Nuclear and Radiation Physics (PHY2005)

Lecture 9

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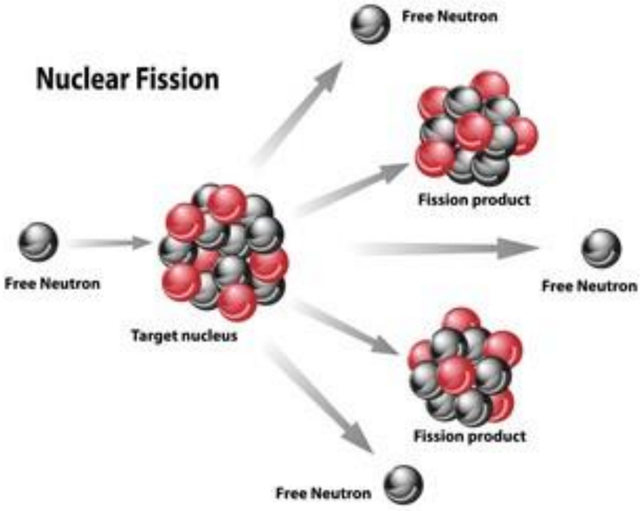
2021-2022



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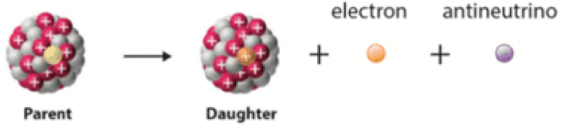
Recap & Learning Goals

Summary of Lecture 8 *(Chap.4)*

- Beta Decay
  - ✓ Properties
  - ✓ Energetics
- Gamma Decay
  - ✓ Properties
  - ✓ Energetics

$$\boxed{T = \frac{1}{R_t} = \frac{1}{R(1+\alpha_t)}}$$



$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + \beta^{-} + \bar{\nu}_e$$

$$\boxed{Q_{\beta^-} = [m({}^{A}X) - m({}^{A}X')]c^2}$$

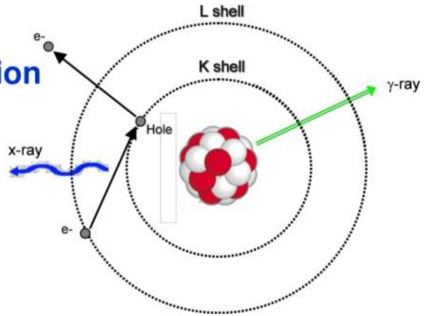
$$\boxed{(T_e)_{max} = (E_{\bar{\nu}})_{max} = Q_{\beta^-}}$$

$$\boxed{Q_{\beta^+} = [m({}^{A}X) - m({}^{A}X') - 2m_e]c^2}$$

$$\boxed{Q_{\varepsilon} = [m({}^{A}X) - m({}^{A}X')]c^2 - B_n}$$

Internal Conversion

- Atomic electron ejection
- Followed by characteristic X-ray emission



Gamma Decay

Learning goals of Lecture 9 *(Chap.4)*

- Knowing the basic theory of *nuclear fission*
- Understanding physical reasoning behind *nuclear fission*

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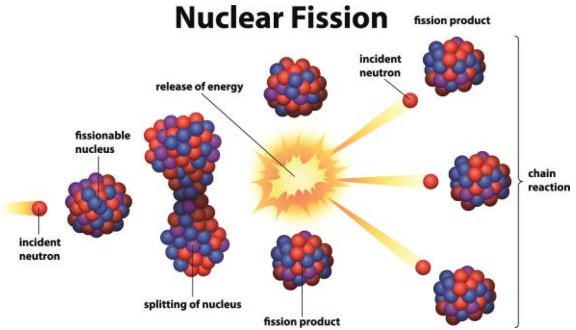
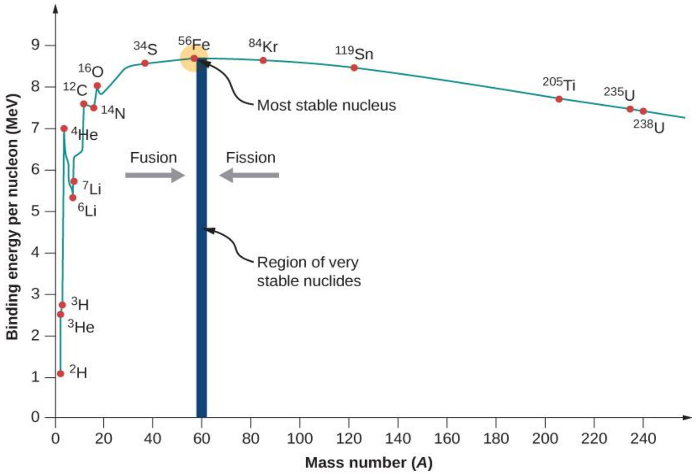
Nuclear fission *(general properties)*

- 1939 (Meitner&Frisch): uranium nuclei splitting in half *(after neutron capture)* → nuclear fission
- competition between nuclear (~A) and Coulomb (~Z^2) forces
- mainly in heavy nuclei *(thorium and beyond)*
- spontaneous reaction *or triggered by low energy neutrons/photons*



- releasing a large total energy *("climbing" the binding energy curve)*
- … also due to "**chain reactions**" induced by produced neutrons
  - rapidly and without control *(fission-based explosives)*
  - slowly and under control *(fission reactors)*



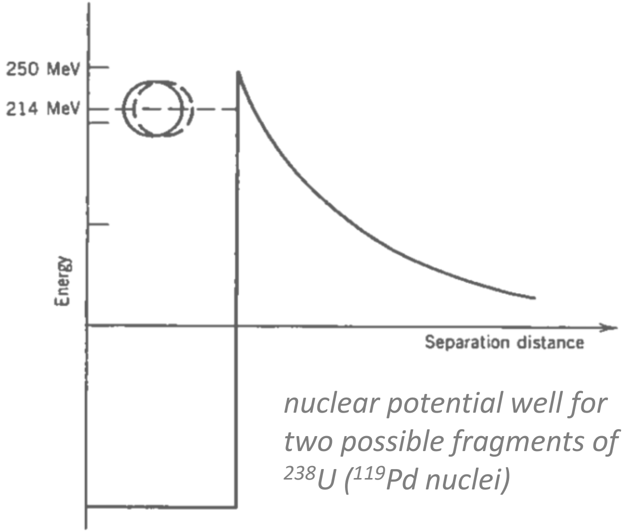
EXAMPLE

^{238}**U** *(B = 7.6 MeV/nucleon)* → 2x ^{119}**Pd** *(B = 8.5 MeV/nucleon)*

- ✓ more tightly bound system → energy release! ☺
- ✓ neutrons, β and γ, but mainly fast heavy fragments
- ✓ ^{238}U: $T_{1/2}$ = 4.5 x 10^9 y (α decay), ~10^{16} y (fission) → Coulomb barrier inhibition ☹

Nuclear fission *(basic theory)*

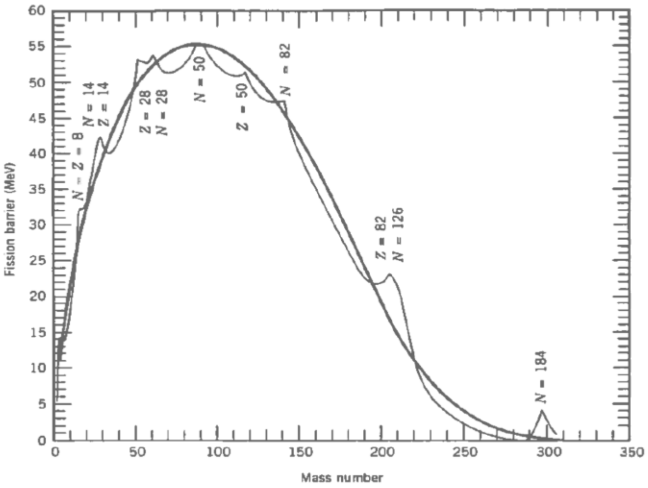
- ^{238}U → 2x ^{119}Pd (touching at their surfaces)
- Coulomb barrier is ~250 MeV → no fission
- ^{238}U splits in different fragments → high penetration probability *(just below Coulomb barrier)* → ***spontaneous fission***
- absorption of low energy *(neutron/photon)* → state at (or above) the barrier → ***induced fission***
  - ✓ thermal/fast neutrons → ***activation energy***
  - ✓ dependence on mass number



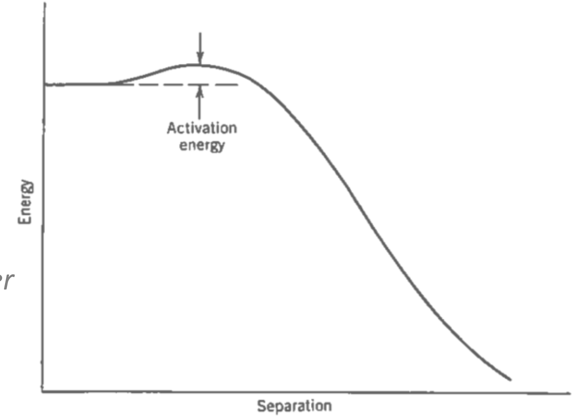
nuclear potential well for two possible fragments of ^{238}U (^{119}Pd nuclei)

Nuclear fission *(basic theory) cont.*

- absorption of low energy *(neutron/photon)* → state at (or above) the barrier → ***induced fission***
  - ✓ thermal/fast neutrons → ***activation energy***
  - ✓ dependence on mass number



variation of fission activation energy with mass number

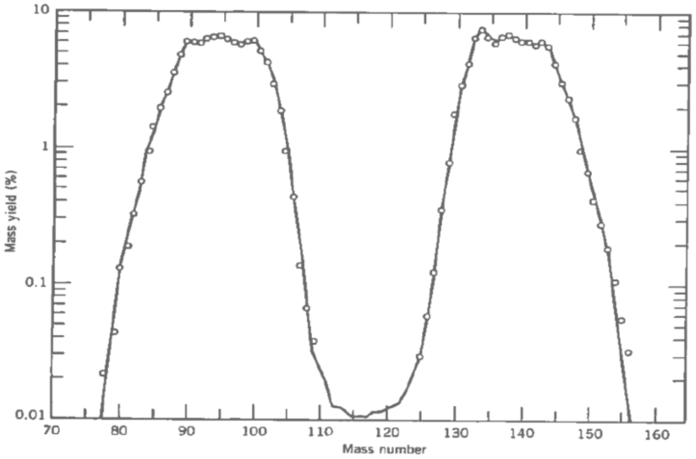


potential barrier opposing the spontaneous fission of ^{238}U

Nuclear fission *(characteristics)*

- typical neutron induced fission → $^{235}U + n \rightarrow {}^{93}Rb + {}^{141}Cs + 2n$ *(thermal neutrons)*
- mass distribution of products *(not unique for low-energy fission)* →
- fission induced by high-energy particles → equal-mass fragments
- fission fragments *(share 92 protons)* → ${}^{95}_{37}Rb_{58}$ and ${}^{140}_{55}Cs_{85}$
- nuclei rich in neutrons → Z/A ≈ 0.39 *(instead of 0.41)*
- compensation of excess neutrons through emission of:
  - ✓ *prompt neutrons (instantaneous)*
  - ✓ *delayed neutrons (~ s)* from fission fragment β decay

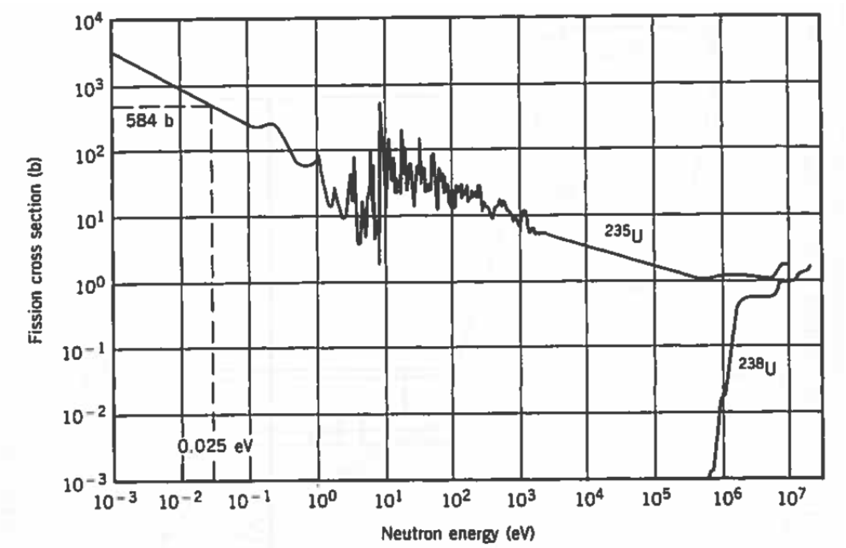
mass distribution of fission fragments from thermal fission of ^{235}U



Nuclear fission *(characteristics) cont.*

- cross sections for neutron-induced fission of ^{235}U and ^{238}U
  - ✓ thermal region for ^{235}U → *1/v* dependence *(v = neutron velocity)*
  - ✓ thermal cross section → 1000 larger than fast neutron one
  - ✓ no fission occurring in the thermal region for ^{238}U →only fast neutron induced fission *(activation energy)*

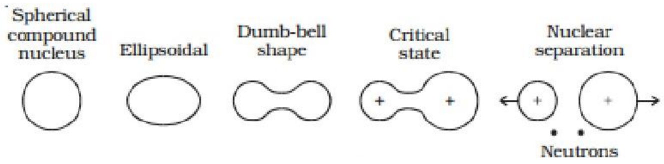
Cross-section for neutron-induced fission of ^{235}U and ^{238}U



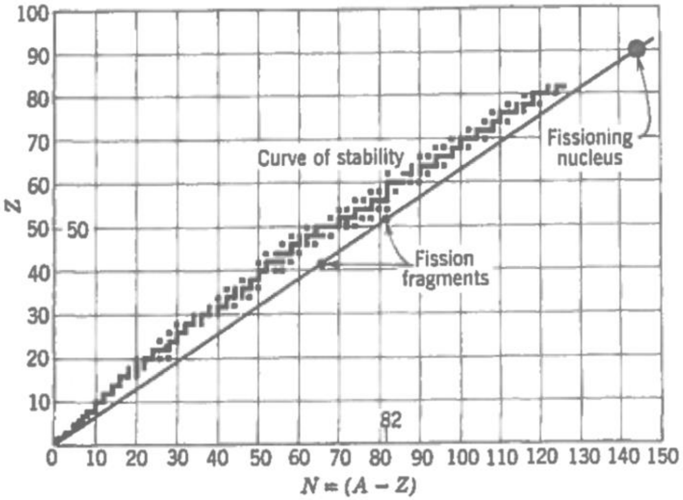
Nuclear fission *(additional considerations)*

- <u>steps</u> of nuclear fission
  - ✓ elongation of fissioning nucleus
  - ✓ separation of fission fragments
- fragments with <u>neutrons in excess</u>
  - ✓ succession of β decays
  - ✓ neutron *evaporation*

schematic representation of the nuclear fission process



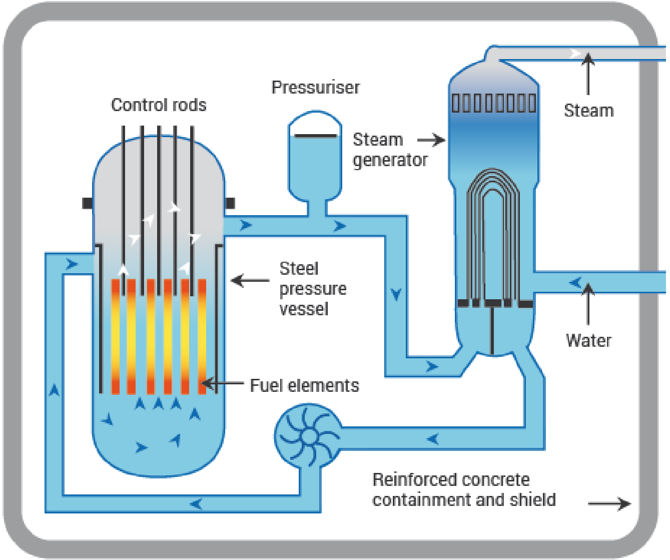
fission fragments showing an excess of neutrons



- <u>controlled fission</u>
  - ✓ infinite mass of uranium → 2.5 n in single fission
  - ✓ "second-generation" n → new fission event → more n → and so on → ***chain reaction***
  - ✓ *neutron reproduction factor* k_∞ *(≥ 1 for a chain reaction to continue)*
  - ✓ *fast neutrons (small fission cross-section)* → neutron moderation *(2.5 fast neutrons per fission can become < 1 thermal neutron)*
  - ✓ chain-reacting *pile* (uranium alternating with graphite)
  - ✓ *k = 1* (pile is *critical*); *k < 1 (subcritical)*, *k > 1 (supercritical)*

Fission reactors

- fission proceeds at carefully controlled rate
- continuous source of power obtained out of thermal energy → fission fragments come to rest in the material of the reactor
- essential elements of a reactor
  - ✓ *moderator* → to thermalize neutrons
  - ✓ *reflector* around the core → to reduce neutron leakage
  - ✓ *containment* vessel → to prevent escape of radioactive products
  - ✓ *shielding* → to prevent biological harms to personnel
  - ✓ *coolant* → to remove heat from the core
  - ✓ *control system* → to allow operators to control the power level
  - ✓ *emergency systems*



Extra material on Canvas!

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Nuclear fission *(energetics)*

- $^{235}U + n \rightarrow {}^{93}Rb + {}^{141}Cs + 2n$

$$^{235}U + \overset{\text{THERMAL}}{n} \rightarrow {}^{236}U^* \rightarrow {}^{236}U \rightarrow \text{FISSION}$$

$^{236}U^* \rightarrow$ compound state

$$E_{ex}(^{236}U) = \left[m(^{236}U^*) - m(^{236}U)\right]c^2$$

$$m(^{236}U^*) = m(^{235}U) + m_n = (235.043924 + 1.008665)\,u = 236.052589\,u$$

$$E_{ex}(^{236}U) = (236.052589 - 236.045563)\,u \times 931.5\ \text{MeV}/u = 6.5\ \text{MeV}$$

$E_{ACTIVATION}(^{236}U) = 6.2$ MeV $< E_{ex} \rightarrow$ no neutron energy needed (thermal neutron)

- $$^{238}U + \overset{\text{FAST}}{n} \rightarrow {}^{239}U^* \rightarrow \text{FISSION}$$

$$E_{ex}(^{239}U) = 4.8\ \text{MeV}$$

$E_{ACTIVATION}(^{239}U) = 6.6$ MeV $> E_{ex} \rightarrow$ fast neutron needed!

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Example 4.9

Calculate the total energy released in one fission event of ^{239}Pu that can be ideally converted into electricity neglecting subsequent chain reaction effects (see the table below)

radiation source (thermal fission of ^{239}Pu)	average energy released [MeV][3]
Kinetic energy of fission fragments	175.8
Kinetic energy of prompt neutrons	5.9
Energy carried by prompt γ-rays	7.8
Energy of β− particles	5.3
Energy of antineutrinos	7.1
Energy of delayed γ-rays	5.2

$$E_{inst.} = T_{frag.} + T_{n-prompt} + E_{\gamma-prompt} = (175.8 + 5.9 + 7.8)\ \text{MeV} = 189.5\ \text{MeV}$$

$$E_{decays} = T_{\beta^-} + \cancel{E_{\bar{\nu}}} + E_{\gamma-delayed} = 5.3 + 5.2 = 10.5\ \text{MeV}$$

$$E_{TOT} = E_{inst.} + E_{decays} = 189.5 + 10.5 = \underline{200\ \text{MeV}}$$