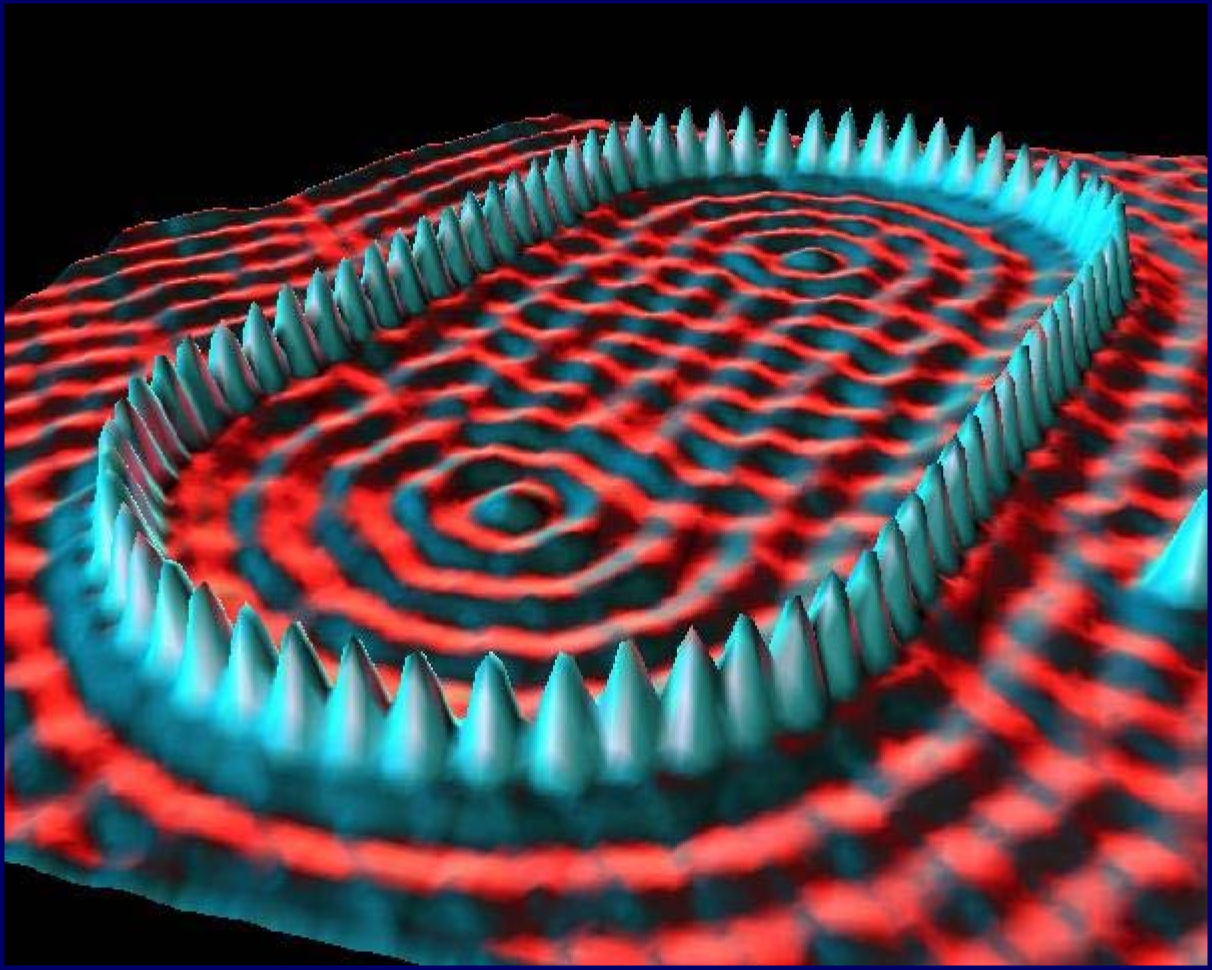
Exam 3 Monday Nov. 18!

- Material covered
  - Mirrors (Lect. 16) – Resolution (Lect. 22)
  - HW 8 – 11
- Review session Sunday, Nov. 17, 2pm, 141 Loomis
  - Prof. Chemla will review HE3 from SP13 (EXCEPT material for previous exam: #3-6, 9-11, 14-15) and selections from FA13
- Updated formula sheet
  - Added equation $f = \pm R/2$

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

Quantum Physics and the Wave-Particle Duality

I. Is Light a Wave or a Particle?

- Wave
  - Electric and Magnetic fields act like waves
  - Superposition: Interference and Diffraction
- Particle
  - Photons (blackbody radiation)
  - Collision with electrons in photo-electric effect

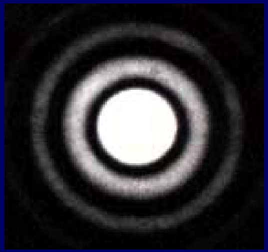
BOTH Particle AND Wave Behavior

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.

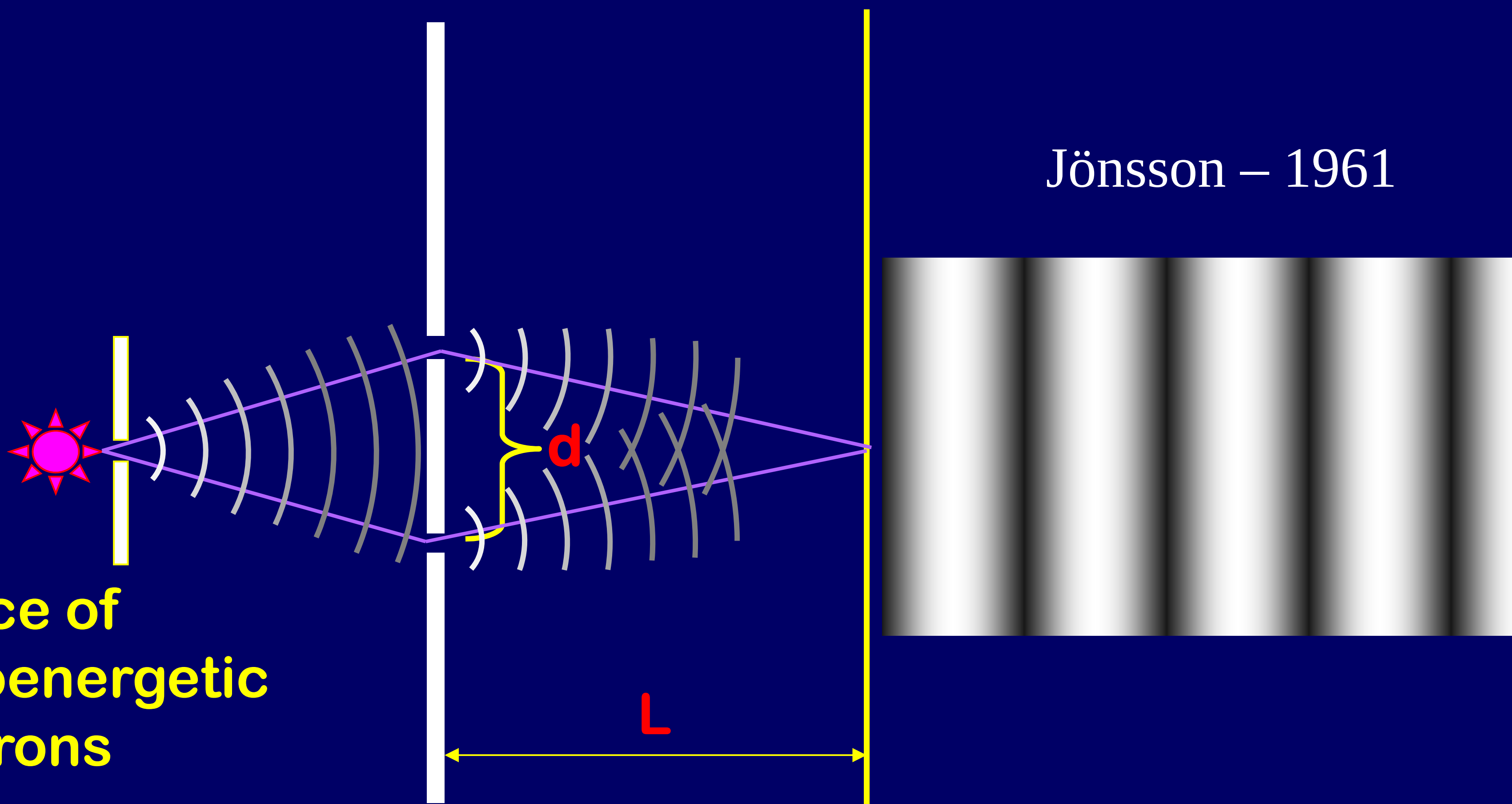
- How would know if electron was a wave?

Look for interference!



Young's Double Slit w/ electron

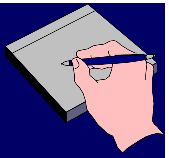
Jönsson – 1961



Source of monoenergetic electrons

2 slits-separated by d

Screen a distance L from slits

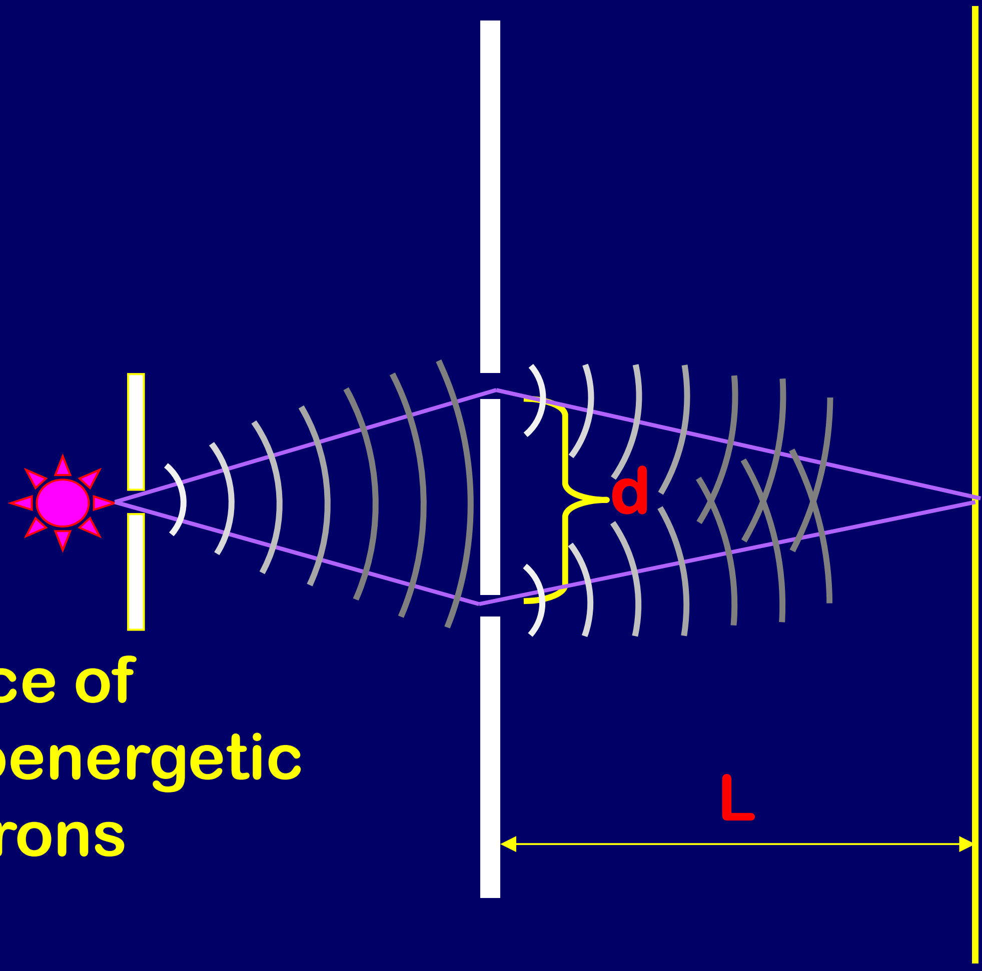


Electrons are Waves?

- **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?**

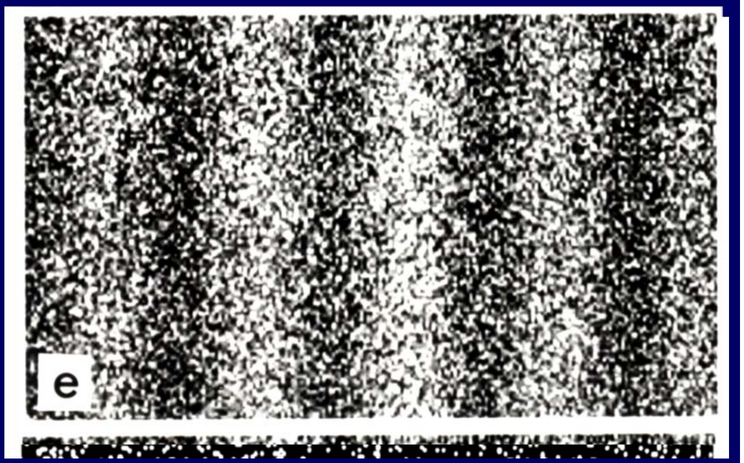
Young’s Double Slit w/ electron

One electron at a time



Source of monoenergetic electrons

Merli – 1974
Tonomura – 1989



Interference pattern = probability

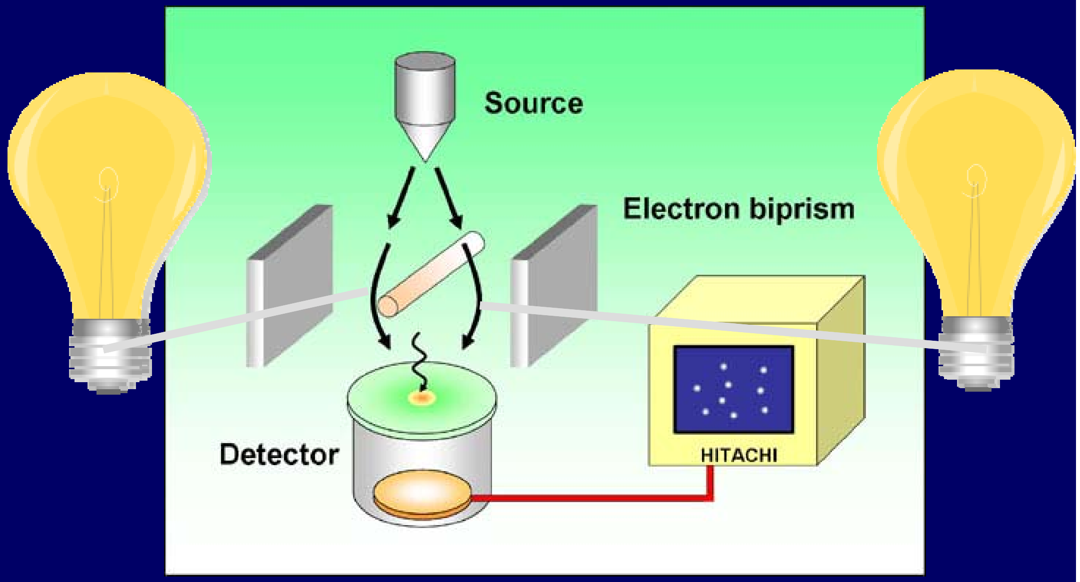
Same pattern for photons

ACT: Electrons are Particles

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

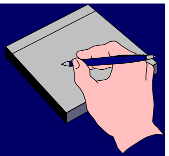
(1) Both Slits

(2) Only 1 Slit



But now the interference is gone!

ACT: Electrons are Particles



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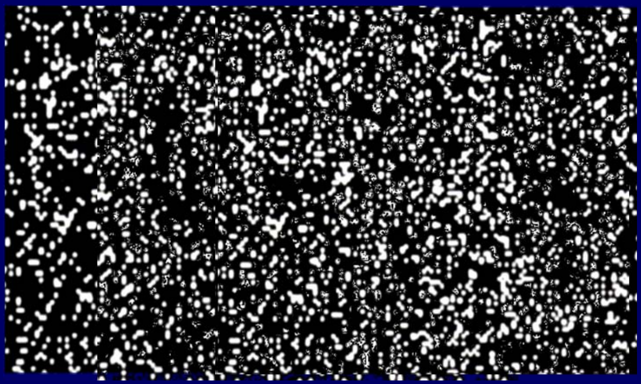


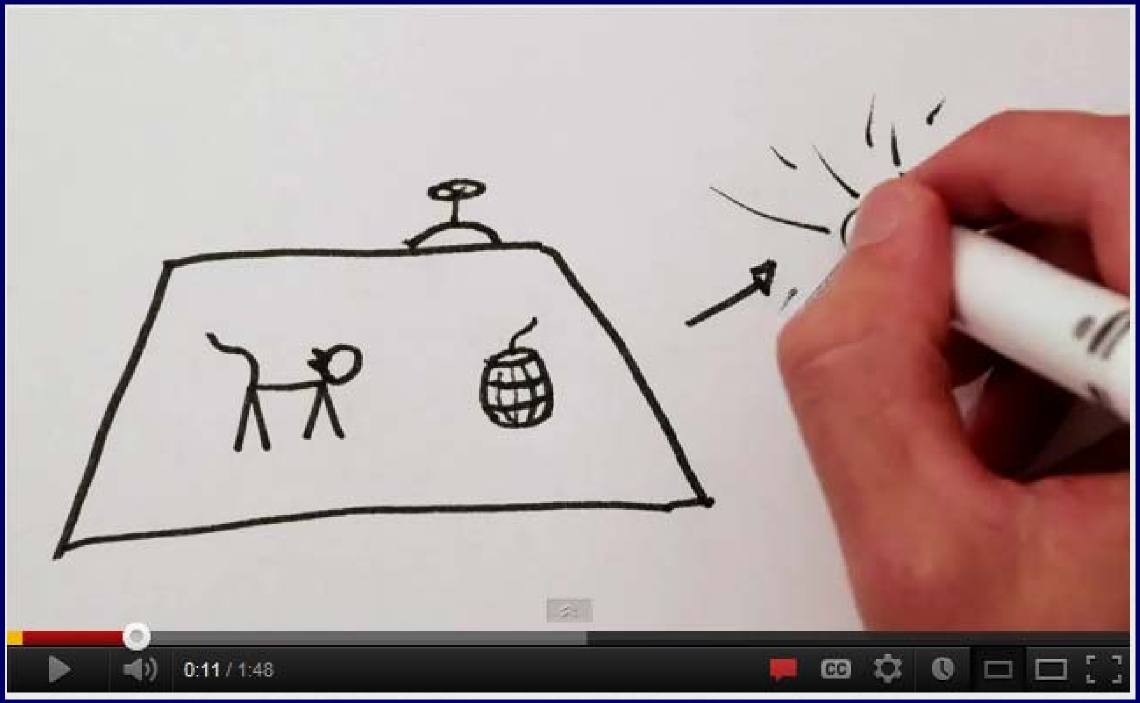
But now the interference is gone!

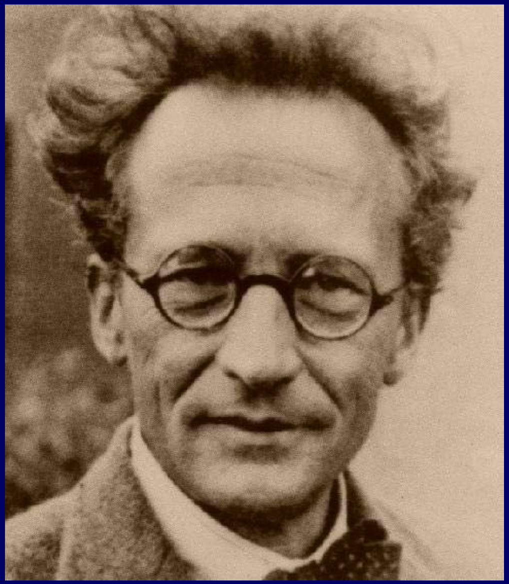
Electrons are Particles and Waves!

- **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

Is Light a Wave or a Particle?

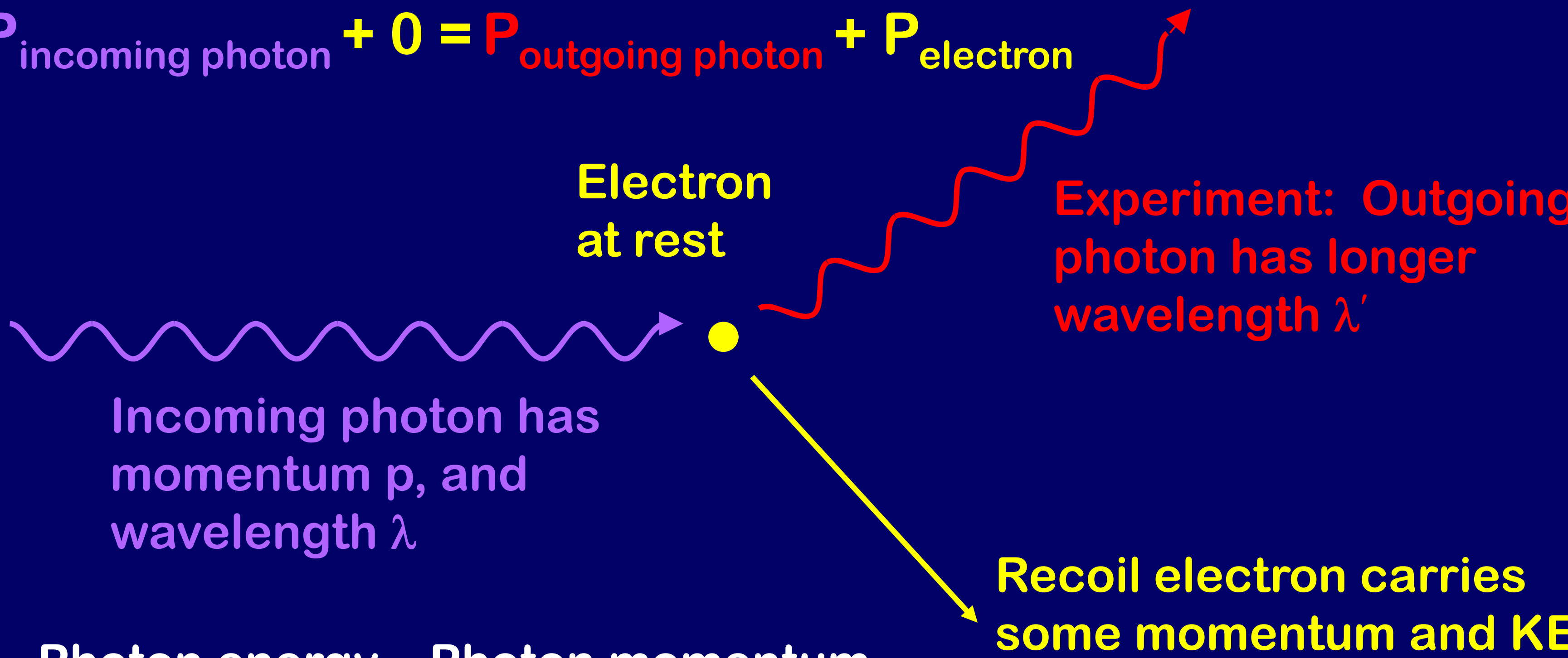
- Wave
  - Electric and Magnetic fields act like waves
  - Superposition, Interference, and Diffraction
- Particle
  - Photons
  - Collision with electrons in photo-electric effect
  - Compton scattering from electrons
    - Shows that photons (massless particles) have momentum!
    - Reminder: for massive particles, $p = mv$…
      so how can a photon have momentum?

BOTH Particle AND Wave Behavior

Compton Scattering

This experiment really shows photon momentum!

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



Photon energy

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

Photon momentum

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

$$\Rightarrow E = pc$$

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

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

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

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

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?

27% (1) A fastball (100 mph)

61% (2) A knuckleball (60 mph)

12% (3) Neither - only curveballs have a wavelength

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

Lower momentum gives higher wavelength.

p = mv, so slower ball has smaller p.

DeBroglie waves for massive objects are small!

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

λ**=h/mv=**3×10^{-35} **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

Speed, v, KE=$mv^2/2$, and momentum, p=mv, increase.

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

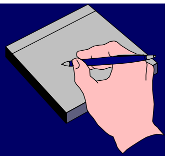
Some Numerology

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 $1\ \text{eV} = 1.6 \times 10^{-19}$ 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*



Equations are different - be careful!

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

- Photon with 1 eV energy:

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

Big difference!

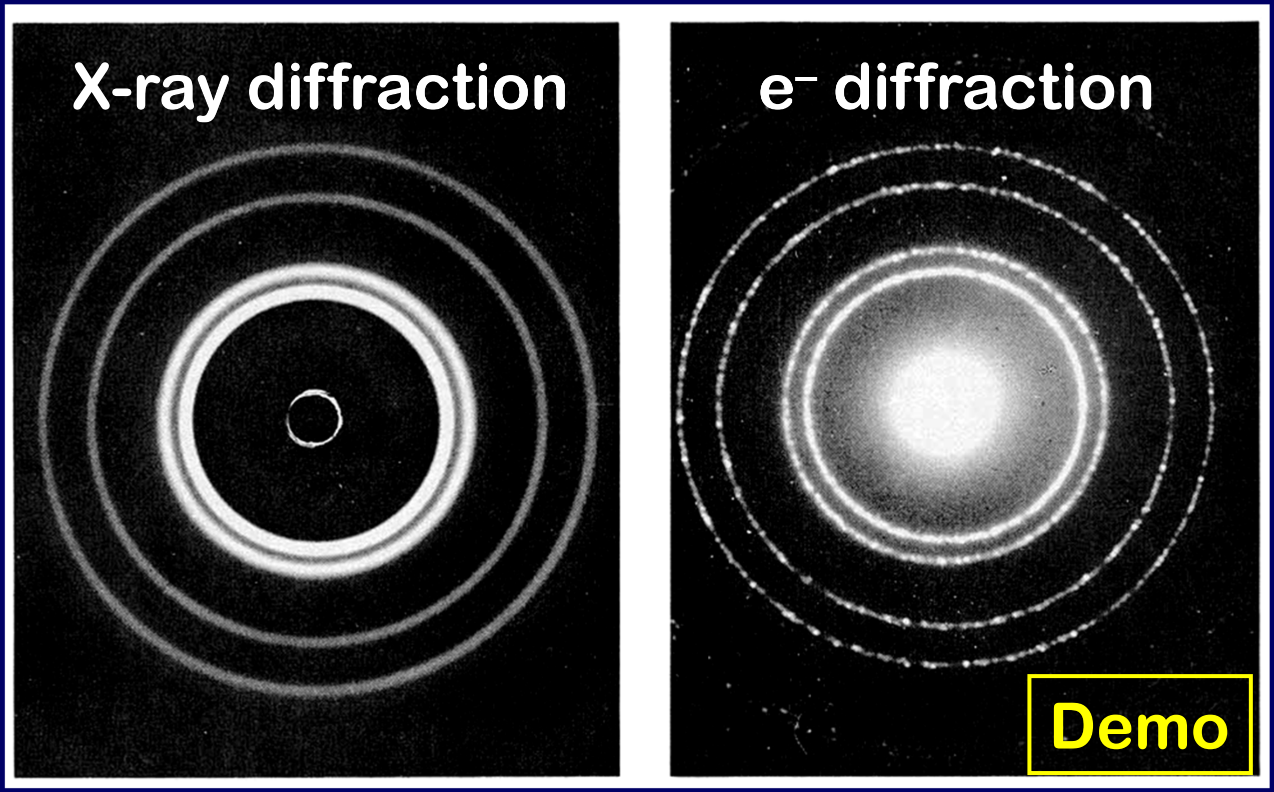
- Electron with 1 eV kinetic energy:

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

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

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

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.

18% • $E_A = E_B$

64% • $E_A = 2\ E_B$

18% • $E_A = 4\ E_B$

$E = \frac{hc}{\lambda}$ and $\lambda = \frac{h}{p}$ so $E = cp$

double p then double E

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

22% • $E_A = E_B$

41% • $E_A = 2\ E_B$

37% • $E_A = 4\ E_B$

$$KE = \frac{1}{2}mv^2 = \frac{p^2}{2m}$$

double p then quadruple E

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) $\lambda_{\text{bowling}} > \lambda_{\text{golf}}$

(2) $\lambda_{\text{bowling}} = \lambda_{\text{golf}}$

(3) $\lambda_{\text{bowling}} < \lambda_{\text{golf}}$

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

$$\lambda = \frac{h}{\sqrt{2m(\text{KE})}}$$