

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.

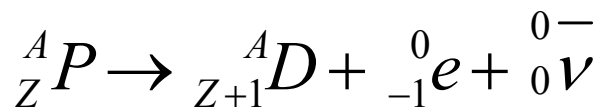
There are three types of beta decay:

- β PP⁻ 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.

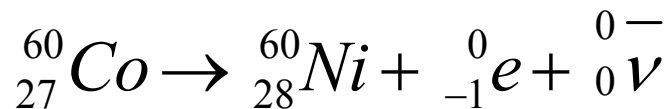
neutron \rightarrow proton + negative electron + antineutrino



Conservation of charge and nucleons must be observed.

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

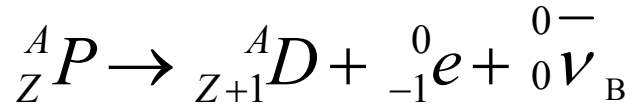
Example:



- ${}^{60}Co$ 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:

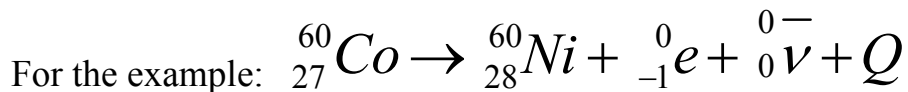


- The β^- decay e^- **leaves** the nucleus.
- Another e^- is **required** to take up an orbital position to balance the new charge (Z+1).
- There is no net gain or loss of electron masses in this reaction.
- No allowance needs to be made in the energy-mass calculations for e^- shifts.

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

$$M_P = M_D + Q, \quad \text{or}$$

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



Use Δ values from App. D

$$Q = -61.651 - (-64.471) = 2.82 \text{ MeV}$$

For β^- decay to be possible,

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

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*, 2Pnd 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*

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

The *average* beta particle energy $\sim Q/3$

Beta decay scheme

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Fig. 3.5 in [Turner].

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

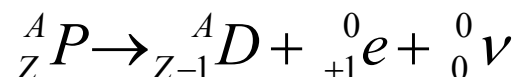
β^-	0.318 max (99.92%)
	1.491 max (0.08%)
γ	1.173 (99.98%)
	1.332 (99.90%)

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 \rightarrow neutron + positive electron + neutrino



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: $M_p \rightarrow M_D + 2 m_e + Q$

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).

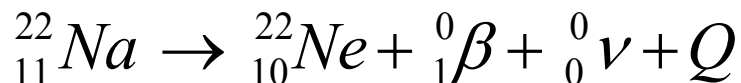
$$M_p > M_D + 2m_e$$

$$M_p = M_D + 2m_e + Q$$

$$Q = M_p - M_D - 2m_e$$

$$[\text{or } Q_{\beta^+} = \Delta_p - \Delta_D - 2m_e]$$

Example:



From App. D: $Q = -5.182 - (-8.025) - 1.022 = 1.821 \text{ MeV}$

Positron Imaging in Nuclear Medicine

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

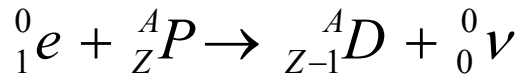
Positron-electron annihilation releases two 0.511 MeV photons traveling in opposite directions.

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

Electron Capture

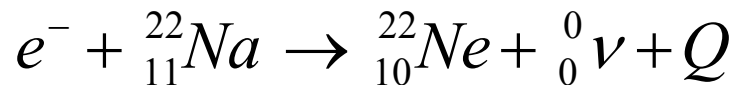
- Nuclide too proton rich for stability
- Positron emission (β^+) decay not possible
 - ($M_P - M_D < 1.022 \text{ MeV}$)

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



proton + electron \rightarrow 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.



Electron capture energetics:

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

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

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

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.

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

Image removed.
Fig. 3.11 in [Turner].

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

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

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

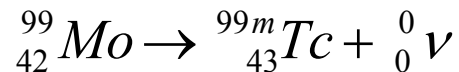
Gamma Emission

- 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 $\sim < 10^{-10}$ sec

Excited nuclear states with longer lifetimes termed *metastable*



- 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

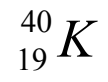
IC coefficient: increases as Z increases
 decreases as E^* increases

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

Summary of Decay Energetics

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Table 3.1 in [Turner].

Decay Scheme Exercise



β^- (89%)
EC (11%)

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