Nothing in life is to be feared. It is only to be understood.

-Marie Curie
Radioactive Decay

- Antoine Henri Becquerel
- Marie Curie, née Sklodowska
- Pierre Curie

Nobel Prize in 1903
Laws of Radioactive Decay

• Activity:

\[ R = -\frac{dN}{dt} \]

• \( N \) = number of nuclei

• Units:
  - 1 Becquerel (Bq) = 1 decay/s
  - 1 Curie (Ci) = \( 3.7 \times 10^{10} \) decays/s

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Laws of Radioactive Decay

• Radiation from a radioactive sample is due to decay of many independent nuclei.

• Let each nuclei have a probability of decay per unit time given by \( \lambda \).

• The activity at time \( t \) is given by the probability times the number of nuclei at time \( t \).

\[ R = \lambda N(t) \]
Laws of Radioactive Decay

• The number of nuclei that decay in $dt$ is given by

$$dN(t) = -R dt = -\lambda N(t) dt$$

$$N(t) = N_0 e^{-\lambda t}$$

$$R = R_0 e^{-\lambda t}$$

Laws of Radioactive Decay

• Half life: time in which the number of nuclei drops to half its original value. $t_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$
Daughter Products

- As one nuclide decays it creates another.
Half-lives

<table>
<thead>
<tr>
<th>Radioisotope</th>
<th>Symbol</th>
<th>Radiation</th>
<th>Half-Life</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tritium</td>
<td>$^3$H</td>
<td>$\beta^-$</td>
<td>12.33 years</td>
<td>Biochemical tracer</td>
</tr>
<tr>
<td>Carbon-14</td>
<td>$^{14}$C</td>
<td>$\beta^-$</td>
<td>5730 years</td>
<td>Archaeological dating</td>
</tr>
<tr>
<td>Phosphorus-32</td>
<td>$^{32}$P</td>
<td>$\beta^-$</td>
<td>14.26 days</td>
<td>Leukemia therapy</td>
</tr>
<tr>
<td>Potassium-40</td>
<td>$^{40}$K</td>
<td>$\beta^-$</td>
<td>$1.28 \times 10^9$ years</td>
<td>Geological dating</td>
</tr>
<tr>
<td>Cobalt-60</td>
<td>$^{60}$Co</td>
<td>$\beta^-, \gamma$</td>
<td>5.27 years</td>
<td>Cancer therapy</td>
</tr>
<tr>
<td>Technetium-99m</td>
<td>$^{99m}$Tc</td>
<td>$\gamma$</td>
<td>6.01 hours</td>
<td>Brain scans</td>
</tr>
<tr>
<td>Iodine-123</td>
<td>$^{123}$I</td>
<td>$\gamma$</td>
<td>13.27 hours</td>
<td>Thyroid therapy</td>
</tr>
<tr>
<td>Uranium-235</td>
<td>$^{235}$U</td>
<td>$\alpha, \gamma$</td>
<td>$7.04 \times 10^8$ years</td>
<td>Nuclear reactors</td>
</tr>
</tbody>
</table>

*The m in technetium-99m stands for metastable, meaning that it undergoes $\gamma$ emission but does not change its mass number or atomic number.

Decay Energetics

- **All Decays:**
  - Energy, Momentum, Angular Momentum
- **Strong Interaction and Electromagnetic decays:**
  - N and Z conserved, Parity Conserved
- **Weak Interaction decays:**
  - Atomic number, $A$, conserved
- **A Nuclide is unstable if**
  - There is another nucleon configuration with a lower total energy.
  - There is a process that can reach the configuration while obeying the conservation rules.
General Criteria for Stability

- All isotopes with $Z > 83$ are unstable.
- Pairing:
  - Most even-even nuclei are stable
  - Many odd-even or even-odd nuclei are stable.
  - Only 4 odd-odd nuclei are stable. ($^2$H, $^6$Li, $^{10}$B, $^{14}$N)
- N/Z ratios
  - For $A < 40$: $N \approx Z$
  - For $A > 40$: $N > Z$

Q-value: Disintegration Energy

- The q-value is the energy difference between the parent nuclide and the daughter products.

$$ Q = [M(^A_X) - M(\text{products})]c^2 $$

- If $Q > 0$ then the nucleus is unstable and will decay into the daughter products.
Decay Processes

Comparing “Rays”
Types of Decay

Alpha Decay

- Alpha particles are helium nuclei.

\[ ^A_Z X \rightarrow ^{A-4}_{Z-2} Y + \alpha \]
Alpha Decay

- Alphas formed inside the nucleus tunnel out of the coulomb barrier.
Alpha Decay and Smoke Detectors

- Smoke detectors are ionization chambers.
- The alpha’s emitted by the Americium-241 ionize the air between the plates allowing a current to flow between the plates.
- When smoke enters the detector the particles combine with the ions and neutralize the air. The current reduces causing the detector alarm to sound.
Beta-minus Decay

• Beta-minus particles are electrons.
• One of a class of weak interaction decays.
**Beta Decay**

- Weak interaction can transform protons $\leftrightarrow$ neutrons
- **Beta-minus:**
  \[ n \rightarrow p + e^- + \bar{\nu} \]
- **Beta-plus:**
  \[ p \rightarrow n + e^+ + \nu \]
- **Electron capture:**
  \[ p + e^- \rightarrow n + \nu \]

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**Beta decay**

- **Beta-minus:**
  \[ \frac{A}{Z} X \rightarrow \frac{A}{Z+1} Y + e^- + \bar{\nu} \]
- **Beta-plus:**
  \[ \frac{A}{Z} X \rightarrow \frac{A}{Z-1} Y + e^+ + \nu \]
- **Electron capture:**
  \[ \frac{A}{Z} X + e^- \rightarrow \frac{A}{Z-1} Y + \nu \]
Valley of Stability

Odd A Isobar Plot
Even A Isobar Plot

The Neutrino Hypothesis
Neutrino Mass

The Beta Decay Spectrum for Molecular Tritium

Neutrino Mass

Catching Neutrinos

A neutrino is detected when it hits a nucleus, causing the nucleus to decay. The energy released in the decay is measured, and if it matches the energy expected for a neutrino, the event is counted as a neutrino detection.

Figure 6

A line graph showing the relationship between L/E and the number of detected neutrinos. The X-axis represents L/E (km/GeV), and the Y-axis represents the number of detected neutrinos. The graph includes data points for different neutrino types, with markers indicating the type of neutrino detected.
Gamma-Decay

- Rearrangement of nucleons in nucleus with the emission of a photon.

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

- Gamma-ray energies are \( \sim 1 \) MeV and higher.

Internal Conversion

- Rather than emit a gamma-ray the nucleus can transfer energy to one of the atomic electrons.
- The characteristic x-ray and electron spectra associated with IC distinguish it from beta decay.
Gamma Decay

- Gamma decay often follows either alpha or beta decay.
- The parent nucleus decays to an excited state in the daughter which de-exites via gamma emission or internal conversion.

Quiz 1

? +
- Proton
- Neutron
Quiz 2

Nucleon Emission

(b)

Proton number

2 8 20 28 50 82 128

2 8 20 28 50 82 126

Proton dripline

Neutron dripline
Decay Processes on the Segre Chart

Spontaneous Fission
Radioactive Series

- Four decay series contain most of the common radionuclides
- Each series consists of a succession of daughter products ultimately derived from a single parent.

Radioactive Series
(Decay Chains)

- Thorium (A = 4n)
  \[ ^{232}_{90}Th \rightarrow ^{208}_{82}Pb \]

- Neptunium (A = 4n+1)
  \[ ^{237}_{93}Np \rightarrow ^{209}_{83}Bi \]

- Uranium (A = 4n+2)
  \[ ^{238}_{92}U \rightarrow ^{206}_{82}Pb \]

- Actinium (A = 4n+3)
  \[ ^{235}_{92}U \rightarrow ^{207}_{82}Pb \]
Radioactive Dating

- $^{204}\text{Pb}$ – stable and not a daughter of any nuclide
- $^{206}\text{Pb}$ and $^{207}\text{Pb}$ are the end of decay chains.
- Ratio of $^{207}\text{Pb}/^{204}\text{Pb}$ is roughly constant as the half-life of the Actinium chain is short $\sim 7 \times 10^8$ yrs.
- Ratio of $^{206}\text{Pb}/^{204}\text{Pb}$ is still changing as the Uranium chain has $t_{\text{half}} \sim 4.5 \times 10^9$ yrs.
- Comparison of the two ratios can give the age of a sample.
Shroud of Turin

Very small samples from the Shroud of Turin have been dated by accelerator mass spectrometry in three independent laboratories. As Controls, three samples whose ages had been determined independently were also dated.

- The results of radiocarbon measurements at Arizona, Oxford and Zurich yield a calibrated calendar age range with at least 95% confidence for the linen of the Shroud of Turin of AD 1260 - 1390 (rounded down/up to nearest 10 yr). These results therefore provide conclusive evidence that the linen of the Shroud of Turin is mediaeval. – (Nature, Vol. 337, No. 6208, pp. 611-615, 16th February, 1989)