Chapter 1

Learning Objectives

- Historical Recap
- Understand the different length scales of nuclear physics
- Know the nomenclature for isotopes and nuclear reactions
- Know the different types of neutron nuclear collisions and their relationship to each other
- Basic principles of nuclear reactor

Learning Objectives

- Neutron Sources
- Basic Principles of Nuclear Reactor
- Binding energy curve
- Liquid drop model
- Fission Reaction
- ODE Review
- Radioactive Decay
- Decay Chains
- Chart of Nuclides

Historical Recap

- Driscoll handout
- New programs
  - GNEP/AFCI
  - Gen-IV
  - Nuclear Power 2010

Why nuclear?

- Power density
  - 1000 MW electric
    - 10 000 tons of coal per DAY!!
    - 20 tons of uranium per YEAR (of which only 1 ton is U-235)

A typical pellet of uranium weighs about 7 grams (0.24ounces). It can generate as much energy as……

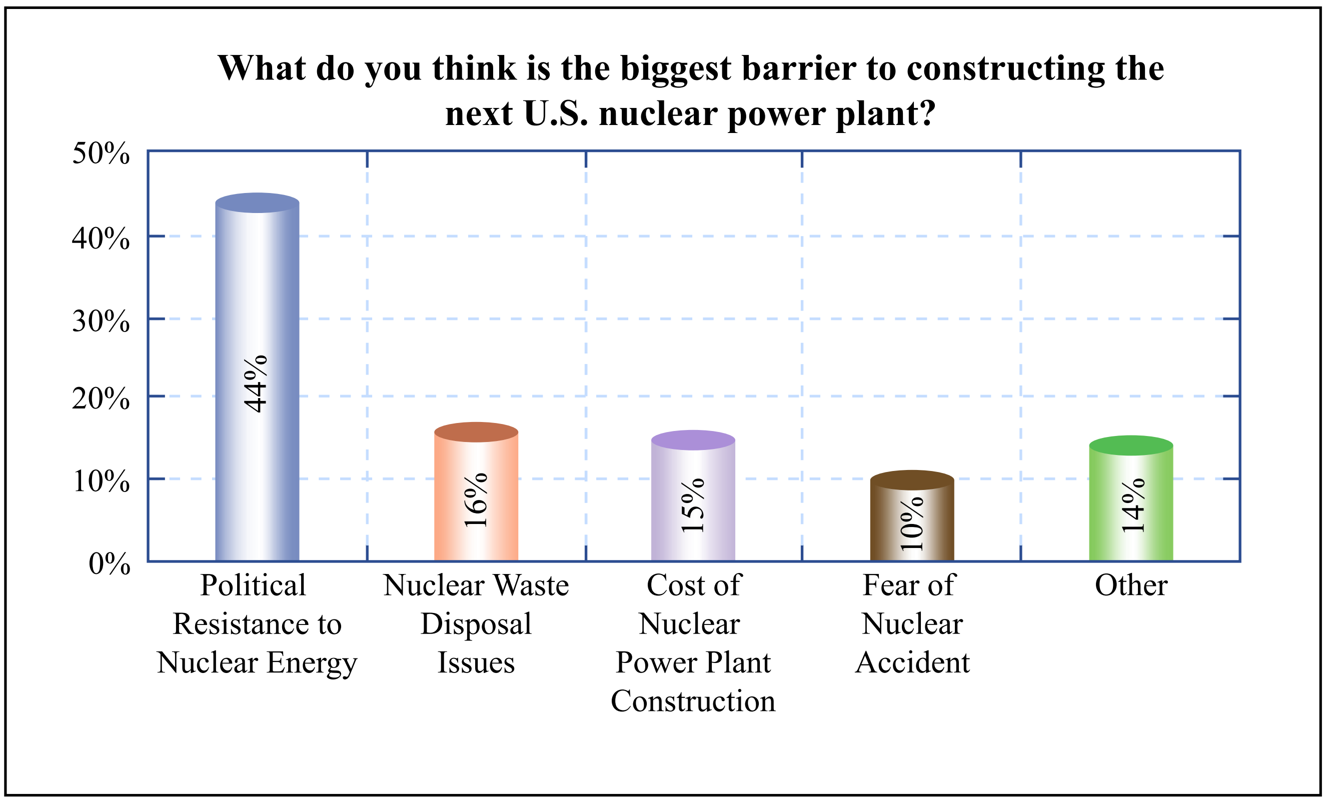
3.5 barrels of oil or……

17,000 cubic feet of natural gas, or…..

1,780 pounds of coal.

Why nuclear?

- Why still use coal
  - Capital cost
  - Politics
  - Public perception of nuclear, nuclear waster issue



- 2008 survey of energy professionals

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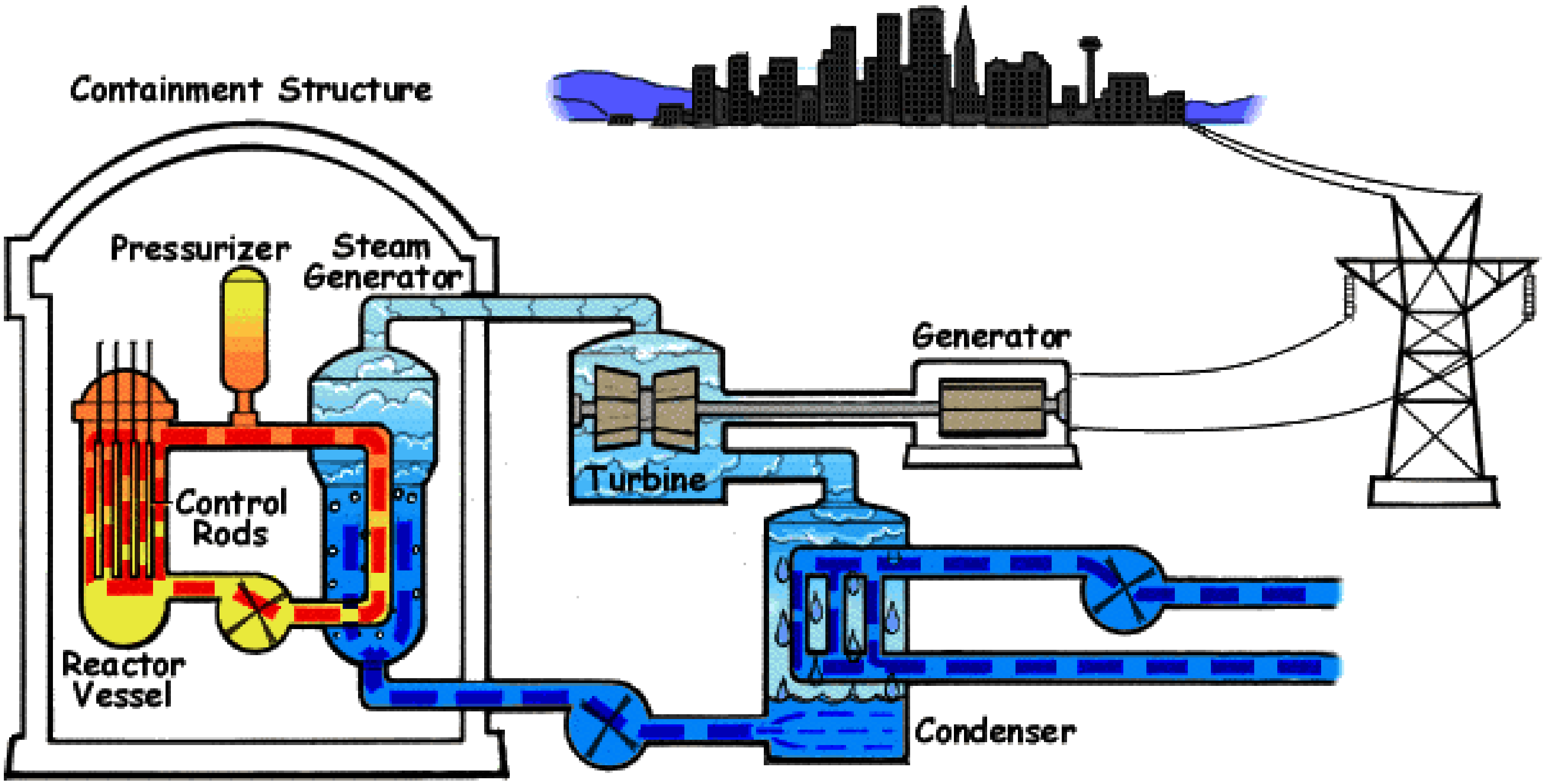
“Eighty-two percent of Americans living in close proximity to nuclear power plants favor nuclear energy, and 71 percent are willing to see a new reactor built near them, according to a new public opinion survey of more than 1,100 adults nationwide.” – NEI, September 2007

Basic Principles of Nuclear Reactor

- Simple device
  - Fissioning fuel releases energy in the “core”
  - Heat is transported away by a coolant which couples the heat source to a Rankine steam cycle
  - Very similar to a coal plant, with the exception of the combustion process
  - Main complication arises from the spent fuel, a mix of over 300 fission products



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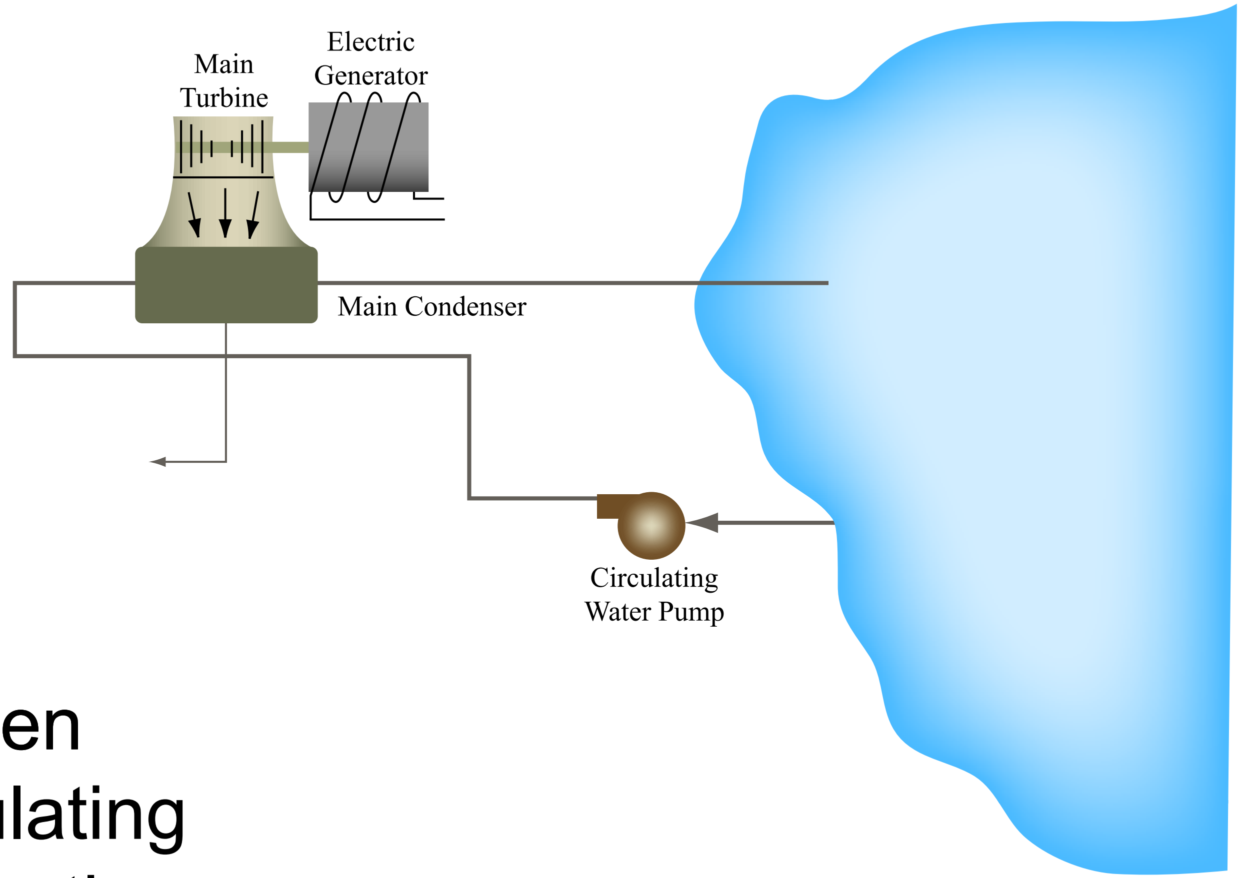

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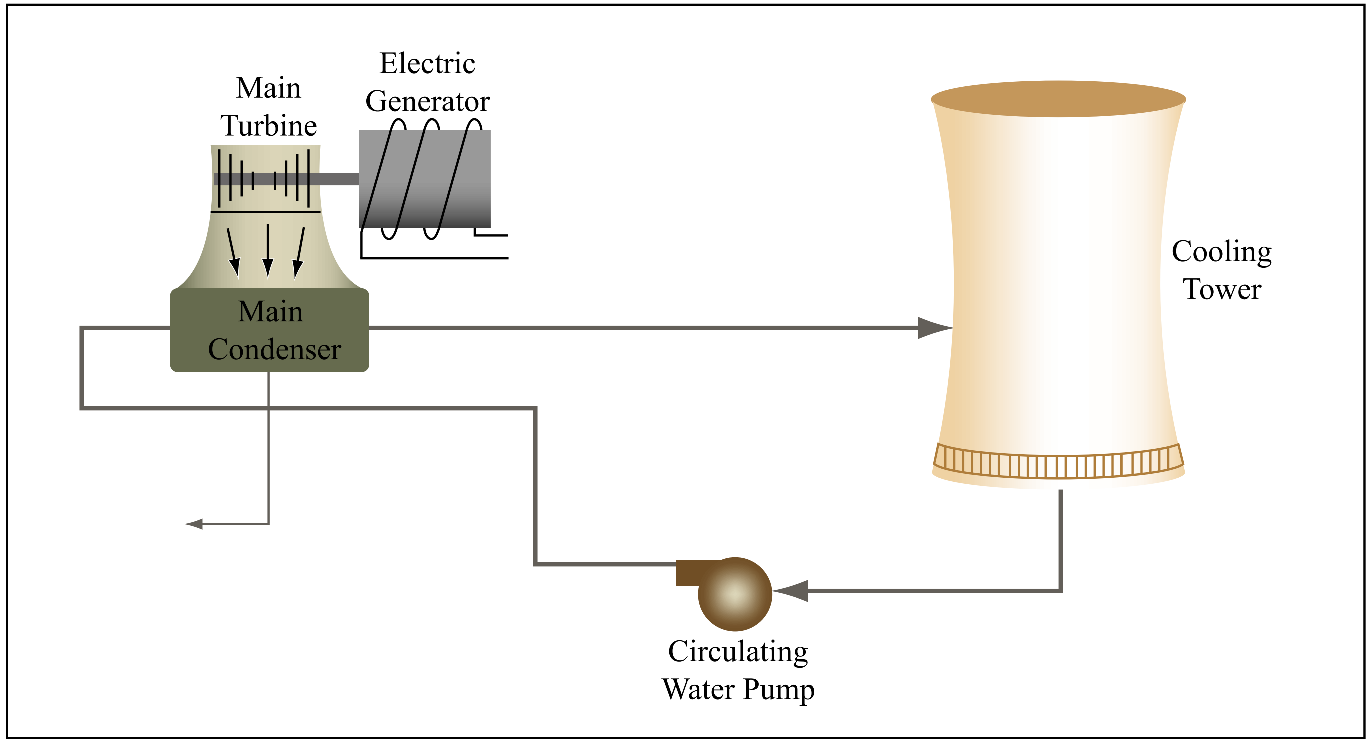
- Power plants will often discharge their circulating water directly back to the ocean
  - Strict environmental protection regulations
  - Temperature increases by 5-10 Farenheits



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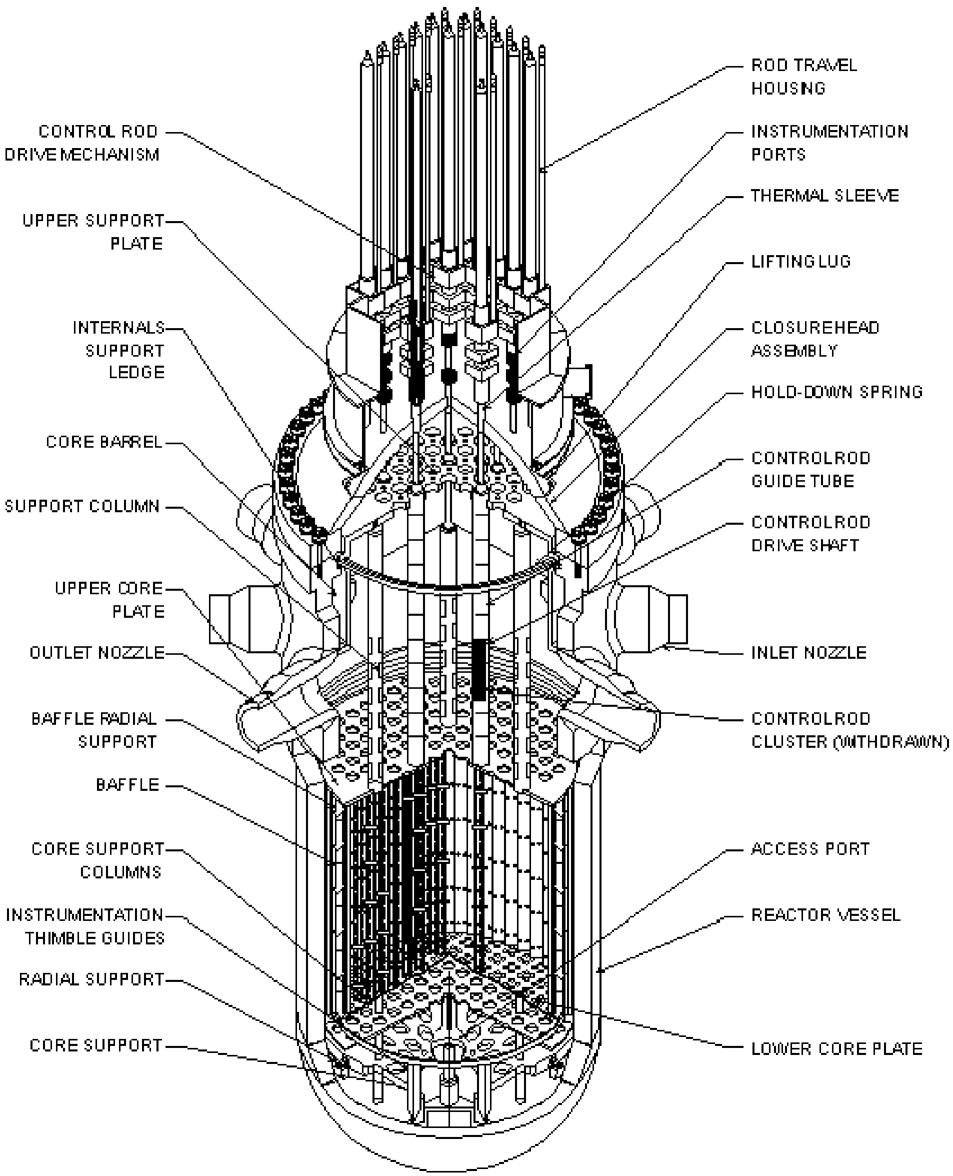
- If far from a water source, cooling towers are used to transfer the heat to air.
  - Water vapor is visible at the contact of the warm wet air inside the tower with the cool dry air outside

Reactors Concepts

- Fuel
  - Uranium
  - Plutonium
  - Thorium
- Moderator (optional)
  - Light water
  - Heavy water
  - Graphite
  - Be
- Coolant
  - Light water
  - Heavy water
  - Sodium
  - Molten salt
  - Helium
  - CO_2
  - Lead-Bismuth
  - …

Macroscopic to microscopic world



Cutaway of PWR pressure vessel and Internals.

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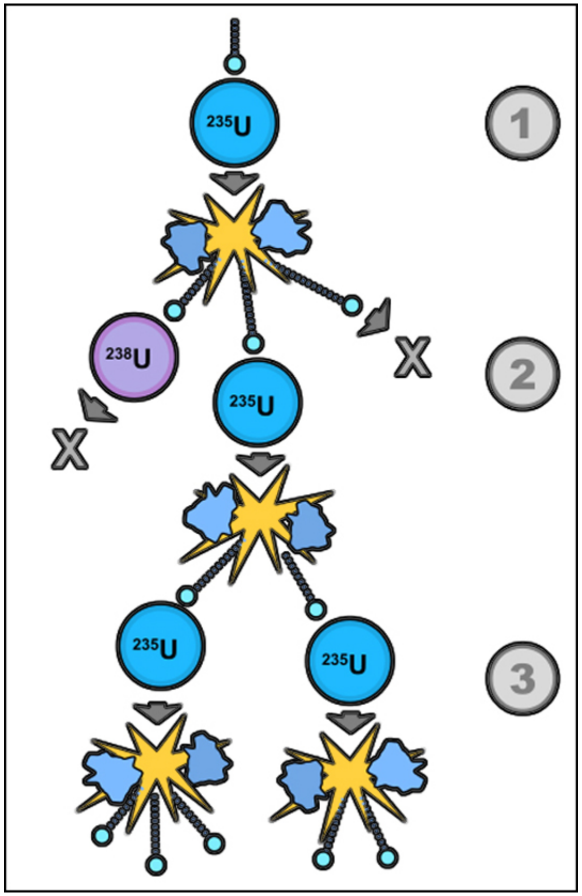
Fission chain reaction



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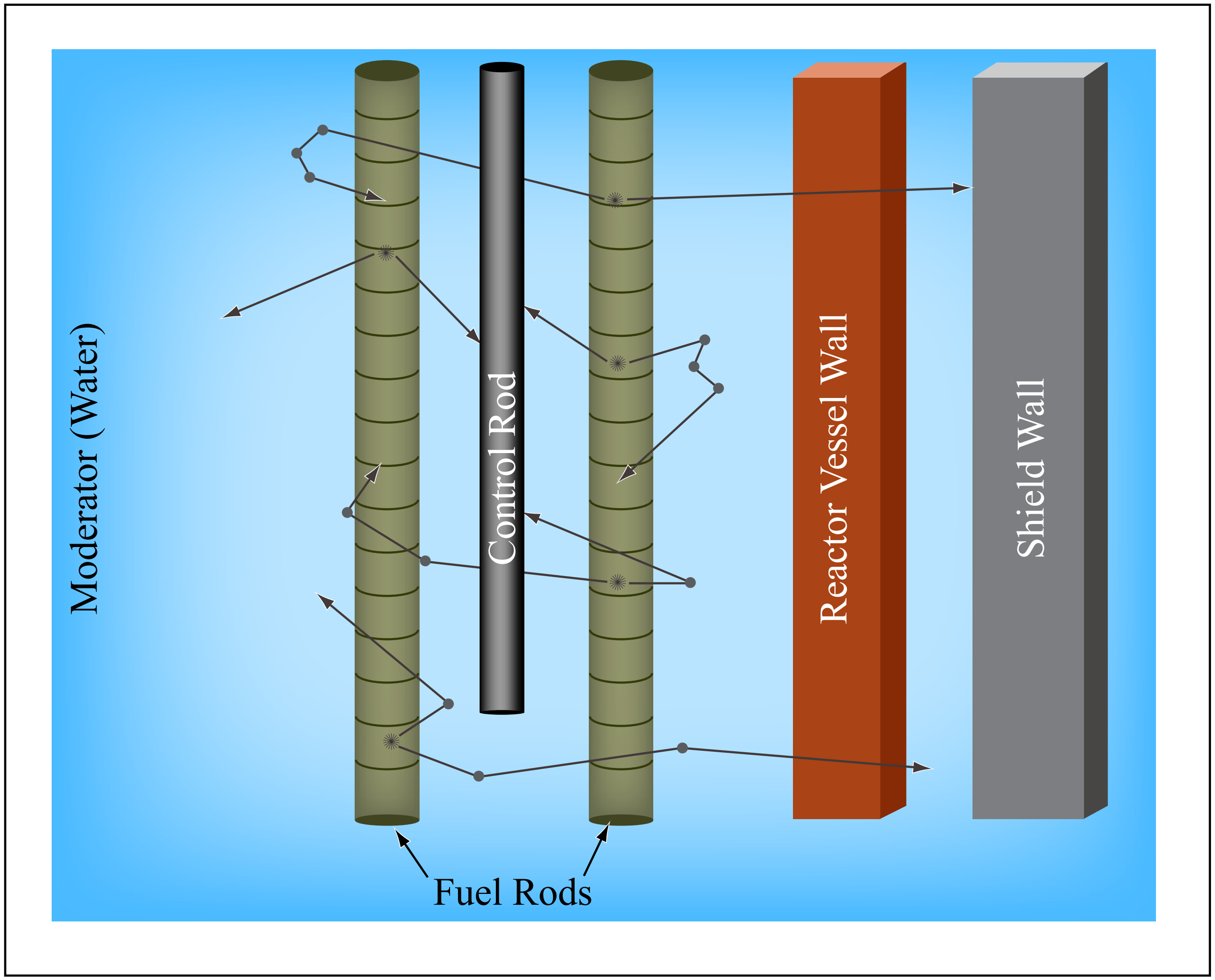
Neutrons in a reactor



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Nomenclature--Isotopes

$$ {}^{A}_{Z}X \text{ such as } {}^{12}_{6}C \text{ or } {}^{235}_{92}U $$

Z is the atomic number
A is the atomic mass
$N = A\text{-}Z$ is the number of neutrons
Nuclei with the same Z and different A are called isotopes.
E.g. ${}^{235}_{92}U$ and ${}^{238}_{92}U$

${}^{1}_{1}H$ and ${}^{2}_{1}H$ and ${}^{3}_{1}H$

Nuclear Stability

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- As Z increases, the long range Coulomb repulsion between protons is balanced by the presence of additional neutrons to provide additional short-range attractive nuclear forces.

Distribution of Stable Nuclides

A	Z	N	# nuclides
Even	Even	Even	159
Odd	Even	Odd	53
Odd	Odd	Even	50
Even	Odd	Odd	4
			266

Nuclear Collision Reactions

$$a + b \rightarrow c + d \qquad\qquad a(b,\ c)d$$

$${}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U + \gamma$$

$${}^{235}_{92}U\,(n,\gamma)\,{}^{236}_{92}U$$

Fundamental Laws

- Conservation of nucleons
  - Total “A” remains the same
- Conservation of charge
  - Total “Z” remains the same
- Conservation of momentum
- Conservation of Energy
  - Energy, including rest mass, is conserved

Rest Mass

$$E^2 - (pc)^2 = (mc^2)^2$$

- Mass is a characteristic of the total energy and momentum of an object or a system of objects that is the same in all frames of reference.

$$m_0 = E/c^2$$

- The invariant mass of the system is equal to the total system energy divided by c^2.

- This total energy in the center of momentum frame, is the **minimum** energy which the system may be observed to have.

Special Relativity Mass

$$m = \frac{m_0}{\sqrt{1 - {v^2}/{c^2}}}$$

- A body's mass increases when it is in motion with speed *v* relative to an observer at rest.

Q - value

Exothermic reaction produces energy
Endothermic reaction requires energy
An exothermic reaction is defined with Q < 0 therefore it is important to understand the concept:

$$E = mc^2$$

$$Q = [(M_a + M_b) - (M_c + M_d)]c^2$$

$$Q > 0 \quad \text{exothermic}$$

$$Q < 0 \quad \text{endothermic}$$

$$E_a + E_b + M_a c^2 + M_b c^2 = E_c + E_d + M_c c^2 + M_d c^2$$

Examples of Q-value

Exothermic

$$Q = [M\,({}^{9}_{4}\mathrm{Be}) + M\,({}^{4}_{2}\mathrm{He}) - M\,({}^{12}_{6}\mathrm{C}) - \mathrm{m}_n]\mathrm{c}^2$$

$$Q = [9.012182\mathrm{u} + 4.002603\mathrm{u} - 12.000000\mathrm{u} - 1.008664\mathrm{u}]931.5\mathrm{MeV/u}$$

$$Q = 5.702\mathrm{MeV}$$

$${}^{9}_{4}\mathrm{Be} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{12}_{6}\mathrm{C} + {}^{1}_{0}n$$

Examples of Q-value

Endothermic

$$Q = [M\,({}^{16}_{8}\mathrm{O}) + \mathrm{m}_n - M\,({}^{13}_{6}\mathrm{C}) - M({}^{4}_{2}\mathrm{He})]\mathrm{c}^2$$

$$Q = [15.994915\mathrm{u} + 1.008664\mathrm{u} - 13.003354\mathrm{u} - 4.002603\mathrm{u}]931.5\mathrm{MeV/u}$$

$$Q = -2.215\mathrm{MeV}$$

$${}^{16}_{8}\mathrm{O} + {}^{1}_{0}n \longrightarrow {}^{13}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He}$$

Examples of Q-value

$^{16}_{8}\mathrm{O}(n,p)^{16}_{7}\mathrm{N}$

- Assumption

$$Q = \left[m_n + M\left({}^{16}_{8}O\right) - M\left({}^{16}_{7}N\right) - m_p \right] c^2$$

- Why is this incorrect?

$${}^{1}_{0}n + {}^{16}_{8}O \rightarrow {}^{16}_{7}N + {}^{0}_{-1}e + {}^{1}_{1}p$$

- This is approximately equivalent to

$${}^{1}_{0}n + {}^{16}_{8}O \rightarrow {}^{16}_{7}N + {}^{1}_{1}H$$

$$Q = \left[m_n + M\left({}^{16}_{8}O\right) - M\left({}^{16}_{7}N\right) - M\left({}^{1}_{1}H\right) \right] c^2$$

Most important Reactions

An Example

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}n \rightarrow {}^{129}_{53}\mathrm{I} + {}^{104}_{39}\mathrm{Y} + 3\,{}^{1}_{0}n$$

Nuclear fission *(n, fission)*

$$^{1}_{0}n + {}^{A}_{Z}X \rightarrow {}^{A_1}_{Z_1}X + {}^{A_2}_{Z_2}X + neutrons + 200MeV$$

Radiative Capture

An Example

$$^{238}_{92}\mathrm{U} + {}^{1}_{0}n \rightarrow ({}^{239}_{92}\mathrm{U})^* \rightarrow {}^{239}_{92}\mathrm{U} + {}^{0}_{0}\gamma$$

Radiative capture *(n, γ)*

$${}^{1}_{0}n + {}^{A}_{Z}X \rightarrow \left({}^{A+1}_{Z}X\right)^* \rightarrow {}^{A+1}_{Z}X + \gamma$$

Scattering

Examples

elastic $^{12}_{6}\mathrm{C} + ^{1}_{0}n \rightarrow ^{12}_{6}\mathrm{C} + ^{1}_{0}n$

inelastic $(^{240}_{94}\mathrm{Pu} + ^{1}_{0}n \rightarrow ^{240}_{94}\mathrm{Pu})^{*} + ^{1}_{0}n \rightarrow ^{240}_{94}\mathrm{Pu} + ^{0}_{0}\gamma + ^{1}_{0}n$

Scattering (n, n) or (n, n')

$$^{1}_{0}n + ^{A}_{Z}X \rightarrow ^{1}_{0}n + ^{A}_{Z}X$$ elastic scattering (n,n)

$$^{1}_{0}n + ^{A}_{Z}X \rightarrow ^{1}_{0}n + \left(^{A}_{Z}X\right)^{*} \rightarrow ^{1}_{0}n + ^{A}_{Z}X + \gamma$$

inelastic scattering (n,n')

Beta decay

When the weak interaction converts a neutron into a proton and emits an electron and an anti-neutrino, Beta (minus) decay occurs. This happens when an atom has an excess of neutrons.

$$_{Z}^{A}X \rightarrow \, _{-1}^{0}e + \, _{Z+1}^{A}Y + \overline{\upsilon} + Energy$$

$$_{55}^{137}\mathrm{Cs} \longrightarrow \, _{56}^{137}\mathrm{Ba} + \, _{-1}^{0}\mathrm{e} + \overline{\upsilon}$$

Positron Emission

- Positron emission cannot occur in isolation unlike Beta decay. This happens because it requires energy (the mass of the neutron is greater than the mass of the proton).
- Positron emission happens inside the nuclei when the absolute value of the binding energy of the mother nucleus is lower than that of the daughter nucleus.

$$ {}^{A}_{Z}X + Energy \rightarrow {}^{A}_{Z\text{-}1}Y + {}^{0}_{1}e + \upsilon $$

$$ {}^{22}_{11}\mathrm{Na} \rightarrow {}^{22}_{10}\mathrm{Ne} + {}^{0}_{1}e + \upsilon $$

Capture of Electron

$$^{A}_{Z}X + {}^{0}_{-1}e + Energy \rightarrow {}^{A}_{Z\text{-}1}Y + \upsilon$$

- In cases where ß+ decay is allowed energetically, it is accompanied by the electron capture process.

$$^{22}_{11}\mathrm{Na} + {}^{0}_{-1}e \rightarrow {}^{22}_{10}\mathrm{Ne} + \upsilon$$

- If the energy difference between initial and final states is low (less than $2m_ec^2$), then β+ decay is not energetically possible and electron capture is the sole mode decay.

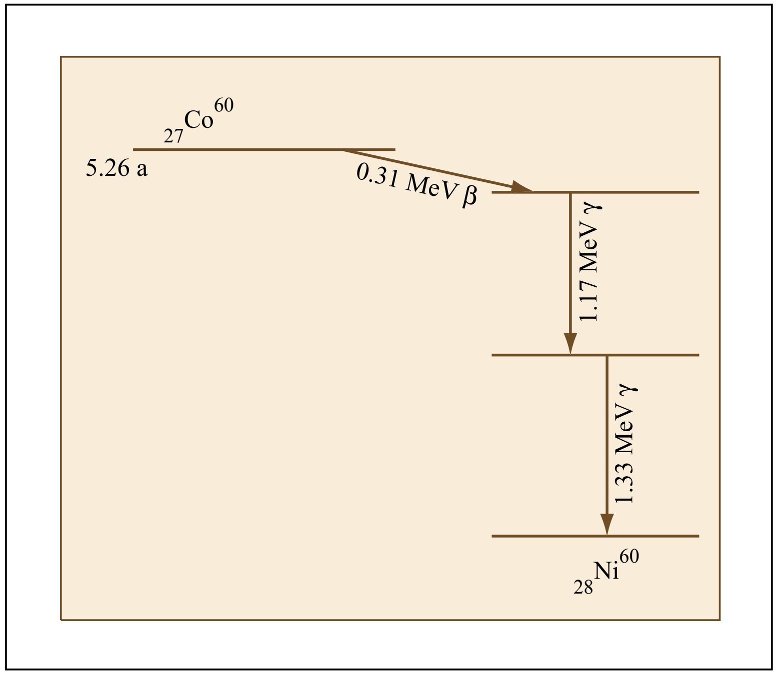
Alpha Decay

- Coulomb repulsion increases ~ Z^2
- Alpha decay occures only in heavy atoms (A > 100 amu)
- Alpha particle has small mass relative to parent nucleus and has very high binding energy
- Nuclear binding force increases ~ A

$$ {}^{A}_{Z}X \longrightarrow \alpha + {}^{A\text{-}4}_{Z\text{-}2}Y + Energy $$

$$ {}^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{Th} + a $$

Gamma decay



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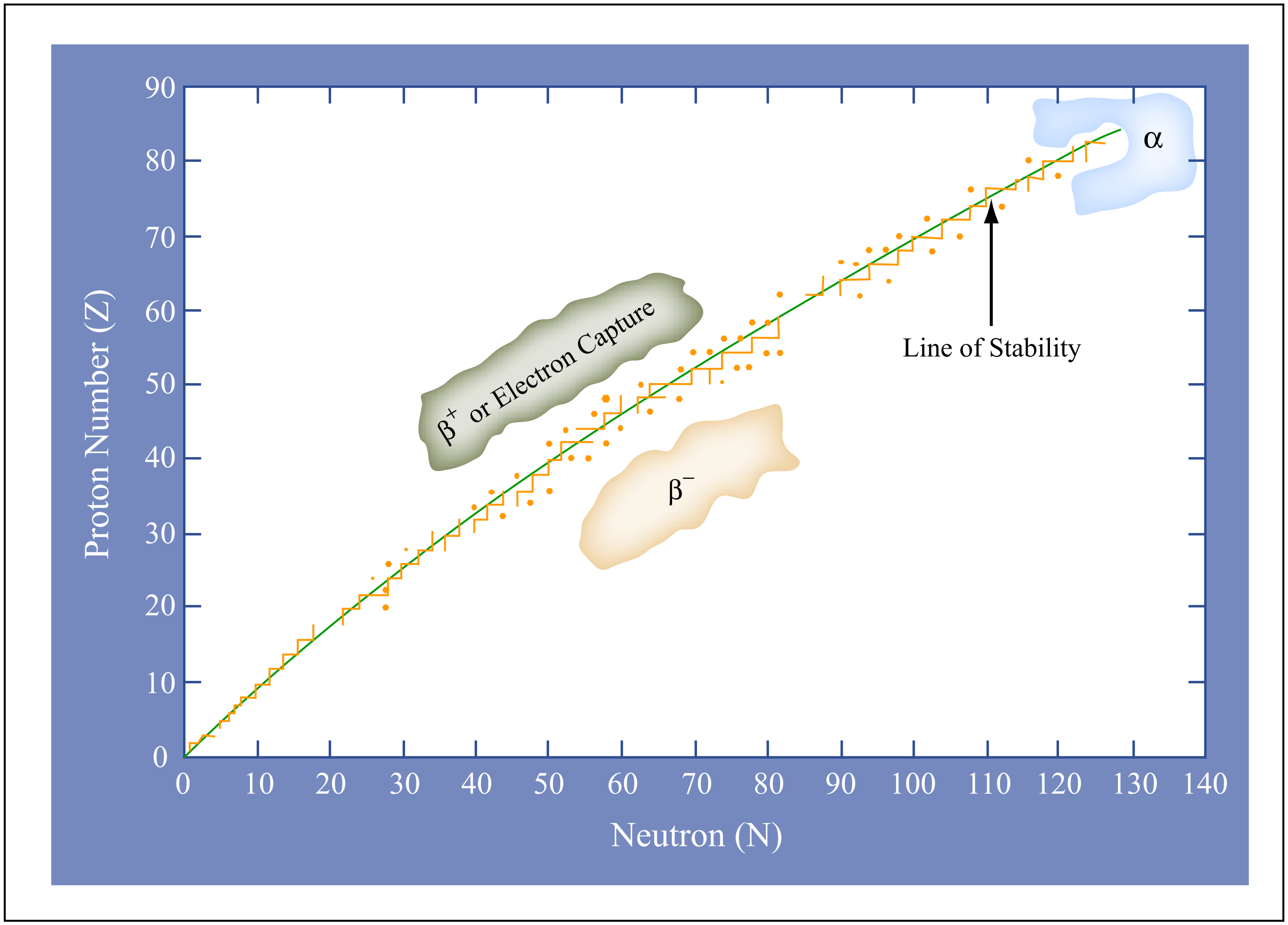
- Gamma decay is the emission of a gamma ray (photon) from a nucleus
- Occurs when nucleus transitions from a higher to lower energy state
- Energy of photon(s) equal to the change in energy of nuclear states
- Nuclear structure does not change so parent and daughter are the same

Predicting type of decay



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Binding Energy

$$\Delta = ZM_p + NM_n - M_X$$

- The weights of these constituent masses exceeds the weight of the nucleus if we add the masses of Z protons and N neutrons that make up a nucleus. The difference is the **mass defect** which is positive for all nuclides. Multiplying by c^2 yields the binding energy of the nucleus.
- When the nucleus is formed, the loss in mass is due to the conversion of mass to **binding energy**. It is defined as the energy that is supplied to a nucleus to completely separate its nucleons.
- A measure of nuclear stability is obtained when the binding energy is normalized to the number of nucleons.

Calculate mass defect and binding energy for uranium-235

Mass of neutron 1.008665 amu

Mass of proton 1.007826 amu

Mass of one atom of U-235 235.043924

Binding energy = mass defect x c^2

- Mass defect = 1.91517 amu

- BE = 1.91517 amu x 931.5 MeV / 1 amu
- BE = 1784 MeV

1 amu = 1.66054 x 10^{-27}kg = 931.5 MeV / c^2

Binding Energy Curve

- Exothermic reactions result in reaction products with higher binding energy
- Two options
  - Fission of heavy nuclides
  - Fusion of light nuclides

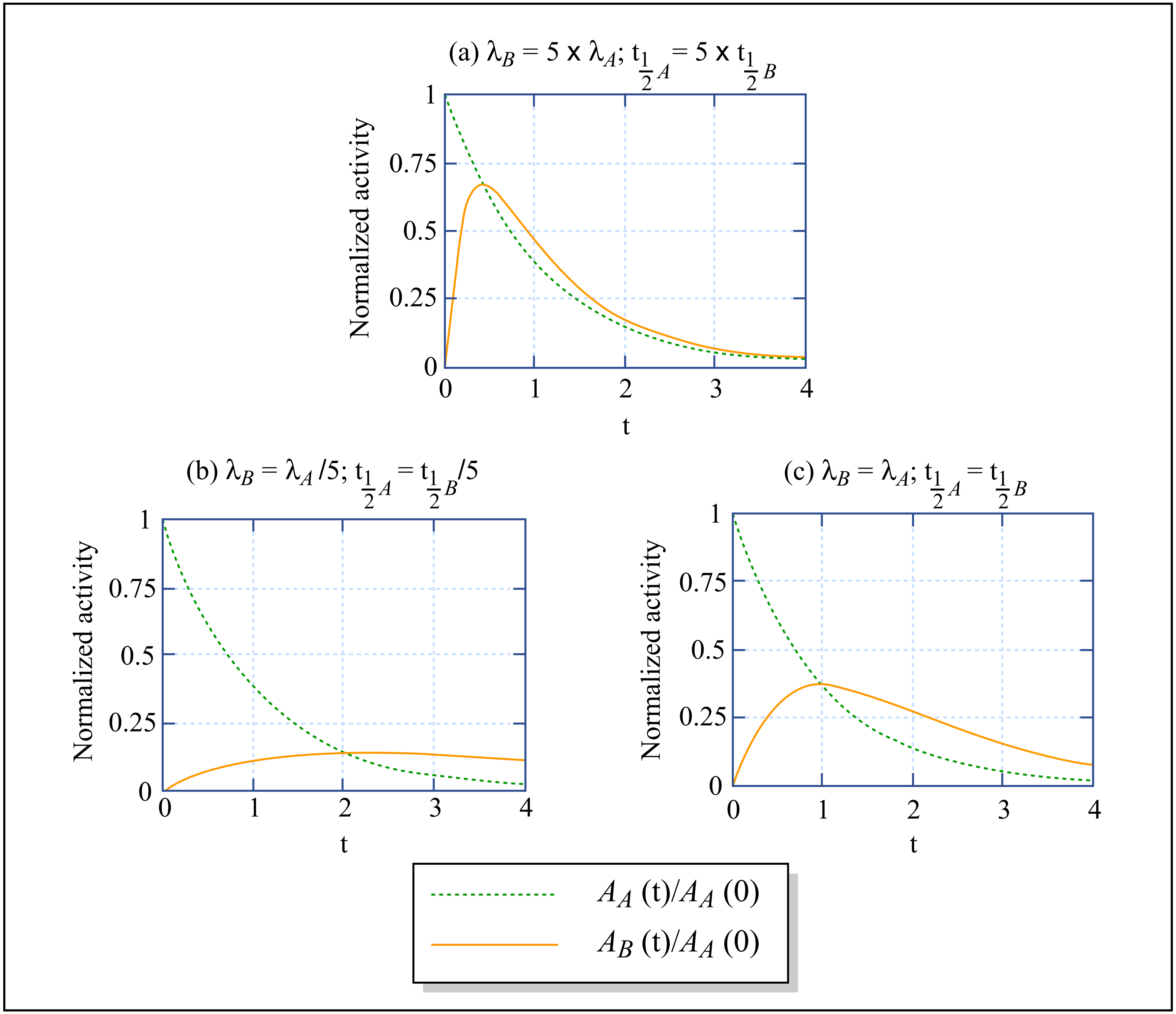
First-Order ODE - Review

- Appendix A of Lewis + Handout

Radioactive Decay

- Lewis, Section 1.7

Decay chain



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Decay Chains

- Definition of Decay Chain: The radioactive decay of different discrete radioactive decay products as a chained series of transformations.
- Decay Chains
  - Thorium series or 4n
  - Neptunium series or 4n + 1
  - Uranium or Radium series 4n + 2
  - Actinium series or 4n + 3

Chart of Nuclides

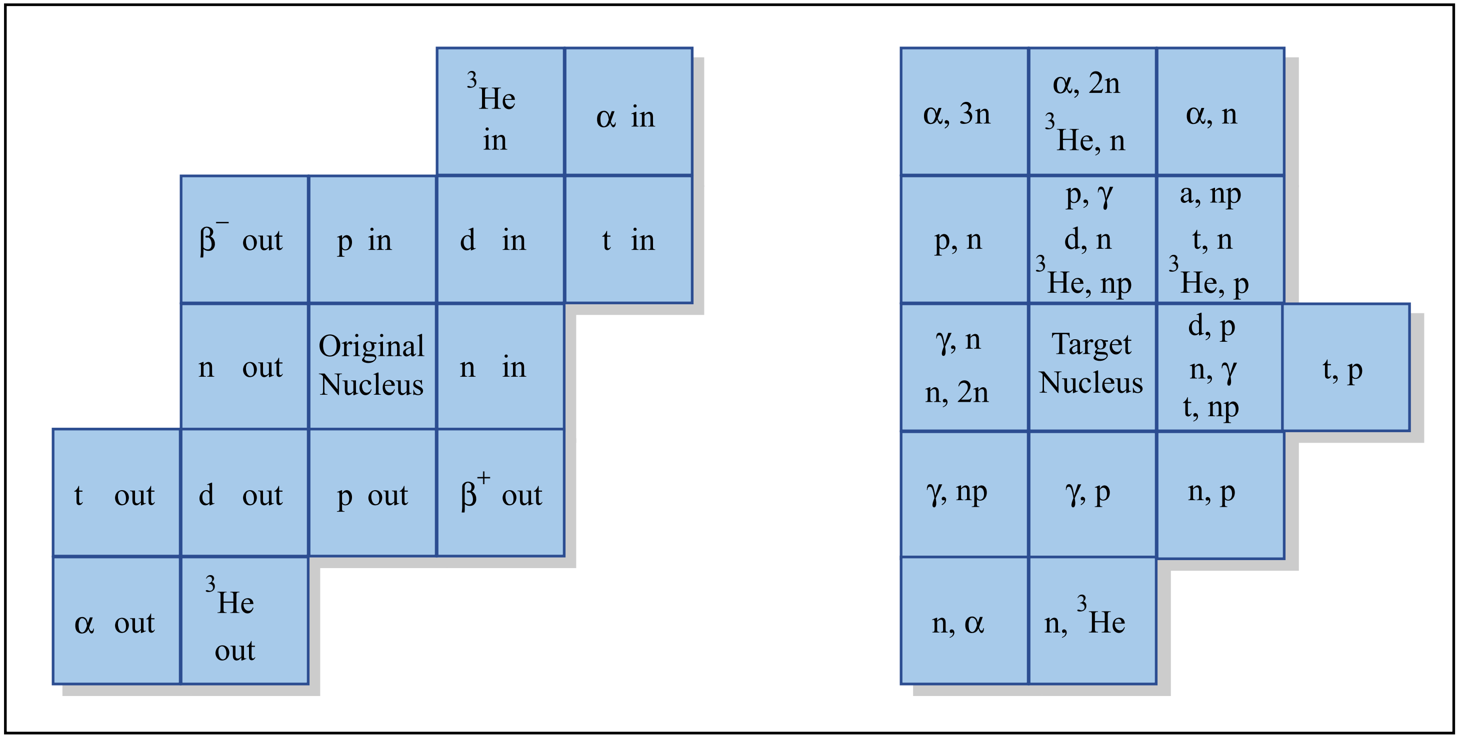

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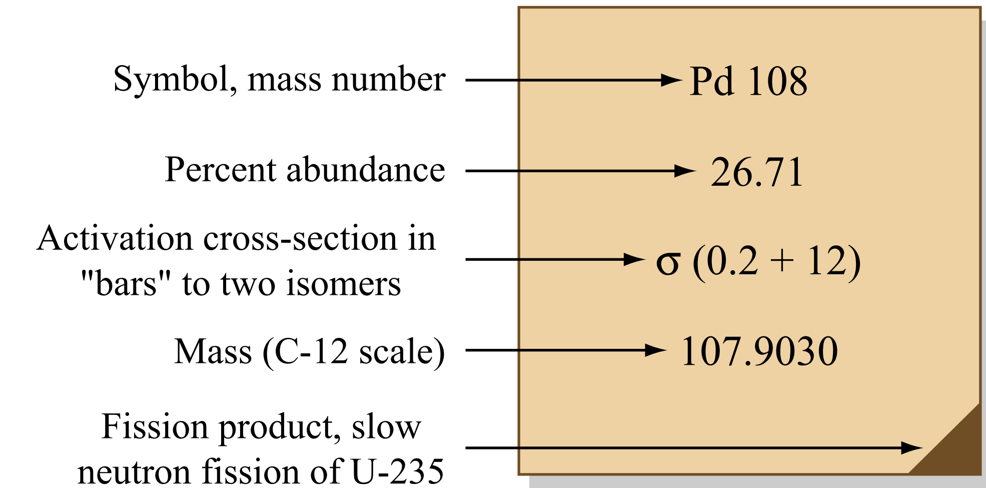
Chart of Nuclides

- Gray shaded square (stable nuclide)



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- White or "color" square: (Artificially Produced Radioactive Nuclide)

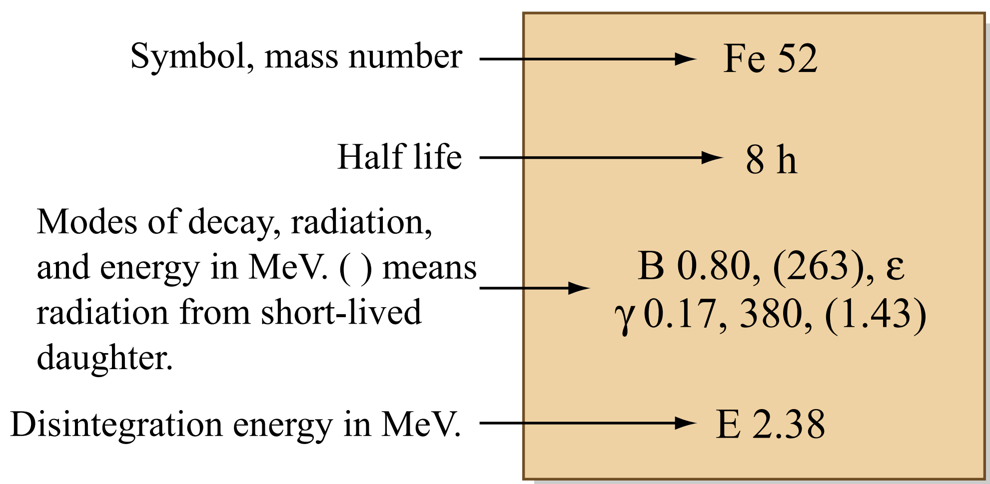

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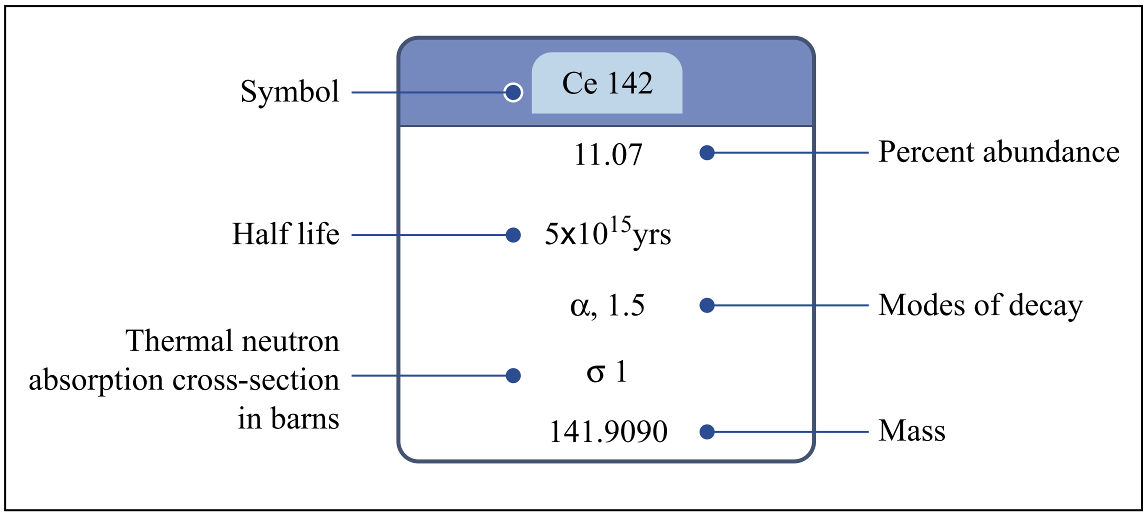
Chart of Nuclides

- Black rectangles across the top of square
  - On gray-shaded square: Radioactive nuclide with long half life (Considered Stable)



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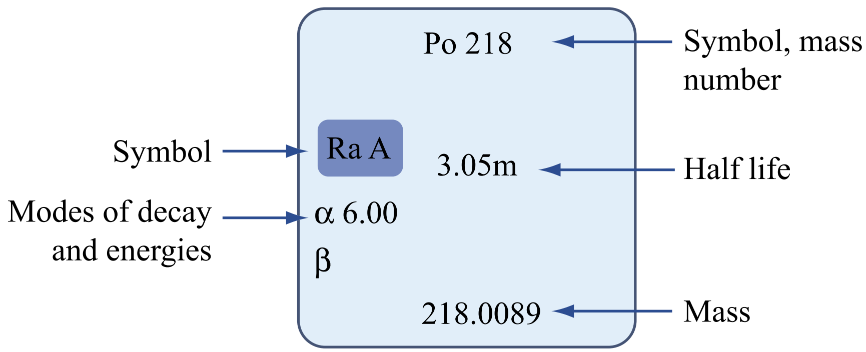
  - On white square: Radioactive nuclide found in nature with relatively short half life

Chart of Nuclides

- Smaller black rectangle near top of square (**Nuclide is a member of a natural radioactive decay chain)**



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- Black triangle at bottom corner of square (**nuclide is formed by fission of U-235 or Pu-239**)

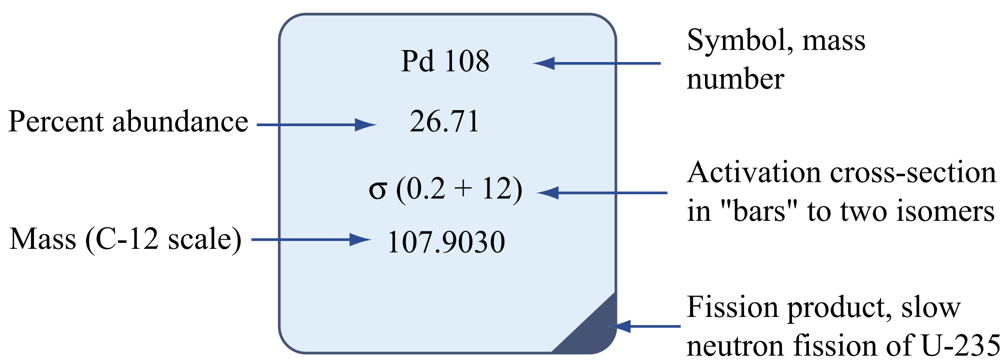

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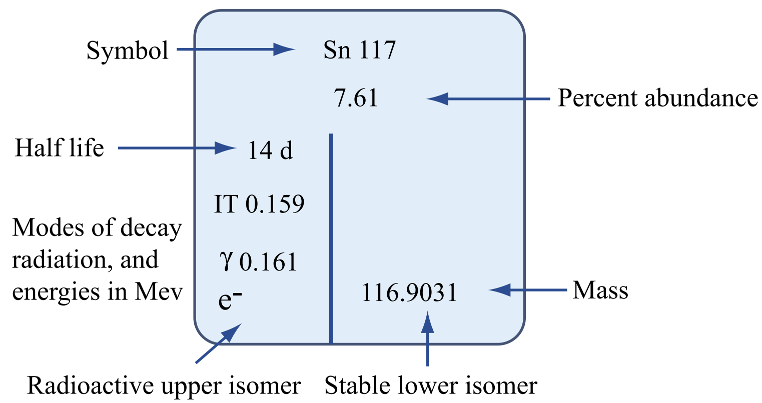
Chart of Nuclides

- Vertically divided square
  - Two isomeric states, one stable



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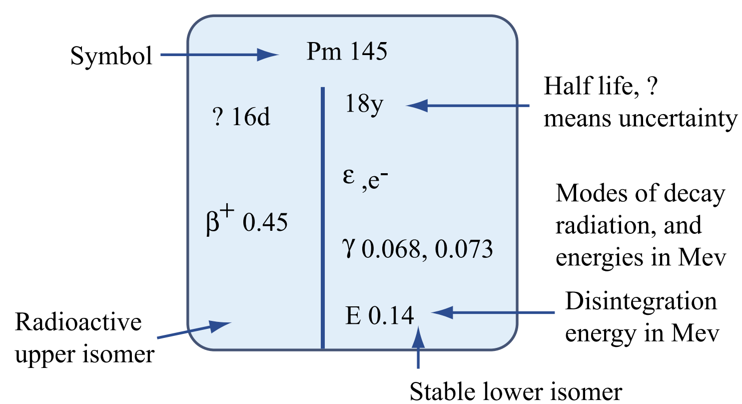
  - Two isomeric states, both radioactive



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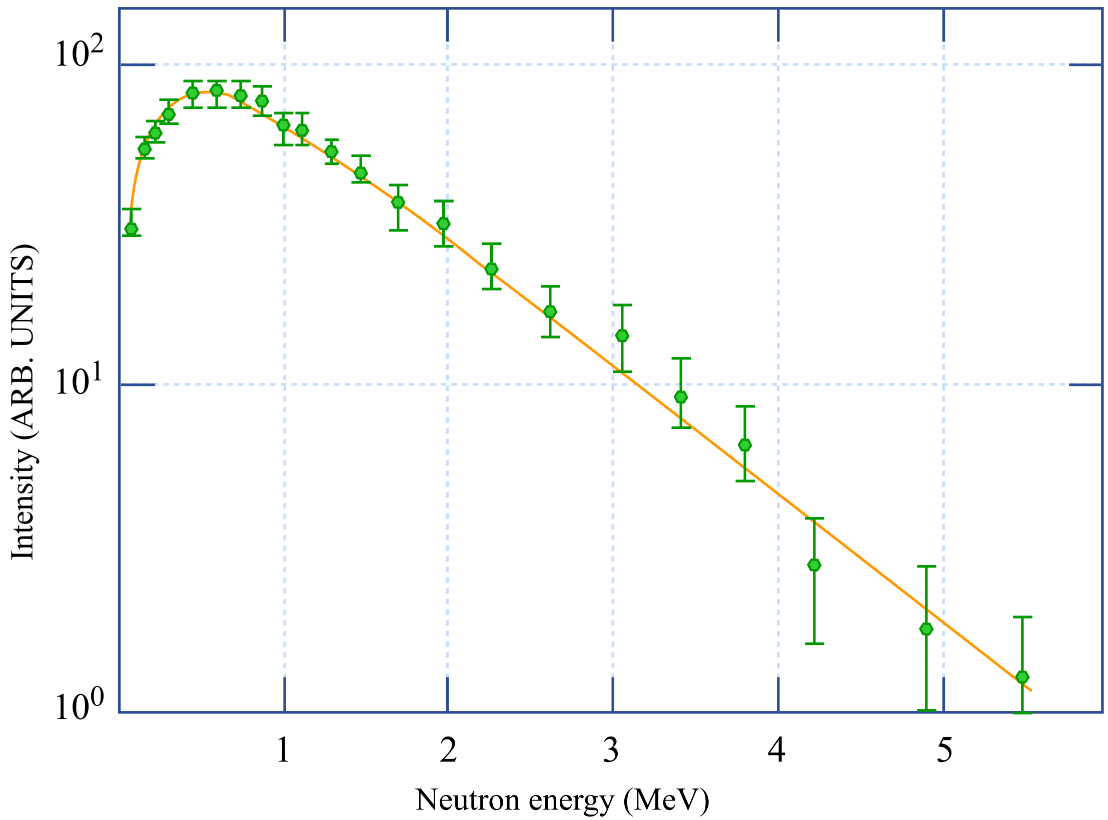
Neutron Sources

- Definition of Spontaneous Fission

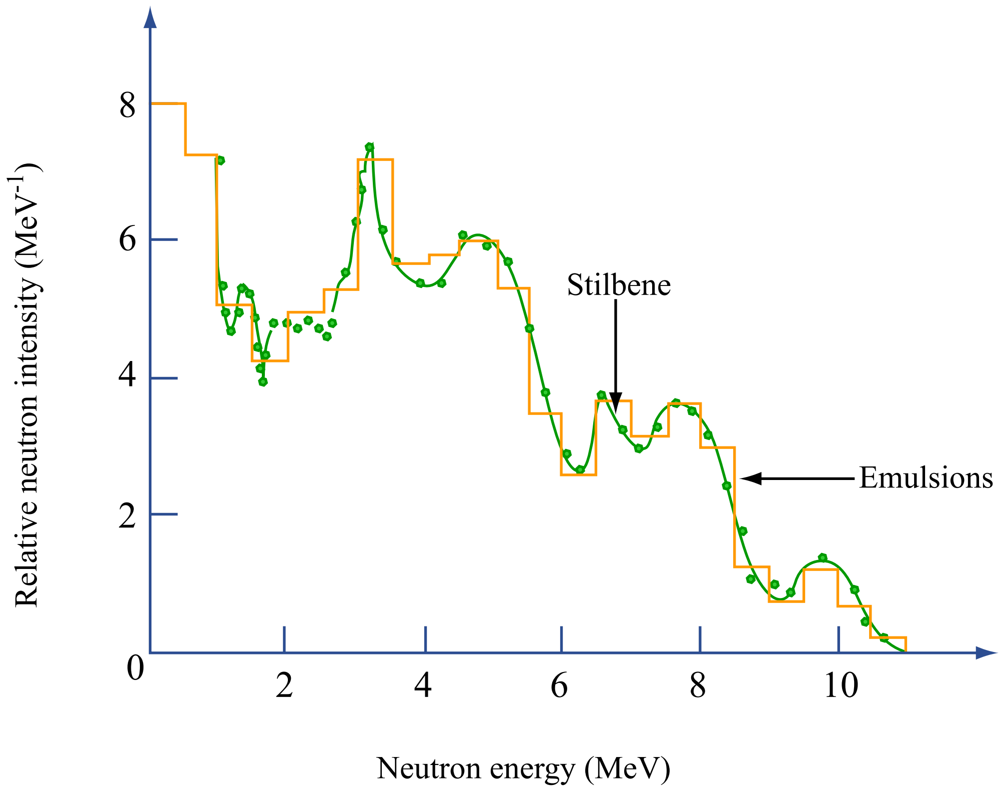
  Spontaneous fission (SF) is a form of radioactive decay characteristic for very heavy isotopes. In practice, only energetically feasible for atomic masses above 230 amu. It is theoretically possible for any atomic nucleus with mass >= 100 amu.

  - Radioisotopes for which spontaneous fission is a nonnegligible decay mode may be used as neutron sources notably Cf-252 (half-life 2.645 years, SF branch ratio 3.09%)



Measured neutron energy spectrum from the spontaneous fission of ^{252}Cf.

- Alpha Neutron Source
  - Neutrons are produced when alpha particles impinge upon any of several low atomic weight isotopes
    - beryllium, carbon and oxygen
    - Must have loosely bound neutron
  - Alpha emitters must be long-lived
    - Radium, polonium, plutonium, americium
  - The low A material and alpha emitter are usually mixed in powdered form
  - Typical emission rates for alpha reaction neutron sources range from 1×10^6 to 1×10^8 neutrons per second.
  - The size and cost of these neutron sources are also comparable to spontaneous fission sources.
  - Usual combinations of materials are plutonium-beryllium (PuBe), americium-beryllium (AmBe), or americium-lithium (AmLi)
  - Radium is not used as much now because of its high gamma emission rate



Measured energy spectra for neutrons from a ^{239} Pu/Be source containing 80g of the isotope.

- Photoneutrons
  - A photon that is absorbed by the nucleus creates an excited state from which a neutron is emitted. There are two such sources:

  - ^{9}Be + >1.7 Mev photon → 1 neutron + 2 ^{4}He
  - ^{2}H (deuterium) + >2.26 MeV photon → 1 neutron + ^{1}H

  - The resulting neutron energies are discrete if the photons are monoenergetic. Roughly, one gamma ray in 106 interacts. So, the gamma ray source needs to be very large (as in a fission reactor) for these sources to be appreciable. The most common use is the deuterium reaction as a source of neutrons for the startup of light-water reactors. The source of the photons would be fission products. (Note: Sufficient D_2O exists in light water for this source to be effective in LWRs.)

- Accelerated charged particles
- Fission
- Fusion
- …

Fission

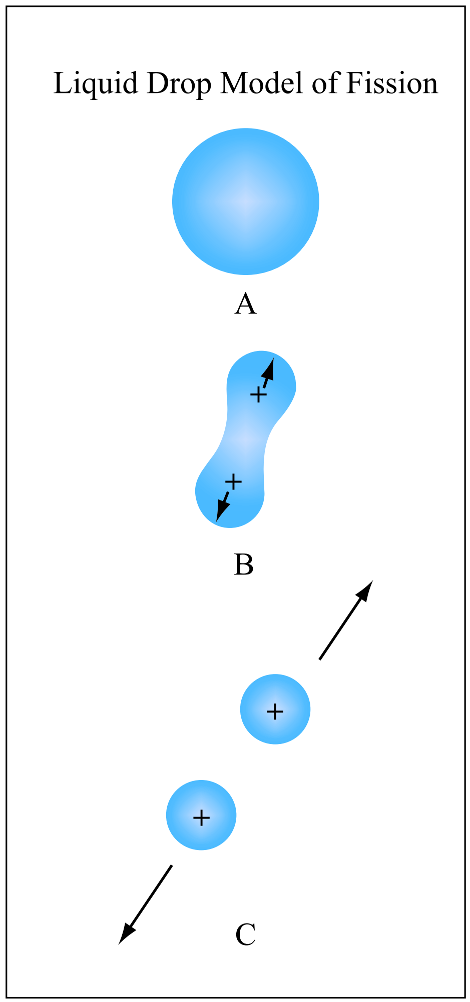
- Consider the following example of U-235 fission

- From binding energy curve, energy released is about ~200 MeV (235*(8.9 – 8))
  – Most of the energy leaves in the form of kinetic energy of the fission products
  – Rest goes to particles emitted during fission

- A distinction must be made between energy produced and energy recuperated
  - Fission products are large ionized particles that travel a short distance, thus energy is deposited locally
  - The electrons released by beta decay of the fission products are also absorbed locally.
  - The gamma rays (photons) travel much greater distances and are sometimes absorbed by the reactor shield.
  - The neutrinos escape entirely

	Energy Released	Energy Recuperated
Fission Products	168	168
Beta (FP)	8	8
Gamma (FP)	7	7
Neutrinos	~12	-
Prompt Gammas	7.5	7
Prompt Neutrons	5	5
(n, gamma)	-	3-12
	~207	198-207

- For fission to occur, we must provide some energy to the nucleus. A potential barrier exists that prevents spontaneous fission from happening very frequently.
- Liquid drop model: A water drop doesn’t separate in two spontaneously even if its energetically favorable. The superficial tension of the drop acts as a barrier that tries to keep the fragments from splitting.



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- In nuclear fission, the short nuclear bonds of the nucleons keeps the nucleus together. Initially, the potential energy of the nucleus is equal to the binding energy of the nucleons (no kinetic energy). To deform the nucleus, energy must be provided in an effort to increase the average distance between the nucleons, thus increasing the potential energy of the nucleus. However, the strong nuclear forces are very short. Thus when the separation starts, the repulsive forces diminish and the potential energy diminishes as well. There is thus a threshold energy required (about 6 MeV) for fission
- Quantum mechanics also explains how spontaneous fission can happen, but with very-low probability, thru a tunnelling effect without any energy input.

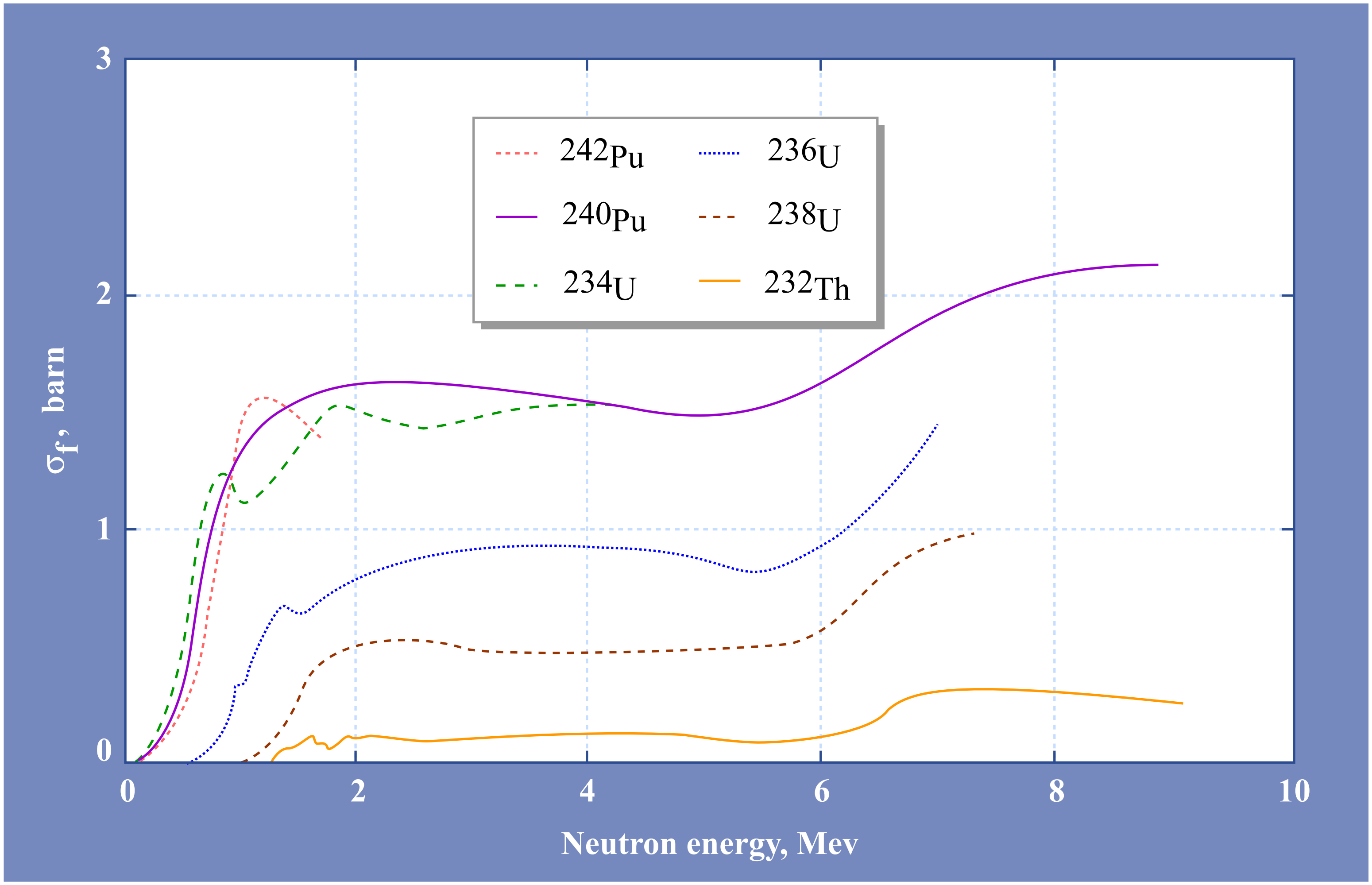
- When a neutron interacts with a nuclide, it forms a compound nucleus. Energy is given to the nucleus by the binding energy of the incident neutron and its kinetic energy
  – If the binding energy is sufficient to get above the fission threshold of the nuclide, than the nuclide is fissile to thermal neutrons
  – If it requires additional kinetic energy, than it is said to be fissile to fast neutrons or fissionable
- Fissile nuclides
  – U-235: only naturally occurring fissile isotope
  – Pu-239: radiative capture of U-238
  – U-233: radiative capture of Th-232
  – Pu-241: radiative capture of Pu-240

Critical Energy

Critical Energies Compared to Binding Energy of Last Neutron

Target Nucleus	Critical Energy E_{crit}	Binding Energy of Last Neutron BE_n	$BE_n - E_{crit}$
$^{232}_{90}Th$	7.5 MeV	5.4 MeV	-2.1 MeV
$^{238}_{92}U$	7.0 MeV	5.5 MeV	-1.5 MeV
$^{235}_{92}U$	6.5 MeV	6.8 MeV	+0.3 MeV
$^{233}_{92}U$	6.0 MeV	7.0 MeV	+1.0 MeV
$^{239}_{94}Pu$	5.0 MeV	6.6 MeV	+1.6 MeV

Fission cross sections for fissionable nuclei



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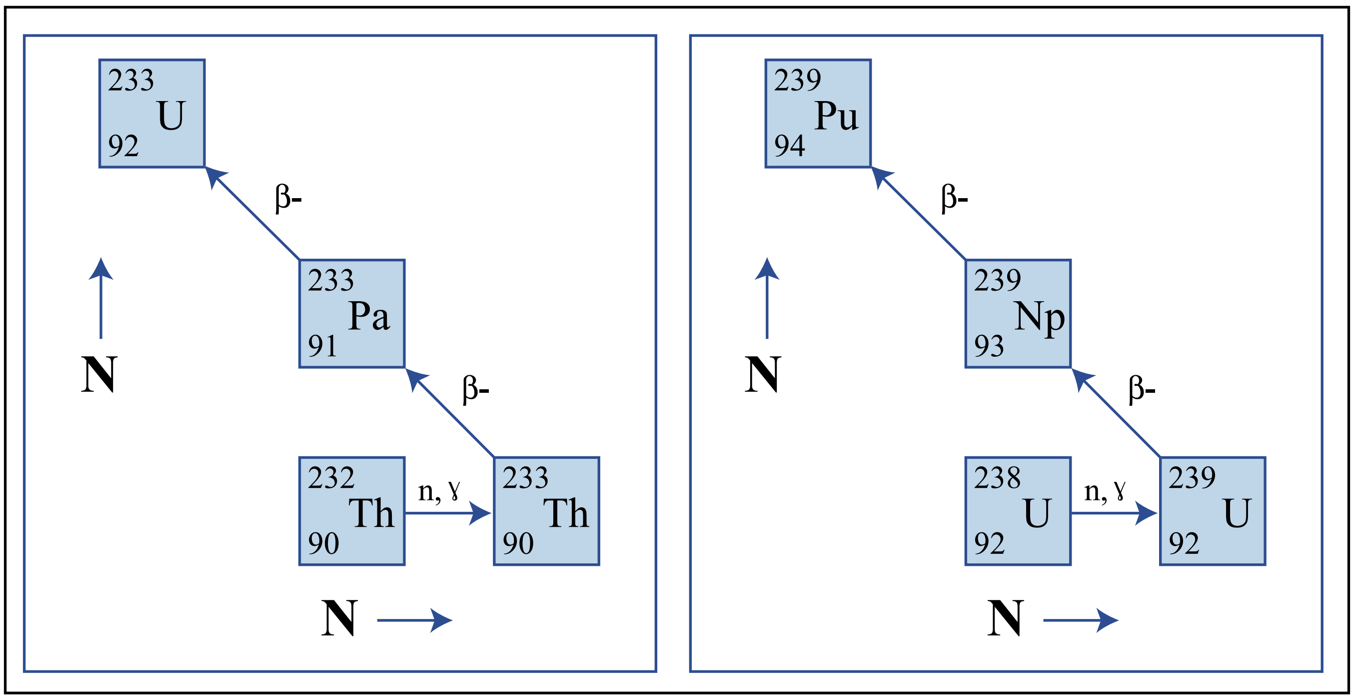
Fertile Materials

- Materials that can undergo transmutation to become fissile materials.



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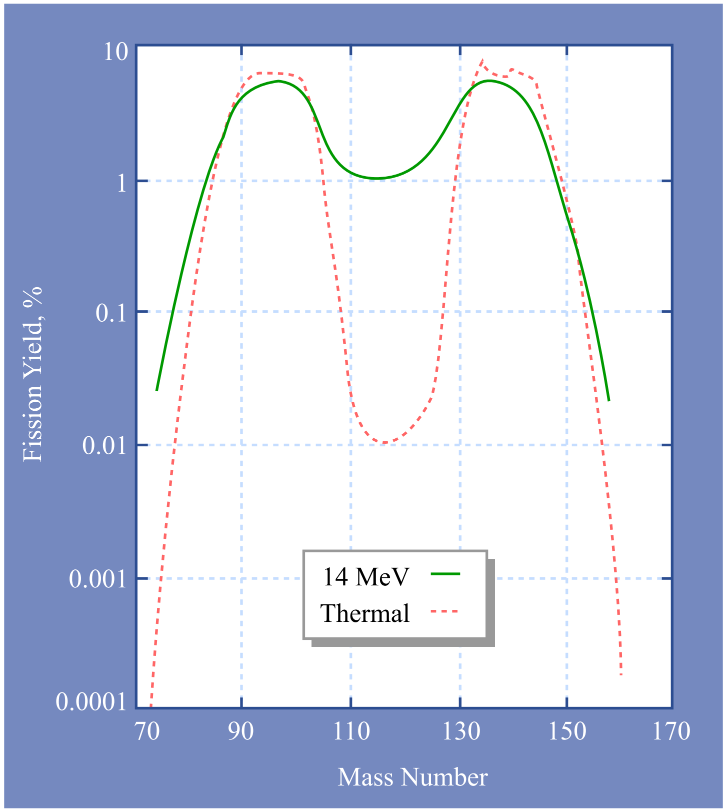
Fission Products

- Generally observe only two fission fragments
  – Note the logarithmic scale



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Stability of fission products

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- Neutron rich fission products beta decay towards stability

Criticality – Neutron Multiplication

$$k \equiv \text{multiplication factor} \equiv \frac{\text{number of neutrons in one generation}}{\text{number of neutrons in preceding generation}}$$

- Critical, k=1
- Sub-critical k<1
- Super-critical k>1

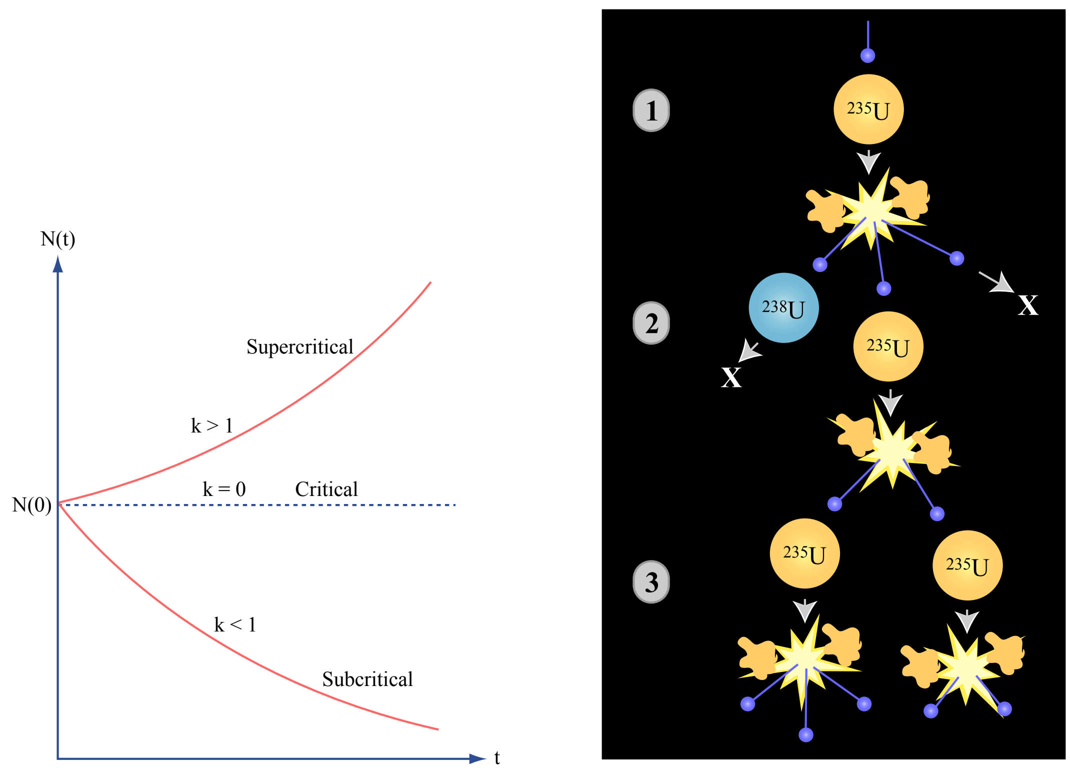


Image by MIT OpenCourseWare.

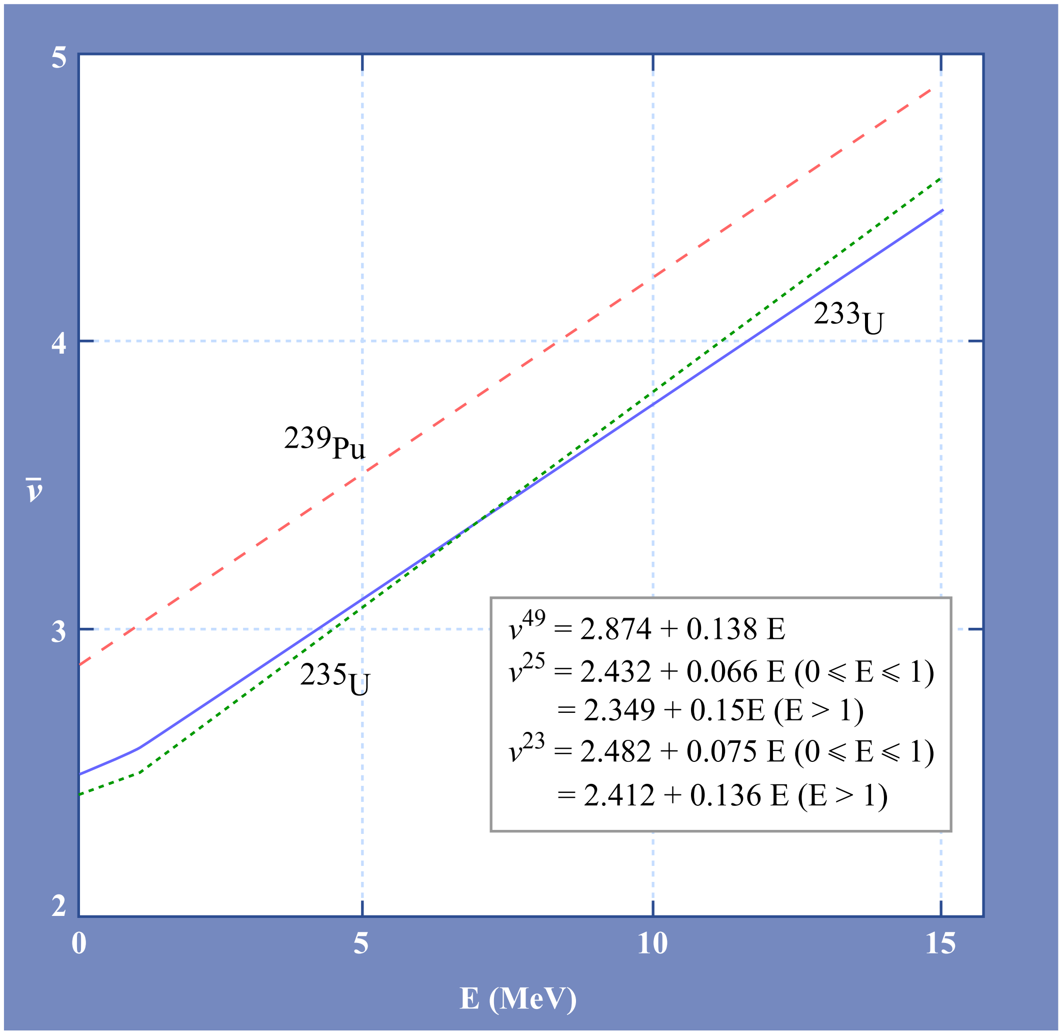
Neutron generation

- Lewis, p.12

Neutrons released from fission

- Prompt
  - Spectra
  - Average energy
- Delayed
  - Delay discussion to kinetics

Neutrons released from fission



ν

Pu-239 produces more neutrons per fission than U-235.

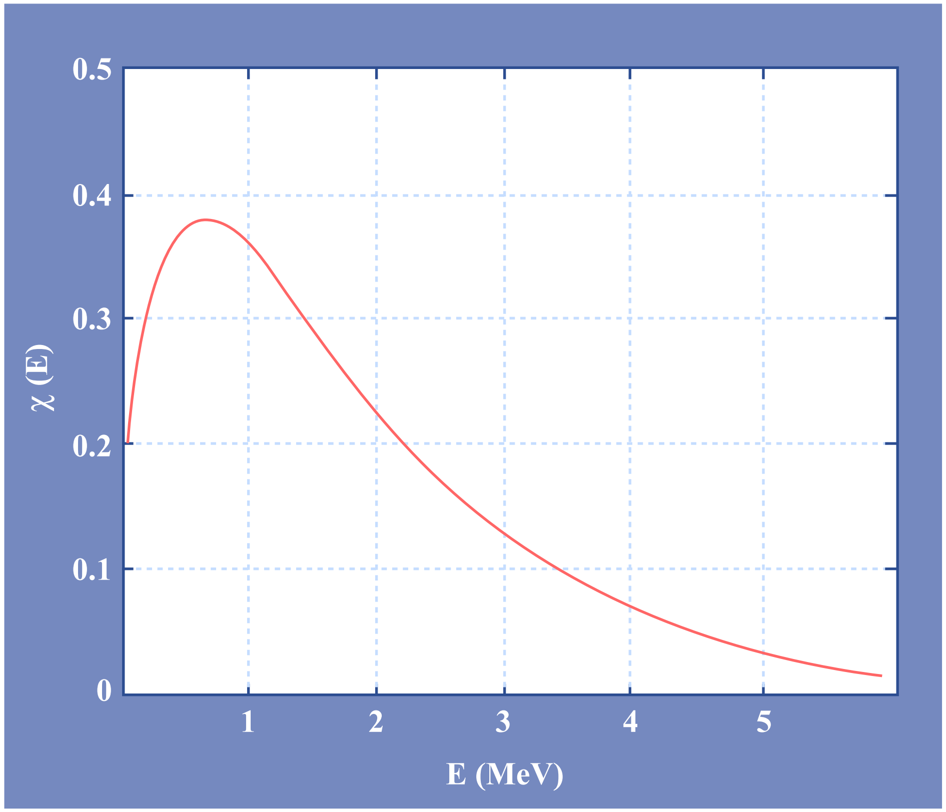
***ν*(E)=average number of neutrons produced per fission**

Image by MIT OpenCourseWare.

Fission prompt neutron energy spectrum

$$\chi(E) = 0.453e^{-1.036E} \sinh\sqrt{2.29E}$$

$\chi(E)dE \equiv$
Average number of fission neutrons emitted with energy in E to $E+dE$ per fission neutron.



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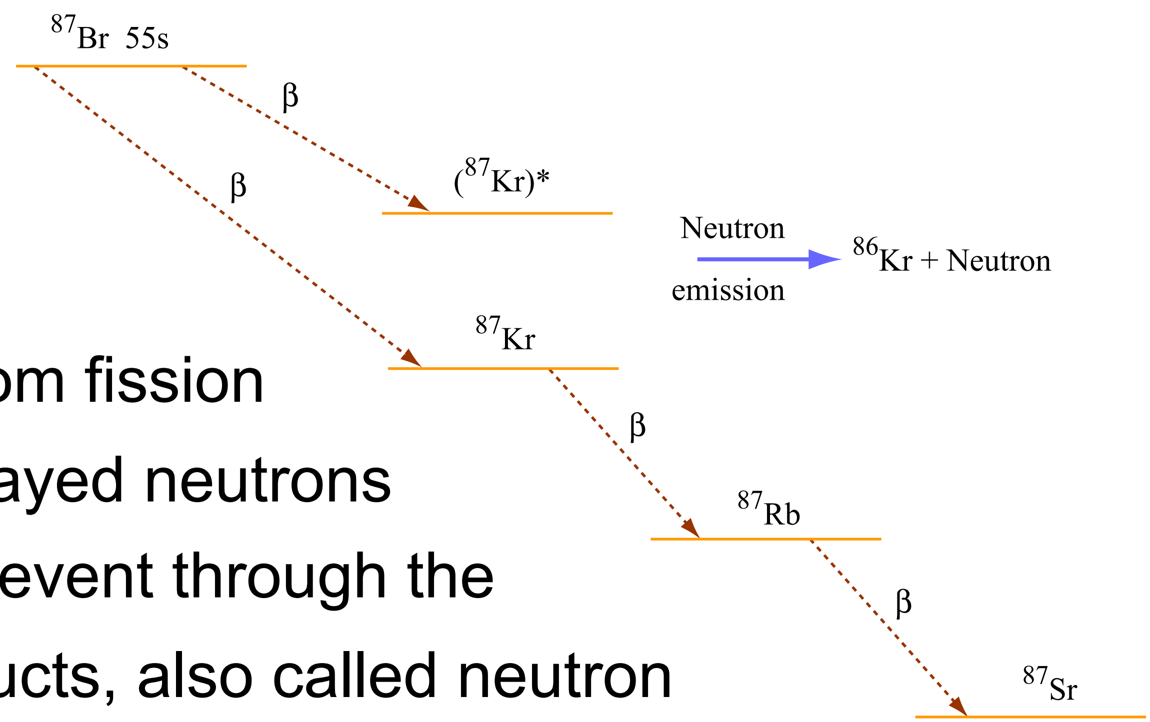
Delayed fission neutrons



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Less than 1% of neutrons from fission are considered delayed. Delayed neutrons appear long after the fission event through the decay of certain fission products, also called neutron precursors. These delayed neutrons are essential to the control of nuclear reactors since they appear many orders of magnitude later than the prompt neutrons.