Photoelectric Effect and Compton Effect

e-content for B.Sc Physics (Honours)

B.Sc Part-II

Paper-IV

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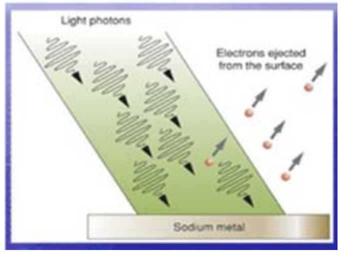
26.1The Photoelectric Effect

First observed by Heinrich Hertz in 1887 - light shining on a metal plate causes electrons to be knocked loose (ejected) from the metal plate.



Several aspects of the phenomena could not be explained in terms of an electromagnetic wave:

Increasing the brightness of the light did not eject faster electrons - think of light as a wave - brighter light (bigger amplitude wave) should eject more energetic (faster) electrons.

Energy and number of ejected electrons depends on light(frequency) - for some metals, red light would not eject any electrons at all even it very high - blue lights ejects very fast electrons even if very dim.

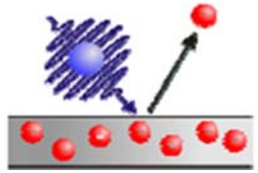
The electrons were emitted immediately - no time lag - if light is dim, expect a delay while the waves wiggle the electrons and break them loose.

The Photoelectric Effect

"The phenomenon that when light shines on a metal surface, electro are emitted"

One type of experiment with the photoelectric effect involves shining light of a single frequency onto the metal plate and adjusting the potential difference V between the metal plate and the collector

- If electrons are hitting the collector, there is a current reading in the ammeter



Photoelectric Effect Schematic

- **When light strikes E, photoelectrons are emitted**
- **Electrons collected at C and passing through the ammeter are a current in the circuit**
- **C is maintained at a positive potential by the power supply**

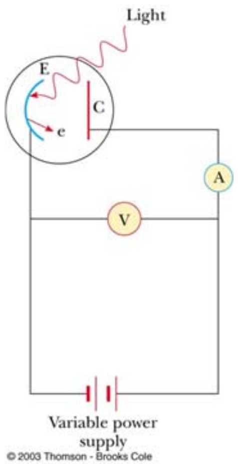
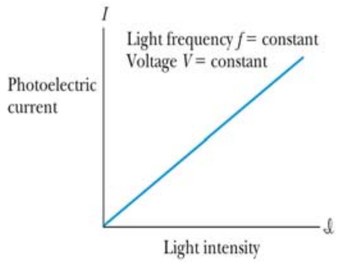


Photo-electric effect observations

- A)The kinetic energy of the photoelectrons is **independent of the light intensity**.



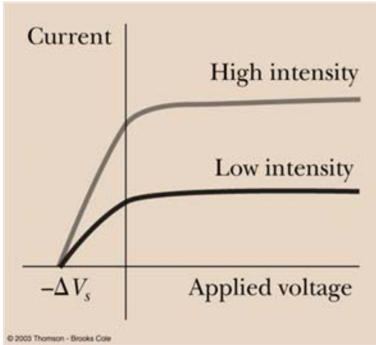
- B)The kinetic energy of the photoelectrons, for a given emitting material, depends only on the **frequency** of the light.

- C)When photoelectrons are produced, their **number** (not their kinetic energy) is proportional to the intensity of light.

d)Also, the photoelectrons are emitted almost instantly following illumination of the photocathode, independent of the intensity of the light.

Photoelectric Current/Voltage Graph

- The current increases with intensity, but reaches a saturation level for large ΔV's
- No current flows for voltages less than or equal to $-\Delta V_s$, the *stopping potential*
- The stopping potential is independent of the radiation intensity



Cutoff Wavelength

- The cutoff wavelength is related to the work function

$$\lambda_c = \frac{hc}{w}$$

- Wavelengths greater than λ_C incident on a material with a work function w don't result in the emission of photoelectrons

A specific value of V can be found at which the ammeter reading just drops to zero

. This is called the stopping potential (*Vstop).*

• When the potential is at *Vstop the most energetic electrons were turned* back just before hitting the collector.

• This indicates that the maximum kinetic energy of the photoelectrons, *Kmax= e Vstop where e is the elementary charge*

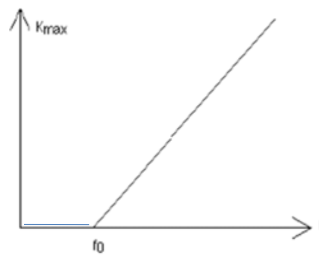
.

interestingly, it was found that *Kmax does not depend upon* the intensity of the incident light.

• It is difficult to explain this observation with classical

When the maximum kinetic energy is plotted as a function of frequency a graph like that on the right results.

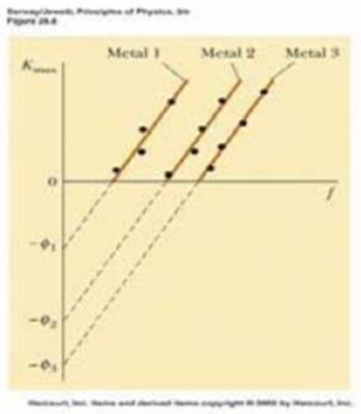
• Note that there is no photoelectric effect if the light is below a certain cutoff frequency, *f0. This* occurs no matter how bright the incident light is.



Dependence of maximal kinetic energy of electrons on the frequency of light

Photoelectric effect graphs for three different metals are shown a tright..

- Looking at the second form of the photoelectric equation, several pieces of information can be determined from the graphs.
  - The work function of each metal can be determined by taking the negative y-intercept of each line.
  - The cutoff frequency of each metal can be determined by taking the x intercept c each line
  - Note that all three lines have the same slope. This slope is Planck's constant



Features Not Explained by Classical Physics/Wave Theory

- No electrons are emitted if the incident light frequency is below some *cutoff frequency* that is characteristic of the material being illuminated
- The maximum kinetic energy of the photoelectrons is independent of the light intensity
- The maximum kinetic energy of the photoelectrons increases with increasing light frequency
- Electrons are emitted from the surface almost instantaneously, even at low intensities

Explanation of Classical "Problems"

- The effect is not observed below a certain cutoff frequency since the photon energy must be greater than or equal to the work function
  - Without this, electrons are not emitted, regardless of the intensity of the light
- The maximum KE depends only on the frequency and the work function, not on the intensity
- The maximum KE increases with increasing frequency
- The effect is instantaneous since there is a one-to-one interaction between the photon and the electron

Quantum Theory of The Atom

- In 1901, Max Planck suggested light was made up of 'packets' of energy:
- $$E = nhf$$

  E (Energy of Radiation)

  v (Frequency)

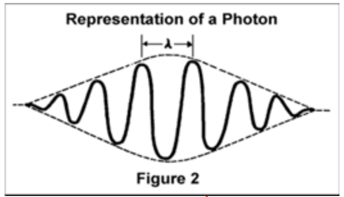
  n (Quantum Number) = 1,2,3.......n

  h (Planck's Constant, a Proportionality Constant)

  6.626 x 10^{-34} J.s) or h =4.135x10^{-15} ev.s

  6.626 x 10^{-34} kg.m^2/s
- Atoms, therefore, emit only certain quantities of energy and the energy of an atom is described as being ***"quantized"***
- Thus, an atom changes its *energy state* by emitting (or absorbing) one or more ***quanta***

Photons



Quantum theory describes light as a particle called a **photon with wave**

According to **quantum theory**, a **photon** has an **energy** given by

$E = h\nu = hc/\lambda$ (h Planck's constant $= 6.6\text{x}10^{-34}$ J.sec) or $h = 4.135 \text{ x}10^{-15}$ eV.s ,

The energy of the light is proportional to the frequency, and inversely proportional to the wavelength! The higher the frequency (lower wavelength) the higher the energy of the photon!

10 photons have an energy equal to ten times a single photon.

The **quantum theory describes experiments to astonishing precision**, whereas the **classical wave description cannot**.

Einsteins explanation

proposed an explanation for the photoelectric effetc which would play a large role in his receiving the Nobel Prize in Physics in 1921.

- Rather than the classical model of light as a continuous wave, Einstein viewed light as discrete packets of energy called photons. hf , 2hf ,3hf…… nhf
- Taking advantage of Planck's discovery of the quantization of energy, Einstein determined that each photon had energy *E=hf.* The energy transferred to an electron • by light was no longer considered to depend on intensity, but on frequency

Einstein's Explanation

The electrons are bound to the material by attractive forces. Hence, work must be done to free an electron:

$$hf = KE_{max} + w$$

"Work function", depends on the material

Incident photon energy

Maximum kinetic energy of dislodged electron

Minimum work required to free electron

Einstein 's Explanation

- Energy from the light beam is transferred to the electrons in the solid by photons which have an energy related to the frequency of the beam.
- The photon's energy would be $E = hf$
- ***Each photon can give all its energy to an electron in the metal***
- The electron is considered to be in a well of height frequency which is called the ***work function*** of the metal
- Because of energy conservation the maximum kinetic energy of the liberated photoelectron is

$$KE = hf - w$$

Work Function

Work function is: The minimum amount of energy that has to be given to an electron to release it from the surface of the material and varies depending on the material

Threshold Frequency

$hf_o = w$

$\frac{hc}{\lambda_o} = w$

c = speed of light

λ_o = wavelength

Light as a Particle (Photon)

- Light propagates as quanta of energy called photons
- Photons
  - **A) move with speed of light**
  - **B) have no mass**
  - **C) electrically neutral**
- **Energy of a photon or electromagnetic wave:**

$$E = hf = \frac{hc}{\lambda}$$

where

h = Planck's constant

f = frequency of a light wave - number of crests passing a fixed point in 1 second

c = velocity of light

λ = wavelength of a light wave - distance between successive crests

Example 26.1

Light is incident on the surface of a metal for which the work function is 2eV (a) what is the minimum frequency the light can have and cause the emission of electron ? (b) If the frequency of the incident light is 2×10^{14}Hz what is the maximum kinetic energy of the electron?

example

What is the wavelength in nm of orange light, which has a frequency of $4.80 \times 10^{14}\ s^{-1}$?

solution

$c = \lambda \times \nu$

$$\lambda = \frac{c}{\nu} = \frac{2.998\times10^{8}\ m\ s^{-1}}{4.80\times10^{14}\ s^{-1}} = 6.25\times10^{-7}\ m$$

$$6.25\times10^{-7}\ m \times \frac{1\ nm}{1\times10^{-9}\ m} = 625\ nm$$

example

What is the maximum kinetic energy of electrons emitted from a zinc surface if they are stopped by a 16 N/C uniform electric field over a distance of 3.0cm?

First calculate the voltage $E = V/d$

$V = E\,d$

$(16 N/C).(0.03 m)$

$V = 0.48V$

Second, calculate the maximum kinetic energy…

$E_{k\,max} = e\,V_{stop}$

$= (1.6 \times 10^{-19} C)\,(0.48V)$

$E_{k\,max} = 7.68 \times 10^{-20}$ J

example

What is threshold frequency of a material with a work function of 10eV?

Since the value for the work function is given in electron volts, we might as well use the value for Planck's constant that is in eV s.

$W = h\,f_o$

$f_o = W / h$

$= (10eV) / (4.14 \times 10^{-15} eVs)$

$f_o = 4.14 \times 10^{-14}$ Hz

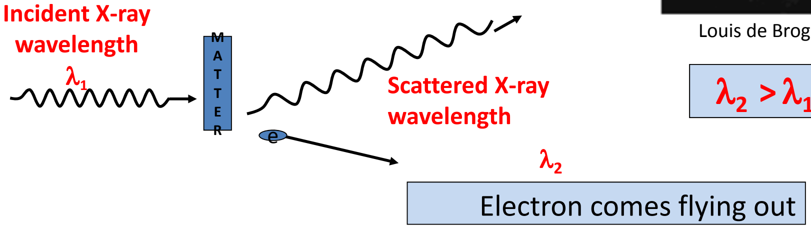
Home work : 26-1, 26-3 ,26-4

26.3 XRAYS

The Compton Effect

In 1924, A. H. Compton performed an experiment where X-rays impinged on matter, and he measured the scattered radiation.

Louis de Broglie



$\lambda_2 > \lambda_1$

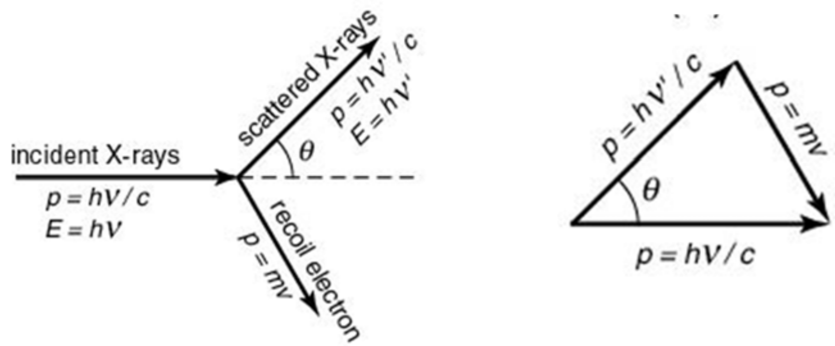
Compton directed a beam of x-rays toward a block of graphite
He found that the scattered x-rays had a slightly longer wavelength that the incident x-rays This means they also had less energy the amount of energy reduction depended on the angle at which the x-rays were scattered
The change in wavelength is called the *Compton shift*
The Compton shift depends on the scattering angle and not on the wavelength

Compton effect was first observed by Arthur Compton in 1923 and this discovery led to his award of the 1927 Nobel Prize in Physics. The discovery is important because it demonstrates that light cannot be explained purely as a wave phenomenon. Compton's work convinced the scientific community that light can behave as a stream of particles (photons) whose energy is proportional to the frequency.

The change in wavelength of the scattered photon is given by:

$$hf' = hf - E_{el}$$

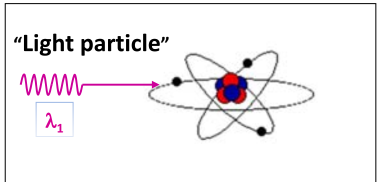
$$\lambda' - \lambda = \frac{h}{m_e c}(1 - Cos\,\theta)$$



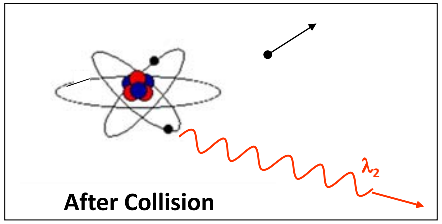
$$\boxed{\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)}$$

$$\boxed{\lambda_C^e = \frac{h}{m_e c} \approx 2.43\times10^{-12}\,m}$$

Interpretation of Compton Effect



Before Collision



After Collision

The Compton Effect describes collisions of light with electrons perfectly if we treat light as a particle with:

p = h/λ and **E = hν**

= hc/λ = (h/λ)c

= pc

example

In the Compton scattering the experiment the incident x ray have a frequency of 10^{20} Hz at certain angle the outgoing x ray have frequency of $8\text{x}10^{19}$ Hz find the energy of the recoiling electron in electron volts

$$E_{el} = hf - hf' = h(f - f')$$

$$= (4.135\times10^{-15}\,ev.s)(10^{20}\,Hz - 8\times10^{19}) = 82.700\,eV$$

Example:

Determine the change in the photon's wavelength that occurs when an electron scatters an x-ray photon (a) at θ=180° and (b) θ=30°.

$\Delta\lambda=\lambda_c(1-\cos\theta)$

(a) $\Delta\lambda=2.43\times10^{-12}\text{ m }(1-\underbrace{\cos180°}_{\boxed{-1}})$

$\Delta\lambda=4.86\times10^{-12}$ m

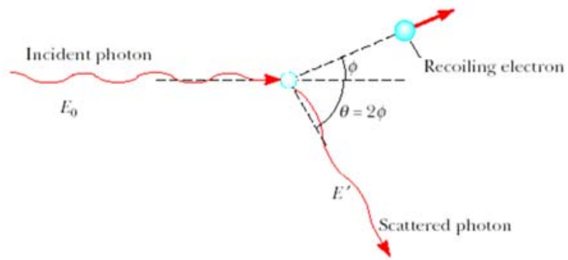
(b) $\Delta\lambda=2.43\times10^{-12}\text{ m }(\underbrace{1-\cos30}_{\boxed{0.134}})$

$\Delta\lambda=(0.134)\times(2.43\times10^{-12}\text{ m})$

$\Delta\lambda=3.26\times10^{-13}$ m

Example

A 0.700-MeV photon scatters off a free electron such that the scattering angle of the photon is twice the scattering angle of the electron (Fig.). Determine (a) the scattering angle for the electron and (b) the final speed of the electron.

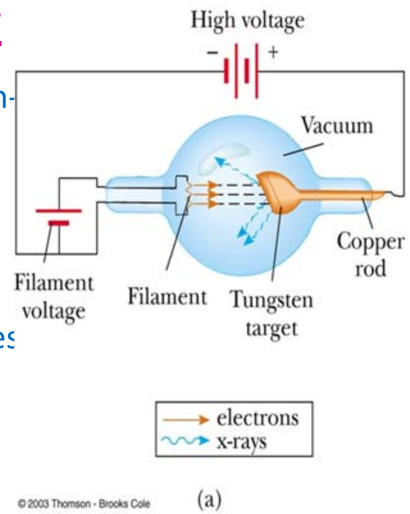


X-Rays

- Electromagnetic radiation with short wavelengths
  - **Wavelengths less than for ultraviolet**
  - **Wavelengths are typically about 0.1 nm**
  - **X-rays have the ability to penetrate most materials with relative ease**
- **Discovered and named by Roentgen in 1895**

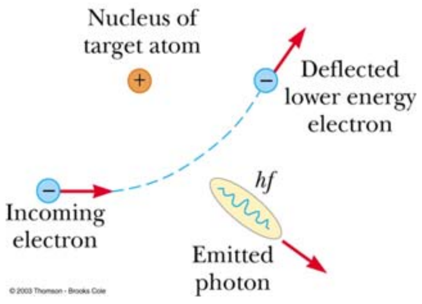
Production of X-rays

- X-rays are produced when high-speed electrons are suddenly slowed down
  - Can be caused by the electron striking a metal target
- A current in the filament causes electrons to be emitted
- These freed electrons are accelerated toward a dense metal target



Production of X-rays

- An electron passes near a target nucleus
- The electron is deflected from its path by its attraction to the nucleus
  - This produces an acceleration
- It will emit electromagnetic radiation when it is accelerated



The maximum x-ray energy, and minimum wavelength results when the electron loses all its energy in a single collision, such that

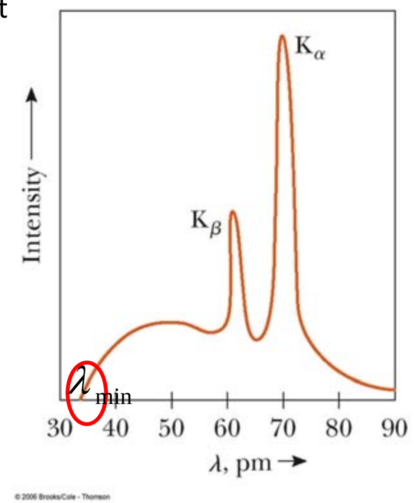
$e\Delta V = hf_{max} = hc/\lambda_{min}$ or therefore $$\lambda_{min} = \frac{hc}{e\Delta V}$$

X-ray Spectrum

- The x-ray spectrum has two distinct components
- 1) Bremsstrahlung:
- A continuous broad spectrum, which depends on voltage applied to the tube
- 2) The sharp, intense lines, which depend on the nature of the target material

$e\Delta V = hf_{max} = hc/\lambda_{min}$

$$\lambda_{min} = \frac{hc}{e\Delta V}$$



Example

An electron is accelerated through 50,000 volts
What is the minimum wavelength photon it can produce when striking a target?

Minimum wavelength ⟷ Maximum energy

$$\lambda_{min} = \frac{hc}{V} = \frac{6.6\times10^{-34}\times3\times10^{8}}{50000} = .0248nm$$

Examples

What is the energy of a copper x-ray if it has momentum $4.267\text{x}10^{-24}$ kgm/s?

a. 0.5 keV
b. 2.0 keV
c. 8 keV
d. 0.25 MeV
e. 8 MeV

(8). If the accelerating voltage in a X ray tube is doubled, the minimum X ray wavelength is multiplied by a factor of
(a) 1 (b) 1/2 (c) 2 (d) 1/4

Electrons in an X ray tube are accelerated through a potential difference of 20,000 V. What is the maximum frequency of the X rays that are produced?
(a) 20,000 Hz (b) 2.07×10^{18} Hz (c) 4.83×10^{18} Hz (d) 9.66×10^{18} Hz

1.3: PHOTOELECTRIC EFFECT EXPLAINED WITH QUANTUM HYPOTHESIS

OVERVIEW

Although Hertz discovered the photoelectron in 1887, it was not until 1905 that a theory was proposed that explained the effect completely. The theory was proposed by Einstein and it made the claim that electromagnetic radiation had to be thought of as a series of particles, called photons, which collide with the electrons on the surface and emit them. This theory ran contrary to the belief that electromagnetic radiation was a wave and thus it was not recognized as correct until 1916 when Robert Millikan experimentally confirmed the theory

Nature, it seemed, was quantized (non-continuous, or discrete). If this was so, how could Maxwell's equations correctly predict this result? Planck spent a good deal of time attempting to reconcile the behavior of electromagnetic waves with the discrete nature of the blackbody radiation, to no avail. It was not until 1905, with yet another paper published by Albert Einstein, that the wave nature of light was expanded to include the particle interpretation of light which adequately explained Planck's equation.

The photoelectric effect was first documented in 1887 by the German physicist Heinrich Hertz and is therefore sometimes referred to as the Hertz effect. While working with a spark-gap transmitter (a primitive radio-broadcasting device), Hertz discovered that upon absorption of certain frequencies of light, substances would give off a visible spark. In 1899, this spark was identified as light-excited electrons (also called photoelectrons) leaving the metal's surface by J.J. Thomson (Figure 1.3.1).

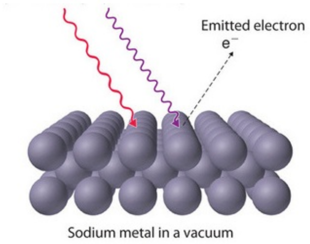


***Figure* 1.3.1*:** *The Photoelectric Effect involves the irradiating a metal surface with photons of sufficiently high energy to causes electrons to be ejected from the metal.*

The classical picture underlying the photoelectron effect was that the atoms in the metal contained electrons, that were shaken and caused to vibrate by the oscillating electric field of the incident radiation. Eventually some of them would be shaken loose, and would be ejected from the cathode. It is worthwhile considering carefully how the *number* and *speed* of electrons emitted would be expected to vary with the *intensity* and *color* of the incident radiation along with the time needed to observe the photoelectrons.

- Increasing the intensity of radiation would shake the electrons more violently, so one would expect more to be emitted, and they would shoot out at greater speed, on average.
- Increasing the frequency of the radiation would shake the electrons faster, so it might cause the electrons to come out faster. For very dim light, it would take some time for an electron to work up to a sufficient amplitude of vibration to shake loose.

LENARD'S EXPERIMENTAL RESULTS (INTENSITY DEPENDENCE)

In 1902, Hertz's student, Philipp Lenard, studied how the energy of the emitted photoelectrons varied with the intensity of the light. He used a carbon arc light and could increase the intensity a thousand-fold. The ejected electrons hit another metal plate, the collector, which was connected to the cathode by a wire with a sensitive ammeter, to measure the current produced by the illumination (Figure 1.3.2). To measure the energy of the ejected electrons, Lenard charged the collector plate negatively, to repel the electrons coming towards it. Thus, only electrons ejected with enough kinetic energy to get up this potential hill would contribute to the current.

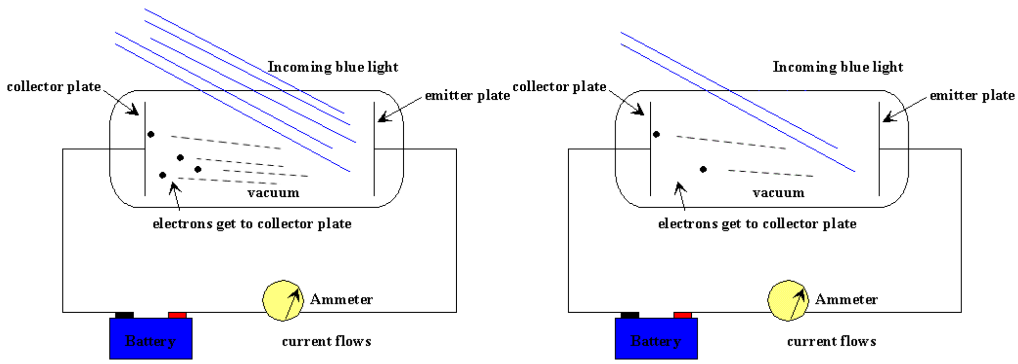


***Figure* 1.3.2:** *Millikan's photoelectric experiment. (left) High light intensity increase photocurrent (number of collected photoelectrons). (right) Low light intensity has reduced photocurrent. However, the kinetic energy of the ejected electrons is independent of incident light intensity.*

Lenard discovered that there was a well defined minimum voltage that stopped any electrons getting through (V_{stop}). To Lenard's surprise, he found that V_{stop} did not depend at all on the intensity of the light! Doubling the light intensity doubled the *number* of electrons emitted, but did not affect the *kinetic energies* of the emitted electrons. The more powerful oscillating field ejected more electrons, but the maximum individual energy of the ejected electrons was the same as for the weaker field (Figure 1.3.2).

MILLIKAN'S EXPERIMENTAL RESULTS (WAVELENGTH DEPENDENCE)

The American experimental physicist Robert Millikan followed up on Lenard's experiments and using a powerful arc lamp, he was able to generate sufficient light intensity to separate out the colors and check the photoelectric effect using light of different colors. He found that the maximum energy of the ejected electrons *did* depend on the color - the shorter wavelength, higher frequency light caused electrons to be ejected with more energy (Figures 1.3.3).

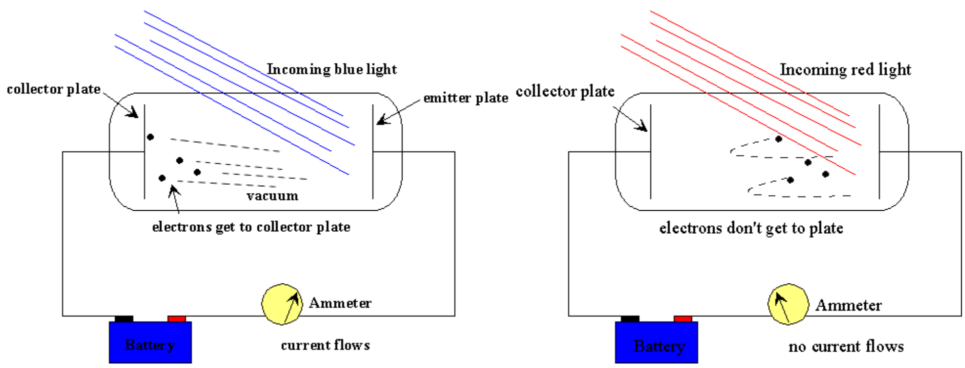


***Figure* 1.3.3*:** *Millikan's photoelectric experiment (left) High-energy blue light. The battery represents the potential Lenard used to charge the collector plate negatively, which would actually be a variable voltage source. Since the electrons ejected by the blue light are getting to the collector plate, the potential supplied by the battery is less than V_{stop}, for blue light. (right) Low-energy red light. Since the electrons ejected by the blue light are not getting to the collector plate, the potential supplied by the battery exceeds V_{stop} for red light.*

As shown in Figure 1.3.4, just the opposite behavior from classical is observed from Lenard's and Millikan's experiments. The intensity affects the number of electrons, and the frequency affects the kinetic energy of the emitted electrons. From these sketches, we see that

- the kinetic energy of the electrons is linearly proportional to the frequency of the incident radiation above a threshold value of ν_0 (no current is observed below ν_0), and the kinetic energy is independent of the intensity of the radiation, and
- the number of electrons (i.e. the electric current) is proportional to the intensity and independent of the frequency of the incident radiation above the threshold value of ν_0 (i.e., no current is observed below ν_0).

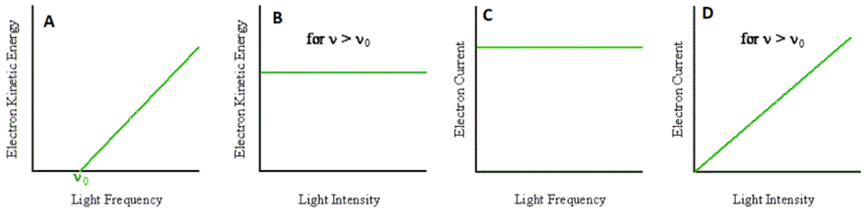


Figure 1.3.4: Schematic drawings showing the characteristics of the photoelectric effect from Lenard's and Millikan's experiments. (A) The kinetic energy of any single emitted electron increases linearly with frequency above some threshold value (B) The electron kinetic energy is independent of the light intensity. (C) The number of electrons emitted per second (i.e. the electric current) is independent of frequency. (D) The number of electrons increases linearly with the light intensity.

CLASSICAL THEORY DOES NOT DESCRIBE EXPERIMENT

Classical theory predicts that energy carried by light is proportional to its amplitude independent of its frequency, and this fails to correctly explain the observed wavelength dependence in Lenard's and Millikan's observations.

EINSTEIN'S QUANTUM PICTURE

In 1905 Einstein gave a very simple interpretation of Lenard's results and borrowed Planck's hypothesis about the quantized energy from his blackbody research and assumed that the incoming radiation should be thought of as quanta of frequency $h\nu$, with ν the frequency. In photoemission, one such quantum is absorbed by one electron. If the electron is some distance into the material of the cathode, some energy will be lost as it moves towards the surface. There will always be some electrostatic cost as the electron leaves the surface, this is usually called the workfunction, Φ. The most energetic electrons emitted will be those very close to the surface, and they will leave the cathode with kinetic energy

$$KE = h\nu - \Phi \tag{1.3.1}$$

On cranking up the negative voltage on the collector plate until the current just stops, that is, to V_{stop}, the highest kinetic energy electrons (KE_e) must have had energy eV_{stop} upon leaving the cathode. Thus,

$$eV_{stop} = h\nu - \Phi \tag{1.3.2}$$

Thus, Einstein's theory makes a very definite quantitative prediction: if the frequency of the incident light is varied, and V_{stop} plotted as a function of frequency, the slope of the line should be $\frac{h}{e}$ (Figure 1.3.4). It is also clear that there is a minimum light frequency for a given metal ν_o, that for which the quantum of energy is equal to Φ (Equation 1.3.1). Light below that frequency, no matter how bright, will not eject electrons.

> *Since, according to both Planck and Einstein, the energy of light is proportional to its frequency rather than its amplitude, there will be a minimum frequency ν_0 needed to eject an electron with no residual energy (Equation 1.3.1).*

Since every photon of sufficient energy excites only one electron, increasing the light's intensity (i.e. the number of photons/sec) only increases the *number* of released electrons and not their kinetic energy. In addition, no time is necessary for the atom to be heated to a critical temperature and therefore the release of the electron is nearly instantaneous upon absorption of the light. Finally, because the photons must be above a certain energy to satisfy the workfunction, a threshold frequency exists below which no photoelectrons are observed. This frequency is measured in units of Hertz (1/second) in honor of the discoverer of the photoelectric effect.

Einstein's Equation 1.3.1 explains the properties of the photoelectric effect quantitatively. A strange implication of this experiment is that light can behave as a kind of massless "particle" now known as a *photon* whose energy $E = h\nu$ can be transferred to an actual particle (an electron), imparting kinetic energy to it, just as in an elastic collision between to massive particles such as billiard balls.

Robert Millikan initially did not accept Einstein's theory, which he saw as an attack on the wave theory of light, and worked for ten years until 1916, on the photoelectric effect. He even devised techniques for scraping clean the metal surfaces inside the vacuum tube. For all his efforts he found disappointing results: he confirmed Einstein's theory after ten years. In what he writes in his paper, Millikan is still desperately struggling to avoid this conclusion. However, by the time of his Nobel Prize acceptance speech, he has changed his mind rather drastically!

Einstein's simple explanation (Equation 1.3.1) completely accounted for the observed phenomena in Lenard's and Millikan's experiments (Figure 1.3.4) and began an investigation into the field we now call *quantum mechanics*. This new field seeks to provide a quantum explanation for classical mechanics and create a more unified theory of physics and thermodynamics. The study of the photoelectric effect has also lead to the creation of new field of photoelectron spectroscopy. Einstein's theory of the photoelectron presented a completely different way to measure Planck's constant than from black-body radiation.

THE WORKFUNCTION (Φ)

The *workfunction* is an intrinsic property of the metal. While the workfunctions and ionization energies appear as similar concepts, they are independent. The workfunction of a metal is the minimum amount of energy (E) necessary to remove an electron from the surface of the bulk (*solid*) metal.

$$\mathrm{M(s) + E \rightarrow M^+(s) + e^-(free)} \tag{1.3.3}$$

This is qualitatively similar to ionization energy, which is the amount of energy required to remove an electron from an atom or molecule in the *gaseous* state.

$$\mathrm{M(g) + E \rightarrow M^+(g) + e^-(free)} \tag{1.3.4}$$

These two energies are generally different (Table 1.3.1). For instance, copper has a workfunction of about 4.7 eV, but has a higher ionization energy of 7.7 eV. Generally, the ionization energies for metals are greater than the corresponding workfunctions (the electrons are more tightly bound in metals).

Table 1.3.1: Workfunctions and Ionization Energies of Select Elements

Element	workfunction Φ (eV)	Ionization Energy (eV)
Copper (Cu)	4.7	7.7
Silver (Ag)	4.72	7.57
Aluminum (Al)	4.20	5.98
Gold (Au)	5.17	9.22
Boron (B)	4.45	8.298
Beryllium (Be)	4.98	9.32
Bismuth (Bi)	4.34	7.29
Carbon (C)	5.0	11.26
Cesium (Ce)	1.95	3.89
Iron (Fe)	4.67	7.87
Gallium (Ga)	4.32	5.99
(Hg) liquid	4.47	10.43
Sodium (Na)	2.36	5.13
Lithium (Li)	2.93	5.39
Potassium	2.3	4.34
Selenium (Se)	5.9	9.75
Silicon (Si)	4.85	8.15
Tin (Sn)	4.42	7.34
Germanium (Ge)	5.0	7.89
Arsenic (As)	3.75	9.81

EXAMPLE 1.3.1: CALCIUM

a. What is the energy in joules and electron volts of a photon of 420-nm violet light?
b. What is the maximum kinetic energy of electrons ejected from calcium by 420-nm violet light, given that the workfunction for calcium metal is 2.71 eV?

Strategy

To solve part (a), note that the energy of a photon is given by $E = h\nu$. For part (b), once the energy of the photon is calculated, it is a straightforward application of Equation 1.3.1 to find the ejected electron's maximum kinetic energy, since Φ is given.

Solution for (a)

Photon energy is given by

$$E = h\nu$$

Since we are given the wavelength rather than the frequency, we solve the familiar relationship $c = \nu\lambda$ for the frequency, yielding

$$\nu = \frac{c}{\lambda}$$

Combining these two equations gives the useful relationship

$$E = \frac{hc}{\lambda}$$

Now substituting known values yields

$$\begin{aligned} E &= \frac{(6.63 \times 10^{-34}\ J \cdot s)(3.00 \times 10^{8} m/s)}{420 \times 10^{-9}\ m} \\ &= 4.74 \times 10^{-19}\ J \end{aligned}$$

Converting to eV, the energy of the photon is

$$\begin{aligned} E &= (4.74 \times 10^{-19}\ J)\left(\frac{1\ eV}{1.6 \times 10^{-19}\ J}\right) \\ &= 2.96\ eV. \end{aligned}$$

Solution for (b)

Finding the kinetic energy of the ejected electron is now a simple application of Equation 1.3.1. Substituting the photon energy and binding energy yields

$$
\begin{aligned}
KE_e &= h\nu - \Phi \\
&= 2.96\ eV - 2.71\ eV \\
&= 0.246\ eV.
\end{aligned}
$$

Discussion

The energy of this 420-nm photon of violet light is a tiny fraction of a joule, and so it is no wonder that a single photon would be difficult for us to sense directly—humans are more attuned to energies on the order of joules. But looking at the energy in electron volts, we can see that this photon has enough energy to affect atoms and molecules. A DNA molecule can be broken with about 1 eV of energy, for example, and typical atomic and molecular energies are on the order of eV, so that the UV photon in this example could have biological effects.

The ejected electron (called a photoelectron) has a rather low energy, and it would not travel far, except in a vacuum. The electron would be stopped by a retarding potential of 0.26 eV. In fact, if the photon wavelength were longer and its energy less than 2.71 eV, then the formula would give a negative kinetic energy, an impossibility. This simply means that the 420-nm photons with their 2.96-eV energy are not much above the frequency threshold. You can show for yourself that the threshold wavelength is 459 nm (blue light). This means that if calcium metal is used in a light meter, the meter will be insensitive to wavelengths longer than those of blue light. Such a light meter would be insensitive to red light, for example.

EXERCISE 1.3.1

What is the longest-wavelength electromagnetic radiation that can eject a photoelectron from silver? Is this in the visible range?

Answer

Given that the workfunction is 4.73 eV from Table 1.3.1, then only photons with wavelengths lower than 263 nm will induce photoelectrons. This is ultraviolet and not in the visible range.

EXERCISE 1.3.2

Why is the workfunction generally lower than the ionization energy?

Answer

The workfunction of a metal refers to the minimum energy required to release an electron from the surface of a metal by a photon of light. The work function will vary from metal to metal. The Ionization energy is the energy needed to release electrons from their bound states around atoms, it will vary with each particular atom, with one outer electron around that atom needing less energy to release it than a lower, more closely bound electron, which requires greater energy because of the greater electrostatic force holding it closer to the nucleus. The electrons in the metal lattice there less bound (i.e., free to move within the metal). Removing one of these electron is much easier than removing an electron from an atom has a more tightly bound electron. So, the metallic bonds make it easier because multiple atoms (nuclei) "share" thes electrons, which reduces their binding energy (i.e., workfunction).

SUMMARY

The photoelectric effect is the process in which electromagnetic radiation ejects electrons from a material. Einstein proposed photons to be quanta of electromagnetic radiation having energy $E = h\nu$ is the frequency of the radiation. All electromagnetic radiation is composed of photons. As Einstein explained, all characteristics of the photoelectric effect are due to the interaction of individual photons with individual electrons. The maximum kinetic energy KE_e of ejected electrons (photoelectrons) is given by $KE_e = h\nu - \Phi$, where $h\nu$ is the photon energy and Φ is the workfunction (or binding energy) of the electron to the particular material.

CONCEPTUAL QUESTIONS

1. Is visible light the only type of electromagnetic radiation that can cause the photoelectric effect?
2. Which aspects of the photoelectric effect cannot be explained without photons? Which can be explained without photons? Are the latter inconsistent with the existence of photons?
3. Is the photoelectric effect a direct consequence of the wave character of electromagnetic radiation or of the particle character of electromagnetic radiation? Explain briefly.
4. Insulators (nonmetals) have a higher BE than metals, and it is more difficult for photons to eject electrons from insulators. Discuss how this relates to the free charges in metals that make them good conductors.
5. If you pick up and shake a piece of metal that has electrons in it free to move as a current, no electrons fall out. Yet if you heat the metal, electrons can be boiled off. Explain both of these facts as they relate to the amount and distribution of energy involved with shaking the object as compared with heating it.

CONTRIBUTORS

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- Adapted from "Quantum States of Atoms and Molecules" by David M. Hanson, Erica Harvey, Robert Sweeney, Theresa Julia Zielinski
- Paul Flowers (University of North Carolina - Pembroke), Klaus Theopold (University of Delaware) and Richard Langley (Stephen F. Austin State University) with contributing authors. Textbook content produced by OpenStax College is licensed under a Creative Commons Attribution License 4.0 license. Download for free at http://cnx.org/contents/85abf193-2bd...a7ac8df6@9.110).

1. You wish to pick a substance for a photocell operable with visible light. Which of the following will be most suitable for red($\lambda = 650\ nm$) and green light($\lambda = 450\ nm$)? Given is the metal work function.

(1) Tantalum (4.2 eV)	(2) Aluminium (4.2 eV)
(3) Tungsten (4.5 eV)	(4) Lithum (2.3 eV)
(5) Barium (2.5 eV)	(6) Cesium (1.9 eV)

2. Light of wavelength 200 nm falls on an aluminium surface, having work function 4.2 eV. What is the K.E. of the fastest emitted photoelectron? Also find the stopping potential and calculate the cutoff wavelength for Al.

3. When a photon energy is increased from hf to $2hf + w_0$, what does the photoelectric current increase by?

4. Why does the photoelectric current not rise vertically to its maximum value when the applied potential difference is slightly more positive than $-V_0$?

5. Do you observe a Compton effect with visible light? why?

6. Why, in Compton scattering, would you expect $\triangle\lambda$ to be independent of materials of which the scatterer is composed?

7. How many collisions does a photon require to lost its energy completely (that is, to disappear), in Compton scattering and in photoelectric effect?

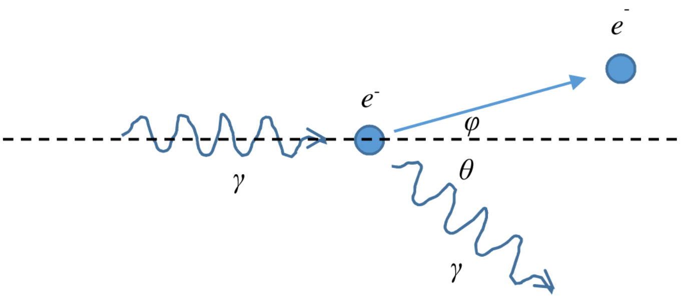
8. Find the shortest wavelength present in the radiation from an X-ray machine whose accelerating potential is $50,000$ V.

9. X-rays of wavelength 10 pm are scattered from a target. Find (a) the wavelength of the X-rays scattered through an angle of 45^0, (b) the maximum wavelength present in the scattered X-rays, (c) the maximum K.E. of the recoil electrons.

The Compton effect

A further demonstration of the particle nature of light was provided by Compton's experiments in which he scattered X-rays from electrons bound in atoms. If the electrons are loosely bound to the atom, they can be treated as free electrons at rest. According to classical physics, the wavelength of the X-rays would not be changed by the interaction with the electrons. However, Compton did find a change in wavelength, which can be explained by treating light as made of particles, i.e. photons.

The scattering of a photon off an electron is shown in the figure:



Denote the energy of the incident photon by E_γ, and that of the scattered photon by E'_γ. The electron is initially at rest and its energy is its rest energy, m_ec^2. After scattering, let the electron energy be E'_e. Conservation of relativistic energy gives

$$E_\gamma + m_ec^2 = E'_\gamma + E'_e. \tag{12.1}$$

Conservation of momentum gives the two equations

$$\begin{aligned} \frac{E_\gamma}{c} &= \frac{E'_\gamma}{c}\cos\theta + p'_e\cos\varphi, \\ 0 &= \frac{E'_\gamma}{c}\sin\theta - p'_e\sin\varphi. \end{aligned} \tag{12.2}$$

Since we are interested in the change in energy of the photon, let's eliminate the electron momentum and energy from equations (12.1) and (12.2). We have

$$\begin{aligned} cp'_e\cos\varphi &= E_\gamma - E'_\gamma\cos\theta, \\ cp'_e\sin\varphi &= E'_\gamma\sin\theta. \end{aligned} \tag{12.3}$$

Squaring and adding gives

$$\left(cp'_e\right)^2 = \left(E_\gamma - E'_\gamma\cos\theta\right)^2 + \left(E'_\gamma\sin\theta\right)^2 = E_\gamma{}^2 - 2E_\gamma E'_\gamma\cos\theta + E'^2_\gamma. \tag{12.4}$$

Now

$$E_e'^2 = (cp_e')^2 + (m_e c^2)^2 . \quad (12.5)$$

Using equation (12.1), this gives

$$\left(E_\gamma - E_\gamma' + m_e c^2\right)^2 = E_\gamma^2 - 2E_\gamma E_\gamma' \cos\theta + E_\gamma'^2 + \left(m_e c^2\right)^2 . \quad (12.6)$$

This simplifies to

$$m_e c^2 \left(E_\gamma - E_\gamma'\right) = E_\gamma E_\gamma' \left(1 - \cos\theta\right), \quad (12.7)$$

which can also be written as

$$m_e c^2 \left(\frac{1}{E_\gamma'} - \frac{1}{E_\gamma}\right) = \left(1 - \cos\theta\right). \quad (12.8)$$

To get an expression involving wavelengths, we note that a photon has energy $E_\gamma = hf = hc/\lambda$. Hence

$$\lambda' - \lambda = \frac{h}{m_e c}\left(1 - \cos\theta\right). \quad (12.9)$$

The combination of physical constants $h/m_e c$ is called the **Compton wavelength of the electron**. Its value is 0.0024 nm. The Compton wavelength lies in the X-ray part of the electromagnetic spectrum, and hence X-rays were necessary to show the Compton effect. For visible light, the relative change in wavelength is about 5 10^{-6}, but for X-rays of wavelength 0.1 nm, the relative change is much larger and of order 0.02.

Note that the greatest change in photon energy occurs when it is back scattered (i.e. $\theta = 180^\circ$). Then from conservation of momentum

$$cp_e' = E_\gamma + E_\gamma'. \quad (12.10)$$

If the energy of the incident photon is much larger than the electron rest energy, conservation of relativistic energy gives

$$E_e' = E_\gamma - E_\gamma'. \quad (12.11)$$

Again neglecting the electron rest energy, so that $cp_e' \approx E_e'$, we see that $E_e' \approx E_\gamma$. Photons with energy much greater than the electron rest energy can transfer most of their energy to the electrons, which is way of making very energetic electrons. Similarly in collisions between energetic electrons and low energy photons, most of the electron's kinetic energy can be transferred to the photon, giving highly energetic photons. This is called the **inverse Compton effect**. The inverse Compton effect can be used to produce high energy photons by backscattering laser light off beams of electrons accelerated in synchrotron facilities. The resulting MeV to GeV range photons are used for nuclear physics experiments.