

Lecture (2)Wave Nature of Light

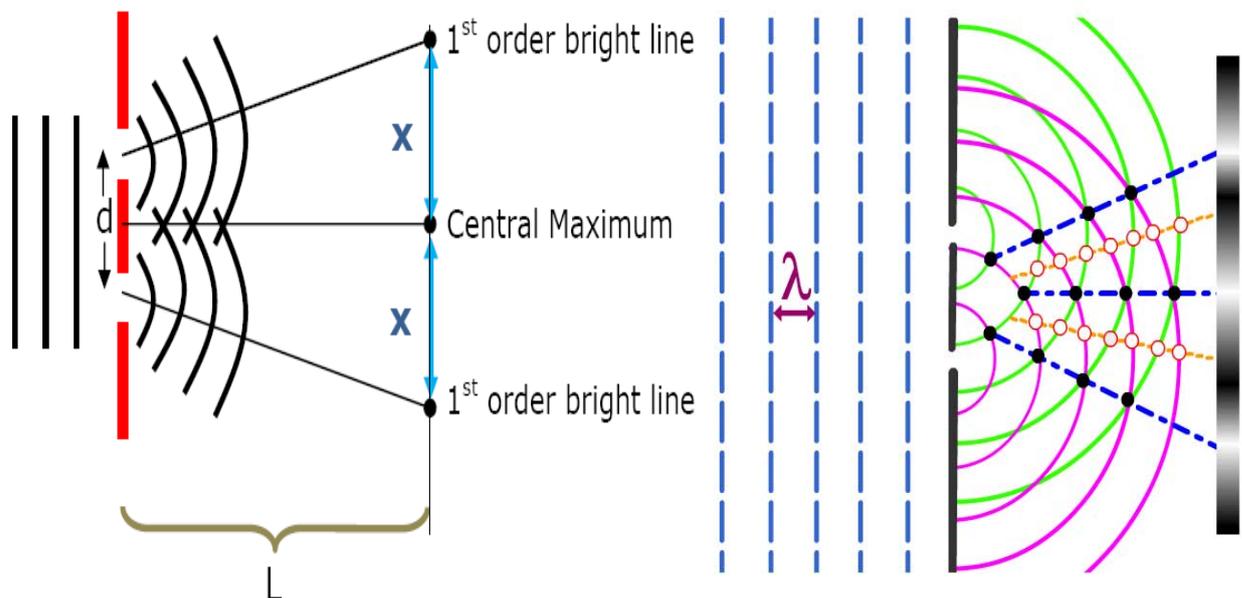
Light is radiant energy (Carries energy through space), it travels very fast 300,000 km/sec. Experiments with light show that it sometimes behaves in unexpected ways. Therefore, it is difficult to describe all of the properties of light with a single model. The two most common models describe light either as a wave or as a stream of particles. Thus Light has, a dualistic nature; it can be treated as a stream of particles (photons) or as a wave motion. When we deal with the optical effects of liquid crystals we sometimes use the first approach to treat light scattering, but normally the latter is used to treat the large number of interesting and often unique optical phenomena.

1-As a wave

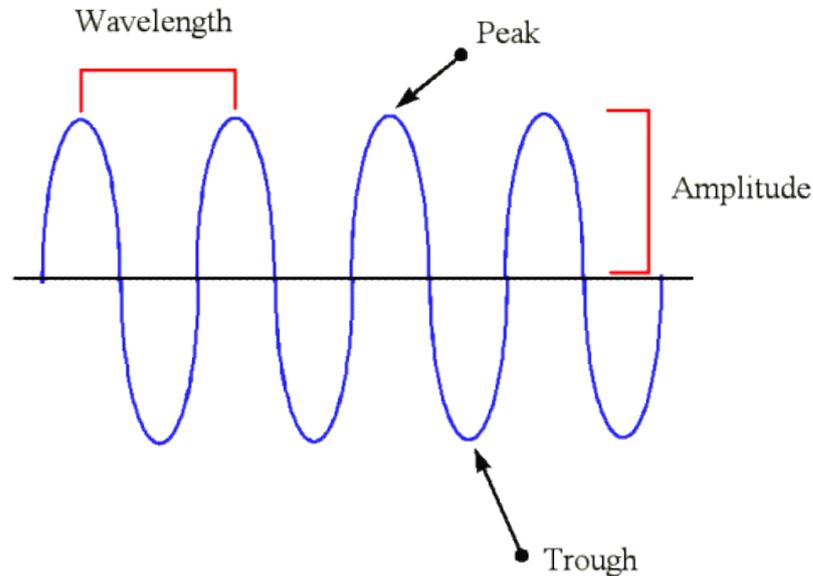
The light wave is a transverse electromagnetic wave motion. This means that it consists of two coupled, electric and magnetic, fields oscillating in a plane perpendicular to the beam direction. A small disturbance in an electric field creates a small magnetic field, which in turn creates a small electric field, and so on. Light propagates itself by its bootstraps!

Light waves can interfere with other light waves, canceling or amplifying them. The color of light is determined by its wavelength.

In 1801, the English scientist Thomas Young devised an experiment to test the nature of light. He passed a narrow beam of red light through two small openings. The light was focused onto a screen on the other side of the openings. He found that the light produced a striped pattern of light and dark bands on the screen. This striped pattern is an interference pattern. It also explains other behaviors of light, such as reflection, refraction, and diffraction. The wave model of light is still used to explain many of the basic properties of light and light's behavior. However, the wave model cannot explain all of light's behavior.



Electromagnetic radiation : An Electromagnetic Wave is an alternating oscillations of the Electric (E) and Magnetic (B) fields . thus Electromagnetic radiation has both *electric* and *magnetic* properties. The wave-like property of electromagnetic radiation is due to the periodic oscillations of these components.



- The number of complete wavelengths, or *cycles*, that pass a given point in 1 second is the **frequency** of the wave, frequency is expressed in *cycles per second*, also known as **hertz (Hz)**

(frequency=cycles/second)

- The distance between wavecrests is called the wavelength ,it is denoted by λ
- We can assign a **frequency** and a **wavelength** to electromagnetic radiation, Because all electromagnetic radiation moves at the same speed (speed of light) **wavelength and frequency are related**

$$\text{frequency} = \left(\frac{1}{\text{wavelength}} \right) * \text{speed of light}$$

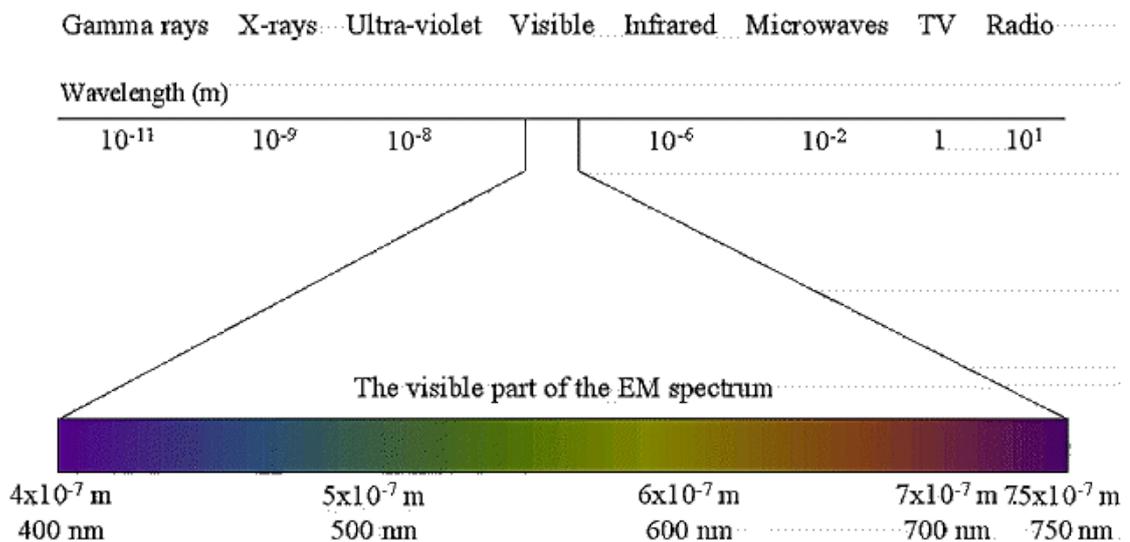
$$v = \left(\frac{1}{\lambda} \right) * c$$

$$v\lambda = c$$

- If the **wavelength is long**, there will be fewer cycles passing a given point per second, thus **the frequency will be low**
- If the **wavelength is short**, there will be more cycles passing a given point per second, and the **frequency will be high**

- Thus, there is *an inverse relationship between wavelength and frequency*
- Order of types of EM waves from long wavelength to short wavelength: (also order of small frequency to high frequency).

Type	Wavelength Range
Radio	wavelength > 1 cm
Microwave	1 mm < wavelength < 1 cm
Infrared	700 nm < wavelength < 1 mm
Visible	400 nm < wavelength < 700 nm
Ultraviolet	20 nm < wavelength < 400 nm
X-rays	0.1 nm < wavelength < 20 nm
Gamma rays	wavelength < 0.1 nm



RADIO WAVES

The wavelength of a radio waves have the longest wavelengths of any kind of wave may be several kilometers. This part of the electro- magnetic spectrum includes TV signals and AM and FM radio signals.

MICROWAVES

Electromagnetic waves that have wavelengths in the range of centimeters are known as microwaves. Microwaves are used to carry communication signals over long distances. Space probes use microwaves to transmit signals back to Earth.

Microwaves are also used in cooking. Microwaves are easily transmitted through air, glass, paper, and plastic. However, the water, fat, and sugar molecules in food all absorb microwaves. The absorbed microwaves can cook food. The energy from the absorbed

waves causes water and other molecules to vibrate. The energy of these vibrations spreads throughout the food and warms it.

INFRARED AND ULTRA VIOLET LIGHT

Electromagnetic waves that have wavelengths slightly longer than wavelengths of red visible light are infrared waves. You cannot see it, but infrared light from the sun warms you. Devices that are sensitive to infrared light can produce images of objects that emit infrared waves.

For example, remote infrared sensors on weather satellites can record temperature changes in the atmosphere and track cloud movements. The invisible light that lies just beyond violet light makes up the ultraviolet (UV) part of the spectrum. UV light has higher energy and shorter wavelengths than visible light does. It has enough energy to pass through clouds and give you a sunburn. Sunscreens absorb or block UV light and can prevent sunburns. UV light also kills germs and can be used to disinfect objects.

X RAYS AND GAMMA RAYS

Beyond the ultraviolet part of the spectrum are waves called X rays and gamma rays. X rays have wavelengths less than 10^{-8} m. Gamma rays have the highest energies and have wavelengths as short as 10^{-14} m.

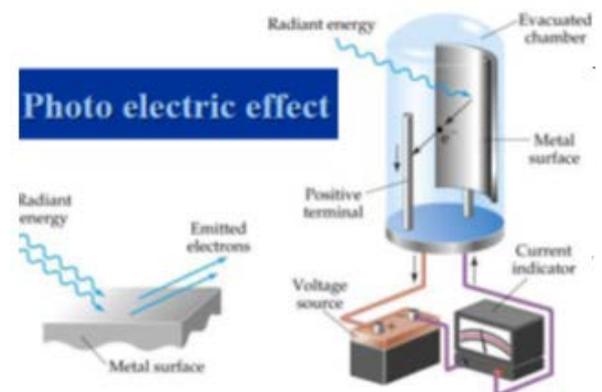
1-As a particle

when light strikes a piece of metal, electrons may fly off the metal's surface. Scientists proposed a new model of light to explain the effects of light striking a metal plate they found that in dim blue light could cause electrons to fly off the metal plate. Scientists also found that very bright red light could not cause electrons to leave the plate. According to the wave model, bright light has more energy than dim light. This is because the waves in bright light have greater amplitude than the waves in dim light.

Therefore, dim light should not be able to knock electrons off the plate, but bright light should.

According to this model, the energy in light is contained in individual particles called photons.

Photons of different colors of light have different amounts of energy. A photon of blue light carries more energy than a photon of red light. Therefore, blue light can cause electrons to fly off a metal plate, but red light cannot. Photons are considered particles, but they are not like particles of matter. Photons do not have mass. Instead, they contain only energy. Unlike the energy in a wave, the energy in a photon is located in a specific area. A beam of light is a stream of photons. The more photons in the beam, the brighter the light



appears. , the particle model better explains how light can knock electrons off metal plates. It also explains why light can travel across empty space without a medium.

In the particle model of light, each photon of light carries a specific, small amount of energy. The amount of energy in a photon of light is related to the frequency of the light waves.

- A photon has a wavelength and frequency associated with it.
- The Energy carried by the photon is

$$E = h f = \frac{h c}{\lambda}$$

- In this equation, h is Planck's constant: $h = 6.625 \times 10^{-34} \text{ J s}$.
- Since $f_{\text{blue}} > f_{\text{red}}$, blue photons carry more energy than red photons!
- The energy of emitted electron equal

$$E = h\nu - \phi$$

Where

$h\nu$ = energy of photon

ϕ = work function of metal = hc/λ_{th}

E = the energy of escape electron from the surface = $V_{\text{stop}} \cdot e$

De Broglie's Law

De Broglie wave, also called matter wave , any aspect of the behavior or properties of a material object that varies in time or space in conformity with the mathematical equations that describe waves.

The relation in which the de Broglie wave associated with a free particle of matter, and the electromagnetic wave in a vacuum associated with a photon, has a wavelength equal to Planck's constant divided by the particle's momentum and a frequency equal to the particle's energy divided by Planck's constant. Also known as de Broglie equation

$$\lambda = h/p$$

$$f = E/h$$

where h is [Planck's constant](#). The equation can also be written as

$$\begin{aligned} \mathbf{p} &= \hbar \mathbf{k} \\ E &= \hbar \omega \end{aligned}$$

where \hbar is the reduced Planck's constant, \mathbf{k} is the [wave vector](#), and ω is the [angular frequency](#).

In each pair, the second is also referred to as the [Planck-Einstein relation](#), since it was also proposed by [Planck](#) and [Einstein](#).

Deriving the De Broglie Wavelength

De Broglie derived his equation using well established theories through the following series of substitutions:

1. De Broglie first used Einstein's famous equation relating [matter and energy](#):

$$E = mc^2$$

with

- E = energy,
- m = mass,
- c = speed of light

2. Using Planck's theory which states every quantum of a wave has a discrete amount of energy given by Planck's equation:

$$E = h\nu \quad (1)$$

with

- E = energy,
- h = Planck's constant (6.62607×10^{-34} J s),
- ν = frequency

3. Since de Broglie believed particles and wave have the same traits, he hypothesized that the two energies would be equal:

$$mc^2 = h\nu \quad (2)$$

4. Because real particles do not travel at the speed of light, De Broglie substituted velocity (v) for the speed of light (c).

$$mv^2 = h\nu \quad (3)$$

5. Through the equation λ , de Broglie substituted v/λ for ν and arrived at the final expression that relates wavelength and particle with speed.

$$mv^2 = hv/\lambda \quad (4)$$

Hence:

$$\lambda = hv/mv^2 = h/mv \quad (5)$$

Quantum Mechanical Model

- The Bohr model is *deterministic*...uses fixed “orbits” around a central nucleus to describe electron structure of atoms.
- The QM model is *probabilistic*...uses probabilities to describe electron structure.
- A probabilistic electron structure is much more difficult to visualize.
- **HOWEVER**, the electronic energy levels are still quantized.
- . Quantum mechanics uses the philosophical problem of wave/particle duality to provide an elegant explanation to quantized orbits around the atom.
- equation with both wave and particle terms• leads to wave functions ψ

Deterministic vs. Probabilistic

- | | |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"> • In the Bohr model, you can always find the electron in an atom, just like you can always find the moon as it orbits the earth. • You can always <i>determine</i> the relative location of the nucleus and electron in Bohr’s model. • This is because the electron follows a particular <i>orbit</i> around the nucleus. | <ul style="list-style-type: none"> • In the QM model, the electron does not travel along a particular path around the nucleus. • You can never determine the electron’s <i>exact</i> location...you can only find where it is <i>likely</i> to be. • The Bohr orbit is replaced by <i>orbital</i> which describes a volume of space in which the electron <i>is likely to be found</i>. |
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Wave Function:

$$Y_{(x,t)} = A \sin (kx-wt) \dots \dots \dots (1)$$

$$Y_{(x,t)} = A \sin (kx+wt) \dots \dots \dots (2)$$

Equ.(1) & (2) describes a wave moving in the direction of increasing (x) and in the opposite direction (x).

Where: A = amplitude of the wave.

k= wave number ($2\pi /\lambda$)

w =angular frequency ($w=2\pi f$),f=frequency.

By take the first direction for equ.1 for (x) we get:

$$\partial y / \partial x = A.k \cos(kx-wt)$$

And second derivative

$$\partial^2 y / \partial x^2 = -A.k^2 \sin(kx-wt)$$

$$\partial^2 y / \partial x^2 = -k^2 y \dots \dots \dots (3)$$

And $\partial y / \partial t = -A.w \cos(kx-wt)$ (derivative for t)

$$\partial^2 y / \partial t^2 = -A.w^2 \sin(kx-wt)$$

$$\partial^2 y / \partial t^2 = -w^2 y \dots \dots \dots (4)$$

Divided eqn.(4) on eqn.(3) we get:

$$(\partial^2 y / \partial t^2) / (\partial^2 y / \partial x^2) = -w^2 y / -k^2 y = w^2 / k^2 = 4 \pi^2 f^2 / 4 \pi^2 / \lambda^2 = \lambda^2 f^2 = v^2 \text{ (phase)}$$

$$(\partial^2 y / \partial t^2) / (\partial^2 y / \partial x^2) = v^2 \dots \dots \dots (5) \text{ where } (w/k) \text{ is the phase velocity.}$$

Then

$$Y = A \sin (kx-wt) \text{ (real)}$$

$$Y = B \cos (kx-wt) \text{ (imaginary)}$$

$$Y = A \sin(kx - \omega t) + B \cos(kx - \omega t) \quad \{\text{use Euler's law } e^{i\theta} = \cos\theta + i \sin\theta\}$$

$$Y = C e^{i(kx - \omega t)}$$

*Schrodinger suggested (derive equation for waves, moving depending on the force that acting on the particle for example (potential and kinetic energies momentum).

$$\text{Let's } \psi(x, t) = C e^{i/\hbar(Px - Et)} \dots\dots\dots(6)$$

Derivative eqn.6 for (x) we get:

$$\partial\psi / \partial x = i/\hbar P_x C e^{i/\hbar(Px - Et)} \quad (P = h/\lambda = 2\pi h/\lambda = \hbar k \quad \& \quad E = \hbar\omega)$$

$$\partial\psi / \partial x = i/\hbar P_x \psi(x, t) \quad \text{OR} \quad \hbar/i \partial\psi / \partial x = P_x \cdot \psi$$

$$P_x = \hbar/i \partial / \partial x = P_{xop} \dots\dots\dots(7)$$

This equation represents the linear momentum by (linear operation $\hbar/i \partial / \partial x$)

$$P_{xop} = \hbar/i \partial / \partial x \quad (\text{in quantum mechanics Q.M})$$

$$P_x = mv_x \quad (\text{in classic mechanic C.M})$$

Similar for (y & z)

$$P_{yop} = \hbar/i \partial / \partial y$$

$$P_{zop} = \hbar/i \partial / \partial z$$

The kinetic energy (T) = $1/2 mv^2$ (in C.M)

$$\text{Then } T = 1/2 mv^2 \cdot (m/m) = P^2/2m$$

$$T_{OP} = P^2/2m = - (\hbar/i \partial / \partial x)^2/2m \quad (i^2 = -1)$$

$$T_{xOP} = (-\hbar/2m) \partial^2 / \partial x^2 \dots\dots\dots(8) \quad (\text{in Q.M})$$

$$\text{By similar for } T_{yOP} = (-\hbar/2m) \partial^2 / \partial y^2 \quad \& \quad T_{zOP} = (-\hbar/2m) \partial^2 / \partial z^2$$

The potential energy in (C.M) as the same in (Q.M) (i.e)

$$V = -\int F_x dx, E_p = V_{op} \dots\dots\dots(9)$$

$$\mathcal{H}_{op} = T_{op} + V_{op} \dots\dots\dots(10)$$

Eqn. 10 represented the Hamilton operator (K.E +P.E) and

The Hamiltonian operator, \mathcal{H} , is a complex function of the electron's potential and kinetic energies:

$$\mathcal{H} = \left[-\frac{\hbar^2}{8\pi^2 m_e} \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) + V(x,y,z) \right] \dots\dots\dots(11)$$

↑
K.E.

↑
P.E.

$$\mathcal{H}\psi = E\psi \dots\dots\dots(12)$$

So sub eqn. (11) in eqn. (12) we obtain

$$-\frac{\hbar^2}{2m} \frac{\partial^2 \psi(x)}{\partial x^2} + V(x)\psi(x) = E\psi(x) \dots\dots\dots(13)$$

Eqn. (13). is called" Schrödinger's equation indepent time" , the solutions to Schrödinger's equation, however, do provide us with very valuable information about the physical and chemical properties of elements and compounds.

- Later we will see how the quantum mechanical model of the atom helps us to understand why the elements are arranged the way they are on the periodic table.
- The spherical atomic orbital described so far is the **ground state** orbital in the hydrogen atom.
- When the hydrogen atom is excited, the electron can transfer to a higher energy state, which will have a different wave function (atomic orbital).

Each different atomic orbital is characterized by a set of numbers called **quantum numbers**.

- These numbers determine the *size*, *shape* and *orientation* of the orbitals.
- There are four types of quantum numbers, we will focus first on three of these:
- *n*, is the **principal quantum number** and is related to the *size* of the orbital. - It is a positive integer, 1, 2, 3, ...
- *l*, is the **angular momentum quantum number** and is related to the *shape* of the orbital. - It has an integer that runs from 0 to (*n*-1), where *n* is the corresponding principal quantum number.
- *ml*, is the **magnetic quantum number** and is related to the *orientation* of the orbital. - It is an integer that runs from -*l* to +*l*, where *l* is the corresponding angular momentum quantum number.

m_s , is the **spin quantum number** and is related to the *spin* of the orbital, it is always taking values (+1/2,-1/2) according to the orientation of electron.

The below table shows the possible values for the l and ml quantum numbers

Table 7.2 The Hierarchy of Quantum Numbers for Atomic Orbitals

Name, Symbol (Property)	Allowed Values	Quantum Numbers
Principal, n (size, energy)	Positive integer (1, 2, 3, ...)	<div style="display: flex; justify-content: space-around; align-items: flex-start;"> <div style="text-align: center;"> <p>1</p> </div> <div style="text-align: center;"> <p>2</p> </div> <div style="text-align: center;"> <p>3</p> </div> </div>
Angular momentum, l (shape)	0 to $n - 1$	<div style="display: flex; justify-content: space-around; align-items: flex-start;"> <div style="text-align: center;"> <p>0</p> </div> <div style="text-align: center;"> <p>0 1</p> </div> <div style="text-align: center;"> <p>0 1 2</p> </div> </div>
Magnetic, m_l (orientation)	$-l, \dots, 0, \dots, +l$	<div style="display: flex; justify-content: space-around; align-items: flex-start;"> <div style="text-align: center;"> <p>0</p> </div> <div style="text-align: center;"> <p>0 0 +1</p> </div> <div style="text-align: center;"> <p>0 -1 0 +1 +2</p> </div> </div>

Multi-electron atoms

How can we determine energy levels of a multi-electron atom?

- We could start with hydrogenic energy levels for atom of nuclear charge Z , and start filling electrons from lowest levels, accounting for Pauli exclusion.
- Degeneracy for quantum numbers (n, ℓ) is $2 \times (2\ell + 1)$. Each energy level, n , accommodates $2 \times n^2$ electrons:

n	ℓ	Degeneracy in shell	Cumulative total
1	0	2	2
2	0, 1	$(1 + 3) \times 2 = 8$	10
3	0, 1, 2	$(1 + 3 + 5) \times 2 = 18$	28
4	0, 1, 2, 3	$(1 + 3 + 5 + 7) \times 2 = 32$	60

- Expect atoms containing 2, 10, 28 or 60 electrons would be especially stable and that, in atoms containing one more electron, outermost electron would be less tightly bound.

Pauli Exclusion Principle

No two electrons in an atom can have identical [quantum numbers](#). This is an example of a general principle which applies not only to electrons but also to other particles of half-integer spin ([fermions](#)). It does not apply to particles of integer spin ([bosons](#)).

The nature of the Pauli exclusion principle can be illustrated by supposing that electrons 1 and 2 are in states a and b respectively. The wavefunction for the two electron system would be

For fermions the negative sign must be used, so that the wavefunction goes to identically zero if the states a and b are identical.

Probability amplitude that electron 1 is in state "a".

Probability amplitude that electron 2 is in state "b".

$$\psi = \psi_1(a)\psi_2(b)$$

Probability amplitude that electron 1 is in state "a" AND electron 2 is in state "b".

but this wave function is unacceptable because the electrons are identical and [indistinguishable](#). To account for this we must use a linear combination of the two possibilities since the determination of which electron is in which state is not possible to determine.

The wavefunction for the state in which both states "a" and "b" are occupied by the electrons can be written

$$\psi = \psi_1(a)\psi_2(b) \pm \psi_1(b)\psi_2(a)$$

Probability amplitude that both states "a" and "b" are occupied by electrons 1 and 2 in either order.

Required for bosons.

Required for fermions.

The Pauli exclusion principle is part of one of our most basic observations of nature: particles of half-integer spin must have antisymmetric wave functions, and particles of integer spin must have symmetric wavefunctions. The minus sign in the above relationship forces the wavefunction to vanish identically if both states are "a" or "b", implying that it is impossible for both electrons to occupy the same state.

The below table shows the distribution of electron in shell and sub-shell ,these shells are identified by the letters (K, L,M ,N)corresponding to (1,2,3,4.....) respectively.

Shell			K	L	M			
1			0	0	1	0	1	2
			s	s	p	s	p	d
m_l			0	0	0,+1,-1	0	0,+1,-1	0,+2,-2
No. of electron			2	2	6	2	6	10
Total	2	8	18					

State	Principal quantum number n	Orbital quantum number	Magnetic quantum number	Spin quantum number	Maximum number of electrons
1s	1	0	0	$+\frac{1}{2}, -\frac{1}{2}$	2
2s	2	0	0	$+\frac{1}{2}, -\frac{1}{2}$	2
2p	2	1	-1,0,+1	$+\frac{1}{2}, -\frac{1}{2}$	6
3s	3	0	0	$+\frac{1}{2}, -\frac{1}{2}$	2
3p	3	1	-1,0,+1	$+\frac{1}{2}, -\frac{1}{2}$	6
3d	3	2	-2,-1,0,1,2	$+\frac{1}{2}, -\frac{1}{2}$	10

$\left. \begin{matrix} 2 \\ 2 \\ 6 \end{matrix} \right\} 8$
 $\left. \begin{matrix} 2 \\ 6 \\ 10 \end{matrix} \right\} 18$

Exp: Write the quantum numbers of all electron in shell

n=3 or in M-shell

Principal Quantum Number, n = 3

n	ℓ	m_ℓ	m_s	n	ℓ	m_ℓ	m_s
3	0	0	$+\frac{1}{2}$	3	2	-2	$+\frac{1}{2}$
3	0	0	$-\frac{1}{2}$	3	2	-2	$-\frac{1}{2}$
3	1	-1	$+\frac{1}{2}$	3	2	-1	$+\frac{1}{2}$
3	1	-1	$-\frac{1}{2}$	3	2	-1	$-\frac{1}{2}$
3	1	0	$+\frac{1}{2}$	3	2	0	$+\frac{1}{2}$
3	1	0	$-\frac{1}{2}$	3	2	0	$-\frac{1}{2}$
3	1	+1	$+\frac{1}{2}$	3	2	1	$+\frac{1}{2}$
3	1	+1	$-\frac{1}{2}$	3	2	1	$-\frac{1}{2}$
				3	2	2	$+\frac{1}{2}$
				3	2	2	$-\frac{1}{2}$