L02 - 9. Jan. 2013

1. Wave-particle duality

(See for example Zettili, Quantum Mechanics, Wiley, 2nd edition 2009; This is not contained in the McIntyre book!)

Physics at the end of the 19th century is characterized by two distinct concepts: Particles and Waves

Classical Physics

Particles:

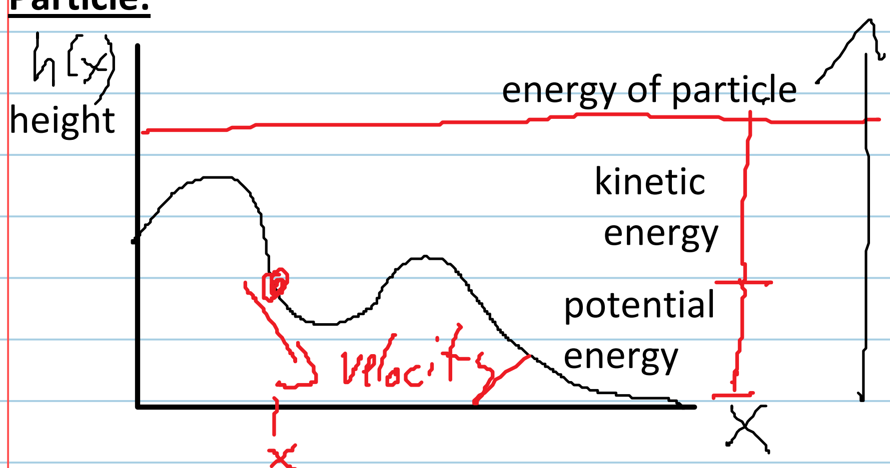
(Abstraction: Point particles)

- described by:
  position and momentum
  (phase space as configuration space)
- have associated energy
  - kinetic energy
  - potential energy
- well defined localized collisions between two particles
  ➔ exchange of energy and momentum

Waves:

- described by
  amplitude over large regions
- energy distributed over whole wave
- interference effects between two waves

Particle:



gravitational potential:
$V(x) = m\, g\, h(x)$
m: mass
g: earth acceleration

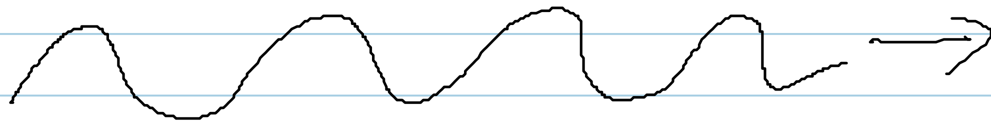
given intial position and velocity (momentum), we have a clear intuition about the movement of the particle!

it is always in some location x with some velocity, and that is all that we need to characterize it (by approximating it as point particle)

particles can transmit energy and moment by collisions. The location of the collisions is clearly defined, and the transfer of energy and momentum is basically instantaneous (for example for point particles)

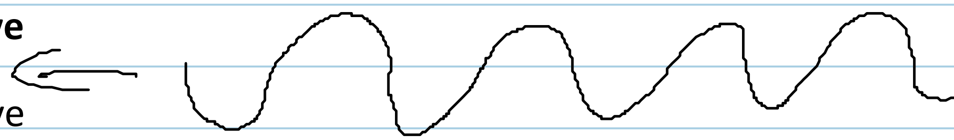
<u>Wave:</u>
characterized by frequency, amplitude, spatial distribution
energy continuously distributed over wave region

Simplest example of interference:

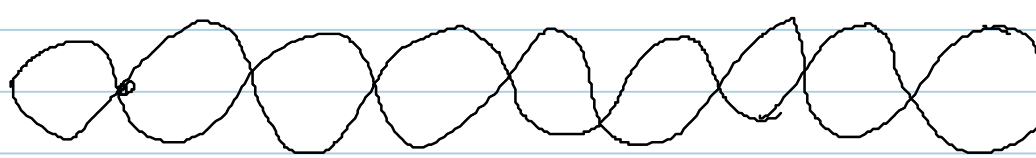


right moving wave
time evolution:
shift of whole wave
to the right

left moving wave
time evolution:
shift of whole wave
to the left



both waves together:
sum up amplitudes ==> standing wave



==> nodes emerge that show no amplitude at any time

Time evolution: at each location, oscillation of amplitude vector at wavefrequency, amplitude of oscillation as shown in graph ...

Challenges to this classical picture:

Light (wave) acting like particles:

- Blackbody radiation (omitted here)
- Photoelectric effect
- Compton effect

Particles acting like waves (interference):

- Davisson-Germer Experiment
- Double slit experiment (Young)

1.1. Photoelectric Effect (Zettili section 1.2.2)

Check out the website

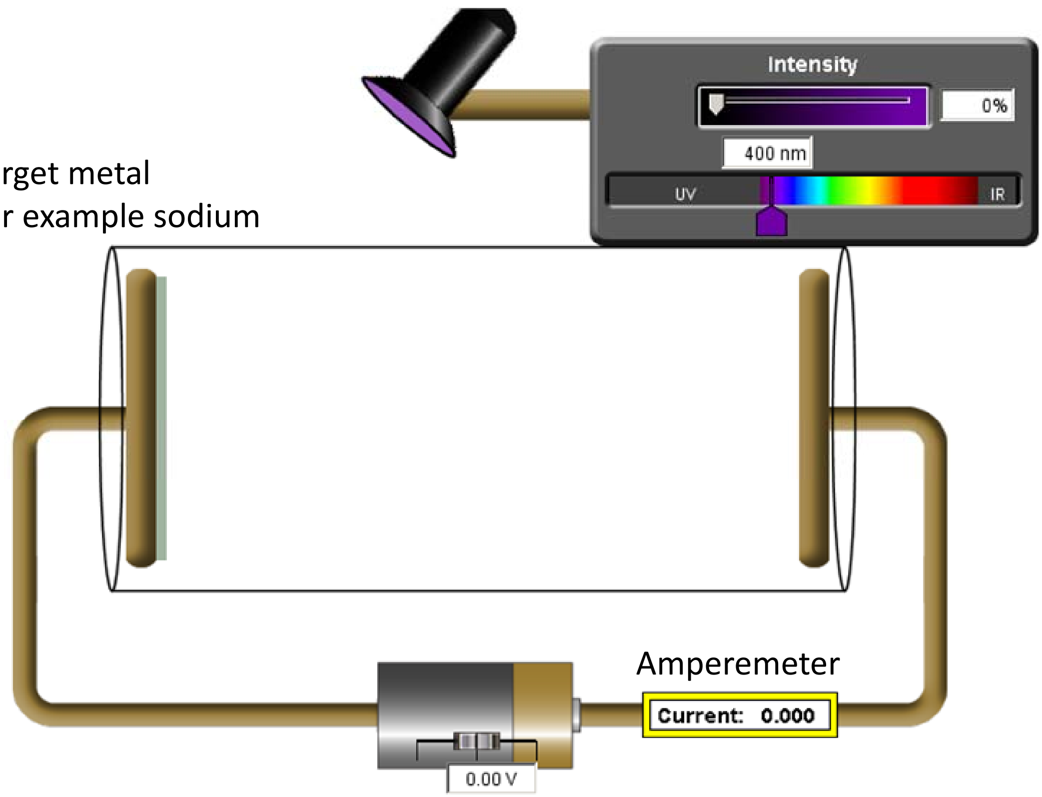
http://phet.colorado.edu/simulations/index.php?cat=Quantum_Phenomena

for a great simulation of the corresponding experiment

Basic Experimental Observations:

light source
frequency ν

target metal
for example sodium



Amperemeter

later added:
external voltage source

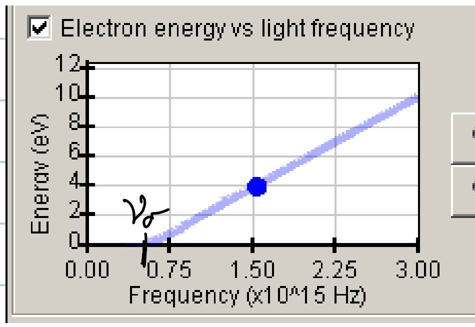
As soon as light falls on the metal surface, a current flows and is measured by the Amperemeter.

Explanation idea in classical physics:

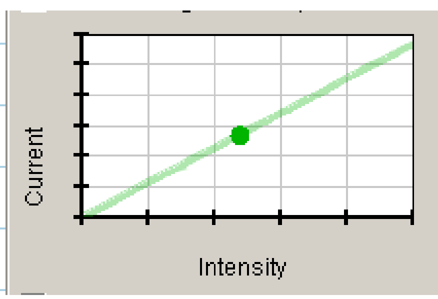
The light (wave) is absorbed by the electrons (particles) in the metal. This energy transfer allows electrons to escape the metal. The electrons are eventually captured by the opposing metal plate and return. This is measured as current.

More detailed experimental observations:

- The experiment depends on the frequency of the light source: if the frequency falls below some value ν_0, then no current flows.



- The frequency cut-off exists independent of the intensity of the incoming light, even very weak light sources will result in some current

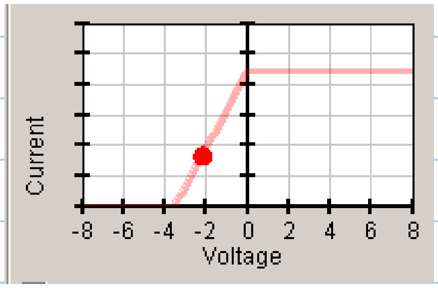


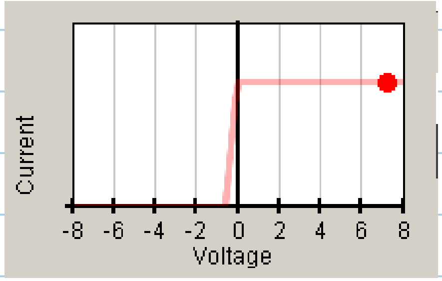
- The effect is instantaneous: there is no delay between switching on the light and the emergence of a current

Problems for classical explanations approach:

- Energy can be transmitted by light (waves) independent of the frequency, so there is no reason why a specific cut-off frequency should exist
- More light (higher intensity) means more energy is deposited, at any frequency
- As the electrons absorb the incoming light, there should be a delay between light being switched on and the current starting to flow, especially for extremely weak light sources

Even more detailed experimental observations:
Add a power source into the circuit:





Change of voltage leads to a change of the cut-off frequency ν_0
==> ν_0 is a function of V: $\nu_0(V)$

Corresponding to that: for any frequency, there is a voltage V_0 which just about stops the current (stopping voltage)

Einstein's Theory of the Photoelectric Effect (1905)

Postulate:

Light comes in quantized units, rather than in continuous form
➔ "photon"
Each photon of frequency ν carries an energy E_ν given by
$\boxed{E_\nu = h\,\nu}$
where h is the Planck constant h = 6.6 10^{-34} Js

Note: for visible light we have $\nu \approx 10^{15}\,s^{-1}$
so that $E_\nu \approx 10^{-19}\,J$

This is very small! So in most applications we will not notice that light comes in individual small units.

Explanation of Photoelectric effect:

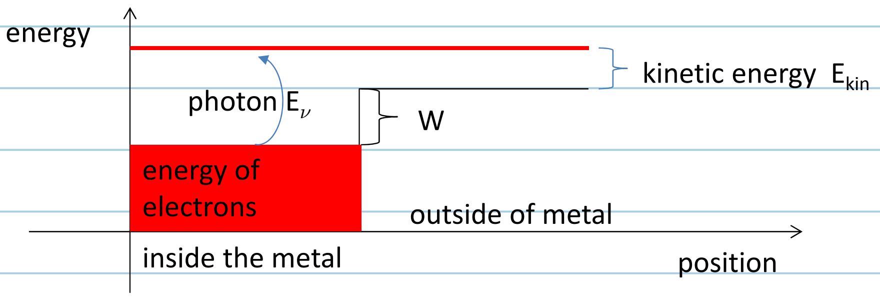
ONE photon interacts with ONE electron

In the interaction, the photon is absorbed and transfers its energy to the electron. The electron uses this energy to free itself from the metal (it needs work to get out of there) and the remaining energy is used as kinetic energy for the electron to fly to the opposite metal plate.

$$E_\nu = W \quad + E_{kin}$$

Here: W is the energy required to get out of the surface (work function)

E_{kin}: is the kinetic energy of the escaped electron



$$E_\nu = W + E_{kin}$$

photon energy

Work function (escape energy)

kinetic energy of released electron

Energy conservation tells us, that the photon has to deposit at least the energy amount W from which we find the cut-off frequency as

$$h\nu_0 = W$$

$$\Rightarrow \nu_0 = \frac{W}{h}$$

In case that the frequency of the photons are too low, the electron cannot leave the metallic surface, and no current flows, no matter how many of those photons impinge on the surface.

Note: If an electrons absorbs one photon below the cut-off frequency, its energy will quickly dissipate through collisions, typically before it has a chance to absorb a second photon.

The additional voltage applied to the circuit can make it harder for the electrons to reach the other plate: after escaping the surface, they need to have sufficient kinetic energy to reach the other plate against an electrostatic potential eV

Where

e is the electric charge of the electron

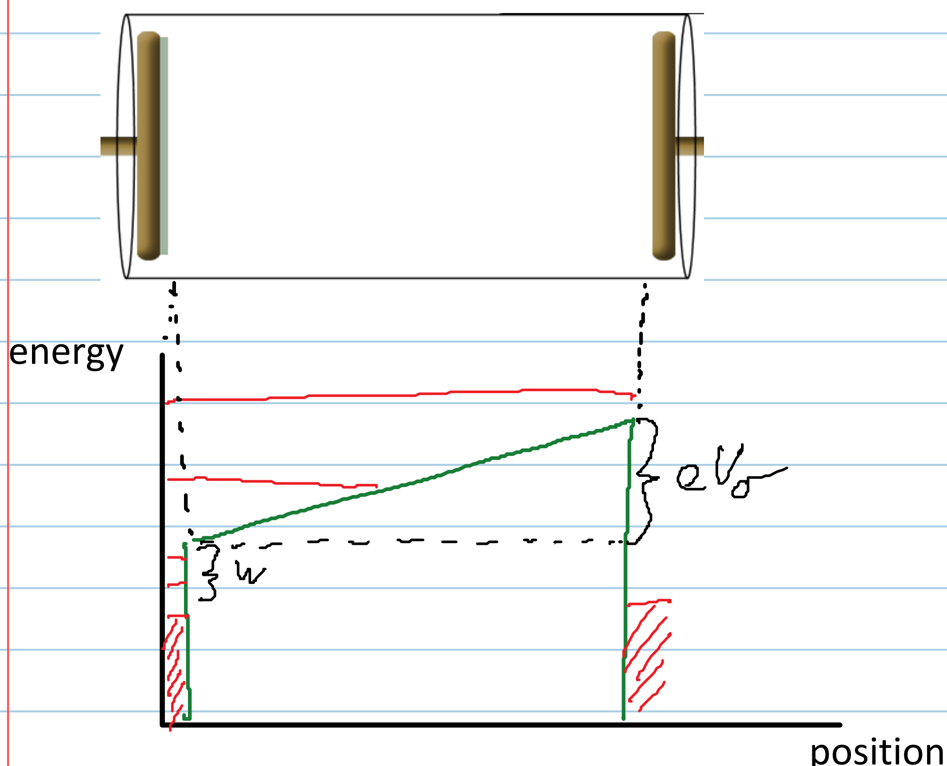
V is the applied voltage

So in total we obtain for the cut-off frequency in the presence of an additional voltage source:

$$h\nu_0 = W + eV_0$$

$$\Rightarrow V_0 = \frac{h}{e}\nu_0 - \frac{1}{e}W$$

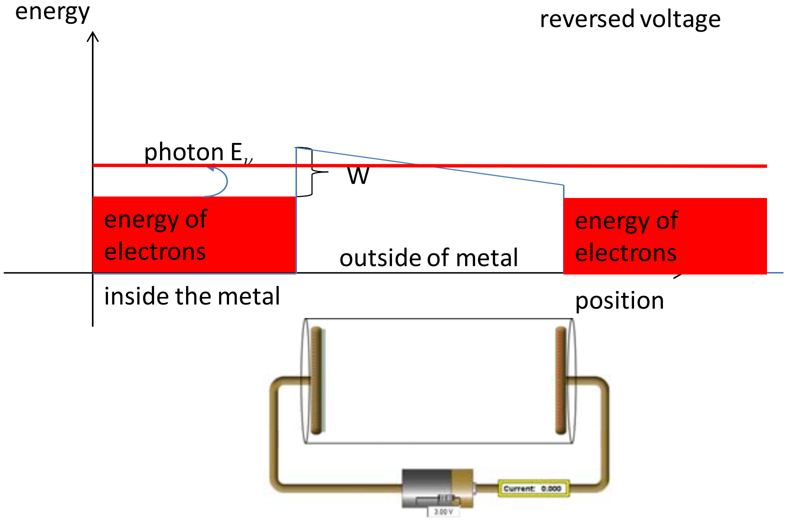
Energy Diagram:



Cleary, this explanation model also explains why the photo-**electric effect is instantaneous:** one photon being absorbed by one electron does not require any type of accumulation, so time does not enter the game.

And if we reverse the direction of the voltage?

External field 2



Clicker question:

Can the electron fly from the left to right piece of metal?

A) Yes

B) No

The answer is:

'No' - at least in the simple picture we developed here. The electron does not get sufficient amount of energy from the photon to exit the metal on the left.

Actually, there is a whole region outside of the metal where the electron could not simply sit (considering it as a particle), as it would have negative kinetic energy, which does not make sense for a classical particle. It does not matter that the electron would be alright at the right side of the setup, it simply can't get there.

At the end of the course, we will learn that a quantum mechanical particle has a chance to tunnel through the region of insufficient energy, but we need to learn more to describe this. Moreover, for the typical energy of light photons and typical voltages in lab experiments (a few volts) and good distance between the two metal plates (millimeter or centimeter), the current resulting from tunneling electrons is so small that it can be neglected. (Not observable.)

So 'basically NO' is also a correct answer, but we will discuss this again at the end of the course.

Conclusion Photo-Electric Effect:

- We can think of light as coming in small energy units
  ➔ Photon
- Photon's carry energy just as a particle would do
- Photon can transfer energy to other particles (electrons)