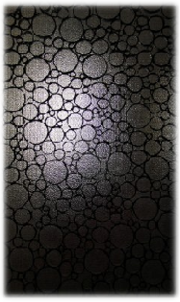
SPH4U UNIVERSITY PHYSICS

REVOLUTIONS IN MODERN PHYSICS: ...

☞ Photons & the Quantum Theory of ... (P.620-623)

The Work Function

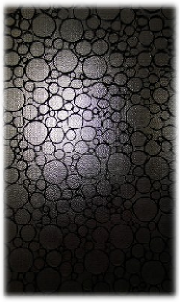
Around 1800, Thomas Young performed his double-slit interference experiment which provided the first clear evidence that light is a wave. Maxwell worked out his theory of electromagnetic waves about 60 years later. Then, physicists developed a detailed theory of light as an electromagnetic wave and thought that the nature of light was well understood. In the 1880s, however, studies of what happens when light shines onto metal gave some very puzzling results that the wave theory of light could not explain.



The Work Function

RECALL!

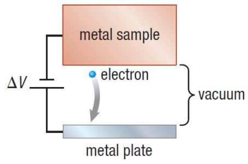
Metals contain electrons that are free to move around within the metal. However, these electrons are still bound as a whole to the metal because of their attraction to the positive charges of the metal atom nuclei. Energy is required to remove electrons from the atoms.



The Work Function

The minimum energy required to remove a single electron from a piece of metal is called the ***work function****. For convenience, researchers often give the value of the work function in electron-volts (eV) rather than joules.*

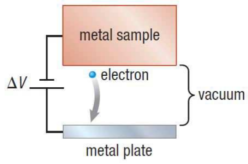
1 eV = 1.60×10^{-19} J



The Work Function

NOTE!

You can measure the work function of a metal by applying an electric potential. The smallest electric potential difference able to eject electrons gives the value of the work function for that material.



The Work Function

WORK FUNCTION (W)

- the minimum energy needed to remove an electron bound to a metal surface
- often expressed in electron-volts (eV) rather than joules (J)

$$W = e\,\Delta V$$

where W is the work function of the metal (J)
e is the charge on an electron (1.6×10^{-19} C)
ΔV is the potential difference (V)

NOTE!

1 eV = 1.60×10^{-19} J

The Work Function

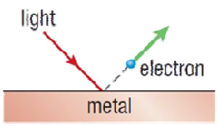
PRACTICE

1. A shiny metal with an unknown work function is connected through a potential difference to another metal plate. The minimum potential that will eject electrons toward the bottom plate is 5.65 V. Determine the metal's work function in joules (J) and electron-volts (eV).

   $W = 9.04 \times 10^{-19}$ J or 5.65 eV

The Photoelectric Effect

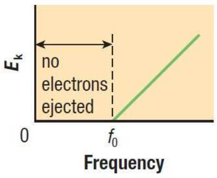
*Another way to extract electrons from a metal is by shining light onto it. Light striking a metal surface is absorbed by the electrons. If an electron absorbs an amount of light energy above the metal's work function, it gets ejected from the metal in a phenomenon called the **photoelectric effect**. The electrons ejected are sometimes referred to as **photoelectrons**.*



The Photoelectric Effect

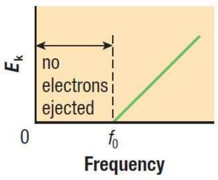
NOTE!

*Experimental studies of the photoelectric effect carried out around 1900 revealed that no electrons are emitted unless the light's frequency is greater than the **threshold frequency**, f_0, which is, the minimum frequency at which electrons are ejected from a material.*



The Photoelectric Effect

Experiments also showed that when the frequency is above f_0, the kinetic energy of the emitted electrons varies linearly with frequency f, as shown.



The Photoelectric Effect

Physicists tried to explain these results using the classical wave theory of light, but two difficulties existed with the classical explanations.

***First**, experiments show that the threshold frequency is independent of the intensity (i.e. the brightness) of the light. According to the classical wave theory, the energy carried by a light wave is proportional to the intensity of the light. As such, it should always be possible to eject electrons by increasing the intensity of the light. However, experiments found that when the frequency is below the threshold frequency no electrons are ejected, no matter how great the light intensity.*

The Photoelectric Effect

Physicists tried to explain these results using the classical wave theory of light, but two difficulties existed with the classical explanations.

***Second**, the kinetic energy of an ejected electron is independent of the light intensity. Classical theory predicts that increasing the intensity will increase the kinetic energy of the electrons, but experiments do not show this.*

The Photoelectric Effect

PHOTOELECTRIC EFFECT

- the phenomenon of electrons being ejected from a material when exposed to em radiation
- could not be explained using classical wave theory of light b/c:
  - f_0 is independent of the light intensity
  - the E_k of the ejected electrons is independent of the light intensity (i.e. the brightness)

THRESHOLD FREQUENCY (f_0)

- the minimum frequency at which electrons are ejected from a material

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The Photoelectric Effect

PRACTICE

2. A wavelength of dim red light ejects no electrons. Suppose you increase the intensity by a factor of 1000. Explain whether the red light can now eject electrons according to the photoelectric effect.

   no – the frequency of the red light is below the threshold frequency, it does not matter if the intensity is increased

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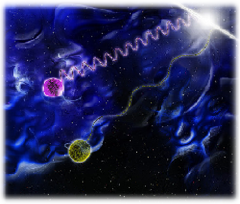
Photons

*In 1905, Albert Einstein proposed that light should be thought of as a collection of particles, called **photons**. However, photons have two very important properties that makes them quite different from classical particles.*



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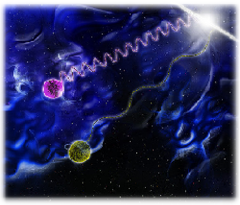
Photons

① *Photons do not have any mass.*

② *Photons exhibit interference effects, just as electrons do in double-slit interference experiments.*



Photons

According to Einstein, each photon carries a parcel of maximum kinetic energy (quantum) according to the following equation:

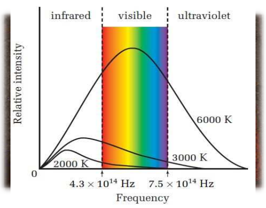
$$E_{photon} = hf$$

where f is the frequency of the light and h is a constant of nature called Planck's constant, which has a value of 6.63 x 10^-34 J·s.

NOTE!
Planck's constant had been introduced a few years earlier by Max Planck to explain an unexpected property of incandescent objects – blackbody radiation.

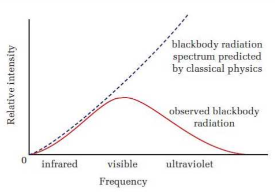
Planck & Blackbody Radiation

*In 1901, Max Planck was studying blackbodies and blackbody radiation. A **blackbody** is an object that absorbs all radiation reaching it, and **blackbody radiation** is radiation emitted by a blackbody. A kiln is an approximate blackbody. As the temperature of the kiln increases, the frequency that is emitted with the highest intensity (the peak of the curve) becomes higher.*



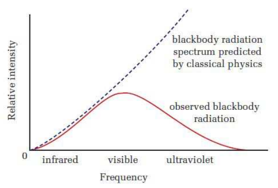
Planck & Blackbody Radiation

At low frequencies, predictions based on classical theory agree with observed data for the intensity of radiation from a blackbody. At high frequencies, however, theory and observation diverge quite drastically. This discrepancy between theory and observation shocked the physicists of the day so much they called it the ***ultraviolet catastrophe****.*



Planck & Blackbody Radiation

Planck resolved this disagreement by hypothesizing that the energy in a blackbody comes in discrete parcels (quanta) and that each parcel has an energy equal to hf where f is the frequency and h is a universal constant. His theory fit the experiments perfectly, but no one (including Planck) knew why it worked. Einstein answered that question in part.



Einstein's Quantum Theory of Light

PHOTONS

- discrete bundles of energy carried by light
- do not have a mass
- exhibit interference effects

$$E_{photon} = hf = \frac{hc}{\lambda}$$

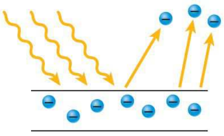
recall that $c = f\lambda$

where E_{photon} is the amount of energy possessed by a photon (J)
h is Planck's constant (6.63×10^{-34} J·s)
f is the frequency of the light (Hz)
c is the speed of light (3.00×10^{8} m/s)
λ is the wavelength of the light (m)

Einstein's Quantum Theory of Light

Einstein's photon, or quantum, theory explains the two puzzles associated with photoelectric experiments.

***First**, the absorption of light by an electron is just like a collision between two particles, a photon and an electron. The photon carries energy (hf), which the electron absorbs. When this energy is less than the work function, the electron is not able to escape from the metal.*



Einstein's Quantum Theory of Light

Einstein's photon, or quantum, theory explains the two puzzles associated with photoelectric experiments.

***Second**, the threshold frequency in the photoelectric effect corresponds to photons whose energy is equal to the work function ($W=hf_0$). In this case, the photon has enough energy to eject an electron from the metal, but the ejected electron then has no kinetic energy. Thus, if a photon has a higher frequency and thus a greater energy, the extra energy above the work function goes into the kinetic energy of the electron. So,*

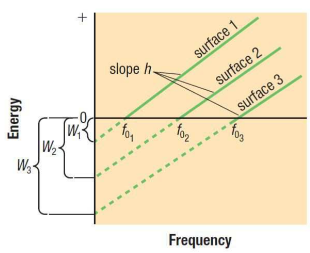
$$E_k = hf - hf_0 \quad \text{or} \quad E_k = hf - W$$

NOTE!

This is the equation of a straight line ☞ $E_k \propto f$

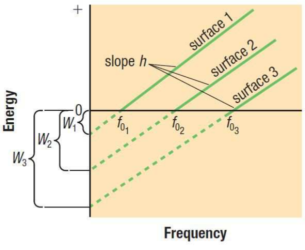
Einstein's Quantum Theory of Light

This linear behaviour is precisely what is found in photoelectric experiments. The slope of the energy of ejected electrons versus the frequency of incident light does not change for the three surfaces, even though they each have different work functions.



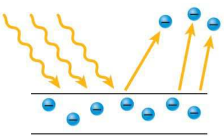
Einstein's Quantum Theory of Light

NOTE!
The slope equals h (Planck's constant).



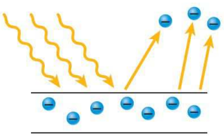
Einstein's Quantum Theory of Light

While Einstein's explanation could account for all of the observations of the photoelectric effect, very few physicists accepted his argument regarding the quantum (or particle) nature of light. It was very difficult to put aside 200 years of observations that supported the wave theory. More evidence would be needed before the scientific community would embrace the theory of the quantization of energy.



Einstein's Quantum Theory of Light

NOTE!
The evidence came later when Millikan verified Einstein's quantum theory of light.



The Photoelectric Effect

PHOTOELECTRIC EFFECT (continued ...)

$$E_k = hf - W$$

where E_k is the maximum kinetic energy of an ejected electron (J)
h is Planck's constant (6.63×10^{-34} J·s)
f is the frequency of the light (Hz)
W is the work function of the metal (J)

NOTE!

- $E_{photon} < W$ electron does not escape
- $E_{photon} = W$ electron just escapes ($E_k = 0$)
- $E_{photon} > W$ electron escapes and flies off ($E_k > 0$)

The Photoelectric Effect

PRACTICE

3. Aluminum is being used in a photoelectric effect experiment. The work function of aluminum is 6.73×10^{-19} J.
   (a) Calculate the minimum photon energy (in J and eV) and frequency needed to emit electrons.

   (a) $E_{min} = 6.73 \times 10^{-19}$ J or 4.21 eV
   $f_{min} = 1.02 \times 10^{15}$ Hz

The Photoelectric Effect

PRACTICE

3. Aluminum is being used in a photoelectric effect experiment. The work function of aluminum is 6.73×10^{-19} J.
   (b) Incident blue light of wavelength 450 nm is used in the experiment. Determine whether any electrons are emitted, and if they are, determine their maximum kinetic energy.

   (b) since 450 nm (4.42×10^{-19} J) is less than the work function of the metal no electrons are ejected

The Photoelectric Effect

PRACTICE

4. When UV radiation is used to eject electrons from a lead metal surface (W = 4.25 eV), the maximum kinetic energy of the electrons emitted is 2.00 eV. What was the (i) frequency and (ii) wavelength of the radiation used?

   $f = 1.51 \times 10^{15}$ Hz
   $\lambda = 199$ nm

The Photoelectric Effect

PRACTICE

5. The electrons emitted from a surface illuminated by light with a wavelength of 460 nm have a maximum speed of 4.2×10^5 m/s. Given that an electron has a mass of 9.11×10^{-31} kg, calculate the work function (in J and eV) of the surface material.

   $W = 3.5 \times 10^{-19}$ J or 2.2 eV

The Photoelectric Effect – DYK?

Like many other theoretical developments in physics, scientists soon found some practical applications for the photoelectric effect. The first light meters used the photoelectric effect to measure the intensity of light. Light meters have specialized metal emitters that are sensitive to visible light. When light strikes the metal, electrons are released and then collected by a positive electrode. The amount of current produced is proportional to the intensity of the light.

The Photoelectric Effect – DYK?

NOTE!
The photon that physicists once had difficulty accepting is now almost a household word.

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TEXTBOOK
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PHYSICS FILE
Albert Einstein never actually carried out any laboratory experiments. He was a genius, however, at interpreting and explaining the results of others. In addition, the technology needed to test many of his theories did not exist until many years after he published them. Einstein was truly a theoretical physicist.