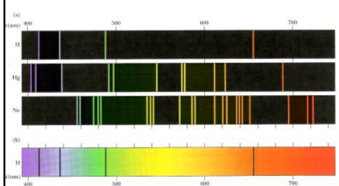
PH300 Modern Physics SP11



*All these fifty years of conscious brooding have brought me no nearer to the answer to the question, '**What are light quanta**?' Nowadays every Tom, Dick and Harry thinks he knows it, but he is mistaken.*
(***Albert Einstein***, *1954*)

2/22 Day 11:
Questions?
Photons
Atomic Spectra

Thursday:
Lasers(!)

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Last time:
- Finished photoelectric effect
- Photons

Today:
- Photons (continued)
- Atomic spectra

Key concepts for quantum physics.
- Light energy is "quantized".
- Light has both wave-like and particle-like properties.

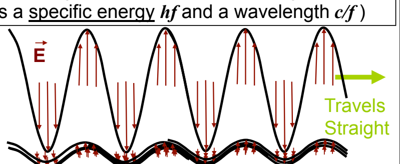
Electromagnetic Waves and Photons are describing the same thing!

Need to have a model where these views/perspectives all fit together and are consistent with each other!

1. Light, Radio waves, X-rays are all electromagnetic waves!
2. The electromagnetic wave is made up from lots of photons.
3. Photons can be thought of as mini E/M wave segments (each has a specific energy hf and a wavelength c/f)

Electromagnetic Wave

Made up from lots of photons



This picture can explain wave view and particle view.
"Particle" = little chunk of the electromagnetic wave.
Energy of photon (hf) is in its oscillating E and B fields.
(Sometimes it also helps to think of a photon as a tiny particle/energy packet).

If you think of photons as particles you probably automatically think of them as perfectly localized - like a tiny billiard ball at a coordinate (x, y, z).

This is what get's you into trouble in QM!!

- Billiard balls never produce a diffraction pattern
- Billiard balls have no wavelength/frequency
- Billiard balls cannot go through two slits at the same time (photons can; electrons too! Will show later)

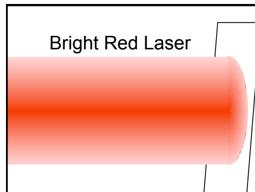
When is it important to think about particle aspect of light?

Only if your "detection system" is good enough to see individual photons!

Examples where important to think about particle behavior:
Photoelectric effect: Individual electrons popping out of metal
Lasers: Electrons in atoms transitioning between energy levels
Molecular bonds: Chemical bonds breaking

Examples where don't need to think about particle behavior (detection system isn't good enough and wave behavior is easier):
Heating: Energy absorbed in microwave or by black asphalt.
Optics: Light bending through lenses or passing through slits
Laser beam: Treat it just like a beam of light… (Understanding the working principle of a laser requires photon picture.)

Bright Red Laser



Consistent descriptions:
Lots of light means …
- Big amplitude E/M wave
- Made from many photons (mini E/M wave segments)

When a photon *interacts* with something (e.g. an electron) all the energy of its wave segment ends up concentrated in one spot (like a particle!)

Until a photon interacts with something (e.g. absorbed by an electron), *it acts like a wave*. How does the wavelength of the photon compare to the wavelength of the light in the red laser?
a. Photon has a smaller wavelength
b. Photon has same wavelength
c. Photon has a larger wavelength
d. Photons are points in space. They have no wavelength.

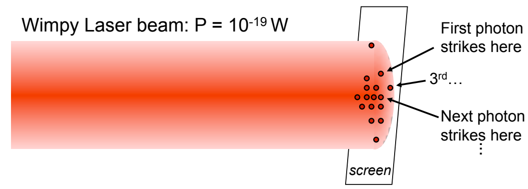
Properties of photons

The energy of a photon is	$E = hf$
The wavelength of a photon is	$\lambda = c/f = hc/E$
The mass of a photon is	$m = 0$
The momentum of a photon is	$p = E/c = h/\lambda$

$h \approx 6.626 \cdot 10^{-34}\, J{\cdot}s$: Plank constant

It sometimes is useful to define $\hbar = h/(2\pi)$
The energy of a photon is then: $E = hf = \hbar\omega$

What if the intensity is really small?



If the laser power is 10^{-19} W, we get only about one photon per second in the beam! (assuming $\lambda \approx 780$ nm)

Where's that one photon?

Well, we can't know anything about its location until it strikes the screen.
Most photons seem to hit the screen where intensity is high.

Where's the photon?

It will strike the screen at random position!

However: We do observe that more photons strike at the places where the intensity of the laser beam is largest.

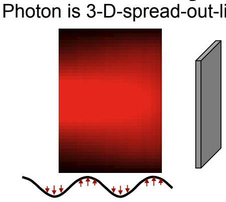
Important conclusion:

The probability to find a photon at a specific location in a beam of light is proportional to the intensity of the beam at that location.

i.e.: Probability is proportional to E^2_{max}

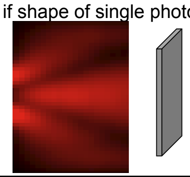
Probability and randomness

Photon is 3-D-spread-out-little-chunk of an EM wave.



Gazillions of electrons in metal:
Which one will be kicked out?
Can't tell, but photon uniformly spread out so pretty much equal probability everywhere.

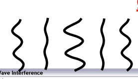
What if shape of single photon wave looked like this?



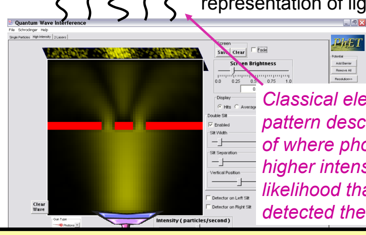
Gazillion electrons
Which one will be kicked out?
Answer: Can't tell, but probability of photon collapse at particular point (kicking out electron) related to intensity of wave (E_{max}^2)

quantum-wave-interference sim

Probability of photon hitting given by where field is biggest
(electric field strength)^2 ~ Intensity &
gives probability of where photon will be!



standard electric field representation of light field



Classical electric field wave pattern describes probability of where photons will be… higher intensity, higher likelihood that photon will be detected there.

If I shoot a photon through the two slits to hit the screen, it has some chance of being detected anywhere on screen, but on average better chance at being where interference pattern in brightest.

Randomness in physics??!

A completely new concept in QM is that the outcome of a measurement can often times not be predicted precisely. We can only predict the **probability of obtaining a certain result**!

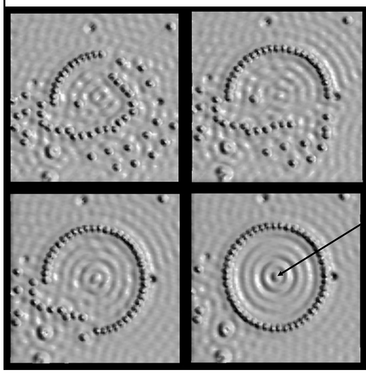
Examples:

Where will a photon hit the screen?
Well, I don't know, but the probability is largest where the intensity of the light is largest ~(field amplitude)^2

Where is the electron in a hydrogen atom?
The probability of where it will be found is largest at the location where the square of the matter-wave amplitude is largest.

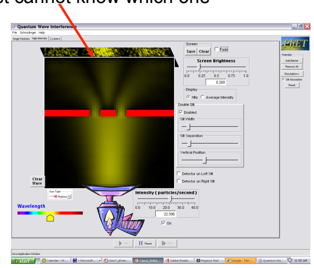
(Randomness is negligible for macroscopic objects but important on atomic scale!)

Remember this picture?



The probability of finding the electron that is trapped inside this ring of atoms is highest at the place, where the square of the wave amplitude for the electron is largest.

Which slit did this photon go through?
a. left
b. right
c. both
d. neither
e. either left or right we just cannot know which one



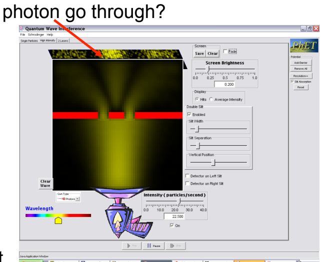
$|E_1|^2$

$|E_2|^2$

$|E_1 + E_2|^2$

$|E_1|^2 + |E_2|^2$

Which slit did this photon go through?
c. both!



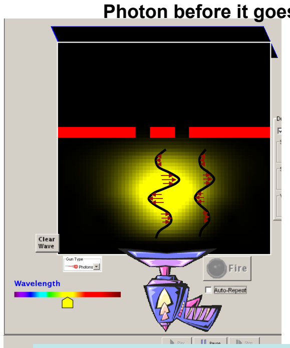
If one slit:
Get single slit pattern
(i.e. no interference)

But: that photon is part of the two slit interference pattern,

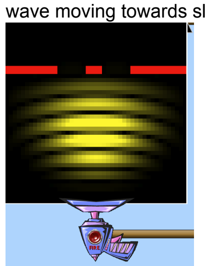
the probability pattern of where it lands is described by the 2 slit interference pattern, **it must have gone through both slits i. e. as a wave!**

When it interacts with the screen it acts like particle!

Photon before it goes through the slits

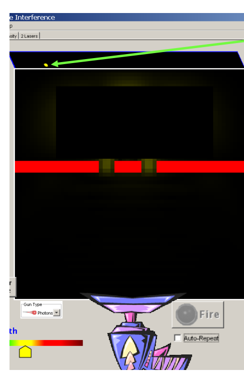


Photon as little segment of wave moving towards slits



Intensity of wave in various places, indicates probability of finding the photon there if you looked at that moment.

Photon after it goes through the slits



When photon *interacts* with an electron or atom, all energy ends up in one spot… behaves like a particle with energy = hc/λ = hf

Photon is a wave… it can interfere with itself.

Intensity of wave in various places still indicates probability of the photon concentrating at that spot if you had detector (e.g. a bunch of atoms or a sheet of metal)

Big Picture: Ideas central to understanding and using Quantum Mechanics

1. Light has both particle-like and wave-like characteristics. (Photoelectric Effect, Interference Patterns) *(application- light detectors)*
2. This implies not everything exactly determined. Behavior fundamentally governed by randomness and probability.

3. How light interacts with and is produced by *individual* atoms. Implications about atoms and behavior of electrons in atoms.
4. Wave-particle duality of photons applies to electrons (and everything else), so does randomness and probability!
5. Mathematical description to calculate.
6. Apply these ideas to all kinds of interesting stuff.

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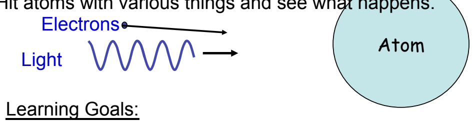
Develop model of how light interacts with and is produced by *individual* atoms & what that tells us about how to describe atoms and about behavior of electrons in atoms

How to look at structure of atoms?

Experiment!

Hit atoms with various things and see what happens.



Learning Goals:

1. What one sees if bash atoms with anything, particularly electrons, as in a discharge lamp.
2. What light coming from atoms ("spectra") imply about behavior of electrons in atom.

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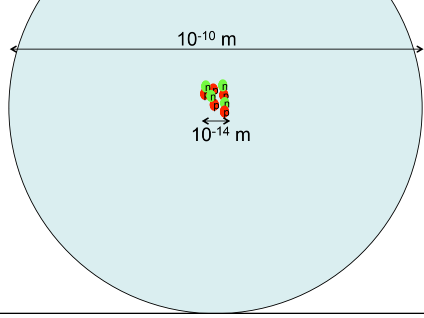
Atom: Tiny nucleus with protons and neutrons (99.9% of mass)
Surrounded by large diffuse cloud of low mass electrons



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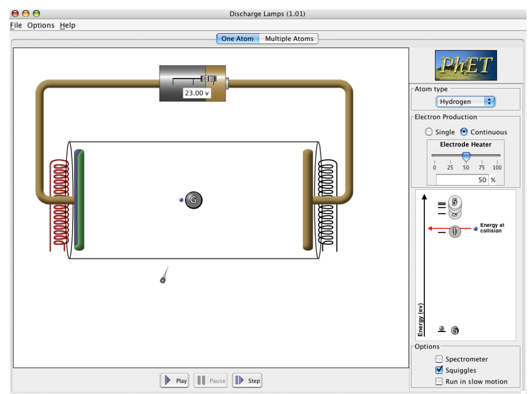


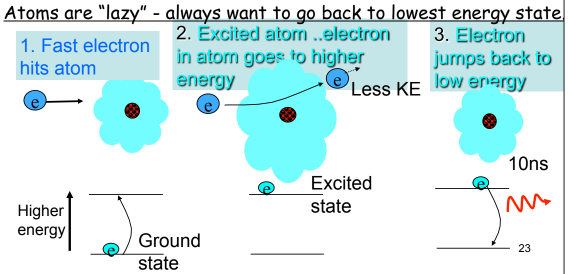
Discussion: Given what we know about light, what does this imply about electrons in atoms?

Implies that electrons only change between very specific energies.

Only way for *individual* atoms to give off energy is as light.

Each time a photon is emitted an electron must be changing in energy by that amount (*releasing* energy).

Atoms are "lazy" - always want to go back to lowest energy state.



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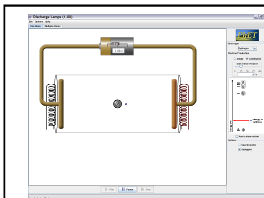

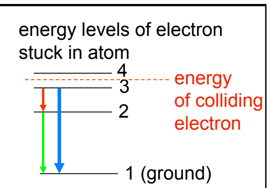

If the colliding electrons have an energy between that of level 3 and level 4 when they hit the atoms

a. no levels will be excited, and so no light will come out.
b. 1 color of light will come out
c. 2 colors of light will come out
d. 3 colors of light will come out
e. 4 colors come out.

ans. d. enough energy to excite level 3, then get 3→2 followed by 2→1, but also can go 3→1.

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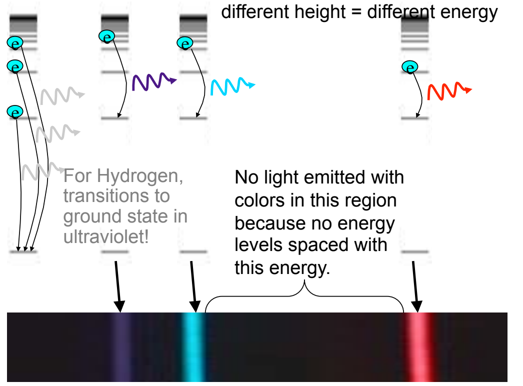
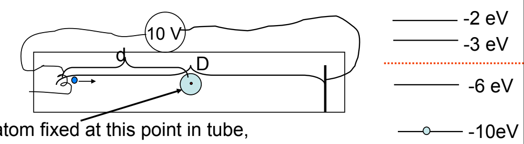
Energy level diagrams- represent energy electron can go to.
different height = different energy



In discharge lamps, one electron bashes into an atom.



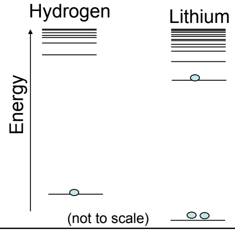
If atom fixed at this point in tube,
list all the possible energy photons (colors) that you might see?

A. 1eV, 2eV, 3eV, 4eV, 7eV, 8eV
B. 4eV, 7eV, 8eV
C. 1eV, 3eV, 4eV
D. 4eV   Answer is D. Electron only gains about 5eV!
E. Impossible to tell.

Electron energy = $q\Delta V = e(Ed)$,
where E is the electric field = (battery V)/(total distance D),
and d is the distance it goes before a collision.

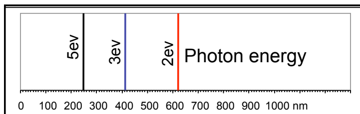
Important Ideas

1) Electrons in atoms only found in specific energy levels
2) Different set of energy levels for different atoms
3) 1 photon emitted per electron jump *down* between energy levels. Photon color determined by energy difference.
4) electron spends very little time (10^{-8} s) in excited state before hopping back down to lowest unfilled level.
5) If electron not stuck in atom, can have any energy.



Electron energy levels in 2 different atoms …
Levels have different spacing.

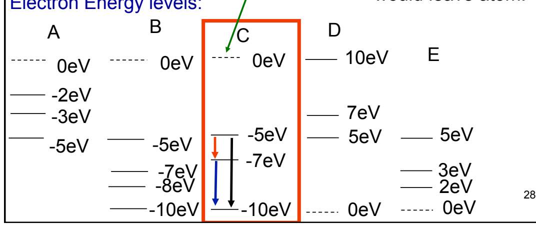
Atoms with more than one electron … lower levels filled.



What energy levels for electrons are consistent with this spectrum for "*Finkel*onium"?

Electron energy levels = PE + KE
Since PE = 0 at infinity (e.g. electron escaping from atom).
A positive total energy would mean that KE>PE and electron would leave atom!

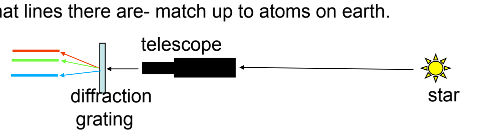
At 0eV, electron has escaped atom.
Electron Energy levels:



Applications of atomic spectroscopy (how it is useful)

1. Detecting what atoms are in a material.
(excite by putting in discharge lamp or heating in flame to see spectral lines)

2. Detecting what sun and stars are made of.
Look at light from star with diffraction grating, see what lines there are- match up to atoms on earth.



3. Making much more efficient lights!
Incandescent light bulbs waste 88% of the electrical energy that goes into them! (12% efficient)
Streetlight discharge lamps (Na or Hg) 80% efficient.
Fluorescent lights ~ 40-60% efficient.