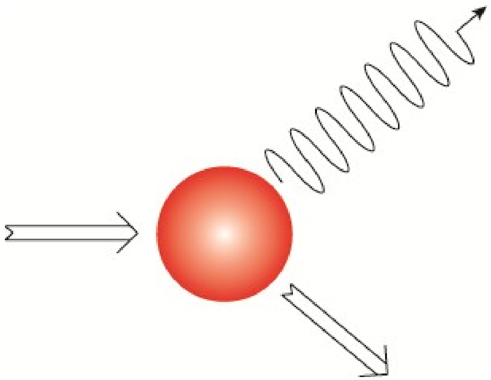
Evaluated neutron cross section libraries



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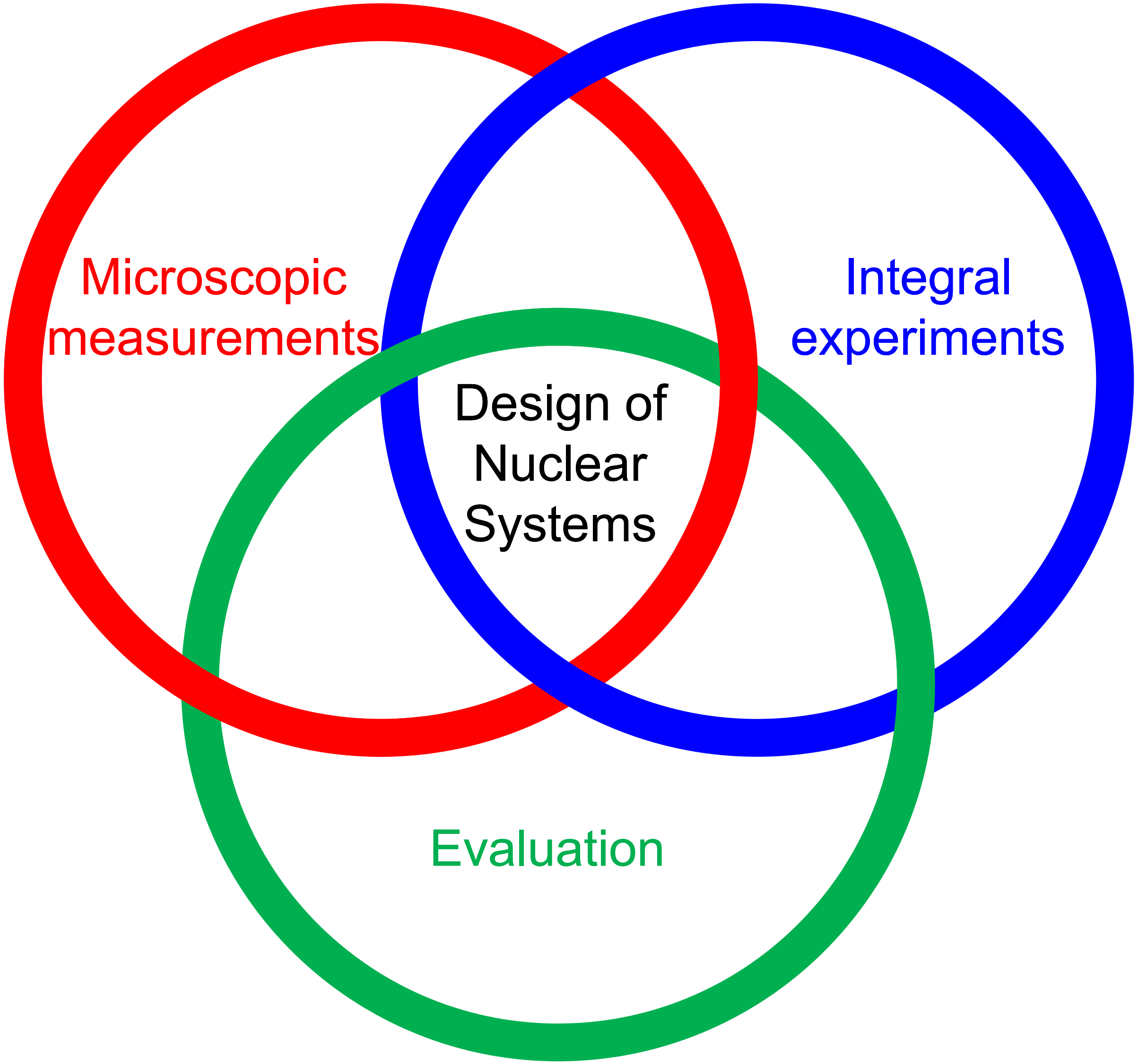
Neutron cross sections (III): how do we obtain them?

Nuclear reaction cross sections at low energies (below 20 MeV, which is a "historical" upper energy limit for the evaluated cross section files) can not be calculated with nuclear models with enough ACCURACY. Example: in the simulation of a reactor, the criticality constant "k" should be determined with an accuracy of 1/1000 or better.

All possible reaction channels have to be **MEASURED** and then **EVALUATED**:

- Comparison and weighting of all the **available experimental data sets**.
- Use of parameter dependent theoretical models for predicting the missing channels (possible at energies above a few hundred keV).
- Further adjustment of the cross sections with **benchmarks** and comparison of the subsequent results to accurate measurements in macroscopic nuclear systems (done by evaluation agencies and research centers).



Microscopic measurements
Integral experiments
Design of Nuclear Systems
Evaluation

Most of the cross section measurements are commonly referred to standard cross sections. Any revision of the standards will lead automatically to changes in the evaluated files.

Reaction	Neutron Energy Range	
	1987	**2002-2005/06**
H(n,n)	1 keV to 20 MeV	1 keV to 20 MeV
^{3}He(n,p)	0.0253 eV to 50 keV	0.0253 eV to 50 keV (1987 adopted)
^{6}Li(n,t)	0.0253 eV to 1 MeV	0.0253 eV to 1 MeV
^{10}B(n,α)	0.0253 eV to 250 keV	0.0253 eV to 1 MeV
^{10}B(n,$\alpha_1\gamma$)	0.0253 eV to 250 keV	0.0253 eV to 1 MeV
C(n,n)	up to 1.8 MeV	up to 1.8 MeV (1987 adopted)
Au(n,γ)	0.0253 eV, and 0.2 to 2.5 MeV	0.0253 eV, and 0.2 to 2.5 MeV
^{235}U(n,f)	0.0253 eV, and 0.15 to 20 MeV	0.0253 eV, and 0.15 to 200 MeV
^{238}U(n,f)	threshold to 20 MeV	2 to 200 MeV

Source: http://www-nds.iaea.org/standards/

Neutron cross sections are measured at different facilities and by different techniques.

-Time of flight method. Pulsed neutron sources.
-Activation. Reactors or irradiation facilities.
-Monochromatic neutron beams.

All the data sets are taken for the “combined” evaluation and the evaluator has to assign an uncertainty to them which is not always the one reported. All reaction channels need to be included.

In one experiment one may measure one or a few specific reaction channels. All of them are correlated and thus careful covariance analysis should be made. This is however not the case for most of the data files (very complex problem) and has started to be done recently.

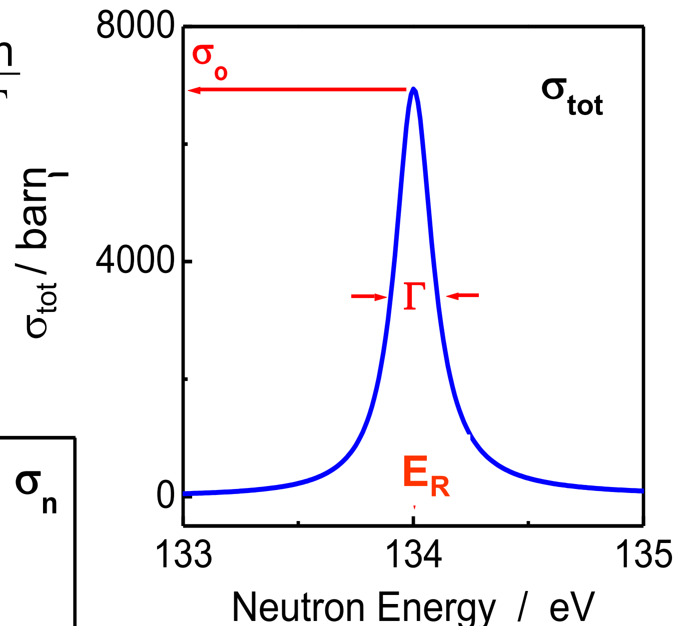
The evaluation has to be done in a very wide energy range, from meV up to tens of MeV (~150 MeV in the most recent files).

-Resolved resonace region (En < 150 eV – hundreds of keV): R-matrix formalism and data fitting.
-Unresolved resonance region: statistical models and nuclear reaction models.

e.g. ^{109}Ag s-wave at E_R = 134 eV

(E_R, Γ_n, Γ_γ , $J^{(\pi)}$, l)

$$\sigma_o = \frac{4\pi}{k_R^2} g_J \frac{\Gamma_n}{\Gamma}$$



E_R = 134 eV

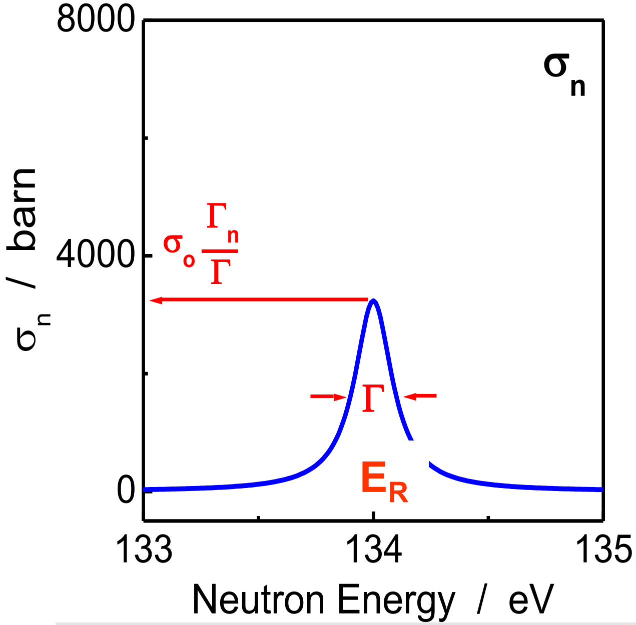
Γ_n = 0.093 eV

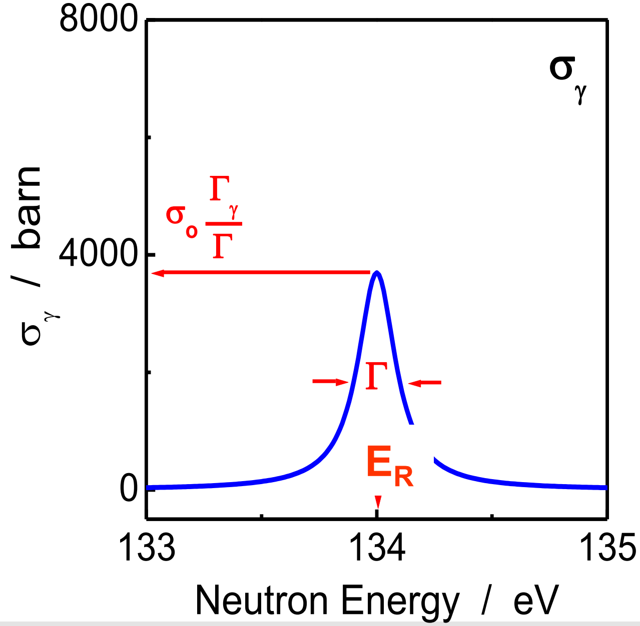
Γ_γ = 0.106 eV

J^π = 1^-

l = 0

g_J = 3/4





SLBW for low energy s-wave
(n,n) and (n,γ)

- (n,γ)

$$\sigma_\gamma(E_n) = g_J \frac{\pi}{k_n^2} \frac{\Gamma_n \Gamma_\gamma}{(E_n - E_R)^2 + (\Gamma/2)^2}$$

$$\Gamma = \Gamma_n + \Gamma_\gamma$$

$$g_J = \frac{2J+1}{2(2I+1)}$$

$$R = 1.23 A^{1/3} \text{ fm}$$

- (n,n)

$$\sigma_n(E_n) = g_J \frac{\pi}{k_n^2} \frac{\Gamma_n \Gamma_n}{(E_n - E_R)^2 + (\Gamma/2)^2} + g_J \frac{4\pi}{k_n} \frac{\Gamma_n (E_n - E_R) R}{(E_n - E_R)^2 + (\Gamma/2)^2} + g_J 4\pi R^2$$

- Total

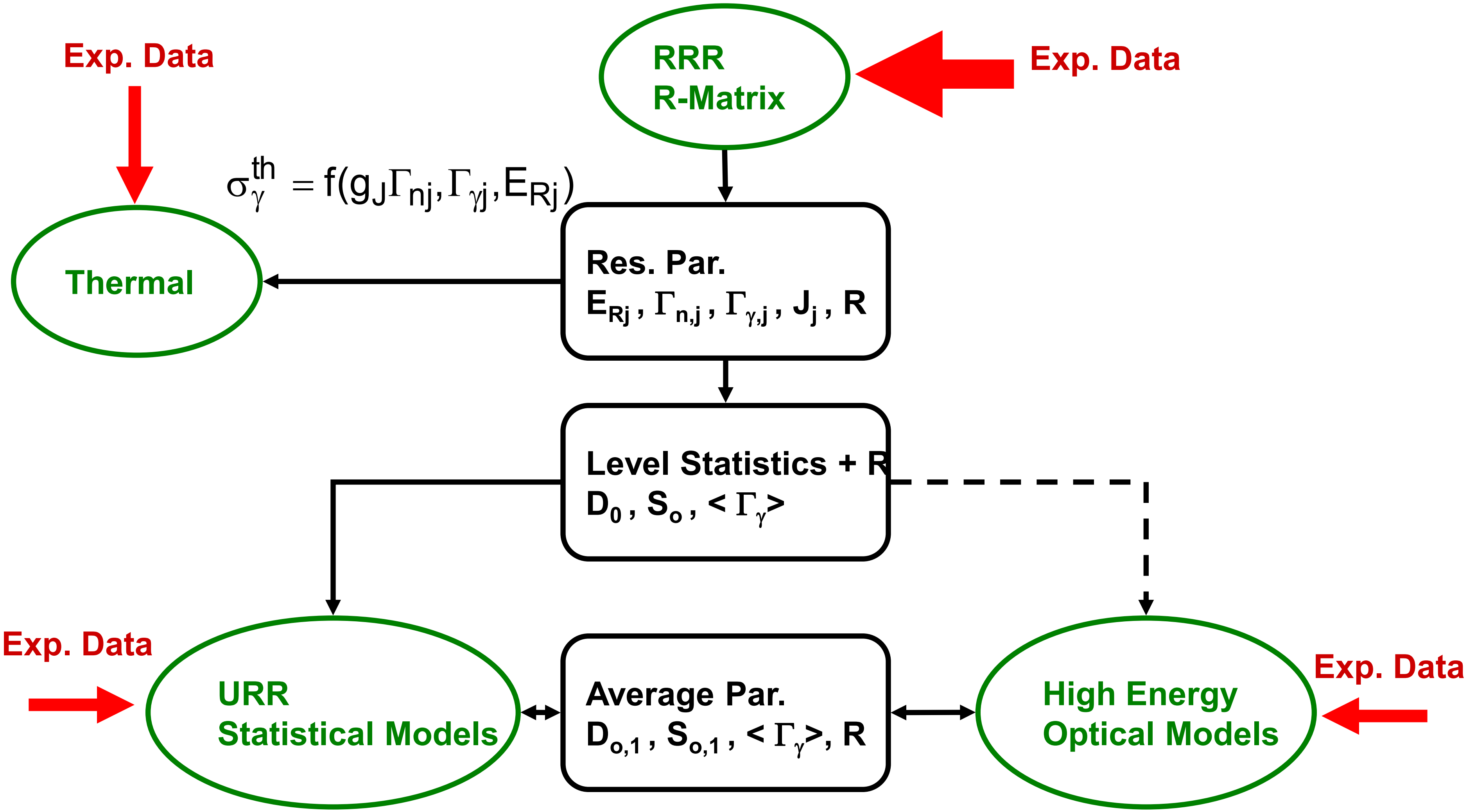
$$\sigma_{tot}(E_n) = g_J \frac{\pi}{k_n^2} \frac{\Gamma_n \Gamma}{(E_n - E_R)^2 + (\Gamma/2)^2} + g_J \frac{4\pi}{k_n} \frac{\Gamma_n (E_n - E_R) R}{(E_n - E_R)^2 + (\Gamma/2)^2} + g_J 4\pi R^2$$

$$\boxed{\Rightarrow \quad (E_R, \Gamma_n, \Gamma_\gamma, J(\pi), \ell)}$$

Parameterisation of neutron cross sections by nuclear reaction theory

- Ensures consistency between partial and total cross sections
- Ensures consistency between cross section data in different energy regions
- Prevents the use and recommendation of unphysical data
- Reliable calculations of Doppler broadened reaction cross sections
- Permits inter - and extrapolation into regions were no experimental data are available
- Permits prediction of reaction cross sections for isotopes not directly accessible to experiments

Parameterisation of neutron cross sections by nuclear reaction theory



Evaluated cross section files are public and can be downloaded from different on-line nuclear data services:

IAEA – free

NEA – free

BNL – free

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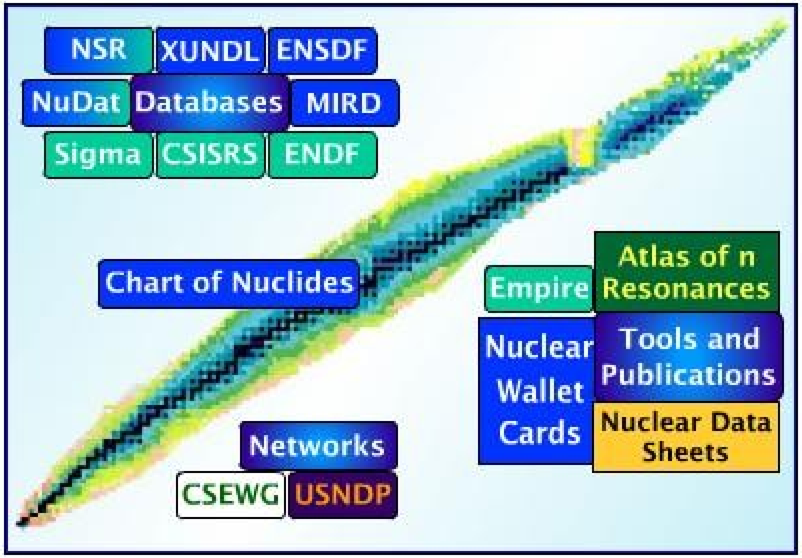
At low energies, the cross section are parameterised in terms of resonance parameters. As soon as the resonance spacing becomes similar to the average level spacing, a point wise description (E_n, σ) is provided. There are however effects of the resonant structure of the cross sections which have to be taken into account.

The cross sections are distributed in the standard ENDF-6 formatted files. Secondary particle production probabilities for the different reaction channels is also provided.

The format is complex (RP + c.s.) and need to be pre-processed before Monte Carlo codes can use them (point wise). Some codes for processing them are restricted (NJOY) and authorisation has to be requested. Some other codes (like PREPRO, distributed by the IAEA are public) are freely distributed.



National Nuclear Data Center

NNDC

BROOKHAVEN NATIONAL LABORATORY

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- Nuclear Structure and Decay Tools
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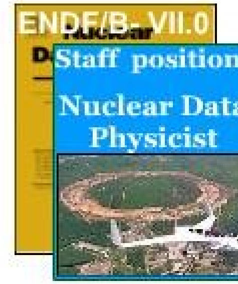

Low-Fidelity Covariances New ENDF Checking Codes

Site Index - Search the NNDC: Go

AMDC Atomic Mass Data Center, *Q-value Calculator*	**Atlas of Neutron Resonances** Parameters & thermal values	**CapGam** Thermal Neutron Capture γ-rays	**Chart of Nuclides** Basic properties of atomic nuclei
CINDA Computer Index of Nuclear (reaction) Data	**CSEWG** Cross Section Evaluation Working Group	**CSISRS alias EXFOR** Nuclear reaction experimental data	**Empire** Nuclear reaction model code system, *Reference paper*
ENDF Evaluated Nuclear (reaction) Data File, *Sigma*	**ENSDF** Evaluated Nuclear Structure Data File	**IRDF** International Reactor Dosimetry File	**MIRD** Medical Internal Radiation Dose
NMMSS & DoE NMIRDC Safeguards & inventory decay data standards	**NSR** Nuclear Science References	**Nuclear Data Sheets** Nuclear structure & decay data journal, *Special Issues on reaction data*	**Nuclear Wallet Cards** Ground & isomeric states properties, *Homeland Security version*
NucRates MACS & Astro-physical reaction rates	**NuDat** Nuclear structure & decay Data	**USNDP** U.S. Nuclear Data Program	**XUNDL** Experimental Un-evaluated Nuclear Data List

http://www.nndc.bnl.gov/

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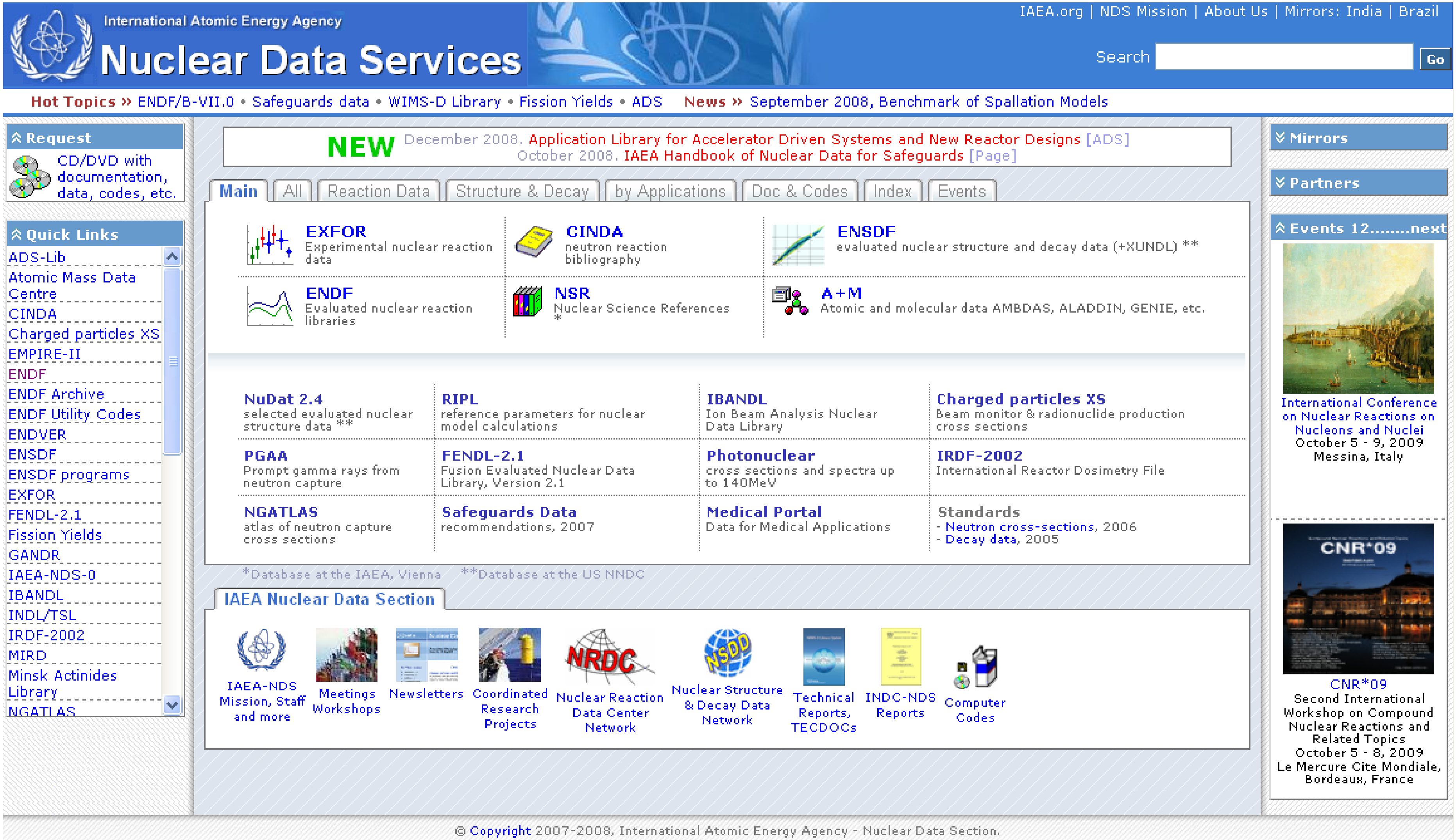

Neutron cross sections: life is not perfect

The cross sections are then released in **Evaluated Nuclear Data library Files** (**ENDF**): ENDF (USA), JEFF (Europe), JENDL (Japan), BROND (Russian Federation), CENDL (China).

•There can exist (sometimes severe) discrepancies between them.
•There are various releases and “new” does not mean “better”.

In addition to the cross sections, also the **secondary particles** produced in a neutron reaction are **tabulated**:

•(n,γ) reaction: sorting of γ-ray energies and multiplicity. No correlation between the energies, just mean values.
•(n,f) reaction: sorting of fission fragments (A,Z), kinetic energies, sorting of neutrons (energy, multiplicity), sorting of γ-rays emitted by the excited fission fragments (energy and multiplicity).

Summary and conclusions

•Evaluating a cross section file for one isotope requires a very complex task, out of the capabilities of the users. It involves both experimental data analysis and nuclear modelling.

•Thus, different agencies and geopolitical areas offer their own evaluated files to the users.

•The files are distributed with no restrictions and this also applies to some processing tools.

•Monte Carlo codes (and other calculational tools) need to have processed data. The oiriginal ENDF-6 format has to processed (RP, Doppler broadening...)

•Differences between the ENDF files do exist and can be sometimes large, thus leading to different results in the calculations.

•Benchmarking is the standard procedure for validating the "correctness" of the files. Therefore, users should have access to all sets of files for a proper systematic uncertainty assessment.