Modern Physics: Quantum Mechanics

- Physics changed drastically in the early 1900's
- New discoveries —
  Relativity and *Quantum Mechanics*

- **Relativity**
  - Changed the way we think about space and time

- **Quantum mechanics**
  - Changed our conceptions of matter.

Course essay

- ***Friday***, Nov 3:
  Due in class — essay topic(review article, operating experiment, noble prize)
  short description - one paragraph
  http://www.hep.wisc.edu/~herndon/107-0609/essay.htm

- Friday, Nov 17
  Due in class — essay outline
  main article reference

- Friday, Dec. 8
  Due in class — final typed essay.

Quantum mechanics

- The quantum mechanical world is VERY different!
  - Energy not continuous, but can take on only particular discrete values.
  - Light has particle-like properties, so that light can bounce off objects just like balls.
  - Particles also have wave-like properties, so that two particles can interfere just like light does.
  - Physics is not deterministic, but events occur with a probability determined by quantum mechanics.

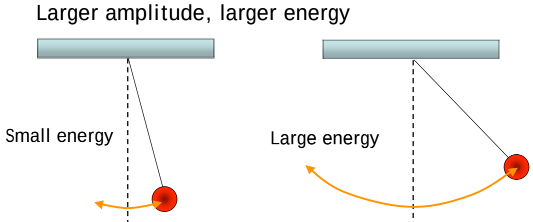
Origins of quantum mechanics

- Late 1800s:
  - Maxwell's equations describe propagation of EM waves in detail.
  - Electricity and magnetism progress from basic science to technological applications.
- Early 1900s:
  - Further Investigations into light, and interaction of light with matter, hint at some scary ideas
  - Simultaneous with relativity

Photoelectric effect,
Blackbody radiation spectrum,
say that **energy is quantized in discrete units**.

Energy quantization in a pendulum

Swinging pendulum.
Larger amplitude, larger energy



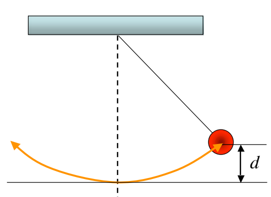
Quantum mechanics:
Not every swing amplitude is possible
energy cannot change by arbitrarily small steps

Energy quantization

- Energy can have only certain discrete values

Energy states are separated by $\Delta E = hf$.
f = frequency
h = Planck's constant= 6.626 x 10^{-34} J-s

$\Delta E = hf$=3.3x10^{-34} J for pendulum
= spacing between energy levels

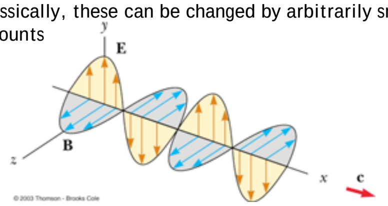


Suppose the pendulum has
Period = 2 sec
Freq = 0.5 cycles/sec

- $E=mgd$=(1 kg)(9.8 m/s^2)(0.2 m) ~ 2 Joules
- $\Delta E_{min}=hf$=3.3x10^{-34} J << 2 J
- *Quantization not noticeable*

Energy of light

- Quantization also applies to other physical systems
  - In the classical picture of light (EM wave), we change the brightness by changing the power (energy/sec).
  - This is the amplitude of the electric and magnetic fields.
  - Classically, these can be changed by arbitrarily small amounts



Quantization of light

•Quantum mechanically, brightness can only be changed in steps, with energy differences of *hf*.

- Possible energies for green light (λ=500 nm)
  - One quantum of energy: *one photon*
  - Two quanta of energy *two photons*
  - etc
- Think about light as a particle rather than wave.

E=4*hf*
E=3*hf*
E=2*hf*
E=*hf*

The particle perspective

- Light comes in particles called photons.
- Energy of one photon is *E=hf*
  f = frequency of light
- Photon is a particle, but moves at speed of light!
  - This is possible because it has zero mass.
- Zero mass, but it does have momentum:
  - Photon momentum *p=E/c*

One quantum of green light

- One quantum of energy *for 500 nm light*

$$E = hf = \frac{hc}{\lambda} = \frac{(6.634\times 10^{-34} J-s)\times(3\times 10^{8} m/s)}{500\times 10^{-9} m} = 4\times 10^{-19} J$$

Quite a small energy!
Quantum mechanics uses new 'convenience unit' for energy:

1 electron-volt = 1 eV = |charge on electron|x (1 volt)
= ($1.602\text{x}10^{-19}$ C)x(1 volt)
1 eV = $1.602\text{x}10^{-19}$ J

In these units,
E(1 photon green) = ($4\text{x}10^{-19}$ *J*)x(1 eV / $1.602\text{x}10^{-19}$ J) = 2.5 eV

Simple relations

- Translation between wavelength and energy has simple form in electron-volts and nano-meters

Green light example:

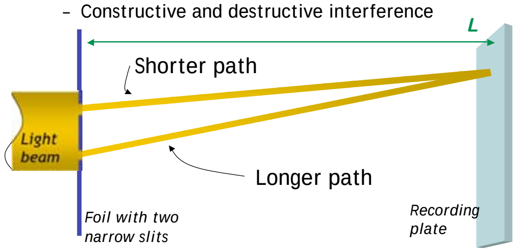
$$E = \frac{hc}{\lambda} = \frac{\text{constant [in } eV-nm]}{\text{wavelength [in } nm]} = \frac{1240\ eV-nm}{500\ nm} = 2.5\ eV$$

Photon properties of light

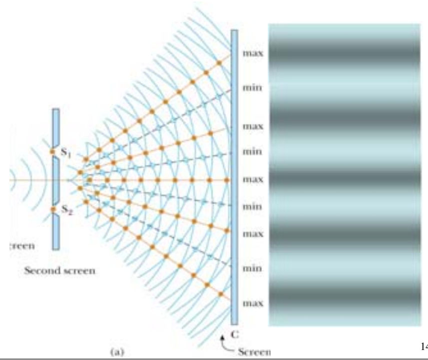
- Photon of frequency *f* has energy *hf*
- Red light made of ONLY red photons
- The intensity of the beam can be increased by increasing the number of photons/second.
- Photons/second = energy/second = power

But light is a wave!

- Light has wavelength, frequency, speed
  - Related by $f\lambda$ = *speed.*
- Light shows interference phenomena
  - Constructive and destructive interference



Wave behavior of light: interference



Particle behavior of light: photoelectric effect

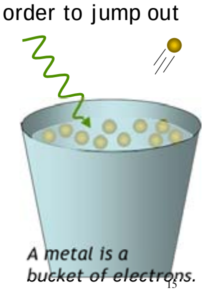
- A metal is a bucket holding electrons
- Electrons need some energy in order to jump out of the bucket.

Light can supply this energy.

Energy transferred from the light to the electrons.

Electron uses some of the energy to break out of bucket.

Remainder appears as energy of motion (kinetic energy).

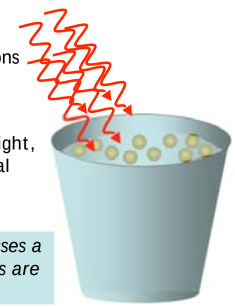


Unusual experimental results

- Not all kinds of light work
- Red light does not eject electrons

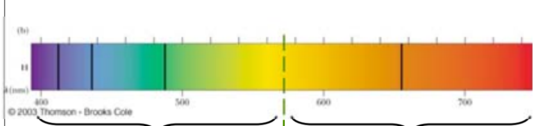
More red light doesn't either

No matter how intense the red light, no electrons ever leave the metal



Until the light wavelength passes a certain threshold, no electrons are ejected.

Wavelength dependence



Short wavelength: electrons ejected

Long wavelength: NO electrons ejected

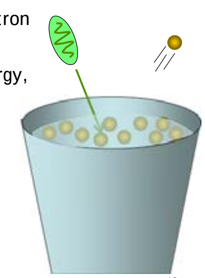
Threshold depends on material

Hi-energy photons

Lo-energy photons

Einstein's explanation

- Einstein said that light is made up of photons, individual 'particles', each with energy *hf*.
- **One** photon collides with **one** electron - knocks it out of metal.
- If photon doesn't have enough energy, cannot knock electron out.
- Intensity (= # photons / sec) doesn't change this.



Minimum frequency (maximum wavelength) required to eject electron

Summary of Photoelectric effect

- Explained by quantized light.
- **Red** light is low frequency, **low energy**.
- (Ultra)**violet** is high frequency, **high energy**.

- Red light will not eject electron from metal, no matter how intense.
  - Single photon energy *hf* is too low.
- Need ultraviolet light

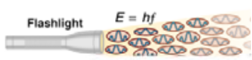
Photon properties of light

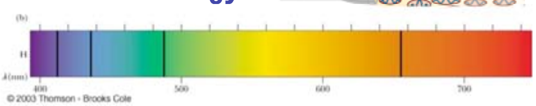
- Photon of frequency *f* has energy *hf*
- Red light made of ONLY red photons
- The intensity of the beam can be increased by increasing the number of photons/second.
- Photons/second = energy/second = power

Interaction with matter

- Photons interact with matter one at a time.
- Energy transferred from photon to matter.
- Maximum energy absorbed is photon energy.

Photon Energy





A red and green laser are produce light at a power level of 2.5mW. Which one produces more photons/second?

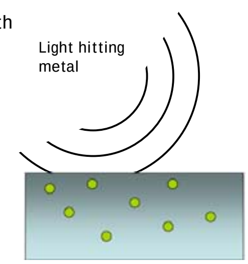
A. Red
B. Green
C. Same

$$\frac{\#\,\text{photons}}{\text{second}} = \frac{\text{Power}}{\text{Energy/photon}} = \frac{\text{Power}}{hf}$$

Red light has less energy per photon so needs more photons!

Why is all this so important?

- Makes behavior of light wave quite puzzling.
- Said that one photon interacts with one electron, electron ejected.
- If this wavefront represents one photon, where is the photon?
- Which electron does it interact with?
- How does it decide?



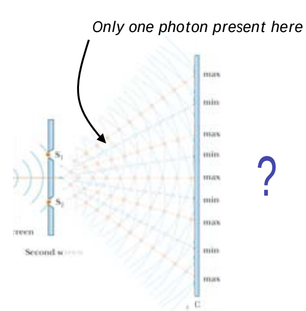
Neither wave nor particle

- Light in some cases shows properties typical of waves
- In other cases shows properties we associate with particles.
- Conclusion:
  - Light is not a wave, or a particle, but something we haven't thought about before.
  - Reminds us in some ways of waves.
  - In some ways of particles.

Photon interference?

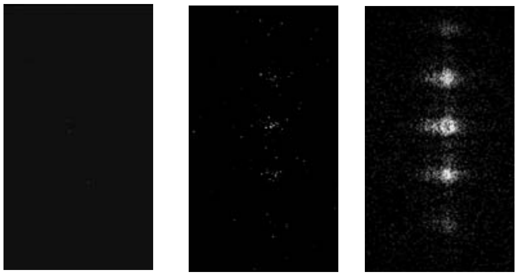
Do an interference experiment again.

But turn down the intensity until only ONE photon at a time is between slits and screen



Is there still interference?

Single-photon interference



1/30 sec exposure | 1 sec exposure | 100 sec exposure

- P.A.M. Dirac (early 20th century):
  - "... each photon interferes with itself. Interference between different photons never occurs."

We now can have 'coherent' photons in a laser, (**L**ight **A**mplification by **S**timulated **E**mission of **R**adiation)

invented 40 years ago.

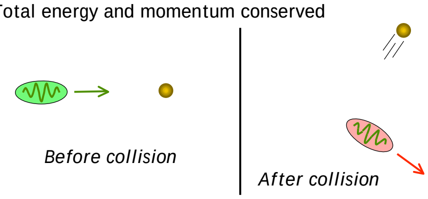
These photons can in fact interfere.

Probabilities

- We detect absorption of a photon at camera.
- Cannot predict where on camera photon will arrive.
- Position of an individual photon hits is determined probabilistically.
- Photon has a **probability amplitude** through space. Square of this quantity gives probability that photon will hit particular position on detector.
- The photon is a probability wave! The wave describes what the particle does.

Compton scattering

- Photon loses energy, transfers it to electron
- Photon loses momentum transfers it to electron
- Total energy and momentum conserved



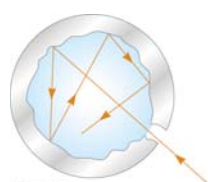
Photon energy $E=hf$
Photon mass = 0
Photon momentum $p=E/c$

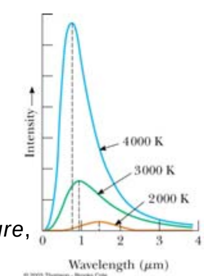
Compton scattering

- Photons can transfer energy to beam of electrons.
- Determined by conservation of momentum, energy.
- Compton awarded 1927 Nobel prize for showing that this occurs just as two balls colliding.

Arthur Compton, Jan 13, 1936

The Black Body spectrum





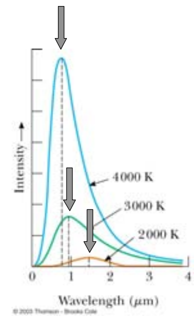
- Light radiated by an object characteristic of its *temperature*, not its surface color.
- Spectrum of radiation changes with temperature

Spectrum changes with temperature

- The wavelength of the peak of the blackbody distribution was found to follow

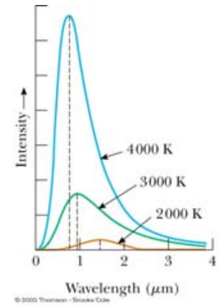
$$\lambda_{max} = \frac{\text{constant}}{\text{Temperature}}$$

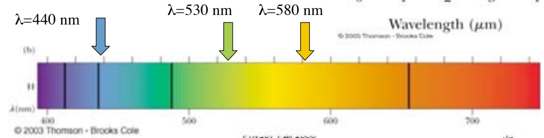
- Peak wavelength shifts with temperature
  - λ_{max} is the wavelength at the curve's peak
  - T is the absolute temperature of the object emitting the radiation



The 'color' of a black body

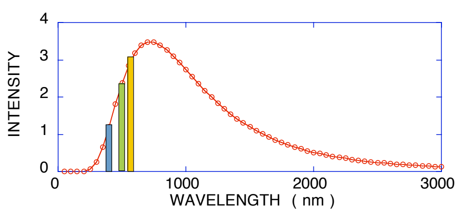
- Eye interprets colors by mixing cone responses.
- Different proportions make object appear different colors.





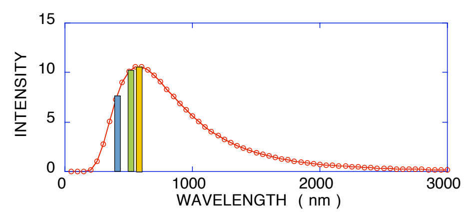
'Orange' hot

- Temperature = 4000 K
- Combine three cone responses
  Long-wavelength cone weighted most heavily

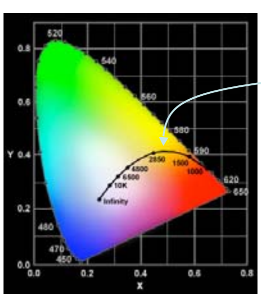


'White' hot

- Temperature = 5000 K
- Spectrum has shifted so that colors are more equally represented — white hot



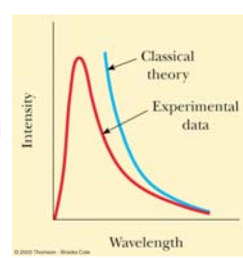
Representation on color chart



- Apparent color of blackbody at various temperatures.

Classical theory

- Classical physics had absolutely no explanation for this.
- Only explanation they had gave ridiculous answer.
- Amount of light emitted became infinite at short wavelength
  - *Ultraviolet catastrophe*



Explanation by quantum mechanics

- Blackbody radiation spectrum could only be explained by quantum mechanics.
- Radiation made up of individual photons, each with energy (Planck's const)x(frequency).
- Very short wavelengths have very high energy photons.
- Minimum energy is 1 photon.
- For shorter wavelength's even 1 photon is too much energy, so shortest wavelengths have very little intensity.