

# Topic 22: Wave-Particle Duality

## Advanced Placement Physics

---

Dr. Timothy Leung

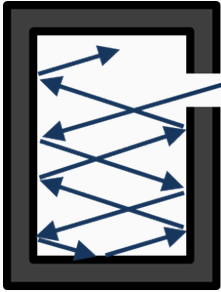
April 2020

Olympiads School  
Toronto, Ontario, Canada

*Anyone who is not shocked by quantum theory has not understood it.*

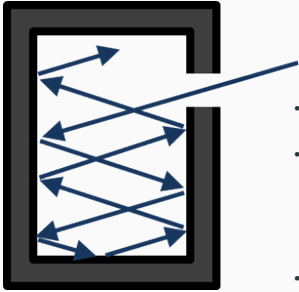
- Niels Bohr

# Blackbody Radiation



- The concept was coined by Gustav Kirchhoff in 1860
- An idealized object that absorbs all incident EM radiation, regardless of frequency or angle of incidence
- Think of a box (“cavity”) with a mirror inside, and a hole where light (EM radiation) is allowed in
- Some of the light reflects inside the cavity, and some gets absorbed by the blackbody
- Eventually all the light inside the cavity is absorbed

# Blackbody Radiation



- The object is in thermodynamic equilibrium; all of the absorbed energy is then immediately radiated back as EM radiation
- The spectral distribution depends on temperature
- A blackbody at room temperature appears black, as most of the radiative energy is infrared and cannot be perceived by the human eye
- Thermal radiation spontaneously emitted by many ordinary objects can be approximated as blackbody radiation

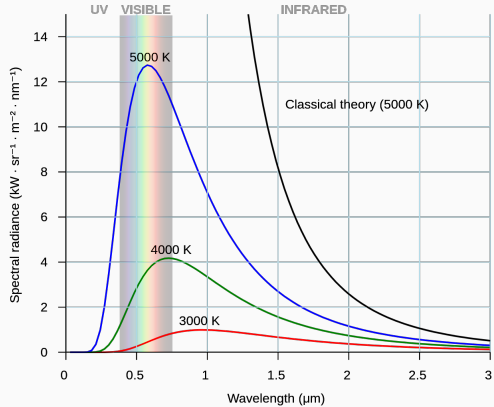
# Raleigh-Jeans Law and the Ultraviolet Catastrophe

- Based on classical thermodynamics

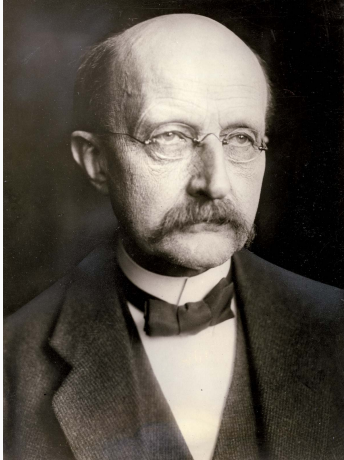
$$P(\lambda, T) = 8\pi kT\lambda^{-4}$$

$T$ =temperature,  $\lambda$ =wavelength,  $k$ =Boltzmann's constant

- Agrees with experimental results for long wavelengths
- But disagrees violently for short wavelengths:
  - Shorter wavelengths (e.g. ultraviolet waves) seem to have infinite intensity
  - Known as “**Ultraviolet catastrophe**”



# Quantization of Energy



Max Planck

- Made a strange modification in the classical calculations
- Derived a function of  $P(\lambda, T)$  that agreed with experimental data for all wavelengths
- First found an empirical function to fit the data
- Then searched for a way to modify the usual calculations
- Energy emitted by blackbody not continuous but discrete
- When energy is emitted from the harmonic oscillator, it drops to the next lower energy level

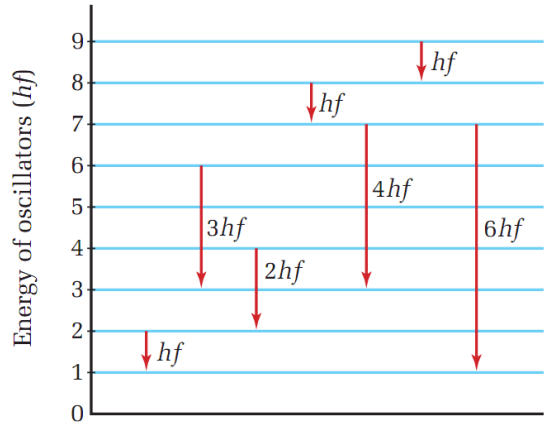
# Quantization of Energy

$$E = hf$$

where

- $h = 6.626 \times 10^{-34}$  Js is “Planck’s constant”, and
- $f$  is the frequency

When a blackbody emits radiation, it has to drop down one or more levels and emit a unit of energy equal to the difference between the allowed energy levels of the oscillator.



# Planck's Law

As for his formula, it's called **Planck's law**:

$$P(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$



# Maxwell's Equations in a Vacuum

$$\nabla \cdot \mathbf{E} = 0$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

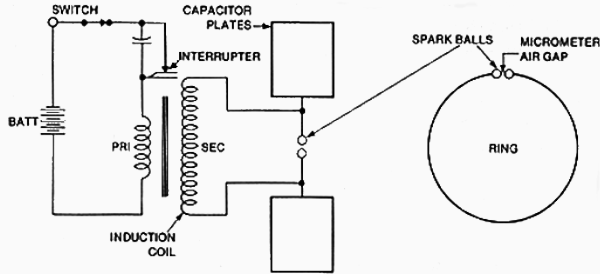
$$\nabla \times \mathbf{B} = \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

Disturbances in  $\mathbf{E}$  and  $\mathbf{B}$  travel as an “electromagnetic wave”, with a speed:

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}} = 299\,792\,458 \text{ m/s}$$

# The Spark Gap Experiment

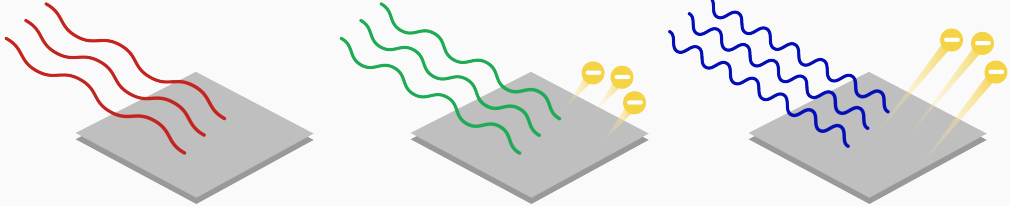
To prove that light is an EM wave, German physicist Heinrich Hertz devised a “spark gap experiment” to generate frequencies in the range of  $10^{14}$  Hz



- Also showed that light has the same wavelengths as predicted by Maxwell's equations
- Discovered **photoelectric effect** that was caused by ultraviolet radiation
- Physicist who repeated his experiments did not have an explanation

# Photoelectric Effect

When electromagnetic waves (e.g. light) hits certain metals, electrons are knocked off the surface.



When observing this **photoelectric effect**, physicists discovered that:

- Increasing intensity of light knocked off more electrons, but doesn't change the maximum kinetic energy of the electrons, but
- Changing the frequency of the light did change  $K$  though, although
- Below a certain frequency, *no* electrons were emitted

# The Photon: Packets of Energy

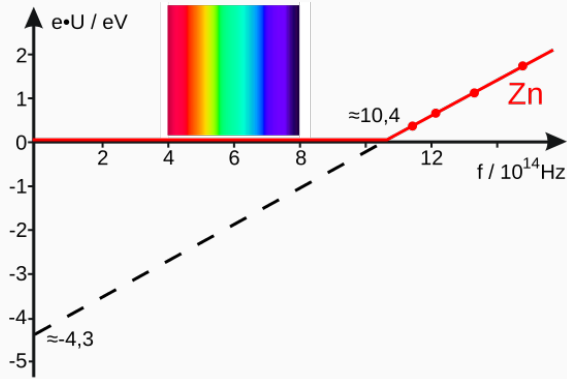
In the 1905 paper *On a Heuristic Viewpoint Concerning the Production and Transformation of Light*, Einstein argued that light is not continuous wave, but a collection of discrete energy packets (photons), each with energy  $E = hf$

$$K_{\max} = \begin{cases} hf - \varphi & \text{if } hf > \varphi \\ 0 & \text{otherwise} \end{cases}$$

| Quantity                   | Symbol     | SI Unit |
|----------------------------|------------|---------|
| Maximum kinetic energy of  | $K_{\max}$ | J       |
| Planck's constant          | $h$        | J s     |
| Frequency of the EM wave   | $f$        | Hz      |
| Work function of the metal | $\varphi$  | J       |

Einstein may have been alerted to the fact that the blackbody radiation curve resembles the distribution of energies in a gas

# Work Function



**Work function** the minimum energy required to remove an electron from a solid to a point immediately outside the solid surface. The minimum frequency at which electrons will be ejected is called the **threshold frequency**.

Slope is  $h$  no matter what metal it is.

# Work Functions of Different Materials

The work function  $\phi$  depends on the metal. They are generally presented in electron volts.

| Metal     | Work function (eV) |
|-----------|--------------------|
| aluminum  | 4.28               |
| calcium   | 2.87               |
| cesium    | 2.14               |
| copper    | 4.65               |
| iron      | 4.50               |
| lead      | 4.25               |
| lithium   | 2.90               |
| nickel    | 5.15               |
| platinum  | 5.65               |
| potassium | 2.30               |
| tin       | 4.42               |
| tungsten  | 4.55               |
| zinc      | 4.33               |

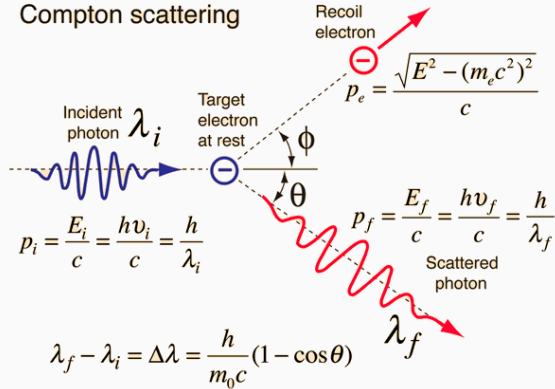
# Compton Scattering

American physicist Arthur Holly Compton studied x-ray scattering by free electrons

- Classical theory cannot account for the scattering behaviour
- Frequency shift only depends on scattering angle
- Prediction possible if treating the x-ray as photons with momentum, just like a particle. Compton used Einstein's invariant and applied to a massless particle:

$$p = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda}$$

# Compton Scattering



If we treat the x-ray as a photon with momentum  $p = h/\lambda$  then we can use Newton's laws of motion to predict both the recoil electron and scattered x-ray!



# Momentum of a Photon

The momentum of a photon is proportional to Planck's constant and inversely proportional to its wavelength.

$$p = \frac{h}{\lambda}$$

| Quantity          | Symbol    | SI Unit |
|-------------------|-----------|---------|
| Momentum          | $p$       | kg m/s  |
| Planck's constant | $h$       | J s     |
| Wavelength        | $\lambda$ | m       |

This is a very odd expression, which treats photon both as a particle (with momentum) and a wave (with a wavelength  $\lambda$ ).

# Matter Waves

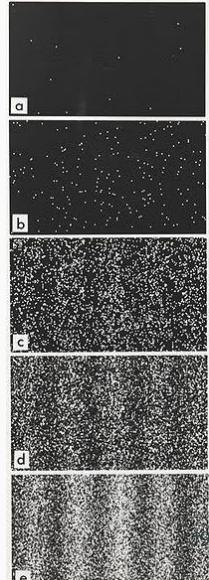
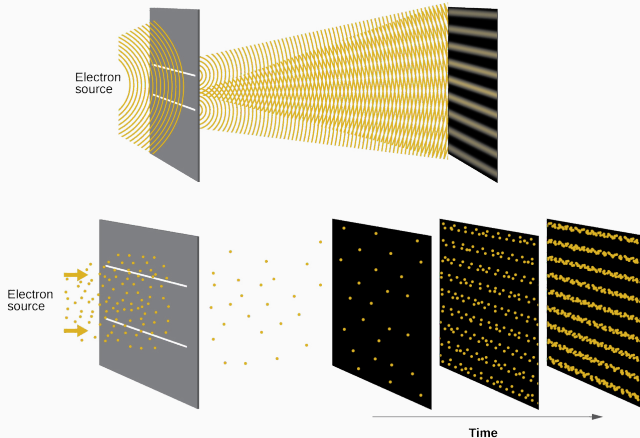
If electromagnetic waves are really particles of energy, then are particles (e.g. electrons) a wave of some sort?

- The De Broglie hypothesis in 1924: a particle can also have a wavelength
- Confirmed accidentally by the Davisson-Germer Experiment in 1927 (beam of electron scattering on nickel crystal surface)

If a particle is also a wave, what *kind* of a wave is it then?

# Electron Interference

If I perform a double-slit experiment with a beam of electrons, will I get an interference pattern?



# De Broglie Wavelength

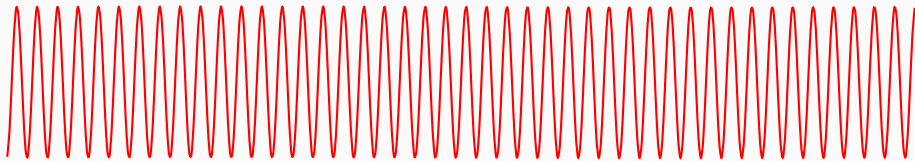
If matter is also a wave, then what would be its wavelength? Solving the momentum equation for  $\lambda$ :

$$p = \frac{h}{\lambda} \rightarrow \lambda = \frac{h}{p} \rightarrow \boxed{\lambda = \frac{h}{mv}}$$

| Quantity                 | Symbol    | SI Unit |
|--------------------------|-----------|---------|
| Wavelength of a particle | $\lambda$ | m       |
| Planck's constant        | $h$       | J s     |
| Mass                     | $m$       | kg      |
| Velocity                 | $v$       | m/s     |

# Uncertainty Principle

If a particle is a wave, how do you tell where it is?

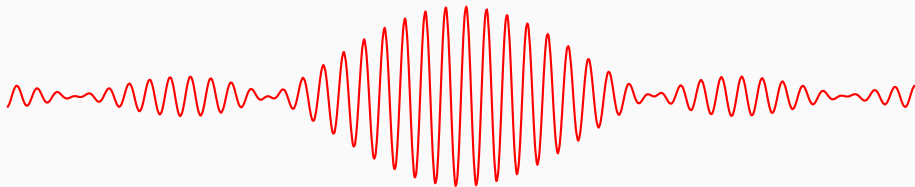


$$\cos(400x)$$

- This wave/particle has a single wavelength  $\lambda$  (therefore momentum  $p$ )
- Has no distinguishing features that can tell you its location  $x$
- When we have precise knowledge of the particle wave's momentum (i.e. its wavelength), then we have no idea where it is.

# Uncertainty Principle

However, if a particle is defined as waves with small variations of wavelengths, when we add up the different waves together, we begin to see a **wave packet**:



$$\cos(380x) + \cos(382.5x) + \cdots + \cos(400x) + \cos(402.5x) + \cdots + \cos(420x)$$

Bottom line: In order to know more about the location of the particle, we *must* lose information about its momentum.

# Heisenberg Uncertainty Principle

Because of the wave properties of particles, you can never be completely certain of the relationship between an object's momentum  $p$  and position  $x$ :

$$\sigma_p \sigma_x \geq \frac{h}{4\pi}$$

| Quantity                | Symbol     | SI Unit |
|-------------------------|------------|---------|
| Uncertainty in momentum | $\sigma_p$ | kg m/s  |
| Uncertainty in position | $\sigma_x$ | m       |
| Planck's constant       | $h$        | J s     |

The more you know about an object's position, the less you know about its momentum, and vice versa.

# Bohr Atomic Model

The “orbital” model of electrons does not work, because as the electron orbits (accelerates around) the nucleus, it radiates electromagnetic radiation, and therefore lose energy. The orbit will eventually collapse.

Bohr postulated that electron can move in certain “non-radiating” orbits, corresponding to energy levels:

$$E_n = -\frac{k^2 e^4 m Z^2}{2\hbar^2 n^2}$$

From the wave-particle duality perspective, the “orbits” correspond more to a standing wave around the nucleus (a standing wave does not lose energy)



# Bohr Atomic Model

$$E_n = -\frac{k^2 e^4 m Z^2}{2\hbar^2 n^2}$$

| Quantity                  | Symbol  | SI Unit                   |
|---------------------------|---------|---------------------------|
| Energy at level $n$       | $E_n$   | J                         |
| Coulomb's constant        | $k$     | $\text{N m}^2/\text{C}^2$ |
| Elementary charge         | $e$     | C                         |
| Atomic mass               | $m$     | kg                        |
| Reduced Planck's constant | $\hbar$ | J s (joule seconds)       |
| Atomic number             | $Z$     | integer; no units         |
| Energy level              | $n$     | integer; no units         |

# Bohr Atomic Model

Successful in describing the behaviour of the hydrogen atom—but fails for heavier atoms—although it still relies on

- Coulomb forces between electrons and protons (classical)
- Centripetal forces (classical)
- Quantization of energy (new physics!)

De Broglie's hypothesis gives us a glimpse of what Bohr is missing

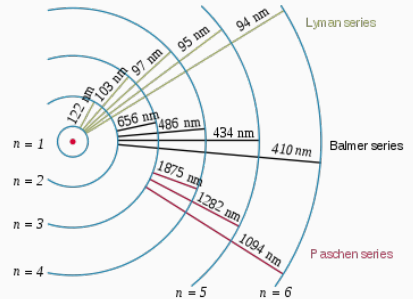
- The “orbits” correspond to a standing wave around the nucleus
- A standing wave does not lose energy

# Hydrogen Emission

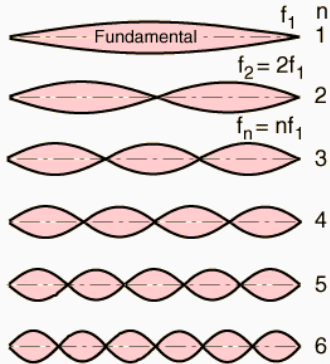
- Lyman series:
  - the EM emissions when the electrons drop from a higher energy state ( $E_n$ ) to the ground state  $n = 1$  (i.e.  $E_1$ )
  - The frequency is given by:

$$f = \frac{E_1 - E_n}{h}$$

- We can apply universal wave equation to get the wavelengths
- Balmer series–dropping to  $E_2$
- Paschen series–dropping to  $E_3$

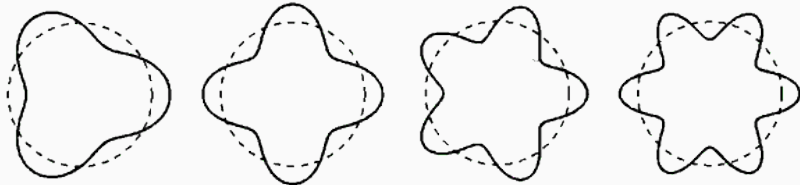


# Standing Wave on a String



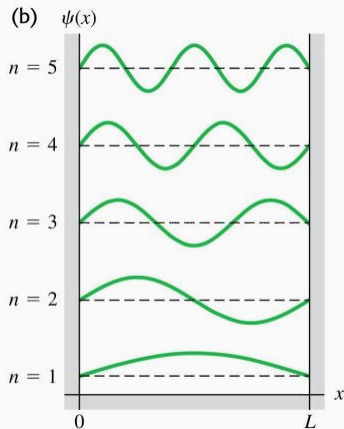
- We have studied standing waves in Grade 11
- If electron is to be in a “stable orbit” around a nucleus, it has to be in a standing wave pattern
- Otherwise, it will interfere with itself

# Circular Standing Wave



Electron resonance states  $n = 3, 4, 5, 6$

# Particle in a Box



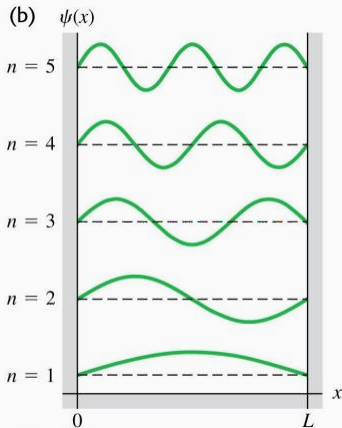
A particle in a 1D box has to behave like a standing wave. The resonance modes (frequencies where a stable standing wave exists) correspond to the wavelengths:

$$\lambda = \frac{2L}{n} \quad n = 1, 2, 3, 4, \dots$$

and the momentum of the particle is:

$$p = \frac{h}{\lambda} = \frac{nh}{2L}$$

# Particle in a Box



Kinetic energy of the particle can be expressed in terms of momentum:

$$K_n = \frac{1}{2}mv^2 = \frac{p^2}{2m} = \frac{n^2 h^2}{8mL^2}$$

If a particle is a standing wave, then kinetic energy of the particle can never be zero (as long as it is confined inside the box), therefore

- It cannot have zero velocity
- The lowest energy level ( $n = 1$ ) is called the **zero-point energy**

# Example

**Example 3:** A 0.150 kg billiard ball is confined to the pool table 1.42 m wide. How long (in seconds) will it take to travel from one side of the table to the other? (Use fundamental mode.)