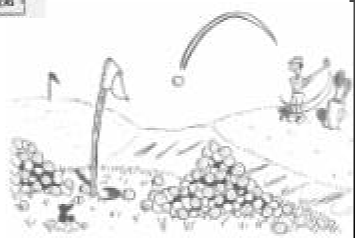
Quantum Theory



FYI
1/3 of exams graded, and average is about 71%.

Reading:
Ch13.1 -13.5
No HW this week !

What is Quantum Theory?

Quantum theory is a theory needed to describe physics on a microscopic scale, such as on the scale of atoms, molecules, electrons, protons, etc.

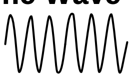
Classical theories:
Newton – Mechanical motion of objects (F = ma)
Maxwell – Light treated as a wave

NEITHER OF THESE THEORIES QUITE WORK FOR ATOMS, MOLECULES, ETC.

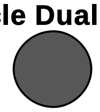
Quantum (from Merriam-Webster)
Any of the very small increments or parcels into which many forms of energy are subdivided.

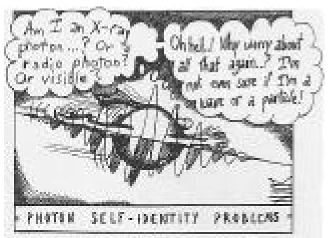
Light is a form of energy is a quantum of EM energy

The Wave – Particle Duality



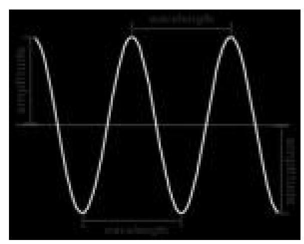
OR





Light Waves

Until about 1900, the classical wave theory of light described most observed phenomenon



Light waves:

Characterized by:

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

Energy of wave α A^2

And then there was a problem...

In the early 20th century, several effects were observed which could not be understood using the wave theory of light.

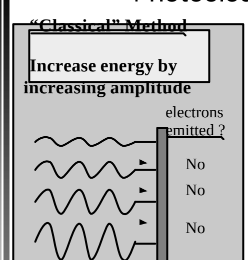
Two of the more influential observations were:

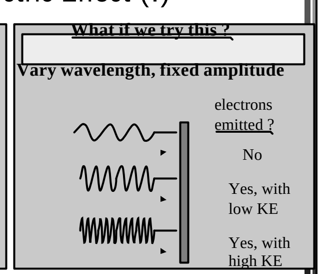
1) **The Photo-Electric Effect**

2) **The Compton Effect**

I will describe each of these today…

Photoelectric Effect (I)





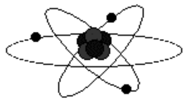
No electrons were emitted until the frequency of the light exceeded a critical frequency, at which point electrons were emitted from the surface! (Recall: small λ → large ν)

Photoelectric Effect (II)

❑ Electrons are attracted to the (positively charged) nucleus bythe electrical force

❑ In metals, the outermost electrons are not tightly bound, and can be easily "liberated" from the shackles of its atom.

❑ It just takes sufficient energy…



Classically, we increase the energy of an EM wave by increasing the intensity (e.g. brightness)

Energy α A^2

But this doesn't work ??

PhotoElectric Effect (III)

❑ An alternate view is that **light** is acting like a **particle**

❑ The light particle must have sufficient energy to "*free*" the electron from the atom.

❑ **Increasing the Amplitude is simply increasing the <u>number of light particles</u>, but its <u>NOT increasing the energy of each one</u>!**
➔ **Increasing the Amplitude does diddly-squat!**

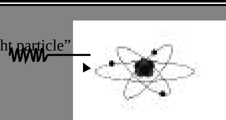
❑ However, if the energy of these "light particle" is related to their frequency, this would explain why higher frequency light can knock the electrons out of their atoms, but low frequency light cannot…

Photo-Electric Effect (IV)

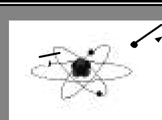
❑ In this "quantum-mechanical" picture, the energy of the light particle (photon) must overcome the *binding energy* of the electron to the nucleus.

❑ If the energy of the photon exceeds the binding energy, the electron is emitted with a $KE = E_{photon} - E_{binding}$.

❑ The energy of the photon is given by **E=hn**, where the constant $h = 6.6x10^{-34}$ [J s] is Planck's constant

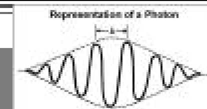


Before Collision



After Collision

Photons



❑ **<u>Quantum theory</u>** describes light as a particle called a **<u>photon</u>**

❑ According to **quantum theory**, a **photon** has an **energy** given by

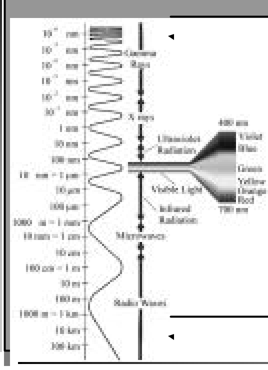
E = h*n* = *hc*/*l* $h = 6.6x10^{-34}$ [J s] Planck's constant, after the scientist Max Planck.

❑ The energy of the light is <u>proportional to the frequency</u> (inversely proportional to the wavelength) ! The higher the frequency (lower wavelength) the higher the energy of the photon.

❑ 10 photons have an energy equal to ten times a single photon.

❑ **<u>Quantum theory describes experiments to astonishing precision</u>**, whereas the **classical wave description cannot**.

The Electromagnetic Spectrum



Shortest wavelengths

E = hn = hc/l

$h = 6.6x10^{-34}$ [J*sec]
(Planck's constant)

Longest wavelengths

Momentum

In physics, there's another quantity which we hold just as sacred as energy, and this is momentum.

For an <u>object with mass</u>, momentum is given by:

$$\vec{p} = m\vec{v}$$

The units are: [kg] [m/s] == [kg m/s]

Unlike energy, which is a scalar, momentum is a **vector.** That is it has both magnitude & direction. The direction is along the direction of the velocity vector.

The reason it is important in physics, is, because like Energy:
TOTAL MOMENTUM IS ALWAYS CONSERVED

Do photons carry momentum ?

DeBroglie's proposed that the a photon not only carries energy, but also carries momentum.

But, p = mv, and photon's have m=0, so how can it be that the momentum is not zero??

$p = h/l$

DeBroglie postulated that photons carry momentum, and their momentum is:

$$p = E / c$$

If we substitute: $E = hc/\lambda$ into this equation, we get:

$$p = h / l$$

Momentum carried by a photon with wavelength λ

DeBroglie's Relation

DeBroglie relation

$p = h / l$ Photons carry momentum !!! $l = h / p$

$E = hc / l$ Photons also carry energy !!!

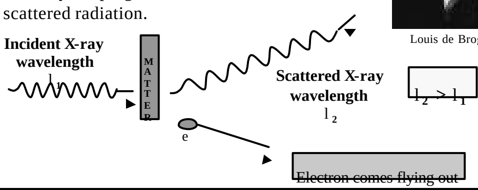
Both **energy & momentum are <u>inversely proportional</u> to the wavelength !!!**

➔ The highest energy photons are those which have small wavelength (that's why gamma rays are so dangerous)

The Compton Effect

Louis de Broglie

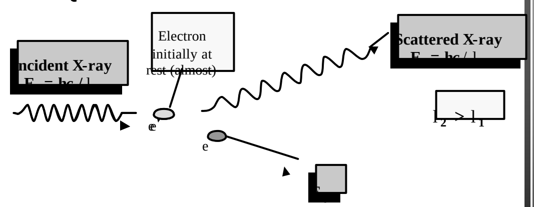
In 1924, A. H. Compton performed an experiment where X-rays impinged on matter, and he measured the scattered radiation.



<u>Problem:</u> According to the wave picture of light, the incident X-ray should give up some of its energy to the electron, and emerge with a lower energy (*i.e.*, the amplitude is lower), but should have $l_2 = l_1$.

It was found that the scattered X-ray did not have the same wavelength ?

Quantum Picture to the Rescue

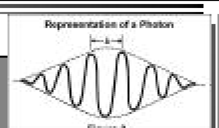


Compton found that if you treat the photons as if they were particles of zero mass, with energy **E=hc/l** and momentum p=h/λ

➔ The collision behaves <u>just as if it were 2 billiard balls colliding</u> !

Photon behaves like a particle with energy & momentum as given above!

Summary of Photons



❑ Photons can be treated as "*packets of light*" which behave as a particle.

❑ To describe interactions of light with matter, one generally has to appeal to the particle (quantum) description of light.

❑ A single photon has an energy given by

E = hc/l,

where

h = Planck's constant = 6.6×10^{-34} [J s] and,
c = speed of light = 3×10^{8} [m/s]
λ = wavelength of the light (in [m])

❑ Photons also carry momentum The momentum is related to the

So is light a wave or a particle ?

On macroscopic scales, we can treat a large number of photons as a wave.

When dealing with subatomic phenomenon, we are often dealing with a single photon, or a few. In this case, you cannot use the wave description of light. It doesn't work !