Physics of Electronics:

July – December 2009

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.
- Unfortunately, the time of the lectures has to be changed for the second part of the course.

Announcements

- Some Thursday lectures will be changed to Monday, since I have to travel to the ALMA site.

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

Announcements

- Grading:
  - 60% Tests (all tests will be taken into account)
    - 2/3 Normal Tests
    - 1/3 Final Exam
  - 40% Exercises

Literature

- Basic:
  - J.Allison, *"Electronic Engineering: Semiconductors and Devices,"* London: Mc Graw Hill Int. Ed., 1990.
- Complementary books:
  - A. van der Ziel, *"Electrónica Física del Estado Sólido,"* New Jersey: Prentice/Hall International, 1972.
  - C. Kittel, *"Introduction to Solid State Physics,"* New York: John Willey & Sons, 1996.
  - B. van Zeghbroeck, *"Principles of Semiconductor Devices,"* http://ecee.colorado.edu/~bart/book/book/index.html

Overview of the Course

- **Review of Quantum Mechanics.**
- **Electronic processes.**
- **Semiconductors.**
- **Semiconductor devices:**
  - **P-n junction.**
  - **Bipolar Transistors.**
  - **JFET's. MOSFET's. SCR´s.**
  - **Fabrication technology.**
- **Introduction to superconductor devices.**

1. Introduction to Quantum Mechanics

Contents overview

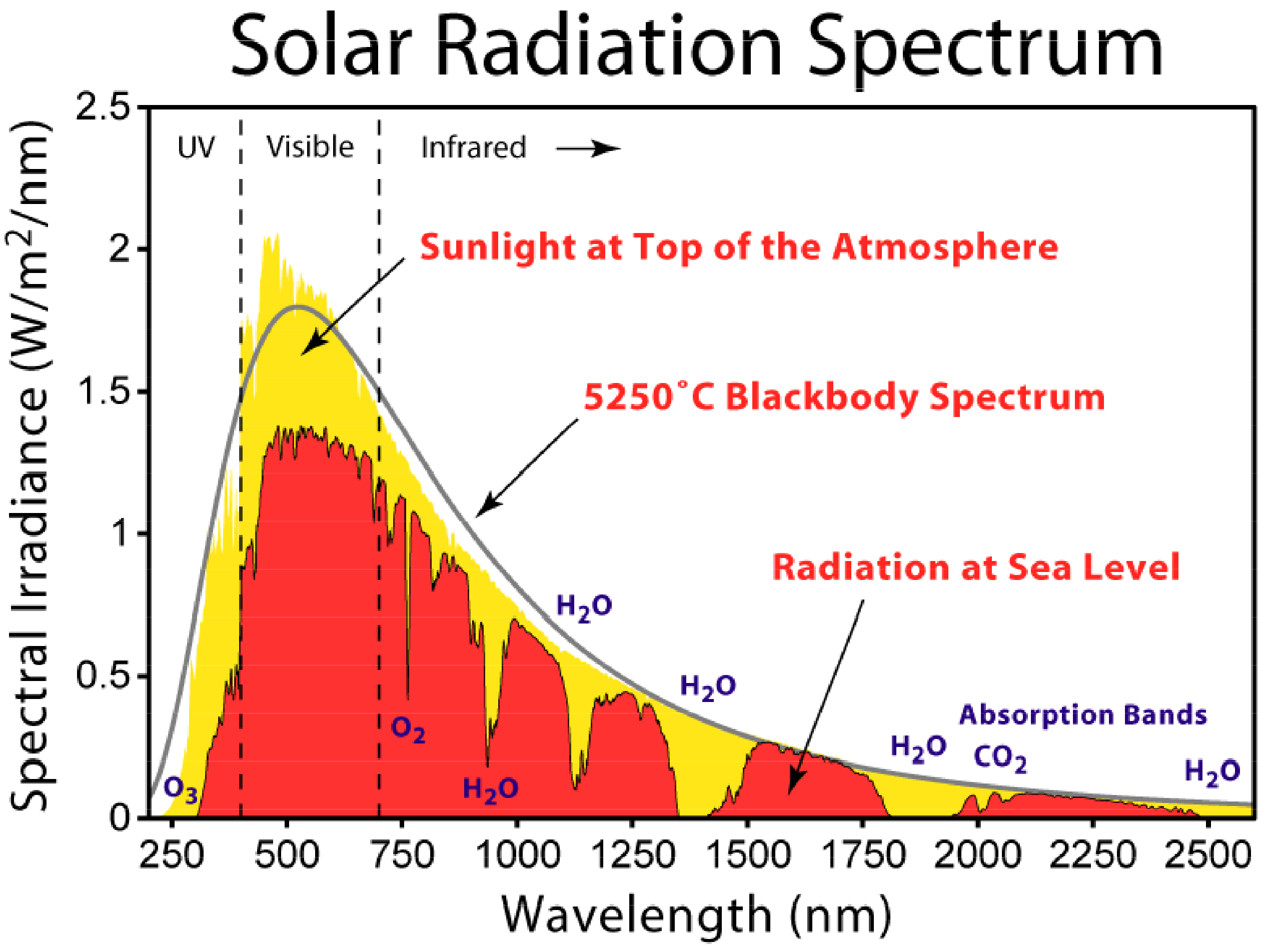
- Introduction
- Blackbody radiation
- Photoelectric effect
- Bohr atom
- Wavepackets
- Schrödinger equation
- Interpretation of wavefunction
- Uncertainty principle
- Beams of particles and potential barriers

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).

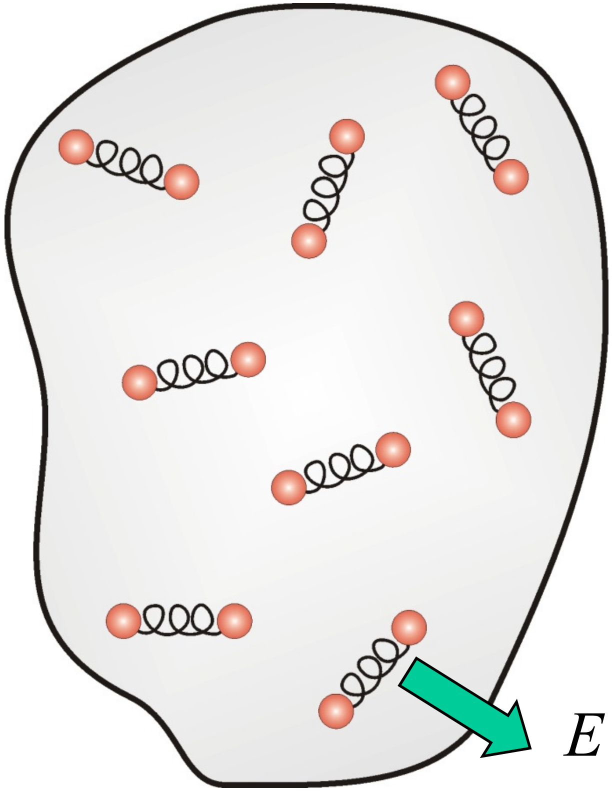
Blackbody Radiation

- 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

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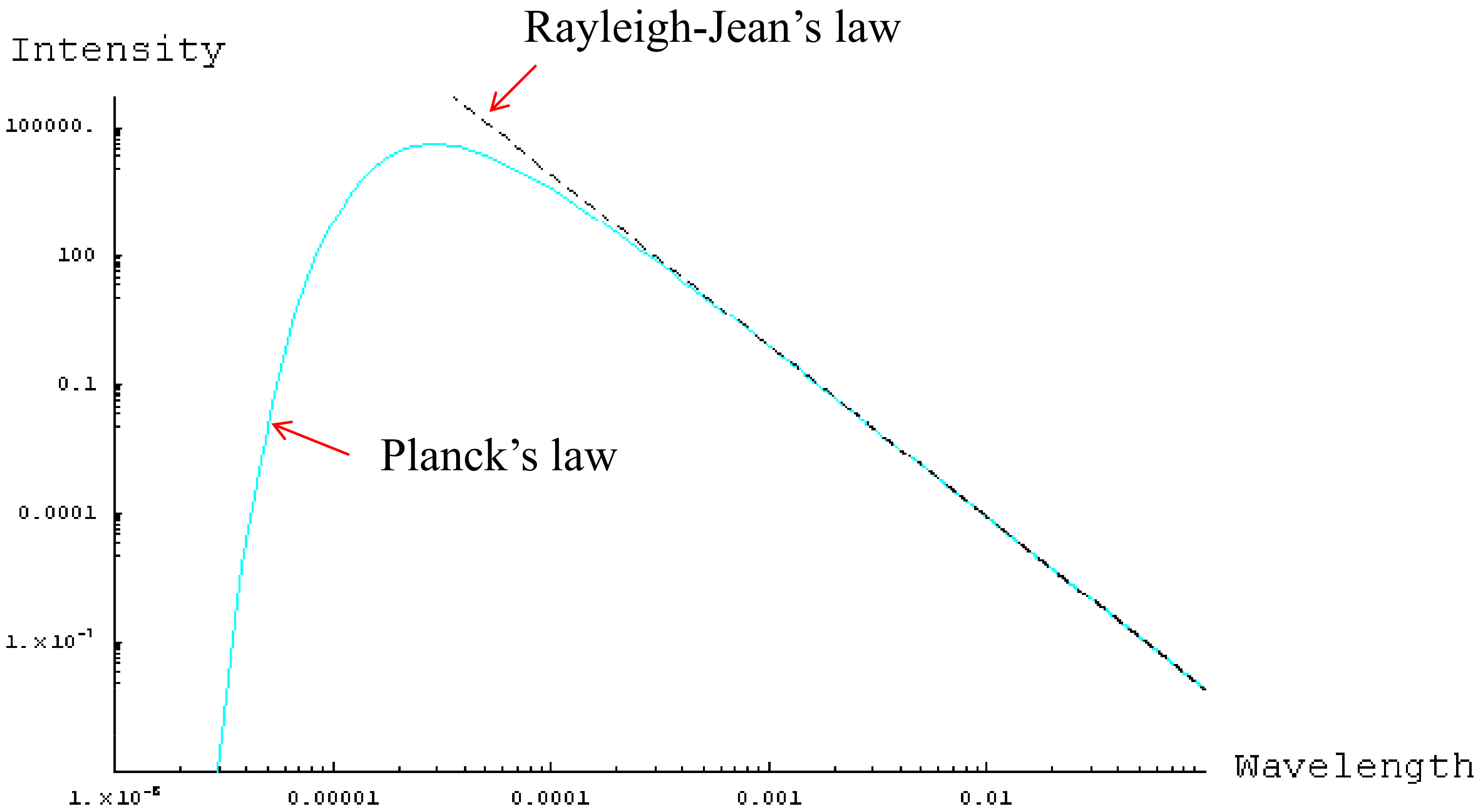
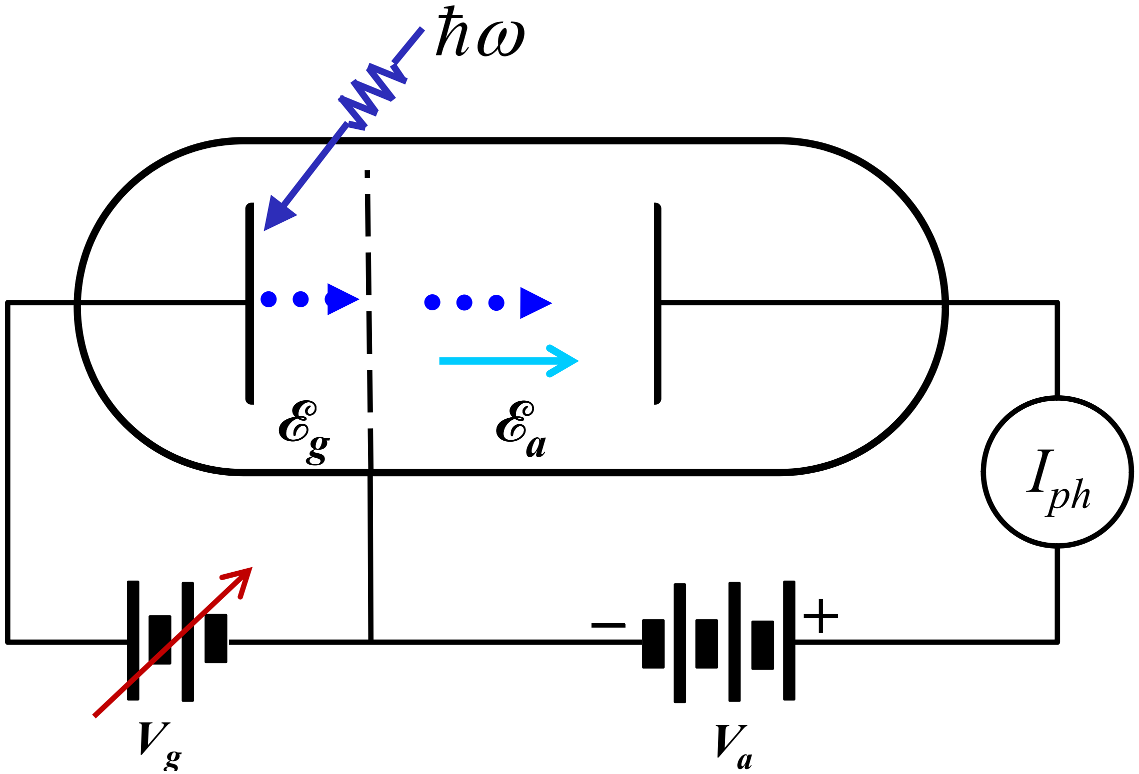


Photoelectric Effect

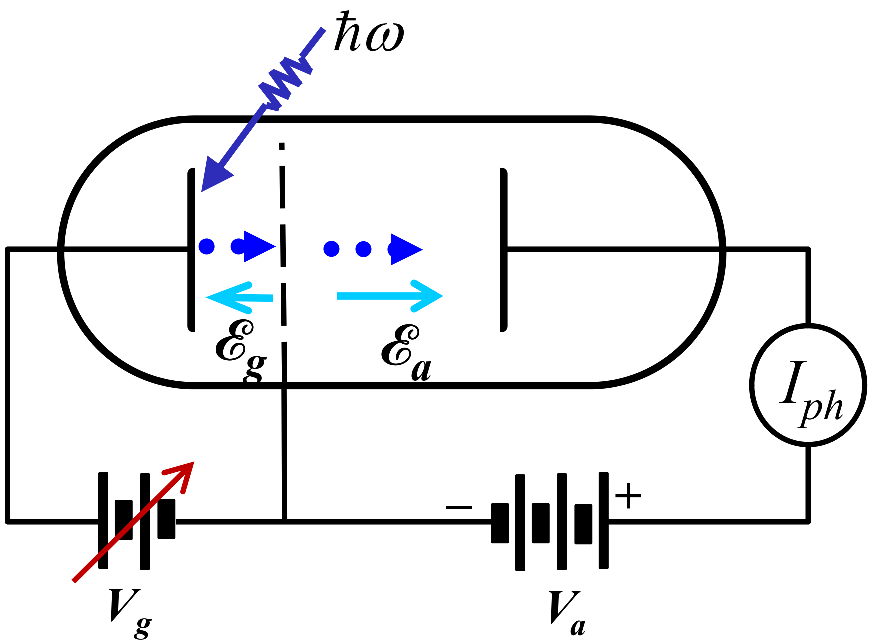
- Experimental setup

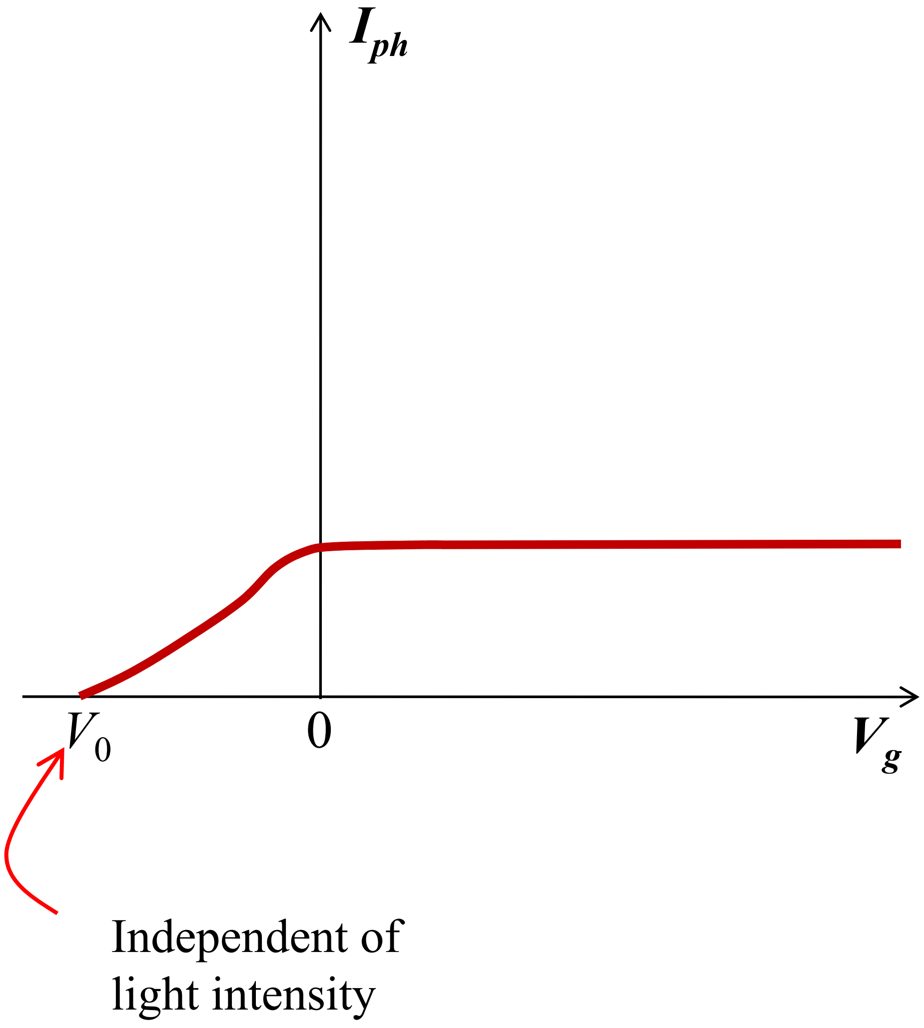


http://phet.colorado.edu/simulations/sims.php?sim=Photoelectric_Effect

Photoelectric Effect

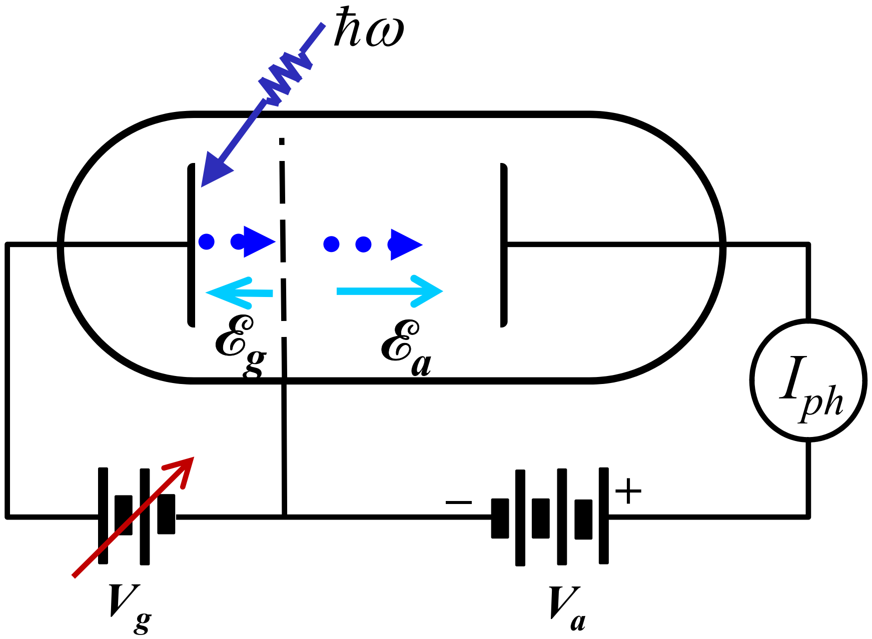
- Experimental results

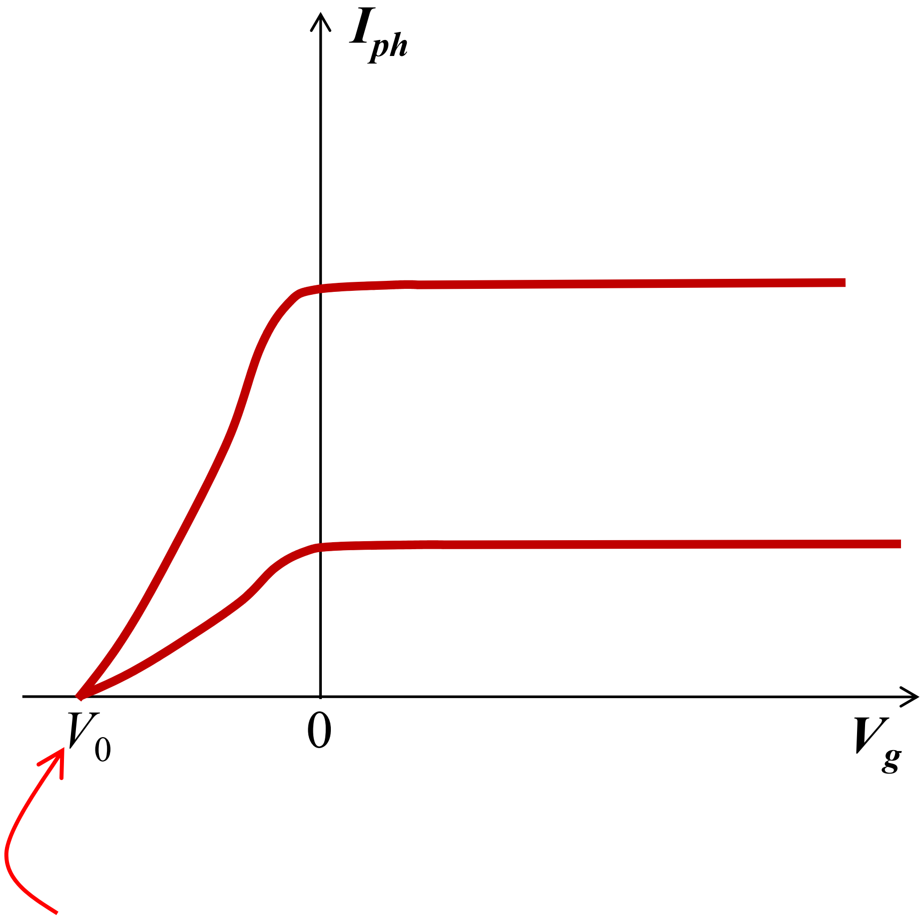




Photoelectric Effect

- Experimental results





Independent of
light intensity

Photoelectric Effect

- Experimental results

It is assumed that light energy is quantized:

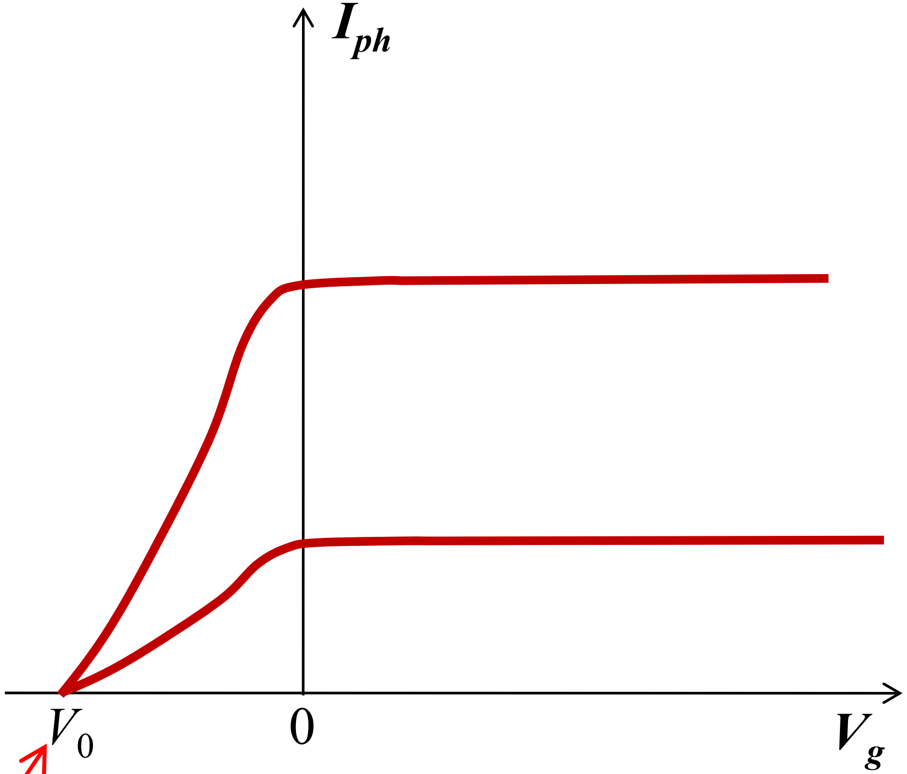
$$\tfrac{1}{2}mv^2 = hf - e\phi$$

• Minimum energy to emit an electron:

$$f = f_0 = \frac{e\phi}{h}$$

• When $I_{ph} = 0$:

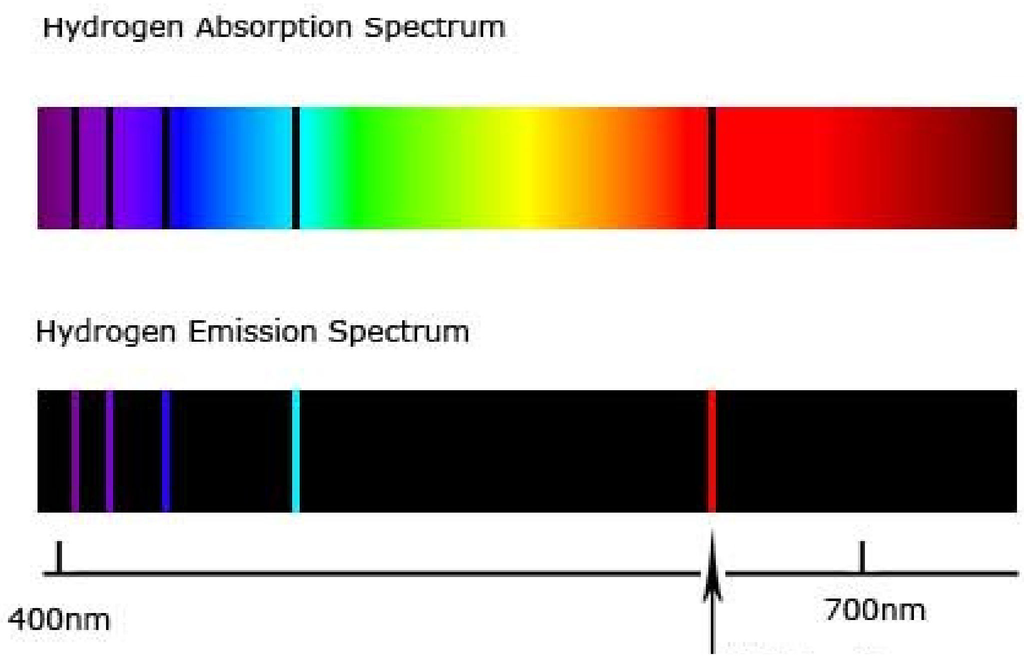
$$eV_0 = hf_0 - e\phi$$



Independent of light intensity

Bohr Atom

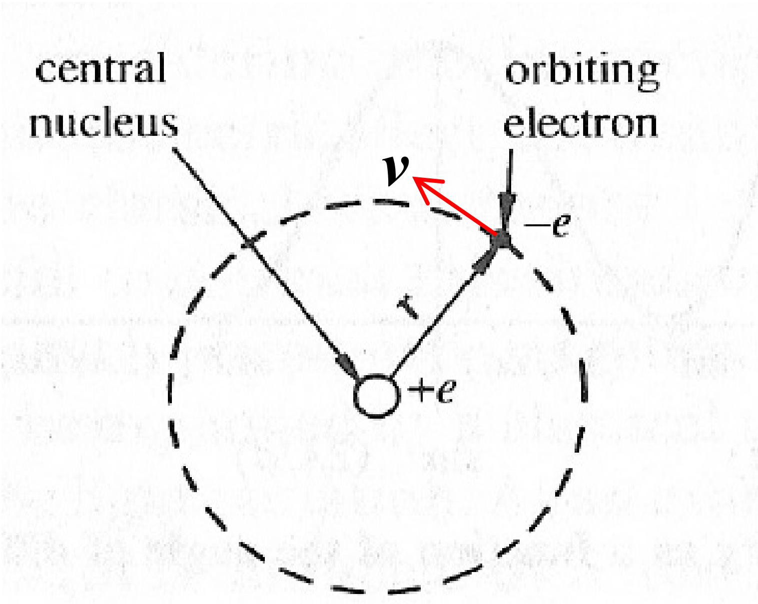
- Experimental fact:
  - An excited hydrogen atom emits radiation at a discrete energies.



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:

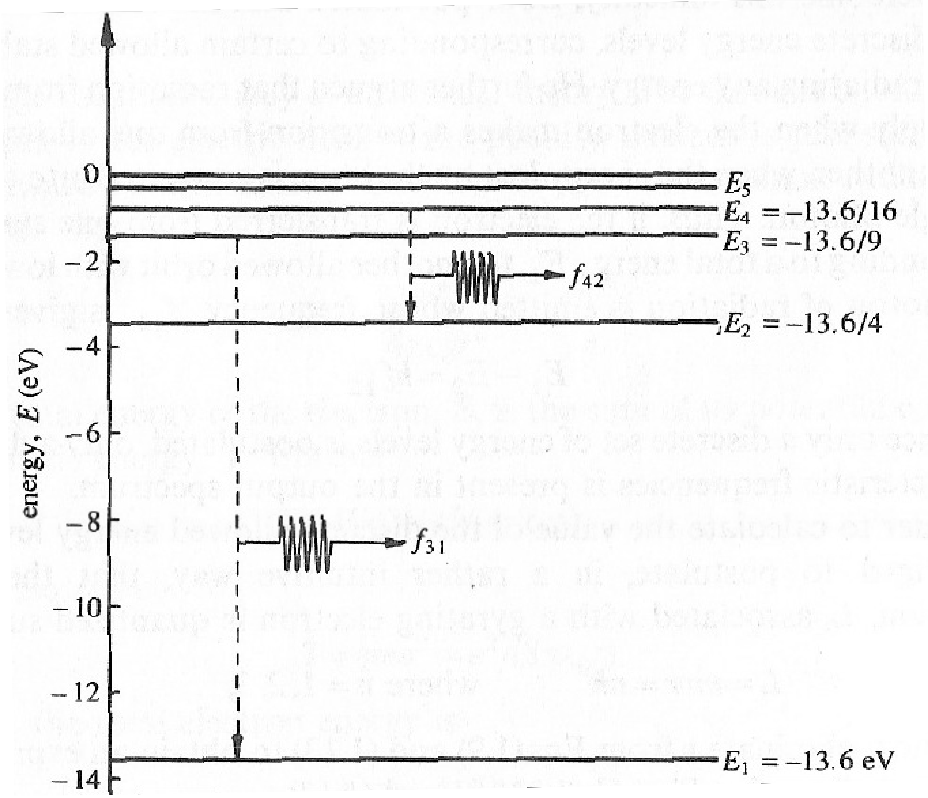
$$r_n = \frac{4\pi n^2 \hbar^2 \varepsilon_0}{e^2 m} \cong 0.05 n^2 [\text{nm}]$$

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

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

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:



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

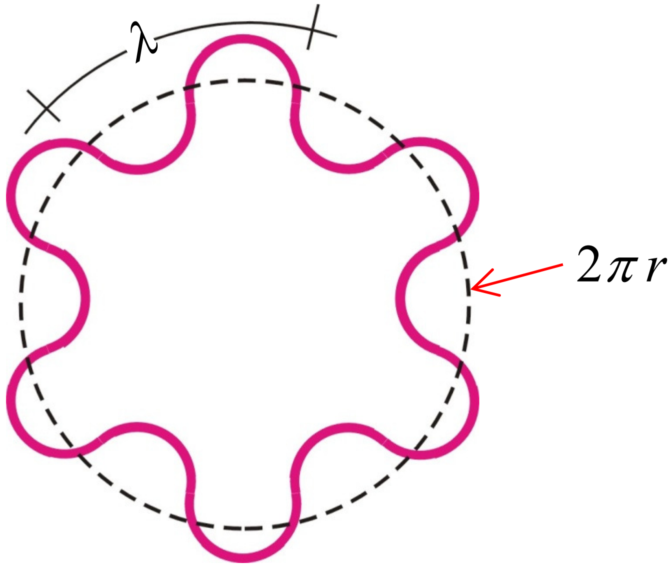
$$E_1 - E_2 = hf_{12}$$

Particle-Wave Duality

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

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

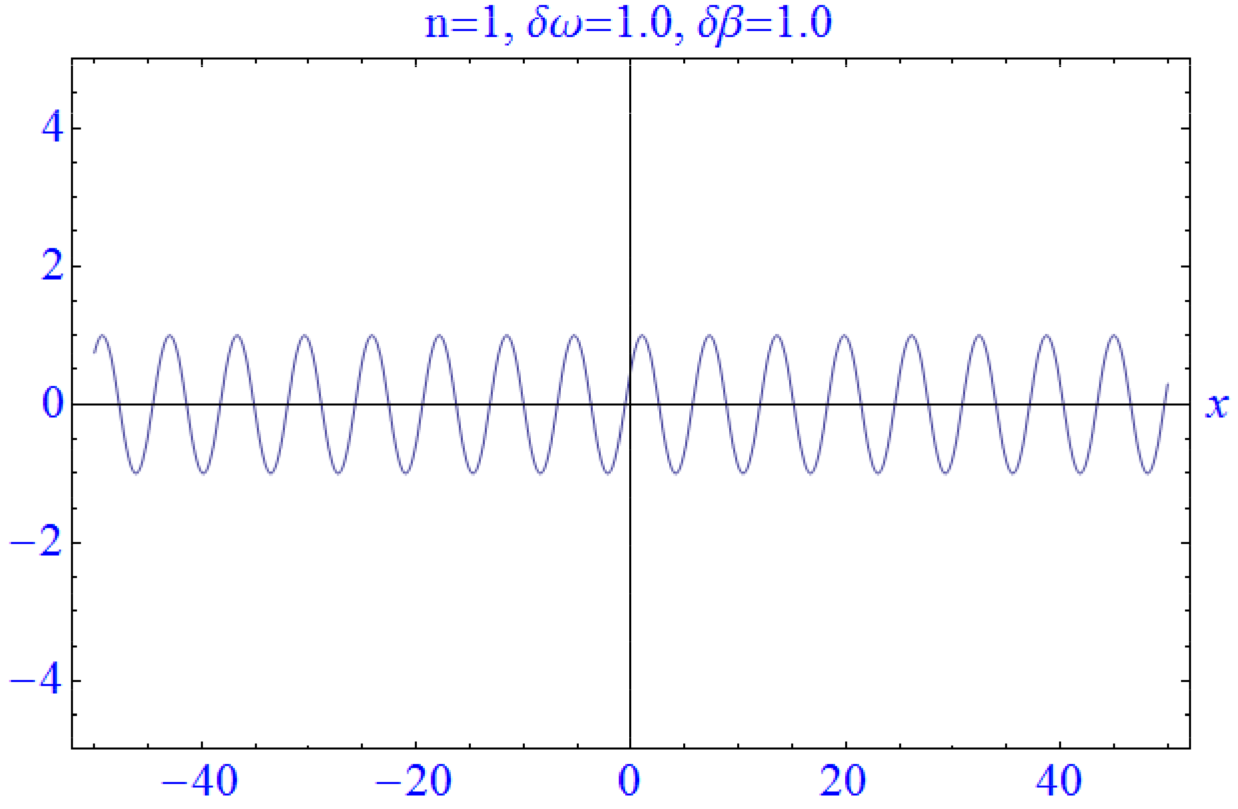
  - De Broglie hypothesized that $p = h/\lambda$ also holds for particles. This can be seen from the Bohr atom:



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

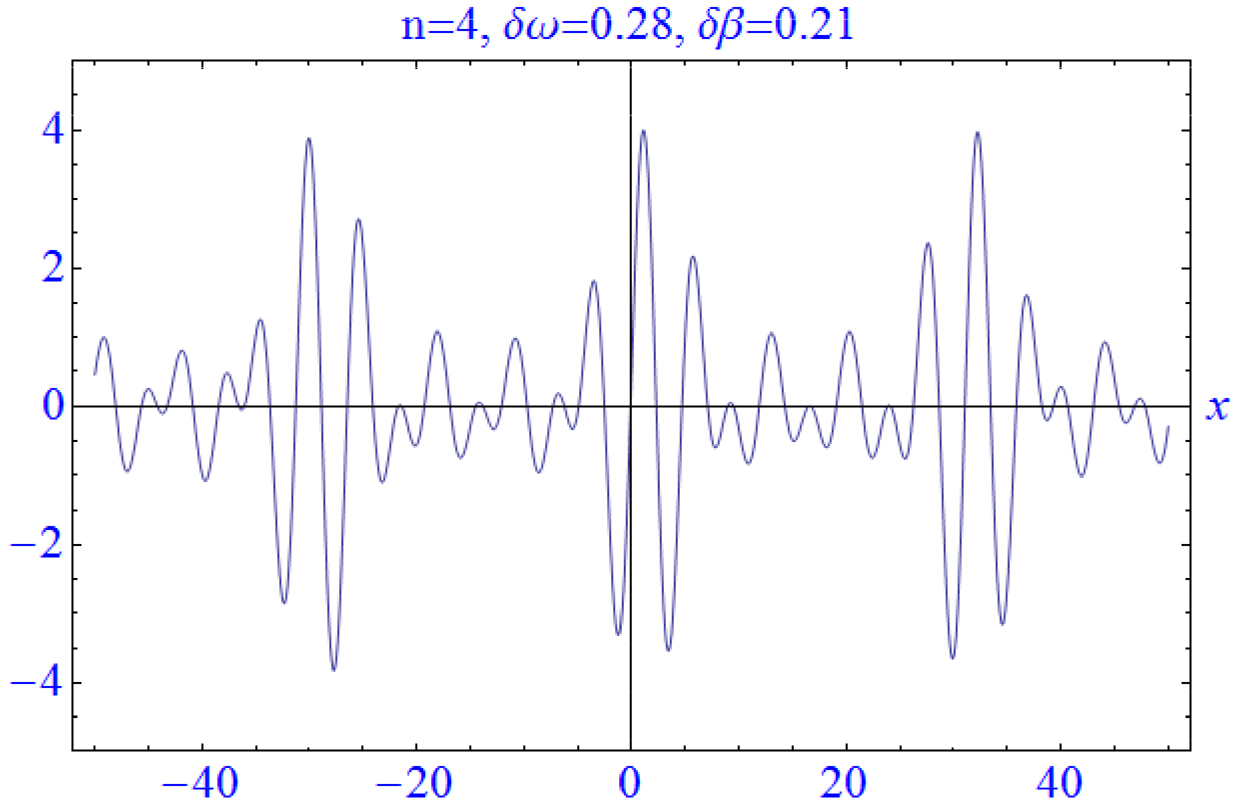
Wavepackets

- Juxtaposition of waves, A $\cos(\omega t\text{-}\beta x)$, of slightly different wavelength ($\delta\beta$) and frequency ($\delta\omega$):



Wavepackets

- Juxtaposition of waves, A cos(ωt-βx), of slightly different wavelength ($\delta\beta$) and frequency ($\delta\omega$):



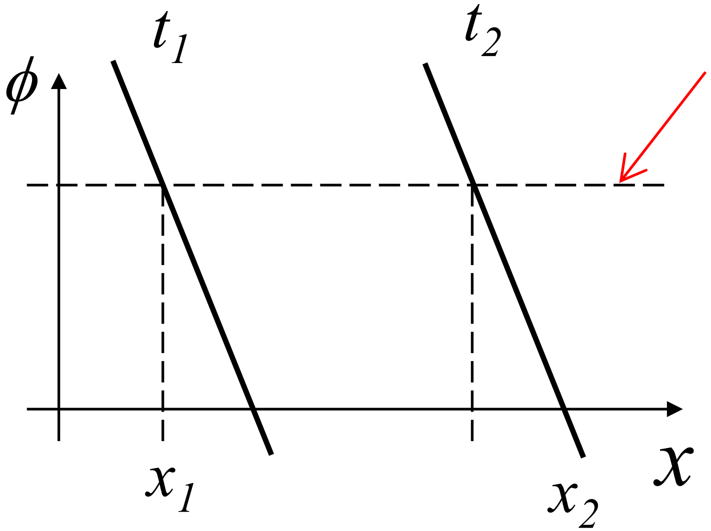
A wavepacket is formed when dw and db are small (or $n \rightarrow \infty$)

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



Line of constant phase

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

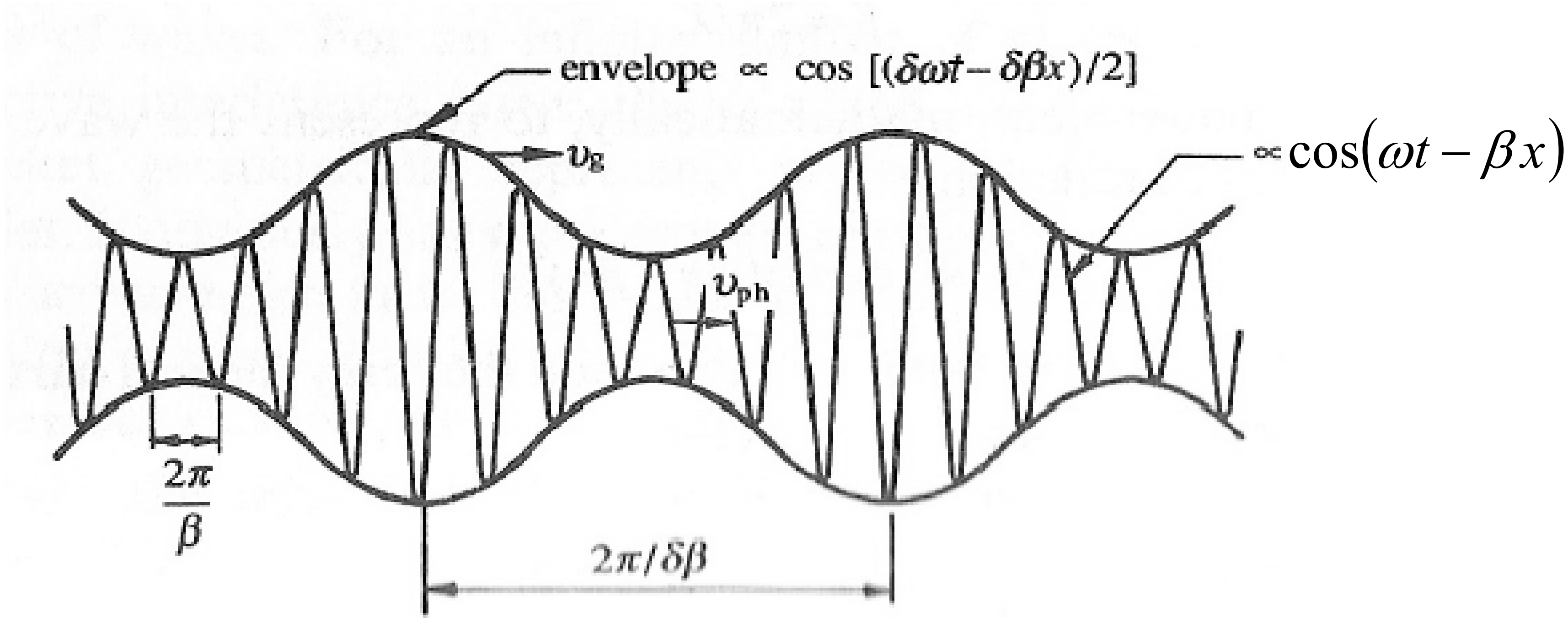
$$\Rightarrow x_2 - x_1 = \frac{\omega}{\beta}(t_2 - t_1)$$

Phase velocity

Wavepackets

- Consider superposition of two waves:

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

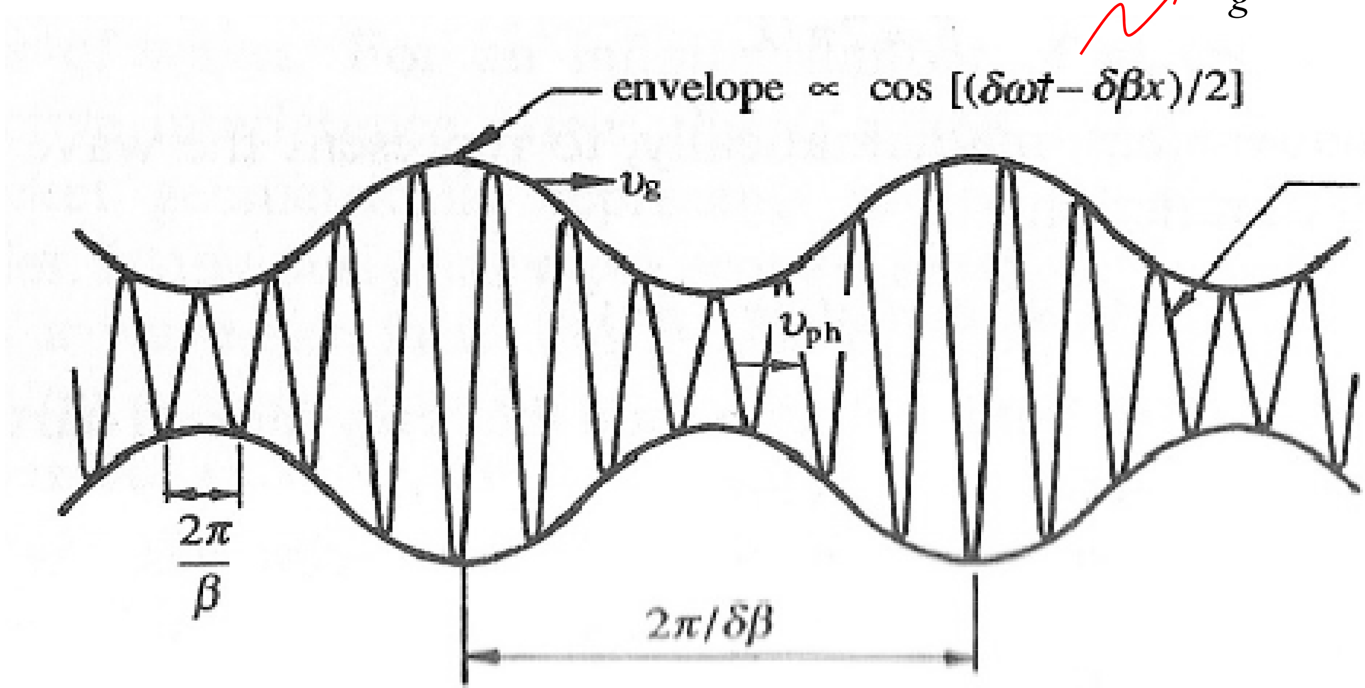


Wavepackets

- Consider superposition of two waves:

$$\overbrace{A_0 \cos(\omega t - \beta x)} + \overbrace{A_0 \cos[(\omega + \delta\omega)t - (\beta + \delta\beta)t]}$$
$$= 2A_0 \cos\{\tfrac{1}{2}[(2\omega + \delta\omega)t - (2\beta + \delta\beta)t]\} \cos[\tfrac{1}{2}(\delta\omega t - \delta\beta x)]$$
$$\simeq 2A_0 \cos[\tfrac{1}{2}(\delta\omega t - \delta\beta x)] \cos(\omega t - \beta x)$$

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



$\propto \cos(\omega t - \beta x)$

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

Wavepackets

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

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

$$T = \tfrac{1}{2}mv^2 = hf \Rightarrow \omega = \frac{2\pi T}{h} = \frac{T}{\hbar}$$

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

  - 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

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

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

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

where $E = T + V$

Conclusions

- We have seen the fundamentals of QM:
  - Some experiments demonstrating quantum world:
    - Blackbody radiation
    - Photoelectric effect
    - Spectrum of hydrogen atom
  - Two fundamental principles:
    - De Broglie’s and Bohr’s.
    - Wavefunction