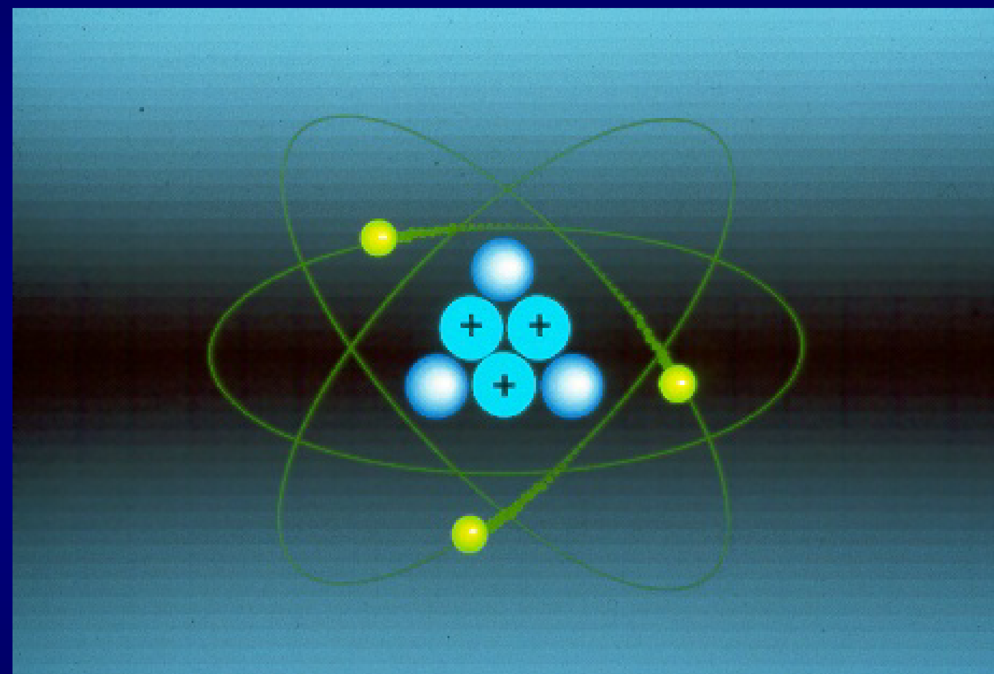
U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

HRTD
Human Resources
Training & Development

BASIC RADIATION PHYSICS

Atomic Structure

- Atomic Structure
  - Protons (p)
  - Neutrons (n)
  - Electrons (e)



Atomic Number (Z)

- The number of protons (p) in the nucleus of an atom

$$^{35}_{16}S$$

Atomic Mass Number (A)

- Sum of the number of protons and neutrons (p + n) in the nucleus of an atom

$$^{125}_{53}\mathrm{I} \qquad ^{32}_{15}\mathrm{P}$$

Isotopes

- Atoms having the same atomic number but different mass numbers

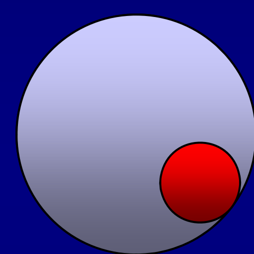
$${}^{12}_{6}C \qquad {}^{14}_{6}C$$

Radioactive Decay

- Some atoms are unstable and undergo a spontaneous decay process in an effort to become stable

- Decay process is the emission of radiation

Radioactive Decay



Activity

- Rate of decay is unique for each radionuclide
- Described by decay constant, λ , which has units of inverse time (e.g. 1/s)
- Given a collection of N atoms, each with decay constant λ , the number of atoms decaying per unit time is called the "activity"

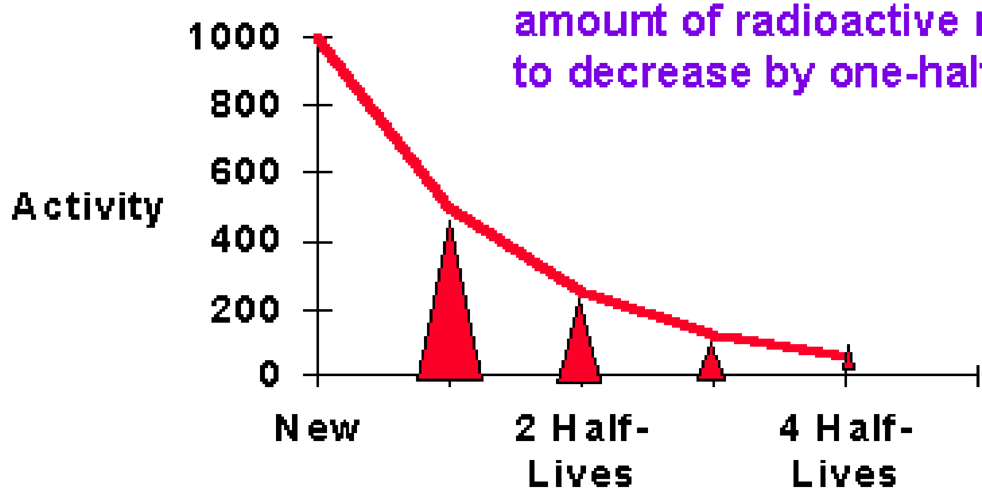
- Activity $A = \lambda N$, in units of disintegrations per second

Half-Life

- Time required for one-half of the initial amount of a radionuclide to decay
- Half-life = $T_{1/2}$ = $0.693/\lambda$ (units of time, e.g., seconds)
- Thus, if we know λ, we can calculate $T_{1/2}$ or vice versa

Half-Life

The time required for the amount of radioactive material to decrease by one-half



Radioactive Decay Equations

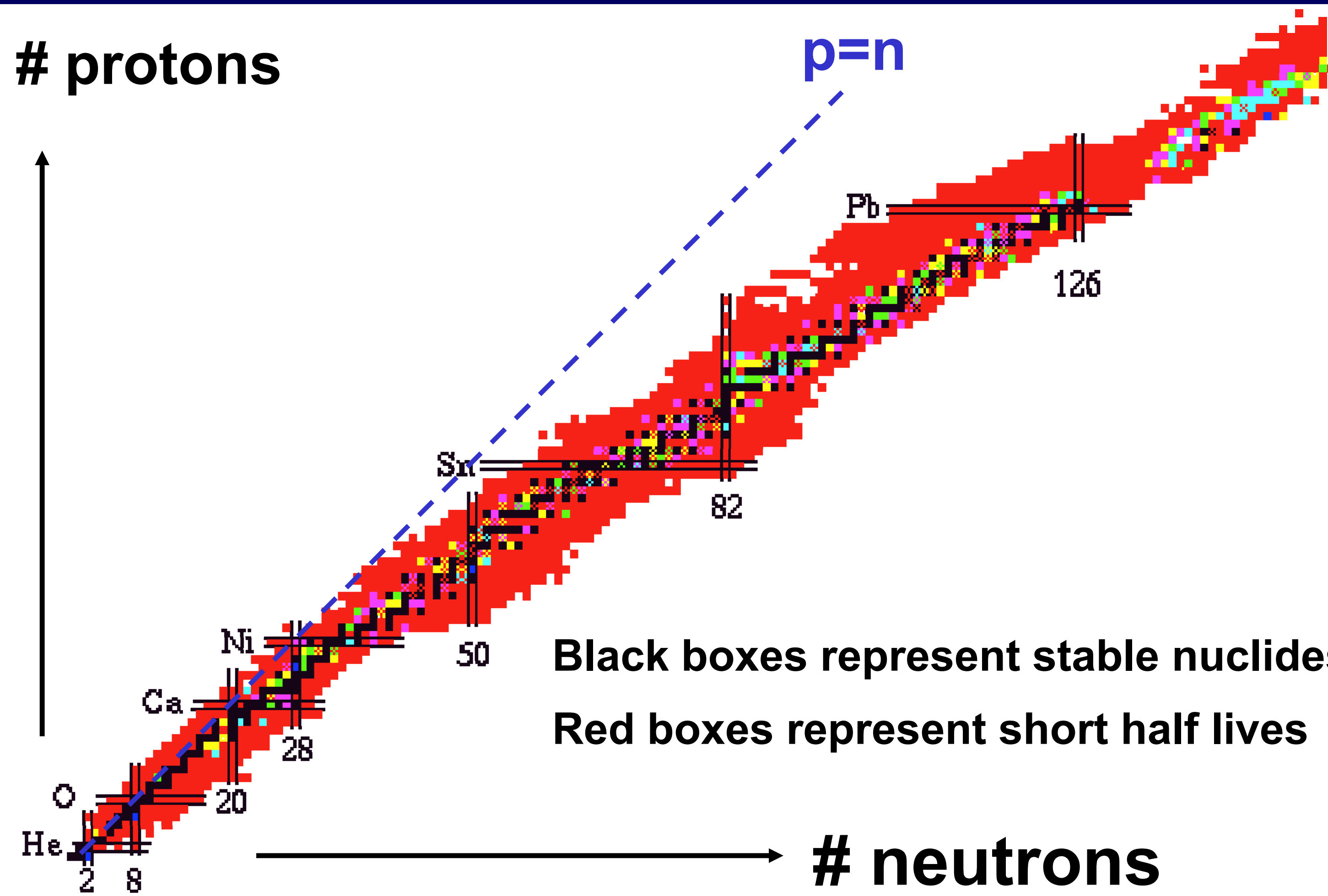
- Given an initial amount of radionuclide A_0, after elapsed time t, the amount left, A_t, is given by:

  $A_t = A_0 \times (1/2^n)$ (Equation 1)

  where n = number of elapsed half-lives

  Or $A_t = A_0 \exp(-\lambda t)$ (Equation 2)

Chart of the Nuclides



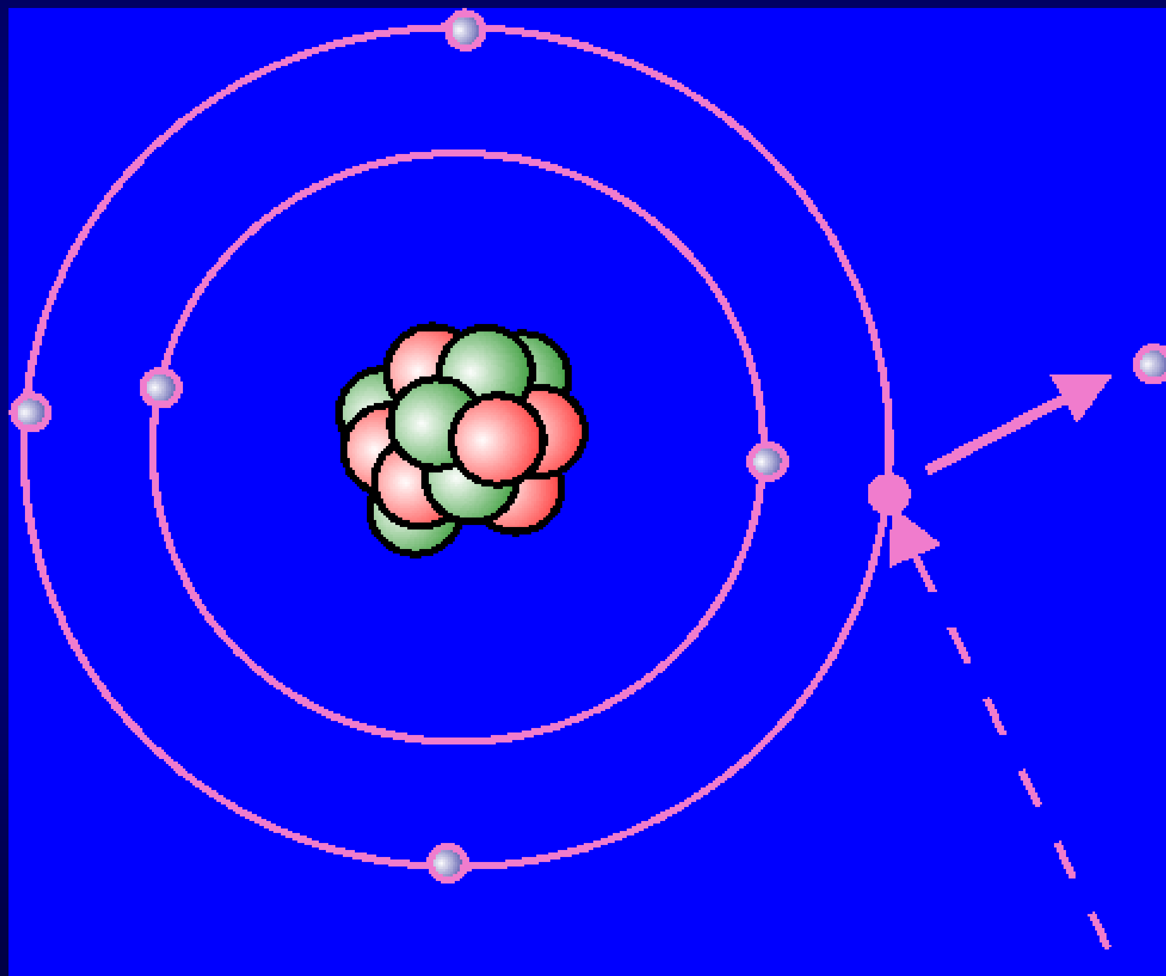
Black boxes represent stable nuclides

Red boxes represent short half lives

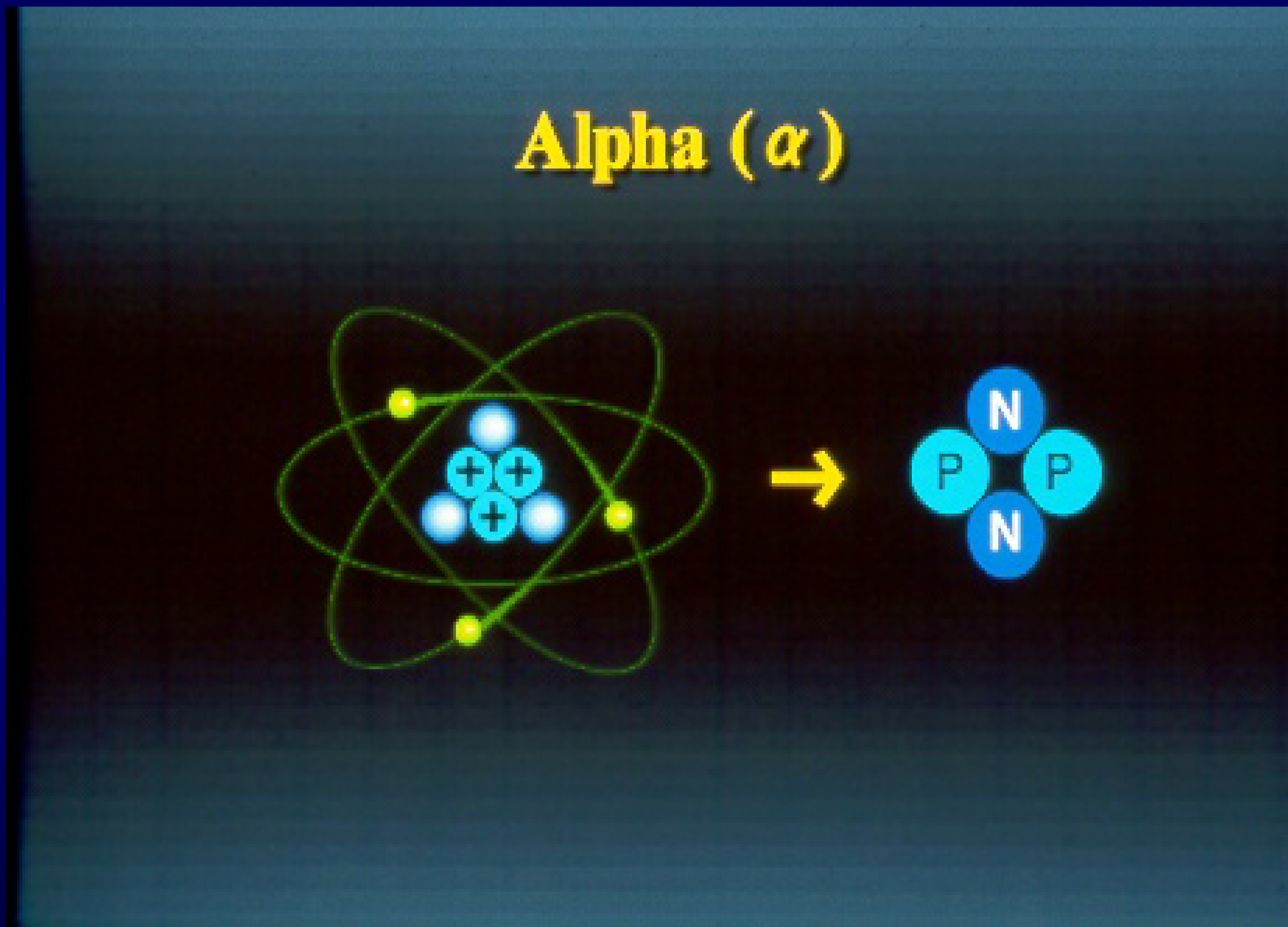
Ionizing Radiation

- Radiation that has enough energy to remove electrons from atoms (ionize) in matter
- Four main types of ionizing radiation
  - Alpha radiation
  - Beta radiation and positrons
  - Photons (Gamma rays and X-rays)
  - Neutrons (indirectly ionizing)

Ionization of Outer Shell Electron



Alpha Decay



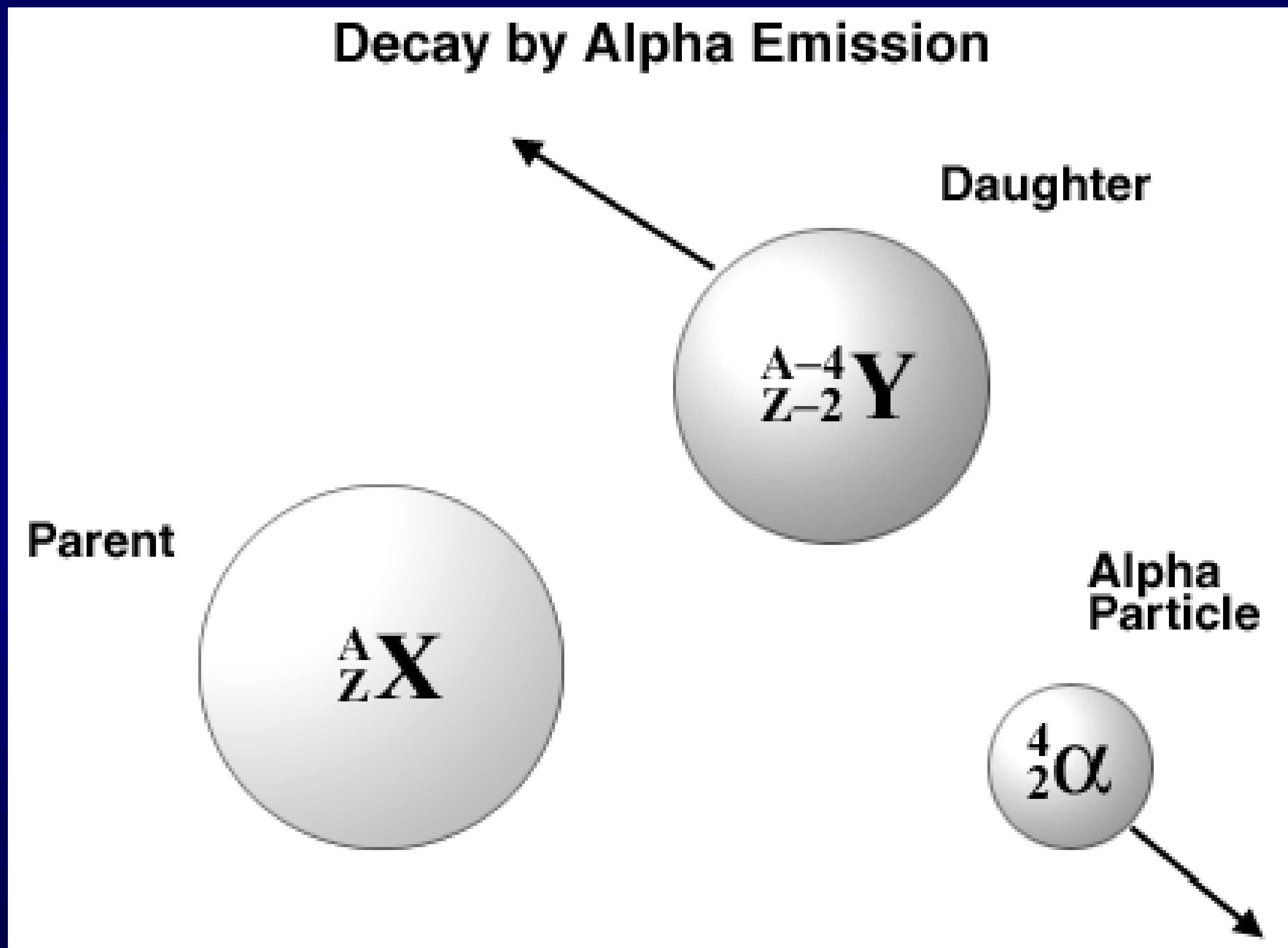
Alpha Emission

- Emission of a highly energetic helium nucleus from the nucleus of a radioactive atom
- Occurs when the neutron to proton ratio is too low

Alpha Emission

- Results in a decay product whose atomic number is 2 < parent and whose atomic mass is 4 < parent

- Alpha particles are monoenergetic


Decay by Alpha Emission
Daughter
$^{A-4}_{Z-2}Y$
Parent
$^{A}_{Z}X$
Alpha
Particle
$^{4}_{2}\alpha$

Alpha Decay Example

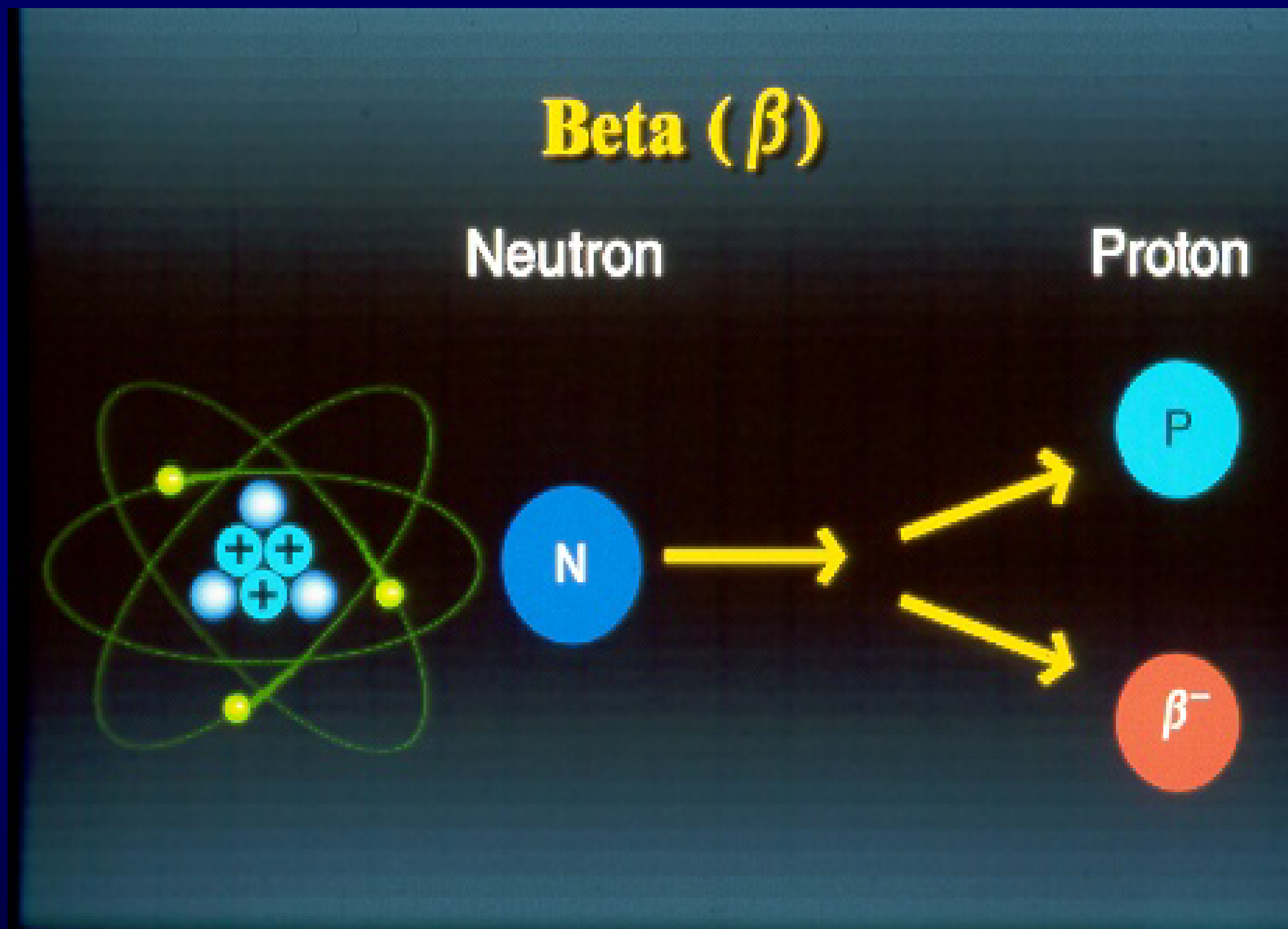
^{226}Ra decays by alpha emission

When ^{226}Ra decays, the atomic mass decreases by 4 and the atomic number decreases by 2

The atomic number defines the element, so the element changes from radium to radon

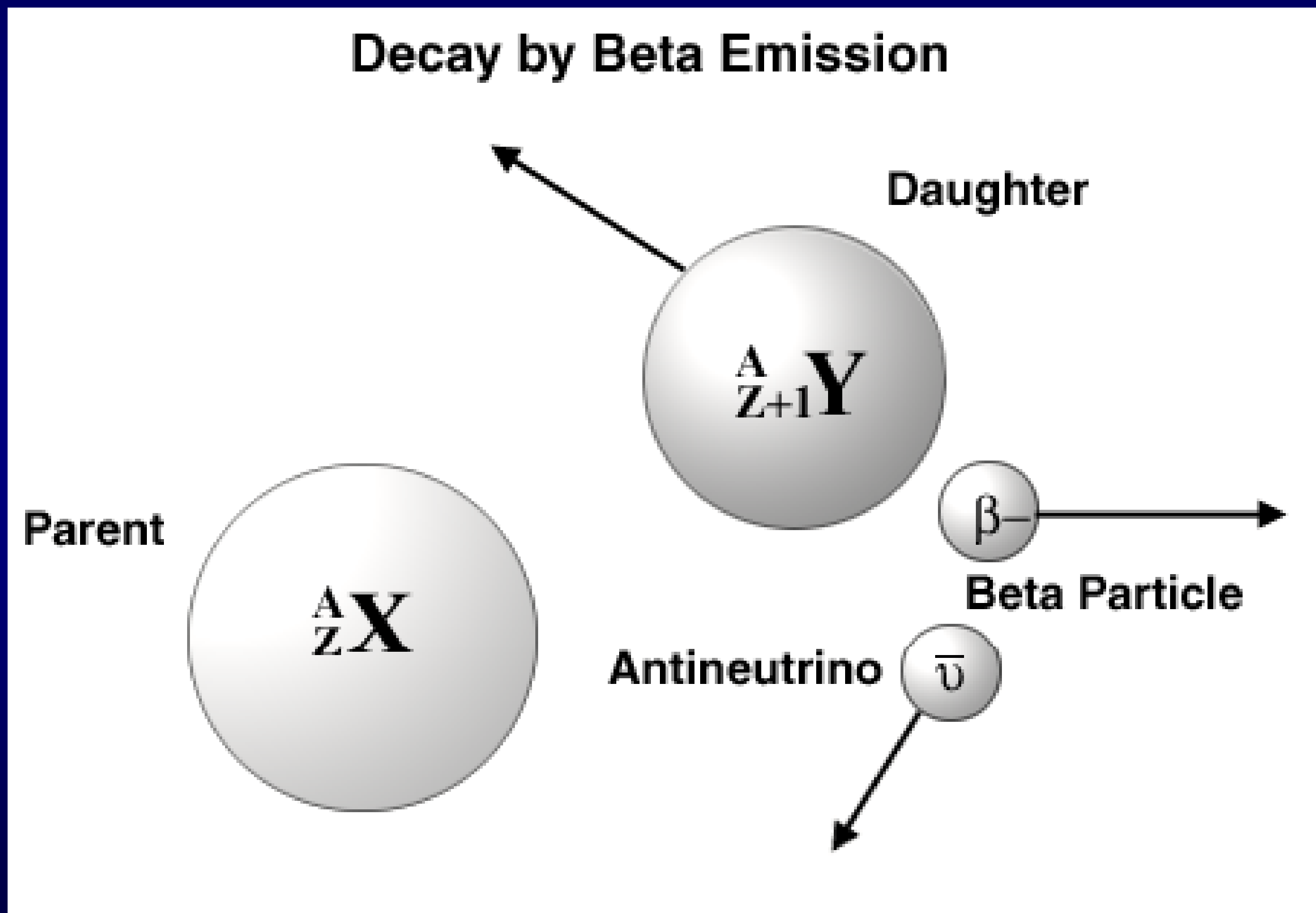
$$^{226}Ra \rightarrow {}^{222}Rn + {}^{4}He$$

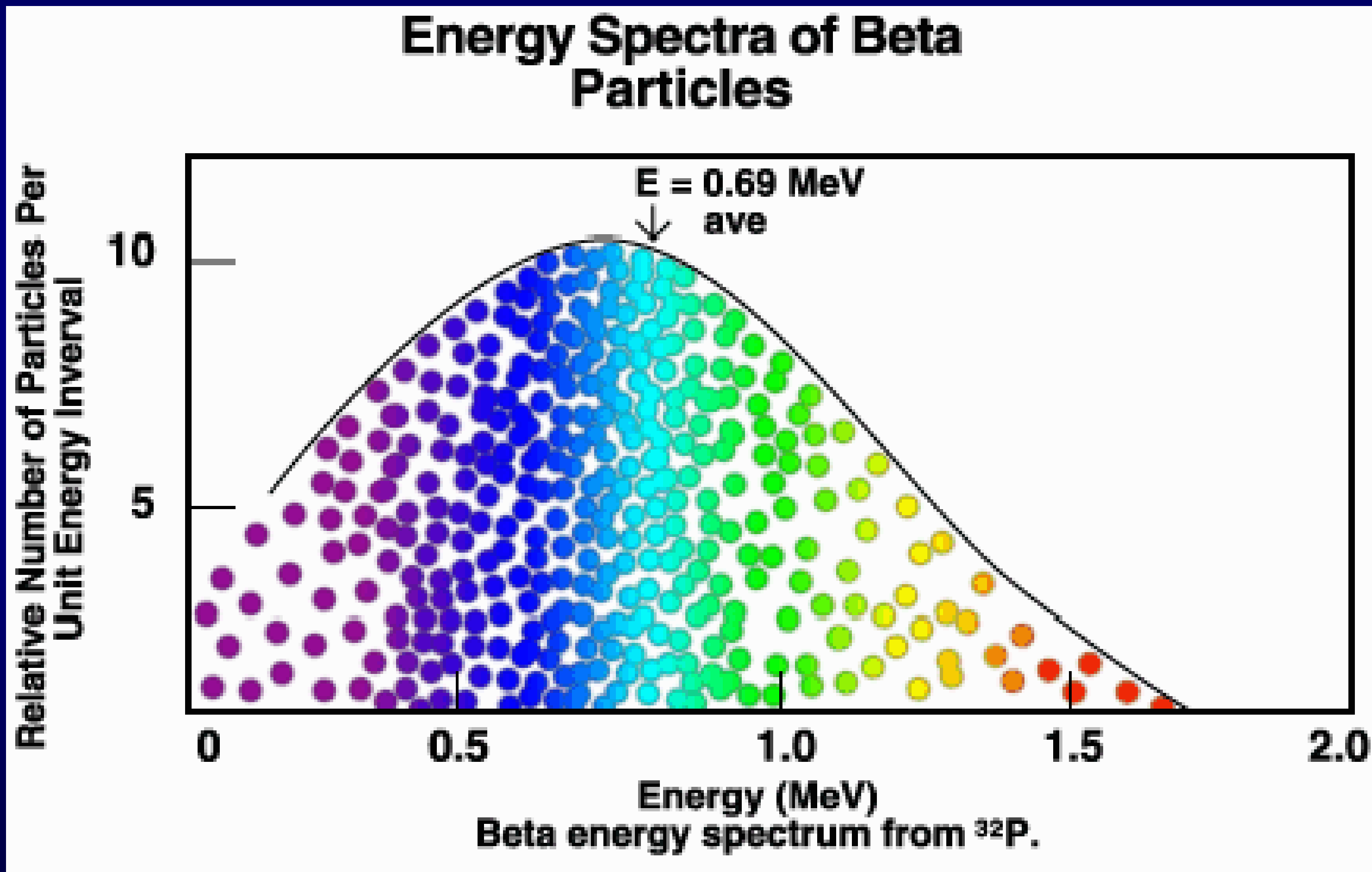
Beta Decay



Beta Emission

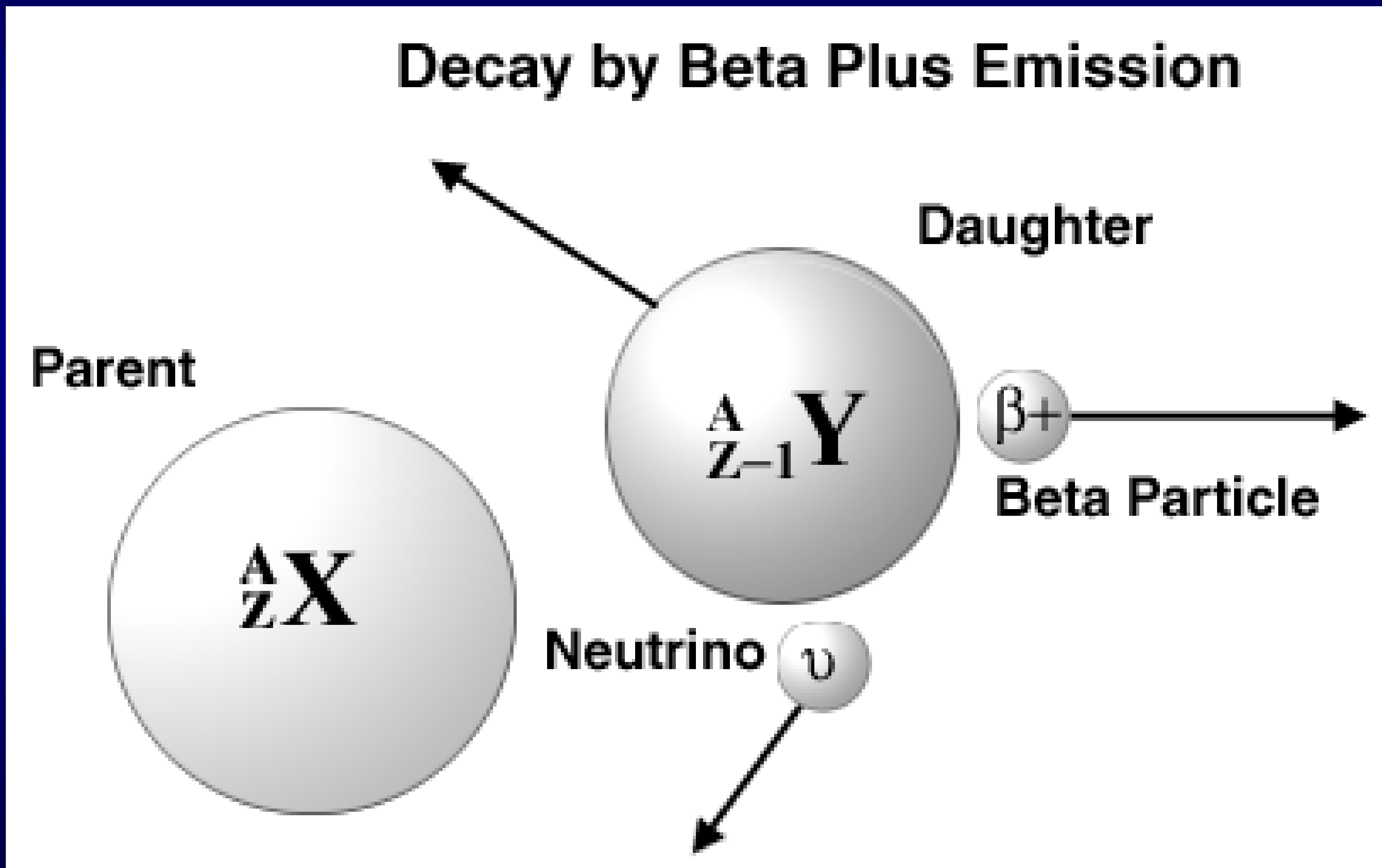
- Emission of an electron from the nucleus of a radioactive atom ($n \rightarrow p^{+} + e^{-1}$)
- Occurs when neutron to proton ratio is too high (i.e., a surplus of neutrons)
- Beta particles are emitted with a whole spectrum of energies (unlike alpha particles)


Decay by Beta Emission
Daughter
$^{A}_{Z+1}Y$
Parent
$^{A}_{Z}X$
β–
Beta Particle
Antineutrino
$\overline{\upsilon}$


Energy Spectra of Beta Particles
E = 0.69 MeV ave
Relative Number of Particles Per Unit Energy Inverval
10
5
0
0.5
1.0
1.5
2.0
Energy (MeV)
Beta energy spectrum from 32P.

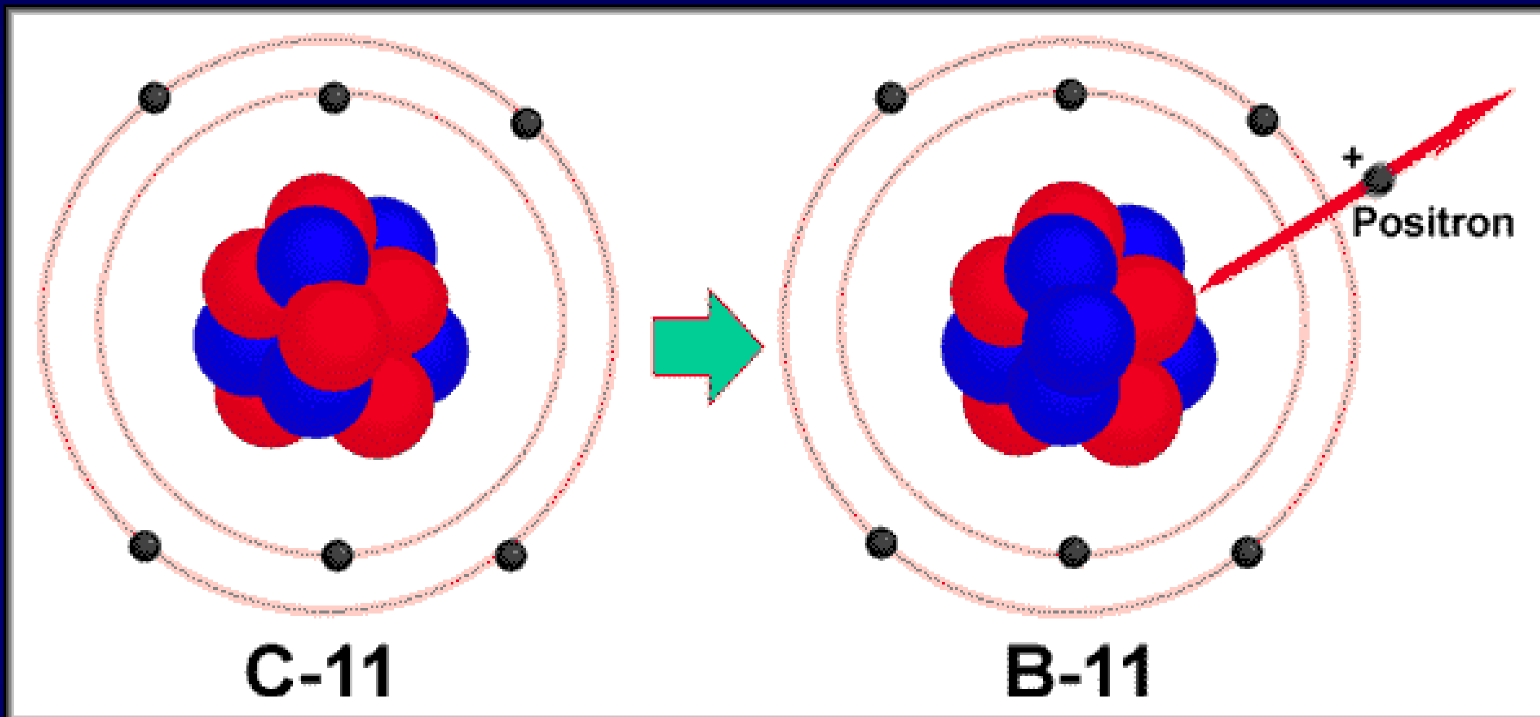
Positron (Beta$^+$ Emission)

- Occurs when neutron to proton ratio is too low ($p^+ \rightarrow n + e^+$)
- Emits a positron (beta particle whose charge is positive)
- Results in emission of 2 gamma rays (more on this later)

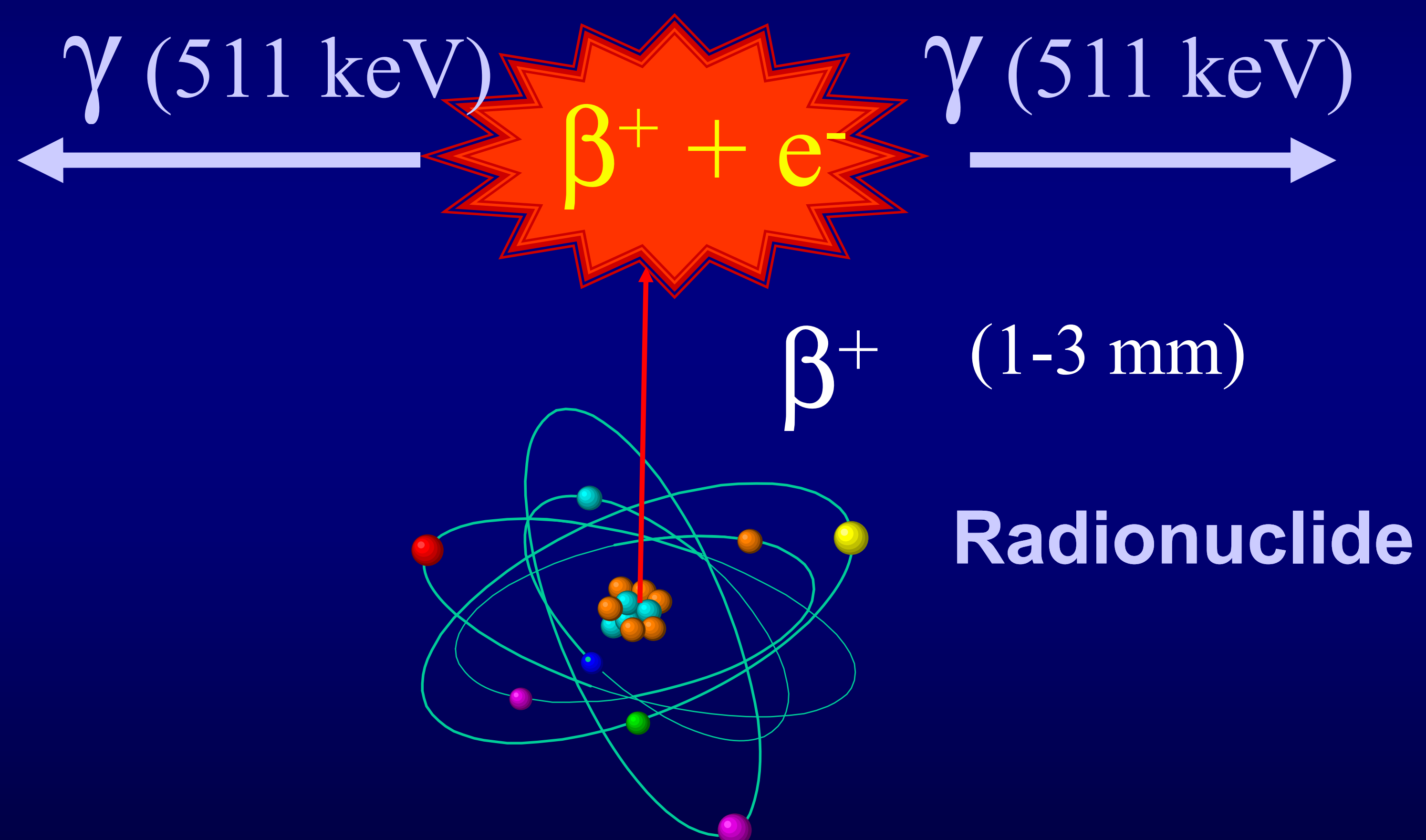


Decay by Beta Plus Emission
Parent
$^{A}_{Z}X$
Daughter
$^{A}_{Z-1}Y$
β+
Beta Particle
Neutrino
υ

Positron Decay



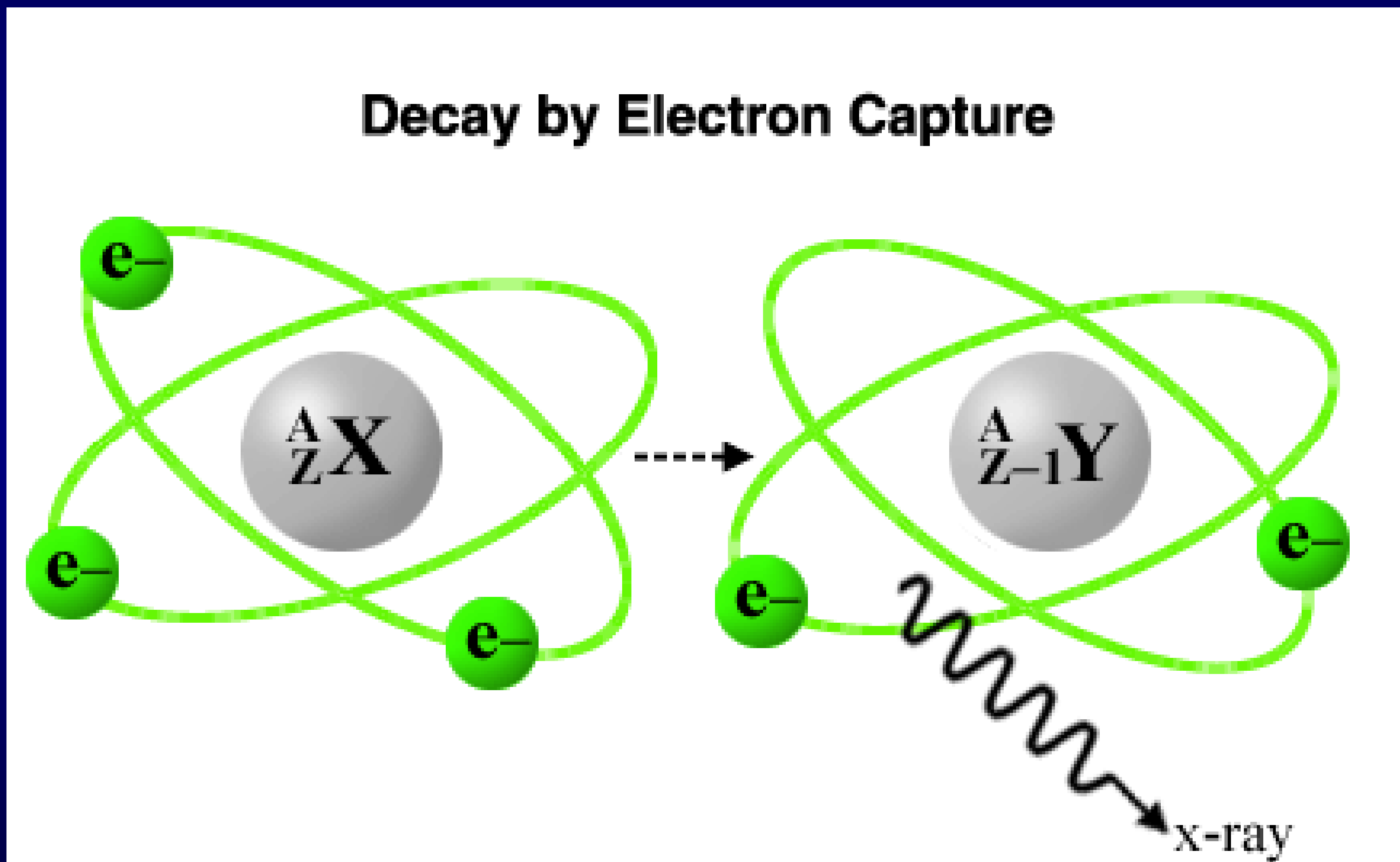
Positron Annihilation



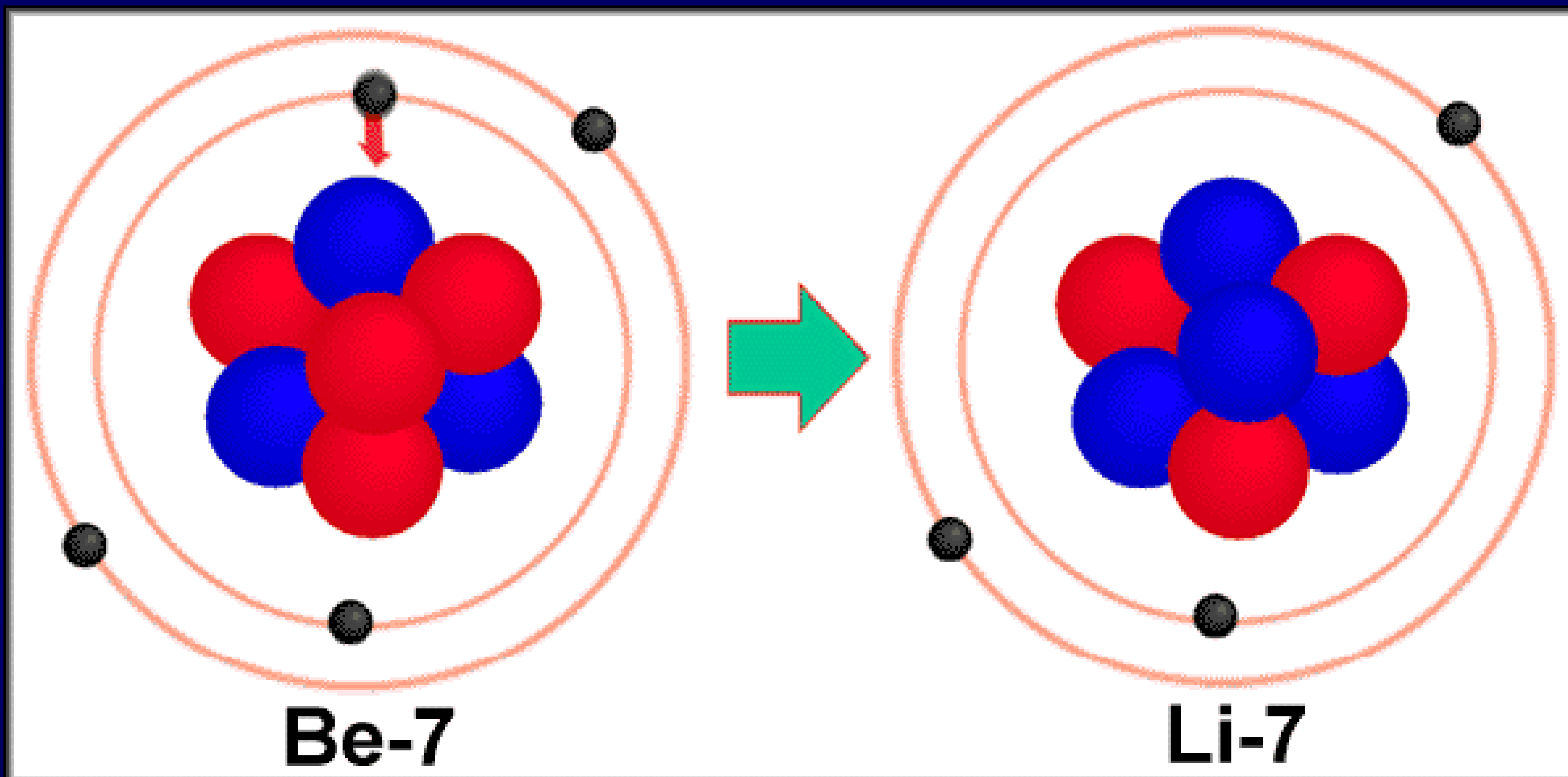
Orbital Electron Capture

- Also called K Capture
- Occurs when neutron to proton ratio is too low
- Form of decay competing with positron emission
- One of the orbital electrons is captured by the nucleus: $e^{-1} + p^{+1} \rightarrow n$
- Results in emission of characteristic x-rays

Electron Capture



Electron Capture



Gamma Ray Emission

- Monoenergetic radiations emitted from nucleus of an excited atom following radioactive decay

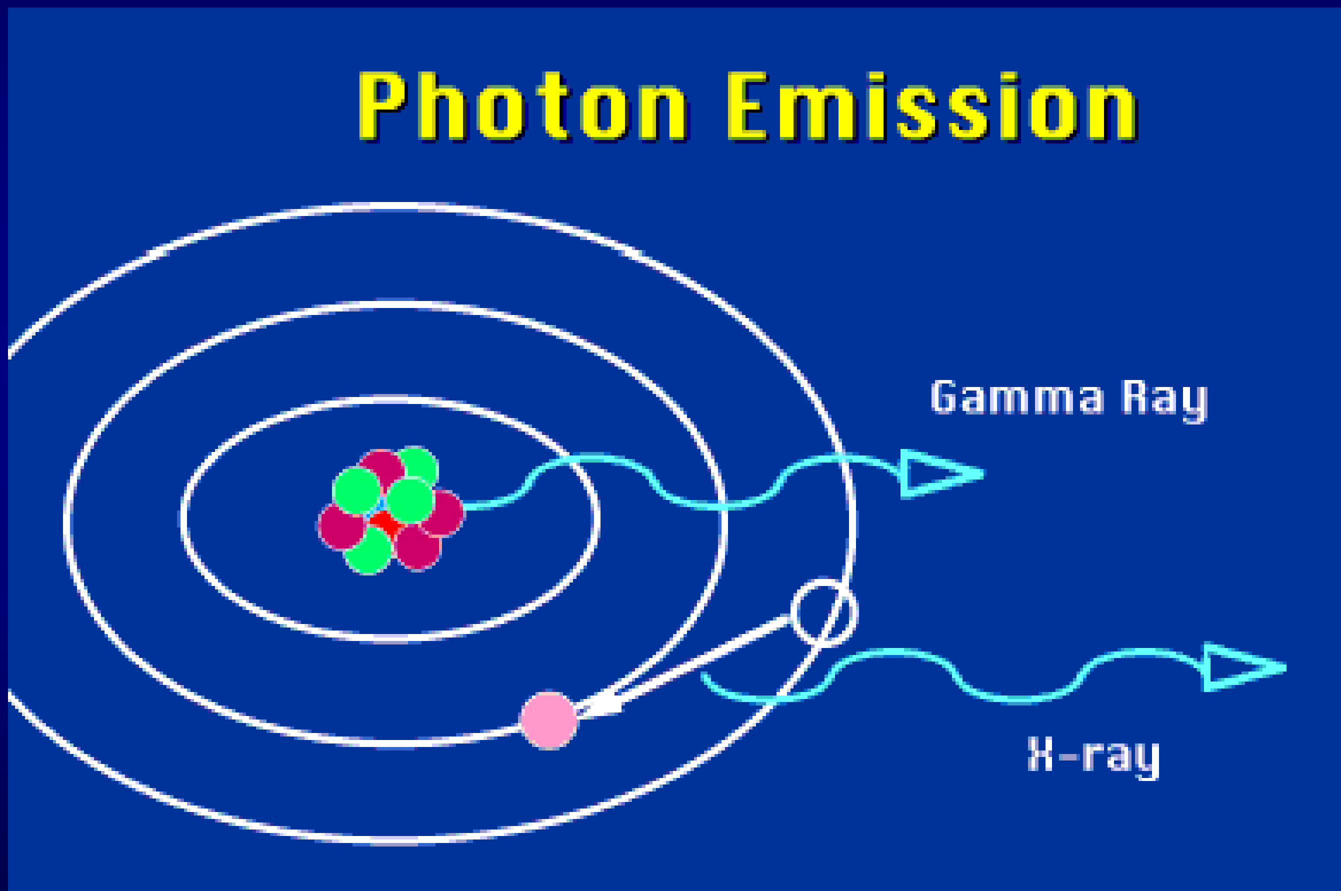
- Rid nucleus of excess energy

Gamma Ray Emission

- Have characteristic energies which can be used to identify the radionuclide

- Excited forms of radionuclides often referred to as “metastable”, e.g., Tc-99m. Also called “isomers”

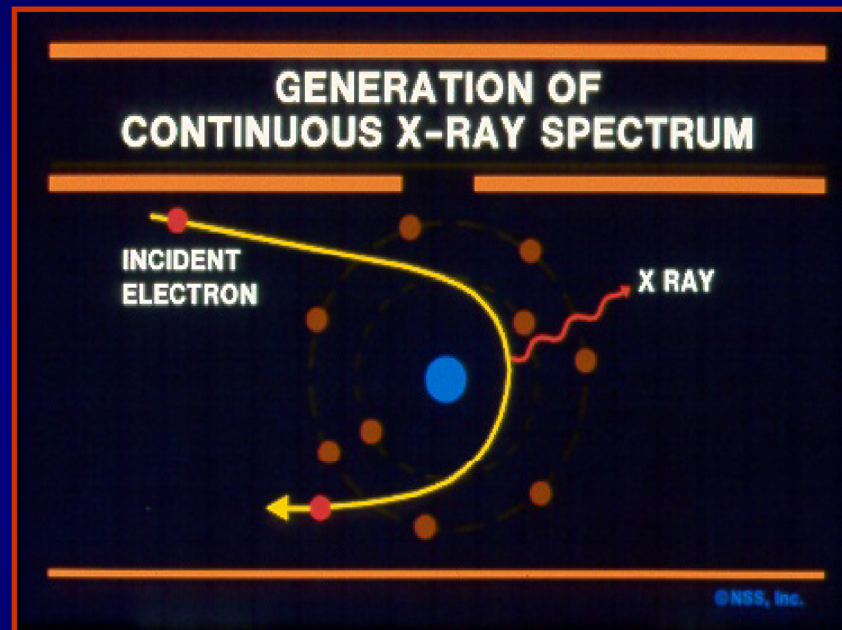
Difference Between X-Rays and Gamma Rays



Characteristic X-rays

- Energetic radiation that exhibits a particle behavior
- Created by electron transitions in the electron cloud
- Identical to gamma rays but typically have lower energies
- X-ray energies are specific to the nuclide
  - can be used to identify elements

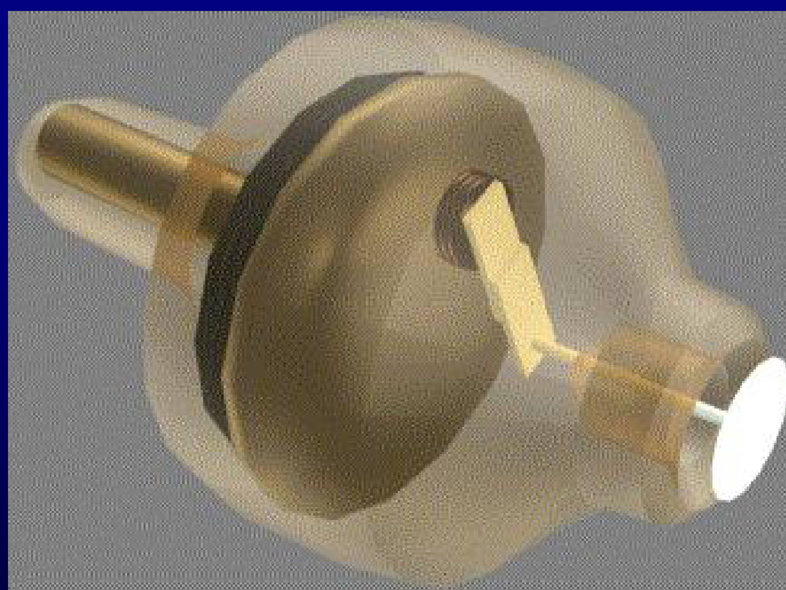
Bremsstrahlung Radiation



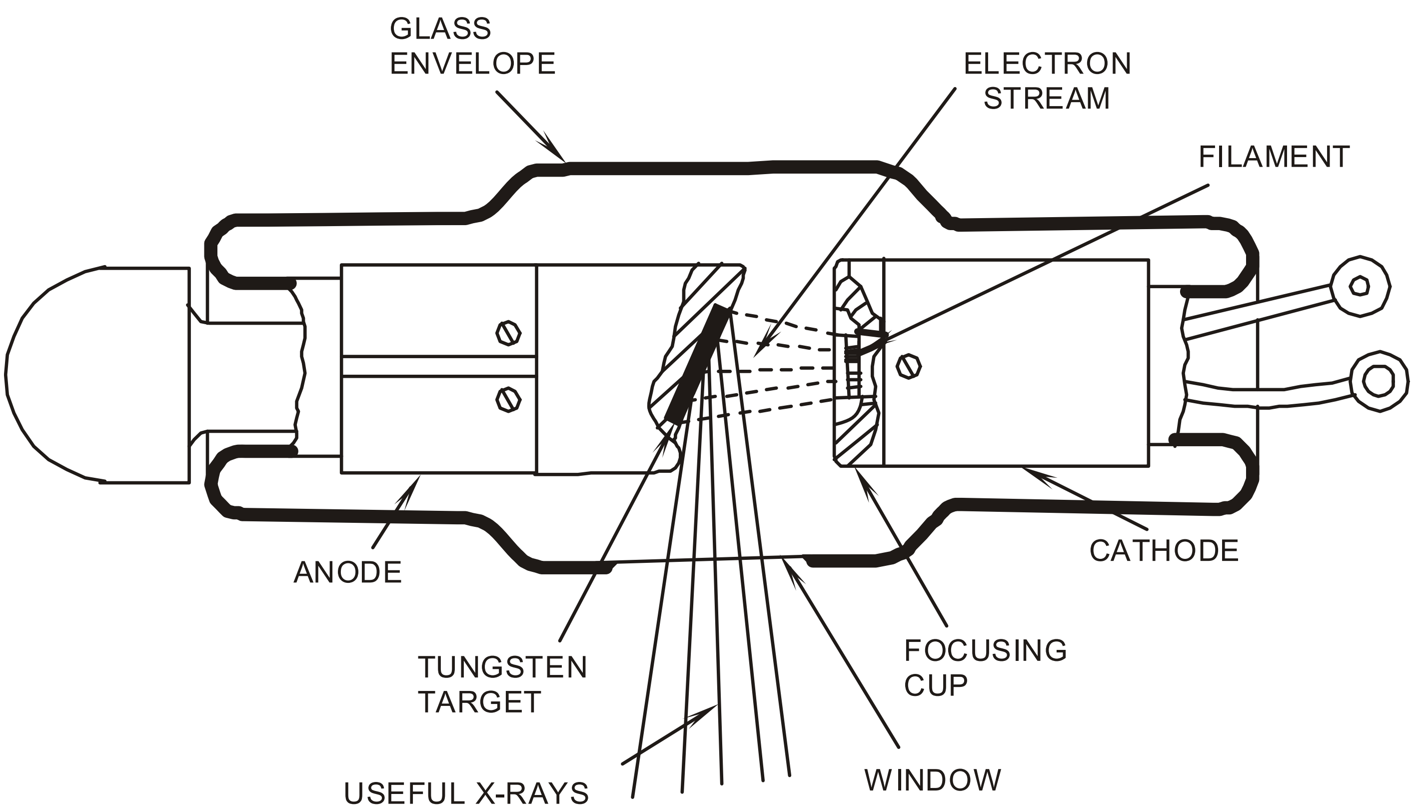
- Braking Radiation
- Electron deflected from its path
- Loses energy in the form of an X-ray
- Minimum to Maximum energies of X-rays

Bremsstrahlung Radiation

- Sources:
  - emitted from beta shielding
  - x-ray machines primarily emit bremsstrahlung



X-Ray Unit



GLASS ENVELOPE
ELECTRON STREAM
FILAMENT
ANODE
CATHODE
TUNGSTEN TARGET
FOCUSING CUP
USEFUL X-RAYS
WINDOW

Internal Conversion

- Alternative process by which excited nucleus of a gamma emitting isotope rids itself of excitation energy

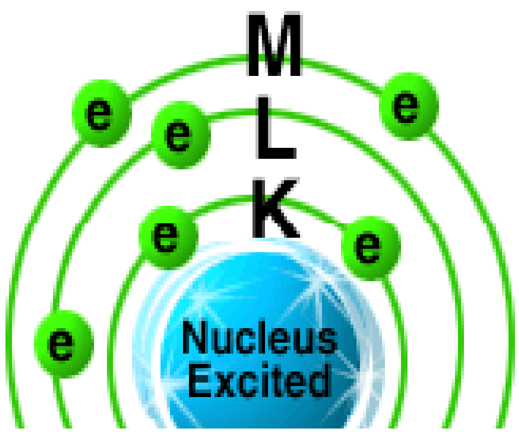
- The nucleus emits a gamma ray which interacts with an orbital electron, ejecting the electron from the atom

- Characteristic x-rays are emitted as outer orbital electrons fill the vacancies left by the conversion electrons

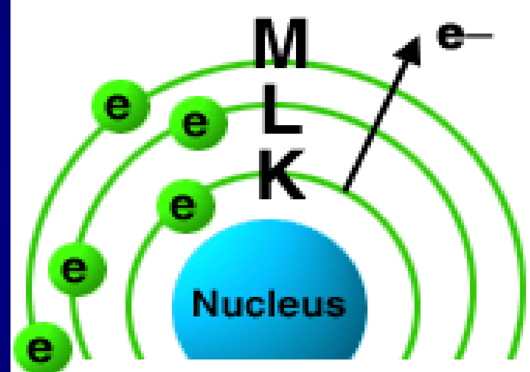
Internal Conversion

- These characteristic x-rays can themselves be absorbed by orbital electrons, ejecting them.
- These ejected electrons are called Auger electrons and have very little kinetic energy

Internal Conversion



Nucleus is excited following decay or nuclear interaction.



Nucleus de-excites by emitting conversion electron (ce-k).

Photon Interactions

- Photon Interactions
  - Photoelectric Effect
  - Compton Scatter
  - Pair Production

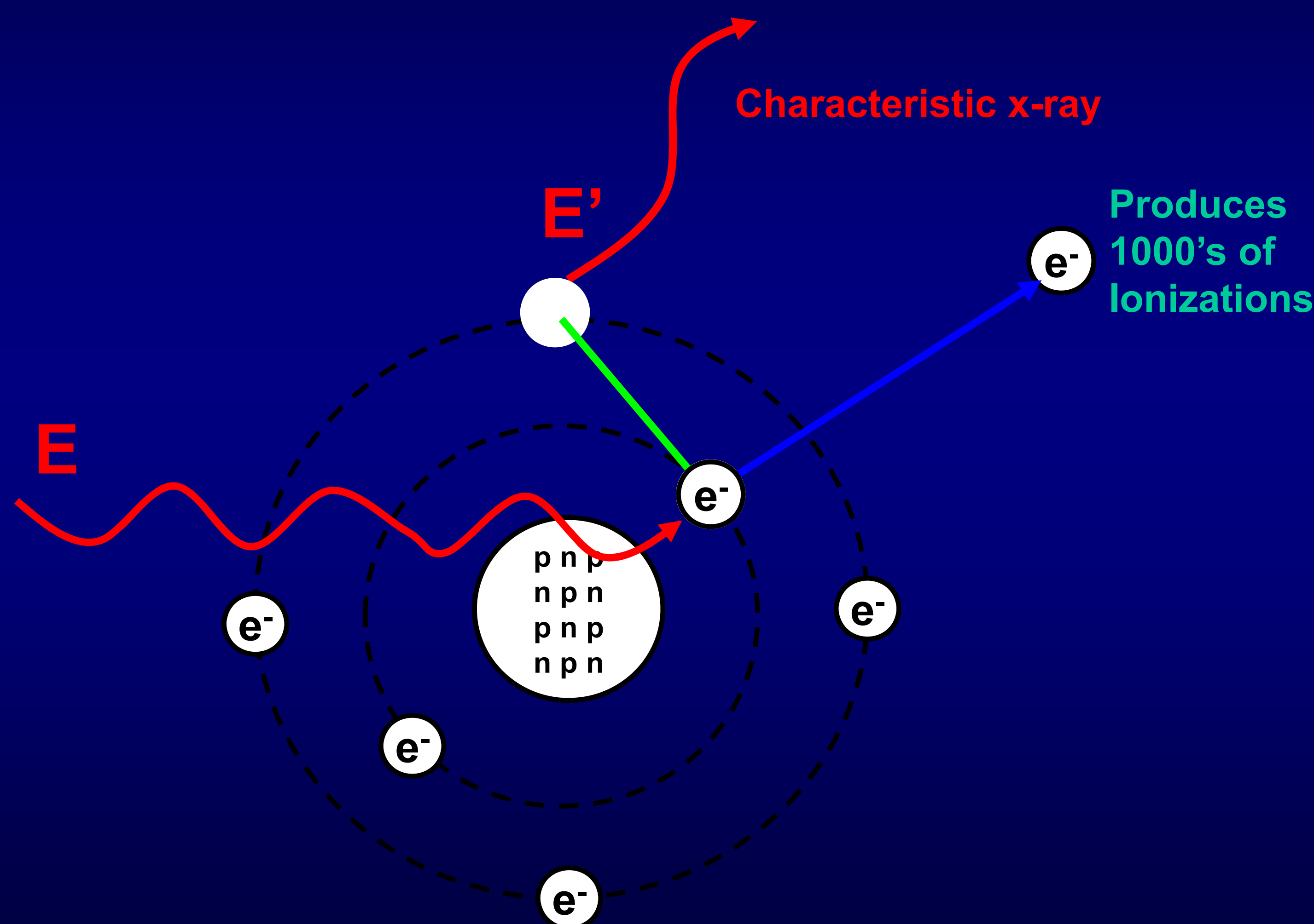
Photoelectric Effect

- Photon interacts with inner shell electron, photon is absorbed, and the electron is ejected from atom

- Resulting electron vacancy is filled by higher-energy-shell electrons, leading to X-ray emission

- Greater probability at low E

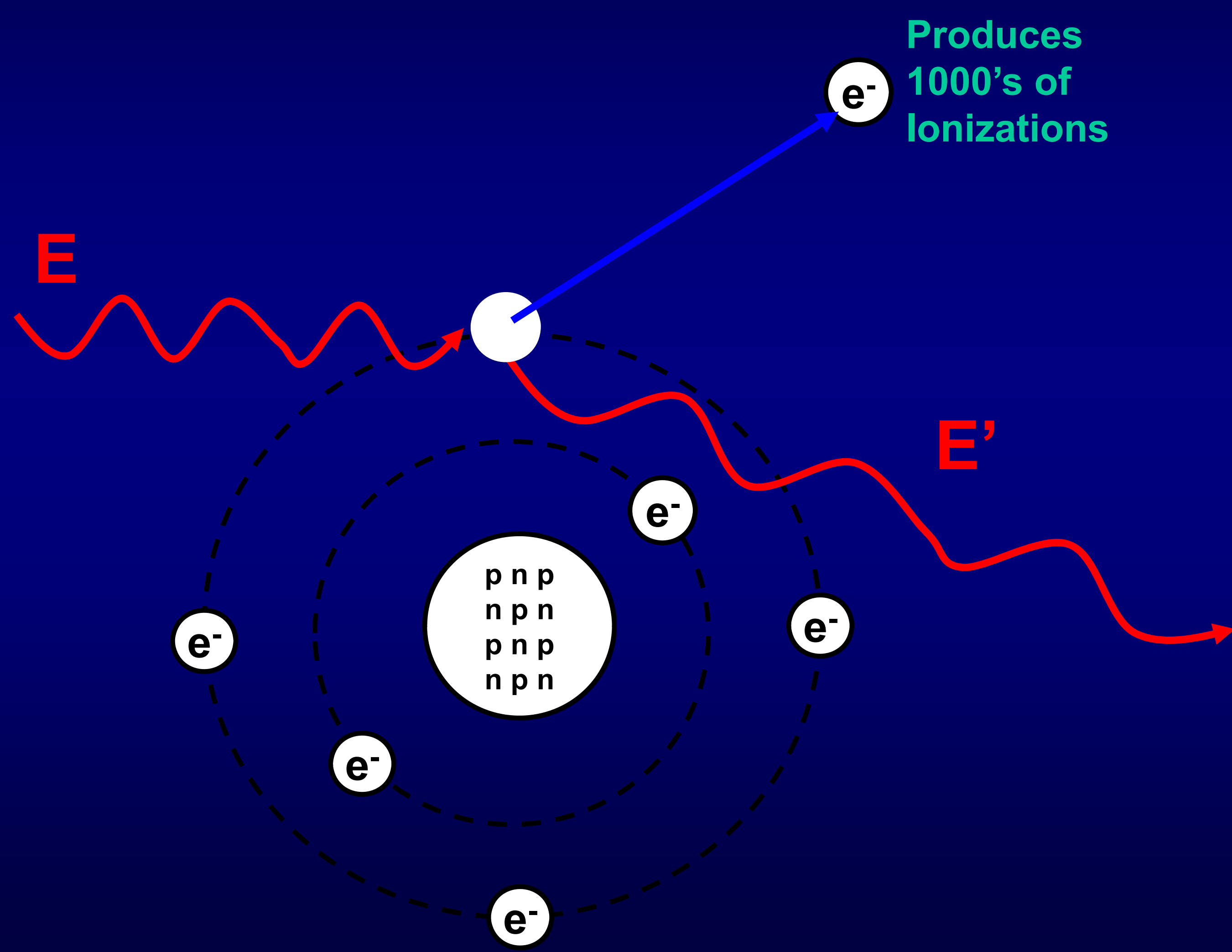
Photoelectric Effect



Compton Scatter

- "Billiard Ball" scattering
- Part of energy of photon is transferred to electron, which is ejected from its shell
- Photon loses energy and changes direction but is not absorbed
- Predominates between 200 keV and 10,000 keV

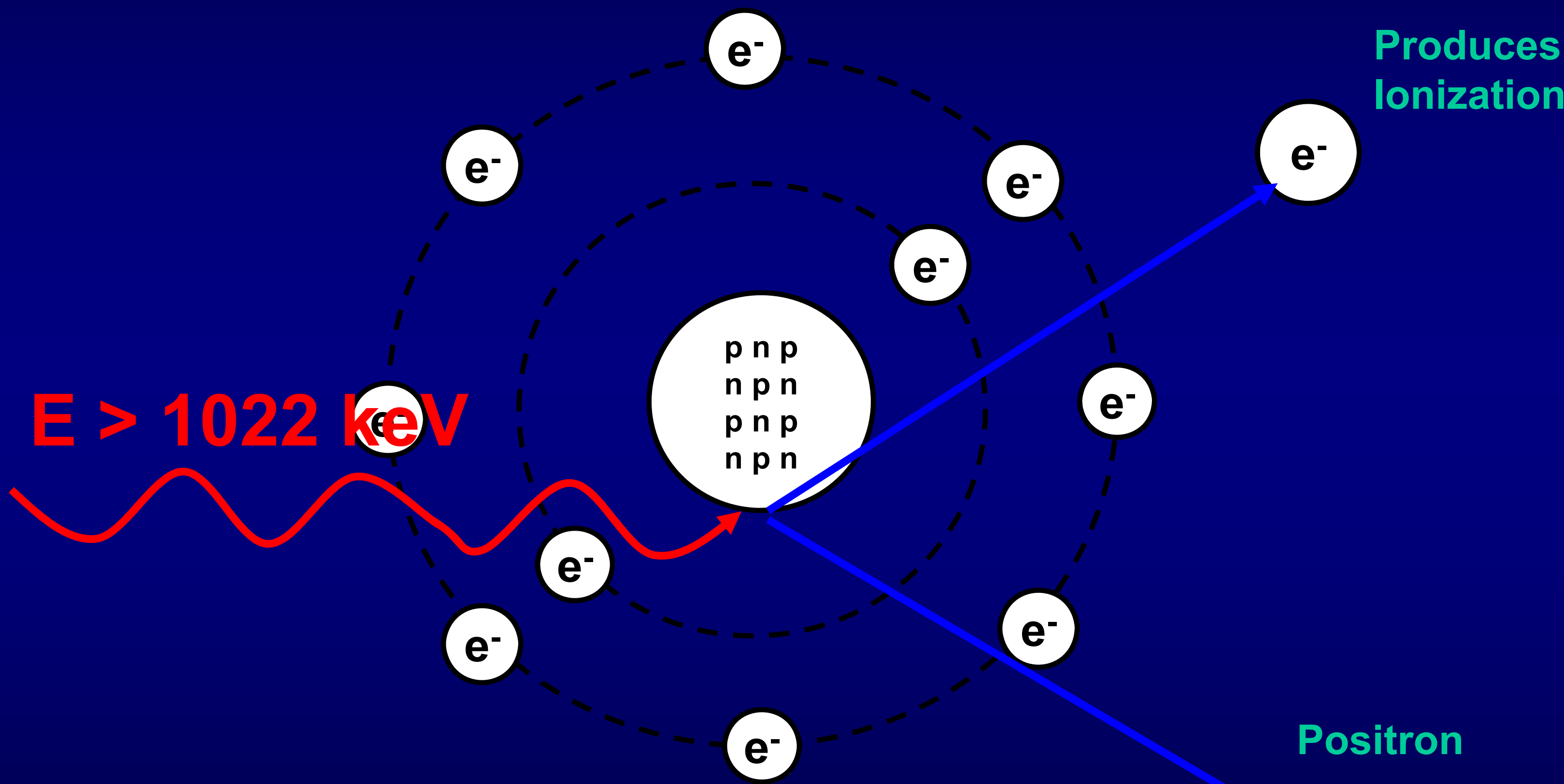
Compton Scatter



Pair Production

- Photon is converted to electron-positron pair in field of atomic nucleus
- No scattered photon
- Positron interacts with another electron to produce two 511 keV photons
- Minimum E = 2*511 keV = 1,022 keV
- Probability increases with E

Pair Production



Slow Neutron Interactions

- **Radiative capture**

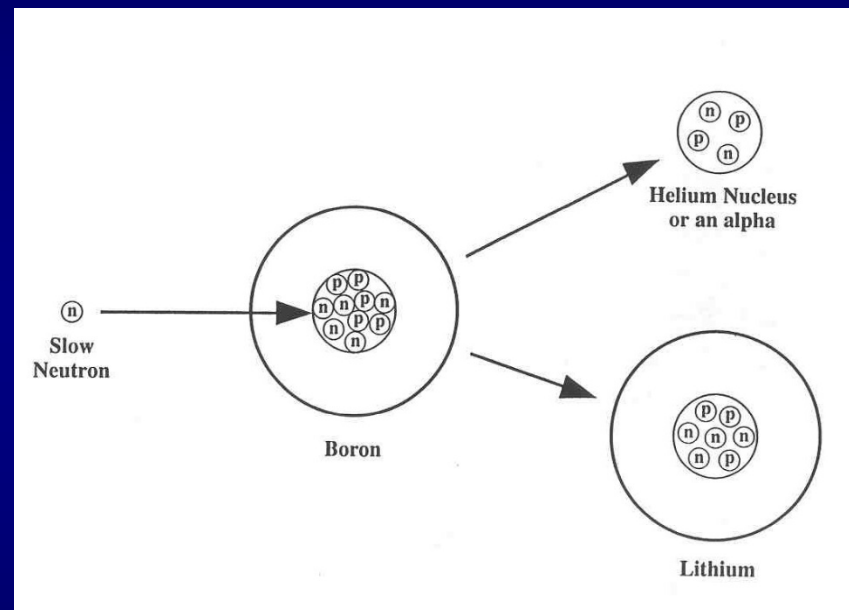
  $^{1}n + {}^{1}H \rightarrow {}^{2}H + \gamma$

  $^{1}H(n, \gamma)\ {}^{2}H$

- **Charged particle emission**

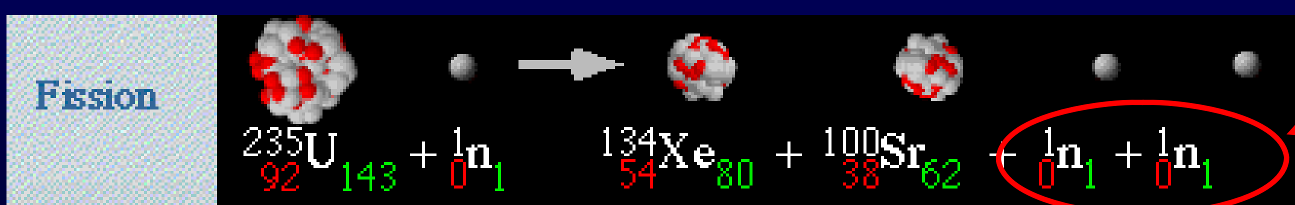
  $^{1}n + {}^{10}B \rightarrow {}^{7}Li + {}^{4}He$

  $^{10}B(n,\alpha)\ {}^{7}Li$



- **Fission**

  $^{1}n + {}^{235}U \rightarrow$ fission products



Available for more fission

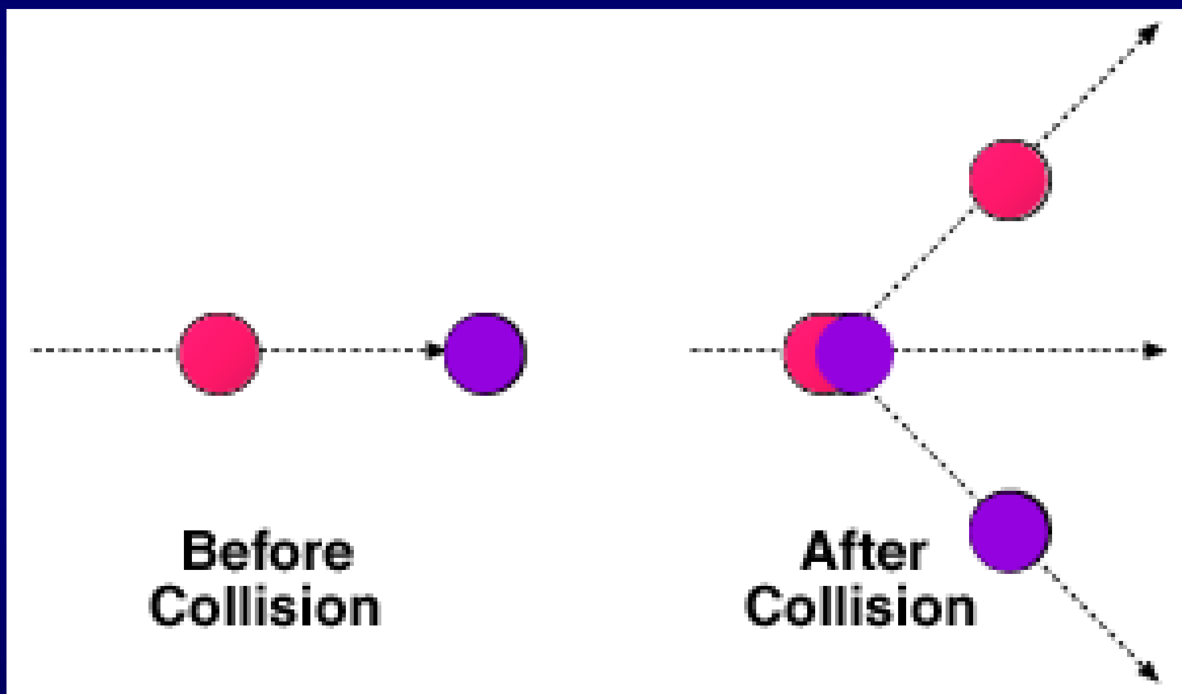
Fast Neutron Interactions

- Elastic scattering - neutrons interact with particles of approximately the same mass such as protons (billiard ball analogy)
    - Occurs in materials rich in hydrogen such as water, wax, concrete
    - Accounts for about 80% of fast neutron dose to tissue

Fast Neutron Interactions

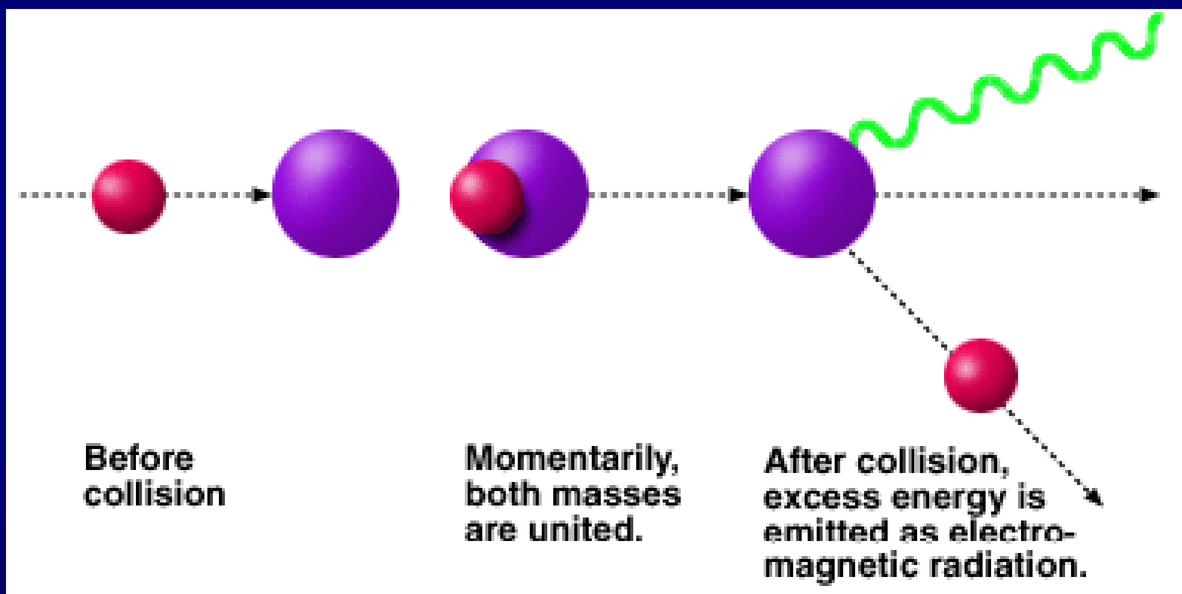
- Inelastic scattering - neutrons interact with particles of much greater mass (e.g. iron) (ping pong ball vs bowling ball analogy)

Elastic Scattering



Elastic Scattering of Neutrons

Inelastic Scattering



Inelastic Scattering of Neutrons

THE END