Physics of Electronics:

July – December 2008

Announcements

- Instructor: Patricio (pmena@ing.uchile.cl).
  - Ph.D. in Solid State Physics, University of Groningen,The Netherlands.
  - Group of Astronomical Instrumentation
  - Off. 509. Telf. 9784888

- Slides will be in English BUT lectures in Spanish.

- Assistants still to be determined.

Announcements

- Some (if not all) Thursday lectures will be changed to Monday, since I have to travel frequently to the ALMA site.

ALMA = Atacama Large Millimeter Array
(66 radio telescopes at 5000 m using the latest technology)

Overview of the Course

- **Review of Quantum Mechanics.**
- **Electronic processes.**
- **Semiconductors**
- **P-n junction.**
- **Bipolar Transistors.**
- **JFET's.**
- **MOSFET's.**
- **SCR´s.**
- **Fabrication technology.**

Semiconductor devices

Literature

- Basic:
  - J.Allison, *"Electronic Engineering: Semiconductors and Devices,"* London: Mc Graw Hill International Editions, 1990.
- Additionally, any other book on semiconductor physics and solid state physics like:
  - A. van der Ziel, *"Electrónica Fsica del Estado Sólido,"* New Jersey: Prentice/Hall International, 1972.
  - C. Kittel, *"Introduction to Solid State Physics,"* New York: John Willey & Sons, 1996.

1. Introduction to Quantum Mechanics

Contents overview

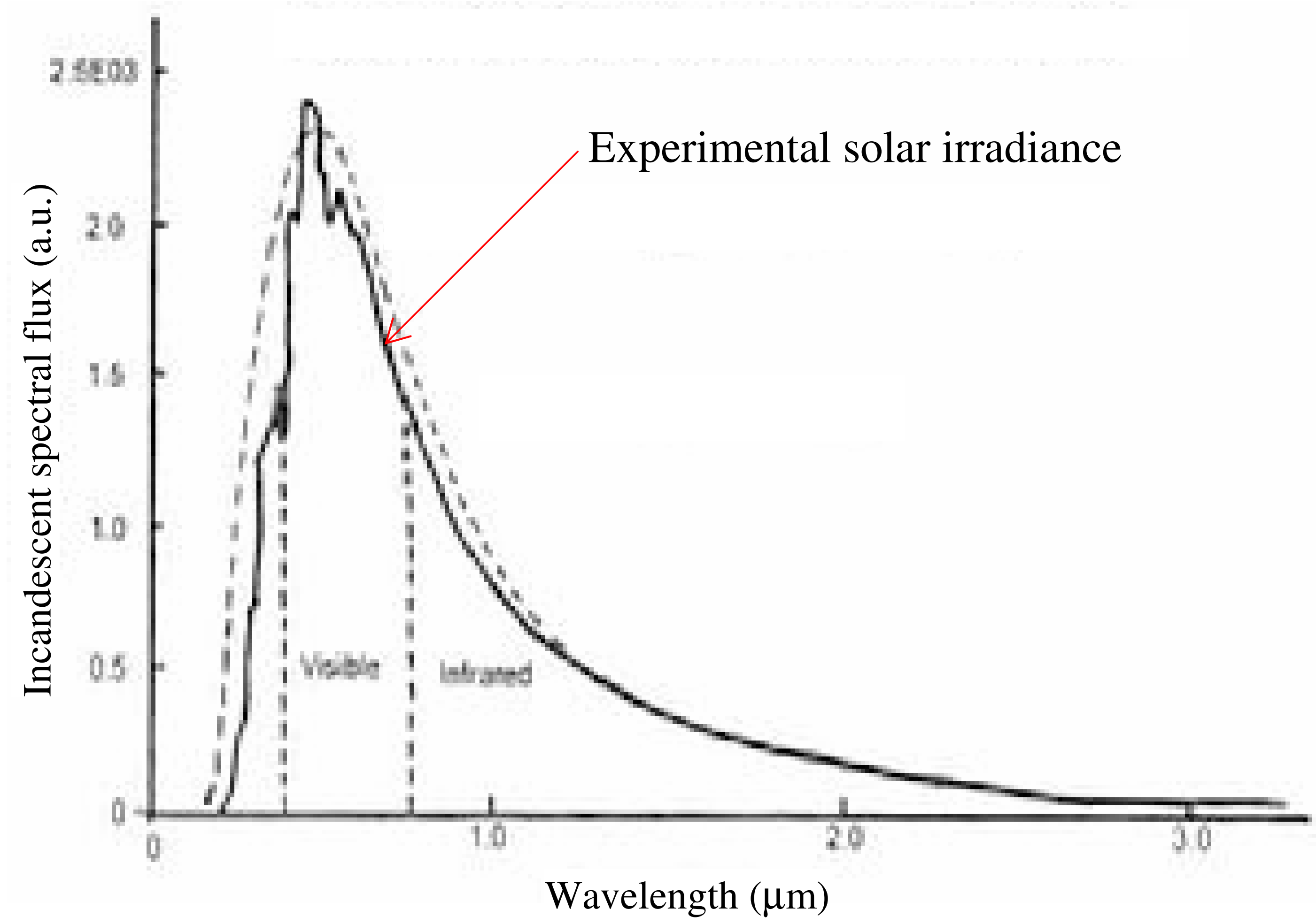
- Introduction
- Blackbody radiation
- Photoelectric effect
- Bohr atom
- Wavepackets
- Schrödinger equation
- Interpretation of wavefunction
- Uncertainty principle
- Beams of particles and potential barriers

Introduction

- What does explain the (electrical, magnetic, thermal) properties of solids?
  - Metals (conductors)
  - Semiconductors
  - Insulators
  - Superconductors
- It is explained by the behavior of the constituent electrons and their interactions inside the structure of the solid.
- To study them we need Quantum Mechanics (as opposed to Newtonian Mechanics).

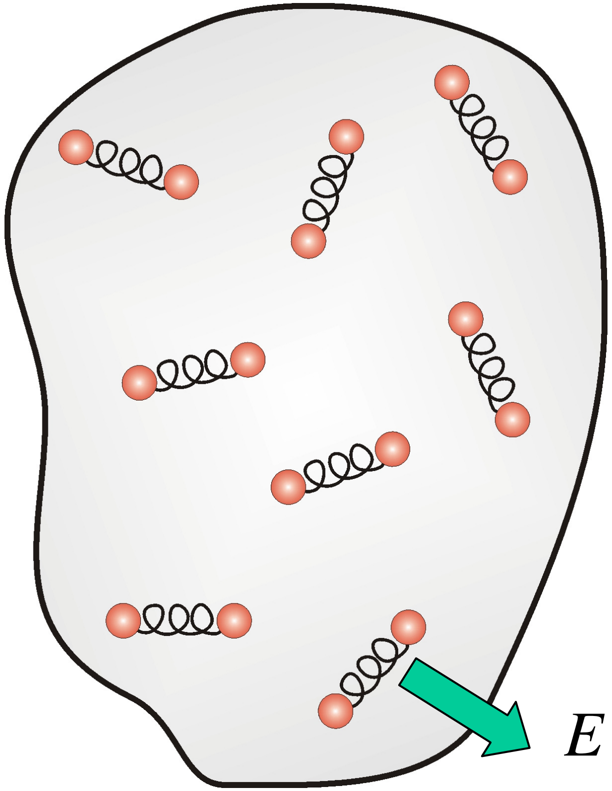
Blackbody Radiation

- Radiation emitted by an incandescent radiator (example the Sun):



Blackbody Radiation

- One can model the radiation of a blackbody by assuming that it is formed by atomic oscillators emitting energy:



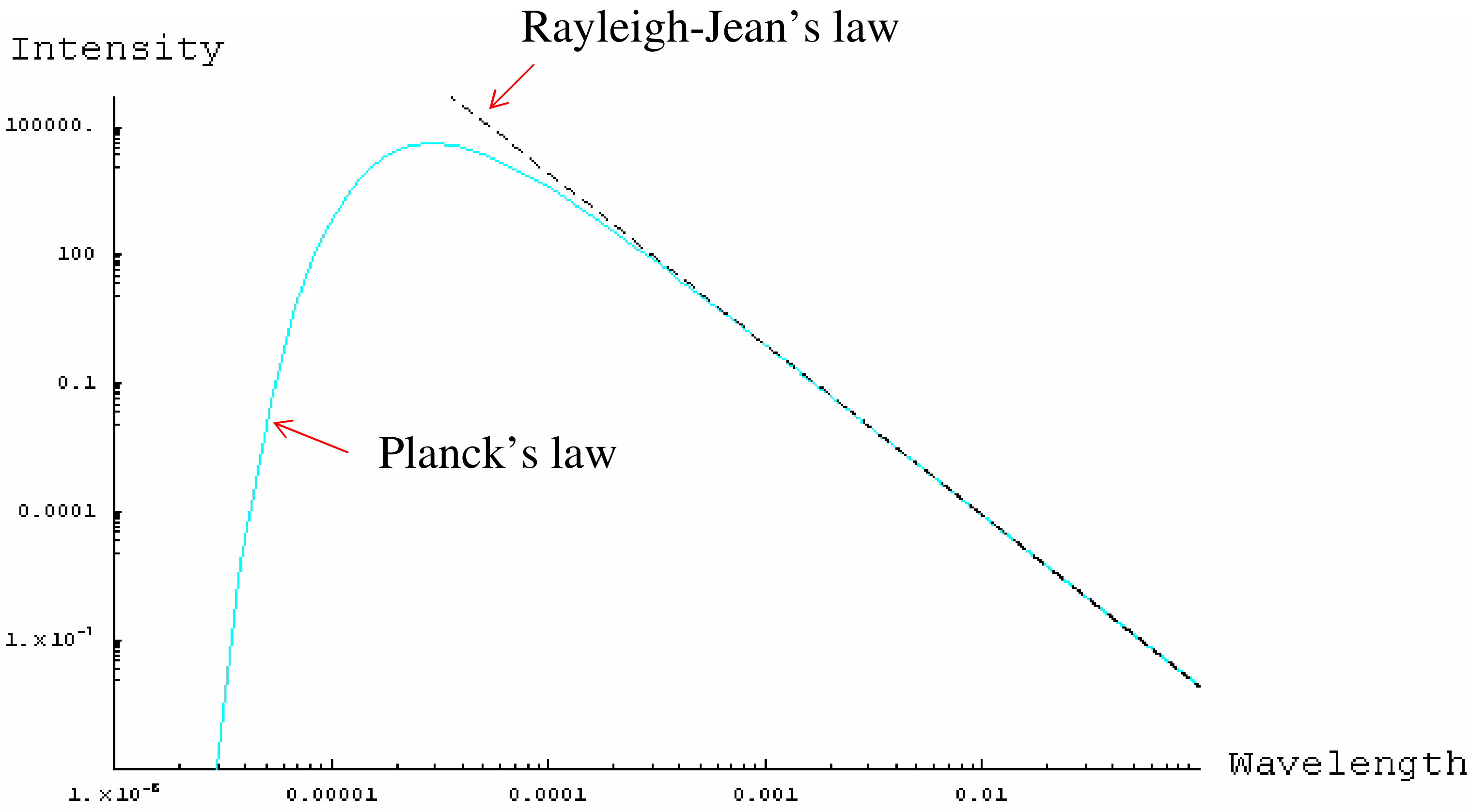
• Classical theory (Rayleigh-Jean's law):
Oscillators emit energy in a continuos way

• Quantum theory (Planck's law):
Oscillators emit energy in a discret way

$$E = 0, \quad \hbar\omega, \quad 2\hbar\omega, \quad 3\hbar\omega, \quad \ldots, \quad n\hbar\omega$$

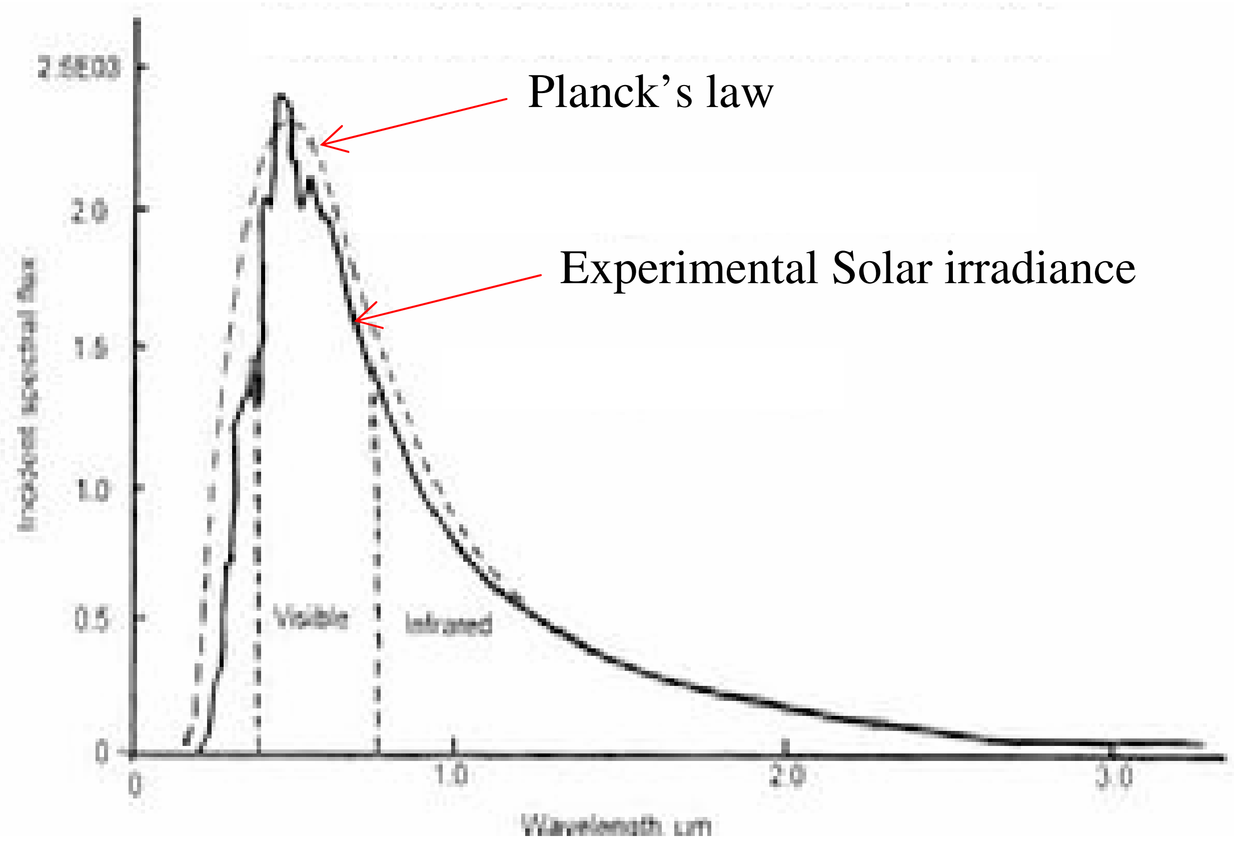
Blackbody Radiation

- One can model the radiation of a blackbody by assuming that it is formed by atomic oscillators emitting energy:



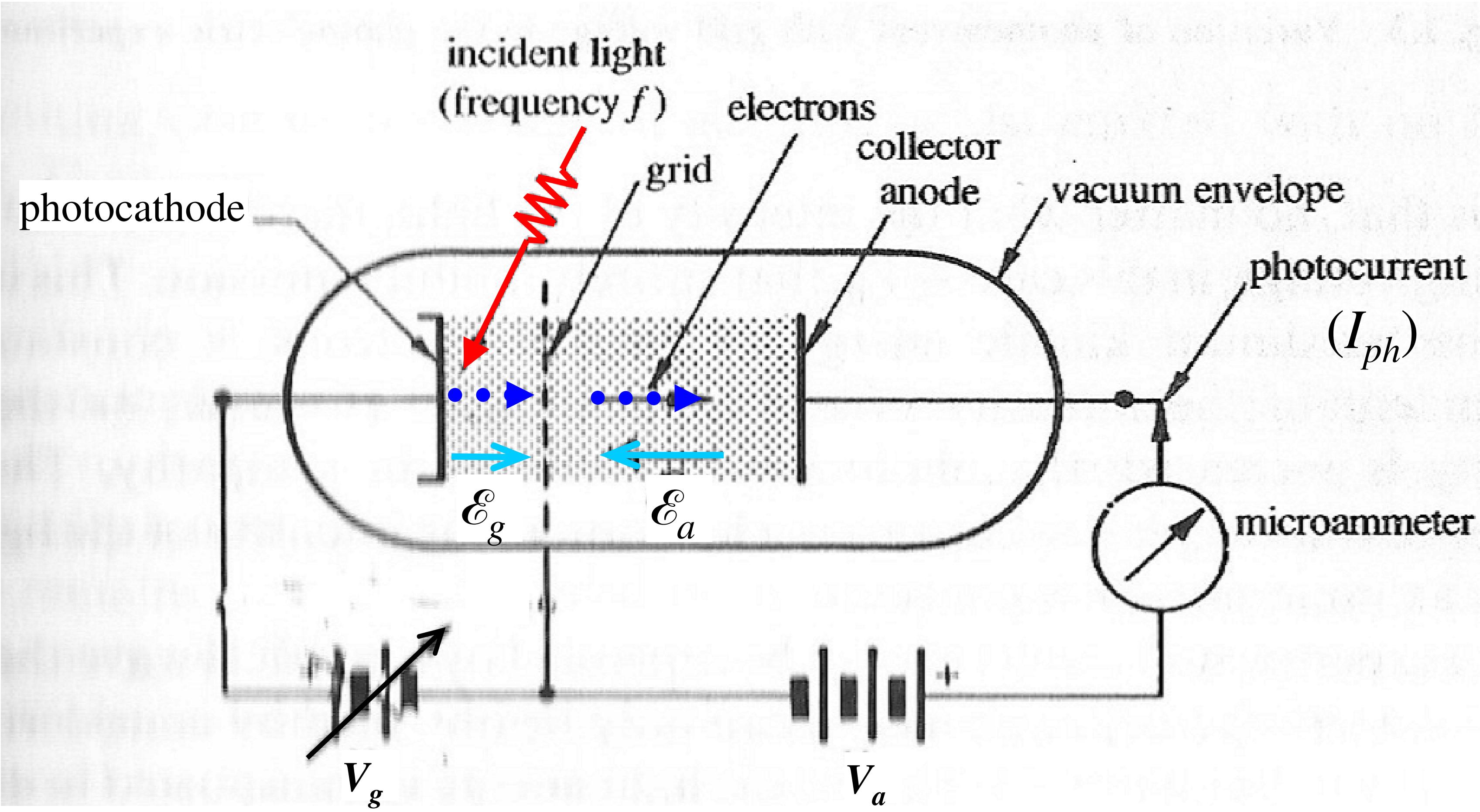
Blackbody Radiation

- One can model the radiation of a blackbody by assuming that it is formed by atomic oscillators emitting energy:



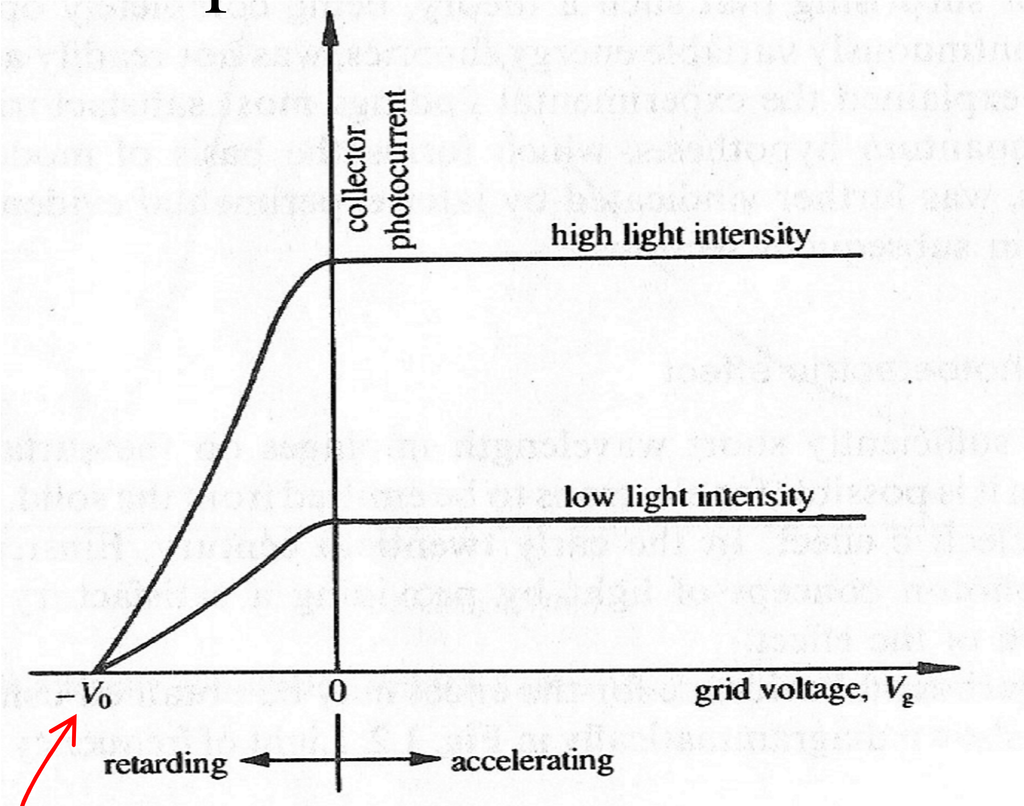
Photoelectric Effect

- Experimental setup



Photoelectric Effect

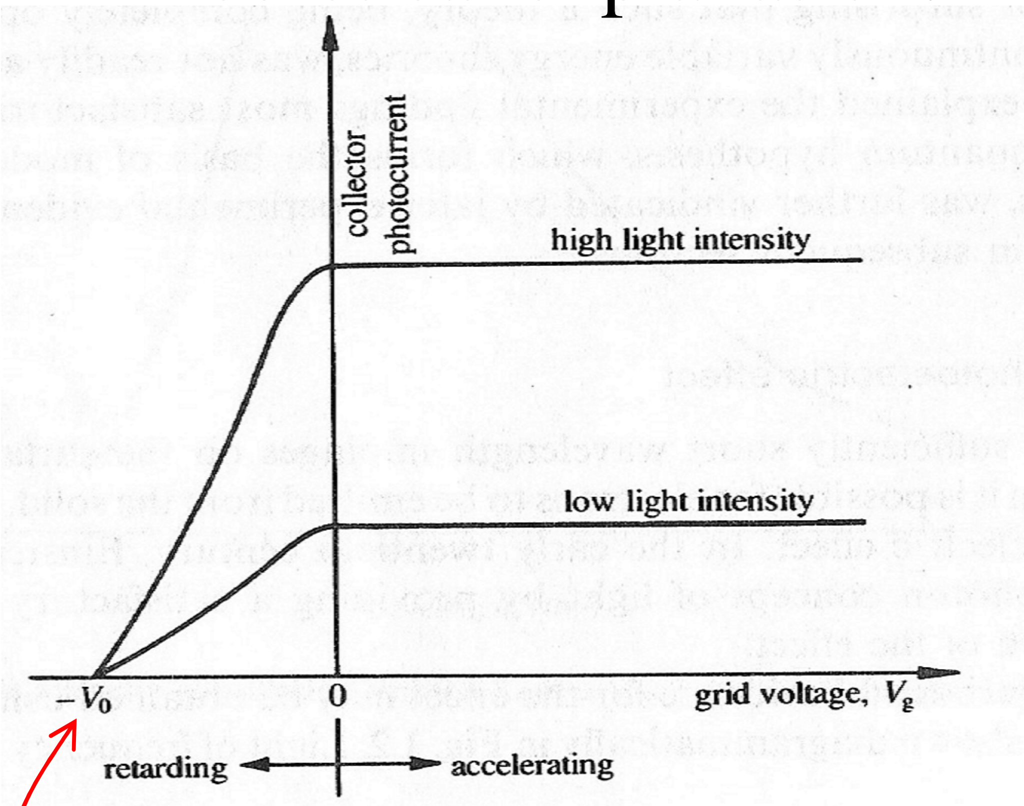
- Experimental results



Independent of
light intensity

Photoelectric Effect

- Theoretical explanation:



Independent of light intensity

It is assumed that light energy is quantized:

$$\tfrac{1}{2}mv^2 = hf - e\phi$$

- Minimum energy to emit an electron:

$$f = f_0 = e\phi/h$$

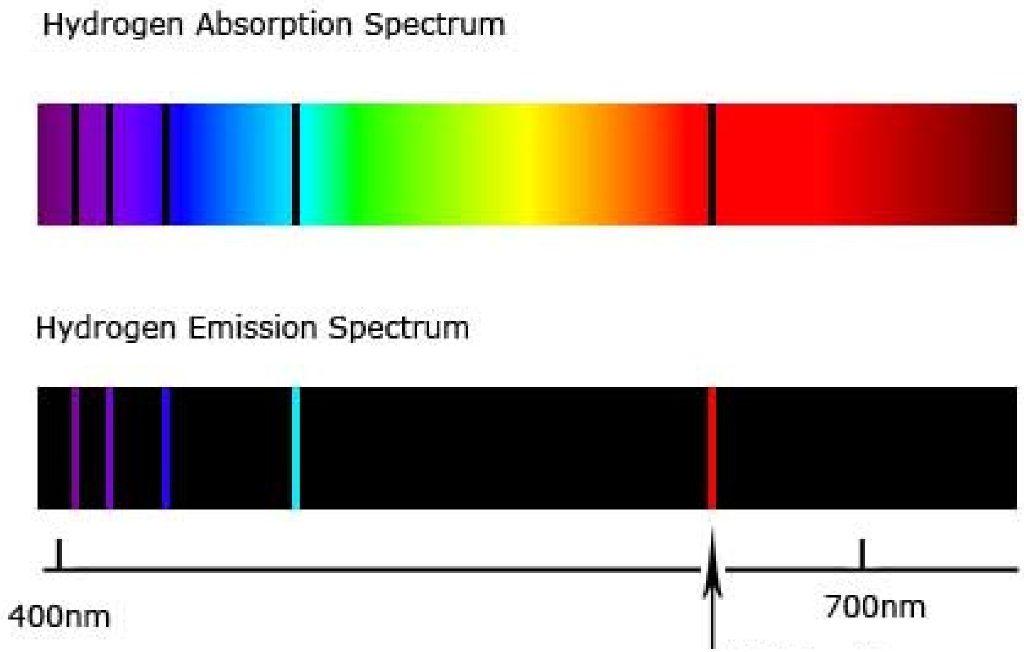
- When $I_{ph} = 0$:

$$eV_0 = hf - e\phi$$

∴ When interacting with matter light to be considered as a particle.

Bohr Atom

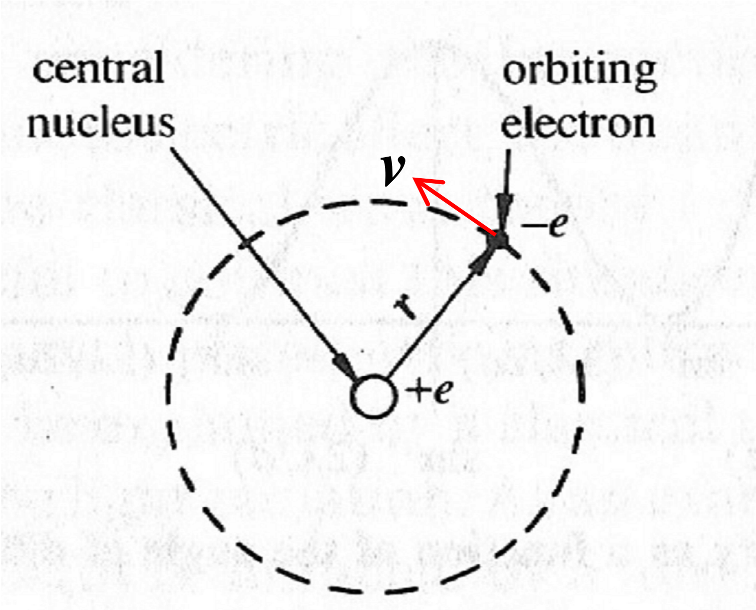
- Experimental fact:
  - An excited hydrogen atom emits radiation at a discrete energies.



From: http://www.solarobserving.com/halpha.htm

Bohr Atom

- Simplest theoretical explanation:
  1. In the hydrogen atom, the electron can only exist in stable (non-radiating) orbits whose angular moment are quantized.



$$L = mvr = n\hbar \qquad \text{where } n = 1, 2, 3, \ldots$$

Which implies the existence of discrete orbits of radius:

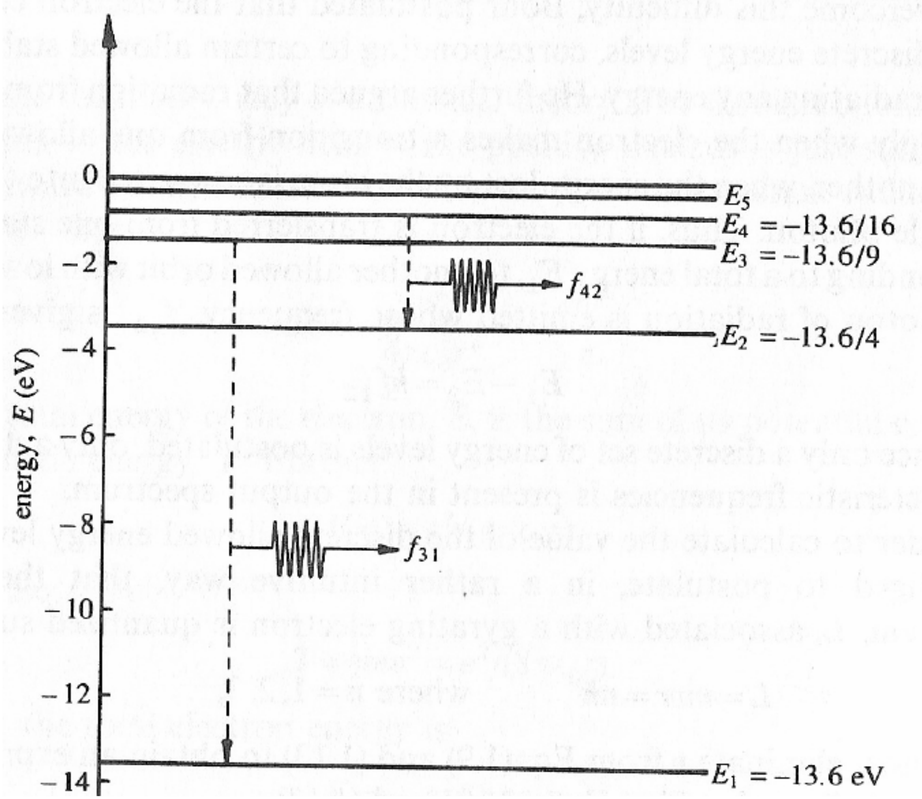
$$r_n = \frac{4\pi n^2 \hbar^2 \epsilon_0}{e^2 m} = \frac{n^2 h^2 \epsilon_0}{\pi e^2 m} \simeq 0.05 n^2 \text{ nm}$$

With energies ($E = T + V$):

$$E_n = -\frac{e^2}{8\pi\epsilon_0} \frac{\pi e^2 m}{n^2 h^2 \epsilon_0} = -\frac{me^4}{8\epsilon_0^2 h^2 n^2} \simeq -\frac{13.6}{n^2} \text{eV}$$

Bohr Atom

- Simplest theoretical explanation:
  2. Radiation occurs only when electron moves from one allowed orbit to another. Energy lost by the atom is converted in a single photon:



$$E_n \simeq -\frac{13.6}{n^2}\,\mathrm{eV}$$

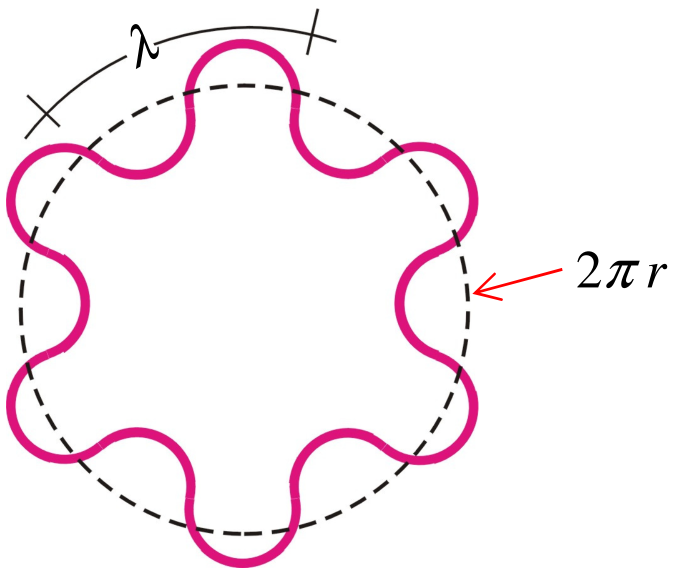
$$E_1 - E_2 = hf_{12}$$

Particle-Wave Duality

- De Broglie hypothesis:
  - For a photon we have:

$$p = E/c \Longrightarrow p = h/\lambda$$

  - De Broglie hypothesized that $p = h/\lambda$ also holds for particles. This can be seen from the Bohr atom:

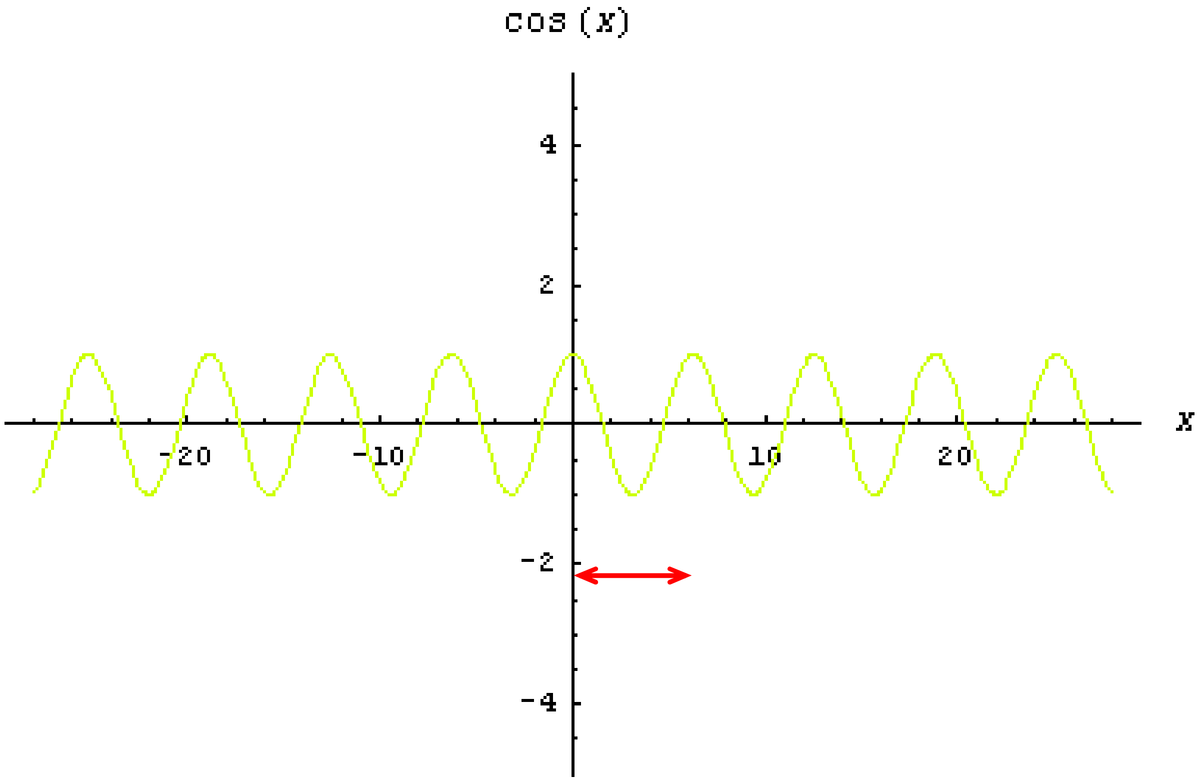


$$2\pi r = n\lambda \Longrightarrow p = h/\lambda$$

Wavepackets

- Consider the juxtaposition of waves, A cos(ωt-βx), of slightly different wavelength:

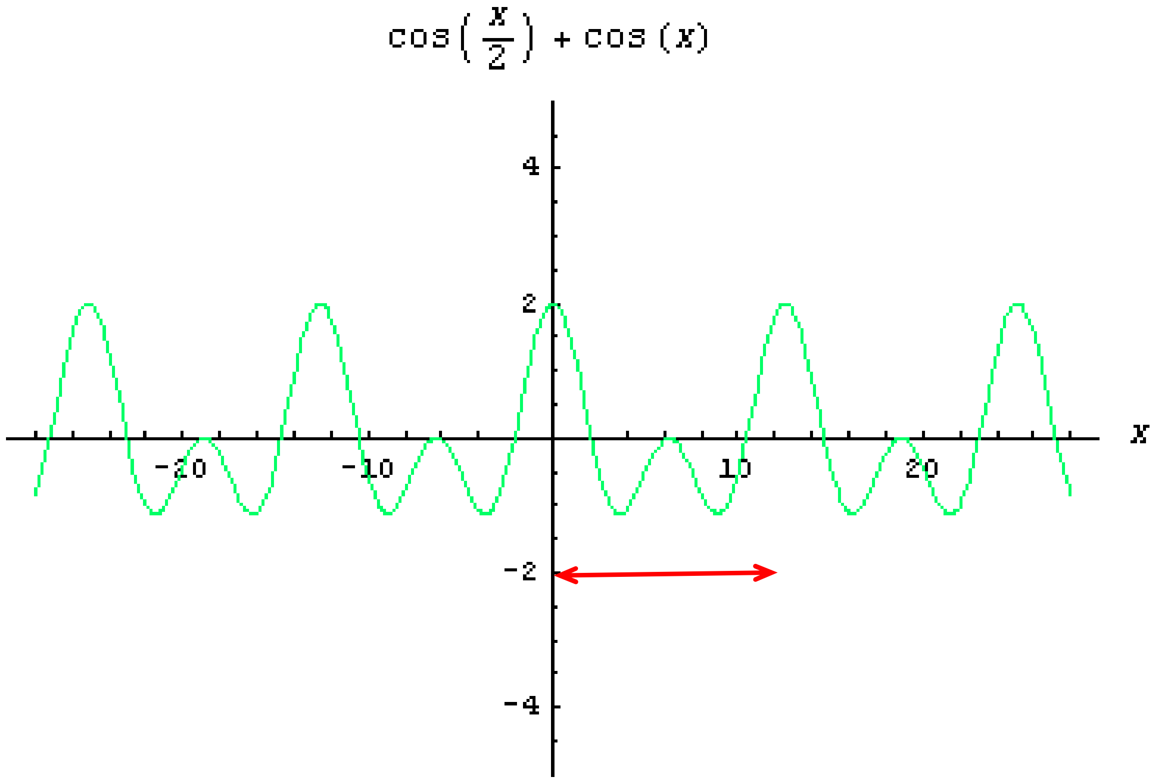
t = 0
n = 1



Wavepackets

- Consider the juxtaposition of waves, A cos(ωt-βx), of slightly different wavelength:

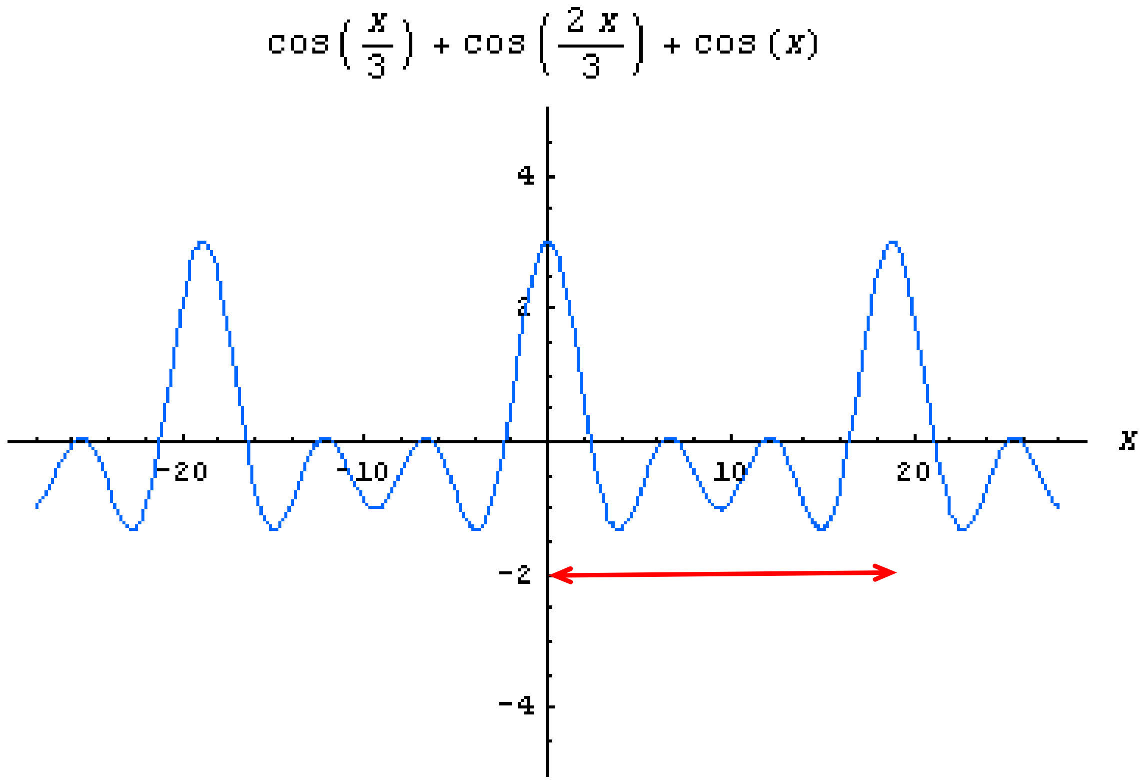
t = 0
n = 2



Wavepackets

- Consider the juxtaposition of waves, A cos(ωt-βx), of slightly different wavelength:

t = 0
n = 3

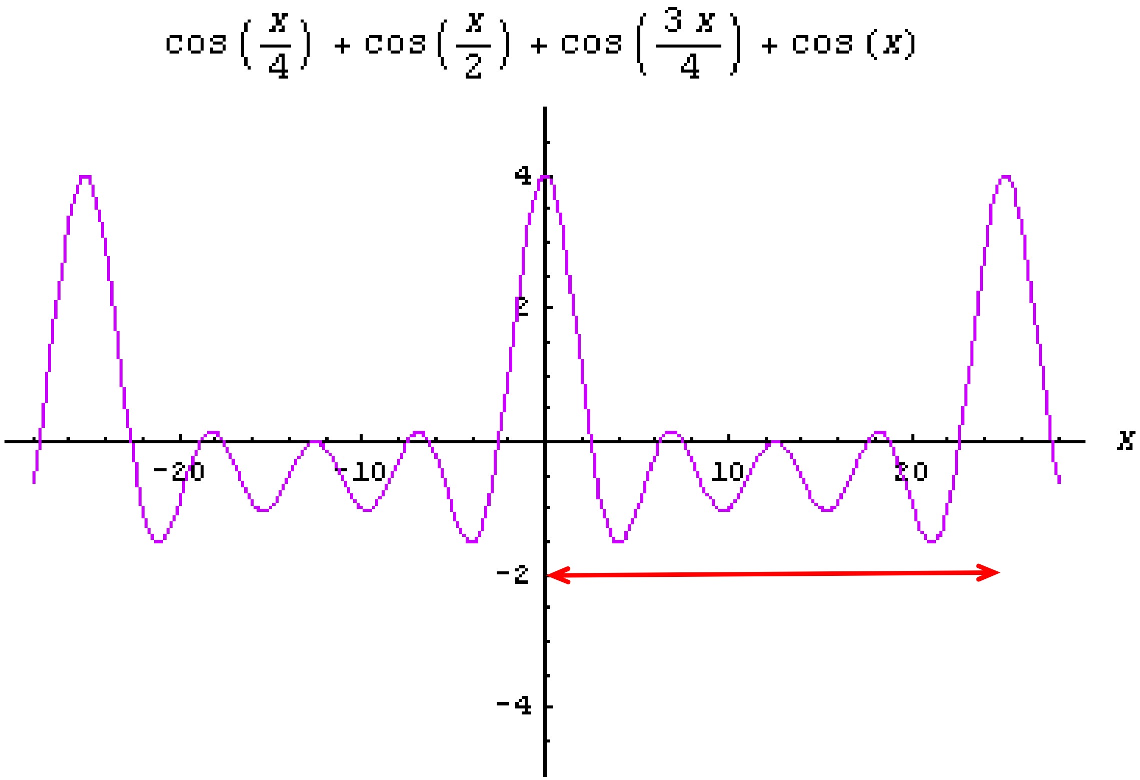


Wavepackets

- Consider the juxtaposition of waves, A cos(ωt-βx), of slightly different wavelength:

t = 0

n = 4



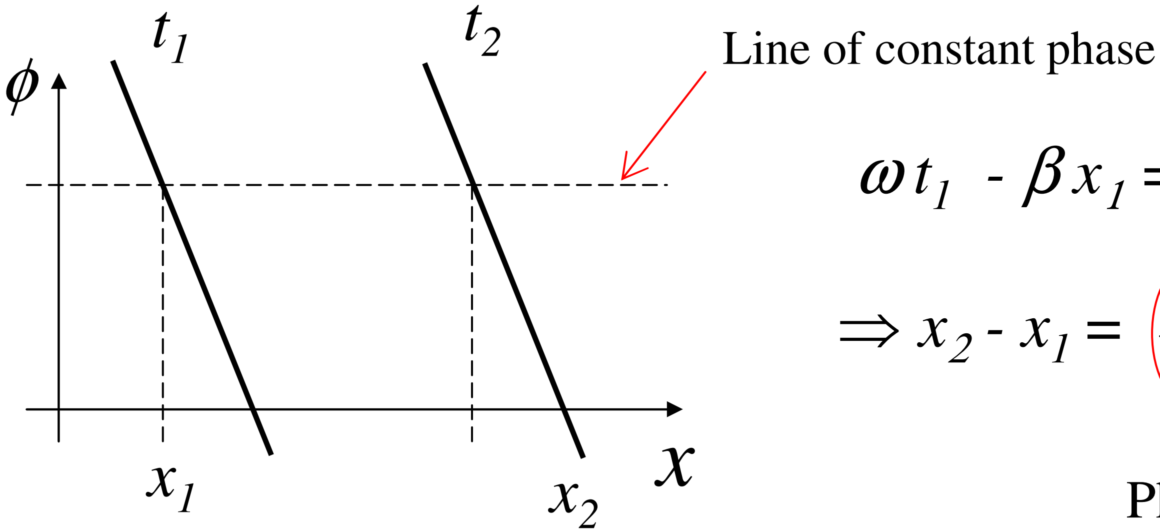
A wavepacket is formed when $n \rightarrow \infty$

Wavepacket ≡ wave (superposition of waves) + particle (localization)

Wavepackets

- Consider a wave: $A_o \cos(\omega t - \beta x) \Leftrightarrow A_o e^{[i(\omega t - \beta x)]}$
  - Phase velocity: velocity of planes of constant phase

phase: $\phi = \omega t - \beta x$



$$\omega t_1 - \beta x_1 = \omega t_2 - \beta x_2$$

$$\Rightarrow x_2 - x_1 = \frac{\omega}{\beta}(t_2 - t_1)$$

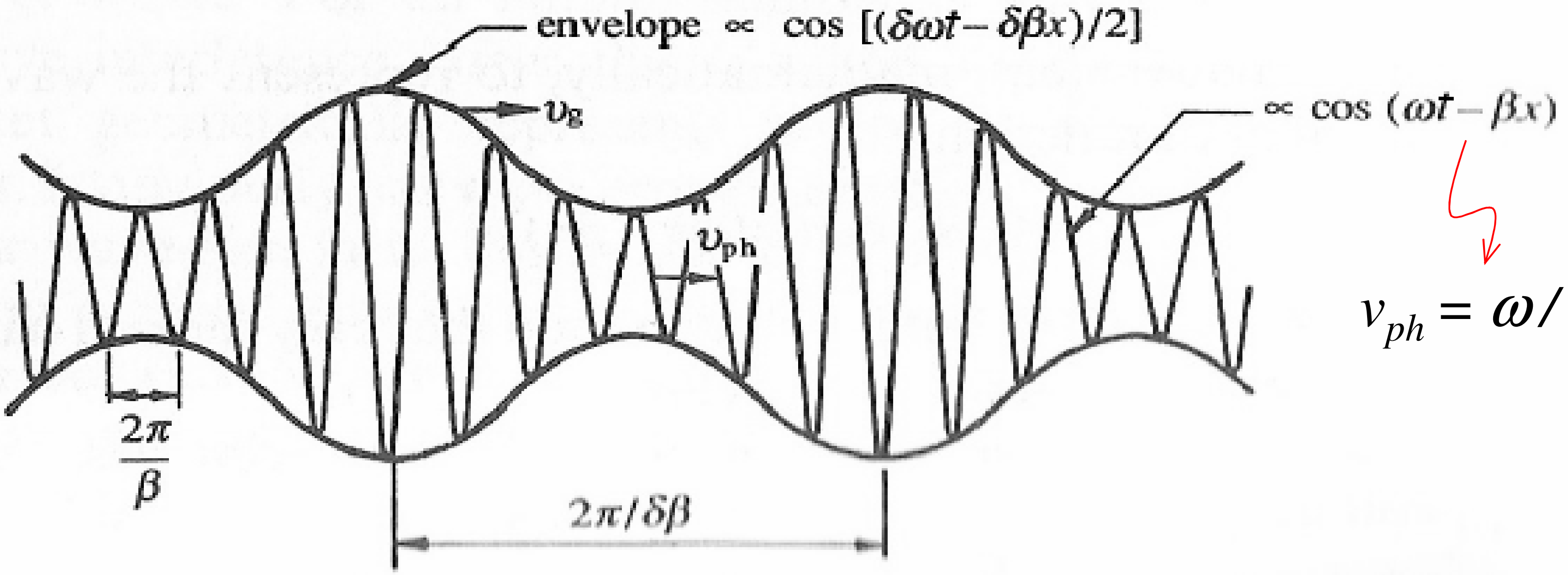
Phase velocity

Wavepackets

- Consider superposition of two waves:

$$\begin{aligned}
&A_0 \cos(\omega t - \beta x) + A_0 \cos[(\omega + \delta\omega)t - (\beta + \delta\beta)t] \\
&\quad = 2A_0 \cos\{\tfrac{1}{2}[(2\omega + \delta\omega)t - (2\beta + \delta\beta)t]\} \cos[\tfrac{1}{2}(\delta\omega t - \delta\beta x)] \\
&\quad \simeq 2A_0 \cos[\tfrac{1}{2}(\delta\omega t - \delta\beta x)] \cos(\omega t - \beta x)
\end{aligned}$$

$$v_g = \delta\omega / \delta\beta$$



$$v_{ph} = \omega / \beta$$

Wavepackets

- Associating a wavepacket to a particle:
  - From De Broglie and Bohr relations:

$$\beta = \frac{2\pi}{\lambda} = \frac{2\pi p}{h} = \frac{p}{\hbar}$$

$$\omega = \frac{2\pi T}{h} = \frac{T}{\hbar}$$

$$\Rightarrow \quad \psi = A_0 \exp[-j(Tt - px)/\hbar]$$

  - Phase and group velocity are:

$$v_{ph} = \frac{\omega}{\beta} = \frac{T}{p} = \frac{\frac{1}{2}mv^2}{mv} = \frac{v}{2} \qquad v_g = \partial\omega/\partial\beta = v$$

  - The wavepacket ψ is called **wavefunction**

Wavepackets

- Associating a wavepacket to a particle:
  - From De Broglie and Bohr relations:

$$\beta = \frac{2\pi}{\lambda} = \frac{2\pi p}{h} = \frac{p}{\hbar}$$

$$\omega = \frac{2\pi T}{h} = \frac{T}{\hbar}$$

$$\Rightarrow \quad \psi = A_0 \exp[-\mathrm{j}(Tt - px)/\hbar]$$

  - In general a particle has also potential energy, therefore its wavefunction will be:

$$\psi = A_0 \exp[-\mathrm{j}(Et - px)/\hbar]$$

where $E = T + V$

Schrödinger Equation

- It is similar to Newton's equation. It describes the behavior of the wavefunction of a particle (and in general of any quantum system).
- Since we are describing a wave, SE should have the form of the well known wave equation that describe, for example, the EM field:

$$\frac{\partial^2 H}{\partial x^2} = \epsilon\mu \frac{\partial^2 H}{\partial t^2} \quad \Longleftrightarrow \quad H = H_0 \exp[-j(\omega t - \beta x)]$$

Schrödinger Equation

- Time-dependant SE:
  - Starting from $\psi = A_0 \exp[-\mathrm{j}(Et - px)/\hbar]$
  - By deriving once respect to time and twice respect to the position, the time-dependent SE can be obtained:

$$\boxed{\frac{\partial^2 \psi}{\partial x^2} - \frac{2m}{\hbar^2} V\psi + \mathrm{j}\frac{2m}{\hbar}\frac{\partial \psi}{\partial t} = 0}$$

  - Generalizing to 3D:

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + \frac{\partial^2 \psi}{\partial z^2} - \frac{2m}{\hbar^2} V\psi + \mathrm{j}\frac{2m}{\hbar}\frac{\partial \psi}{\partial t} = 0$$

  - Given a potential energy and the mass of the system, this equation can be solved.

Schrödinger Equation

- Time-independent SE:
  - **If** V is time independent, we can assume the following form of the wavefunction (variable separation):

$$\psi = \Psi(x)\Gamma(t)$$

  - Then replacing it in the time-dependent SE:

$$\frac{\hbar^2}{2m}\frac{1}{\Psi}\frac{d^2\Psi}{dx^2} - V = -j\frac{\hbar}{\Gamma}\frac{d\Gamma}{dt} = C$$

  - Two independent equations (one in x, one in t).

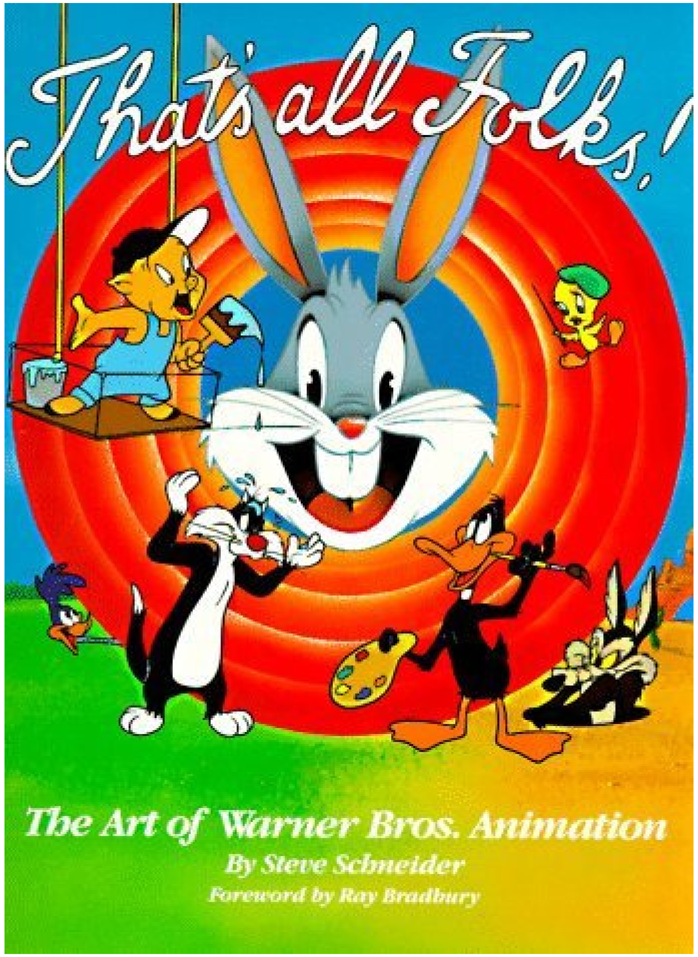
Schrödinger Equation

- Time-independent SE:
  - Solving the one in t:

$$\Gamma(t) = \exp(-jEt/\hbar)$$

  - The one in x is, then:

$$\boxed{\frac{d^2\Psi}{dx^2} + \frac{2m}{\hbar^2}(E - V)\Psi = 0}$$



That´s all folks!!

(for today)