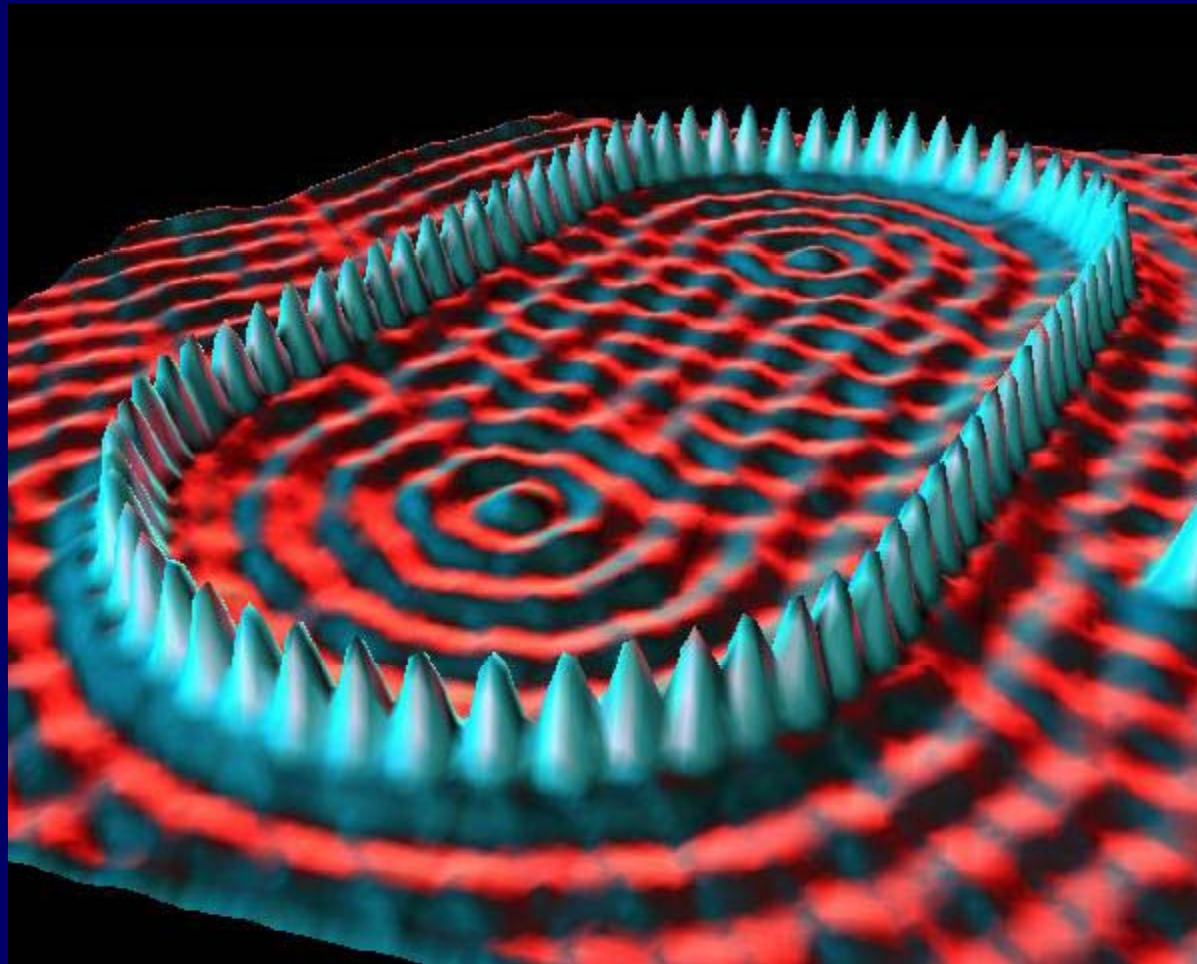


Exam 3 Monday April 15!

- **Material covered**
 - RLC circuits (Lect. 12) – Thin film interference (Lect. 21)
 - Discussion 7 – 10 & HW 7 – 11 (first half)
- **Sign up for conflict exams this week!**
- **Review session Sunday, April 14, 3pm, 141 Loomis**
 - Sara Rose will review HE3 from Fall '12 (PLUS questions in HE2 Fall '12 pertaining to Lect. 12 – 15)
- **Next week's lectures**
 - Tom Kuhlman will give Lect. 24, Monday April 15
 - I will be back for Lect. 25

Physics 102: Lecture 23

De Broglie Waves & Compton Scattering



Early Indications of Problems with Classical Physics

- Blackbody radiation
 - Photoelectric effect
 - Wave-particle duality
 - Compton scattering
 - DeBroglie waves
 - Heisenberg Uncertainty Principle
- Lecture 22
- Today
- 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?

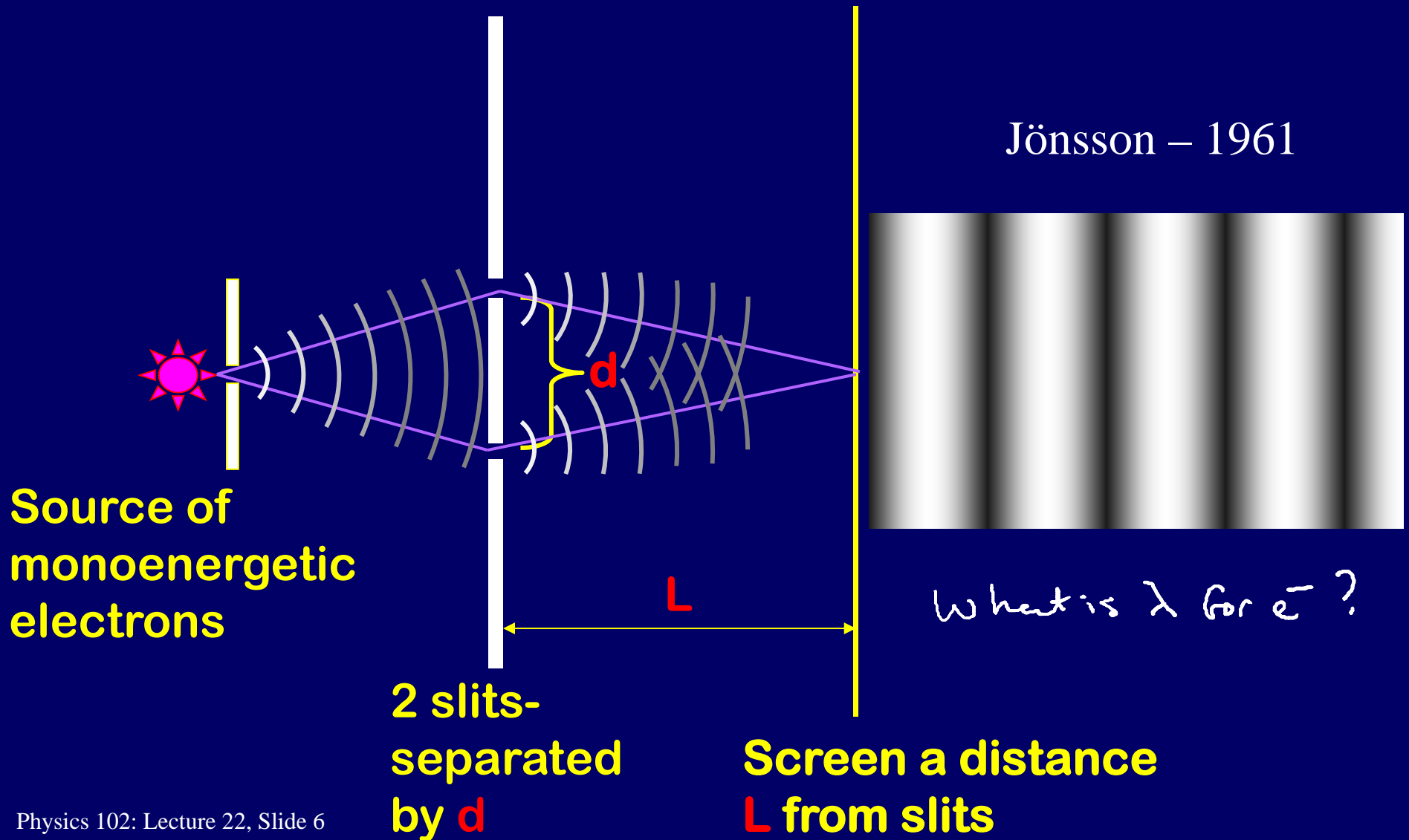
- Particles, definitely particles.
- You can “see them”.
- You can “bounce” things off them.
- You can put them on an electroscope.

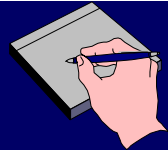
- How would know if electron was a wave?

Look for interference!



Young's Double Slit w/ electron



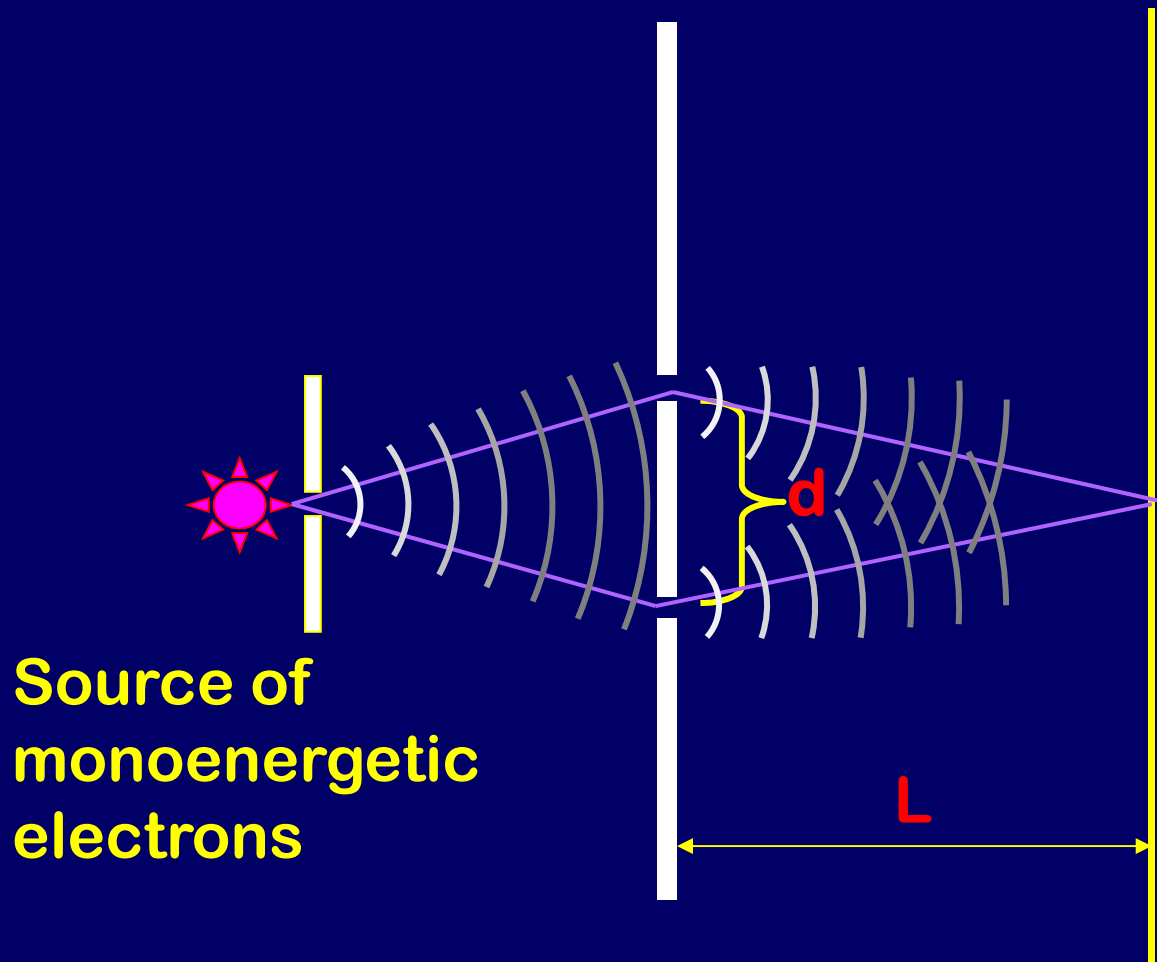


Electrons are Waves?

- **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



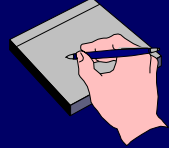
Merli – 1974

Tonomura – 1989



Interference pattern =
probability

Same pattern for photons

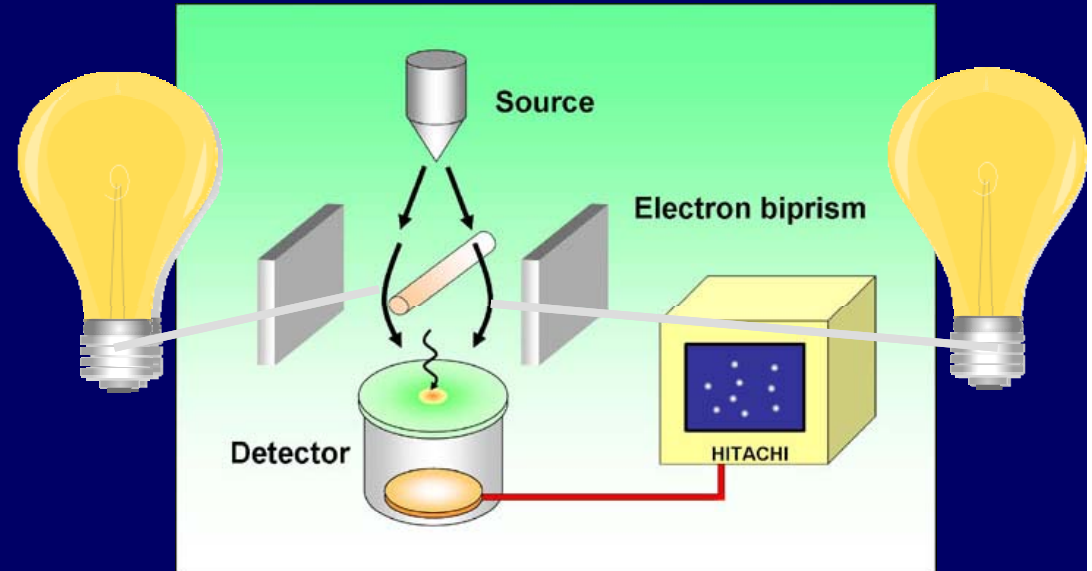


ACT: Electrons are Particles

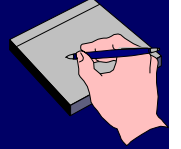
- Let's detect which hole the electron goes through. Does the electron pass through...

(1) Both Slits

(2) Only 1 Slit



But now the interference is gone!

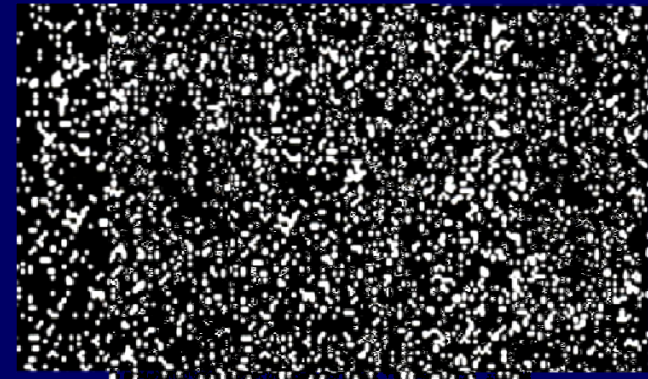


ACT: Electrons are Particles

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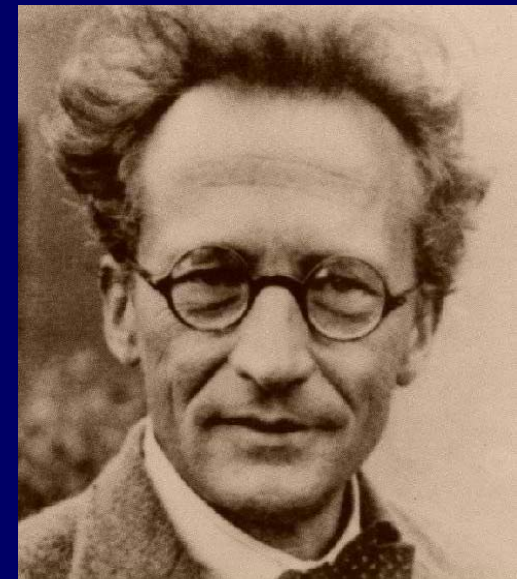
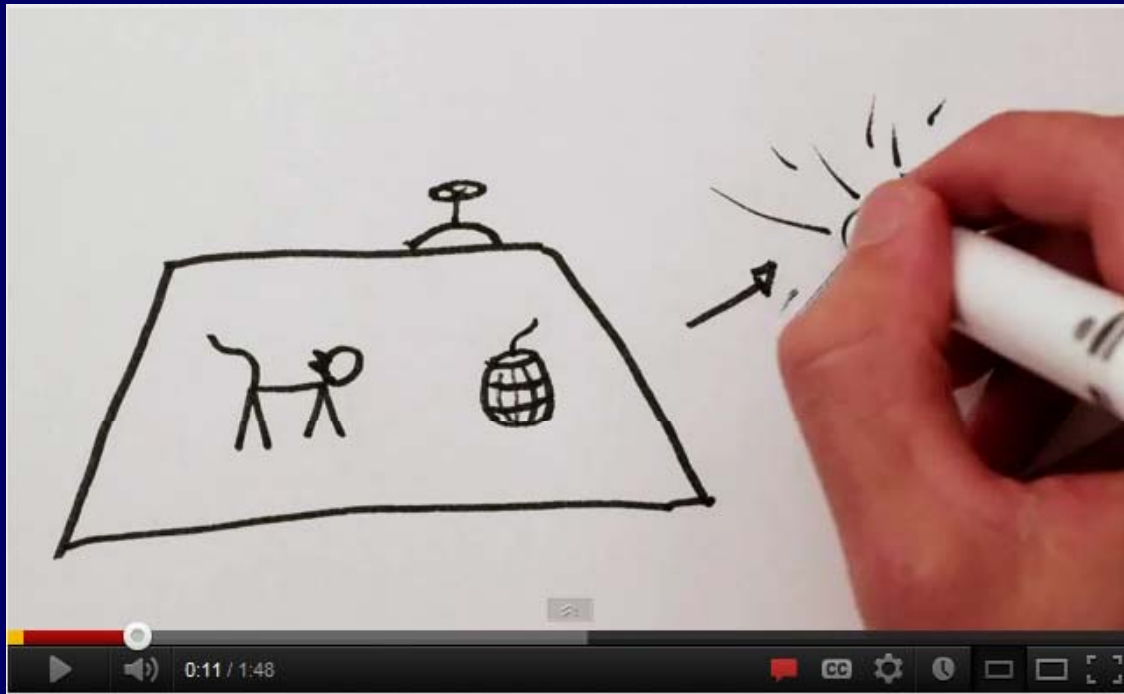


But now the interference is gone!

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



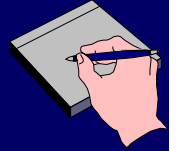
<http://www.youtube.com/watch?v=IOYyCHGWJq4>

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**

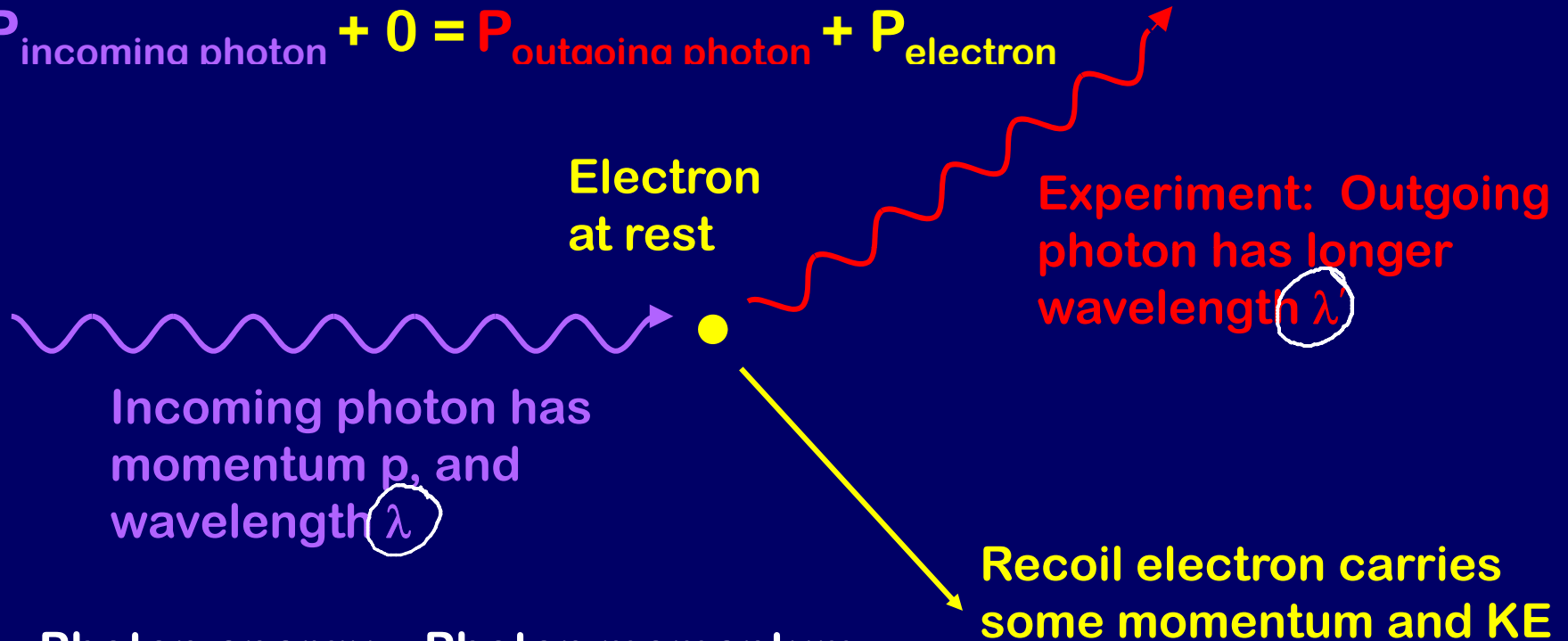
BOTH Particle AND Wave Behavior

Compton Scattering



This experiment really shows photon momentum!

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



Incoming photon has momentum p , and wavelength λ

Experiment: Outgoing photon has longer wavelength λ'

Recoil electron carries some momentum and KE

Photon energy

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

Photon momentum

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

$$\Rightarrow E = pc$$

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

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

Phys. 100
 $p = mv$

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

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

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?

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



$$\lambda = h/mv = 3 \times 10^{-35} \text{ m}$$

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

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



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

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.

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

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
– $e = 1.6 \times 10^{-19} \text{ C}$ so $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$
- $h = 6.626 \times 10^{-34} \text{ J}\cdot\text{sec}$
- $c = 3 \times 10^8 \text{ m/s}$
 - $hc = 1.988 \times 10^{-25} \text{ J}\cdot\text{m} = \underline{1240} \text{ eV}\cdot\text{nm}$
- mass of electron $m = 9.1 \times 10^{-31} \text{ kg}$
 - $mc^2 = 8.2 \times 10^{-13} \text{ J} = 511,000 \text{ eV} = 511 \text{ keV}$

$$U = qV$$

$$E =$$

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.

- Photon with 1 eV energy:

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

IR

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

- Electron with 1 eV kinetic energy:

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

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

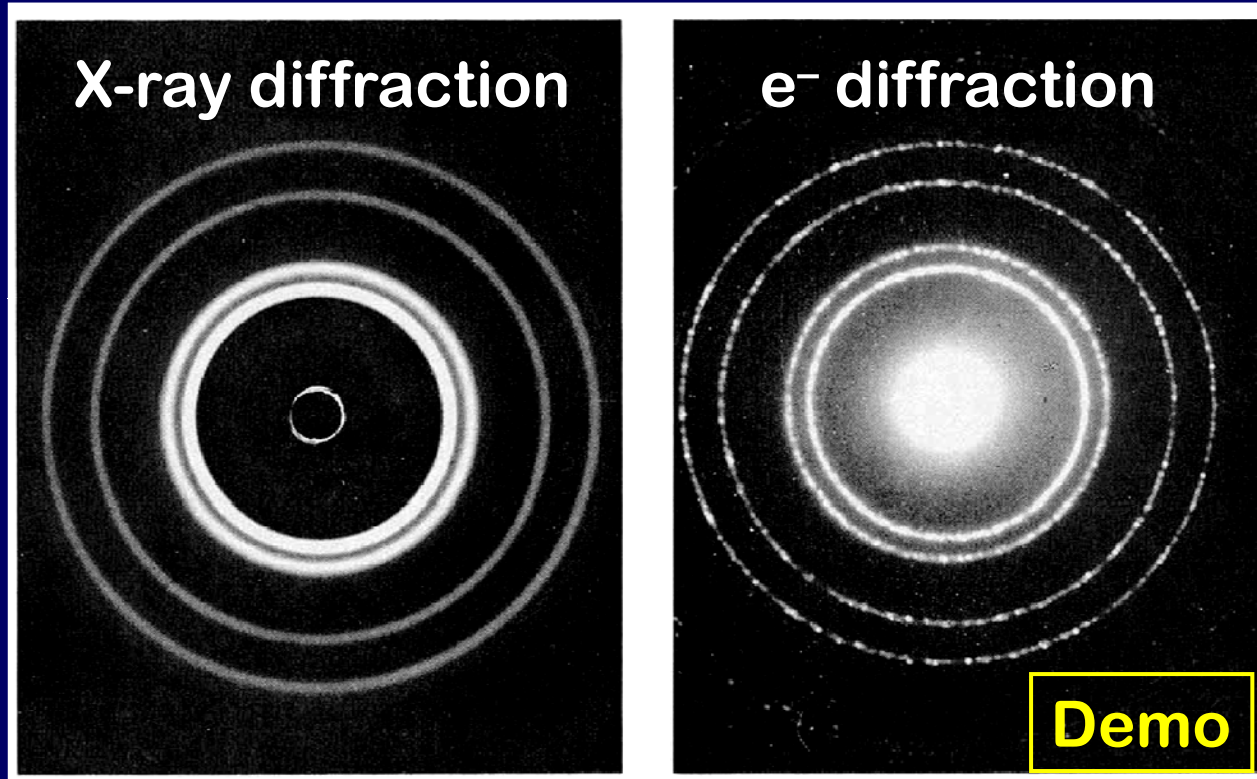
$$\lambda = \frac{h}{\sqrt{2m(\text{KE})}} = \frac{hc}{\sqrt{2mc^2(\text{KE})}} = \frac{1240 \text{ eV nm}}{\sqrt{2(511,000 \text{ eV})(1 \text{ eV})}} = 1.23 \text{ nm}$$

X-ray

Big difference!

Equations are different - be careful!

X-ray vs. electron diffraction



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

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% • $E_A = 4 E_B$

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

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

$m_{\text{golf}} < m_{\text{bowling}}$

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