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. 500-750 words

Title / paragraph example

Topic: *Quantum Computers*

Outlook

Description of topic

Paragraph:

Over the last decade, scientists have developed new approaches to computing using basic ideas of quantum mechanics. Individual atomic particles are used as 'bits' of a computer, but instead of representing only '0' and '1', the quantum-mechanical wavefunction is used to simultaneously represent an infinitely variable range of values.
Such systems have the potential to revolutionize computing, but only for specialized problems such as factoring large numbers.
The scientific aspect I will discuss is the use of trapped atoms as quantum bits.
I will also discuss the background and operating principles of quantum computers, and the potential achievements of quantum computers.

What else I will write

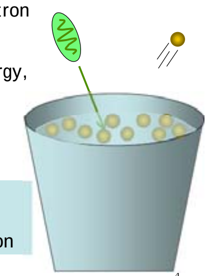
Science aspect

From Last Time...

- Light shows both particle and wavelike properties
  - Interference is an example of wavelike property
  - Photoelectric effect is an example of particle like property: Einstein's Nobel prize
- Photons are particles of light.
- Even in interference experiments light showed some particle like properties
  - Introduced idea of probabilities of outcomes happening to explain this

Photoelectric effect summary

- Light is made up of photons, individual 'particles', each with energy: $E = hf = \frac{hc}{\lambda} = \frac{1240 \;\; eV - nm}{\lambda}$
- **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.



Photon greater than a minimum frequency (less than a maximum wavelength) required to eject electron

Photoelectric effect question

An electron is bound inside copper by a 'binding energy' of 4 eV. Which wavelength will eject electrons from copper?

A. 300 nm
B. 500 nm
C. 700 nm

Minimum photon energy to eject electron is 4 eV. Corresponding photon energy is given by

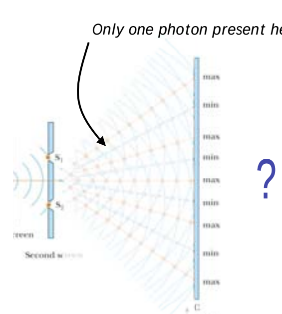
$$4.0 \;\; eV = \frac{hc}{\lambda} = \frac{1240 \;\; eV - nm}{\lambda \;\; nm}$$

So λ_{max}=310 nm

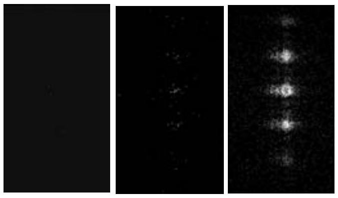
Photon interference?

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 — 100 sec

- P.A.M. Dirac (early 20th century):

"… each photon interferes with itself. Interference between different photons never occurs."

Needed the idea of probabilities of an outcome happening to explain the wavelike and particle like results of interference experiments.

Probabilities

- We detect absorption of a photon at the screen.
- Cannot predict exactly where on the screen the 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 form of that probability amplitude is a wave!

Laser

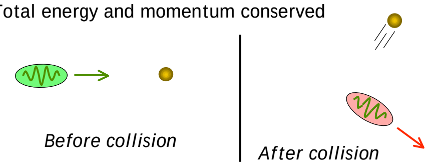
We now can have 'coherent' photons in a laser,
(Light Amplification by Stimulated Emission of Radiation)

invented 40 years ago.

These photons can in fact interfere with each other.

Compton scattering

- Collision of photon and electron in vacuum
- 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

Compton scattering question

A green photon collides with a stationary electron. After the the collision the photon color is

A. unchanged

B. shifted toward red

C. shifted toward blue

Photon transfers energy to electron. Photon energy goes down, so photon wavelength gets longer

Photon: particle and wave

- *Light: Is quantized. Has energy and momentum:*

$$E = hf = \frac{hc}{\lambda} = \frac{1240 \ \ eV - nm}{\lambda} \qquad p = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda}$$

- *Light has a dual nature.*
  It exhibits both wave and particle characteristics
  - Applies to all electromagnetic radiation
- The photoelectric effect
  show the particle characteristics of light
  - Light can behave as if it were composed of particles
- Interference and diffraction
  - shows the wave and particle and probabilistic characteristics of light

Matter waves

- If light waves have particle-like properties, maybe matter has wave properties?
- de Broglie postulated that the wavelength of matter is related to momentum as

$$\lambda = \frac{h}{p}$$

- This is called the de Broglie wavelength.

Nobel prize, 1929

Why *h / p* ? Works for photons

- We argue that $\lambda = \frac{h}{p}$ applies to everything
- Photons and footballs both follow the same relation.
- Everything has both **wave-like** and **particle-like** properties

Wavelengths of massive objects

- deBroglie wavelength = $\lambda = \frac{h}{p}$
- *p=mv* for a nonrelativistic (*v<<c*) particle **with mass**.

$$\left.\begin{array}{l}\lambda = \frac{h}{p} \\ p = mv\end{array}\right\} \lambda = \frac{h}{mv}$$

Wavelength of a football

- *Make the Right Call: The NFL's Own interpretations and guidelines plus 100s of official rulings on game situations.* National FootBall League, Chicago. 1999: "... short circumference, 21 to 21 1/4 inches; weight, 14 to 15 ounces." **(0.43 - 0.40 kg)**
- "Sometimes I don't know how they catch that ball, because Brett wings that thing 60, 70 mph," Flanagan said. **(27 - 32 m/s)**

- Momentum: $mv = (0.4 \ \ kg)(30 \ \ m/s) = 12 \ \ kg - m/s$

$$\lambda = \frac{h}{p} = \frac{6.6 \times 10^{-34} \ \ J - s}{12 \ \ kg - m/s} = 5.5 \times 10^{-35} m = \boxed{5.5 \times 10^{-26} nm}$$

This is very small

- 1 nm = 10^{-9} m
- Wavelength of red light = 700 nm
- Spacing between atoms in solid ~ 0.25 nm
- Wavelength of football = 10^{-26} nm
- What makes football wavelength so small?

$$\lambda = \frac{h}{p} = \frac{h}{mv} \Rightarrow$$

Large mass, large momentum
short wavelength

Quantum Mechanics: Physics of the microscopic world

- Macroscopic objects don't show effects of quantum mechanics.
- Saw this previously in pendulum:
  - Energy levels are quantized, but discreteness is too small to be detected.
  - Wave properties also too 'small' to be detected

Wavelength of electron

- Need less massive object to show wave effects
- Electron is a very light particle
- Mass of electron = 9.1×10^{-31} kg

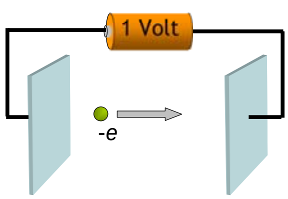
$$\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{6 \times 10^{-34}\,J-s}{\left(9 \times 10^{-31}\,kg\right) \times \left(velocity\right)}$$

Wavelength depends on mass and velocity

Larger velocity, shorter wavelength

How do we get electrons to move?

- Electron is a charged particle.
- Constant electric field, applies constant force,
  - accelerates electron
- Work done on electron is (charge) x (voltage applied)
- Energy is more direct quantity than velocity



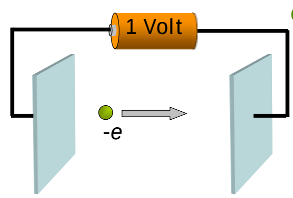
Work done = change in kinetic energy

= $(1/2)mv^2$

= (charge)x(voltage)

The electron-volt

- Unit of energy used in quantum mechanics:
- 1 electron-volt = energy gained by electron accelerating through 1 volt potential difference.
- 1 electron volt = 1 eV = $(\underbrace{1.6 \times 10^{-19} C}_{\text{charge}})(\underbrace{1V}_{\text{potential}}) = 1.6 \times 10^{-19}$ J



eV a small unit of energy, but useful for small particles such as electrons

Same energy unit we used last time.

Wavelength of 1 eV electron

- Fundamental relation is wavelength = $\lambda = \frac{h}{p}$
- Need to find momentum in terms of kinetic energy.
- $p = mv$, so $E_{kinetic} = \frac{p^2}{2m} \Rightarrow p = \sqrt{2mE_{kinetic}}$

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mE_{kinetic}}} = \frac{hc}{\sqrt{2mc^2 E_{kinetic}}}$$

A little complicated

- But look at this without calculating it

$$\lambda = \frac{h}{p} = \frac{\boxed{hc}}{\sqrt{2\,\boxed{mc^2}\,\boxed{E_{kinetic}}}}$$

Same constant as before

kinetic energy

rest energy

$$\text{Wavelength} = \frac{\text{constant}}{\sqrt{\text{rest energy}}\sqrt{\text{Kinetic energy}}}$$

Matter wave question

A neutron has almost 2000 times the rest mass of an electron. Suppose they both have 1 ev of energy. How do their wavelengths compare?

A. both same

B. neutron wavelength < electron wavelength

C. neutron wavelength > electron wavelength

Wavelength depends on **momentum**, as h/p.
Same momentum -> same wavelength.
Momentum = $\sqrt{2mE}$, depends on energy **AND** mass

Why use rest energy?

- Particles important in quantum mechanics are characterized by their rest energy
  - In relativity all observers measure same rest energy.

electron: mc^2~ 0.5 *MeV*
proton: mc^2~ 940 *MeV*
neutron: mc^2~ 940 *MeV*

Different for different particles

1 MeV = 1 million electron-volts

General trends

$$\text{Wavelength} = \frac{\text{constant}}{\sqrt{\text{rest energy}}\sqrt{\text{Kinetic energy}}}$$

- Wavelength decreases as rest energy (mass) increases
- Wavelength decreases as kinetic energy (energy of motion) increases

Wavelength of 1 eV electron

- For an electron,

$$\lambda = \frac{\overbrace{\boxed{1240\ eV-nm}}^{\text{constant}}}{\sqrt{2\times\underbrace{\boxed{0.511\ MeV}}_{\text{rest energy}}}}\frac{1}{\sqrt{\underbrace{\boxed{E_{kinetic}}}_{\text{kinetic energy}}}} = \frac{1.23\ eV^{1/2}-nm}{\sqrt{E_{kinetic}}}$$

- 1 eV electron, λ=1.23 nm
- 10 eV electron λ=0.39 nm
- 100 eV electron λ=0.12 nm

Question

A 10 eV electron has a wavelength of ~ 0.4 nm. What is the wavelength of a 40 eV electron?

A. 0.2 nm

B. 0.4 nm

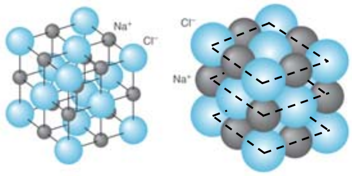
C. 0.8 nm

$$\text{Wavelength} = \frac{\text{constant}}{\sqrt{\text{rest energy}}\sqrt{\text{Kinetic energy}}}$$

Can this be correct?

- If electrons are waves, they should demonstrate wave-like effects
  - e.g. Interference, diffraction
- A 25 eV electron has wavelength 0.25 nm, similar to atomic spacings in crystals

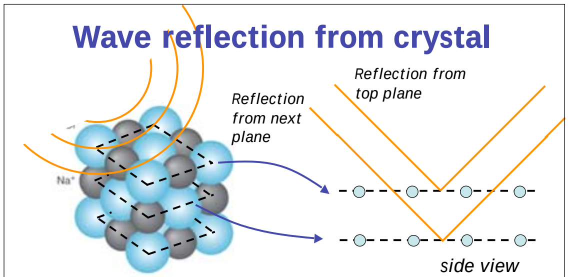
Crystals: regular arrays of atoms



Layered planes of atoms

- Table salt (NaCl = Sodium Chloride)
- Very common “cubic” structure.
- Na and Cl atoms alternate in a regular pattern
- Typical spacings ~ 0.3 nm.

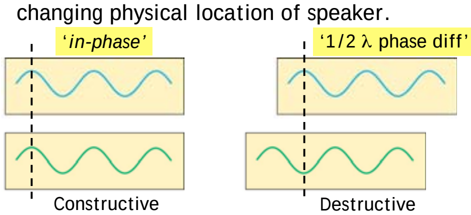
Wave reflection from crystal



- Interference of waves reflecting from different atomic layers in the crystal.
- Difference in path length ~ spacing between atoms

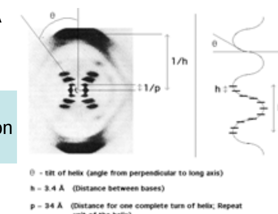
Constructive & Destructive Interference

- Interference arises when waves change their ‘phase relationship’.
- Can vary phase relationship of two waves by changing physical location of speaker.



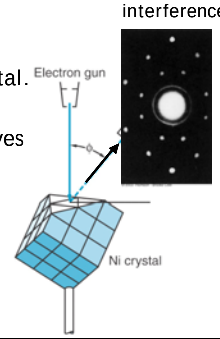
X-ray diffraction

- Diffraction spot arrangement indicates atomic arrangement
- Used to determine atomic arrangements of complex molecules.
  - e.g. DNA



Davisson-Germer experiment

- Diffraction of electrons from a nickel single crystal.
- Established that electrons are waves



Davisson: Nobel Prize 1937

Particle-wave duality

- Like light, particles also have a dual nature
  - Can show particle-like properties (collisions, etc)
  - Can show wavelike properties (interference).
- Like light, they are neither particle nor wave, but some new object.
- Can describe them using “particle language” or “wave language” whichever is most useful