Chemical Engineering 412

Introductory Nuclear Engineering

Lecture 6

Nuclear Radiation Types

Key Points

- Types of Decay
  - Name
  - Properties
  - Mathematical Descriptions
  - Caveats
- Decay Charts (KNOW HOW TO USE!)
- Nuclear Equation for Decay
- Q-Values for Decay

Decay Conservations

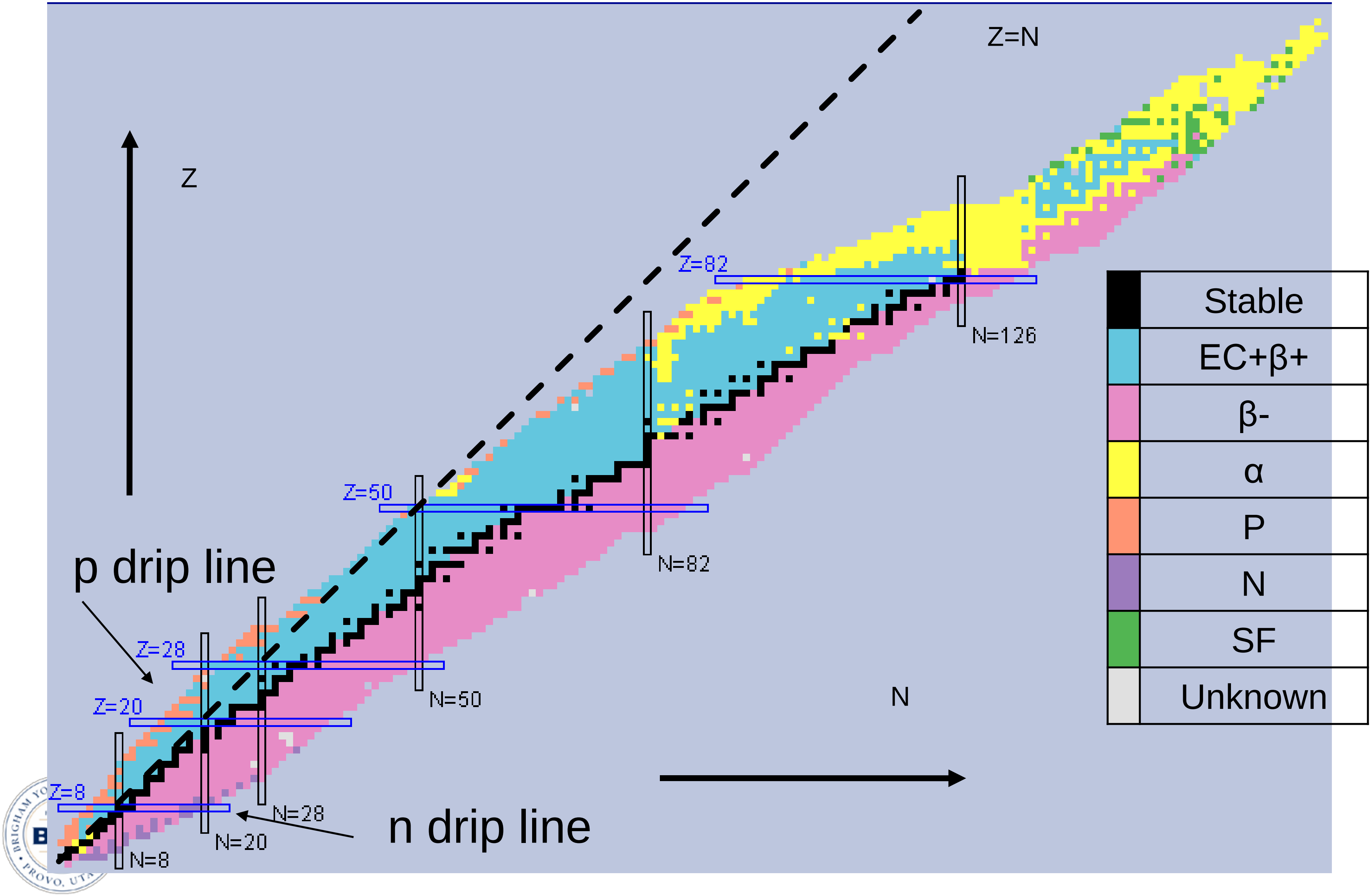
- Charge
- Nucleon Number
- Mass/Energy (Total Energy)
- Momentum

- Classical behavior if liberated energy is much less than rest mass energy

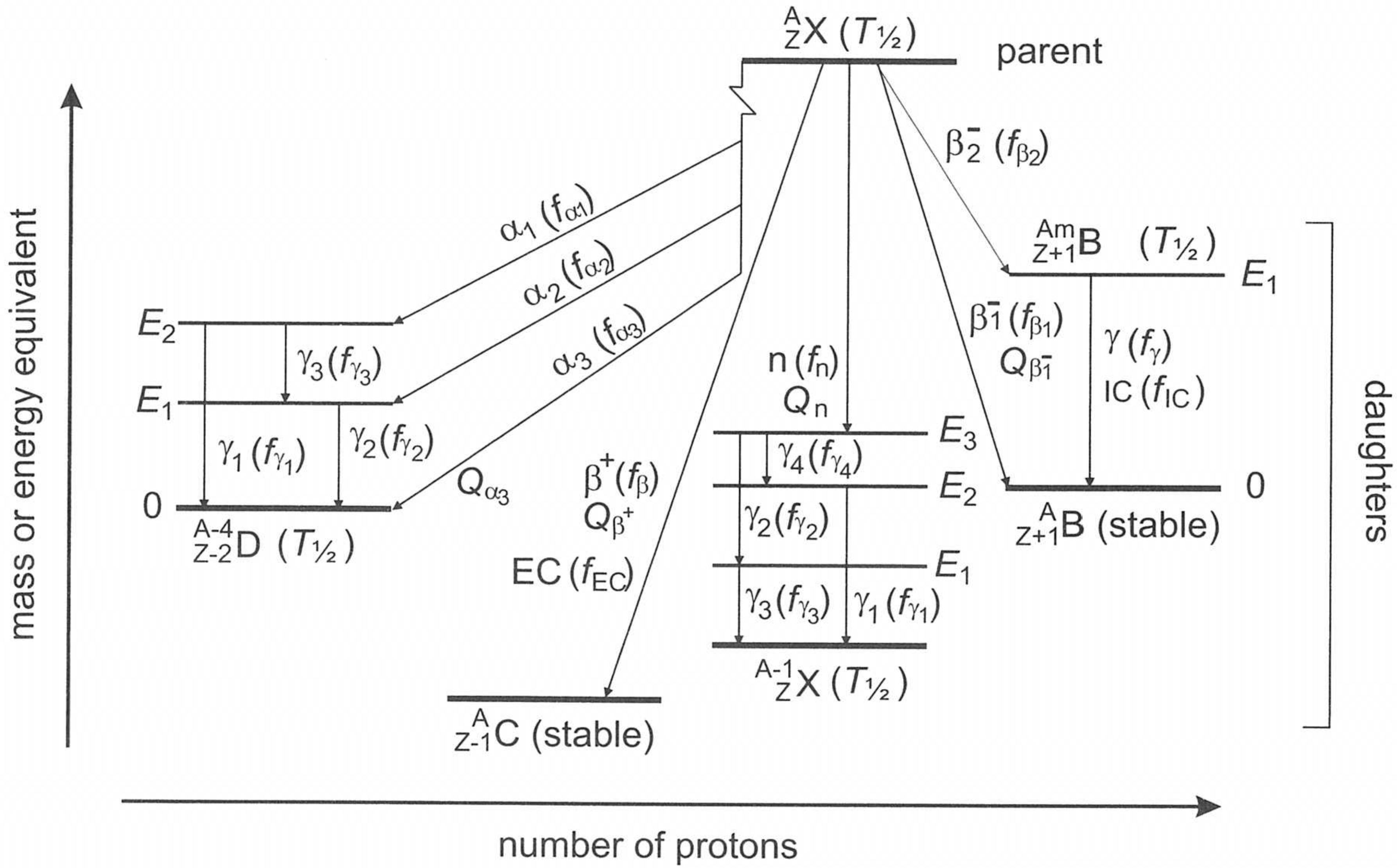
Decay Mechanisms

- Alpha ($\boldsymbol{\alpha}$)
- Beta (+/-) ($\boldsymbol{\beta}^{+}, \boldsymbol{\beta}^{-}$)
- Gamma ($\boldsymbol{\gamma}$)
- Electron capture (EC)
- Proton (P), Deuteron (D) and Triton (T)
- Neutron (N)
- Internal conversion (IC)
- Spontaneous fission (SF)

Chart of the Nuclides



Energy Diagram



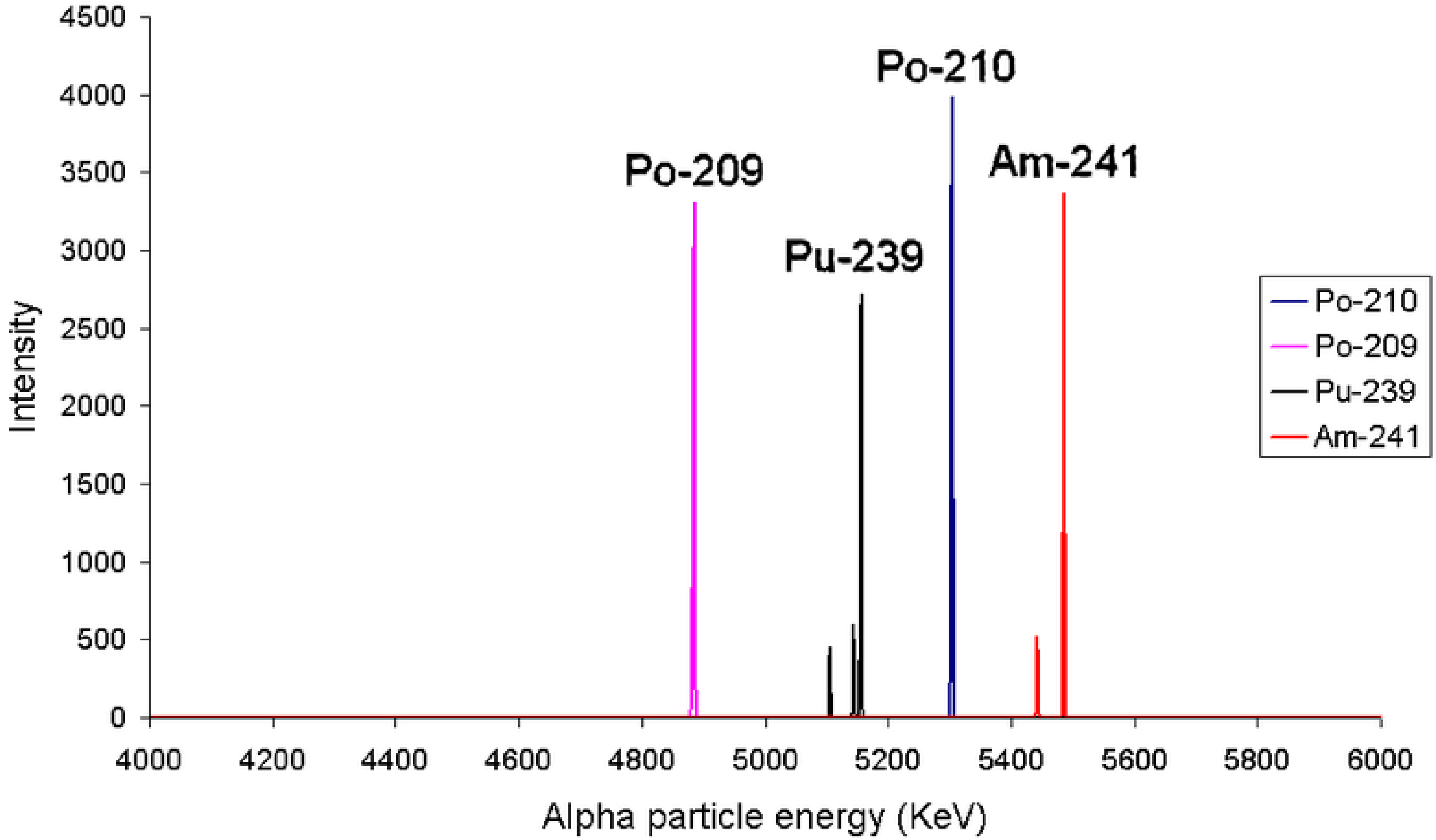
Main Radiation Types – Qualitative

- You probably know about most of these already
- So we'll go over a few more advanced concepts

Alpha Decay

- Emission of a ^4He nucleus – a (2+) charged particle.
- Reduces Z by 2, N by 2, and A by 4.
- Common in heavy (> Pb, 82) nuclides, otherwise rare.
- Alpha particles have discrete energies (quantized)
- Very highly energetic (LARGE)
  - rapidly absorbed by other material – WHY?
  - generally stopped by piece of paper or outer layers of skin.

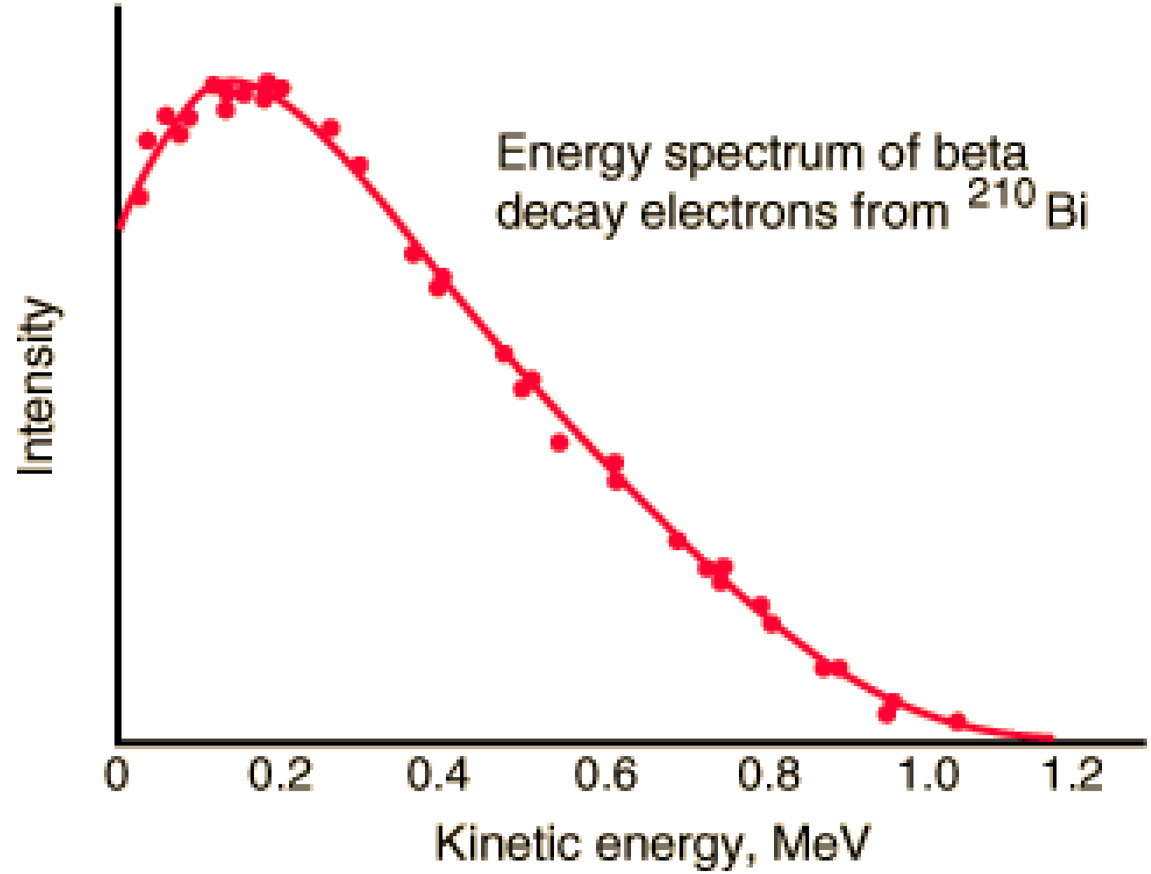
Alpha Decay Example



Beta Decay (I)

- β^+ (positron) decay
  - occurs in proton-rich nuclei.
  - proton transforms to a neutron
    - positron and neutrino emitted
    - reduces Z and increases N by 1 without changing A.
- β^- (electron) decay
  - occurs in neutron-rich nuclei
  - neutron transforms to a proton
    - electron and anti-neutrino emitted
    - increases Z and decreases N by 1 without changing A.

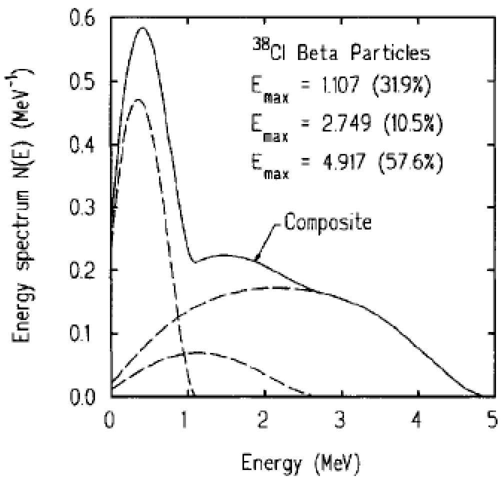
Experimental Decay Spectrum



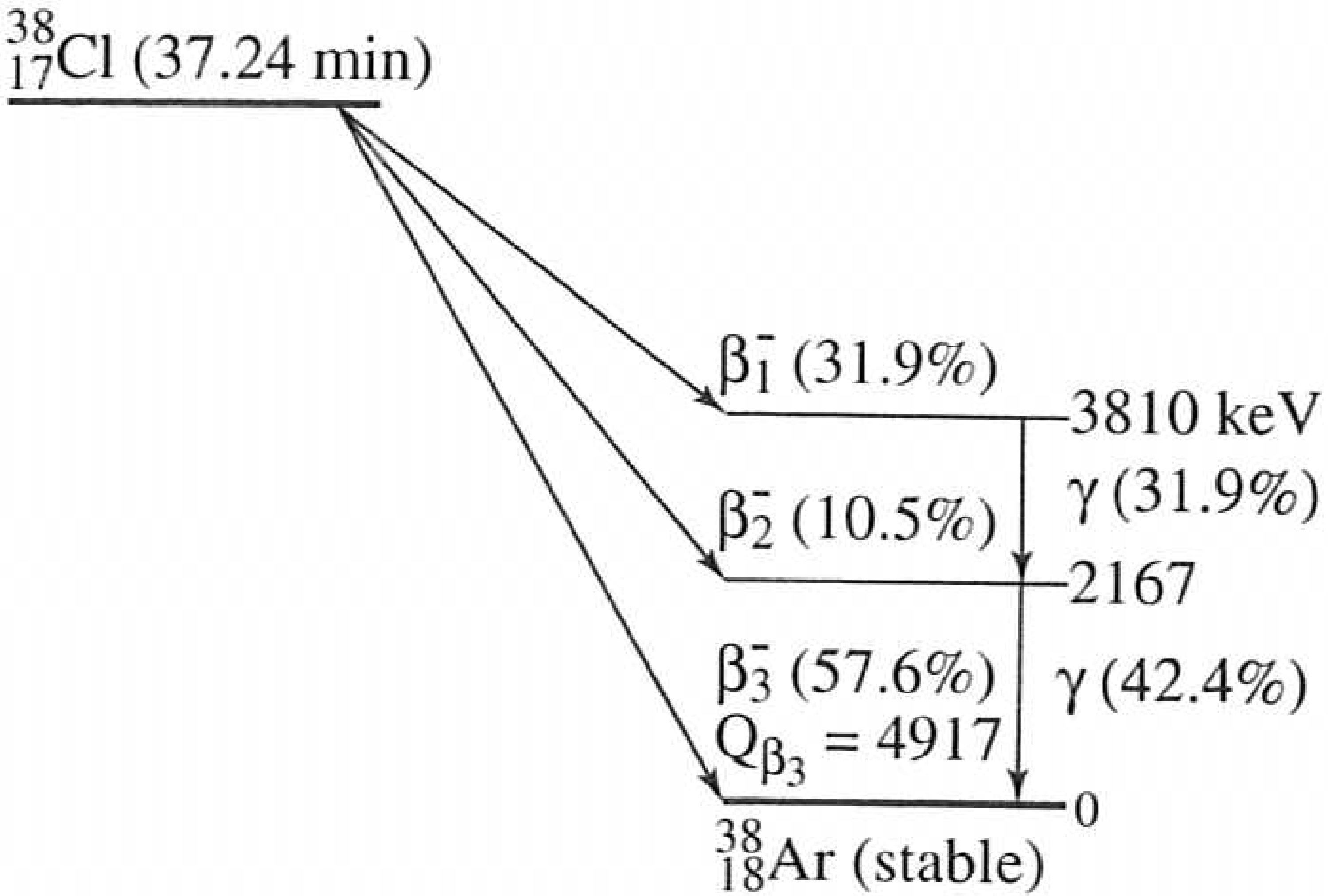
Source: G. J. Neary, Roy. Phys. Soc. (London), A175, 71 (1940).

Beta Decay (II)

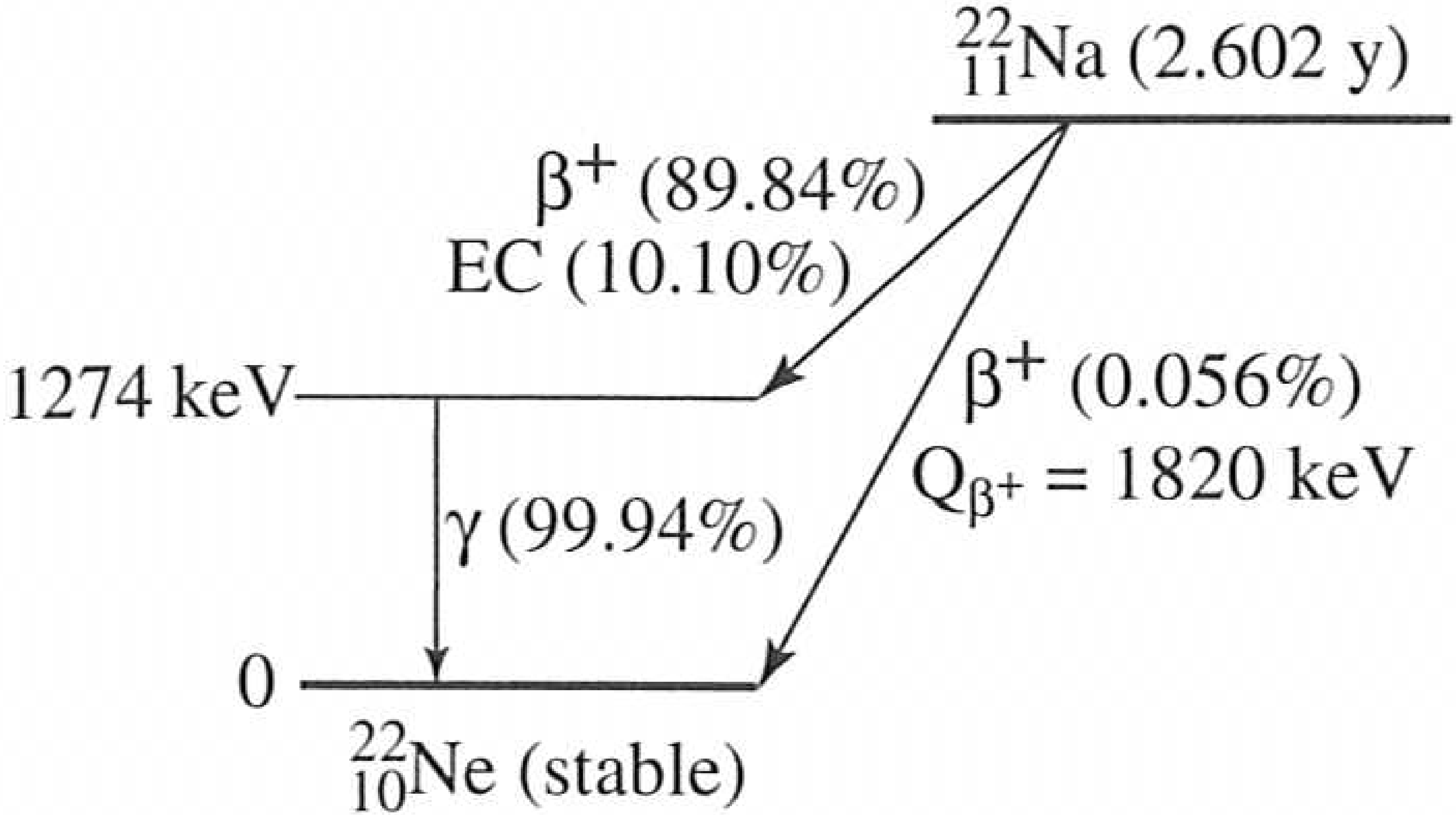
- Continuous energy spectrum (not discrete)
  - shares its energy with the neutrino.
- High-energy ionizing radiation
  - penetrates outer skin
  - Doesn't penetrate plywood or most construction materials.
- Responsible for both external and internal exposures.



β^- Decay Example: Chlorine-38



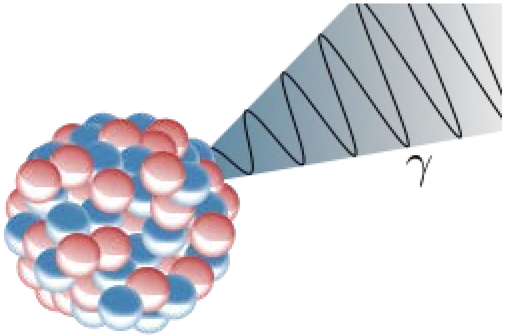
Positron/β⁺ Decay: Sodium-22



Gamma Emission

- Results from energy level rearrangement of nuclides
- Does not change Z, N, or A
- Exhibits discrete energy levels (quantized)
  - Because quantized energy states in nucleus.
- Low energy compared to α or β+/-
  - Not an ion, thus not easily absorbed
  - penetrates deeply in skin, concrete, etc.
  - Stopped by thick lead
- Major source of external radiation exposure.

Gamma emission

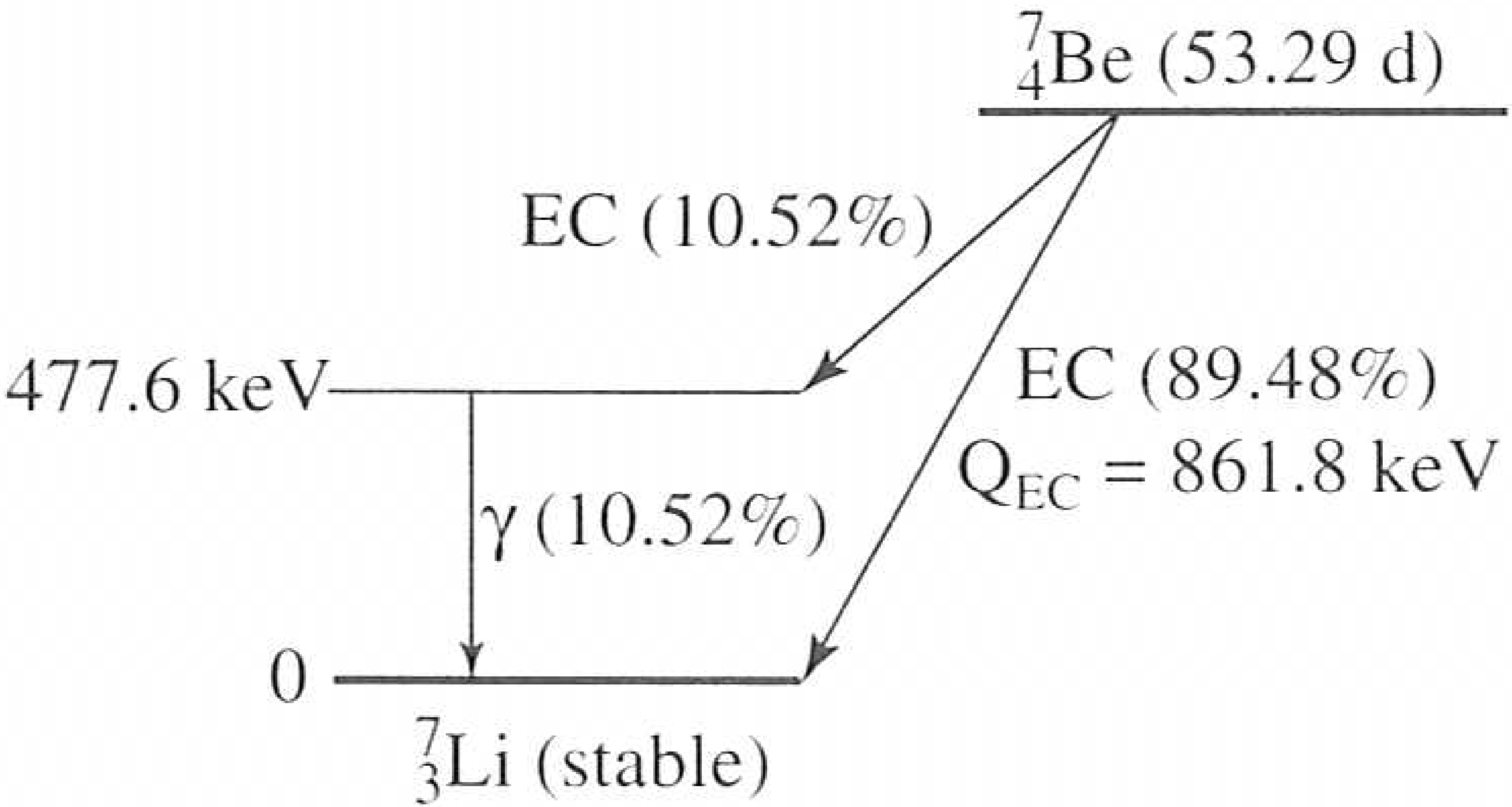


No change in Z, N, or A. Energy determined by nuclear states.

Electron Capture

- Conversion of proton to neutron & neutrino by capture of inner shell electron.
- Similar to (competes with) β^+:
  - Z decreases and N increases, no change in A
- Differs from β^+:
  - Consumes an electron
- No charged particle ***must*** be emitted - unique
- Gamma rays – excited state decay

Electron Capture: Beryllium-7



Neutron Decay

- Too many protons!
- Some drip line isotopes emit a neutron
  - Daughter has one less nucleon
  - Daughter generally in an excited state, releases gamma
- Critical to reactor control
  - Find out more in a few weeks! :D

Proton Decay

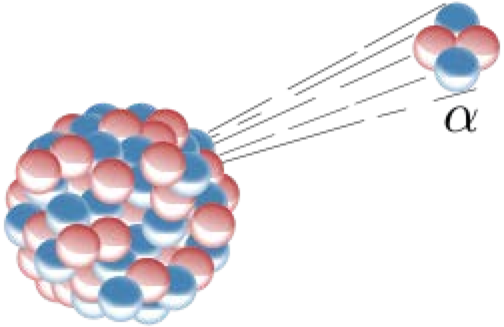
- Proton emission happens at the proton drip line.
- Generally rare and relatively unimportant.

Radiation Types – Quantitative

- Main question: How to get the decay energy?
- In general, just find Q
- There are a lot of equations on the next few slides, but they’re pretty much all the same (so don’t worry!)

Alpha Decay

$$ {}_{Z}^{A}P \rightarrow \left[{}_{Z-2}^{A-2}D\right]^{2-} + {}_{2}^{4}\alpha \rightarrow {}_{Z-2}^{A-2}D + {}_{2}^{4}He $$



First look at Q for mass (mass difference)

$$ \frac{Q_\alpha}{c^2} = M\left({}_{Z}^{A}P\right) - \left[M\left({}_{Z-2}^{A-4}D^{2-}\right) + m\left({}_{2}^{4}\alpha\right)\right] $$

$$ \cong M\left({}_{Z}^{A}P\right) - \left[M\left({}_{Z-2}^{A-4}D\right) + 2m_e + m\left({}_{2}^{4}\alpha\right)\right] $$

$$ \cong M\left({}_{Z}^{A}P\right) - \left[M\left({}_{Z-2}^{A-4}D\right) + m\left({}_{2}^{4}He\right)\right] $$

- Two approximations;
  - Neglect daughter electron Binding Energy (1st Eq.)
  - Neglect He electron Binding energy (2nd Eq.)
- ^{4}He atom differs from an α particle?
  - two electrons – the α particle has a net 2+ charge.

Alpha Decay

$$ {}^{A}_{Z}P \rightarrow \left[{}^{A-2}_{Z-2}D\right]^{2-} + {}^{4}_{2}\alpha \rightarrow {}^{A-2}_{Z-2}D + {}^{4}_{2}He $$

Now look at Q for energy (kinetic energy)

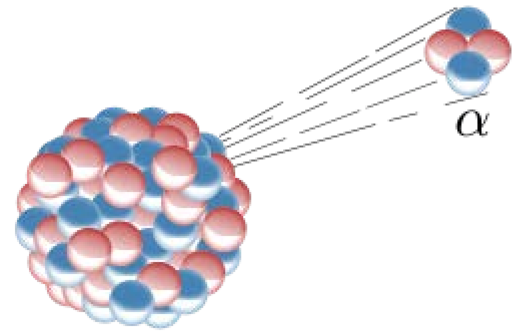
$$ Q_\alpha = E_D + E_\alpha = \frac{1}{2}M_\alpha v_\alpha^2 + \frac{1}{2}M_D v_D^2 $$

$$ M_D v_D = M_\alpha v_\alpha $$

$$ \Rightarrow Q_\alpha = \frac{1}{2}M_\alpha v_\alpha^2\left(\frac{M_\alpha}{M_D} + 1\right) $$

$$ E_\alpha = Q_\alpha\left[\frac{M_D}{M_D + M_\alpha}\right] \cong Q_\alpha\left[\frac{A_D}{A_D + A_\alpha}\right] $$

$$ E_D = Q_\alpha\left[\frac{M_\alpha}{M_D + M_\alpha}\right] \cong Q_\alpha\left[\frac{A_\alpha}{A_D + A_\alpha}\right] $$



Energies of alpha and daughter particles are fixed, and alpha particle energy is uniquely associated with isotope.

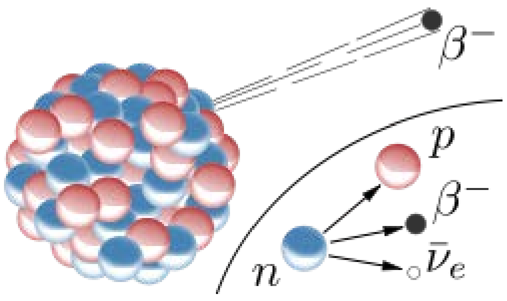
β^- Decay

$$ {}^{A}_{Z}P \rightarrow \left[{}^{A}_{Z+1}D\right]^{+} + {}^{0}_{-1}e + \overline{\nu}_e $$

$$ \frac{Q_{\beta^-}}{c^2} = M\left({}^{A}_{Z}P\right) - \left[M\left({}_{Z+1}^{A}D^{+}\right) + m_{\beta^-} + m_{\overline{\nu}_e}\right] $$

$$ \cong M\left({}^{A}_{Z}P\right) - \left\{\left[M\left({}_{Z+1}^{A}D\right) - m_e\right] + m_{\beta^-} + m_{\overline{\nu}_e}\right\} $$

$$ = M\left({}^{A}_{Z}P\right) - M\left({}_{Z+1}^{A}D\right) $$ ground-state daughter



β^- decay

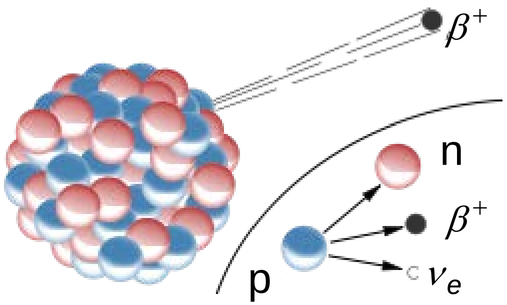
$$ \frac{Q_{\beta^-}}{c^2} = M\left({}^{A}_{Z}P\right) - M\left({}_{Z+1}^{A}D\right) - \frac{E^*}{c^2} $$ excited-state daughter

$$ E_{\beta^-,\max} = \left(\frac{M_D}{M_D + M_e}\right) Q_{\beta^-} \cong Q_{\beta^-} $$

- specific particle energies cannot be determined
- continuous range of energies with a defined maximum value.

β⁺ or Positron Decay

$$ {}^{A}_{Z}P \rightarrow \left[{}^{\;\;\;A}_{Z-1}D \right]^{-} + {}^{0}_{+1}e + \nu_e $$



β^+ decay

$$ \frac{Q_{\beta^-}}{c^2} = M\left({}^{A}_{Z}P\right) - \left[M\left({}^{\;\;\;A}_{Z-1}D^-\right) + m\left({}^{0}_{+1}e\right) + m_{\nu_e} \right] $$

$$ \cong M\left({}^{A}_{Z}P\right) - \left\{ \left[M\left({}^{\;\;\;A}_{Z-1}D\right) + m_e \right] + m_{\beta^+} + m_{\nu_e} \right\} $$

$$ = M\left({}^{A}_{Z}P\right) - M\left({}^{\;\;\;A}_{Z-1}D\right) - 2m_e $$

ground-state daughter

$$ \frac{Q_{\beta^+}}{c^2} = M\left({}^{A}_{Z}P\right) - M\left({}^{\;\;\;A}_{Z-1}D\right) - 2m_e - \frac{E^*}{c^2} $$

excited-state daughter

$$ E_{\beta^+,\max} \cong Q_{\beta^+} $$

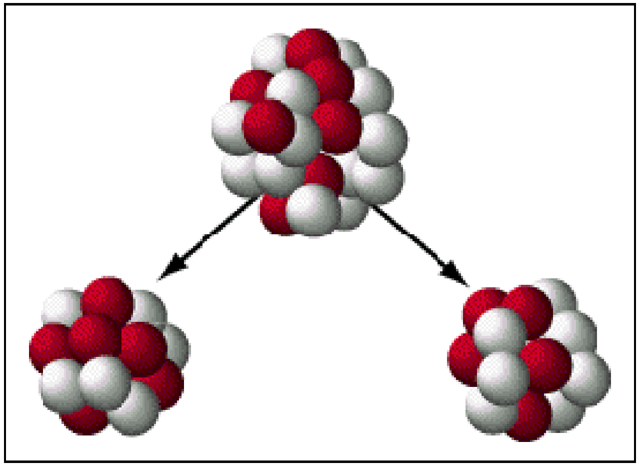
The parent mass must exceed the daughter mass by at least 2 m_e for this to spontaneously proceed.

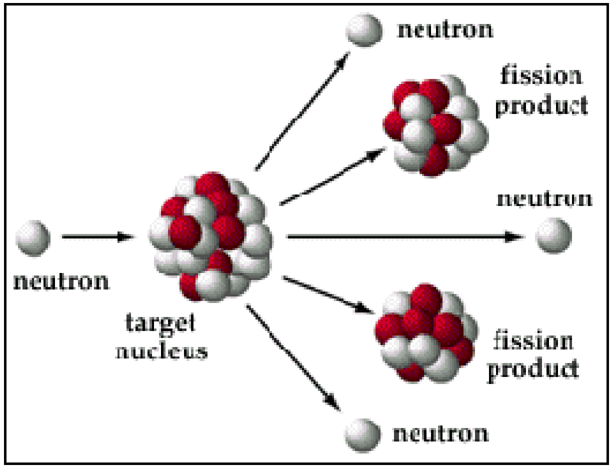
Neutron Decay

$$ {}_{Z}^{A}P \rightarrow {}_{Z}^{A-1}P^{*} + {}_{0}^{1}n \qquad \frac{Q_n}{c^2} = M\left({}_{Z}^{A}P\right) - \left[M\left({}_{Z}^{A-1}P^{*}\right) + m_n\right] $$

$$ = M\left({}_{Z}^{A}P\right) - M\left({}_{Z}^{A-1}P^{*}\right) - m_n - \frac{E^{*}}{c^2} $$

- Relatively rare
- slow (sometimes minutes)
- Makes fission reactions controllable.





Proton Decay

$$ {}_{Z}^{A}P \rightarrow \left[{}_{Z-1}^{A-1}D^{*} \right]^{-} + {}_{1}^{1}p $$

$$ \frac{Q_n}{c^2} = M\left({}_{Z}^{A}P\right) - \left[M\left({}_{Z-1}^{A-1}D^{*}\right)^{-} + m_p \right] $$

$$ \cong M\left({}_{Z}^{A}P\right) - \left[M\left({}_{Z-1}^{A-1}D^{*}\right) + m_e + m_p \right] $$

$$ = M\left({}_{Z}^{A}P\right) - \left[M\left({}_{Z-1}^{A-1}D\right) + \frac{E^{*}}{c^2} + m_e + m_p \right] $$

$$ \cong M\left({}_{Z}^{A}P\right) - M\left({}_{Z-1}^{A-1}D\right) - M\left({}_{1}^{1}H\right) - \frac{E^{*}}{c^2} $$