Introduction: Quantum and Particle Physics

Unit: Quantum and Particle 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.

- *Photoelectric Effect* describes the observation that light of a sufficiently high frequency can remove electrons from an atom.
- *Bohr Model of the Hydrogen Atom* describes the development of quantum theory to describe the behavior of the electrons in an atom.
- *Wave-Particle Duality* and *Quantum Mechanical Model of the Atom* describe the idea that matter can behave like a wave as well as a particle, and the application of that idea to the modern quantum mechanical model of the atom.
- *Fundamental Forces* describes the four natural forces that affect everything in the universe: the strong and weak nuclear forces, the electromagnetic force, and the gravitational force.
- *The Standard Model* describes and classifies the particles that make up atoms.
- *Particle Interactions* describes interactions between subatomic particles.

One of the challenging aspects of this chapter is that it describes processes that happen on a scale that is much too small to observe directly. Another challenge is the fact that the Standard Model continues to evolve. Many of the connections between concepts that make other topics easier to understand have yet to be made in the realm of quantum & particle physics.

Standards addressed in this chapter:

Massachusetts Curriculum Frameworks (2016):

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HS-PS4-3. Evaluate the claims, evidence, and reasoning behind the idea that electromagnetic radiation can be described by either a wave model or a particle model, and that for some situations involving resonance, interference, diffraction, refraction, or the photoelectric effect, one model is more useful than the other.

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

15.1.A: Describe the properties and behavior of an object that exhibits both particle-like and wave-like behavior.

15.1.A.1: Quantum theory was developed to explain observations of matter and energy that could not be explained using classical mechanics. These phenomena include, but are not limited to, atomic spectra, blackbody radiation, and the photoelectric effect.

15.1.A.1.i: Quantum theory is necessary to describe the properties of matter at atomic and subatomic scales.

15.1.A.1.ii: In quantum theory, fundamental particles can exhibit both particle-like and wave-like behavior.

15.1.A.2: Light can be modeled both as a wave and as discrete particles, called photons.

15.1.A.2.i: A photon is a massless, electrically neutral particle with energy proportional to the photon's frequency.

15.1.A.2.ii: Photons travel in straight lines unless they interact with matter.

15.1.A.3: The speed of a photon depends on the medium through which the photon travels.

15.1.A.3.i: The speed of all photons in free space is equal to the speed of light, $c = 3.00 \times 10^{8}\,\frac{\text{m}}{\text{s}}$.

15.1.A.3.ii: In general, the speed of photons through a given medium is inversely proportional to the index of refraction of that medium.

15.1.A.4: Particles can demonstrate wave properties, as shown by variations of Young's double-slit experiment.

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15.1.A.4.i: A wave model of matter is quantified by the de Broglie wavelength, which increases as the momentum of a particle decreases.

15.1.A.4.ii: Quantum theory is necessary to describe systems where the de Broglie wavelength is comparable to the size of the system.

15.1.A.5: Values of energy and momentum have discrete, or quantized, values for bound systems described by quantum theory.

15.2.A: Describe the properties of an atom.

15.2.A.1: Atoms have internal structure.

15.2.A.1.i: Atoms consist of a small, positively charged nucleus surrounded by one or more negatively charged electrons.

15.2.A.1.ii: The nucleus of an atom is made up of protons and neutrons.

15.2.A.1.iii: The number of neutrons and protons in an atom can be represented using nuclear notation.

15.2.A.1.iv: An ion is an atom with a nonzero net electric charge.

15.2.A.2: Each atomic element has a unique number of protons.

15.2.A.2.i: The number and arrangements of electrons affect how atoms interact.

15.2.A.2.ii: The total number of neutrons and protons identifies the isotope of an element.

15.2.A.2.iii: The mass of an atom is dominated by the total mass of the protons and neutrons in its nucleus.

15.2.A.3: The Bohr model of the atom is based on classical physics and was the historical representation of the atom that led to the description of the hydrogen atom in terms of discrete energy states.

15.2.A.3.i: In the Bohr model of the atom, electrons are modeled as moving around the nucleus in circular orbits determined by the electron's charge and mass, as well as the electric force between the electron and the nucleus.

15.2.A.3.ii: The standing wave model of electrons accounts for the existence of specific allowed energy states of an electron in an atom, because the electron orbit's circumference must be an integer multiple of the electron's de Broglie wavelength.

15.3.A: Describe the emission or absorption of photons by atoms.

15.3.A.1: Energy transfer occurs when photons are absorbed or emitted by an atom, which is modeled as a system consisting of a nucleus and an electron.

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15.3.A.2: Energy can only be absorbed or emitted by an atom if the amount of energy being absorbed or emitted corresponds to the energy difference between two atomic energy states.

15.3.A.2.i: An atom in a given energy state may absorb a photon of the appropriate energy and transition to a higher energy state.

15.3.A.2.ii: An atom in an excited energy state may emit a photon of the appropriate energy to spontaneously move to a lower energy state.

15.3.A.2.iii: Because an atom is modeled as a system consisting of an electron and a nucleus, a change in the energy state of an atom corresponds to a change in the interaction energy between the electron and the nucleus.

15.3.A.3: Transitions between two energy states of an atom correspond to the absorption or emission of a photon of a single frequency and, therefore, a single wavelength.

15.3.A.4: Atoms of each element have a unique set of allowed energy levels and thereby a unique set of absorption and emission frequencies. The unique set of frequencies determines the element's spectrum.

15.3.A.4.i: An emission spectrum can be used to determine the elements in a source of light.

15.3.A.4.ii: An absorption spectrum can be used to determine the elements composing a substance by observing what light the substance has absorbed.

15.3.A.4.iii: Energy level diagrams are commonly used to visually represent the energy states of an atom.

15.3.A.5: Binding energy is the energy required to remove an electron from an atom, causing the atom to become ionized. An atom in the lowest energy level (ground state) will require the greatest amount of energy to remove the electron from the atom.

15.4.A: Describe the electromagnetic radiation emitted by an object due to its temperature.

15.4.A.1: Matter will spontaneously convert some of its internal thermal energy into electromagnetic energy.

15.4.A.2: A blackbody is an idealized model of matter that absorbs all radiation that falls on the body. If the body is in equilibrium at a constant temperature, then it must in turn emit energy.

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15.4.A.3: A blackbody will emit a continuous spectrum that only depends on the body's temperature. The radiation emitted by a blackbody is often modeled by plotting intensity per unit wavelength as a function of wavelength.

15.4.A.3.i: The distribution of the intensity of a blackbody's spectrum as a function of temperature cannot be modeled using only classical physics concepts. A blackbody's spectrum is described by Planck's law, which assumes that the energy of light is quantized.

15.4.A.3.ii: The peak wavelength emitted by a blackbody (the wavelength at which the blackbody emits the greatest amount of radiation per unit wavelength) decreases with increasing temperature, as described by Wien's law.

15.4.A.3.iii: The rate at which energy is emitted (power) by a blackbody is proportional to the surface area of the body and to the temperature of the body raised to the fourth power, as described by the Stefan-Boltzmann law.

15.5.A: Describe an interaction between photons and matter using the photoelectric effect.

15.5.A.1: The photoelectric effect is the emission of electrons when electromagnetic radiation is incident upon a photoactive material.

15.5.A.2: The emission of electrons via the photoelectric effect requires a minimum frequency of incident light, called the threshold frequency.

15.5.A.2.i: Light that is incident on a material and is at the threshold frequency or higher will induce electron emission, regardless of the number of photons that strike the material.

15.5.A.2.ii: The energy of the emitted electrons is not dependent on the number of photons that are incident upon the material, which provides evidence that light is a collection of discrete, quantized energy packets called photons.

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15.5.A.3: The maximum kinetic energy of an emitted electron is related to the frequency of the incident light and the work function of the material, ϕ.

15.5.A.3.i: The work function of a material is the minimum energy required to emit an electron from atoms in the material.

15.5.A.3.ii: The maximum kinetic energy of an emitted electron is given by the equation $K_{max} = hf - \phi$.

15.5.A.3.iii: In a typical experimental setup to demonstrate the photoelectric effect and determine the work function of a metal, two metal plates are placed in a vacuum chamber and connected to a variable source of potential difference. One of the plates is illuminated by monochromatic light that causes electrons to be ejected and the potential difference between the plates is adjusted until no current is measured in the circuit.

15.6.A: Describe the interaction between photons and matter using Compton scattering.

15.6.A.1: In Compton scattering, a photon interacts with a free electron. The Compton effect is when a photon that emerges from the interaction has a lower energy and longer wavelength than the incoming photon. The magnitude of the change is related to the direction of the photon after the collision.

15.6.A.2: Compton scattering provides evidence that light is a collection of discrete, quantized energy packets called photons.

15.6.A.2.i: Compton scattering can be explained by treating a photon as a particle and applying conservation of energy and conservation of momentum to the collision between the photon and electron.

15.6.A.2.ii: The transfer of a photon's energy to an electron results in the energy, momentum, frequency, and wavelength of the photon changing.

15.6.A.3: The change in wavelength experienced by a photon after colliding with an electron is related to how much the photon's direction changes.