Semiconductor Devices (EE336)

Lec. 1: Course Introduction and Quick Review

Wed. Sep. 28th, 2016

Dr. Mohamed Hamdy Osman

Course Staff

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- Office Hours: Wednesday 10.00 AM - 1:00 PM

Basic Course Inforrmation

- Textbook
  - “Solid State Electronic Devices” 6th ed. by Ben Streetman, Sanjay K. Banerjee
- Other reference books and supplementary material
  - “Modern semiconductor devices for integrated circuits,” by Chenming Hu Prentice Hall, 2010.
  - Devices course at http://ecee.colorado.edu/~bart/book/book/contents.htm
  - Quantum physics course at http://users.aber.ac.uk/ruw/teach/237/
  - Quantum physics course at https://ocw.mit.edu/courses/physics/8-04-quantum-physics-i-spring-2013/lecture-videos/
- Prerequisites
  - **Modern Physics EE131** (Atomic Physics part)
  - **Solid state electronics EE233** (quantum mechanics principles and Schrodinger wave equation, free electron theory of metals and band theory of semiconductors)

Basic Course Inforrmation

- Grading (150 marks)
  - Final (90 marks)
  - Year work (60 marks)
    - Midterm (30 marks or more)
    - Year work (30 marks or less) → lab + attendance + quizzes

- Course Webpage

  http://eng.staff.alexu.edu.eg/~mosman/page3/

Course Outline

- Semiconductor physics
  - Energy bands, carrier concentrations at equilibrium and carrier transport in semiconductors
- Semiconductor devices
  - PN junction diode, bipolar junction transistors (BJT), Metal oxide semiconductor field effect transistor (MOSFET)
- Semiconductor technology
  - Crystal growth and wafer manufacturing, film formation, photolithography and fabrication process

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Lecture Outline

- Particle-wave duality
- Experimental observations that led to quantum theory and modern atomic structure
- Bohr’s atomic model
- Schrodinger’s wave equation and its solution in some fundamental systems (e.g. Infinite potential barrier)
- Schrodinger equation for the Hydrogen atom → four quantum numbers (n, l, m, s)
- The periodic table and electronic configuration of other more complicated atoms

Particle-wave duality

- Historically in 19^{th} century, light was thought to consist of electromagnetic (EM) waves whose propagation is governed by Maxwell equations whereas matter was thought to consist of localized particles whose motion can be described by classical mechanics (Newton's laws)
- Later on, experimental observations led to the so-called particle-wave duality concept in the early 20^{th} century
- Any particle with energy *E* and momentum *p* has an associated wave with frequency ν and wavelength λ related to E and p as

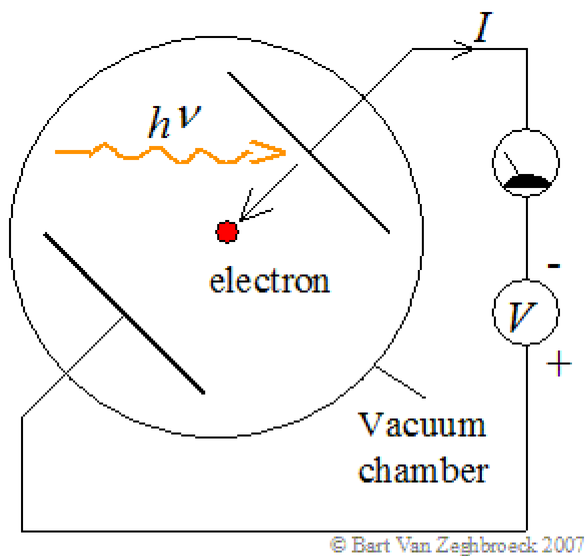
$$E = h\upsilon$$

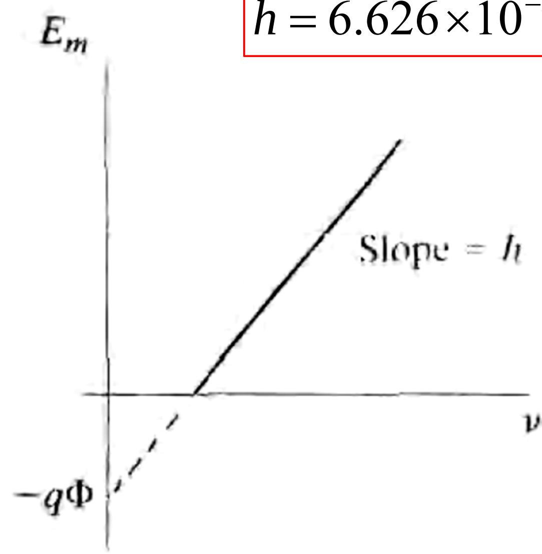
$$p = \frac{h}{\lambda}$$

Experimental observations

- The photoelectric effect experiment demonstrated the discrete (quantized) nature of light which could not be explained by treating light as waves

$$h = 6.626 \times 10^{-34} \;\; m^2.kg/s$$





- Maximum kinetic energy of emitted electrons (measured by stopping potential *V*) grows linearly with frequency of incident light (constant of proportionality is later called Plank’s constant)
- Maximum kinetic energy of emitted electrons does not depend on incident light intensity!!! (Only number of emitted electron, i.e. resulting current *I* depends on incident light intensity)

Experimental observations

- Einstein later explained the photoelectric effect as follows "Light consists of photons each with energy $h\nu$ "
- Unless the energy of one photon is not enough to release one electron from the potential barrier binding it to metal, no electrons will be released regardless of how many photons are incident (light intensity means nothing)

$$E_{elect} = h\nu - q\Phi$$

Kinetic energy of emitted electrons

Workfunction of metal (minimum energy required to release an electron from the barrier)

- This experiment demonstrates particle-like behavior of light
- Wave-like behavior of light has been already established experimentally by e.g. interference of two light beams

De Broglie hypothesis

- Not only light has both particle- and wave-like behavior but all particles in a matter do so!!! → Hypothesis that was later confirmed experimentally
- Any particle with energy *E* and momentum *p* has an associated wave with frequency ν and wavelength λ related to E and p as

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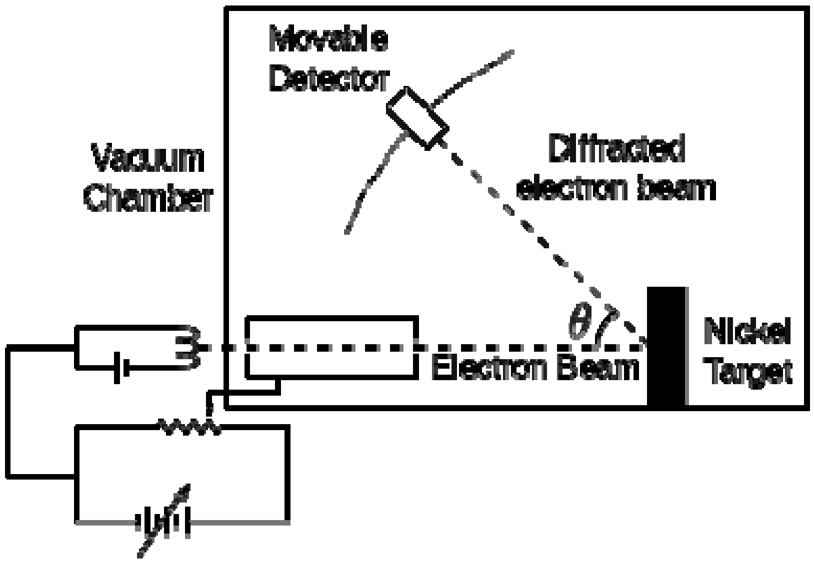
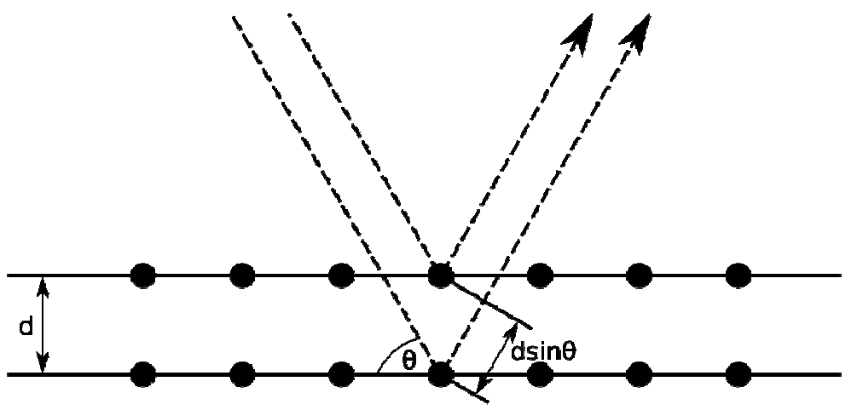
Experimental observations

- Davisson-Germer experiment showed that electron beams also cause interference patterns when diffracted from a periodic crystal





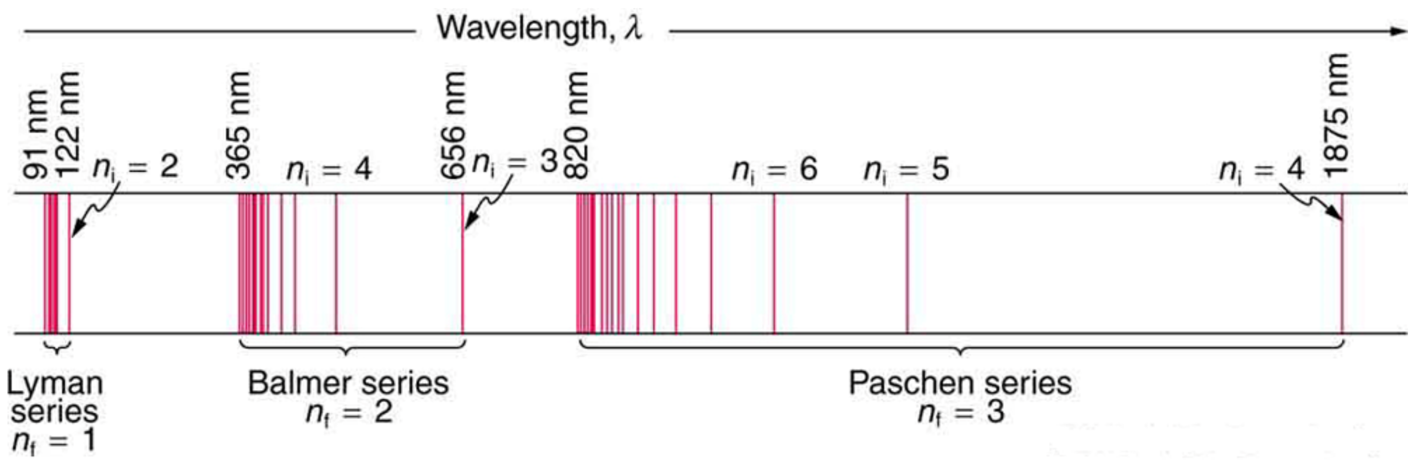
Constructive interference condition (Bragg's condition)

$$2d\,\sin\theta = n\lambda$$

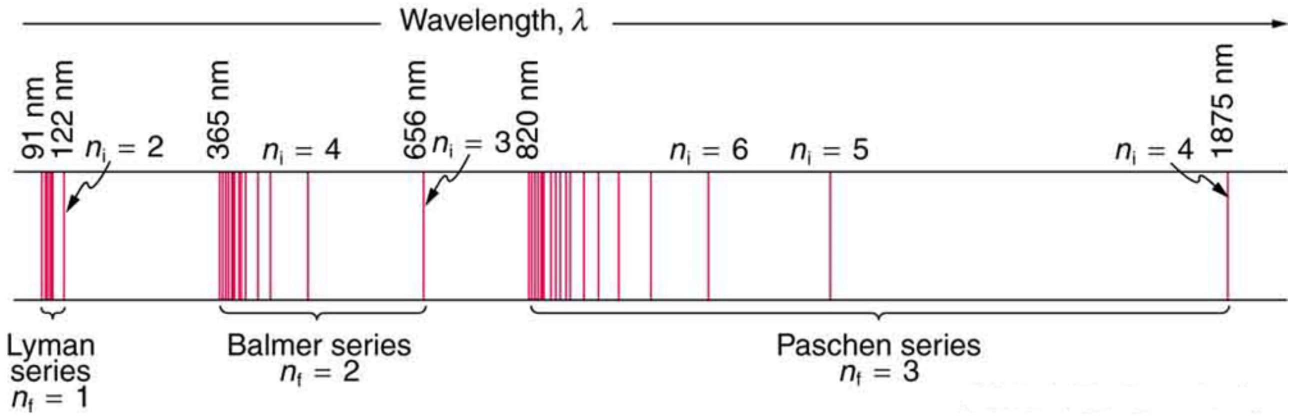
- In the experiment, maximum energy (constructive interference) was obtained at a certain θ which results in a certain λ from Bragg's equation
- This λ matches the wavelength obtained from De Broglie's relation $\lambda = h/p$ for an electron with the same measured experimental momentum

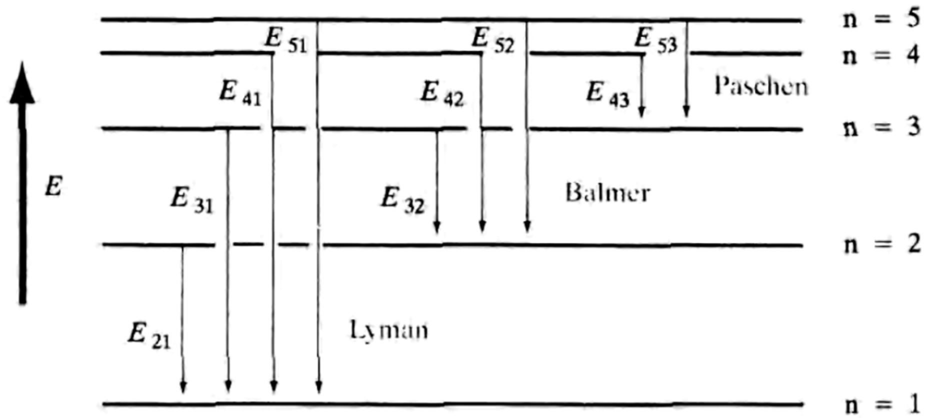
Hydrogen spectrum and Bohr's model

- Spectrum of light emitted from hydrogen gas is measured when electric discharge is created in the Hydrogen gas
- From the peaks of the measured spectrum, the main features of the Hydrogen atom were discovered
- Since the energy of the emitted photons (related to their frequencies by E = hv) corresponds to the energy released by an electron inside the atom and hence to the energy separation between two allowable energy levels where the electron moves from the higher to lower level



Hydrogen spectrum and Bohr's model





$$E = h\upsilon = -13.6eV\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

Hydrogen spectrum and Bohr's model

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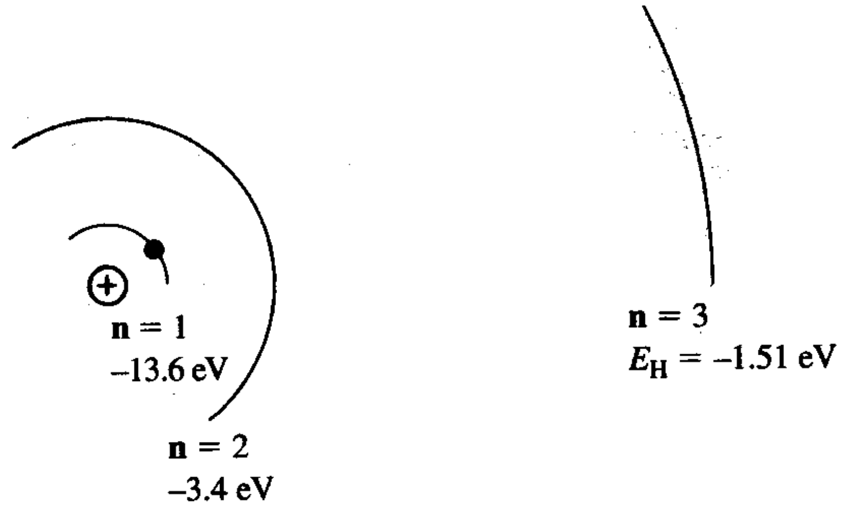

- Emission spectrum led Bohr to construct his model based on following postulates
  - Electrons have certain quantized allowable energy levels where they can shift from one to another releasing the energy difference on form of photon
  - Angular momentum of an electron is quantized $p_\theta = n\hbar, \quad n = 1,2,3,\ldots$
- Without going through math (see 2.3 in Streetman), we can derive

$$E_n = -\frac{mq^4}{2(4\pi\varepsilon_0)^2\hbar^2} \times \frac{1}{n^2} = \frac{-13.6eV}{n^2}$$

Hydrogen spectrum and Bohr's model

- Bohr's model prediction matches the experimental emission peaks in the Hydrogen spectrum

$$E_n = -\frac{mq^4}{2(4\pi\varepsilon_0)^2\hbar^2} \times \frac{1}{n^2} = \frac{-13.6eV}{n^2}$$

- Shortcomings of Bohr's model
  - It only accounts for gross features of the atom → only 1 quantum number *n* exists where later quantum mechanics will result in 4 quantum numbers (*n,l,m,s*) to fully describe/identify a state (orbital) of an electron
  - Cannot be extended to more complicated atoms with more than one electron
- Bohr's model was a step towards a more comprehensive theory based on Quantum mechanics

Schrodinger’s wave equation

- One can find the wave function ψ associated with a particle (e.g. electron) in a system (e.g. atom) by solving the following partial differential equation

$$-\frac{\hbar^2}{2m}\nabla^2\psi + V\psi = E\psi$$

$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V\right]\psi = E\psi$$

$$\hat{H}\psi = E\psi$$

$$where \quad \nabla^2\psi = \frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial y^2} + \frac{\partial^2\psi}{\partial z^2}$$

V : the potential affecting the particle which is a function of x, y, z

m : particle's mass

E : Total energy of particle (P.E. + K.E.)

$\hbar$: reduced Plank's const. equals $h/2\pi$

$\hat{H}$: Hamlitonian operator

Properties of wavefunction

- The probability of finding the particle in a certain volume **M** is calculated as

$$\underbrace{\iiint_{volume}}\, \underbrace{\psi^*(x,y,z)\psi(x,y,z)}_{\text{Probability density function}}dxdydz$$

and hence

$$\iiint_{entire\,\mathrm{space}} \psi^*(x,y,z)\psi(x,y,z)dxdydz = 1$$

- Classical quantities such as momentum and energy are random in quantum mechanical language and instead their averages (Expected values) are calculated within the limits of Heisenberg uncertainty principle

$$\langle Q \rangle = \iiint_{entire\,\mathrm{space}} \psi^*(x,y,z)Q_{op}\psi(x,y,z)dxdydz$$

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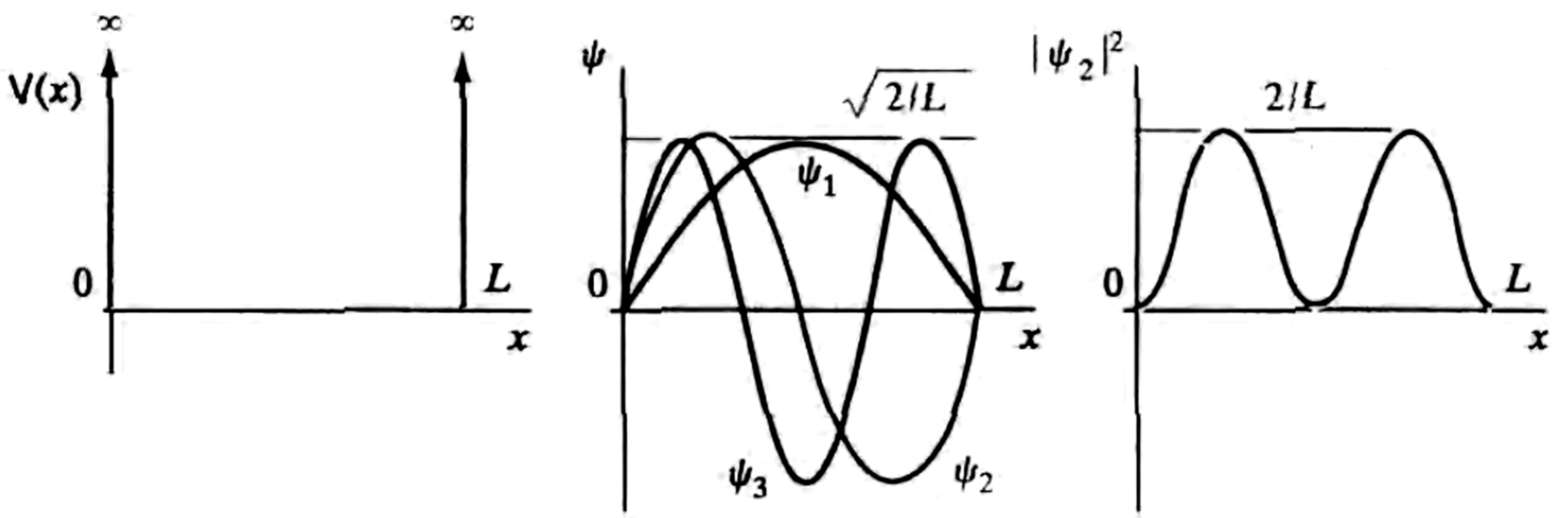
Classical variable	Quantum operator
x	x
$f(x)$	$f(x)$
$p(x)$	$\frac{\hbar}{j}\frac{\partial}{\partial x}$
E	$-\frac{\hbar}{j}\frac{\partial}{\partial t}$

Infinite potential well (particle in a box)



$$-\frac{\hbar^2}{2m}\nabla^2\psi + V\psi = E\psi$$

$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2} + V\psi = E\psi \quad \text{(1D)}$$

$$V = \begin{cases} \infty & x = 0 \text{ and } L \\ 0 & \text{elsewhere} \end{cases}$$

Infinite potential well (particle in a box)

$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2} = E\psi$$

$$\psi(x) = A\sin(kx) + B\cos(kx), \quad \text{where} \quad k = \frac{\sqrt{2mE}}{\hbar}$$

$$But \quad \psi(0) = 0 \quad \text{hence } B = 0$$

$$\psi(x) = A\sin(kx)$$

$$But \quad \psi(L) = 0 \Rightarrow \sin(kL) = 0 \Rightarrow k = \frac{n\pi}{L} \quad n = 1,2,3$$

$$\psi(x) = A\sin\left(\frac{n\pi}{L}x\right), \quad 0 < x < L$$

$$Also \quad \int_{-\infty}^{\infty}\psi^*\psi dx = 1 \quad \Rightarrow \quad A = \sqrt{\frac{2}{L}}$$

Bottom Line, Energy and wavenumber are quantized due to boundary condition

$$E_n = \frac{\hbar^2}{2m}k^2 = \frac{\hbar^2\pi^2}{2mL^2}n^2$$

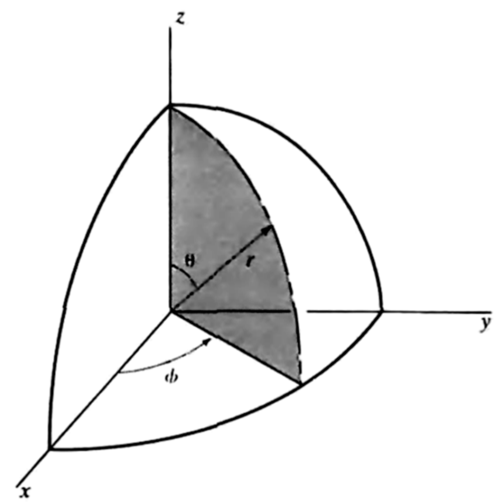
Schrodinger equation for a Coulomb's potential well

- For H atom, we use spherical coordinates (r,θ,φ) (nucleus in the center of coordinate system)

$$-\frac{\hbar^2}{2m}\nabla^2\psi + V\psi = E\psi$$

$$V(r,\theta,\phi) = V(r) = -\frac{q^2}{4\pi\varepsilon_0 r}$$

$$\nabla^2 = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial}{\partial r}\right) + \frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial}{\partial\theta}\right) + \frac{1}{r^2\sin^2\theta}\frac{\partial^2}{\partial\phi^2}$$



- Details of math are beyond the scope of the course but you basically do separation of variables by decomposing wavefunction into three parts

$$\psi(r,\theta,\phi) = R(r)\Theta(\theta)\Phi(\phi)$$

and then solve each differential equation separately

Schrodinger equation for a Coulomb's potential well

- As an example, solution of phi-dependent equation

$$\Phi(\phi) = \frac{1}{\sqrt{2\pi}} e^{jm\phi}$$

where the exponent *m* denotes the magnetic quantum number

- Also the radial and theta dependent parts will produce two more quantum numbers *n* and *l* respectively

$$\psi(r,\theta,\phi) = R_n(r)\Theta_l(\theta)\Phi_m(\phi)$$

- The three quantum numbers are inter-related as

$$\mathbf{n} = 1, 2, 3, \ldots$$

$$\boldsymbol{l} = 0, 1, 2, \ldots, (\mathbf{n} - 1)$$

$$\mathbf{m} = -\boldsymbol{l}, \ldots, -2, -1, 0, +1, +2, \ldots, +\boldsymbol{l}$$

- In addition, there is a fourth quantum number that identifies the spin of the electron

$$s = \pm 1/2$$

- *n*, *l*, *m*, *s* uniquely define a quantum state (sometimes called orbital)

Allowable states of an electron in H atom

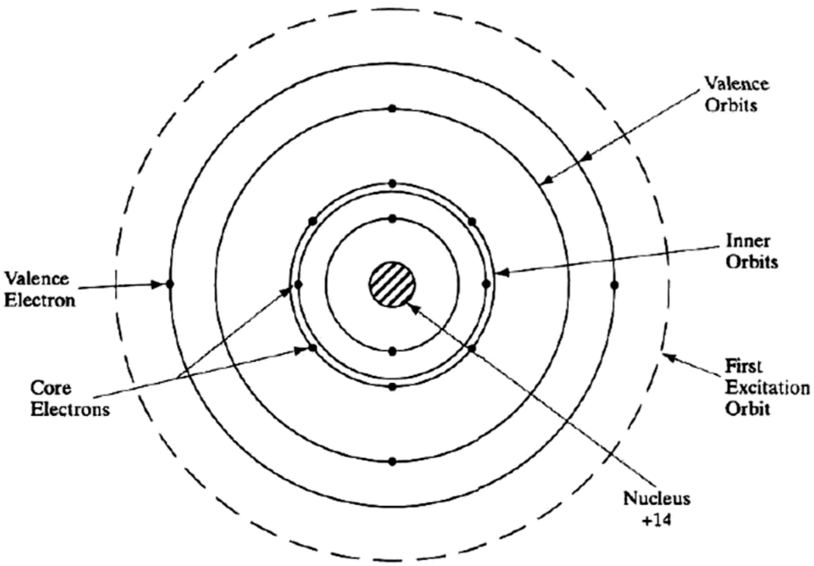
n	*l*	m	s/ħ	Allowable states in subshell	Allowable states in complete shell
1	0	0	$\pm\frac{1}{2}$	2	2
2	0	0	$\pm\frac{1}{2}$	2	8
	1	−1 0 1	$\pm\frac{1}{2}$ $\pm\frac{1}{2}$ $\pm\frac{1}{2}$	6	
3	0	0	$\pm\frac{1}{2}$	2	18
	1	−1 0 1	$\pm\frac{1}{2}$ $\pm\frac{1}{2}$ $\pm\frac{1}{2}$	6	
	2	−2 −1 0 1 2	$\pm\frac{1}{2}$ $\pm\frac{1}{2}$ $\pm\frac{1}{2}$ $\pm\frac{1}{2}$ $\pm\frac{1}{2}$	10	

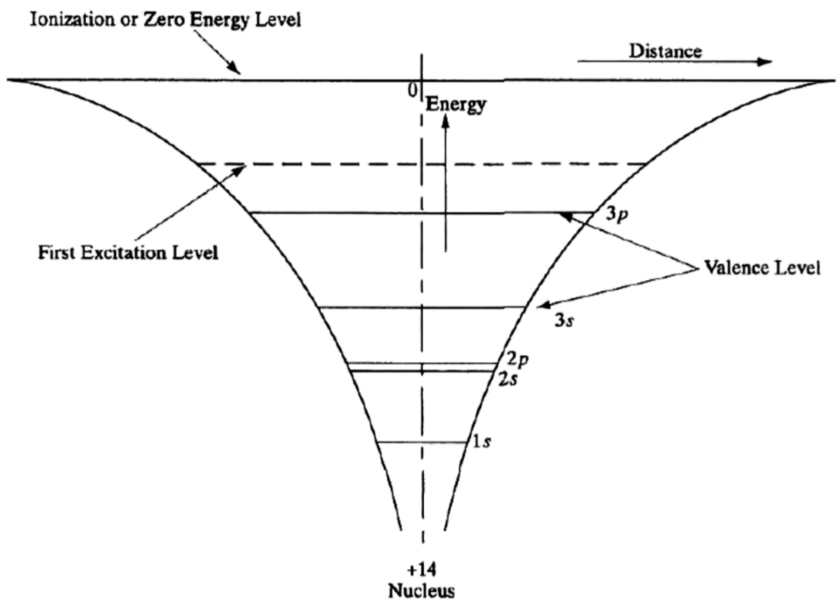
- <u>Standard notation for electronic configuration</u>

l = 0 → s   l = 1 → p   l = 2 → d   l = 3 → f

Electronic configuration of other atoms

- For Si with Z = 14 → $1s^2 2s^2 2p^6 3s^2 3p^2$ → [Ne] $3s^2 3p^2$





- For Ge with Z = 32 → $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^2$ → [Ar] $3d^{10} 4s^2 4p^2$
- All previous discussion is for an isolated atom but what happens for if atoms are brought closer as in a crystal??