Electron Emission

Electron emission is the process when an electron escapes from a metal surface. Every atom has a positively charged nuclear part and negatively charged electrons around it. Sometimes these electrons are loosely bound to the nucleus. Hence, a little push or tap sets these electrons flying out of their orbits.

Electron Emission

There are free electrons inside a metal surface. If these electrons are not bound to any nucleus, why don't they escape the metal surface? This is because metals are neutral and if an electron escapes the surface, the surface gets a positive charge. This will attract the electron back to the surface and prevent it from escaping. As a result, a barrier forms near the surface. We call it the surface barrier. So the free electrons are "free" only inside the metal. To get them out of the metal surface, we need some force to overcome this surface barrier.

Inside a metal

As we said earlier, inside metals electrons are free to roam around but to escape the surface, they need to overcome an electric force or potential. The energy for this may be supplied from outside causing the electrons to be emitted from the surface of the metal. The electrons are inside a well. They can move freely inside the well but to take them out of it, we have to provide them with some energy.

We call this the finite potential well. The energy required to liberate these electrons from the potential well (metal surface) is known as the work function of the metallic surface. Once an electron gets energy equal to the work function, it overcomes the potential well and is free to leave the metal surface.

Types of Electron Emission

The process of emission happens in the following steps:

- Step – 1: Delivery of Energy equal to or greater than the work function to the metal surface.
- Step – 2: The electron absorbs the energy. Thus it escapes the metal surface.

Depending on how you deliver the energy to the metal surface, the emission is of different types.

Thermionic emission

The emission is a thermionic emission if the energy responsible for it is in the form of heat energy.

Field Emission

The electric field has an electric potential energy associated with it. If a charge ‘q’ is present in a potential V, then $E = qV$. The emission is a field emission if the energy responsible for it is in the form of electric energy.

Photo-electric emission

Light consists of packets of energy called photons. The Plank-Einstein relation E = hν gives the energy of a photon beam of wavelength 'ν'. If the frequency of the photons is greater than a specific value known as the threshold frequency, then electrons are emitted from the metal surface. This is the photoelectric effect. These electrons are the photoelectrons.

Solved Examples For You

Two photons, each of energy 2.5eV are simultaneously incident on the metal surface. If the work function of the metal is 4.5eV, then from the surface of metal

A. Two electrons will be emitted.
B. Not even a single electron will be emitted.
C. One electron will be emitted.
D. More than two electrons will be emitted.

Solution: B) Not even a single electron will be emitted.

Since the energy of each photon (2.5 eV) is lesser than the work function (4.5 eV), There will not be any emission of electrons. Both the photons will be absorbed and will excite the electrons. But the electrons will still remain bound to the metal.

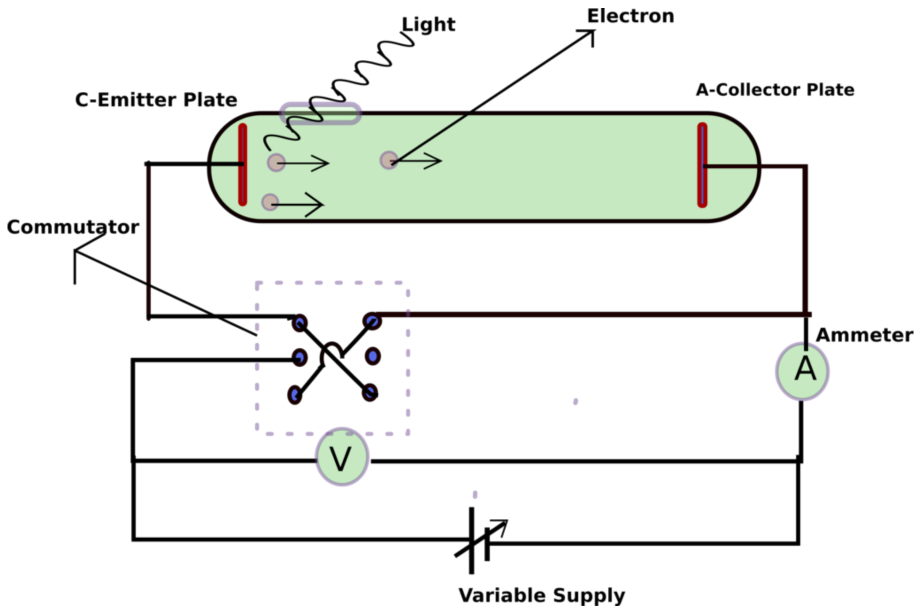
Experimental Study of Photoelectric Effect

The photoelectric effect is the name given to the phenomenon of emission of electrons from a metal surface when the light of a suitable frequency is incident on it. What happens when light falls on a metal surface? How can we study it? Let’s find out.

Experimental Study of Photoelectric Effect

The aim of the experiment is to study the emission of electrons by light. We also try and measure the energy of the electrons emitted in the process. In addition to this, we will also observe the relation of these electrons with the frequency of light used. To study the effect, we use an evacuated cathode ray tube connected in a circuit as shown below:

Apparatus used



Quartz Window

Near one of the plates inside the evacuated tube, there is present a small quartz window. The Quartz window has two functions – it lets light in and it only lets the Ultra Violet light in. Hence by using a Quartz window, we make sure that light of a specific frequency falls on the metal plate inside the evacuated chamber.

The circuit

We connect a voltmeter across the two plates. This measures the potential difference between the plates. Moreover, we have a sensitive galvanometer in the circuit. This measures the photocurrent.

The Collector plate-C emits electrons which are then collected at the collector plate-A. These plates are connected to the battery via the commutator. Let's switch on this experiment and see what happens!

In The Beginning!

Well, in the beginning, let us have a zero potential. We open the quartz window and observe the reading of the Voltmeter and the Ammeter. Both will give a non-zero reading (say for alkali metals), proving the occurrence of the Photoelectric effect. As we increase the Voltage and change it again, we will make the following observations:

The Effect of Intensity

The number of electrons emitted per second is observed to be directly proportional to the intensity of light. "Ok, so light is a wave and has energy. It takes electrons out of a metal, what is so special about that!"

First of all, when the intensity of light is increased, we should see an increase in the photocurrent (number of photoelectrons emitted). Right?

As we see, this only happens above a specific value of frequency, known as the threshold frequency. Below this threshold frequency, the intensity of light has no effect on the photocurrent! In fact, there is no photocurrent at all, howsoever high the intensity of light is.

The graph between the photoelectric current and the intensity of light is a straight line when the frequency of light used is above a specific minimum threshold value.

The Effect of The Potential

Suppose you connect C to a positive terminal and A to a negative terminal. What do you expect will happen to the photocurrent?

Since electrons are negatively charged, if we increase the negative potential at C, more and more electrons will want to escape this region and run to the attractive plate A. So the current should increase. Similarly, if we decrease the negative potential at C, removing electrons will become difficult and the photocurrent will decrease. Hence the maximum current flowing at a given intensity of incoming light is the saturation current.

As you can see in the graph, the value of saturation current is greater for higher intensities, provided the frequency is above the threshold frequency. Imagine you are an electron and you just escaped the metal surface. Now you are merrily accelerating towards A. What if we became mischievous and increased the negative potential at A? You will feel a repulsion and consequently you will lose speed.

What if the potential is very strong? You will not be able to escape the metal surface at all! As a result, we call this value of the potential for which the photocurrent becomes zero as the stopping potential or the retarding potential. The more the negative potential of the collector plate, the more is the effort that an electron has to make if it wants to escape successfully from the metal surface.

Thus we will get the following relationship between the stopping potential and the photocurrent.

Effect of Frequency

We see that for higher frequency values like ν_3, stopping potential is more negative or greater than the stopping potential for smaller frequencies like ν_1. What does this mean? This means that there should be a relationship between the frequency and energy.

In the End

We can sum up the observations as follows:

A. For a given metal (photosensitive material), the photoelectric current is directly proportional to the intensity of the light used, above a minimum value of frequency called the threshold frequency.

B. The saturation current depends on the intensity for a known value of frequency. At the same time, we see that the stopping potential does not depend on the intensity over a specific value of frequency.

C. The Photoelectric effect does not occur below a certain frequency. This is the threshold frequency. If the frequency of light is above the threshold frequency, the stopping potential is directly proportional to the frequency. In other words, to stop an electron emitted by a higher frequency, we require more energy. The stopping potential provides this energy.

D. All of this happens instantaneously. As soon as we open the quartz window, electron emission starts.

All this is beautifully explained by the Einstein's Photoelectric equation.

Solved Examples For You

On reducing the wavelength of light incident on a metal, the velocity of emitted photoelectrons will become

A) Zero

B) Less

C) More

D) Remains Unchanged

Solution: C) It will become more.

We know that the energy of photoelectrons increases as we increase the frequency. This means that their kinetic energy will be more. Hence higher frequency means a greater speed of a photoelectron. We also know that $\lambda = c/\nu$. Hence if the wavelength is increased, the frequency will be decreased and vice-versa. So lesser wavelength means greater frequency and greater speed of the photoelectrons.

Wave Nature of Matter

What does wave nature of matter mean? Can a small particle be at multiple places at the same time? Do I have a wave nature? Why can't I see it? Let's try to answer these questions.

Wave Nature of Matter

In the earlier articles, we saw how light behaves both as a wave and particle. A particle is confined at a place. On the other hand, a wave is spread in space. We say that the nature of light depends on the nature of our observation. If you are observing phenomenon like the interference, diffraction or reflection, you will find that light is a wave. However, if you are looking at phenomena like the photoelectric effect, you will find that light has a particle character.

You might ask, which is it? Is light a wave or a particle? The answer is that it has a dual nature. You may also wonder whether it is a specific property of light! Does only light have a dual nature? What if other quantities had dual nature? How could we measure and prove that? Maybe these were the questions that led Louis Victor de Broglie to come up with one of the most revolutionary equations in Physics, the de Broglie equation.

Next up – A Few Lines of Math That Go A Long Way!

Let us recall the mass-energy equivalence of Einstein, $E = mc^2$ …(1)

Also from Einstein-Plank relation, we have: $E = h\nu$ …(2)

Furthermore, we see that equation (1) is applicable to particles with some "mass". In other words equation (1) can be applied to particles and equation (2) is an equation for a wave of frequency ν. So the two were not equated until de Broglie had a breakthrough! We know that light can be a wave as well as a particle. In that case, we can say that equation (1) and (2) represent the same quantity. Consequently, we must have: $h\nu = mc^2$. Since we know that $\nu = c/\lambda$, we have:

$h(c/\lambda) = mc^2$

$\lambda = h/mc$; where 'c' is the velocity of light. If we have a wave of velocity, say 'v', we can write: $\lambda = h/mv$

or $\lambda = h/p$ …(3)

where 'p' is the momentum of the wave-particle! See what we did here? We have mass – a particle property, in the same equation as wavelength – a wave property. Thus if matter exhibits wave properties, it must be given by equation (3). Equation (3) is the de Broglie equation and represents the wave-particle duality. Hence we say that everything in the Cosmos exhibits a dual nature. This is the wave nature of radiation and matter.

Wavelength of Macroscopic Objects

"So you are telling me that I am not a particle but a wave? Where is it then?" First of all, you are both. Let us find out your wavelength. Suppose you have a mass of 55 kg. If you are at rest i.e. if the velocity

= 0, then we see from equation (3), that λ is not defined. So not much help there! Let us say that you are moving at a velocity of 5 m/s. Using equation (3), we can see that

$\lambda = h/(55)\times5$

$\lambda = 6.63\times10-34/275 \approx 2.4\times10-36$ m

As you can see, you can't "see" this small wavelength. Thus the wavelength of macroscopic objects is too small to have any observable effects on any property at normal velocities.

Learn more about Wave Optics.

So de Broglie Guessed An Equation And Everyone Just Agreed?

Fortunately, there was a way to verify this equation. Let us see the equation again, $\lambda = h/p$

We know that K.E. = 1/2(mv2)

or K.E. =

(mv

)

2

(2m)

=

(p

)

2

(2m)

Here, p is the momentum. Thus we have: p =

2mE

–

–

–

–

√

…. (4)

Using (4) in (3), we have: $\lambda = h/$

2mE

–

–

–

–

√

…(5)

Also for a charged particle, $E = eV$ and we have: $\lambda = h/$

2meV

–

–

–

–

–

√

So for an electron e = 1.6×10-19 C and m = 9.10938356 × 10-31 kilograms, we have:

λ = 1.227/
V
–
–
√
nm

Hence we can verify the de Broglie equation if we observe the motion of an electron. This was done in the Davisson and Germer Experiment.

Solved Examples For You

The de-Broglie wavelength of an electron (mass 1×10^{-30}kg, charge=1.6×10^{-19} C) with a kinetic energy of 200eV is: (Planck's constant 6.6×10^{-34}J):

A) 9.60×10^{-11}m

B) 8.25×10^{-11}m

C) 6.25×10^{-11}m

C) 5.00×10^{-11}m

Solution: B) 8.25×10^{-11}m

We can directly use equation (5) i.e. $\lambda = h/$

2mE

–

–

–

–

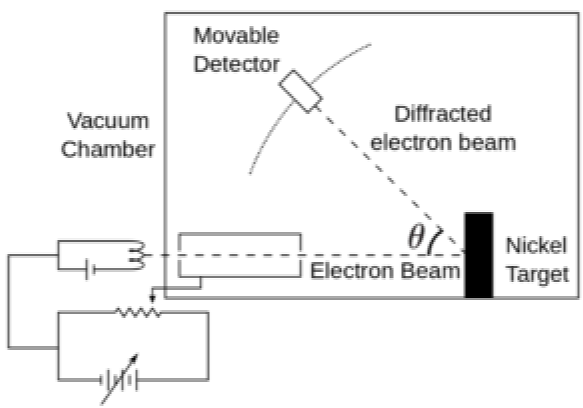
√

. Substitution of the respective values gives the required result.

Davisson and Germer Experiment

Davisson and Germer Experiment, for the first time, proved the wave nature of electrons and verified the de Broglie equation. de Broglie argued the dual nature of matter back in 1924, but it was only later that Davisson and Germer experiment verified the results. The results established the first experimental proof of quantum mechanics. In this experiment, we will study the scattering of electrons by a Ni crystal. Let's find out more.

Davisson and Germer Experiment



(Source: Wikipedia)

The experimental setup for the Davisson and Germer experiment is enclosed within a vacuum chamber. Thus the deflection and scattering of electrons by the medium are prevented. The main parts of the experimental setup are as follows:

- Electron gun: An electron gun is a Tungsten filament that emits electrons via thermionic emission i.e. it emits electrons when heated to a particular temperature.
- Electrostatic particle accelerator: Two opposite charged plates (positive and negative plate) are used to accelerate the electrons at a known potential.
- Collimator: The accelerator is enclosed within a cylinder that has a narrow passage for the electrons along its axis. Its function is to render a narrow and straight (collimated) beam of electrons ready for acceleration.
- Target: The target is a Nickel crystal. The electron beam is fired normally on the Nickel crystal. The crystal is placed such that it can be rotated about a fixed axis.
- Detector: A detector is used to capture the scattered electrons from the Ni crystal. The detector can be moved in a semicircular arc as shown in the diagram above.

The Thought Behind the Experimental Setup

The basic thought behind the Davisson and Germer experiment was that the waves reflected from two different atomic layers of a Ni crystal will have a fixed phase difference. After reflection, these waves will interfere either constructively or destructively. Hence producing a diffraction pattern.

In the Davisson and Germer experiment waves were used in place of electrons. These electrons formed a diffraction pattern. The dual nature of matter was thus verified. We can relate the de Broglie equation and the Bragg's law as shown below:

From the de Broglie equation, we have:

$\lambda = h/p$

$= h/$

2mE

–

–

–

–

√

= h/

2meV

–

–

–

–

–

√

… (1)

where, m is the mass of an electron, e is the charge on an electron and h is the Plank’s constant.

Therefore for a given V, an electron will have a wavelength given by equation (1).

The following equation gives Bragg's Law:

$$n\lambda = 2d \sin(90^{0} - \theta/2) \quad \ldots(2)$$

Since the value of d was already known from the X-ray diffraction experiments. Hence for various values of θ, we can find the wavelength of the waves producing a diffraction pattern from equation (2).

Observations of the Davisson and Germer Experiment

The detector used here can only detect the presence of an electron in the form of a particle. As a result, the detector receives the electrons in the form of an electronic current. The intensity (strength) of this electronic current received by the detector and the scattering angle is studied. We call this current as the electron intensity.

The intensity of the scattered electrons is not continuous. It shows a maximum and a minimum value corresponding to the maxima and the minima of a diffraction pattern produced by X-rays. It is studied from various angles of scattering and potential difference. For a particular voltage (54V, say) the maximum scattering happens at a fixed angle only (

50

0

) as shown below:

Plots between I *– the intensity of scattering (X-axis) and the angle of scattering θ for given values of Potential difference.*

Results of the Davisson and Germer Experiment

From the Davisson and Germer experiment, we get a value for the scattering angle θ and a corresponding value of the potential difference V at which the scattering of electrons is maximum. Thus these two values from the data collected by Davisson and Germer, when used in equation (1) and (2) give the same values for λ. Therefore, this establishes the de Broglie's wave-particle duality and verifies his equation as shown below:

From (1), we have:

λ = h/

2meV

–

–

–

–

–

√

For V = 54 V, we have

λ = 12.27/

54

–

–

√

 = 0.167 nm …. (3)

Now the value of 'd' from X-ray scattering is 0.092 nm. Therefore for V = 54 V, the angle of scattering is

50

0

, using this in equation (2), we have:

nλ = 2 (0.092 nm)sin(

90

0

–

50

0

/2)

For n = 1, we have:

λ = 0.165 nm ….. (4)

Therefore the experimental results are in a close agreement with the theoretical values got from the de Broglie equation. The equations (3) and (4) verify the de Broglie equation.

Can a small particle be at multiple places at the same time? Learn more about Wave Nature of Matter here.

Solved Example for You

Q. Statement-1: Davisson- Germer experiment established the wave nature of electrons.

Statement-2: If electrons have wave nature, they can interfere and show diffraction.

A. Statement -1 is false, statement -2 is true.
B. Both the statements are false.
C. Statement – 1 is true, statement – 2 is true, Statement – 2 is correct explaination of Statement – 1
D. Statement – 1 is true, statement – 2 is true, Statement – 2 is not the correct explaination of Statement – 1.

Solution: C. The Davisson and Germer experiment showed that electron beams can undergo diffraction when passed through the atomic crystals. This shows that the wave nature of electrons as waves can exhibit interference and diffraction.

Einstein's Photoelectric Equation: Energy Quantum of Radiation

In 1905, the annus mirabilis (miracle year) of Physics, Albert Einstein proposed an equation to explain this effect. Einstein argued that light was a wave that interacts with matter in the form of a packet of energy or a quantum of energy. This quantum of radiation was a photon and the equation was called Einstein's photoelectric equation.

Einstein's Photoelectric Equation

The Photoelectric Effect

Let us recall the Photoelectric effect.

- Firstly, above a specific value of the frequency (threshold frequency), the strength of the photoelectric current depends on the intensity of the light radiation.
- The reverse potential at which the photo-current stops (stopping potential) is independent of the intensity of light. Therefore, no matter how intense your source of light is, it can't defeat the stopping voltage.
- Any values of frequency below the threshold value are unable to produce a photoelectric current. Therefore, even if you take a metallic strip to the surface of your nearest star (Sun), you will never get a photocurrent if the frequency of the radiation is smaller than the threshold frequency.

- The photoelectric effect was almost instantaneous. This meant that as soon as you turn your source of light on, pop goes the electron!

Enter Einstein and His Equation of The Photoelectric Effect

Einstein’s view of light was magnificent as well as revolutionary. He proposed a weird but effective model of radiation. Light consisted of very small particles. These particles were not matter but pure energy. He called each of these a quantum of radiation. Therefore, light must be made up of these quantas or packets of energy or quantum energy. We call them photons and they carry the momentum and energy from our source of light.

According to the Einstein-Plank relation, we have E = hν   …(1)

Where ‘h’ is the Plank’s constant and ‘ν’ is the frequency of the radiation emitted.

Also from the experiment on Photoelectric effect, we see that there is a threshold frequency below which the electrons won’t come out of the metallic surface. In equation (1) we see that Energy is a function of frequency. Hence this observation is explained by equation (1). This also explains the instantaneous nature of the photoelectric emission.

Once a photo-electron is outside the metallic surface, what will be its energy? Since there is no electric field outside the metal surface, the energy of an electron will be purely Kinetic in nature. The quantum energy absorbed from the photon will be partly used to overcome the attraction of the metallic surface.

So, we have K.E. of the photo-electrons = (Energy obtained from the Photon) – (The energy used to escape the metallic surface)

This energy is a constant for a given surface. We denote it by Φ. We call it the work function and it is constant for a given substance. Thus we can write:

$K.E. = h\nu - \Phi$ … (2)

This is the Einstein's Photoelectric equation.

More About Work Function

Imagine a football trapped inside a tub. Let us say that you have to get this football out of the tub by hitting it with smaller balls. The balls you throw in the tub must have a minimum energy in order to be able to extract the football from the tub. This energy is the work function of the tub and the football.

Similarly, an electron needs some minimum energy to be extracted from a metallic surface. In equation (2), if ν = threshold frequency (ν_0)

then the electrons will have just enough quantum energy to come out of the metal. The Kinetic Energy of such an electron will be supposedly zero. Since it only gets energy enough to liberate itself from the metal surface. using these values of ν and K.E. in equation (2), we have:

$h\nu_0 - \Phi = 0$ or $h\nu_0 = \Phi$ ....(3)

using in (2), we have K.E. $= h\nu - h\nu_0$

or K.E. $= h(\nu - \nu_0)$

Also if V_0 is the Stopping Potential, then

K.E. $_{(max)} = eV_0$; using this in equation (3), we have:

$eV_0 = h(\nu - \nu_0)$ ......(4)

The values of 'h' are got from the photoelectric experiment by the above equation. The values so obtained were in agreement with the actual values and thus confirmed Einstein's explanation of the Photoelectric effect.

Solved Examples For You

Example 1: If a photocell is illuminated with a radiation of $1240A_o$, then stopping potential is found to be 8 V. The work function of the emitter and the threshold wavelength are

A) 1eV, 5200 A_0 B) 2eV, 6200 A_0

C) 3 eV, 7200 A_0 D) 4eV, 4200 A_0

Solution: B) We know that $\nu = c/\lambda$. Thus Einstein's equation for Photoelectric effect can be written as $K.E._{(max)} = hc/\lambda - \Phi$ …(5)

$K.E._{(max)} = eV_0 = e\ (8V)$; using this in (5), we have:

$8e = hc/1240\times10^{-10} - \Phi$

Substituting $h = 6.62\times10^{-34}$ J.s and $c = 3\times10^{-8}$ m/s, we get

$\Phi = 3.2\times10^{-19}$ J or 2 eV ($1eV = 1.6\times10^{-19}$ J)

Also, we have $h\nu_0 = \Phi$ or $hc/\lambda_0 = \Phi$ and $\lambda_0 = 6200\ A_0$