Radioactive Decay Mechanisms (cont.)

Beta (β) Decay: Radioactive decay process in which the charge of the nucleus is changed without any change in the number of nucleons.
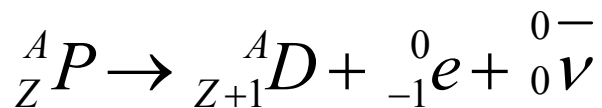
There are three types of beta decay:
- $βPP^-$ decay
- $β^+$ decay
- electron capture

β⁻ decay

Nuclides with ***excess neutrons*** need to ***convert a neutron to a proton*** to move closer to the line of stability.
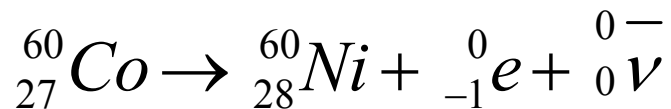
neutron → proton + negative electron + antineutrino

$$\,_Z^A P \rightarrow \,_{Z+1}^A D + \,_{-1}^0 e + \,_0^0 \bar{\nu}$$

Conservation of charge and nucleons must be observed.

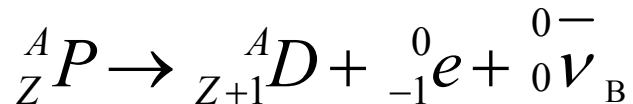The symbol ν represents the neutrino, and $\bar{\nu}$ represents its antiparticle, the antineutrino.

Example:

$$\,_{27}^{60} Co \rightarrow \,_{28}^{60} Ni + \,_{-1}^0 e + \,_0^0 \bar{\nu}$$

- ^{60}Co has too many neutrons to be stable.
- One of the ^{60}Co neutrons is converted to a proton.
- An electron is ***created in the nucleus*** then ejected from the nucleus.

β⁻ decay energetics

Mass-energy conservation:

$$_Z^A P \rightarrow _{Z+1}^A D + _{-1}^0 e + _0^0 \bar{\nu}_B$$

- The β⁻ decay e⁻ **leaves** the nucleus.
- Another e⁻ is **required** to take up an orbital position to balance the new charge (Z+1).
- There is no net gain or loss of electron masses in this reaction.
- No allowance needs to be made in the energy-mass calculations for e⁻ shifts.

Equivalent (from a mass-balance point of view) to

$M_P = M_D + Q,$ or

$Q = M_P - M_D$ [or $Q_{\beta-} = \Delta_P - \Delta_D$]

For the example: $_{27}^{60} Co \rightarrow _{28}^{60} Ni + _{-1}^0 e + _0^0 \bar{\nu} + Q$
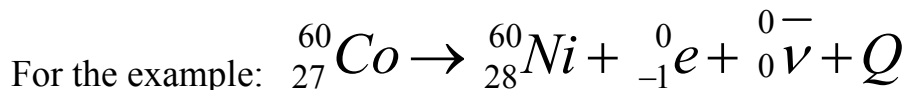
Use Δ values from App. D

$Q = -61.651 - (- 64.471) = 2.82$ MeV

For β⁻ decay to be possible,

$$\mathbf{M_P > M_D} \quad \mathbf{(i.e., Q = M_P - M_D)}$$

Any excess energy Q will be shared by the *3 decay products.*

β⁻ decay requirements (or what is a neutrino??)

"Neutrinos, they are very small/ They have no charge and have no mass / And do not interact at all"
"Cosmic Gall" John Updike, 1960

Early 1900s: Observations of beta decay puzzled investigators.
- They thought they were studying a 2-body decay process.
- This should produce electrons of a fixed energy.
- Same exact same β⁻ reaction produced electrons with ***variable energy***.
- It appeared as if energy were being destroyed.
- This violated Conservation of Energy.
- The ejected electron and the recoil nucleus did not move apart on a straight line.
- This violated Conservation of Momentum.

Enter the neutrino:

"I have done a terrible thing. I have postulated a particle that cannot be detected."
Wolfgang Pauli, 1930

- To explain the apparent violations of momentum and energy, Pauli "invented" the neutrino, a particle of no charge and little or no mass that would carry away energy and momentum.
- Actually he proposed the name "neutron" (the neutron we know was discovered in 1932)
- Enrico Fermi proposed the name "neutrino: ***little neutral one***"

In 1956 the neutrino was first detected.
- Elaborate experimental detectors are required.
- Neutrinos have a very small, but non-zero, mass.
- Implications?
- Neutrinos are everywhere: fusion in the sun, reactors produce copious amounts of neutrinos.
- Billions of neutrinos pass through your body every second.
- Only a few interactions expected in a light-year thickness of lead!!!
- Neutrino mass is a big issue in cosmology.

How is the energy, Q, distributed?

β^- decay produces ***three products,*** the daughter nucleus, the beta particle and the antineutrino.

The daughter nucleus, because of its large mass, receives ***negligible*** energy.

$$Q = E_{\beta^-} + E_{\bar{\nu}}$$

The energy is shared between the beta particle and the antineutrino.

Depending on the ***orientation***, the particles can have any energy between 0 and Q.

Thus, the ***beta particle energy spectrum is continuous***

$$0 \leq E_{\beta^-} \leq 0$$

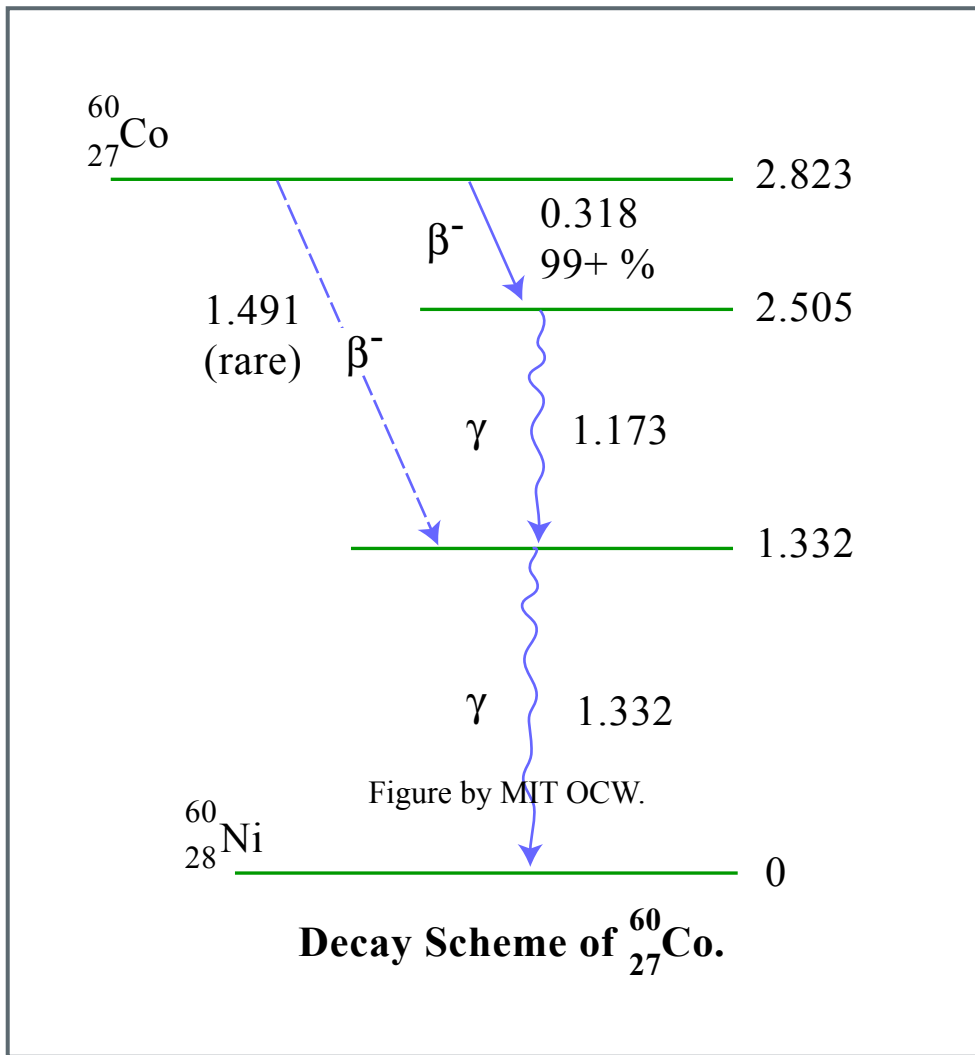The ***average*** beta particle energy ~ Q/3

Beta decay scheme

Decay Scheme of $^{60}_{27}$Co.

Figure by MIT OCW.

^{60}Co decay details from Turner, Appendix D

β^-	**0.318 max (99.92%)**
	1.491 max (0.08%)
γ	**1.173 (99.98%)**
	1.332 (99.90%)

β⁺ **Decay**

Nuclides that are excessively ***proton rich*** can decay by positive electron (positron) emission.

The nuclide attempts to gain stability by increasing the N/Z ratio by ***conversion of a proton to a neutron***.

$$\text{proton} \rightarrow \text{neutron} + \text{positive electron} + \text{neutrino}$$

$$^A_Z P \rightarrow\, ^{A}_{Z-1} D +\, ^{0}_{+1} e +\, ^{0}_{0} \nu$$
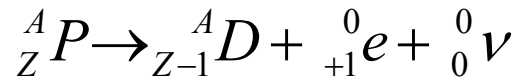
β⁺ **Decay Energetics**

- β⁺ ejected from the nucleus: loss of 1 m_e

- The daughter Z-1 nucleus must shed an orbital electron to balance charge: loss of 1 m_e

Net result is: $M_P \rightarrow M_D + \boldsymbol{2\,m_e} + Q$

Note: two electron masses ***must be accounted for*** in the mass-energy calculations.

β⁺ decay is energetically possible only if the mass of the parent atom exceeds the mass of the daughter atom by at least two electron masses
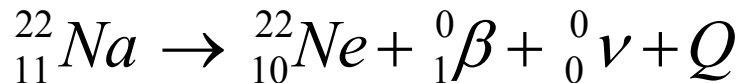(2 x 0.000549 AMU or its energy equivalent, 1.02 MeV).

$$M_P > M_D + 2m_e \qquad\qquad M_P = M_D + 2m_e + Q$$

$$Q = M_p - M_D - 2m_e \qquad [\text{or } Q_{\beta+} = \Delta_P - \Delta_D - 2m_e]$$

Example:

$$^{22}_{11} Na \rightarrow\, ^{22}_{10} Ne +\, ^{0}_{1}\beta +\, ^{0}_{0}\nu + Q$$

From App. D: Q = -5.182 – (-8.025) – 1.022 = 1.821 MeV

Positron Imaging in Nuclear Medicine

β^+ is a *positron*, the antiparticle of the electron.

Positron-electron annihilation releases two 0.511 MeV photons traveling in opposite directions.

This is the basis of *positron emission tomography (PET)*.

Electron Capture

- Nuclide too proton rich for stability
- Positron emission (β^+) decay not possible
  - ($M_P - M_D < 1.022$ MeV)

Electron capture has the same effect on the nucleus as β^+ decay.

$$_{1}^{0}e + {}_{Z}^{A}P \rightarrow {}_{Z-1}^{A}D + {}_{0}^{0}\nu$$
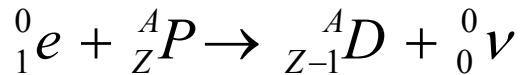
proton + electron → neutron + neutrino

- An orbital electron is ***captured*** by the parent nucleus.
- Energy "spent" overcoming the electron binding energy, E_B
- Products are the daughter nucleus and the neutrino.

$$e^- + {}_{11}^{22}Na \rightarrow {}_{10}^{22}Ne + {}_{0}^{0}\nu + Q$$
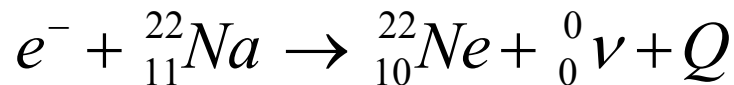
Electron capture energetics:

- Mass-energy is conserved
- Compare the masses on both sides of the arrow.

$$(m_e - E_B) + M_P = M_D + Q \qquad M_P - E_B = M_D + Q$$

$$Q = M_P - M_D - E_B \quad [\text{or } Q_{EC} = \Delta_P - \Delta_D - E_B]$$

Electron capture is only possible if $\Delta_P - \Delta_D > E_B$.

Electron capture produces ***only two reaction products*** (unlike β^- and β^+ decay).

M_D and the neutrino share the energy, move in opposite directions ***with the same momentum.***

Because of the mass difference, the (virtually undetectable) neutrino carries away almost all of the energy.

$_{11}^{22}Na$ **can decay by both EC and β⁺ pathways**

Image removed due to copyright restrictions.
Fig. 3.11 in [Turner].

$_{10}^{22}$Ne	8.82	−8.025	—	—		—
$_{11}^{22}$Na	—	−5.182	β⁺ 89.8% EC 10.2%	2.602 y		β⁺: 0.545 max (avg 0.215) γ: 0.511 (180%, γ±), 1.275 (100%), Ne X rays

$Q_{\beta+} = \Delta_P - \Delta_D - 2m_e = 1.821$ MeV

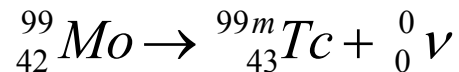$Q_{EC} = \Delta_P - \Delta_D - E_B = 2.843$ MeV

Gamma Emission

- Spectrum is discrete, characteristic of element

- Many decay modes emit gamma rays from excited nuclear states

- Gamma emission with no change in Z or A = *isomeric transition*

Metastable states

Excited nuclear states usually decay in ~ $< 10^{-10}$ sec
Excited nuclear states with longer lifetimes termed *metastable*

$$_{42}^{99}Mo \rightarrow \,_{43}^{99m}Tc + \,_{0}^{0}v$$

- halflife of ^{99m}Tc = 6 hrs
- the 0.14 MeV gamma emission is used in nuclear medicine imaging

Internal Conversion

- Energy of excited nuclear state transferred to orbital electron
- Electron is ejected from the atom (K or L shell)

IC is an alternative to gamma emission from the nucleus.

$$\text{IC coefficient} \; = \; \frac{N_e}{N_\gamma} \; \text{[ratio of branching]}$$

$$E_e = \; E^* - E_B$$

Energy of the ejected electron = excitation energy – electron binding energy

IC coefficient: increases as Z increases
            decreases as E* increases

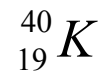IC prevalent in heavy nuclei from low-lying excited nuclear states

Summary of Decay Energetics

Formulas for Energy Release (Q), in Terms of Mass
Differences, Δ_P and Δ_D, of Parent and Daughter Atoms

Type of Decay	Formula
α	$Q_\alpha = \Delta_P - \Delta_D - \Delta_{Hc}$
β^-	$Q_{\beta^-} = \Delta_P - \Delta_D$
γ	$Q_{IT} = \Delta_P - \Delta_D$
EC	$Q_{EC} = \Delta_P - \Delta_D - E_B$
β^+	$Q_{\beta^+} = \Delta_P - \Delta_D - 2mc^2$

Decay Scheme Exercise

$^{40}_{19}K$

β⁻ (89%)   β⁻: 1.312 (max)
EC (11%)   γ: 1.461 (11%) Ar x rays