Chemical Engineering 412

Introductory Nuclear Engineering

Lecture 8

Radiation Interactions with Matter

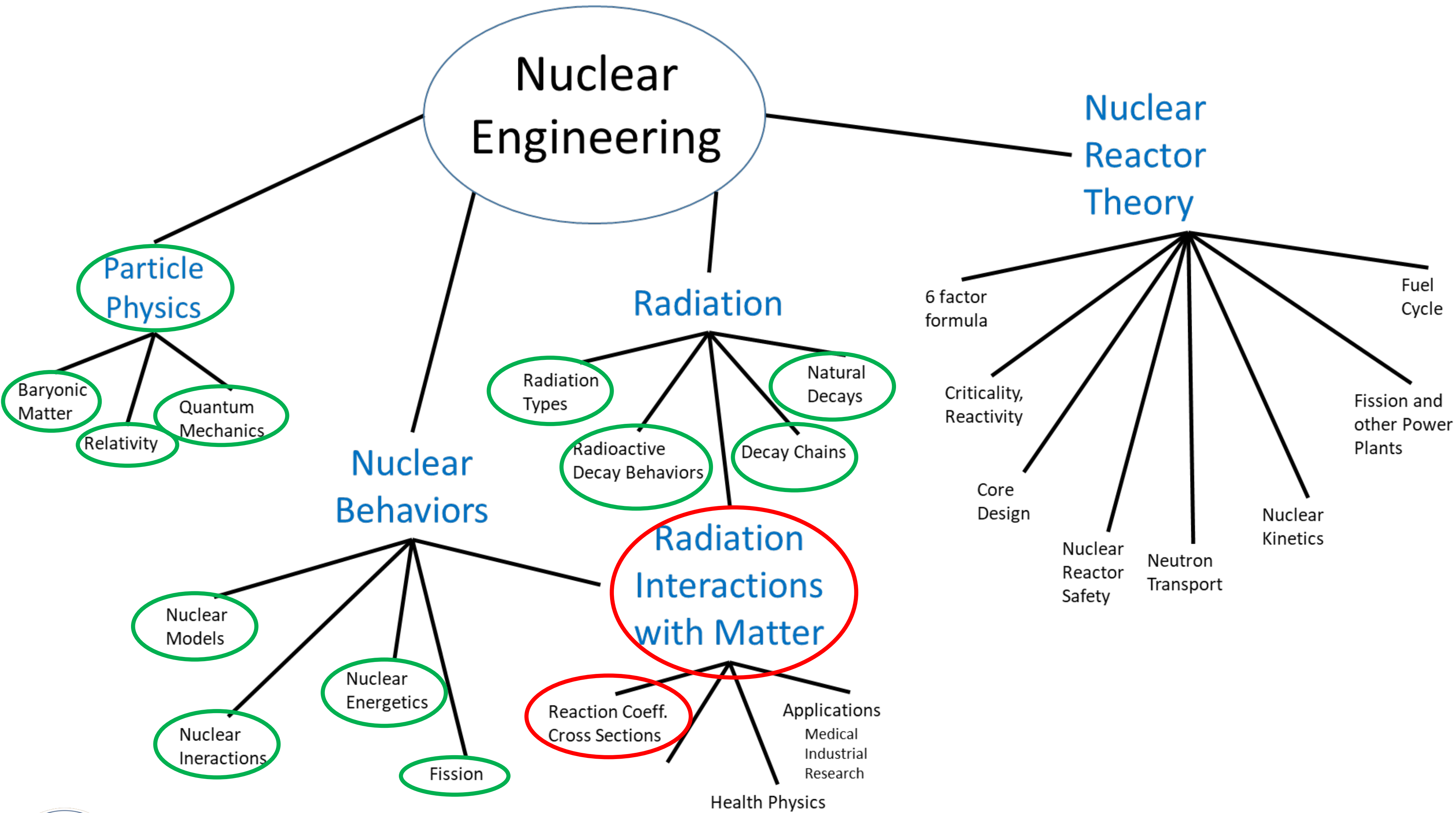
Exam Review

Spiritual Thought

"No man, having put his hand to the plough, and looking back, is fit for the kingdom of God." When difficult things are asked of us, even things contrary to the longings of our heart, remember that the loyalty we pledge to the cause of Christ is to be the supreme devotion of our lives. Although Isaiah reassures us it is available "without money and without price"—and it is—we must be prepared, using T. S. Eliot's line, to have it cost "not less than everything."

Jeffery R. Holland

Roadmap



Nuclear Engineering
Particle Physics
Baryonic Matter
Relativity
Quantum Mechanics
Nuclear Behaviors
Nuclear Models
Nuclear Ineractions
Nuclear Energetics
Fission
Radiation
Radiation Types
Radioactive Decay Behaviors
Natural Decays
Decay Chains
Radiation Interactions with Matter
Reaction Coeff. Cross Sections
Health Physics
Applications
Medical
Industrial
Research
Nuclear Reactor Theory
6 factor formula
Criticality, Reactivity
Core Design
Nuclear Reactor Safety
Neutron Transport
Nuclear Kinetics
Fission and other Power Plants
Fuel Cycle

Objectives

- Be able to calculate probabilities of interaction and radiation field intensities
- Understand both linear interaction coefficients and cross-sections
- Be able to calculate or find μ, σ, and Σ
- Be able to read, understand and take values from cross section libraries: plots or tables
- Know how to calculate reaction rates!!!

Conceptual Interpretations

- The linear attenuation coefficient can be thought of in three ways:
  - Probability that a particle interacts in a differential length of material (does not assume constant $\boldsymbol{\mu_i}$)
  - Inverse of the mean free path of a particle (assumes constant $\boldsymbol{\mu_i}$).
  - Related to distance at which half of particles have interacted ($\boldsymbol{x_{1/2,\,i} = \frac{\ln 2}{\mu_i}}$) (assumes constant $\boldsymbol{\mu_i}$)
- Analogous to decay constants
  - Decay probabilities
  - Average lifetimes
  - Half lives.

Flux and Reaction Rate

- If σ is probability of one particle interacting with one nucleus
- And Σ is the probability of one particle interacting with many nuclei
- How do we evaluate many particles with many nuclei?
- FLUX- Essentially particle density per time
- Reaction Rate (number of reactions per volume per time)

$$\boxed{\hat{R}_i = \emptyset \sum\nolimits_i = \emptyset N \sigma_i = \emptyset \sigma_i \frac{\rho N_a}{A}}$$

Example

- What is the power generation in a $1cm^3$ section of U^{235} fuel, assuming a thermal neutron flux of $1x10^{22}$ neutrons/cm^2-s?

Mass Interaction Coefficient

- Photons – mass interaction coefficient
  - Interaction coefficient (macroscopic) divided by density
  - which depends only weakly on the properties of the medium (for photons)

$$\frac{\mu_i}{\rho} = \frac{\sigma_i N}{\rho} = \frac{N_a}{A}\sigma_i$$

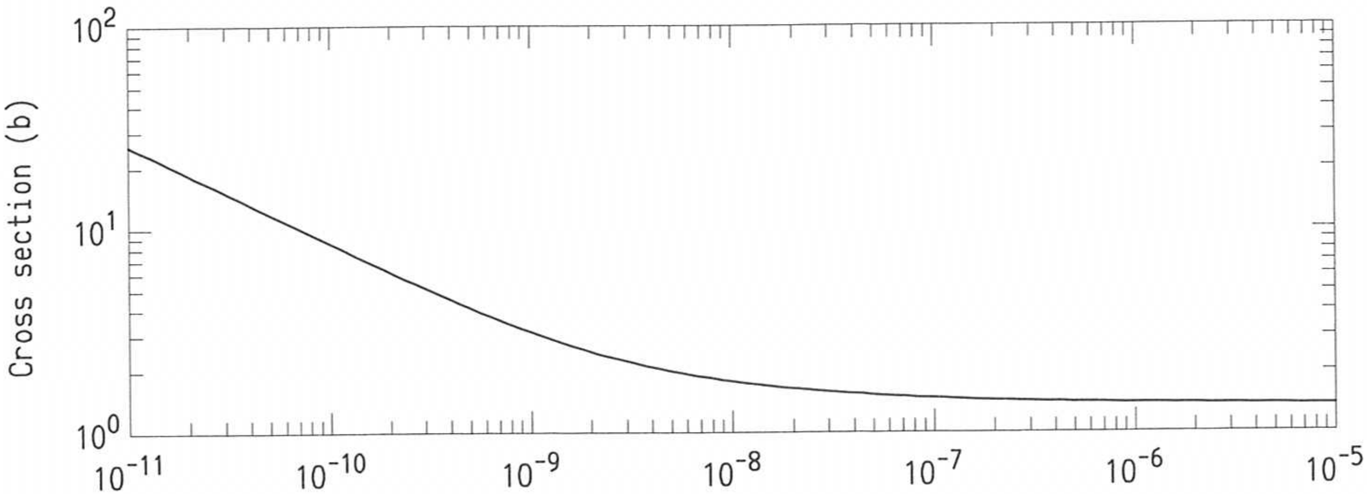
- Homogeneous mixture properties can be determined from

$$\mu_i = \sum_j \mu_{i,j} = \sum_j N_j \sigma_{i,j} \qquad \frac{\mu_i}{\rho} = \sum_j w_j \left(\frac{\mu_i}{\rho}\right)_j$$

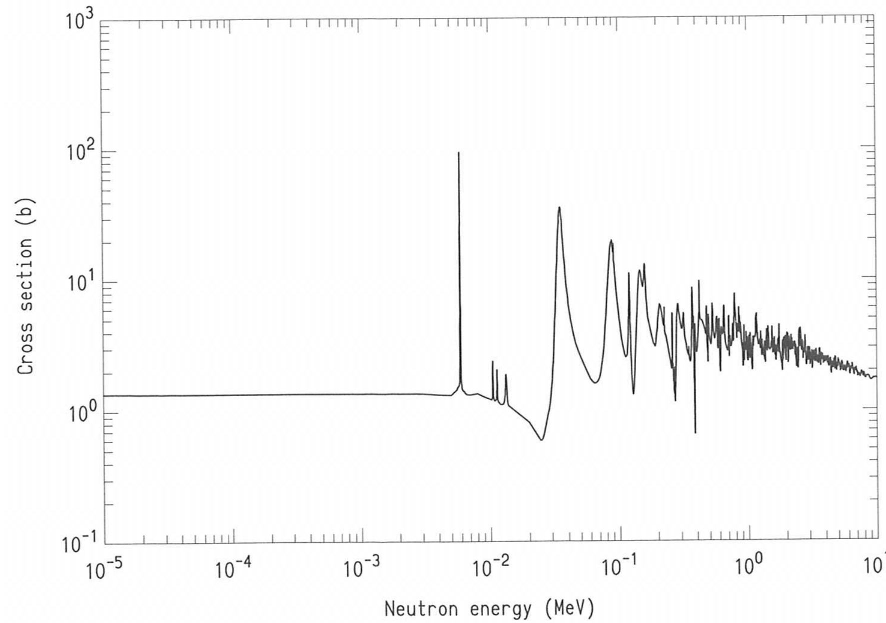
Cross Section Trends

- Most Isotopes
  - Cross sections rise as neutron energy decreases.
  - Resonance regions with narrow and rapidly varying interactions that eventually are not resolvable
- Light isotopes (A < 25)
- Heavy isotopes (A > 150)
- Intermediate

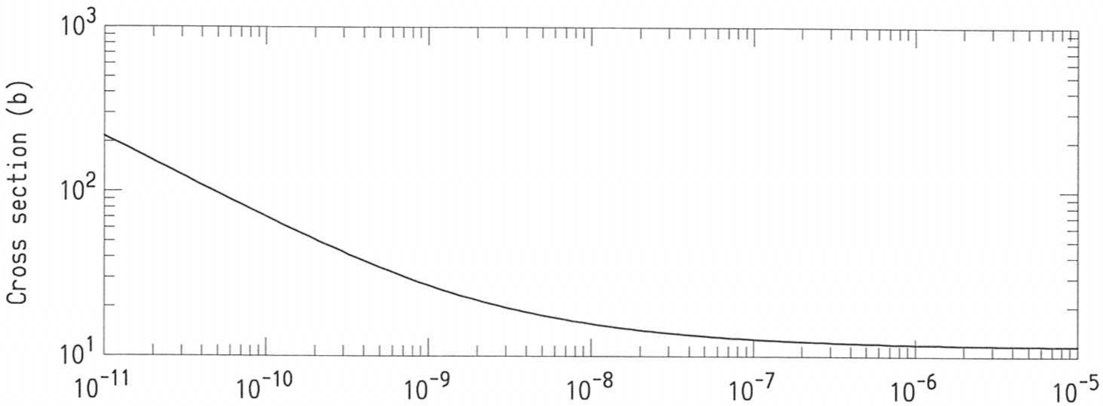
Al Total Neutron Cross Section



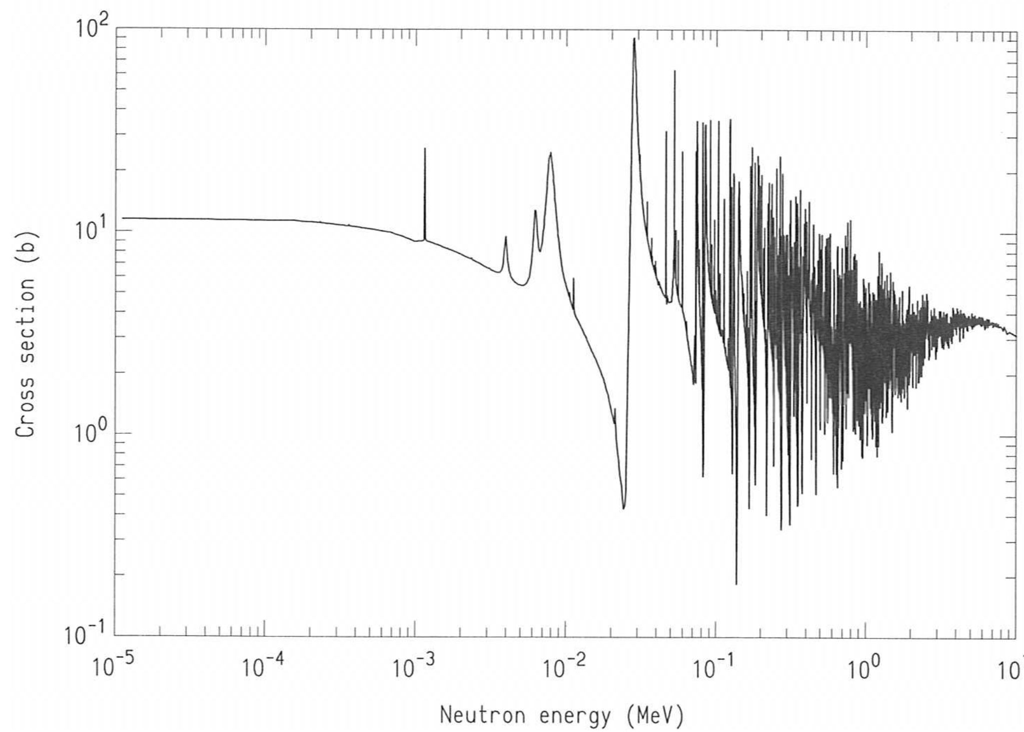
Neutron Energy (MeV)



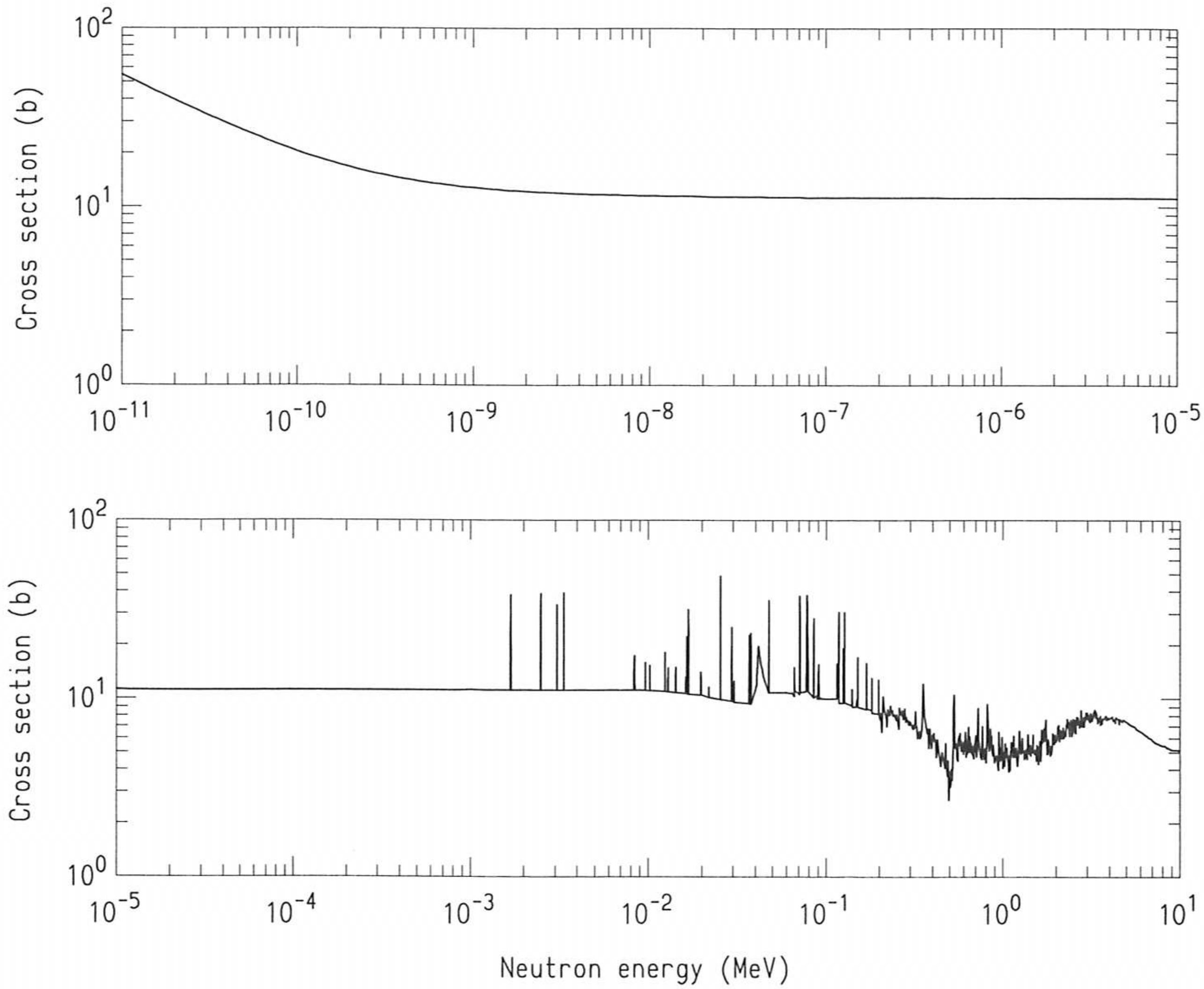
Fe total neutron cross section



Neutron Energy (MeV)

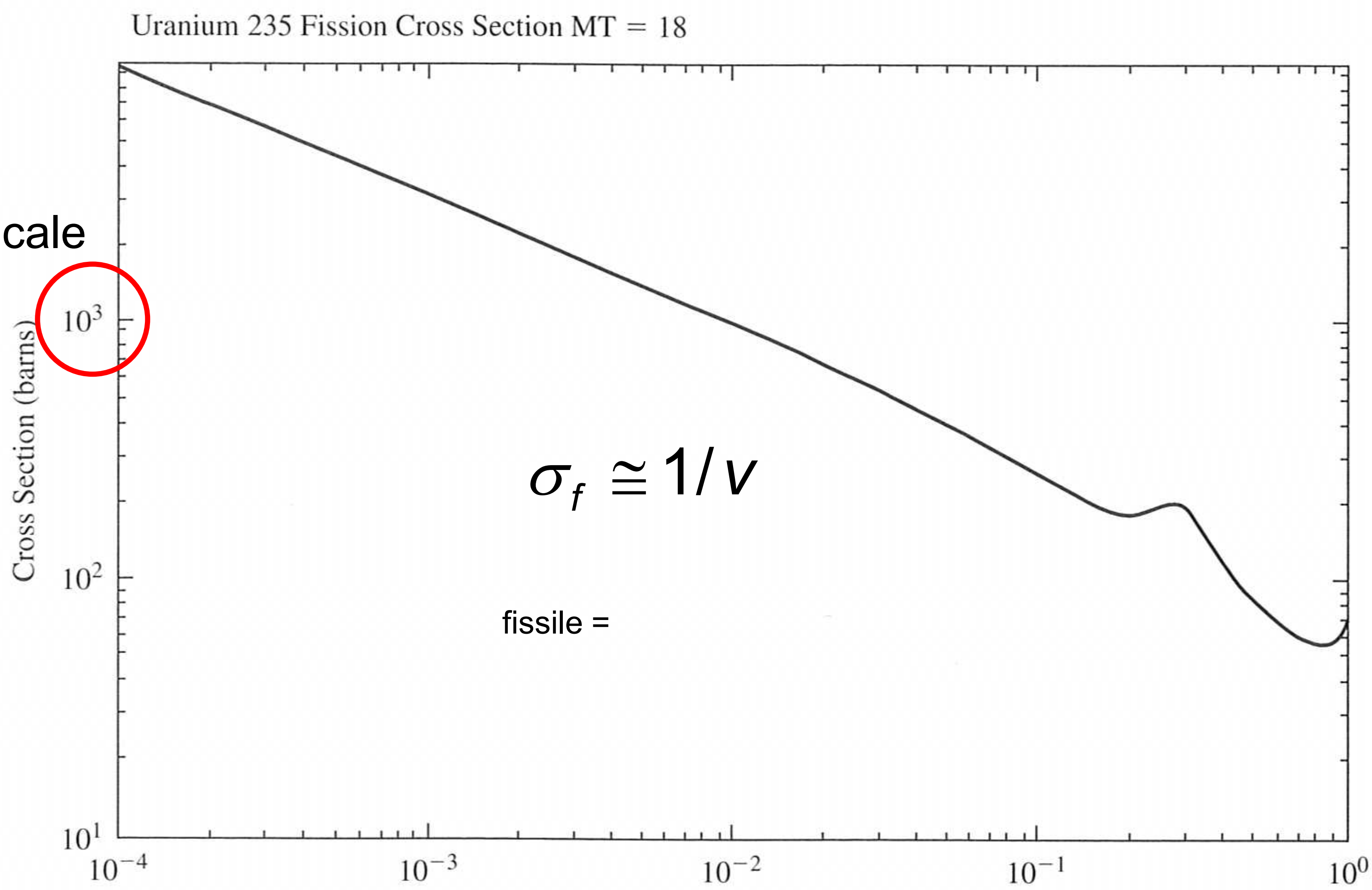


Lead Total Neutron Cross Section



Fission Cross Sections ^{235}U

note scale

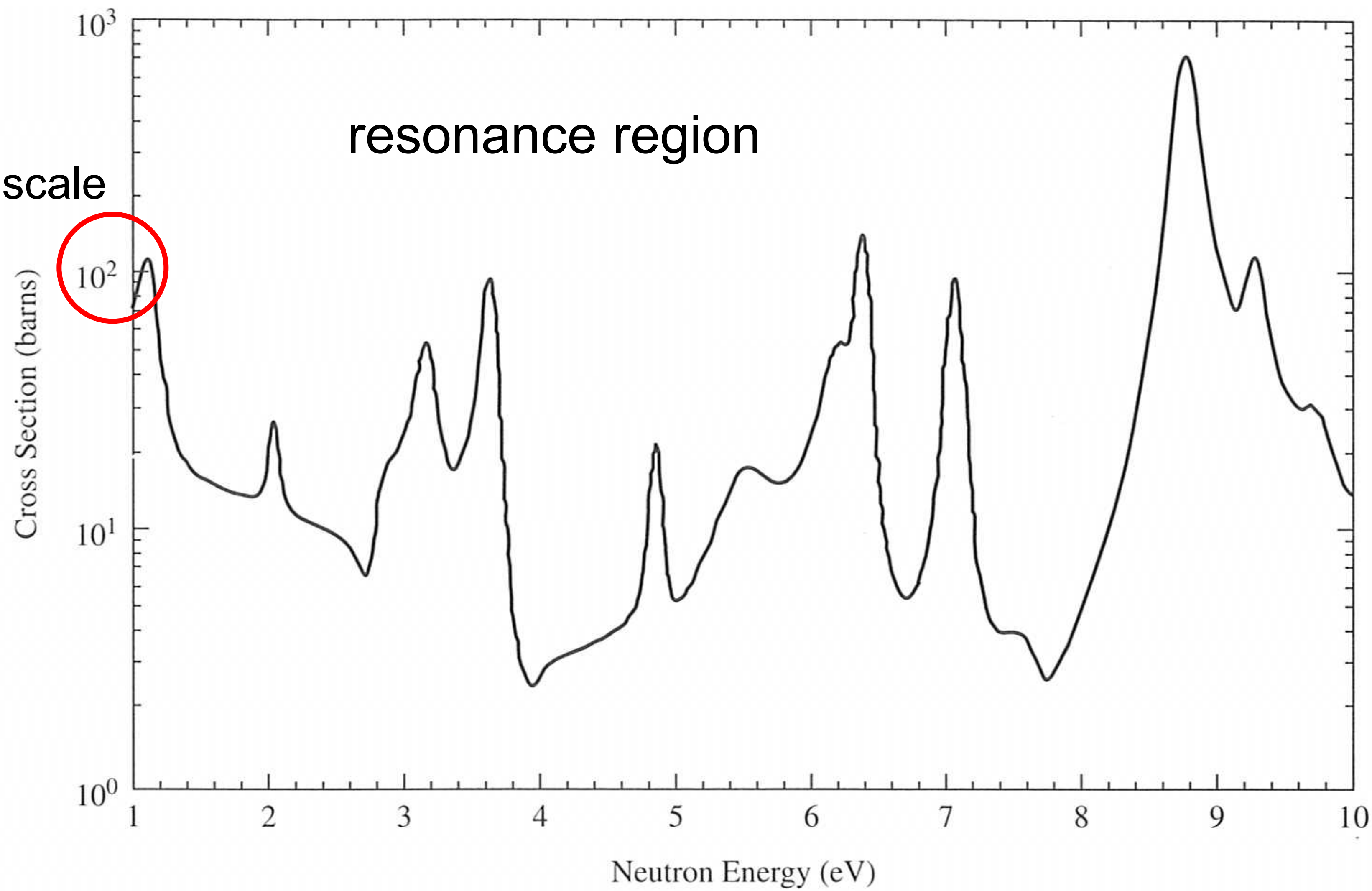


$\sigma_f \cong 1/v$

fissile =

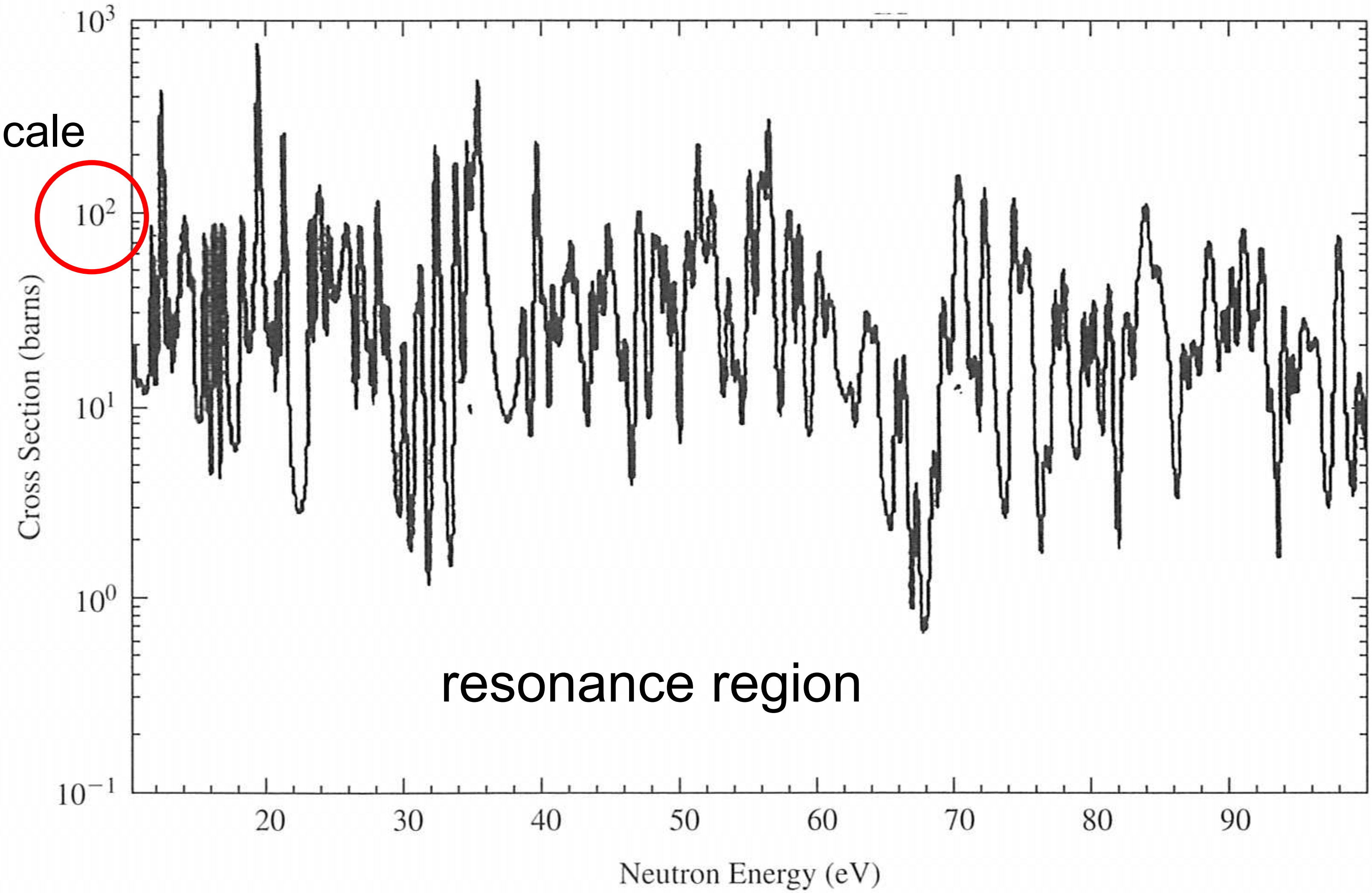
Fission Cross Sections ^{235}U

note scale

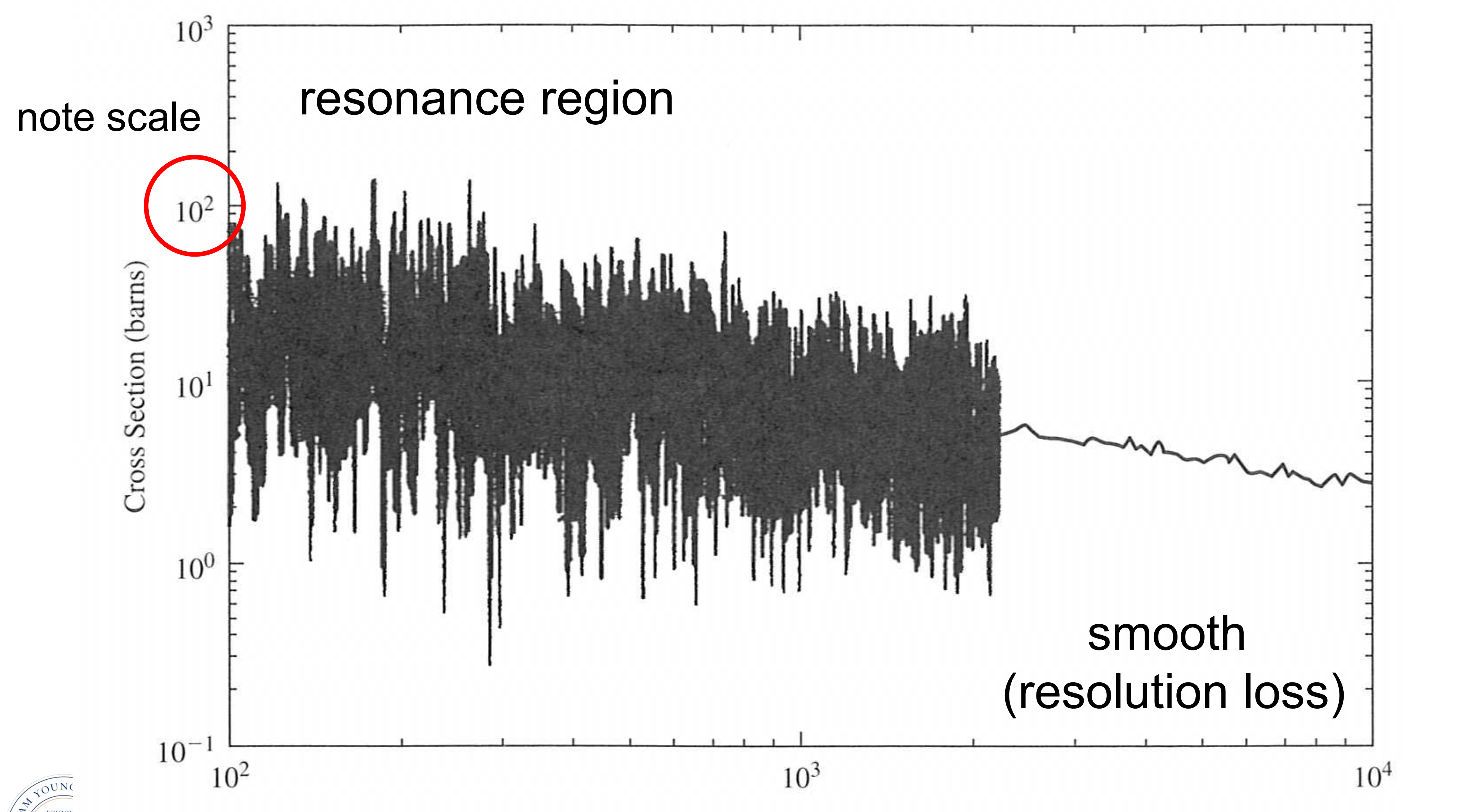


Fission Cross Sections ^{235}U

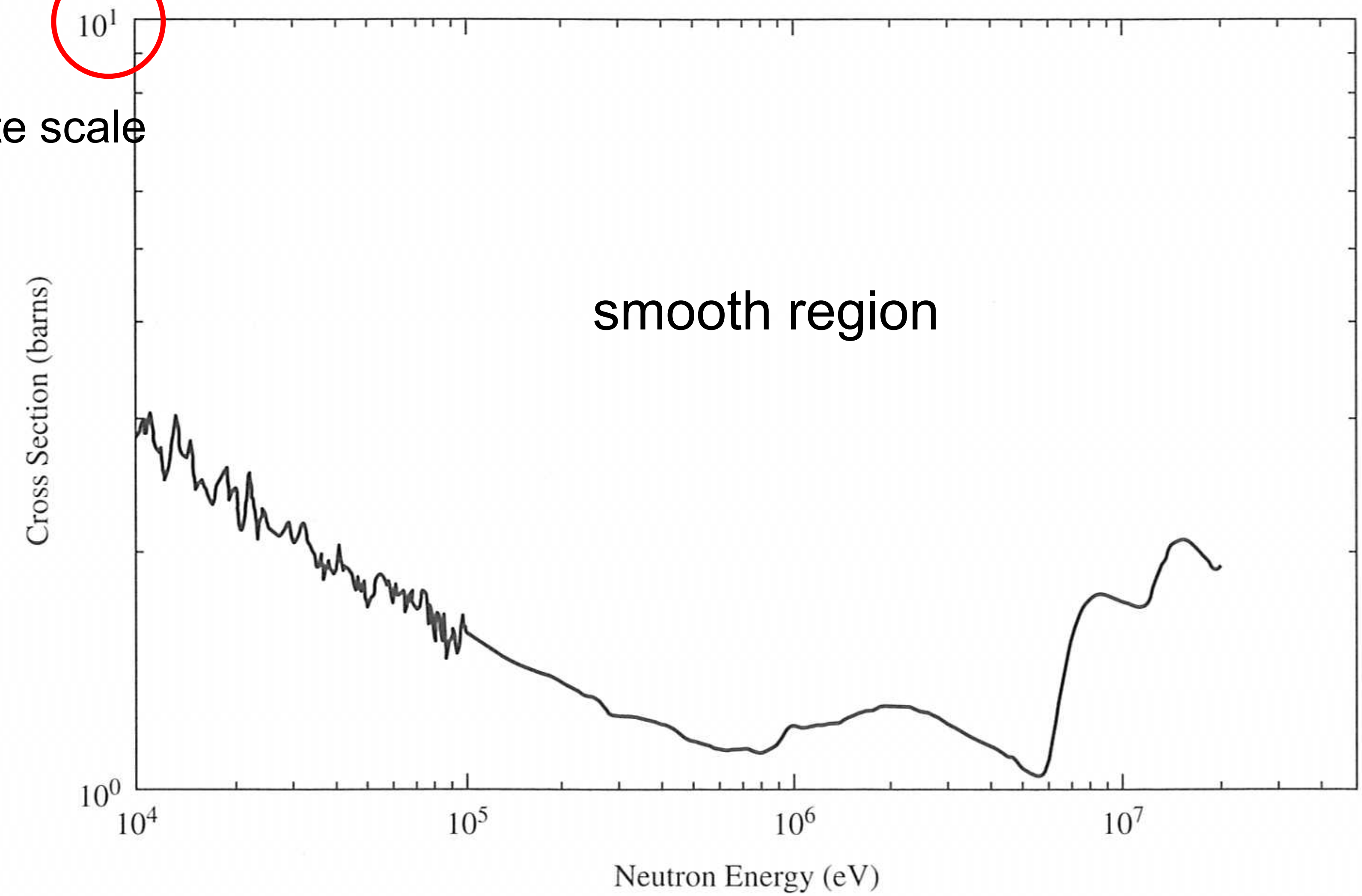
note scale



Fission Cross Sections ^{235}U



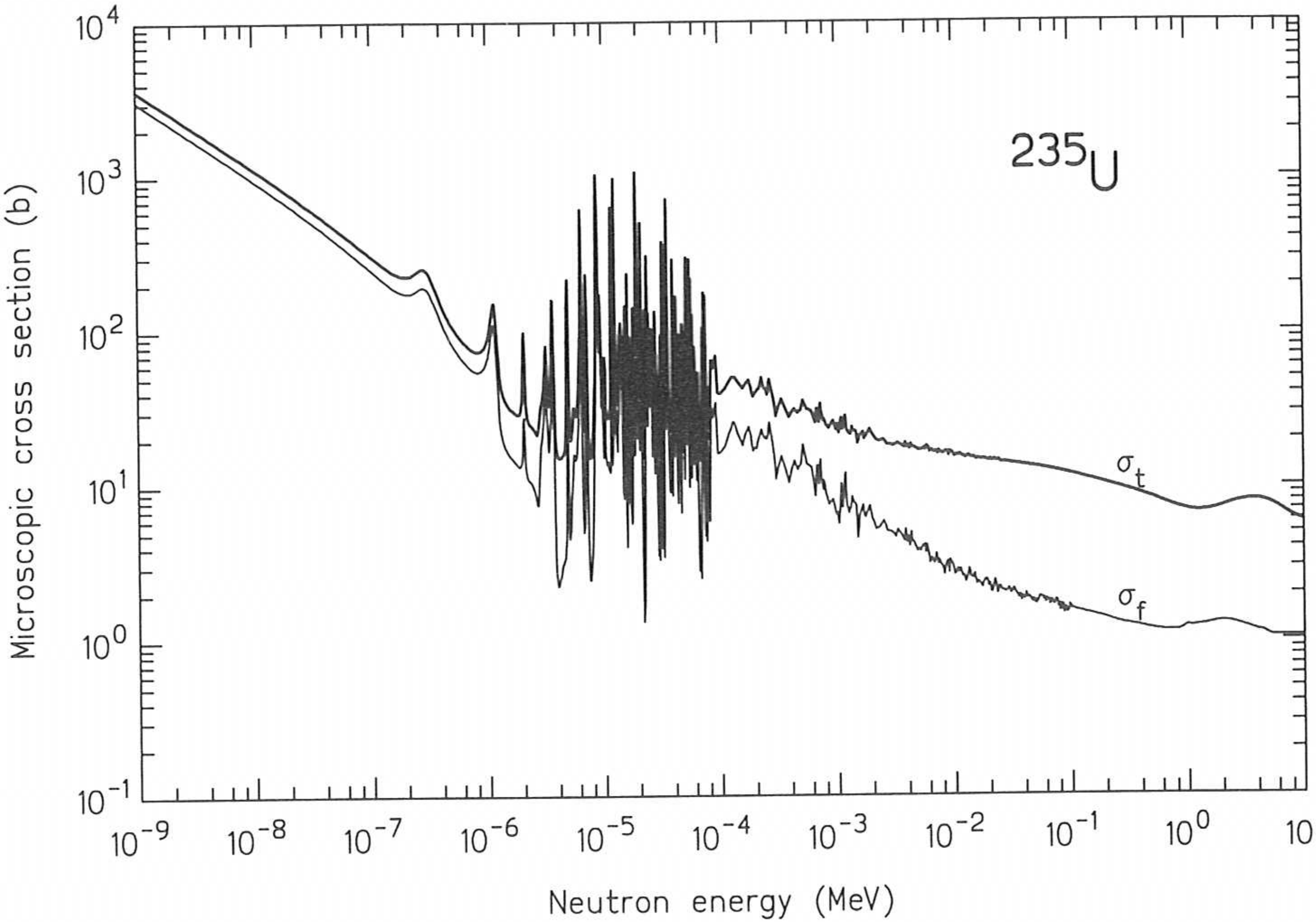
Fission Cross Sections ^{235}U



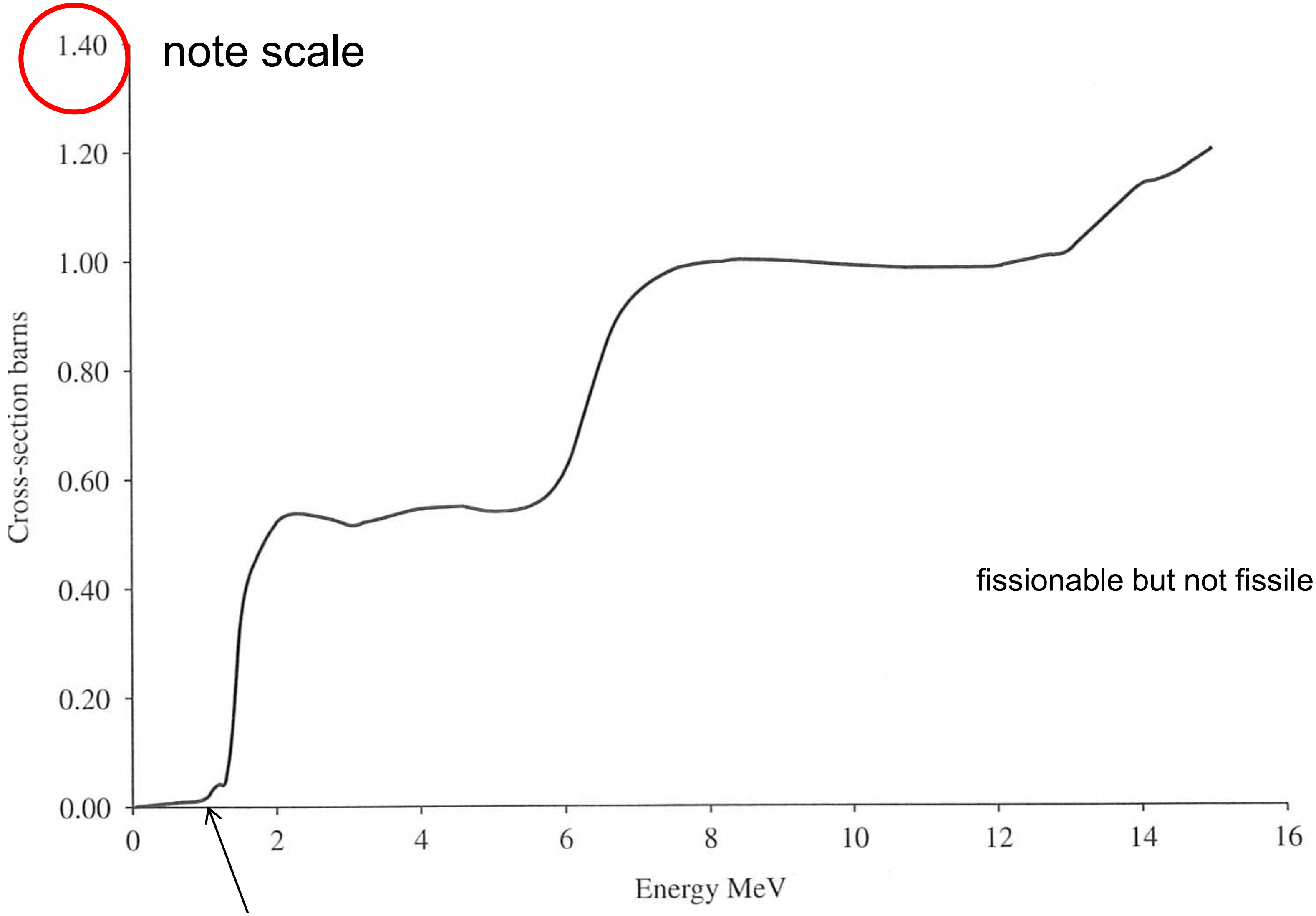
note scale

smooth region

Cross section over entire range

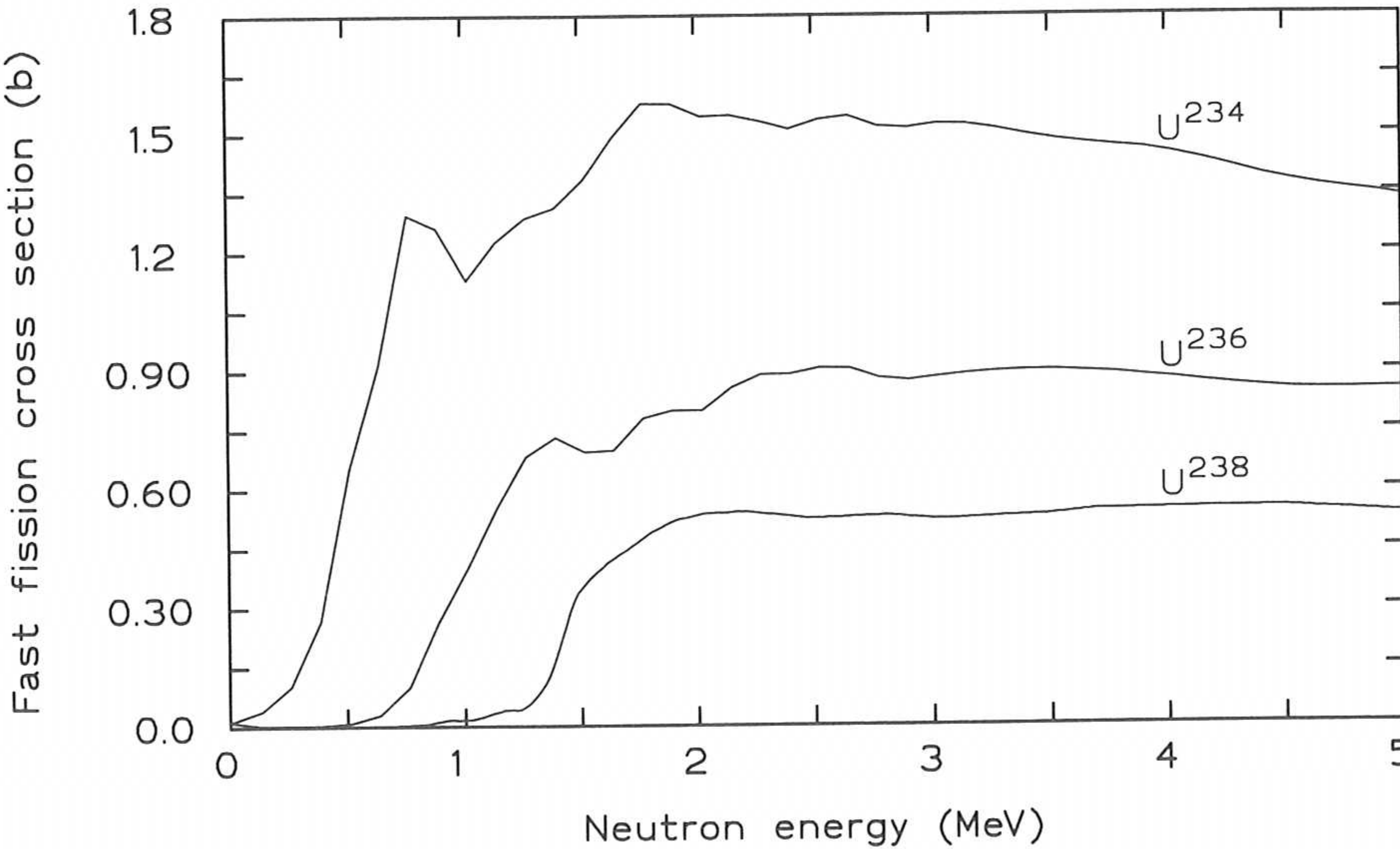


Fission Cross Section of ^{238}U



threshold energy (> resonance region energy)

Fissionable Cross Sections



Chemical Engineering 412

Introductory Nuclear Engineering

Exam 1 Review

Chapter 1 - Fundamentals

- Nuclear units
- Elementary particles/particle physics
- Isotopic nomenclature
- Atomic weight/number density
- Chart of nuclides
- Mass energy equivalency

Chapter 2 – Quantum Mechanics

- Special Relativity – time, length, mass changes
- Relativistic mass/momentum/energy relations
- Particle-wave duality
- Schrödinger’s wave equation
- Heisenberg’s uncertainty principle

Chapter 3 – Nuclear Models

- Nuclear energy states
- Liquid Drop Model
- Nuclear mass equation
- Shell Model
- Nuclear stability
- Binding energy/mass excess
- Modern Nucleus concepts

Chapter 4 – Nuclear Energetics

- Terminology
- Mass defect/BE
- Nuclear reactions
- Conserved quantities for various situations (not all the same!)
- **<u>****Q-Value**** (know how to calculate for ALL reactions)</u>**
  - Know how to deal with charge
  - Know how to deal with excited nuclei
  - Know how to deal with electrons/binding energy of electrons

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Chapter 5 – Nuclear Decay

- Conservations
- Decay mechanisms – distinguishing features, Q values, energy/momentum balances
- ***Energy Diagrams***
- Alpha/Beta particle energy distribution
- Decay Constant
- Half-Life
- Activity

Chapter 5 – Nuclear Decay (cont)

- Parallel/Series Decay Routes
- Decay Chains
- Solutions to decay chain equations
  Secular Equilibrium
- Radionuclides in nature
- Carbon 14 dating
- Other isotopic dating methods
- Three component decays
- Isobars and most stable masses

Chapter 6 – Binary Nuclear Reactions

- Definitions
- Types of binary reactions
- Reaction Mechanisms
- Kinematics (scattering example)
- Threshold Energy
- Neutron Reactions
- Neutron Scattering/slowing
- Neutron Energy Spectrums
- Lethargy

Chapter 6 – Binary Nuclear Reactions (cont.)

- Neutron capture vs. slowing
- Fission reactions
- Emitted/recoverable fission energy
- Critical energies for fission
- Fertile vs. fissile vs. fissionable
- Fission product distribution
- Prompt vs. delayed neutrons
- Fission steps/timeline

Chapter 7 – Radiation Interactions with matter

- Linear Interaction Coefficient (micro vs. macro)
- Cross section (micro vs. macro)
- Attenuation in Material
- Derivation of material interaction
- Buildup factor
- Mass Attenuation Coefficient
- Energy dependence of cross sections
- Cross section Trends

Chapter 7 – Radiation Interactions with matter (cont.)

- Cross Section of mixture
- Total intensity/flux
- Neutron flux
- Time/space/position dependence of flux
- Fluence
- Uncollided flux transmission
- Thermal vs. fast neutrons
- Photon Interactions – types, trends, energies, cross sections
- Charged Particle interactions
- Stopping Power (collision vs. radiative)
- Range

Example 1

- The Radionuclide ^{41}Ar decays by β^- emission to an excited level of ^{41}K that is 1.293 MeV above the ground state. What is the maximum kinetic energy of the emitted β^- particle?
- What makes this the maximum energy?

Solution

Q Equation

$Q_{\beta-}$ = {M($^{41}_{18}Ar$) - [M($^{41}_{19}K$)+E^*/c^2]}c^2

[40.9645008 – 40.9618259]*931.5 – 1.293 MeV

=1.199 MeV

B) Because an antineutrino is also released, which carries away some energy – this maximum is when the antineutrino has zero energy

Example 2

Assume a fuel rod has a diameter of 1 cm and a length of 5 m. Assuming an enrichment of 5% ^{235}U and a thermal flux of $2\text{x}10^{13}$ neutrons, what is the reaction rate in the fuel rod for:

a) scattering?

b) fission?

Example 2 key

- $\sigma.s235 = 13.7b$, $\sigma.f235 = 587b$
- $\sigma.s238 = 9.47b$, $\sigma.f238 = 0b$
- $N235 = 2.447E21\ cm^{-3}$, $N238 = 4.591E22\ cm^{-3}$
- $Vf = 392.7\ cm^3$
- $Rs = 3.678E15 s^{-1}$
- $Rf = 1.128E16 s^{-1}$

Example 3

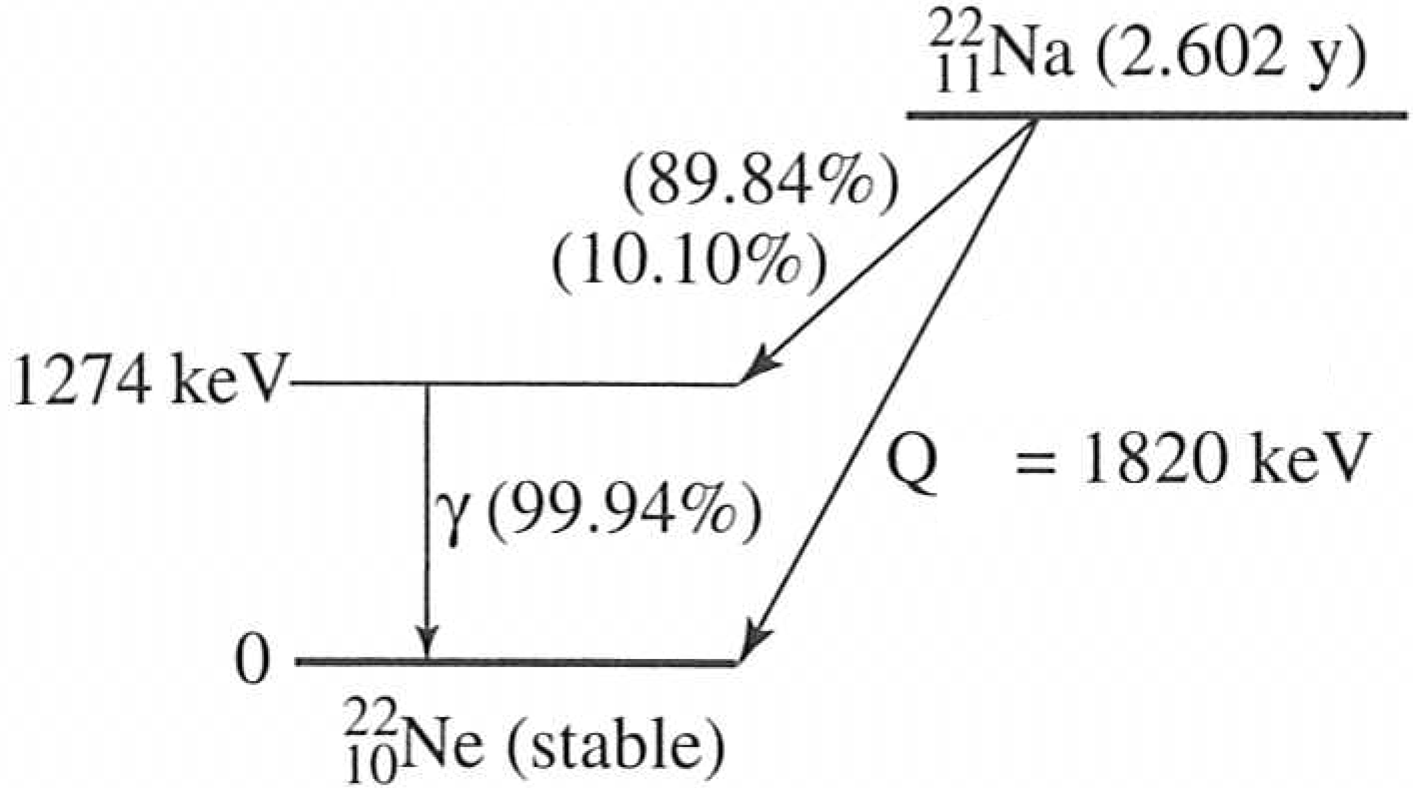
- What is the probability of producing ^{91}Br in a fission reaction?
- Use fission product mass distribution chart:
- ~8.5%

Example 4

- What is the amount of thermal neutrons that are absorbed in water per cm^3 over 1 hour in a fission reactor if the thermal flux is $2.2*10^{16}$ neutrons/cm^2/s? ($\Sigma_a = 0.0197\ cm^{-1}$)

- $1.56*10^{18}$ absorptions per cm^3

Example 5



$^{22}_{11}$Na (2.602 y)
(89.84%)
(10.10%)
1274 keV
γ (99.94%)
Q = 1820 keV
0
$^{22}_{10}$Ne (stable)