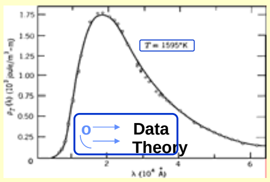
# Lecture 20b  The Birth of Quantum Mechanics

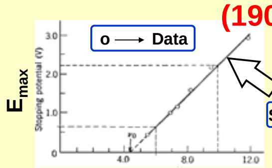
## The Origins of the Quantum Theory

**Planck (1900)**

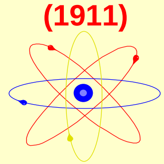



**E = h ν**

**Einstein (1905)**




**Bohr (1911)**



## Announcements

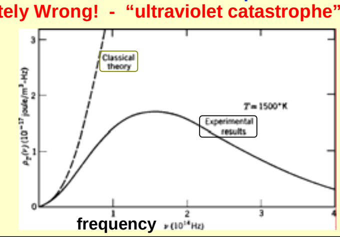
- **Schedule:**
  - **Today: The beginnings of Quantum Mechanics**
    **Planck, Einstein & Bohr**
    **March Chapt. 15**
  - **Next Time: Particles act like waves!**
    **Prince DeBroglie and the wave equation**
    **March Chpt. 16**
    **lightman, Chpt. 4**
- **Report/Essay**
  - **Outline due MONDAY, November 17**

## Introduction

- **Last time: Atoms, Electrons, Nuclei**
  - **Evidence for atoms**
  - **Discovery of the electron**
  - **“Planetary model” with electrons around a small heavy nucleus**
- **Today: Origins of Quantum Theory**
  - **Blackbody radiation: Max Planck (1900)**
  - **Photoelectric effect: Albert Einstein (1905)**
  - **Atomic Model: Niels Bohr (1912)**

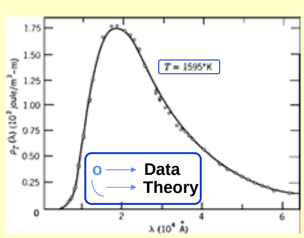
## Blackbody Radiation

- **The true beginnings of the quantum theory lie in a strange place: the frequency spectrum emitted by a solid when it is heated (“blackbody” radiation).**
- **Experimental measurements: the frequency spectrum was well determined.. a continuous spectrum with a shape that depended only on the temperature (light bulb, … )**
- **Theoretical prediction: Classical kinetic theory predicts the energy radiated to increase as the square of the frequency (Completely Wrong! - “ultraviolet catastrophe”).**




## Planck’s Solution

- **Max Planck (1901): In order to describe the data Planck made the bold assumption that light is emitted in packets or quanta, each with energy $E = h\nu$, where $\nu$ is the frequency of the light.**
- **The factor h is now called Planck’s constant, $h = 6.626\ (10^{-27})$ erg-sec.**




## E = h ν

- **The two most important formulas in modern physics**
  **$E = mc^2$ (Einstein – special relativity - 1905)**
  **$E = h\nu$ (Planck – quantum mechanics - 1901)**
- **Planck initially called his theory “an act of desperation”.**
  - **“I knew that the problem is of fundamental significance for physics; I knew the formula that reproduces the energy distribution in the normal spectrum; a theoretical interpretation had to be found , no matter how high.”**
- **Leads to the consequence that light comes only in certain packets or “quanta”**
- **A complete break with classical physics where all physical quantities are always continuous**

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## Photoelectric Effect: The Phenomena

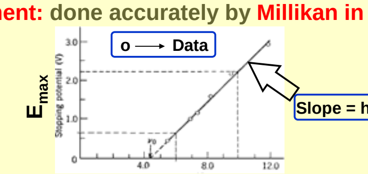
- Einstein took Planck's hypothesis seriously in order to explain the photoelectric effect.
  (Nobel Prize)
  - Effect: Shining light on a metal can liberate electrons from its surface.
  - Experimental facts:
    - Easy for ultraviolet light (high frequency) and difficult for red light (low frequency).
    - Energy of the electrons liberated depends on frequency of light
    - Increasing intensity of light increases number of electrons emitted, but not the energy of each electron
- If light is generated then quantized units, Einstein reasoned that it would also arrive at the metal with quantized amounts of energy

## Photoelectric Effect: The Theory

- Einstein's explanation: Suppose the energy in the light is concentrated in particle-like objects (now we call them photons) whose energy depend on the frequency of the light according to Planck's equation: $E = h\nu$.
- Prediction: Maximum energy of electrons liberated = energy of photon - binding energy of electron.

$$\boxed{E_{max} = h\nu - h\nu_0}$$

- Experiment: done accurately by Millikan in 1916:

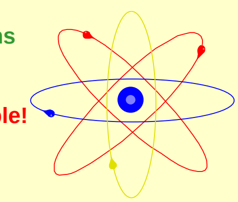



## What is the Significance of h?

- The fact that the slope in Millikan's experiment was equal numerically to Planck's constant establishes the importance of incorporating h into physics in a fundamental way. But how?
- Usual approach: Try to understand h in terms of previous theory (classical physics) applied to atoms.
- Revolutionary approach: Planck's constant h is fundamental - more fundamental than our previous classical conceptions.
- What are the tests?
  - Niels Bohr (1911): atomic spectra: obvious quantum effect (lines, not continuous spectra).
  - Question: how can h explain these spectral lines?

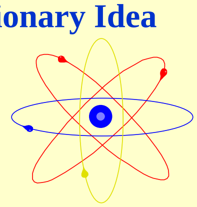
## The Problem of the atom

- Last time we saw that experiments supported the picture that an atom is composed of light electrons around a heavy nucleus
- Problem: if the electrons orbit the nucleus, classical physics predicts they should emit electromagnetic waves and loose energy.
  If this happens, the electrons will spiral into the nucleus!



- The atom would not be stable!
- What is the solution to this problem?

## Bohr's Revolutionary Idea



- Can the new quantum theory explain the stability of the atom?
- If the energies can take on only certain discrete values, I.e., it is quantized, there would be a lowest energy orbit, and the electron is not allowed to fall to a lower energy!
- What is the role of Planck's Constant h?

## Planck's Constant h and the atom

- Bohr (and others) noted that the combination

$$a_0 = (h/2\pi)^2/ me^2$$

has the units of length about the size of atoms

- Bohr postulated that it was not the atom that determined h, but h that determined the properties of atoms!
- Since the electron is bound to the nucleus by electrical forces, classical physics says that the energy should be

$$E = - (1/2)\ e^2/a_0$$

- If the radii are restricted to certain values, the the energy can only have certain values

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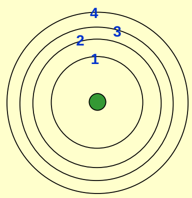
## The Bohr Atom (NOT Correct in detail!)

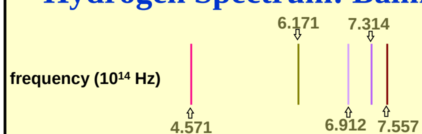
- The allowed orbits are labeled by the integers: $n = 1, 2, 3, 4$.
- The radii of these orbits can be determined from the quantization condition:
  radius = $n^2 a_0 = n^2 (h/2\pi)^2 / me^2$
- The energy can only have the values $E_n = E_1/n^2$, $E_1 = -(1/2)(e^2/a_0)/n^2$
- The spectra are the result of transitions between these orbits, with a single photon ($\nu = E/h$) carrying off the difference in energy E between the two orbits.




## Ideas agree with Experiment

- **Bohr's picture:**
  - The only stable orbits of the electrons occur at definite radii.
  - When in these orbits, contrary to classical E&M, the electrons do not radiate.
  - The radiation we see corresponds to electrons moving from one stable orbit to another.
- **Experiments (already known before 1912)**
  - Experiment: Balmer had previously noticed a regularity in the frequencies emitted from hydrogen:
    $\nu = \nu_0 ((1/n^2) - (1/m^2))$ where n and m are integers.
  - Bohr's Theory: Fits exactly using the value of h determined from other experiments
    Photon carries energy ($=h\nu$) = difference of stable orbits.

## Hydrogen Spectrum: Balmer series



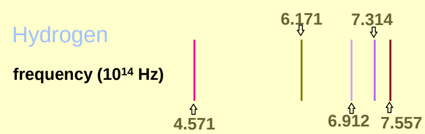

Balmer Formula: $\nu = \nu_0 ((1/n^2) - (1/m^2))$

32.91 ( 1/4 - 1/9 ) = 4.571
32.91 ( 1/4 - 1/16 ) = 6.171
32.91 ( 1/4 - 1/25 ) = 6.911
32.91 ( 1/4 - 1/36 ) = 7.313
32.91 ( 1/4 - 1/49 ) = 7.556

IT WORKS!

## Demonstration: Spectra of different atoms

- Observe spectra of different gases
  - Individual grating for each student
  - Using interference - wave nature of light - to separate the different frequencies (colors)




Neon - strong line in Red
Sodium - strong line in yellow (street lights)
Mercury - strong lines in red, blue (street lights)

## Summary

- A hot body emits light with frequencies that defy the laws of classical physics.
- Max Planck (1900) had the idea that this could be explained if light was emitted in quanta with $E=h\nu$
- Einstein (1905) reasoned that this would also explain the photoelectric effect (light transfers quanta of energy to emitted electrons)
- Niels Bohr (1912) realized the significance that the quantization could explain the stability of the atom
- But at what price?
  - Must give up classical physics - physical properties that are quantized and not continuous is completely different from the ideas of continuous space and time in classical physics
  - Also completely different from Einstein's relativity
- Two most important Eqs in physics: $E = mc^2$ $E=h\nu$