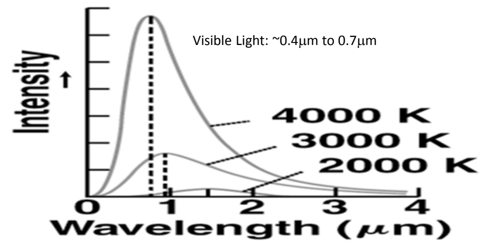
Blackbody Radiation

Hot objects glow (toaster coils, light bulbs, the sun).

As the temperature increases the color shifts from Red to Blue.

Blackbody Radiation Spectrum



Blackbody Radiation: First evidence for Q.M.

Max Planck found he could explain these curves if he assumed that electromagnetic energy was radiated in discrete chunks, rather than continuously.

The "quanta" of electromagnetic energy is called the photon.

Energy carried by a single photon is

Planck's constant: $h = 6.626 \times 10^{-34}$ Joule sec

Light Bulbs & Stove Checkpoints

A series of lights are colored red, yellow, and blue. Which of the following statements is true?

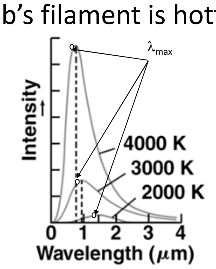
a. Red photons have the least energy; blue the most.
b. Yellow photons have the least energy; red the most.
c. Blue photons have the least energy; yellow the most.

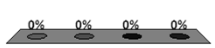
Which is hotter?

(1) stove burner glowing red
(2) stove burner glowing orange

Three light bulbs with identical filaments are manufactured with different colored glass envelopes: one is red, one is green, one is blue. When the bulbs are turned on, which bulb's filament is hottest?

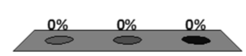
1. Red
2. Green
3. Blue
4. Same





A red and green laser are each rated at 2.5mW. Which one produces more photons/second?

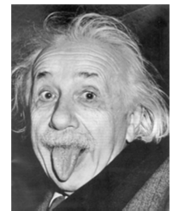
1. Red
2. Green
3. Same



Wien's Displacement Law

- To calculate the peak wavelength produced at any particular temperature, use Wien's Displacement Law:

For which work did Einstein receive the Nobel Prize?



1. Special Relativity $E = mc^2$
2. General Relativity Gravity bends Light
3. Photoelectric Effect Photons
4. Einstein didn't receive a Nobel prize.

Photoelectric Effect
Checkpoint

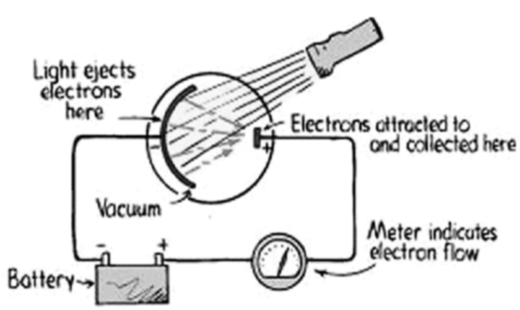
In the photoelectric effect, suppose that the intensity of light is increased, while the frequency is kept constant and above the threshold frequency f_0.
Which of the following increases?

a. Maximum KE of emitted electrons
b. Number of electrons emitted per second
c. Both of the above
d. None of the above

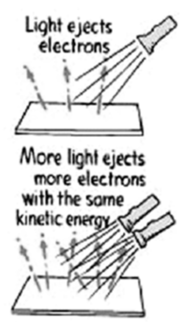
Photoelectric Effect

- Light shining on a metal can "knock" electrons out of atoms.
- Light must provide energy to overcome Coulomb attraction of electron to nucleus
- Light Intensity gives power/area (i.e. Watts/m^2)
  - Recall: Power = Energy/time (i.e. Joules/sec.)

Photoelectric Effect



Light Intensity



Threshold Frequency

- Glass is not transparent to ultraviolet light
- Light in visible region is lower frequency than ultraviolet

Difficulties With Wave Explanation

Photoelectric Effect Summary

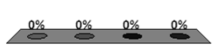
- Each metal has "Work Function" (W_0) which is the minimum energy needed to free electron from atom.
- Light comes in packets called Photons
  - E = h f — **h=6.626 x 10^{-34} Joule sec**
  - **h=4.136 x 10^{-15} eV sec**
- Maximum kinetic energy of released electrons
  - hf = KE + W_0

If hf for the light incident on a metal is equal to the work function, what will the kinetic energy of the ejected electron be?

1. the kinetic energy would be negative
2. the kinetic energy would be zero
3. the kinetic energy would be positive
4. no electrons would be released from the metal

If hf for the light incident on a metal is less than the work function, what will the kinetic energy of the ejected electron be?

1. the kinetic energy would be negative
2. the kinetic energy would be zero
3. the kinetic energy would be positive
4. no electrons would be released from the metal



Photoelectric: summary table

	Wave	Particle	Result
• Increase Intensity			
– Rate			
– KE			
• Increase Frequency			
– Rate			
– KE			

Light is composed of particles: photons

Is Light a Wave or a Particle?

- Wave
  - Electric and Magnetic fields act like waves
  - Superposition, Interference and Diffraction
- Particle
  - Photons
  - Collision with electrons in photo-electric effect

Both Particle and Wave !

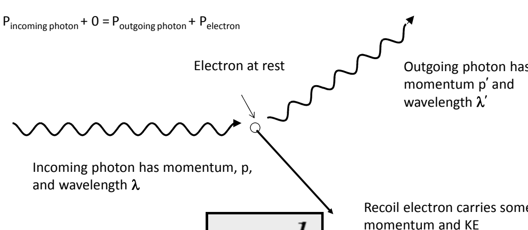
The approximate numbers of photons at each stage are
(a) 3 × 103, (b) 1.2 × 104, (c) 9.3 × 104, (d) 7.6 × 105, (e) 3.6 × 106, and (f) 2.8 × 107.

Are Electrons Particles or Waves?

Compton Scattering

This experiment really <u>shows</u> photon momentum!

$P_{\text{incoming photon}} + 0 = P_{\text{outgoing photon}} + P_{\text{electron}}$



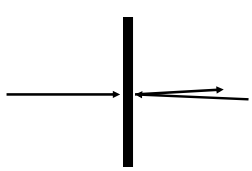
$$E = hf = \frac{hc}{\lambda}$$

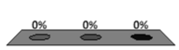
$$p = \frac{h}{\lambda}$$

Energy of a photon

Photons with equal energy and momentum hit both sides of a metal plate. The photon from the left sticks to the plate, the photon from the right bounces off the plate. What is the direction of the net impulse on the plate?

1. Left
2. Right
3. Zero





De Broglie Waves

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

De Broglie postulated that it holds for any object with momentum- an electron, a nucleus, an atom, a baseball,……

⇒ Explains why we can see interference and diffraction for material particles like electrons!!

Baseball Wavelength Checkpoint

Which baseball has the longest De Broglie wavelength?

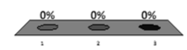
(1) A fastball (100 mph)

(2) A knuckleball (60 mph)

(3) Neither - only curveballs have a wavelength

A stone is dropped from the top of a building. What happens to the de Broglie wavelength of the stone as it falls?

1. It decreases.
2. It increases.
3. It stays the same.



Example

Comparison: Wavelength of *Photon* vs. *Electron*

Say you have a photon and an electron, both with 1 eV of energy. Find the de Broglie wavelength of each.

Equations are different - be careful!

- Photon with 1 eV energy:

$$E = \frac{hc}{\lambda} \Rightarrow \lambda = \frac{hc}{E} = \frac{1240 \text{ eV nm}}{1 \text{ eV}} = 1240 \text{ nm}$$

- Electron with 1 eV kinetic energy:

$$\text{KE} = \frac{1}{2}mv^2 \quad \text{and} \quad p = mv, \quad \text{so} \quad \text{KE} = \frac{p^2}{2m}$$

Solve for $p = \sqrt{2m(\text{K.E.})}$

Big difference!

$$\lambda = \frac{h}{\sqrt{2m(\text{KE})}} = \frac{hc}{\sqrt{2mc^2(\text{KE})}} = \frac{1240 \text{ eV nm}}{\sqrt{2(511{,}000 \text{ eV})(1 \text{ eV})}} = 1.23nm$$

Photon & Electron Checkpoints

Photon A has twice as much momentum as Photon B. Compare their energies.

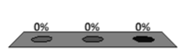
- $E_A = E_B$
- $E_A = 2\ E_B$
- $E_A = 4\ E_B$

Electron A has twice as much momentum as Electron B. Compare their energies.

- $E_A = E_B$
- $E_A = 2\ E_B$
- $E_A = 4\ E_B$

Compare the wavelength of a bowling ball with the wavelength of a golf ball, if each has 10 Joules of kinetic energy.

1. $\lambda_{bowling} > \lambda_{golf}$
2. $\lambda_{bowling} = \lambda_{golf}$
3. $\lambda_{bowling} < \lambda_{golf}$

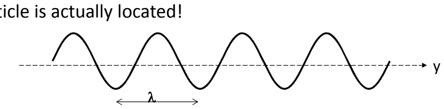


Heisenberg Uncertainty Principle

$$\Delta p_y \Delta y \geq \frac{h}{2\pi}$$

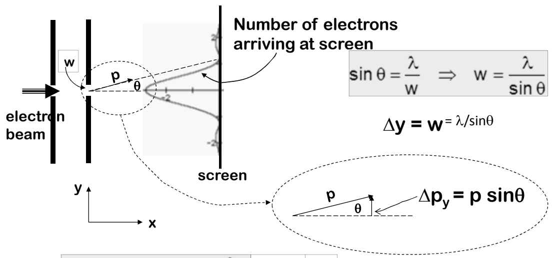
Rough idea: if we know momentum very precisely, we lose knowledge of location, and vice versa.

If we know the momentum p, then we know the wavelength λ, and that means we're not sure where along the wave the particle is actually located!



Heisenberg Test

$$\Delta p_y \Delta y \geq \frac{h}{2\pi}$$



$$\sin\theta = \frac{\lambda}{w} \Rightarrow w = \frac{\lambda}{\sin\theta}$$

Δy = w = $\lambda/\sin\theta$

$$\Delta p_y \Delta y = p \sin\theta \frac{\lambda}{\sin\theta} = \lambda p = h$$

Use de Broglie λ

to be precise...

$$\Delta p_y \Delta y \geq \frac{h}{2\pi}$$

Of course if we try to locate the position of the particle along the x axis to Δx we will not know its x component of momentum better than Δp_x, where

$$\Delta p_x \Delta x \geq \frac{h}{2\pi}$$

and the same for z.

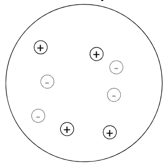
Uncertainty Principle Checkpoint

According to the H.U.P., if we know the x-position of a particle, we can not know its:

(1)	Y-position	(2)	x-momentum
(3)	y-momentum	(4)	Energy

Early Model for Atom

- **Plum Pudding**
  - **positive and negative charges uniformly distributed throughout the atom like plums in pudding**



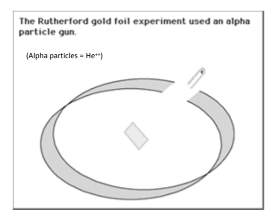
But how can you look inside an atom 10^{-10} m across?

Light	(visible)	$\lambda = 10^{-7}$ m
Electron	(1 eV)	$\lambda = 10^{-9}$ m
Helium atom		$\lambda = 10^{-11}$ m

Rutherford Scattering

Scattering He^{++} nuclei (alpha particles) off of gold. Mostly go through, some scattered back!

Only something really small (i.e. nucleus) could scatter the particles back!



Atom is mostly empty space with a small (r = 10^{-15} m) positively charged nucleus surrounded by cloud of electrons (r = 10^{-10} m)

Atomic Scale

- Kia – Sun Chips Model

Recap

- Photons carry momentum p=h/λ
- Everything has wavelength λ=h/p
- Uncertainty Principle $\Delta p \Delta x > h/(2\pi)$

- Atom
  - Positive nucleus 10^{-15} m
  - Electrons "orbit" 10^{-10} m
  - Classical E+M doesn't give stable orbit
  - Need Quantum Mechanics!