Nuclear Instability and Radioactive Decay

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Nuclear Instability and Radioactive Decay

• Five Kinds of Radioactive Decays
• Experiments I
• Five Decays and Reasons of Instability
• Alpha Decay
• Theory of Tunnel Effect
• Alpha Decay Constant
• Energies of Alpha Decay
• Beta Stability
• Beta Decay
• Gamma Decay
• Alpha Decay Chains
# Five Kinds of Radioactive Decays

<table>
<thead>
<tr>
<th>Decay</th>
<th>Transformation</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha decay</td>
<td>$^{A}<em>{Z}X \rightarrow ^{A-4}</em>{Z-2}Y + ^{4}_{2}\text{He}$</td>
<td>$^{238}<em>{29}\text{U} \rightarrow ^{234}</em>{90}\text{Th} + ^{4}_{2}\text{He}$</td>
</tr>
<tr>
<td>Beta decay</td>
<td>$^{A}<em>{Z}X \rightarrow ^{A}</em>{Z+1}Y + e^{-}$</td>
<td>$^{14}<em>{6}\text{C} \rightarrow ^{14}</em>{7}\text{N} + e^{-}$</td>
</tr>
<tr>
<td>Positron emission</td>
<td>$^{A}<em>{Z}X \rightarrow ^{A}</em>{Z-1}Y + e^{+}$</td>
<td>$^{64}<em>{29}\text{Cu} \rightarrow ^{64}</em>{28}\text{Ni} + e^{+}$</td>
</tr>
<tr>
<td>Electron capture</td>
<td>$^{A}<em>{Z}X + e^{-} \rightarrow ^{A}</em>{Z-1}Y$</td>
<td>$^{64}<em>{29}\text{Cu} + e^{-} \rightarrow ^{64}</em>{28}\text{Ni}$</td>
</tr>
<tr>
<td>Gamma decay</td>
<td>$^{A}<em>{Z}X^{*} \rightarrow ^{A}</em>{Z}X + \gamma$</td>
<td>$^{87}<em>{38}\text{Sr}^{*} \rightarrow ^{87}</em>{38}\text{Sr} + \gamma$</td>
</tr>
</tbody>
</table>
General Properties of Radioactive Decays

- When a nucleus undergoes alpha or beta decay, its atomic number $Z$ changes and it becomes the nucleus of a different chemical element. - No chemistry explanation.

- The energy liberated during radioactive decay comes from within individual nuclei without external excitations, unlike the case of atomic radiation. Explanation? Not until Albert Einstein proposed the equivalence of mass and energy - $E = mc^2$.

- Radioactive decay is a statistical process that obey the law of chance. No cause-effect relationship is involved in the decay of a particular nucleus, only certain probability per unit time. Classical physics cannot account for such behavior - quantum mechanics can.
Experiments I

When rays enter magnetic field, α and β rays are deflected in opposite directions,...

\[ \vec{F} = q\vec{v} \times \vec{B} \]

\[
\begin{align*}
q < 0 & \quad \vec{F} \uparrow\downarrow \vec{v} \times \vec{B} \\
q = 0 & \quad \vec{F} = 0 \\
q > 0 & \quad \vec{F} \uparrow\uparrow \vec{v} \times \vec{B}
\end{align*}
\]

...and γ rays are undeflected.
Experiments II

Diagram showing different materials (cardboard, aluminum, lead) and different types of radiation (α, β, γ).
Stability Curve

- For $A \leq 40 \rightarrow N \approx Z$ for stable nuclei
- For $A > 40 \rightarrow N > Z$ for stable nuclei
Nuclear Stability

- Ignore electrostatic repulsion between protons for light nuclei ($A \leq 40$)
- Energy is smallest if $A/2$ are neutrons and $A/2$ are protons
- Energy is greatest if there only one type of particle (exclusion principle)
<table>
<thead>
<tr>
<th>Decay Type</th>
<th>Decay Event</th>
<th>Final Nucleus</th>
<th>Reason for Instability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma decay</td>
<td>Emission of gamma ray reduces energy of nucleus</td>
<td></td>
<td>Nucleus has excess energy</td>
</tr>
<tr>
<td>Alpha decay</td>
<td>Emission of alpha particle reduces size of nucleus</td>
<td></td>
<td>Nucleus too large</td>
</tr>
<tr>
<td>Beta decay</td>
<td>Emission of electron by neutron in nucleus changes the neutron to a proton</td>
<td></td>
<td>Nucleus has too many neutrons relative to number of protons</td>
</tr>
<tr>
<td>Electron capture</td>
<td>Capture of electron by proton in nucleus changes the proton to a neutron</td>
<td></td>
<td>Nucleus has too many protons relative to number of neutrons</td>
</tr>
<tr>
<td>Positron emission</td>
<td>Emission of positron by proton in nucleus changes the proton to a neutron</td>
<td></td>
<td>Nucleus has too many protons relative to number of neutrons</td>
</tr>
</tbody>
</table>

- Proton (charge = +e)
- Electron (charge = -e)
- Neutron (charge = 0)
- Positron (charge = +e)
Can one predict decay mode?

Example: The helium isotope $^6_2\text{He}$ is unstable. What kind of decay would you expect it to undergo?

Solution: $^4_2\text{He}$ is a most stable He nucleus ($N = Z$) and has lowest possible energy levels. $^6_2\text{He}$ has 2 extra neutrons compared to stable $^4_2\text{He}$ configuration. This suggests that $^6_2\text{He}$ will undergo $\beta^-$ decay that turns one neutron into proton and it will become $^6_3\text{Li}$ isotope with ($N = Z$)

$^6_2\text{He} \rightarrow ^6_3\text{Li} + e^- + (\text{missing part of this reaction will be discussed later})$
Alpha Decay

- \( \approx 25 \text{ MeV} \) - work done against repulsive electrostatic force to bring \( \alpha \)-particle from infinity to a position adjacent to the nucleus (but just outside of the range of attractive nuclear force).
- Energy of \( \alpha \)-particle to surmount the walls should be more than 25 MeV
- \( \alpha \)-particle energies are 4-9 MeV (16-21 MeV short)
- No classical explanation, but straightforward quantum mechanical explanation.
Alpha Decay

Total Energy of $\alpha$-particle

\[ E = K + U \]

$E > U \rightarrow K > 0$

$E < U \rightarrow K < 0$

- Uncertainty Principle prevents us from measuring a negative K.E. as long as tunneling does not take more time than

\[ \Delta t \leq \frac{\hbar}{2K} = \frac{\hbar}{2(U - E)} \]
Theory of Tunnel Effect

Approximate Transmission Probability

\[ T = e^{-2k(r)L} \]

\[ k(r) = \sqrt{\frac{2m(U(r) - E)}{\hbar}} = \left( \frac{2mE}{\hbar^2} \right)^{1/2} \left( \frac{R}{r} - 1 \right)^{1/2} \]

\[ \ln T = -2 \int_{R_0}^{R} k(r) \, dr \]

\[ \ln T = -2 \left( \frac{2mE}{\hbar^2} \right)^{1/2} R \left[ \frac{\pi}{2} - 2 \left( \frac{R_0}{R} \right)^{1/2} \right] \]

\[ \ln T = 2.972Z^{1/2} R_0^{1/2} - 3.95ZE^{-1/2} \]

\[ \rightarrow \log_{10} T = 1.29Z^{1/2} R_0^{1/2} - 1.72ZE^{-1/2} \]
Alpha Decay Constant

- $\alpha$ – particle may exist as an entity within a heavy nucleus

- $\alpha$-particle is in constant motion and is held in the nucleus by a potential barrier

- There is a small likelihood that the particle may tunnel through the barrier during collisions.

$\lambda = \nu T$ - decay probability per unit time; \[\nu \quad \text{number of collisions per second with barrier}\]

$2R_0$ - nuclear diameter ($\sim 10^{-14}$ m)
\[\nu \quad \text{alpha particle speed} \quad (\sim 2 \times 10^7 \text{ m/s})\]

$2R_0 = \nu \tau \rightarrow \nu = \frac{1}{\tau} = \frac{\nu}{2R_0} \sim 10^{21} \text{s}^{-1}$

- $\alpha$-particle knocks at the barrier wall $10^{21}$ times per second!

- But because of small probability of tunneling it may have to wait on average $10^{10}$ years to escape!!
**Alpha Decay Constant**

\[
\log_{10} T = 1.29 Z^{1/2} R_0^{1/2} - 1.72 Z E^{-1/2}
\]

\[
\nu = \frac{\nu}{2 R_0}
\]

\[
\lambda = \nu T
\]

\[
\log_{10} \lambda = \log \left( \frac{\nu}{2 R_0} \right) + 1.29 Z^{1/2} - 1.72 Z E^{-1/2}
\]

\[
\lambda = \frac{1}{\tau} = \frac{\ln 2}{T_{1/2}}
\]

\(\tau\) - mean life time

\(T_{1/2}\) - half-life
Energies of Alpha Decay

\[ ^{227}\text{Th} \rightarrow ^{223}\text{Ra} + ^{4}\text{He} \]

- \(\alpha\)-particle spectrum from decay of \(^{227}\text{Th}\)
- Highest energy peak \(\alpha_0\) (6.04 MeV) corresponds to the ground state of \(^{223}\text{Ra}\)
- Next highest peak \(\alpha_{30}\) results from transition to first excited state of \(^{223}\text{Ra}\) - 30 keV above the G.S.
Energies of Alpha Decay

\[ ^{227}\text{Th} \rightarrow ^{223}\text{Ra} + ^{4}\text{He} \]
Energies of Alpha Decay

- Energy released in $\alpha$-decay - $Q$ is determined by the difference in mass of the parent nucleus and decay products:

$$Q = \left[ M_p - \left( M_D + M_{He} \right) \right] c^2 = M_p c^2 - \left( M_D c^2 + M_{He} c^2 \right)$$

$m_p$ - mass of the parent nucleus, $M_D$ - mass of the daughter nucleus, $M_{He}$ - mass of the $\alpha$-particle

$^{227}\text{Th} \rightarrow ^{223}\text{Ra} + ^4\text{He}$ $T_{1/2} = 18.72$ d

$^{227}\text{Th} - 227.027701$ u

$^{223}\text{Ra} - 223.018499$ u

$^4\text{He} - 4.002603$ u

$$Q = 227.027701 \text{ u} - \left( 223.018499 \text{ u} + 4.002603 \text{ u} \right) = 0.006599 \text{ u}$$

$$Q = \left( 0.006599 \text{ u} \right) \left( 931.49 \text{ MeV/u} \right) = \boxed{6.15 \text{ MeV}}$$
Energies of Alpha Decay

$^{227}\text{Th} \rightarrow ^{223}\text{Ra} + ^{4}\text{He}$

$Q = (0.006599 \text{ u})(931.49 \text{ MeV/u}) = 6.15 \text{ MeV}$

$\tilde{P}_p = 0 = \tilde{P}_D + \tilde{P}_{He} \rightarrow P_D = M_D V = P_{He} = M_{He} \nu = p$

$Q = \frac{p^2}{2M_D} + \frac{p^2}{2M_{He}} = \frac{p^2}{2M_{He}} \left(1 + \frac{M_{He}}{M_D}\right) = E_\alpha \left(1 + \frac{M_{He}}{M_D}\right)$

$E_\alpha = \frac{Q}{1 + \frac{M_{He}}{M_D}} = \frac{6.15 \text{ MeV}}{4.002603 \text{ u}} \approx \frac{6.15 \text{ MeV}}{1.017951} \approx 6.04 \text{ MeV}$

$E_{Ra} = Q - E_\alpha = 6.15 - 6.04 = 0.11 \text{ MeV}$
Beta Stability

\[ M(Z, A)c^2 = Zm_p c^2 + Nm_n c^2 - [a_1A - a_2A^{2/3} - a_3Z^2A^{-1/3} - a_4(A - 2Z)^2A^{-1} \pm a_5A^{-1/2}]c^2 \]

Beta decay
Positron emission
Electron capture

For isobaric nuclei \((A = \text{const})\) → \(M(Z, A) \sim Z^2\)

For Even-Odd and Odd-Even nuclei
\(a_5 = 0\)

One parabola → one minimum → One stable lowest energy state
Figure (b) shows the possible double beta decay from $^{60}\text{Fe}$ to $^{60}\text{Ni}$. 1985 double beta decay was observed (half life $1.1 \times 10^{20}$ years)

$^{82}\text{Se} \rightarrow ^{82}\text{Kr} + \beta^- + \beta^- + \bar{\nu}_e + \nu_e$
- $n \rightarrow p + e^- + ??$ (half-life 10.8 min)

- The electron energies in beta decay are found to vary continuously from $0 \rightarrow KE_{\text{max}}$
  \[ E_{\text{max}} = mc^2 + KE_{\text{max}} \]
  Energy Conservation??

- Directions of the emitted electron and of the recoiling nuclei are never exactly opposite...
  Momentum Conservation??

- The spin of $n \rightarrow 1/2$, $p \rightarrow 1/2$, $e^- \rightarrow 1/2$
  Left side has half-integer spin, right side integer spin...
  Angular Momentum Conservation??
Neutrino – “Little Neutral One”

- 1930 Wolfgang Pauli suggested existence of a particle - named neutrino Enrico Fermi.

- $\nu$ - spin-1/2, mass is very small, maybe zero ... All conservation laws were restored

- 1933 Enrico Fermi developed a highly successful theory of $\beta$-decay

- Later he realized that $\beta$-decay is part of a wider class of reactions/decays governed by more general principles of weak interactions.

- He has explained all weak decays/scatterings when charge of parent particle (nuclei) and daughter particle (nuclei) were different. So called, charged weak current interactions...

- Fact that weak interaction may change a electric charge of the particle suggested that there is hidden connection between electromagnetic and weak interactions

- Experiments discovered neutral weak current reactions (electron-neutrino scatterings) that Fermi's theory could not explain...
Neutrino Detection

- Sun produces $10^{38}$ neutrinos/second

- $10^{14}$ neutrinos from the Sun (Solar neutrinos) pass through each $m^2$ of Earth per second.

- 1960 Raymond Davis (BNL) - neutrino discovery
  Gold Mine in S. Dakota, using 600 tons (100,000 gallons) of perchlorethylene - $C_2Cl_4$ (dry-cleaning liquid).

- 1 neutrino per day struck the $^{37}Cl$ nucleus
  \[ \nu + ^{37}_{17}Cl \rightarrow ^{37}_{18}Ar + e^- \]

- Rate of $^{37}_{18}Ar$ production $\sim$ neutrino flux
Energetics of $\beta^-$ Decay

\[ ^A_Z X \rightarrow ^{A}_{Z+1} Y + e^- + \bar{\nu} \]

\[ M(A, Z) \rightarrow M(A, Z + 1) + m_e \]

\[ \frac{Q}{c^2} = M_P - M_D > 0 \quad \text{in order for } \beta^- \text{ decay to take place} \]
Positron Emission – $\beta^+$ Decay

\[ p \rightarrow n + e^+ + \nu \] (simplest $\beta^+$ decay - not possible for free proton, or we would be in a big trouble...)

\[ ^\frac{A}{Z}X \rightarrow ^\frac{A}{Z-1}Y + e^+ + \nu \]

\[ M(A,Z) \rightarrow M(A,Z-1) + m_e \]

\[ \underbrace{M(A,Z) + Zm_e}_{M_p} \rightarrow M(A,Z-1) + Zm_e + m_e \rightarrow \underbrace{M(A,Z-1) + (Z-1)m_e + 2m_e}_{M_D} \]

\[ \frac{Q}{c^2} = M_p - M_D - 2m_e > 0 \quad \text{or} \quad M_p - M_D > 1.022 \text{ MeV in order for $\beta^+$ decay to take place} \]
Average Energy of Electron and Positron Emitters

\[ \overline{E}_{\beta^-} = \frac{1}{3} E_{\beta^-}^{\text{max}} \left(1 - \sqrt{\frac{Z}{50}}\right) \left(1 + \frac{E_{\beta^-}^{\text{max}}}{4}\right); \quad \overline{E}_{\beta^+} = \frac{1}{3} E_{\beta^+}^{\text{max}} \left(1 + \frac{E_{\beta^+}^{\text{max}}}{4}\right) \]

\[ \overline{E}_{\beta^-} = \frac{1}{3} E_{\beta^-}^{\text{max}}; \quad \leftrightarrow \quad \text{Rule of Thumb} \quad \leftrightarrow \quad \overline{E}_{\beta^+} = \frac{1}{3} E_{\beta^+}^{\text{max}} \]

Example:
Determine the average beta energy for electron emission of \(^{64}\text{Cu}\) which by Q-value calculations has a maximum beta energy of 0.5787 MeV. How does this compare with the rule of thumb calculation?

Solution:
\[ \overline{E}_{\beta^-} = \frac{1}{3} (0.5787) \left(1 - \frac{\sqrt{29}}{50}\right) \left(1 + \frac{\sqrt{0.5787}}{4}\right) = 0.2049 \text{ MeV} \]
\[ \overline{E}_{\beta^-} = \frac{1}{3} (0.5787) = 0.1929 \text{ MeV} \]
Electron Capture

- Wave function of orbital electron overlaps with wave function of proton reach unstable nucleus
- Nuclear proton absorbs orbital electron (Usually from K-shell) and becomes neutron
- Characteristic X-ray photon emitted as a result of atomic electron transition into resulting vacant state.

\[ \frac{A}{Z} X + e^- \rightarrow \frac{A}{Z-1} Y \]

\[ M(A,Z) + m_e \rightarrow M(A,Z-1) \Rightarrow \underbrace{M(A,Z) + m_e + (Z-1)m_e}_{M_p} \rightarrow \underbrace{M(A,Z-1) + (Z-1)m_e}_{M_D} \]

\[ \frac{Q}{c^2} = M_p - M_D \]
Electron Capture

- E.C. competes with positron emission when $M_P - M_D > 2m_e c^2$
- E.C. dominates positron emission when $M_P - M_D < 2m_e c^2$ ($\beta^+$ does not take place)
Gamma Decay

\[ \frac{A}{Z} X^* \rightarrow \frac{A}{Z} X + \gamma + Q_\gamma \]

The decay energy \( Q_\gamma \) in \( \gamma \) emission is the sum of the \( \gamma \)-photon energy \( E_\gamma \) and the recoil kinetic energy of the daughter \( (E_K)_D \) or

\[ Q_\gamma = E_\gamma + (E_K)_D \]

\[ E_\gamma = p_\gamma c = M(D)v_Dc \]

\[ (E_K)_D = \frac{1}{2} M(D)v_D^2 \]

\[ (E_K)_D = \frac{M(D)v_D^2}{2} = \frac{E_\gamma^2}{2M(D)c^2} \]

\[ Q_\gamma = E_\gamma + (E_K)_D = E_\gamma \left\{ 1 + \frac{E_\gamma}{2M(D)c^2} \right\} \]
Gamma Decay

$^{60}_{27}\text{Co (5.2714y)}$ → $^{60}_{28}\text{Ni (Stable)}$

- $\beta^{-}$ with $0.3179 \text{ MeV}$ and $99.9\%$
- $\gamma_3$ with $1.1730 \text{ MeV}$ and $99.9\%$
- $\gamma_4$ with $1.3330 \text{ MeV}$ and $100\%$
Internal Conversion

\[ KE_e = E_\gamma - BE_e \]

\[ \frac{A}{Z}X^* \rightarrow \frac{A}{Z}X^+ + e^- + Q_{IC} \rightarrow \frac{A}{Z}X \]

\( \frac{A}{Z}X^* \) is the excited state of the nucleus most likely attained as a result of \( \alpha \) or \( \beta \) decay.

\( \frac{A}{Z}X^+ \) is the singly ionized state of atom \( \frac{A}{Z}X \) following internal conversion decay.

\( Q_{IC} \) is the decay energy for internal conversion.
Internal Conversion

\[ Q_{IC} = Q_\gamma - E_B = (E_K)_{IC} + (E_K)_D \]

\( Q_\gamma \) is the energy difference between two excited nuclear states, equal to the energy of a \( \gamma \) photon in \( \gamma \) decay.

\((E_K)_{IC}\) is the kinetic energy of the internal conversion electron ejected from the atom.

\((E_K)_D\) is the recoil kinetic energy of the daughter nucleus with nuclear mass \( M(D) \).

\[
(E_K)_D = \frac{m_e c^2}{M(D)c^2} (E_K)_{IC} + \frac{(E_K)_{IC}^2}{2M(D)c^2}
\]

\[ Q_{IC} = Q_\gamma - E_B = (E_K)_{IC} \left\{ 1 + \frac{m_e c^2}{M(D)c^2} + \frac{(E_K)_{IC}}{2M(D)c^2} \right\} \]
Internal Conversion vs. Gamma Decay

**total internal conversion factor** $\alpha_{IC}$

$$\alpha_{IC} = \frac{\text{conversion probability}}{\gamma\text{-emission probability}} = \frac{N_{IC}}{N_\gamma}$$

$N_{IC}$ is the number of conversion electrons ejected from all shells per unit time.

$N_\gamma$ is the number of $\gamma$ photons emitted per unit time.

$$\frac{N_{IC}}{N_\gamma} = \frac{N_{IC}(K) + N_{IC}(L) + N_{IC}(M) + \cdots}{N_\gamma}$$

$$= \alpha_{IC}(K) + \alpha_{IC}(L) + \alpha_{IC}(M) + \cdots,$$
Internal Conversion vs. Gamma Decay

\[ \alpha_{IC} = \frac{(7.8 + 1.8)}{85} = 0.113 \]
Example: The Decay of $^{233}$Np

$\alpha$-decay: $^{233}_{93}$Np → $^{229}_{91}$Pa + $^{4}_{2}$He

\[
\frac{Q}{c^2} = 233.040805 - (229.032085 + 4.002603)u = 0.006117 \ u = 5.70 \text{ MeV}/c^2 > 0 \text{ allowed}
\]

$\beta^{-}$-decay: $^{233}_{93}$Np → $^{233}_{94}$Pu + $^{e-} + \bar{\nu}$

\[
\frac{Q}{c^2} = 233.040805 - 233.042963 = -0.002158 \ u = -2.01 \text{ MeV}/c^2 < 0 \text{ forbidden}
\]

$\beta^{+}$-decay: $^{233}_{93}$Np → $^{233}_{92}$U + $^{e^{+}} + \nu$

\[
\frac{Q}{c^2} = 233.040805 - (233.0329630 + 2 \times 5.4858 \times 10^{-4})u = 0.000078 \ u = 0.07 \text{ MeV}/c^2 > 0 \text{ allowed}
\]

E.C.: $^{233}_{93}$Np → $^{233}_{92}$U + $\nu$

\[
\frac{Q}{c^2} = 233.040805 - 233.039630 = 0.001175 \ u = 1.09 \text{ MeV}/c^2 > 0 \text{ allowed}
\]

$^{233}_{93}$Np - 99% Electron Capture, 0.3% $\alpha$ – decay, $\beta^{+}$-decay has not been observed, $\beta^{-}$-decay forbidden
Alpha Decay Chains
$^{137}\text{Cs Decay}$

$^{137}_{55}\text{Cs} Q_{\beta^-} = 1.1756 \text{ MeV}$

$T_{1/2} = 30.07 \text{ a}$

$\beta^- : 100\%$

$\beta_1^-, E_{\beta^-,\text{max}} = 0.514 \text{ MeV (94.4\%)}$

$\beta_2^-, E_{\beta^-,\text{max}} = 0.892 \text{ MeV (5.8} \times 10^{-4}\%)$

$\beta_3^-, E_{\beta^-,\text{max}} = 1.1756 \text{ MeV (5.6\%)}$

$\gamma = 0.6617 \text{ MeV (85.1\%)}$

$\gamma = 0.283 \text{ MeV (5.8} \times 10^{-4}\%)$

$\frac{Q}{c^2} = M_p - M_D = 136.907078u - 136.905816u = (0.001262u)(931.49 \text{ MeV/u}) = 1.1756 \text{ MeV/c}^2$

$Q_{\beta^-} = 1.1756 \text{ MeV} \rightarrow E_{\beta^-\text{max}} = \boxed{1.1756 \text{ MeV}} \ (5.6\% \text{ probability)}$
$^{60}\text{Co}$ Decay

$^{27}_{27}\text{Co}$ $Q_{\beta^{-}} = 2.89239$ MeV

$T_{1/2} = 5.2714$ a

$\beta^{-} : 100\%$

$\beta_{1}^{-}, E_{\beta^{-},\text{max}} = 0.318$ MeV (99.88\%)

$\beta_{2}^{-}, E_{\beta^{-},\text{max}} = 0.670$ MeV (0.0\%)

$\beta_{3}^{-}, E_{\beta^{-},\text{max}} = 1.491$ MeV (0.12\%)

$^{60}_{28}\text{Ni}^{*}$

$\gamma = 0.347$ MeV (8 x $10^{-3}\%$)

$\gamma = 0.826$ MeV (8 x $10^{-3}\%$)

$\gamma = 1.1732$ MeV (99.85\%)

$\gamma = 2.506$ MeV (2 x $10^{-6}\%$)

$\gamma = 2.159$ MeV (1.2 x $10^{-3}\%$)

$\gamma = 1.3325$ MeV (99.98\%)

$^{28}_{28}\text{Ni}$
$^{192}\text{Ir Decay}$
$^{125}\text{I}$ Decay

$^{125}_{53}\text{I}$

$Q_{EC}=0.1858$ MeV

$T_{1/2}=59.49$ d

$EC: 100\%$

$^{125}_{52}\text{Te}^*$

$\gamma=0.3549$ MeV (6.68\%)

$^{125}_{52}\text{Te}$
Neutrino – “Little Neutral One”

• 1930 Wolfgang Pauli suggested existance particle - named *neutrino* Enrico Fermi.

• $\nu$ - spin-1/2, mass is very small, maybe zero ... All conservation laws were restored

• 1933 Enrico Fermi developed highly successful theory of $\beta$-decay

• Later he realized that $\beta$-decay is part of wider class of reactions/decays governed by more general principles of weak interactions.

• He has explained all weak decays/scatterings when charge of parent particle (nuclei) and daughter particle (nuclei) were different. So called, charged weak leptonic current interactions...

• Fact that weak interaction may change a electric charge of the particle suggested that there is hidden connection between electromagnetic and weak interactions

• Experiments discovered neutral weak current reactions (electron-neutrino scatterings) that Fermi's theory could not explain...
Fermi Theory of Beta Decay

\[ \lambda_{if} = \frac{2\pi}{\hbar} |M_{if}|^2 \rho_f \]

Fermi's Golden Rule

Transition probability \hspace{1cm} Matrix element for the interaction \hspace{1cm} Density of final states

Fermi function to account for the nuclear coulomb interaction with the emitted particle.

\[ N(p) = C p^2 (Q - KE_e)^2 F(Z', p) |M_{fi}|^2 S(p, q) \]

Distribution of electron momentum \hspace{1cm} Statistical factor derived from the density of final states available to the emitted particles. \hspace{1cm} Matrix element for allowed transitions gives the strength of the interaction between initial and final states.

\[ \beta^- \]
Electron kinetic energy

\[ \beta^+ \]
Electron momentum
Real Theory of Beta Decay ...

\[ ^{60}_{27}\text{Co} \rightarrow ^{60}_{28}\text{Ni} + e^- + \bar{\nu}_e \]

Only one of 33 neutrons are affected

\[ n \rightarrow p + e^- + \bar{\nu}_e \]

Neutron is not elementary particle

\[ d \left(-\frac{1}{3}\right) \rightarrow u \left(+\frac{2}{3}\right) + W^- \quad (m_w = 80 \text{ GeV}) \]

\[ W^- \text{ boson can only exist as long as Unc.Principle Allows} \]

\[ \Delta t = \frac{\hbar}{\Delta E} \quad \rightarrow \quad R = \frac{\hbar c}{m_w c^2} = \frac{(197.3 \text{ eV} \cdot \text{nm})}{(80 \times 10^7 \text{ eV})(10^9 \text{nm/m})} = 2.47 \times 10^{-3} \text{ fm} \]

\[ W^- \rightarrow e^- + \bar{\nu}_e \]
Electroweak Interaction

Stage 1: $p + \bar{p} \rightarrow W^+ + W^-$

Stage 2: $W^+ \rightarrow \tau^+ + \nu_\tau$
Electroweak Interaction

- CERN SppS proton-antiproton collider and UA1 bubble chamber
- Detection of $Z^0$-boson by Rubia group
- $p + \bar{p} \rightarrow Z^0 \rightarrow e^- + e^+$
Electro-Weak as a Part of “Big Picture”

<table>
<thead>
<tr>
<th>Type</th>
<th>Symbol</th>
<th>Value</th>
<th>Charge</th>
<th>Electric Charge</th>
<th>q, e, μ, τ, W±</th>
<th>W±, Z0</th>
<th>α</th>
<th>αw</th>
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</thead>
<tbody>
<tr>
<td>Electromagnetic</td>
<td>photon</td>
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<td>1</td>
<td>electric charge</td>
<td>q, e, μ, τ, W±</td>
<td>W±, Z0</td>
<td>10⁻¹⁸</td>
<td>10⁻¹⁵</td>
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<td>1, 1</td>
<td>weak charge</td>
<td>q, e, μ, τ,</td>
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<td>10⁻¹⁶</td>
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<td>W±, Z0</td>
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<td>10⁻¹⁸</td>
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<td>10⁻¹⁵</td>
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</tbody>
</table>
People to Formulate E-W Theory

The Nobel Prize in Physics 1979
"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"

Sheldon Lee Glashow
- 1/3 of the prize
- USA
- Harvard University, Lyman Laboratory
- Cambridge, MA, USA

Abdus Salam
- 1/3 of the prize
- Pakistan
- International Centre for Theoretical Physics
- Trieste, Italy; Imperial College
- London, United Kingdom

Steven Weinberg
- 1/3 of the prize
- USA
- Harvard University
- Cambridge, MA, USA

The Nobel Prize in Physics 1999
"for elucidating the quantum structure of electroweak interactions in physics"

Gerardus 't Hooft
- 1/2 of the prize
- the Netherlands
- Utrecht University
- Utrecht, the Netherlands
- b. 1945

Martinus J.G. Veltman
- 1/2 of the prize
- the Netherlands
- Bilkhoven, the Netherlands
- b. 1931

Theoretical Physicists
People to Formulate E-W Theory

The Nobel Prize in Physics 1984

"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"

Experimental Physicists

Carlo Rubbia
- 1/2 of the prize
- Italy
- CERN, Geneva, Switzerland
- b. 1934

Simon van der Meer
- 1/2 of the prize
- the Netherlands
- CERN, Geneva, Switzerland
- b. 1925