CHM 535/635
Molecular and Supramolecular Photochemistry

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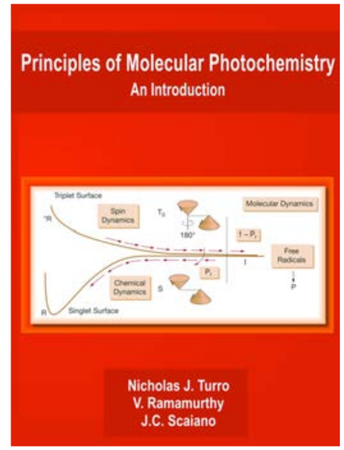
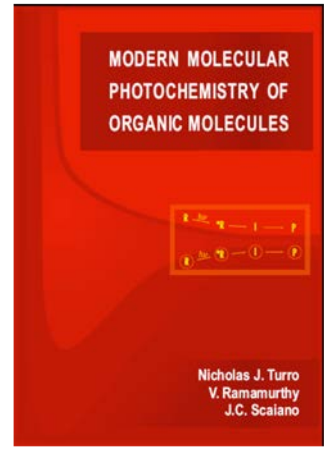


~ 500 pages



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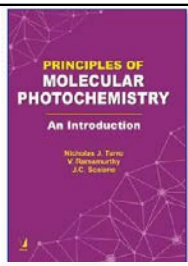

Principles of Molecular Photochemistry
An Introduction

Nicholas J. Turro, V. Ramamurthy, J C Scaiano

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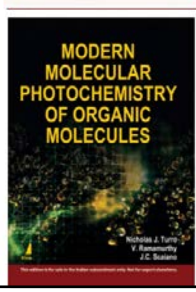

Modern Molecular Photochemistry of Organic Molecules

Nicholas J. Turro, V. Ramamurthy & J.C. Scaiano

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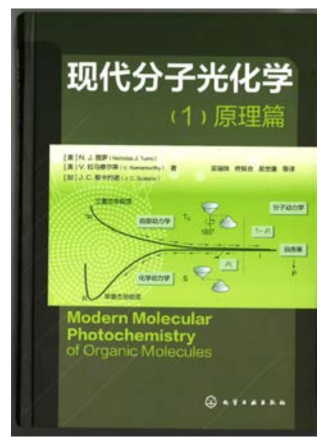
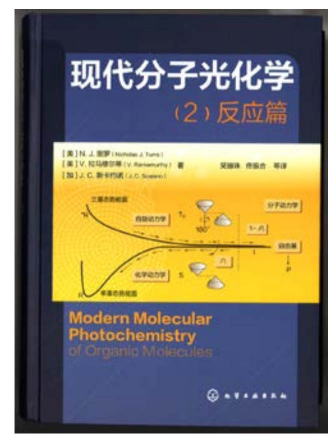
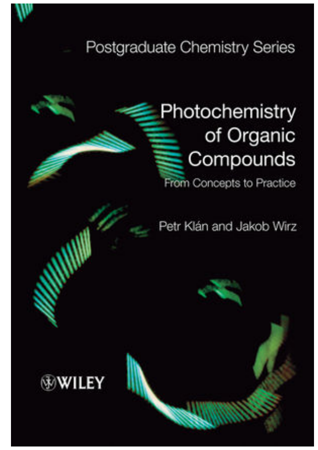
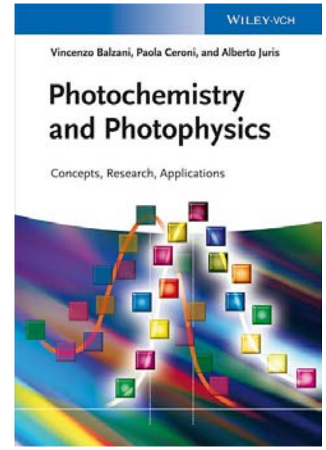








This Course

Deals with interaction of Light with

Materials, Molecules, Electrons

What is light?
What is a material?
What is a molecule?
What is an electron?
How do light and an electron interact?
What are the consequences of interaction?
What are the uses of light in our everyday life?

Syllabus

Introduction (Ch. 1)
- The Nature of Photon (Photon of photochemistry)
- Light and Life (Real life applications of photons)

Molecules: Electronic, Vibrational and Spin States (Ch 2)

Radiative Transitions between Electronic States (Ch 3 & 4)
- Selection rules for spin allowed and spin forbidden transitions
- Fluorescence, Phosphorescence, Excimer/exciplex, Delayed fluorescence, TICT emission, Applications of emission

Back to Triplet and Spin (selected publications)

Radiationless Transitions (Ch 5)
- Mechanism of spin inter-conversion, Spin-orbit coupling, Heavy atom effect; Properties of triplets

Energy and Electron Transfer (Ch 7)
- Singlet-Singlet ET, Triplet-Triplet ET, Triplet-Triplet annihilation and Singlet fission
- Mechanism of electron transfer, Contributions of Weller and Marcus, Long range electron transfer
- Role of energy and electron transfer in natural and artificial photosynthesis

Visualizing Organic Photoreactions in terms of Surfaces (Ch 6)

Supramolecular Photochemistry (Ch 13)

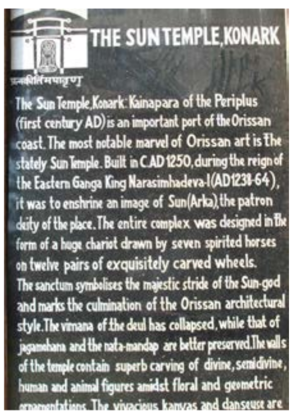
The Photon Theory of Light

Suryanar koil, India

Ise Jingū- the Naikū, Japan

Temple of Heaven, Beijing

Recognizing the importance of light, SUN-its ultimate source has been worshipped in many ancient cultures. Only a few have gone beyond to probe its nature.



Our fore-fathers recognized the overall impact of light on our life

Surya

From the Sun arise all beings.
The Sun sustains them all.
Into the Sun they all vanish.
What the Sun is,
that I am.

—*Surya Upanishad* (~1000 BCE)
(~3000 yrs ago)

Light is made up of particles

Democritus
c. 460 – c. 370 BC
(~2500 yrs ago)

Sunlight is presumably, like fire, composed of small, swift-moving round atoms.

Vision occurs by means of the images flowing from objects, which enter the eye.

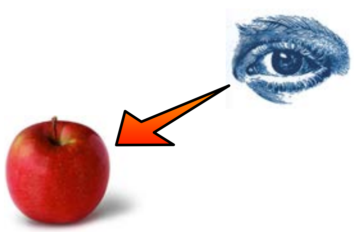
Light is made up of particles

Euclid, 300 BC

Euclid's *Optics,* 300 BC

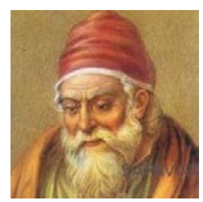
"*The light and heat of the sun are composed of minute atoms which, when they are shoved off, lose no time in shooting right across the interspace of air in the direction imparted by the shove.*"

Euclid's view of vision: Eye to the object



Certain forms of radiation are emitted from the eyes onto the object which is being seen. When these rays reached the object they allowed the viewer to perceive its color, shape and size.

Ḥasan Ibn al-Haytham on vision



Ḥasan Ibn al-Haytham
965-1040 AD
(~1000 yrs ago)

Book of Optics
7 volumes

Eye to brain

Ḥasan Ibn al-Haytham on light and vision

Light travels in straight lines

Vision occurs when light reflects from an object and then passes to one's eyes.

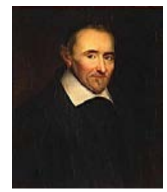
The object sends an infinite number of rays of light to the eye, only one of these lines falls on the eye perpendicularly. All the rays other than the one that hits the eye perpendicularly are not involved in vision.

Vision occurs in the brain, rather than in the eyes.

Light is made up of particles

René Descartes
1596 –1650 AD
(~500 yrs ago)

Light is made up **of** small discrete **particles** called "corpuscles" (little **particles**) which travel in a straight line with a finite velocity and possess impetus.

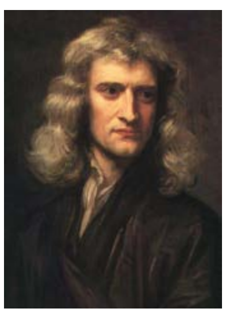


Pierre Gassendi
(1592–1655)

Light is composed of corpuscles (particles of matter) which were emitted in all directions from a source.

Light is made up of particles

Corpuscular theory of light



Sir Isaac Newton (1643-1727)

(~400 yrs ago)

Every source of light emits large numbers of tiny particles that are elastic, rigid, and weightless.

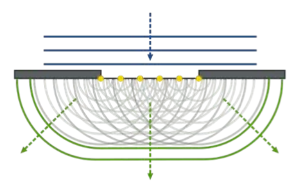
Light is a particle because the periphery of the shadows it creates is extremely sharp and clear.

Newton argued that the geometric nature of reflection and refraction of light could only be explained if light were made of particles, because waves do not tend to travel in straight lines.

Light is a wave

Francesco Maria Grimaldi
1618 –1663
(~400 yrs ago)

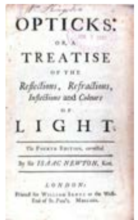
In 1665, Italian physicist Francesco Maria Grimaldi discovered the phenomenon of light diffraction and pointed out that it resembles the behavior of waves.



Christian Huygens
(1629 to 1695)

In 1678, Huygens proposed that every point to which a luminous disturbance reaches becomes a source of a spherical wave; the sum of these secondary waves determines the form of the wave at any subsequent time.

What is light?



Treatise on Light

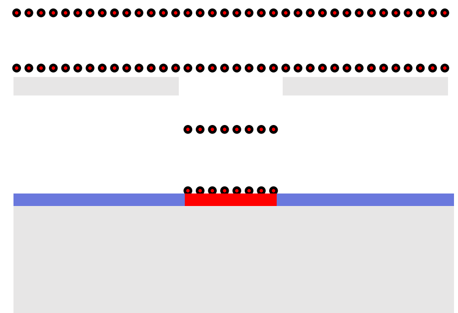
In the late 1600's Newton explained many of the properties of light by assuming it was made of particles.

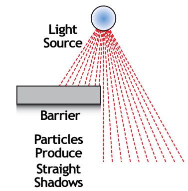
In 1678 Christian Huygens argued that light was a pulse traveling through a medium, or as we would say, a wave.

Because of Newton's enormous prestige, his support of the particle theory of light tended to suppress other points of view. This continued for 100 years.

Corpuscular theory of light

Light moves in straight lines

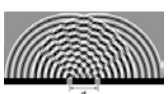




"Light does not bend into the shadow"

Light is a wave: A new evidence

Thomas Young
(1773 to 1829)
(~250 yrs ago)

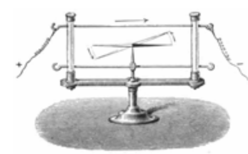


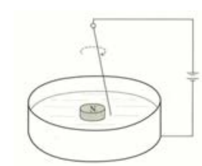
The bright and dark bands demonstrated that the slits were causing light waves to interfere with each other. Sometimes this interference is constructive and sometimes destructive. This leads to light waves adding together to create a bright patch and cancelling each other out creating dark patches.

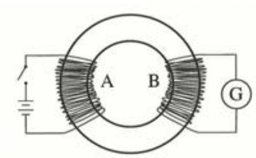
Double-slit experiment demonstrated interference in the context of light as a wave

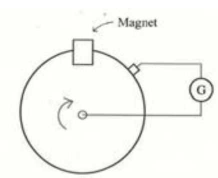
Electricity and magnetism are interconnected

Michael Faraday
1791-1867
(~220 yrs ago)



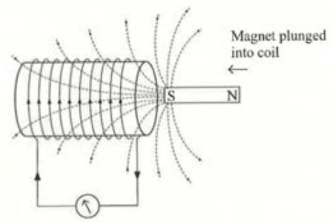






Nonlinear Magnetic Lines of force
A different concept from Newton

Fig. 5.6. Magnetic lines of force shown by iron filings sprinkled on paper over a magnet. (Courtesy of Windell H. Oksay / www.evil madscientist.com.)



Establishing for the first time a link between magnetism and light

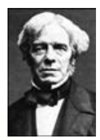
In March 1832, Faraday left a note in the safe of the Royal Society.

> "I am inclined to compare the diffusion of magnetic forces from a magnetic pole to the vibrations upon the surface of disturbed water or those of air in the phenomenon of sound; i.e. I am inclined to think the vibratory theory will apply to these phenomena, as it does to sound and, most probably, to light."

To Ampere, Nov 1845

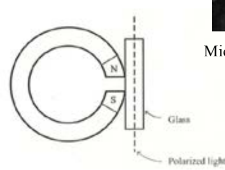
> "I happen to have discovered a direct relation between magnetism and light also Electricity and Light---and the field it opens is so large & I think rich that I naturally wish to look at it first"

Much larger discovery
Light is an electromagnetic wave

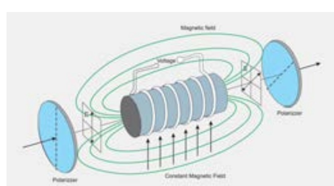


Michael Faraday
1791-1867

In 1845, Michael Faraday discovered that the plane of polarization of linearly polarized light is rotated when the light rays travel along the magnetic field direction in the presence of a transparent dielectric, an effect now known as Faraday rotation



Faraday Effect: Magnetic field rotates plane polarized light



Maxwell: Light is an electromagnetic wave

"The electromagnetic theory of light, as proposed by Faraday, is the same in substance as that which I have begun to develop in this paper, except that in 1846 there were no data to calculate the velocity of propagation. ---- Faraday discovered that when a plane polarized ray transverses a transparent diamagnetic medium in the direction of the lines of magnetic force produced by magnets or currents in the neighborhood, the plane of polarization is caused to rotate."

Maxwell, a publication in 1865

"I think we have now strong reason to believe, whether my theory is a fact or not, that the luminiferous and the electromagnetic medium are one." In other words, light is indeed an electromagnetic undulation-a "ray-vibration," as you had called it in 1846.

Maxwell to Faraday, October 1861

James Clerk Maxwell
(1831-1879)
(~180 yrs ago)

"…it seems we have strong reason to conclude that light itself is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws."

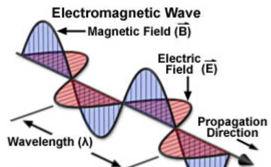


Figure 1

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$

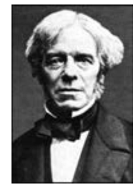
$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

In the 1860's Maxwell, building on Faraday's work, developed a mathematical model of electromagnetism. He was able to show that these electromagnetic waves travel at the speed of light.

Light is indeed Electromagnetic Waves

- Faraday laid the groundwork with his discovery of electromagnetic induction
- Maxwell predicted theoretically that electromagnetic waves should exist; light is an electromagnetic wave
- Heinrich Hertz showed experimentally in 1886 that EM waves exist (radiowaves)



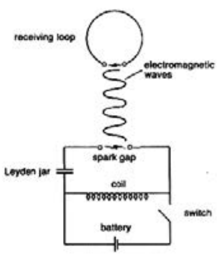
Michael Faraday
1791-1867

James Clerk Maxwell
(1831-1879)

Heinrich Rudolf Hertz
1857-1894

All discoveries less than 200 yrs old

Experimental support for light is a wave



- ➢ Sparks were induced across the gap of the receiving electrodes when the frequency of the receiver was adjusted to match that of the transmitter.
- ➢ In a series of other experiments, Hertz also showed that the radiation generated by this equipment exhibited wave properties.
- ➢ Interference, diffraction, reflection, refraction and polarization
- ➢ He also measured the speed of the radiation.
- ➢ It was close to the known value of the speed of light.

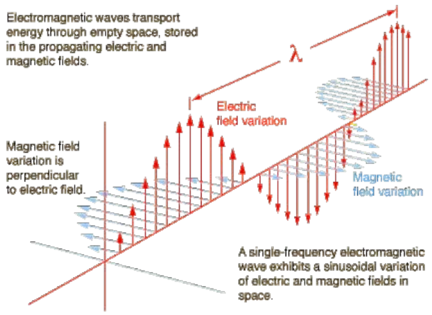
"I do not think that the wireless waves I have discovered will have any practical application."

Basis of radio & television industry

How does light wave travel?

- Ocean waves — water molecules
- Sound — molecules in air
- Light — **ether**

Light as EM waves



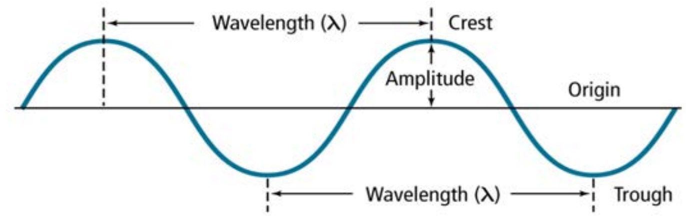
Characterized by:

- Wavelength (λ)
- Amplitude (A)
- Frequency (ν)

$$\nu = \frac{c}{\lambda}$$

The Wave Nature of Light

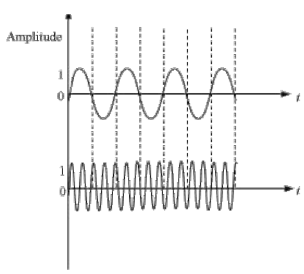
- The amplitude is the wave's height from the origin to a crest.



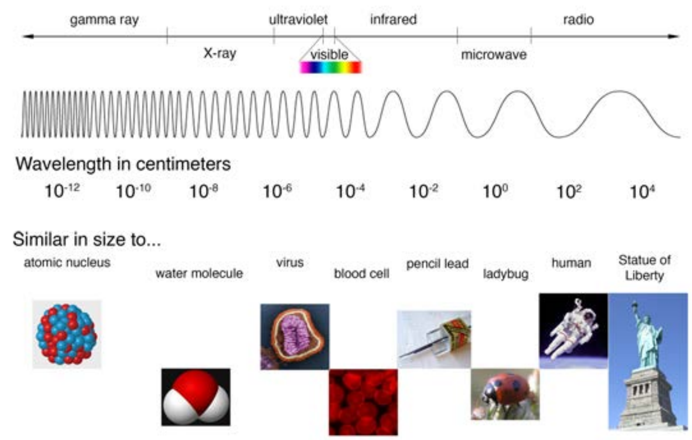
Classical: Energy carried by a light wave is proportional to the *Amplitude* of wave

The Wave Nature of Light

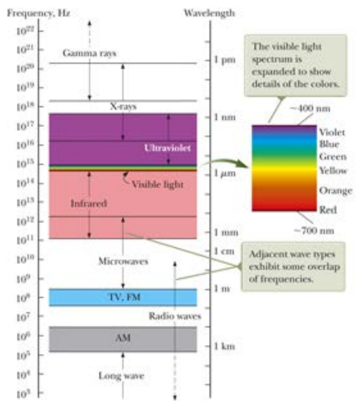
- The frequency (υ) is the number of waves that pass a given point per second.
- Wavelength and frequency are inversely related—the shorter the wavelength, the higher the frequency.
- Light is a type of energy that travels through space at a constant speed of 3.0×10^8 m/s (186,000 mi/s).
- Classical: Energy carried by a light wave is proportional to the *Amplitude* of wave. $E \propto A^2$

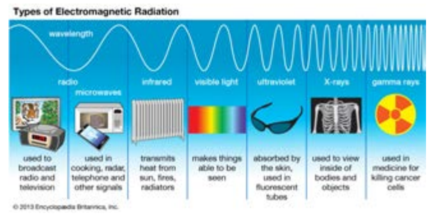


Wavelengths and the sizes we are familiar with



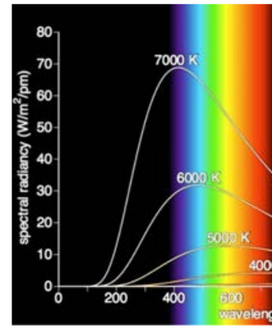
Uses of electromagnetic radiations of different wavelengths





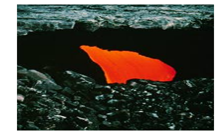
Relationship between color, temperature and energy

Volcanic lava



Bulb

Volcanic lava



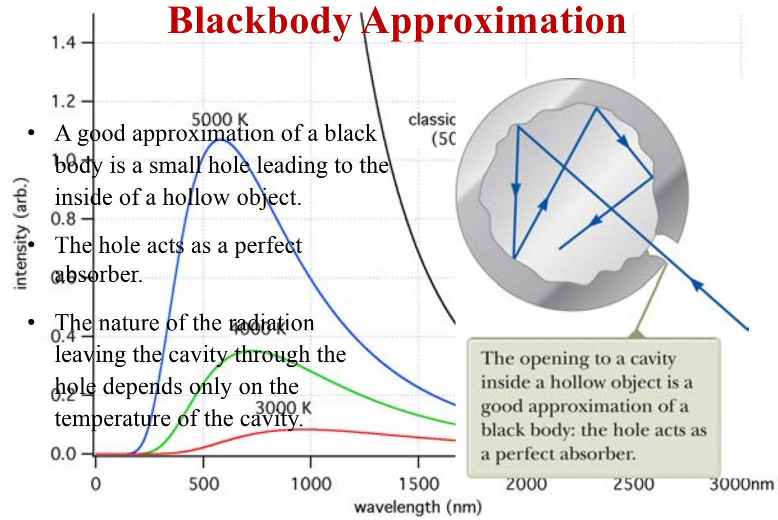
- The **intensity** increases with increasing temperature.
- The peak **wavelength** decreases with increasing temperature.

Charcoal in a grill

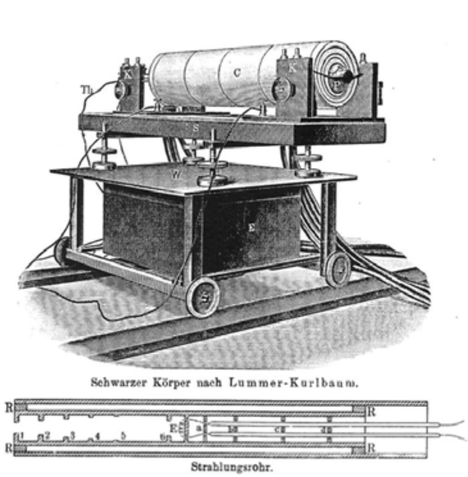
Fahrenheit	The Color of the Steel
2000°	Bright Yellow
1900°	Dark Yellow
1800°	Orange Yellow
1700°	Orange
1600°	Orange Red
1500°	Bright Red
1400°	Red
1300°	Medium Red
1200°	Dull Red
1100°	Slight Red
1000°	Very Slightly Red, Mostly Grey
800°	Dark Grey
575°	Blue
540°	Dark Purple
520°	Purple
500°	Brown/Purple
480°	Brown
465°	Dark Straw
445°	Light Straw
390°	Faint Straw

- At relatively low temperatures, most radiation is emitted at wavelengths longer than 700 nm.
- As the temperature of the object increases, the maximum intensity shifts to shorter wavelengths, successively resulting in orange, yellow, and finally white light.
- Note the sharp decrease in the intensity of radiation emitted at wavelengths below 400 nm, which constituted the ultraviolet catastrophe.

Blackbody Approximation

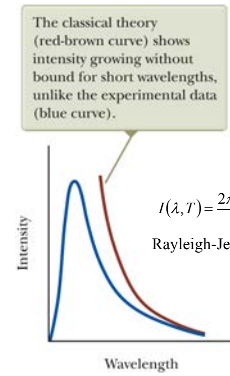


- A good approximation of a black body is a small hole leading to the inside of a hollow object.
- The hole acts as a perfect absorber.
- The nature of the radiation leaving the cavity through the hole depends only on the temperature of the cavity.



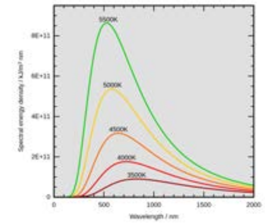
Apparatus of Lummer and Kurlbaum to measure the spectrum of black-body radiation. An electrical current heats the filament E located in a tube inside the cylinder C to a fixed temperature T, giving rise to black-body radiation inside this cylinder. The spectrum of this radiation is observed by some radiation exiting through the hole at one end along the axis of the cylinder.

Classical Theory of Radiation



$I(\lambda,T)=\frac{2\pi ckT}{\lambda^4}$

Rayleigh-Jeans law



$\lambda_{peak} = \frac{b}{T}$

$\nu_{peak} = \frac{\alpha}{h}kT \approx (5.879 \times 10^{10}\ \mathrm{Hz/K}) \cdot T$

Wien was able to predict the λ_{max} for a given temp.

The Lord Rayleigh
Nobel Prize 1904

W. Wien
Nobel Prize 1911

Classical prediction: the intensity and frequency increased rapidly with temperature, hence the ultraviolet catastrophe.

An Extraordinary Claim

1858 – 1947
Nobel Prize 1918

Publication by Max Planck in 1900


Zur Theorie des Gesetzes der Energieverteilung im Normalspectrum; von M. Planck.

Planck made the extraordinary suggestion that states (oscillators) that absorb and emit light are quantized rather than being continuous.

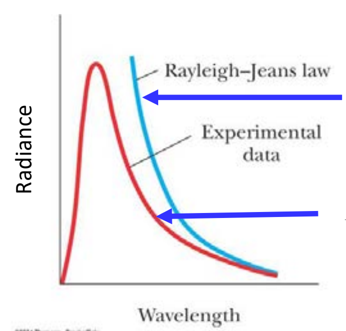
The suggestion was considered bizarre and not physically realistic at the time, but is now universally accepted by the scientific community.

"New scientific truth usually becomes accepted, not because its opponents become convinced, but *because opponents gradually die* and because the rising generations are familiar with the new truth at the outset."

M. Planck, Naturwissenschaften, *33*, 230 (1946).

Comparison between Planck's law of BB radiation and Rayleigh-Jean's law

- In 1900 Planck developed a theory of blackbody radiation that leads to an equation that correctly predicted the intensity and wavelength of the radiation with temperature.
- This equation is in complete agreement with experimental observations.
- He assumed the cavity radiation came from atomic oscillations in the cavity walls.
- **Planck made two assumptions about the nature of the oscillators in the cavity walls.**



$I(\lambda,T)=\frac{2\pi ckT}{\lambda^4}$

correctly fit by Planck's derivation

$I(\lambda,T)=\frac{2\pi c^2 h}{\lambda^5}\frac{1}{e^{hc/\lambda kT}-1}$

$h = 6.626 \times 10^{-34}\ [J \cdot s]$

Planck's Assumption #1

The energy of an oscillator can have only certain discrete values $E_{n.}$

$$E_n = n\ h\ v$$

n is a positive integer called the quantum number

v is the frequency of oscillation

h is Planck's constant

This implies the energy is quantized.

Each discrete energy value corresponds to a different quantum state.

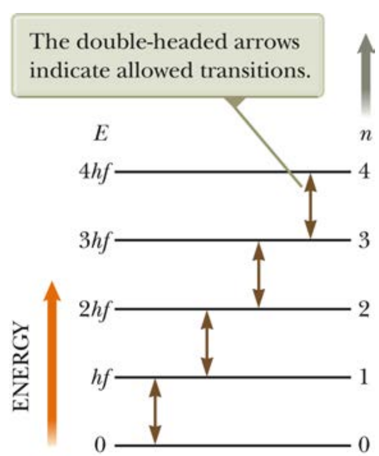
Each quantum state is represented by the quantum number, *n*.

Planck's Assumption #2

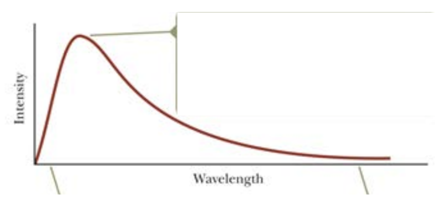
- The oscillators emit or absorb energy when making a transition from one quantum state to another.
  - The entire energy difference between the initial and final states in the transition is emitted or absorbed as a single quantum of radiation.
  - An oscillator emits or absorbs energy only when it changes quantum states.
  - The energy carried by the quantum of radiation is $E = hv$.

Energy-Level Diagram

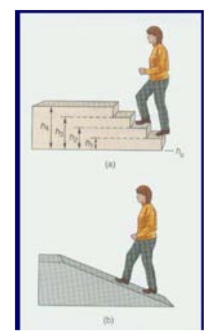
- An energy-level diagram shows the quantized energy levels and allowed transitions.
- Lines represent the allowed energy levels.
- The double-headed arrows indicate allowed transitions.



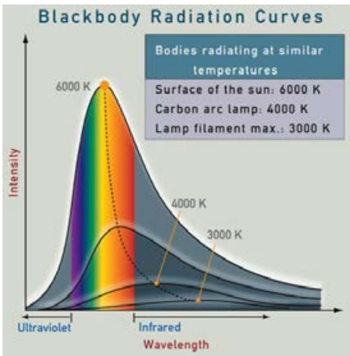
Planck's Model: Energy of an Oscillator is Quantized



To solve the BB catastrophe one has to assume that the energy of individual radiation oscillator in the cavity of a BB is quantized as per $E_n = nhv$



Temperature and light distribution of galaxy



Color of the star is related to surface temperature

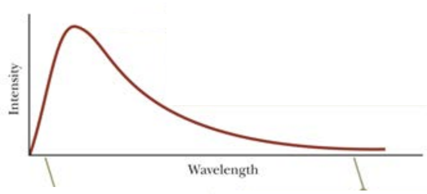
Max K. E. L. Planck
The Nobel Prize in Physics 1918

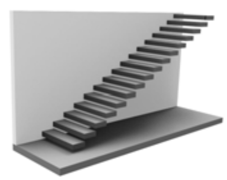
"in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta."

- **When a black body is heated, electromagnetic radiation is emitted with a spectrum corresponding to the temperature of the body, and not to its composition.**
- **Calculating the form of the spectrum using then-known physical laws gave an unreasonable result; the radiation in the high-frequency area of the spectrum became infinite.**
- **Max Planck solved this problem in 1900 by introducing the theory of "quanta", that is, that radiation consists of quanta with specific energies determined by a new fundamental constant, thereafter called Planck's constant.**

This marked a turning point in the history of physics. The importance of the discovery although not appreciated at first, its validity gradually became overwhelming as its application accounted for many discrepancies between observed phenomena and classical theory.

Planck's Model: Energy of an Oscillator is Quantized





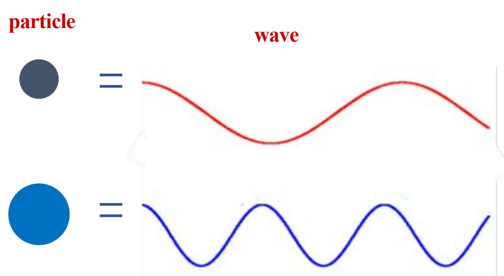
Energy of an Oscillator is Quantized

- Classical BB presents an "ultraviolet catastrophe"
- The spectral energy distribution of electromagnetic radiation in a black body CANNOT be explained in terms of classical Maxwell EM theory.
- To solve the BB catastrophe one has to assume that the energy of individual radiation oscillator in the cavity of a BB is quantized as per $E_n = nh\nu$

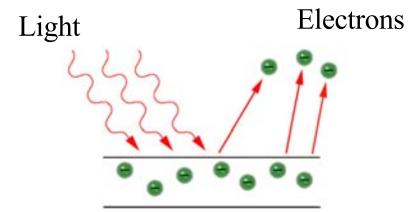
$$h = 6.626 \times 10^{-34} \, [J \cdot s]$$

- This picture is in conflict with classical physics because in classical physics energy is in principle a continuous variable that can take any value between 0 →∞
- One is then lead to the revolutionary concept that **ENERGY OF AN OSCILLATOR IS QUANTISED**

Light as a particle and a wave



Photoelectric Effect



Metal's electrons near the surface are ejected upon light absorption

In 1887 H. Hertz (1857-1894) of Germany was the first person to see the photoelectric effect.

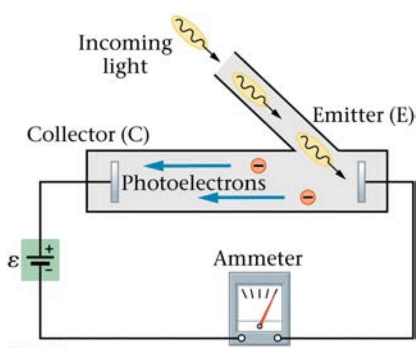
In 1899, in England, J. J. Thompson demonstrated that ultraviolet light hitting a metal surface caused the ejection of electrons

In 1905 Einstein, then a young patent clerk in Switzerland, explained the phenomenon.

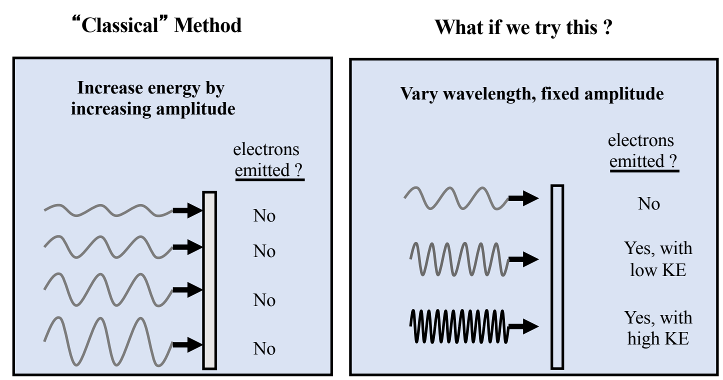
In 1921 Einstein received the Nobel Prize after Robert Millikan confirmed the work.

Photons and the Photoelectric Effect

- Light incident on a metal will eject electrons
- The emitted electrons are called photoelectrons

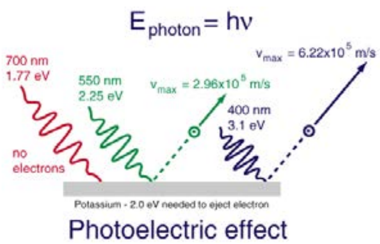


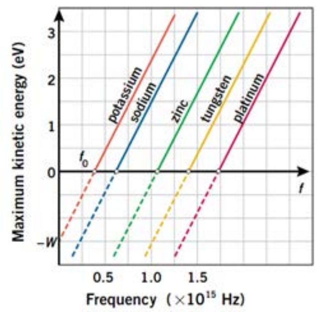
Observation of the Photoelectric Effect



No electrons were emitted until the frequency of the light exceeded a critical frequency! Not the intensity, but the wavelength matter!

Photoelectric Effect





For a given metal, there exists a threshold energy below which no photoelectrons are emitted.

Each metal has a different threshold frequency (Energy)

Analysis of Photoelectric Effect Based on Classical Mechanics-1

•Dependence of photoelectron kinetic energy on light intensity

- ***Classical Prediction***
  - **Electrons should absorb energy continually from the electromagnetic waves.**
  - **As the light intensity incident on the metal is increased, the electrons should be ejected with more kinetic energy.**
- ***Experimental Result***
  - **The maximum kinetic energy is independent of light intensity.**
  - **The maximum kinetic energy is proportional to the stopping potential (DV_s).**

Analysis of Photoelectric Effect Based on Classical Mechanics-2

•Time interval between incidence of light and ejection of photoelectrons

- ***Classical Prediction***
  - **At low light intensities, a measurable time interval should pass between the instant the light is turned on and the time an electron is ejected from the metal.**
  - **This time interval is required for the electron to absorb the incident radiation before it acquires enough energy to escape from the metal.**
- ***Experimental Result***
  - **Electrons are emitted almost instantaneously, even at very low light intensities.**

Analysis of Photoelectric Effect Based on Classical Mechanics-3

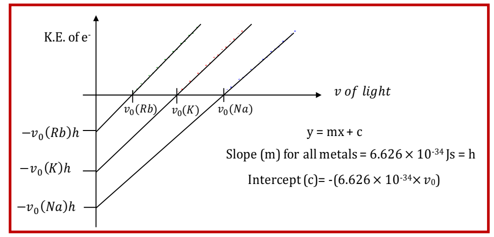
•Dependence of ejection of electrons on light frequency

- ***Classical Prediction***
  - **Electrons should be ejected at any frequency as long as the light intensity is high enough.**
- ***Experimental Result***
  - **No electrons are emitted if the incident light falls below some cutoff frequency, ν_c.**
  - **The cutoff frequency is characteristic of the material being illuminated.**
  - **No electrons are ejected below the cutoff frequency regardless of intensity.**

Analysis of Photoelectric Effect Based on Classical Mechanics-4

- Dependence of photoelectron kinetic energy on light frequency
  - *Classical Prediction*
    - **There should be no relationship between the frequency of the light and the electric kinetic energy.**
    - **The kinetic energy should be related to the intensity of the light.**
  - *Experimental Result*
    - **The maximum kinetic energy of the photoelectrons increases with increasing light frequency.**

Einstein analyzed plots of K.E. of photoelectrons as a function of freq. for different metals (1905)

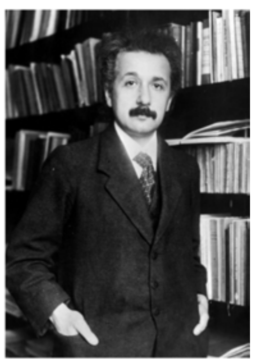


$$\hbar\omega = W + \frac{1}{2}mv^2$$

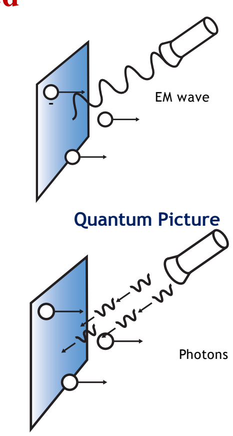
PHOTON ENERGY — BINDING ENERGY OF ELECTRON — ELECTRON KINETIC ENERGY

1. Slope is same for all the metal and is equal to Planck's constant (h)
2. KE = h ν - h ν_0 (Incident energy; Threshold energy (Work function))
3. The surface takes only h ν_0 and that needs to be delivered in one packet.
4. **Light is made up of energy "packets" called photons,** Light energy is quantized.

Light is quantized



Albert Einstein
Nobel Prize, 1921



Annalen der Physik, **1905**, 26 years old, six weeks before submission of his Ph. D. thesis

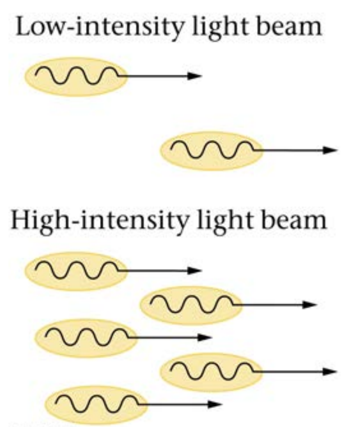
Light comes in quantas

Light = Photon

GN Lewis, *Nature*, **118**, 874–875(1926)

Intensity of Light Beam

- A more intense beam of light will contain more photons. The total energy will change but not the individual photon energy.
- 5 x 20 kCal = 100 kCal
- If 100 kCal is required to kick out an electron from surface 5 x 25 kCal would mot do. All 100 kCal must be delivered in one shot.



Einstein's Model of Light: Photon Torpedoes

Light can be represented as separate, discontinuous quanta called **photons**.

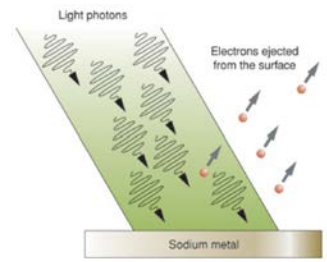
Light energy comes in packets. Each photon has an energy of E = hν

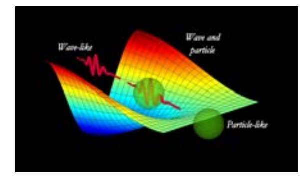
Light interacts with matter as a stream of particle-like photons.

Light travels as a wave.

One photon interacts only with single electron

Light is complex – it has a wave-particle duality behavior.





Do photons have mass?

Since photons have particle-like properties, they should have mass.

The (relativistic) mass of photons can be calculated from Einstein's equation for special relativity.

$$E = h\nu = \frac{hc}{\lambda} \qquad E = mc^2$$

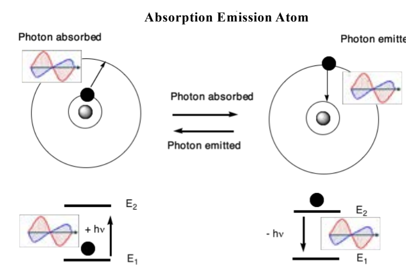
$$m = \frac{E}{c^2} = \frac{hc/\lambda}{c^2} = \frac{h/\lambda}{c}$$

Electronic transitions (oscillators) are quantized

Niels Bohr
Nobel Prize 1922

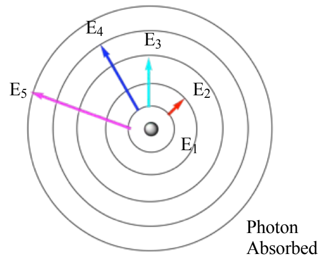
Light is emitted when an electron jumps from a higher orbit to a lower orbit and is absorbed when it jumps from a lower to higher orbit.

The energy and frequency of light emitted or absorbed is given by the difference between the two orbit energies,
E(photon) = E_2 - E_1 (energy difference)

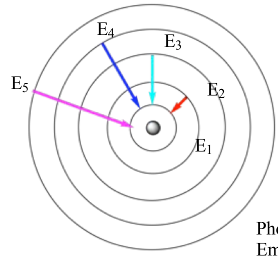


The basis of all photochemistry and spectroscopy!

Absorption and Emission



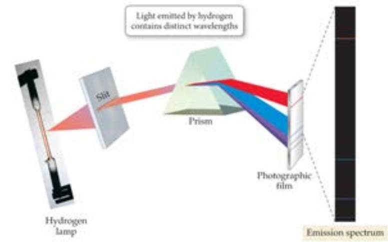
Photon Absorbed



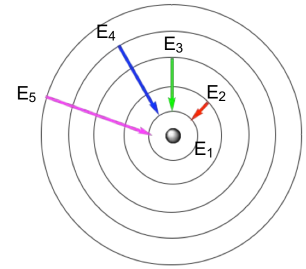
Photon Emitted

Bohr atom: Light absorption occurs when an electron absorbs a photon and makes a transition for a lower energy orbital to a higher energy orbital. ***Absorption spectra appear as sharp lines.***

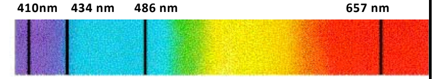
Bohr atom: Light emission occurs when an electron makes a transition from a higher energy orbital to a lower energy orbital and a **photon is emitted.** ***Emission spectra appear as sharp lines.***



Schematic of the Experiment



If all this is true then you should be able to "see" the spectrum of the electrons jumping from E_5, E_4, E_3, E_2 to E_1 and here is what we see.



The "line" spectrum of hydrogen

What is LIGHT?

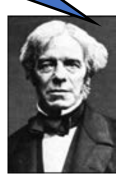
Democritus
c. 460 – 370 BC

Particles!

Action at a distance, Particles!

Electromagnetic field, wave-like

Newton
1643-1727

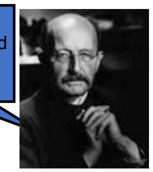


Faraday
1791-1867

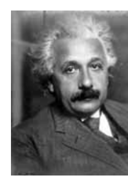
Maxwell
(1831-1879)

Waves! Electro-magnetic

Waves! Absorption and emission are quantized



Max Planck (1918)



Albert Einstein (1921)

E = hν, Particles, Light is quantized, photons

$E_2 - E_1 = h\nu$
Energy levels are quantized; Light is absorbed and emitted in quantas.

Niels Bohr (1922)

Wave and/or Particle

Particles and Waves

- Some experiments are best explained by the particle model.
- Some are best explained by the wave model.
- We must accept both models and admit that the true nature of light is not describable in terms of any single classical model.
- The particle model and the wave model of light complement each other.
- A complete understanding of the observed behavior of light can be attained only if the two models are combined in a complementary matter.

Liquid water is made up of molecules. Amount is measure in terms of mole (M). One mole contains 6.022×10^{23} molecules (**Avogadro**'s number). Weight of one M depends on the weight of the molecule.

Light is made up of photons. Light is measured in terms of **Einstein**. One Einstein is the energy in one mole (6.022 x 10^{23}) of photons. Energy of one E depends on the frequency of photon.

An Unsettling Dilemma

What becomes of the energy of a photon after complete emission? Does it spread out in all directions with further propagation in the sense of Huygens' wave theory, so constantly taking up more space, in boundless progressive attenuation? Or does it fly out like a projectile in one direction in the sense of Newton's emanation theory? In the first case, the quantum would no longer be in the position to concentrate energy upon a single point in space in such a way as to release an electron from its atomic bond, and in the second case, the main triumph of the Maxwell theory – the continuity between the static and the dynamic fields and, with it, the complete understanding we have enjoyed, until now, of the fully investigated interference phenomena – would have to be sacrificed, both being very unhappy consequences for today's theoreticians.

Max Planck, Nobel Prize, 1918
Nobel Lecture, June 2, 1920

Photon

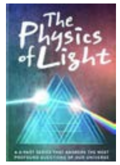
"Thus light is something like raindrops-each little lump of light is called a photon-and if the light is all one color, all the "raindrops" are the same size."

Richard P. Feynman
Nobel Prize, 1965

Strange particles

Photon 'state' is defined by:

- momentum
- energy
- polarization
- spin (s=1)



"Nobody knows, and it's best if you try not to think about it."

Richard Feynman

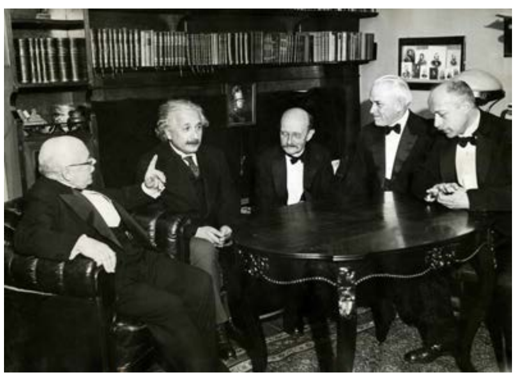
"These days, every Tom, Dick and Harry thinks he knows what a photon is, but he is wrong",

Albert Einstein, 1951

Read more

- Thomas Young's double slit experiment
- Faraday rotation
- Maxwell's equations
- Hertz' experiment on electromagnetic radiation
- Blackbody radiation
- Ultraviolet catastrophe
- Planck's quantization of energies of absorption and emission
- Einstein's quantization of light
- Bohr's atom model and electronic transition

W. Nernst	A. Einstein	**M. Planck**	R.A. Millikan	von Laue
1920	1921	1918	1923	1914



At a dinner given by von Laue in Berlin on 11 November 1931