Chapter 27 & 29

Wave Properties, Waves and Particles

27.1 The Principle of Linear Superposition—Constructive Interference

When two or more light waves pass through a given point, their electric fields combine according to the principle of superposition.

The waves emitted by the sources start out in phase and arrive at point P in phase, leading to constructive interference.

\[ \ell_2 - \ell_1 = m\lambda \quad m = 0, 1, 2, 3, \ldots \]

27.1 The Principle of Linear Superposition—Destructive Interference

The waves emitted by the sources start out in phase and arrive at point P out of phase, leading to destructive interference.

\[ \ell_2 - \ell_1 = (m + \frac{1}{2})\lambda \quad m = 0, 1, 2, 3, \ldots \]

27.2 Young's Double Slit Experiment

In Young's experiment, two slits act as coherent sources of light.

Light waves from these slits interfere constructively and destructively on the screen.

The waves coming from the slits interfere constructively or destructively, depending on the difference in distances between the slits and the screen.
27.2 Young’s Double Slit Experiment

**Example 1 Young’s Double-Slit Experiment**

Red light (664 nm) is used in Young’s experiment with slits separated by 0.000120 m. The screen is located a distance 2.75 m from the slits. Find the distance on the screen between the central bright fringe and the third-order bright fringe.

\[
\theta = \sin \left( m \frac{\lambda}{d} \right) = \sin \left( \frac{3 \times 664 \times 10^{-9} \text{ m}}{1.20 \times 10^{-4} \text{ m}} \right) = 0.951^\circ
\]

\[
y = L \tan \theta = (2.75 \text{ m}) \tan(0.951^\circ) = 0.0456 \text{ m}
\]

27.5 Diffraction

Diffraction is the bending of waves around obstacles or the edges of an opening.

**Huygens’ principle**

Every point on a wave front acts as a source of tiny wavelets that move forward with the same speed as the wave; the wave front at a latter instant is the surface that is tangent to the wavelets.
The extent of the diffraction increases as the ratio of the wavelength to the width of the opening increases.

These drawings show how destructive interference leads to the first dark fringe on either side of the central bright fringe.

Dark fringes for single slit diffraction: 
\[ \sin \theta = m \frac{\lambda}{W} \quad m = 1, 2, 3, \ldots \]

Conceptual Example 8 What You See is Not What You Get

The French postimpressionist artist Georges Seurat developed a technique of painting in which dots of color are placed close together on the canvas. From sufficiently far away the individual dots are not distinguishable, and the images in the picture take on a more normal appearance.

Why does the camera resolve the dots, while his eyes do not?
27.7 The Diffraction Grating

An arrangement consisting of a large number of closely spaced, parallel slits is called a diffraction grating.

The bright fringes produced by a diffraction grating are much narrower than those produced by a double slit.

Principal maxima of a diffraction grating

\[ \sin \theta = \frac{m}{d} \]

where \( m \) is the order of the maximum, \( d \) is the distance between slits.

29.1 Wave Particle Duality

Wave-particle duality: Waves can exhibit particle-like characteristics, and particles can exhibit wave-like characteristics.

Can a beam of electrons passing through a double slit produce dark and bright fringes too?

If electrons only exhibit particle-like characteristics, only shape of the slits would be seen on the screen.

Can particles exhibit wave-like characteristics?

Can waves exhibit particle-like characteristics??

When a beam of electrons is used in a Young’s double slit experiment, a fringe pattern occurs, indicating interference effects.

Wave-particle duality: Waves can exhibit particle-like characteristics, and particles can exhibit wave-like characteristics.

29.2 Blackbody Radiation and Planck’s Constant

Max Planck calculated the blackbody radiation curves. Assumed that each energy of each atomic oscillator can only have discrete values. Electromagnetic energy is quantized. It has values in multiples of \( hf \):

\[ E = nhf, 2hf, 3hf, \ldots \]

The energy of EM wave is continuous but this cannot explain the radiation produced by a black body.

All bodies, no matter how hot or cold, continuously radiate electromagnetic waves. A black body is a perfect absorber & emitter.

We see glow of hot objects because the emitted EM wave is in the visible region. Human body (T=310K) emit EM wave.

The energy lost by oscillators is energy carried by electromagnetic wave.

\[ E = hf \]

\[ p = \frac{h}{\lambda} \]

Planck’s constant \( h = 6.626 \times 10^{-34} \text{ J s} \)

\[ E = n hf, 2hf, 3hf, \ldots \]

\[ E = n hf, \]

where \( n = 0, 1, 2, 3, \ldots \)

29.3 Photons and the Photoelectric Effect

Particles have energy \( E \) which is continuous and have momentum \( p = mv \)

Electromagnetic waves are composed of particle-like entities or energy packets called photons.

\[ E = hf \]

\[ p = \frac{h}{\lambda} \]
Experimental evidence shows that light consists of photons comes from a phenomenon called the photoelectric effect. When light shines on a metal, a photon can give up its energy to an electron in that metal. The minimum energy required to remove the least strongly held electrons is called the work function.

\[ hf = KE_{\text{max}} + W_a \]

\[ f_a = \frac{W_a}{h} = \frac{(4.73 \text{ eV})\sqrt{1.60 \times 10^{-19} / \text{J/eV}}}{6.626 \times 10^{-34} \text{ J/s}} = 1.14 \times 10^{15} \text{ Hz} \]

Photoelectric theory: Einstein explained the photoelectric effect by asserting that light of frequency \( f \) is made up of packets of energy called photons. Each photon has energy \( E = hf \).

Increase in intensity only increase the number of photons and hence the number of photoelectrons ejected if the frequency of incident light exceeds the threshold frequency.
29.4 The Momentum of a Photon and the Compton Effect

Conceptual Example 4 Solar Sails and the Propulsion of Spaceships

One propulsion method that is currently being studied for interstellar travel uses a large sail. The intent is that sunlight striking the sail creates a force that pushes the ship away from the sun, much as wind propels a sailboat. Does such a design have any hope of working and, if so, should the surface facing the sun be shiny like a mirror or black, in order to produce the greatest force?

29.4 The Momentum of a Photon and the Compton Effect

Momentum and energy are conserved in the collision.

\[ \lambda' = \frac{h}{mc} (1 - \cos \theta) \]

29.5 The de Broglie Wavelength and the Wave Nature of Matter

All matter exhibits wave characteristics, interference & diffraction (Davisson & Germer). Hence can associate wavelength to material matter.

The wavelength of a particle is given by the same relation that applies to a photon:

\[ \lambda = \frac{h}{p} \]

de Broglie wavelength

Only particles of mass equivalent to an electron or proton will have \( \lambda \) that are observable.

Neutron diffraction is a manifestation of the wave-like properties of particles.

29.5 The de Broglie Wavelength and the Wave Nature of Matter

Example 5 The de Broglie Wavelength of an Electron and a Baseball

Determine the de Broglie wavelength of (a) an electron moving at a speed of \( 6.0 \times 10^6 \) m/s and (b) a baseball (mass = 0.15 kg) moving at a speed of 13 m/s.

\[ \lambda = \frac{h}{p} = \frac{[6.63 \times 10^{-34} \text{J} \cdot \text{s}]}{[9.1 \times 10^{-31} \text{kg} \times 6.0 \times 10^6 \text{m/s}]} = 1.2 \times 10^{-10} \text{m} \]

\[ \lambda = \frac{h}{p} = \frac{[6.63 \times 10^{-34} \text{J} \cdot \text{s}]}{[0.15 \text{kg} \times 13 \text{m/s}]} = 3.3 \times 10^{-34} \text{m} \]

Particles are waves of probability.

<table>
<thead>
<tr>
<th>Concepts</th>
<th>Particle</th>
<th>Photon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>( E = KE + PE ) continuous</td>
<td>( E = hf ) quantized</td>
</tr>
<tr>
<td>Momentum</td>
<td>( p = mv )</td>
<td>( p = h/\lambda )</td>
</tr>
<tr>
<td>Wavelength</td>
<td>( \lambda = h/p )</td>
<td>( \lambda = \text{off} )</td>
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Characteristic interference fringes only observable after a large number of electrons have struck the screen.
29.6 The Heisenberg Uncertainty Principle

Wave nature of electrons

Diffraction pattern of dark and bright fringes after sufficient number of electrons pass through a single slit

Location of first dark fringe

\[ \sin \theta = \frac{\Delta y}{W} \]

But \( \tan \theta = \frac{\Delta y}{\lambda} \)

For small \( \theta \), \( \sin \theta \approx \tan \theta \)

Then

\[ \frac{\Delta y}{W} = \frac{\Delta p_x}{p_x} \]

But electrons at the slit can pass thru anywhere within slit width \( W \). Then

\[ \frac{\Delta y}{\lambda} = \frac{\Delta p_x}{h/\lambda} \]

And \( \Delta p_y \Delta y \approx h \)

29.6 The Heisenberg Uncertainty Principle

THE HEISENBERG UNCERTAINTY PRINCIPLE

Limits (imposed by nature) on specifying simultaneously the accuracy in position and momentum of a particle

\[ (\Delta p_y \Delta y) \geq \frac{\hbar}{4\pi} \]

Uncertainty in the energy of a particle when the particle is in a certain state

Energy and time

Uncertainty in the energy of a certain state of a particle and the time interval of the particle in that state

\[ (\Delta E \Delta t) \geq \frac{\hbar}{4\pi} \]

Conceptual Example 7 What if Planck's Constant Were Large?

A bullet leaving the barrel of a gun is analogous to an electron passing through the single slit. With this analogy in mind, what would hunting be like if Planck's constant has a relatively large value? \( h = 6.6 \times 10^{-34} \) J.s