University of Pittsburgh

ME/ENGR 2100 Fundamentals of Nuclear Engineering

Radiation and Nuclear Reactions

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Relevant Reading Assignments

- Chapter 2/3 of "Introduction to Nuclear Engineering," Lamarsh and Baratta, 3rd edition, Prentice-Hall (2001)
- Chapter 2 of "Nuclear Engineering: Theory and Technology of Commercial Nuclear Power," Knief, 2nd edition, American Nuclear Society (1992, reprint by ANS 2008)
- Chapter 2 of "Nuclear Reactor Analysis," Duderstadt and Hamilton, Van Nostrand (1976)
- Module 1 of DOE Fundamentals Handbook, "Nuclear Physics and Reactor Theory," U.S.DOE (1993)Available at:

https://www.standards.doe.gov/standards-documents/1000/1019-bhdbk-1993-v1

- Not required but useful and clear is the discussion of nuclear masses and binding energies at the beginning of Chapter 7 of "Concepts of Nuclear Physics" by Bernard L. Cohen, McGraw-Hill, 1971, available in most scientific libraries.

Learning Objectives

- Define binding energy and calculate for a nuclide using the principle of mass defect
- Explain the differences among the mechanisms by which charged particles, electromagnetic radiation, and neutrons interact in materials
- Be able to write nuclear reactions / balance equations and calculate the Q value of a given reaction
- Define fissile, fissionable, and fertile. Identify the major nuclides in each of these three categories.
- Describe the distribution of energy among the product particles and radiations associated with fission. Explain the basis for decay heat.
- Calculate the atomic density of different types of materials
- Define microscopic cross sections. Sketch the first three of the four tiers in the cross section hierarchy.
- Define macroscopic cross section and mean free path.
- Define neutron flux and explain the equation for neutron reaction rate.
- Describe the energy distribution of fission neutrons.
- Interpret the energy dependencies of neutron-reaction cross sections.

Nuclear Binding Energy

- Due to the structure of the nucleus and the balance of forces, nucleons bound in a nucleus are more stable (have a lower energy) than free nucleons.
- When bound, each nucleon turns a small fraction of its mass into energy, which is typically radiated from the nucleus.
- This binding energy must then be added to the nucleus if we wish to remove (unbind) a nucleon.

Nuclear Binding Energy

- Mass Defect:

$$\Delta = \text{Mass}_{\text{bound nucleus}} - \sum \text{Mass}_{\text{constituents}}$$

- Mass Energy Equivalence: $E = m\,c^2$
  - Watch your units!

- Binding Energy:

$$\text{Binding Energy} = \left[\text{Mass}_{\text{bound nucleus}} - \sum \text{Mass}_{\text{constituents}}\right] c^2$$

Calculating Binding Energy

- To calculate mass defect using tabulated masses of neutral atoms

$$\boxed{\Delta = ZM(^{1}H) + NM_n - M}$$

  - Z is the atomic number
  - N is neutron number
  - M is atomic mass of the neutral atom
  - $M(^{1}H)$ is atomic mass of ^{1}H
  - M_n is neutron mass
- We need to use the formula above because binding energy represent the change in mass between the constituents of the nucleus and the bound nucleus but we commonly tabulate neutral atom masses and not just nucleus masses
- **The difference between the mass of H1 and a proton is the electron**

Radiation

- Energy transmitted in the form of waves or particles (or both).
- Types of radiation
  - Charged particles (electrons, protons, α particles)
  - Electromagnetic (radio, visible, x-rays, γ rays)
    - Photoelectric effect, Compton scattering, Pair production
  - Neutrons
    - Scattering (elastic or inelastic), Absorption, Fission
  - Others (neutrinos, other exotic particles)
- Categorized as either ionizing or non-ionizing
  - Depending on whether they can ionize other particles (i.e., rip off electrons from atoms)

Question: Multiple Choice

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b) Compton scattering
c) Electrostatic (coulomb) attraction / repulsion
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a) Radiation can ionize a gas and the ions can be collected in an electric field
b) We spike radiation with an aroma so we can smell it
c) Radiation can interact with the air and give off visible light
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- Generally No: the apple may absorb the energy of the radiation, making it a little warmer, but the apple doesn't start giving off nuclear radiation.
- If the gamma energy were very high, a nuclear reaction might occur that produces a radioactive product.

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- Yes, the material of the apple can capture neutrons which can produce some radioactive isotopes.

Nuclear Reactions

An incident neutron can produce a variety of outcomes, each with its own probability of occurring.

$${}^{235}_{92}U + {}^{1}_{0}n \longrightarrow \left({}^{236}_{92}U\right)^{*} \longrightarrow$$

(n,n) $\longrightarrow {}^{235}_{92}U + {}^{1}_{0}n$ ELASTIC SCATTERING

(n,n′) $\longrightarrow {}^{235}_{92}U^{*} + {}^{1}_{0}n$ INELASTIC SCATTERING

(n,γ) $\longrightarrow {}^{236}_{92}U + {}^{0}_{0}\gamma$ RADIATIVE CAPTURE

(n,2n) $\longrightarrow {}^{234}_{92}U + 2\,{}^{1}_{0}n$ MULTIPLE NEUTRON

(n,f) $\longrightarrow$ FISSION

- After formation, unstable compound nuclei may stabilize through one of several decay mechanisms.

Reaction Energy Balance

- The energy balance can be rewritten to give

$$E_A + M_A c^2 + E_B + M_B c^2 = E_C + M_C c^2 + E_D + M_D c^2$$

$$\underbrace{(E_C + E_D)}_{\textit{Products}} - \underbrace{(E_A + E_B)}_{\textit{Reactants}} = \underbrace{(M_A + M_B - M_C - M_D)c^2}_{\text{=Q-Value (change in binding energy)}}$$

Sensible energy change during reaction

=Q-Value
(change in binding energy)

- Q-Value – Sensible energy change during reaction
  - Q > 0: Exothermic Reaction (Energy released)
  - Q < 0: Endothermic Reaction (Energy absorbed)
- Threshold Reactions
  - Some reactions require a minimum energy for reactants for a reaction to take place

Nuclear Fission

- Nuclides in the Actinide period are classified by their potential to undergo fission events when their nucleus is struck by a neutron
- A nuclide is said to be Fissionable if neutron-induced fission is possible in the nuclide.
  - All nuclides with atomic number $Z > 89$ are fissionable.
- Fissionable nuclides are further classified as
  - Fissile, if fission can be caused by neutrons with any amount of kinetic energy (Typically even-odd, odd-even, or odd-odd)
  - Non-Fissile, if fission is a threshold reaction that can only be caused by high energy neutrons with a certain amount of kinetic energy (Typically even-even nuclides)

Fissionable Nuclides

$$^{240}_{94}Pu + ^{1}_{0}n \longrightarrow ^{241}_{94}Pu + ^{0}_{0}\gamma$$

- Major Fissionable Nuclides
  - Fissile ^{235}U ^{233}U ^{239}Pu ^{241}Pu
  - Fertile ^{232}Th ^{238}U ^{240}Pu

^{232}Th → ^{233}U, ^{238}U → ^{239}Pu, ^{240}Pu → ^{241}Pu: Conversion or Breeding

$$^{232}_{90}Th + ^{1}_{0}n \longrightarrow ^{233}_{90}Th + ^{0}_{0}\gamma \xrightarrow[\text{22 m}]{\beta^-} ^{233}_{91}Pa \xrightarrow[\text{27 d}]{\beta^-} ^{233}_{92}U$$

$$^{238}_{92}U + ^{1}_{0}n \longrightarrow ^{239}_{92}U + ^{0}_{0}\gamma \xrightarrow[\text{24 m}]{\beta^-} ^{239}_{93}Np \xrightarrow[\text{2.4 d}]{\beta^-} ^{239}_{94}Np$$

Sensible Energy Released During Fission

	MeV	%
Fission Fragments (Kinetic Energy)	168	84.0
Neutrons (Kinetic Energy)	5	2.5
Prompt Gamma Rays	7	3.5
Delayed Radiations		
Beta Particles* (Kinetic Energy)	8	4.0
Gamma Rays	7	3.5
Radiative Capture Gammas	5	2.5
TOTAL	200	100

7.5 %
Max. Decay Heat

Calculating Number Density

- Calculating macroscopic cross sections requires calculation of the number density of nuclei in a material.
  - This information can be calculated using Avogadro's number.

Avogadro's Number $N_A = 6.022 \times 10^{23}$ atoms/mol

Atomic mass of atom in amu = Mass [g] per mol of atoms

$$\boxed{N = \rho\, N_A / A}$$

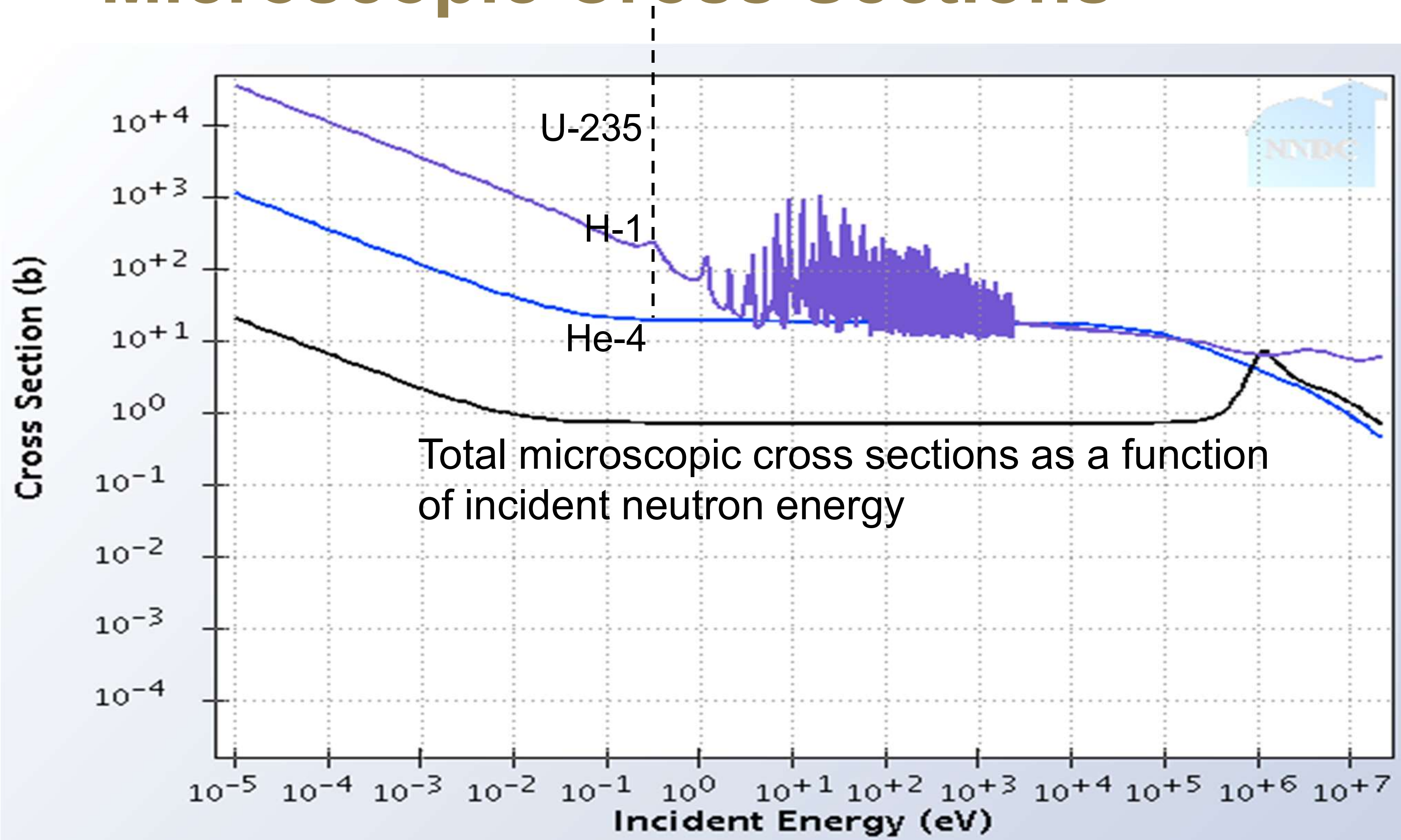
N = Atomic number density
ρ = Material density
N_A = Avogadro's Number
A = Atomic mass

Units: [atoms/cm^3] = [g/cm^3] × [atoms/mol] / [g/mol]

Microscopic Cross Section

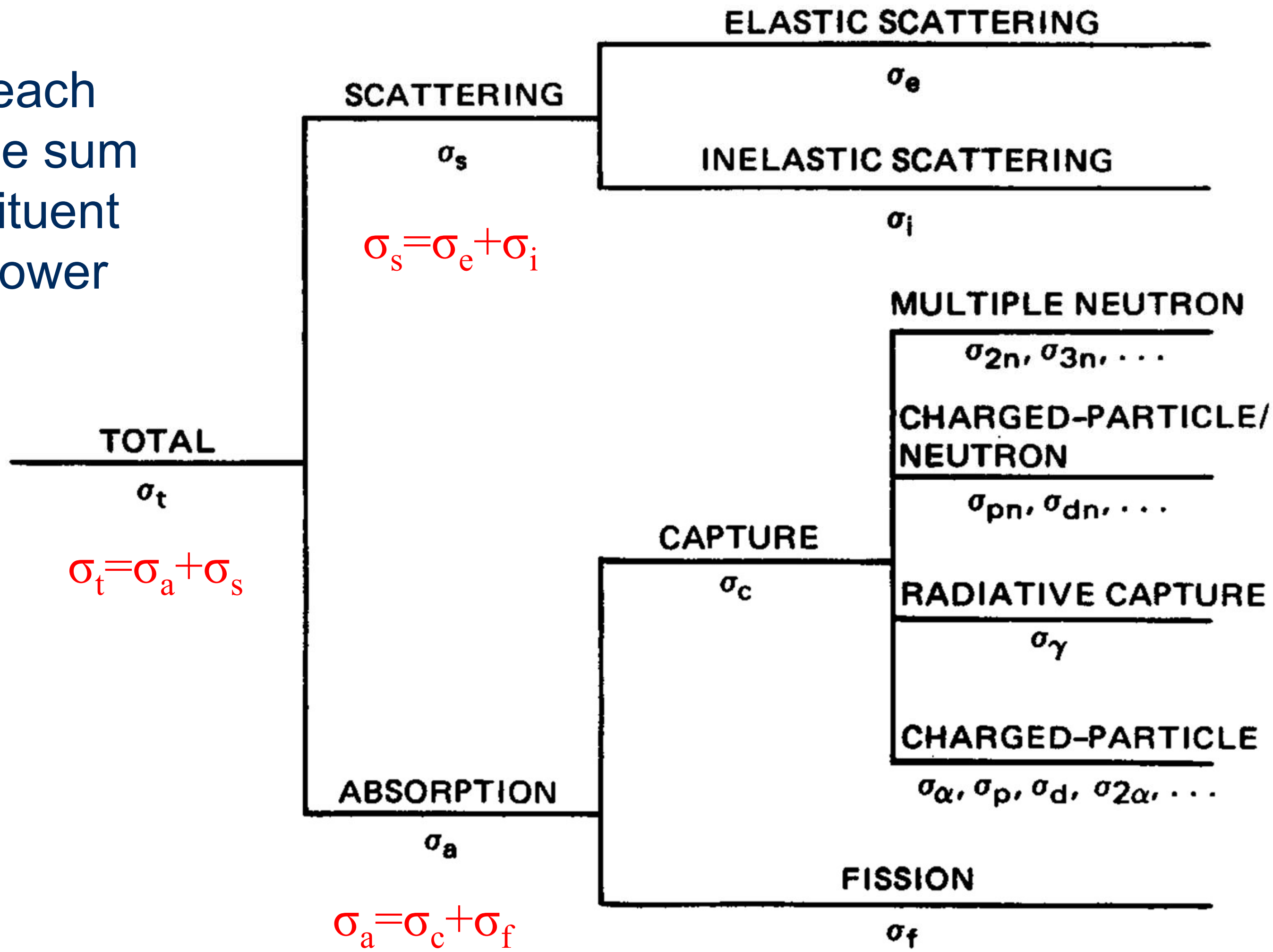
- Microscopic cross section
  - Cross sectional area of nucleus as seen by neutron, denoted by symbol σ
  - Has units of area, given in units of barns
    - 1 barn = 10−24 cm2
  - Proportional to the probability that a neutron will strike the nucleus and undergo a reaction
  - Nuclide dependent

Microscopic Cross Sections



Cross Section Hierarchy

Micros on each level are the sum of all constituent micros on lower levels.



Macroscopic Cross Sections

- To form macroscopic cross sections we multiply the probability of interacting with a single nucleus by the number (density) of nuclei in the material.
  - The quantity Σ is called the macroscopic cross section, it has units of 1/cm.

$$\boxed{\Sigma_t = N\sigma_t}$$

Units: [nuclei/cm^3] x [cm^2/nucleus]

  - These will be used subsequently as we learn to calculate reaction rates.

Scalar Neutron Flux

- $\phi(r, t)$represents the *neutron flux* as a function of position and time.
- "Flux" in physics represents generally the number of entities (neutrons, photons, magnetic field lines, raindrops, other…) impinging on a unit area of a system per unit time.
- Neutron flux is calculated as the number density of neutrons multiplied by their speed, i.e., :$\phi = nv$, where n = number of neutrons per cc and v is their speed in cm/sec. Hence the unit of flux is [neutrons / cm^2 / sec], representing the number of neutrons passing through a given area per unit time.

Reaction Rates

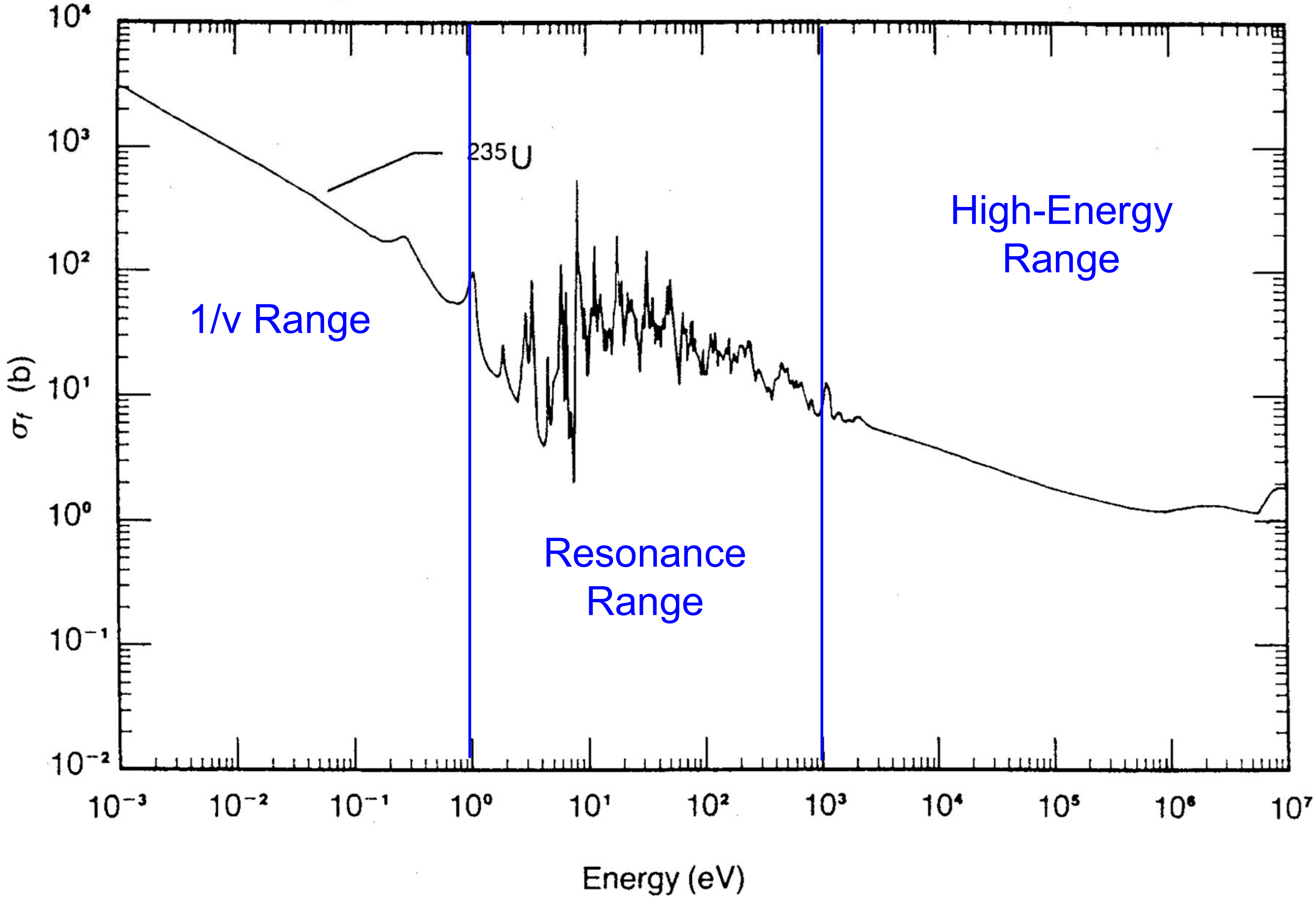
- The rate of (all) neutron interactions (per unit volume) in a material is given by:

$$\boxed{R = \Phi \Sigma_t}$$

Units: [neutrons/cm^2/sec] × [reactions/cm]
= [reactions/cm^3/sec]

  - The rate of any individual reaction can be calculated by substituting the individual reaction macroscopic cross section for the total macroscopic cross section shown above.

Microscopic Cross Section



Neutron Attenuation