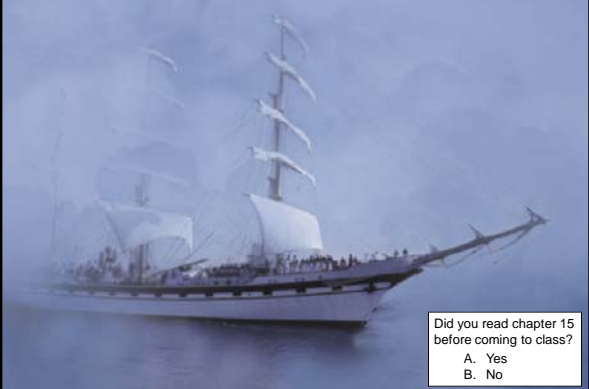
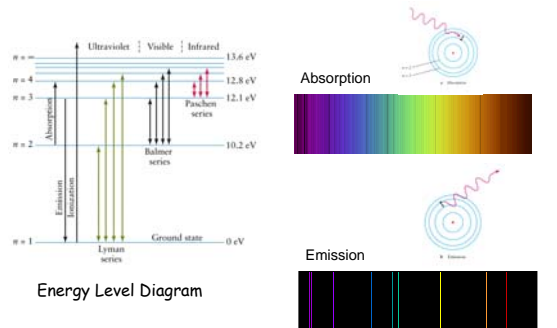


Chapter 15: Duality of Matter



Did you read chapter 15 before coming to class?
 A. Yes
 B. No

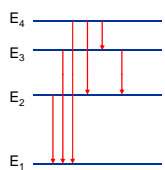
Review: How the Bohr model explains the Hydrogen Atom spectrum



Energy Level Diagram


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



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 originally hailed as the “French Comedy”...

- In 1923 a struggling 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:

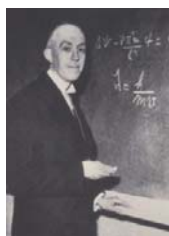
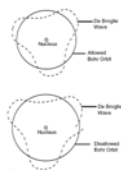
$$\text{wavelength} = h / (\text{mass} \times \text{speed})$$

where h = Planck's constant = 6×10^{-34}



But it turned out to describe what we observe.

- De Broglie's idea explained the Bohr orbitals
- The quantized orbits of the Bohr model are predicted perfectly by requiring electrons to exactly wrap 1, 2, 3, etc waves around the nucleus.



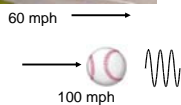
Nobel Prize, 1929

Examples

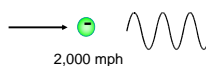
wavelength = $h / (\text{mass} \times \text{speed})$
 where $h = \text{Planck's constant} = 6 \times 10^{-34}$



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



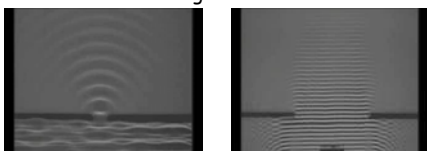
Wavelength = 10^{-34} m
 (again nonsense?)



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

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

- To observe wave effects, your "slits" need to be similar to the wavelength

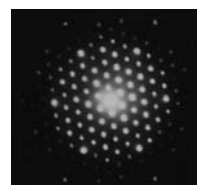


wavelength = $h / (\text{mass} \times \text{speed})$
 $h = 6 \times 10^{-34}$

- 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.

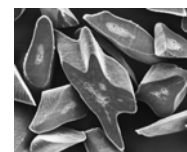
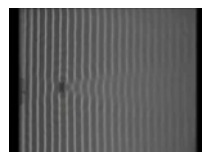
But are electrons really waves?

- 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!



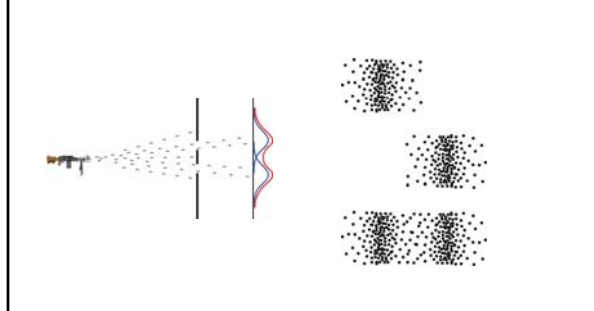
Small electron wavelength is useful in electron microscopes

- 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.

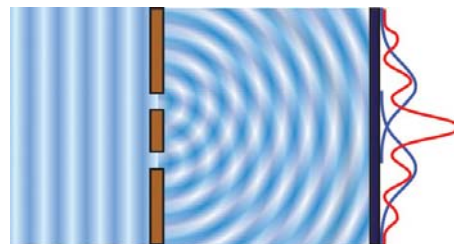


- Electron wavelengths can be $1/1000^{\text{th}}$ the size of optical wavelengths. So using electron beams we can "see" things 1000 times smaller with the same clarity.

The concept of a probability distribution

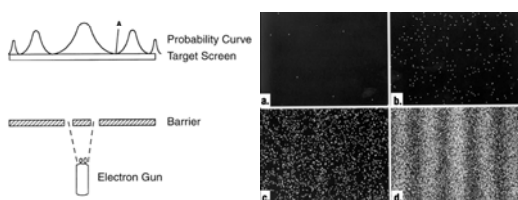


For waves, we can use the amplitude as a measure of where the wave "is"

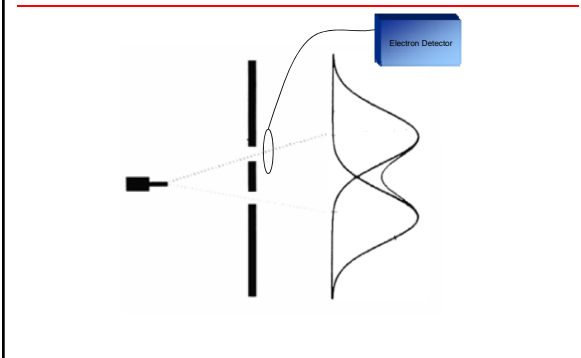


Experimental double slit experiment using electrons

- 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 behavior**.
- 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)

I hope this bothers you some...

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

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 acts 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.

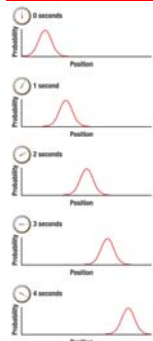
Schrodinger's wave mechanics

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

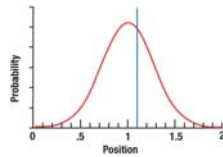


- I don't like it and I'm sorry I ever had anything to do with it.

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 sine wave →
unclear position but clear frequency.



Sharp pulse →
clear position but unclear frequency.



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

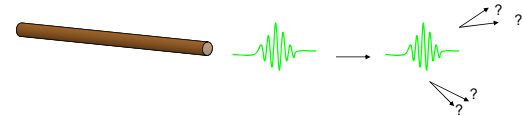
- If we try to find out where an electron is, we know less about where it is going.
 - Measuring position more accurately makes uncertainty in momentum larger.
 - This is an alternative explanation for electron diffraction.

Philosophical shift in wave mechanics

- We could predict this interaction perfectly using Newton's Laws of motion.



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



Philosophy

- Is probability all there is to electron motions? Does God really "play at dice" with the universe?
- Do we determine reality by our interactions with it? Or does it just seem that way?
- Bear in mind that these effects are only noticeable for sizes on the order of an atomic diameter.

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 cannot have an exact position and an exact momentum at the same time.

