PHY127

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Lecture 3
Mar. 10th, 2023

Quiz questions (difficult ones) will be explained in exercise sessions.

Reminder: please participate in weekly quizzes. These kind of questions will be on the exam, so this is a good self-assessment for you.

Reminder from last time:

Intensity of radiation from a hot object

This was solved by Planck.

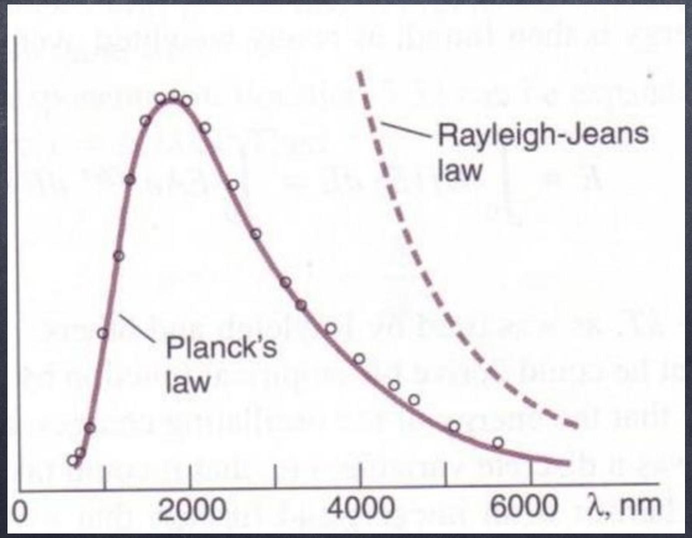
$$\text{Intensity} = I = \frac{2\pi c^2 h}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}$$

k: Boltzmann constant $k = 1.38E{-23}\ J/K$

same as $(pV = nkT)$

h: Planck constant $= h = 6.261\ E{-34}\ J.s$

planck's



Intensity

← classical theory

solution of Planck:
Considers that a blackbody radiates light as if radiation was produced by little harmonic oscillators,
Each one with energy $E = \frac{hc}{\lambda}$

This worked, but no one understood why.

Einstein solved this mystery by realizing that these oscillators were producing quanta of light.

↑

particle

Light is a wave, but it's also made of particles called photons. A photon is massless and always travels at the speed of light. Each photon has a momentum and energy.

But wait! $\bar{p} = m\bar{v}$ & $K = \frac{1}{2}mv^2$

so how do we get energy & momentum for a photon?

If K depends on velocity, how can the photon energy change.

The truth is that $\bar{p} = m\bar{v}$ & $K = \frac{1}{2}mv^2$ are approximations, valid when $v \ll c$, & also these are not true for photons.

The momentum of a photon depends on its frequency & wavelength.

$$\boxed{p = \frac{h\nu}{c}}$$

h = Planck constant

Since $v = \lambda\nu$, so $\nu = \frac{v}{\lambda} = \frac{c}{\lambda}$ for light

so $\boxed{p = \frac{h}{\lambda}}$

this formula relates the particle-like property of <u>momentum</u> with the wave-like property of <u>wavelength</u>

(we will see that this works for particles that behave like waves) (electrons, ...)

Energy of a photon:

You may have heard of $\underbrace{E = mc^2}$

rest energy of a ptcl with mass, m.

But photons are always moving

For any moving particle, the full formula is $E^2 = (mc^2)^2 + (cp)^2$

so if $p=0 \Rightarrow E = mc^2$

For photons of mass $= 0$,

$$E^2 = (\cancelto{0}{mc^2})^2 + (cp)^2 = (cp)^2$$

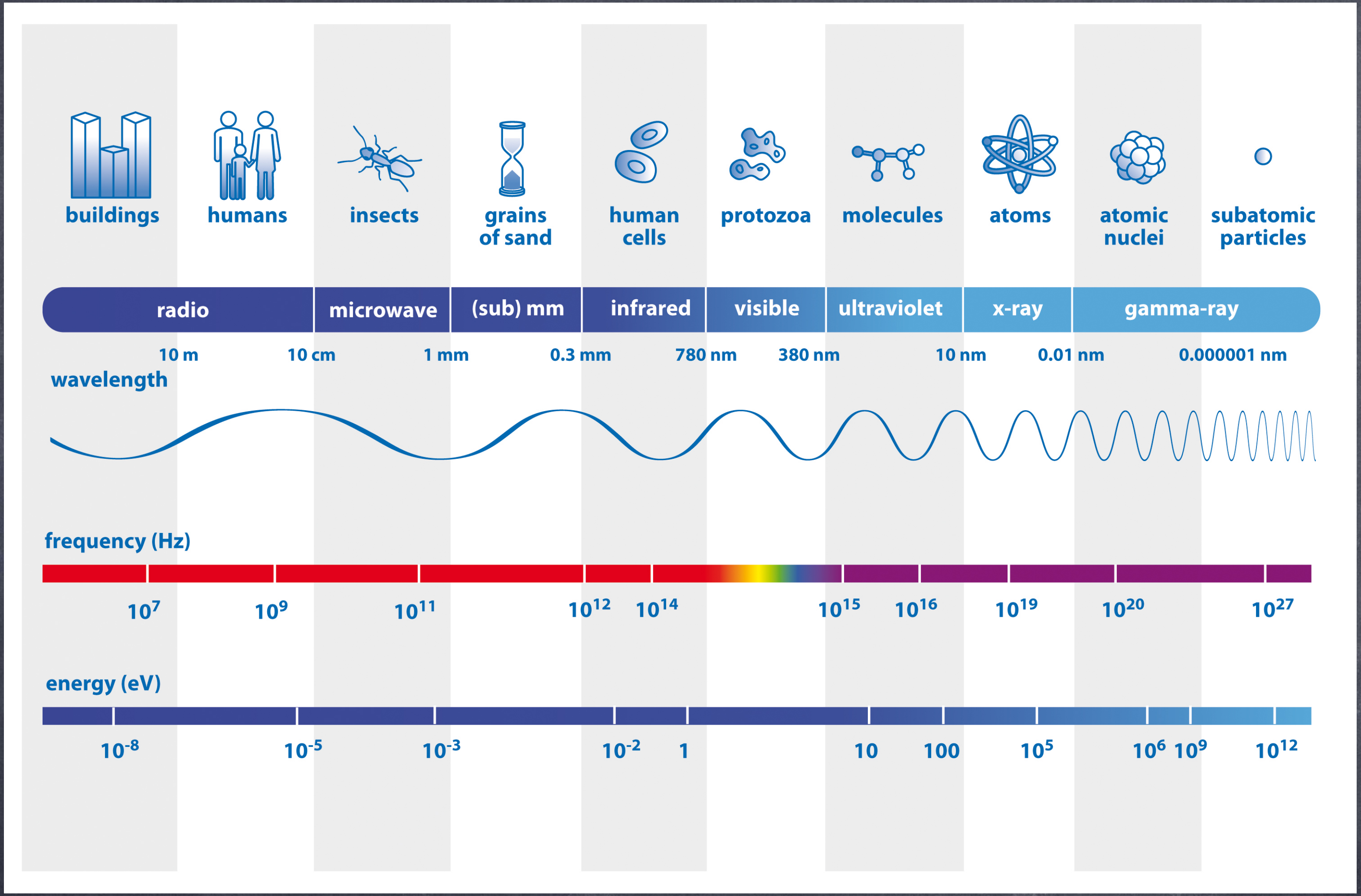
$$\boxed{E = cp} \leftarrow \text{formulas for light} \rightarrow \boxed{E = \frac{hc}{\lambda}}$$

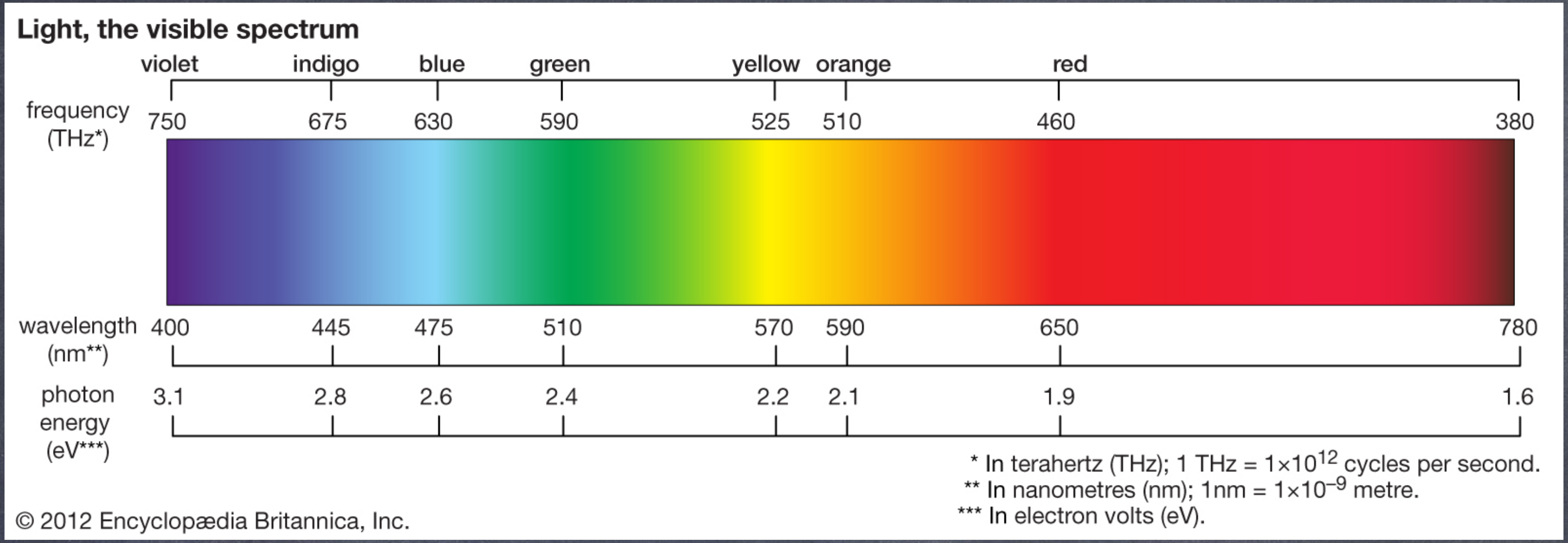
photons

$$E = cp = c\left(\frac{h\nu}{c}\right) = h\nu \qquad \boxed{E = h\nu}$$

Figure: relates ν, λ, ϵ for light

energy →





Light, the visible spectrum

* In terahertz (THz); 1 THz = 1×10^{12} cycles per second.
** In nanometres (nm); 1nm = 1×10^{-9} metre.
*** In electron volts (eV).

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Note: energies of visible light are 1.6 - 3.1 eV

Can be produced with 2 AA batteries in series :

Today, we will investigate the wave-particle duality of the photon. We will start with some experiments.

(+ charge means we removed electrons)

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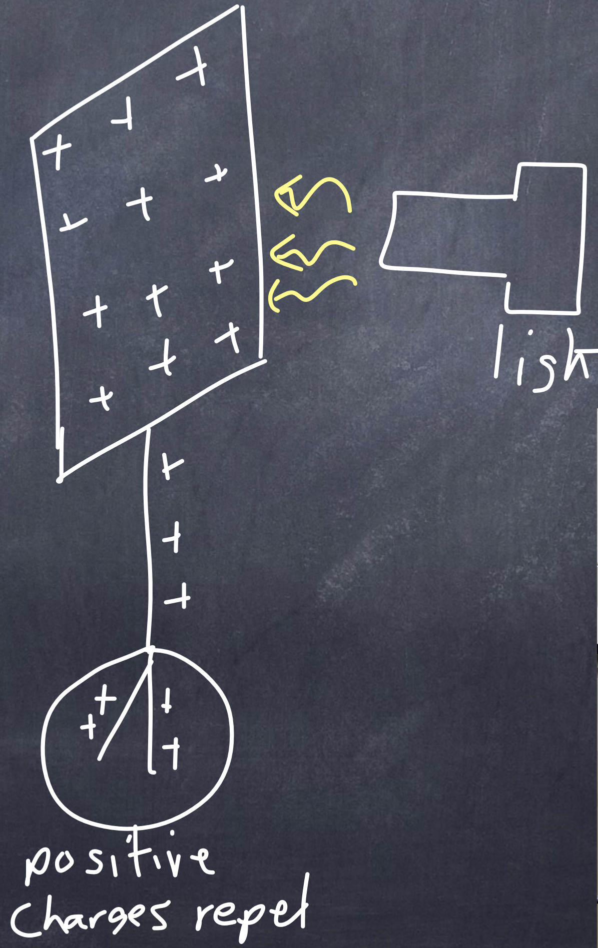
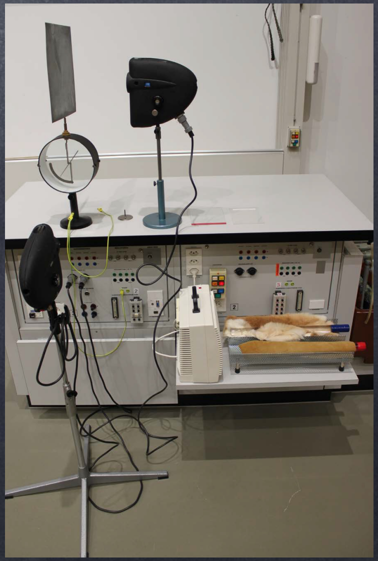
Experiment 1



electrometer measures electric potential, (V)



conclusions:

1) negative charges can be ejected by light.
2) positive charges are not ejected.

Electrons are attracted to a positively charged surfac

3) By stopping ultraviolet light with glass, we stop negatively charged ptcls from escaping.
Seems to indicate an energy dependence.

$$E_{uv} > E_{visible}$$

4) Rate of emission of electrons increases with intensity of light.

we check further experiments using the following Setup :

(Figures from Thornton + Rex "Modern physics" PDF online)

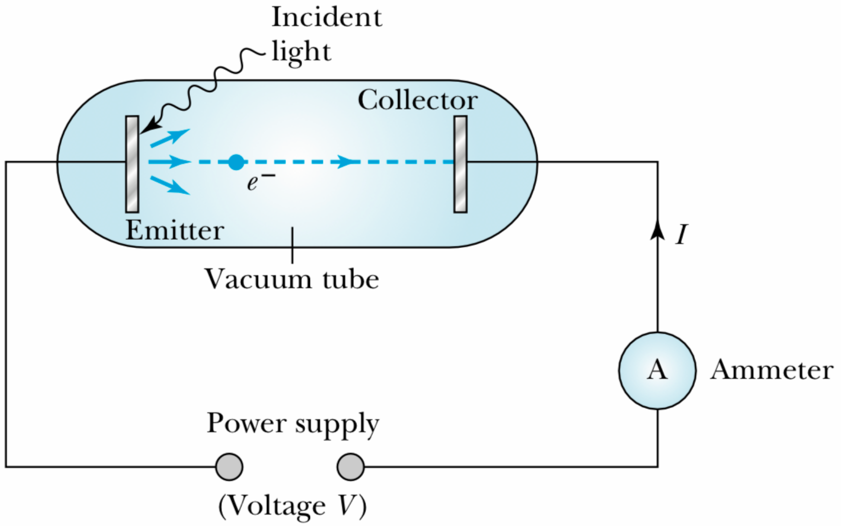


Figure 3.11 Photoelectric effect. Electrons emitted when light shines on a surface are collected, and the photocurrent I is measured. A negative voltage, relative to that of the emitter, can be applied to the collector. When this retarding voltage is sufficiently large, the emitted electrons are repelled, and the current to the collector drops to zero.

we can change voltage (V) to stop electrons, or change frequency of light (ν), or change intensity of light ($\mathcal{I}$). And we can measure current (I) of electrons produced by light.

The next sets of results come from this setup.

IF we set the collector voltage (anode voltage) to a $\oplus$ value, electrons will be attracted

Electrons would gain an energy of $U = eV$ as they travel to anode.

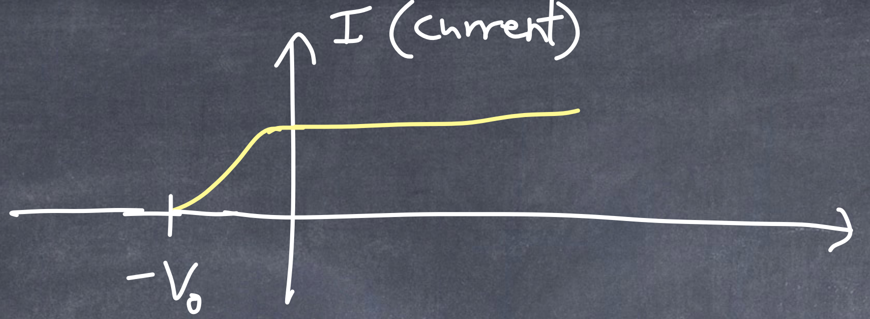
If we set the collector voltage to a $\ominus$ value, electrons would lose an energy of $U = eV$

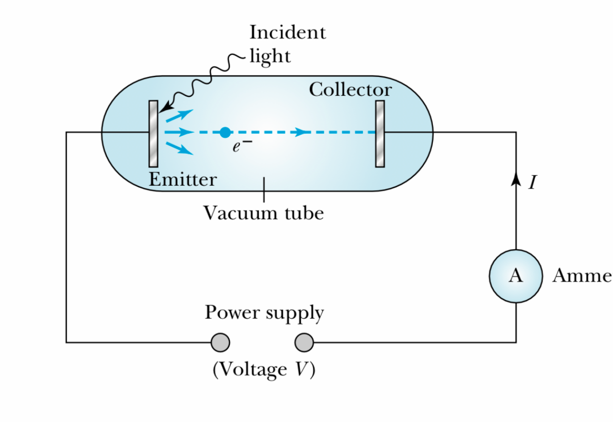
Experiment 2

ν: constant

$\mathcal{I}$: constant

Here we change Voltage, V, & measure current I.





As the voltage gets more negative, current decreases because the electrons are repelled. Below a value of $-V_0$, no current is produced.

V_0 is known as the stopping voltage. (by convention, it is a positive value.)

V_0 is related to the maximum kinetic energy of the electrons.

$$\left(\frac{1}{2}mv^2\right)_{max} = eV_0$$

(Kinetic energy) = (potential energy needed to stop the fastest electrons)

Experiment 3

we repeat experiment 2, but try it for different light intensities.

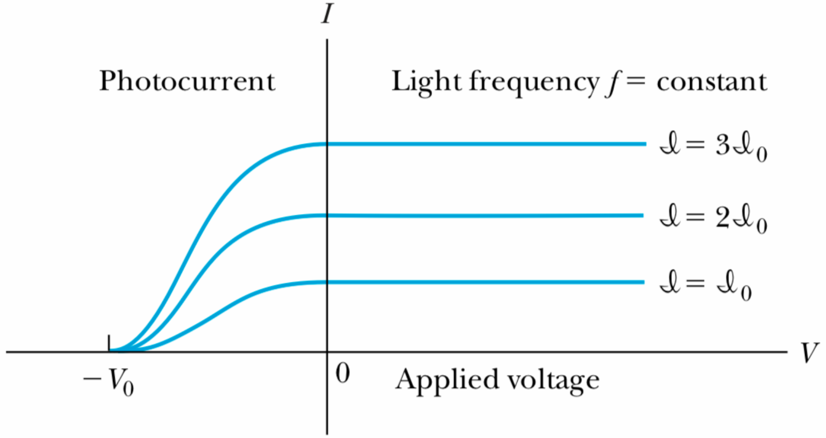


Figure 3.12 The photoelectric current I is shown as a function of the voltage V applied between the emitter and collector for a given frequency f of light for three different light intensities. Notice that no current flows for a retarding potential more negative than $-V_0$ and that the photocurrent is constant for potentials near or above zero (this assumes that the emitter and collector are closely spaced or in spherical geometry to avoid loss of photoelectrons).

The electric current increases with intensity of light.
But V_0 stays the same.

Experiment 4

$f = \nu$ (frequency)

we repeat expt. 2, but try it for different frequencies of light.

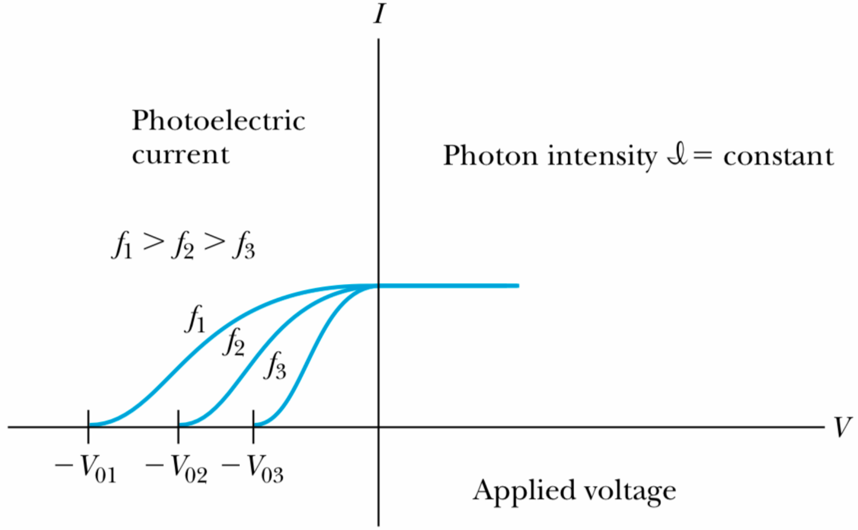


Figure 3.13 The photoelectric current I is shown as a function of applied voltage for three different light frequencies. The retarding potential $-V_0$ is different for each f and is more negative for larger f.

If we increase the frequency of light, then we need a more negative V_0 to stop the fastest electrons from reaching the collector.

$\Rightarrow$ Higher frequency light gives electrons more energy.

Experiment 5)

Here we measure electric current when we change light intensity.

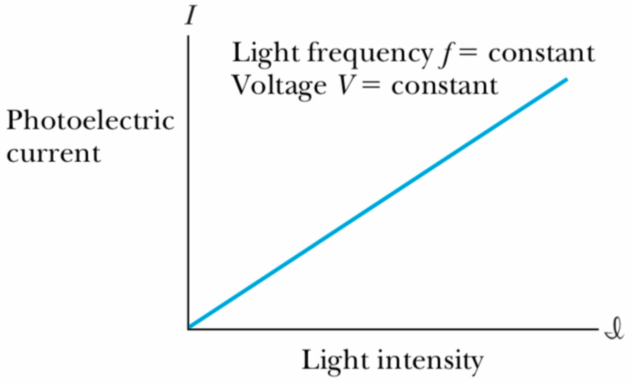


Figure 3.15 The photoelectric current I is a linear function of the light intensity for a constant f and V.

Current is proportional to light intensity.

Experiment 6

Here we measure how much voltage is necessary to stop light of different frequencies. We do this for different materials.

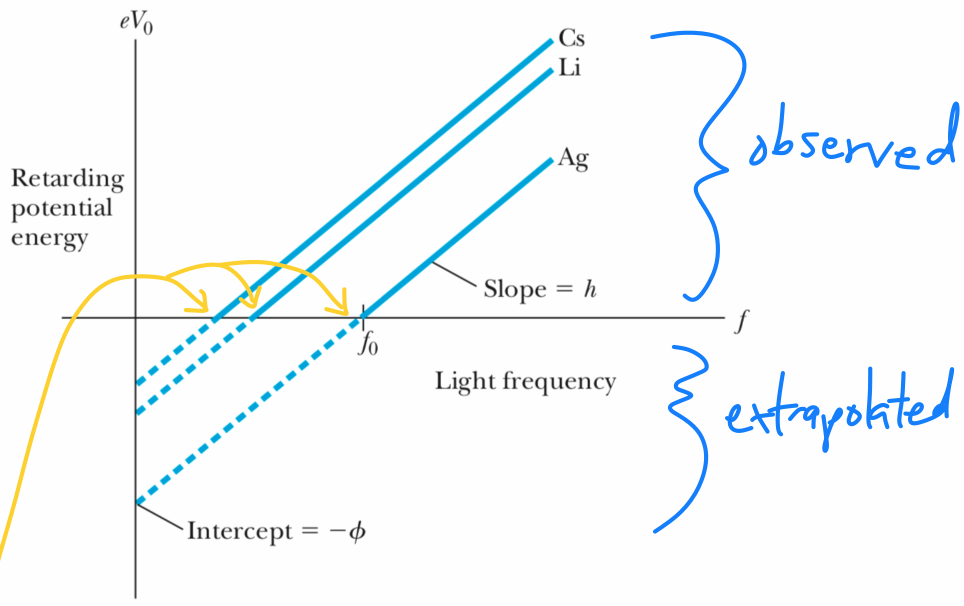


Figure 3.14 The retarding potential energy eV_0 (maximum electron kinetic energy) is plotted versus light frequency for three emitter materials.

The stopping voltage required is higher for higher frequency light.

There is a minimum frequency required to produce photo electrons!

Different materials have the same slope, but different intercepts.

Formula for a straight line:

$$y = \overset{\uparrow}{m}x + \overset{\uparrow}{b}$$

slope intercept

$$\underbrace{eV_0}_{\text{y-axis}} = \overbrace{(\text{slope})\,\underbrace{\nu}_{\text{frequency}}}^{\text{energy of photons} = h\nu} - \phi \leftarrow \text{binding energy of mater}$$

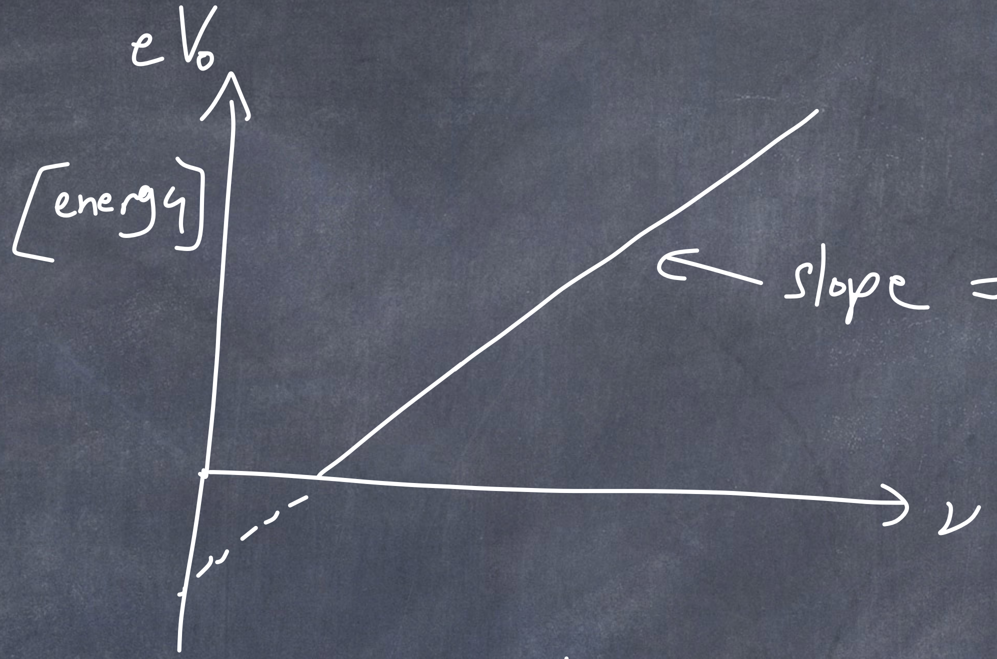
energy to stop electrons

slope ↑ h

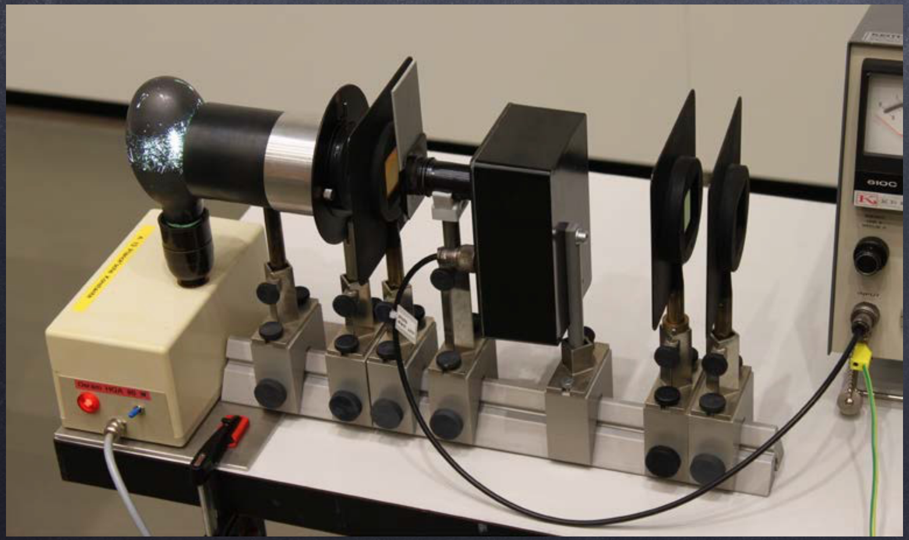
φ ↑ intercept

work function of material, φ

Experiment 7: We measure Planck constant, h.



The actual answer $h \equiv 4.1357 \text{ E-}15 \; \underbrace{eV \cdot s}_{[\text{energy} * \text{time}]}$



what we understand from the experiments :

Energy conservation : energy before ≡ energy after

Energy before = Energy after
(photon) (electron absorbs photon)

$$h\nu = \underset{\substack{\text{binding}\\ \text{energy}\\ \text{of material}}}{\phi} + \underset{\substack{\text{kinetic}\\ \text{energy}\\ \text{of electron}}}{K}$$

The minimum stopping voltage (potential) is the energy of the photon minus the ϕ (work function)

$$\boxed{eV_0 = \left(\frac{1}{2}mv^2\right)_{max} = h\nu - \phi} \quad ①$$

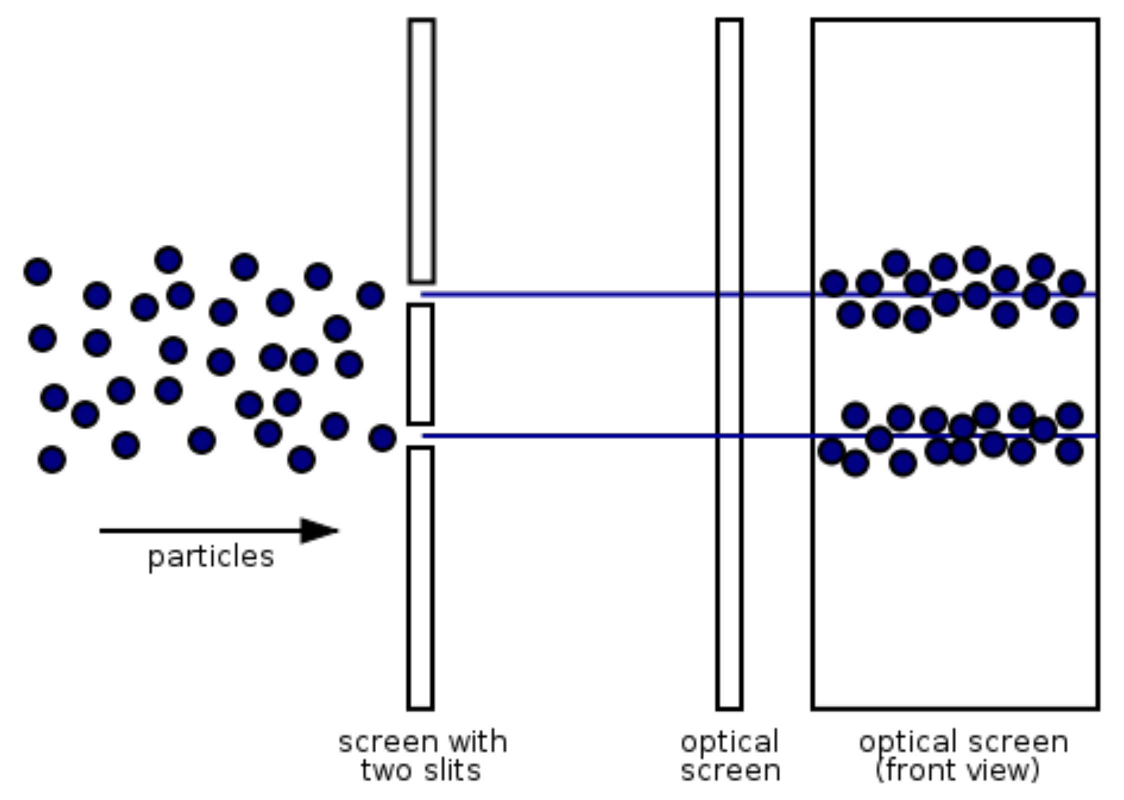
Note: V_0 + ϕ are positive numbers by convention.

Einstein figured out eq. ① in 1905 from available data. Big changes :

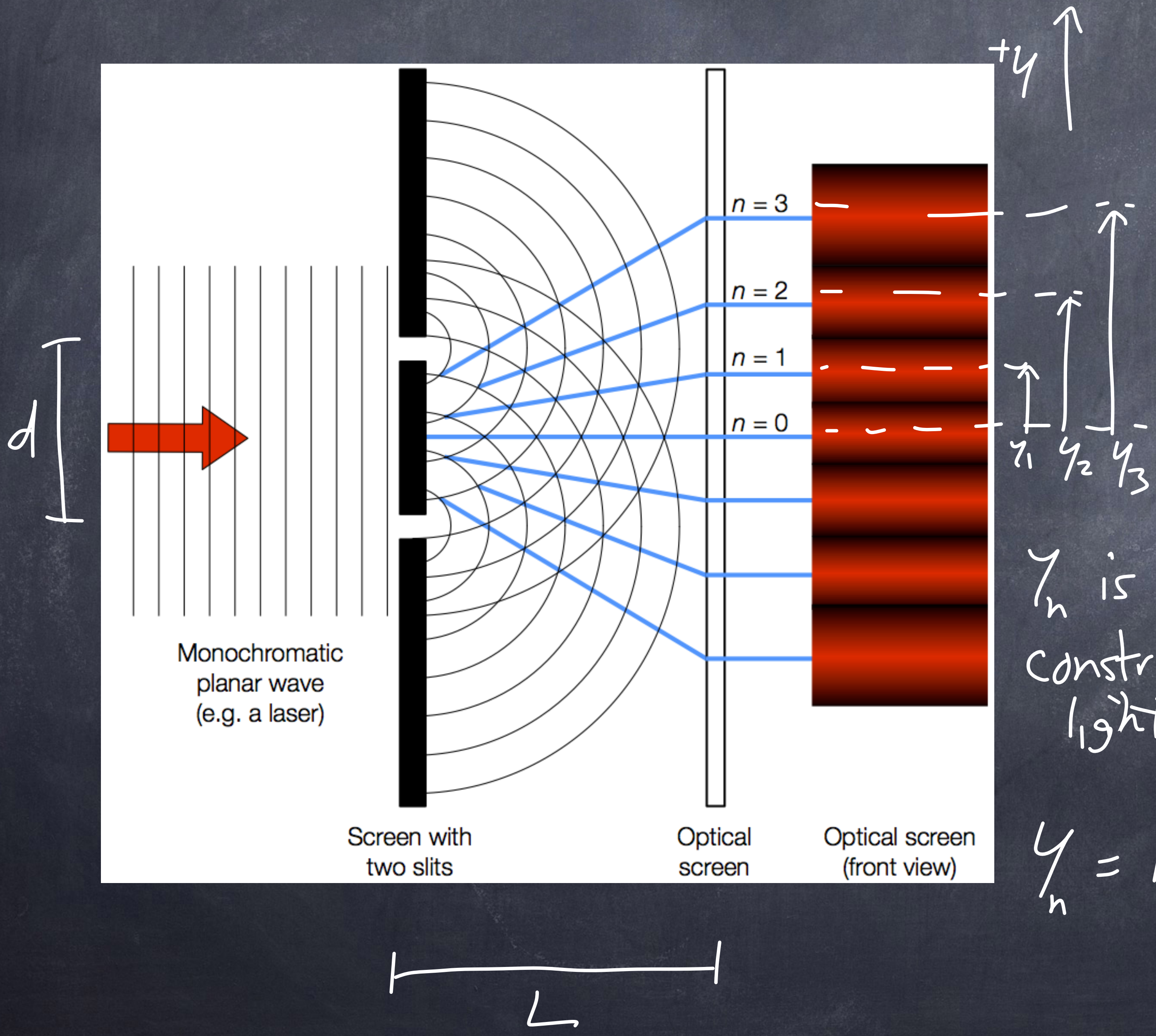
- → Light is made of photons, each with energy, $E = h\nu$.
- → Photons are particles.

⟶ It gets more crazy.

Particles (here, balls) pass through a screen with two slits, + produce two bunches of particles.



But light is an electromagnetic wave, which exhibits interference.



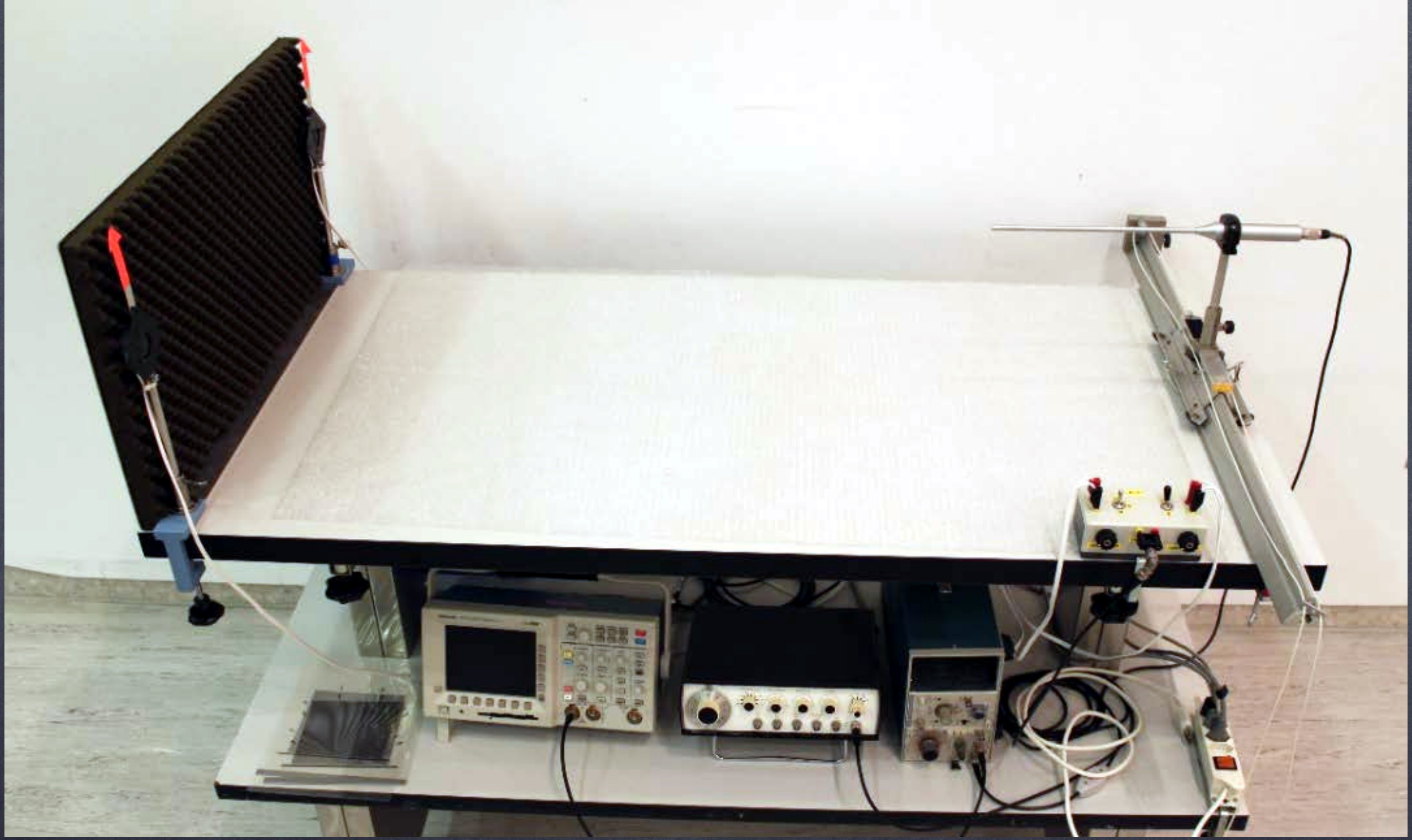
y_n is the location of constructive interference of light.

$$y_n = \frac{n\lambda L}{d}$$

$n = 1, 2, 3, \ldots$
$-1, -2, -3, \ldots$

Experiment 8

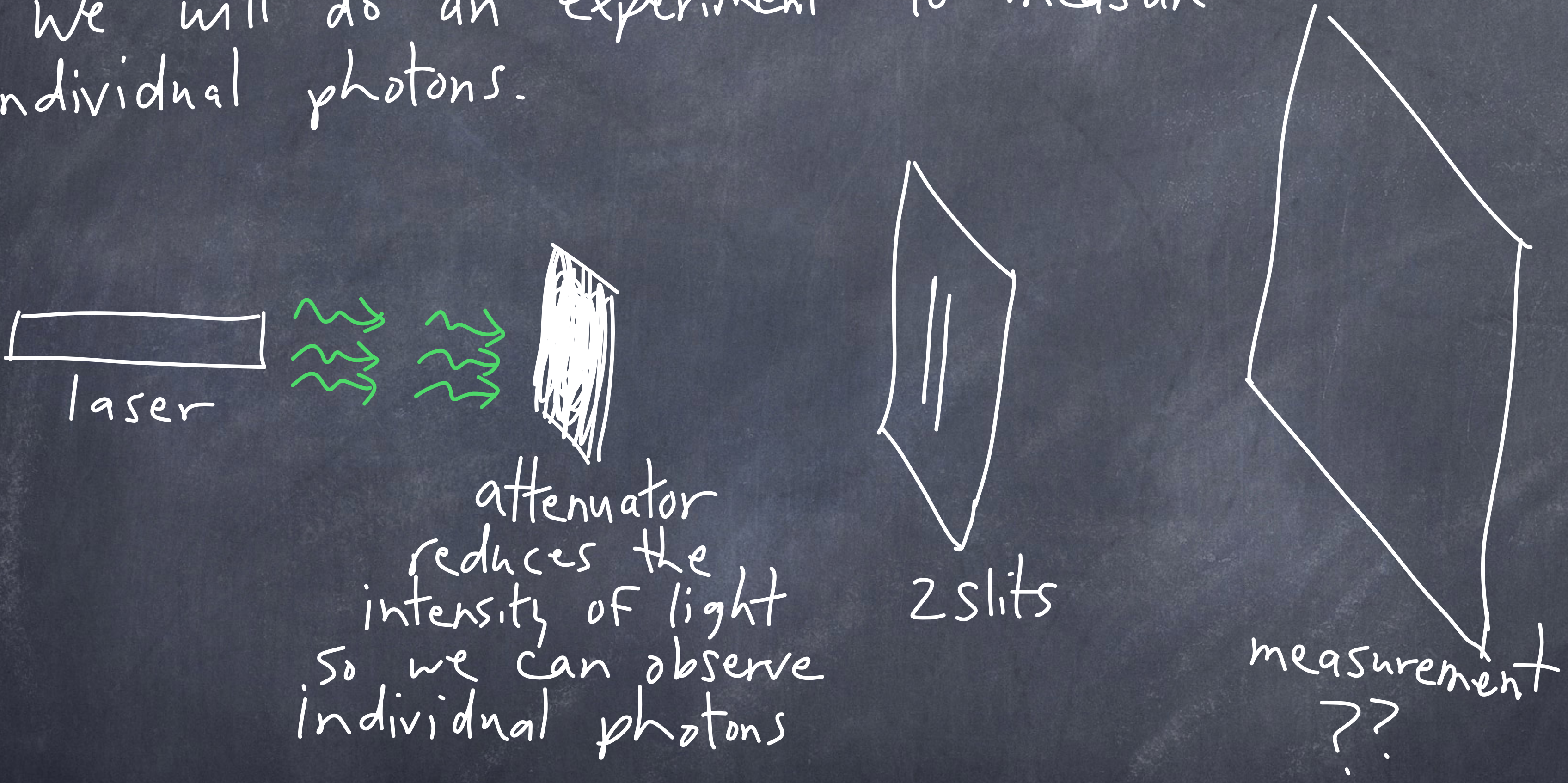
Demonstration of interference of waves using sound waves.



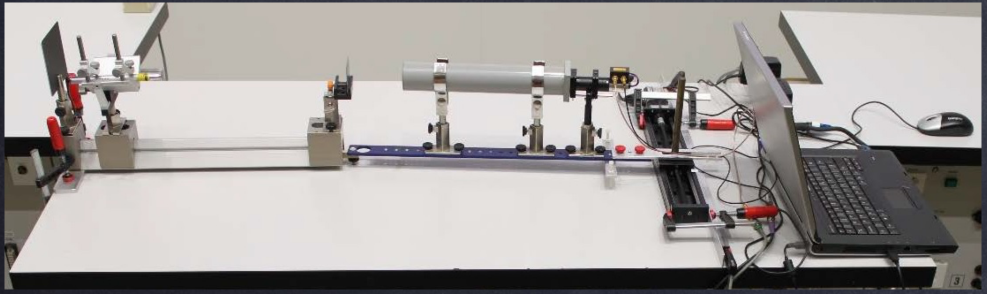
Experiment 9

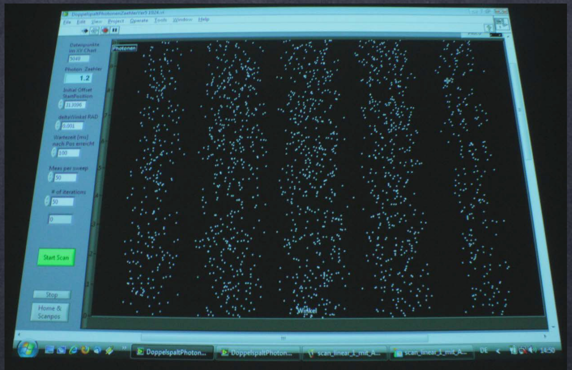
But what about photons? Are they particles?

we will do an experiment to measure individual photons.



attenuator reduces the intensity of light so we can observe individual photons



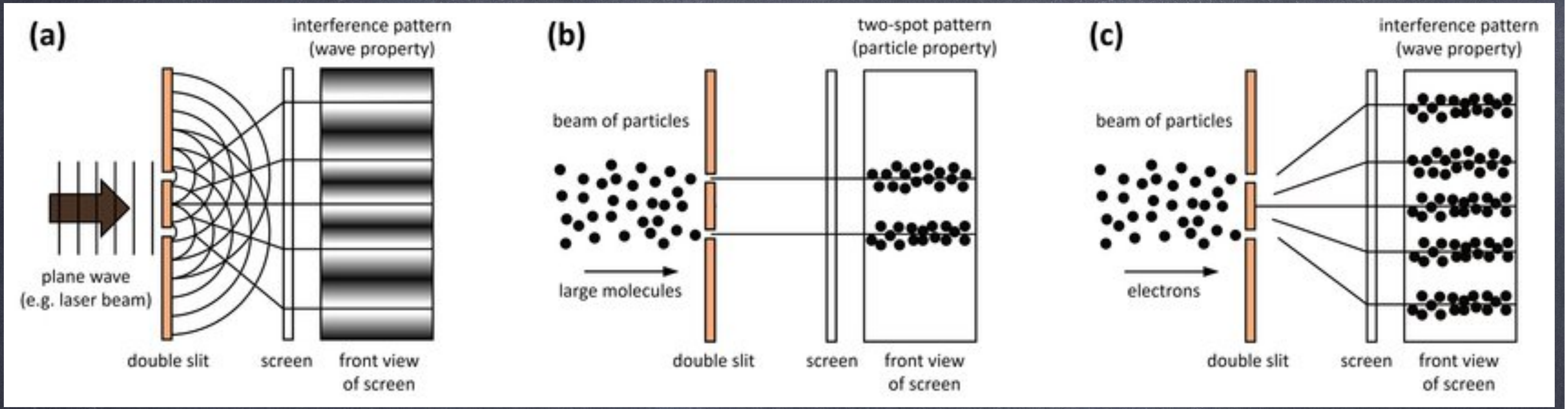


we observe that particles (photons) create an interference pattern!!

waves:

particles:

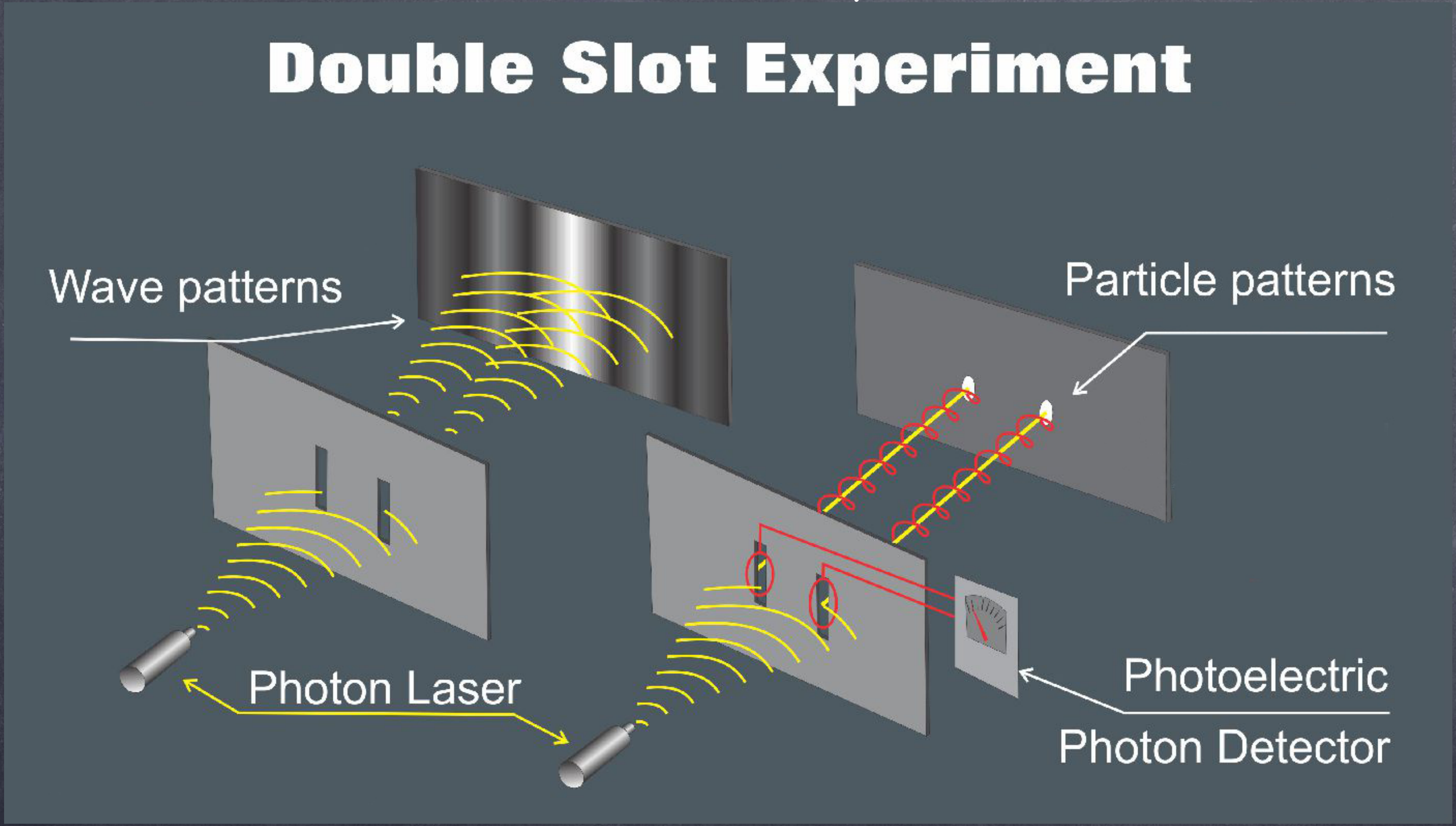
photons



A particle goes through only one slit.
But a wave can go through both at the same time
+ create an inteference pattern.
A photon is a particle, that behaves like it has a wave.

Explanation: quantum physics. the photon has a probability of going through both slits.

The strange thing is that if we measure which slit the photons go through, the interference pattern will disappear.



This means that the act of measuring the photon changes it to become a particle instead of a wave.
A wave has a location represented as a probability.
Measuring the photon collapses the probability to a single point.