Quantum Hypothesis

Quantization of EM Waves

In 1905, Einstein proposed that the energy of an electromagnetic wave is carried by discrete units (particles) called **photons** whose energy depends on the frequency, *f*, of the EM wave. This hypothesis forms the basis for the explanation of the **Photoelectric Effect**.

Energy of a photon : $E = hf$,

Where h is Planck's constant = 6.626 x 10-34 J s.

The electron volt

An electron volt is the amount of energy associated with accelerating an electron through a potential difference of 1 V. Photons of visible light where 400nm ≤ λ ≤ 700nm have energies in the order of an eV. 1 eV = 1.60 x 10^{-19} J

Use $c = f\lambda$ and $E = hf$, we can determine the frequency ($f = c/\lambda$) and energy for photons ($E = hc/\lambda$ (in J) = $hc/e\lambda$ (in eV)) in the visible spectrum (i.e., 400nm<λ<700nm).

Wavelength	Frequency	Energy
400 nm (violet)	7.5 × 10^{14} Hz	3.1 eV
700 nm (red)	4.3 × 10^{14} Hz	1.8 eV

The Photoelectric Effect

In 1921, Einstein won the Nobel Prize for Physics not for his work on relativity, but for explaining the photoelectric effect.

The photoelectric effect occurs when light shines on a metal – this may enable the electrons to overcome the work function, W_0 of the metal and be emitted.

This is closely related to how solar panels generate electricity.

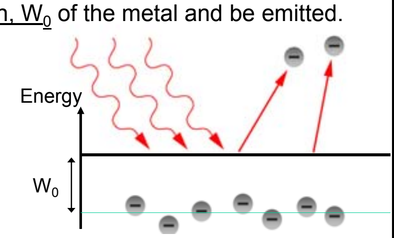

Figure modified from Wikipedia

Two competing models

The wave theory – electromagnetic waves interact with the electrons in the metal. These waves transfer energy to the electrons.

The particle theory – light can be thought of as particles, called photons. We can analyze the photoelectric effect in terms of individual photons interacting with individual electrons.

Two competing models

Prediction	Wave model?	Particle model?
Light of any frequency will cause electrons to be emitted if one waits long enough for sufficient energy to be absorbed by the metal to overcome the work function, W_0.	Yes	No
If the frequency is below W, no electrons will be emitted.	No	Yes
↑ the intensity of the light ↑ the kinetic energy of the emitted electrons.	Yes	No
↑ the intensity of the light ↑ the number of photons and hence the number of electrons emitted, but not the electrons' maximum kinetic energy.	No	Yes

Actual Observations

Prediction	Wave model?	Particle model?
~~Light of any frequency will cause electrons to be emitted if one waits long enough for sufficient energy to be absorbed by the metal to overcome the work function, W_0.~~	Yes	No
If the frequency is below W, no electrons will be emitted.	No	Yes
~~↑ the intensity of the light ↑ the kinetic energy of the emitted electrons.~~	Yes	No
↑ the intensity of the light ↑ the number of photons and hence the number of electrons emitted, but not the electrons' maximum kinetic energy.	No	Yes

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The photoelectric effect

Applying energy conservation, the energy of the photon goes into liberating the electron from the metal (an energy of at least the work function of the metal), and whatever energy is left takes the form of the electron's kinetic energy.

$$hf = W_0 + K_{max}$$

Simulation

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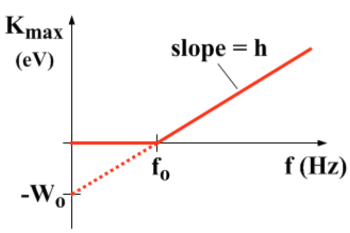
The photoelectric effect – a graph

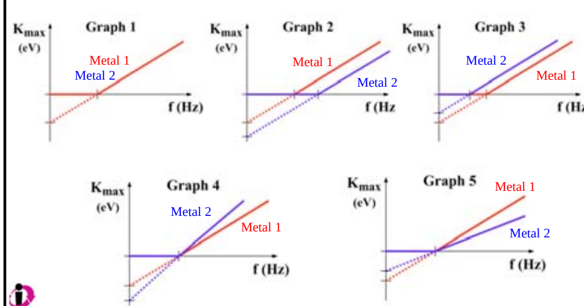
A graph of K_{max} vs. photon frequency gives a line with a slope of Planck's constant, a y-intercept equal to the negative of the work function, and an x-intercept of the threshold frequency.

$$hf = W_0 + K_{max}$$
$$K_{max} = hf - W_0$$



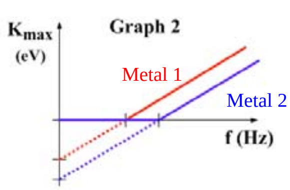
Which graph?

Which graph shows that metal 2 has a larger work function than metal 1?



Which graph?

All such graphs should have the same slope, because the slope is Planck's constant. Increasing the work function means you have to go to higher frequency light before electrons are emitted, and that the y-intercept is more negative.



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Changing frequency

We shine a red laser on a metal surface. The energy of the photons is larger than the work function of the metal, so electrons are emitted. Let's say N photons are incident on the surface per second, and N electrons are emitted every second. If we replace the red laser with a green laser of exactly the same intensity, how many electrons are emitted every second?

1. N
2. more than N
3. less than N
4. We don't even know if any electrons are emitted - that depends on whether the energy of the photons from the green laser exceeds the work function of the metal.

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Changing frequency

Green light has a shorter wavelength, and a higher frequency, than red light, so a green photon has more energy than a red photon. That rules out choice 4. Also, if the intensities are the same, the green laser beam has fewer photons per second than the red laser beam, so fewer electrons are emitted per second. The electrons come off with more kinetic energy, however.

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Wave-particle duality

Light exhibits both wave-like behavior and particle-like behavior.

Some experiments (double-slit, thin films) can be explained in terms of light acting as a wave.

Some experiments (photoelectric effect, and others) can be explained in terms of light acting as a particle.

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Sample problem

Iron has a work function of 4.50 eV.

(a) What is the minimum frequency of light necessary to cause electrons to be ejected from an iron plate?

(b) Is this in the visible spectrum?

(c) If the iron plate is exposed to light with a frequency of 1.50 x 10^{15} Hz, what is the maximum kinetic energy of the ejected electrons?

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Sample problem

Iron has a work function of 4.50 eV.

(a) What is the minimum frequency of light necessary to cause electrons to be ejected from an iron plate?

The minimum frequency is when the photon energy exactly matches the work function: $hf_{\min} = W_0$

$$f_{\min} = \frac{W_0}{h} = \frac{(4.50\text{ eV})(1.60\times10^{-19}\text{ J/eV})}{6.63\times10^{-34}\text{ J s}} = 1.09\times10^{15}\text{ Hz}$$

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Sample problem

$$f_{\min} = \frac{W_0}{h} = \frac{(4.50\text{ eV})(1.60\times10^{-19}\text{ J/eV})}{6.63\times10^{-34}\text{ J s}} = 1.09\times10^{15}\text{ Hz}$$

(b) Is this in the visible spectrum?

Let's find the corresponding wavelength.

$$\lambda = \frac{c}{f_{\min}} = \frac{3.00\times10^{8}\text{ m/s}}{1.09\times10^{15}\text{ Hz}} = 2.76\times10^{-7}\text{ m} = 276\text{ nm}$$

The smallest wavelength in the visible spectrum is 400 nm, so this is ultraviolet light.

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Sample problem

(c) If the iron plate is exposed to light with a frequency of 1.50 x 10^{15} Hz, what is the maximum kinetic energy of the ejected electrons?

$$K_{\max} = hf - W_0$$

$$= \frac{(6.63\times10^{-34}\text{ J s})\times(1.50\times10^{15}\text{ Hz})}{1.60\times10^{-19}\text{ J/eV}} - 4.50\text{ eV}$$

$$= 6.22\text{ eV} - 4.50\text{ eV}$$

$$= 1.72\text{ eV} \qquad (\text{or } 2.75\times10^{-19}\text{ J})$$

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