Modern Physics (EP1108)
Course organization

Class Structure and Timings

This course will be taught in two divisions:

- EP1a (AI+CH+CS+EP+ES+MS)
- EP1b (CE+EE+ME+MnC+BME+BT+Comp.Engg)

Class Timings :

- EP1a Q-slot (Mon 4-5:30, Thu 2:30-4)
- EP1b A slot (Mon 9-10, Wed 11-12, Thu 10-11)

Course Instructors and Teaching schedule

- Shantanu Desai (shantanud@phys.iith.ac.in)
- Kirit Makwana
- Mayukh Pahari (mayukh@phy.iith.ac.in)
- Prem Pal

In a given week, separate topics will be taught by different instructors to the two sections, and in the following week, the instructors will swap

After **every two weeks,** both divisions should have covered the same syllabus

Course Evaluation

- Two exams (80%)
- Assignments (20%)

Exams will be conducted simultaneously for both the divisions at a common time outside of regular class hours. Details to be provided later

Assignments should be submitted on google classroom

Course content (brief outline)

Black Body Radiation

Special Theory of Relativity

Young's double-slit experiment

Uncertainty principle

Quantum Mechanics and Boundary value problems

Lasers and Plasmas

Phase Transitions

Saha Equation

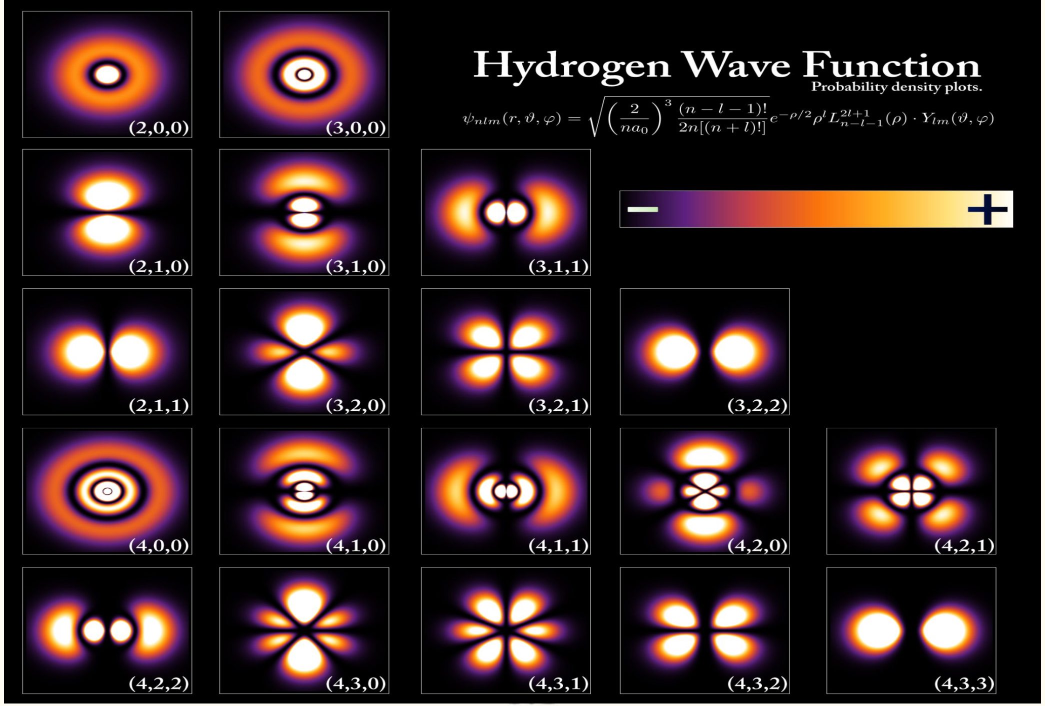
Band Theory of Semiconductors

Phonons

Nuclear and Particle Physics and General Relativity (if time permits)

Please join the classroom

https://classroom.google.com/c/NDQzODA5OTI5NjIy?cjc=qexr4ke



Quantum Mechanics

Small things are weird

Course Structure

1	LEC1	Origin of quantum mechanics, De broglie hypothesis, Young's double slit experiment
2		
3	LEC2	Wave packet, phase velocity and group velocity, Heisenberg uncertainty priciple, modern applications
4		
5	LEC3	Schroedinger's wave equation: development, normalisation, expectations, The Ehrenfest theorem
6		
7	LEC4	Time dependent and independent Schroedinger's equation, quatum mechanical operator
8		
9	LEC5	Eigen functions: orthogonality, properties and boundary conditions
10		
11	LEC6	Quantum description of free particle and wave packets

Reference BookS

Introduction to Quantum Mechanics - D J Griffith

Quantum Mechanics, Statistical Mechanics and Solid State Physics : Chattopadhyay D. & Rakshit P.C

Basics of Quantum Mechanics
- Why Quantum Physics? -

Classical mechanics (Newton's mechanics) and Maxwell's equations (electromagnetics theory) can explain MACROSCOPIC phenomena such as motion of billiard balls or rockets.

Quantum mechanics is used to explain microscopic phenomena such as photon-atom scattering and flow of the electrons in a semiconductor.
QUANTUM MECHANICS is a collection of postulates based on a huge number of experimental observations.

The differences between the classical and quantum mechanics can be understood by examining both
The classical point of view
The quantum point of view

Basics of Quantum Mechanics
- Classical Point of View -

In Newtonian mechanics, the laws are written in terms of PARTICLE TRAJECTORIES.
A PARTICLE is an indivisible mass point object that has a variety of properties that can be measured, which we call observables. The observables specify the state of the particle (position and momentum).
A SYSTEM is a collection of particles, which interact among themselves via internal forces, and can also interact with the outside world via external forces.
The STATE OF A SYSTEM is a collection of the states of the particles that comprise the system.
All properties of a particle can be known to infinite precision.

Conclusions:
TRAJECTORY state descriptor of Newtonian physics,
EVOLUTION OF THE STATE Use Newton's second law
PRINCIPLE OF CAUSALITY Two identical systems with the same initial conditions, subject to the same measurement will yield the same result.

Basics of Quantum Mechanics
- Quantum Point of View -

Quantum particles can act as both particles and waves WAVE-PARTICLE DUALITY

Quantum state is a conglomeration of several possible outcomes of measurement of physical properties Quantum mechanics uses the language of PROBABILITY theory (random chance)

An observer cannot observe a microscopic system without altering some of its properties. Neither one can predict how the state of the system will change.

QUANTIZATION of energy is yet another property of "microscopic" particles.

The Quantum Mechanics View

- All matter (particles) has wave-like properties
  - so-called particle-wave *duality*
- Particle-waves are described in a probabilistic manner
  - electron doesn't whiz around the nucleus, it has a probability distribution describing where it might be found
  - allows for seemingly impossible "quantum tunneling"
- Some properties come in dual packages: can't know both simultaneously to arbitrary precision
  - called the Heisenberg Uncertainty Principle
  - not simply a matter of measurement precision
  - position/momentum and energy/time are example pairs
- The act of "measurement" fundamentally alters the system
  - called entanglement: information exchange alters a particle's state

Basics of Quantum Mechanics
- Heisenberg Uncertainty Principle -

It is impossible to mention accurately and simultaneously the values of both the members of particular pairs of physical quantities that dictate the behaviour of an atomic system

One cannot unambiguously specify the values of particle's position and its momentum for a microscopic particle, i.e.

$$\Delta x(t_0) \cdot \Delta p_x(t_0) \geq \frac{1}{2} \frac{h}{2\pi}$$

Position and momentum are, therefore, considered as incompatible variables.

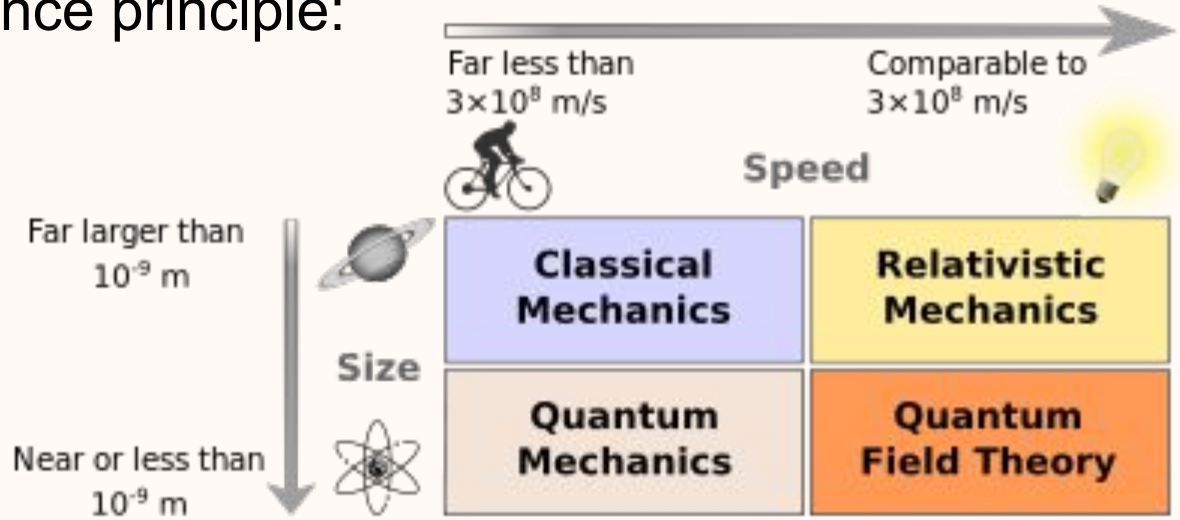
The Heisenberg uncertainty principle strikes at the very heart of the classical physics => the particle trajectory.

Some Applications of Heisenberg's uncertainty principle

- Measurement of the position of a particle and its momentum in a Gamma ray Microscope is in accordance with the Heisenberg's uncertainty principle
- It explain why free electrons cannot reside inside an atomic nucleus
- The diffraction of electrons through a narrow slit takes place in accordance with Heisenberg's uncertainty principle.
- We can estimate the ground state energy of a linear harmonic oscillator
- Natural broadening of the spectral line

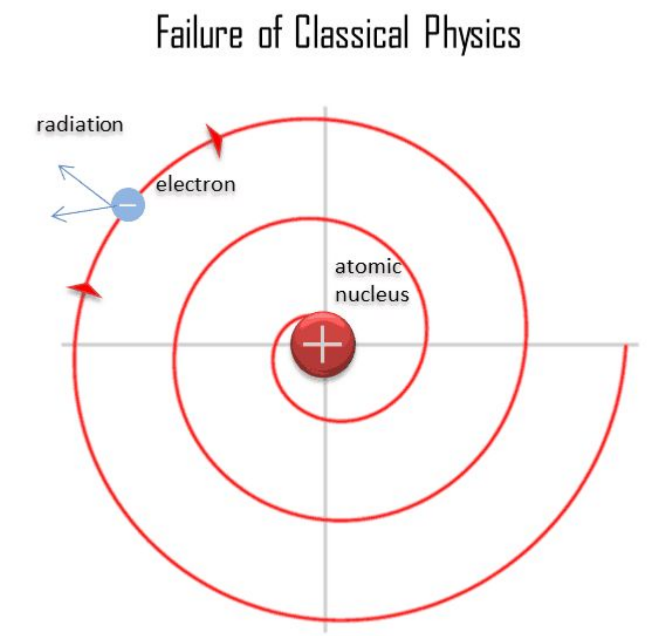
Basics of Quantum Mechanics
- The Correspondence Principle -

When Quantum physics is applied to macroscopic systems, it must reduce to the classical physics. Therefore, the nonclassical phenomena, such as uncertainty and duality, must become undetectable. Niels Bohr codified this requirement into his Correspondence principle:



Crises in physics that demanded Q.M.

- **Why don't atoms disintegrate in nanoseconds?**
  - if electron is "orbiting", it's accelerating (wiggling)
  - wiggling charges emit electromagnetic radiation (energy)
  - loss of energy would cause prompt decay of orbit



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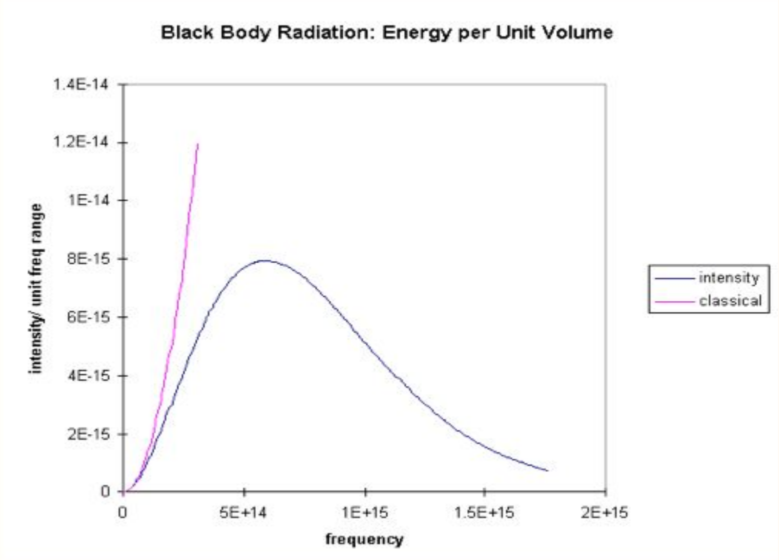
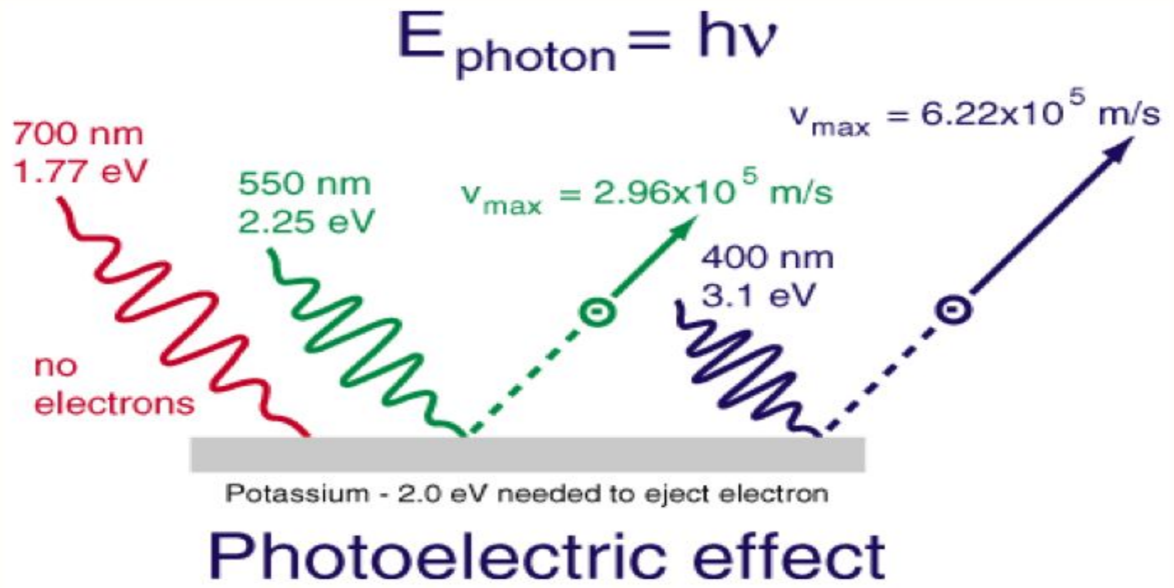
- Why don't hot objects emit more ultraviolet light than they do?
  - classical theory suggested a "UV catastrophe," leading to obviously nonsensical infinite energy radiating from hot body
  - Max Planck solved this problem by postulating light quanta (now often called the father of quantum mechanics)



Pre-quantum problems, cont.

- Why was red light incapable of knocking electrons out of certain materials, no matter how bright
  - yet blue light could readily do so even at modest intensities
  - called the photoelectric effect
  - Einstein explained in terms of photons, and won Nobel Prize



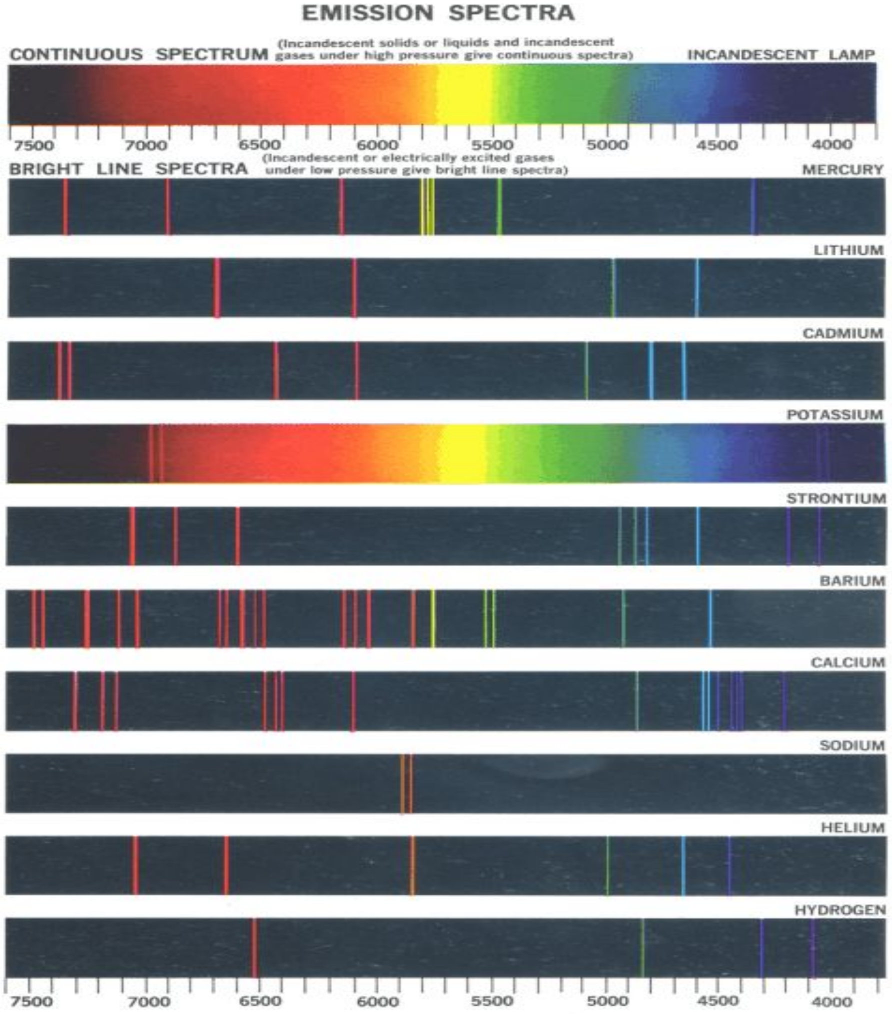


Fig. 5

Problems, cont.

- What caused spectra of atoms to contain discrete "lines"
  - it was apparent that only a small set of optical frequencies (wavelengths) could be emitted or absorbed by atoms
- Each atom has a distinct "fingerprint"
- Light only comes off at very specific wavelengths
  - or frequencies
  - or energies
- Note that hydrogen (bottom), with only one electron and one proton, emits several wavelengths

The victory of the weird theory

- **Without Quantum Mechanics, we could never have designed and built:**
  - semiconductor devices
    - computers, cell phones, etc.
  - lasers
    - CD/DVD players, bar-code scanners, surgical applications
  - MRI (magnetic resonance imaging) technology
  - nuclear reactors
  - atomic clocks (e.g., GPS navigation)
- **Physicists didn't embrace quantum mechanics because it was gnarly, novel, or weird**
  - it's simply that the #$!&@ thing worked so well

Let's start with photon energy

- Light is *quantized* into packets called *photons*
- Photons have associated:
  - frequency, ν (nu)
  - wavelength, λ ($\lambda\nu = c$)
  - speed, c (always)
  - energy: $E = h\nu$
    - higher frequency photons → higher energy → more damaging
  - momentum: $p = h\nu/c$
- The constant, h, is Planck's constant
  - has *tiny* value of: $h = 6.63\times10^{-34}$ J·s

How come *I've* never seen a photon?

- Sunny day (outdoors):
  - 10^{15} photons per second enter eye (2 mm pupil)
- Moonlit night (outdoors):
  - 5×10^{10} photons/sec (6 mm pupil)
- Moonless night (clear, starry sky)
  - 10^{8} photons/sec (6 mm pupil)
- Light from dimmest naked eye star (mag 6.5):
  - 1000 photons/sec entering eye
  - integration time of eye is about 1/8 sec $\rightarrow$ 100 photon threshold signal level

Quantum Wavelength

- Every particle or system of particles *can* be defined in quantum mechanical terms
  - and therefore have wave-like properties
- The quantum wavelength of an object is:

  $\lambda = h/p$ (p is momentum)
  - called the de Broglie wavelength
- typical macroscopic objects
  - masses ~ kg; velocities ~ m/s $\rightarrow p \approx 1$ kg·m/s
  - $\lambda \approx 10^{-34}$ meters (too small to matter in macro environment!!)
- typical "quantum" objects:
  - electron (10^{-30} kg) at thermal velocity (10^5 m/s) $\rightarrow \lambda \approx 10^{-8}$ m
  - so λ is 100 times larger than an atom: very relevant to an electron!

Example: Diffraction

- Light emerging from a tiny hole or slit will diverge (diffract)
- We know its position very well (in at least one dimension)
  - so we give up knowledge of momentum in that dimension—thus the spread

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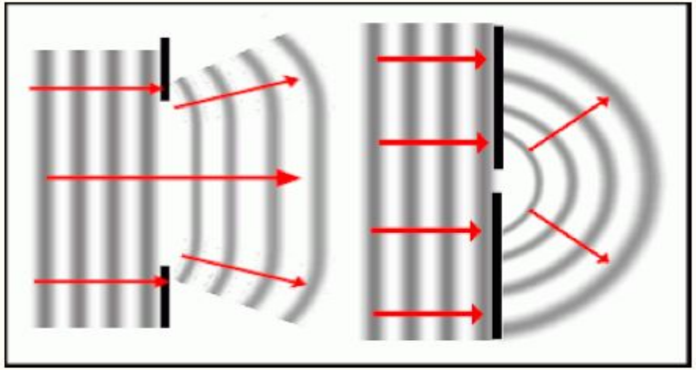

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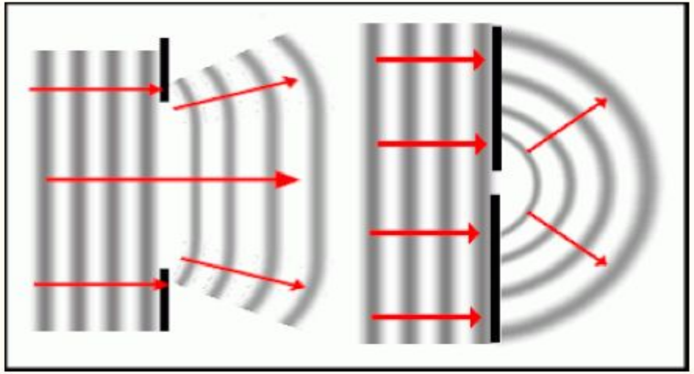
large opening: greater position uncertainty results in smaller momentum uncertainty, which translates to less of a spread angle



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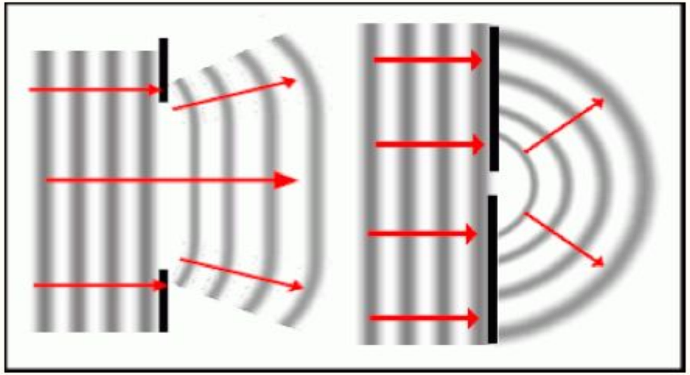
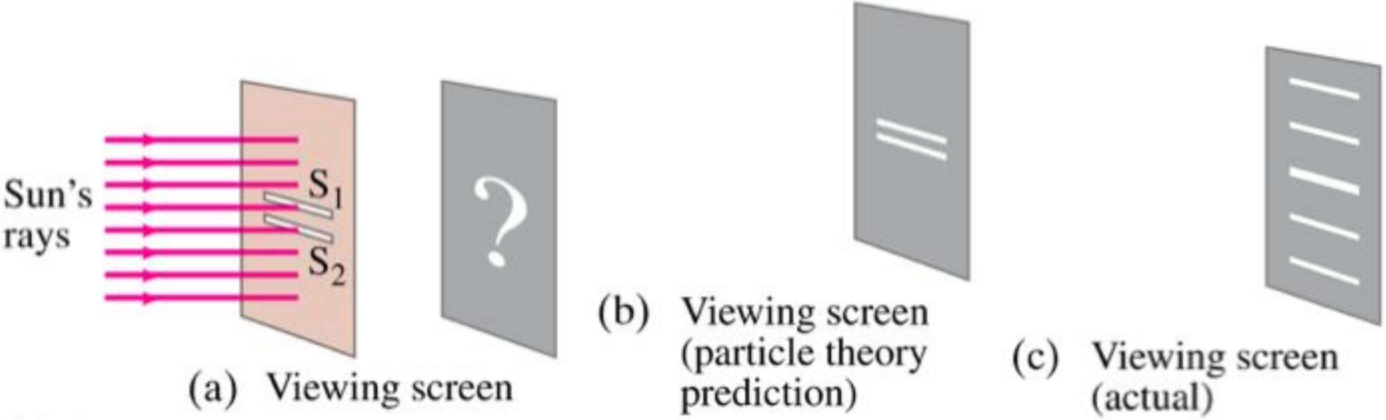


small opening: less position uncertainty results in larger momentum uncertainty, which translates to more of a spread angle

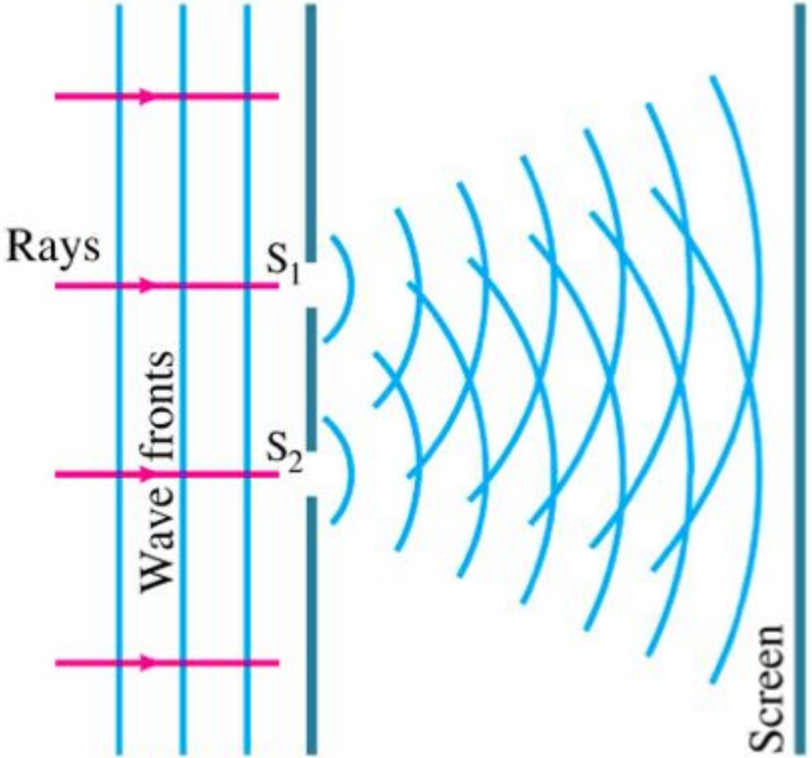
Interference—Young's Double-Slit Experiment

If light is a wave, interference effects will be seen, where one part of wavefront can interact with another part.

One way to study this is to do a double-slit experiment:



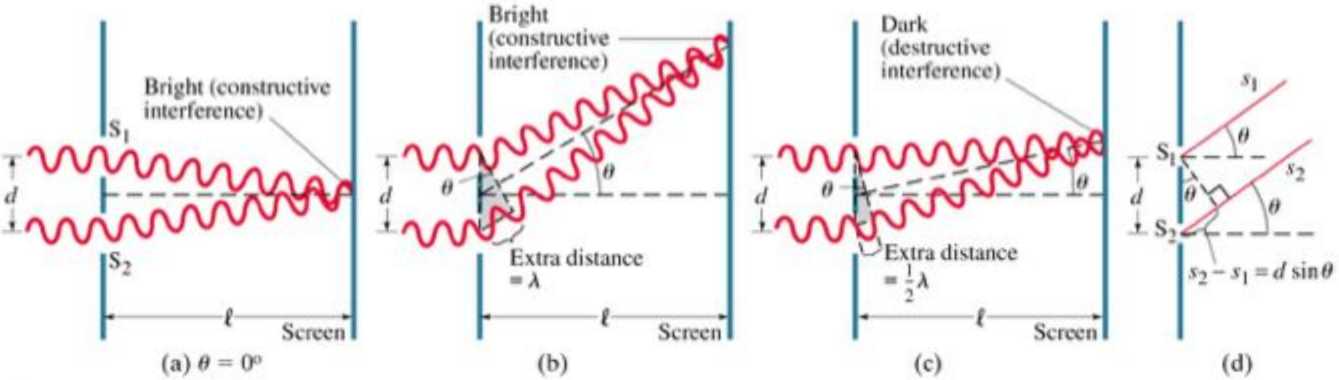
Interference—Young's Double-Slit Experiment



If light is a wave, there should be an interference pattern.

Interference—Young's Double-Slit Experiment

The interference occurs because each point on the screen is not the same distance from both slits. Depending on the path length difference, the wave can interfere constructively (bright spot) or destructively (dark spot).



Interference—Young's Double-Slit Experiment

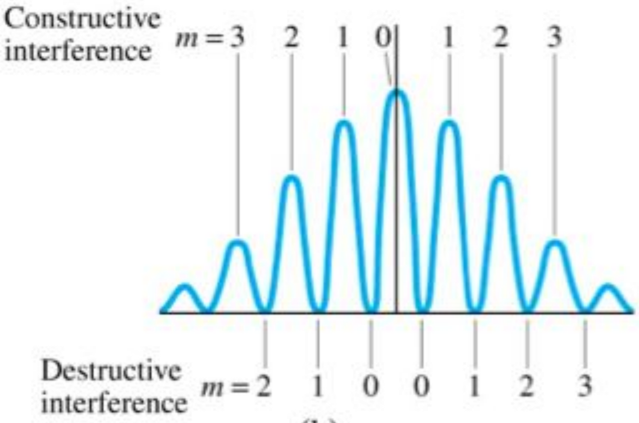
We can use geometry to find the conditions for constructive and destructive interference:

$$d \sin\theta = m\lambda, \quad m = 0, 1, 2, \cdots. \qquad \begin{bmatrix}\text{constructive} \\ \text{interference} \\ \text{(bright)}\end{bmatrix} \qquad (24\text{-}2a)$$

$$d \sin\theta = \left(m + \tfrac{1}{2}\right)\lambda, \quad m = 0, 1, 2, \cdots. \qquad \begin{bmatrix}\text{destructive} \\ \text{interference} \\ \text{(dark)}\end{bmatrix} \qquad (24\text{-}2b)$$

Interference—Young's Double-Slit Experiment

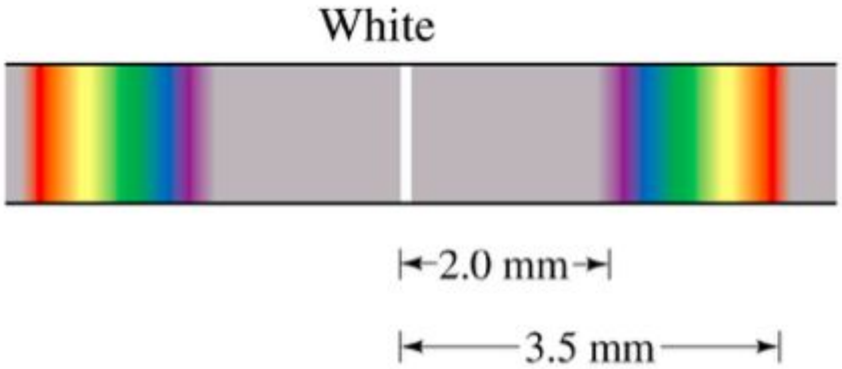
Between the maxima and the minima, the amplitude varies smoothly.



(b)

Interference—Young's Double-Slit Experiment

Since the position of the maxima (except the central one) depends on wavelength, the first- and higher-order fringes contain a spectrum of colors.



Wave-Particle Duality: Light

Does light consist of particles or waves? When one focuses upon the different types of phenomena observed with light, a strong case can be built for a wave picture:

Phenomenon	Can be explained in terms of waves.	Can be explained in terms of particles.
Reflection	∿∿∿ ✓	•→ ✓
Refraction	∿∿∿ ✓	•→ ✓
Interference	∿∿∿ ✓	•→ ⊗
Diffraction	∿∿∿ ✓	•→ ⊗
Polarization	∿∿∿ ✓	•→ ⊗
Photoelectric effect	∿∿∿ ⊗	•→ ✓
Compton scattering	∿∿∿ ⊗	•→ ✓

Most commonly observed phenomena with light can be explained by waves. But the photoelectric effect and the Compton scatering suggested a particle nature for light. Then electrons too were found to exhibit dual natures.