

Broad topic	Lecture title
Basic principles of NPP	Introduction / Review of nuclear physics
	Interaction of neutrons with matter
	Nuclear fission
	Fundamentals of nuclear reactors
	LWR plants
Modeling the beast	The diffusion of neutrons - Part 1
	The diffusion of neutrons - Part 2
	Neutron moderation without absorption
	Neutron moderation with absorption
	Multigroup theory
	Element of lattice physics
	Neutron kinetics
	Depletion
Reactor Concepts Zoo	Advanced LWR technology
	Breeding and LFR
	AGR, HTGR
	Channels, MSR and thorium fuel
Review session	

- Interaction of neutrons with matter
- Cross sections
- Mechanisms of neutron interactions
- Illustrations of cross sections
- The Doppler effect
- Anisotropic scattering
- On cross section libraries

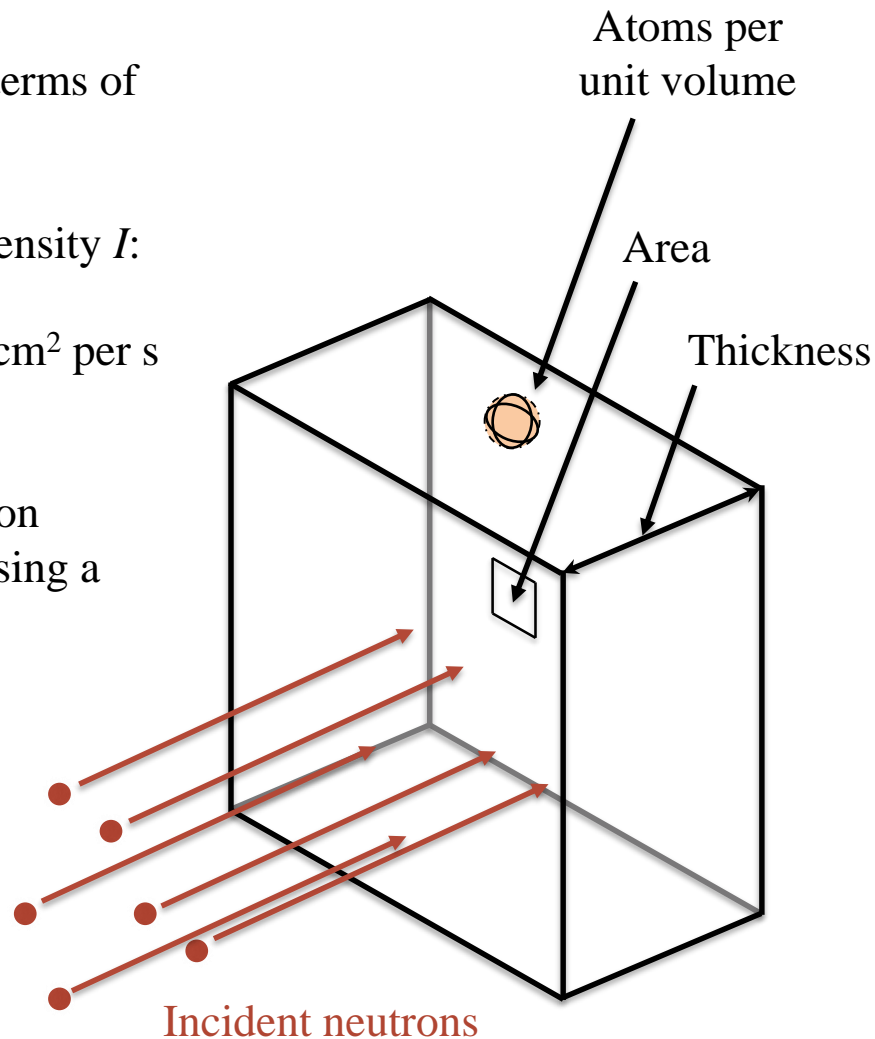
- The operation of a nuclear reactor depends fundamentally on the way in which neutrons interact with atomic nuclei.

Reaction	Is isotopic composition of nucleus changed ?	Is internal energy of nucleus changed ?	Neutron after	Particles after
(n,n)	No	No	1	-
(n,n')	No	Yes	1	-
(n, γ)	Yes	Yes	0	γ
(n,p)	Yes	Yes	0	p
(n, α)	Yes	Yes	0	α
(n,2n)	Yes	Yes	2	-
(n,3n)	Yes	Yes	3	-
(n,np)	Yes	Yes	1	p
(n,fiss)	Yes	Yes	2-3	γ , ...

Interactions of neutrons with matter are described in terms of cross sections (XS).

Considering monodirectional beam of neutrons of intensity I :

- I = number of neutrons which strike the target per cm^2 per s
 $I = n \times v = \text{neutron density} \times \text{neutron velocity}$
- In this case the beam intensity is equal to the neutron (scalar) flux Φ [$\text{n}/\text{cm}^2\text{s}$] – number of neutrons crossing a unit area per s



Neutrons incident on a target

- Intuitive concept: *Number of interactions* per unit time per unit volume
(Interaction rate) $[1/\text{cm}^3\text{s}] =$

Nucleus *cross section* $[\text{cm}^2] \times$

Number of *nuclei per unit volume* $[1/\text{cm}^3] \times$

Beam *intensity* (neutron flux) $[\text{n}/\text{cm}^2\text{s}]$

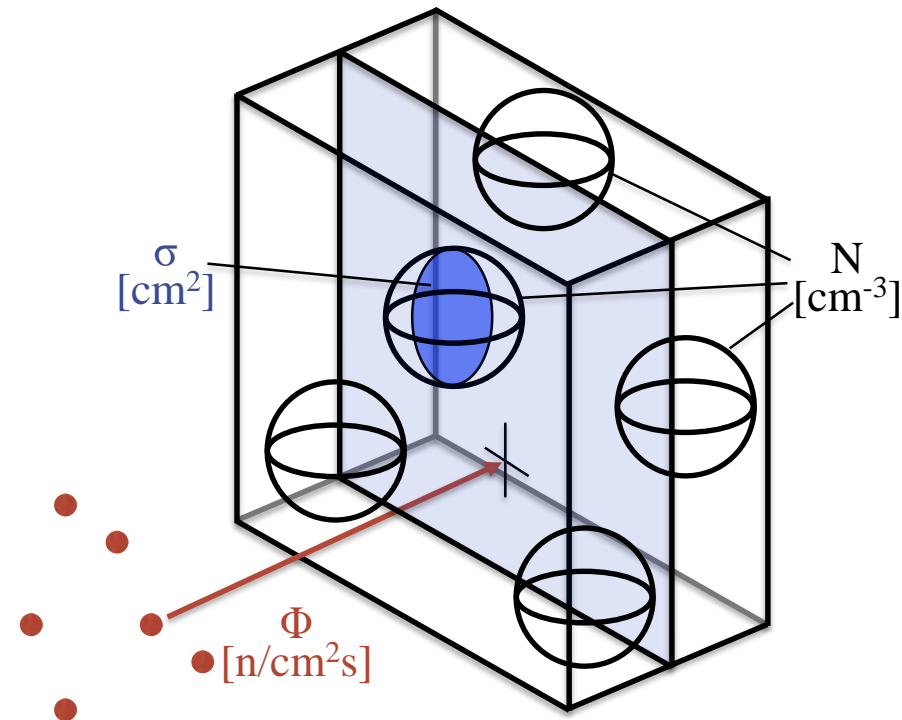
→ Interaction (or reaction) rate: $F = \sigma \times N \times \Phi$

- σ is the *microscopic* cross section [barn]

→ 1 barn (1b) is equal to 10^{-24} cm^2

- $\Sigma = \sigma \times N$ is the *macroscopic* cross section $[1/\text{cm}]$

→ Interaction (or reaction) rate: $F = \Sigma \times \Phi$



Neutrons incident on a target

Neutrons interact with nuclei in a number of ways and each type of interaction is described by a characteristic cross section:

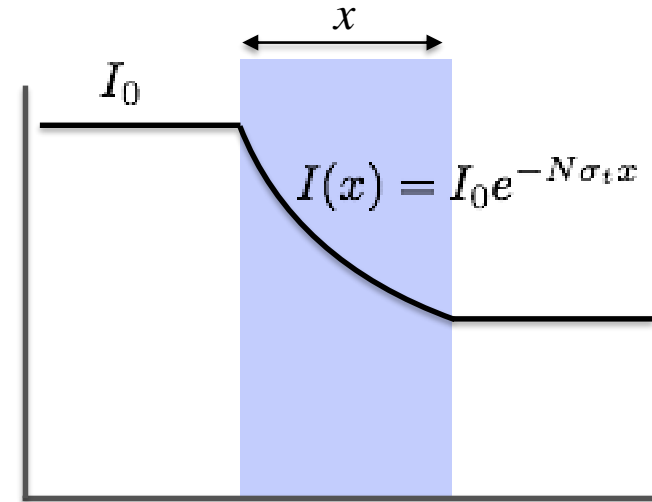
- Elastic scattering cross section σ_e
 - Inelastic scattering cross section σ_i
 - Radiative capture (n, γ) cross section σ_γ
 - Fission cross section σ_f
 - Cross section for (n,p) reaction σ_p
 - Cross section for (n, α) reaction σ_α
 - ...
- $\left. \begin{array}{l} \text{Scattering} \\ \text{cross section } \sigma_s \end{array} \right\}$
- $\left. \begin{array}{l} \text{Absorption} \\ \text{cross section } \sigma_a \end{array} \right\}$
- $\left. \begin{array}{l} \text{Total} \\ \text{cross section } \sigma_t \end{array} \right\}$

- Consider a target in monodirectional beam of intensity I_0 .
- $I(x)$ is the intensity of non-interacted neutrons.
- Decrease of I while traversing dx of the target:

$$-dI(x) = N\sigma_t I(x) dx$$

$$\frac{-dI(x)}{I(x)} = \underbrace{N\sigma_t}_{\Sigma_t} dx$$

- $\frac{dI(x)}{I(x)}$ is the fraction of neutrons which penetrated x without interaction and which interacted in dx
- $\Sigma_t dx$ = Probability that a neutron interacts in dx
- Σ_t is the probability per unit path length that a neutron will undergo some sort of interaction



- Probability that a neutron has its first interaction in dx around x $p(x)dx$

=

Probability that neutron survives up to x without interaction: $I(x)/I_0 = e^{-N\sigma_t x} = e^{-\Sigma_t x}$

X

Probability that neutron does interact in the next dx : Σ_t

$$p(x)dx = \Sigma_t e^{-\Sigma_t x} dx$$

- $p(x)$ is a first interaction (or first collision) probability distribution function
- It represents the distribution of distances which neutron moves between interactions – *free path*.
- The average distance between two interactions – *mean free path*

$$\lambda = \frac{\int_0^{\infty} xp(x)dx}{\int_0^{\infty} p(x)dx} = \Sigma_t \int_0^{\infty} xe^{-\Sigma_t x} dx = \frac{1}{\Sigma_t}$$

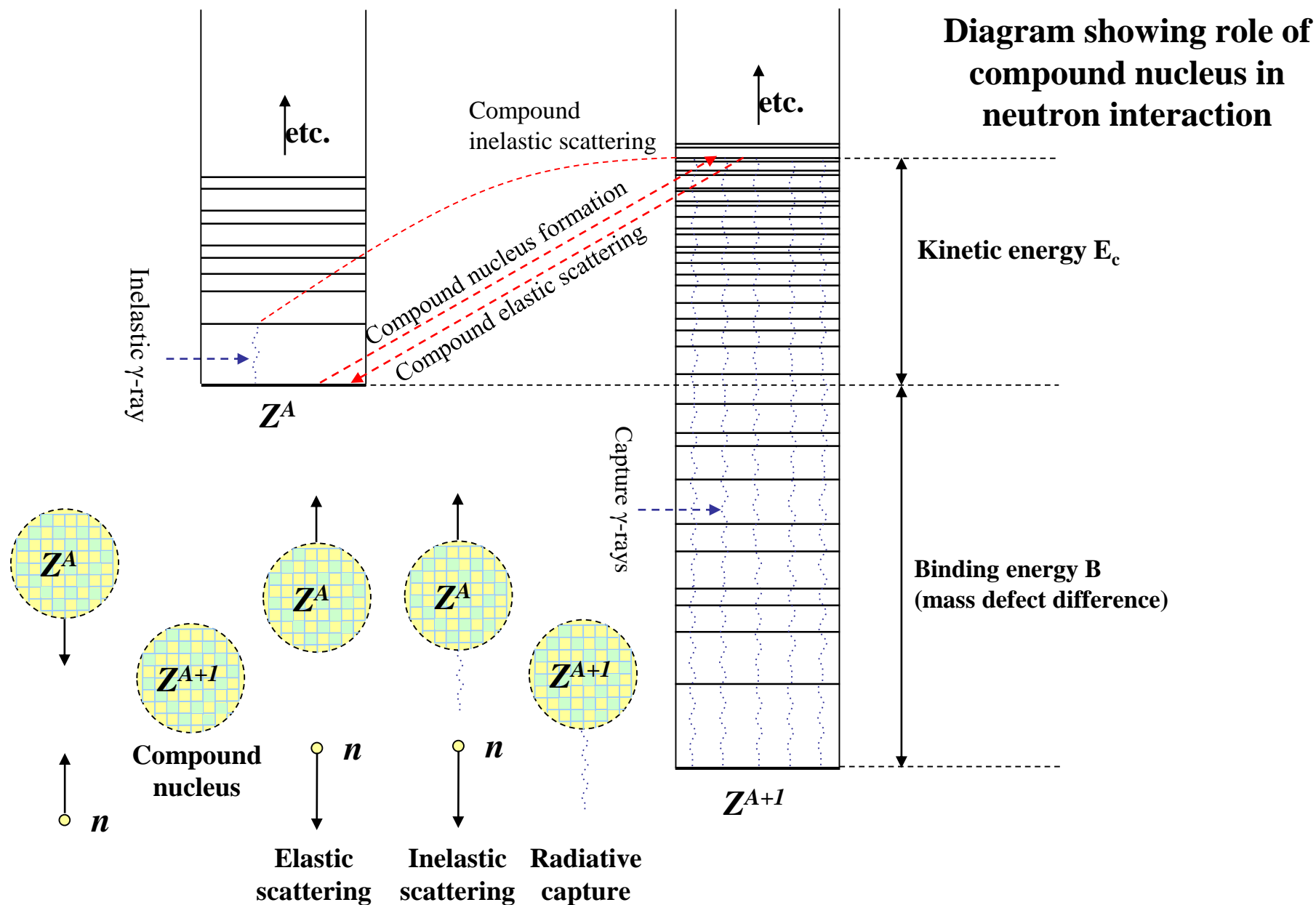


- Homogeneous mixture of two nuclear species X and Y (N_X and N_Y atoms per cm^3)
 - $N_X \sigma_X$ - Probability per unit path that neutron interacts with a nucleus X
 - $N_Y \sigma_Y$ - Probability per unit path that neutron interacts with a nucleus Y
 - Probability per unit path that neutron interacts with *either* X or Y :

$$\Sigma = \Sigma_X + \Sigma_Y = N_X \sigma_X + N_Y \sigma_Y$$
 - For the molecule $X_m Y_n$

$$\Sigma = N_{X_m Y_n} \sigma_{X_m Y_n} = N_{X_m Y_n} (m \sigma_X + n \sigma_Y)$$
- These equations are based on the assumption that the nuclei X and Y act independently when they interact with neutrons.
 - for low-energy neutrons undergoing elastic scatterings on molecules, this assumption is not valid.

- **Neutron-electron** interactions are *negligible* (infinitesimal cross sections)
- **Neutron-neutron** interactions are *negligible* (probability to meet a nucleus is $\sim 10^{14}$ times higher than to meet another neutron)
- Two fundamentally different mechanisms of neutron interaction with nucleus:
 - ***compound nucleus formation:***
neutron is absorbed, exciting nucleus which then relaxes by emission of:
 - . one neutron: elastic scattering
 - . one neutron and γ -ray: inelastic scattering
 - . γ -ray: (n, γ) reaction
 - . proton: (n,p) reaction
 - . α -particle: (n, α)
 - . in special case, fission (Chapter 3)
 - ***potential or shape scattering:***
neutron is not absorbed, but interacts with a nucleus as billiard balls do.



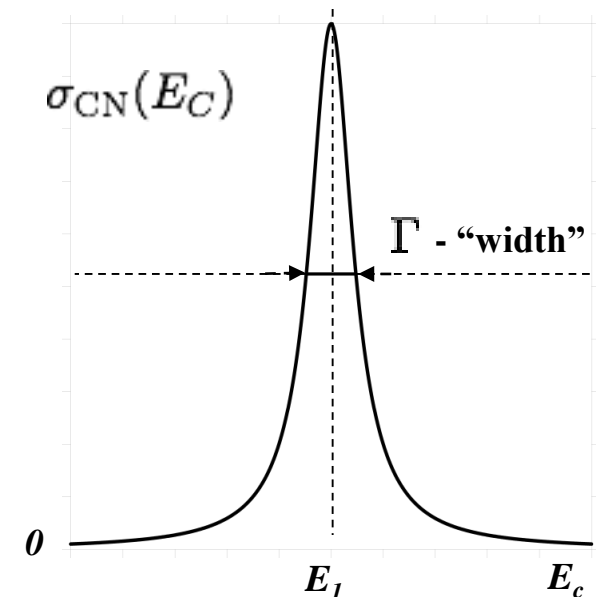
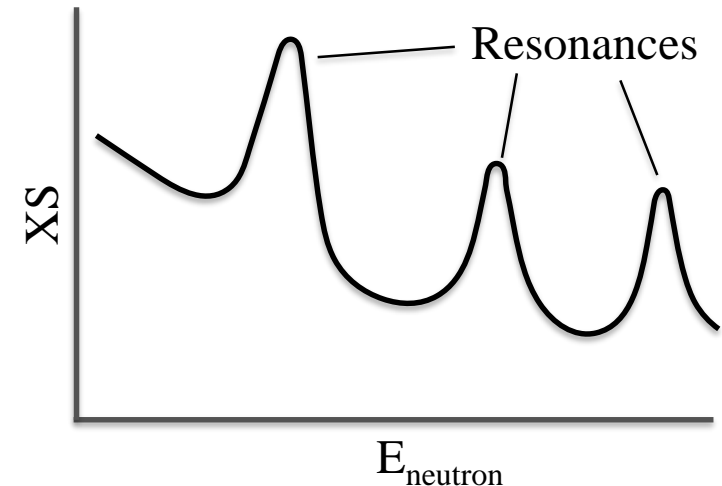
- Probability of formation of the compound nucleus is high if there is an excited state in the nucleus Z^{A+1} near $E_c + B$.
- The cross sections for neutron interactions (e.g. elastic scattering) through a compound nucleus formation can be written as:

$$\sigma_s(E_c) = \sigma_{\text{CN}}(E_c) \frac{\Gamma_n}{\Gamma}$$

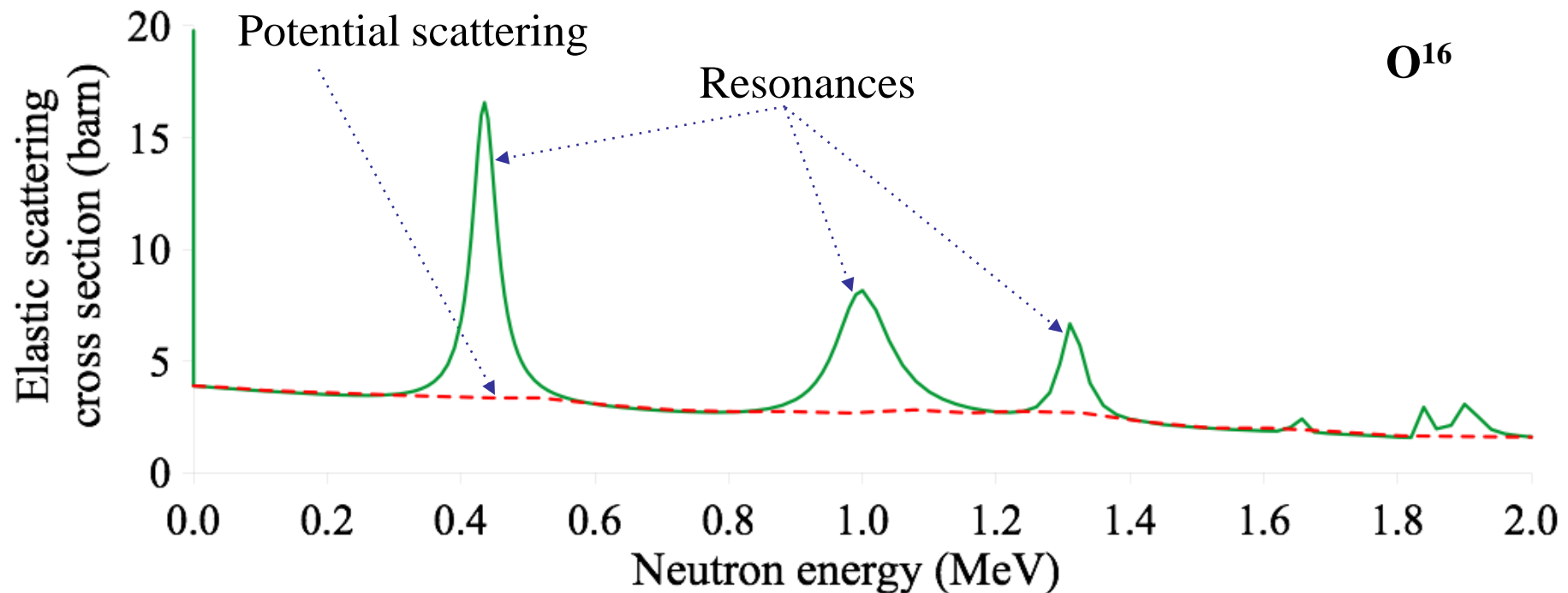
Total cross section for the formation of a compound nucleus \times Probability that the compound nucleus decays by elastic neutron emission

- The energy dependence near an isolated resonance E_1 can be approximated by

$$\sigma_{\text{CN}}(E_c) = \frac{\text{constant}}{(E_c - E_1)^2 + \Gamma^2/4}$$

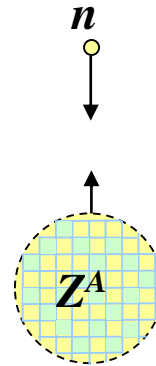


- The cross section for compound elastic scattering is significant only when neutron energy is close to the nucleus resonance.
- Potential elastic scattering on a nucleus takes place at *any* energy of incident neutrons.



Let us consider now (in a limited way) actual experimental cross-section data. These data depend on:

- the energy of the incident neutron
- the nature of the target nucleus.



- **Light** ($A \lesssim 25$)

● **Magic** (N or $Z = 2, 6, 8, 14, 20, 28, 50, 82, 126$)

● **Intermediate** ($25 \lesssim A \lesssim 150$)

Heavy ($A \gtrsim 150$)

1

H

Hydrogen

1.00794

3

Li

Lithium

6.941

11

Na

Sodium

22.989770

19

K

Potassium

39.0983

37

Rb

Rubidium

85.4678

55

Cs

Cesium

132.90545

87

Fr

Francium

(223)

4

Be

Beryllium

9.012182

12

Mg

Magnesium

24.3050

20

Ca

Calcium

40.078

38

Sr

Strontium

87.62

56

Ba

Barium

137.327

88

Ra

Radium

(226)

21

Sc

Scandium

44.955910

39

Y

Yttrium

88.90585

57

La

Lanthanum

138.9055

89

Ac

Actinium

(227)

22

Ti

Titanium

47.867

40

Zr

Zirconium

91.224

72

Hf

Hafnium

178.49

104

Rf

Rutherfordium

(261)

23

V

Vanadium

50.9415

41

Nb

Niobium

92.90638

73

Ta

Tantalum

180.9479

105

Db

Dubnium

(262)

24

Cr

Chromium

51.9961

42

Mo

Molybdenum

95.94

74

W

Tungsten

183.84

106

Sg

Seaborgium

(263)

25

Mn

Manganese

54.938049

43

Tc

Technetium

(98)

75

Re

Rhenium

186.207

107

Bh

Bohrium

(262)

26

Fe

Iron

55.845

44

Ru

Ruthenium

101.07

76

Os

Osmium

190.23

108

Hs

Hassium

(265)

27

Co

Cobalt

58.933200

45

Rh

Rhodium

102.90550

77

Ir

Iridium

192.217

109

Mt

Meitnerium

(266)

28

Ni

Nickel

58.6934

46

Pd

Palladium

106.42

78

Pt

Platinum

195.078

110

29

Cu

Copper

63.546

47

Ag

Silver

107.8682

79

Au

Gold

196.96655

111

30

Zn

Zinc

65.39

48

Cd

Cadmium

112.411

80

Hg

Mercury

200.59

112

31

Ga

Gallium

69.723

49

In

Indium

114.818

81

Tl

Thallium

204.3833

113

32

Ge

Germanium

72.61

50

Sn

Tin

118.710

82

Pb

Lead

207.2

114

33

As

Arsenic

74.92160

51

Sb

Antimony

121.760

83

Bi

Bismuth

208.98038

34

Se

Selenium

78.96

52

Te

Tellurium

127.60

84

Po

Polonium

(209)

35

Br

Bromine

79.904

53

I

Iodine

126.90447

85

At

Astatine

(210)

36

Kr

Krypton

83.80

54

Xe

Xenon

131.29

86

Rn

Radon

(222)

2

He

Helium

4.003

10

Ne

Neon

20.1797

18

Ar

Argon

39.948

36

Kr

Krypton

83.80

54

Xe

Xenon

131.29

71

Lu

Lutetium

174.967

5

B

Boron

10.811

13

Al

Aluminum

26.981538

21

Sc

Scandium

44.955910

29

Cu

Copper

63.546

37

Rb

Rubidium

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45

Rh

Rhodium

102.90550

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I

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Pm

Promethium

(145)

69

Tm

Thulium

168.93421

77

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Iridium

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85

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Np

Neptunium

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117

6

C

Carbon

12.0107

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Sm

Samarium

150.36

70

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Ytterbium

173.04

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Platinum

195.078

86

Rn

Radon

(222)

94

Pu

Plutonium

(244)

102

No

Nobelium

(259)

110

7

N

Nitrogen

14.00674

15

P

Phosphorus

30.973761

23

V

Vanadium

50.9415

31

Ga

Gallium

69.723

39

Y

Yttrium

88.90585

47

Ag

Silver

107.8682

55

Cs

Cesium

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196.96655

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Fr

Francium

(223)

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Am

Americium

(243)

103

Lr

Lawrencium

(262)

111

8

O

Oxygen

15.9994

16

S

Sulfur

32.066

24

Cr

Chromium

51.9961

32

Ge

Germanium

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Cm

Curium

(247)

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Rf

Rutherfordium

(261)

112

9

F

Fluorine

18.9984032

17

Cl

Chlorine

35.4527

25

Mn

Manganese

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As

Arsenic

74.92160

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Nb

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Tb

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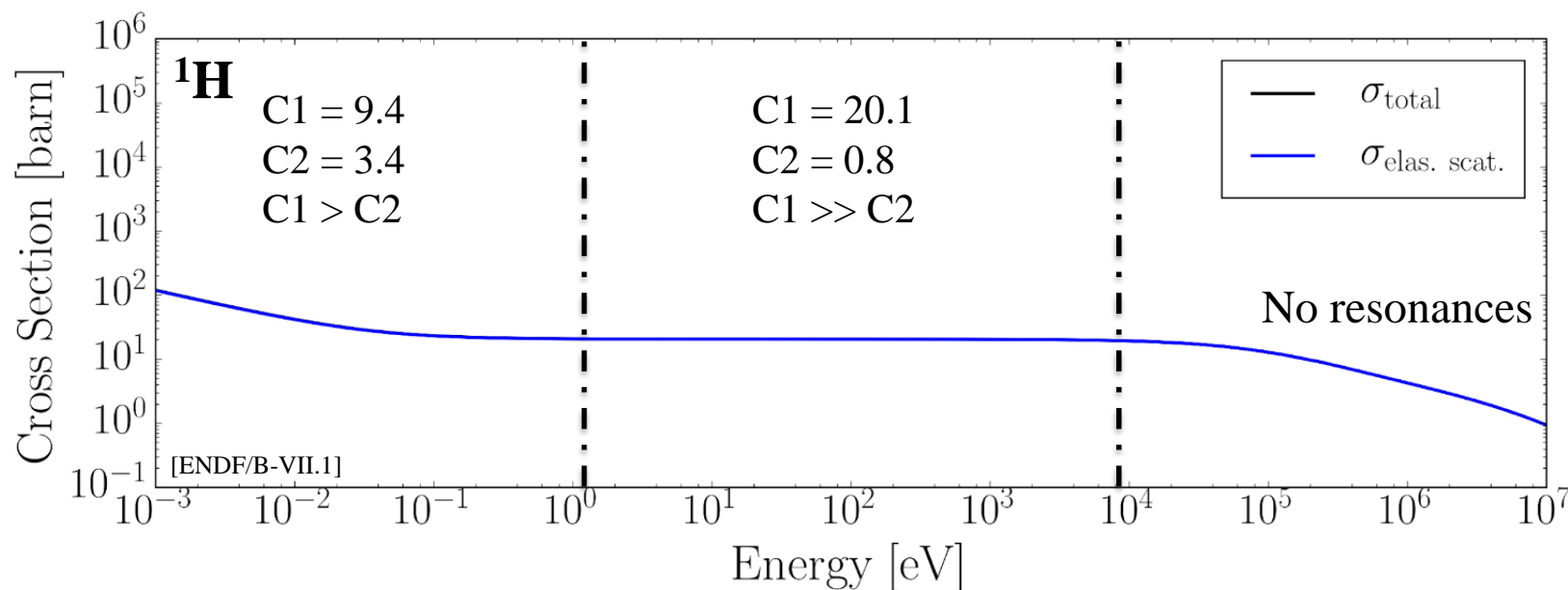
131.29

Measured in transmission experiments

$$\sigma_t = C_1 + \frac{C_2}{\sqrt{E}} \quad \text{or} \quad \sigma_t = C_1 + \frac{C'_2}{v}$$



- C_1 is determined by the elastic scattering cross sections
- C_2 depends on (n,γ) or any other exothermic reaction

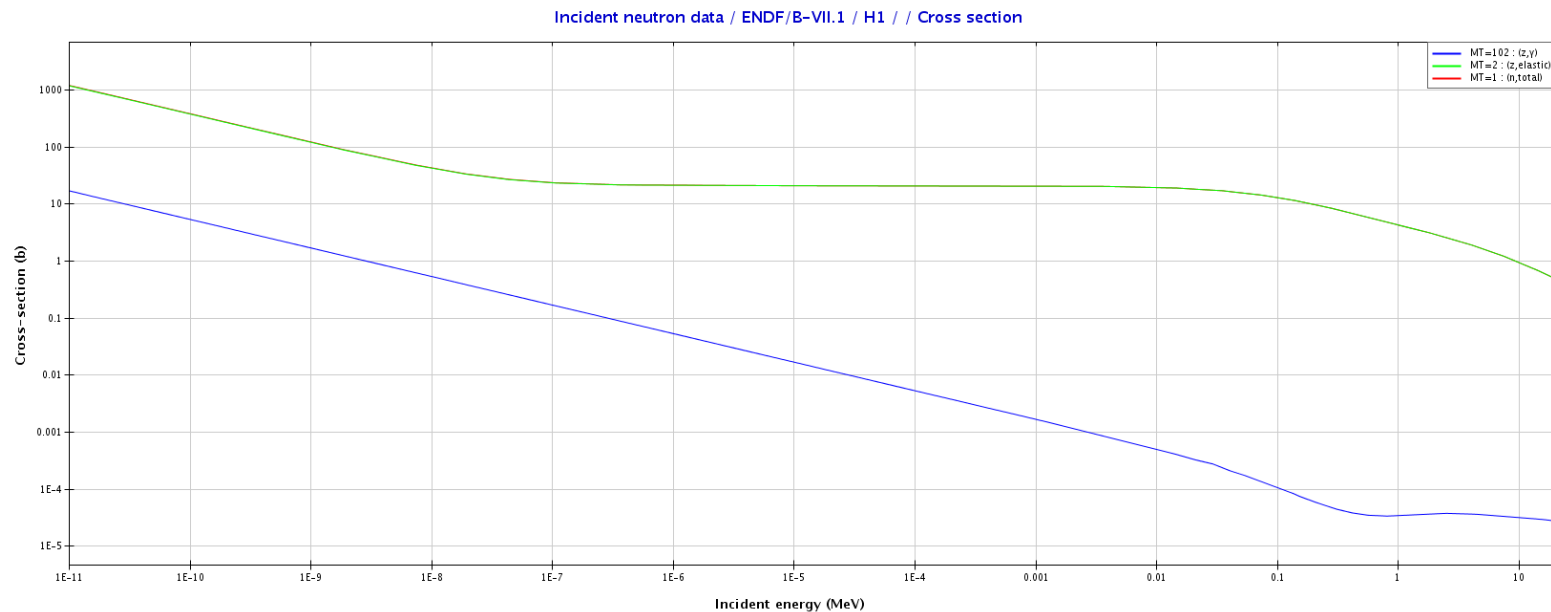


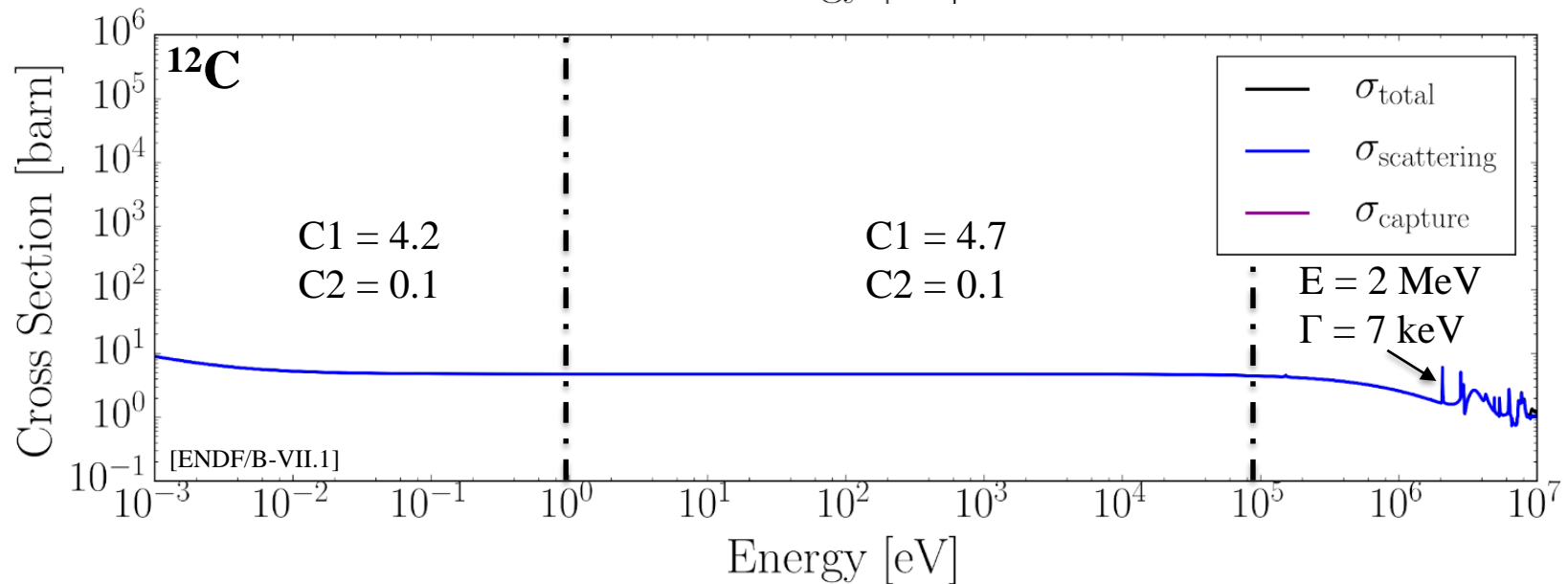
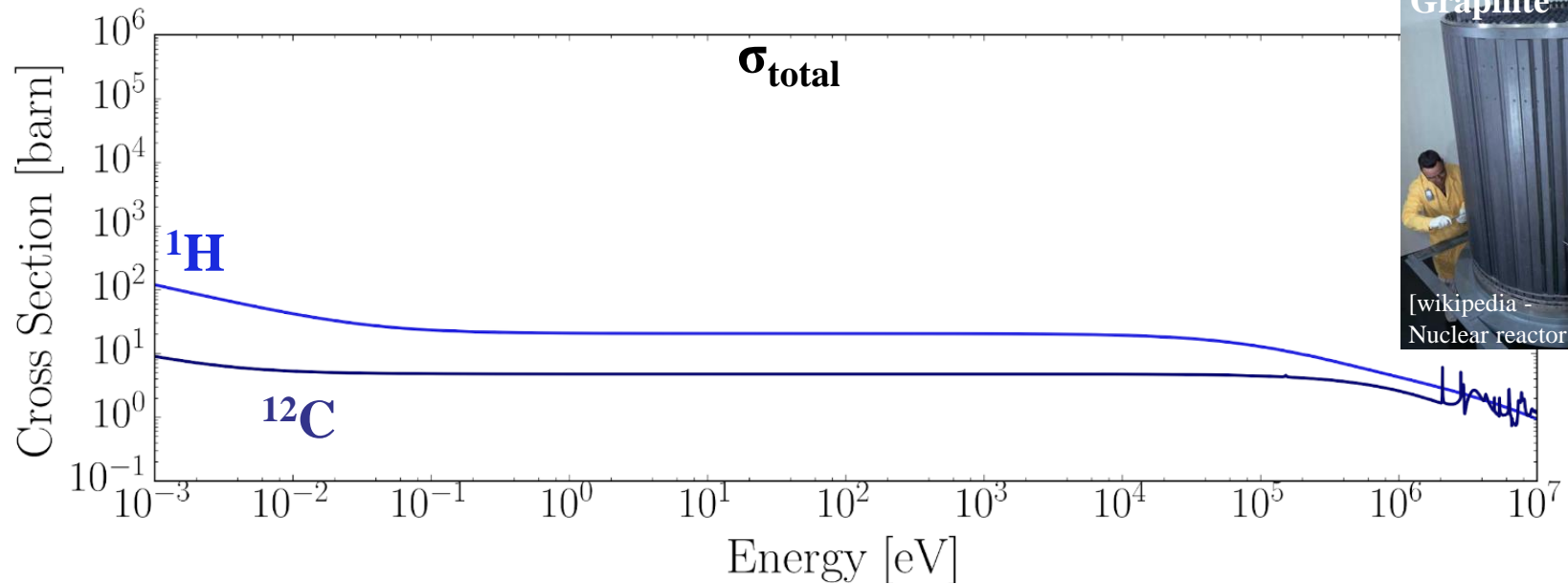
Measured in transmission experiments

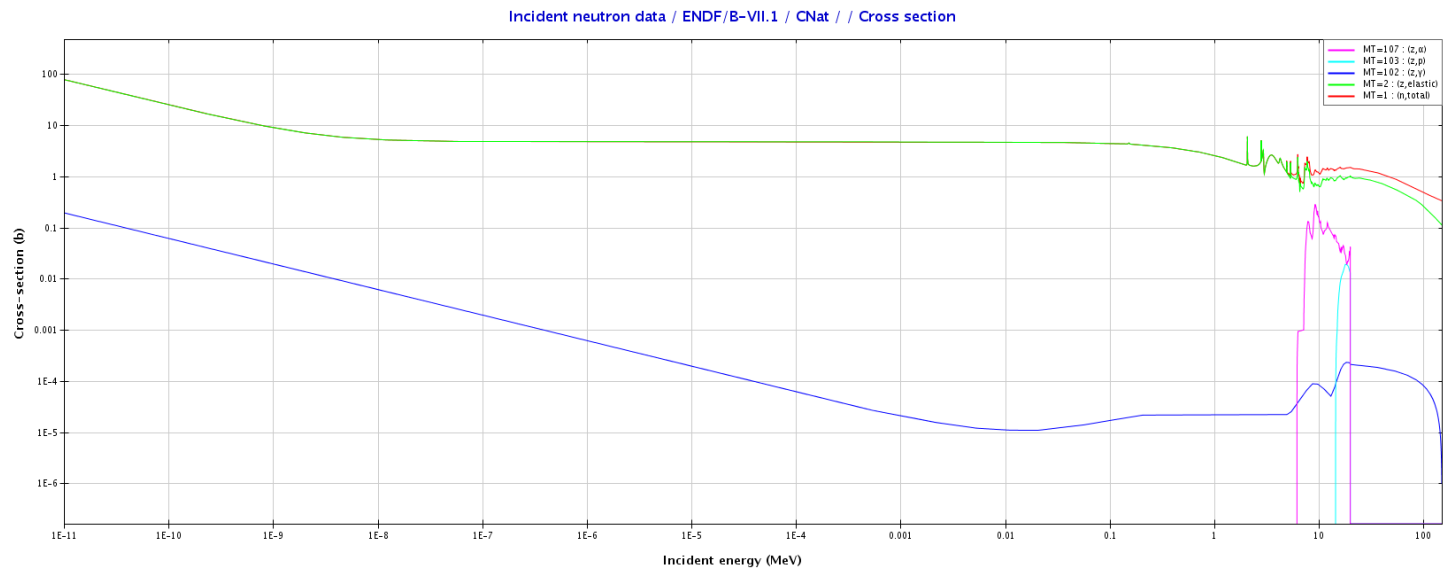
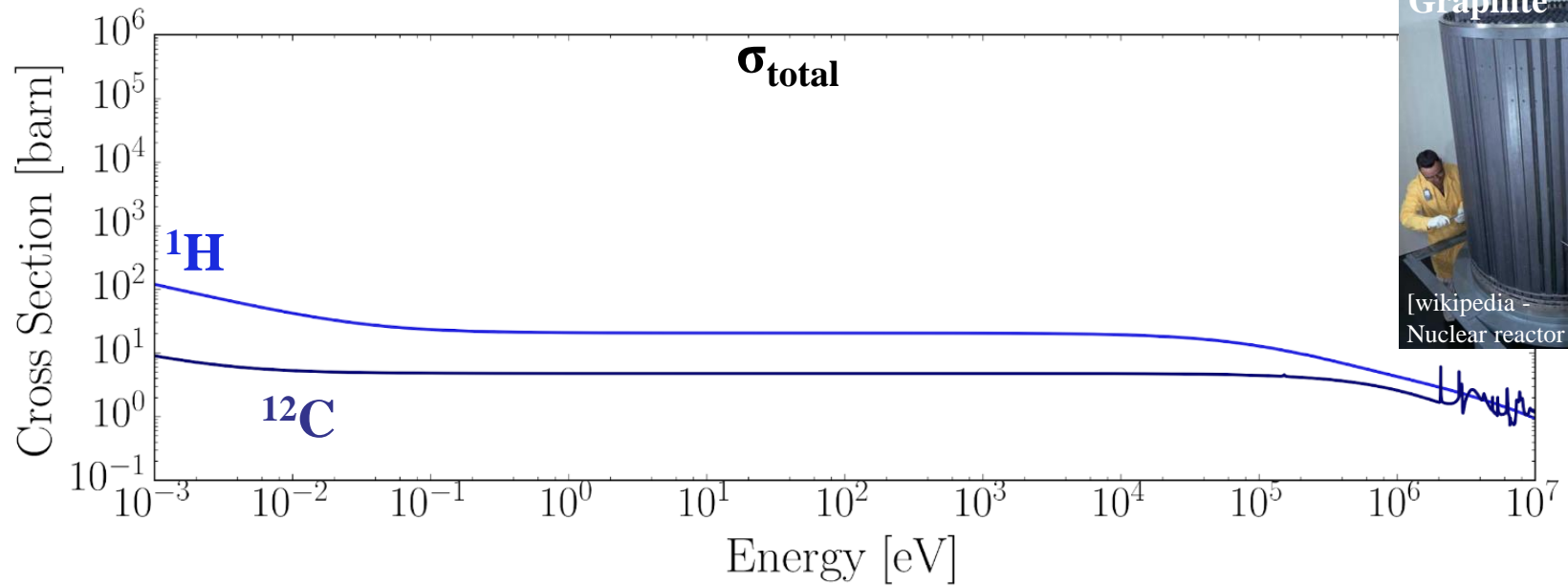
$$\sigma_t = C_1 + \frac{C_2}{\sqrt{E}} \quad \text{or} \quad \sigma_t = C_1 + \frac{C'_2}{v}$$

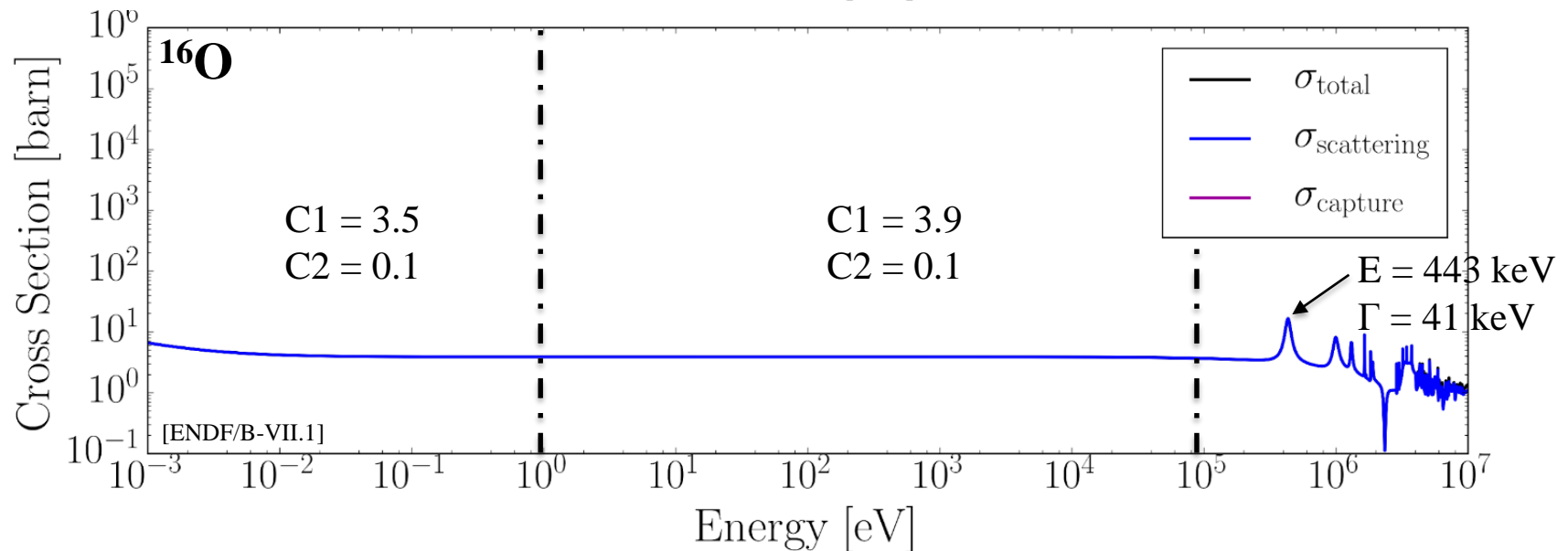
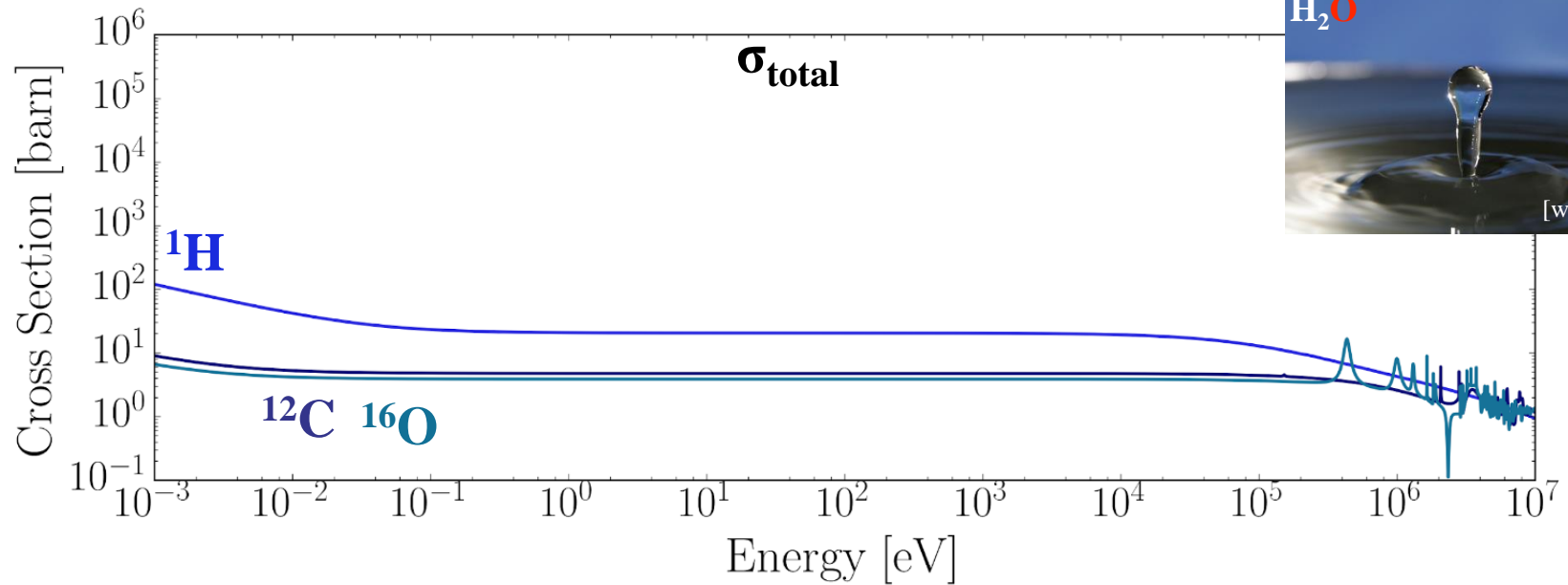


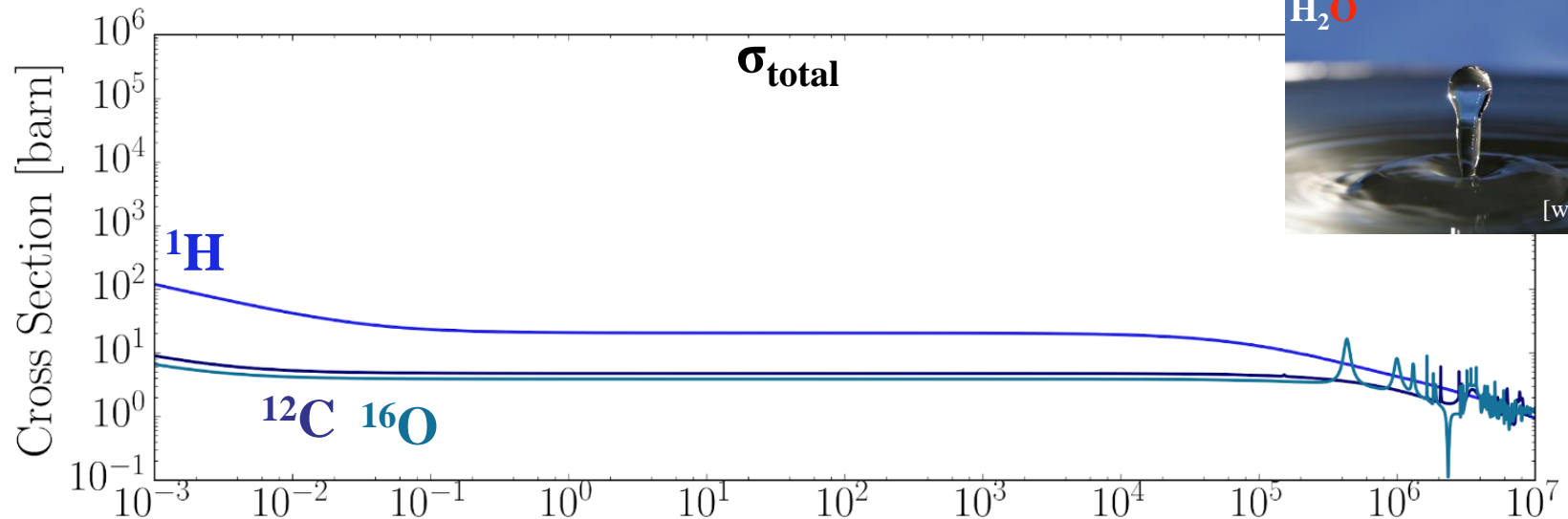
- C_1 is determined by the elastic scattering cross sections
- C_2 depends on (n,γ) or any other exothermic reaction



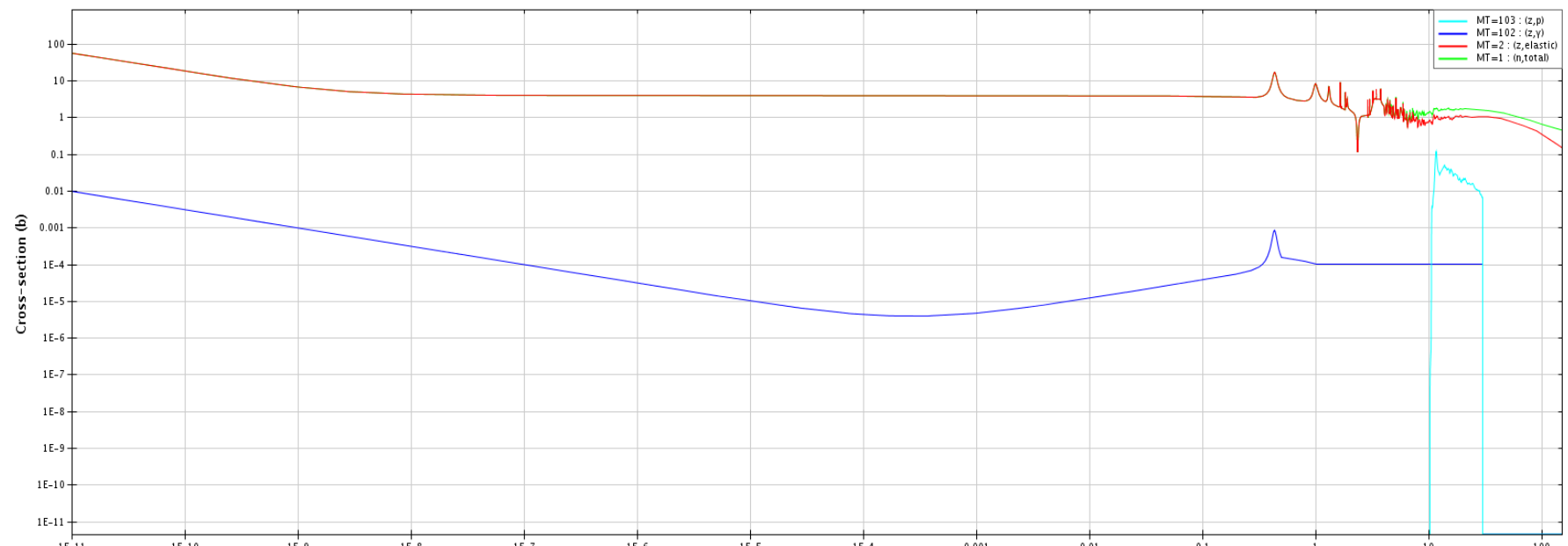


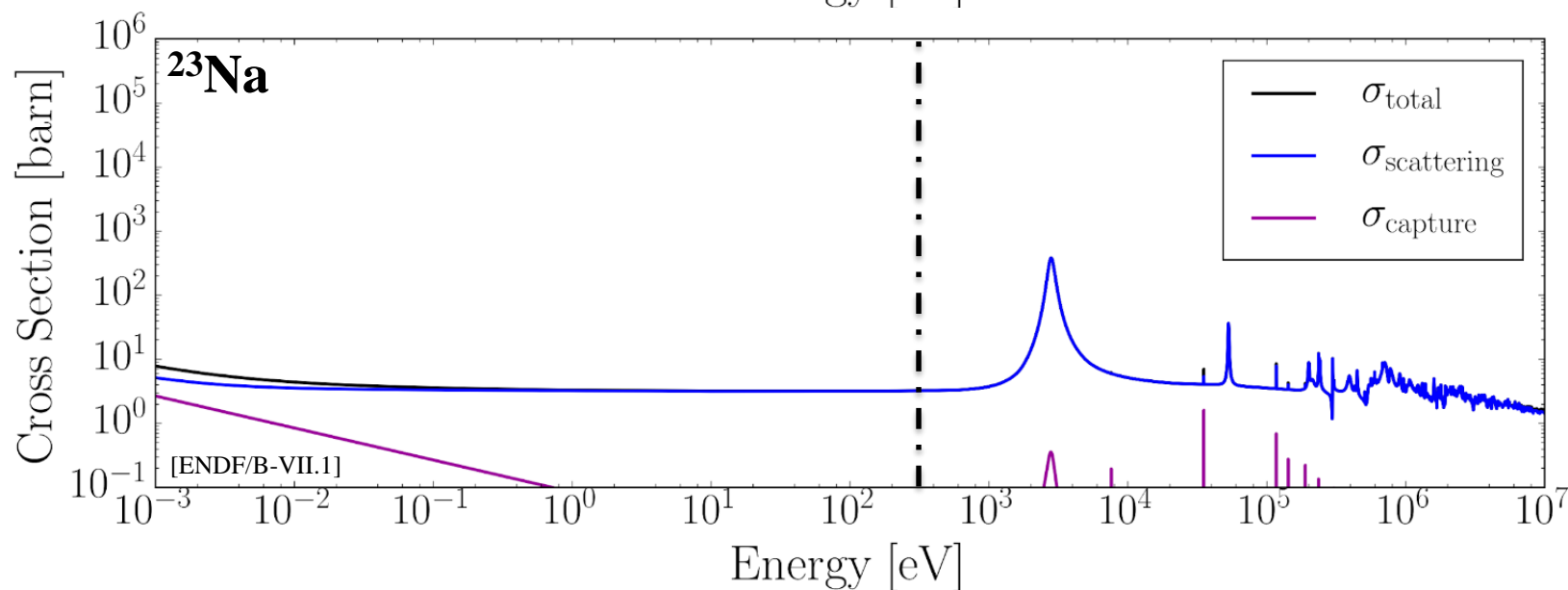
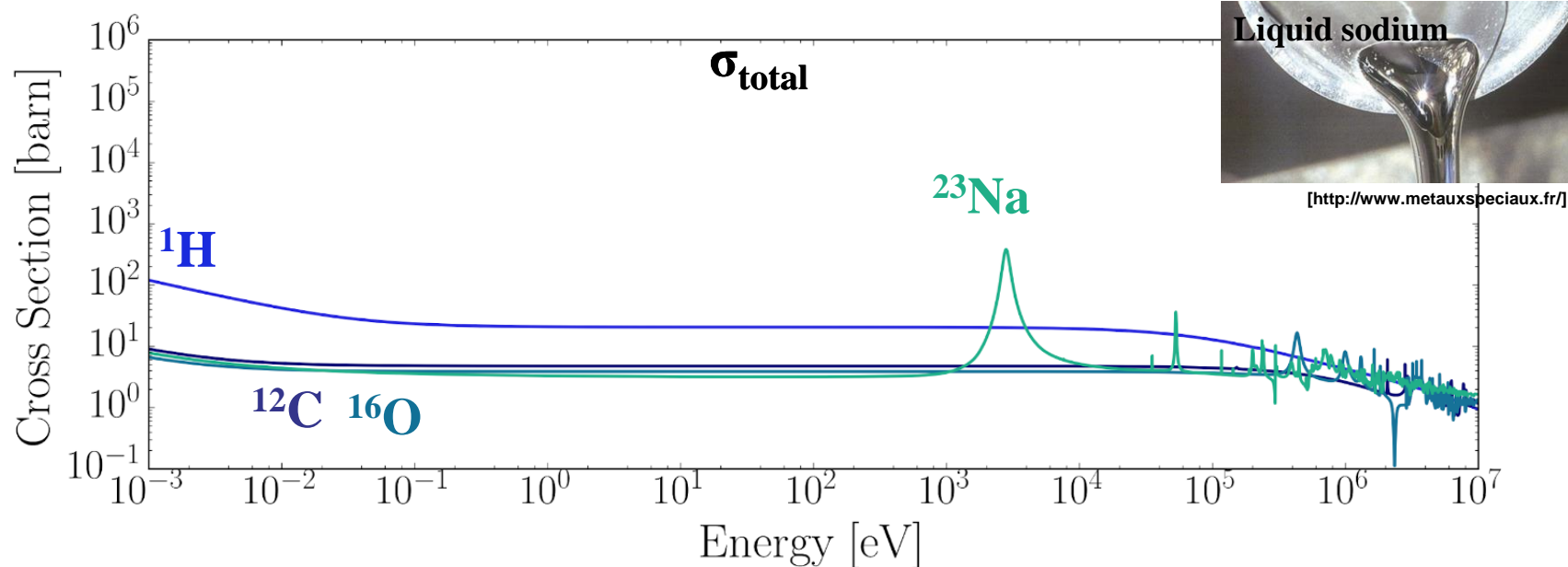


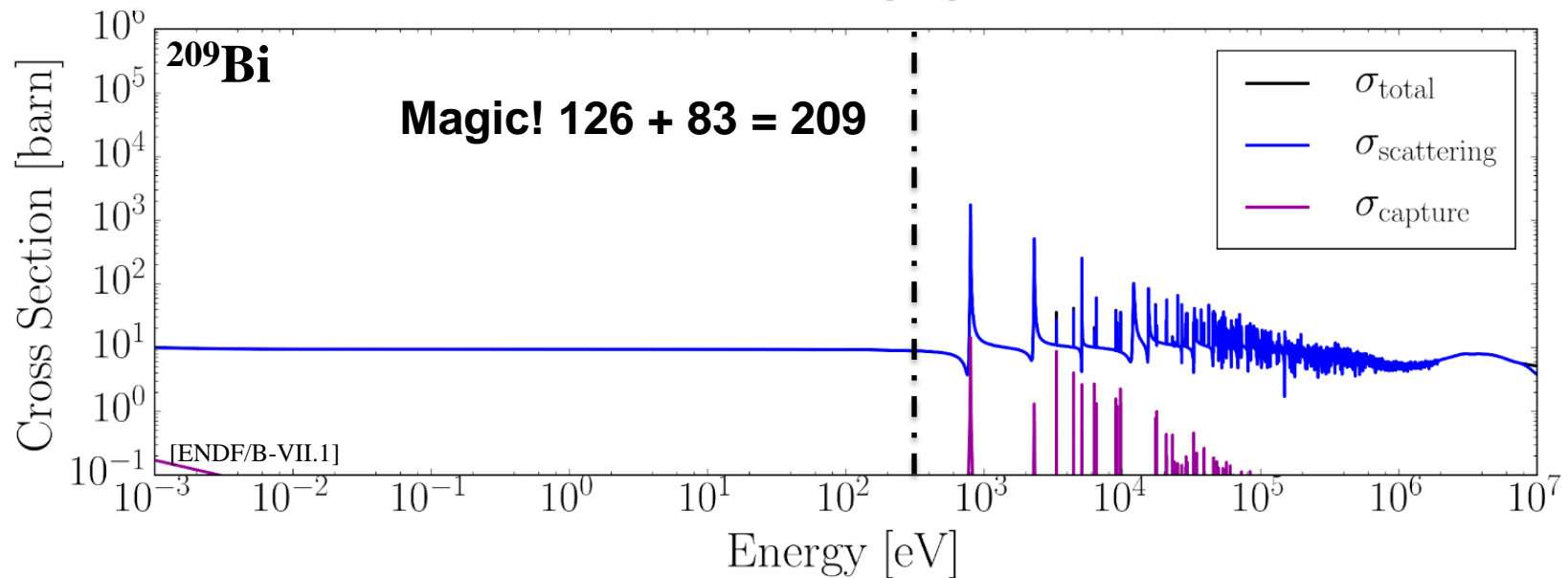
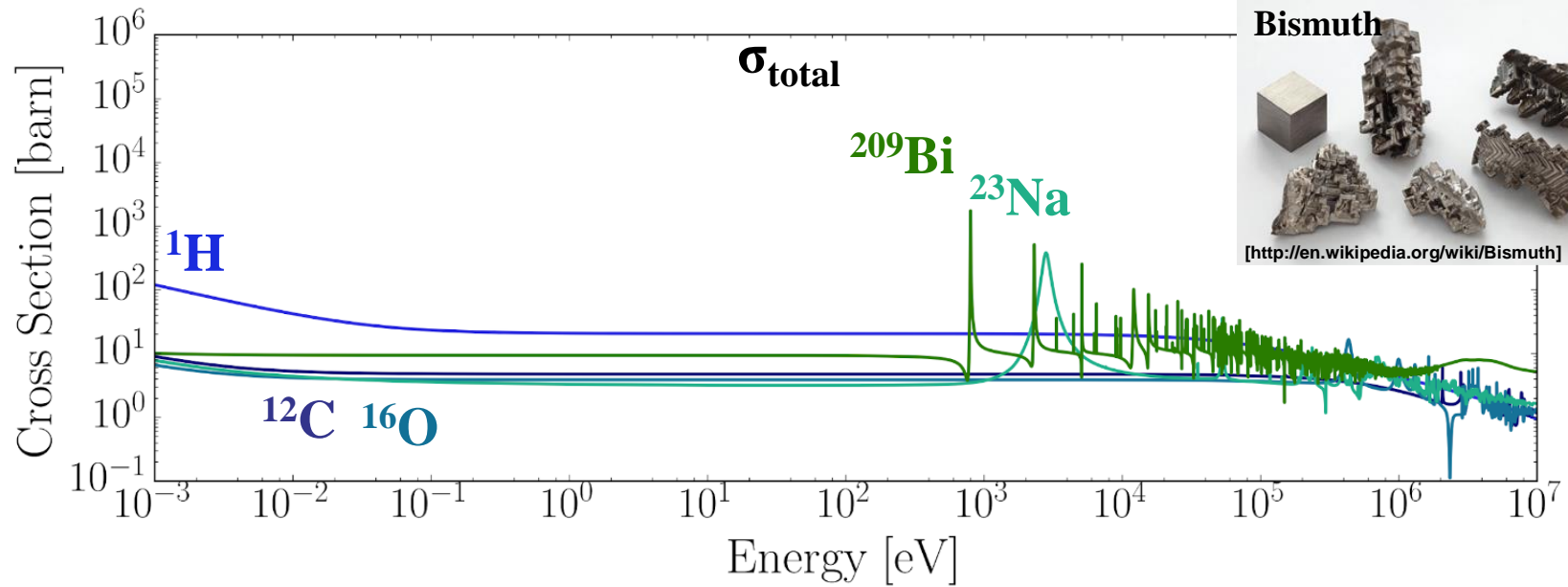


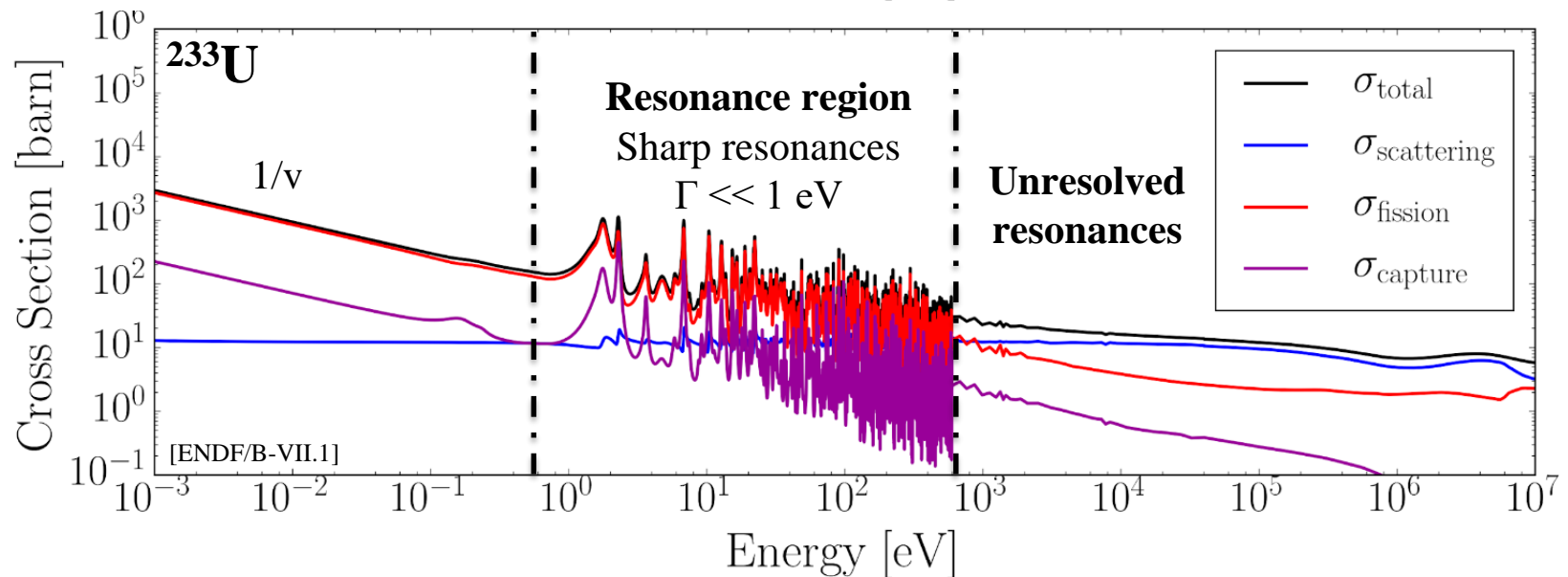
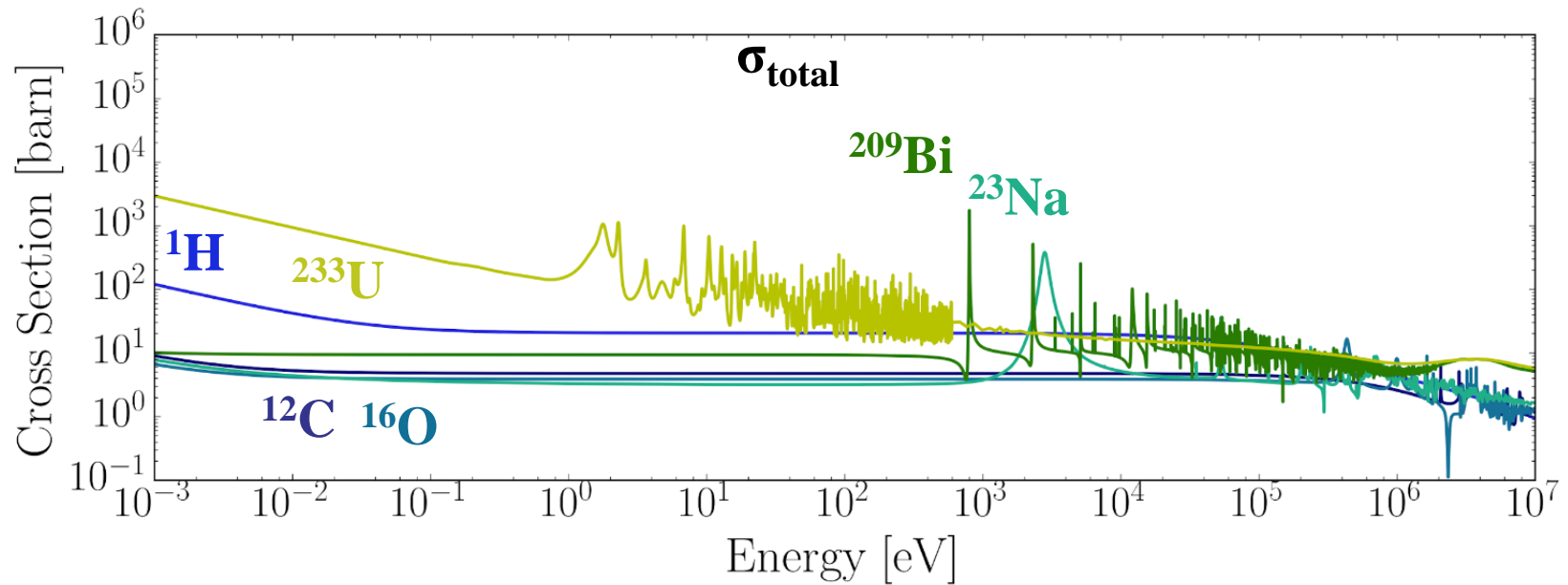


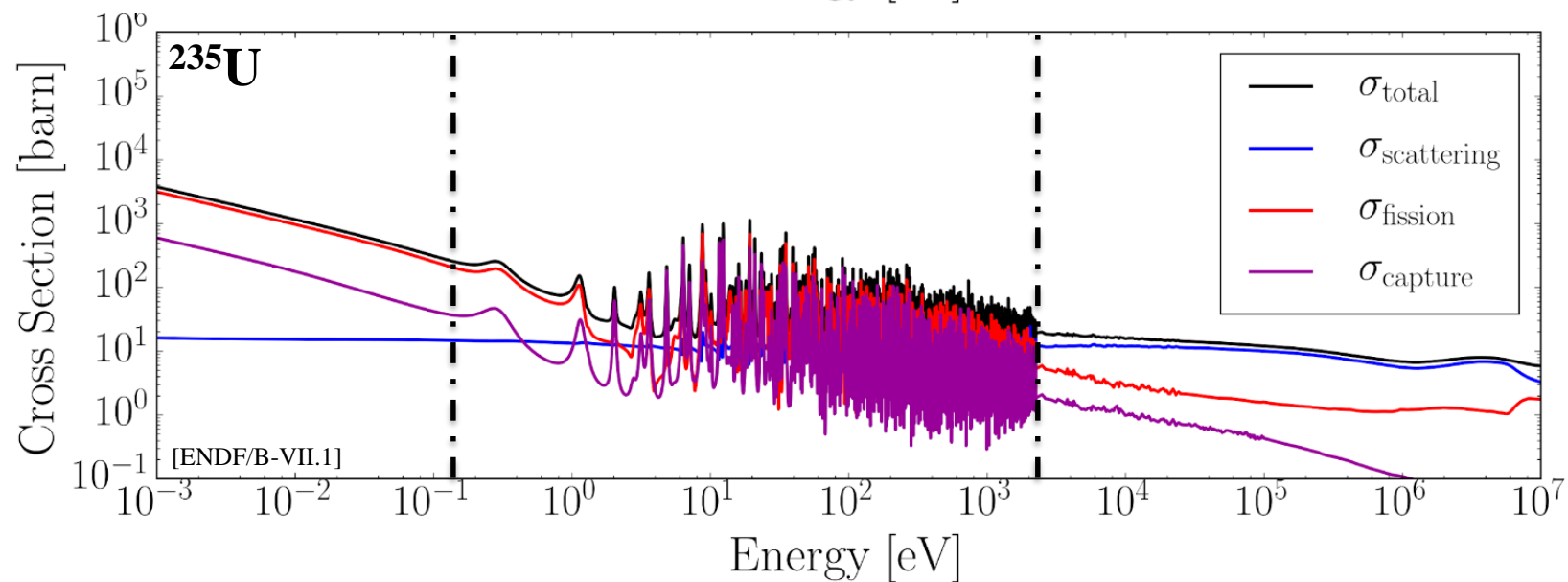
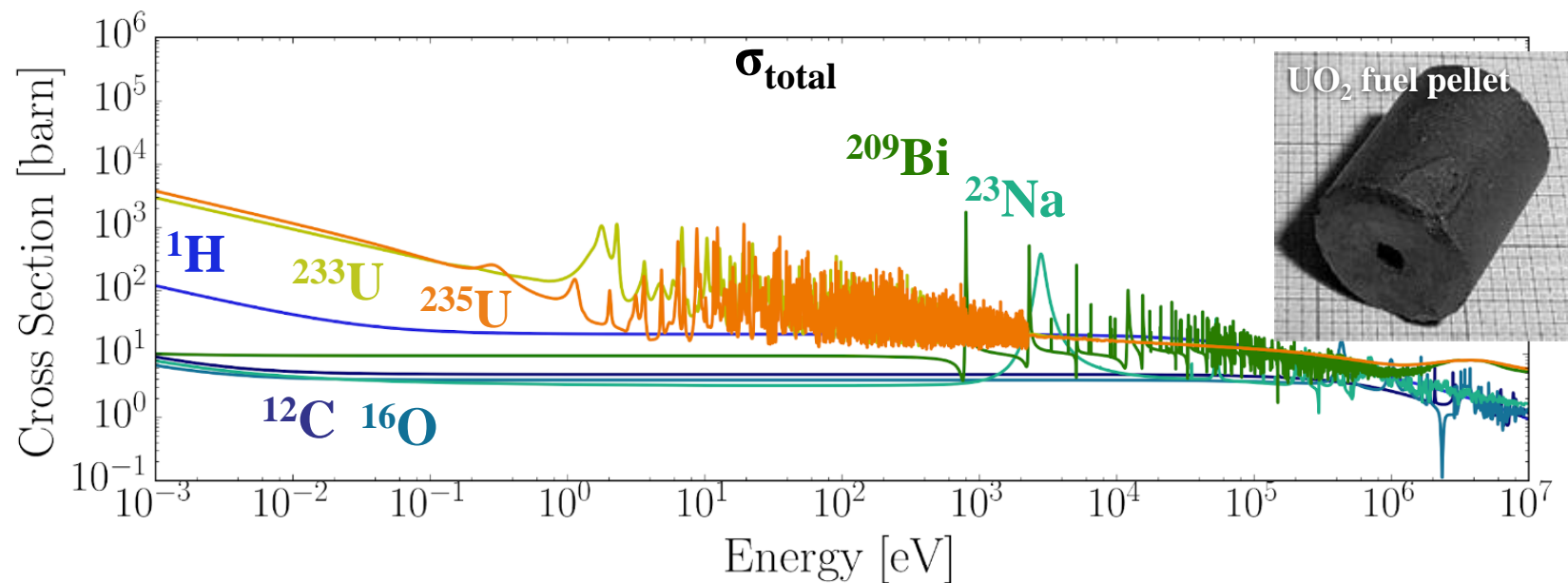
Incident neutron data / ENDF/B-VII.1 / O16 / / Cross section

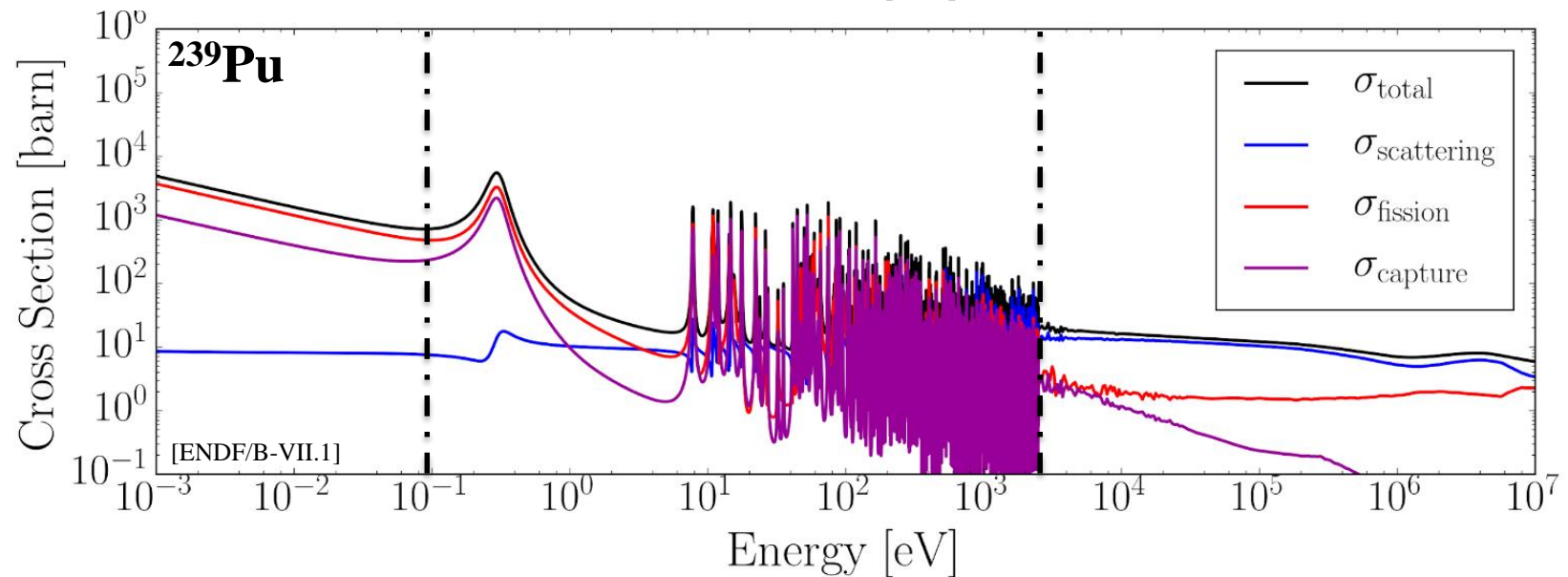
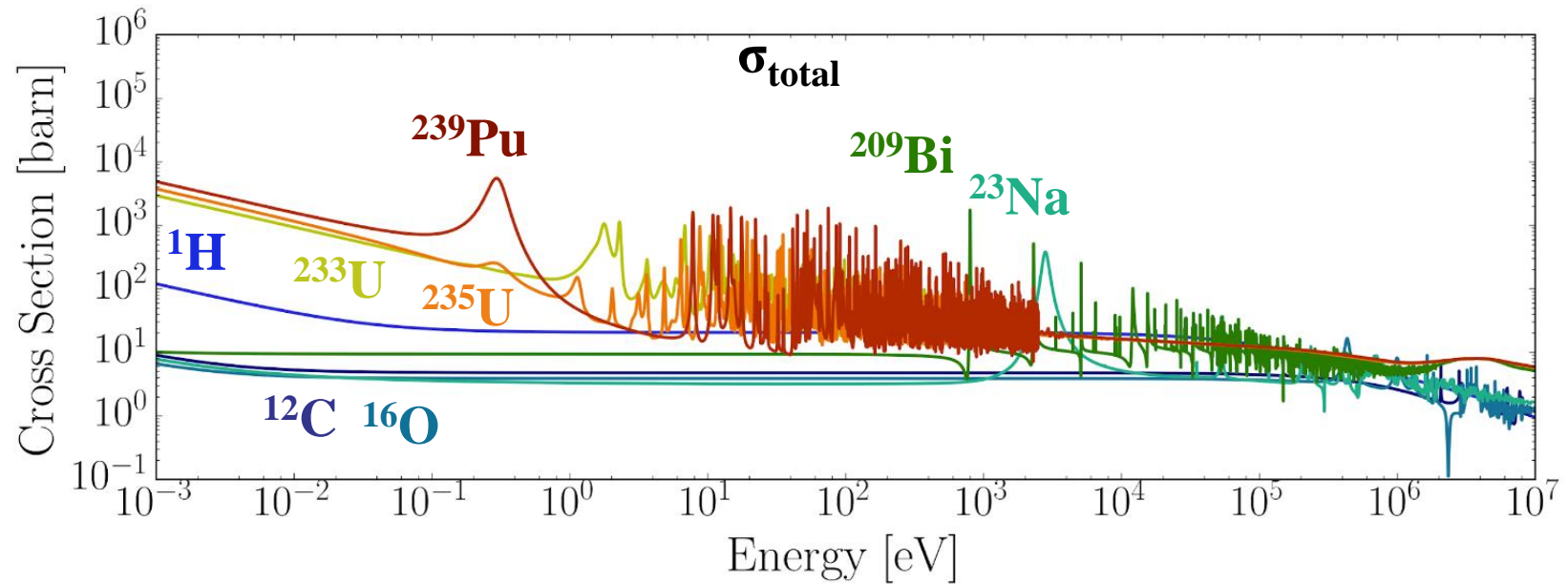


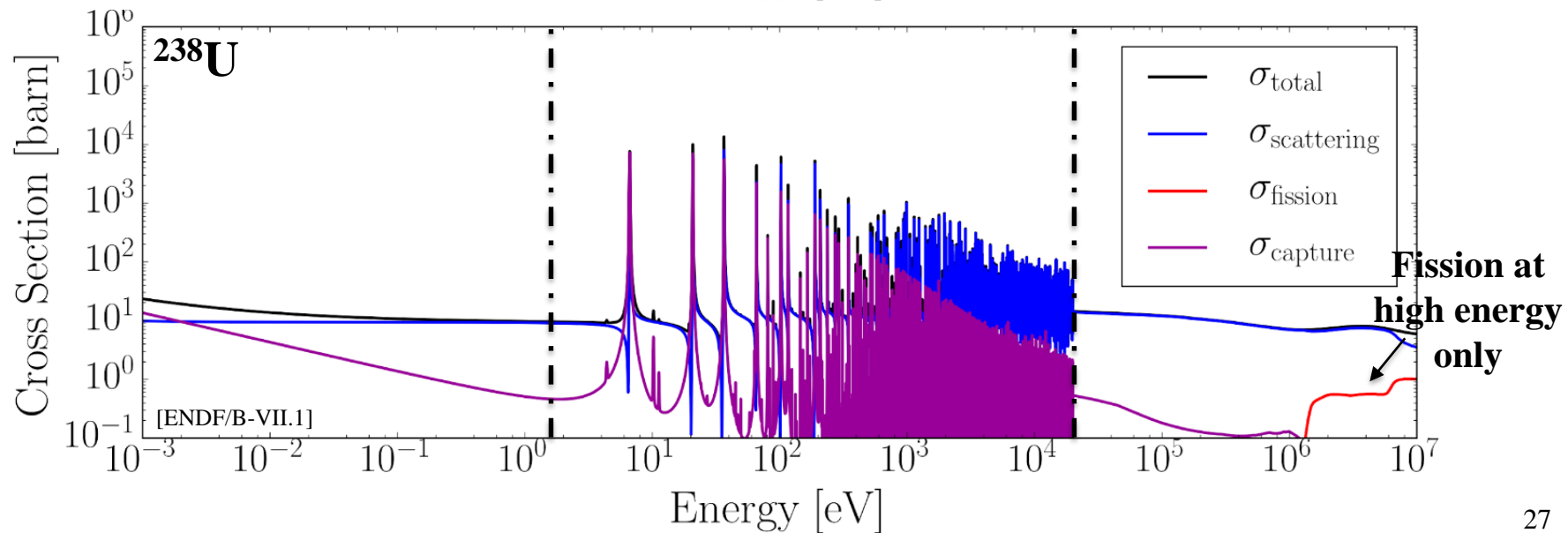
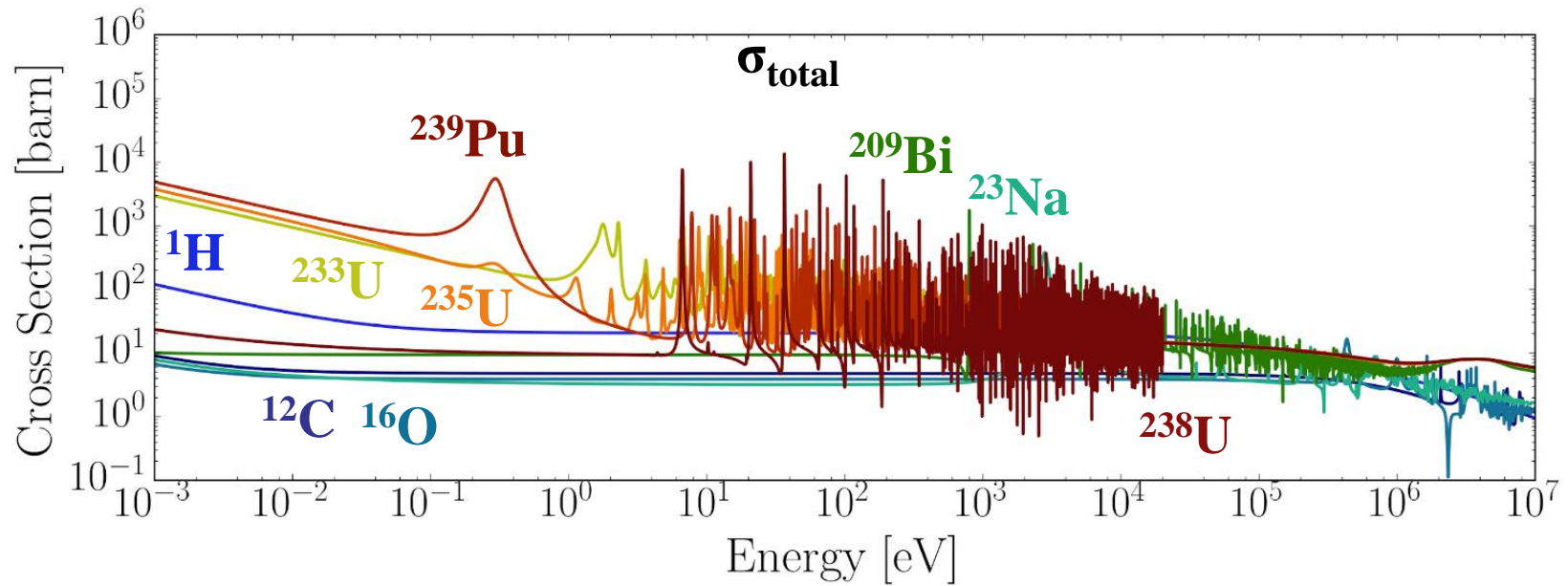


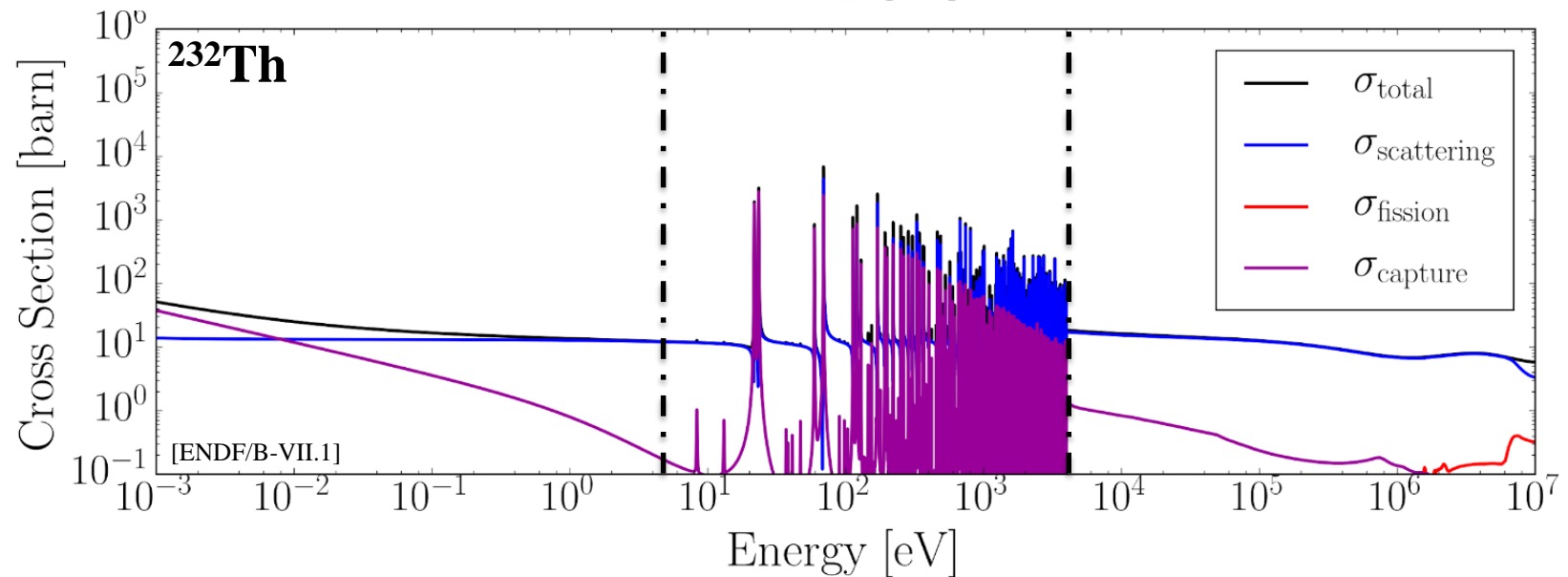
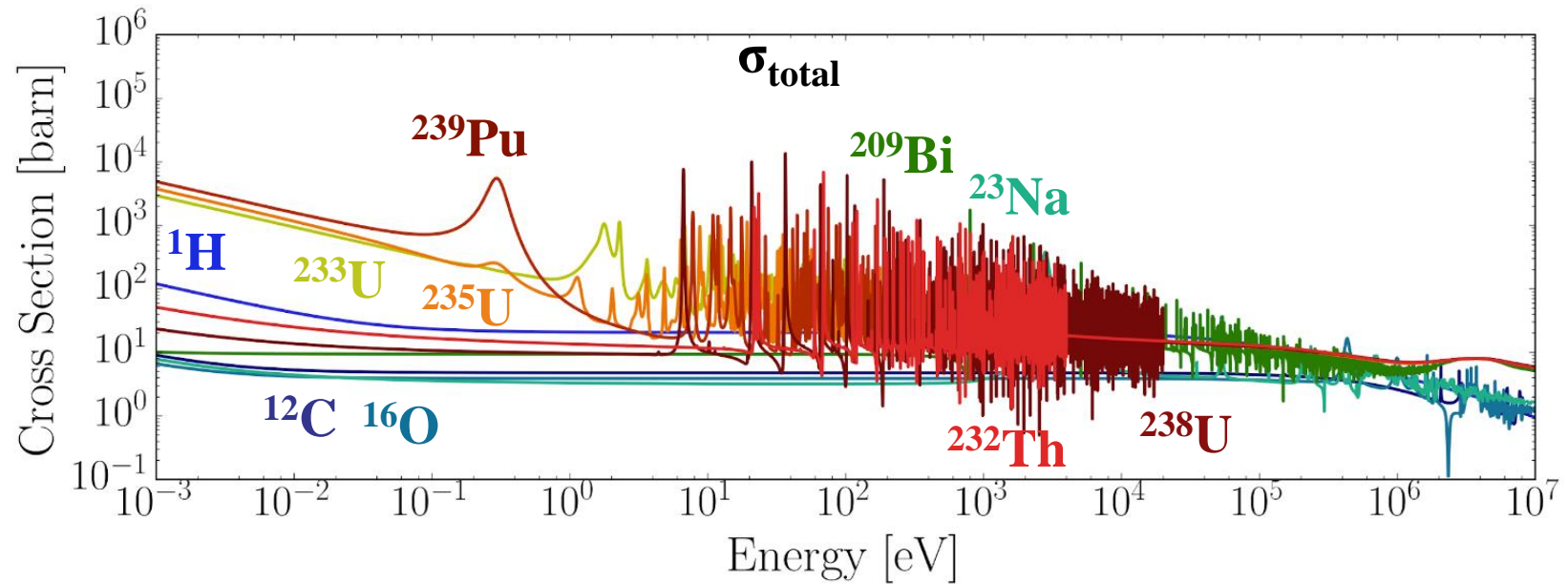


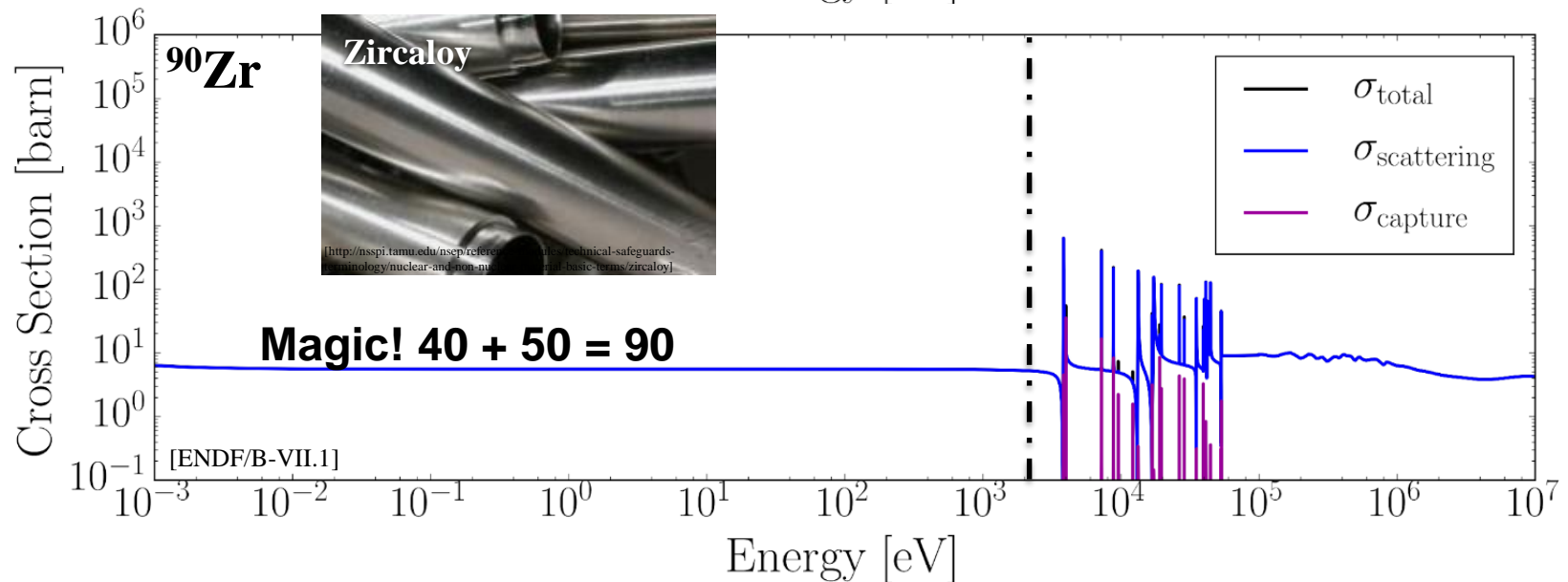
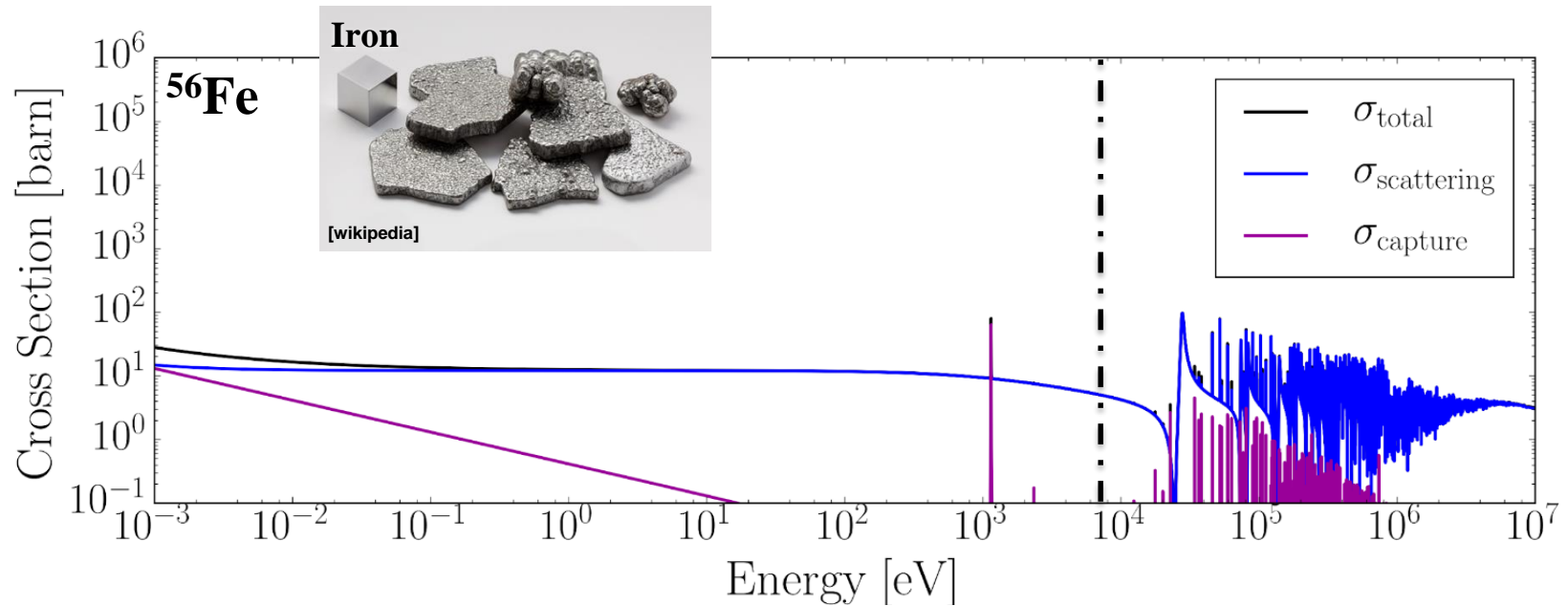






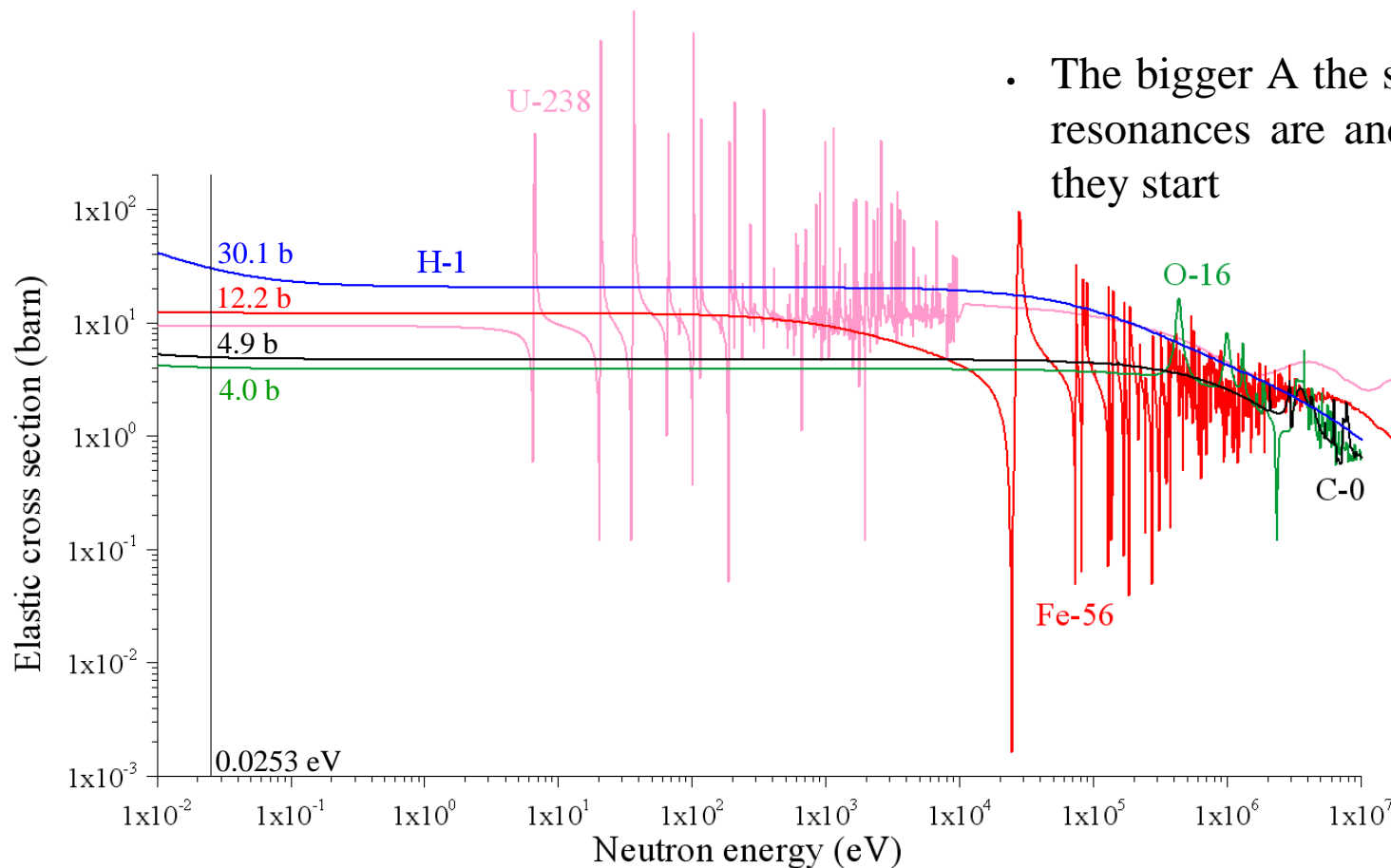




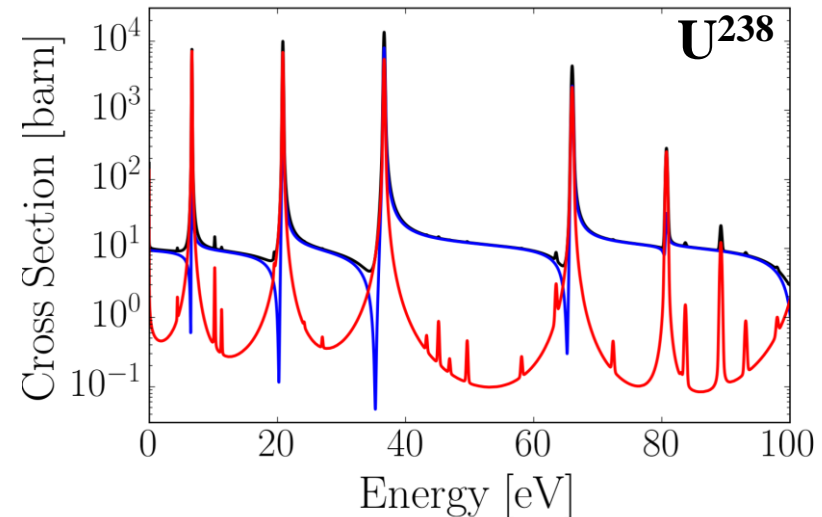
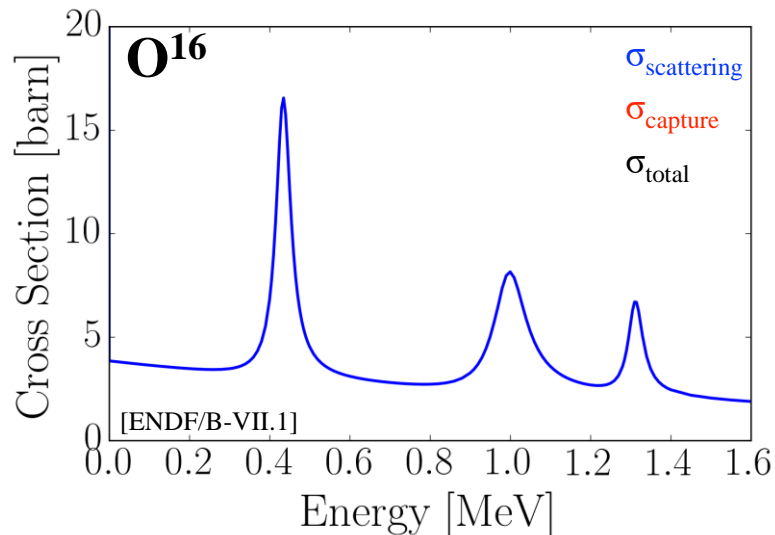


- Difficult to measure and analyze theoretically
- Low energy to \sim keV region: almost constant

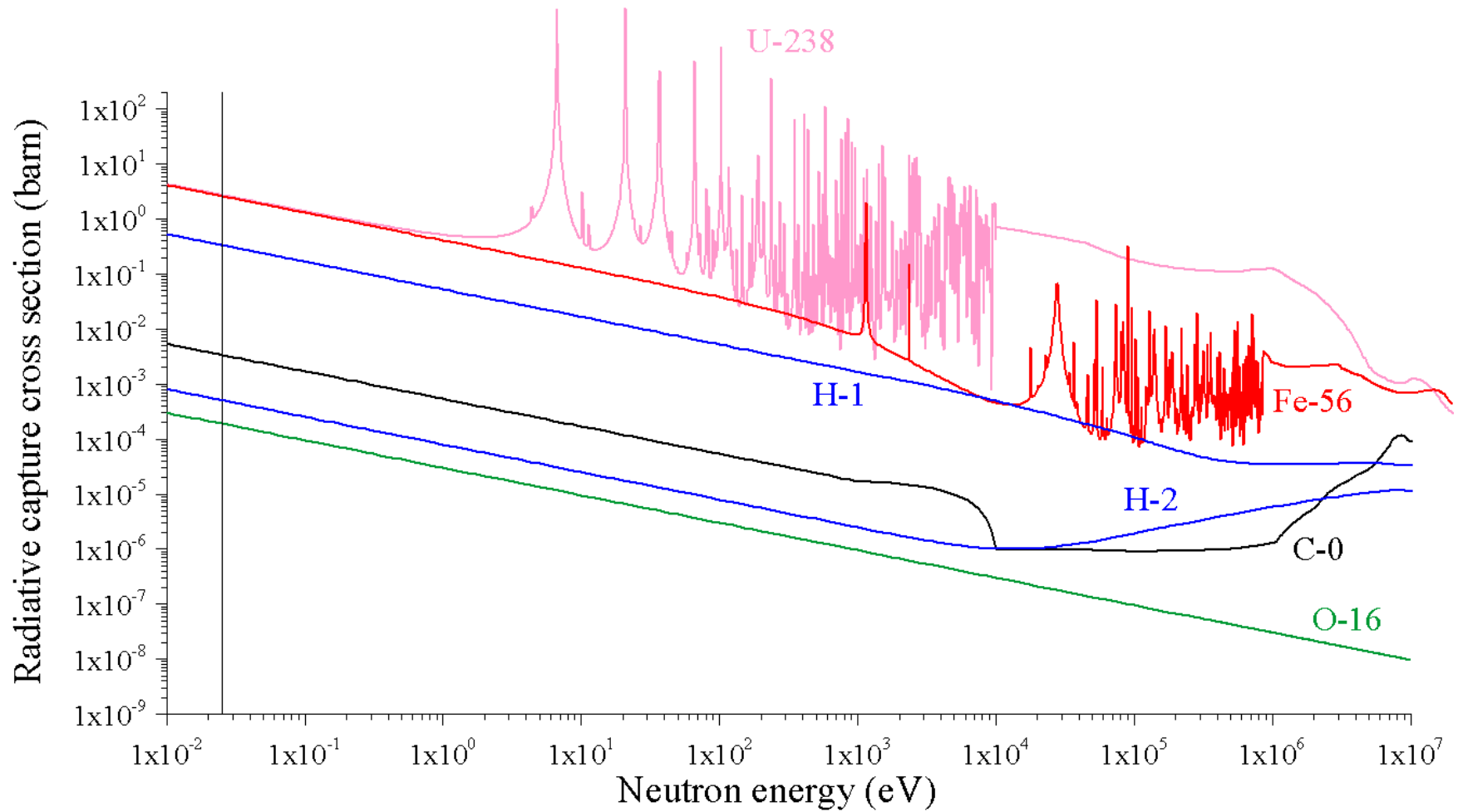
- High energy: reduction + resonances
- The bigger A the sharper and higher resonances are and at lower energy they start

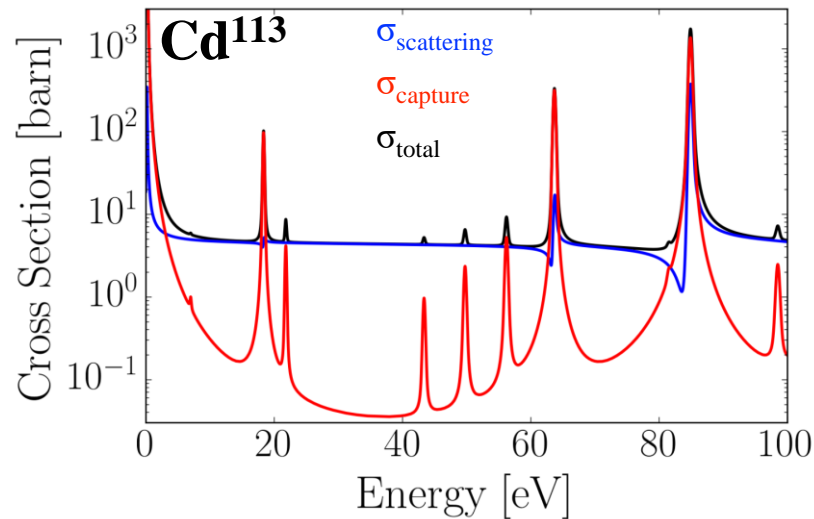


- Possible at all energies, but most probable at low energies
- For high A isotopes, **capture** and **scattering** resonances don't have the same shapes

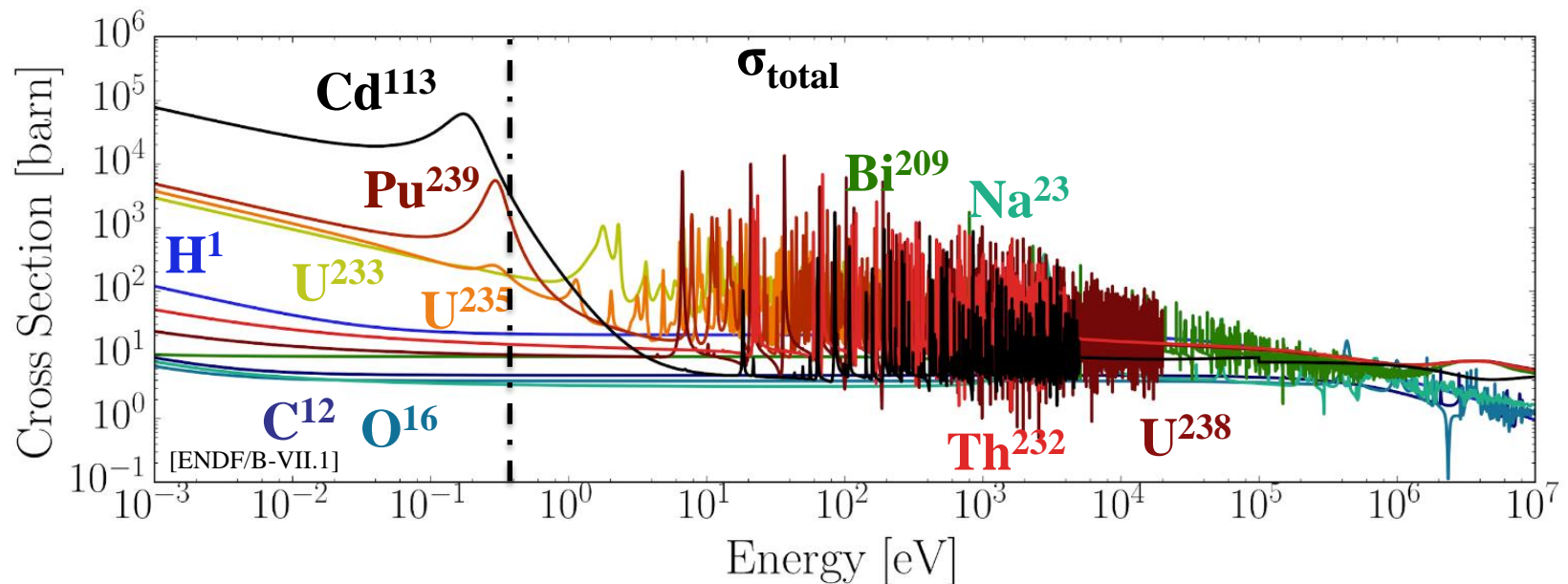


- Possible for all nuclei, but becomes increasingly important with increase of atomic number:
 - After a neutron absorption the excitation energy is above the virtual state (either nucleon or γ -ray can be emitted)
 - The excitation energy is divided between nucleons
 - The more nucleons the lower probability that one nucleon receives enough energy to leave the nucleus

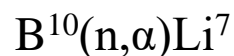




- (Very) high capture cross section at low energy
- Energy cut below 0.5 eV

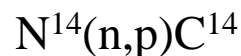


- Examples: (n,p), (n,α). Usually endothermic and threshold reactions with few exceptions.
- The most important exothermic charged particle reaction in nuclear reactor is:



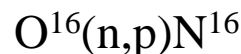
B^{10} enriched B_4C is widely used as an absorber material in control and shutdown systems

- Another important reaction is:

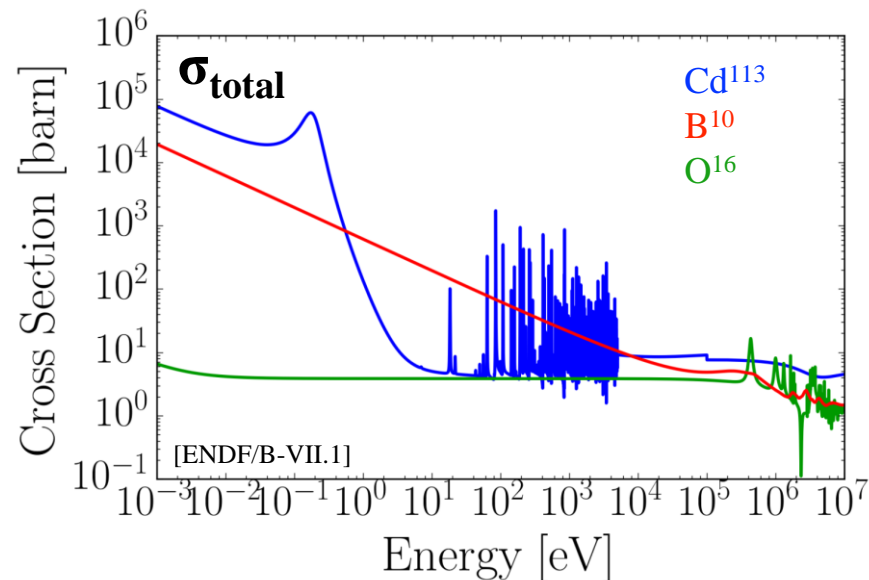
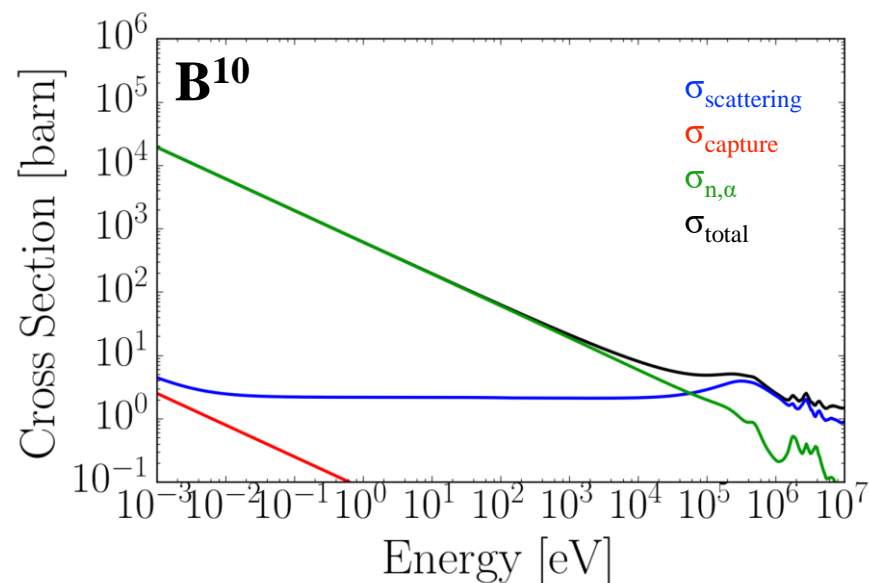


$\text{C}^{14} \rightarrow$ long-lived potentially dangerous β^- emitter.
Nuclear explosion: nitrogen in atmosphere.

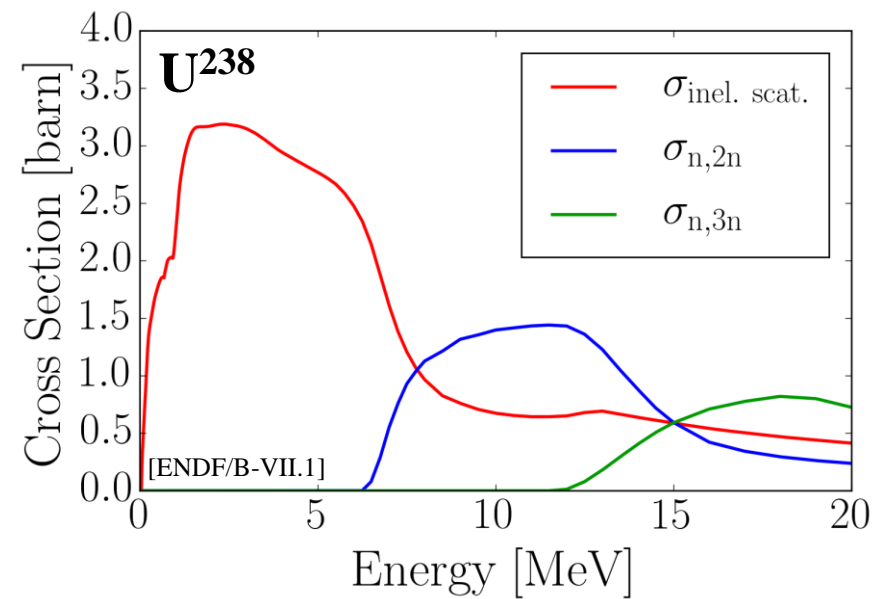
- A source of water radioactivity :



$\text{N}^{16} \rightarrow \beta^-$ decay with emission of 6-7 MeV γ -rays.



- In an inelastic scattering most of the initial kinetic energy of an incident neutron remains in the residual nucleus (after emission of an inelastic neutron) and is released as γ -rays.
- When the initial energy becomes high enough, the emission of the inelastic neutron can be followed by the **emission of another neutron** (instead of a γ -ray).
- Most nuclei have an (n,2n) threshold in the range of 7-10 MeV. An important exception is ^9Be : 1.8 MeV.

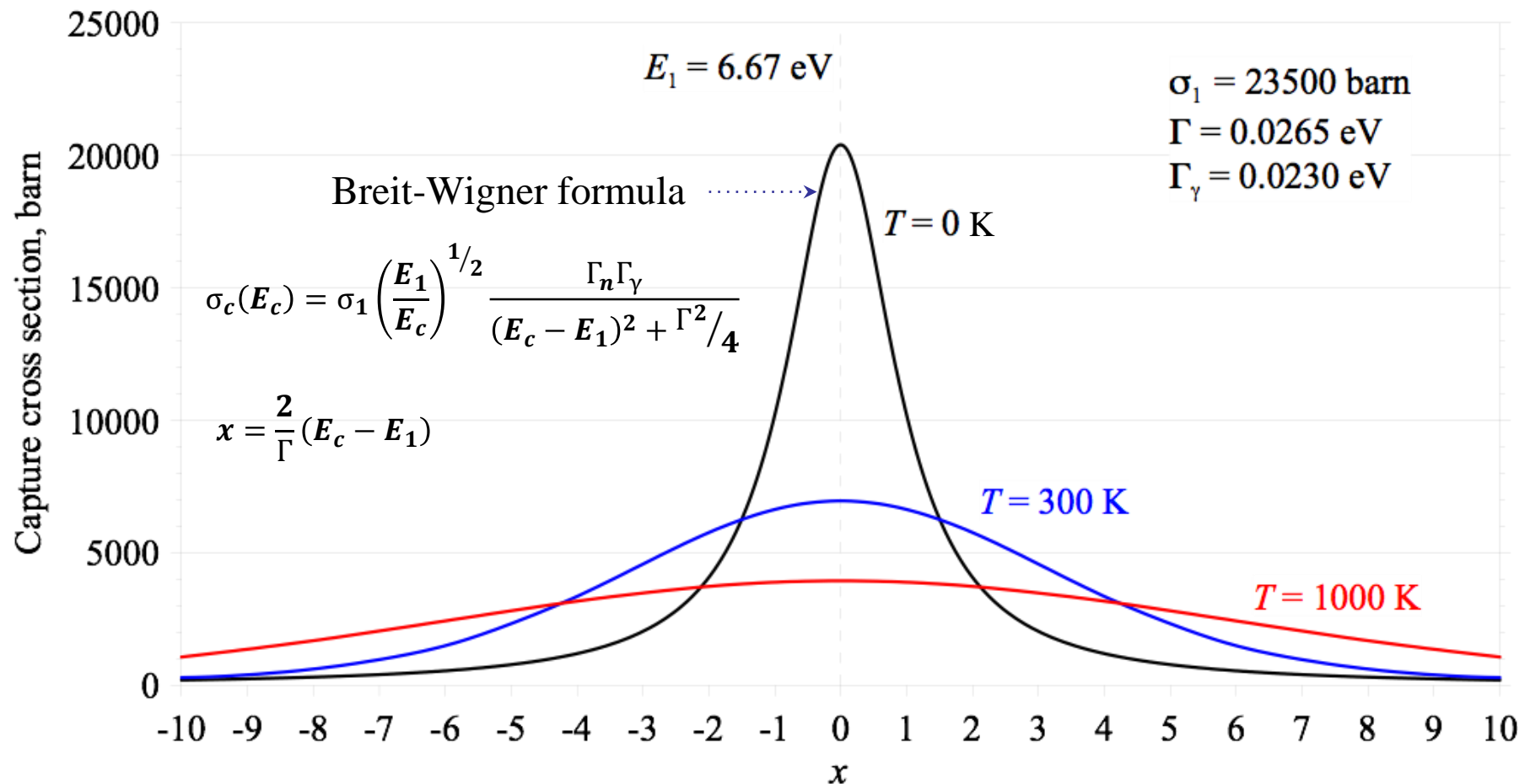


- Energetic γ -rays are produced in a nuclear reactor as a result of:
 - fission;
 - neutron-nucleus interactions (radiative capture, inelastic scattering, etc.);
 - radioactive decay of fission products.
- An absorption of the most energetic γ -rays can result in the excited states of a nucleus which can decay with emission of a neutron: (γ, n) reaction
- The thresholds of $(n, 2n)$ and (γ, n) reactions are identical
- Unlike the $(n, 2n)$ reaction, (γ, n) reaction continues after the reactor shutdown.

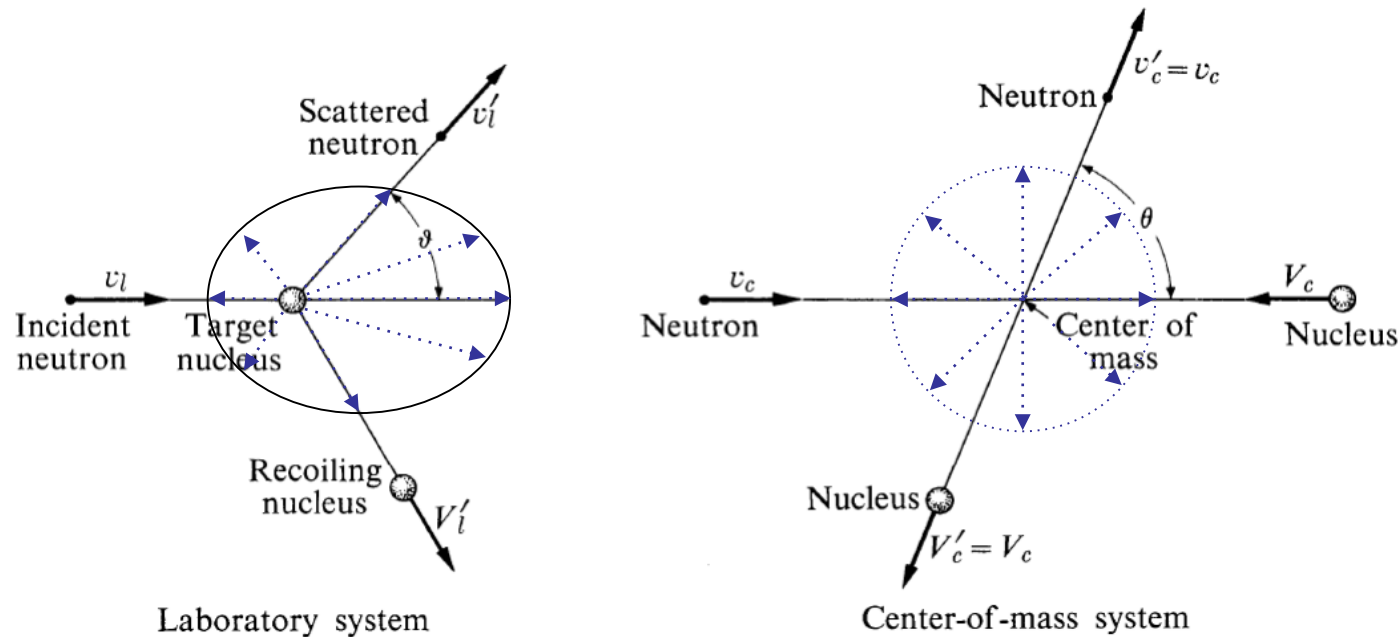
- Up to now : before a neutron-nucleus interaction nucleus was supposed at rest in the laboratory (L) system.
- However, atoms are in continual motion due to their thermal energy.
- The monoenergetic (in L-system) beam of neutrons appears to have a smear of energies in center-of-mass (C) system, because of the thermal motion of the target nuclei.
- By analogy to similar phenomena in acoustics and optics this effect is known as *nuclear Doppler effect*.



Christian Doppler (1803 – 1853)



- Increase of the temperature results in widening of resonances (radiative capture, scattering, fission, ...)
 → The neutron behaviour depends on the material temperature!



Elastic scattering of neutron by nucleus, as observed in laboratory and center-of-mass coordinates.

To take into account the effect of scattering angular distribution on the neutron motion, a concept of the *transport cross section* is used. Consider scattering but non-absorbing medium.

- Before the first collision: $\bar{x}_0 = \lambda_s$
- After the first collision: $\bar{x}_1 = \overline{\lambda_s \cos \theta_1} = \lambda_s \bar{\mu}$
projection to the axis of the original motion
- After the second collision: $\bar{x}_2 = \overline{\lambda_s \cos \alpha} = \overline{\lambda_s \cos \theta_1 \cos \theta_2} = \lambda_s \bar{\mu}^2$
projection to the axis of the original motion
- After the n^{th} collision: $\left. \begin{array}{l} \bar{x}_n = \lambda_s \bar{\mu}^n \\ \bar{\mu} < 1 \end{array} \right\} \Rightarrow \lim_{n \rightarrow \infty} \bar{x}_n = 0$

average value of the cosine of the scattering angle

One can define the *Transport mean free path*:

$$\lambda_{\text{tr}} = \bar{x}_0 + \bar{x}_1 + \bar{x}_2 + \dots = \lambda_s + \lambda_s \bar{\mu} + \lambda_s \bar{\mu}^2 + \dots = \frac{\lambda_s}{1 - \bar{\mu}}$$

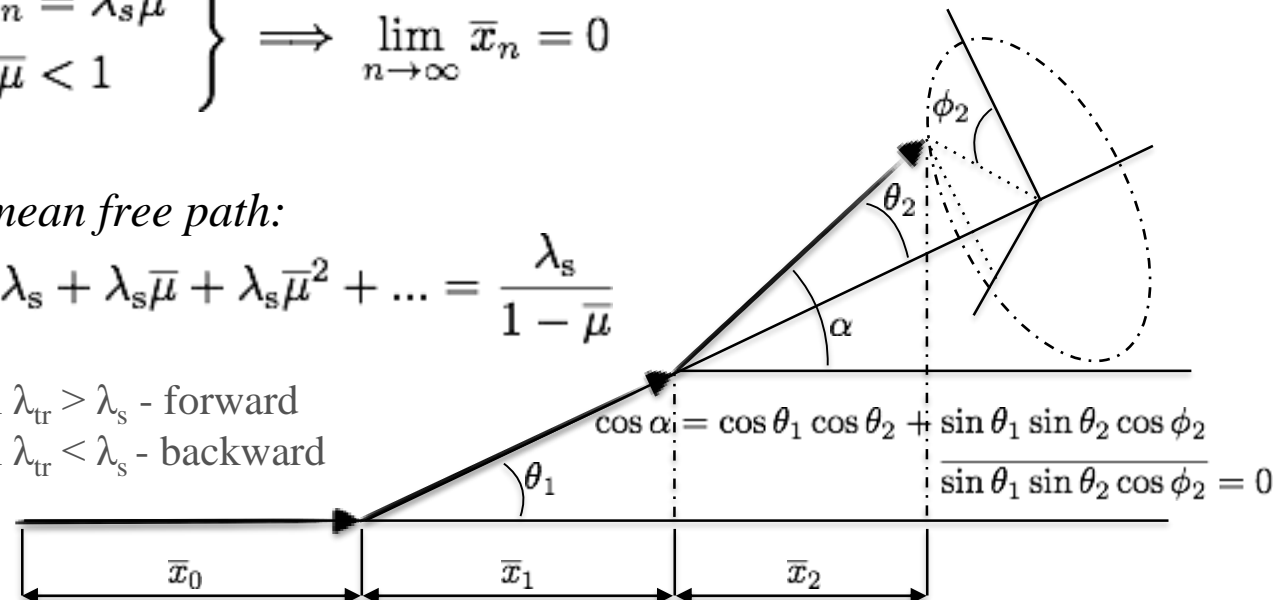
Transport cross section:

$$\lambda_{\text{tr}} = \frac{1}{N \sigma_{\text{tr}}}$$

$$\sigma_{\text{tr}} = \sigma_s (1 - \bar{\mu})$$



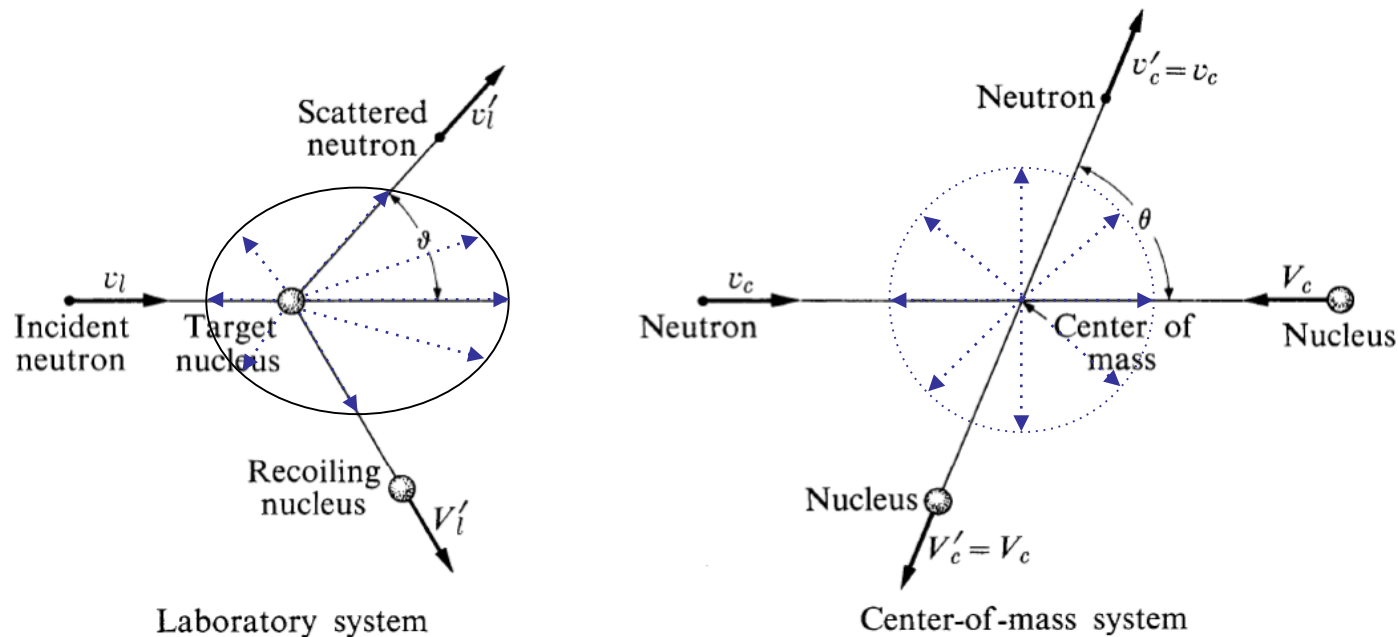
When $\lambda_{\text{tr}} > \lambda_s$ - forward
When $\lambda_{\text{tr}} < \lambda_s$ - backward



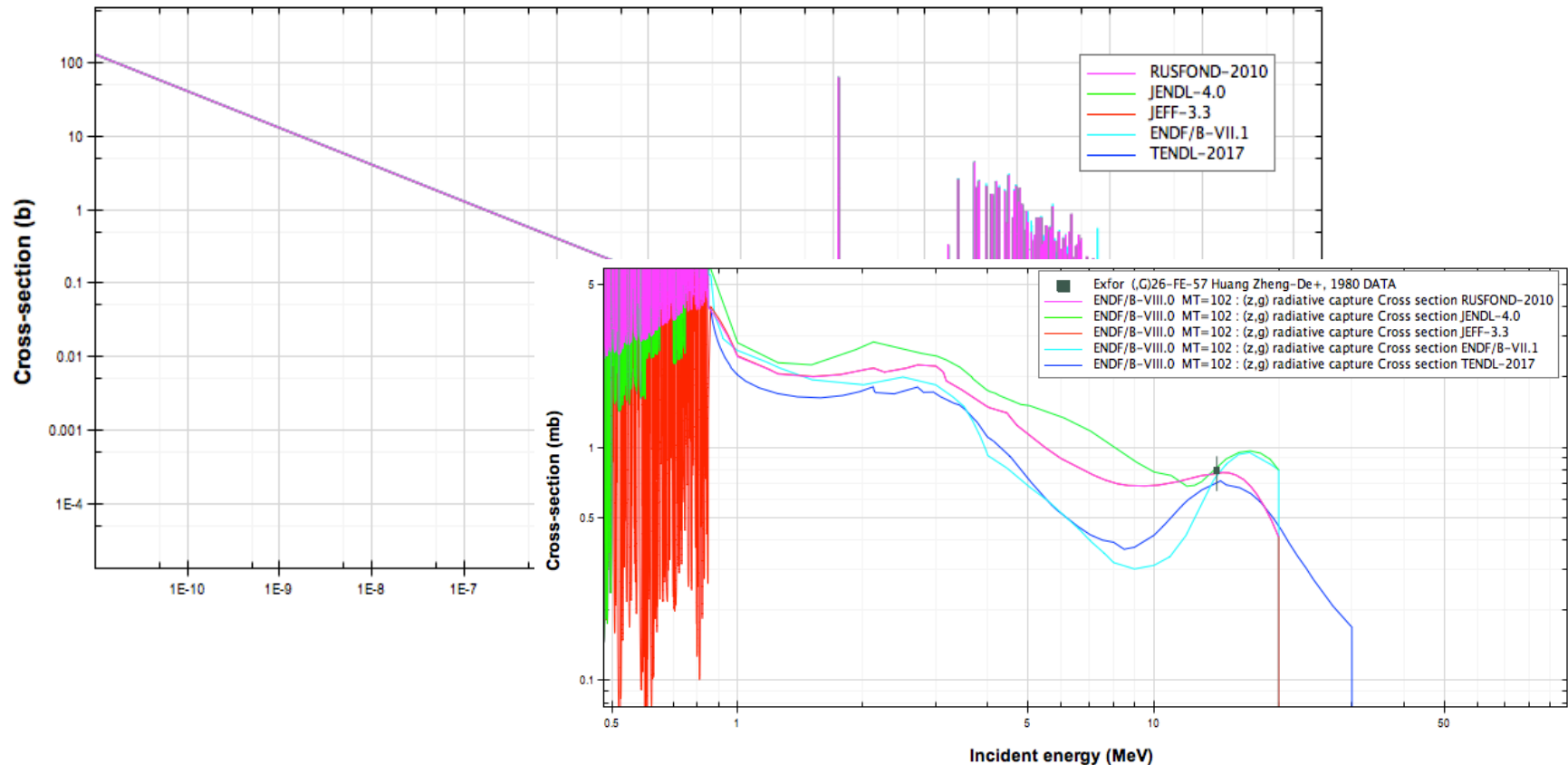
- In the case of isotropic scattering in the center-of-mass system:

$$\bar{\mu} = \frac{2}{3A} \quad \text{!}$$

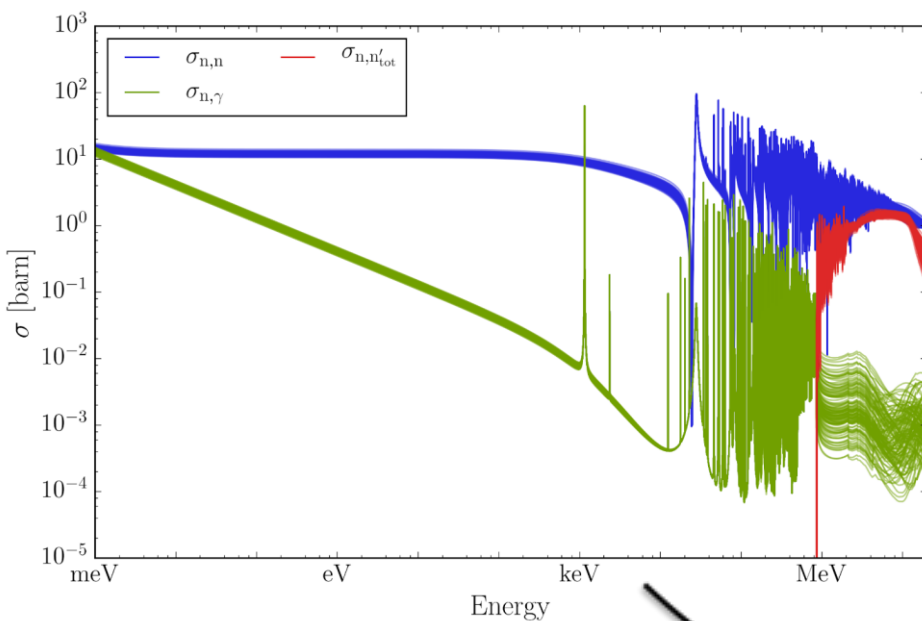
- If absorption is present: $\sigma_{\text{tr}} = \sigma_a + \sigma_s (1 - \bar{\mu}) = \sigma_t - \sigma_s \bar{\mu}$ $\frac{1}{\lambda_{\text{tr}}} = \frac{1}{\lambda_t} - \frac{\bar{\mu}}{\lambda_s}$!



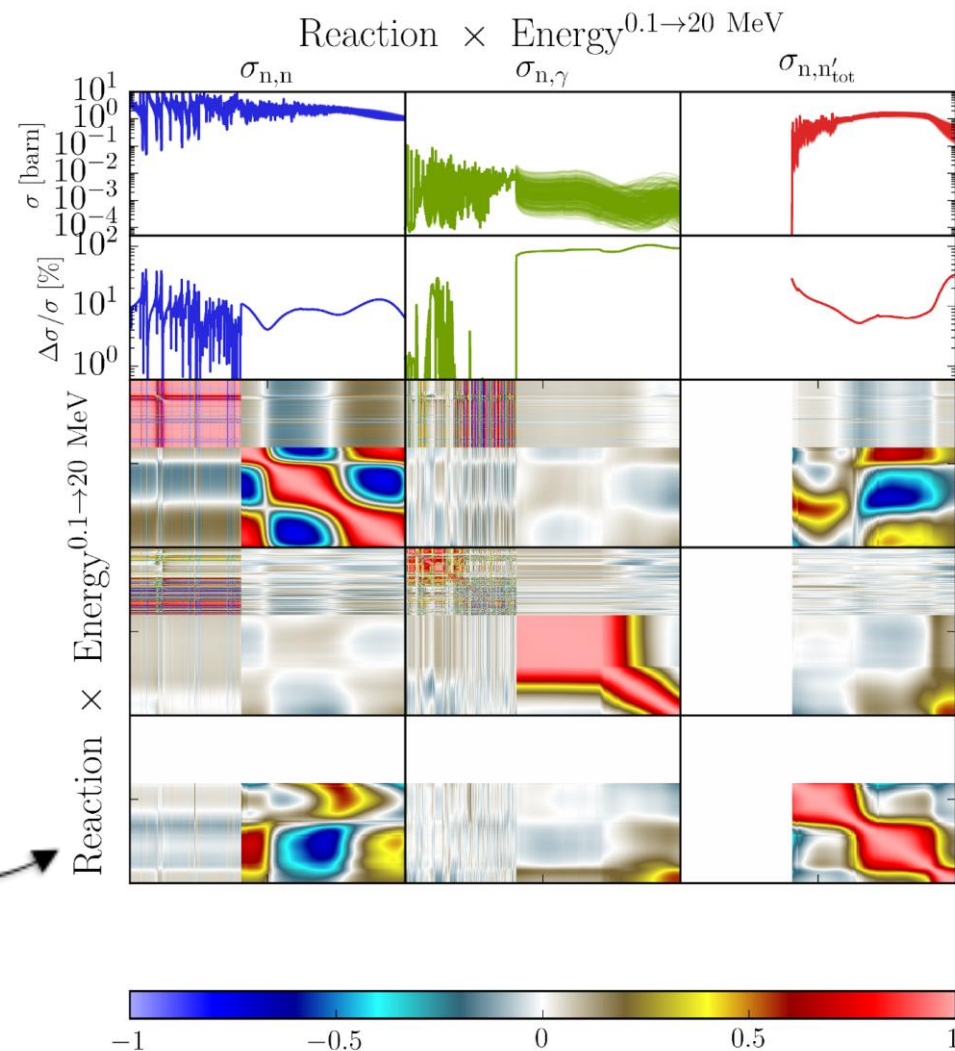
Elastic scattering of neutron by nucleus, as observed in laboratory and center-of-mass coordinates.

Incident neutron data / ENDF/B-VIII.0 / ^{56}Fe / MT=102 : (z,g) radiative capture / Cross section

- The different libraries do not provide the same cross sections “values”...



same
“information”



Cross section dispersion

Uncertainty + correlation matrix

- Reaction rate = Flux x Cross-section (microscopic, macroscopic)
- Different types of reactions: absorption (fission, capture,...), scattering (elastic, inel.),...
- Energy dependence of cross-sections