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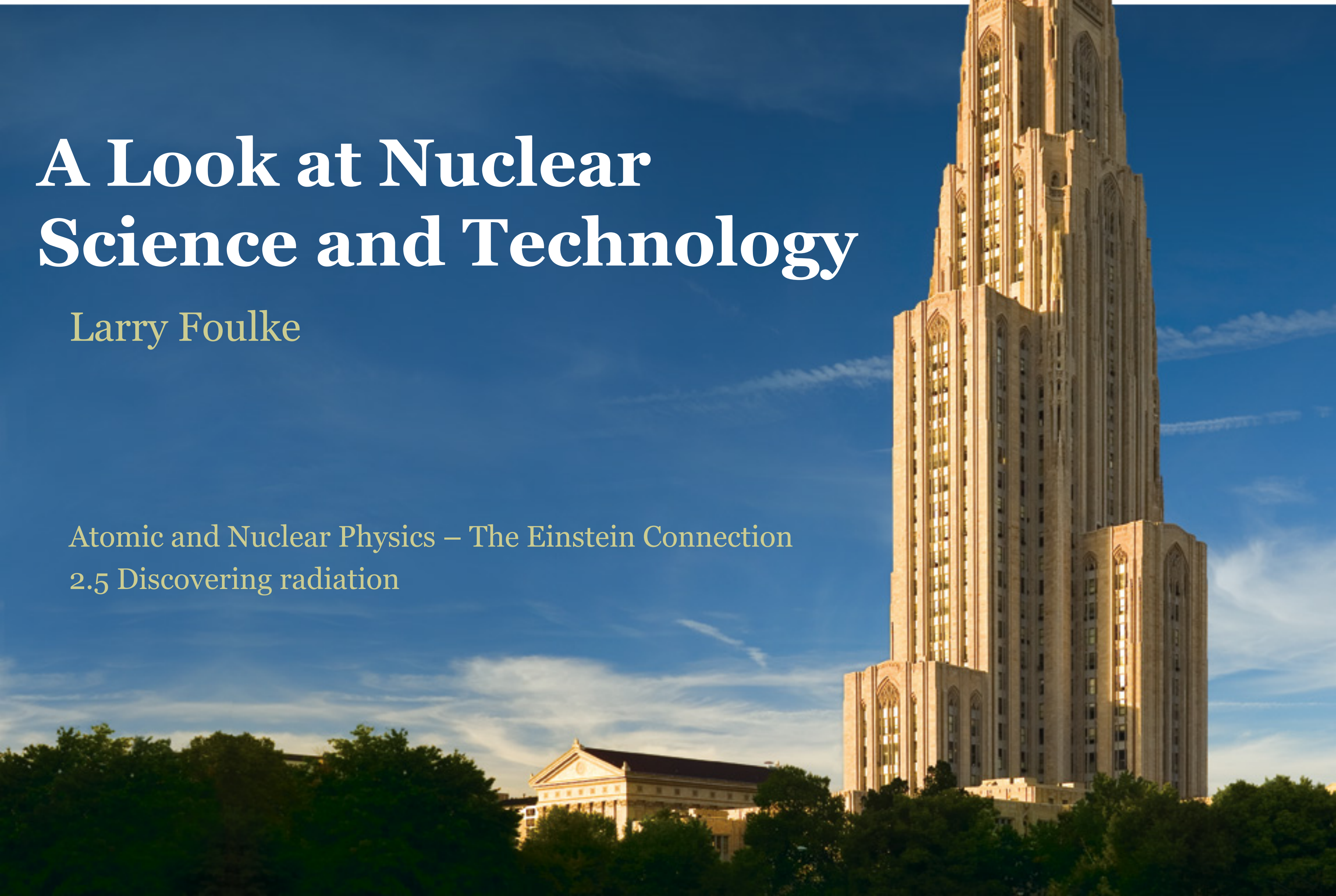

A Look at Nuclear Science and Technology

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Atomic and Nuclear Physics – The Einstein Connection
2.5 Discovering radiation

Radioactive Decay

- When an unstable nucleus decays it (eventually) transitions to a lower energy state and radiates away excess energy.
- Radiated energy can take two forms:
  - Emitted Particles
    - Released immediately as a part of nuclear decay.
  - Electromagnetic Radiation (EM)
    - Nuclear decay can leave the nucleus and/or orbital electrons in an excited state. As the atom returns to ground state it releases EM radiation.

Radioactive Decay

- Any atomic process that releases energy is referred to as **radioactive decay**
  - Energy may be due to nuclear decay or to de-excitation of nucleons or electrons to a lower energy state.
  - Energy emitted from the atom is called **radiation**.

- Nuclides subject to radioactive decay are referred to as **radionuclides** or **radioisotopes**.
- All radionuclides will eventually undergo radioactive decay.
- Any material containing measurable quantities of one or more radionuclides is referred to as being **radioactive**.

Radioactive Decay - Example

Given 10 grams of I-131, which decays by beta emission with a half-life of 8.020 days, and has an atomic mass of 130.906124 amu:

1. Write the balance equation for this decay.
2. Determine the decay constant.
3. Determine how many atoms of I-131 are initially in the sample.
4. Determine the initial activity in the sample
5. Determine the activity after 1 half-life

Radioactive Decay - Example

1. Write the balance equation for this decay.

$$^{131}_{53}I \rightarrow {}^{0}_{-1}\beta + {}^{A}_{Z}X + {}^{0}_{0}\overline{\nu}$$

$$^{A}_{Z}X = {}^{131}_{54}X = {}^{131}_{54}Xe$$

2. Determine the decay constant.

$$\lambda = \frac{\ln 2}{t_{1/2}} = {0.693}/{8.202\ days} = 0.0864\,days^{-1} = 1.00x10^{-6}\sec$$

Concept of a Mole

- A mole is the number of atoms or molecules of a substance or element equal to 6.022 x 10^{23} (Avogadro's number, N_{AV}).

For example: a mole of uranium is taken to be 6.022 x 10^{23} uranium atoms.

A mole of water molecules is taken to be 6.022 x 10^{23} water molecules.

Image Source: See Note 1

Concept of a Mole and Molecular Mass

- The number of moles, n, of a mass, m, of material is given by:

n *moles* = *mass of material, m, in* grams divided by the molecular mass M (gm/mole)

$$n\,moles = \frac{m\,(grams)}{M\left(grams / mole\right)}$$

- M – molecular mass (weight) in gm/mole
  - For Iodine-131, use 130.9 gm/mole
  - The molecular mass of an isotope is just its atomic weight

Radioactive Decay - Example

3. Determine how many atoms of I-131 are initially in the sample.

$$N = \frac{mN_A}{M}$$

m=10 grams
N_A*=6.022x10*^{23} *atoms/mole*
M=130.9 gms/mole

$$N = \frac{10\,gm\left(6.022x10^{23}\,atoms/mole\right)}{130.9\,gm/mole}$$

$$N = 4.60x10^{22}\,atoms\ of\ \ I-131$$

4. Determine the initial activity in the sample

$$A = \lambda N = \left(1.0x10^{-6}\sec^{-1}\right)\left(4.60x10^{22}\,atoms\right)$$

$$A = 4.60x10^{16}\,decays/\sec$$

$$A = 4.60x10^{16}\,Bq = \frac{4.60x10^{16}\,decays/\sec}{3.7x10^{10}\,decays/\sec - Ci} = 1.24x10^{6}\,Ci$$

Radioactive Decay - Example

5. Determine the activity after 1 half-life

$$A(t=8.020\ d)=\lambda N(t=8.020\ d)=\lambda N_0 e^{-\lambda(8.020\ d)}$$

$$A(t=8.020\ d)=A_0 e^{-\lambda(8.020\ d)}$$

$$A(t=8.020\ d)=\left(1.24x10^6\,Ci\right)e^{-\left(0.0864\,d^{-1}\right)(8.020\ d)}$$

$$A(t=8.020\ d)=6.2x10^5\,Ci$$

Radiation

- What is radiation?
  - Energy transmitted in the form of waves or particles (or both).
- Types of radiation
  - Electromagnetic (radio, visible light, x-rays, γ rays)
  - Charged particles (electrons, protons, α particles)
  - Other (neutrons, neutrinos, other exotic beasts)
- Categorized as either ionizing or non-ionizing
  - Depending on whether they can ionize other particles
    - Ionization can be direct or indirect

Radioactivity

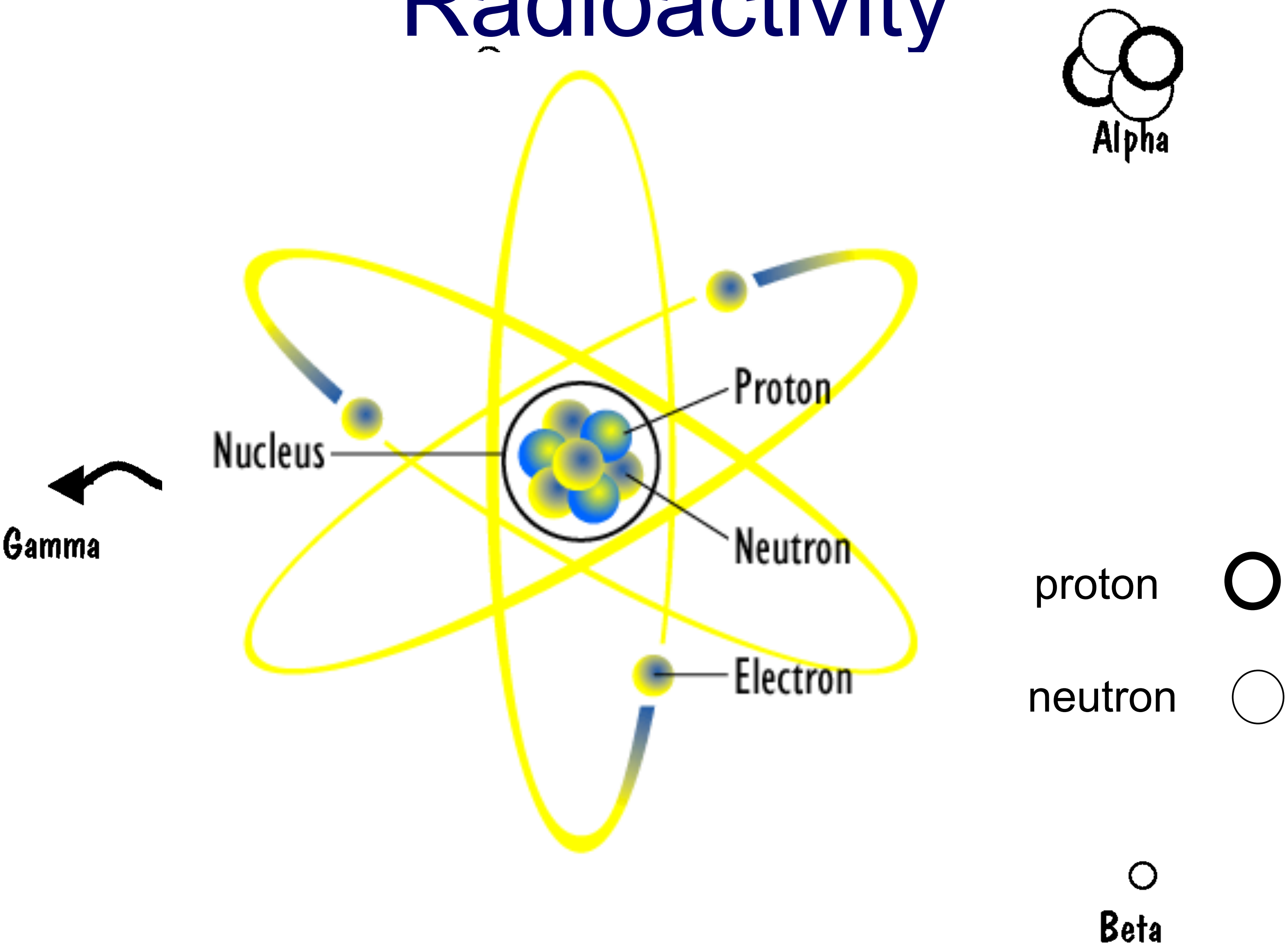
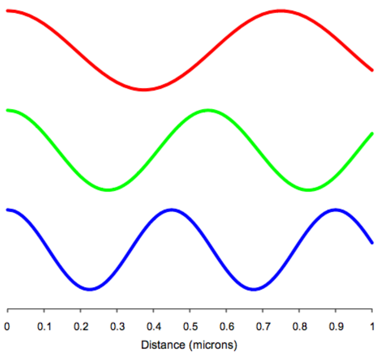


Image Source: See Note 2

Electromagnetic Radiation

- Energy transmitted in a wave form
  - Radio, microwave, infrared, visible light, ultraviolet, x-rays, γ rays
- EM radiation is characterized by its frequency (or wavelength)



- In the quantum world EM radiation behaves as a particle rather than a wave
  - Individual quanta of EM radiation are **photons**
  - Photon energy is proportional to frequency

Image Source: See Note 3

Electromagnetic Spectrum

High energy

Low energy

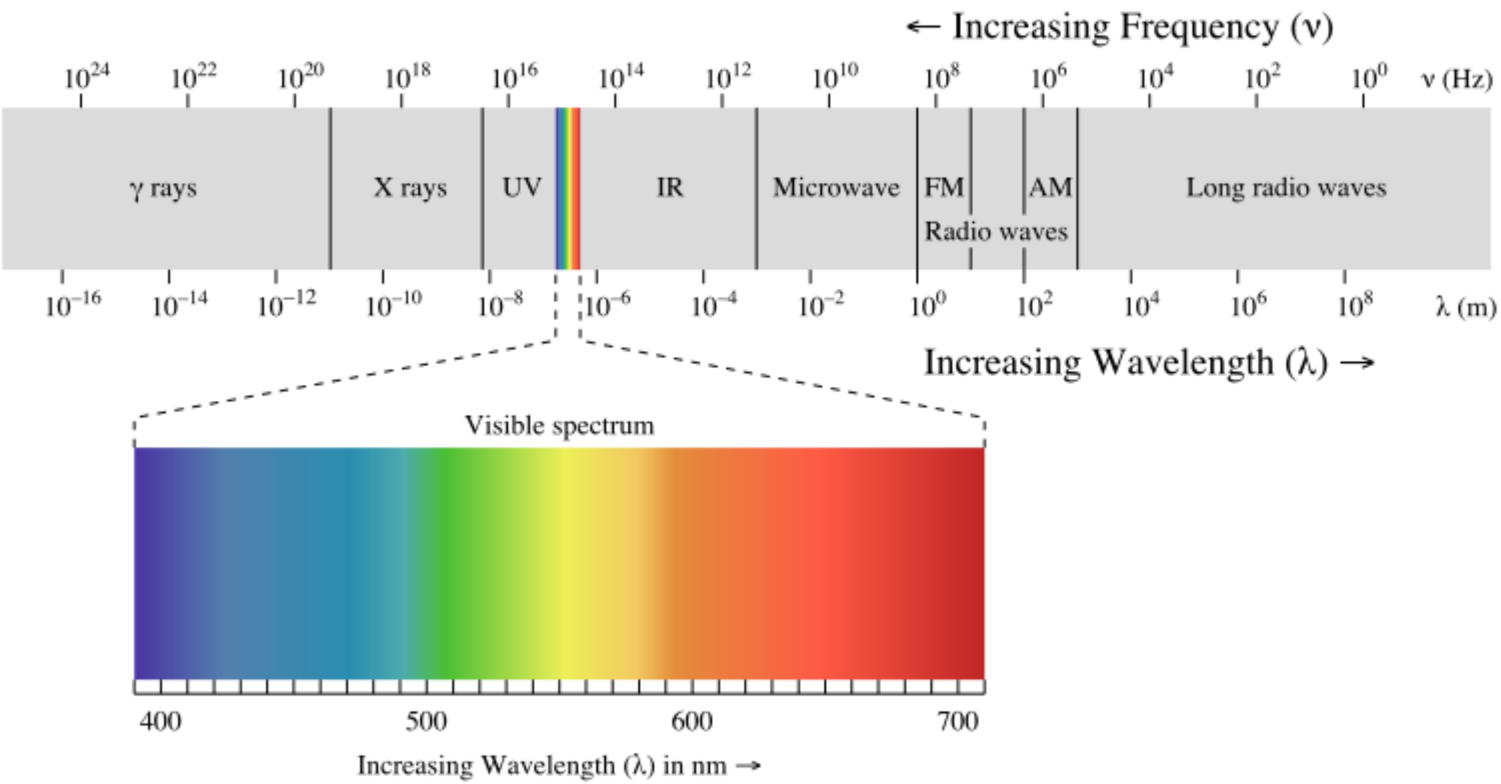


Image Source: See Note 4

Structure of the Atom

- Nucleus
  - Protons & Neutrons
  - Organized in shells arranged according to their stability
- Electron cloud
  - Electrons are arranged in orbitals (spatial distribution) and shells (energy) according to stability

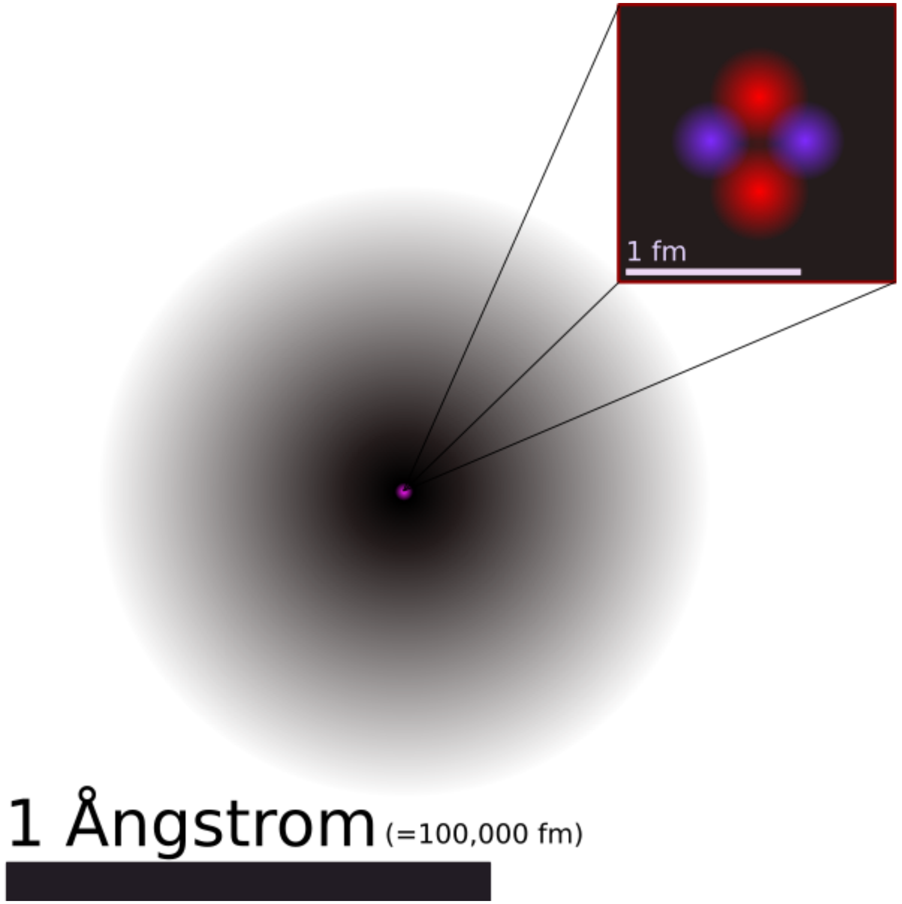


Image Source: See Note 5

X-Rays

- When individual atoms absorb energy above their lowest electron ionization energy, electron(s) can be stripped from the atom.

- If the electron is removed from a lower shell, the atom will move electrons from the outer shells in to fill the gap and become more stable.

- As electrons move to lower shells their potential energy decreases; the excess energy is released as a photon.

γ Rays

- Nucleons (protons and neutrons) are also arranged in shells.
- Just as with electrons, atoms want to have their nucleus in the most stable state.
- High-energy particle collisions or nuclear (beta) decay can leave the nucleus in an unstable state.
- When the nucleus rearranges nucleons, excess energy is emitted as gamma rays.

X-rays and gamma rays

- *X-Rays*
  - Electrons moving between orbital shells
- *γ Rays*
  - Nucleons moving between shells in the nucleus
- Transitions between energy levels are all characterized by a unique decay constant, λ
- Decay calculations for photons are identical to the corresponding calculations for nuclear decay

Ionizing Radiation

- Radiation that contains enough energy to remove one or more electrons from an atom or molecule.
  - All charged particles are ionizing.
  - Only photons with an energy greater than the ionization energy of a given atom or molecule are considered ionizing.
  - Some molecules are affected by photons in the visible or UV range, but typically only X-rays and gamma rays are considered ionizing.
  - Neutrons are ionizing (by indirect means).

Ionizing Radiation

- Radiation that contains enough energy to remove one or more electrons from an atom or molecule.
  - Neutrons are ionizing (by indirect means)
    - Neutrons do not have a charge.
    - Neutron interactions with nuclei can produce secondary particles that cause ionizations.
      - Elastic collisions with light (H, C, O, N) nuclei cause the positively charged nucleus to recoil.
      - Inelastic collisions or absorption by a nucleus can produce ionizing gamma rays.
      - Fission events produce positively charged fission fragments as well as ionizing gamma rays.

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