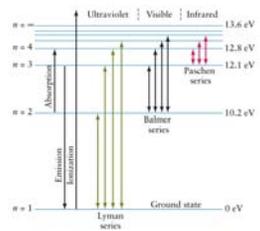## Chapter 15: Duality of Matter
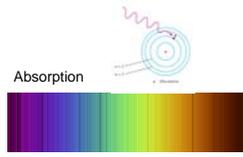
Did you read chapter 15 before coming to class?
A. Yes
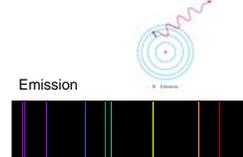B. No

## Review: How the Bohr model explains the Hydrogen Atom spectrum
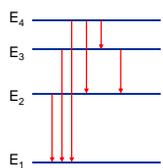
Energy Level Diagram

Absorption

Emission

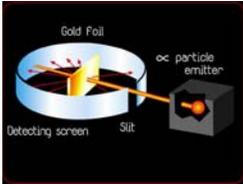## An atom has only the following possible energy levels. How many discrete colors can it emit?

A. 2
B. 4
C. 5
D. 6
E. 7 or more

$E_4$

$E_3$

$E_2$

$E_1$

## The "bullets" used by Rutherford to probe gold atoms were:

A. Electrons
B. Neutrons
C. Positively charged particles

## Matter Models (continued…)

- At least two puzzles remain at this point:
  - The wave-particle duality of light.
  - The physical basis for the Bohr model.

## The de Broglie Hypothesis was hailed by some as the "French Comedy"…

- In 1923 a graduate student named Louis de Broglie proposed a radical idea about matter: In addition to light, matter should also exhibit a wave-particle duality.
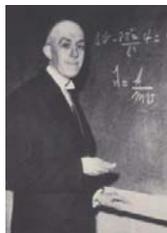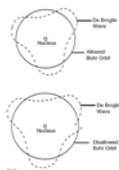- A particle of mass should have a wavelength defined by:

  wavelength = h / (mass × speed)

  where h = Plank's constant = $6 \times 10^{-34}$

## But it turned out to describe what we observe.

- De Broglie's idea gave a reason for the Bohr orbits
  - The quantized orbits of the Bohr model are predicted perfectly by requiring electrons to exactly wrap 1, 2, 3, etc waves around the nucleus.
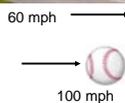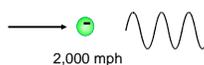
Nobel Prize, 1929

## Examples

wavelength = h / (mass×speed)

where h = Plank's constant = $6 \times 10^{-34}$

Wavelength = $10^{-38}$ m (nonsense?)

60 mph

Wavelength = $10^{-34}$ m (again nonsense?)

100 mph

Wavelength = $10^{-10}$ m
Diameter of an atom...

2,000 mph

## Why don't we observe the wave nature of matter?

- To observe wave effects, your "slits" need to be similar to the wavelength
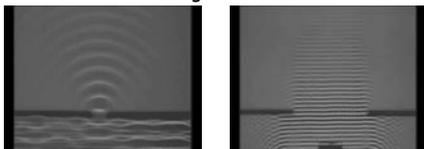
wavelength = h / (mass×speed)
$h = 6 \times 10^{-34}$

- Example: It would take $10^{27}$ years for a student to "diffract" through a doorway.
- For all material objects except the very least massive (such as electrons and protons), the wavelength is so immeasurably small that it can be completely ignored.

## But are electrons really waves?

- Let's see if they diffract. We need slits about the size of the electron wavelength ($\sim 10^{-10}$ m) to witness it.
- How do you make a slit that small? You can't manufacture one, but nature provides something we can use: the space between atoms in a crystal.
- Fire an electron beam at a crystal and we DO get diffraction and interference patterns! Electrons ARE waves!
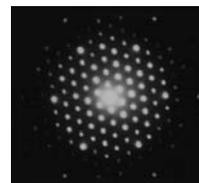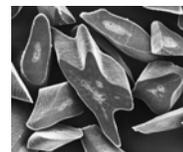
Video Encyclopedia of
Physics Demonstrations

**ELECTRON DIFFRACTION**

Playing Time: 0:54

## Small electron wavelength is useful in electron microscopes

- Diffraction limits how small you can see with an optical microscope
  - When objects are about the size of the wavelength of light, light diffracts around the object so you can't get a clear image.
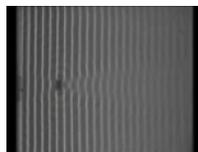
- Electron wavelengths can be 1/1000th the size of optical wavelengths. So using electron beams we can "see" things 1000 times smaller with the same clarity.

## Review:
## The concept of a probability distribution
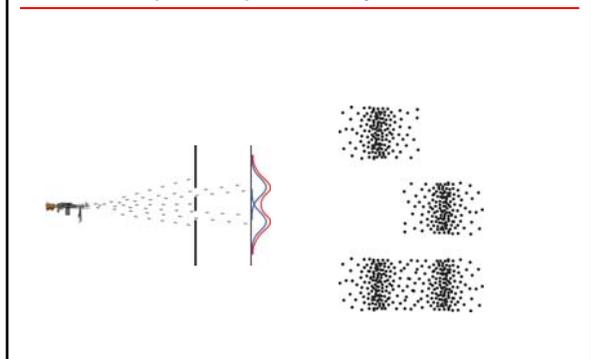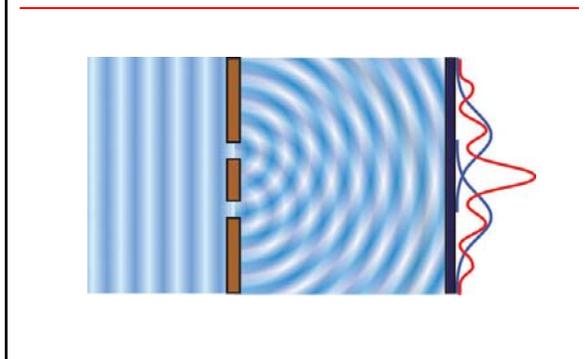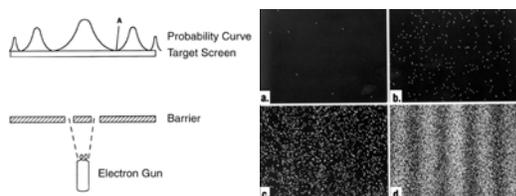


## For waves, we can use the amplitude as a measure of where the wave "is"
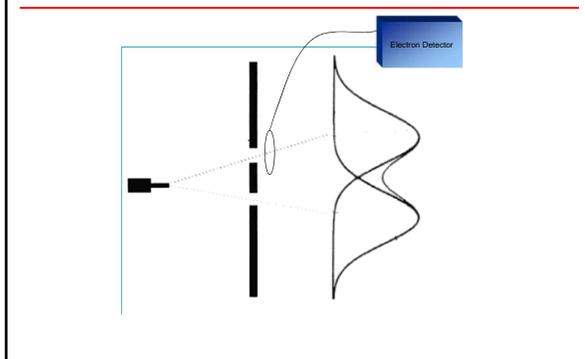


## Experimental double slit experiment using electrons

- Electrons are detected like particles, but the places that they are detected show interference patterns.
- This is essentially the same behavior we observed with photons!



## So, which slit does the electron go through?



## The results depend on how and what we measure.

- Don't measure which hole the electron goes through → wave-like interference.
- Do measure which hole the electron goes through → particle-like behavior.
- How the electron behaves depends on whether it is observed.
  - Deep thought: How does one study an unobserved electron.
- We have found the truth; and the truth makes no sense. (G. K. Chesterton)

## So what is waving?

- The mass of the particle *is not* spread out and mechanically oscillating.
- The "wave" is interpreted as being the *probability* of *locating the particle*.
  - High amplitude corresponds to high probability of detection.
- It propagates like a pure wave with diffraction, interference, refraction, etc.
- Somehow electrons "know" about the existence of both slits even when we cannot prove that they ever go through more than one slit at a time.
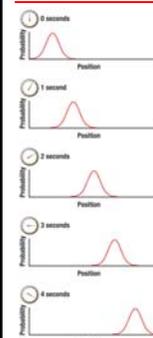- Clearly we need another model.
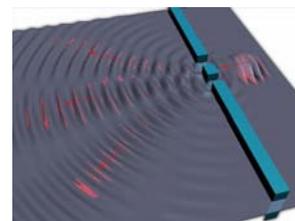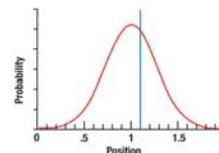
## Schodinger's wave mechanics

$$i\hbar \frac{\partial \psi(\mathbf{r},t)}{\partial t} = \frac{\hbar^2}{2m}\nabla^2 \psi(\mathbf{r},t) + V(\mathbf{r},t)\psi(\mathbf{r},t)$$

## The electron position is described with a probability wave

- When we measure the position, we find it at a certain position. We refer to this as the collapse of the wave function.

## The Uncertainty Principle and waves

- To find the trajectory of a particle we must know its position and velocity at the same time.
- How do you locate the position of a wave/particle electron?
- A well-defined momentum has a well-defined wavelength according to De Broglie.
  - wavelength = h / momentum

Pure frequency wave →
unclear position but clear
wavelength (momentum).

Sharp pulse →
clear position but unclear
wavelength (momentum).

## Heisenberg Uncertainty Principle

- Electrons: fuzzy position and fuzzy wave properties.

- The uncertainty in position times the uncertainty in momentum (mass x velocity) is greater than Planck's constant. Or

$$\Delta x \, \Delta(mv) > h$$



The Mechanical Universe...and Beyond
THE UNCERTAINTY PRINCIPLE

Playing Time: 0:59

## Consequences

- If we try to find out where an electron is, we know less about where it is going.
  - Measuring position more accurately makes uncertainty in momentum larger.
  - This is an alternative explanation for electron diffraction.

### Philosophical shift in wave mechanics

- We <u>could</u> predict this interaction perfectly using Newton's Laws of motion.

- We <u>cannot</u> predict the results of this interaction perfectly in quantum mechanics.  We can only give probabilities that certain outcomes will happen.

### So does the electron "know" where it is and where it is going?

- Quantum mechanics experiments demonstrate that there is fundamental uncertainty in nature.

- It is not a matter of the experimentalist not being clever enough to measure both position and momentum at the same time.  A particle simply does not have an exact position and an exact momentum at the same time.

### You are in good company if  this bothers you a little…

I remember discussions with Bohr which went through many hours till very late at night and ended almost in despair; and when at the end of the discussion I went alone for a walk in the neighboring park I repeated to myself again and again the question: Can nature possibly be as absurd as it seemed to us in these atomic experiments?

~Werner Heisenberg