaxation Data (ARD)	100	100	0	0	0	0	0
6	Incident-Neutron Data (N)	795	557	562	272	410	372	2813
7	Neutron-Induced Fission Product Yields (N/FPY)	31	31	19	0	31	0	0
8	Thermal Neutron Scattering Data (TSL)	62	34	20	0	0	0	0
9	Electro-Atomic Interaction Data (E)	100	100	0	0	0	0	0
10	Incident-Proton Data (P)	239	49	0	0	78	0	2812
11	Incident-Deuteron Data (D)	9	5	0	0	0	0	2903
12	Incident-Triton Data (T)	0	5	0	0	0	0	2810
13	Incident-He3 Data (He3)	0	3	0	0	0	0	2809
14	Incident-Alpha Data (He4)	18	1	0	0	0	0	2808
15	Activation Data	Special purposed lib			0	818		

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Herbert Muether (Tue. Uni.) … …

Thank you for your attention!