The neutron_hp neutron transport code.

J.P. Wellisch
CERN/PH
A sketch of model management
Models for neutron interaction and thermalization.

- Neutron_hp sampling codes for ENDF/B-VI derived data formats are completely generic.
- Simulate the cross-sections and interactions of neutrons with kinetic energies below 20 MeV down to thermal energies.
- The upper limit is set only by the evaluated data libraries the code is based on.
- I consider elastic scattering, fission, capture and inelastic scattering as separate models.

J.P. Wellisch, CERN/PH
The neutron_hp transport models

- neutron_hp models and cross-sections:
  - Uses the unix file-system to ensure granular and transparent access/usage of data sets.
  - More than $10^{11}$ events run.
  - Uses point-wise cross-sections
    ➔ no artifacts due to multi-group structure.
Low energy neutron data:
G4NDL0.2, 3.7

- Are granular selections of data from (alphabetic)
  - Brond 2.1
  - CENDL 2.2
  - EFF-3
  - ENDF/B (VI.0, VI.1, VI.5)
  - ENSDF
  - FENDL/E2.0
  - JEF 2.2
  - JENDL (3.1, 3.2, FF; 3.3 currently under study)
  - MENDL-2(P)

- Large parts of the initial (0.2) selection is guided by the FENDL-2
- G4NDL0.2 for non-thermal application

J.P. Wellisch, CERN/PH
Example of data driven modeling: neutron capture, and isotope production

![Graphs showing neutron capture and isotope production](image)

Figure 48: Isotope production cross-sections for neutron induced production of important isotopes as simulated using the isotope production code in GEANT4. Large points show simulation results, small points show evaluated data from the MENDL data library.
Doppler broadening

- Does exact doppler broadening on the fly, based on 0K data
  - No pre-formatting of data to fixed temperatures, and easy simulation of set-ups with mixed temperatures.
  - Adds the doppler bias to the nuclear momentum distribution
- Point one is to the best of my knowledge not possible with any other transport code.
Doppler broadening
The Doppler bias illustrated for Carbon

J.P. Wellisch,
CERN/PH
Elastic scattering

- Two representations of the differential cross section are supported
  - Tabulation as a function of the cosine of the scattering angle and incident neutron energy
    \[
    \frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}(\cos \theta, E_n)
    \]
  - Legendre polynomial expansion
    \[
    \frac{2\pi}{\sigma(E)} \frac{d\sigma}{d\Omega}(\cos \theta, E_n) = \sum_{l=0}^{n_l} \frac{2l + 1}{2} a_l(E) P_l(\cos(\theta))
    \]
Elastic scattering

J.P. Wellisch, CERN/PH
Radiative Capture

- Described using
  - Photon multiplicities or photon production cross sections.
  - Discrete and continuous contributions to the photon energy spectrum.
  - Photon angular distributions.
Radiative Capture (2)

- Multiplicity representations
  - Full transition probability array.
  - Or tabulation of the multiplicity for each discrete line and a continuum contribution
    - For the continuum contribution, we write the normalized emission probability as:

\[
f(E \rightarrow E') = \sum_{i} p_{i}(E) g_{i}(E \rightarrow E')
\]

- Cross section representations
  - Tabulation only.
Low energy neutron capture

J.P. Wellisch,
CERN/PH
Fission

- I include first, second, third, and fourth chance fission.
  - Neutron yields are tabulated as a function of incident and outgoing neutron energies
  - Angular distributions are either tabulated, or represented as a Legendre polynomial expansion.
    - If angular distributions are missing, isotropic distributions are assumed.
Fission (2)

- Six representations are available for neutron energy spectra
  - General evaporation spectrum
    \[ f(E \rightarrow E') = f(E', \Theta(E)) \]
  - Maxwell spectrum
    \[ f(E \rightarrow E') \propto \sqrt{E'} e^{E'/\Theta(E)} \]
  - Evaporation spectrum
    \[ f(E \rightarrow E') \propto E' e^{E'/\Theta(E)} \]
  - Watt spectrum
    \[ f(E \rightarrow E') \propto e^{E'/a(E)} \sinh \sqrt{b(E)E'} \]
Fission (3)

- **Madland Nix Spectrum**
  \[ f(E \to E') \propto \frac{1}{2} \left[ g(E', \langle K_i \rangle) + g(E', \langle K_h \rangle) \right] \]

- **Where**
  \[ g(E', \langle K \rangle) = \frac{1}{3\sqrt{\langle K \rangle} \Theta} \left[ u_2^{3/2} E_1(u_2) - u_1^{3/2} E_1(u_1) + \gamma(3/2, u_2) - \gamma(3/2, u_1) \right] \]

- **E_1 is the exponential integral, and**
  \[ u_1(E', \langle K \rangle) = \frac{(\sqrt{E'} - \sqrt{\langle K \rangle})^2}{\Theta} \]
  \[ u_2(E', \langle K \rangle) = \frac{(\sqrt{E'} + \sqrt{\langle K \rangle})^2}{\Theta} \]
Fission simulation

J.P. Wellisch, CERN/PH
Inelastic scattering

- The following channels are currently included:

  \[ n'(\gamma), np, nd, nt, n^3He, n\alpha, nd2\alpha, nt2\alpha, n2p, n2\alpha, np\alpha, n3\alpha, 2n, 2np, 2nd, 2n\alpha, 2n2\alpha, nX, 3\alpha, 3np, 3n\alpha, 4n, p, pd, p\alpha, 2p, d, d\alpha, d2\alpha, dt, t, t2\alpha, ^3He, \alpha, 2\alpha, \text{ and } 3\alpha. \]

- Photons that may be associated to the individual channels are described as in the case of capture.
Neutron induced isotope production
Isotope production

J.P. Wellisch, CERN/PH
Summary

- I have provided a neutron code suitable for a wide range of neutron transport problems.
- Future improvements will focus on details of the thermal scattering law, and the unresolved resonance region.

J.P. Wellisch, CERN/PH