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Joint ICTP-IAEA Workshop on Nuclear Reaction Data for Advanced Reactor Technologies

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Neutron Induced Cross Section Measurements.

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Neutron Induced Cross Section Measurements

Workshop on Nuclear Reaction Data for Advanced Reactor Technologies

Trieste, Italy, 19 – 30 May 2008

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Joint Research Centre (JRC)
IRMM - Institute for Reference Materials and Measurements
Geel - Belgium
http://irmm.jrc.ec.europa.eu/
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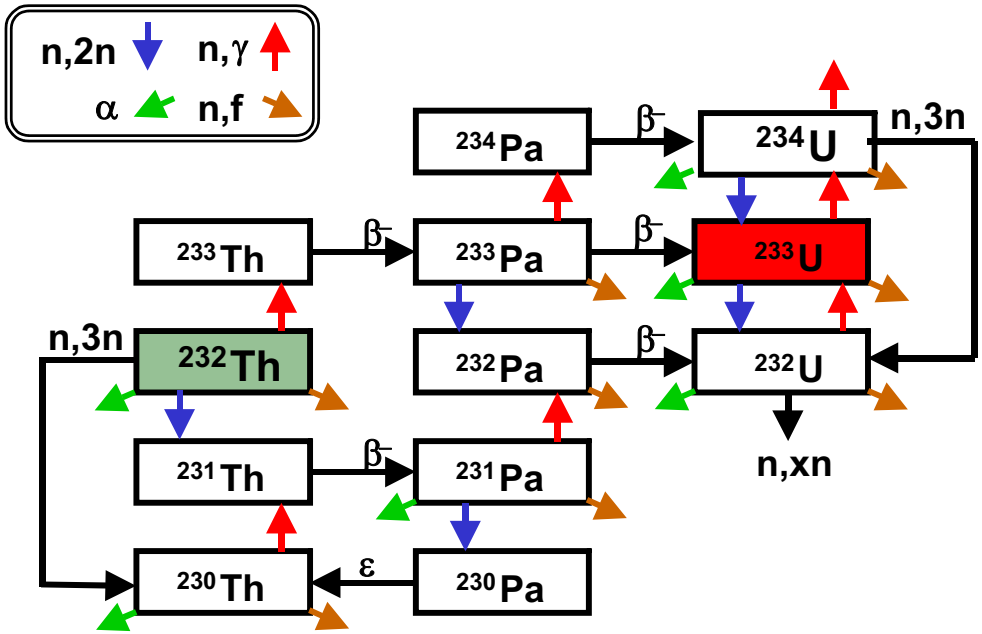
Importance of neutron induced reactions for reactor operation

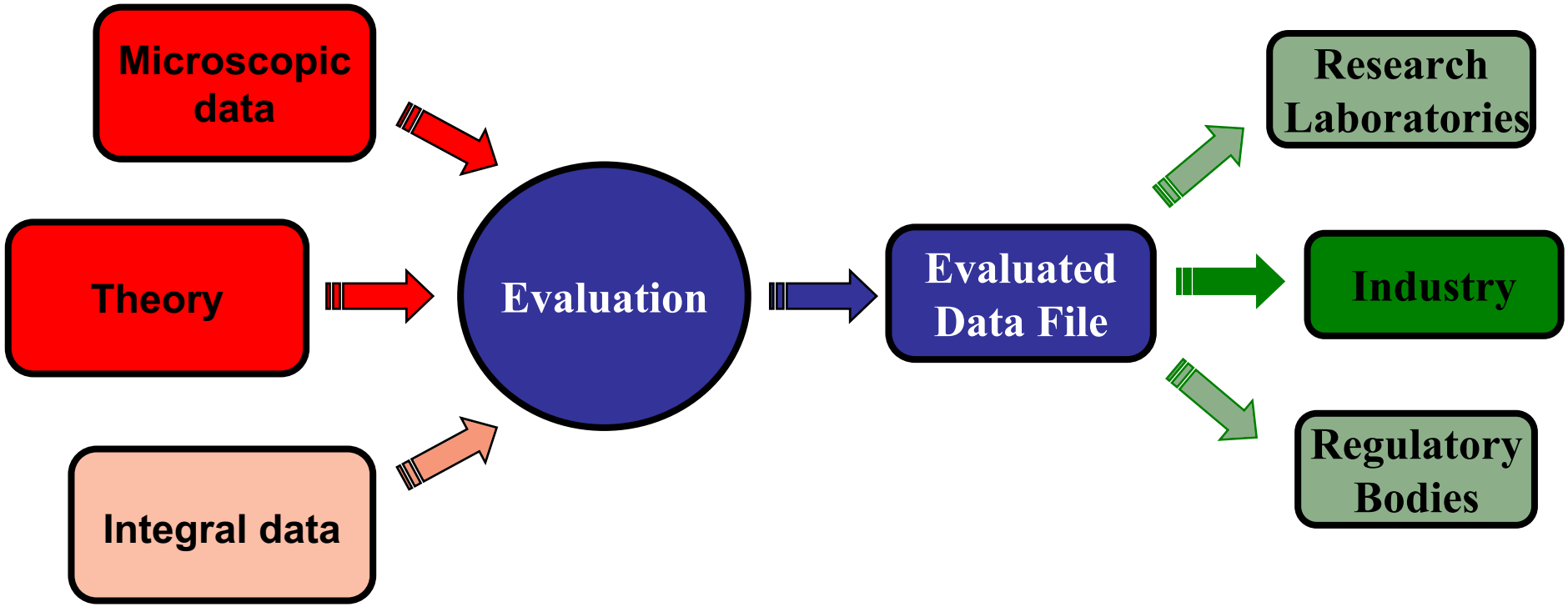
e.g. Th-U cycle



Safety + Economics

- **Nuclear fuel**
  U, Pu, Th (n,f), (n,γ), …
- **Fission products ("neutron poisoning")**
  ^{103}Rh, ^{135}Xe, ^{135}Cs, ^{149}Sm (n,γ)
- **Structural materials**
  Fe, Cr, Ni

Cross section data



Benchmark measurements

Neutron induced reactions

- **Neutron induced reactions**

  $n + X \rightarrow Y + r$

- **Various reaction channels**

$n + X \rightarrow$	$X + n$	(n,n)	elastic scattering	σ_n
	$\rightarrow Y + \gamma$	(n,γ)	capture	σ_γ
	$\rightarrow Y_1 + Y_2$	(n, f)	fission	σ_f
	$\rightarrow Y + p$	(n,p)		σ_p
	$\rightarrow$ ...			

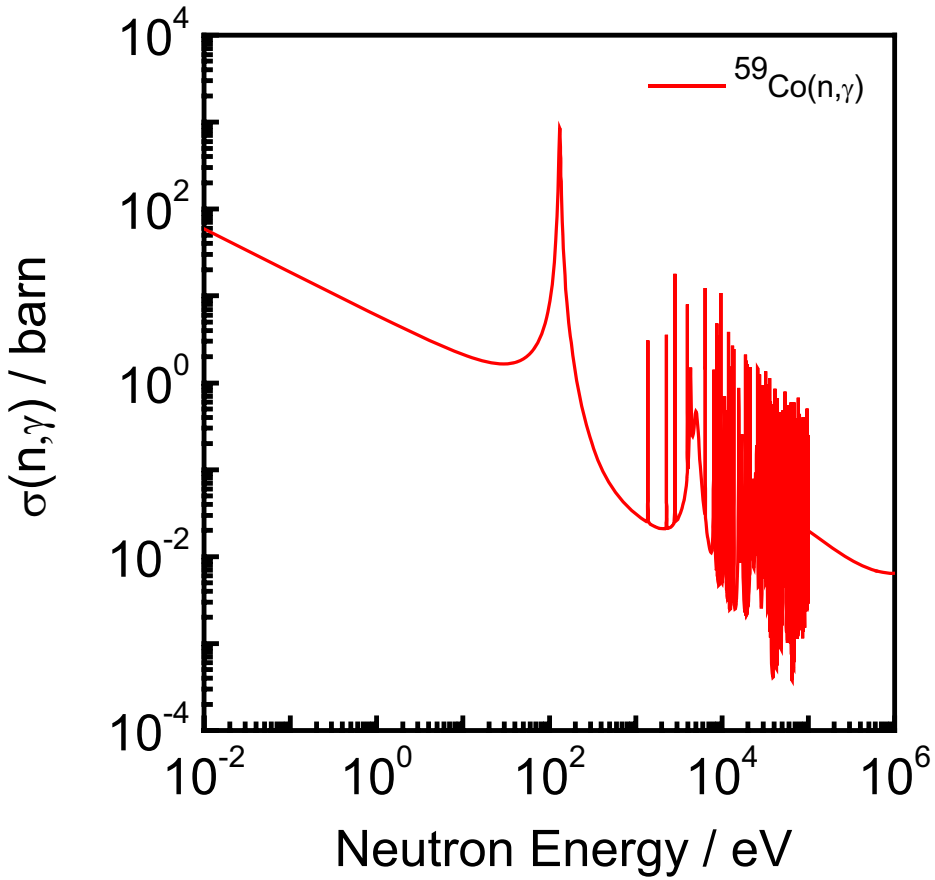
- **Probability for a reaction (n,r) to occur:**

  Partial cross section: σ_r

- **Total cross section**

  $\sigma_{tot} = \sum\sigma_r = \sigma_n + \sigma_\gamma + \sigma_f + \sigma_p + \ldots$

Cross section



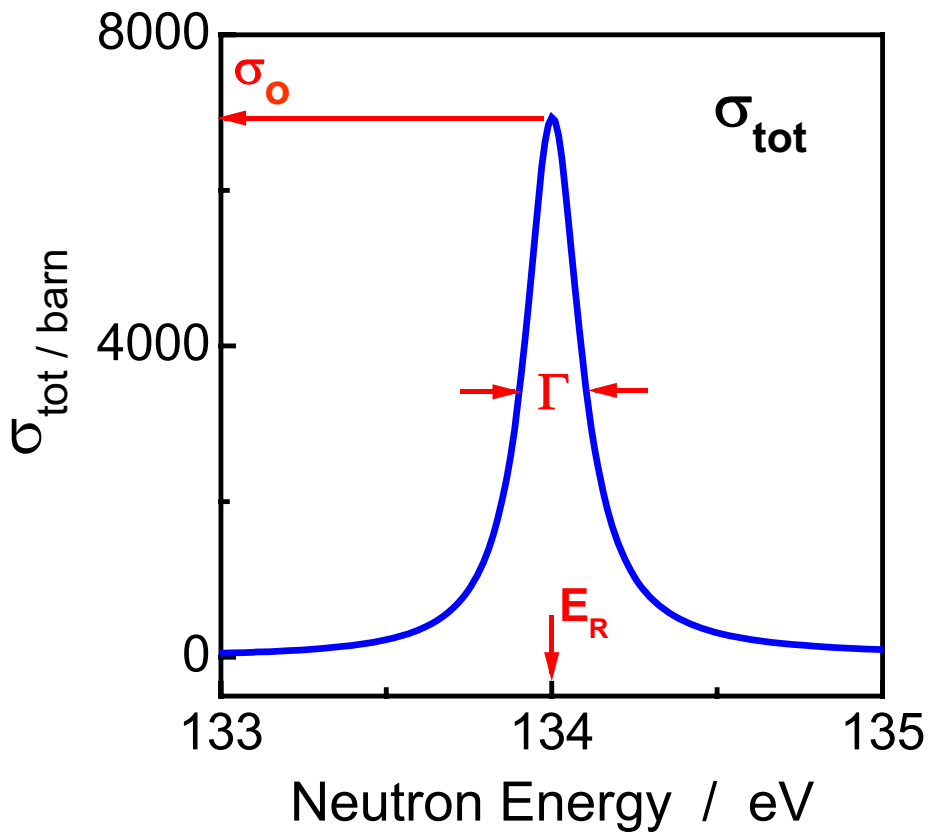
- **A cross section σ has the dimension of an area.**
- **The unit of a cross section is taken as: 1 barn, 1 b = 10^{-24} cm^2.**
- **Reaction rate for a neutron beam on a target (thin layer) :**

$$R \propto N_X \; \sigma \; \varphi_n \qquad N_X = \frac{N_A}{M_X} m(X)$$

φ_n	:	**neutron flux**
N_A	:	**Avogadro constant**
N_X	:	**number of nuclei**
M_X	:	**molar mass of nucleus X**
m(X)	:	**mass of X**

in most cases the number of nuclei per unit area are required (these will be denoted by n)

Resonance structure



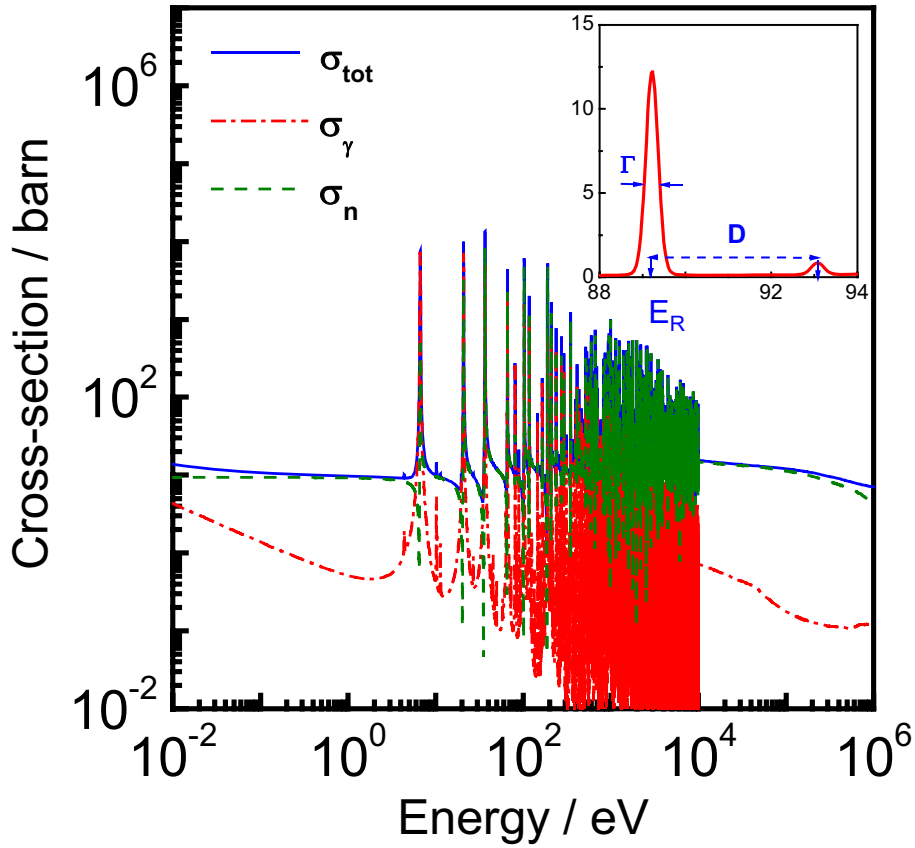
A cross section as a function of E_n shows a resonant structure, which can be described by a Breit-Wigner shape :

$$\sigma_{tot} \sim \frac{1}{(E_n - E_R)^2 + (\Gamma/2)^2}$$

with

- Γ **natural line width (FWHM)**
- E_R **resonance energy**

Cross sections : energy dependent



$^{238}U(n,tot) = {}^{238}U(n,n) + {}^{238}U(n,\gamma)$

$\sigma_{tot} = \sigma_n + \sigma_\gamma$

- **Resonance Region : D > Γ**

  Resolved Resonance Region : $\Delta_R <$ D

  Unresolved Resonance Region : $\Delta_R >$ D

- **High Energy Region : D < Γ**

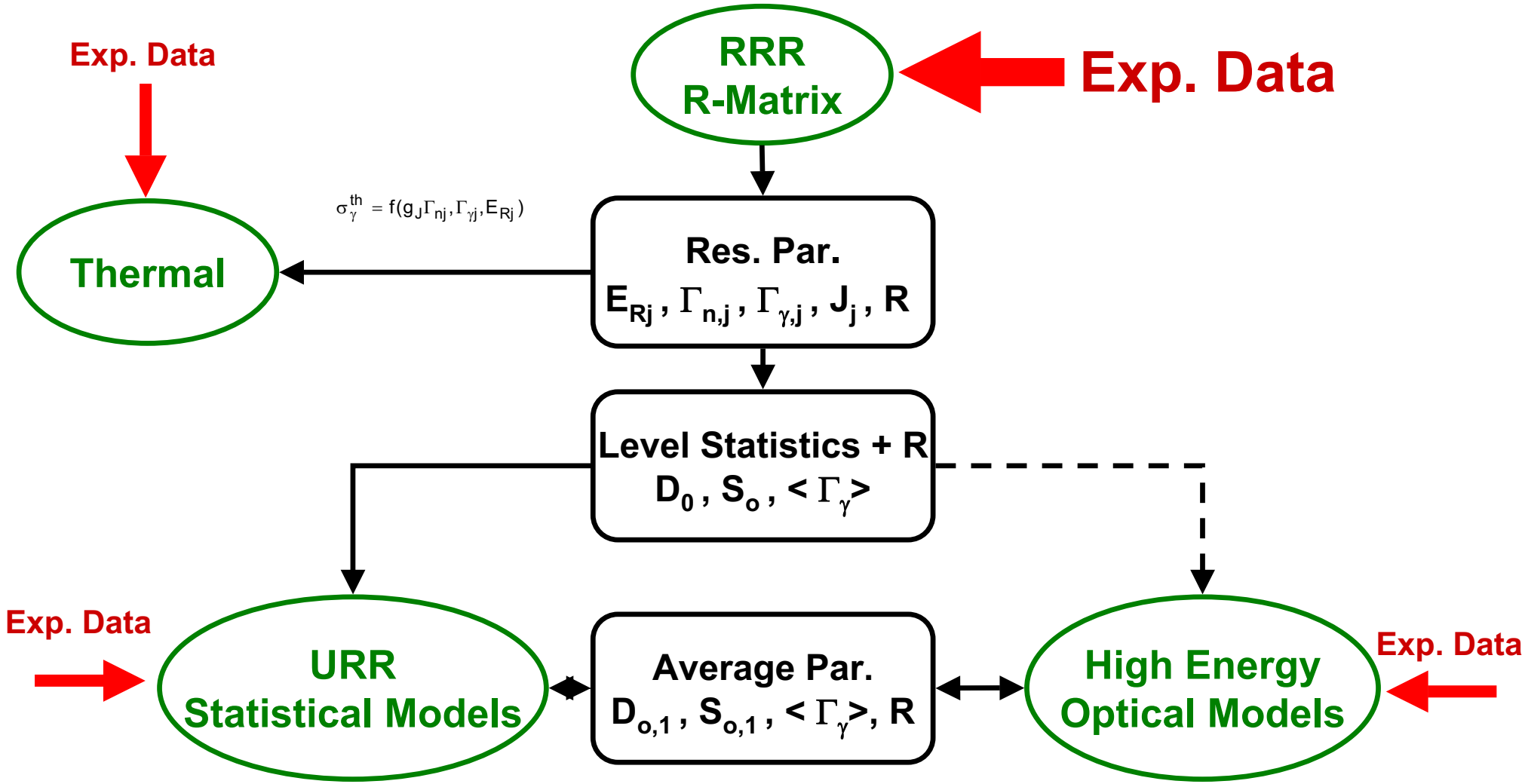
Parameterisation of neutron cross sections by nuclear reaction theory

- **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

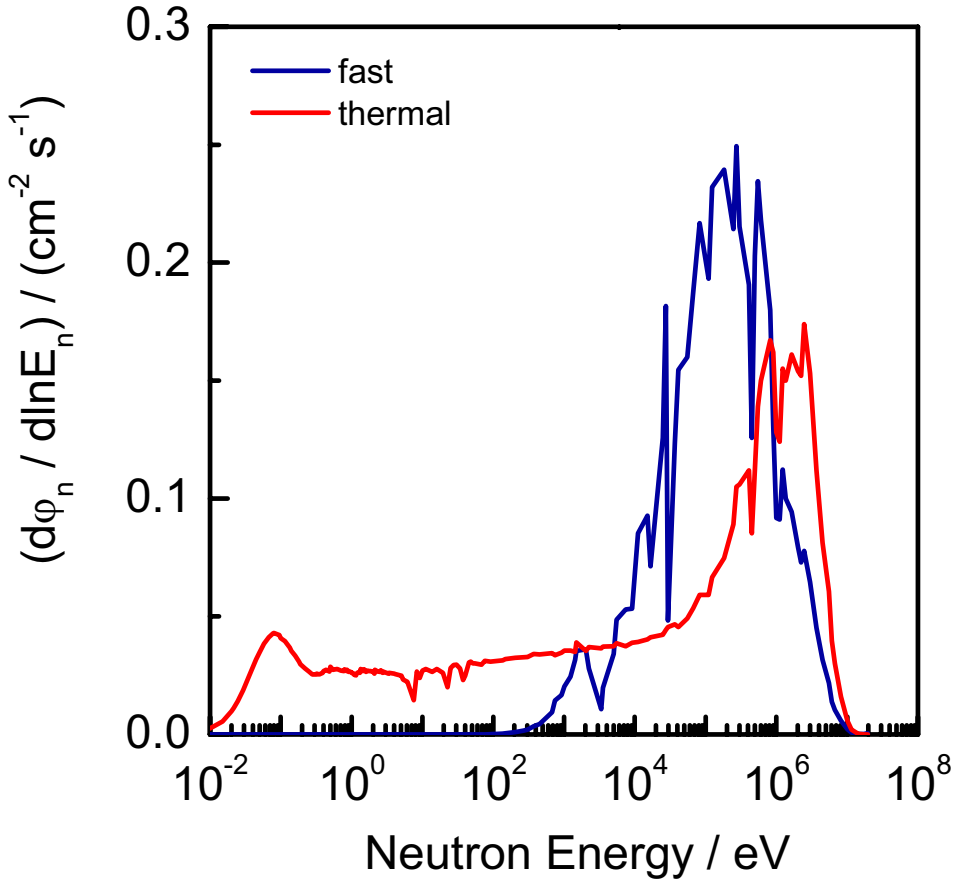
- **Thermal : R - Matrix**
- **RRR : R - Matrix (SLBW, Reich-Moore)**
- **URR : Statistical Models (Hauser – Feshbach + WF)**
- **High : Optical Model, precompound, direct reactions, …**

Parameterisation of neutron cross sections by nuclear reaction theory

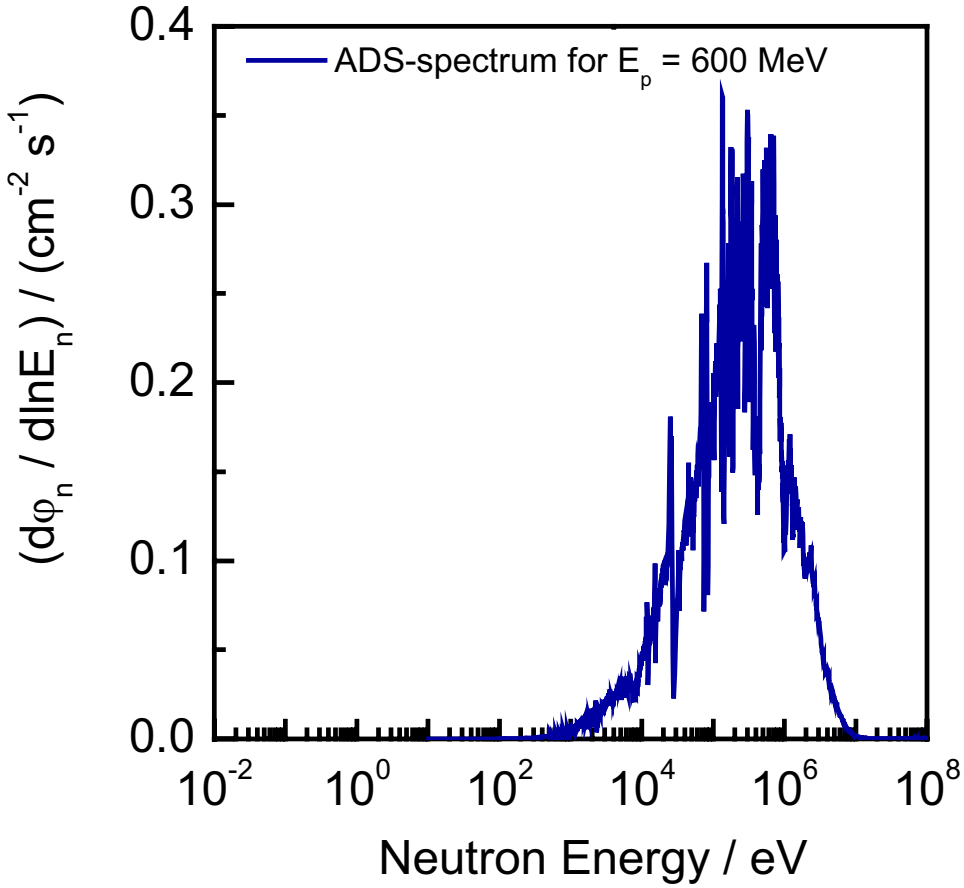


Neutron energy spectrum

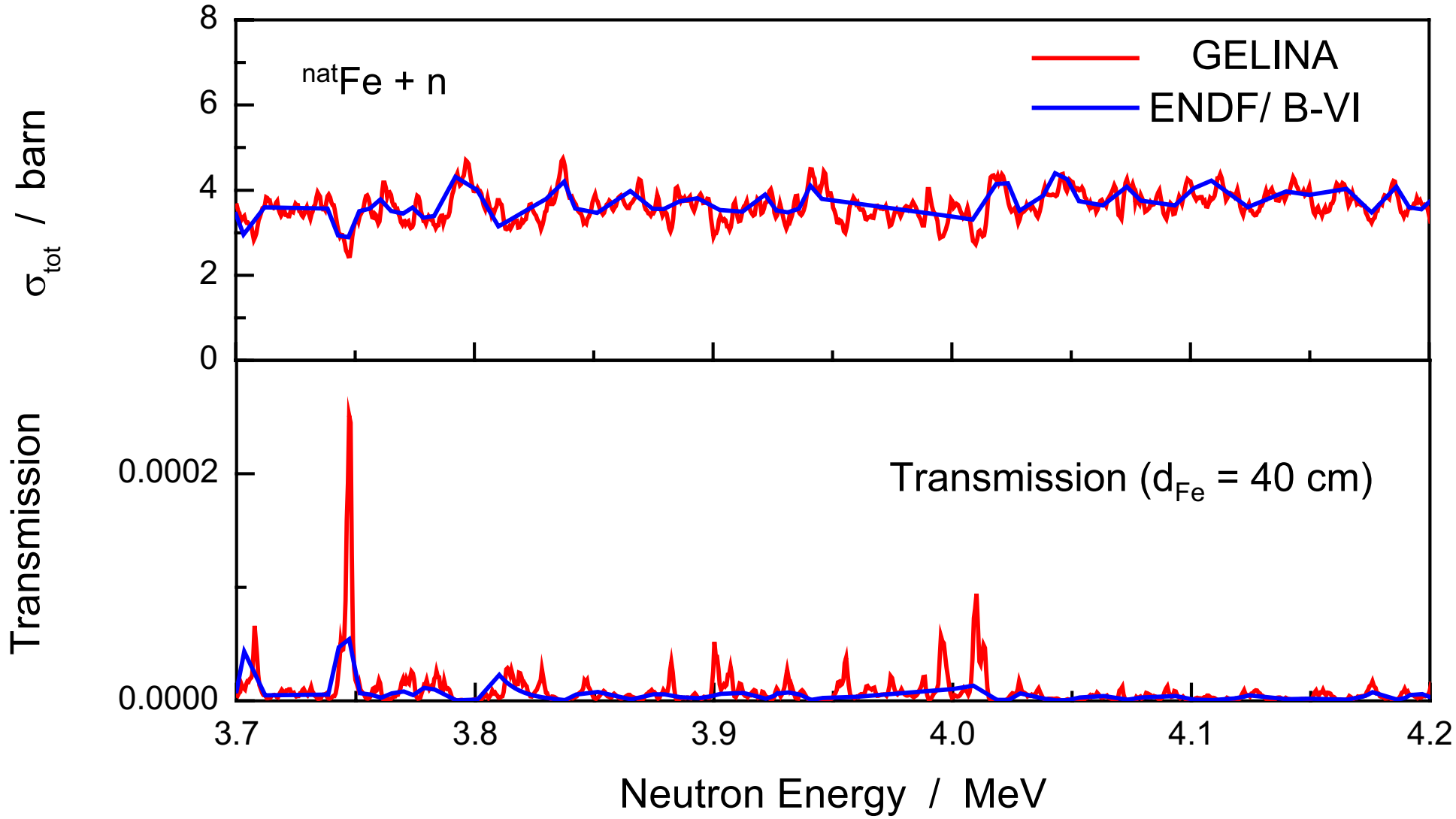
Reactor



ADS : E_p = 600 MeV

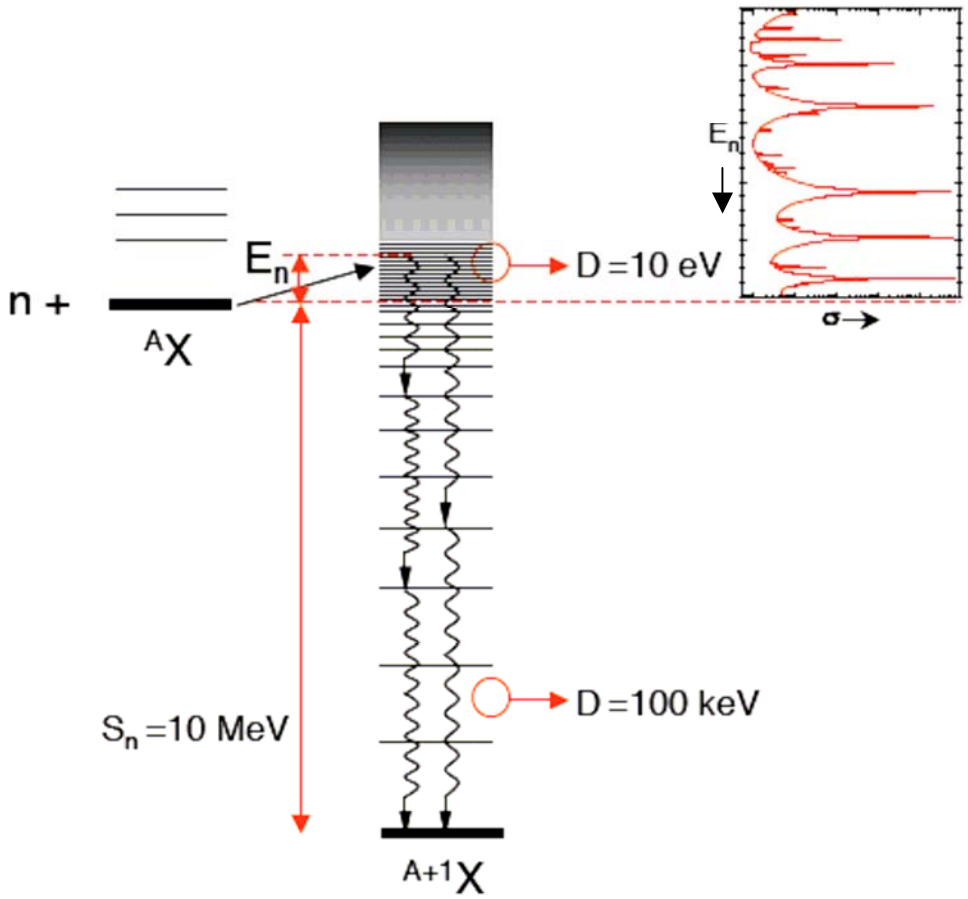


Importance of resonance structure



Resonances : compound nucleus reactions

n + X	→	C^*	→	Y + r
Entrance channel		Compound nucleus		Exit channel



Bohr's hypothesis : compound nucleus reaction
Resonance part of cross section

- **Two step process**

(1) Formation of compound nucleus σ_{C^*}

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

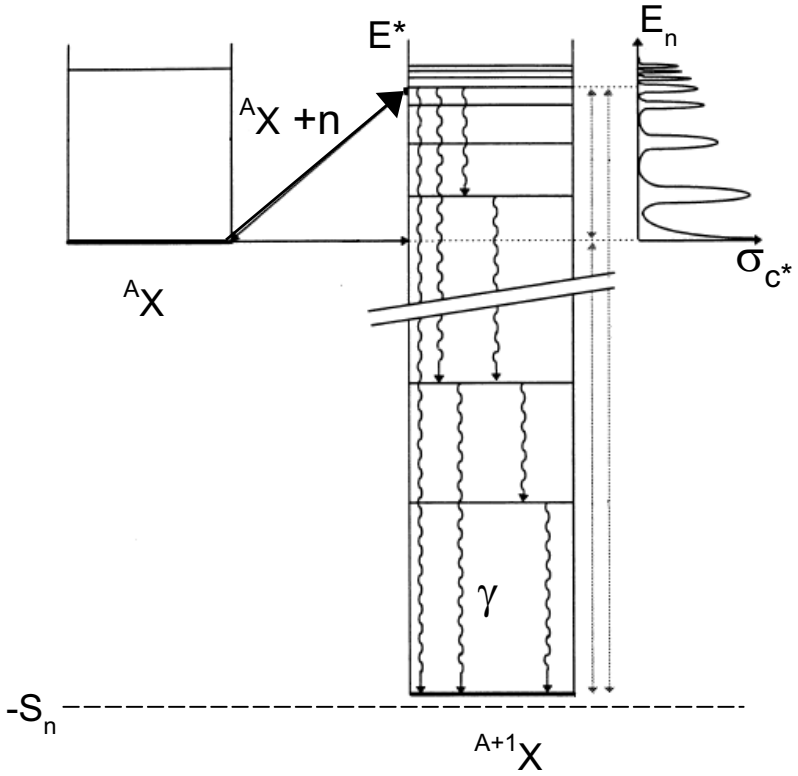
$$\Gamma = \sum_r \Gamma_r \quad (r = n, \gamma, f, \ldots)$$

(2) Decay of compound nucleus P_r

$$P_r = \frac{\Gamma_r}{\Gamma} \quad (r = n, \gamma, f, \ldots)$$

- **Partial cross section**

$$\sigma_r = \sigma_{C^*} P_r$$

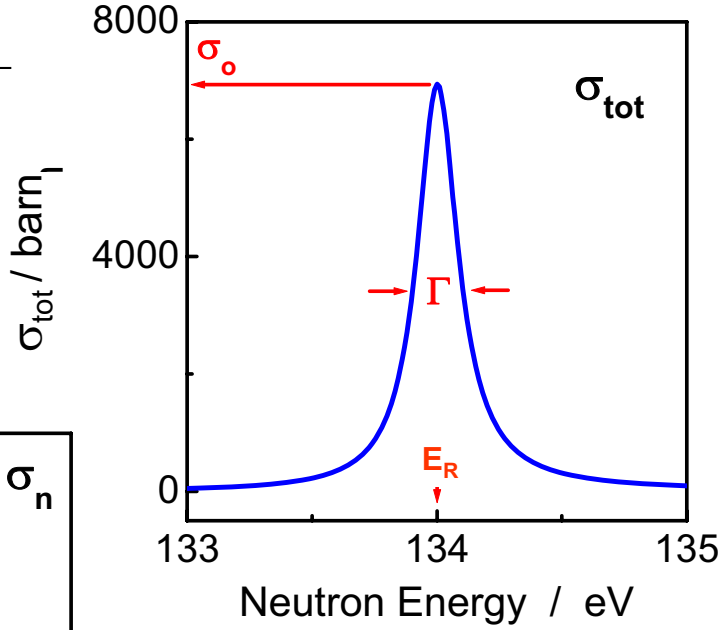


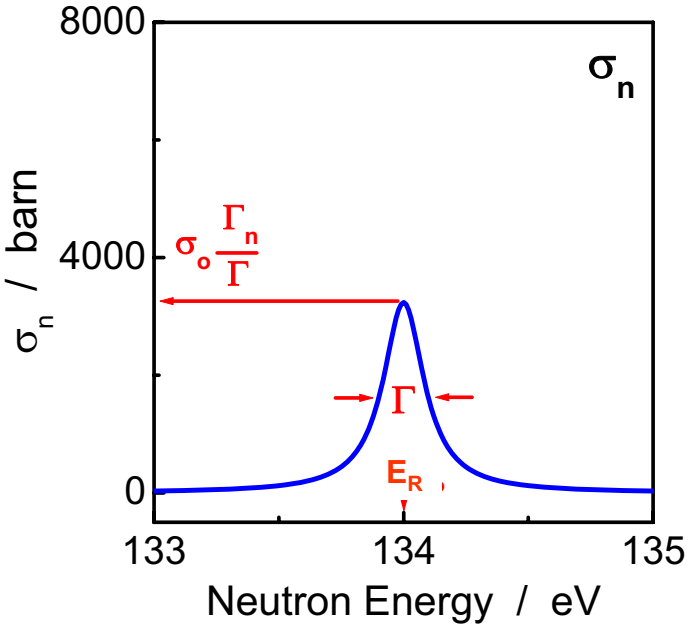
$$E^* = S_n + \frac{A}{A+1} E_n$$

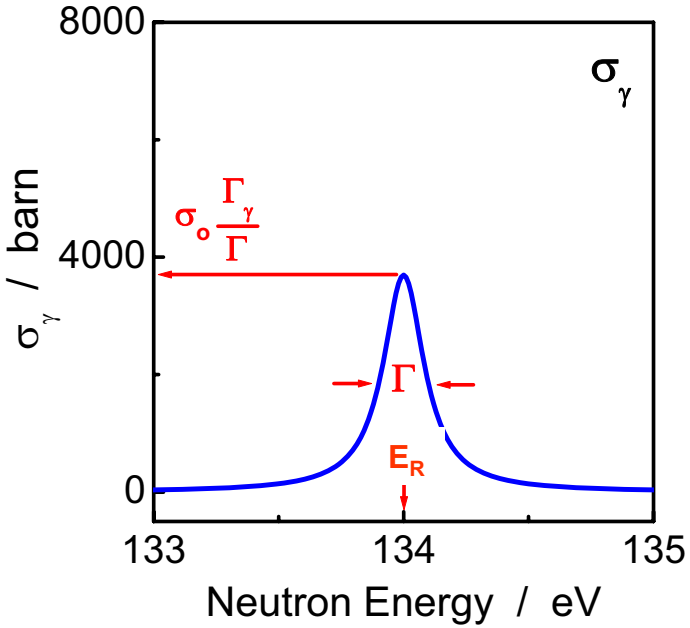
e.g. ^{109}Ag s-wave at E_R = 134 eV
(E_R, Γ_n, Γ_γ , $J^{(\pi)}$, ℓ)

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

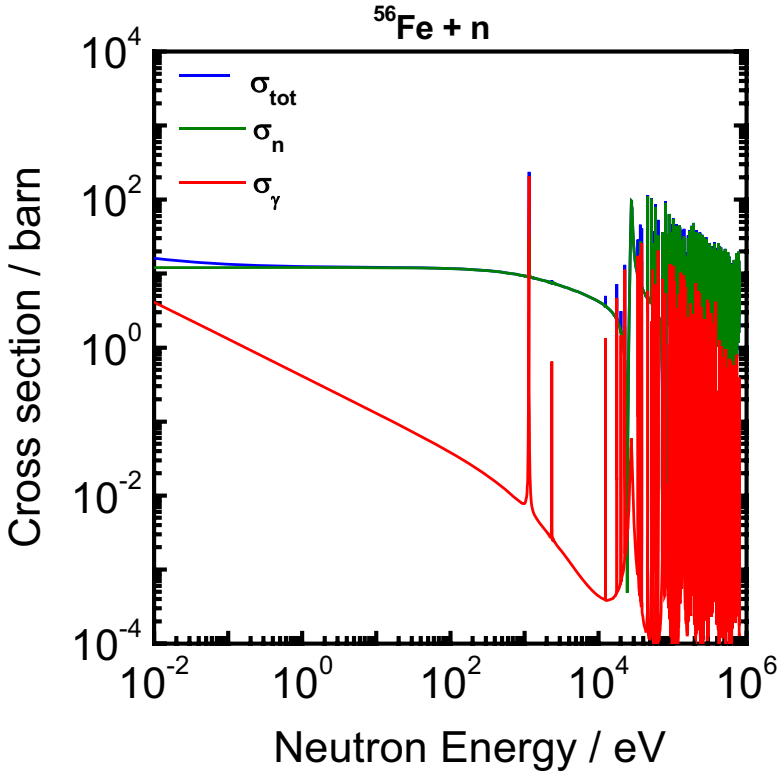
E_R = 134 eV
Γ_n = 0.093 eV
Γ_γ = 0.106 eV
J^π = 1^-
ℓ = 0
g_J = 3/4

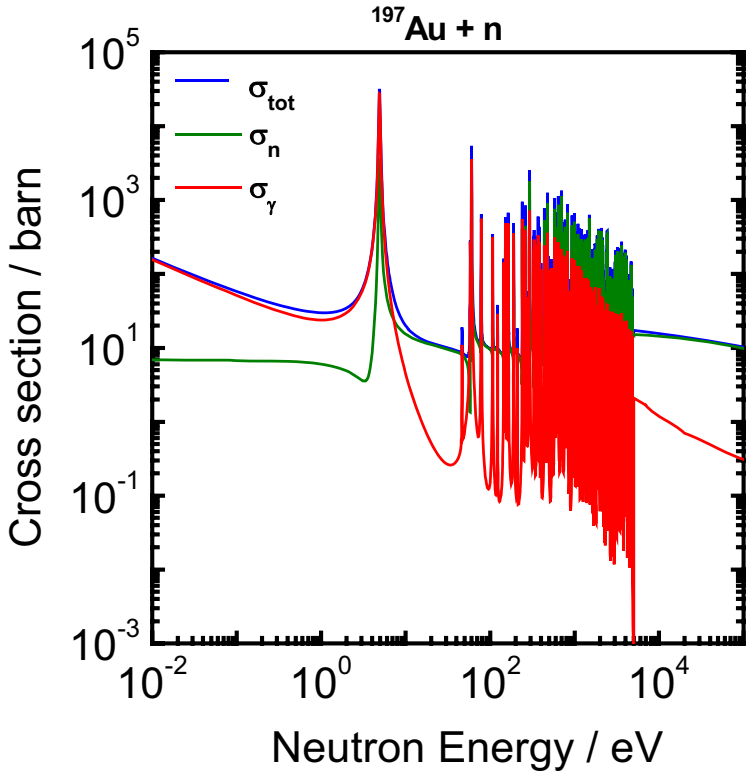






Compound nucleus reactions





- No capture without scattering
- Relative contribution of σ_n and σ_γ to σ_{tot} may be different
- Boundaries of the resonance region differ
- Not only resonances (see ^{58}Fe + n)

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

- **(n,γ)**

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

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

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

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

- **(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**

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

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