Recap I

- Key Ideas in Quantum Physics:
  - waves act as particles: particles act as waves
  - Quantization: only certain values possible
  - Uncertainty in quantities: probability distributions
- Energies at small scales:

  use $1\,eV = 1$ electron volt $= 1.6 \cdot 10^{-19}\,J$

- Photons:

Electromagnetic radiation is composed of photons [concentrated bundles of energy and momentum] whose motion is described by an analysis that closely parallels the classical wave description in terms of "interfering amplitudes".

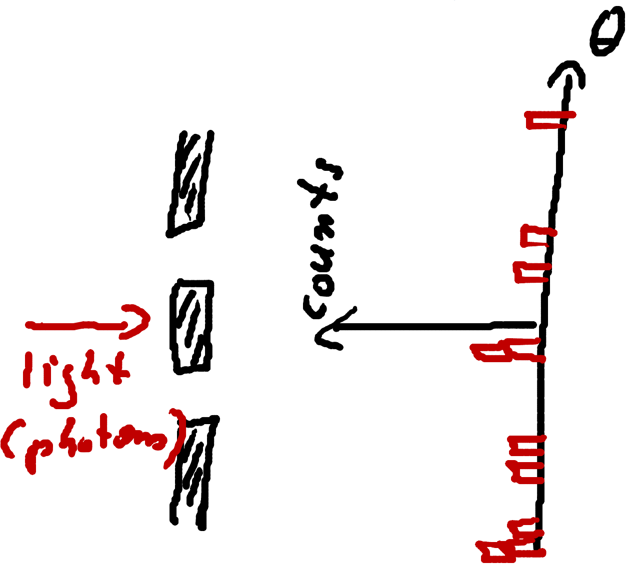
⇒ For light of frequency f and wavelength λ:

$$E_{photon} = hf \qquad p_{photon} = \frac{h}{\lambda}$$

h = Planck's constant $= 4.136 \cdot 10^{-15}\,eV \cdot s$

Recap II

• Evidence of Photons: 2-slit experiment at low intensity

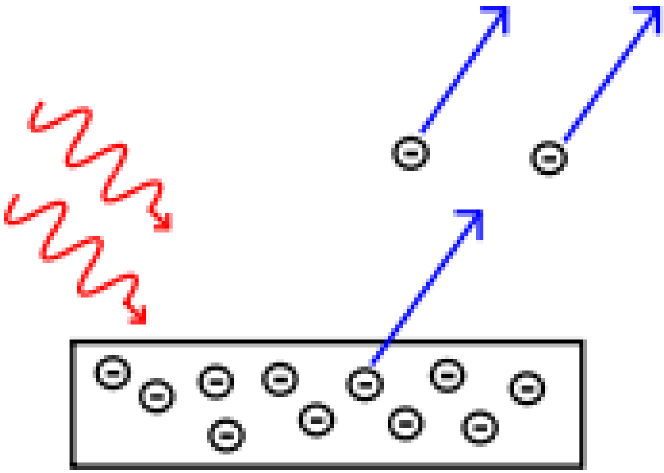


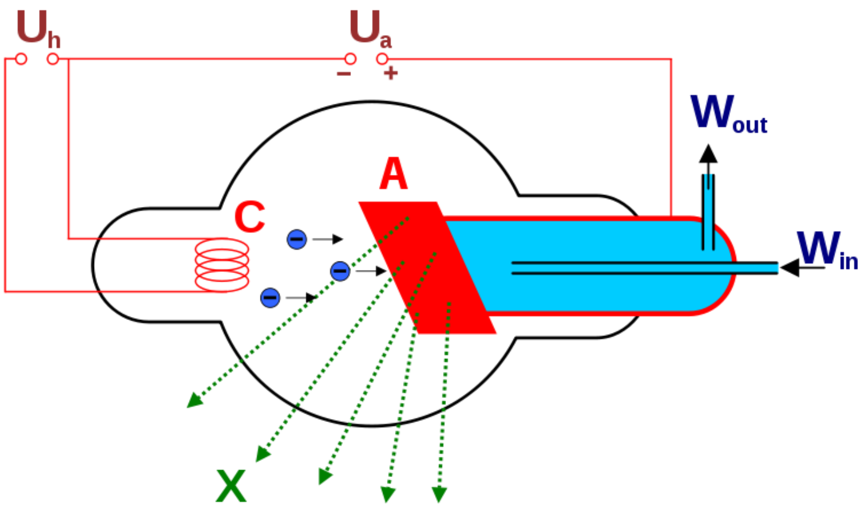
Observations:

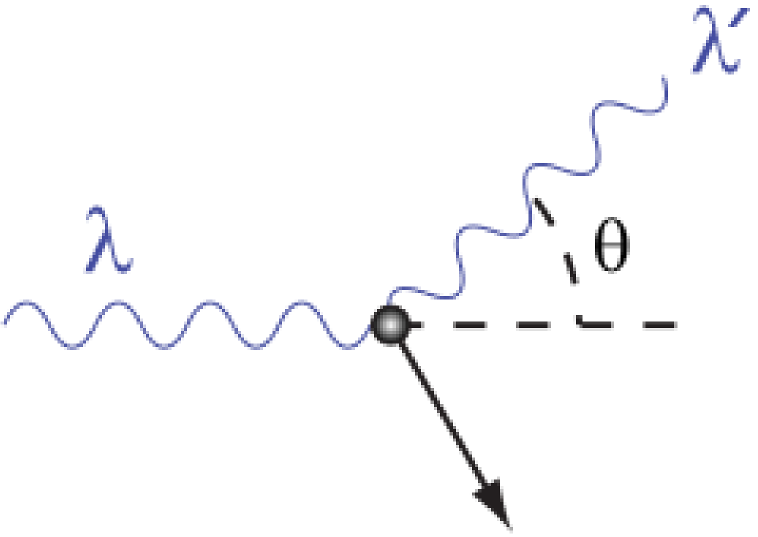
- Classical intensity pattern is built up gradually
- Signals on screen arrive localized in position and time → photons!
- both slits need to be open simultaneously to get classical interference pattern at high intensity
- can not conclude that photon must have passed through one of the two slits
- can not predict where a given photon will arrive on the screen. Just can give probabilities!
- if one measures through which slit photons pass, interference pattern on screen disappears!

Today:

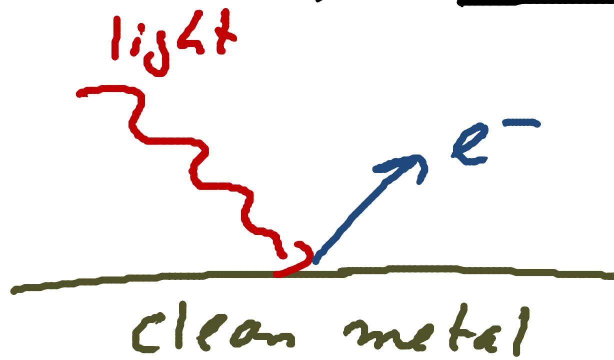
- Enter quantum mechanics:
  - The photoelectric effect
  - Compton scattering
  - X-ray production







Evidence for Photons (2): The Photoelectric Effect



Light energy is used to eject an electron ("photoelectron") from the metal.

Q: How does this photoelectric effect depend on the frequency f and intensity I of the light?

Photoelectric effect: Experiment 1

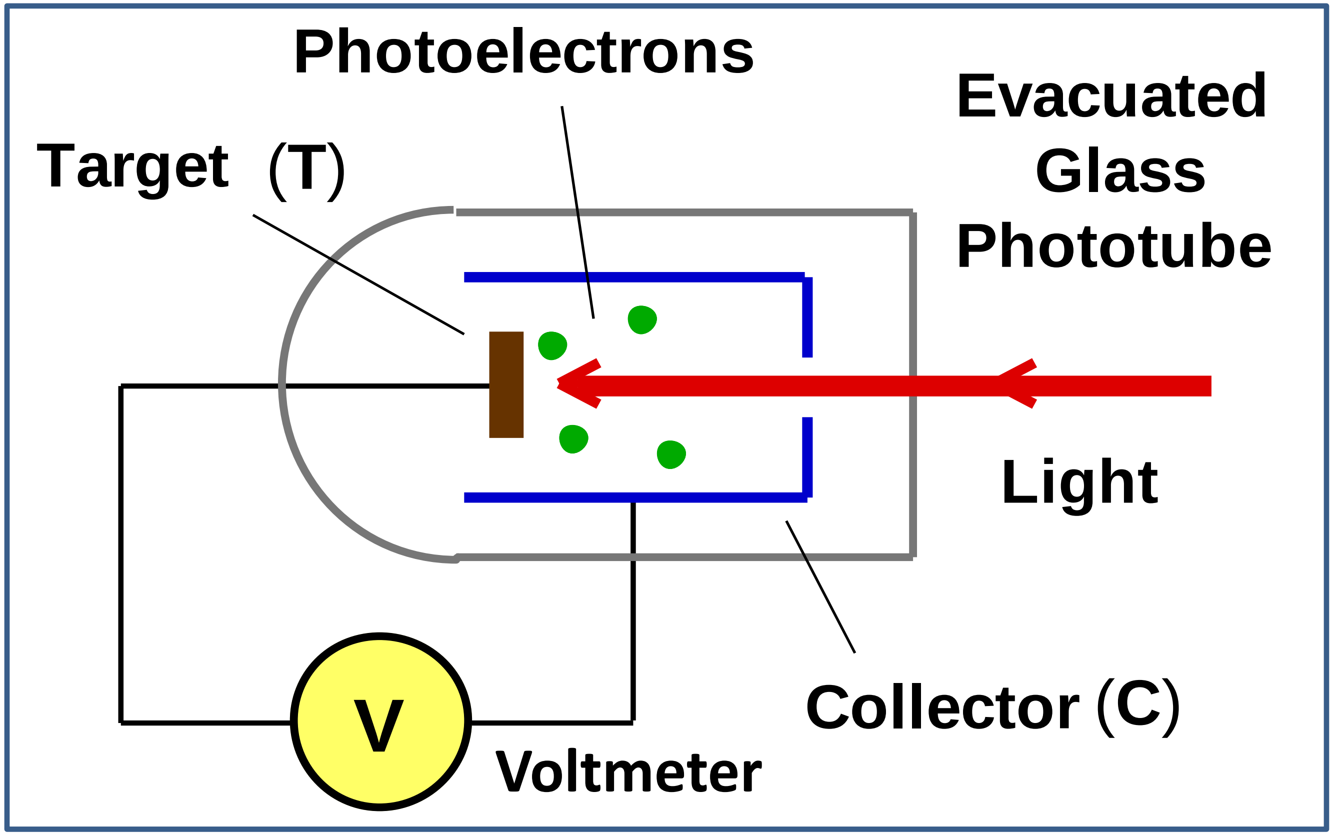
Zink plate connected to electroscope

Observations:

⇒ Effect **depends on the frequency of the light**. Only light of high enough frequency (here: ultraviolet light) produces the effect ⇒ **cutoff frequency**

⇒ Effect is seen **immediately** after the metal is exposed to light.

Photoelectric effect: Experiment 2



Electrons are ejected by the light from the target T and hit the collector C

$\Rightarrow$ T & C charge up like a capacitor

$\Rightarrow$ ΔV_{CT} between T and C

An electron must overcome an electric potential energy barrier in order to go from **T** to **C**:

$$\Delta U = q(V_C - V_T) = -e\Delta V_{CT} > 0$$

Observations:

(1) The T-C capacitor charges up to a final potential $\Delta V_{TC,max} = \Delta V_{stop}$ = stopping potential

$\Rightarrow$ Electrons come off the metal with some maximum kinetic energy $K_{max} = e\Delta V_{stop}$

$\Rightarrow$ charging stops once ΔV_{TC} reaches ΔV_{stop} since electrons no longer reach the collector.

(2) The stopping potential (therefore also K_{max}) is independent of light intensity!

(3) The stopping potential ΔV_{stop} <u>depends</u> on frequency f of the light!

From data:

$$K_{max} = hf - hf_0$$

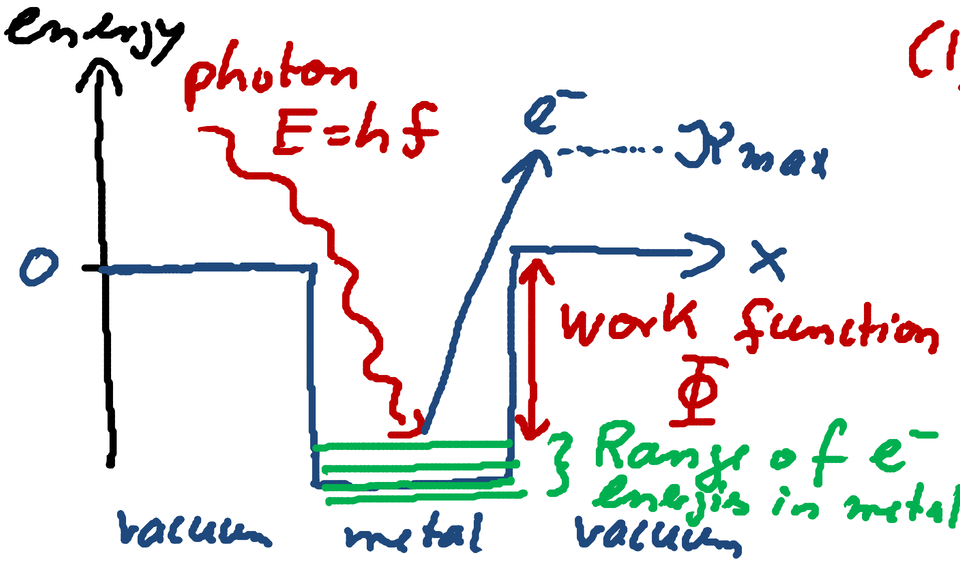
f_0 ← cutoff-frequency (depends on metal)

⇒ for $f < f_0$ there is <u>no</u> photoemission!

(4) Photoemission occurs instantly ($< 10^{-9}$ s), even for very low intensities.

Photoelectric Effect: Quantum Picture

[Einstein 1905; 1921 Nobel Prize in Physics]



(1) Energy of light of frequency f is quantized

Energy of one photon:

$$E_{photon} = hf$$

h ↑ Planck's constant

⇒ visible light: $E_{ph} = 1.8\,eV \ldots 3.1\,eV$

(2) In the photoelectric effect, one photon is completely absorbed by one electron

⇒ gives all of its energy to the electron

(3) It takes a certain minimum energy (work function Φ) to remove an electron from the metal.

$\Rightarrow$ property of the metal

$\Rightarrow$ Examples: $\Phi_{cesium} = 2.1\,eV$

$\Phi_{zinc} = 4.3\,eV$

$\Phi_{gold} = 5.1\,eV$

(4) Apply energy conservation:

$$E_{photon} = hf = K_{max} + \Phi \iff K_{max} = hf - \Phi = hf - hf_0$$

$K_{max} = e\Delta V_{stop}$ $\Phi = hf_0$

⇒ This explains <u>all</u> observations:

- No time lag: one photon → one photoelectron
- K_{max} (and therefore the stopping potential ΔV_{stop}) does <u>not</u> depend on intensity, since $E_{photon} \propto f$, but indep. of intensity.
- K_{max} increases linearly with frequency f
- No photoemission, if $E_{ph} = hf < \Phi$ (i.e. $f < f_0$)

Evidence of Photons (3): The Compton Effect

⇒ Measures dynamics of individual x-ray photon in collision with a (almost) free electron

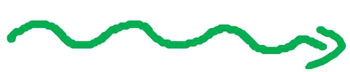
⇒ Key Idea: Photons carry momentum

$$p_{photon} = \frac{E_{photon}}{c} = \frac{hf}{c} = \frac{h}{\lambda}$$

and obey energy and momentum conservation laws!

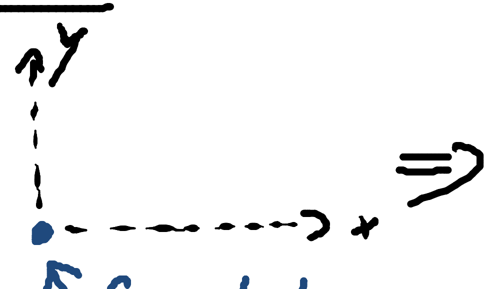
Before collision:

x-ray photon λ



$E_{photon} = hf = \frac{hc}{\lambda}$

$p_{photon} = h/\lambda$



free electron, $v \approx 0$

⇒ $K_{e^-,i} = 0$ (kinetic energy)

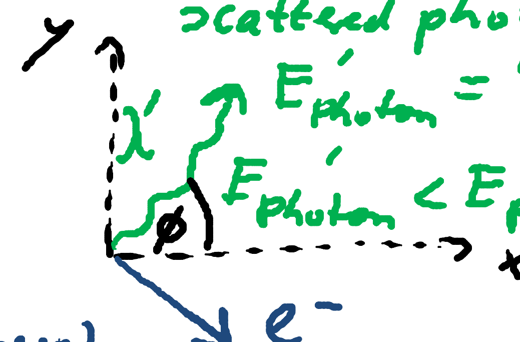
$\vec{p}_{e^-,i} = 0$ (momentum)

After collision:

scattered photon

$E'_{photon} = hc/\lambda'$

$E'_{photon} < E_{photon}$

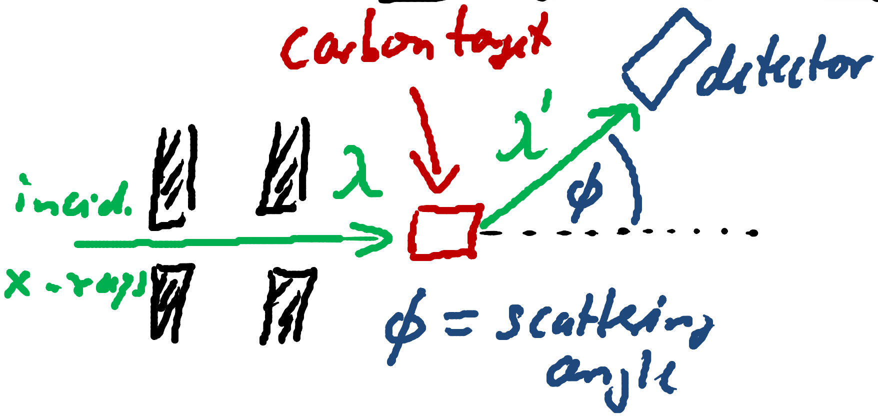


e^-

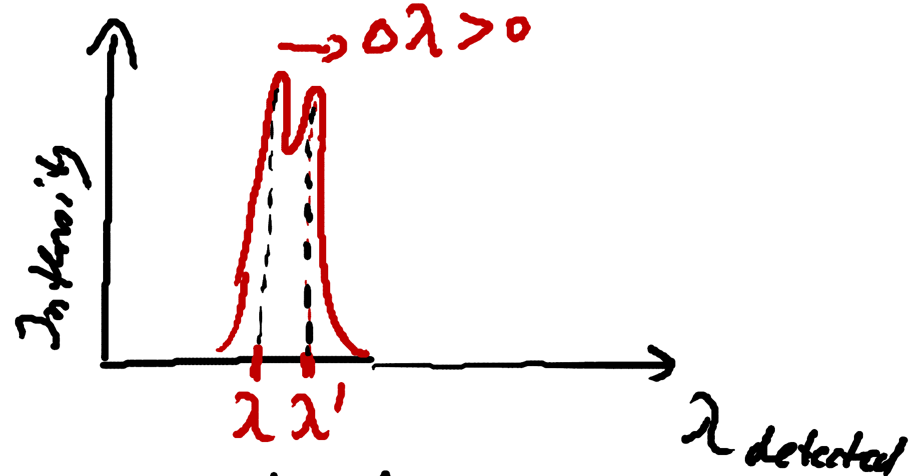
$K_{e^-,f}$

$\vec{p}_{e^-,f}$

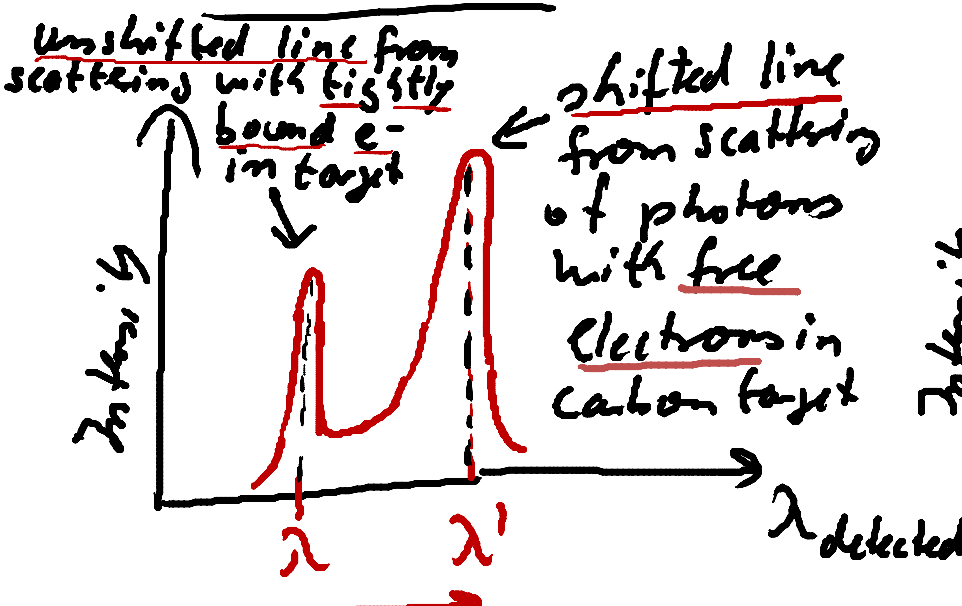
Setup and Results:



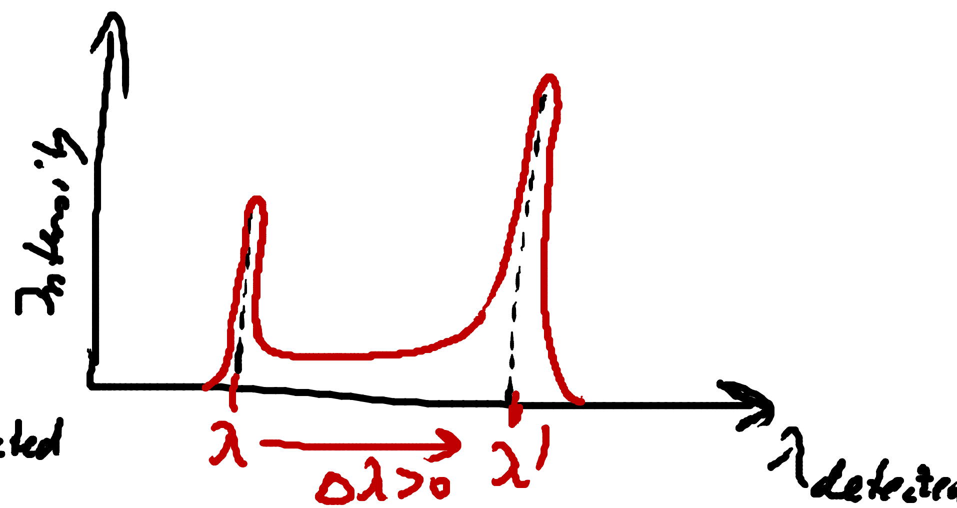
At φ = 45°:



at φ = 90°:



At φ = 135°:



$\Delta\lambda$ = Compton shift ; depends on scattering angle ϕ