Modes of Radioactive Decay I

RTT4220 – LECTURE #3

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09/02/2025

Radioactive Decay Basics

yeah

Instability

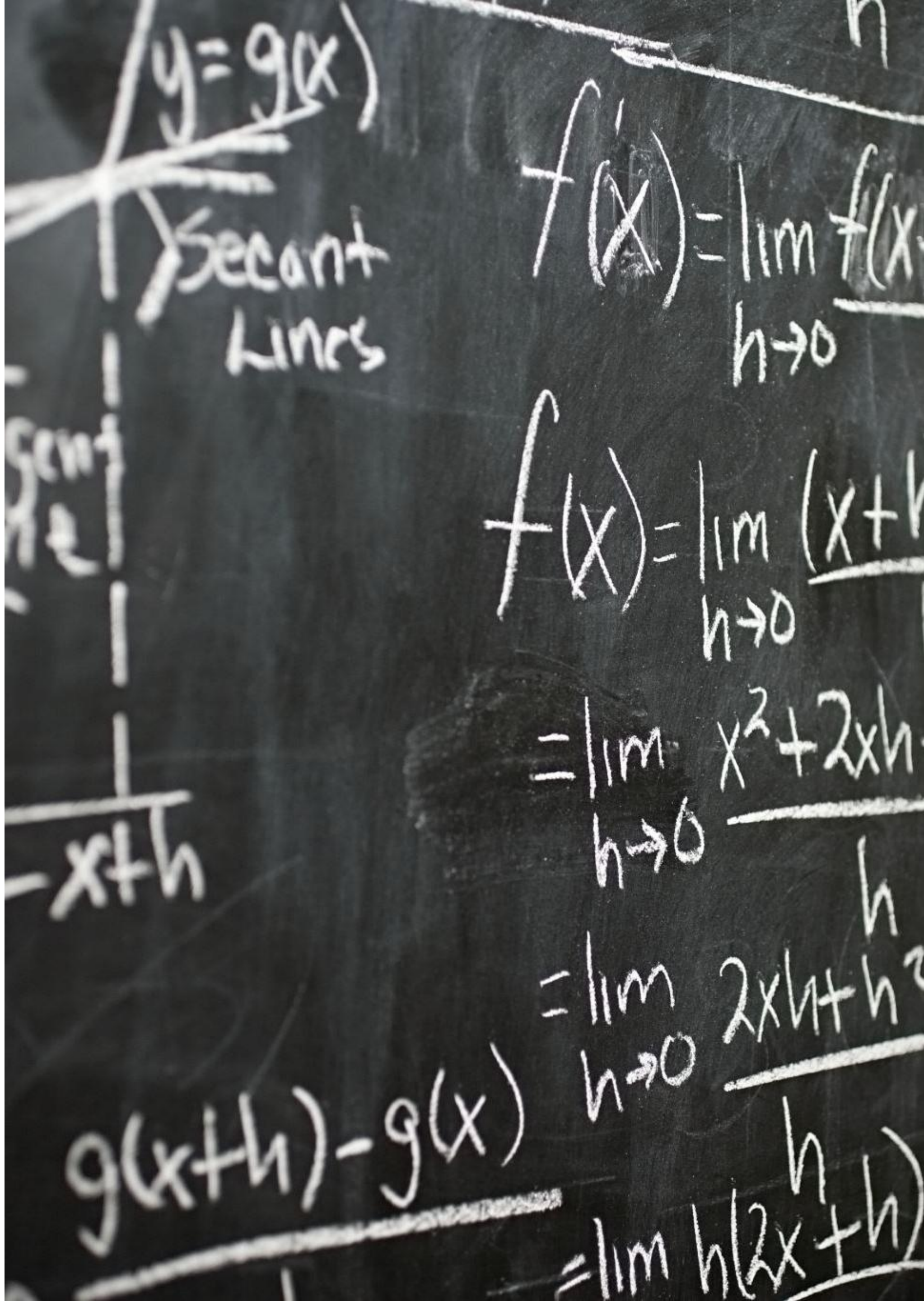
When nuclear forces are unbalanced, the nucleus is UNSTABLE

Three modes of reaching stability:

Fission	Fusion	Radioactive Decay

Terminology

- Parent/Daughter – "before and after of decay"
- **Spontaneous** – each decay **cannot** be predicted, but **can** be modeled statistically
- **Conservation of Mass** and **Conservation of Charge**
- **Transition Energy (Q)** – decay converts **ENERGY TO MASS**
  - Typically written as: ${}^{A}_{Z}\mathrm{X} \xrightarrow{\text{Particle:Half}-\text{Life}} {}^{A-?}_{Z-?}\mathrm{Y} + \ ? + \mathrm{Q}$



Radioactive Isotope Chemistry

Chemistry primarily depends on VALENCE electrons

Isotopes have the same base electron shell

Minor relative differences in mass → no difference in chemistry

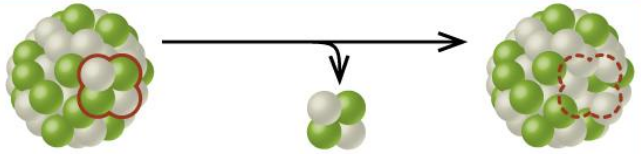
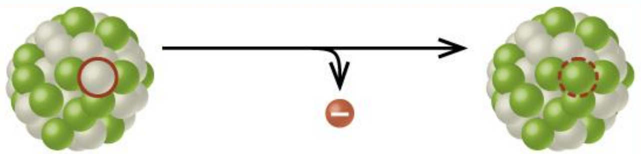
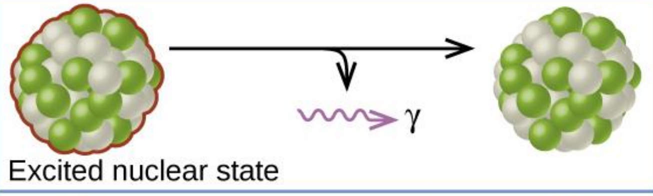
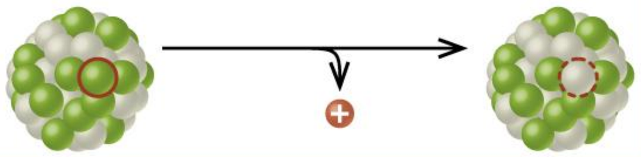
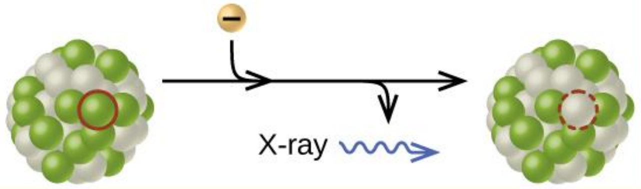
Major relative differences in mass → some effect on chemistry

Tracers use radioactive isotopes to image the body

Modes of Radioactive Decay

DEPECHE ANYONE?

Modes of Radioactive Decay

Type	Nuclear equation	Representation	Change in mass/atomic numbers
Alpha decay	$^{A}_{Z}X \quad ^{4}_{2}He + ^{A-4}_{Z-2}Y$		A: decrease by 4 Z: decrease by 2
Beta decay	$^{A}_{Z}X \quad ^{0}_{-1}e + ^{A}_{Z+1}Y$		A: unchanged Z: increase by 1
Gamma decay	$^{A}_{Z}X \quad ^{0}_{0}\gamma + ^{A}_{Z}Y$		A: unchanged Z: unchanged
Positron emission	$^{A}_{Z}X \quad ^{0}_{+1}e + ^{A}_{Y-1}Y$		A: unchanged Z: decrease by 1
Electron capture	$^{A}_{Z}X \quad ^{0}_{-1}e + ^{A}_{Y-1}Y$		A: unchanged Z: decrease by 1

Modes of Radioactive Decay

We can use the LINE OF STABILITY chart to predict which category of decay is most likely!

- Alpha Emission
- Beta Emission
  - Electron Emission
  - Positron Emission
  - Internal Conversion
- Gamma Emission
  - Excited States
  - Isomeric Transition
  - Electron Capture
- Nuclear Fission

Alpha Emission

- Helium radiation $^{4}_{2}\mathrm{He}$
  - Massive (~4 amu)
  - High Energy (~8 MeV)
  - Low Range in attenuating material (<0.1 mm in tissue, CANT HURT UNLESS…)

$$^{A}_{Z}X \xrightarrow{\alpha} {}^{A-4}_{Z-2}Y$$

- Daughter nuclide has A-4 and Z-2 (protons+neutrons, protons)
- Sometimes results in excited state → gamma emission
- Only heavy elements (Z>82, Lead)
- Potentially gaining importance (theranostics) Tb-149 Alpha/Positron

Concept: Alpha Emission Cause

Given what we know about the “tug-of-war” for stability, what is the imbalance that leads to alpha-particle decay?

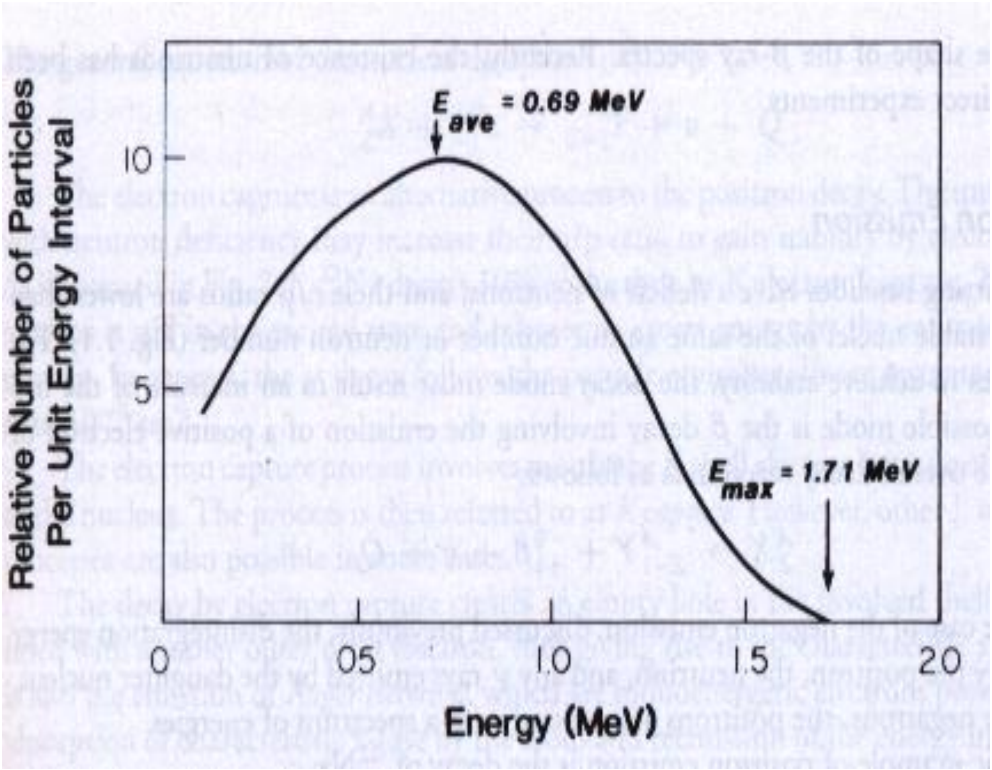
Repulsive forces are too great (electromagnetic force between protons to great, not enough neutrons to balance things out); this is reflected in the LINE OF STABILITY

$$ {}^{A}_{Z}X \xrightarrow{\beta^{-} decay} {}^{A}_{Z+1}Y + {}^{0}_{-1}\beta^{-} + \bar{\nu} + Q $$

$$ {}^{A}_{Z}X \xrightarrow{\beta^{+} decay} {}^{A}_{Z-1}Y + {}^{0}_{+1}\beta^{+} + \nu + Q $$

Beta Emission

- Beta is overarching term for ELECTRONS (e^- or β^-) and POSITRONS (e^+ or β^+)
  - Wide range of maximum energies
  - Decent range in attenuating material → dangerous!
- When beta emission occurs the nucleus GAINS or LOSES charge, respectively (conservation of charge)
- Energy Spectrum for emitted electron
- Use line of stability to predict what kind of emission
  - Too many neutrons: β^- → Z+1 and A+0
  - Too many protons: β^+ → Z-1 and A+0



Neutrino and Anti-Neutrino

- Basically never interact with matter
  - Essentially massless
  - No charge
- Only importance to us is that it carries away excess energy for BETA decay → spectrum

Positron Energy Requirement

- The transition energy $\mathbf{Q}$ must be AT LEAST +1.022 MeV (511 keV x 2)
- The requirement is due to the result of matter-antimatter annihilation (discussed more later)
- The maximum energy changes: $\mathbf{E}_{\mathbf{max}}^{\beta^{+}} = \mathbf{Q\text{-}1.022\ MeV}$ → Average is 1/3 this value

Gamma Emission

- Gamma emission refers to photons
- Three primary routes:
  - Excited states after other decays $(\beta^{-}, \gamma), (\beta^{+}, \gamma)$, (α, γ), (EC, γ)
  - Isomeric Transition (IT) basically just a long-lived excited state
  - Electron Capture (EC)
- Of note is Internal Conversion (IC): where a gamma would be emitted except the energy goes directly to an electron → conversion electron → Char. Rad./Auger
  - Typically inner shell and the gamma must have had enough energy to overcome binding energy

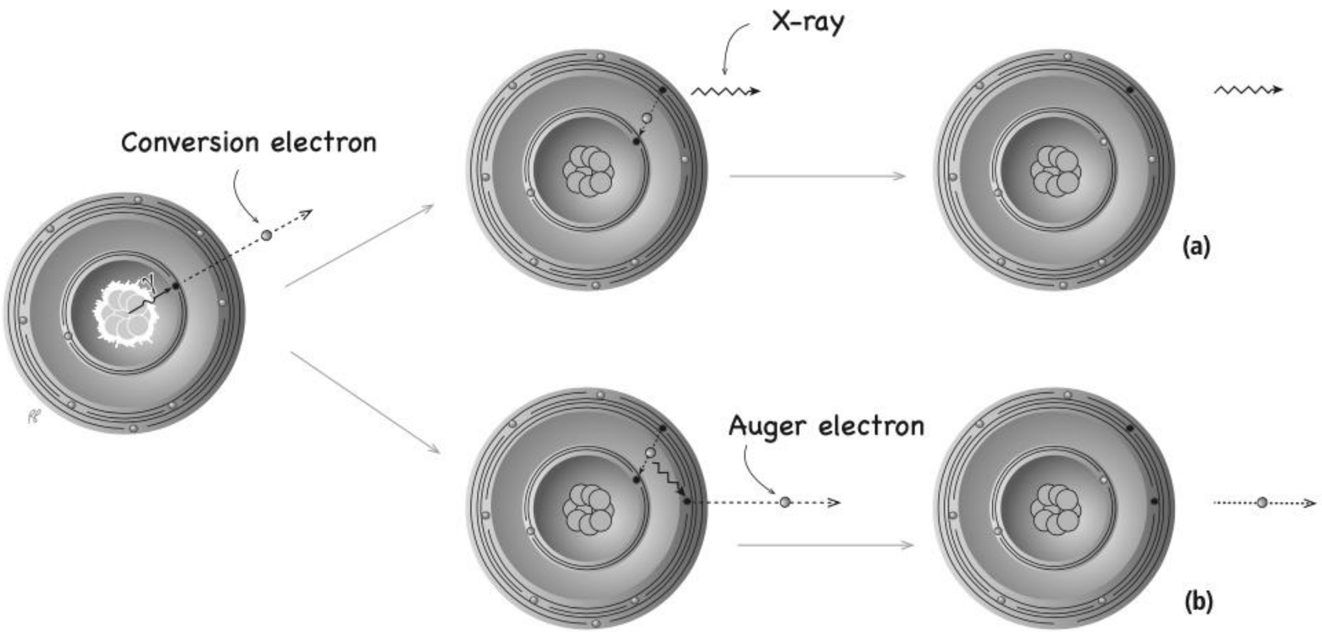
Internal Conversion VS β

- Both result in emitted electron
- Origin of electron is different:
  - Beta-: electron originates from conversion of neutron in the nucleus
  - IC: electron originates from shell → vacancy
- Energy differs:
  - Beta-: Spectrum of energies
  - IC: Discrete series of energies E_γ - BE

Electron Capture

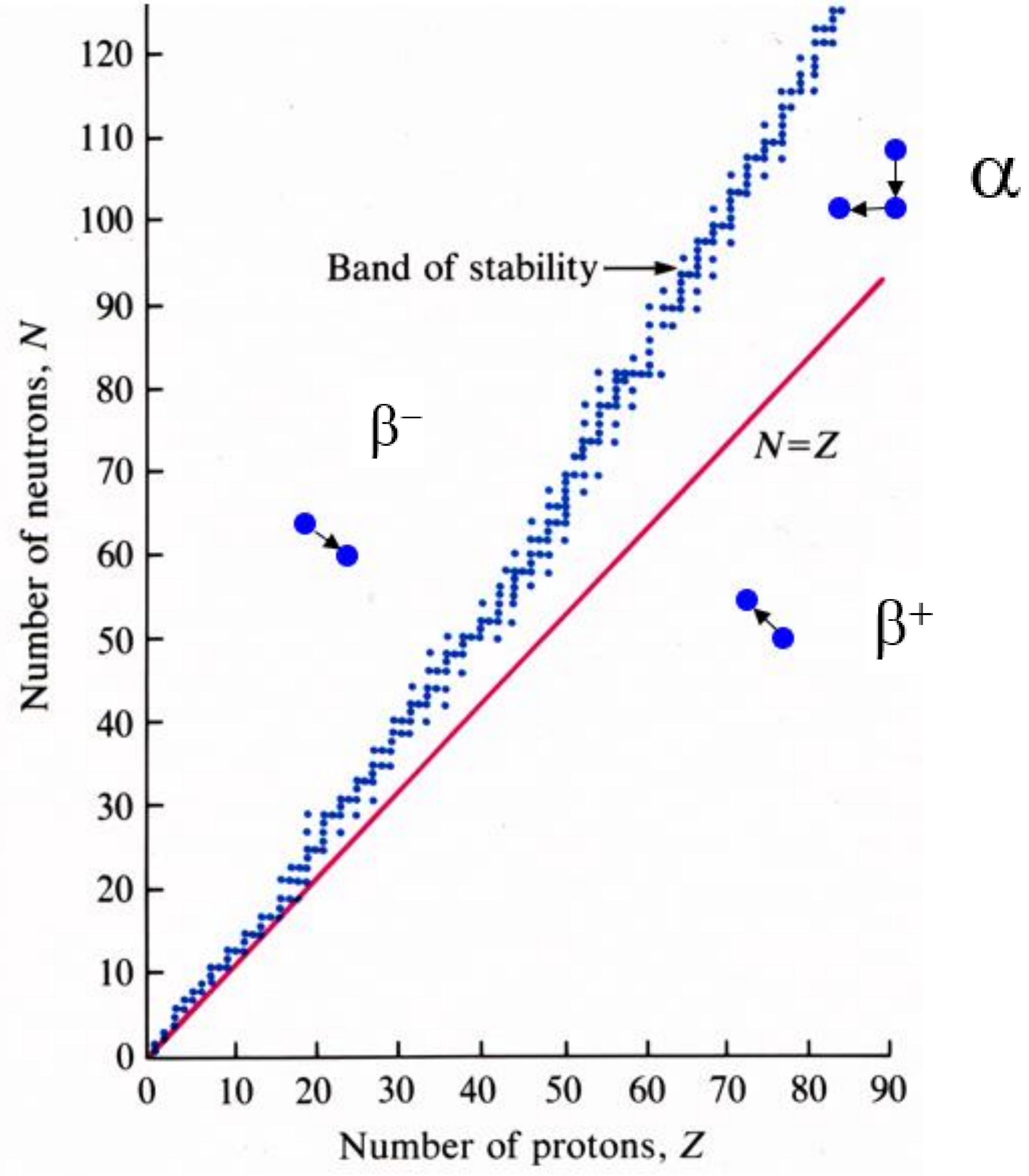
$$^{A}_{Z}X + {}^{0}_{-1}e^{-} \xrightarrow{e^{-}capture} {}^{A}_{Z-1}Y + \nu + Q$$

- The nucleus CAPTURES and CONVERTS its OWN ELECTRON and CONSUMES a PROTON
- Occurs when there are too many protons
  - Competitive with β^{+}
  - If $\mathbf{Q < 1.022\ MeV}$ then EC always occurs
- Almost always K-shell electrons
- Leaves a vacancy → Char. Rad./Auger



Line of Stability

- α -decay (Z-2; N-2; A-4)
- β^- -decay (Z+1; N-1)
- β^+ -decay (Z-1; N+1)



Line of Stability