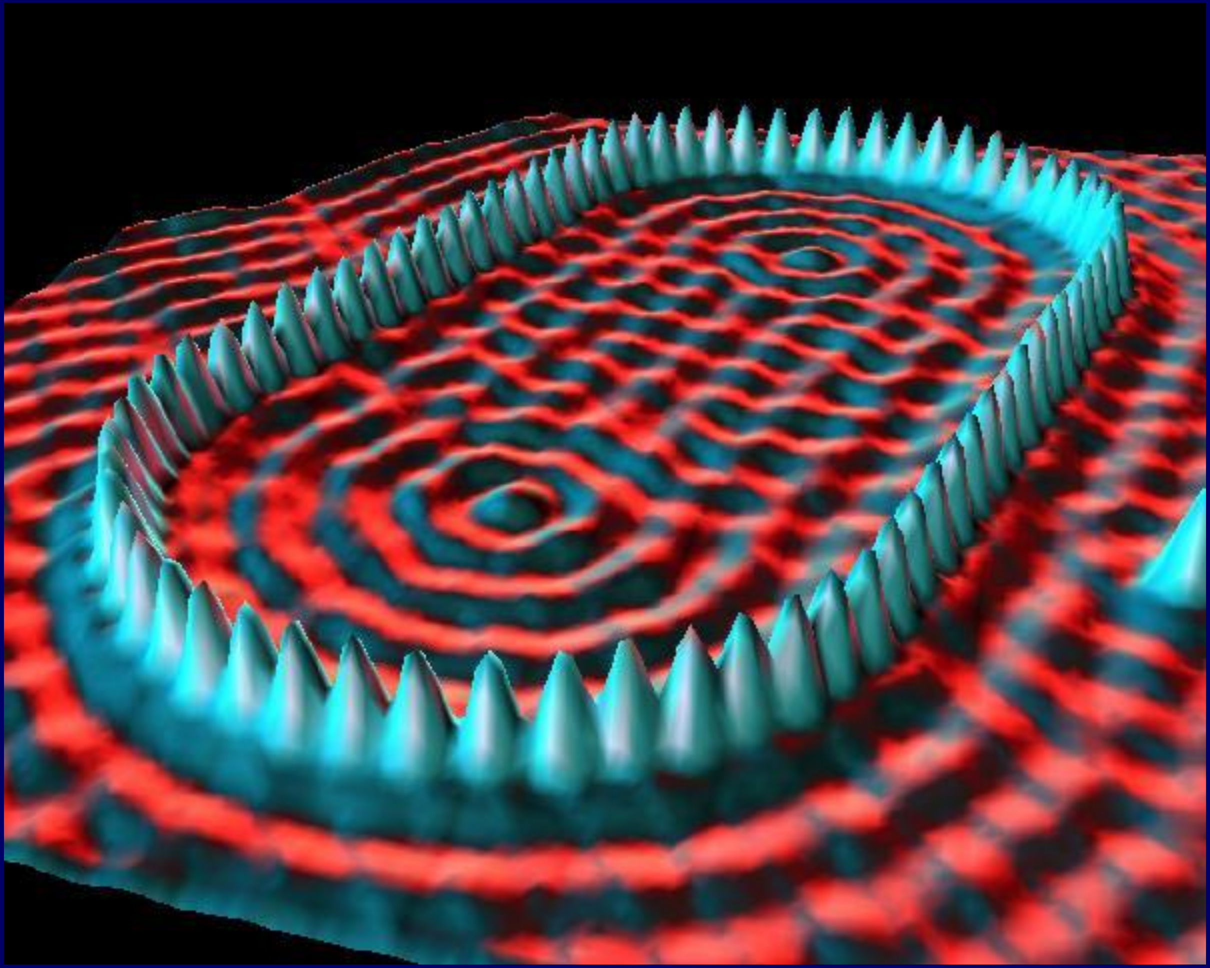
Physics 102: Lecture 23

De Broglie Waves & Compton Scattering



Early Indications of Problems with Classical Physics

- Blackbody radiation
- Photoelectric effect

Lecture 22

- Wave-particle duality
- Compton scattering
- DeBroglie waves

Today

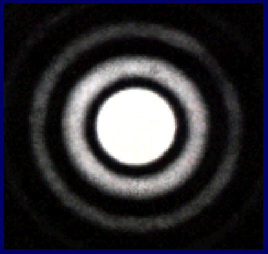
- Heisenberg Uncertainty Principle Next lecture

Are Electrons Particles or Waves?

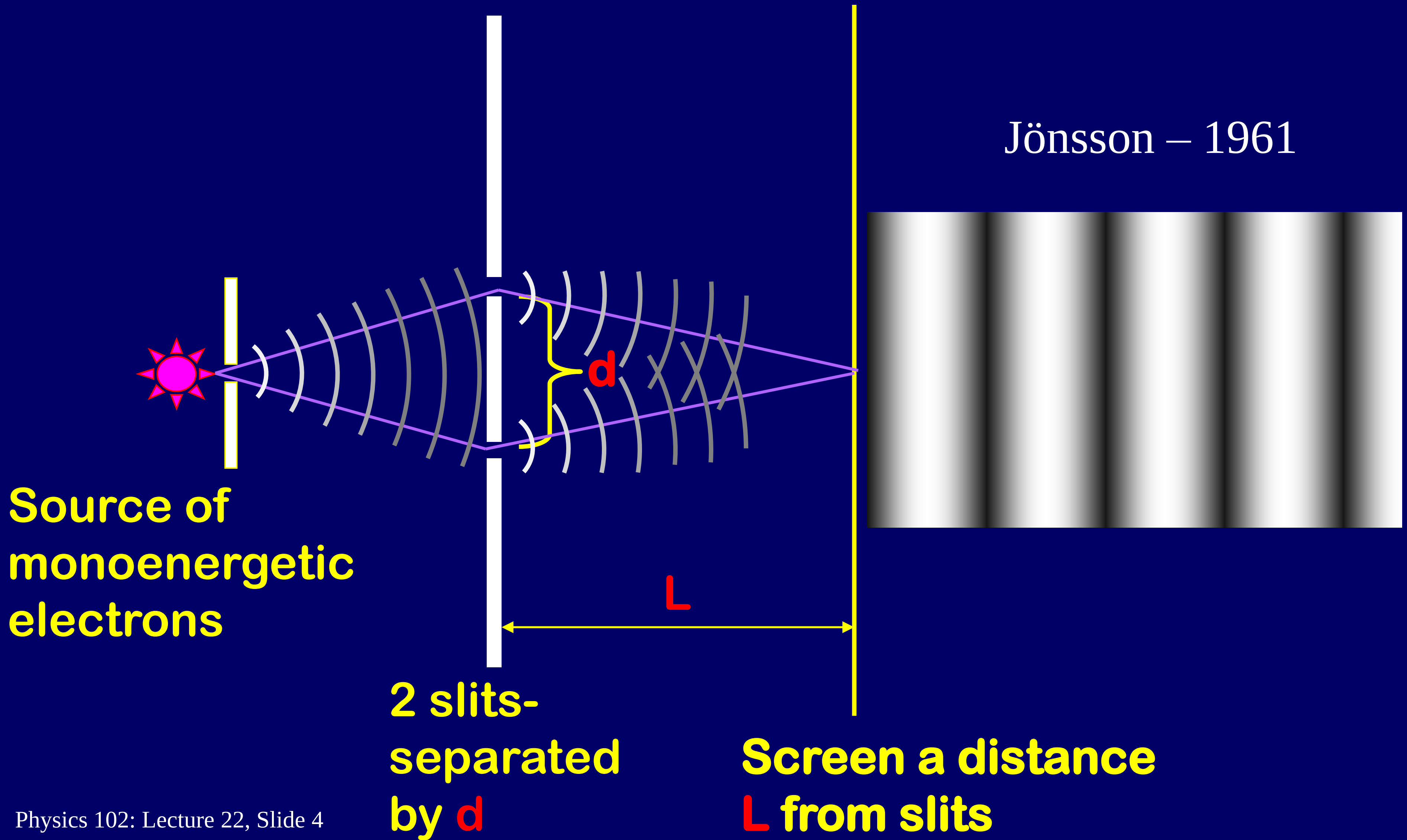
- Particles, definitely particles.
- You can "see them".
- You can "bounce" things off them.
- You can put them on an electroscope.

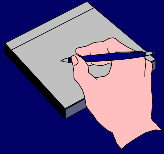
- How would know if electron was a wave?

Look for interference!



Young's Double Slit w/ electron



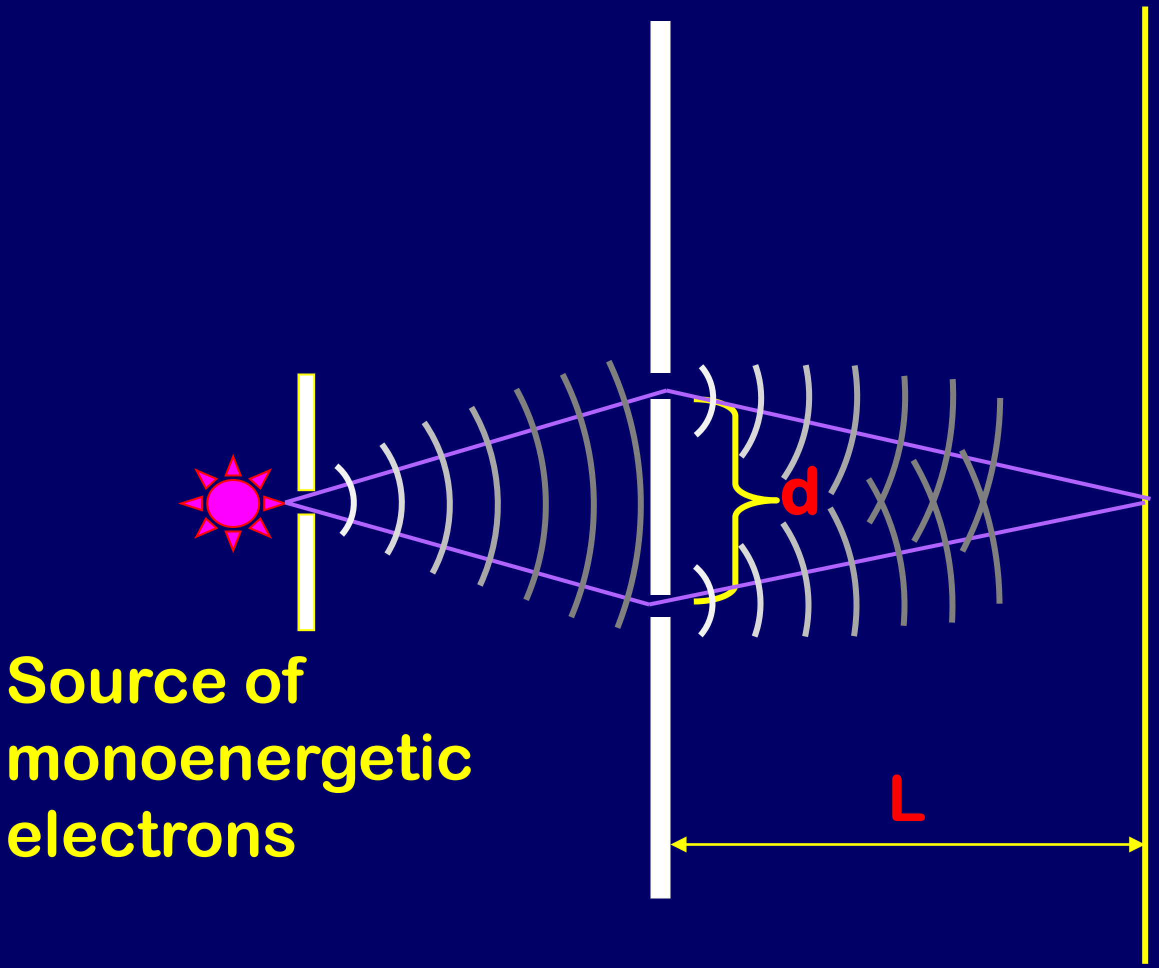


Electrons are Waves?

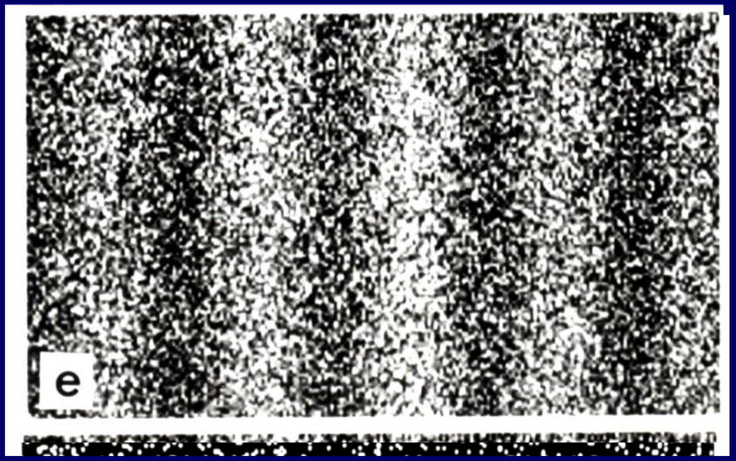
- **Electrons produce interference pattern just like light waves.**
  - **Need electrons to go through both slits.**
  - **What if we send 1 electron at a time?**
  - **Does a single electron go through both slits?**

Young's Double Slit w/ electron

One electron at a time



Merli – 1974
Tonomura – 1989



Interference pattern = probability

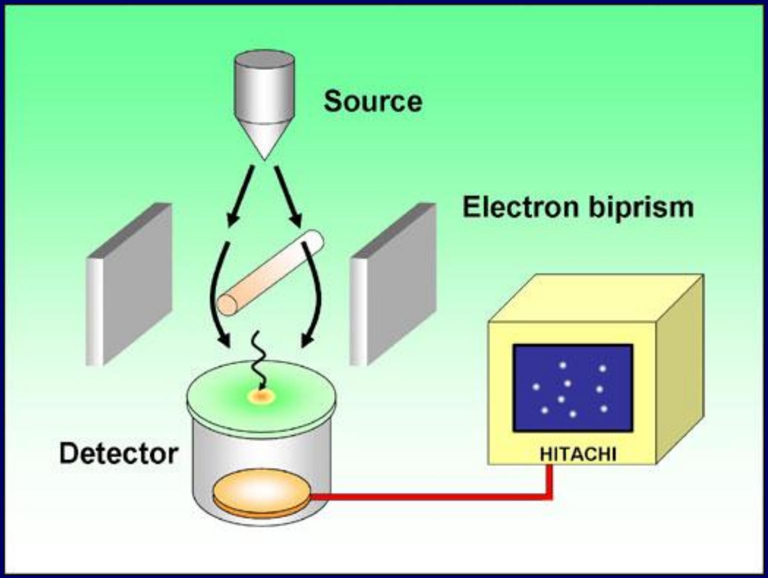
Same pattern for photons

ACT: Electrons are Particles

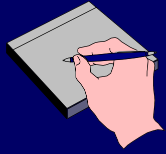
- Let's detect which hole the electron goes through. Does the electron pass through...

(1) Both Slits

(2) Only 1 Slit



ACT: Electrons are Particles



- Let's detect which hole the electron goes through. Does the electron pass through...

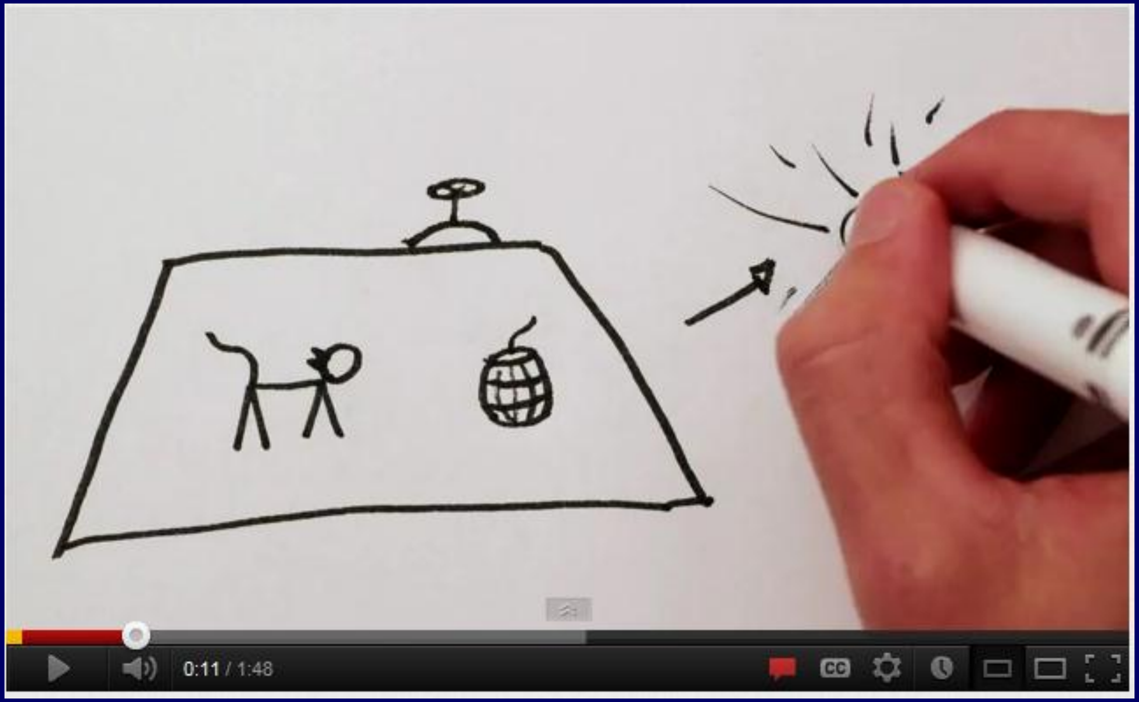
(1) Both Slits

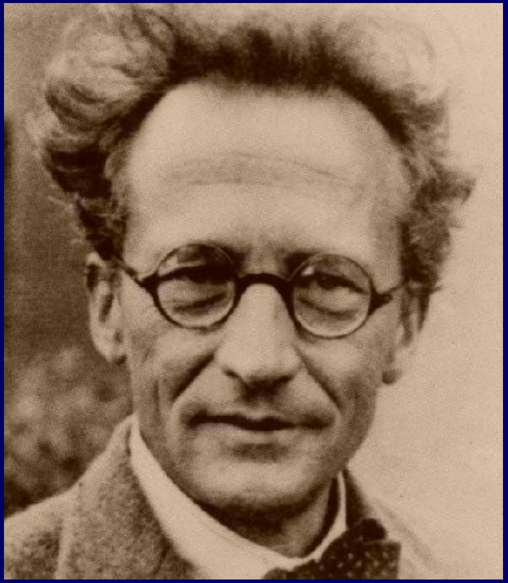
(2) Only 1 Slit

Electrons are Particles and Waves!

- Depending on the experiment electron can behave like
  - wave (interference)
  - particle (localized mass and charge)
- If we don't look, electron goes through both slits. If we do look it chooses one.

Schrödinger's Cat



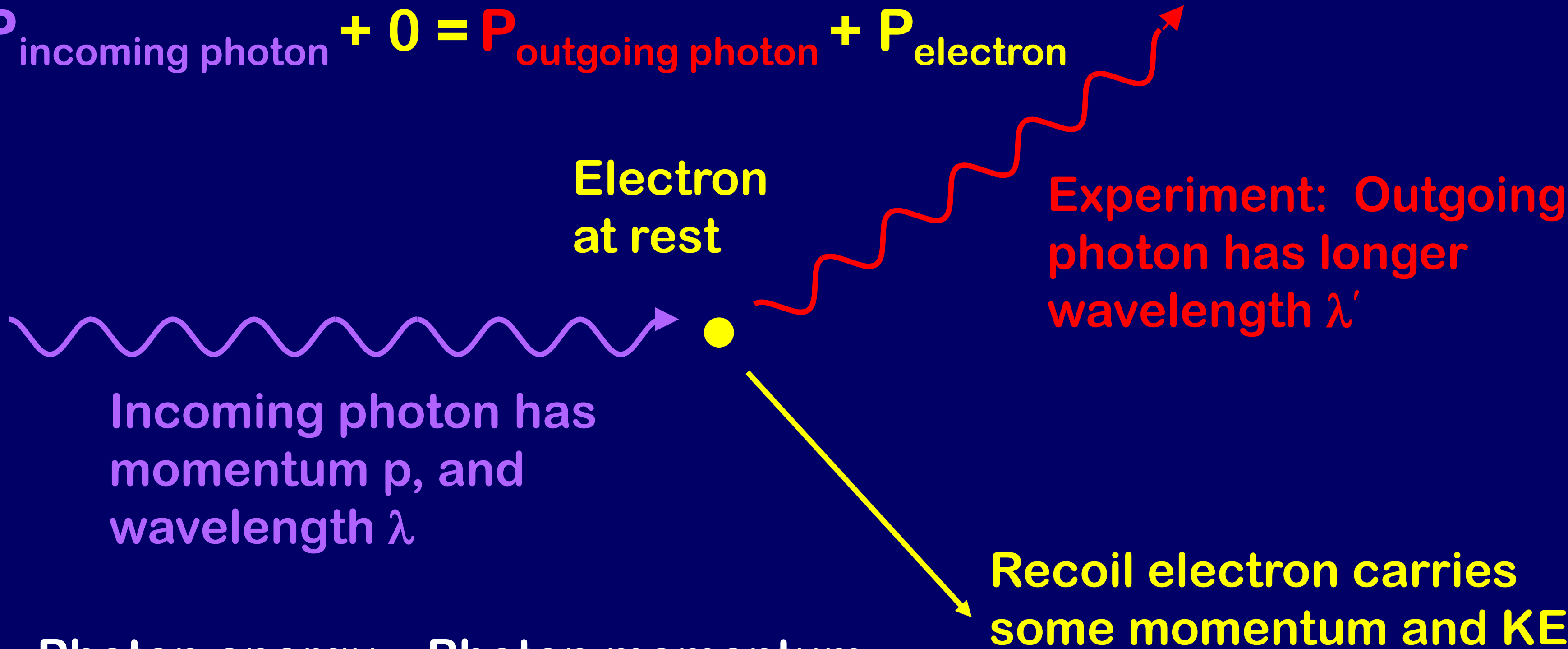


http://www.youtube.com/watch?v=IOYyCHGWJq4

Compton Scattering

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

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



<u>Photon</u> energy **<u>Photon</u> momentum**

$$E = hf = \frac{hc}{\lambda} \qquad p = \frac{h}{\lambda} \qquad \Rightarrow E = pc$$

Compton Scattering

- Incident photon loses momentum, since it transfers momentum to the electron
- Lower momentum means longer wavelength
- This is proof that a photon has momentum

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

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
  - Compton scattering from electrons

BOTH Particle AND Wave Behavior

Electrons are Particles and Waves!

- Depending on the experiment electron can behave like
  - wave (interference)
  - particle (localized mass and charge)

- Recall Young's double slit experiment:
  - If we measure which slit the electron went through, then there is no interference pattern!!

De Broglie Waves

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

So far only photons have wavelength, but 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!!

Checkpoint 2

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

DeBroglie waves for massive objects are small!

Baseball: m=0.5 kg
Fastball: v=100 mph=45 m/s

λ=h/mv=   m

Remember: single-slit diffraction $sin\theta = \lambda/w$

Imagine "slit" is an atom, $w = 10^{-10}m$

$\theta = 2 \times 10^{-23}$ **degrees**

This is one reason we don't observe macroscopic interference!

ACT: De Broglie Wavelength

A stone is dropped from the top of a building.

What happens to the de Broglie wavelength of the stone as it falls?

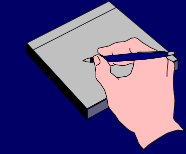
1. It decreases
2. It stays the same
3. It increases

Some Numerology

Standard units (m, kg, s) are not convenient for talking about *photons* & *electrons*

- 1 eV = energy gained by a charge +e when accelerated through a potential difference of 1 Volt
  - $e = 1.6 \times 10^{-19}$ C so 1 eV = 1.6×10^{-19} J
- $h = 6.626 \times 10^{-34}$ J·sec
- $c = 3 \times 10^{8}$ m/s
  - $hc = 1.988 \times 10^{-25}$ J·m = 1240 eV·nm
- mass of electron $m = 9.1 \times 10^{-31}$ kg
  - $mc^2 = 8.2 \times 10^{-13}$ J = 511,000 eV = 511 keV

Example



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

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:

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

- Electron with 1 eV kinetic energy:

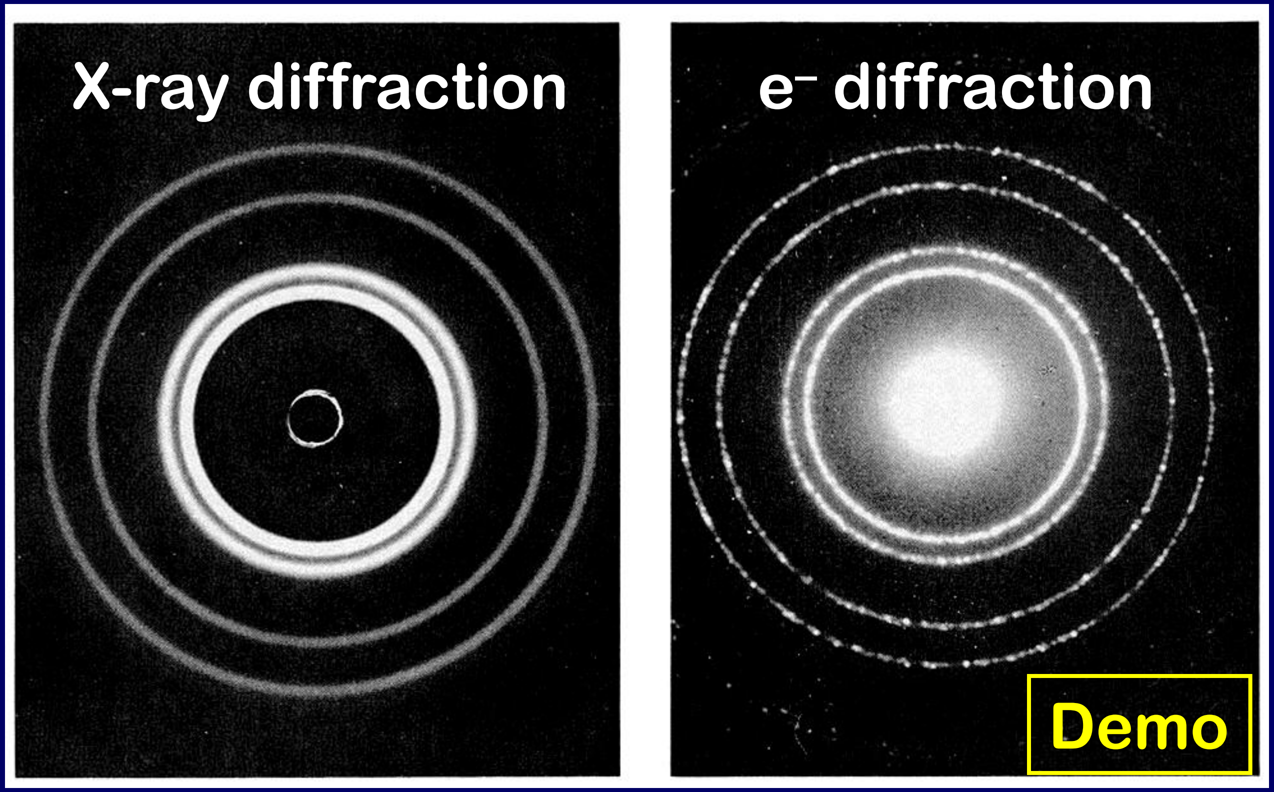
$$\boxed{\text{KE}=\frac{1}{2}\text{mv}^2}\quad \text{and}\quad \text{p}=\text{mv},\quad \text{so}\quad \text{KE}=\frac{\text{p}^2}{2\text{m}}$$

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

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

Big difference!

X-ray vs. electron diffraction



Identical pattern emerges if de Broglie wavelength of e^- equals the X-ray wavelength!

From College Physics, Vol. Two

Checkpoints 3.1, 3.2

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.

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

ACT: De Broglie

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) $\lambda_{bowling} < \lambda_{golf}$