Introduction: Atomic and Nuclear Physics

Unit: Atomic and Nuclear Physics

Topics covered in this chapter:

This chapter discusses the particles that atoms and other matter are made of, how those particles interact, and the process by which radioactive decay can change the composition of a substance from one element into another.

- *Radioactive Decay* and *Nuclear Equations* describe the process of radioactive decay and how to predict the results.
- *Mass Defect & Binding Energy* uses Einstein's equation $E = mc^2$ to determine the energy that was converted to mass in order to hold the nucleus of an atom together.
- *Half-Life* explains how to calculate the rate at which radioactive decay happens and the amount of material remaining.
- *Nuclear Fission & Fusion* and *Practical Uses for Nuclear Radiation* describe ways that radioactive materials are used to produce energy or otherwise provide benefits to society.

One of the challenges of this chapter is remembering concepts from chemistry, including numbers of protons, neutrons and electrons, and how to use the Periodic Table of the Elements.

Standards addressed in this chapter:

Massachusetts Curriculum Frameworks (2016):

HS-PS1-8: Develop a model to illustrate the energy released or absorbed during the processes of fission, fusion, and radioactive decay.

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AP® Physics 2 Learning Objectives/Essential Knowledge (2024):

15.7.A: Describe the physical properties that constrain the behavior of interacting nuclei, subatomic particles, and nucleons.

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15.7.A.1: The strong force is exerted at nuclear scales and dominates the interactions of nucleons (protons or neutrons).

15.7.A.2: Possible nuclear reactions are constrained by the law of conservation of nucleon number.

15.7.A.3: The behavior of the constituent particles of a nuclear reaction is constrained by laws of conservation of energy, energy-mass equivalence, and conservation of momentum.

15.7.A.4: For all nuclear reactions, mass and energy may be exchanged due to mass-energy equivalence.

15.7.A.5: Energy may be released in nuclear processes in the form of kinetic energy of the products or as photons.

15.7.A.6: Nuclear fusion is the process by which two or more smaller nuclei combine to form a larger nucleus, as well as subatomic particles.

15.7.A.7: Nuclear fission is the process by which the nucleus of an atom splits into two or more smaller nuclei, as well as subatomic particles.

15.7.A.8: Nuclear fission may occur spontaneously or may require an energy input, depending on the binding energy of the nucleus.

15.7.B: Describe the radioactive decay of a given sample of material consisting of a finite number of nuclei.

15.7.B.1: Radioactive decay is the spontaneous transformation of a nucleus into one or more different nuclei.

15.7.B.1.i: The time at which an individual nucleus undergoes radioactive decay is indeterminable, but decay rates can be described using probability

15.7.B.1.ii: The half-life, $t_{½}$, of a radioactive material is the time it takes for half of the initial number of radioactive nuclei to have spontaneously decayed.

15.7.B.1.iii: The decay constant can be related to the half-life of a radioactive material with the equation $\lambda = \dfrac{\ln 2}{t_{½}}$.

15.7.B.2: A material's decay constant may be used to predict the number of nuclei remaining in a sample after a period of time, or the age of a material if the initial amount of material is known.

15.7.B.3: Different unstable elements and isotopes may have vastly different half-lives, ranging from fractions of a second to billions of years.

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15.8.A: Describe the processes by which individual nuclei decay.

15.8.A.1: Some processes by which nuclei decay emit subatomic particles with unique properties.

15.8.A.1.i: An alpha particle, or helium nucleus, consists of two neutrons and two protons and is symbolized by α or He^{2+}.

15.8.A.1.ii: Neutrinos and antineutrinos are subatomic particles that have no electrical charge, have negligible mass, and are symbolized by ν and $\bar{\nu}$, respectively.

15.8.A.1.iii: Neutrinos and antineutrinos only interact with matter via the weak force and the gravitational force, which results in very little interaction with normal matter.

15.8.A.1.iv: Positrons, or antielectrons, are subatomic particles that have an electric charge opposite that of an electron, have the same mass as an electron, and are symbolized by e^{+} or β+.

15.8.A.2: Nuclei can undergo radioactive decay via alpha decay, beta-minus decay (β−), beta-plus decay (β+), and gamma decay (γ).

15.8.A.2.i: In all nuclear decays, nucleon number (the number of neutrons and protons), lepton number (the number of electrons and neutrinos), and charge are conserved.

15.8.A.2.ii: Alpha decay occurs when a nucleus ejects an alpha particle.

15.8.A.2.iii: Beta-minus decay occurs when a neutron changes to a proton by emitting an electron and antineutrino.

15.8.A.2.iv: Beta-plus decay occurs when a proton changes to a neutron by emitting a positron and neutrino.

15.8.A.2.v: Gamma decay occurs after a nucleus has undergone alpha or beta decay and the excited nucleus decays to a lower energy state by emitting a photon.

15.8.A.3: The type of decay exhibited by a given nucleus is determined by the isotope of the element.