CENDL STATUS AND UPDATES

GE Zhigang

China Nuclear Data Center (CNDC)
China Nuclear Data Key Laboratory
China Committee of Nuclear Data (CCND)
China Institute of Atomic Energy (CIAE)
P.O.Box 275-41, Beijing 102413, P.R. China
E-Mail: gezg@ciae.ac.cn

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**CENDL library and CENDL Project**

Based on the measurements and evaluations collaborated with China Nuclear Data Coordination Network, the main output of CENDL project is the CENDL library.

**Chinese Evaluated Nuclear Data Library (CENDL project)**
- CENDL-1, 1985 version 36
- CENDL-2, 1992 version 68
- CENDL-3, 2000 version 214
- CENDL-3.1, 2009 version 245
- CENDL-3.2, 2020 version 270 (May, 2020)

**Other Data Library**
- Nuclear Structure and Decay Data Library (NSDD)
- Fission Product Yield Data Library (FPYD)
- Charged-Particle Nuclear Data Library (CPND)
- Neutron Activation Dosimetry Data Library

Motivated by fulfill the requirement of domestic users, a new revision of Chinese Evaluated Nuclear Data Library, CENDL3.2 has been started under the joint efforts of CENDL working group since 2010.
The first stage
The second stage
The third stage
<table>
<thead>
<tr>
<th>Nucl.</th>
<th>Content of Nuclei in CENDL-3.2 (270)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Light Elements</strong></td>
<td>n-1, 1-3H, 3,4He, 6,7Li, 9Be, 10,11B, 12C, 14N, 16O, 19F</td>
</tr>
<tr>
<td><strong>Structural Materials</strong></td>
<td>23Na, 24-26Mg, 27Al, 28-30Si, 31P, 32,33,34,36S, 0Cl, 0K, 40Ca, 46-50Ti, 0V, 50,52-54Cr, 55Mn, 54,56-58Fe, 59Co, 58,60-62,64Ni, 0,63,65Cu, 64,66-68,70Zn, 90-92,94,96Zr, 92-100Mo, 0,107,109Ag, 174,176-180Hf, 181Ta, 180,182,183,184,186W, 197Au, 0Hg, 0Tl, 204,206-208Pb, 209Bi</td>
</tr>
<tr>
<td><strong>Fission Products &amp; Medium Elements</strong></td>
<td>69,71Ga, 0,70-78Ge, 75,77,79As, 74,76-80,82Se, 74,88,85,86,87,88Kr, 85,87Rb, 88-90Sr, 89,91Y, 93,95Zr, 93,95Nb, 99Tc, 99-105Ru, 103,105Rh, 105,107Pd, 0,113Cd, 113,115In, 112,114-120,122,124,125Sn, 121-127Sb, 130Te, 127,129-131,135I, 123,124,129,131-136Xe, 133-135,137Cs, 130,132,134,138Ba, 139La, 136,138,140-142,144Ce, 141Pr, 142-148,150Nd, 147,148,148m,149Pm, 144,147-152,154Sm, 151,153-155Eu, 152,154-158,160Gd, 164Dy, 165Ho</td>
</tr>
<tr>
<td><strong>Actinides</strong></td>
<td>232Th, 232-241U, 236-239Np, 236-246Pu, 240-244,242mAm, 249Bk, 249Cf</td>
</tr>
</tbody>
</table>
The total number of CENDL is 270. 75 evaluated and calculated covariance files including.

- 72 nuclides are newly evaluated and updated in CENDL-3.2;
- the key elements are revised based on CENDL-3.1, including the key elements $^{235}\text{U}, ^{239}\text{Pu}, ^{233}\text{U}, ^{232}\text{Th}, ^{56}\text{Fe}, ^{1}\text{H}$;
- Covariance are systematically updated for 70 fission product nuclei.

The incident neutron energy $E_n \leq 20\text{MeV}$;

MF contains 1, 2, 3, 4, 5, 6, 12, 14, 15, 33.
Light mass: n-n & n-p data based on the microscopic N-N interaction

High precision NN potential fits about 6000 pp and np data with $\chi^2 \sim 1.0$.

CD-Bonn meson exchange nuclear force is able to explain CIB and CSB. Low energy pp, nn and np scattering in $^1S_0$ channel, their $a$ and $r$ almost identify.

$$a_{pp} = -17.3 \pm 0.4 \text{ fm} \quad a_{nn} = -18.9 \pm 0.4 \text{ fm} \quad a_{np} = -23.74 \pm 0.02 \text{ fm}$$

$$r_{pp} = 2.85 \pm 0.04 \text{ fm} \quad r_{nn} = 2.75 \pm 0.11 \text{ fm} \quad r_{np} = 2.77 \pm 0.05 \text{ fm}$$

1. Solving Lippmann-Schwinger equation in momentum space to obtain phase shift $\delta_{lj}$.
2. For spin triplet $S = 1$, coupling orbit $L$ and spin $S$ to provide $J$. 6 summation must be taken into account.

$$\frac{d^3\sigma(\theta)}{d\Omega} = \frac{1}{3k^2} \sum_{J_1} \sum_{l_1} \sum_{l_1'} \sum_{J_2} \sum_{l_2} \sum_{l_2'} \sum_{l_1l_1'} \sum_{l_2l_2'} i^{-l_1+l_1'+l_2-l_2'} (1 - S_{l_1l_1})^* (1 - S_{l_2l_2}) K(J_1l_1l_1', J_2l_2l_2')$$
nn and np data in CENDL3.2
Comparisons of nn and np scattering cross section between ENDF/B-8.0 and CENDL-3.2

\[ \sigma = 22.6 \text{ b} \]
\[ a_{nn} = -18.9 \text{ fr} \]

\[ \sigma = 21.5 \text{ b} \]
\[ a_{nn} = -18.5 \text{ fm} \]

\[ \sigma_{np} = 20.4 \text{ b} \]
CENDL-3.1 is adopted in CENDL-32

\[ n + ^2 \text{H} (\text{D}) \rightarrow n + ^2 \text{H} (\text{D}) \quad (\text{n, el}) \]
\[ \rightarrow 2n + p \quad (\text{n, 2n}) \]
\[ \rightarrow \gamma + ^3 \text{H} (\text{T}) \quad (\text{n, } \gamma) \]

\[ \sigma_{\text{tot}} = \sigma_{n,n} + \sigma_{n,2n} + \sigma_{n,\gamma} \]

D(n,2n)p is updated considering the new experimental data:


13 sets of experimental data are measured by TOF and STANK, considering the technique of particle identification to separate the proton and deuteron
Experimental data evaluation are performed, and some reaction cross sections and angular distributions of neutron elastic scattering of $^6,^7\text{Li}$ are updated.

$\sigma(n, \text{el})$ is derived through Legendre polynomial function fitting to the experimental data of $d\sigma/d\omega$.

CENDL-3.1 is adopted in CENDL-32

$^7\text{Li}(n,\text{el}), (n,\text{nt}), (n,\text{g})$ are updated via the new experimental data:

<table>
<thead>
<tr>
<th>Channels</th>
<th>Q values $\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma + ^8\text{Li}$</td>
<td>2.033</td>
</tr>
<tr>
<td>$n' + ^7\text{Li}$</td>
<td>-0.4776</td>
</tr>
<tr>
<td>$d + ^4\text{He}$</td>
<td>-7.750</td>
</tr>
<tr>
<td>$t + ^7\text{He}$</td>
<td>-3.3362</td>
</tr>
<tr>
<td>$2n + ^6\text{Li}$</td>
<td>-7.2490</td>
</tr>
<tr>
<td>$n, p + ^6\text{He}$</td>
<td>-9.9740</td>
</tr>
<tr>
<td>$n, d + ^3\text{He}$</td>
<td>-9.618</td>
</tr>
<tr>
<td>$n + t + \alpha$</td>
<td>-2.476</td>
</tr>
<tr>
<td>$2n, p + ^5\text{He}$</td>
<td>-11.842</td>
</tr>
<tr>
<td>$2n + d + \alpha$</td>
<td>-8.724</td>
</tr>
</tbody>
</table>

$\sigma(n,\text{el})$ is derived through Legendre polynomial function fitting to the experimental data of $d\sigma/d\omega$. 
Angular distribution of elastic scattering of $^7\text{Li}$

Nuclear data are updated with new Legendre fitting.
New calculation and evaluation are performed to the isotopes of Sulphur in CENDL-32.
**Approach:**

- New evaluation and covariance based on the experimental data for \((n,\text{tot})\) and \((n, a)\)
- Koning-Delaroche potential is utilized to calculate the neutron scattering. This function is incorporated in the latest UNF2015
- The discrete levels are adopted as the data JENDL-4

New calculation and evaluation are performed to the isotopes of Calcium-40 in CENDL-32
3. CENDL-3.2 – medium heavy: \( n + ^{40}\text{Ca} \)
3. CENDL-3.2 – medium heavy : \( n^+^{56}\text{Fe} \)

Medium-heavy nuclei: Re-evaluation of \( ^{56}\text{Fe(n,inl)} \) reaction cross section

- The (n,inl) evaluation in smooth region for both B8b4 and C32b1 are based on the experimental data recommended by QIAN Jing in the CIELO project.
  - Above 6MeV, Nelson (2004) is recommended based on the (n,el) XS measured by Schmidt.
- The new evaluations of \( ^{56}\text{Fe} \) leads to a serious under prediction of neutron leakage from IPPE iron sphere.
Medium-heavy nuclei: Re-evaluation of $^{56}$Fe(n, inl) reaction cross section

- To solve the problem of under prediction neutron leakage in iron shielding, the experimental data of $^{56}$Fe(n, inl) 847keV gamma production cross sections have been re-evaluated and a new curve for $^{56}$Fe(n, inl) reaction has been evaluated.

  - Nelson(2004) was corrected based on the experiment data around 14MeV.
Medium-heavy nuclei: Re-evaluation of $^{56}$Fe(n, inl) reaction cross section

- Significant improvement of validation results have been achieved in testing with the 70cm dia. IPPE iron sphere and the LLNL pulsed iron sphere.
Fission product nuclei evaluation

The neutron reaction data of medium-heavy nuclei (mass number around 100~200) are systematically updated in CENDL. **All the modifications are based on the calculations with the UNF code.** Parts of them are new evaluations concerning the latest measurements. The others are the systematic reproductions to the previous CENDL library, some odd structures are removed from previous CENDL.

The new evaluations for La-139 (n,tot),(n,incl)
3. CENDL-3.2 – medium heavy : n+Fission product

Systematics of (n,2n) cross sections

New calculation and evaluation

1986 Tang Dan
1996 M.Bismann
1997 Y.Katsugai
2011 Chuangxin Zhu
1999 A.A.Filatenkov
1995 Kong Xiangzhong
1974 Sh.M.Qaim
1968 W.Dilig
1971 A.Bird
1978 S.L.Selfradas
1969 J.Cavai
ENDF/B-VII.1
CENDL-3.1
JENDL-4.0
present
**Fission nuclei**: revision of U-235

- Nubar and resonance parameters of $^{235}$U(rev.C32b11) which refer as CENDL-3.2 now, were modified to reproduce the thermal quantities of the IAEA 2006 standard, which improves the prediction of $k_{eff}$ for the HMT system.

<table>
<thead>
<tr>
<th>Thermal quantities</th>
<th>IAEA2006 standard</th>
<th>C32b11 evaluation</th>
<th>C32b11 Eval./Std.</th>
<th>Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n,f)</td>
<td>584.33</td>
<td>5.84177E+02</td>
<td>-0.03%</td>
<td>-0.15%</td>
</tr>
<tr>
<td>(n,γ)</td>
<td>99.401</td>
<td>9.94001E+01</td>
<td>0.00%</td>
<td>0.70%</td>
</tr>
<tr>
<td>(n,el)</td>
<td>14.087</td>
<td>1.51081E+01</td>
<td>7.25%</td>
<td>-0.05%</td>
</tr>
<tr>
<td>(n,tot)</td>
<td>697.818</td>
<td>6.98685E+02</td>
<td>0.12%</td>
<td>-0.03%</td>
</tr>
<tr>
<td>$G_f$</td>
<td>0.97729</td>
<td>0.97667</td>
<td>-0.07%</td>
<td>0.00%</td>
</tr>
<tr>
<td>$G_γ$</td>
<td>0.99118</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$G_a$</td>
<td>0.97881</td>
<td>0.97878</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>$ν$</td>
<td>2.43550</td>
<td>2.4359</td>
<td>0.01%</td>
<td>-0.03%</td>
</tr>
<tr>
<td>$η$</td>
<td>2.08143</td>
<td>2.0816</td>
<td>0.01%</td>
<td>-0.16%</td>
</tr>
<tr>
<td>$α$</td>
<td>0.17011</td>
<td>0.17015</td>
<td>0.03%</td>
<td>0.85%</td>
</tr>
</tbody>
</table>
**Fission nuclei**: revision of U-235

- $(n,\gamma)$ cross sections were revised based on $(n,f)$ cross sections recommended by IAEA 2006 standard and re-evaluated alpha values.
- Benchmark testing with the selected HMF, IMF and HMI cores show that the prediction of $k_{eff}$ gets closer to 1 than before.

![Graph showing fission nuclei data for $^{235}\text{U}$](image-url)
3. CENDL-3.2 - Actinides: $n + ^{233}\text{U}$

**233U**

- Delayed fission neutron multiplicity vs. Incident Neutron Energy (MeV)
- $^{233}\text{U}(n, f)$ Reaction
  - Cross Sections (barn) vs. Incident Neutron Energy (MeV)
- $^{233}\text{U}(n, el)$ Reaction
  - Cross Sections (barn) vs. Incident Neutron Energy (MeV)
- $^{233}\text{U}(n, inl)$ Reaction
  - Cross Sections (barn) vs. Incident Neutron Energy (MeV)
3. CENDL-3.2 – Actinides: n+^{239}U

Nu-barn experimental data evaluation for ^{239}U

Before
Nu-barn experimental data evaluation for $^{239}\text{U}$
(n, fission) experimental data evaluation for $^{241}$Am

$^{241}$Am

Before
(n, fission) experimental data evaluation for $^{241}\text{Am}$
### Calculation system for FP nuclei (CENDL-3.1 to 3.2)

<table>
<thead>
<tr>
<th>Command</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>sunf2unf.pl</td>
<td>Convert sunf -&gt; unf</td>
</tr>
<tr>
<td>Batchcal</td>
<td>Produce unf.newunf</td>
</tr>
<tr>
<td>batchmincard.pl</td>
<td>Auto-produce inputs SEMAW.in, DPPMI.in, Min.in, sys.dat, exp</td>
</tr>
<tr>
<td>Correctmin</td>
<td>Correct the energy margin of min.in</td>
</tr>
<tr>
<td>get14MevCSInl</td>
<td>Produce the direct reaction cross section based on</td>
</tr>
<tr>
<td>batchmincard14.pl</td>
<td>Adjust DWUCK para. to fit 14MeV</td>
</tr>
<tr>
<td>NDPlot</td>
<td>Plot the figures for 10 reactions</td>
</tr>
</tbody>
</table>
with the help of MINUIT, we have adjusted the parameters of the UNF program, such as the parameter of the level density, pairing interaction and Giant dipole resonance of (n, gamma) channel. As shown in Figure, the dotted line is the results of the CENDL3.1, the solid line is the cross sections we have calculated with the new parameter set. For the (n,n1) and (n,n2) channel, the new parameter set gives the reasonable cross section at 8 to 10 MeV.
Descriptions to COV scheme in CENDL-3.2:

① Technology for non-model & model dependent
② Energies for structure & smooth regions
③ COV data types for NI & NC
④ Technology deal with single & multiple measurements
⑤ Technology for parameter sensitivity selection
⑥ COV matrix positive definition treatment

Deterministic approach: Data recommendation together with COV

| Generalized LS | Optical model
| --- | --- |
| Model parameters determination for structure & fission nuclei | Direct reaction
| (UM,FUNE, DZG, fixes) | Compound nucl.
| Sensitivity calculation for reactions (SEMAW) | ~40 parameters
| Covariance of model parameters (COVAC, Least Square methodology) | MODEL
| Covariance of reactions C.S. (COVAC, Linear error propagation) | MODEL

CENDL

NJOY
Processing & S/U analysis

Highlight for covariance eval.
Covariance for $n^{90}\text{Zr}$ reaction cross sections

3. CENDL-3.2 – Covariance for 70 Fis. products.
The covariance of main reactions are contained in the data file, the averaged uncertainties are about:

- $(n,\text{tot}) < 10\%$
- $(n,\text{inl}) < 20\%$
- $(n,\text{na}) < 80\%$
- $(n,\text{np}) < 50\%$
- $(n,\text{g}) < 30\%$

3. CENDL-3.2 – Covariance for 70 Fis. products.
CENDL-Sub-library of photon data

270 new evaluations have been performed based on the new GLUNF, MEND-G systems.

Evaluation Scheme for PD

EXFOR data

Experimental analysis for (G,abs)

GDR parameter calculation

(G,abs) calculation (GDR + QD)

Input to GLUNF and MEND-G

Experimental analysis for partial photon-neutron emission reactions and (n,p), (n,alpha) ...

GLUNF for Be-9

MEND-G for medium-heavy nuclei

ENDF/B-6 output and format check

\[ ^{9}\text{Be} \rightarrow ^{209}\text{Bi} \quad 274 \text{ nuclei} \]
Data validation for CENDL-3.2 via ENDITS
Overall view with statistics
- CENDL-3.2 gives the best $\chi^2$ in comparison.
- The prediction for $^{235}\text{U}$ and Pu systems get remarkable improvement.

<table>
<thead>
<tr>
<th>Type</th>
<th>Cores</th>
<th>Quantity</th>
<th>CENDL-3.2</th>
<th>CENDL-3.1</th>
<th>ENDF/B-VIII.0</th>
<th>JENDL-4.0</th>
<th>JEFF-3.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-235</td>
<td>698</td>
<td>C/E-1(pcm)</td>
<td>-13</td>
<td>197</td>
<td>-8</td>
<td>59</td>
<td>158</td>
</tr>
<tr>
<td></td>
<td></td>
<td>STDEV</td>
<td>828</td>
<td>912</td>
<td>825</td>
<td>906</td>
<td>868</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\chi^2$</td>
<td>16.94</td>
<td>31.91</td>
<td>21.61</td>
<td>19.33</td>
<td>21.29</td>
</tr>
<tr>
<td>U-Pu</td>
<td>7</td>
<td>C/E-1(pcm)</td>
<td>155</td>
<td>-36</td>
<td>-170</td>
<td>-1233</td>
<td>176</td>
</tr>
<tr>
<td></td>
<td></td>
<td>STDEV</td>
<td>277</td>
<td>285</td>
<td>225</td>
<td>572</td>
<td>221</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\chi^2$</td>
<td>20.40</td>
<td>11.89</td>
<td>5.89</td>
<td>249.26</td>
<td>4.58</td>
</tr>
<tr>
<td>Pu</td>
<td>388</td>
<td>C/E-1(pcm)</td>
<td>27</td>
<td>729</td>
<td>68</td>
<td>541</td>
<td>217</td>
</tr>
<tr>
<td></td>
<td></td>
<td>STDEV</td>
<td>511</td>
<td>788</td>
<td>485</td>
<td>562</td>
<td>494</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\chi^2$</td>
<td>2.80</td>
<td>8.90</td>
<td>2.13</td>
<td>4.81</td>
<td>2.72</td>
</tr>
<tr>
<td>U-233</td>
<td>165</td>
<td>C/E-1(pcm)</td>
<td>-449</td>
<td>-36</td>
<td>-581</td>
<td>-649</td>
<td>-313</td>
</tr>
<tr>
<td></td>
<td></td>
<td>STDEV</td>
<td>1206</td>
<td>1196</td>
<td>1116</td>
<td>1030</td>
<td>1120</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\chi^2$</td>
<td>5.18</td>
<td>6.52</td>
<td>4.78</td>
<td>4.74</td>
<td>4.39</td>
</tr>
<tr>
<td>All</td>
<td>1261</td>
<td>C/E-1(pcm)</td>
<td>-58</td>
<td>327</td>
<td>-63</td>
<td>106</td>
<td>112</td>
</tr>
<tr>
<td></td>
<td></td>
<td>STDEV</td>
<td>821</td>
<td>958</td>
<td>809</td>
<td>914</td>
<td>828</td>
</tr>
</tbody>
</table>
CENDL-3.2: Kerma factors calculations

NJOY 2016 input

heatr /Add heating kerma and damage energy
-21 -23 -24/
2631 2 0 0 0 1/
443 444/ 443-total kinematic kerma
Conclusion:

✓ As the main output of CENDL project, CENDL-3.2 library is built with the general purpose to provide high-quality nuclear data for the modern nuclear science, engineering and nuclear technology etc applications.

✓ CENDL-3.2 library is constituted by neutron, fission yield, decay and activation files, which is difference comparison with previous CENDL libraries, and provide more nuclear reaction information for application.

✓ Comparing with previous CENDL library, the updated evaluation of nuclear reaction data for several key nuclides, such as U-235, Pu-239, U-233, Th-232, Fe-56 and et al. has been revised and improved.

✓ The library was tested with the criticality and shielding benchmarks with ENDITS-1.0, better results have been obtained, and used for applications for CEFR, TMSR, CAP1400, ADS, BIRF, JUNA, BISOL etc projects.

✓ All CENDL project also benefit from the international cooperation such as NRDC network, IAEA/CRP, OECD/WPEC and et al;

✓ The CENDL-3.2(C32) will be officially released at the end of May 2020.
6. Conclusion & Perspective

**Perspective:**

CENDL- future will benefit from the issues related to the fundamental nuclear physics in nuclear data:

- Physics for Fission process
- Physics for few body theory and light nuclei
- Physics around the reaction and structure data for neutron-rich nuclei

also from the issues related to the international nuclear data measurements, evaluation, library construction:

- Measurements for key elements with better accuracy
- Modern facilities with better quality for broader beam energy region and good intensity…
- Systematic theoretical and evaluation studies for unstable nuclei
- Uncertainty evaluation based on nuclear data
- The microscopic study applied to the ND data production

and from:

- Deeper and further international co-operation …