

The Photoelectric Effect

This topic is so important, it deserves its own note set.

In 1887, Heinrich Hertz discovered that certain metals emit electrons when light is incident on them. This was the first instance of light interacting with matter, so it was very mysterious. In 1905 Albert Einstein, a 3rd Class Technical Expert in the Swiss Patent Office and a bureaucrat, published a paper which provided the explanation for the effect - light is made up of small particles.

Surface electrons are bound to metals with a small amount of energy. Some of the incident photons enter the surface, collide with atoms of the metal and are totally absorbed. They give their energy to an electron, which, if the absorbed energy was great enough, then break free from the atom. The photoelectric effect is the result of collisions between photons and electrons that knock the electrons out of the metal.

ϕ = **work function**: amount of energy binding the electron to the metal

Recall that $E=hf$ gives the energy of the photon.

The electron that gets kicked out of the metal gets its energy from that photon. Some of the energy is used to break the electron from the metal (that's ϕ).

Metal	ϕ (eV)
Sodium	2.28
Zinc	4.31
Cobalt	3.90
Silver	4.73
Platinum	6.35

$$KE_{\max} = hf - \phi$$

Exercise

Calculate the maximum kinetic energy of an electron ejected from silver by a $3.13 \cdot 10^{15}$ Hz photon.

$$KE_{\max} = hf - \phi$$

$$KE_{\max} = 4.14 \cdot 10^{-15} \text{ eVs} \cdot 3.13 \cdot 10^{15} \text{ Hz} - 4.73 \text{ eV}$$

$$KE_{\max} = 8.22 \text{ eV}$$

Wavelength and the Photoelectric Effect

We have related the ejected electron's kinetic energy to the frequency, but physicists prefer using wavelength instead of frequency.

$$v = f\lambda$$

$$f = v / \lambda$$

$$E = hf$$

$$E = hc / \lambda$$

$$KE_{\max} = (hc / \lambda) - \phi$$

I think they meant to use the
greek symbol nu here (for
frequency) instead of v

You have to remember that $\cancel{v} = f = v / \lambda$ if you see wavelength on the test.

Intensity is a measure of how many photons are incident on the surface in a given amount of time. If the frequency is large enough and you **increase the intensity, the current increases** because there will be more electrons ejected.

If light shining on the metal has **too low a frequency, nothing will happen**, no matter how bright it is.

The KE of the electrons is independent of the intensity of the light. More intense light will dislodge more electrons, so the current will increase, but the kinetic energy of the electrons will all be limited to the same value (the maximum kinetic energy).

Exercise

Calculate the maximum KE and velocity of an electron ejected from zinc by a 275nm photon.

$$KE_{\max} = (hc / \lambda) - \phi$$
$$KE_{\max} = (4.14 \cdot 10^{-15} \text{eVs} \cdot 3 \cdot 10^8 \text{m/s} / 275 \cdot 10^{-9} \text{m}) - 4.31 \text{eV}$$
$$KE_{\max} = 0.2 \text{eV}$$

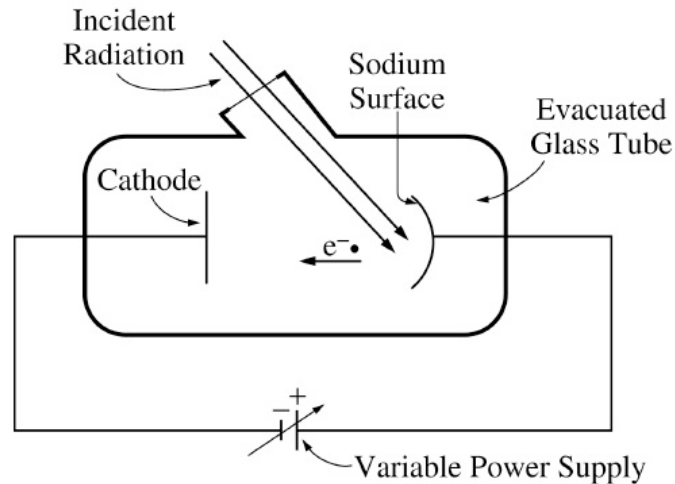
$$0.2 \text{eV} \cdot (1 \text{Joule} / 6.24 \cdot 10^{18} \text{eV}) = 3.2 \cdot 10^{-20} \text{J}$$

$$KE = \frac{1}{2}mv^2$$
$$v = 2KE / m$$

$$v = 2 \cdot 3.2 \cdot 10^{-20} \text{J} / 9.11 \cdot 10^{-31} \text{kg}$$

$$v = 2.65 \cdot 10^5 \text{m/s}$$

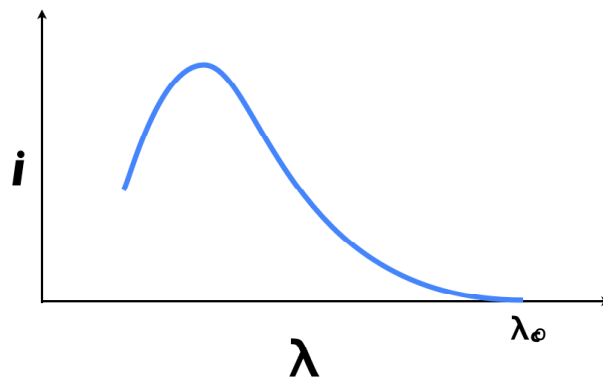
Experimental Setup



A typical setup for a photoelectric experiment consists of a metal plate on which light shines. This plate is called the emitter (sodium in the diagram). Across from the emitter is a plate called the cathode (or collector). The emitter is connected to the negative terminal of a variable dc voltage source, and the collector is connected to the positive terminal.

Light strikes the emitter, which causes photoelectric electrons to be emitted. The electrons are attracted to the positively charged cathode and a current is established. One measures the current and voltage.

If the **wavelength** of the incident light is varied, but the intensity of the light is kept constant, then we get a graph of current VS. wavelength that looks like this:



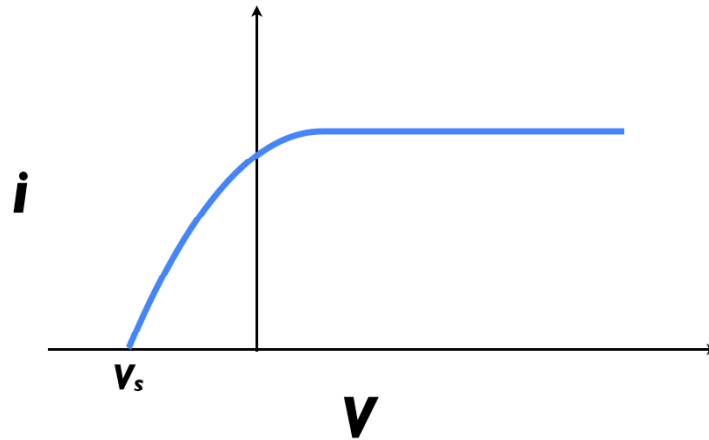
Notice that the current is emitted only for wavelengths less than λ_0 . For longer wavelengths, no current is emitted. These represent photons that don't have enough energy to knock the electrons out of the metal. For high wavelengths, the light does not interact with the metal (e.g. gamma rays).

λ_0 : photoelectric threshold wavelength. At wavelengths longer than this, there is never any current, no matter how bright the light is.

At wavelengths that do cause the photoelectric effect, current does depend on intensity.

Collector Voltage and Stopping Potential

If the power supply is wired such that it makes the collector negative, then it's harder for ejected electrons to bridge the gap. More and more are turned away as the voltage becomes more negative. At some voltage, called the "stopping potential," no electrons reach the collector, and there will be no current. V_s is also independent of the intensity of the light.



The power source sets up an electric field between the emitter and the collector. The ejected electron moves through this field. If the collector is negative, the PE is highest at the collector, and the electron loses KE as it moves toward the collector. In order to make it across the gap, the initial KE of the ejected electron must be greater than the PE at the collector. When the voltage equals the stopping potential, we know that the KE for the ejected electrons just equals the potential energy at the collector or...

$$KE = PE$$

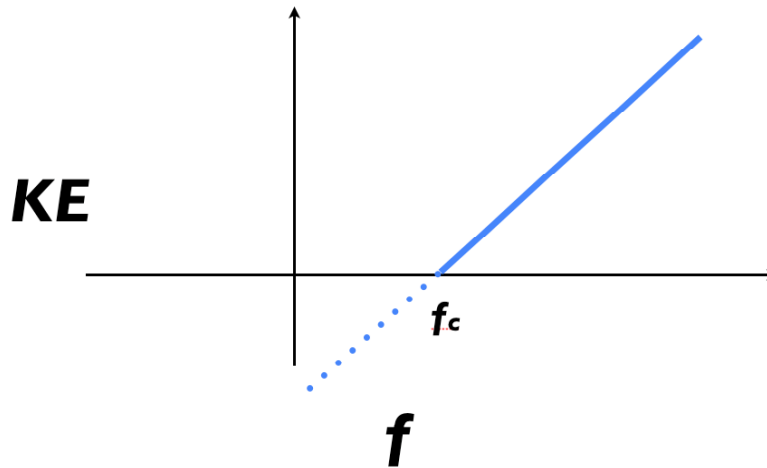
$hf - \phi = qV$. This equation is very useful.

You can find the stopping potential with

$$V = (hf - \phi) / q$$

Frequency and Kinetic Energy

For light shining on the metal, there is a minimum “cutoff” frequency before the ejected electrons have any KE. Photons with a frequency less than f_c don’t have enough energy to dislodge the electrons from the metal.



The slope of the graph is h , Planck’s constant.

The value for the cutoff frequency is simply the x intercept.

The work function would be the y intercept, but KE cannot be less than zero.

Since $KE_{\max} = hf - \phi$ and $KE_{\max} = 0$ at f_c ,

$f_c = \phi / h$ This is another useful one that won’t be on the test’s equations sheet.

Reasons This is Important

Classical Physics could not explain why:

no electrons are emitted if the light frequency falls below f_c

maximum KE doesn’t depend on intensity.

electrons are ejected almost instantaneously

KE increases with increasing frequency

The only viable explanation is that Newton, Planck, and Einstein are right.

Of course, Maxwell, Young, and DeBroglie are right too...

Here is the last photoelectric effect question to appear as a free response question. It was asked in 2000 as the fifth of seven questions. It was worth 10 points. They've asked about everything else in the intervening 8 tests, so it might be time for Einstein to make a comeback. Try it out, and check your answers.

2000 Question 5 (10 points)

A sodium photoelectric surface with work function 2.3eV is illuminated and emits electrons. The electrons travel toward a negatively charged cathode and complete a circuit. The potential difference supplied by the power supply is increased, and when it reaches 4.5V , no electrons reach the cathode.

(a) For the electrons emitted from the sodium surface, calculate the following.

i. The maximum kinetic energy

ii. The electron speed at this maximum kinetic energy

(b) Calculate the wavelength of the radiation that is incident on the sodium surface.

(c) Calculate the minimum frequency of light that will cause photoemission from this sodium surface.

2000 Question 5 (10 points)

(a) For the electrons emitted from the sodium surface, calculate the following.

i. The maximum kinetic energy

At the stopping potential, maximum $KE = qV$.

$$KE_{\max} = qV$$

$$KE_{\max} = e(4.5V) \quad \text{or} \quad KE_{\max} = 1.6 \cdot 10^{-19} C (4.5V)$$

$$KE_{\max} = 4.5eV \quad \text{or} \quad KE_{\max} = 7.2J$$

ii. The electron speed at this maximum kinetic energy

$$KE = \frac{1}{2} mv^2$$

$$v = \sqrt{(2 KE / m)}$$

$$v = \sqrt{(2 \cdot 7.2J / 9.11 \cdot 10^{-31} kg)}$$

$$v = 1.26 \cdot 10^6 m/s$$

(b) Calculate the wavelength of the radiation that is incident on the sodium surface.

$$E = hf$$

$$E = h c / \lambda$$

$$\lambda = (hc) / E$$

$$\lambda = (4.14 \cdot 10^{-15} eVs \cdot 3 \cdot 10^8 m/s) / 6.8eV$$

$$\lambda = 1.83 \cdot 10^{-7} m$$

I used 6.8eV for E because the electron had 4.5eV when it ejected and it overcame the 2.3eV work function for sodium. The incident photon must have given it 6.8eV.

(c) Calculate the minimum frequency of light that will cause photoemission from this sodium surface.

$$KE_{\max} = hf - \phi$$

$$\text{At } f_c, KE_{\max} = 0$$

$$f = \phi / h$$

$$f = 2.3eV / 4.14 \cdot 10^{-15} eVs$$

$$f = 5.56 \cdot 10^{14} Hz$$