Today: 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.

Exam 2 scores

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MEAN = 68%

Course essay

- Wednesday, next week:
  - Due in class — essay topic
  - Short description
  - Journal article

- Wednesday, Nov. 16
  - Due in class — essay outline
  - Main article reference

- Monday, Dec. 5
  - Due in class — final typed essay.

Origins of quantum mechanics

- Late 1800s:
  - Maxwell’s equations describe propagation of EM waves in exquisite 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

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

Energy quantization in a pendulum

Swinging pendulum. Larger amplitude, larger energy

- Small energy
- Large 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 $\Delta E = h f$.
- $f$ = frequency
- $h$ = Planck’s constant = $6.626 \times 10^{-34}$ J-s

$\Delta E = h f = 3.3 \times 10^{-34}$ J for pendulum
- $\Delta E_{\text{min}} = hf = 3.3 \times 10^{-34}$ J << 2 J
- Quantization not noticeable

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

- $E = mgd = (1 \text{ kg})(9.8 \text{ m/s}^2)(0.2 \text{ m}) = 2 \text{ Joulies}$
- $\Delta E = hf = 3.3 \times 10^{-34} \text{ J} < 2 \text{ J}$
**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 ($\lambda=500$ nm)
  - One quantum of energy: one photon
  - Two quanta of energy two photons
  - etc
- Think about light as a particle rather than wave.

**One quantum of green light**

- One quantum of energy for 500 nm light
  
  $$E = hf = \frac{hc}{\lambda} = \frac{(6.634 \times 10^{-34} J \cdot s) \times (3 \times 10^8 m/s)}{500 \times 10^{-9} m} = 4 \times 10^{-19} J$$

  Quite a small energy!
  Quantum mechanics uses new ‘convenience unit’ for energy:
  1 electron-volt = 1 eV = |charge on electron| x (1 volt) = (1.602x10^{-19} C) x (1 volt) = 1.602x10^{-19} J

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

**Simple relations**

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

  Green light example:
  
  $$E = \frac{hc}{\lambda} = \frac{1240 \text{ eV} \cdot \text{nm}}{500 \text{ nm}} = 2.5 \text{ eV}$$

**How many photons can you see?**

In a test of eye sensitivity, experimenters used 1 milli-second (0.001 s) flashes of green light. The lowest power light that could be seen was $4 \times 10^{-14}$ Watt.

How many green (500 nm, 2.5 eV) photons is this?

A. 10 photons  
B. 100 photons  
C. 1,000 photons  
D. 10,000 photons

**Or could say...**

- Light comes in particles called photons.
- Energy of one photon is $E=hf$
  
  $$f = \text{frequency of light}$$

- 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 $p=E/c$
But light is a wave!
- Light has wavelength, frequency, speed
  - Related by $f \lambda = \text{speed}$.
- 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
- 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
explained by quantization of light

- Light comprised of discrete particles (photons)
- Each photon has energy $hf$
  ($h =$ Planck’s constant)

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

Intensity 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 photon flux.

Interaction with matter

- Photons are absorbed one at a time
- Interaction depends on individual photon frequency / 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

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

Nobel Trivia

For which work did Einstein receive the Nobel Prize?

A. Special Relativity: $E=mc^2$
B. General Relativity: gravity bends Light
C. Photoelectric Effect & Photons

Why 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 it?
- 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, (Light Amplification by Stimulated Emission of Radiation) 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 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 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
  \[ \lambda_{\text{max}} = \text{constant} \frac{1}{\text{Temperature}} \]
- Peak wavelength shifts with temperature
  - \( \lambda_{\text{max}} \) 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)\(\times\)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.