Status of CENDL Project

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I. CENDL Project

The CENDL Project was initiated in the 1970s, led by the China Nuclear Data Centre (CNDC) and the China Nuclear Data Coordination Network. The main output of the project is the CENDL library.

There are 6 versions of CENDL from 1985 to 2020. The new version is coming.

List of the Chinese Evaluated Nuclear Data Library:

CENDL-1	1985version	36	
CENDL-2	1992version	68	
CENDL-3	2000version	214	
CENDL-3.1	2009version	245	
CENDL-3.2 β0	2016version	250	
CENDL-3.2	2019version	272	(June 12.2020)

II. New CENDL

the new evaluations and measurements for the next CENDL version has been started since 2021 and new CENDL will be completed by the end of 2025, where the neutron data will cover 410 materials and include 150 covariance files for cross sections.
Besides the neutron data, 6 sub-libraries will also be presented, including photonuclear, activation, decay, fission yield, TSL and Proton data.

No	Sub-library	CENDL - 3.2 2020	CENDL - 4.0 2025
1	Incident - Neutron Data (N)	272	**410**
2	Photo - Nuclear Data (G)	0	**264**
3	Radioactive Decay Data (DECAY)	0	**2354 (A = 66~172)**
4	Activation Data	0	**818**
5	Fission Product Yields	0	**40**
6	Thermal Neutron Scattering Data (TSL)	0	**20**
7	Incident - Proton Data (P)	0	**78**

II. New CENDL

2.1 Neutron Data

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

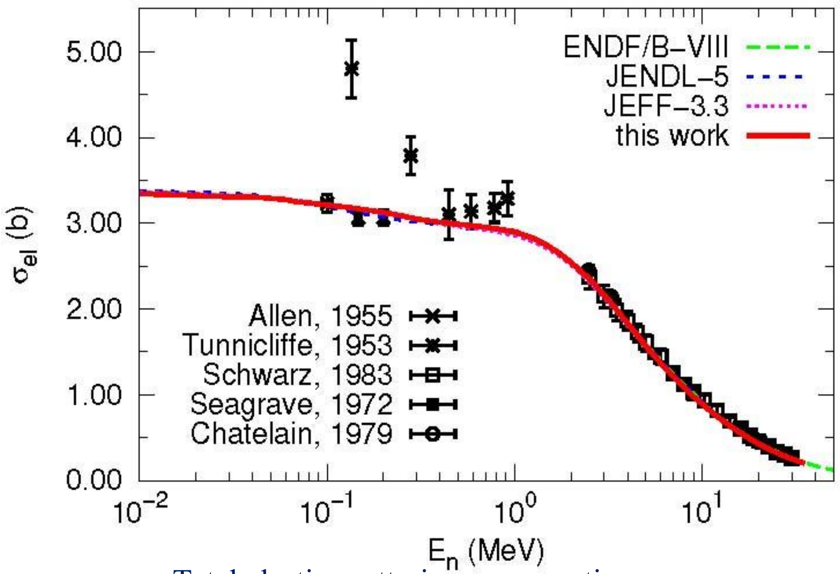
light elements: ^{6}Li, ^{9,10,11}B, ^{12,13,14,15}C, ^{14,15}N

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

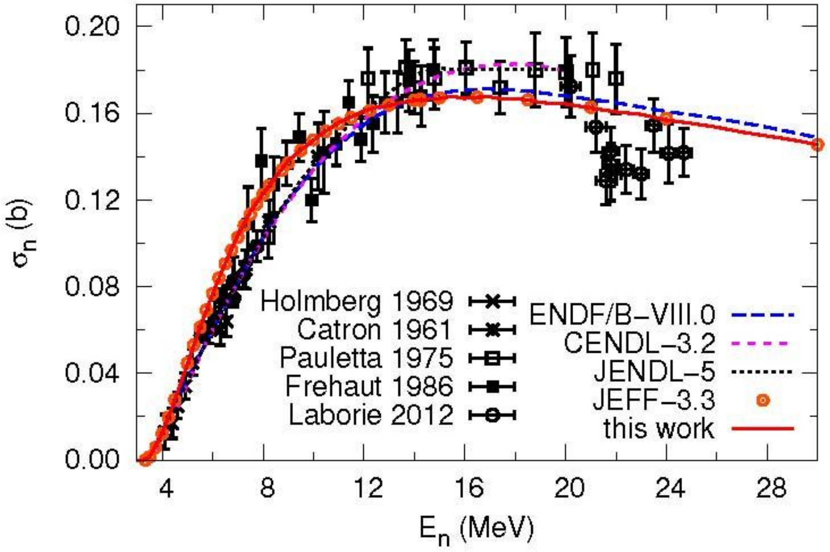
Actinides: ^{235,238}U, ^{239,240,241}Pu

Evaluation for n+^{2}H

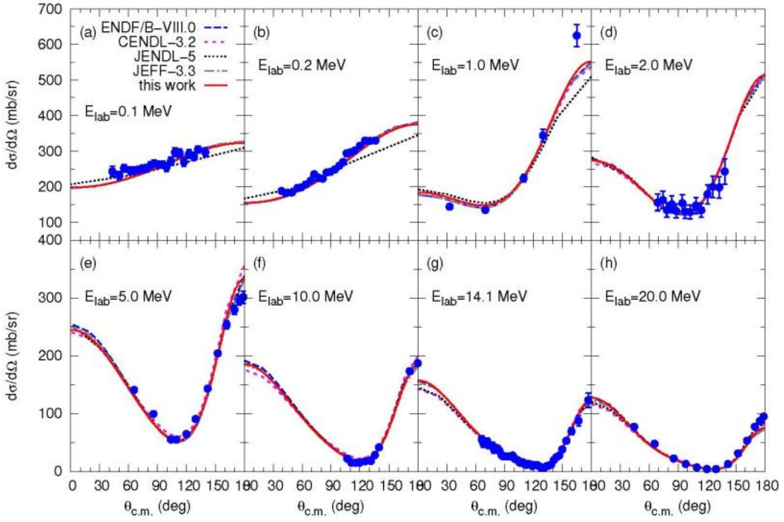
The ^{2}H neutron nuclear data is re-evaluated by solving the Faddeev-AGS equation, elastic scattering and breakup reaction are calculated and the new neutron cross sections, angular distribution and energy-angle distribution of deuterium are given and in good agreement with experiments.



Total elastic scattering cross sections



d(n,2n)p cross sections

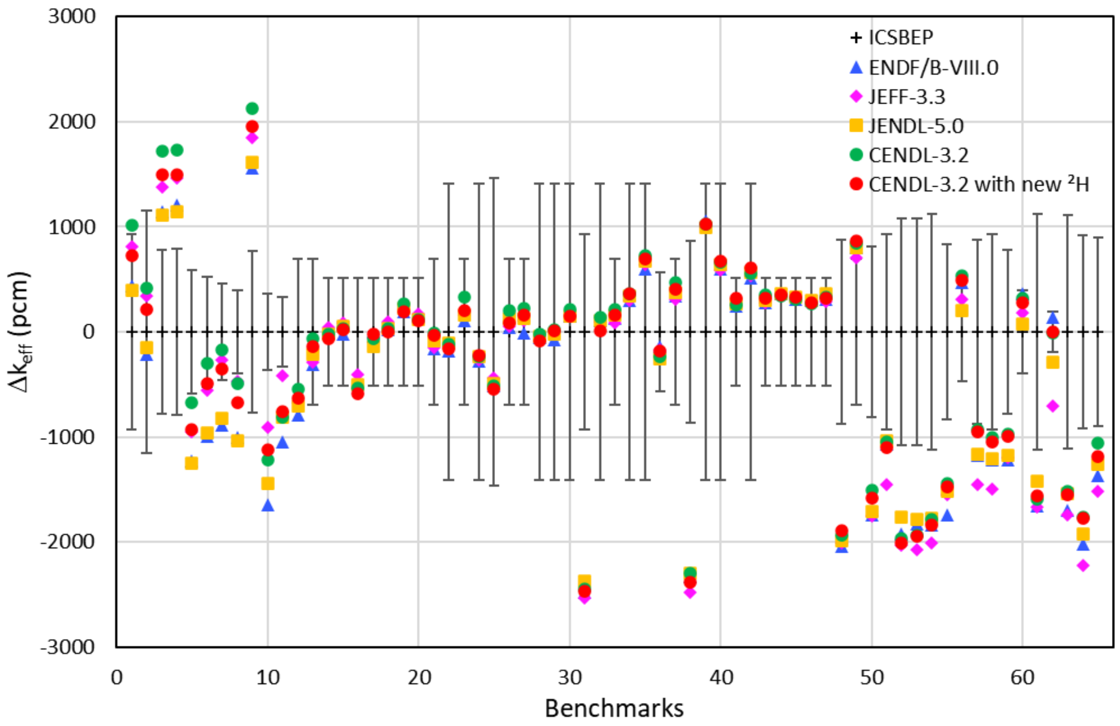


Elastic scattering angular distributions

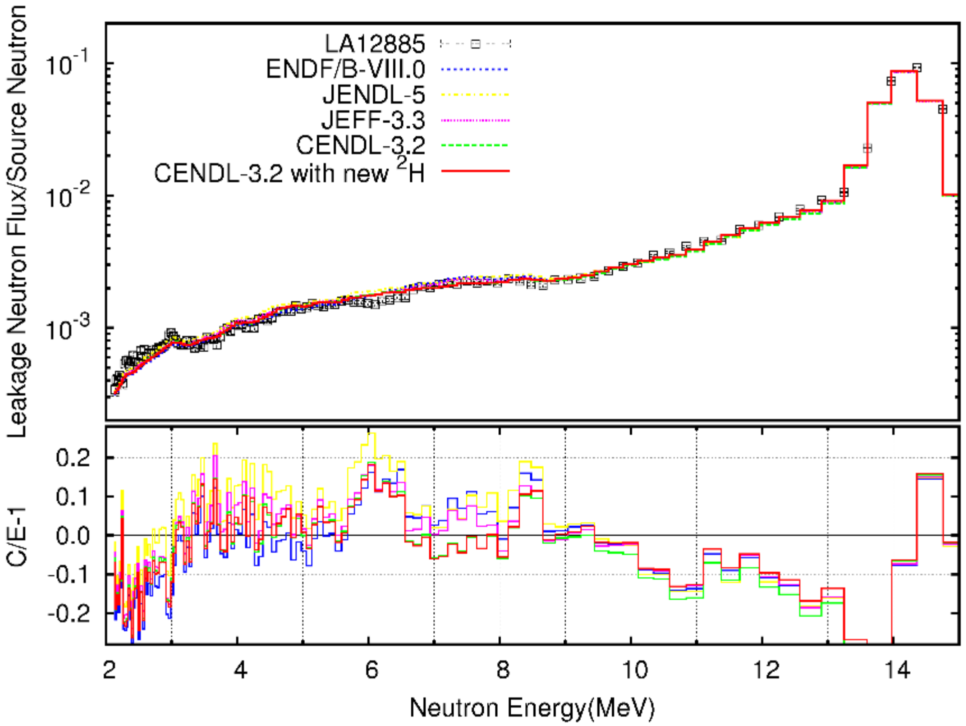
Atomic Energy Science and Tech.. Vol.56,No5(2022).

65 high sensitivity criticality benchmarks were selected to test new evaluation of deuterium. Among all the 65 criticality benchmarks, the chi-square of the results using CENDL-3.2 and the re-evaluated ^{2}H nuclear data is the smallest.

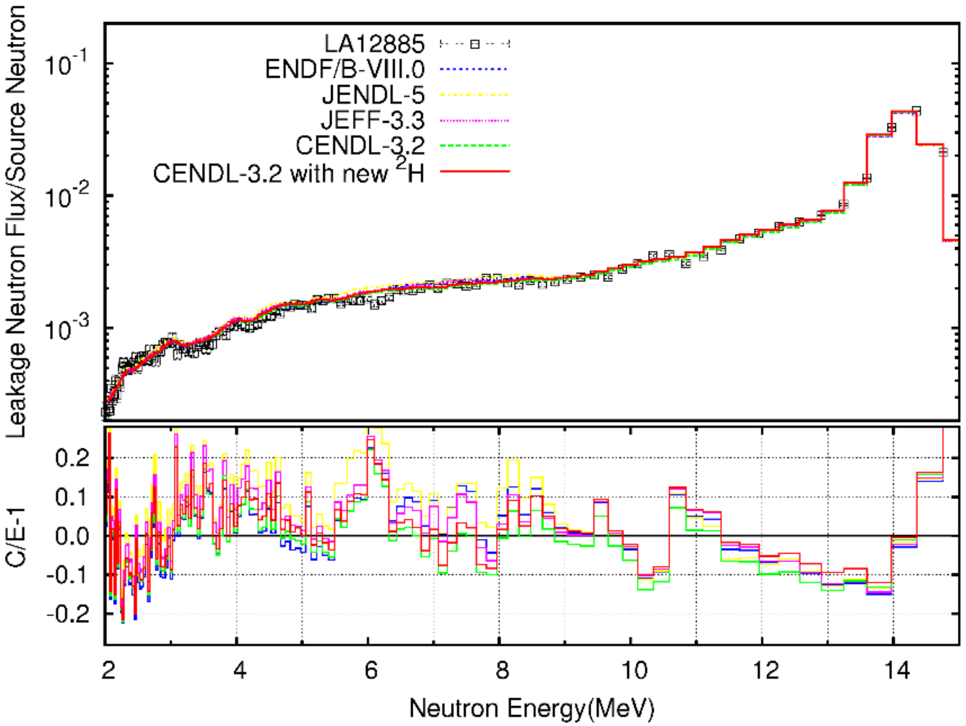
Type	Cases	Quantity	CENDL-3.2 with new ^{2}H	CENDL-3.2	ENDF/B-VIII.0	JEFF-3.3	JENDL-5.0
FAST	7	Δk_{eff} (pcm)	-587	-548	-678	-974	-784
		STDEV (pcm)	851	847	991	950	797
		χ2	1.35	1.32	1.86	3.97	1.74
INTER	3	Δk_{eff} (pcm)	-1451	-1493	-1725	-1288	-1543
		STDEV (pcm)	896.63	851.64	720.81	1107.37	783.67
		χ2	7.39	8.15	12.69	5.15	9.55
MIXED	11	Δk_{eff} (pcm)	-1665	-1635	-1733	-1812	-1637
		STDEV (pcm)	402.42	400.41	348.25	352.75	353.41
		χ2	3.23	3.11	3.52	3.77	3.18
THERM	44	Δk_{eff} (pcm)	241	307	138	235	158
		STDEV (pcm)	503.57	503.50	527.75	467.19	525.37
		χ2	0.68	0.69	0.80	0.58	0.80
ALL	65	Δk_{eff} (pcm)	-304	-280	-344	-378	-324
		STDEV (pcm)	901	916	917	948	876
		χ2	1.49	1.51	1.92	1.70	1.71



The leakage neutron spectra were calculated for Lawrence Livermore pulsed spheres. In 7.5-15 MeV, the elastic scattering channel makes most contribution. The results of the re-evaluated ^{2}H show better agreement with experiment than those of CENDL-3.2.



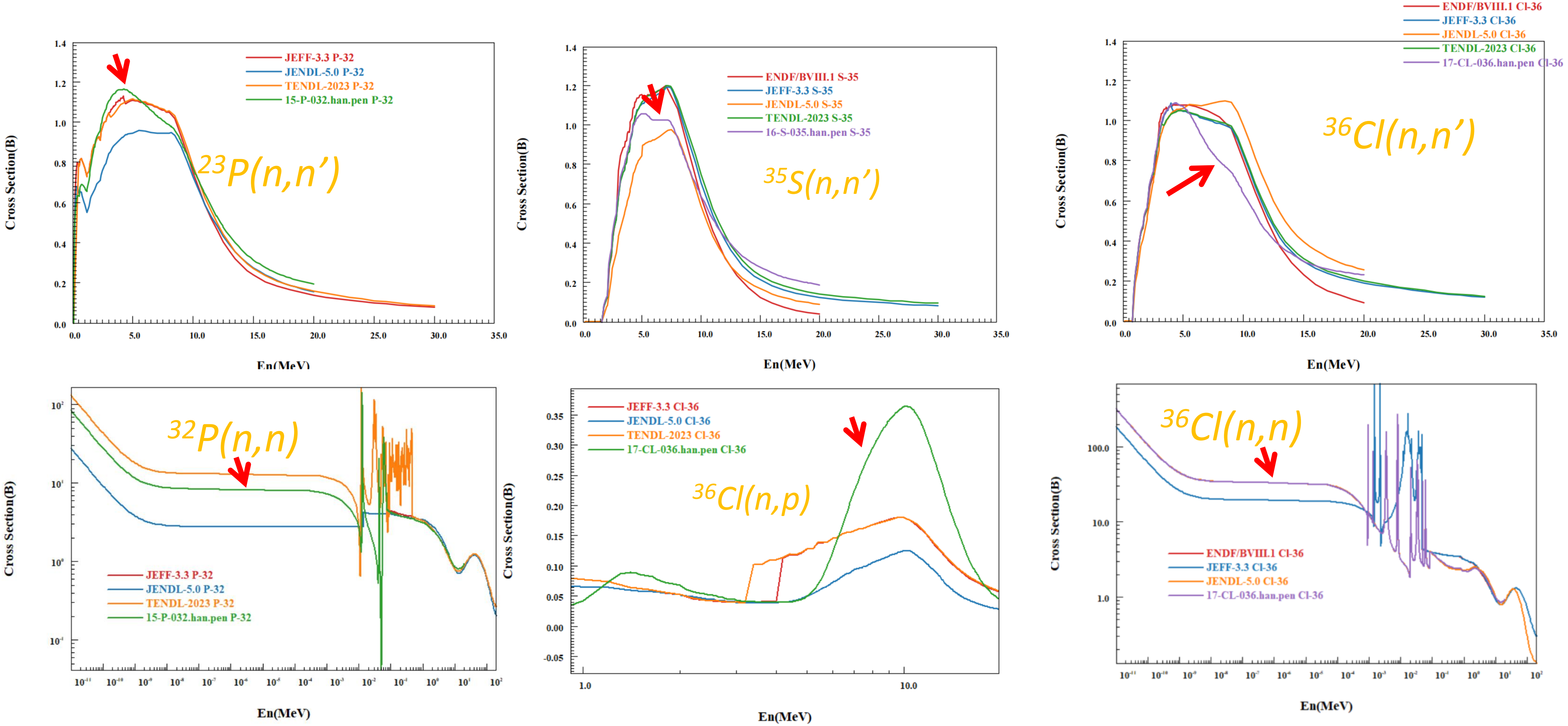
Leakage neutron spectra for the LLNL Pulsed Sphere, D2O (1.2 mfp) benchmark



Leakage neutron spectra for the LLNL Pulsed Sphere, D2O (2.1 mfp) benchmark

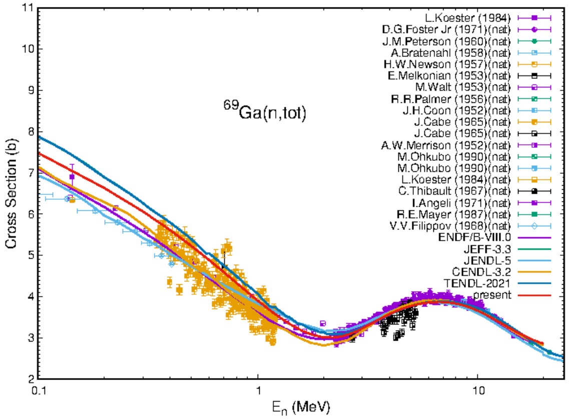
- Evaluation for the n+^{36}Cl、^{32,33}P、^{35}S

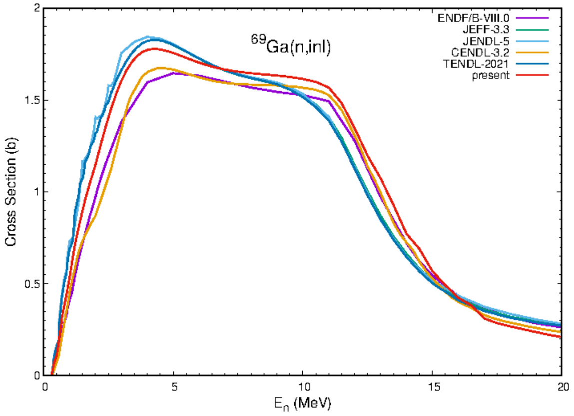
New evaluations have been conducted for the unstable nuclei ^{36}Cl, ^{32,33}P, and ^{35}S. These isotopes lack experimental data. The evaluated results show good agreement with data from other nuclear reaction libraries.

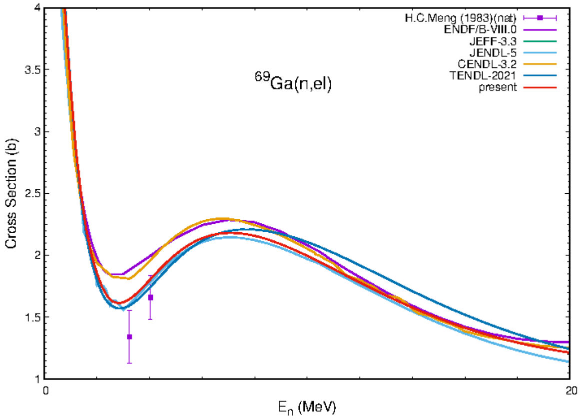


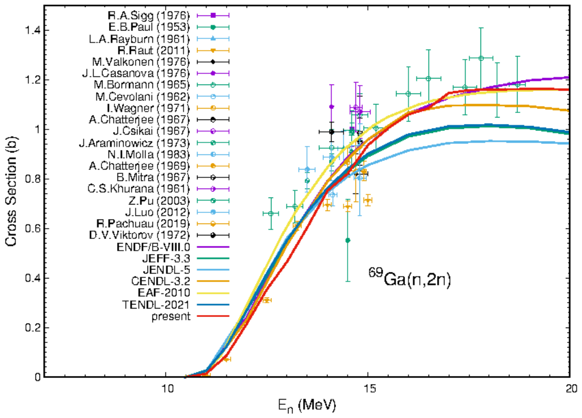
Evaluation for n+^{69}Ga

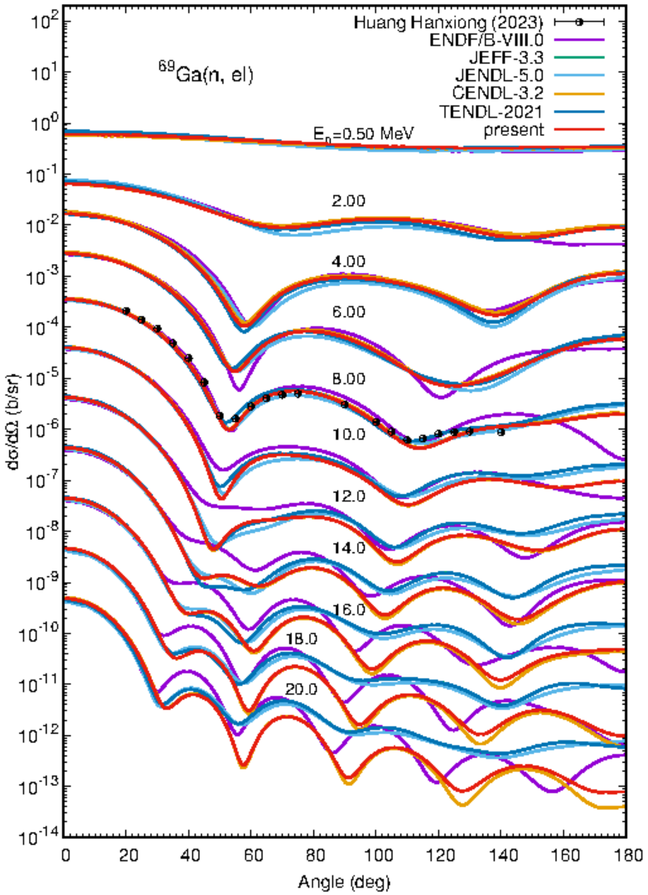
The evaluations for the n+^{69}Ga reactions, including (n,t), (n,el), (n,inl), (n,2n), (n,p), (n,α), and (n,γ) reactions. Covered data of angular distribution and double differential cross section (DDCS) for each reaction channel.

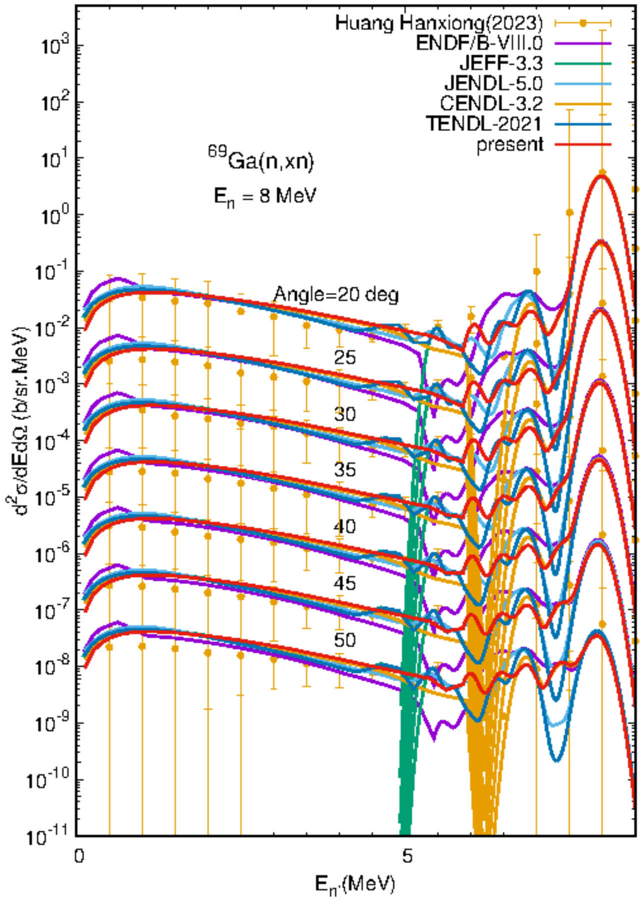




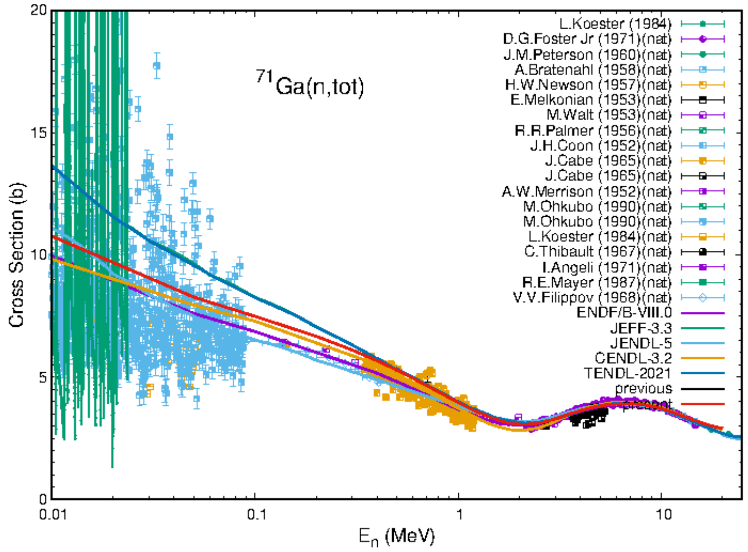


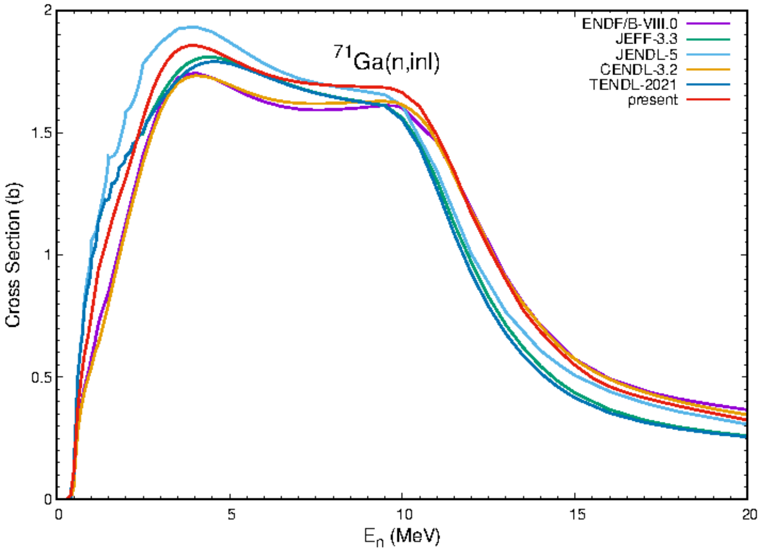


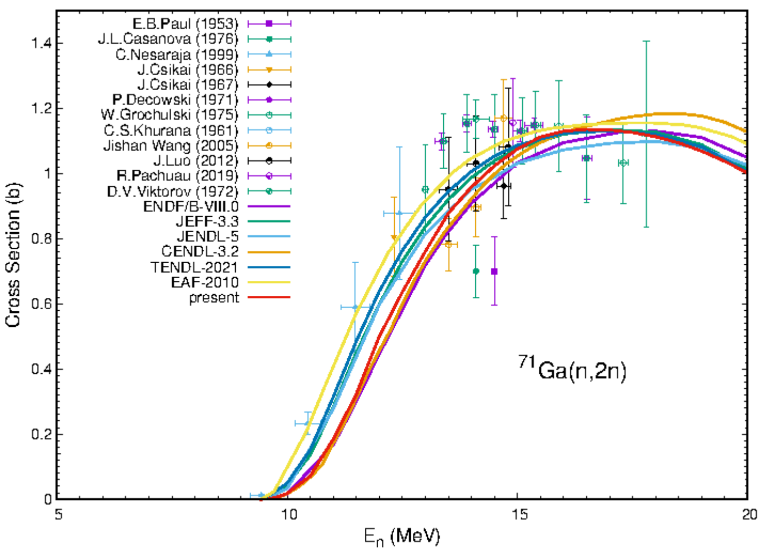


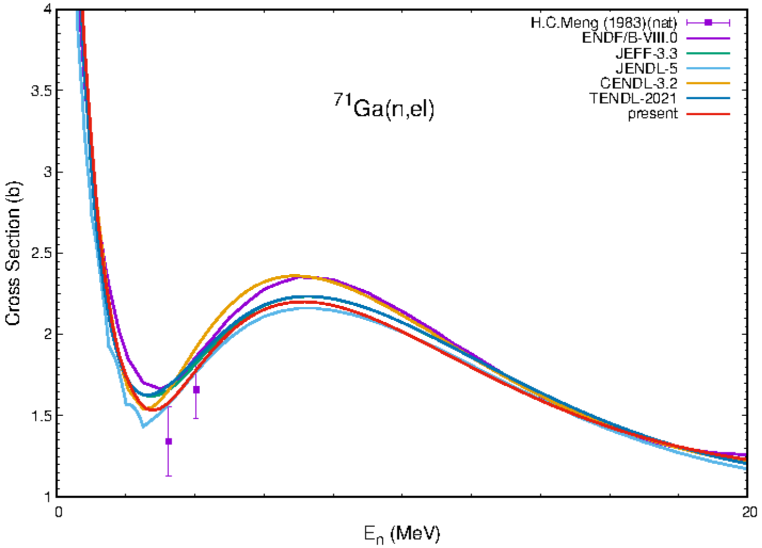


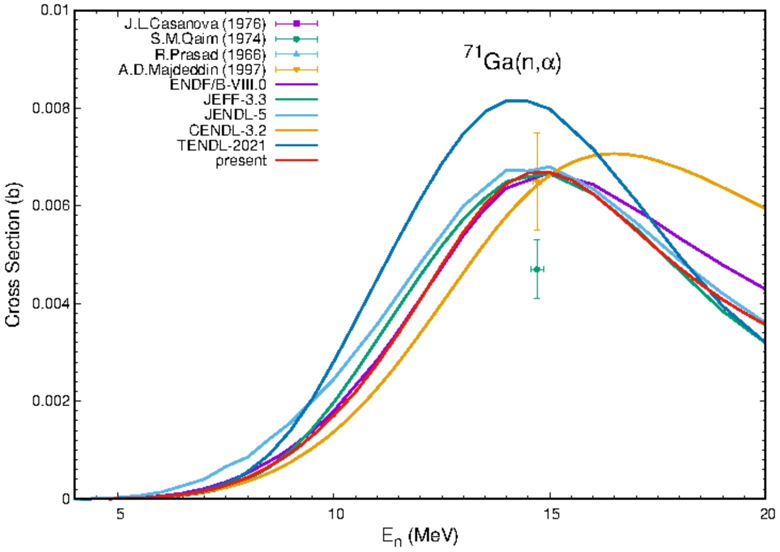
- **Evaluation for n+^{71}Ga**

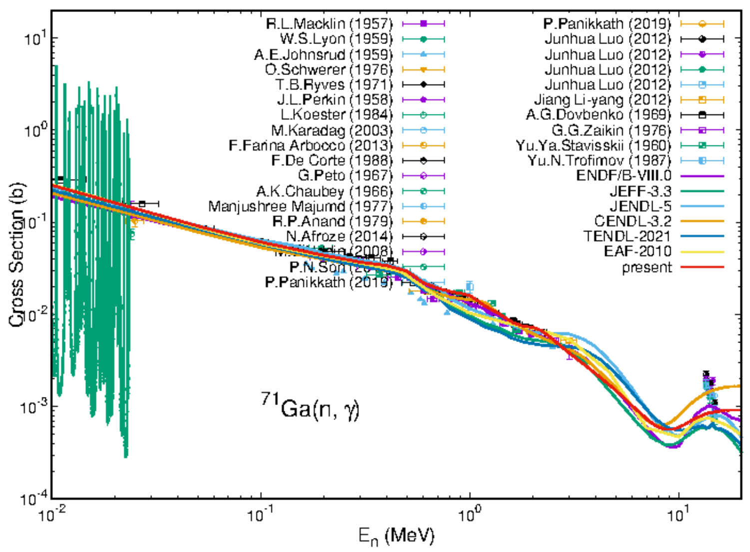






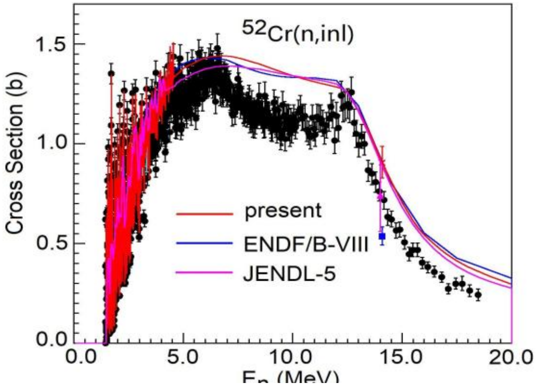


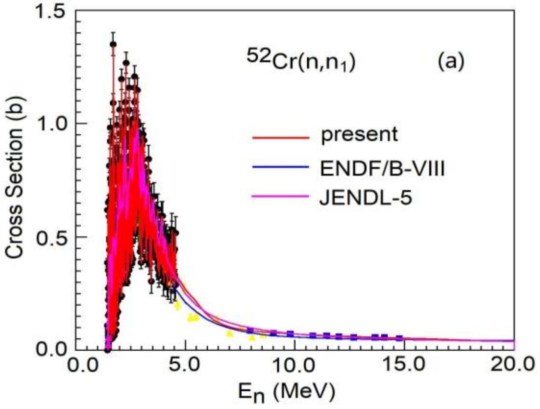


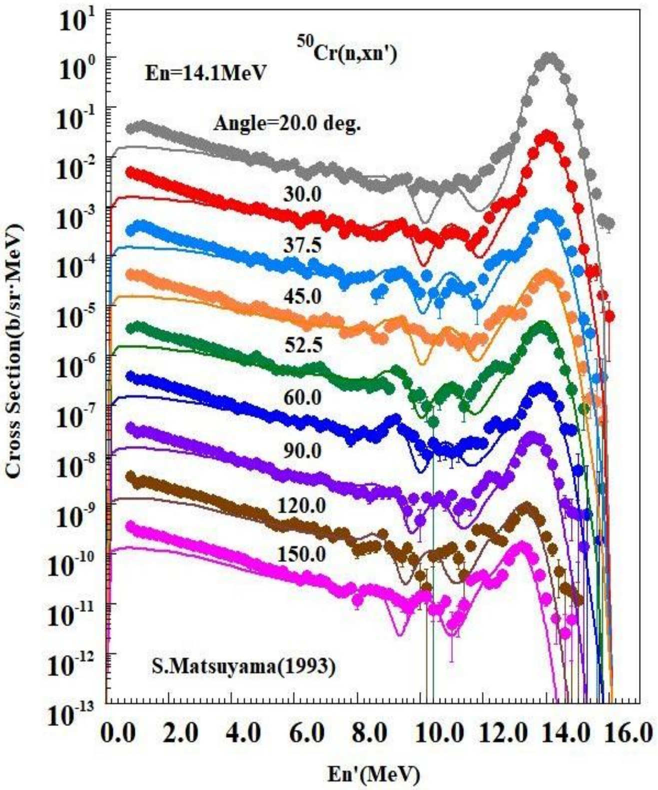


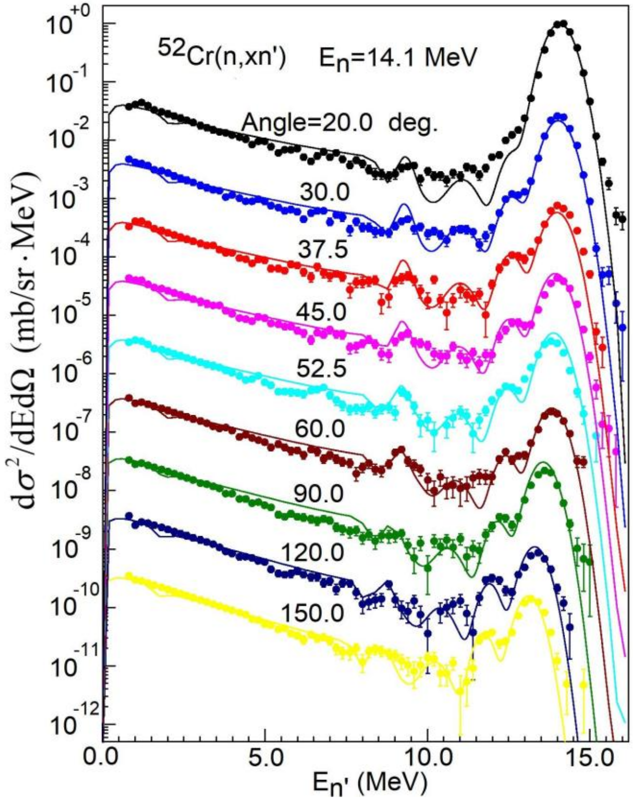
Evaluation for n+^{52}Cr

On the basis of the spherical optical model, the unified Hauser–Feshbach theory and exciton model, we systematically calculated various cross sections, angular distributions, energy spectrum, double-differential cross sections, and γ production cross sections for the reaction of the n+^{52}Cr reactions below 20 MeV.





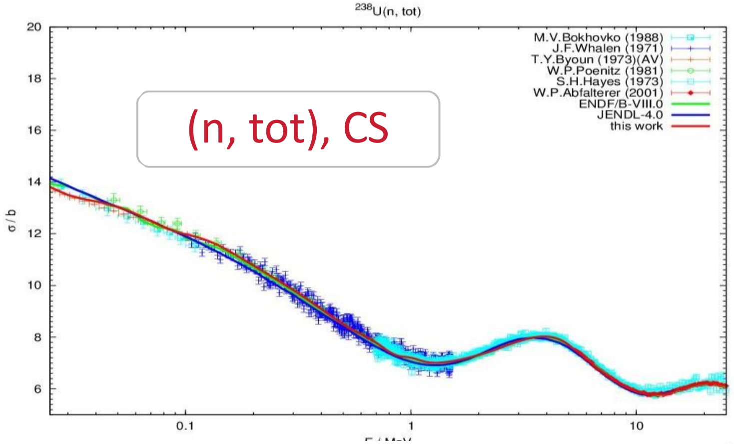


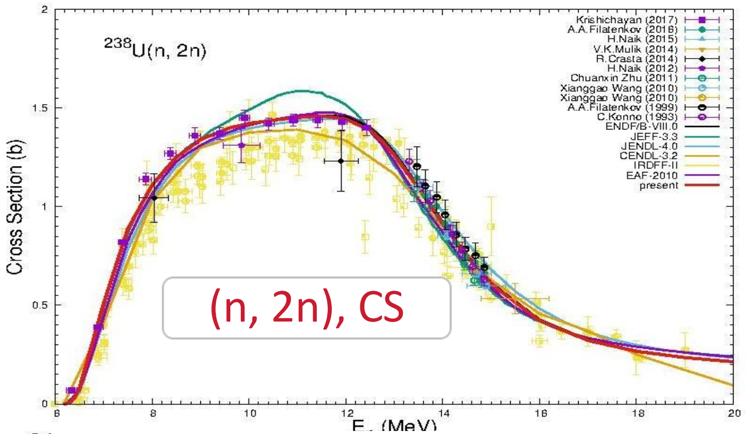


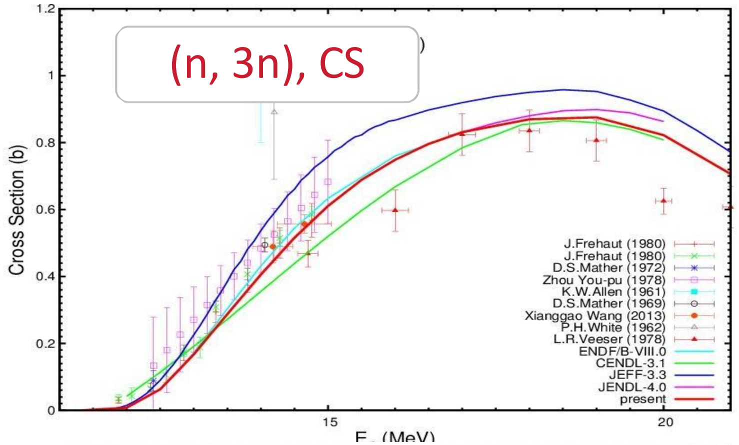
Wenye Wang, et.al., Nuclear Sci. and Eng., 2024.02.

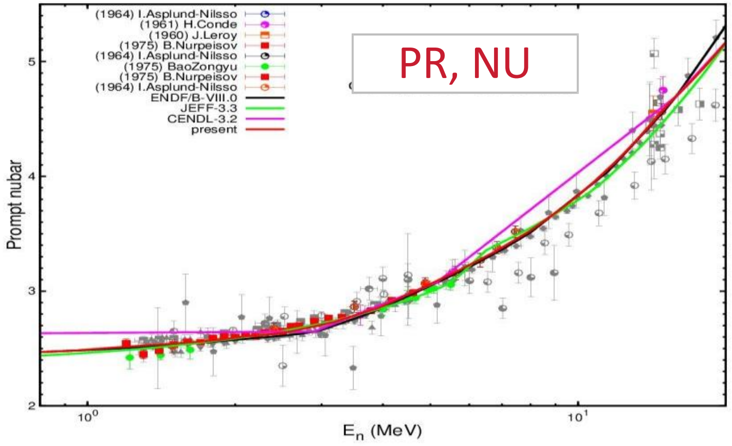
Evaluation for n+^{238}U

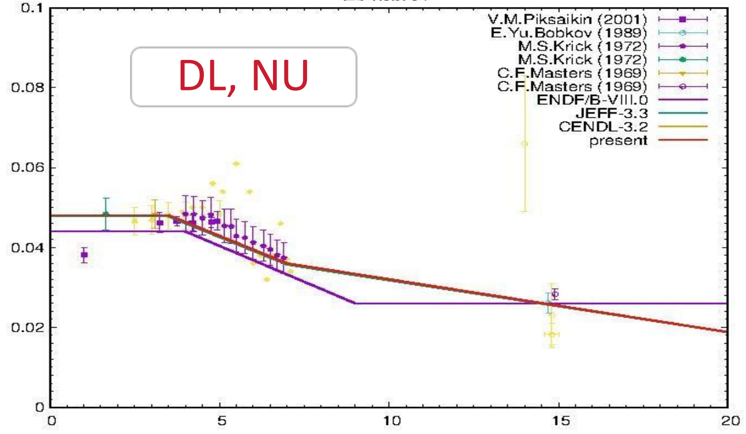
- Based on experimental data analysis, Nu-bar, (n,tot), (n,γ), (n,f), (n,2n) and (n,3n) cross sections evaluated.
- Experimental data evaluation based on factors such as experimental methods, experimental objectives, neutron monochromaticity, detector resolution capability, sample quantification, monitor cross-section selection, data correction, and uncertainty analysis.

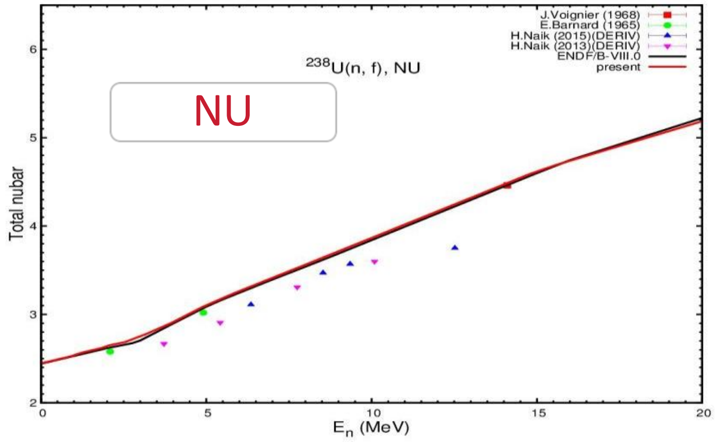






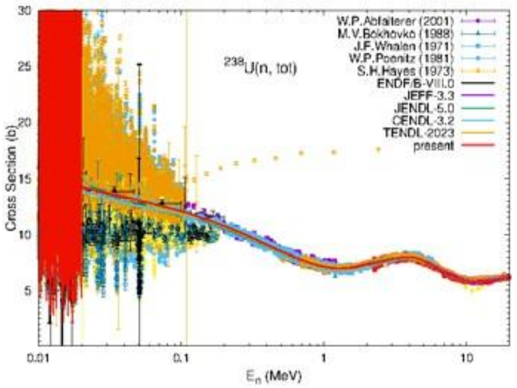


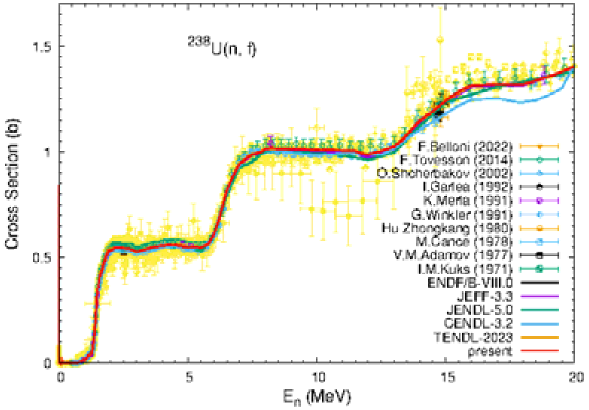


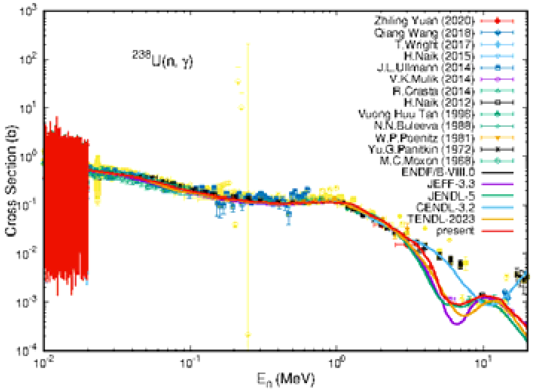


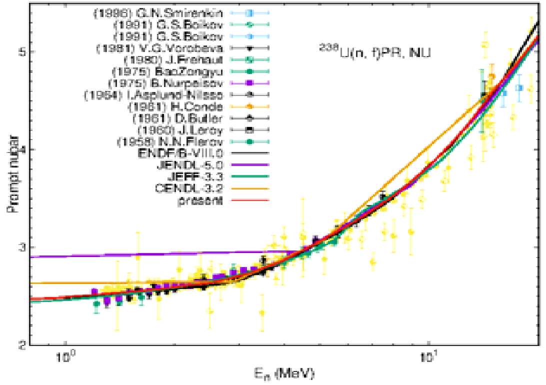
Evaluation for n+^{238}U

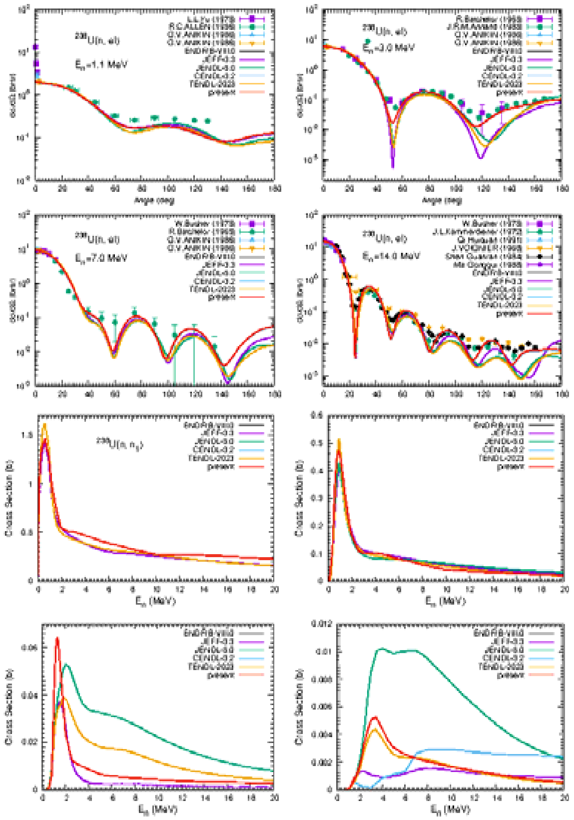
- New theoretical calculations based on Hauser-Feshbach and pre-equilibrium carried out.
- ENDF-6 file obtained with resonance parameters and prompt fission neutron spectrum taken from ENDF/B-VIII.0.
- Guided by integral benchmark, (n,inl), (n,γ) and (n,f) cross sections underwent multiple adjustments.
- The final benchmark results indicates a significant improvement in the final data quality.

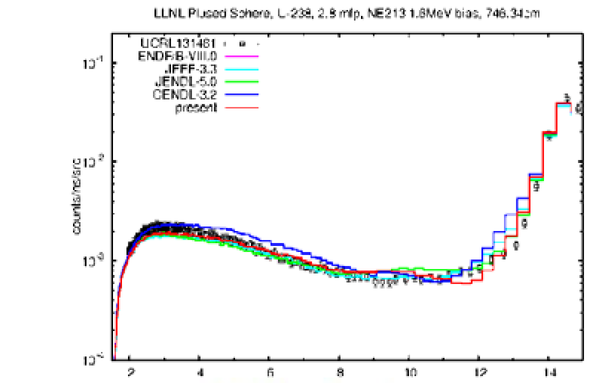


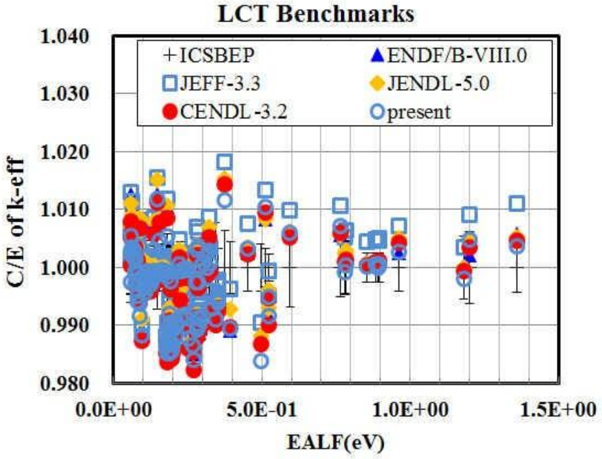










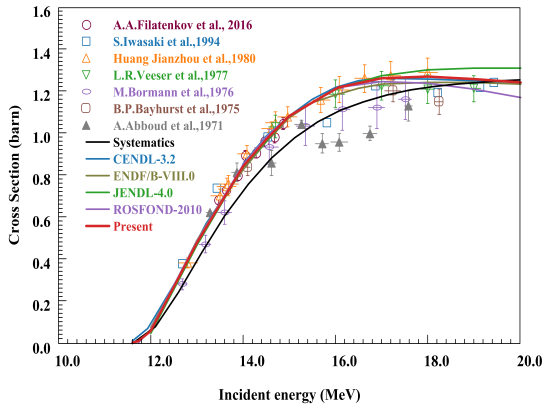


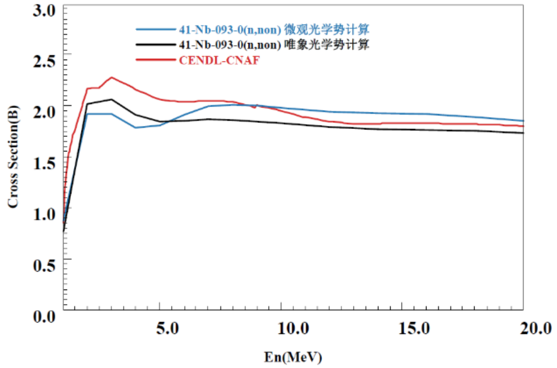
Zhang Yue, Xu Ruirui, Tian Yuan, et.al., Nuclear Engineering and Technology, 2024.08.

2.2 Neutron Activation: CENDL-CNAF

- ✓ The CENDL-CNAF included 818 nuclei(^{1}H to ^{257}Fm), the neutron energy region of from 10^{-5} eV to 20 MeV.
- ✓ The ENDF-6 format was adopted. The general information, comments (MF=1), reactions cross sections (MF=3), nucleus dictionary (MF=8), and split threshold reaction channels (MF=10) are included in the library.
- ✓ Evaluations were obtained by using APMN, Unified Hauser-Feshbach and Exciton model (UNF series) , Full and Diagonal Reduced R-matrix (FDRR) model calculations or systematic analysis based on available experimental data.
- ✓ When there have many experimental data for a reaction channel, the evaluated experimental data were selected for curve fitting using orthogonal polynomial fit or spline function fit from threshold to 20 MeV. And the fitting results were adopted.
- ✓ For convenient used in applications, all resonance parameters are already converted into a linearised point-wise format, and properly connected at the boundary energy. To calculate the point-wise cross section, The ENDF/B Pre-processing codes (PREPRO) were used.

MT	File types
102	(n,γ) reaction
16	(n,2n) reaction
17	(n,3n) reaction
18	(n,f) reaction
103	(n,p) reaction
107	(n,α) reaction
105	(n,t) reaction
106	(n,^{3}He) reaction
104	(n,d) reaction
28	(n,n'p) reaction
22	(n,n'α) reaction





Chin. Phys. B 8, 2022,31(6):060102

2.3 Radioactive Decay Data: CENDL/DDL

- ✓ The CENDL-DDL included 2350 nuclei between A=66 to A=172 FY region. ENSDF and ENDF format were adopted. Evaluations taken from :
  (1) CNDC(& Jilin Univ.): ~500 nuclei； (2) DDEP: ~200 nuclei; (3) ENSDF: ~1500 nuclei; (4) JEFF-3.2: ~150 nuclei (only for stable nuclei);
- ✓ **The Q-values** of the decay modes are updated to the Atomic Mass Evaluation (AME) released in 2021Wa16
- ✓ **Jπ for g.s.**(Jilin Univ.): by systematical comparison, physical analysis and theoretical calculation, spin for ground states is re-assigned for which lacks measurement or questionable
- ✓ **All T1/2** are revised by new measurements(2021.12).
- ✓ **Mean energies for β & γ:** from TAGS measurements when available, otherwise from theoretical calculation. For even-even nuclides, from theoretically analysis which employed the self-consistent quasi particle random phase approximation (QRPA) approach based on covariant density functional theory (CDFT) in Jilin University.
- ✓ **Beta-delayed n, p, α** emitted are adopted: P1n, P2n from eva. of 2015Bi05, 2020Li32; P1p,P1α from eva. of 2020Ba07 when measurements available. Otherwise from systematics or theoretical calculation.

偶偶核	TAGS	GROSS	ENSDF	Present
^{94}Sr	$E_β$: 0.842	1.093	0.833	0.698
	$E_γ$: 1.419	0.454	1.427	1.727
^{142}Ba	$E_β$: 0.397	0.637	0.404	0.372
	$E_γ$: 1.046	0.362	1.081	1.111
^{144}Ba	$E_β$: 0.902	0.940	-	0.986
	$E_γ$: 0.785	0.450	-	1.121
^{146}Ce	$E_β$: 0.215	0.310	-	0.232
	$E_γ$: 0.353	0.280	-	0.128
^{148}Ce	$E_β$: 0.586	0.598	-	0.581
	$E_γ$: 0.485	0.355	-	0.783
^{154}Nd	$E_β$: 0.849	1.056	-	0.862
	$E_γ$: 1.876	1.640	-	1.307
^{158}Sm	$E_β$: 0.514	0.314	-	0.570
	$E_γ$: 0.594	0.283	-	1.115

Comparsion mean energies for β & γ

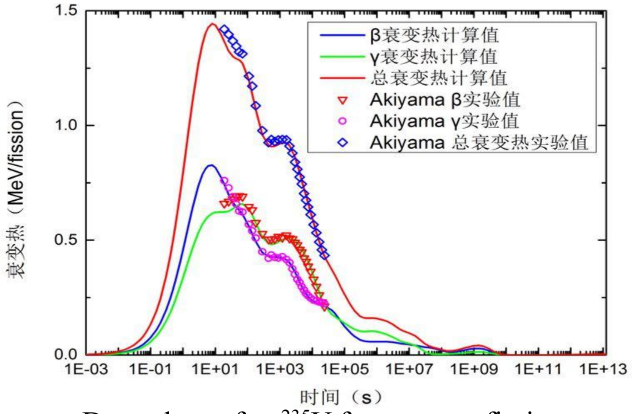
1, Decay branch

Mode	Present	DDEP	ENSDF
%IT	7.44(20)	9.1(6)	8.7(9)
%ε	92.56(20)	90.9(6)	91.3(9)

2, γ emission probability.

Eγ/keV	Present	DDEP	ENSDF
79.138(IT)	5.68(18)	6.9(5)	6.6(5)
433.937(ε)	91.73(20)	90.1(6)	90.5
614.276(ε)	92.3(22)	90.5(16)	89.8(19)
722.907(ε)	92.4(22)	90.8(16)	90.8(19)

Eva. Example:-Decay branch for ^{108m}Ag



Decay heat after ^{235}U fast neutron fission

2.4 Photonuclear Data: CENDL-PD

The photonuclear data for a total number of 264 materials are evaluated and outputted with the standard ENDF-6 format.

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 258 nuclei.

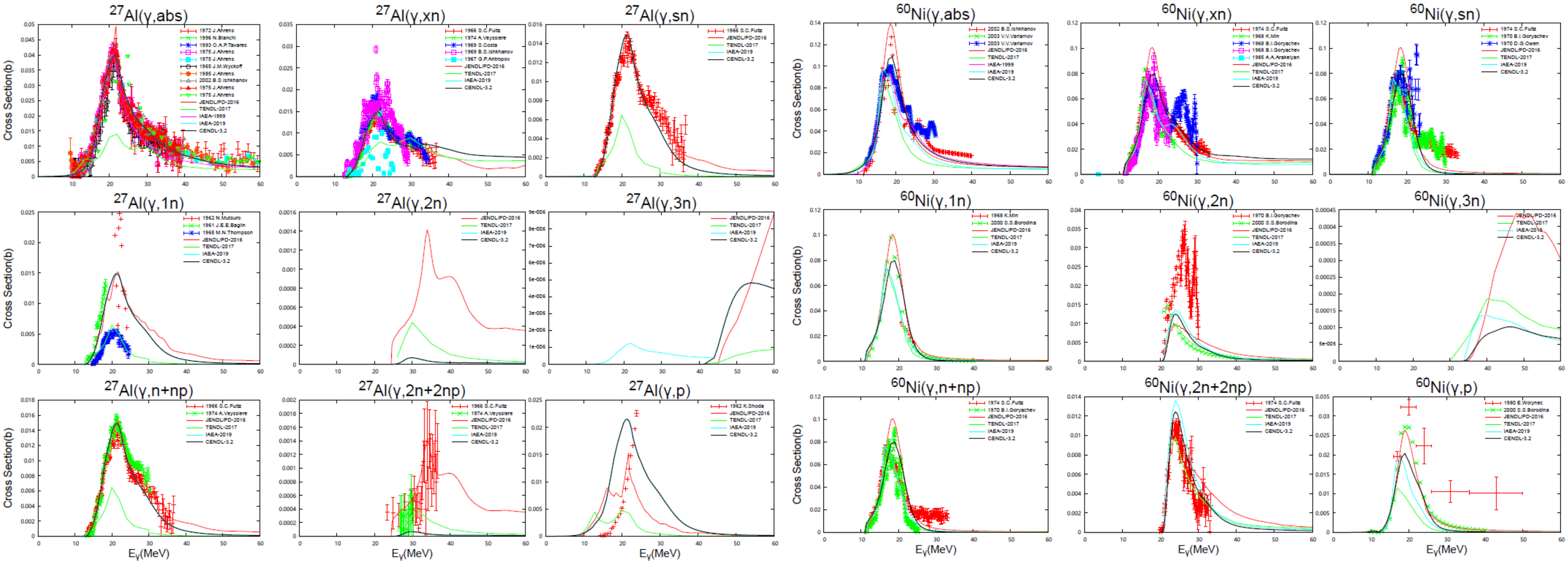
The incident photon energies for the medium-heavy nuclei are up to 200MeV. In order to extend the incident energy to 200MeV, the n, p, d, t, He-3, α are considered to totally 18th particle emission reactions in the MEND-G code. Moreover, the new measurements.

Nuclides List for CENDL-PD

Light elements	Be-9,B-10,11,C-12,N-14,O-16	6
Medium-heavy elements	Mg-25,26,Al-27,Si-28,29,30,P-31,S-32,33,34,36,Cl-35,37,Ar-36,38,40,K-39,40,41,Ca-40,42,43,44,46,Sc-45,Ti-46,47,48,49,50,V-50,51,Cr-50,52,53,54,Mn-55,Fe-54,56,57,58,Co-59,Ni-58,60,61,62,64,Cu-63,65,Zn-64,66,67,68,70,Ga-69,71,Ge-70,72,73,74,76,As-75,Se-74,76,77,78,80,82,Br-79,81,Kr-78,80,82,83,84,86,Rb-85,87,Sr-84,86,87,88,Y-89,Zr-90,91,92,94,96,Nb-93,Mo-100,92,94,95,96,97,98,Ru-100,101,102,104,96,98,99,Rh-103,Pd-102,104,105,106,108,110,Ag-107,109,Cd-106,108,110,111,112,113,114,116,In-113,115,Sn-112,114,115,116,117,118,119,120,122,124,Sb-121,123,Te-120,122,123,125,126,128,130,I-127,Xe-124,126,128,129,130,131,132,134,136,Cs-133,Ba-130,132,134,135,136,137,138,La-138,139,Ce-136,138,140,142,Pr-141,Nd-142,143,144,145,146,148,150,Sm-144,147,148,149,150,152,154,Eu-151,153,Gd-152,154,155,156,157,158,160,Tb-159,Dy-156,158,160,161,162,163,164,Ho-165,Er-162,164,166,167,168,170,Tm-169,Yb-168,170,171,172,173,174,176,Lu-175,176,Hf-174,176,177,178,179,180,Ta-180,181,W-180,182,183,184,186,Re-185,187,Os-184,186,187,188,189,190,Ir-191,193,Pt-190,192,194,195,196,198,Au-197,Hg-196,198,199,200,201,202,204,Tl-203,205,Pb-204,206,207,208, Bi-209	258

2.4 Photonuclear Data: CENDL-PD

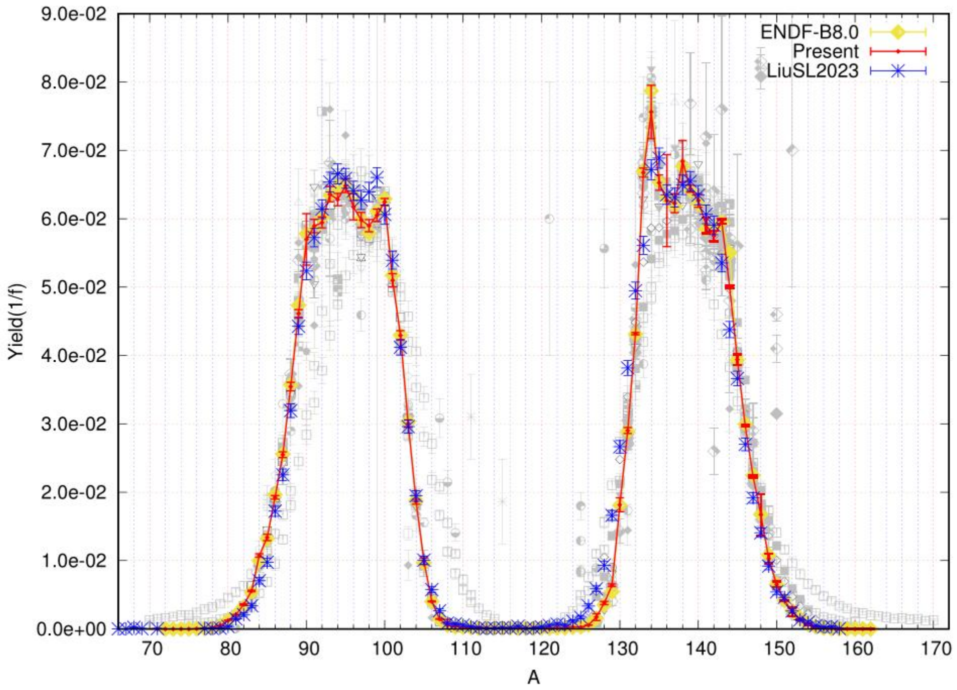
The comparisons of the photonuclear data of CENDL-PD, JENDL/PD-2016, TENDL-2017, IAEA/PD-2019 and the experimental data for ^{27}Al and ^{60}Ni

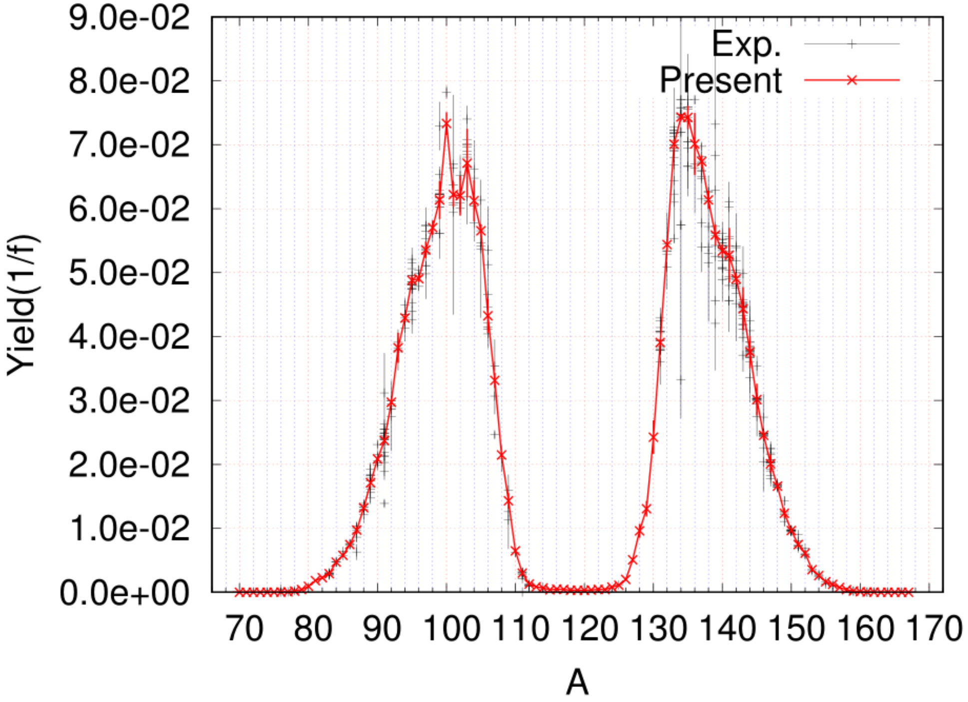


To ensure the availability and reliability of the PD file, nuclear data processing code system NJOY2016 and are used Monte Carlo code to verify and validate the PD library. The testing results show that the data structure of each nuclide is complete, the data content is reasonable, and can be applied to the simulation of Monte Carlo transport.

2.5 Fission Yield Data: CENDL-FPY

The FPY sub-library will cover about 40 fission systems, where the ^{233}U, ^{235}U, ^{238}U and ^{239}Pu, ^{241}Pu fission yields were newly evaluated. Others were based on the data from ENDF and JEFF libraries and adjusted with decay data of CENDL-DDL.





2.6 Thermal Scattering Law Data

A module named sab_calc is developed for evaluation of thermal scattering law, in NECP-Atlas of Xi'an Jiaotong Universty.

Crystalline material:

The phonon expansion based method is adopted with some improvement to remove the traditional approximations.

- Incoherent approximation for inelastic scattering
- Cubic approximation and atom site approximation for coherent elastic scattering

Liquid material:

Quantum Correction method is used to avoid the separation and convolution technique adopted in LEAPR.

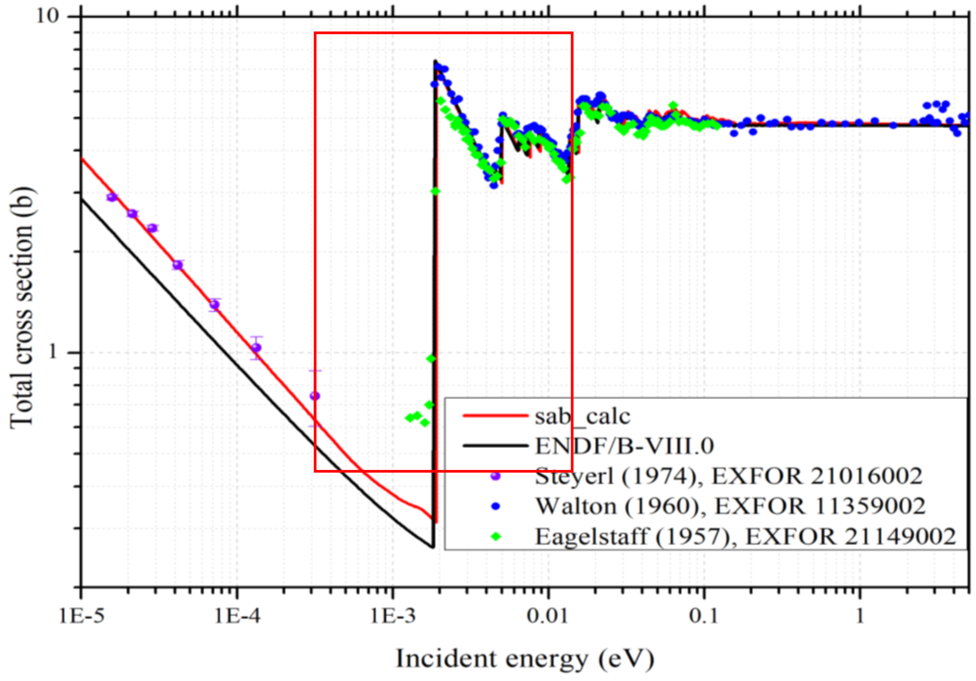
2.6 Thermal Scattering Law Data

Thermal scattering law data for more than 20 materials have been evaluated using NECP-Atlas.

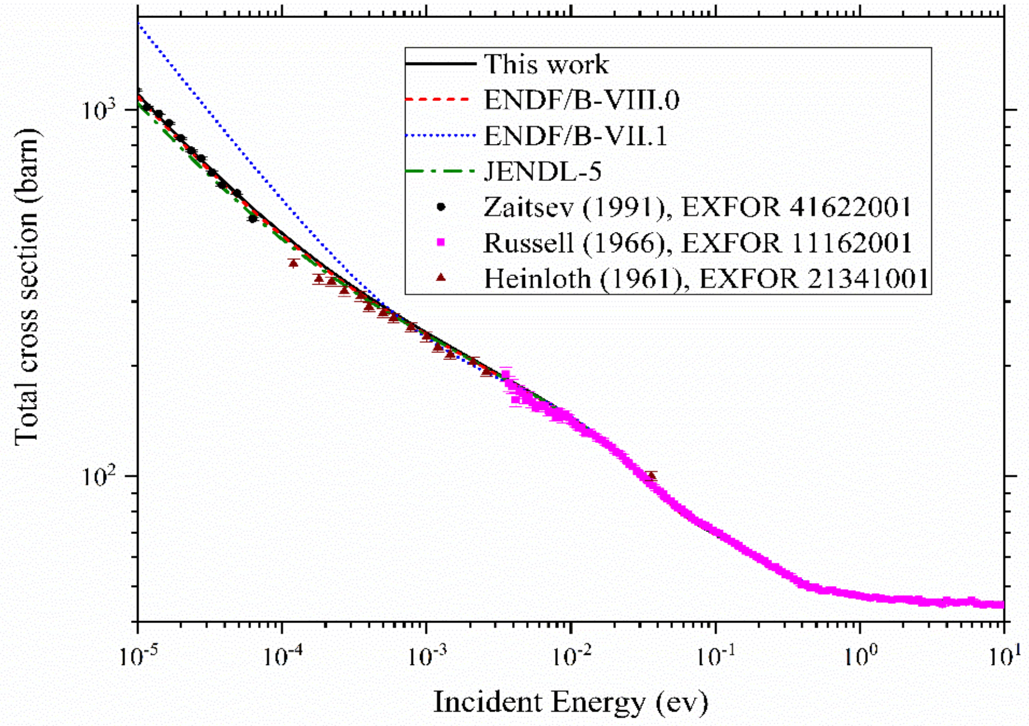
No.	Materials	Elastic scattering	Inelastic scattering
1	Be	ADPs method for coherent elastic scattering	One-phonon correction method
2	graphite		
3	SiC		
4	UO_2		
5	α-SiO_2		
6	BeO		
7	ZrC		
8	UN		
9	α-Al_2O_3		
10	MgO		
11	Fe		
12	Al		
13	δ-YH_2	H incoherent elastic scattering；ADPs method for the coherent elastic scattering of Y and Zr	
14	ε-ZrH_2		
15	δ-$ZrH_{1.5}$		
16	H_2O	No elastic scattering	Quantum correction
17	D_2O		
18	Liquid FLiBe		

2.6 Thermal Scattering Law Data

The thermal scattering cross sections obtained show good agreement with the experiment results



Total cross sections of graphite at 296 K

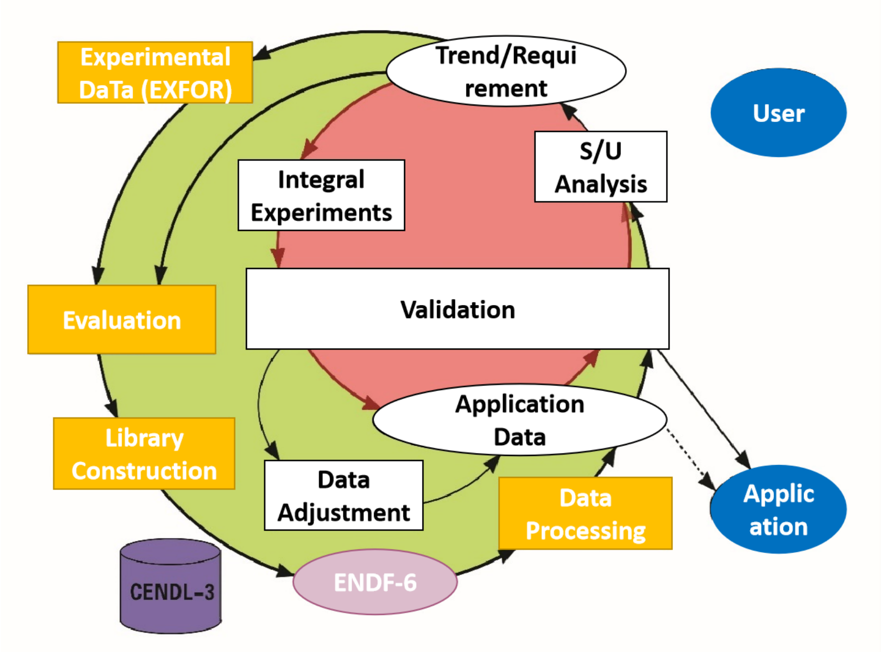


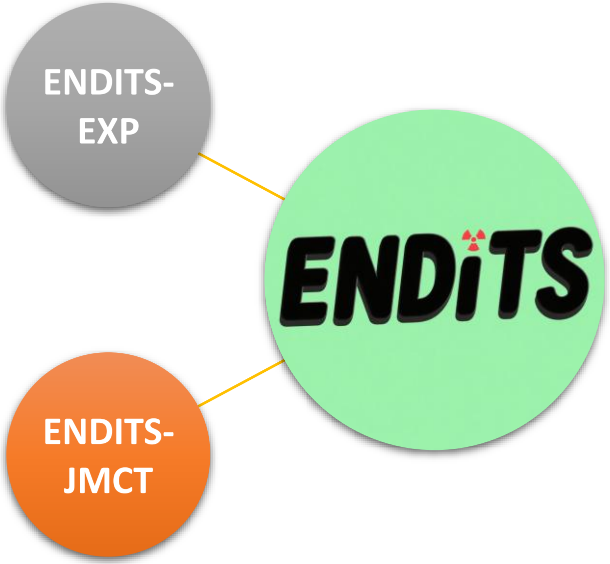
Total cross section of H_2O at 293.6 K

III. Tools for Nuclear data Validation

It is necessary to utilize a large number and various types of benchmark experiments and integral quantities to verify different aspects of nuclear data.

A system named ENDITS(Evaluated Nuclear Data Integral Testing System) was developed for nuclear data V&V.



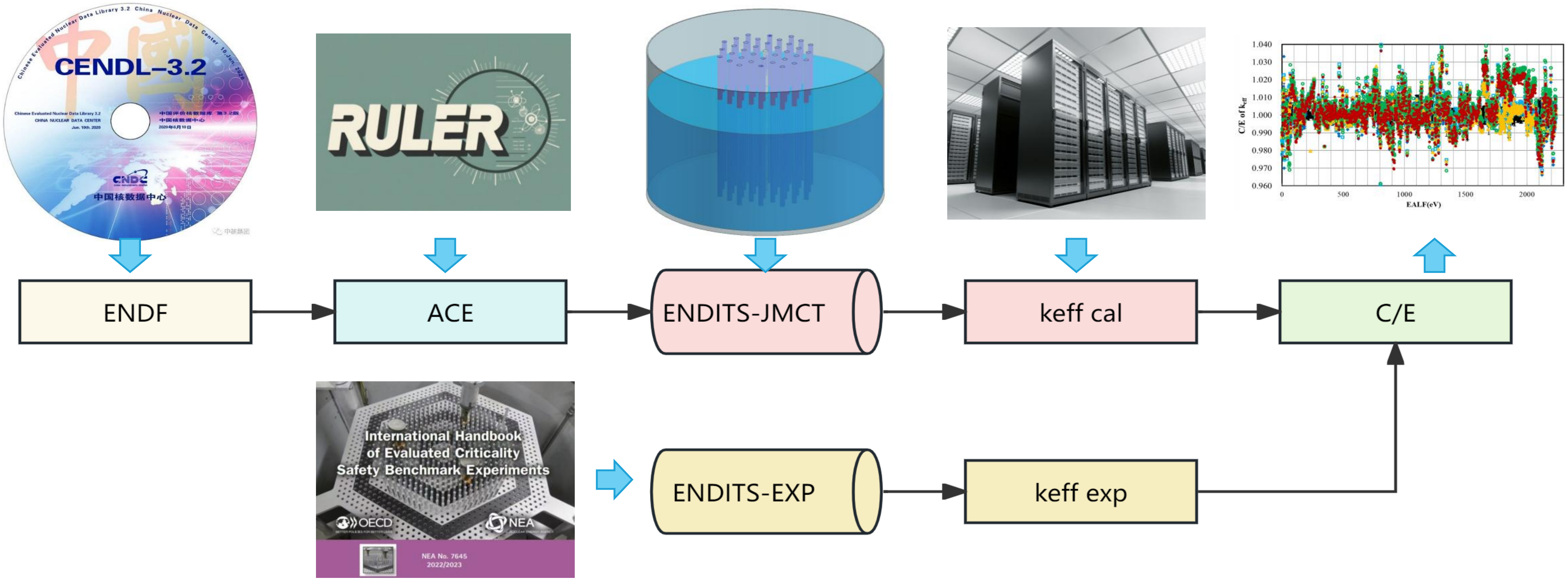


ENDITS-EXP： Benchmark experiment information database

ENDITS-JMCT： Standard physical model suite

III. Tools for Nuclear Data Validation

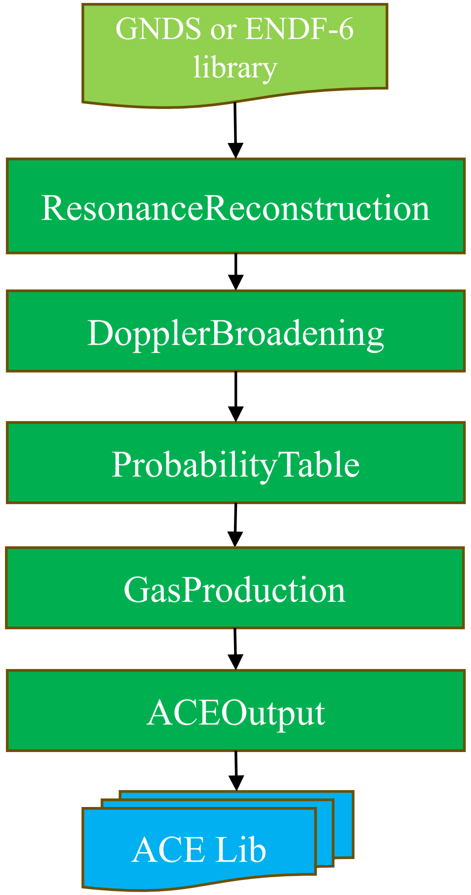
ENDITS-EXP contains 2237 critical benchmarks.

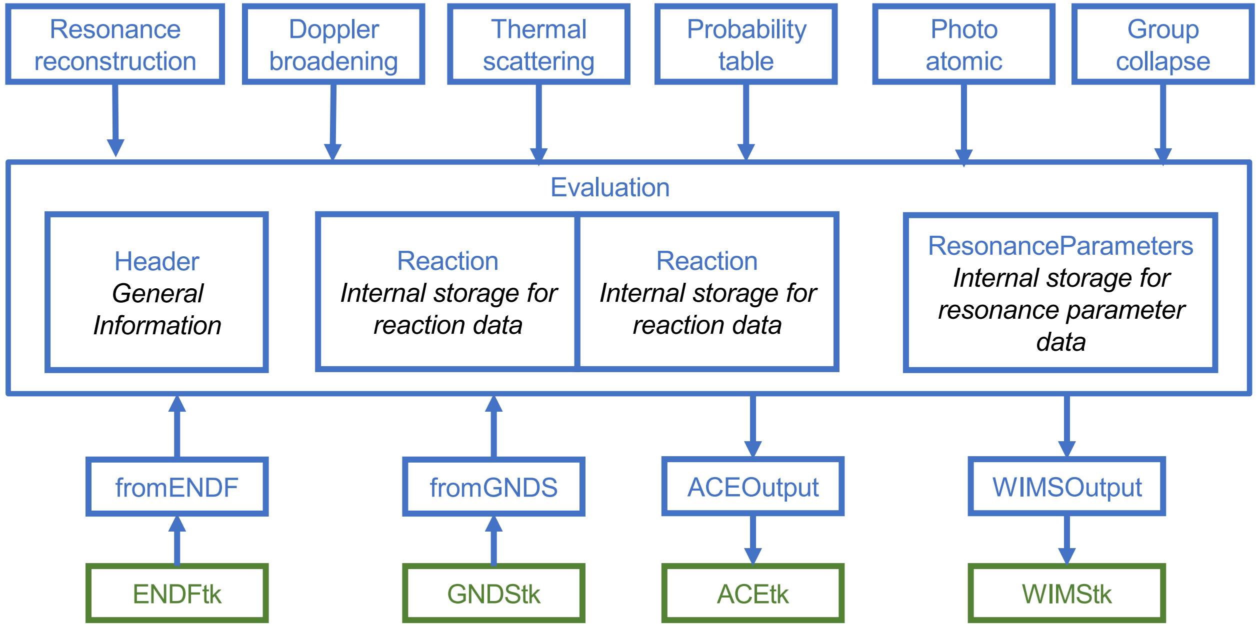


III. Tools for Nuclear Data Validation

An in-house nuclear data processing code Ruler was developed to process GNDS or ENDF-6 format evaluations into ACE format library.

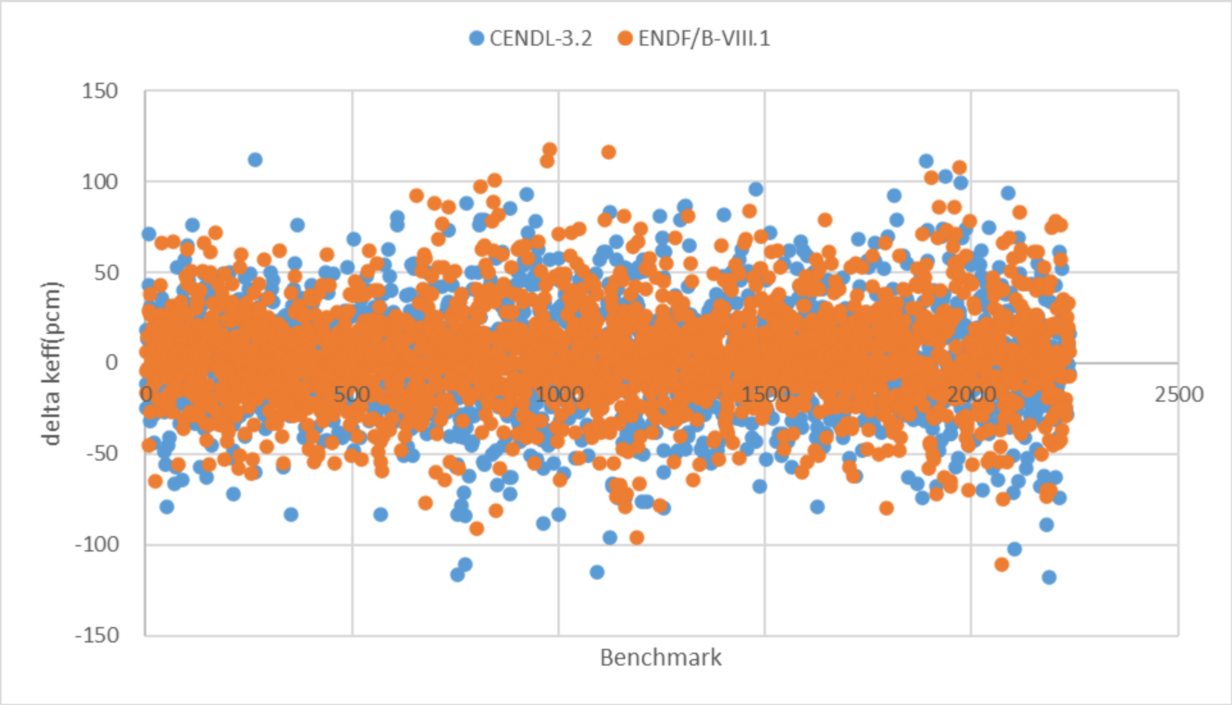
A format agnostic nuclear data was developed to store the evaluated data in ENDF-6 and GNDS formats, and transfer data among various functional modules.





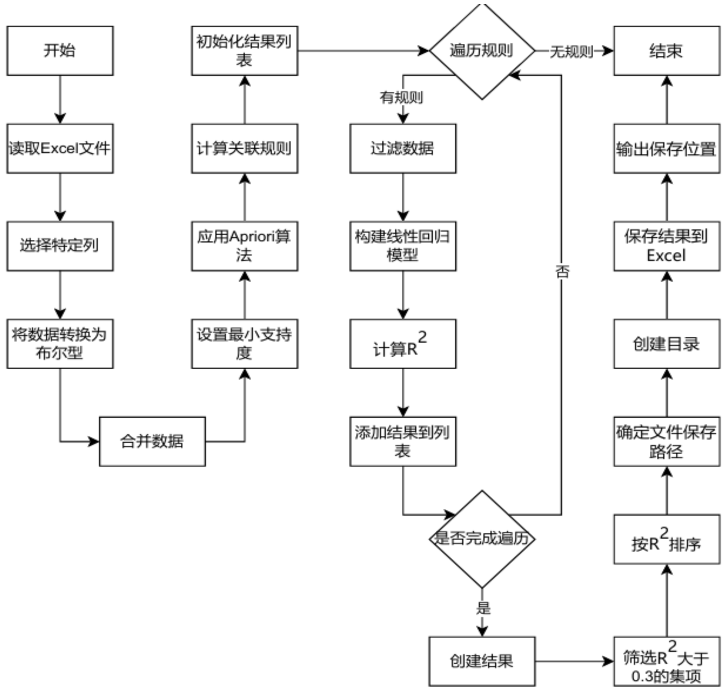
III. Tools for Nuclear Data Validation

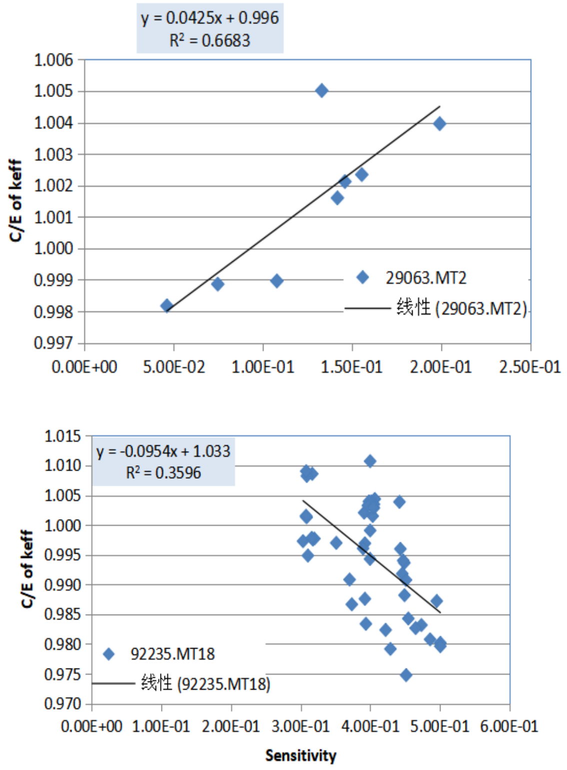
Ruler was tested against several libraries and verified with various benchmarks, K_{eff} biases of most benchmarks from ICSBEP between Ruler and NJOY2016 are less than 100 pcm.

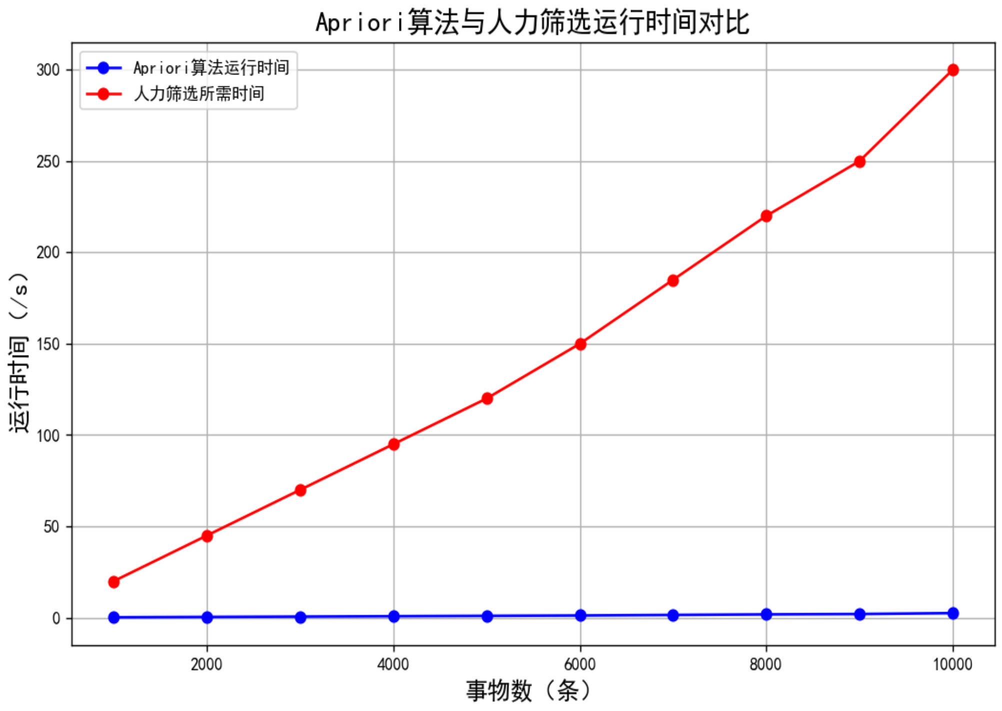


III. Tools for Nuclear Data Validation

Apriori algorithm in association learning was utilized to screen baseline experimental features from large datasets, identifying feature combinations with strong correlations. trend analysis are conducted based on sensitivity values under these combination conditions. It greatly improves the efficiency.







IV. Remarks

- The CENDL project has made significant progress in various aspects, from data evaluation to methodology development.
- With the upcoming release of CENDL - 4.0 in 2025, we expect to provide more accurate and comprehensive nuclear data .
- We also look forward to further cooperation with the international nuclear data community to improve the nuclear data and methodology. And welcome everyone to visit the China Nuclear Data Center.

Thank you for your attention !