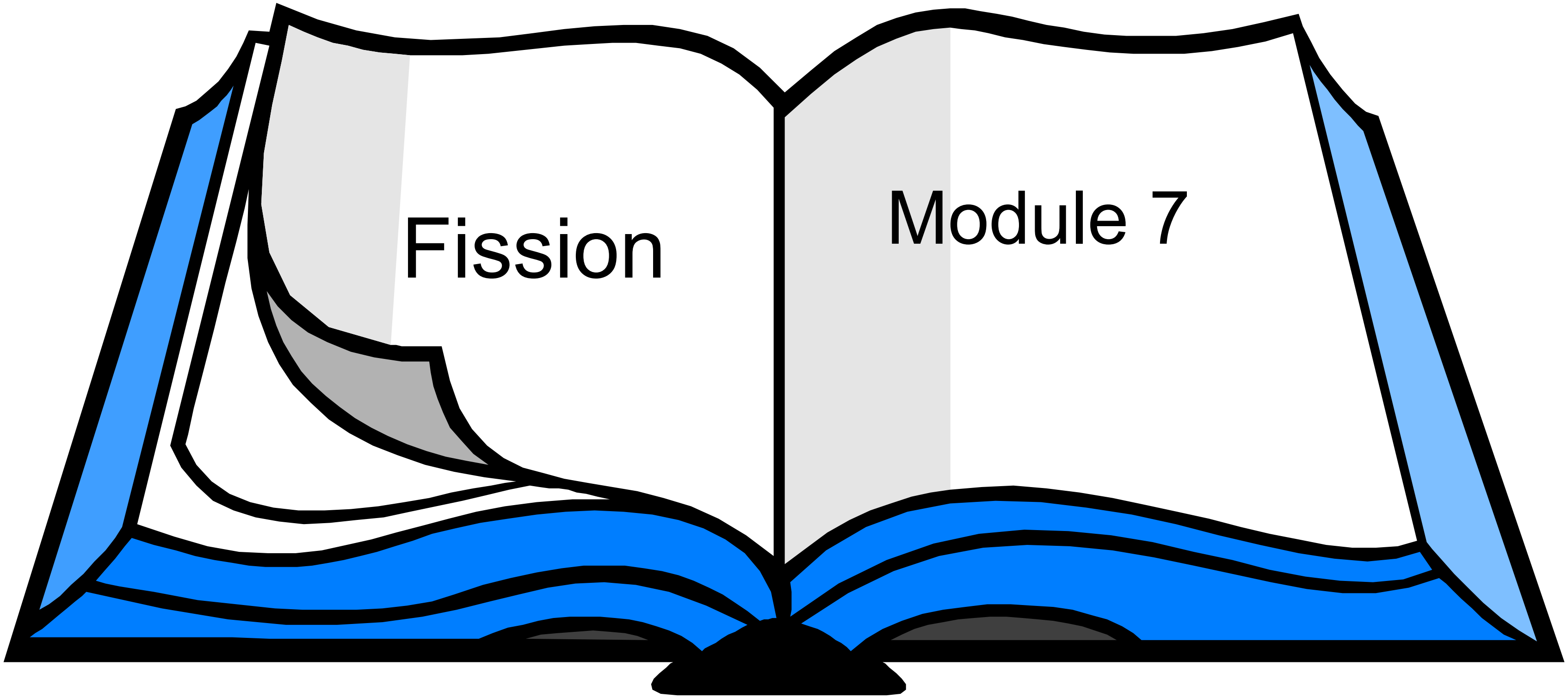
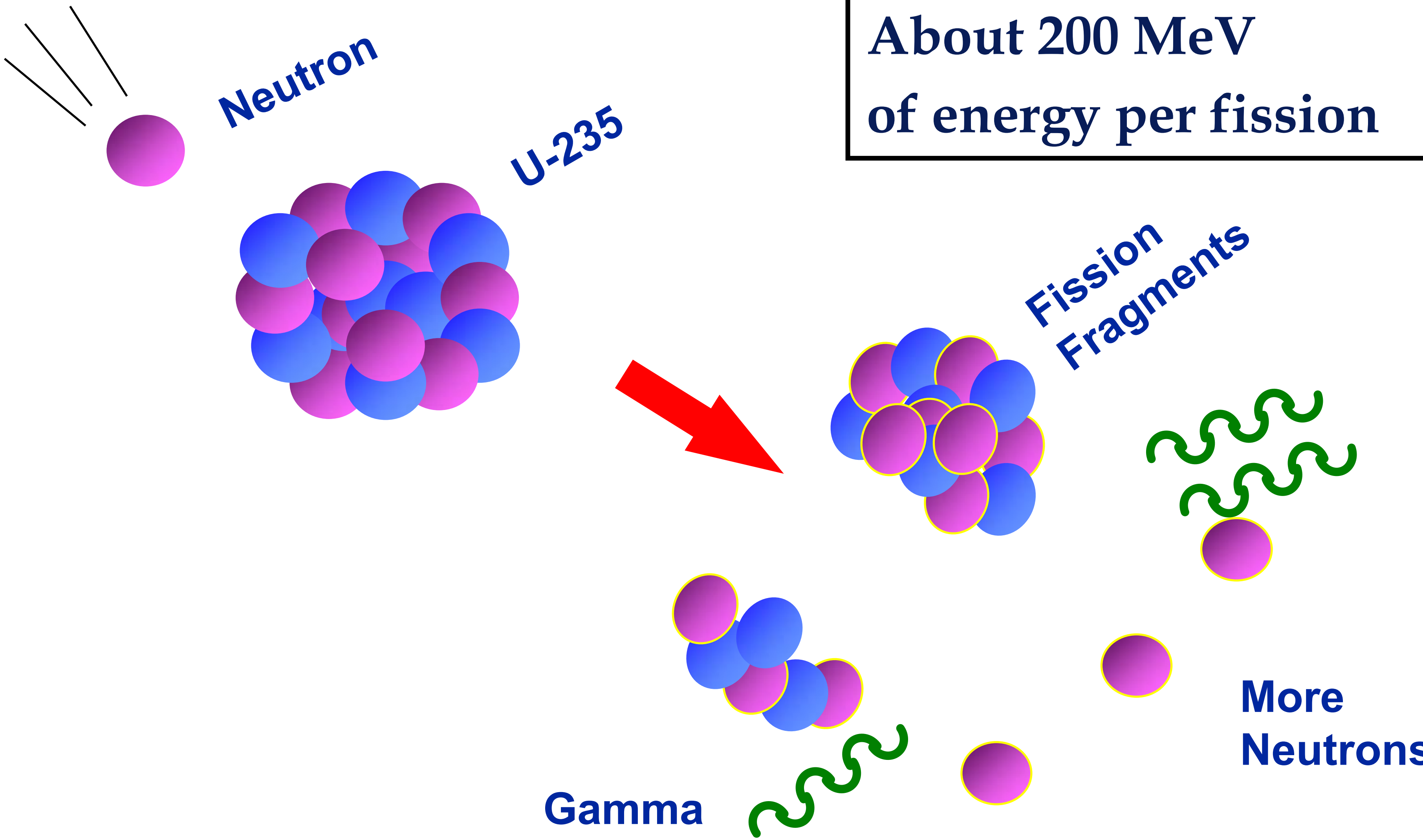

Fission
Module 7

Fission

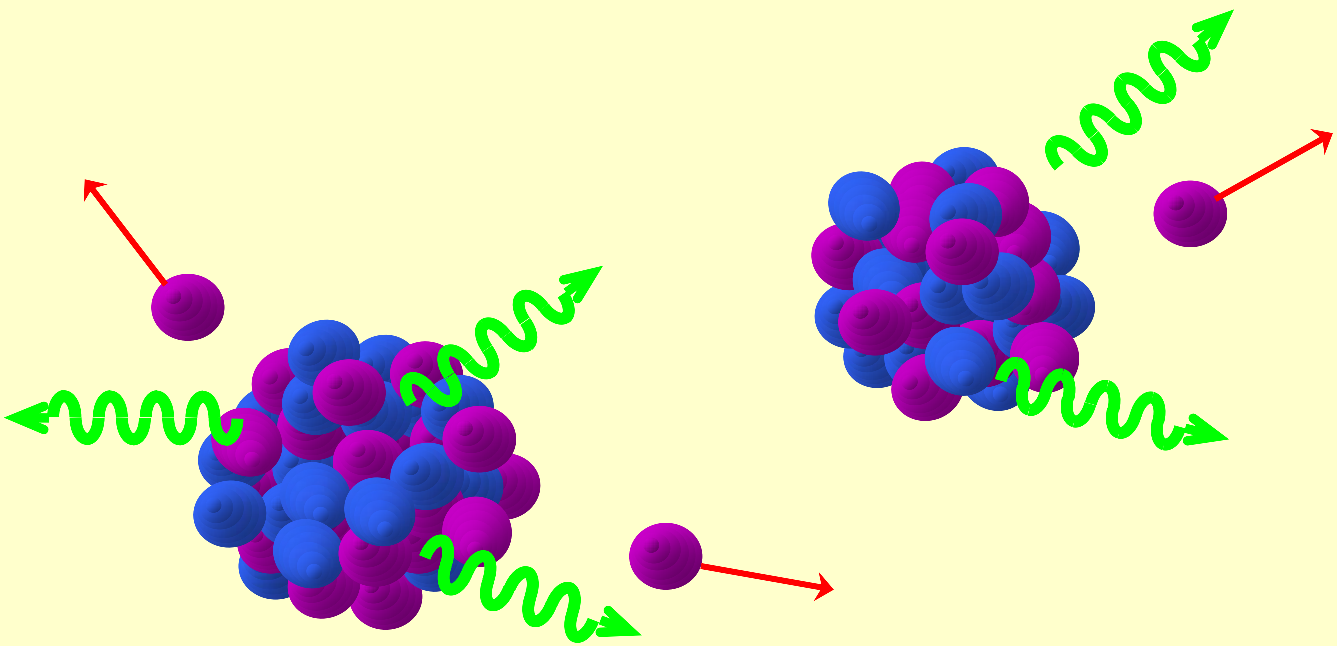
About 200 MeV of energy per fission



OH #2

Fission - Before

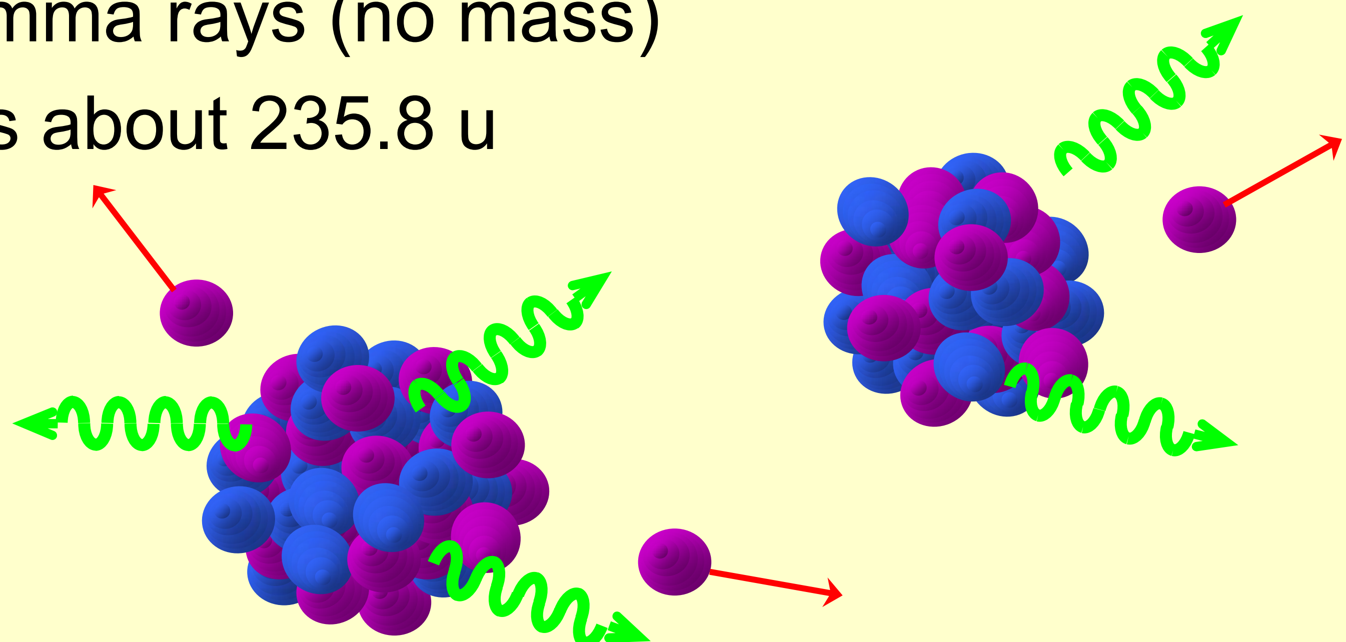
- Before the neutron "falls" into the U-235 nucleus:
  - ➔235 bound particles, average mass 1.000 u each
  - ➔1 free neutron with a mass of about 1.009 u



  - ➔total mass about 236.009 u

Fission - After

- **After:**
  - ➔234 or 233 particles (two fragments) 0.999 u each
  - ➔2 or 3 free neutrons (typical): mass 1.009 u each
  - ➔Some gamma rays (no mass)
  - ➔total mass about 235.8 u

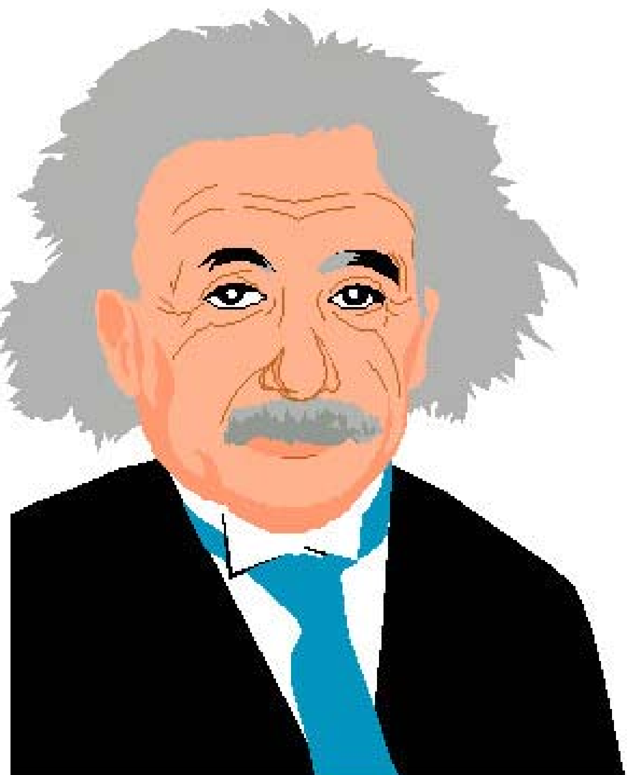


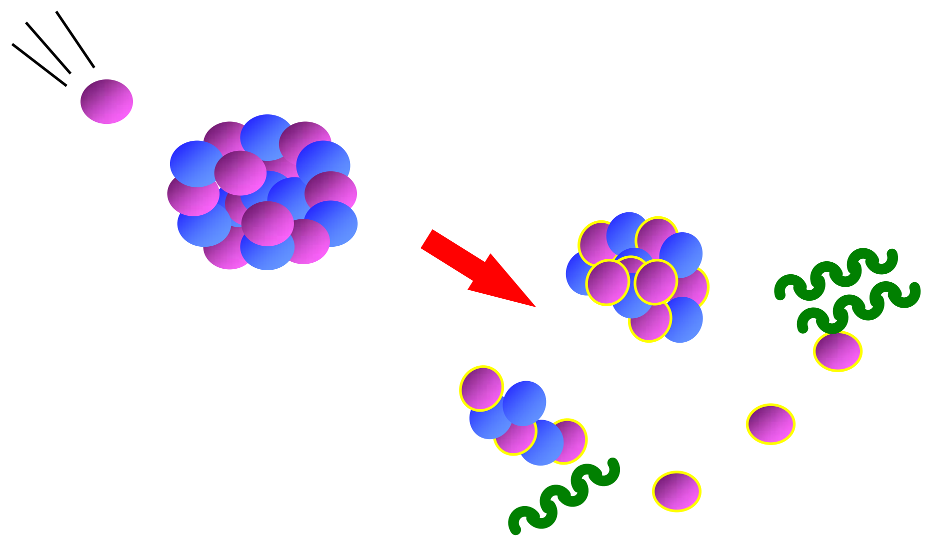
  - ➔The missing mass (0.2 u ≈ 200 MeV) shows up mostly as **kinetic energy of the fission products**

Where does the energy come from?

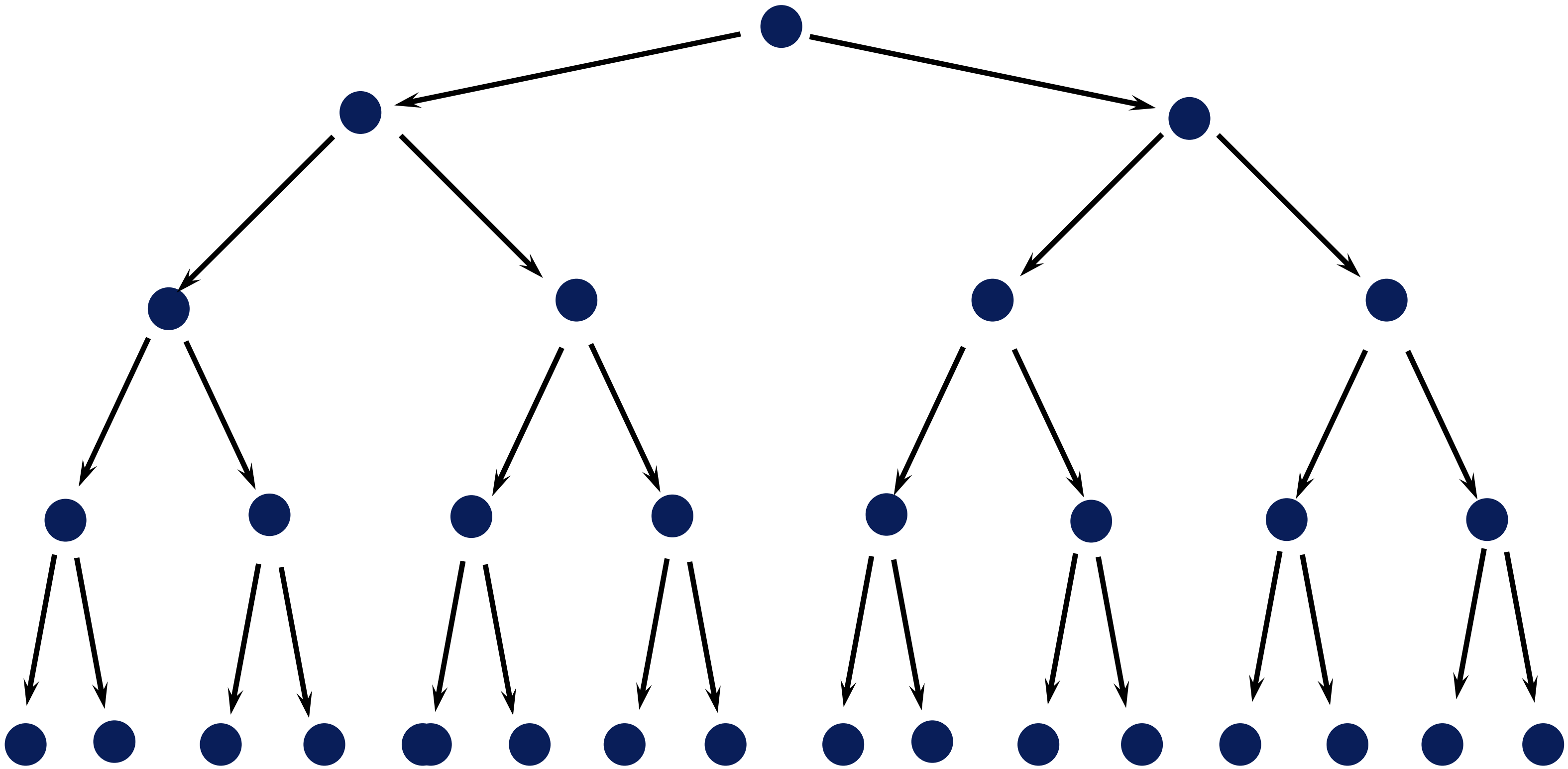
$$E = mc^2$$

Mass "Disappears" and Energy Appears in its place.

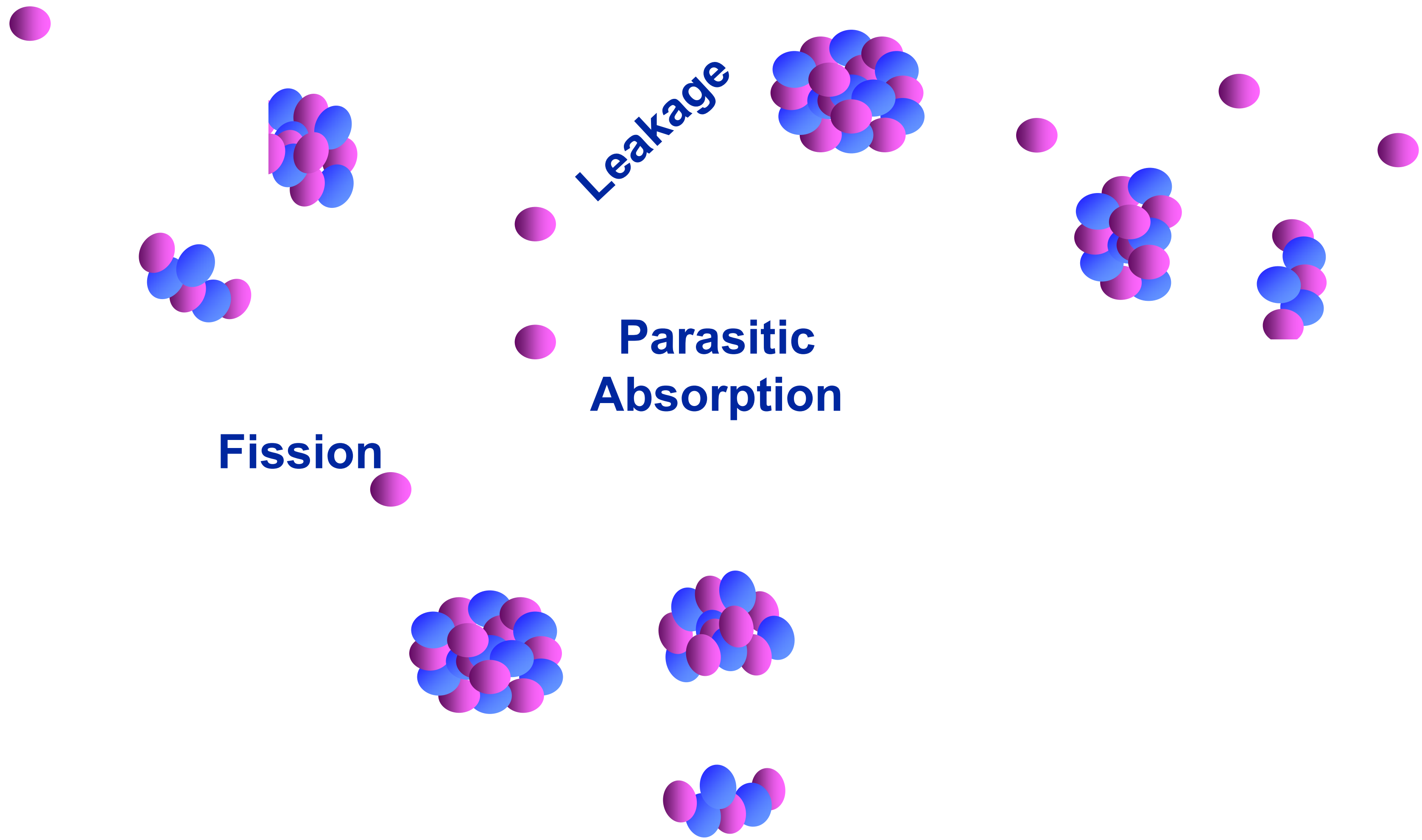




Chain Reaction



Controlled Chain Reaction



Neutron Multiplication Factor

$$k = \frac{\text{number of neutrons in this generation}}{\text{number of neutrons in the previous generation}}$$

Reactivity

$$\rho = \frac{k-1}{k} = \frac{\Delta k}{k}$$

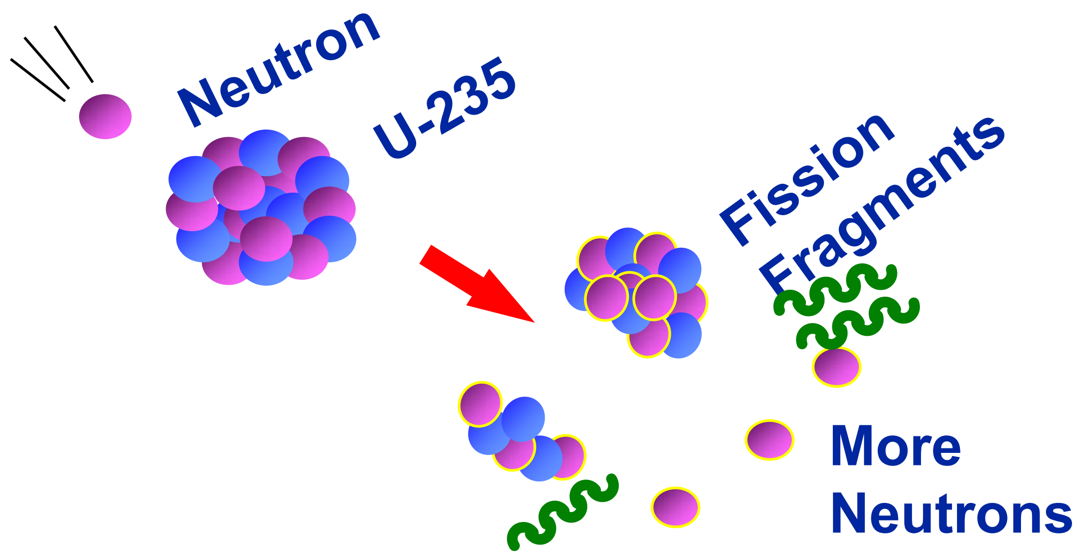
Units of Reactivity

$$1\ \text{mk} = 10^{-3}\ \rho$$

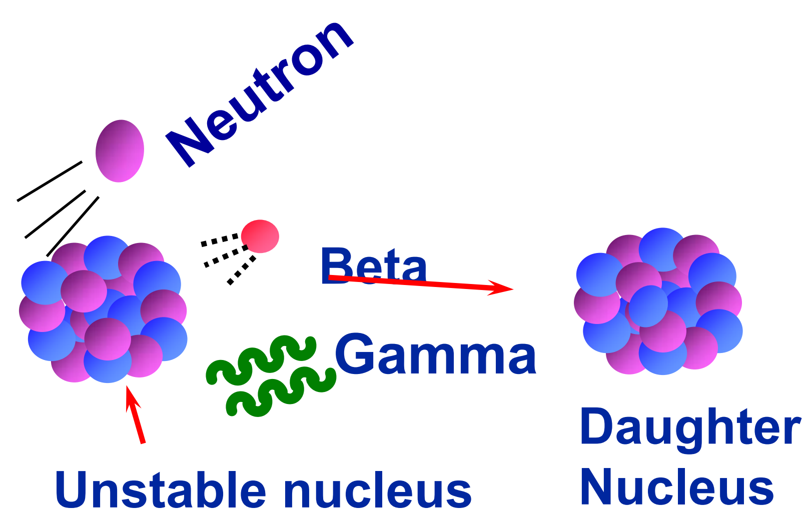
$$1\ \text{pcm} = 10^{-5}\ \rho$$

Where do neutrons come from?

- ➔ Induced Fission

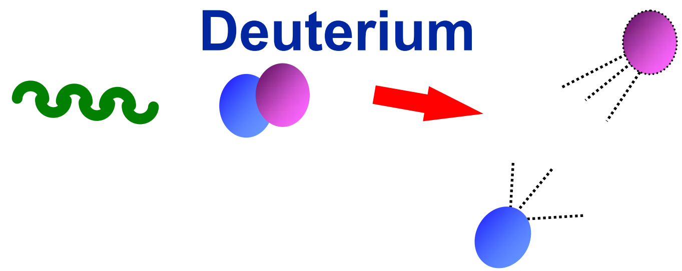


- ➔ Delayed Neutrons

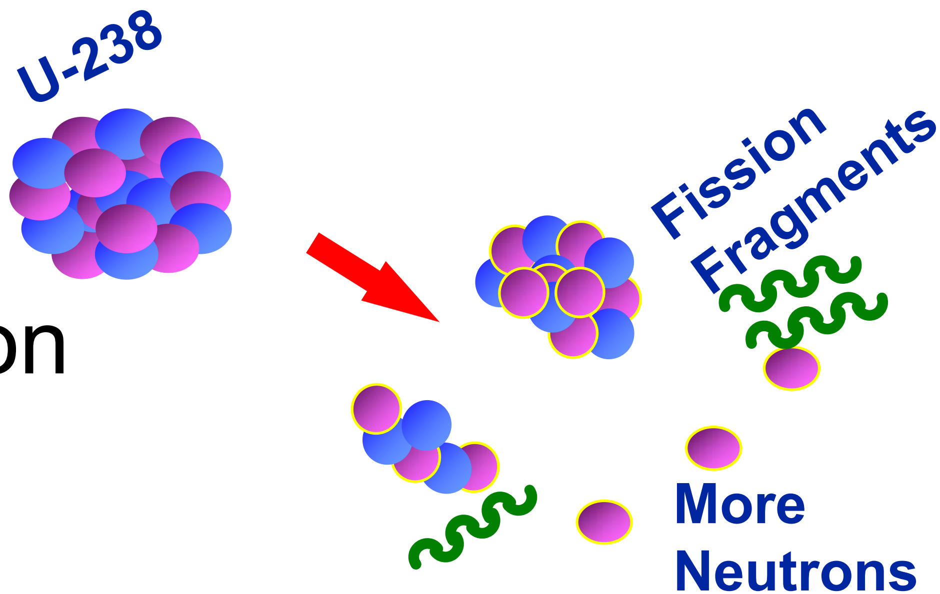


Where do more neutrons come from?

➔Photo-neutrons



➔Spontaneous Fission



More about neutrons

- **Induced Fission**
  - Most of the neutrons at high power
  - 99.35% of all neutrons
- **Delayed Neutrons**
  - Half-lives up to about 1 minute
  - Delay changes in power
  - 0.65% of neutrons
- **Photo-neutrons**
  - A decade less than delayed neutrons
  - hold power to about $5x10^{-5}$ FP after 1 day shutdown
  - Longest lived decay chain with 2.2 MeV gammas is 15 days
  - Usually considered part of the source neutrons

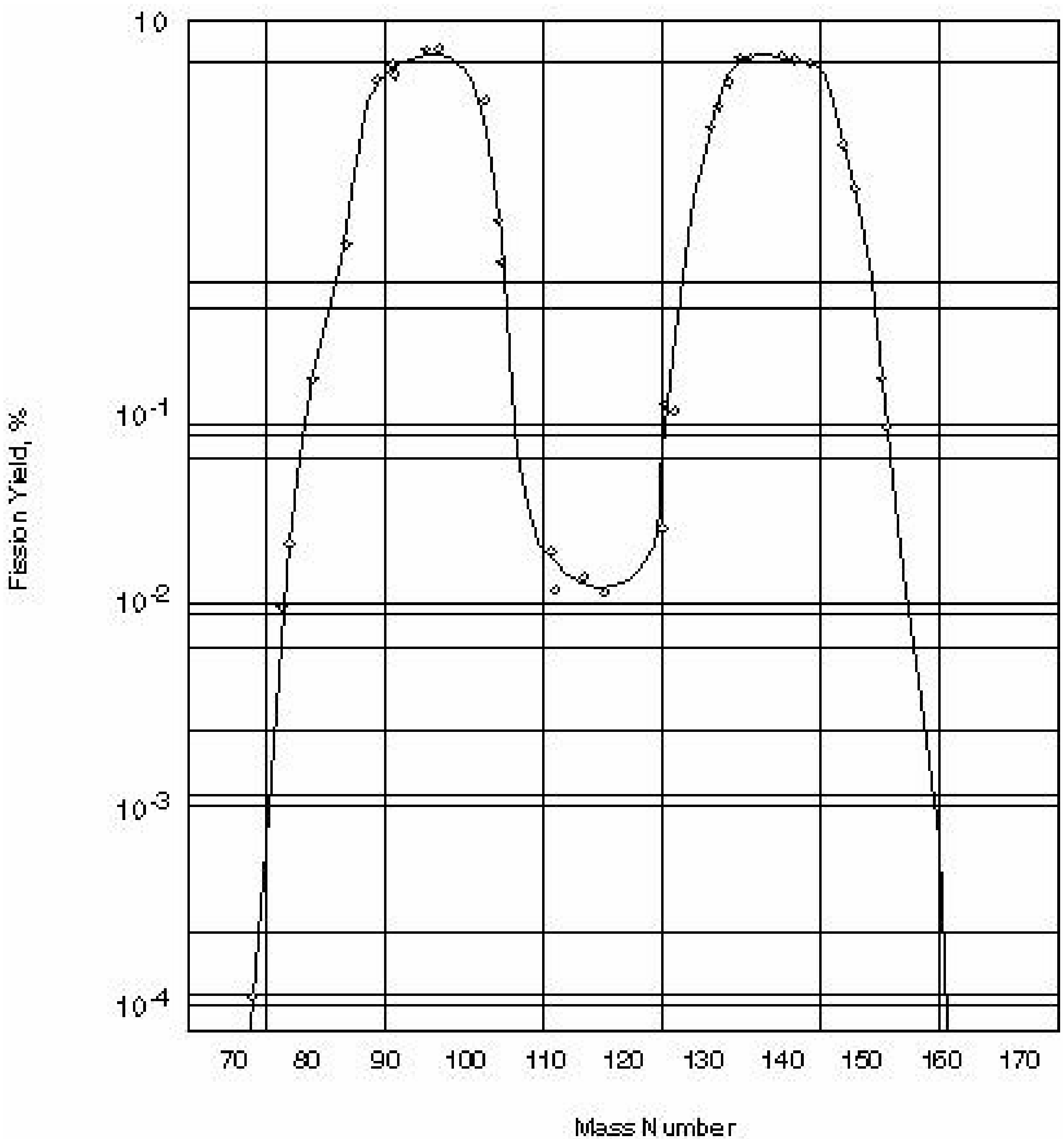
Even more about neutrons

- **Spontaneous Fission**
  - Very small number of neutrons
  - Contribution is about 10^{-12}%F.P.
  - Only source in newly fuelled cores and after long shutdowns

So What ????

Neutron Population in CANDUs is relatively high for significant time periods following shutdown

Camel Curve



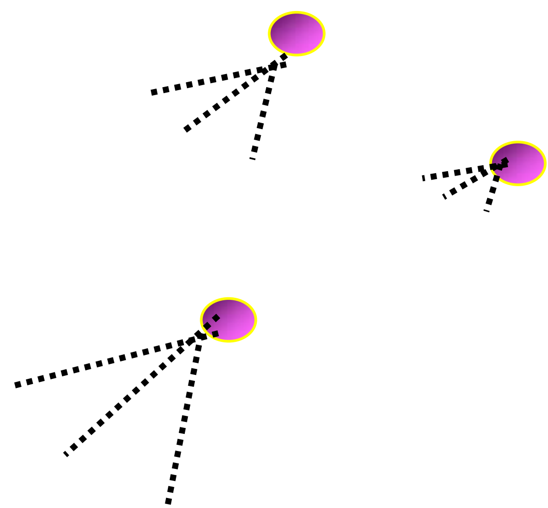
10
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Fission Yield, %
70
80
90
100
110
120
130
140
150
160
170
Mass Number

Neutron Energies

- Fast
- Slow or thermal
- Epi-thermal

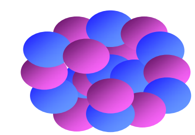
Neutron Energies

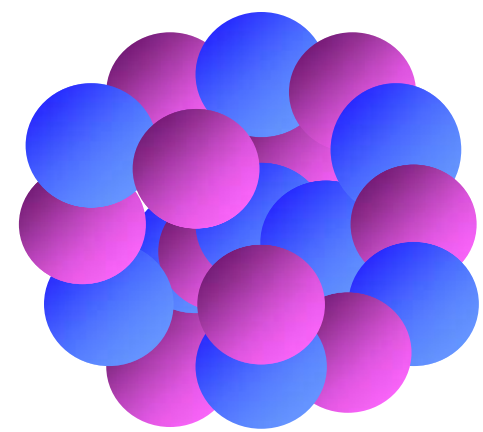
- **Fast**
  - ➔ **Spectrum of fission neutrons 1-10 MeV, 2 MeV is typical**
- **Slow or thermal**
  - ➔ **Slowed to thermal equilibrium**
  - ➔ **0.0253 eV at 20°C**
- **Epi-thermal**
  - ➔ **anything in between**



Cross Sections

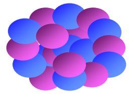
- Probability of a specific nuclear reaction
- Depends on
  - reaction
  - target nucleus
  - neutron energy



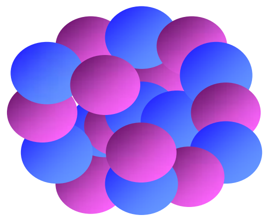


Cross sections vary with neutron energy

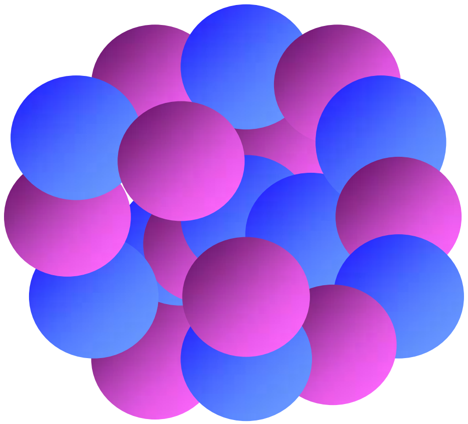
U-235 to a fast neutron



U235 to an epi-thermal neutron

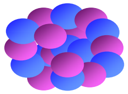


U235 to a slow neutron

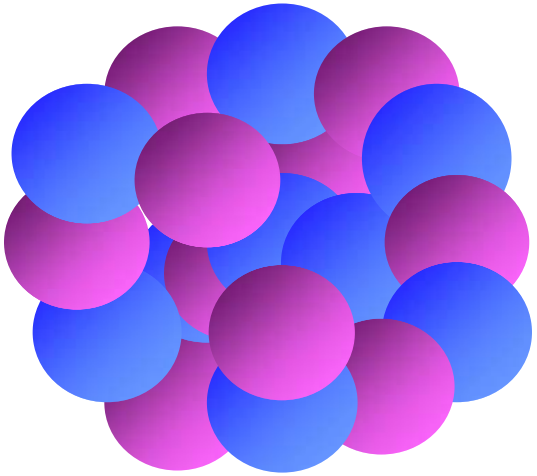


Cross sections vary with target nucleus

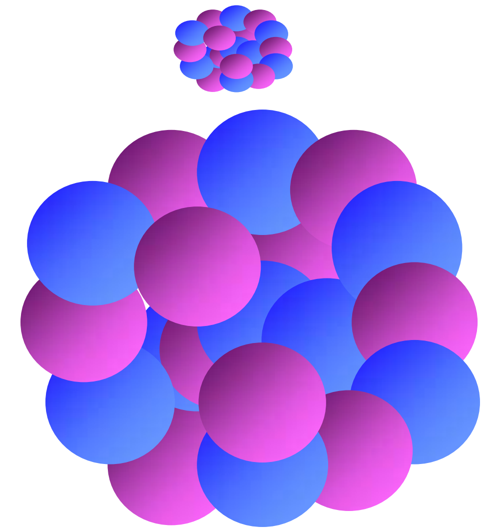
U-238 to a slow neutron



U235 to slow neutron

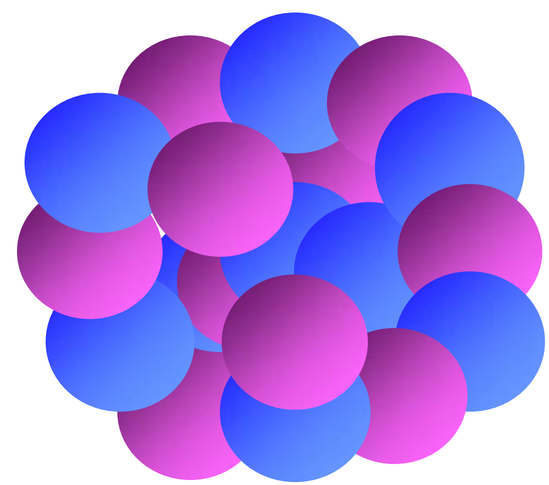


Cross sections vary with specific reaction



U-235 (n,γ) σ_γ

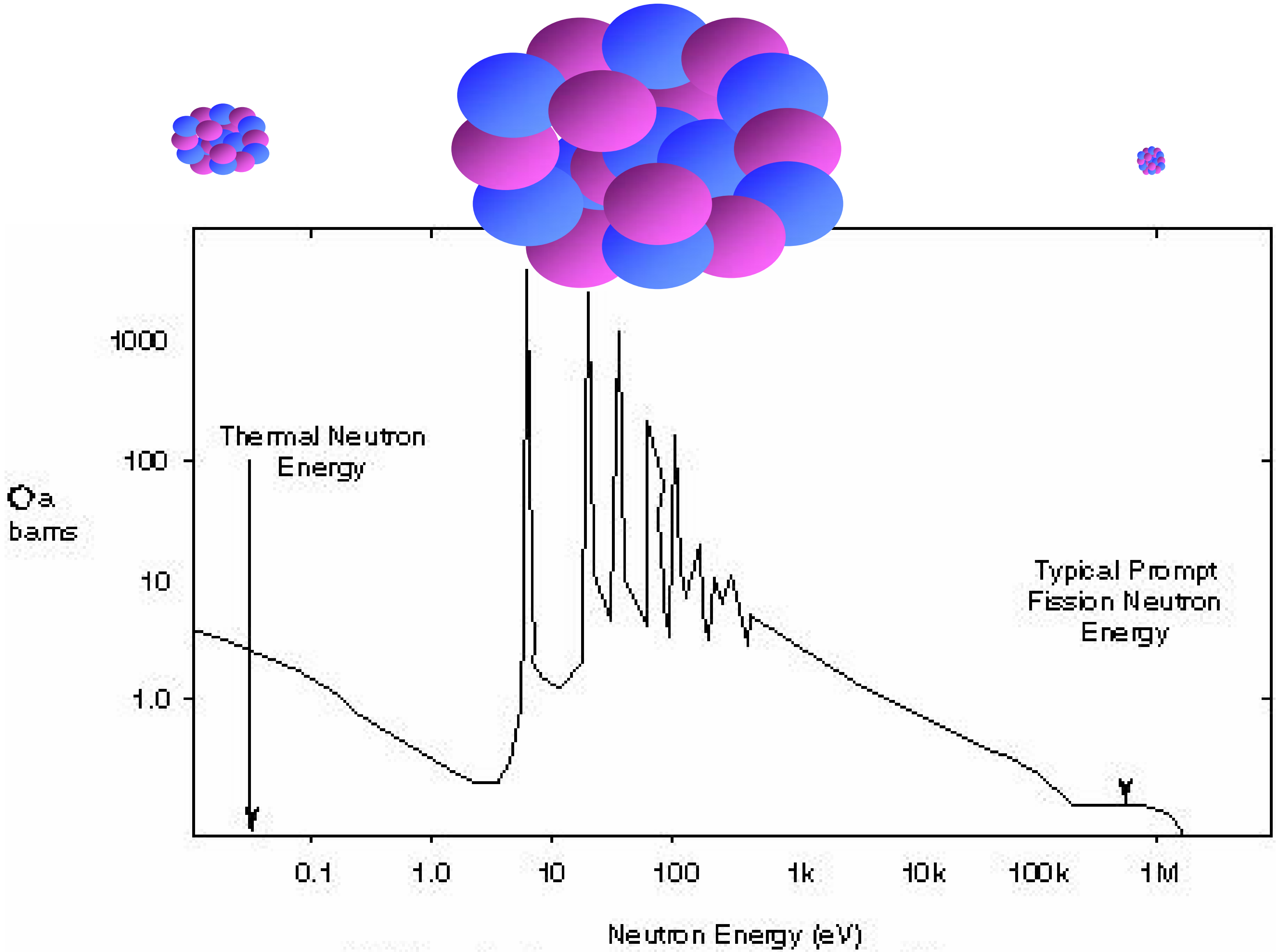
U235 to fission (n,f) σ_f



U235 to absorption σ_a

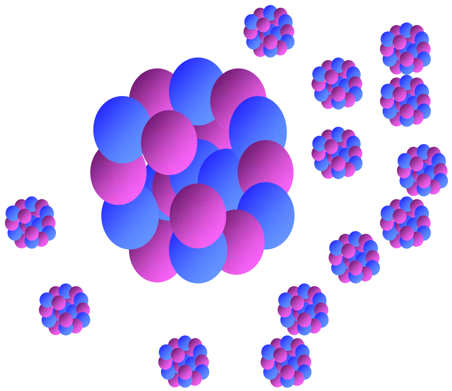
$$\sigma_a = \sigma_\gamma + \sigma_f$$

Resonance Capture

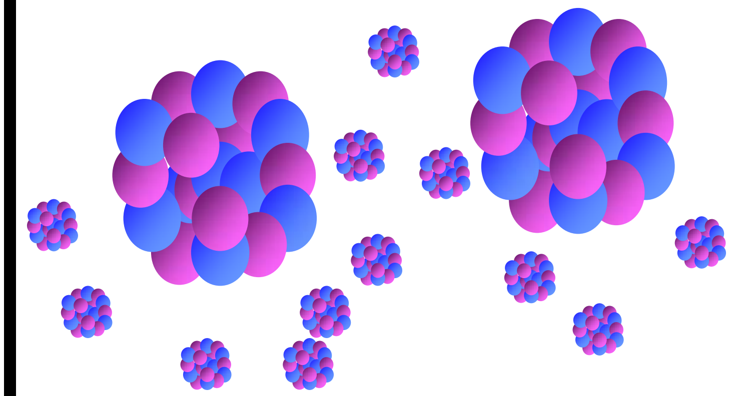


Variation of the absorption cross section of U238 with neutron energy

Effect of Enriching Fuel



Natural Uranium



Enriched Uranium

0.7 % U-235

2-4% U-235

Chance of a neutron capture in fuel causing a fission is much increased.

Reactors with enriched fuel do not need to return as many atoms to the fuel to achieve criticality