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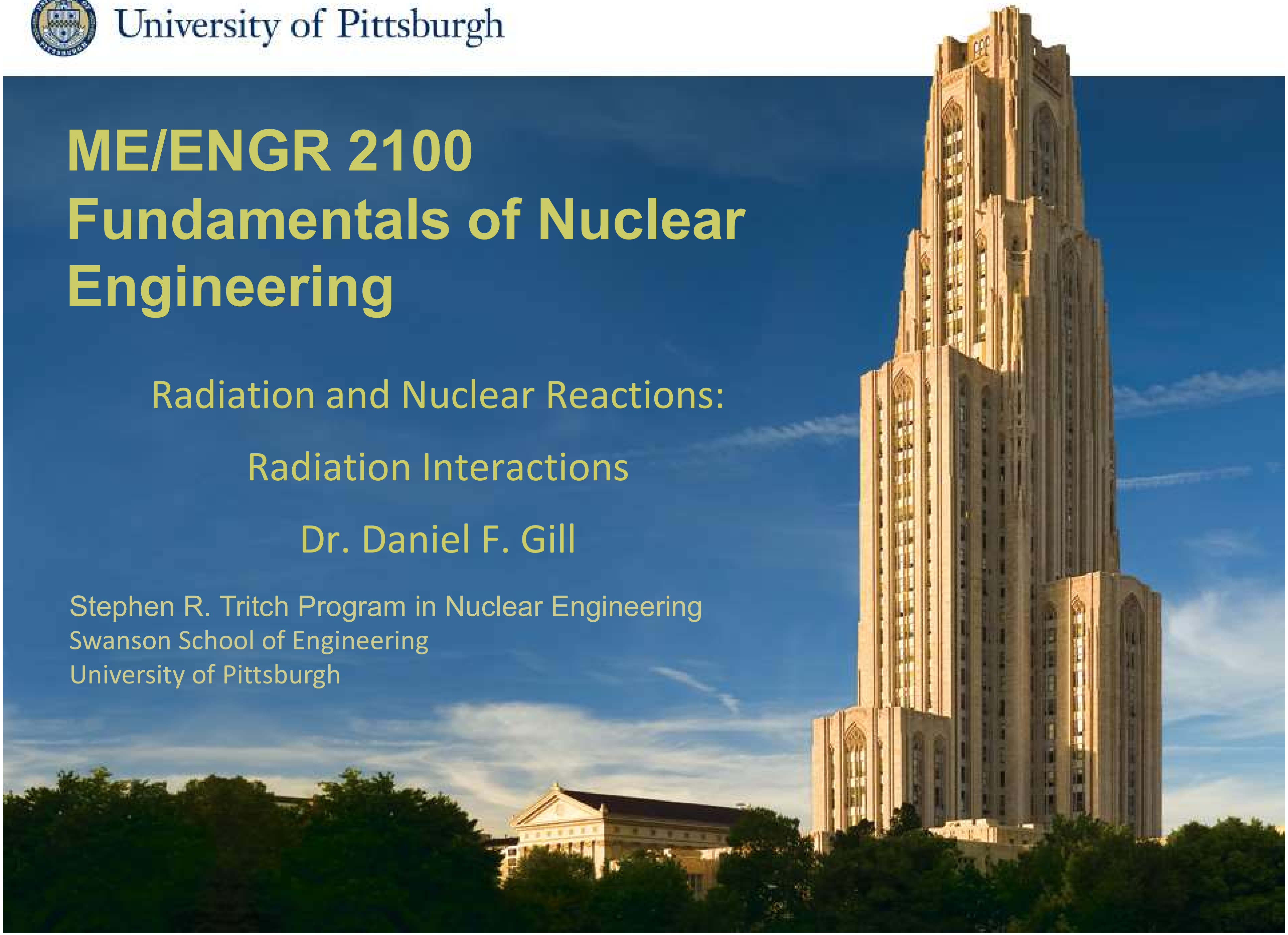

ME/ENGR 2100 Fundamentals of Nuclear Engineering

Radiation and Nuclear Reactions:

Radiation Interactions

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Relevant Reading Assignments

- Chapter 2/3 of "Introduction to Nuclear Engineering," Lamarsh and Baratta, 3rd edition, Prentice-Hall (2001)
- Chapter 2 of "Nuclear Engineering: Theory and Technology of Commercial Nuclear Power," Knief, 2nd edition, American Nuclear Society (1992, reprint by ANS 2008)
- Chapter 2 of "Nuclear Reactor Analysis," Duderstadt and Hamilton, Van Nostrand (1976)
- Module 1 of DOE Fundamentals Handbook, "Nuclear Physics and Reactor Theory," U.S.DOE (1993)Available at:

https://www.standards.doe.gov/standards-documents/1000/1019-bhdbk-1993-v1

- Not required but useful and clear is the discussion of nuclear masses and binding energies at the beginning of Chapter 7 of "Concepts of Nuclear Physics" by Bernard L. Cohen, McGraw-Hill, 1971, available in most scientific libraries.

Learning Objectives

- Explain the differences among the mechanisms by which charged particles, electromagnetic radiation, and neutrons interact in materials

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Radiation

- What is radiation?
  - Energy transmitted in the form of waves or particles (or both).
- Types of radiation
  - Charged particles (electrons, protons, α particles)
  - Electromagnetic (radio, visible, x-rays, γ rays)
  - Other (**neutrons**, neutrinos, other exotic particles)
- Categorized as either ionizing or non-ionizing
  - Depending on whether they can ionize other particles (i.e., rip off electrons from atoms)

Radiation Interactions

- During an interaction an incoming particle (a "quantum") of radiation deposits some (or all) of its energy into a target atom or molecule.
- During an interaction:
  - The incident radiation loses some amount of energy
  - The target atom or molecule gains the same amount of energy
  - The actual amount of energy transferred during an interaction is determined by the type and kinetics of the interaction.
    - The energy transfer can lead to a change in either the local chemistry or crystal structure of the target material
    - We will talk at length about effects of nuclear interactions in future lectures

Charged Particle Interactions

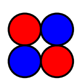
Charge: -1

- Beta particle (electron)

Charge: +1

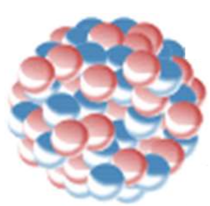
- Positron
- Proton

Charge: +2



α-particle

Charge: > +2

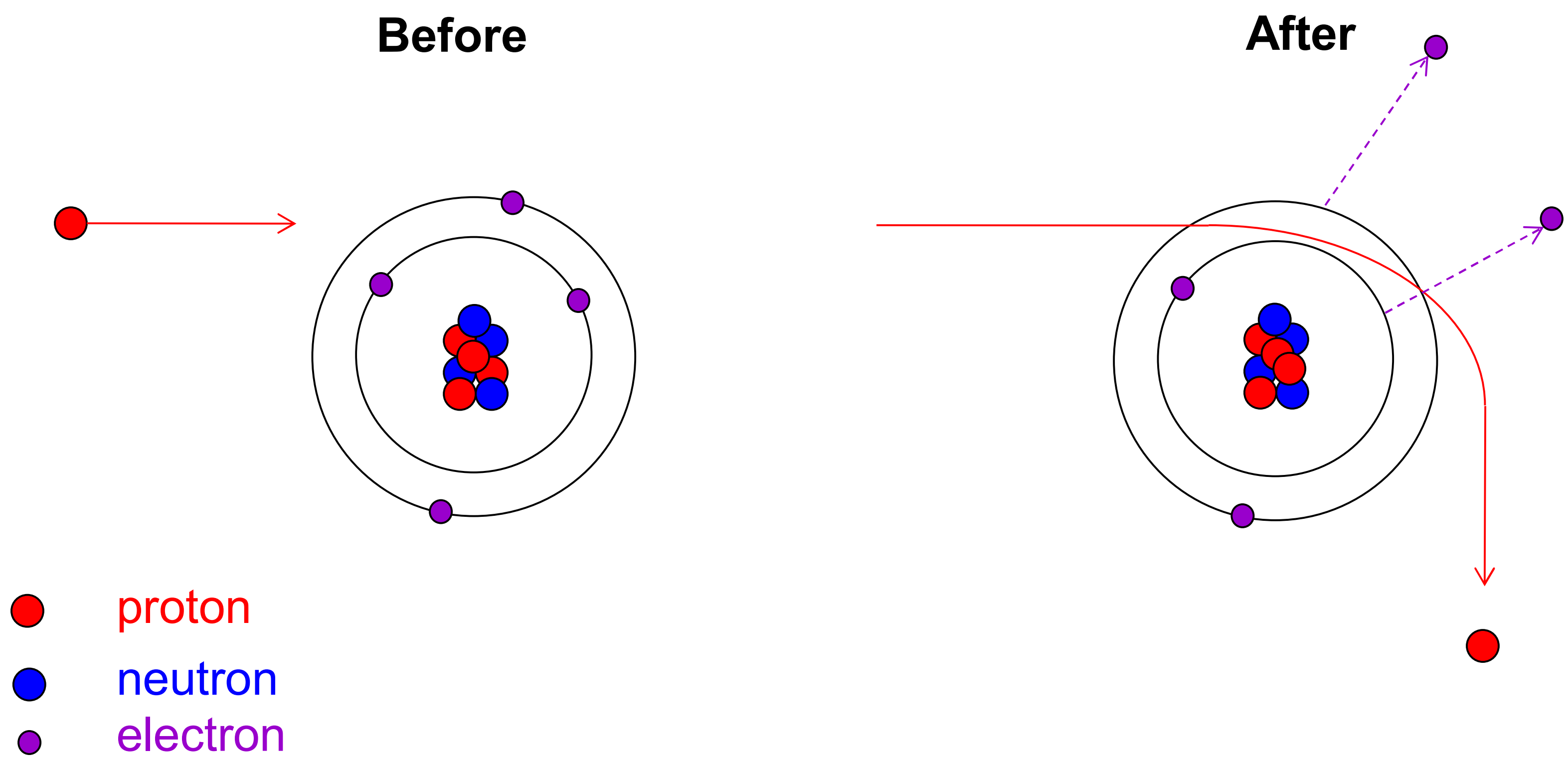


Ionized atom
(positive ion)

- Charged particles (by ascending charge)
  - Electrons, positrons, protons, alpha particles, recoil nuclei, fission fragments.
- As particles travel through a sea of negatively charged electrons, long range electrostatic forces act as a drag force.
  - The same electrostatic forces slowing the radiation down can rip outer shell electrons from host atoms in the material.
  - Charged particle LET is proportional to mz2/E (m=particle mass, z=particle charge, E=particle kinetic energy), and to the atomic number Z of the target medium.

Example of Charged Particle Interaction

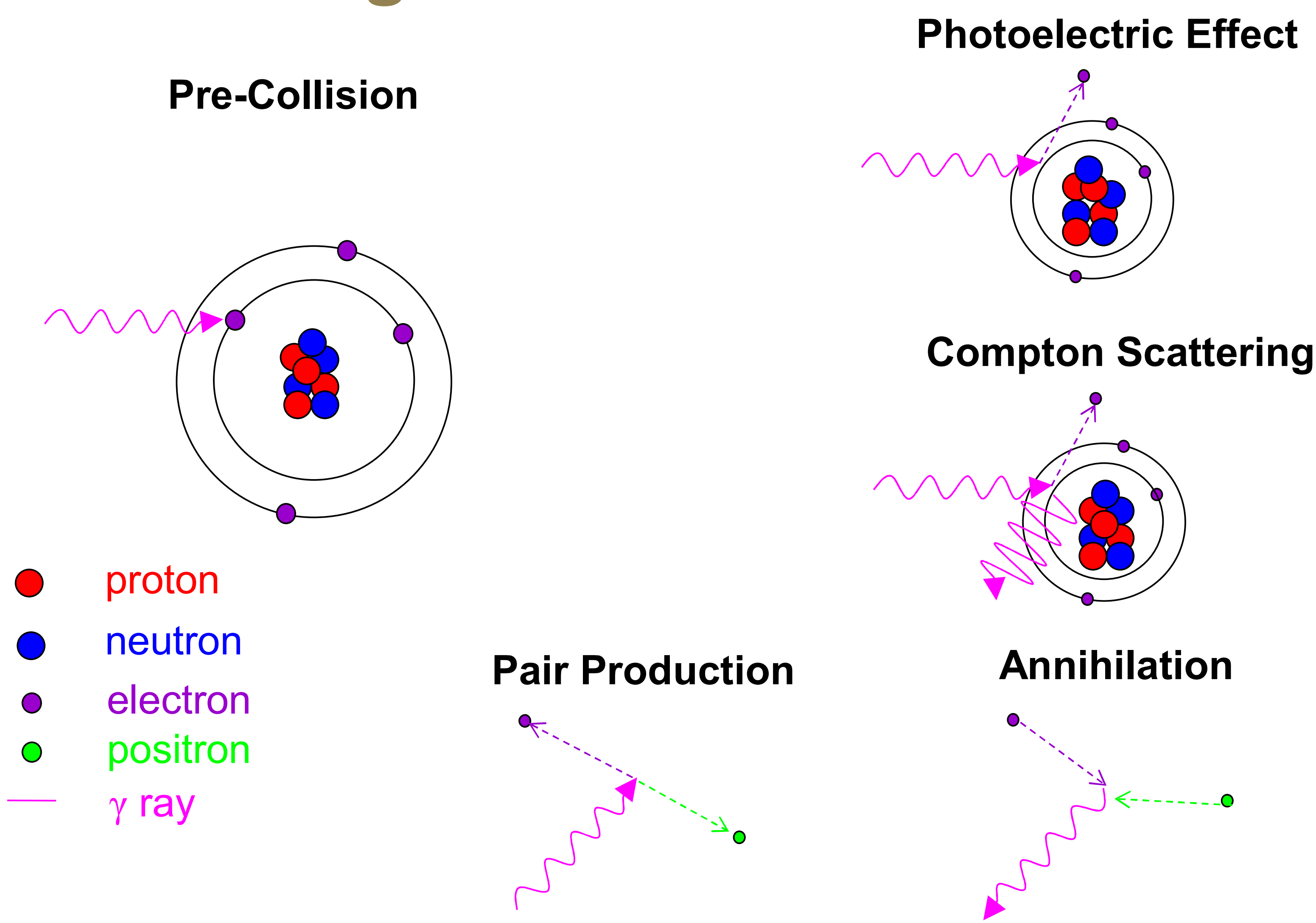
Consider an incident energetic proton that ionizes an atom



Electromagnetic Interactions

- X and γ rays interact with free and bound electrons in the material.
- Photoelectric Effect
  - Photon energy is transferred to bound electron, causing it to be ejected.
- Compton Scattering
  - Photon scatters off of an electron, reducing the photon's energy and giving kinetic energy to the electron.
- Pair production
  - Photon with energy > 1.022 MeV spontaneously turns into an electron and a positron. (Photons of sufficiently greater energy can give rise to more massive antiparticle pairs.)

Electromagnetic Interactions



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.

Neutron Interactions

- **Neutrons interact with atomic nuclei or other protons or neutrons.**

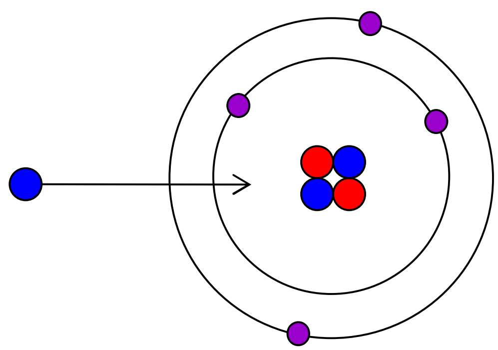
- Neutron Elastic Scattering
  - Occurs when a neutron strikes a nucleus and transfers only kinetic energy, creating a charged recoil nucleus.
  - Conserves two-body kinetic energy. (Only fast neutrons (>1keV) striking light nuclei (H to C) can transfer enough energy to cause a significant recoil.)
- Neutron Inelastic Scattering
  - Occurs when a neutron strikes a nucleus and causes excitation within the nucleus. Nuclear de-excitation then releases a γ ray.
  - Does not conserve kinetic energy.
- Nuclear reactions (i.e., transmutation) can only be caused by neutrons above a reaction-specific threshold energy (recall the mass defect).

Neutron Interactions

- Neutron Absorption (Capture)
  - Capture occurs when a neutron strikes a nucleus and is absorbed, increasing the mass number of the isotope by 1.
    - Addition of the extra neutron leaves the neutron in an excited state, with too much energy.
    - Nuclear de-excitation releases γ rays.
    - Certain combinations of neutrons and protons are fundamentally unstable. Isotopes with these combinations undergo further stabilization by emitting a particle:
      - β^- decay, β^+ decay, α decay, proton emission, neutron emission, internal conversion, electron capture
      - This process is **Radioactive Decay**

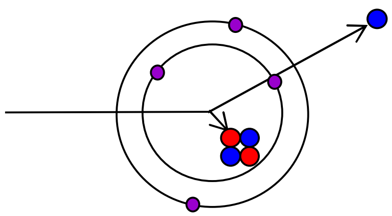
Neutron Interactions

Pre-Collision

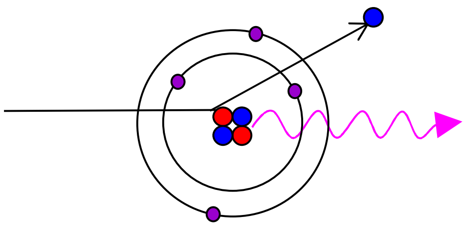


proton
neutron
electron
γ ray

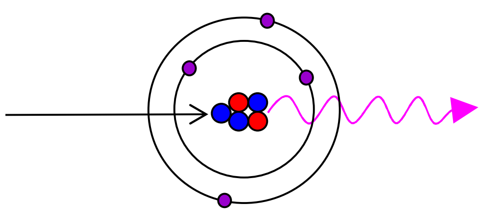
Elastic Collision



Inelastic Collision



Neutron Capture

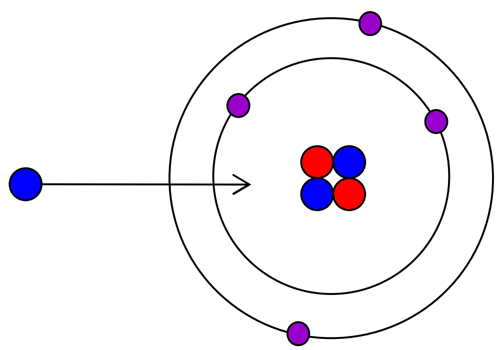


Neutron Interactions

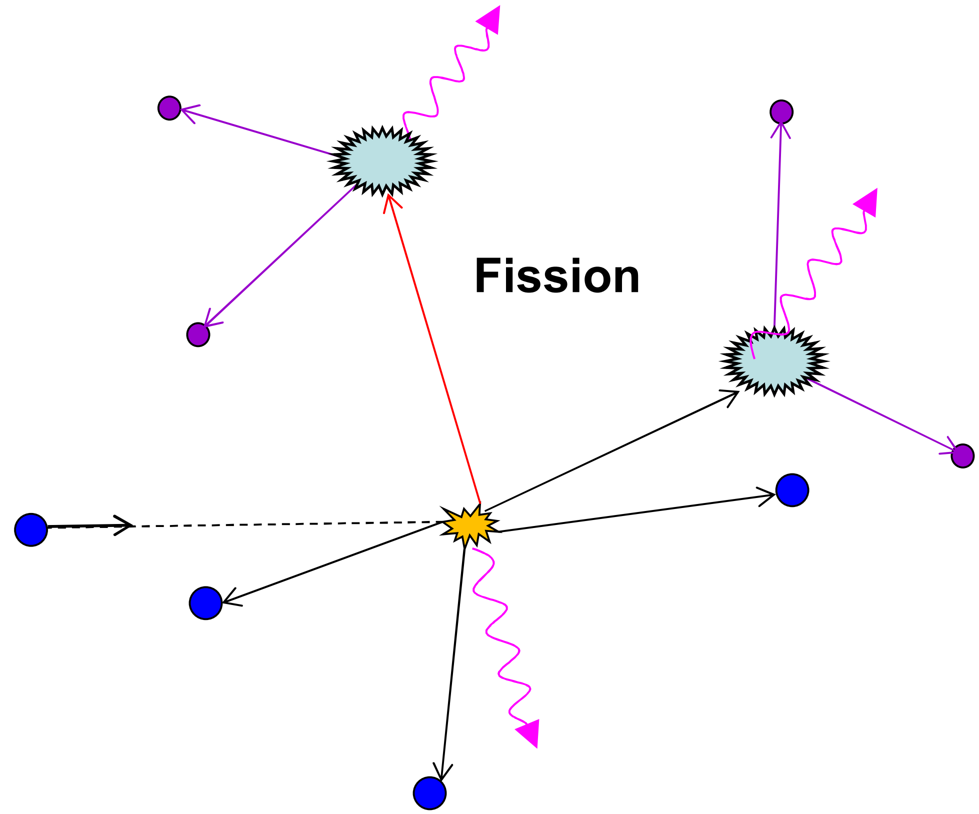
- Fission(after Capture)
  - Some high-mass isotopes are so unstable following a neutron absorption that they split apart into two smaller nuclides rather than undergoing simple radioactive decay.
  - Fission rips the nucleus apart, immediately releasing
    - Neutrons (prompt)
    - Ionized and excited fission fragments (daughter nuclides)
    - γ rays (prompt)
    - Neutrinos
  - As the fission products de-excite and decay over time they release
    - γ rays
    - α particles, β particles, and neutrons from radioactive decay
    - These emissions are referred to as delayed. (Note that not all fission neutrons are emitted promptly at the time of fission; this will be important later!)

Neutron Interactions: fission

Pre-Collision



Fission



proton
neutrons
Electrons (beta particles)
γ ray

- Fission fragments (some unstable)
- High energy prompt neutrons
- Delayed neutrons
- γ rays