

Photoelectric effect

Explaining the experiments on the photoelectric effect . How these experiments led to the idea of light behaving as a particle of energy called a photon.

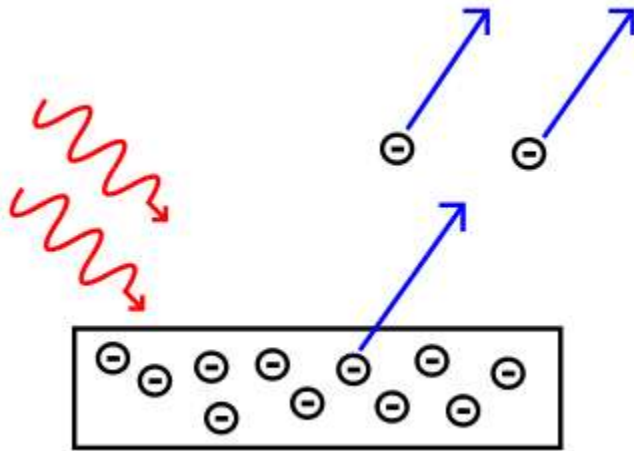
- Based on the wave model of light, physicists predicted that increasing light amplitude would increase the kinetic energy of emitted photoelectrons, while increasing the frequency would increase measured current.
- Contrary to the predictions, experiments showed that increasing the light frequency increased the kinetic energy of the photoelectrons, and increasing the light amplitude increased the current.
- Based on these findings, Einstein proposed that light behaved like a stream of particles called *photons* with an energy of $E=h\nu$.
- The work function, Φ , is the minimum amount of energy required to induce photoemission of electrons from a metal surface, and the value of Φ depends on the metal.
- The energy of the incident photon must be equal to the sum of the metal's work function and the photoelectron kinetic energy:

$$E_{\text{photon}} = KE_{\text{electron}} + \Phi$$

The photoelectric effect

When light shines on a metal ,electrons can be ejected from the surface of the metal in a phenomenon known as the *photoelectric effect*. This process is also often referred to as *photoemission*, and the electrons that are ejected from the metal are called *photoelectrons*. In terms of their behavior and their properties, photoelectrons are no

different from other electrons. The prefix, *photo-*, simply tells us that the electrons have been ejected from a metal surface by incident light.

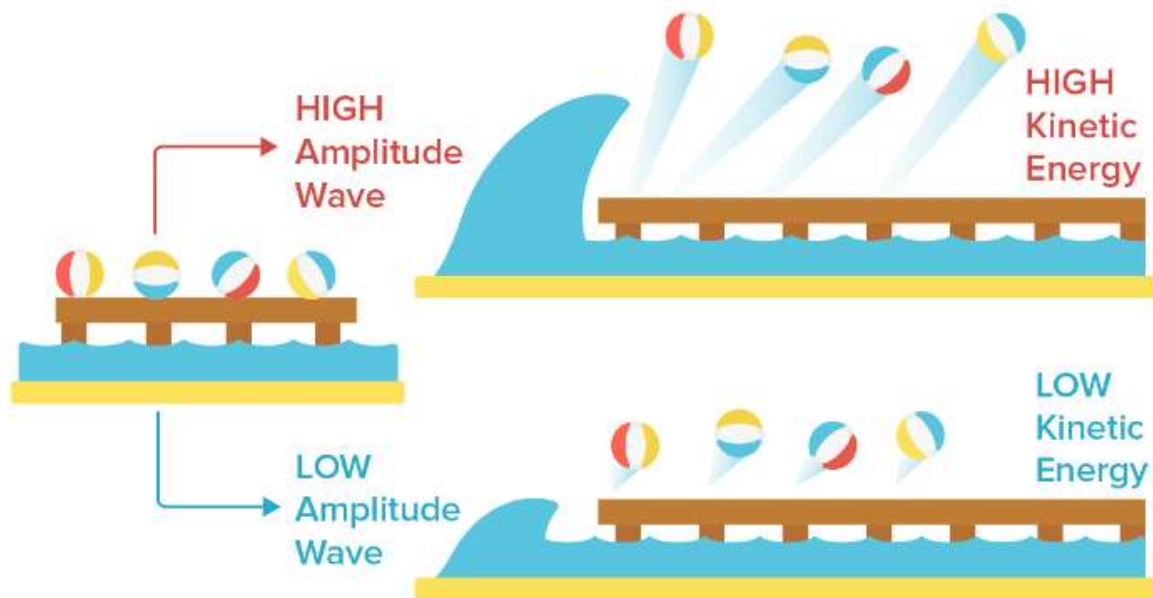


In the photoelectric effect, light waves (red wavy lines) hitting a metal surface cause electrons to be ejected from the metal.

Based on the classical description of light as a wave, Scientists made the following predictions:

- The kinetic energy of emitted photoelectrons should increase with the light amplitude.
- The rate of electron emission, which is proportional to the measured electric current, should increase as the light frequency is increased.

To help us understand why they made these predictions, we can compare a light wave to a water wave. Imagine some beach balls sitting on a dock that extends out into the ocean. The dock represents a metal surface, the beach balls represent electrons, and the ocean waves represent light waves.



If a single large wave were to shake the dock, we would expect the energy from the big wave would send the beach balls flying off the dock with much more kinetic energy compared to a single, small wave. This is also what physicists believed would happen if the light intensity was increased. Light amplitude was expected to be proportional to the light energy, so higher amplitude light was predicted to result in photoelectrons with more kinetic energy.

Classical physicists also predicted that increasing the frequency of light waves (at a constant amplitude) would increase the rate of electrons being ejected, and thus increase the measured electric current. Using our beach ball analogy, we would expect waves hitting the dock more frequently would result in more beach balls being knocked off the dock compared to the same sized waves hitting the dock less often.

When experiments were performed to look at the effect of light amplitude and frequency, the following results were observed:

- The kinetic energy of photoelectrons increases with light frequency.

- Electric current remains constant as light frequency increases.
- Electric current increases with light amplitude.
- The kinetic energy of photoelectrons remains constant as light amplitude increases.

These results were completely at odds with the predictions based on the classical description of light as a wave! In order to explain what was happening, it turned out that an entirely new model of light was needed. That model was developed by Albert Einstein, who proposed that light sometimes behaved as particles of electromagnetic energy which we now call *photons*. The energy of a photon could be calculated using Planck's equation:

$$E_{\text{photon}} = h\nu$$

where E_{photon} is the energy of a photon in joules (J), h is Planck's constant ($6.626 \times 10^{-34} \text{ J} \cdot \text{s}$), and ν is the frequency of the light in Hz. According to Planck's equation, the energy of a photon is proportional to the frequency of the light, ν . The amplitude of the light is then proportional to the number of photons with a given frequency.

Q As the wavelength of a photon increases, what happens to the photon's energy?

According to Planck's equation, the energy of a photon is proportional to the light frequency, ν :

$$E = h\nu$$

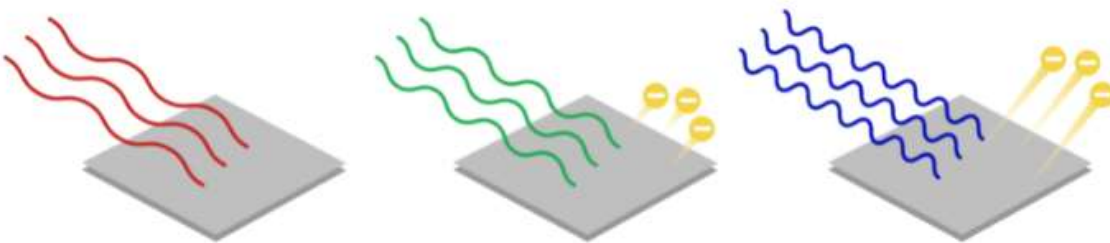
The light frequency ν is inversely proportional to wavelength λ :

$$c = \lambda\nu$$

where c is the speed of light. That means that increasing the wavelength decreases the light's frequency. Therefore, as the wavelength of a photon increases, its energy decreases.

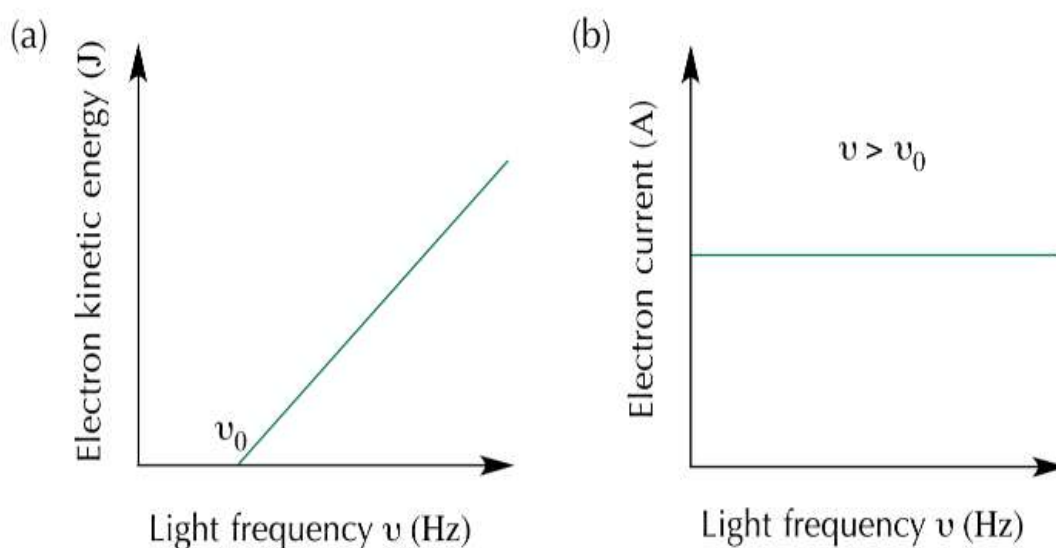
Light frequency and the threshold frequency ν_0

We can think of the incident light as a stream of photons with an energy determined by the light frequency. When a photon hits the metal surface, the photon's energy is absorbed by an electron in the metal. The graphic below illustrates the relationship between light frequency and the kinetic energy of ejected electrons.



The frequency of red light (left) is less than the threshold frequency of this metal ($\nu_{\text{red}} < \nu_0$) so no electrons are ejected. The green (middle) and blue light (right) have $\nu > \nu_0$, so both cause photoemission. The higher energy blue light ejects electrons with higher kinetic energy compared to the green light.

The scientists observed that if the incident light had a frequency less than a minimum frequency ν_0 , then no electrons were ejected regardless of the light amplitude. This minimum frequency is also called the *threshold frequency*, and the value of ν_0 depends on the metal. For frequencies greater than ν_0 , electrons would be ejected from the metal. Furthermore, the kinetic energy of the photoelectrons was proportional to the light frequency. The relationship between photoelectron kinetic energy and light frequency is shown in graph (a) below.



Because the light amplitude was kept constant as the light frequency increased, the *number* of photons being absorbed by the metal remained constant. Thus, the rate at which electrons were ejected from the metal (or the electric current) remained constant as well. The relationship between electron current and light frequency is illustrated in graph (b) above.

We can analyze the frequency relationship using the law of conservation of energy. The total energy of the incoming photon, E_{photon} , must be equal to the kinetic energy of the ejected electron, KE_{electron} , plus the energy required to eject the electron from the metal. The energy required to free the electron from a particular metal is also called the metal's *work function*, which is represented by the symbol Φ (in units of J):

$$E_{\text{photon}} = KE_{\text{electron}} + \Phi$$

Like the threshold frequency ν_0 , the value of Φ also changes depending on the metal. We can now write the energy of the photon in terms of the light frequency using Planck's equation:

$$E_{\text{photon}} = h\nu = KE_{\text{electron}} + \Phi$$

Rearranging this equation in terms of the electron's kinetic energy, we get:

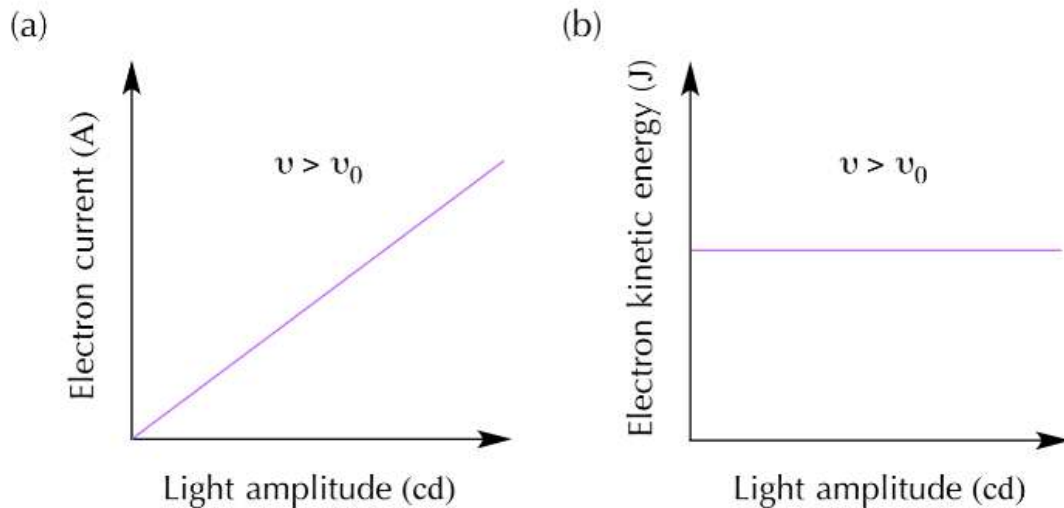
$$KE_{\text{electron}} = h\nu - \Phi$$

We can see that kinetic energy of the photoelectron increases linearly with ν as long as the photon energy is greater than the work function Φ , which is exactly the relationship shown in graph (a) above. We can also use this equation to find the photoelectron velocity v , which is related to KE_{electron} as follows:

$$KE_{\text{electron}} = h\nu - \Phi = \frac{1}{2}m_e v^2$$

where m_e is the rest mass of an electron, 9.1094×10^{-31} kg.

In terms of photons, higher amplitude light means more photons hitting the metal surface. This results in more electrons ejected over a given time period. As long as the light frequency is greater than ν_0 , increasing the light amplitude will cause the electron current to increase proportionally as shown in graph (a) below.



Since increasing the light amplitude has no effect on the energy of the incoming photon, the photoelectron kinetic energy remains constant as the light amplitude is increased (see graph (b) above).

If we try to explain this result using our dock-and-beach-balls analogy, the relationship in graph (b) indicates that no matter the height of the wave hitting the dock-whether it's a tiny swell, or a huge tsunami-the individual beach balls would be launched off the dock with the exact same speed! Thus, our intuition and analogy don't do a very good job of explaining these particular experiments.

Example 1: The photoelectric effect for copper

The work function of copper metal is $\Phi = 7.53 \times 10^{-19} \text{ J}$. If we shine light with a frequency of $3.0 \times 10^{16} \text{ Hz}$ on copper metal, will the photoelectric effect be observed?

In order to eject electrons, we need the energy of the photons to be greater than the work function of copper. We can use Planck's equation to calculate the energy of the photon, E_{photon} :

$$\begin{aligned} E_{\text{photon}} &= h\nu \\ &= (6.626 \times 10^{-34} \text{ J} \cdot \text{s})(3.0 \times 10^{16} \text{ Hz}) \quad \text{plug in values for } h \\ &= 2.0 \times 10^{-17} \text{ J} \end{aligned}$$

If we compare our calculated photon energy, E_{photon} , to copper's work function, we see that the photon energy is greater than Φ :

$$\begin{array}{ccc} 2.0 \times 10^{-17} \text{ J} & > & 7.53 \times 10^{-19} \text{ J} \\ E_{\text{photon}} & & \Phi \end{array}$$

Thus, we would expect to see photoelectrons ejected from the copper. Next, we will calculate the kinetic energy of the photoelectrons.

Example 2: Calculating the kinetic energy of a photoelectron

What is the kinetic energy of the photoelectrons ejected from the copper by the light with a frequency of 3.0×10^{16} Hz?

We can calculate the kinetic energy of the photoelectron using the equation that relates KE_{electron} to the energy of the photon, E_{photon} , and the work function, Φ :

$$E_{\text{photon}} = KE_{\text{electron}} + \Phi$$

Since we want to know KE_{electron} , we can start by rearranging the equation so that we will be solving for the kinetic energy of the electron:

$$KE_{\text{electron}} = E_{\text{photon}} - \Phi$$

Now we can insert our known values for E_{photon} and Φ from **Example 1**:

$$KE_{\text{electron}} = (2.0 \times 10^{-17} \text{ J}) - (7.53 \times 10^{-19} \text{ J}) = 1.9 \times 10^{-17} \text{ J}$$

Therefore, each photoelectron has a kinetic energy of $1.9 \times 10^{-17} \text{ J}$.

Summary

- Based on the wave model of light, physicists predicted that increasing light amplitude would increase the kinetic energy of emitted photoelectrons, while increasing the frequency would increase measured current.
- Experiments showed that increasing the light frequency increased the kinetic energy of the photoelectrons, and increasing the light amplitude increased the current.
- Based on these findings, Einstein proposed that light behaved like a stream of *photons* with an energy of $E = h\nu$.
- The work function, Φ , is the minimum amount of energy required to induce photoemission of electrons from a specific metal surface.
- The energy of the incident photon must be equal to the sum of the work function and the kinetic energy of a photoelectron: $E_{\text{photon}} = KE_{\text{electron}} + \Phi$

When we shine light with a frequency of 6.20×10^{14} Hz on a mystery metal, we observe the ejected electrons have a kinetic energy of 3.28×10^{-20} J. Some possible candidates for the mystery metal are shown in the table below:

Metal	Work function Φ (Joules, J)
Calcium, Ca	4.60×10^{-19}
Tin, Sn	7.08×10^{-19}
Sodium, Na	3.78×10^{-19}
Hafnium, Hf	6.25×10^{-19}
Samarium, Sm	4.33×10^{-19}

Based on this information, what is the most likely identity of our mystery metal?

Choose 1 answer:

☐ (A) Calcium, Ca

☐ (B) Tin, Sn

☐ (C) Samarium, Sm

☐ (D) Sodium, Na

Since we know the frequency of the incident light and the kinetic energy of the photoelectrons, we can find the work function of our mystery metal using the following equation:

$$E_{\text{photon}} = h\nu = \text{KE}_{\text{electron}} + \Phi$$

We can rearrange the equation so that we are solving for Φ :

$$\Phi = h\nu - \text{KE}_{\text{electron}}$$

We can plug in our known values for ν and $\text{KE}_{\text{electron}}$ to calculate Φ :

$$\begin{aligned}\Phi &= h\nu - \text{KE}_{\text{electron}} \\ &= (6.626 \times 10^{-34} \text{ J} \cdot \text{s})(6.20 \times 10^{14} \text{ Hz}) - 3.28 \times 10^{-20} \text{ J} \\ &= (4.11 \times 10^{-19} \text{ J}) - (3.28 \times 10^{-20} \text{ J}) \\ &= 3.78 \times 10^{-19} \text{ J}\end{aligned}$$

Based on the work function, $3.78 \times 10^{-19} \text{ J}$, our mystery metal is most likely sodium, Na.