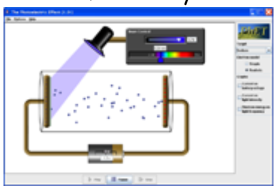
PH300 Modern Physics SP11



"I learned very early the difference between knowing the name of something and knowing something."
- Richard Feynman

2/17 Day 10:
Questions?
Photoelectric Effect (continued)
Photons

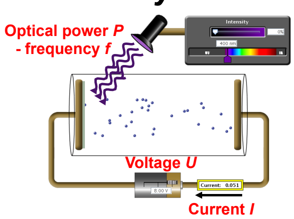
Next week:
Early atomic models
Atomic spectra
Lasers(!)

Today:
- Finish photoelectric effect
- Photons

Next Week:
- Atomic spectra/Balmer series
- Lasers

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

What did *you* think would happen?



1. Current vs. Voltage with the lamp on (fixed color of light, say UV).
2. Current vs. Frequency (color) at a fixed voltage (right plate is on positive potential)
3. Current vs. Intensity for fixed color (right plate is at positive voltage)

PE summary from last class:

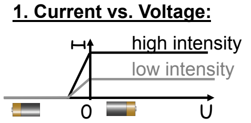
http://phet.colorado.edu/simulations/photoelectric/photoelectric.jnlp

- Current responds instantaneously to light on/off → Not just a heating effect!
- Color matters: Below a certain frequency: No electrons. → Not just a heating effect!
- Positive voltage does not increase the current (remember the 'pool analogy')
- Negative voltages do decrease current → Stopping voltage is equal to initial kinetic energy!
- Initial kinetic energy depends on color of the light.
- Current is proportional to the light intensity.

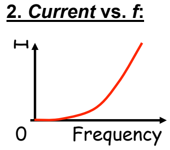
how do these compare with classical wave predictions?

Summary PE effect:

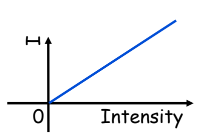
1. Current vs. Voltage:



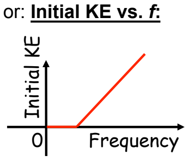
2. *Current* vs. *f*:



3. *Current* vs. intensity:



or: **Initial KE vs. *f*:**



Classical wave predictions vs. experimental observations

• Increase intensity, increase current.
experiment matches

• Current vs voltage step near zero then flat.
(flat part matches, but experiment has tail of energetic electrons, *energy of which depends on frequency*)

• Frequency does not matter, only intensity.
experiment shows strong dependence on frequency

•Takes time to heat up ⇒ current low and increases with time.
experiment: electrons come out immediately, no time delay to heat up

Summary of what we know so far:

1. If light can kick out electron, then even smallest intensities of that light will continue to kick out electrons. KE of electrons does not depend on intensity.

2. Lower frequencies of light means lower initial KE of electrons & KE changes linearly with frequency.

3. Minimum frequency below which light won't kick out electrons.

(Einstein) Need "photon" picture of light to explain observations:
- Light comes in chunks ("particle-like") of energy ("photon")
- a photon interacts only with single electron
- Photon energy depends on frequency of light, …

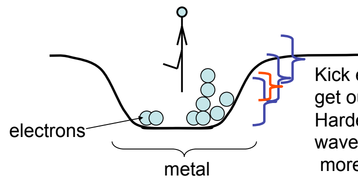
for lower frequencies, photon energy not enough to free an electron

Kicker analogy: a ball in a pit

Light like a Kicker…
Puts in energy. All concentrated on one ball/electron.
Blue kicker always kicks the same, and harder than red kicker always kicks.

Ball emerges with:
KE = kick energy - mgh

mgh = energy needed to make it up hill and out.
mgh for highest electron analogous to work function.



Kick energy. Top ones get out, bottom don't. Harder kick (shorter wavelength light), more get out.

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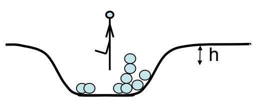
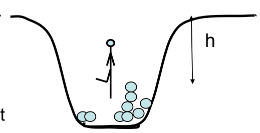


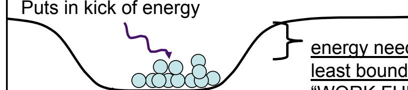
sodium- easy to kick out
small work function Φ = shallow pit



platinum, hard to kick out
large work function Φ = deep pit

If photon has enough energy, electron emerges with: KE = photon energy – work function

Photon…
Puts in kick of energy



<u>energy needed to kick out least bound electron. "WORK FUNCTION"</u> (Φ)

Each photon has: Energy =h f = Planks constant * Frequency

(Energy in Joules) $E=hf=(6.626*10^{-34}\text{ J-s})*(f\text{ s}^{-1})$
$E=hc/\lambda = (1.99*10^{-25}\text{ J-m})/(\lambda\text{ m})$

(Energy in eV) $E=hf= (4.14*10^{-15}\text{ eV-s})*(f\text{ s}^{-1})$
$E= hc/\lambda=(1240\text{ eV-nm})/(\lambda\text{ nm})$

$$\text{Initial KE of electron as it comes out of metal} = E_{photon} - \underbrace{\text{energy needed to kick electron out of metal}}_{\text{Depends on type of metal.}}$$

Typical energies

Photon Energies:

Each photon has: Energy =h f = Planks constant * Frequency

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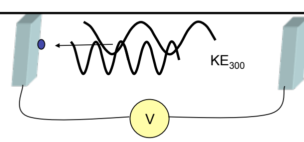
$E= hc/\lambda=(1240\text{ eV-nm})/(\lambda\text{ nm})$

Red Photon: 650 nm $E_{photon} = \frac{1240\text{ eV-nm}}{650\text{ nm}} = 1.91\text{ eV}$

Work functions of metals (in eV):

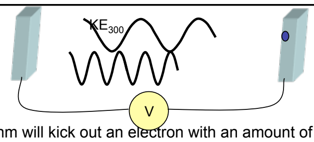
Aluminum	4.08 eV	Cesium	2.1	Lead	4.14	Potassium	2.3
Beryllium	5.0 eV	Cobalt	5.0	Magnesium	3.68	Platinum	6.35
Cadmium	4.07 eV	Copper	4.7	Mercury	4.5	Selenium	5.11
Calcium	2.9	Gold	5.1	Nickel	5.01	Silver	4.73
Carbon	4.81	Iron	4.5	Niobium	4.3	Sodium	2.28
				Uranium	3.6		
				Zinc	4.3		



A photon at 300 nm will kick out an electron with an amount of kinetic energy, KE_{300}. If the wavelength is halved and it hits an electron in the metal with same energy as the previous electron, the energy of the electron coming out is…

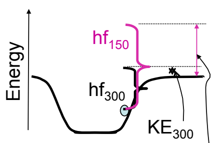
a. less than ½ KE_{300}.
b. ½ KE_{300}
c. = KE_{300}
d. 2 x KE_{300}
e. more than 2 x KE_{300}

(remember hill analogy, draw pictures to reason out answer, don't just pick answer without careful reasoning)



CQ: A photon at 300 nm will kick out an electron with an amount of kinetic energy, KE_{300}. If the wavelength is halved and it hits an electron in the metal with same energy as the previous electron, the energy of the electron coming out is

e. more than 2 x KE_{300}



KE = photon energy-energy to get out
= hf – energy to get out
if λ is ½ then, f twice as big, $E_{phot} = 2hf_{300}$

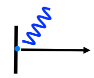
New $KE_{new} = 2hf_{300}$ - energy to get out

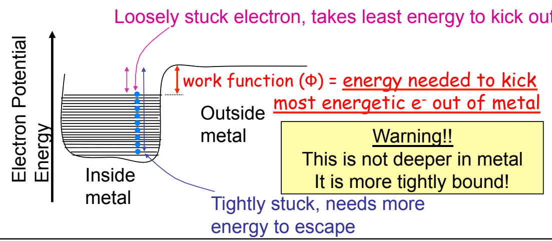
Old $KE_{300} = hf_{300}$ - energy to get out

so KE_{new} is more than twice as big.

Photoelectric effect experiment: Apply Conservation of Energy

Energy in = Energy out
Energy of photon = energy needed to kick electron out of metal + Initial KE of electron as exits metal

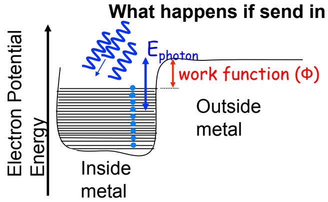




Apply Conservation of Energy.

Energy in = Energy out
Energy of photon = energy needed to kick electron out of metal + Initial KE of electron as exits metal

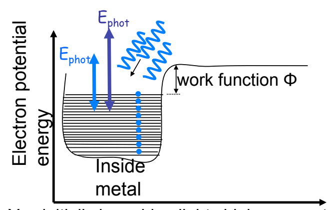
What happens if send in bunch of blue photons?



Photon gives electron "kick of energy".

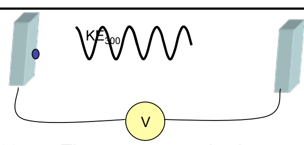
Electrons have equal chance of absorbing photon:
→ Max KE of electrons = photon energy - Φ
→ Min KE = 0
→ Some electrons, not enough energy to pop-out, energy into heat

Electrons over large range of energy have equal chance of absorbing photons.



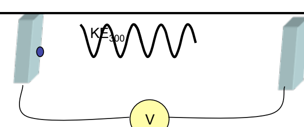
You initially have blue light shining on metal. If you change the frequency to violet light (at same # of photons per second), what happens to the number of electrons coming out?

a. fewer electrons kicked out
b. same # of electrons
c. more electrons kicked out
d. not enough information



Shine in light of 300 nm. The most energetic electrons come out with kinetic energy, KE_{300}. A voltage diff of 1.8 V is required to stop these electrons. What is the work function Φ for this plate? (e.g. the minimum amount of energy needed to kick electron out of metal?)

a. 1.2 eV
b. 2.9 eV
c. 6.4 eV
d. 11.3 eV
e. none of the above



Shine in light of 300 nm, most energetic electrons come out with kinetic energy, KE300. A voltage diff of 1.8 V is required to stop these electrons. What is the work function Φ for this plate? (e.g. the minimum amount of energy needed to kick e^- out of metal?)

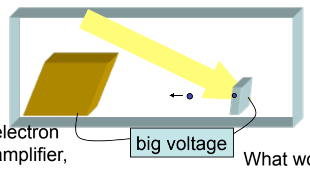
a. 1.2 eV
b. 2.9 eV
c. 6.4 eV
d. 11.3 eV
e. none

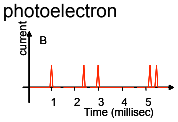
Energy is conserved so:
the energy at the start (E_{phot}) = energy at end
E_{phot}= energy of the electron + energy to escape metal

so Φ= E_{phot} - electron energy
but electron energy = e x 1.8V = 1.8 eV, and
E_{phot} = 1240 eV nm/300 nm = 4.1 eV.

So Φ = 4.1eV - 1.8 eV = 2.3 eV

Photomultiplier tubes- application of photoelectric effect
most sensitive way to detect visible light, see single photons
(eye is incredibly good, can see a few photons)





What would be the best choice of these materials to make this out of?

a. Platinum Φ = 6.35 eV
b. Magnesium = 3.68 eV
c. Nickel = 5.01 eV
d. lead = 4.14 eV
e. Sodium = 2.28 eV

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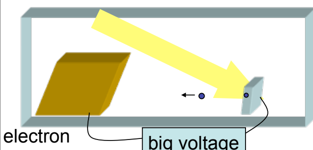

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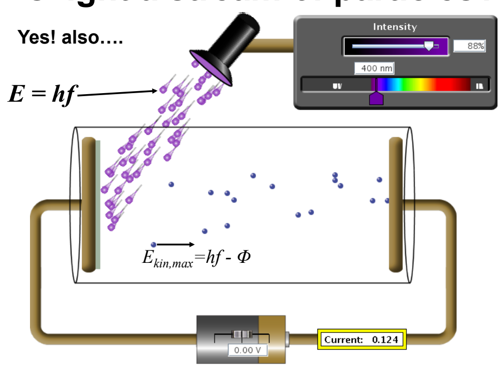
e. sodium. 2.28 eV
lower work function means most visible light (<544 nm) will be detected. Enough energy to eject electrons.

Is light a stream of particles?

Yes! also….



Photons

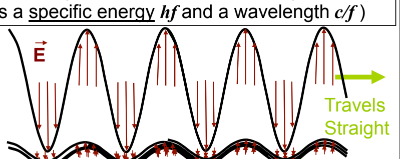
The frequency of a beam of light is decreased but the light's intensity remains unchanged. Which of the following is true?

A. There are more photons per second but each photon has less energy.
B. There are more photons per second but each photon has more energy.
C. There are fewer photons per second and each photon has less energy.
D. There are fewer photons per second but each photon has more energy.
E. Nothing happens to the photon number because light is a wave.

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 <u>specific energy</u> hf and a wavelength c/f)



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.)