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

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

Conservation of charge and nucleons must be observed.

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

Example:

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

- ^{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:

$${}^{A}_{Z}P \rightarrow {}^{A}_{Z+1}D + {}^{0}_{-1}e + {}^{0}_{0}\overline{\nu}_{\mathrm{B}}$$

- 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: ${}^{60}_{27}Co \rightarrow {}^{60}_{28}Ni + {}^{0}_{-1}e + {}^{0}_{0}\overline{\nu} + Q$

Use Δ values from App. D

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

For β^{-} decay to be possible,

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

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?

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Fig. 3.5 in Turner J. E. *Atoms, Radiation, and Radiation Protection*, 2P^{ndP} ed. New York: Wiley-Interscience, 1995.

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***

$$0 \le E_{\beta-} \le 0$$

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

Beta decay scheme

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Fig. 3.5 in [Turner].

^{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***.

proton → neutron + positive electron + 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).

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

$Q = M_p - M_D - 2m_e$ $\qquad$ [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.

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

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.

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

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.

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

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Fig. 3.11 in [Turner].

$^{22}_{10}$Ne	8.82	−8.025	—	—	—
$^{22}_{11}$Na	—	−5.182	β^+ 89.8% EC 10.2%	2.602 y	β^+: 0.545 max (avg 0.215) γ: 0.511 (180%, $\gamma^\pm$), 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***

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

- 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.

IC coefficient $= \dfrac{N_e}{N_\gamma}$ [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

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Table 3.1 in [Turner].

Decay Scheme Exercise

$^{40}_{19}K$

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