Physics Notes (Modern Physics)

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9. Models of the Atom

9.1 Various Models of the Atom

- **Dalton's Atomic Theory (Early 19th Century):**
  - Atoms are indivisible, indestructible particles.
  - Atoms of the same element are identical.
  - Atoms combine in simple whole-number ratios to form compounds.
- **Thomson's Plum Pudding Model (1897):**
  - After discovering electrons, Thomson proposed atoms are a sphere of uniformly distributed positive charge with negatively charged electrons embedded in it, like plums in a pudding.
- **Rutherford's Nuclear Model (1911):**
  - Based on the gold foil experiment (alpha particle scattering).
  - Proposed a small, dense, positively charged nucleus at the center of the atom.
  - Electrons orbit the nucleus in mostly empty space.
  - Flaw: Could not explain why orbiting electrons don't lose energy and spiral into the nucleus.
- **Bohr's Atomic Model (1913):**
  - Postulated that electrons orbit the nucleus in specific, quantized energy levels (stationary orbits) without radiating energy.
  - Electrons can jump between energy levels by absorbing or emitting specific amounts of energy (photons).
  - Explained the discrete line spectra of hydrogen.
  - Flaw: Only worked well for hydrogen and hydrogen-like atoms.

- **Quantum Mechanical Model (Modern Model):**
    - Based on quantum mechanics, proposing that electrons exist in probability clouds (orbitals) rather than fixed orbits.
    - Electrons have wave-like properties.
    - This is the most accurate and widely accepted model.

9.2 Atomic Structure and Chemical Behaviour

- **Atomic Structure:**
    - **Nucleus:** Contains protons (positive charge) and neutrons (no charge). Accounts for most of the atom's mass.
    - **Electrons:** Negatively charged particles orbiting the nucleus in energy shells/orbitals.
- **Atomic Number (Z):** Number of protons in the nucleus. Defines the element.
- **Mass Number (A):** Total number of protons and neutrons in the nucleus (A = Z + N).
- **Isotopes:** Atoms of the same element (same Z) but with different numbers of neutrons (different A).
- **Ions:** Atoms that have gained or lost electrons, resulting in a net positive (cation) or negative (anion) charge.
- **Chemical Behaviour:** Primarily determined by the number and arrangement of electrons in the outermost shell (valence electrons), which dictates how atoms interact and form bonds.

9.3 Summary

- Atomic models evolved from simple particles to complex quantum descriptions.
- Rutherford established the nuclear atom; Bohr introduced quantized energy levels.
- The modern atomic model describes electron probability distributions.
- Atomic structure (protons, neutrons, electrons) determines an element's identity and chemical properties.

10. Nucleus, Radioactivity, Nuclear Reactions

10.1 Radioactivity - Natural and Artificial

- **Radioactivity (Radioactive Decay):** The spontaneous disintegration of unstable atomic nuclei, accompanied by the emission of radiation (alpha, beta, gamma particles/rays) and the transformation of one element into another.
- **Natural Radioactivity:** Occurs in naturally unstable isotopes (e.g., Uranium-238, Radium-226).
- **Artificial Radioactivity (Induced Radioactivity):** Occurs when stable nuclei are bombarded with particles, making them unstable and radioactive (e.g., in nuclear reactors or particle accelerators).

- **Types of Radiation:**
  - **Alpha (α) particles:** Consist of two protons and two neutrons (helium nucleus, ${}_{2}^{4}\mathrm{He}$). Positively charged. Low penetrating power (stopped by paper). High ionizing power.
  - **Beta (β) particles:** High-speed electrons (${}_{-1}^{0}\mathrm{e}$) or positrons (${}_{+1}^{0}\mathrm{e}$). Negatively or positively charged. Moderate penetrating power (stopped by aluminum). Moderate ionizing power.
  - **Gamma (γ) rays:** High-energy electromagnetic waves. No charge, no mass. Very high penetrating power (requires thick lead or concrete to stop). Low ionizing power.
- **Half-life ($T_{1/2}$):** The time taken for half of the radioactive nuclei in a sample to decay. It is a constant for a given isotope.

10.2 Nuclear Energy, Nuclear Reactions

- **Nuclear Energy:** Energy released from changes in the nucleus of an atom. Much larger than chemical energy.
- **Mass-Energy Equivalence:** Einstein's famous equation $E = mc^2$, stating that mass can be converted into energy and vice versa. This explains the energy released in nuclear reactions (mass defect).
- **Nuclear Reactions:** Processes that involve changes in the nucleus of an atom.
    - **Nuclear Fission:** The splitting of a heavy, unstable nucleus (e.g., Uranium-235) into two or more lighter nuclei, along with the release of a large amount of energy and neutrons.
        - **Applications:** Nuclear power plants (controlled chain reactions), atomic bombs (uncontrolled chain reactions).
    - **Nuclear Fusion:** The combining of two light nuclei to form a heavier nucleus, with the release of an even greater amount of energy.
        - **Examples:** Energy source of the Sun and stars.
        - **Challenges for Earth:** Requires extremely high temperatures and pressures.

10.3 Summary

- Radioactivity is the spontaneous decay of unstable nuclei, emitting alpha, beta, or gamma radiation.
- Half-life is the characteristic decay time.
- Nuclear energy comes from mass-energy conversion in fission (splitting) or fusion (combining) reactions.

11. Energy Quantization

11.1 Atomic Energy Levels

- **Quantization of Energy:** The concept that electrons in atoms can only exist in specific, discrete energy levels (or orbits), rather than at any arbitrary energy.
- **Ground State:** The lowest possible energy level for an electron.
- **Excited States:** Higher energy levels to which an electron can jump by absorbing a specific amount of energy (a quantum or photon).
- **Energy Transitions:** When an electron moves from a higher energy level to a lower one, it emits a photon with energy equal to the difference between the two levels ($E = hf$). When it absorbs a photon of the correct energy, it jumps to a higher level.

11.2 Franck-Hertz Experiment

- **Purpose:** Demonstrated the existence of discrete energy levels in atoms.
- **Setup:** Electrons are accelerated through a gas (e.g., mercury vapor).
- **Observation:** As the accelerating voltage is increased, the current passing through the gas increases, but then drops sharply at specific voltages. This indicates that electrons lose energy only in specific, quantized amounts by inelastic collisions with gas atoms, exciting them to higher energy levels.

11.3 Atomic Spectra; Colour and Light Frequency

- **Atomic Spectra:** The unique pattern of electromagnetic radiation absorbed or emitted by an element when its atoms undergo energy transitions.
    - **Emission Spectrum:** Produced when excited atoms release energy by emitting photons. Appears as bright lines on a dark background. Each element has a unique emission spectrum, acting as its "fingerprint."

    - **Absorption Spectrum:** Produced when white light passes through a cool gas, and atoms absorb specific wavelengths corresponding to their excitation energies. Appears as dark lines on a continuous background.
- **Colour and Light Frequency:** The colour of visible light is determined by its frequency (or wavelength).
    - Red light has the lowest frequency (longest wavelength).
    - Violet light has the highest frequency (shortest wavelength).

11.4 The Photoelectric Effect

- **Definition:** The emission of electrons from a metal surface when light of a sufficiently high frequency shines on it.
- **Key Observations (that classical wave theory could not explain):**
    1. **Threshold Frequency (f0):** No electrons are emitted unless the light frequency is above a certain minimum value, regardless of intensity.
    2. **Instantaneous Emission:** Electrons are emitted almost instantaneously if the threshold frequency is met.
    3. **Kinetic Energy of Electrons:** The maximum kinetic energy of emitted electrons depends on the frequency of light, not its intensity.
    4. **Intensity and Number of Electrons:** The number of emitted electrons is proportional to the intensity of light.

- **Einstein's Explanation (Photon Theory):** Light consists of discrete packets of energy called photons ($E = hf$).
  - A single photon interacts with a single electron.
  - **Work Function (Φ):** The minimum energy required to liberate an electron from the metal surface.
  - **Photoelectric Equation:** $hf = \Phi + KE_{max}$ (Energy of photon = Work function + Maximum kinetic energy of emitted electron).
  - This effect provided strong evidence for the particle nature of light.

11.5 X-rays

- **Production:** Produced when high-speed electrons are suddenly decelerated upon striking a metal target (anode) in a vacuum tube.
- **Properties:** High energy electromagnetic radiation, highly penetrating, can ionize matter, cause fluorescence.
- **Applications:** Medical imaging (radiography, CT scans), security screening, crystallography.
- **Continuous Spectrum:** Produced when electrons lose energy randomly as they decelerate (bremsstrahlung).
- **Characteristic Spectrum:** Sharp peaks at specific wavelengths, produced when accelerated electrons knock out inner-shell electrons from target atoms, and outer-shell electrons fall to fill the vacancies.

11.6 Summary

- Atomic energy is quantized, leading to discrete energy levels and specific photon emissions/absorptions.
- Franck-Hertz experiment confirmed discrete energy levels.
- Atomic spectra are unique fingerprints of elements.
- Photoelectric effect provides evidence for light's particle nature (photons).
- X-rays are high-energy EM waves produced by decelerating electrons.

12. Wave-Particle Paradox (Wave-Particle Duality)

12.1 Wave Nature of Matter (De Broglie Hypothesis)

- **De Broglie Hypothesis:** Proposed that all matter (particles like electrons, protons, atoms) exhibits wave-like properties.
- **De Broglie Wavelength (λ):** The wavelength associated with a particle.
  - **Formula:** $\lambda = \frac{h}{p} = \frac{h}{mv}$ (where h is Planck's constant, p is momentum).

- **Experimental Evidence:** Electron diffraction experiments (Davisson-Germer experiment) showed that electrons can be diffracted, just like waves.

12.2 Particle Nature of Matter (Photoelectric Effect)

- The photoelectric effect provides strong evidence for the particle nature of light (photons). Light energy is delivered in discrete packets, not continuously like a classical wave.

12.3 Wave-Particle Duality

- **Concept:** The idea that light and matter can exhibit properties of both waves and particles, depending on the experiment or observation. Neither model alone can fully explain all phenomena.
- **Complementarity Principle:** Wave and particle descriptions are complementary; they are both necessary to understand the full nature of quantum entities.

12.4 Uncertainty Principle (Heisenberg's Uncertainty Principle)

- **Principle:** It is impossible to simultaneously know precisely both the position and momentum (or energy and time) of a particle. The more accurately one is known, the less accurately the other can be known.

- **Formula (simplified):** $\Delta x \Delta p \geq \frac{h}{4\pi}$ (where Δx is uncertainty in position, Δp is uncertainty in momentum, h is Planck's constant).
- **Implication:** It's a fundamental limit on the precision with which certain pairs of physical properties of a particle can be known, not a limitation of measurement technology. It arises from the wave-particle duality.

12.5 Summary

- Matter exhibits wave-like properties (de Broglie wavelength).
- Light exhibits particle-like properties (photons in photoelectric effect).
- Wave-particle duality states that both descriptions are needed.
- Heisenberg's Uncertainty Principle imposes fundamental limits on simultaneous measurements of certain pairs of properties.

13. Basic Electronics

13.1 Semiconductors

- **Definition:** Materials that have electrical conductivity between that of a conductor (e.g., copper) and an insulator (e.g., glass). Their conductivity can be controlled.
- **Key Semiconductor Materials:** Silicon (Si) and Germanium (Ge).
- **Conduction Mechanism:** Unlike metals (where only electrons are charge carriers), semiconductors have two types of charge carriers:
    - **Electrons:** Negative charge carriers, moving in the conduction band.
    - **Holes:** Positive charge carriers, representing the absence of an electron in the valence band.

13.2 Modes of Conduction in Semiconductors - Electrons and Holes

- **Intrinsic Semiconductors:** Pure semiconductors (e.g., pure silicon) where the number of free electrons is equal to the number of holes, created by thermal excitation (breaking of covalent bonds). Poor conductors at room temperature.
- **Extrinsic Semiconductors (Doping):** Intrinsic semiconductors whose conductivity is greatly enhanced by adding small amounts of impurities (dopants). This process is called **doping**.
    - **N-type Semiconductors:** Doped with pentavalent impurities (e.g., phosphorus, arsenic) which have 5 valence electrons. These impurities donate extra electrons, making electrons the **majority carriers** and holes the minority carriers.
    - **P-type Semiconductors:** Doped with trivalent impurities (e.g., boron, gallium) which have 3 valence electrons. These impurities create "holes" that can accept electrons, making holes the **majority carriers** and electrons the minority carriers.

13.3 Types of Semiconductors (Devices)

- **Diode (p-n junction diode):** Formed by joining a p-type semiconductor with an n-type semiconductor.
    - Allows current to flow easily in one direction (forward bias) and largely blocks it in the opposite direction (reverse bias).
    - **Applications:** Rectifiers (converting AC to DC), LED (Light Emitting Diode), Solar cells.
- **Transistor (Bipolar Junction Transistor - BJT, Field-Effect Transistor - FET):** A semiconductor device used for amplifying electronic signals and electrical power, or for switching electronic signals and electrical power.
    - Acts as an electronic switch or amplifier.
    - **Applications:** Computers, mobile phones, amplifiers, almost all modern electronic devices.
- **Integrated Circuits (ICs) / Microchips:** Tiny electronic circuits fabricated on a single piece of semiconductor material (usually silicon). Contain millions or billions of transistors, resistors, capacitors, and diodes.
    - **Applications:** Processors in computers, memory chips, microcontrollers in various devices.

13.4 Summary

- Semiconductors have conductivity between conductors and insulators.
- Conduction occurs via both electrons and holes.
- Doping creates n-type (electron majority) and p-type (hole majority) semiconductors.
- Diodes are one-way current valves; transistors are amplifiers/switches.
- Integrated circuits are the foundation of modern electronics.