

Class Note: B.Sc. Chemistry (Hons.)

Atomic Structure

Title: De Broglie Equation of Matter Waves

Introduction: In the early 20th century, the wave-particle duality of matter was established, challenging the classical understanding of particles as purely localized entities. The pioneering work of Louis de Broglie proposed that particles, such as electrons, possess both wave-like and particle-like properties. He postulated that all matter, regardless of its mass, exhibits wave characteristics, and this wave nature can be described using a fundamental equation known as the De Broglie equation. This lecture note explores the De Broglie equation and its significance in understanding the behavior of matter waves.

1. Wave-Particle Duality:

- In classical physics, particles were considered to be point-like entities with definite positions and momenta.
- In the early 20th century, experiments, such as the double-slit experiment and photoelectric effect, revealed that particles could exhibit wave-like properties.
- The wave-particle duality suggests that all entities, including matter particles, possess both particle-like and wave-like characteristics.

2. De Broglie Hypothesis:

- In 1924, Louis de Broglie proposed his hypothesis that matter particles, such as electrons or atoms, have associated wave properties.
- De Broglie suggested that the wavelength (λ) associated with a particle is inversely proportional to its momentum (p): $\lambda = h/p$.
- Here, λ represents the wavelength, h is the Planck constant ($h = 6.626 \times 10^{-34}$ J·s), and p is the momentum of the particle.

3. Mathematical Formulation:

- The De Broglie equation relates the wavelength of a matter wave to the momentum of the particle.
- For a particle with mass m and velocity v , the momentum (p) is given by $p = mv$.
- Substituting this into the De Broglie hypothesis, we obtain the De Broglie equation: $\lambda = h/mv$.

4. Implications of the De Broglie Equation:

- The De Broglie equation provides a quantitative relationship between the wavelength and momentum of matter waves.

- It suggests that particles with higher momentum have shorter wavelengths and particles with lower momentum have longer wavelengths.
- The wave nature of matter becomes more pronounced for particles with smaller masses, such as electrons.
- The De Broglie wavelength is significant in various phenomena, including electron diffraction, atomic and molecular spectroscopy, and wave-particle interference experiments.

5. Experimental Verification:

- The wave nature of matter predicted by the De Broglie equation has been experimentally confirmed in numerous experiments.
- Electron diffraction experiments, similar to the famous double-slit experiment, have demonstrated the interference patterns produced by electron waves.
- The diffraction patterns observed in experiments using electrons, neutrons, and even large molecules provide evidence for the validity of the De Broglie hypothesis.

Conclusion: The De Broglie equation is a fundamental equation describing matter's wave-particle duality. It provides a mathematical relationship between the wavelength and momentum of matter waves, highlighting the wave-like nature of particles. The experimental confirmation of the De Broglie hypothesis has revolutionized our understanding of the microscopic world and paved the way for the development of quantum mechanics. The De Broglie equation remains a cornerstone in modern physics, enabling us to explore and comprehend the behavior of matter waves.

Difference between de Broglie wave and electromagnetic wave:

De Broglie waves and electromagnetic waves are two distinct types of waves that arise in different physical contexts. Here are some key differences between De Broglie waves and electromagnetic waves:

1. Nature of Wave:

- **De Broglie Waves:** De Broglie waves are matter waves associated with particles, such as electrons, atoms, or larger objects. They arise due to the wave-particle duality, suggesting that particles can exhibit wave-like properties.
- **Electromagnetic Waves:** Electromagnetic waves are waves composed of oscillating electric and magnetic fields. They do not require the presence of matter particles and can propagate through vacuum.

2. Particle vs. Field:

- **De Broglie Waves:** De Broglie waves are associated with the motion of particles. They describe the wave-like behavior and characteristics of matter particles.

- **Electromagnetic Waves:** Electromagnetic waves are associated with the oscillation and interaction of electric and magnetic fields. They do not correspond to the motion of particles but rather the propagation of energy through space.

3. Wavelength and Frequency:

- **De Broglie Waves:** The wavelength of a De Broglie wave is determined by the momentum of the associated particle, as given by the De Broglie equation ($\lambda = h/p$). The frequency of a De Broglie wave is not explicitly defined.
- **Electromagnetic Waves:** Electromagnetic waves have both wavelength (λ) and frequency (f). They are related by the speed of light (c), according to the equation $c = \lambda f$.

4. Interaction and Propagation:

- **De Broglie Waves:** De Broglie waves are typically localized around the particle they are associated with. They are involved in phenomena such as diffraction and interference, suggesting a wave-like propagation and interaction of matter.
- **Electromagnetic Waves:** Electromagnetic waves can propagate over long distances through space, exhibiting properties such as reflection, refraction, and interference. They interact with charged particles and matter through the electric and magnetic fields.

5. Experimental Observations:

- **De Broglie Waves:** The wave nature of particles described by De Broglie Waves has been experimentally confirmed in diffraction experiments with electrons, neutrons, and even larger molecules. These experiments reveal interference patterns similar to those observed for light waves.
- **Electromagnetic Waves:** Electromagnetic waves have been extensively studied and observed in various phenomena, including optics, radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, and gamma rays.

In summary, De Broglie and electromagnetic waves represent different waves arising in distinct physical contexts. De Broglie waves are matter waves associated with the wave-particle duality, while electromagnetic waves are waves resulting from the oscillation of electric and magnetic fields. They differ in terms of their nature, associated particles or fields, wavelength and frequency characteristics, propagation behavior, and experimental observations.

Relation Between de Broglie's theory and Bohr's Theory :

The De Broglie wave theory and Bohr's theory of atomic structure are two important concepts in the field of quantum mechanics, and they are interconnected in understanding the behavior of electrons in atoms. Here are the key relations between De Broglie wave theory and Bohr's theory of atomic structure:

1. Wave-Particle Duality:

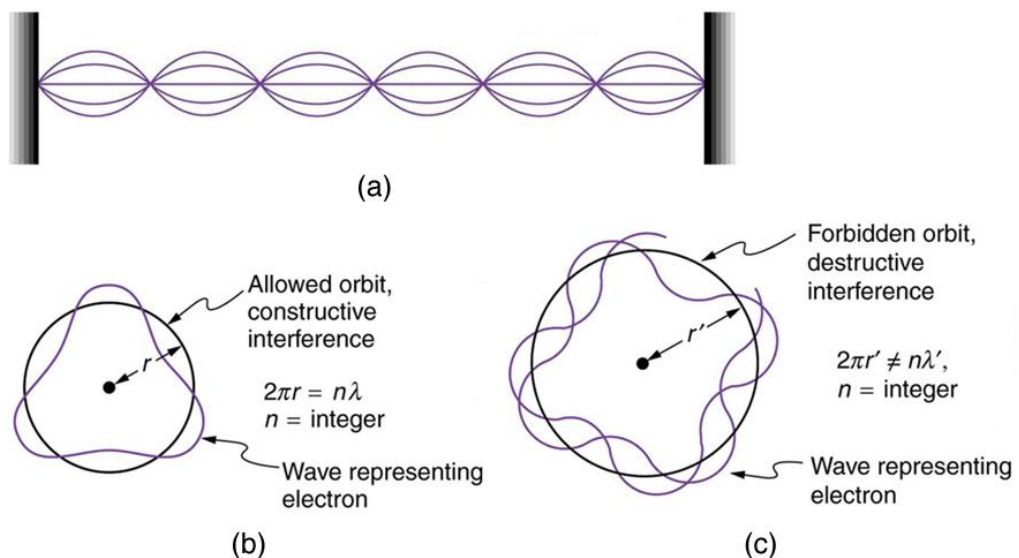
- De Broglie Wave Theory: De Broglie wave theory proposes that particles like electrons have wave-like properties. It suggests that particles can exhibit both particle-like and wave-like characteristics.
- Bohr's Theory of Atomic Structure: Bohr's theory postulates that electrons in atoms can exist only in certain discrete energy levels or orbits. This implies that electrons possess both particle-like behaviors (localized in orbits) and wave-like behavior (described by their associated wavefunctions).

2. Electron Orbits and De Broglie Waves:

- Bohr's Theory: According to Bohr's theory, electrons in atoms can occupy only specific quantized orbits with well-defined energy levels. Electrons transition between these orbits by emitting or absorbing energy in discrete packets or quanta.
- De Broglie Wave Theory: De Broglie wave theory suggests that electrons moving in these quantized orbits can be described by matter waves. The electrons' motion around the nucleus is associated with a corresponding De Broglie wavelength, which depends on the electron's momentum and energy.

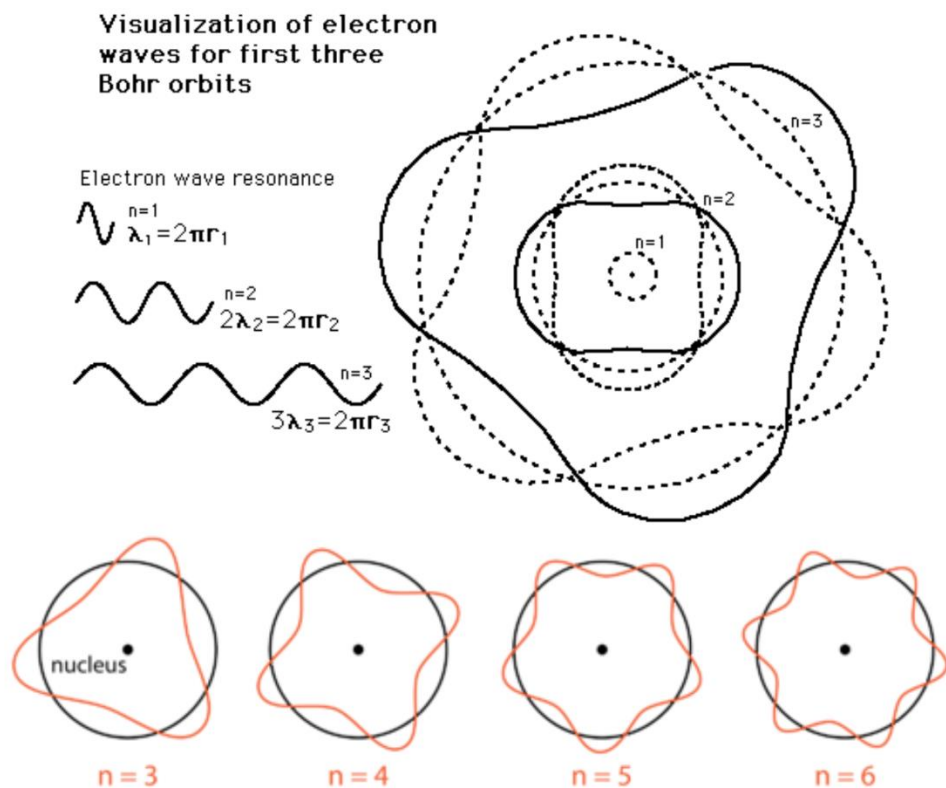
3. Quantization of Electron Momentum:

- De Broglie Wave Theory: De Broglie wave theory establishes that the wavelength (λ) associated with a particle is inversely proportional to its momentum (p): $\lambda = h/p$, where h is the Planck constant. This implies that the momentum of a particle is quantized in discrete values.
- Bohr's Theory: Bohr's theory incorporates the concept of quantized momentum indirectly through its quantized energy levels. The electron's energy is related to its momentum, and only specific energy levels are allowed in the atom.



4. Explanation of Atomic Spectra:

- **Bohr's Theory:** Bohr's theory successfully explains the discrete emission and absorption spectra observed in atoms. The allowed transitions between energy levels correspond to the emission or absorption of photons with specific frequencies.
- **De Broglie Wave Theory:** The De Broglie wave theory provides an underlying wave-like description of the electron's motion during these transitions. The emission or absorption of photons is associated with changes in the electron's orbital motion and its associated De Broglie wave.
- Bohr's Theory and De Broglie Wave Theory provide complementary descriptions of atomic behavior. Bohr's theory focuses on the quantization of energy levels and the transitions between them, while De Broglie's wave theory emphasizes the wave-like nature of particles, including electrons.



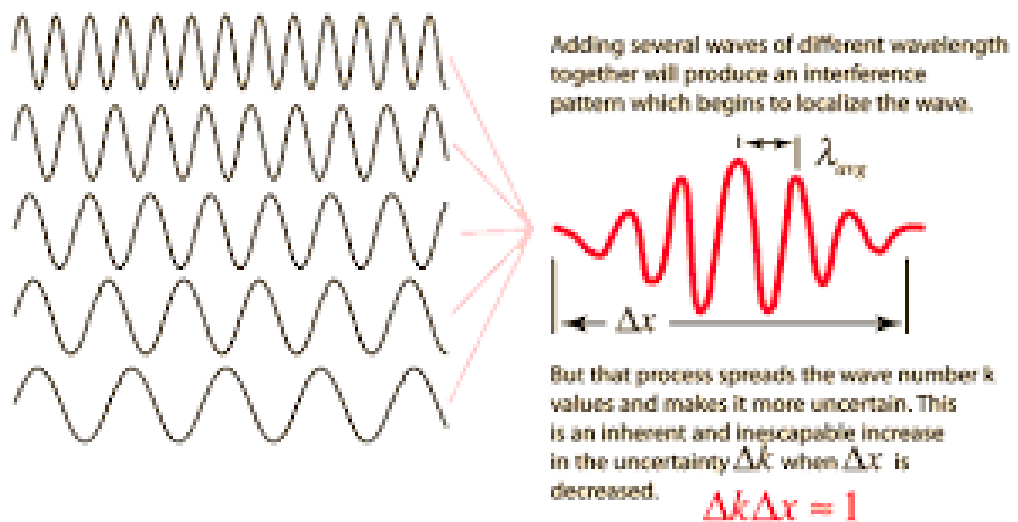
In summary, De Broglie's wave theory and Bohr's theory of atomic structure are interrelated concepts in quantum mechanics. De Broglie wave theory provides a wave-like description of electrons in atoms, while Bohr's theory incorporates this wave-particle duality to explain the quantization of energy levels and the discrete behavior of atomic spectra. Together, these theories form the foundation of our understanding of atomic structure and the behavior of electrons within atoms.

Concept of a wave packet in determining the position and momenta of an electron in an atom:

The concept of a wave packet is a fundamental aspect of quantum mechanics and is particularly relevant when considering the behavior of electrons. A wave packet represents a localized and coherent group of waves that describes the spatial and temporal distribution of a particle's wave function. In the case of electrons, wave packets are used to describe the probabilistic behavior and motion of these particles. Here are the key points about the concept of a wave packet in an electron:

1. Superposition of Waves:

- According to quantum mechanics, the wave function of a particle, such as an electron, can be described as a superposition of different waves with various wavelengths and momenta.
- Each component wave contributes to the overall behavior of the particle, and the resulting wave function represents the probability distribution of finding the particle at different positions.



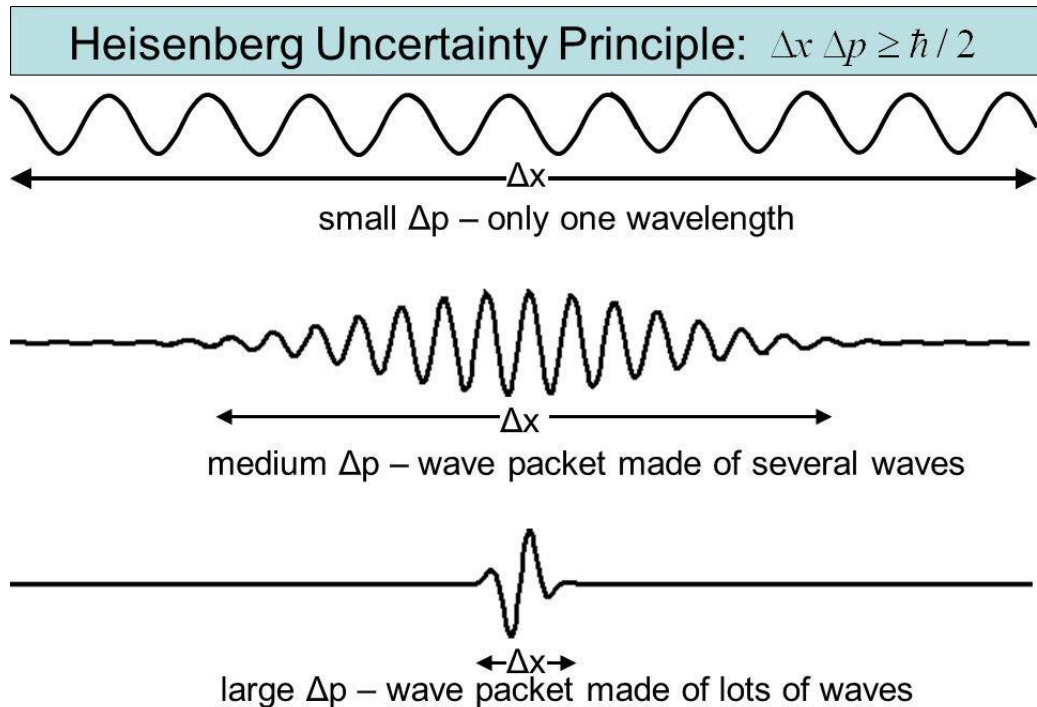
2. Localization and Dispersion:

- A wave packet represents a localized region of the particle's wave function where the probability of finding the particle is significant.
- Unlike a plane wave, which extends infinitely in space, a wave packet has a finite spatial extent, implying a more localized position of the particle.
- The width or spread of the wave packet determines the degree of localization or dispersion of the particle's position.

3. Uncertainty Principle:

- The concept of a wave packet is closely related to the Heisenberg uncertainty principle, which states that there is an inherent trade-off between the precision of measuring a particle's position and its momentum.
- A more localized wave packet (i.e., a narrower spatial distribution) corresponds to a larger spread in momentum values, and vice versa.

- This uncertainty in position and momentum arises from the wave-like nature of particles and is a fundamental feature of quantum mechanics.



4. Evolution in Time:

- The wave packet of an electron evolves in time according to the Schrödinger equation, which governs the dynamics of quantum systems.
- As the wave packet propagates, it undergoes dispersion and spreads out, resulting in a broadening of its spatial distribution.
- The rate of dispersion depends on various factors, including the initial conditions of the wave packet and the potential it interacts with.

5. Wave Packet Interference:

- Wave packets can exhibit interference phenomena, similar to other types of waves.
- When two or more wave packets with different momenta or wavelengths overlap, their superposition can lead to constructive or destructive interference patterns.
- This interference behavior is essential in understanding phenomena such as electron diffraction and interference experiments, where the wave-like nature of electrons is observed.

In summary, a wave packet in an electron represents a localized and coherent group of waves that describes the probability distribution of finding the electron at different positions. It takes into account the superposition of waves, the uncertainty principle, and the temporal evolution of the particle's wave function. Wave packets provide a more realistic and nuanced description

of the probabilistic behavior and motion of electrons, allowing us to understand their wave-like nature and phenomena associated with interference and diffraction.