PAUL SCHERRER INSTITUT

PSI

D. Rochman

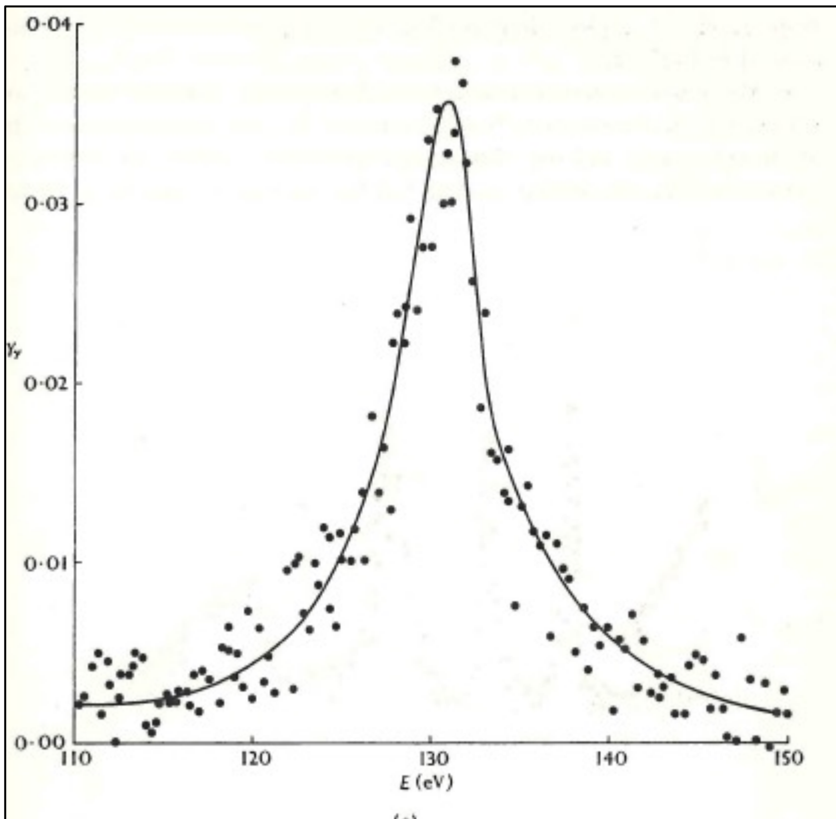
Resonance parameters and related nuclear reactions

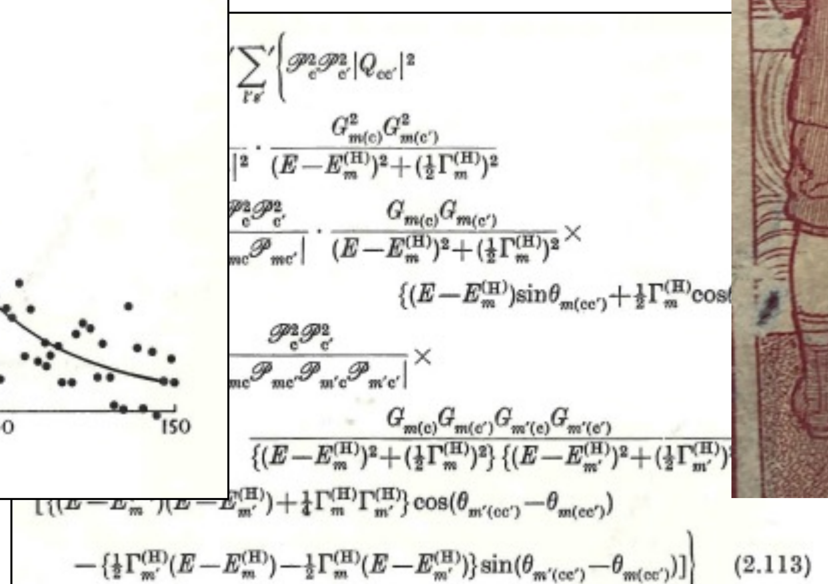
Joint ICTP-IAEA workshop, Trieste, Italy, October 16-20th, 2023

Zertifiziertes Managementsystem STARS ISO 9001

Summary

- Resonance energy range
  - Fitting
  - Resolved resonance range
  - Unresolved resonance range





$$\sum_{l's'}{}' \Big\{ \mathscr{P}_c^2 \mathscr{P}_{c'}^2 |Q_{cc'}|^2$$

$$\cdot \frac{G^2_{m(c)} G^2_{m(c')}}{(E-E_m^{(H)})^2 + (\tfrac{1}{2}\Gamma_m^{(H)})^2}$$

$$\cdot \frac{G_{m(c)} G_{m(c')}}{(E-E_m^{(H)})^2 + (\tfrac{1}{2}\Gamma_m^{(H)})^2} \times$$

$$\{(E-E_m^{(H)}) \sin\theta_{m(cc')} + \tfrac{1}{2}\Gamma_m^{(H)} \cos$$

$$\frac{G_{m(c)} G_{m(c')} G_{m'(c)} G_{m'(c')}}{\{(E-E_m^{(H)})^2 + (\tfrac{1}{2}\Gamma_m^{(H)})^2\}\{(E-E_{m'}^{(H)})^2 + (\tfrac{1}{2}\Gamma_{m'}^{(H)})^2\}}$$

$$+\tfrac{1}{4}\Gamma_m^{(H)}\Gamma_{m'}^{(H)}\} \cos(\theta_{m'(cc')} - \theta_{m(cc')})$$

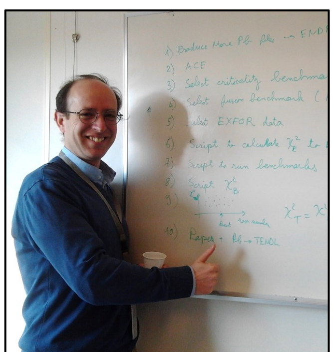
$$-\{\tfrac{1}{2}\Gamma_{m'}^{(H)}(E-E_m^{(H)}) - \tfrac{1}{2}\Gamma_m^{(H)}(E-E_{m'}^{(H)})\} \sin(\theta_{m'(cc')} - \theta_{m(cc')})]\Big\} \quad (2.113)$$

PAUL SCHERRER INSTITUT PSI

A short CV

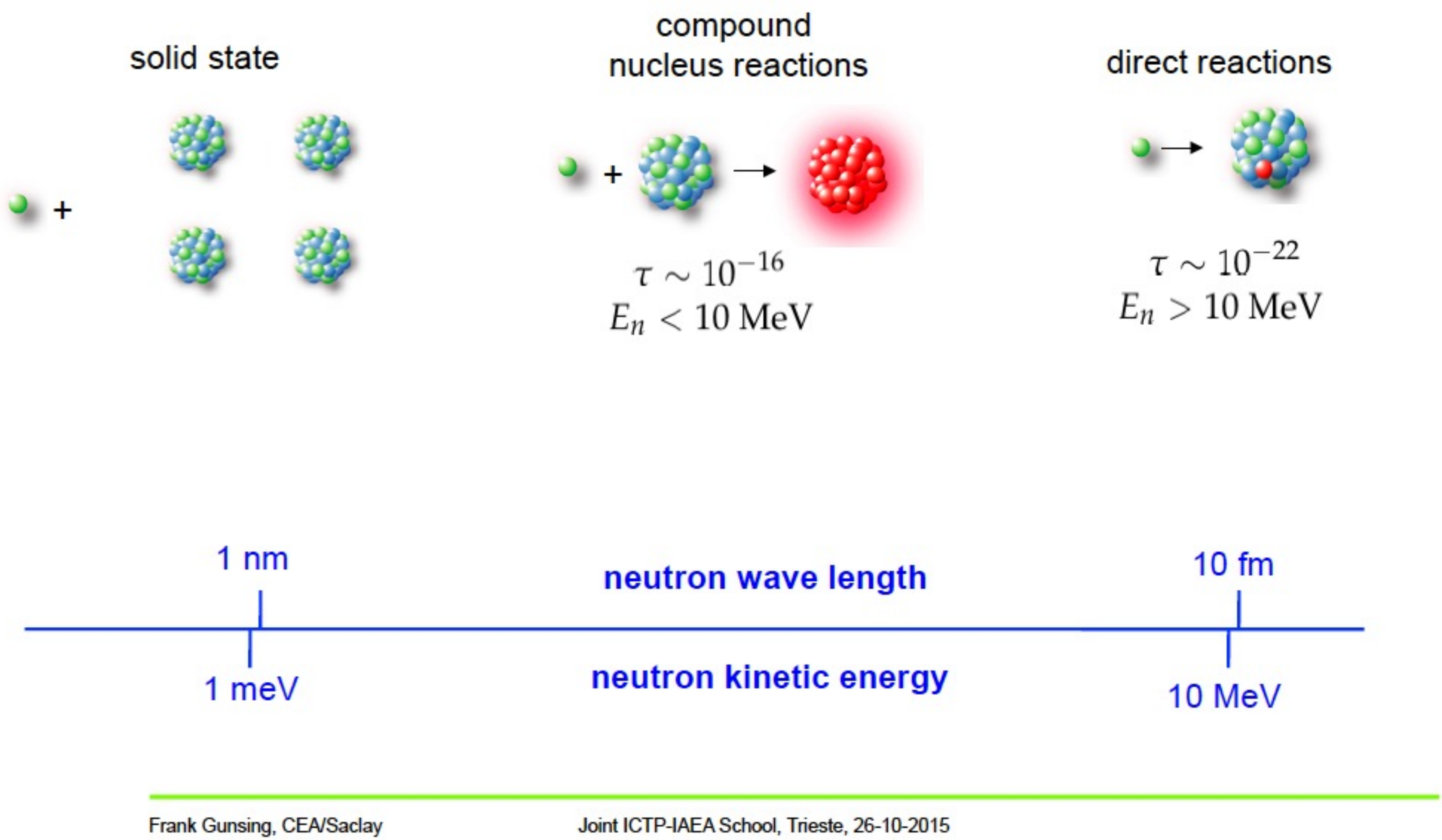
- 50 years old, married, two kids, one dog

1999-2002	2002-2004	2004-2007	2007-2014	2015-
PhD ILL	Post Doc. Los Alamos	Scientist Brookhaven	Scientist NRG Petten (^{99}Mo production)	Scientist PSI



- PhD on fission yield measurements
- Postdoc on cross section measurements
- Scientist:
  - nuclear data evaluation
  - reactor calculations
  - spent nuclear fuel characterization

Neutron induced reactions



Neutron induced reactions

Reaction:
- $X + a \rightarrow Y + b$
  - $X(a,b)Y$
  - $X(a,b)$

Examples of equivalent notations:

$^{10}B + {^1n} \rightarrow {^7Li} + {^4He}$
$^{10}B + n \rightarrow {^7Li} + \alpha$
$^{10}B(n,\alpha)$

$^{238}U + n \rightarrow {^{239}U^*}$
$^{238}U + n \rightarrow {^{239}U} + \gamma$
$^{238}U(n,\gamma)$

Reaction cross section σ, expressed in barns, $1\ b = 10^{-28}\ m^2$

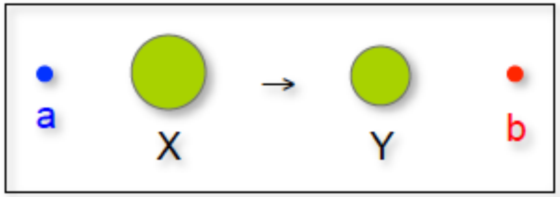
Neutron induced nuclear reactions:
- elastic scattering (n,n)
- inelastic scattering (n,n')
- capture (n,γ)
- fission (n,f)
- particle emission (n,α), (n,p), (n,xn)

Total cross section σ_{tot}: sum of all reactions

Neutron induced reactions

Reaction: • X + a → Y + b

• X(a,b)Y



Cross section:
function of the kinetic energy of the particle a

$$\sigma(E_a) = \int\int \frac{d^2\sigma(E_a, E_b, \Omega)}{dE_b d\Omega} dE_b d\Omega$$

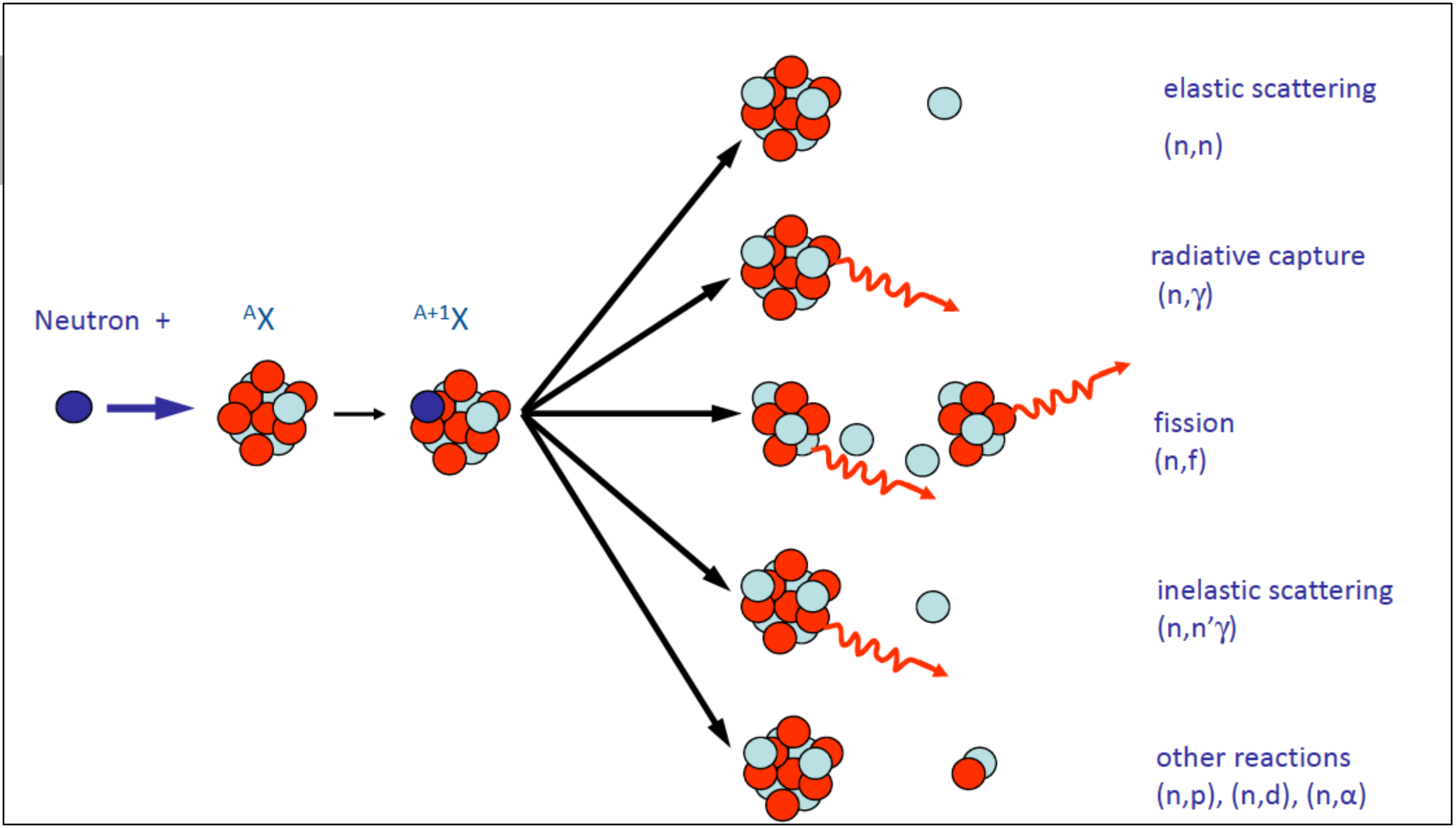
Differential cross section:
function of the kinetic energy of the particle a
and function of the kinetic energy **or** the angle
of the particle b

$$\frac{d\sigma(E_a, E_b)}{dE_b} \qquad \frac{d\sigma(E_a, \Omega)}{d\Omega}$$

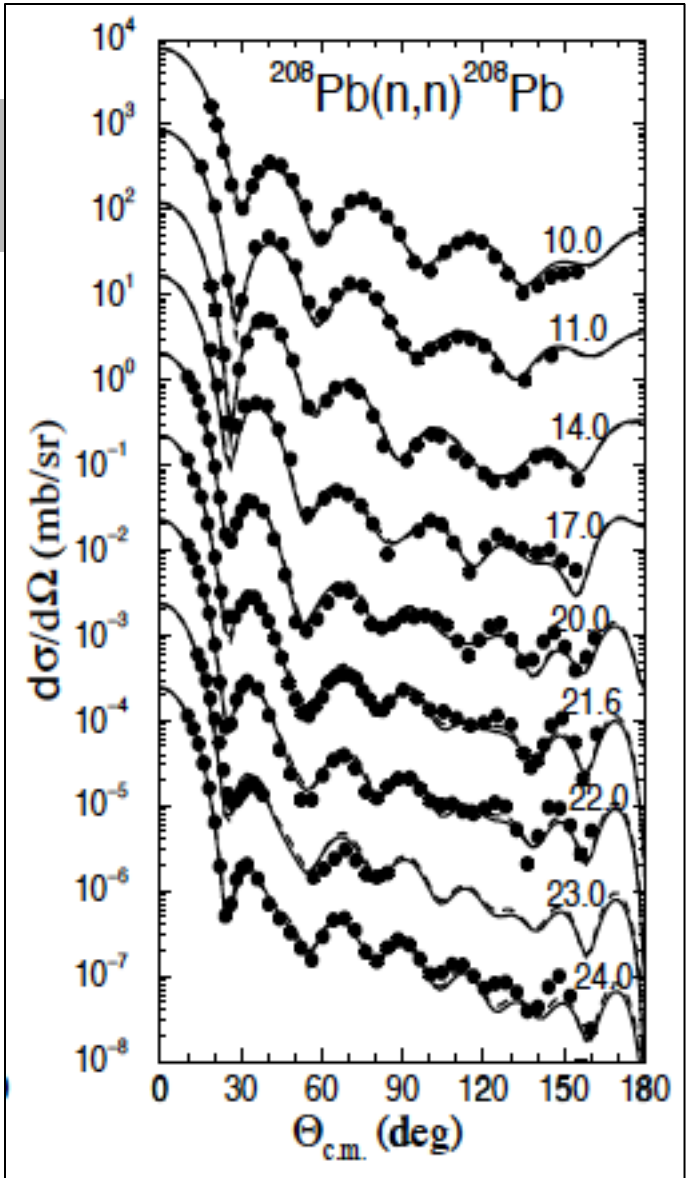
Double differential cross section:
function of the kinetic energy of the particle a
and function of the kinetic energy **and** the angle
of the particle b

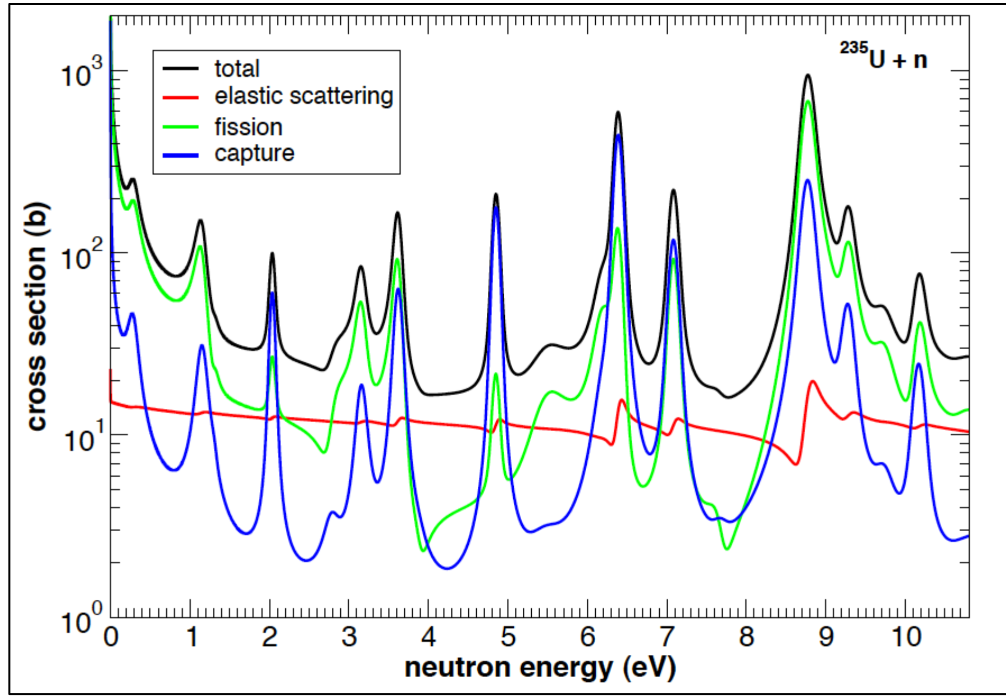
$$\frac{d^2\sigma(E_a, E_b, \Omega)}{dE_b d\Omega}$$

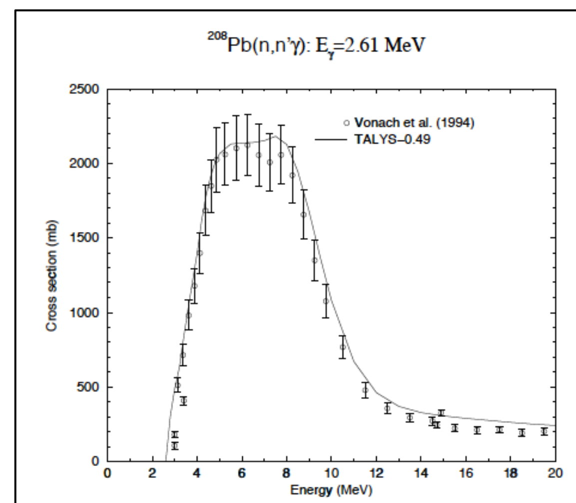
Neutron induced reactions



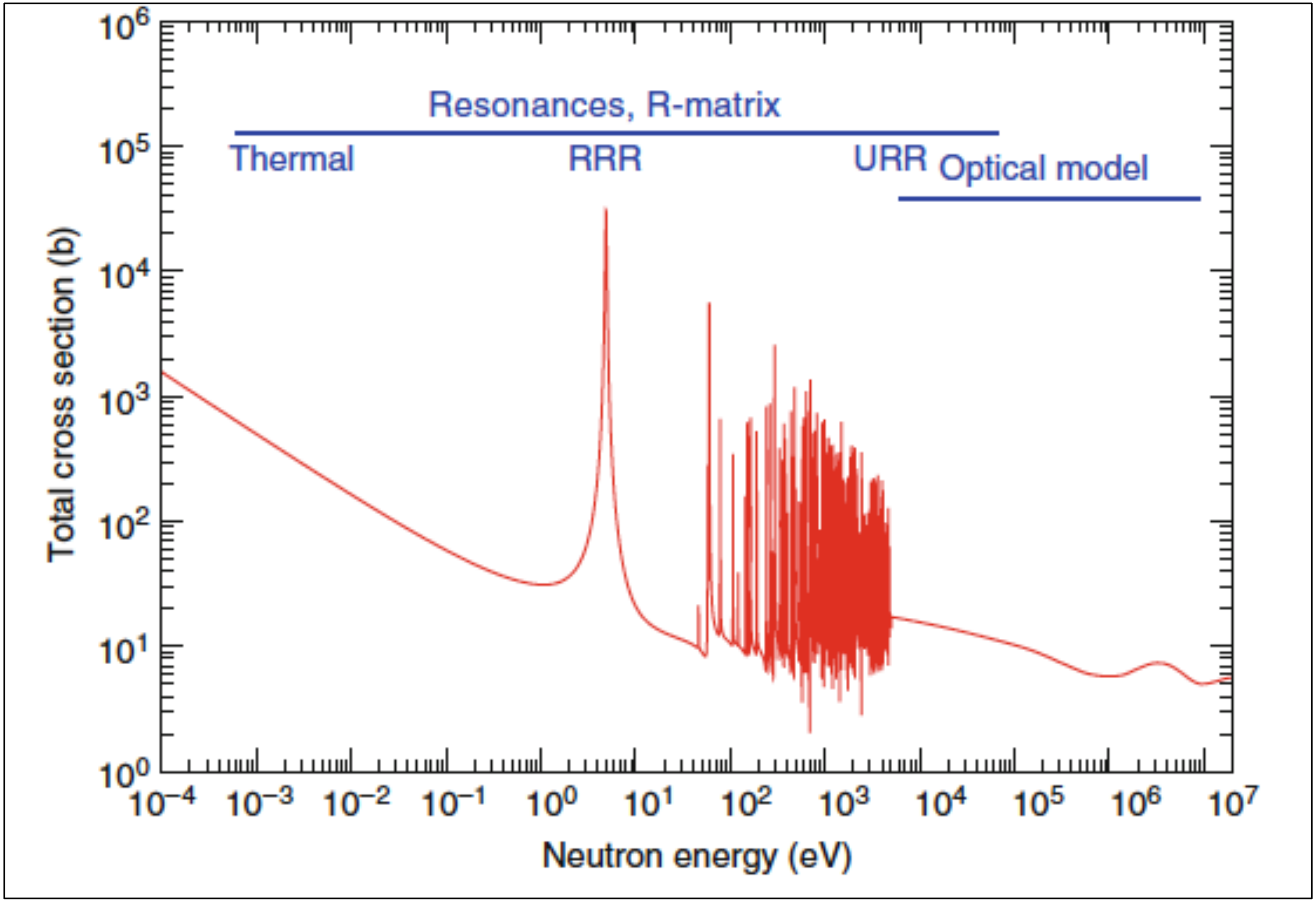
Neutron induced reactions: examples



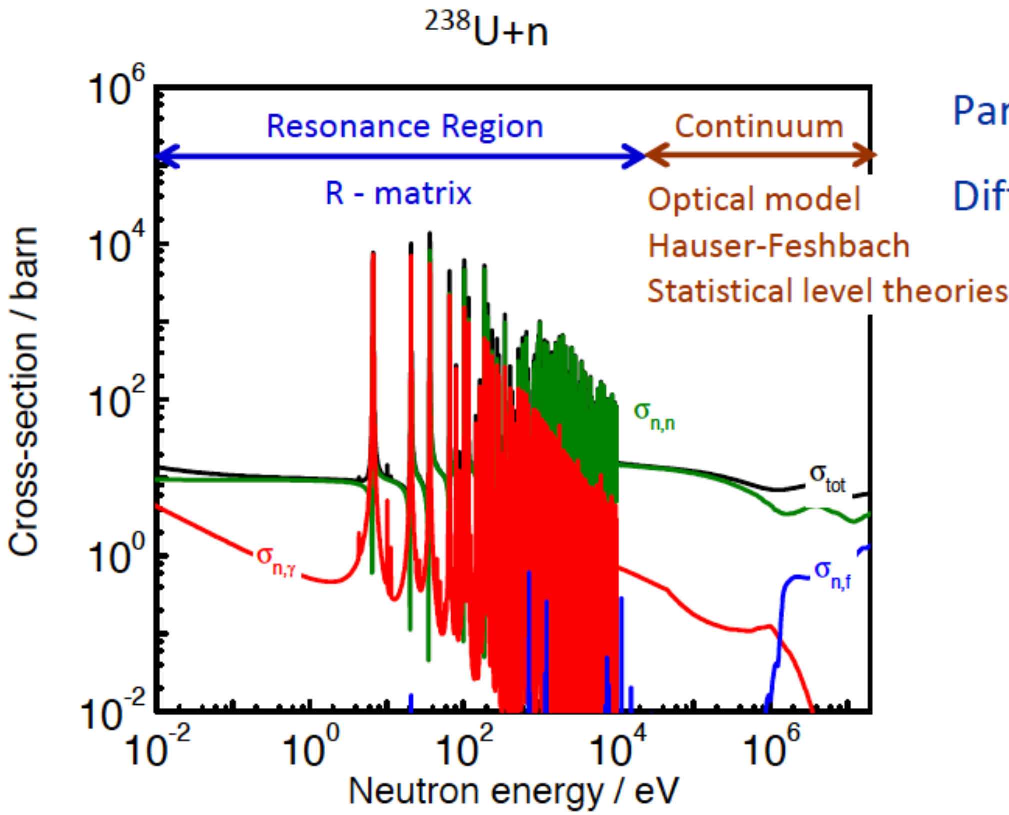




Neutron induced reactions: separation



Neutron induced reactions: separation



Parameterised by nuclear reaction model

Different regions : different theories

- Resonance region
  - R-matrix theory
- Continuum
  - Optical model
  - Hauser-Feshbach
  - Statistical level theories
  - ...

P. Schillebeeckx, Trieste, 2017

Compound nucleus: spin and parity

$n + X$	$\rightarrow$	C^*	$\rightarrow$	$Y + r$
entrance channel	(1)	compound nucleus	(2)	exit channel

$\vec{I}$ spin target nucleus

π_o parity target nucleus

$\vec{i}$ spin incoming neutron $(i = 1/2)$

$\vec{\ell}$ orbital angular momentum

$(\ell = 0, 1, 2 \rightarrow s, p, d - \text{wave})$

E_n incident neutron energy

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

$$\vec{J} = \vec{I} + \vec{i} + \vec{\ell}$$

$$\vec{J} = \vec{\ell} + \vec{s} \qquad |\ell - s| \leq J \leq |\ell + s|$$

$$\vec{s} = \vec{I} + \vec{i} \qquad |I - i| \leq s \leq |I + i|$$

$$\boxed{\pi = (-1)^{\ell} \pi_o}$$

Conservation of :

- Energy
- Total angular momentum
- **Parity**

P. Schillebeeckx, Trieste, 2017

PAUL SCHERRER INSTITUT

Compound nucleus: spin and parity

$n + X \rightarrow C^*$

entrance channel — compound nucleus

$\vec{J} = \vec{I} + \vec{i} + \vec{\ell}$

$\vec{s} = \vec{I} + \vec{i} \qquad |I - i| \leq s \leq |I + i|$

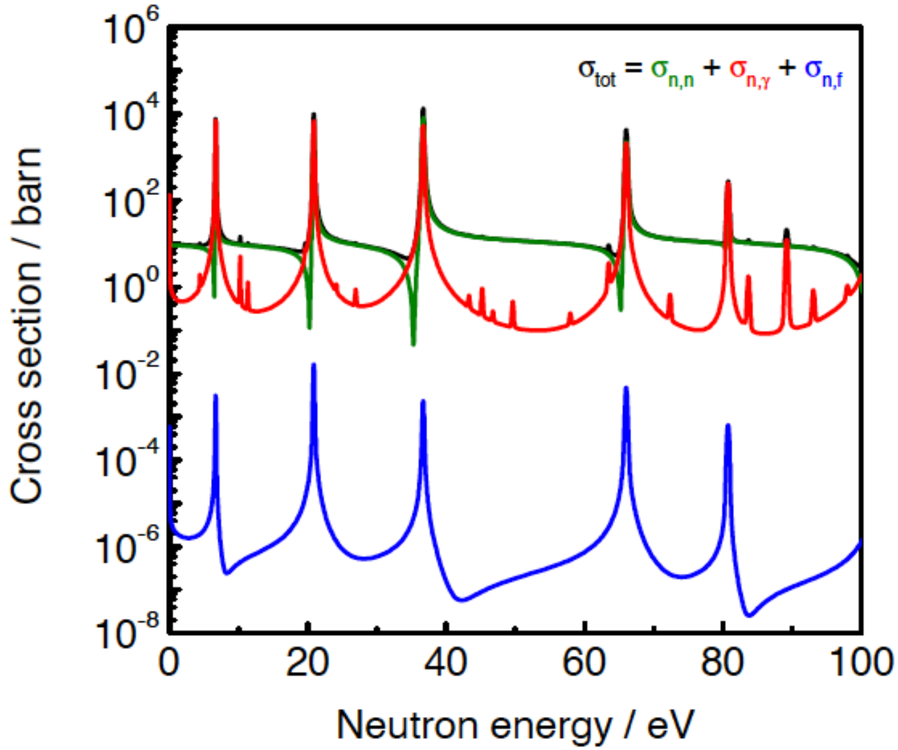
$\vec{J} = \vec{\ell} + \vec{s} \qquad |\ell - s| \leq J \leq |\ell + s|$

Incident neutron: i = 1/2

Target nucleus	Orbital angular momentum	Channel spin	Compound nucleus Spin & Parity		Spin factor
I^{π_o}	ℓ	s $\lvert I - i\rvert \leq s \leq \lvert I + i\rvert$	$\pi = (-1)^{\ell}\pi_o$	J^{π} $\lvert \ell - s\rvert \leq J \leq \lvert \ell + s\rvert$	$g = \frac{2J+1}{2(2I+1)}$
0^+	0 (s-wave)	1/2	+	$1/2^+$	1
	1 (p-wave)	1/2	−	$1/2^-$, $3/2^-$	1, 2
	2 (d-wave)	1/2	+	$3/2^+$, $5/2^+$	2, 3
$1/2^+$	0 (s-wave)	0	+	0^+	1/4
		1		1^+	3/4
	1 (p-wave)	0	−	1^-	3/4
		1		0^-, 1^-, 2^-	1/4 3/4 5/4
	2 (d-wave)	0	+	2^+	5/4
		1		1^+, 2^+, 3^+	3/4 5/4 7/4

P. Schillebeeckx, Trieste, 2017

Thermal and resonance region



R-matrix theory

Lane and Thomas, Rev. Mod. Phys. 30 (1958) 257

Model parameters

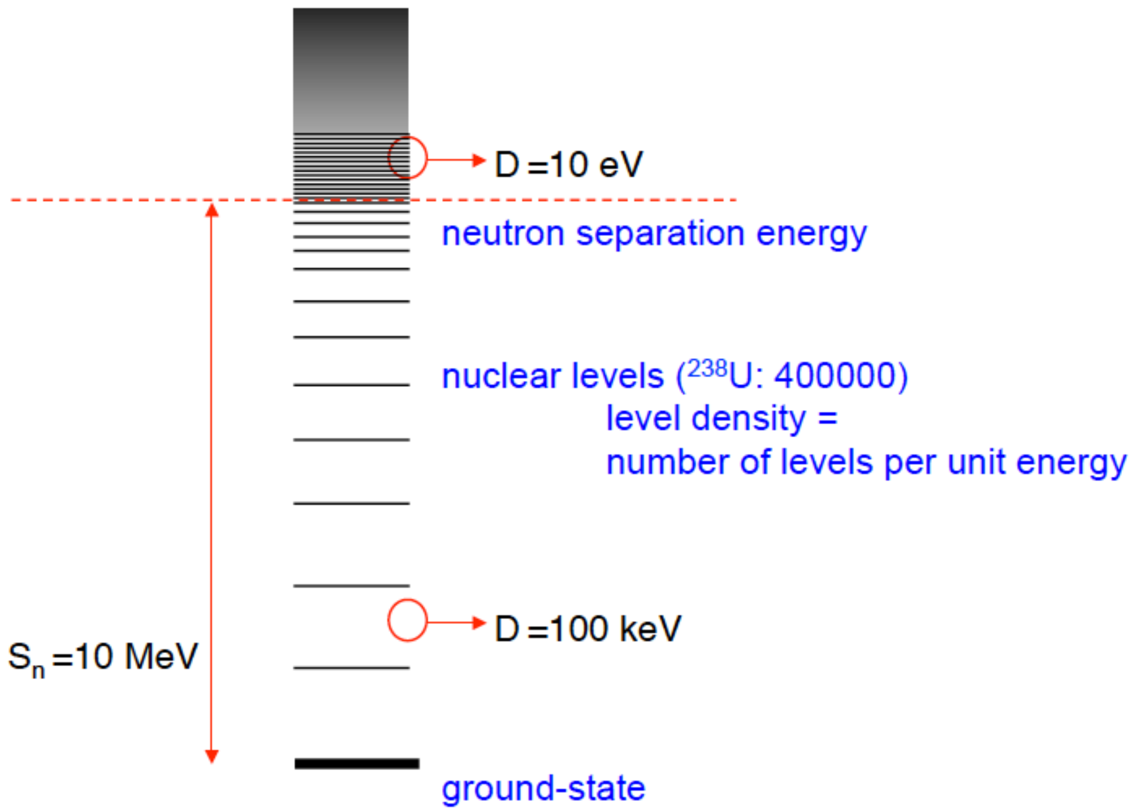
R and $(E_R, J^{\pi}, \Gamma_n, \Gamma_\gamma, \ldots)_j$

E_R	resonance energy
Γ_n, Γ_γ, Γ_f	partial widths
Γ	total width
	$(\Gamma = \Gamma_n + \Gamma_\gamma + \Gamma_f \ldots)$
R	scattering radius

P. Schillebeeckx, Trieste, 2017

Thermal and resonance region

Nuclear levels

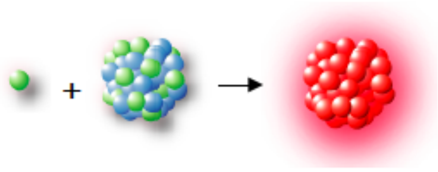


Frank Gunsing, CEA/Saclay
Joint ICTP-IAEA School, Trieste, 26-10-2015

Thermal and resonance region

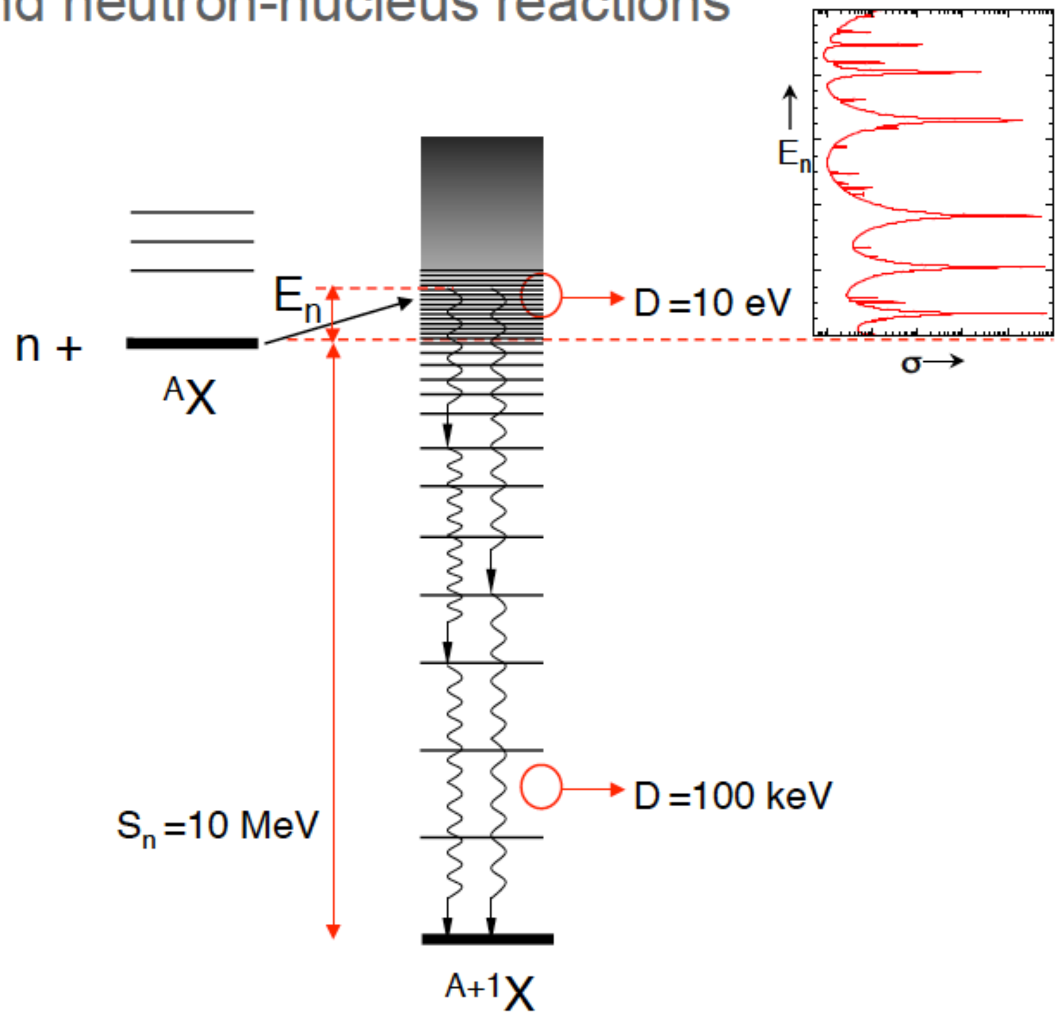
Compound neutron-nucleus reactions

compound
nucleus reaction



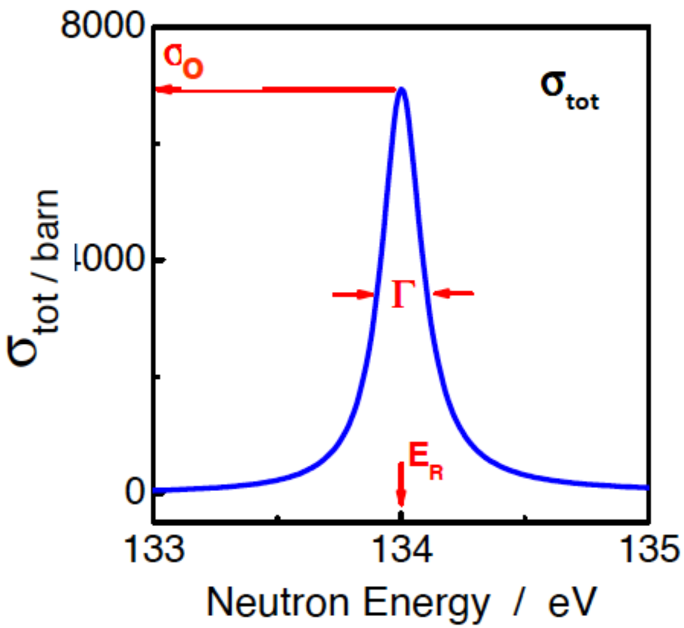
$\tau \sim 10^{-16}$

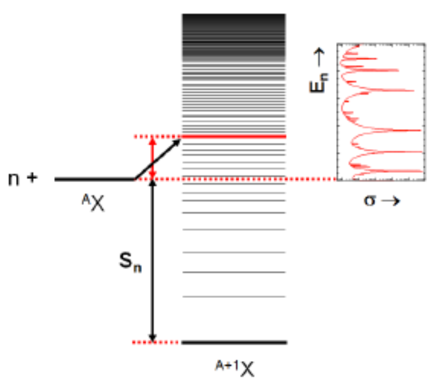
$E_n < 10$ MeV



Frank Gunsing, CEA/Saclay
Joint ICTP-IAEA School, Trieste, 26-10-2015

Thermal and resonance region





The resonant structure can be described by a Breit-Wigner shape :

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

with

Γ total width (FWHM)

E_R resonance energy

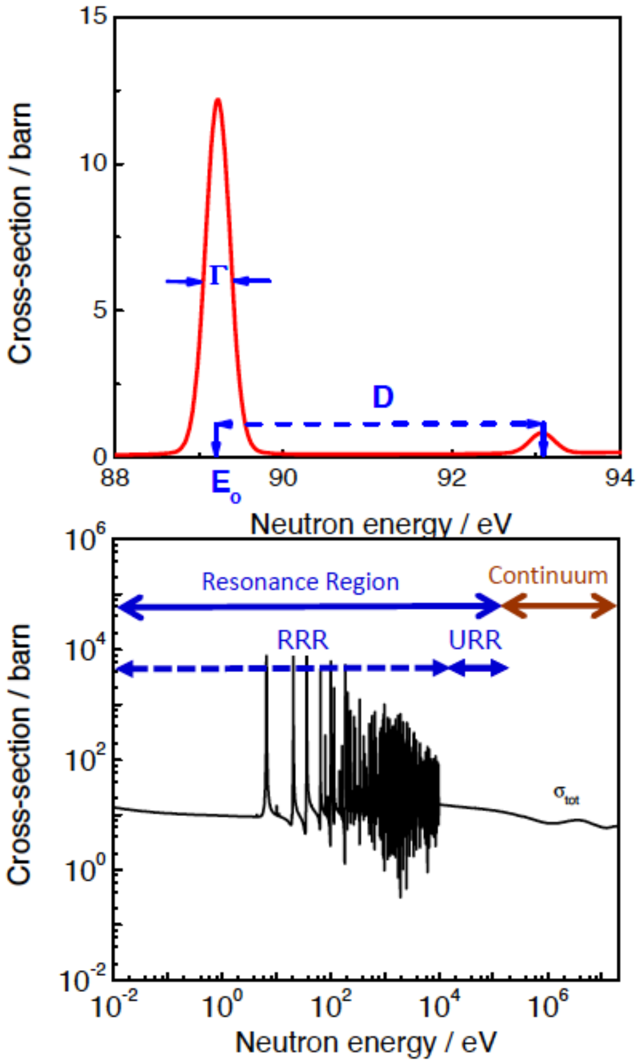
Heisenberg uncertainty principle

$$\Delta E \Delta t = \frac{\hbar}{2} \qquad \Gamma \, \Delta t = \frac{\hbar}{2}$$

P. Schillebeeckx, Trieste, 2017

13 October, 2017, ICTP Trieste

Thermal and resonance region



D : level distance

Γ : resonance width

Δ_R : instrument resolution

- Resonance Region : D > Γ

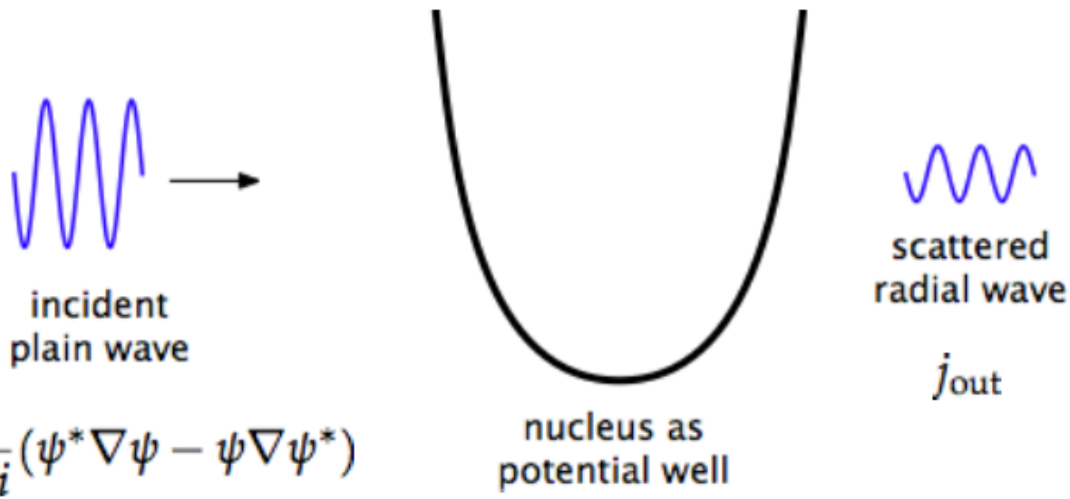
  Resolved Resonance Region : Δ_R < D

  Unresolved Resonance Region : Δ_R > D

- Continuum Region : D < Γ

P. Schillebeeckx, Trieste, 2017

Thermal and resonance region



$$j_{\text{out}}$$

$$j_{\text{inc}} = \frac{\hbar}{2mi}(\psi^* \nabla \psi - \psi \nabla \psi^*)$$

Conservation of probability density: $$\sigma(\Omega) = \frac{r^2 j_{\text{out}}(r, \Omega)}{j_{\text{inc}}}$$

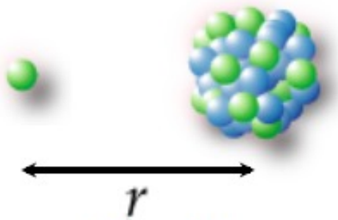
Solve Schrödinger equation of system to get cross sections.
Shape of wave functions of in- and outgoing particles are known,
potential is unknown. Two approaches:

- **calculate potential (optical model calculations, smooth cross section)**
- **use eigenstates (R-matrix, resonances)**

Frank Gunsing, CEA/Saclay — Joint ICTP-IAEA School, Trieste, 26-10-2015

Thermal and resonance region

Find the wave functions



separation distance

$r > a_c$ external region

$r < a_c$ internal region

$r = a_c$ match value and derivate of Ψ

$$\left[\frac{d^2}{dr^2} - \frac{\ell(\ell+1)}{r^2} - \frac{2m_c}{\hbar^2}(V-E)\right] rR(r) = 0$$

External region: **easy**, solve Schrödinger equation
central force, separate radial and angular parts.

$$\psi(r,\theta,\phi) = R(r)\Theta(\theta)\Phi(\phi)$$

solution: solve Schrödinger equation of relative motion:

- Coulomb functions
- special case of neutron particles (neutrons): fonctions de Bessel

Internal region: **very difficult**, Schrödinger equation cannot be solved directly
solution: expand the wave function as a linear combination of its eigenstates.
using the R-matrix:

$$R_{cc'} = \sum_{\lambda} \frac{\gamma_{\lambda c}\gamma_{\lambda c'}}{E_\lambda - E}$$

Frank Gunsing, CEA/Saclay Joint ICTP-IAEA School, Trieste, 26-10-2015

Thermal and resonance region

- Approximation of the R-matrix:
  - Single level Breit Wigner
  - Multi level Breit Wigner (& Multi Niveau Breit Wigner)
  - Reich Moore
  - R-Matrix limited
- Applied to (n,el), (n,g), (n,f)

For an isolated, neutron resonance, we write the Breit-Wigner equation for capture reactions in the form

$$\sigma_\gamma = \sigma_0 \frac{\Gamma_\gamma}{\Gamma} \left(\frac{E_0}{E}\right)^{1/2} \frac{1}{1+y^2},$$

where

$$y = \frac{2}{\Gamma}(E - E_0),$$

$$\sigma_0 = 4\pi \lambdabar_0^2 \frac{g\Gamma_n}{\Gamma} = \frac{2.608 \times 10^6}{E_0(\mathrm{eV})} \left(\frac{A+1}{A}\right)^2 \frac{g\Gamma_n}{\Gamma}.$$

Thermal and resonance region

- For resonances far from the resonance range, the capture cross section at 0.0253 eV is

$$\sigma_\gamma^0 = 4.099 \times 10^6 \left(\frac{A+1}{A}\right)^2 \sum_j^N \frac{g\Gamma_{nj}^0 \Gamma_{\gamma j}}{E_{0j}^2}.$$

- G_n^0 is the reduce width:
  - For l=0, V_l=1

$$\Gamma_{nj}^\ell = \sqrt{\frac{1\ \mathrm{eV}}{E_0}} \frac{\Gamma_{nj}}{V_\ell}.$$

$$\Gamma_n^1 = \frac{\Gamma_n}{\sqrt{E_0}} \left(1 + \frac{11369}{E(\mathrm{keV})\ A^{2/3}}\right)$$

- orbtial momentum of incoming neutron relative to nucleus: ℓ
- Resonance spin and parity:

$$\mathbf{J} = \mathbf{I} + \mathbf{1/2} + \ell$$
$$\pi = \pi_i \times (-1)^\ell$$

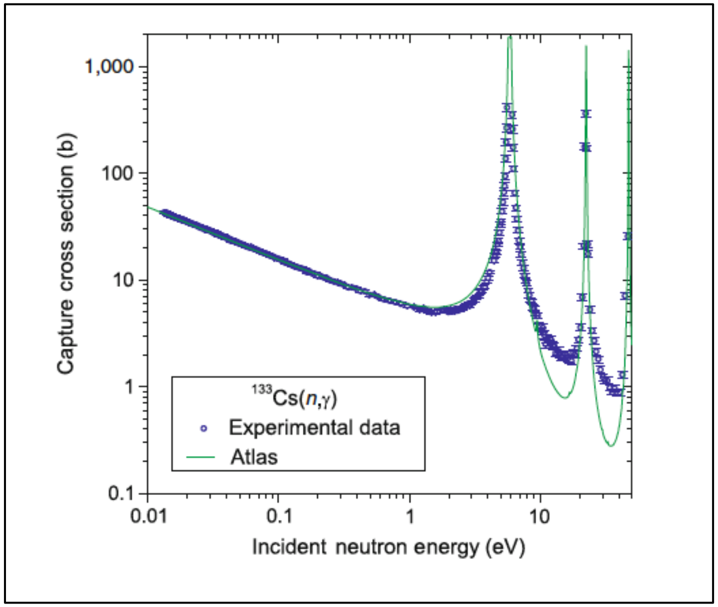
- partial waves:

s-wave $\ell = 0$

p-wave $\ell = 1$

d-wave $\ell = 2$

f-wave $\ell = 3$

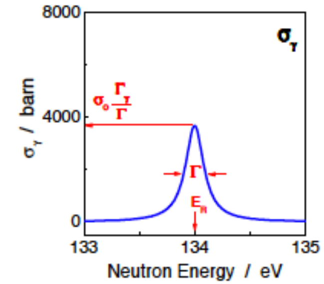


Thermal and resonance region

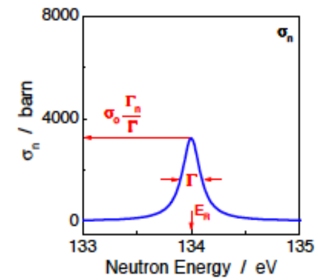
- Example for SLBW, l=0

$(E_R, \Gamma_n, \Gamma_\gamma, J^\pi, R_{\ell=0})$

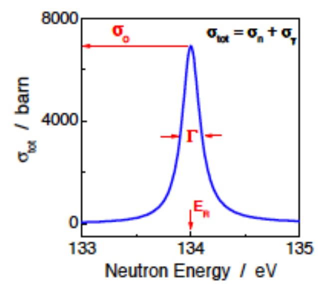
- (n,γ) $$\sigma_\gamma(E_n) = g\frac{\pi}{k_n^2}\frac{\Gamma_n\Gamma_\gamma}{(E_n - E_R)^2 + (\Gamma/2)^2}$$



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



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

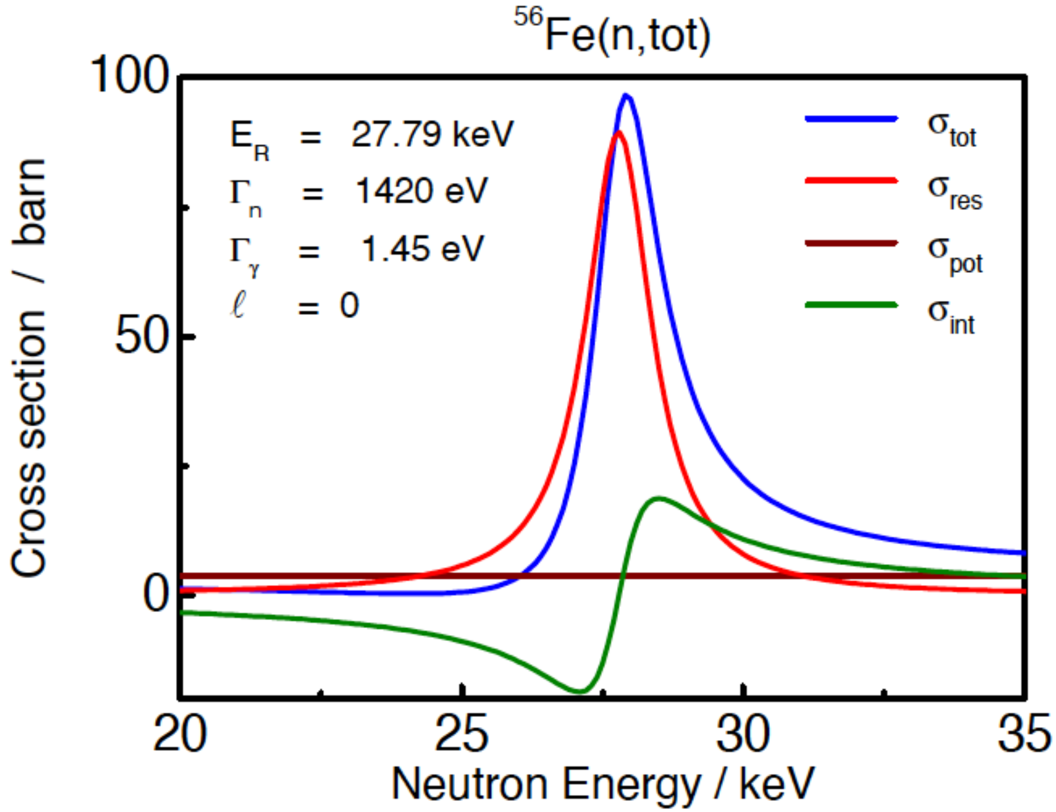


P. Schillebeeckx, Trieste, 2017

Thermal and resonance region: interference

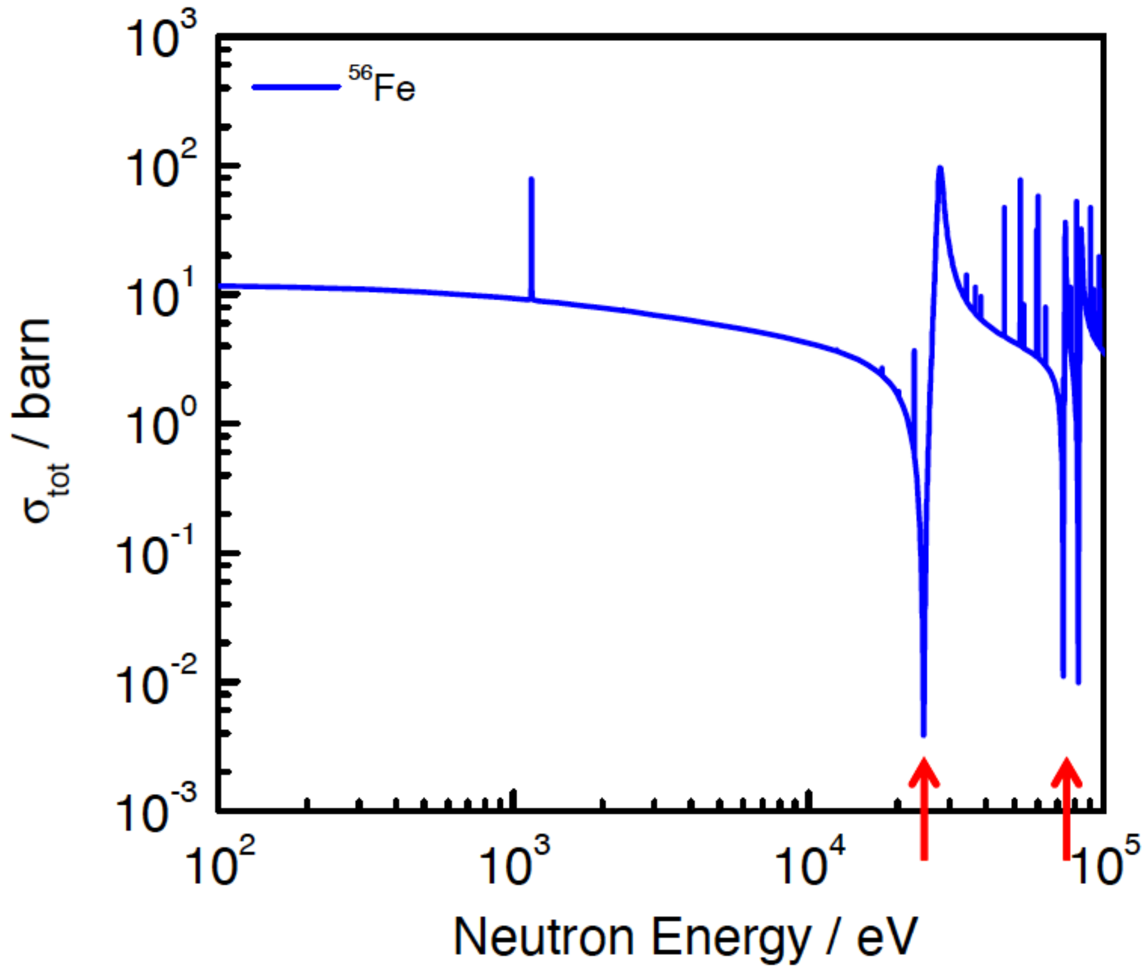
- Example for SLBW, l=0

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



P. Schillebeeckx, Trieste, 2017

Thermal and resonance region: interference

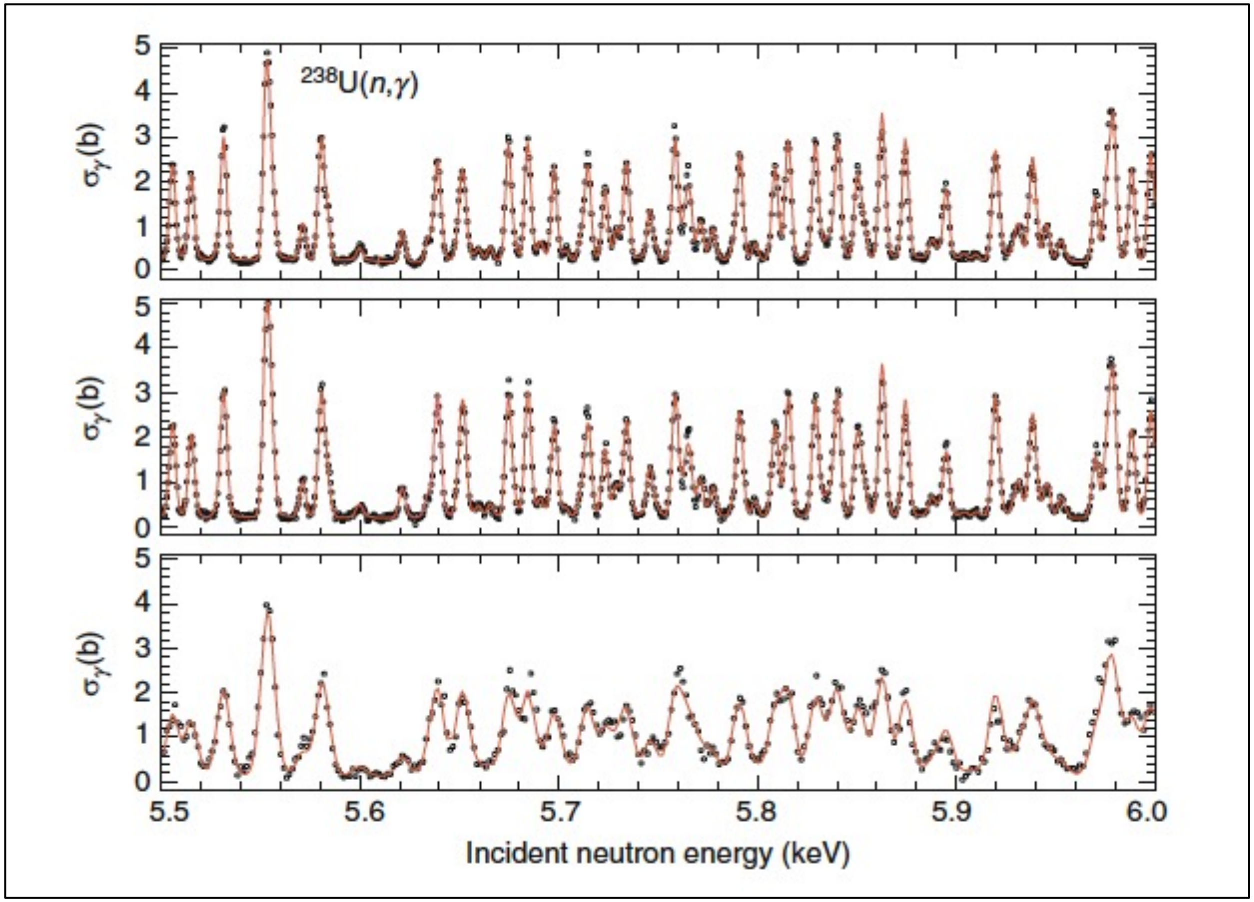


- Iron filtered beams
- Shielding problems

P. Schillebeeckx, Trieste, 2017

Thermal and resonance region

- Specific codes are used to “fit” observed resonances: SAMMY, REFIT



- And extract resonance parameters

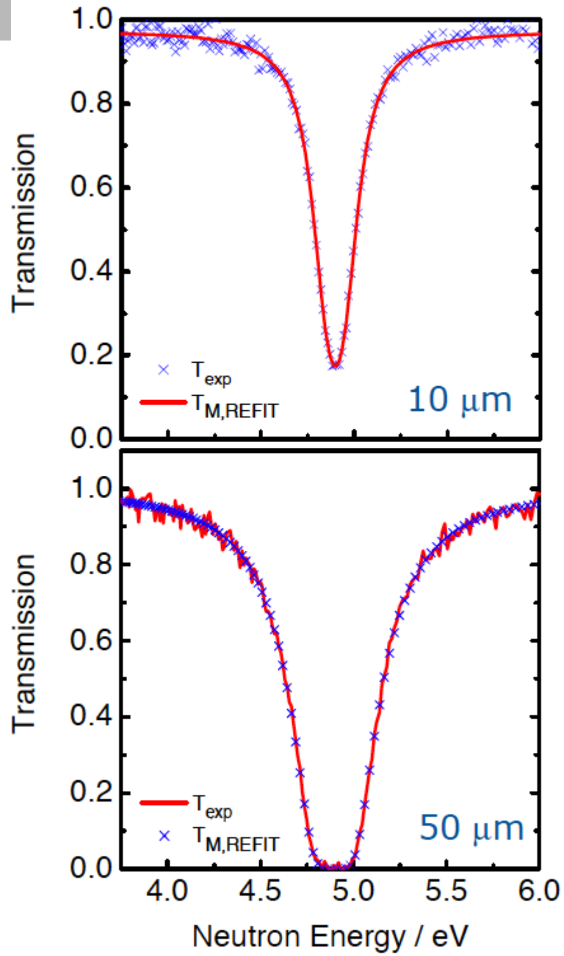
PAUL SCHERRER INSTITUT PSI

Thermal and resonance region

- Specific codes are used to “fit” observed resonances: SAMMY, REFIT

4.9 eV resonance for ^{197}Au+n

^{197}Au : $I^{\pi} = 3/2^{+}$



Resonance shape analysis with REFIT

$\ell = 0$ from shape, *spin J = 2 from fit with capture data*

$\Delta_D \sim 80$ meV and $\Delta_R \sim 5$ meV (L = 50 m)

$\Rightarrow$

$$\Gamma_n = (15.06 \pm 0.08) \text{ meV}$$

$$\Gamma_\gamma = (121.7 \pm 1.3) \text{ meV}$$

$\Rightarrow$

$$\Gamma_n = (14.66 \pm 0.30) \text{ meV}$$

$$\Gamma_\gamma = (124.8 \pm 3.7) \text{ meV}$$

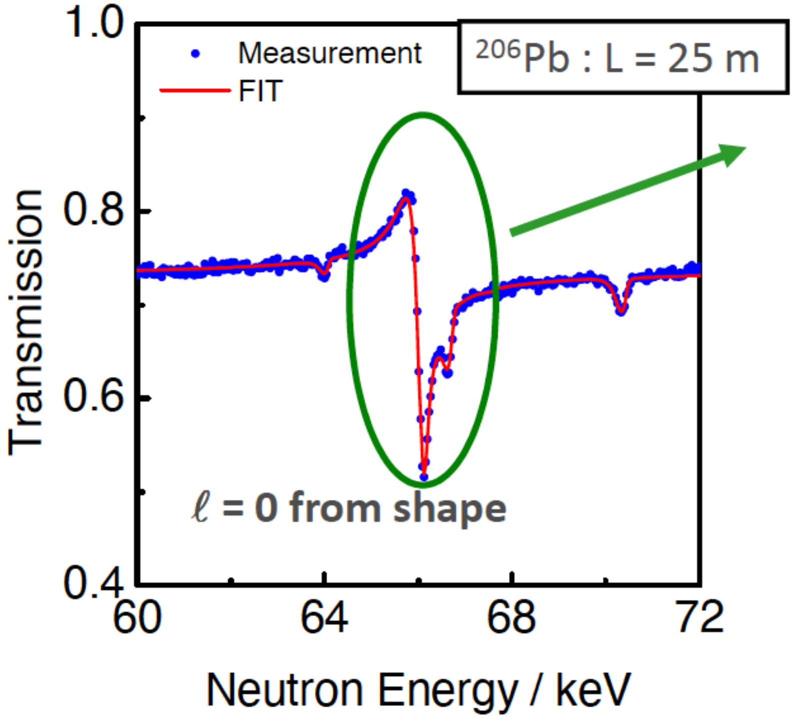
Uncertainties only due to counting statistics

Thermal and resonance region

- Specific codes are used to "fit" observed resonances: SAMMY, REFIT

Determination of scattering radius

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



Interference

R = 9.55 (0.02) fm

Borella et al., Phys. Rev. C 76 (2007) 014605

European Commission

Thermal and resonance region

- Specific codes are used to “fit” observed resonances: SAMMY, REFIT

Determination of statistical factor

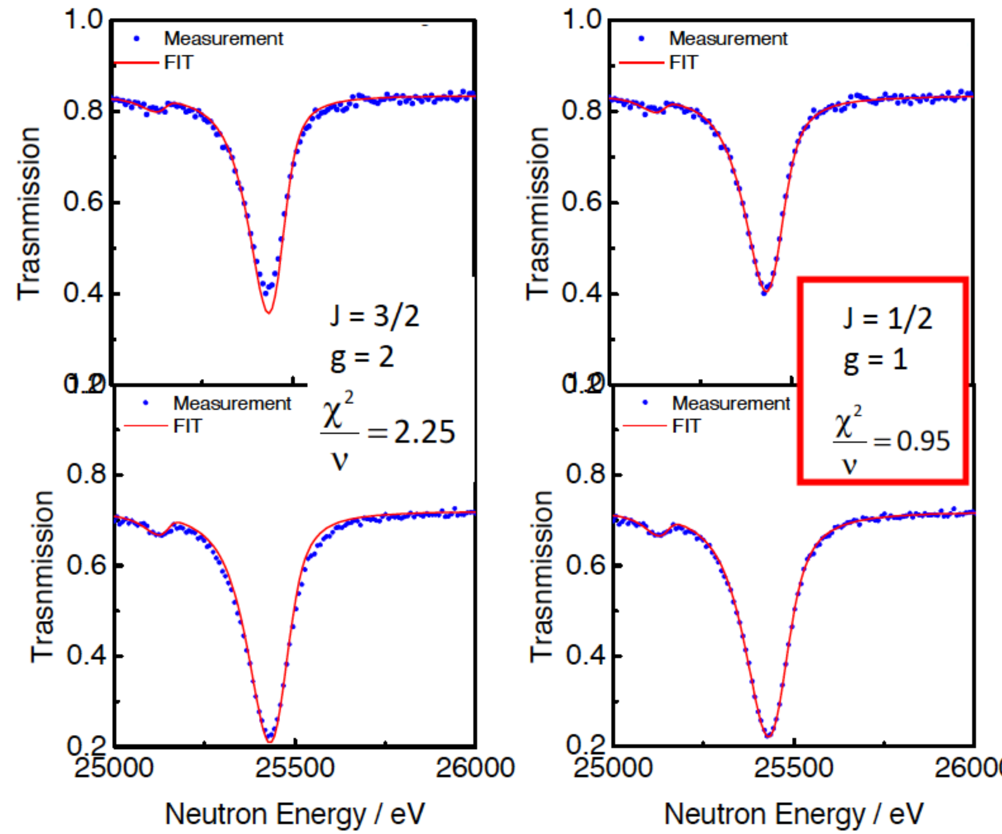
^{206}Pb ($I^{\pi} = 0^{+}$) + n

ℓ = 1 from shape

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

⇒ J = 1/2

⇒ g = 1

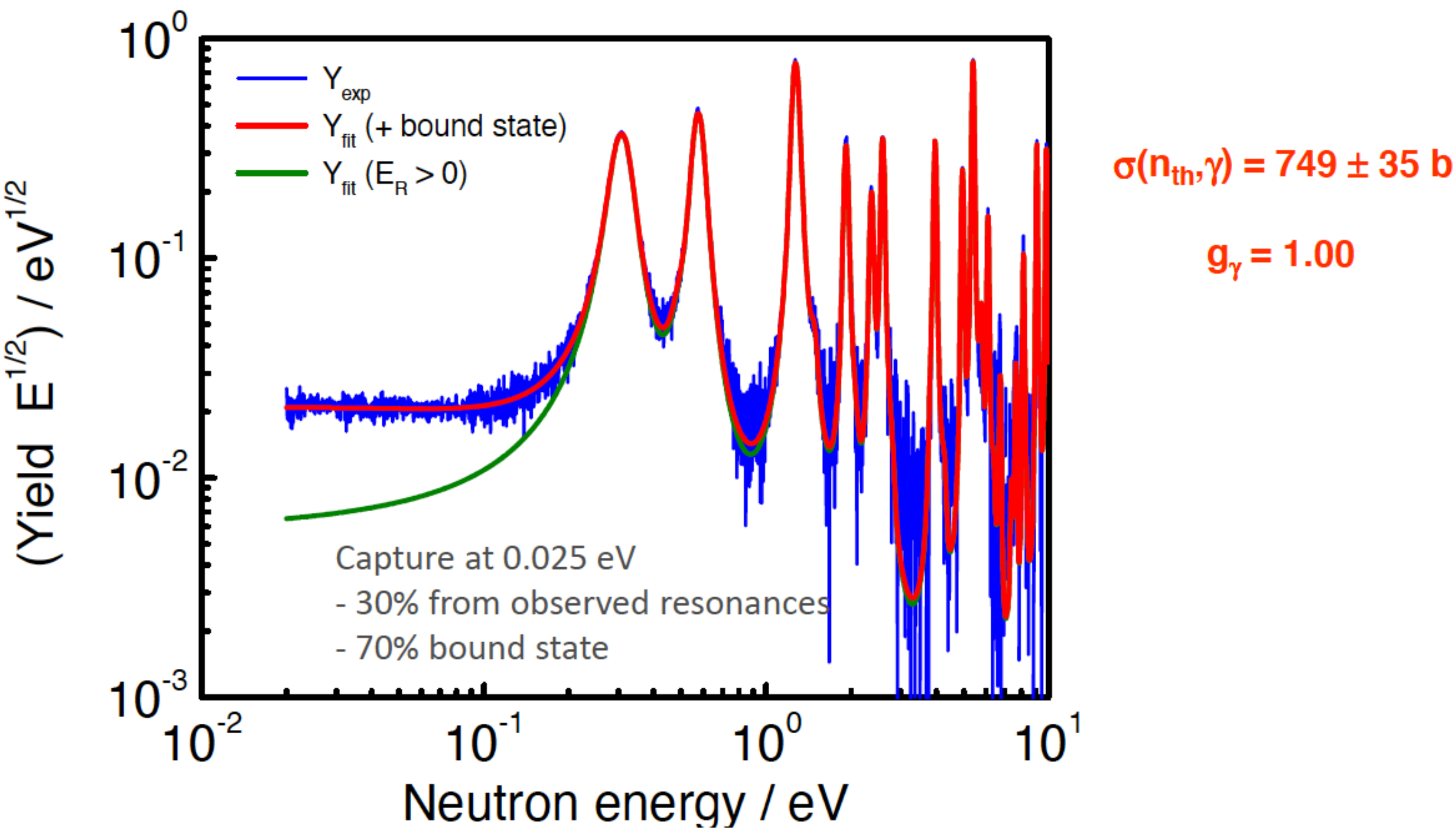


Borella et al., Phys. Rev. C 76 (2007) 014605

Thermal and resonance region

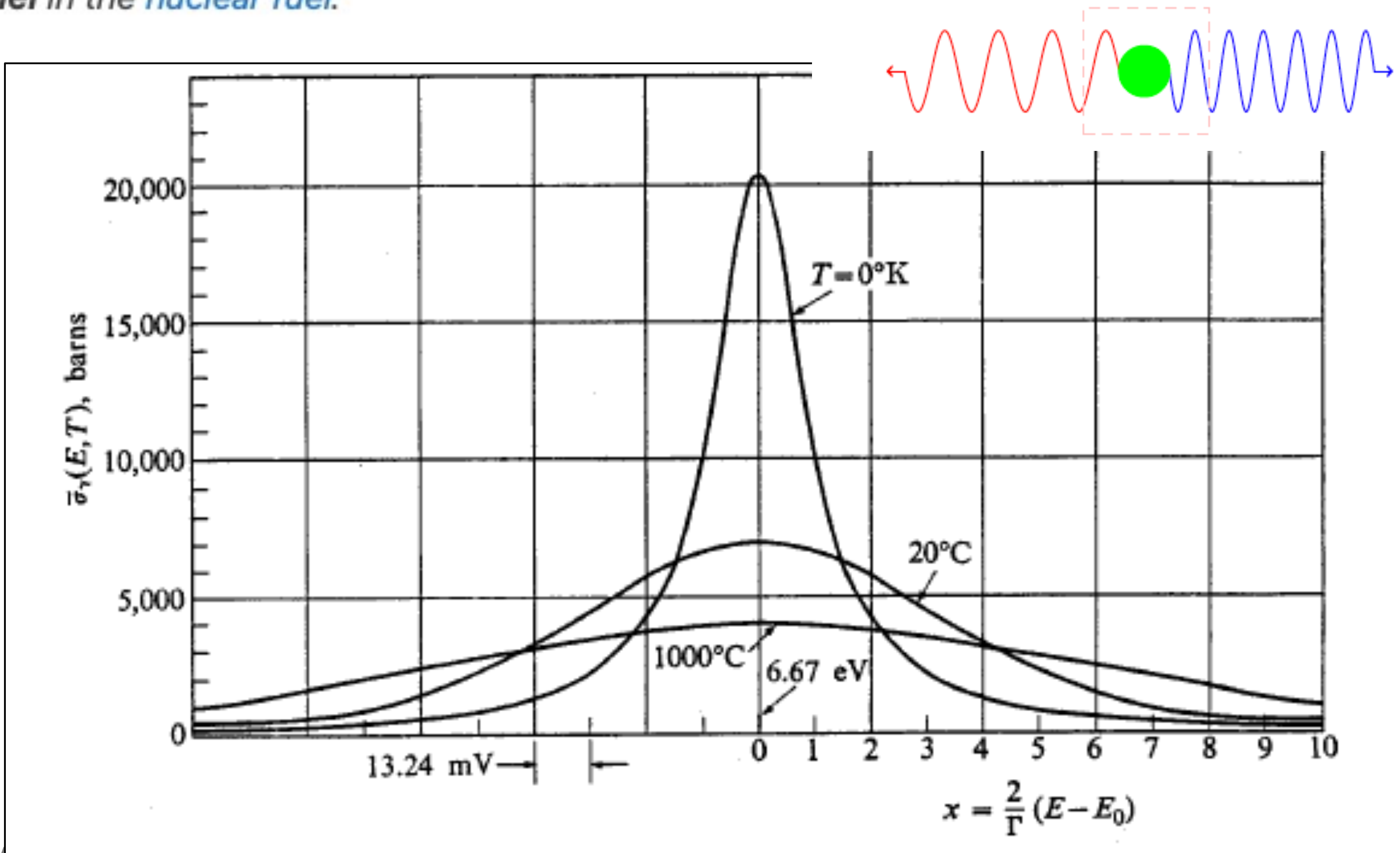
- Specific codes are used to “fit” observed resonances: SAMMY, REFIT

$^{241}Am(n,\gamma)$: results of RSA with REFIT



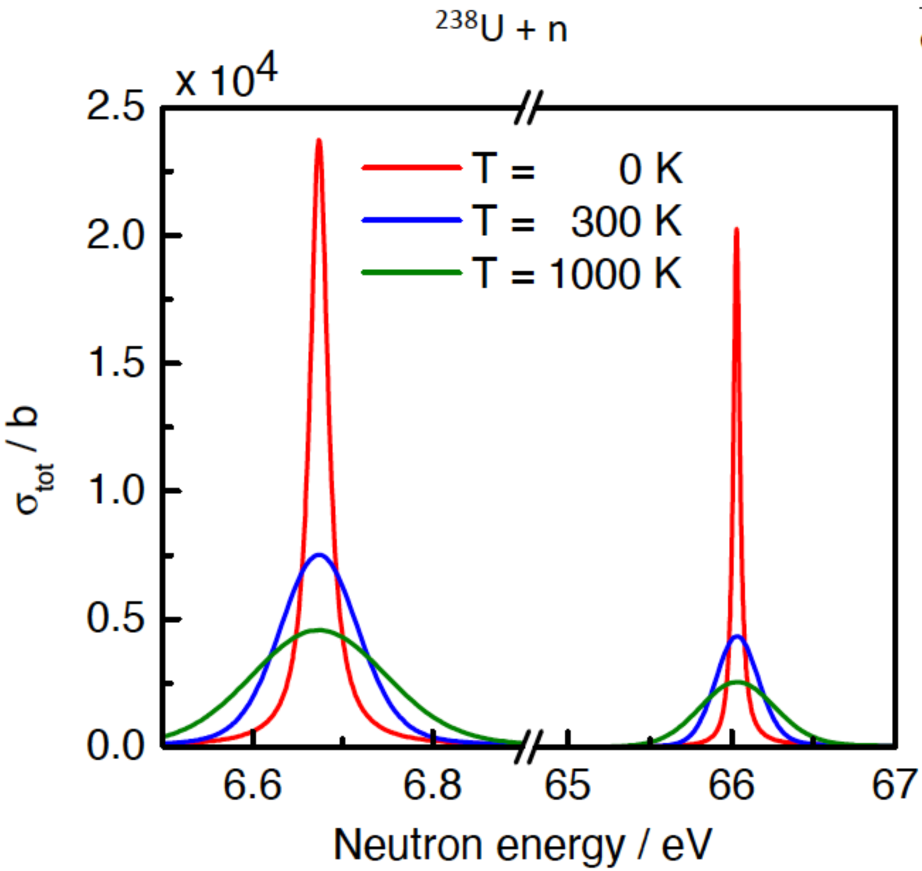
Resonance region: Doppler broadening

*In general, Doppler broadening is the broadening of spectral lines due to the **Doppler effect** caused by a distribution of kinetic energies of molecules or atoms. In reactor physics, a particular case of this phenomenon is the **thermal Doppler broadening of the resonance capture cross-sections** of the fertile material (e.g.,, ^{238}U or ^{240}Pu) caused by the **thermal motion of target nuclei** in the nuclear fuel.*



Resonance region: Doppler broadening

- The reaction rate is maintained



$$\bar{\sigma}(v,T)=\frac{1}{v}\int |v-V|\,\sigma(|v-V|)\,P(V)\,dV$$

Free gas model

$$\bar{\sigma}(E,T)=\int S(E,E')\,\sigma(E',T=0)\,dE'$$

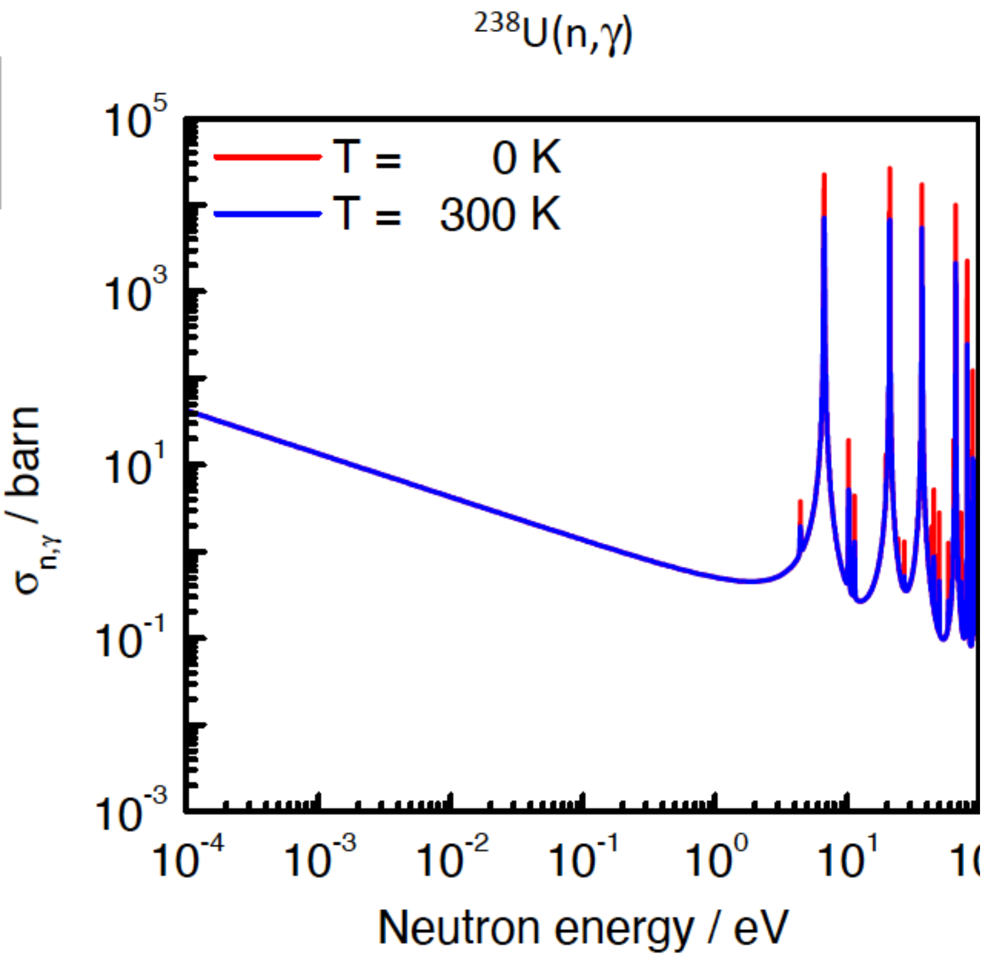
$$S(E,E')=\frac{1}{\Delta_D\sqrt{\pi}}\,e^{-\left(\frac{E'-E}{\Delta_D}\right)^2}\sqrt{\frac{E'}{E}}$$

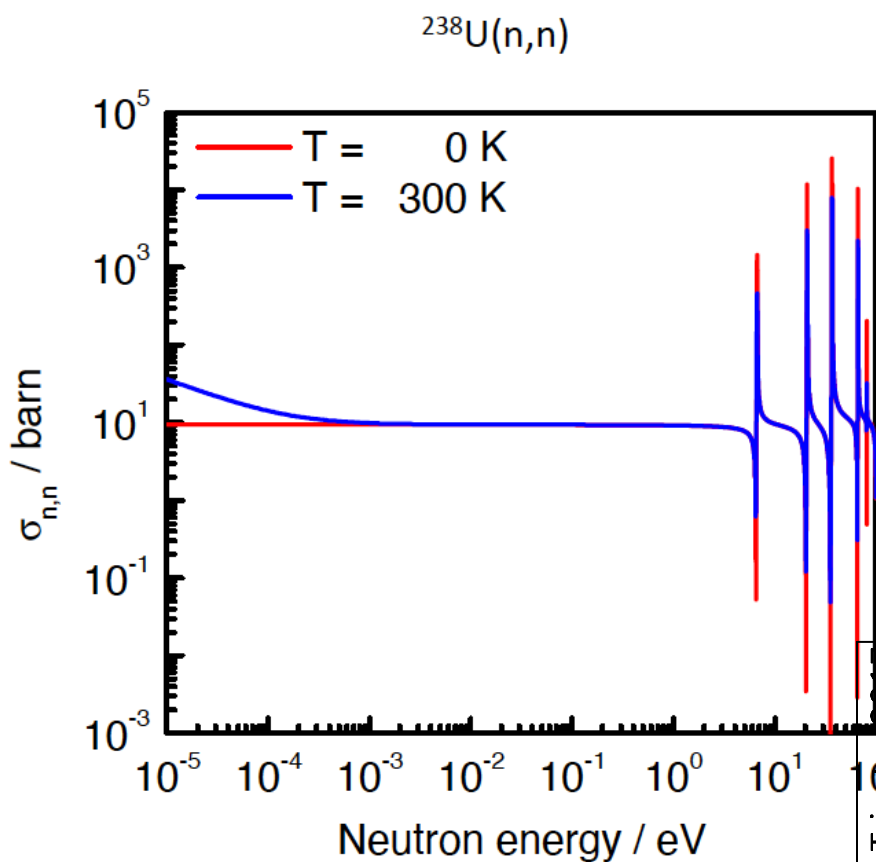
$$\Delta_D=\sqrt{\frac{4\,E\,k_B T}{m_X/m_n}}$$

$$FWHM=2\sqrt{\ln 2}\,\Delta_D$$

P. Schillebeeckx, Trieste, 2017

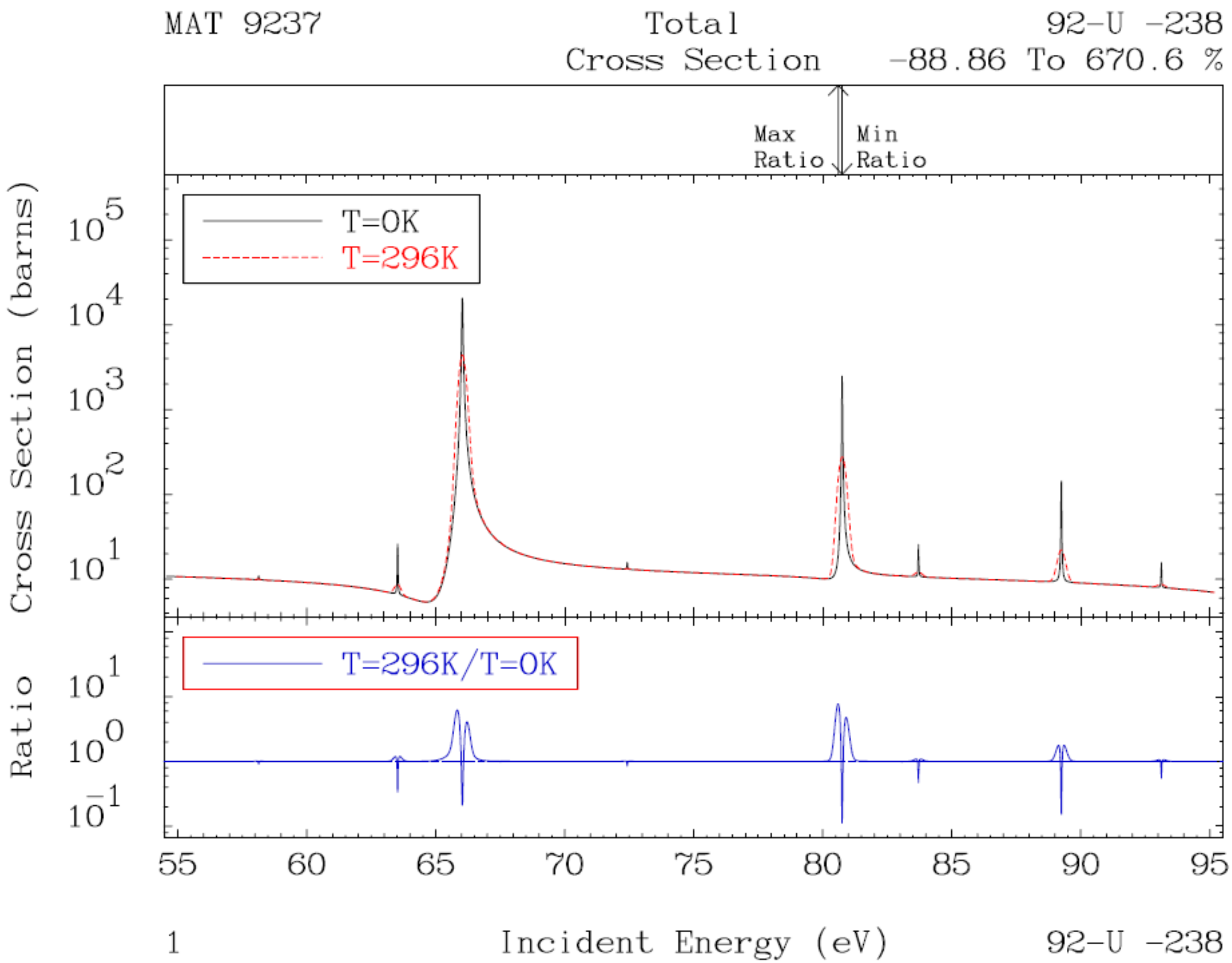
Resonance region: Doppler broadening





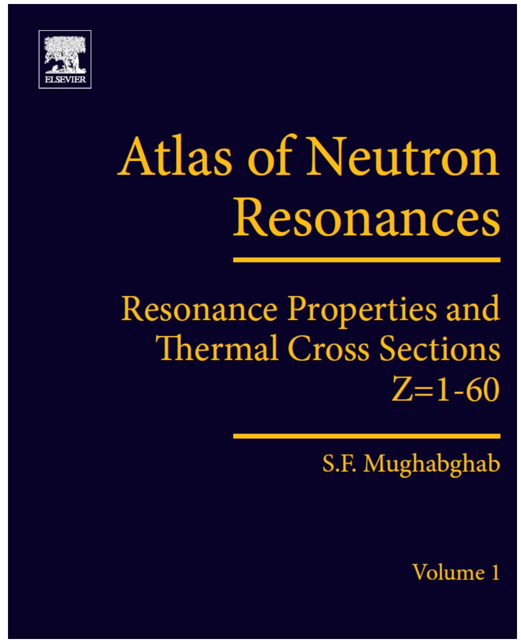
P. Schillebeeckx, Trieste, 2017

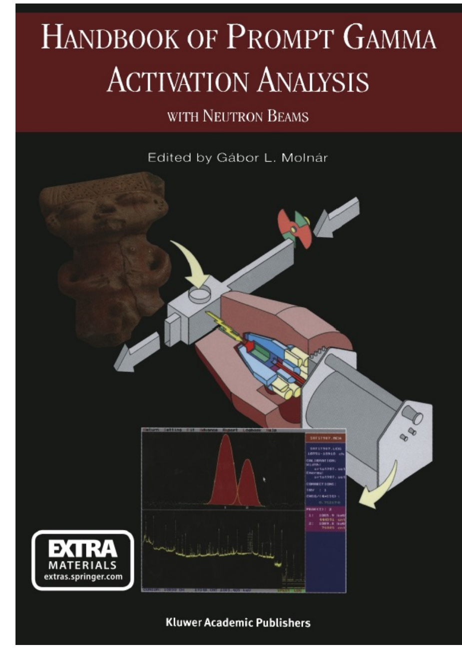
Resonance region: Doppler broadening

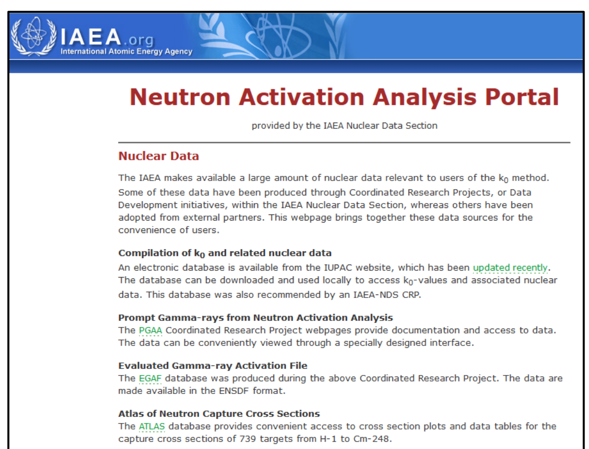


Thermal and resonance region

- Additionally, recommended resonance parameters can be found, such as in the "Atlas of Neutron Resonances"






IAEA.org International Atomic Energy Agency

Neutron Activation Analysis Portal

provided by the IAEA Nuclear Data Section

Nuclear Data

The IAEA makes available a large amount of nuclear data relevant to users of the k_0 method. Some of these data have been produced through Coordinated Research Projects, or Data Development initiatives, within the IAEA Nuclear Data Section, whereas others have been adopted from external partners. This webpage brings together these data sources for the convenience of users.

Compilation of k_0 and related nuclear data

An electronic database is available from the IUPAC website, which has been updated recently. The database can be downloaded and used locally to access k_0-values and associated nuclear data. This database was also recommended by an IAEA-NDS CRP.

Prompt Gamma-rays from Neutron Activation Analysis

The PGAA Coordinated Research Project webpages provide documentation and access to data. The data can be conveniently viewed through a specially designed interface.

Evaluated Gamma-ray Activation File

The EGAF database was produced during the above Coordinated Research Project. The data are made available in the ENSDF format.

Atlas of Neutron Capture Cross Sections

The ATLAS database provides convenient access to cross section plots and data tables for the capture cross sections of 739 targets from H-1 to Cm-248.

PAUL SCHERRER INSTITUT PSI

Thermal and resonance region

- Additionally, recommended resonance parameters can be found, such as in the "Atlas of Neutron Resonances"

$^{66}_{30}$Zn $^{66}_{30}$Zn

THERMAL CROSS SECTIONS

σ_γ=0.62±0.06 b
σ_s=4.4±0.3 b
σ_α<0.020 mb
b_{coh}=5.98±0.05 fm
g_γ =1.004
R' =6.21±0.30 fm

RESONANCE PROPERTIES

D_0=4.7±0.4 keV
D_1=0.84±0.05 keV
S_0=1.9±0.2
S_1=0.70±0.07
$<\Gamma_{\gamma 0}>$=0.400±0.020 eV
$<\Gamma_{\gamma 1}>$=0.190±0.060 eV
$S_{\gamma 0}$=0.85±0.09
$S_{\gamma 1}$=2.26±0.73
I_γ^c=0.92±0.06 b
σ_γ^c(5 keV) =87.2±9.5
σ_γ^c(30 keV) =36.7±4.0 mb
σ_γ^c(30 keV) =37.1±4.0 mb

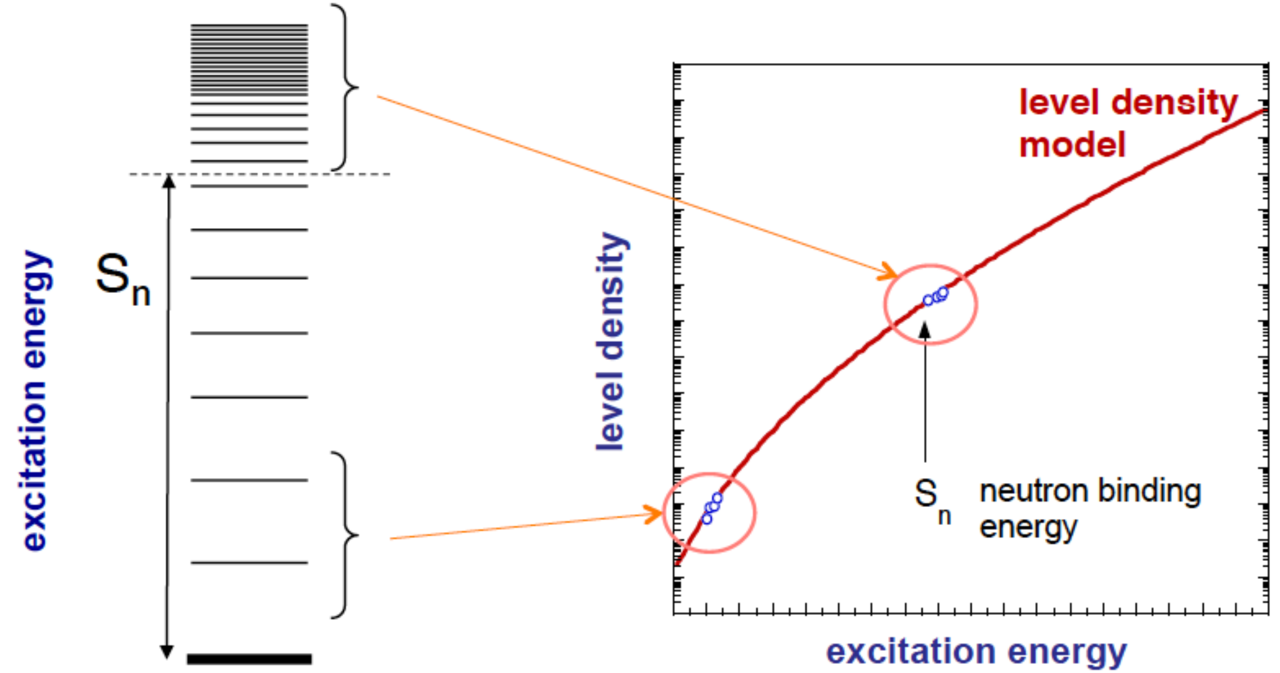
RESONANCE PARAMETERS

I^π = 0+ %Abn = 27.90 Sn = 7052.33±0.22 keV
σ_γ(+) = 0.227 b σ_γ(B) = 0.393 b σ_γ(D) = 0.050 b

E_0 (keV)	J	l	$g\Gamma_n$ (eV)	Γ_γ (eV)	$g\Gamma_n^0$ (meV)	$g\Gamma_n^1$ (meV)	$g\Gamma_n\Gamma_\gamma/\Gamma$ (meV)
−4.108	1/2	0		(0.4)	3930		
0.3235±0.0009			0.011 ± 0.001	0.1865±0.0200	0.61± 0.06		
3.2300±0.0015		1	0.01			40	
3.5580±0.0015	(1/2)	1	0.006 ± 0.002	(0.17)		20 ± 7	5.79± 0.18
4.046 ±0.002	1/2	0	5.2 ± 0.5	0.198 ±0.002	82 ± 8		194.6 ± 1.8
4.385 ±0.002	(1/2)	1	0.07	0.156 ±0.006		200	49.27± 0.64
5.204 ±0.002	(1/2)	1	0.0021 ± 0.0002	(0.17)		3.9 ± 0.4	2.04± 0.19
5.3430±0.0025	(1/2)	1	0.15	0.206 ±0.005		270	85.10± 0.77

Resonance region: level density

- Used both in the resonance range and fast neutron range



low-lying levels:
Count levels, all J^π

neutron resonances:
Count levels, selected J^π, extract $\mathbf{D_0}$

- **All level density models reproduce the low-lying levels and D_0 at S_n**

Frank Gunsing, CEA/Saclay   Joint ICTP-IAEA School, Trieste, 26-10-2015

Resonance region: level spacing

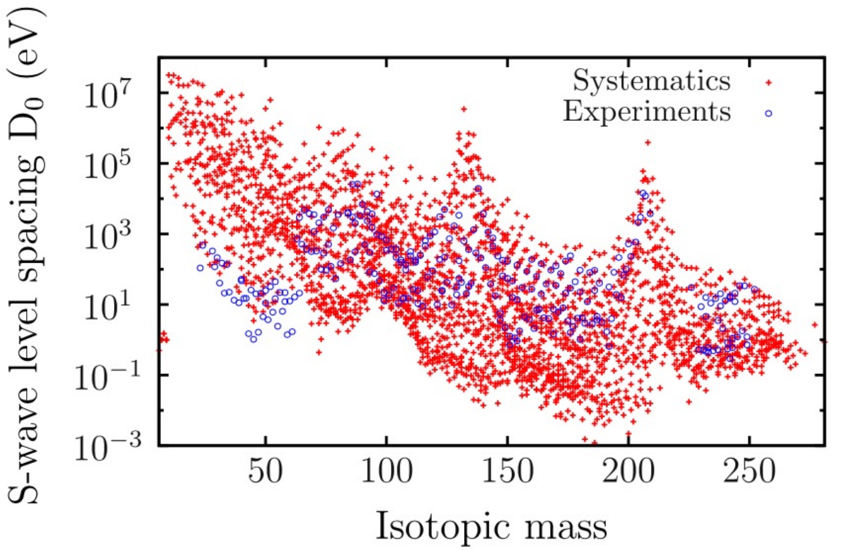
- Used both in the resonance range and fast neutron range

- The level spacing D_0 at the neutron binding energy is a crucial input parameter for calibrating level density models. Level density: $\rho = 1/D$.

- D_0 is the spacing between levels excited by neutrons on nuclei bringing in zero orbital momentum (s-wave resonances).

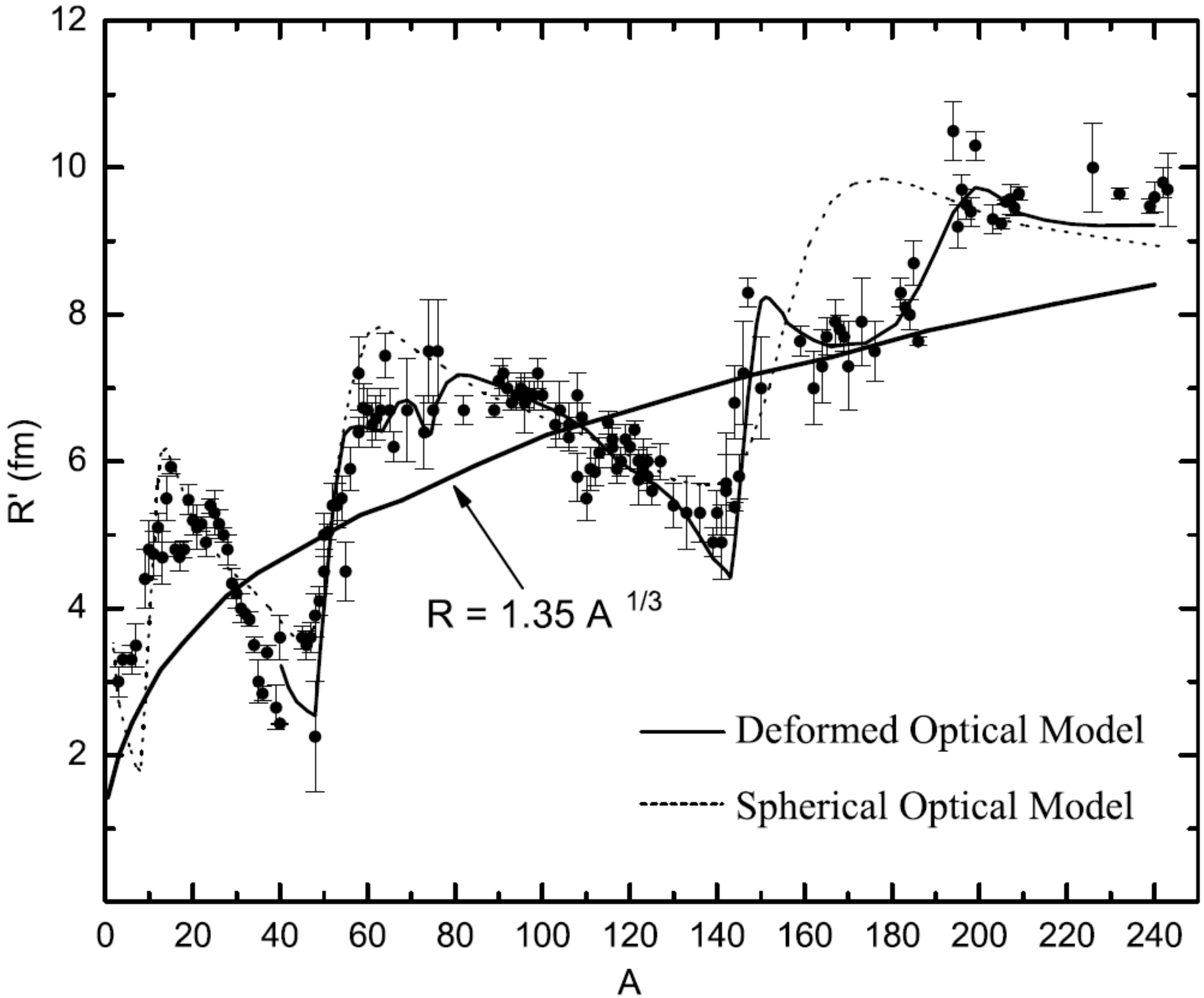
- Spacings from higher orbital momentum are equally important, but in general much more affected by missing levels.

- Problems concerning the determination of D_0:
  - spin and parity assignment of levels
  - corrections for missing levels (which are not observed experimentally)



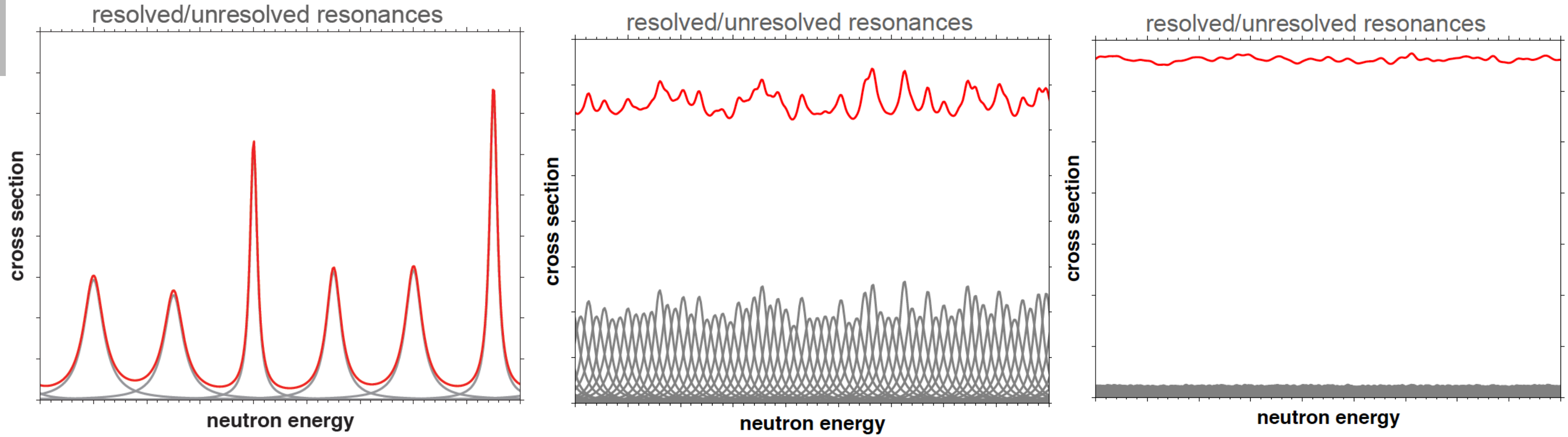
Resonance region: scattering radius R

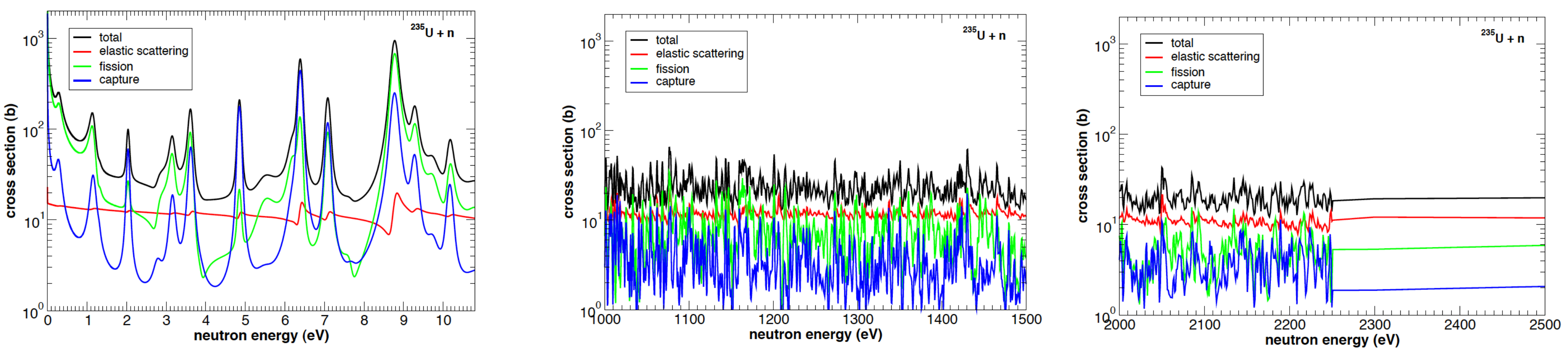
- Used for the potential scattering cross section ($1.35A^{1/3}$, A target mass)



Limit Resonance – fast neutron range

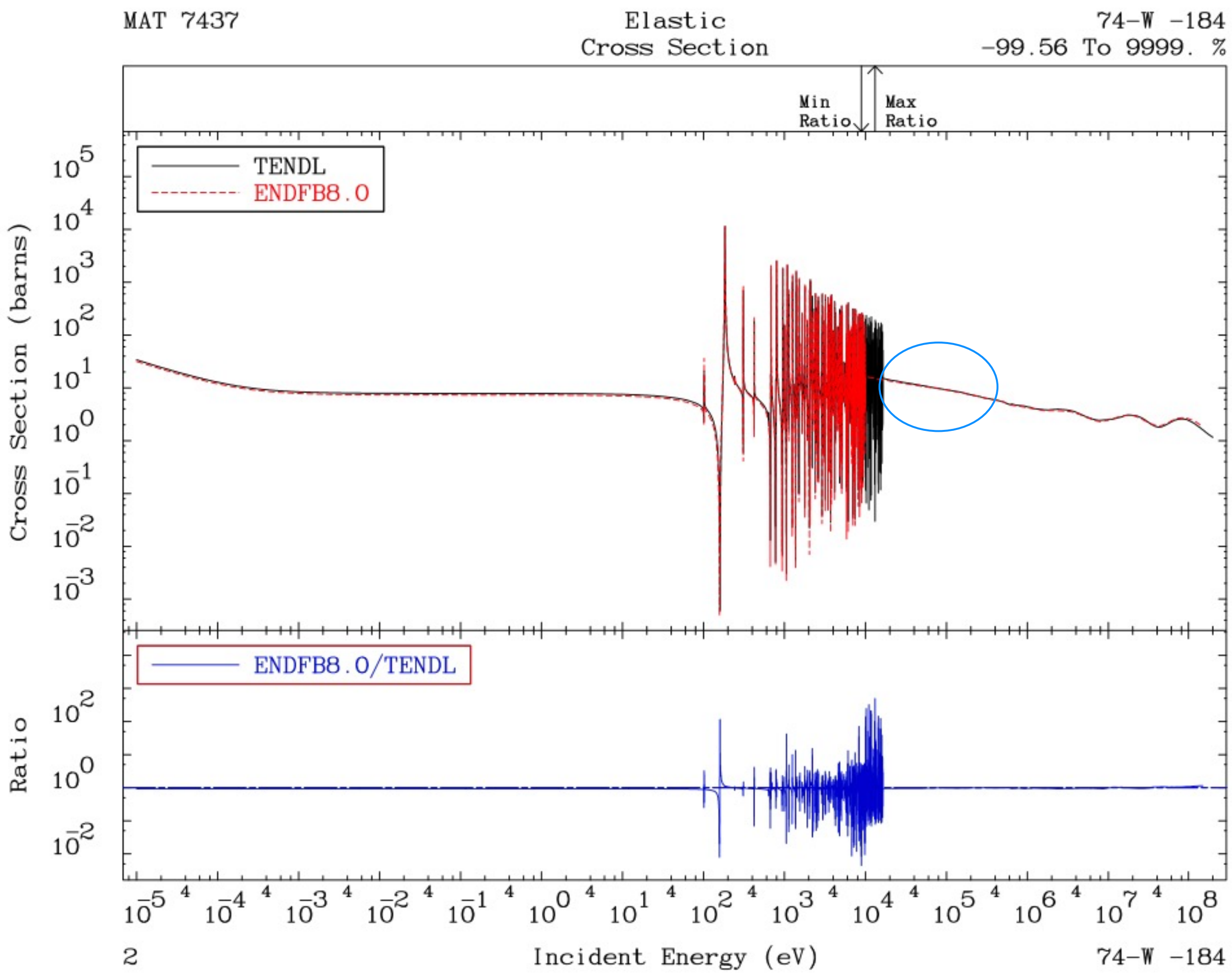
- The limit between the resonance energy range and fast neutron range is called the **unresolved resonance range**





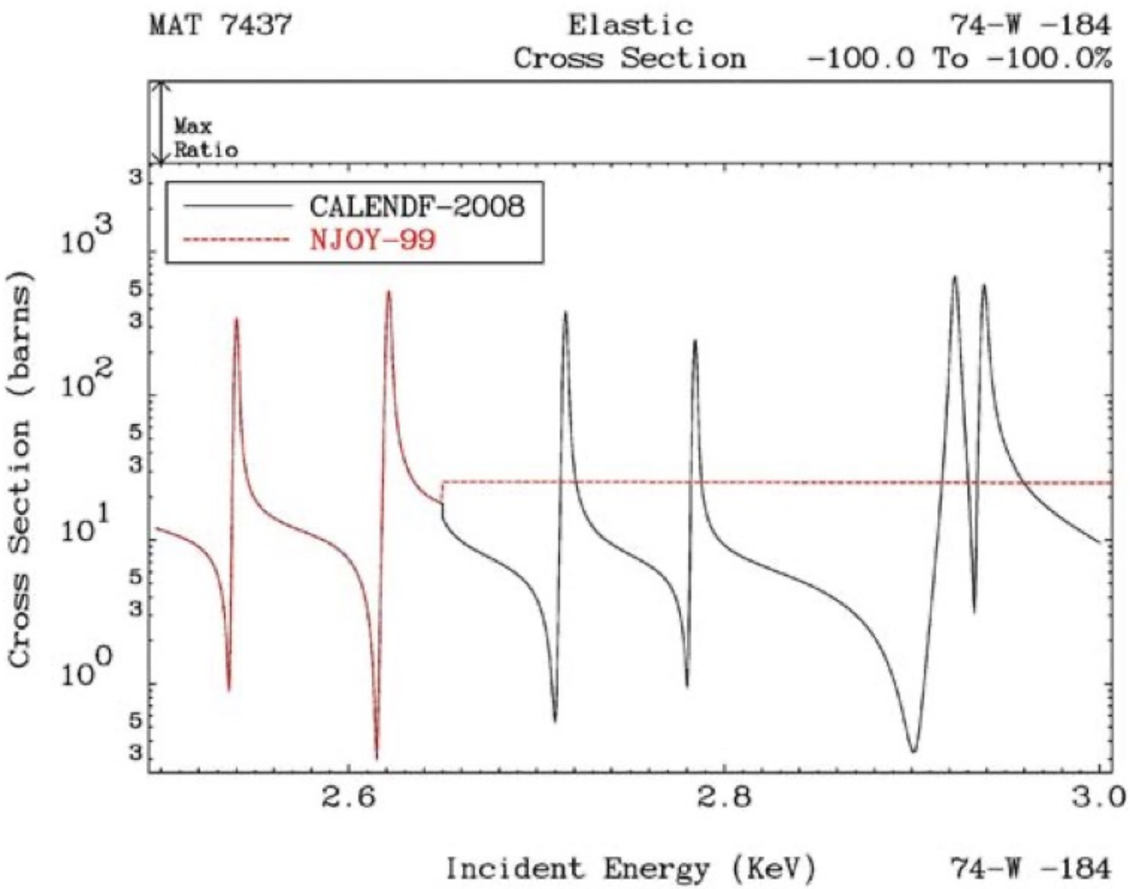
Unresolved resonance range

- The limit between the resonance energy range and fast neutron range is called the **unresolved resonance range**



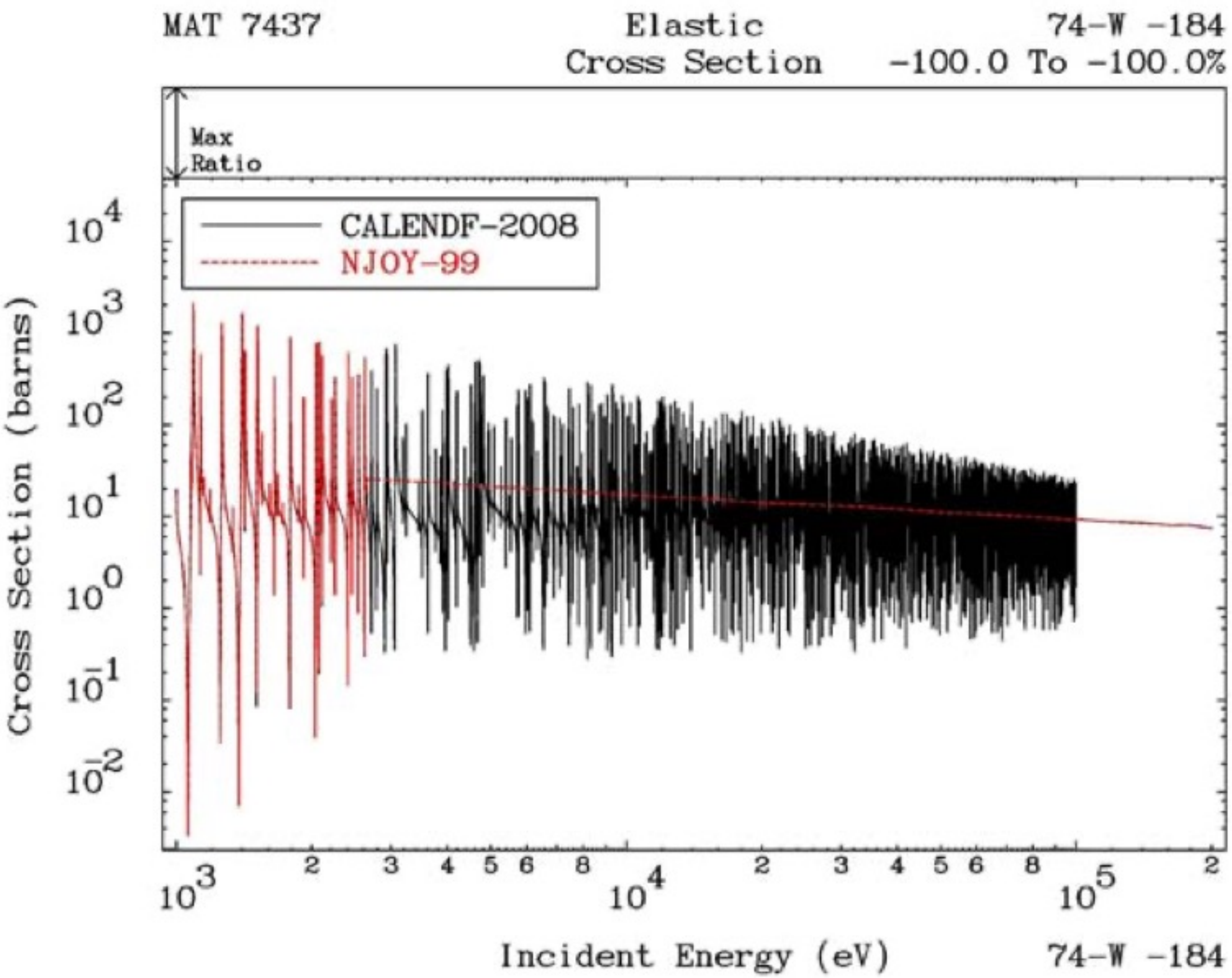
Unresolved resonance range

- The limit between the resonance energy range and fast neutron range is called the **unresolved resonance range**

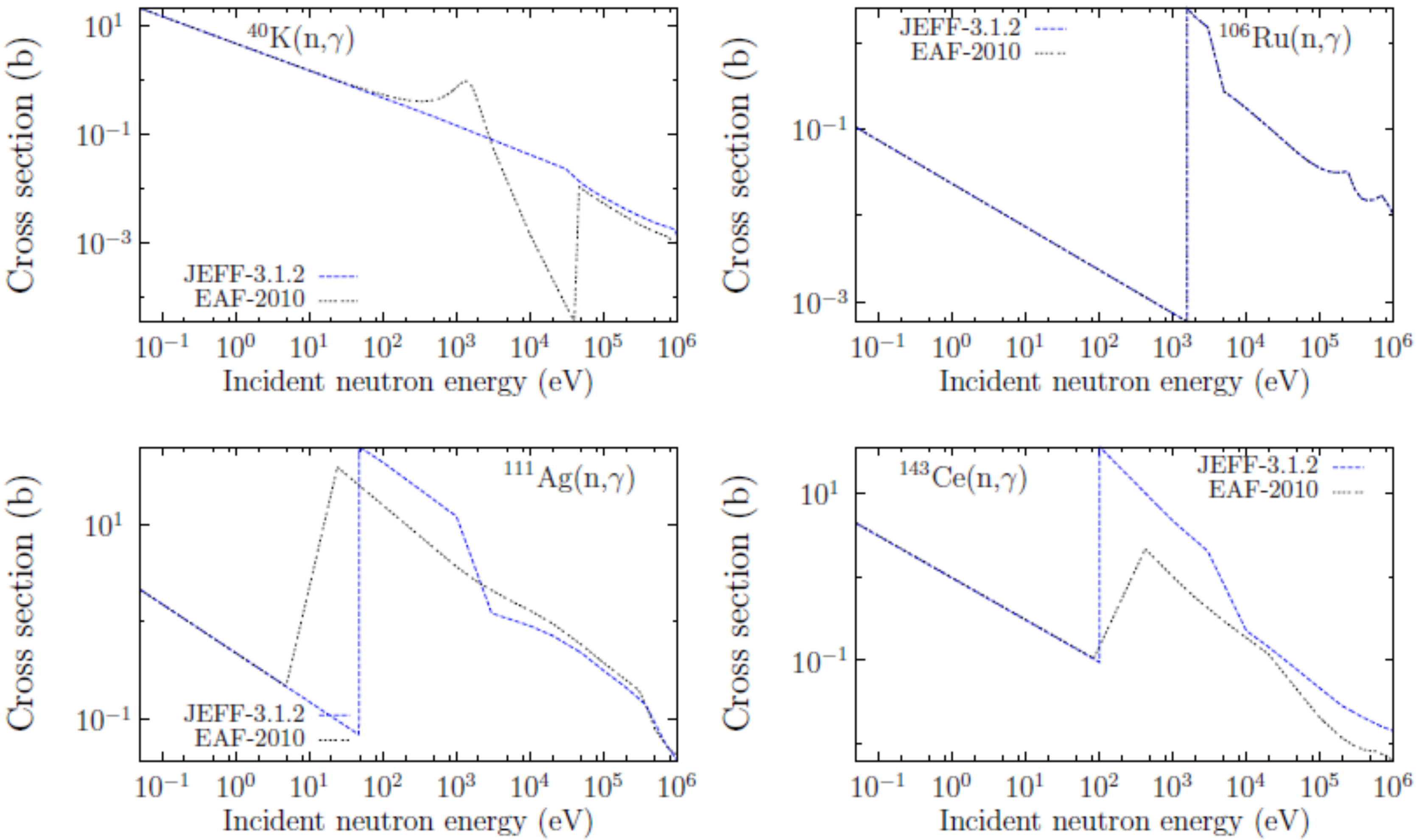


Unresolved resonance range (URR)

- The limit between the resonance energy range and fast neutron range is called the **unresolved resonance range**

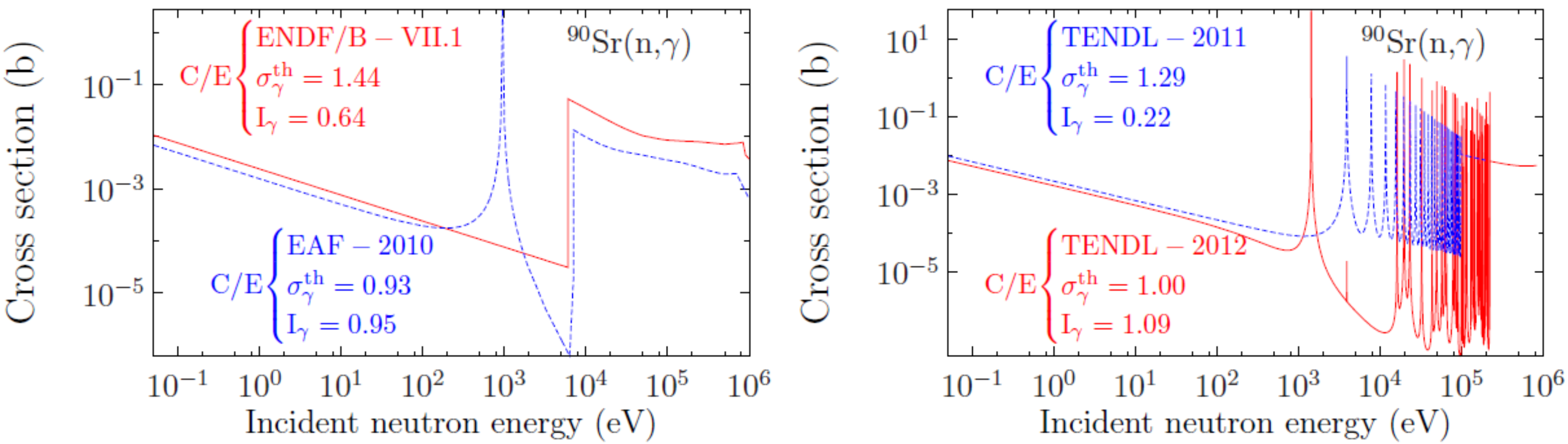


URR: create “statistical” resonances



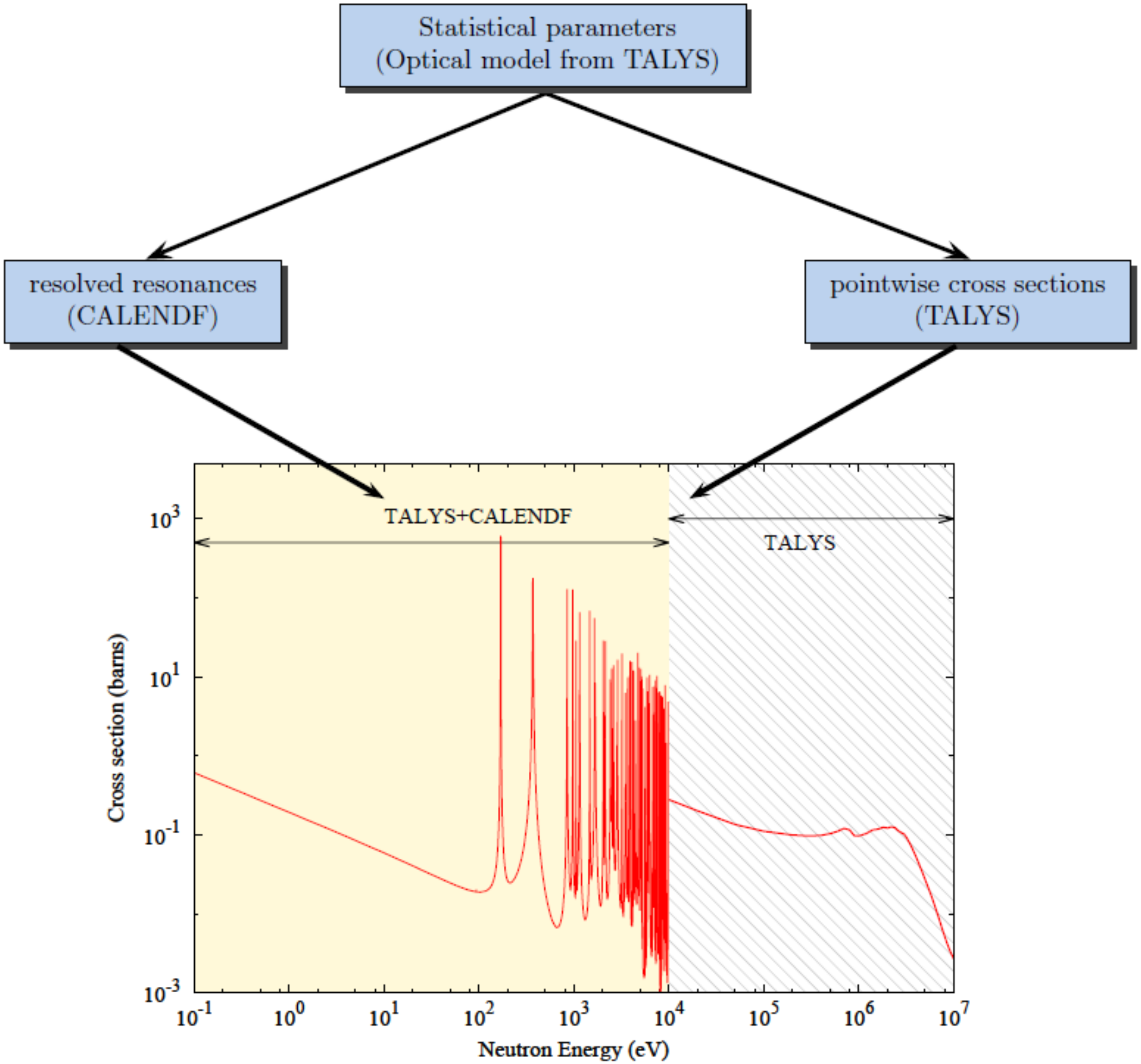
URR: create "statistical" resonances

Examples of different approaches for ^{90}Sr ($h_{1/2} = 28$ sec) in the low energy region.



Left: basic optical model calculation for ENDF/B-VII.1 and Single Resonance Approximation (SRA) for EAF-2010. Right: multi-SRA for TENDL-2011 and the present methodology for TENDL-2012.

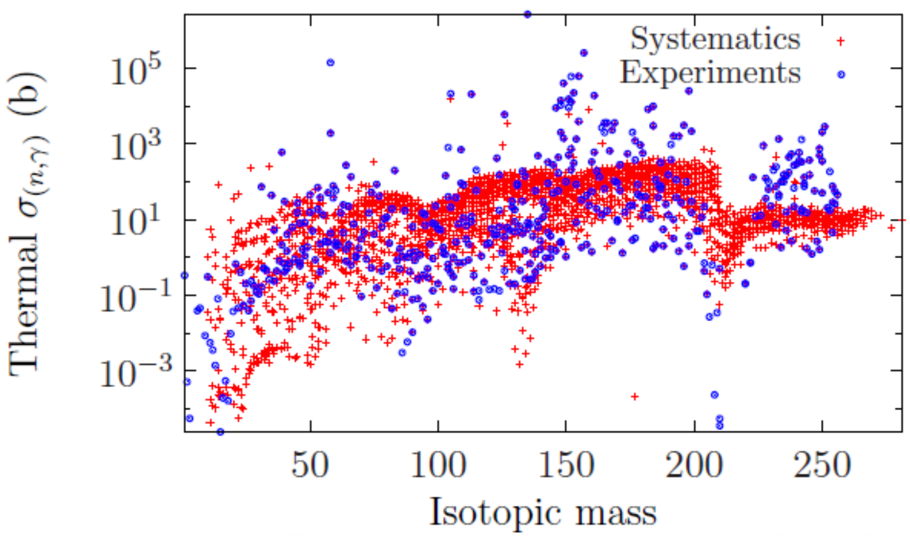
URR: create “statistical” resonances

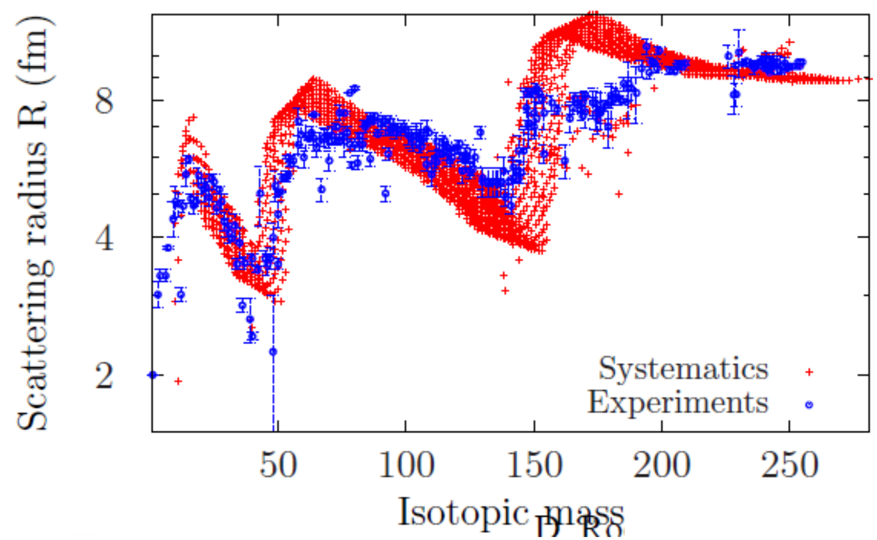


Statistical resonances

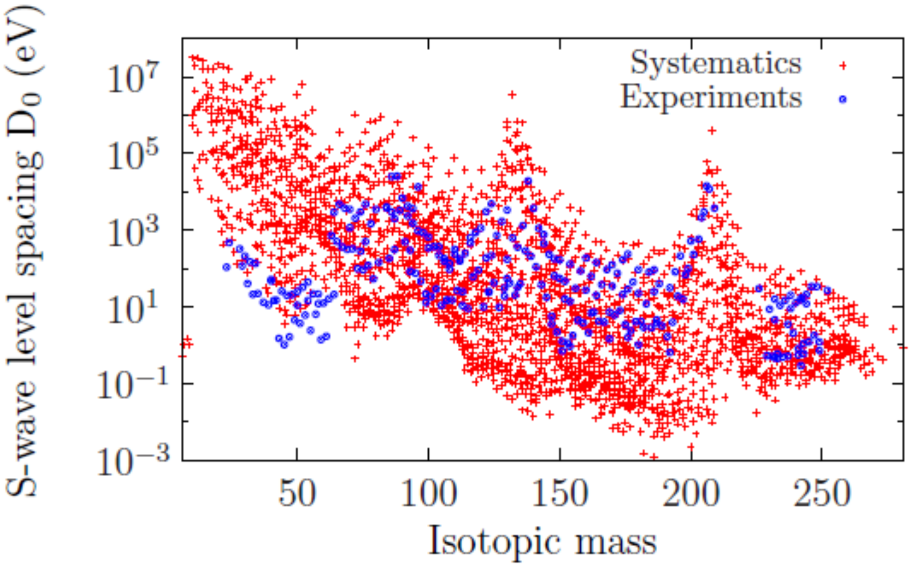
As a starting point energy-dependent statistical parameters as well as specific cross sections are needed in the whole energy range. These parameters are for each orbital angular momentum l and spin of the resonance state j:

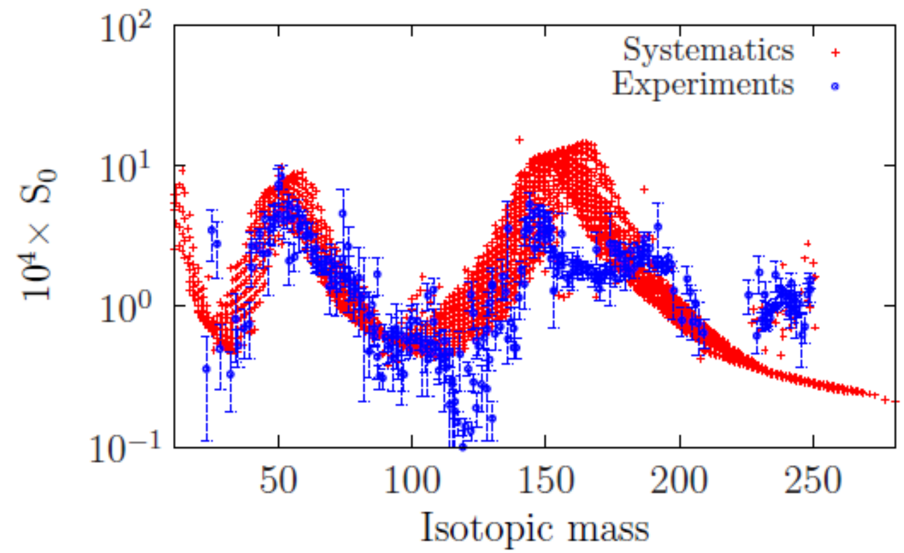
- the scattering radius r,
- the average level spacing D_0,
- the average reduced neutron width Γ_n^0,
- the average radiation width Γ_γ,
- and if relevant the average fission width Γ_f.

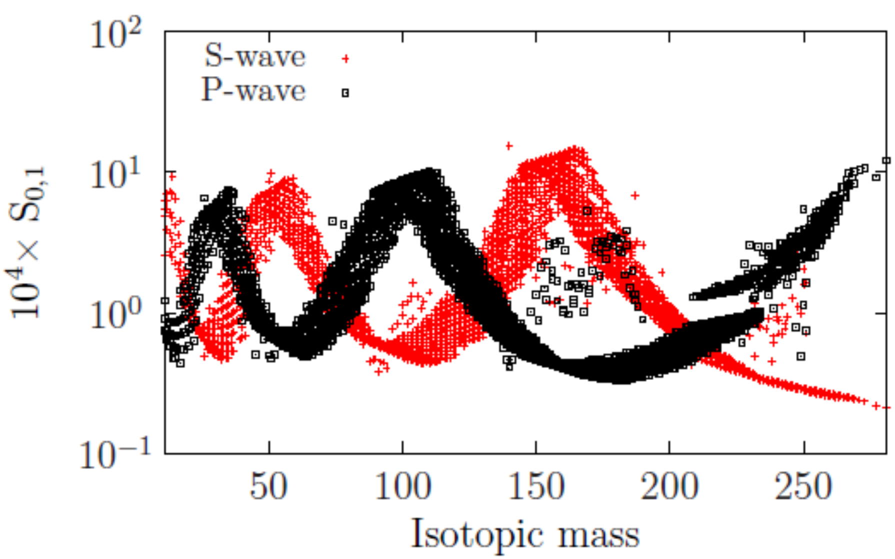


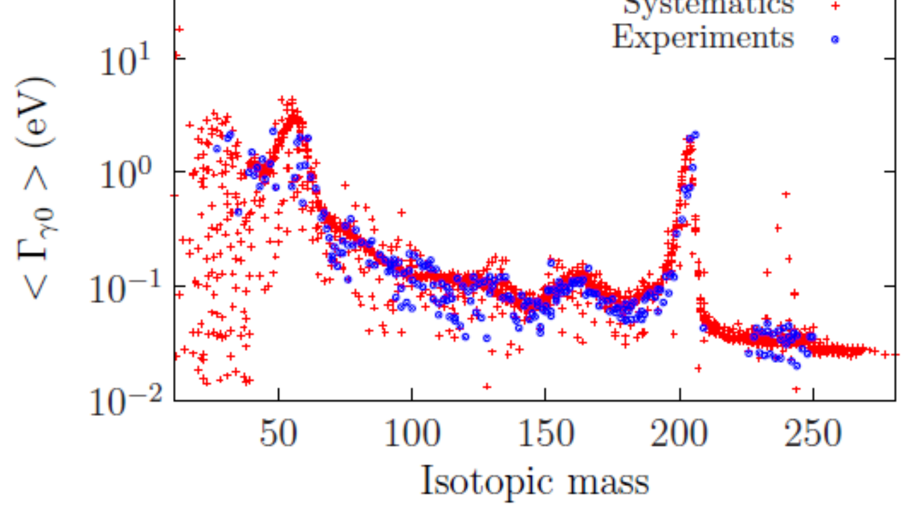


Statistical resonances









Statistical resonances: 3 groups of isotopes

1. isotopes without any experimental reaction information (about 1600 isotopes). In this case, as no specific information can be used to adjust calculations, we fully rely on systematics, as defined in TALYS.
2. isotopes with scarce experimental data, such as thermal cross sections, resonance integrals, average cross sections at high energy (about 400 isotopes). Such isotopes are for instance ^{40}K, ^{54}Mn, ^{60}Co, ^{90}Sr, ^{105}Rh, ^{106}Ru, ^{109}Cd, ^{111}Ag, ^{138,143}Ce or ^{204}Hg.
3. isotopes with measured pointwise cross sections, resonances, integral measurements, and resolved resonance parameters (about 400 isotopes).

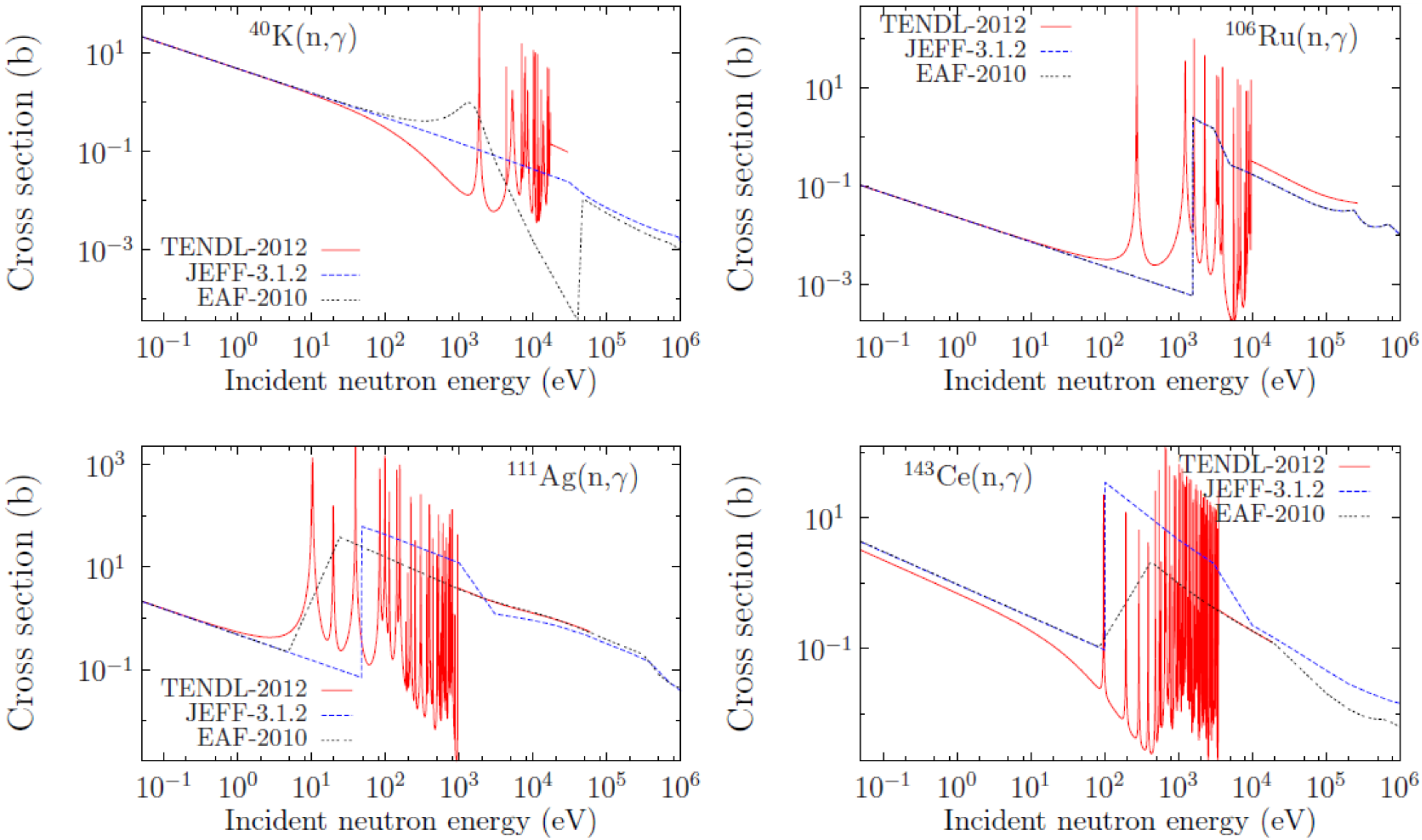
PAUL SCHERRER INSTITUT PSI

URR: Converting average parameters to statistical resonances

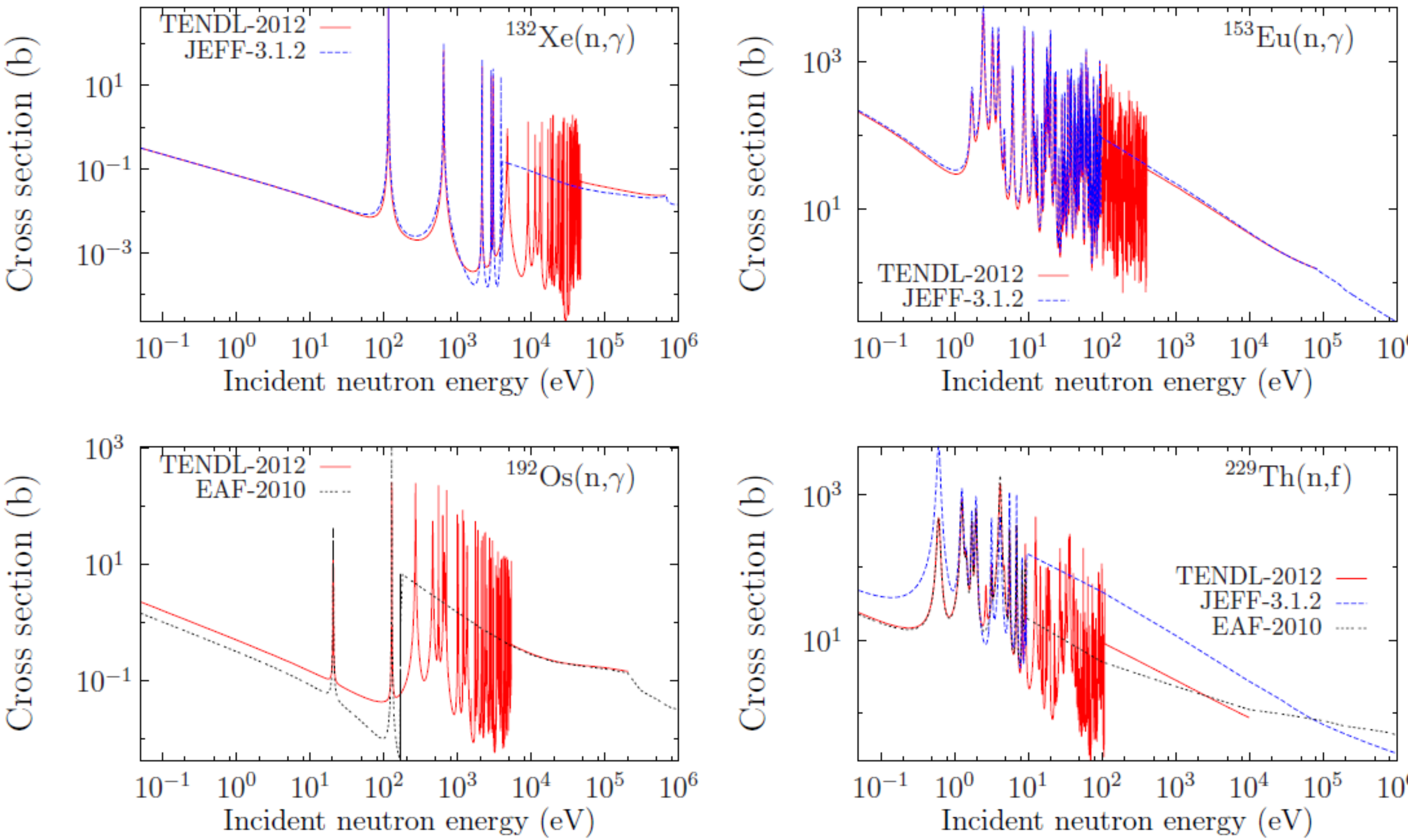
The idea is to generate random ladders of resonances using the statistical properties (as in the unresolved resonance range):

1. one ladder can be generated for an energy E by randomly selecting a starting resonance energy for one (l, j) sequence, and also randomly selecting a set of widths for that resonance using the appropriate average widths and χ^2 distribution functions.
2. We can then select the next higher resonance energy by sampling from the Wigner distribution for resonance spacings, and a new set of widths for that resonance can be chosen.
3. The process is continued until a long ladder of resonances for that (l, j) is obtained.
4. The process for the other (l, j) sequences is then repeated, each such sequence being uncorrelated in positions from the others.
5. for each (l, j) couples, a GOE random matrix (Gaussian Orthogonal Ensemble) is used to generate resonance energies (allowing to follow the Wigner law and to include correlations between two successive resonances).

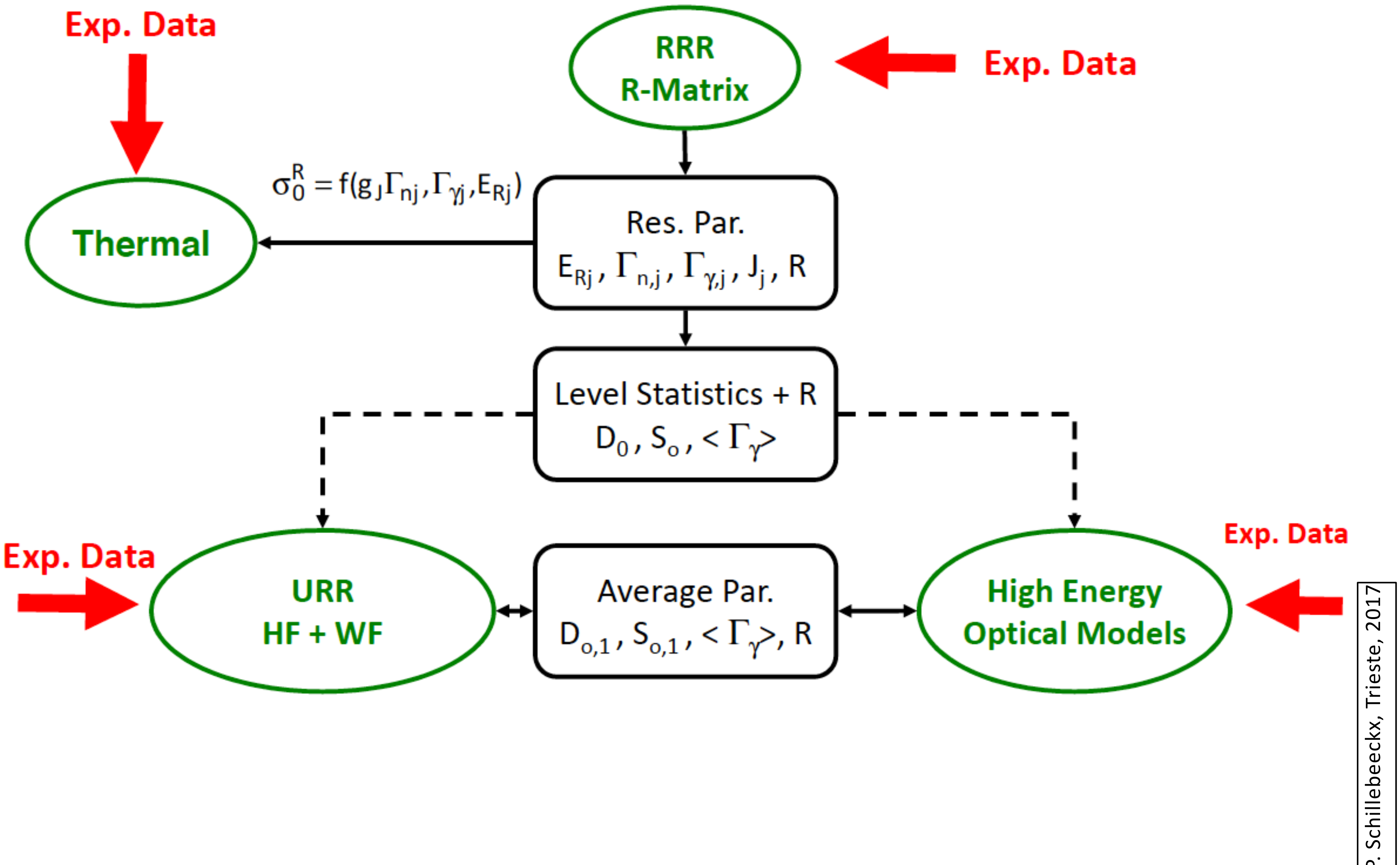
URR: example for known thermal cross sections



URR: example for known resonances

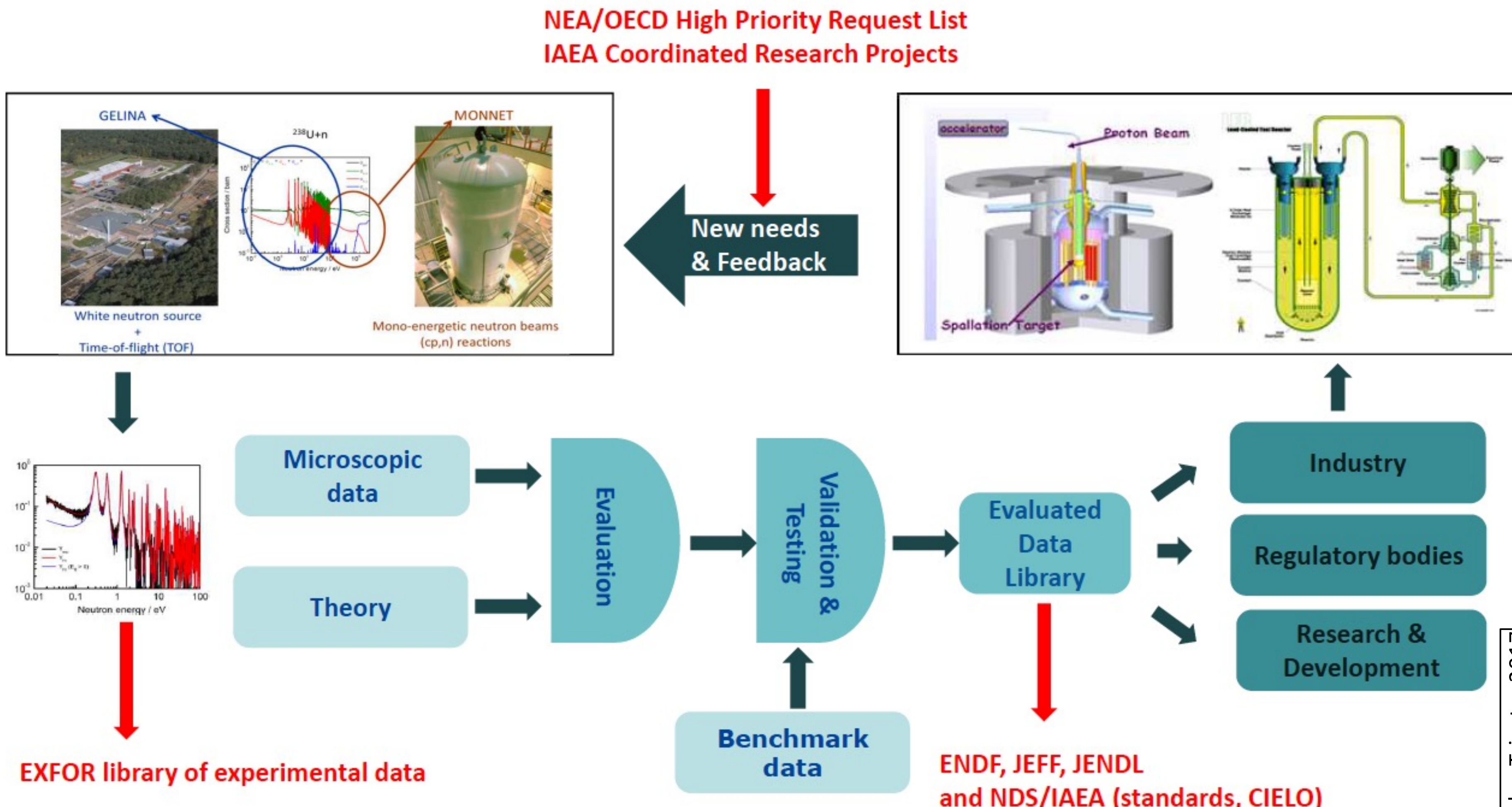


Conclusion



Exp. Data
RRR
R-Matrix
Exp. Data
$\sigma_0^R = f(g_J \Gamma_{nj}, \Gamma_{\gamma j}, E_{Rj})$
Thermal
Res. Par.
E_{Rj}, $\Gamma_{n,j}$, $\Gamma_{\gamma,j}$, J_j, R
Level Statistics + R
D_0, S_o, $<\Gamma_\gamma>$
Exp. Data
URR
HF + WF
Average Par.
$D_{o,1}$, $S_{o,1}$, $<\Gamma_\gamma>$, R
Exp. Data
High Energy
Optical Models
P. Schillebeeckx, Trieste, 2017

Conclusion



P. Schillebeeckx, Trieste, 2017

Wir schaffen Wissen – heute für morgen