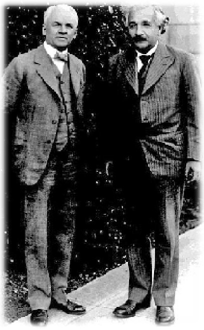
SPH4U UNIVERSITY PHYSICS

REVOLUTIONS IN MODERN PHYSICS: ...

☞ Photons & Momentum
(P.624-626)

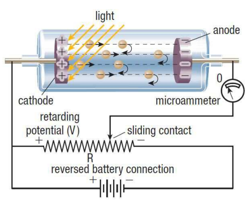
Millikan & The Photoelectric Effect

By 1916, Robert Millikan had established that the magnitude of the charge on an electron was 1.60 x 10^{-19} C. With this "ammunition" in hand, Millikan set out to prove that Einstein's assumptions regarding the quantum nature of light were incorrect. Like others, Millikan felt that the evidence for the wave nature of light was overwhelming.



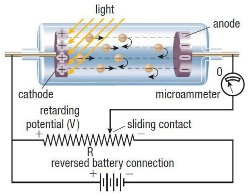
Millikan & The Photoelectric Effect

In order to do this, Millikan used a photoelectric device similar to the one shown (except his used emitters composed of various metals). It was an improvement on a device originally designed in 1902 by physicist Philip Lenard. It contained a very sensitive galvanometer to measure any current passing through the circuit as well as a variable power supply that could make either electrode positive or negative.



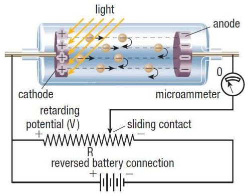
Millikan & The Photoelectric Effect

When the cathode was exposed to light of various frequencies the microammeter registered a current. The light had ejected electrons, which were attracted to the anode and then passed through the circuit. And when the intensity of the light was increased, the current increased.



Millikan & The Photoelectric Effect

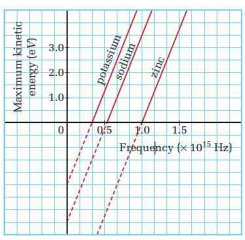
To learn more about the kinetic energies of the ejected electrons, the polarity of the power supply was reversed so that the electric field between the electrodes would oppose the motion of the electrons. Millikan discovered that as he increased the potential difference, the current gradually decreased until it finally stopped flowing entirely. The opposing potential had turned back even the most energetic electrons.



NOTE!
The potential difference that stopped all photoelectrons (i.e. the current is zero) is called the ***stopping potential****.*

Millikan & The Photoelectric Effect

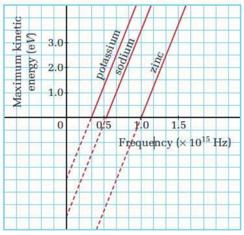
When Millikan plotted his data, they resulted in straight lines. The slopes of the lines from all experiments were the same and were equal to Planck's constant ($h = 6.63 \times 10^{-34}$ J·s). And when Millikan extrapolated the lines to cross the vertical axis, the value gave the negative of the work function of the metal.



Millikan & The Photoelectric Effect

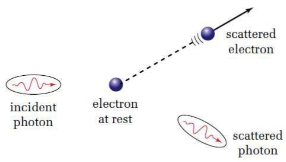
Much to Millikan's disappointment, he had proven that Einstein's equations perfectly predicted all of his results. He begrudgingly had to concede that Einstein's assumptions about the quantum nature of light were probably correct.

$E_{photon} = hf$ & $E_k = hf - W$



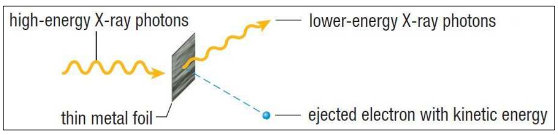
Photons, Energy & Momentum

When Millikan's experimental results verified Einstein's interpretation of the photoelectric effect, the scientific community began to accept the particle nature of light. Physicists started to ask more questions about the extent to which particles of light, or photons, resembled particles of matter. American physicist Arthur Compton decided to study elastic collisions between photons and electrons. Would the law of conservation of momentum apply to such collisions? How could physicists determine the momentum (mv) of a particle that has no mass?



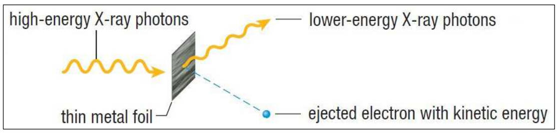
Photons, Energy & Momentum

*In 1923, Compton discovered a phenomenon that provided experimental evidence of the momentum carried by individual photons. Instead of using visible light, Compton directed a beam of high-energy X-ray photons at a thin metal foil. The foil ejected both electrons and lower-energy X-ray photons. This effect, in which incident X-ray photons lose energy and scatter off a metal foil along with free electrons, is called the **Compton effect**.*



Photons, Energy & Momentum

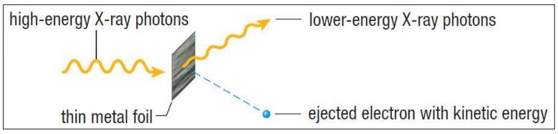
Compton conducted a series of experiments using different metal foils and different beams of X-rays. Each test produced similar results that could not be explained using electromagnetic wave theory. The results suggested to Compton that each incident X-ray photon acts like a particle in an elastic collision with an electron in the metal. The photon emerges from the collision with lower energy and a different momentum. The electron deflects with kinetic energy and momentum lost by the photon.



Photons, Energy & Momentum

NOTE!

Compton's data indicted that the effect conserves both energy and momentum. Compton had to use equations of special relativity to correctly analyze the collisions, including the expressions for relativistic momentum. In this way, Einstein's ideas on relativity and the speed of light influenced work that confirmed Einstein's ideas about the behaviour and characteristics of photons.



Photons, Energy & Momentum

COMPTON EFFECT

- the elastic scattering of photons by high-energy photons
- energy and momentum are conserved

$$p_{photon} = \frac{hf}{c} = \frac{h}{\lambda}$$

recall that $c = f\lambda$

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

Photons, Energy & Momentum

PRACTICE

1. A certain AM radio station has a frequency near 1.0 MHz, and a certain FM station has a frequency near 110 MHz. Radio waves are electromagnetic waves, so the radio waves produce photons.
   (a) Compare the momentum of the photons from the AM station with the momentum of the photons from the FM station.

   (a) $p_{AM} = 2.2 \times 10^{-36}$ kg·m/s & $p_{FM} = 2.4 \times 10^{-34}$ kg·m/s

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Photons, Energy & Momentum

PRACTICE

1. A certain AM radio station has a frequency near 1.0 MHz, and a certain FM station has a frequency near 110 MHz. Radio waves are electromagnetic waves, so the radio waves produce photons.
   (b) Compare the energy of the photons from the AM and the FM stations.

   (b) $E_{AM} = 6.6 \times 10^{-28}$ J & $E_{FM} = 7.3 \times 10^{-26}$ J

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Photons, Energy & Momentum

PRACTICE

2. A photon possesses a momentum of 2.45×10^{-32} kg·m/s.
   (a) What is the frequency of the photon?
   (b) Where in the electromagnetic spectrum would this photon be?

   (a) $f = 1.11 \times 10^{10}$ Hz
   (b) radio

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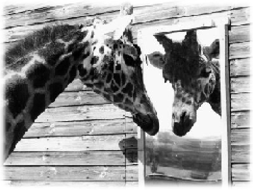
Photon Interactions

In both the photoelectric effect and the Compton effect, when a photon comes into contact with matter, an interaction takes place. Five main interactions can occur:

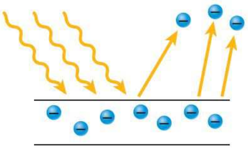
1. *A photon may simply* ***reflect****, as when photons of visible light undergo perfectly elastic collisions with a mirror.*



Photon Interactions

In both the photoelectric effect and the Compton effect, when a photon comes into contact with matter, an interaction takes place. Five main interactions can occur:

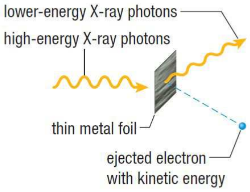
2. *A photon may free an electron and be absorbed in the process. This is the* ***photoelectric effect****.*



Photon Interactions

In both the photoelectric effect and the Compton effect, when a photon comes into contact with matter, an interaction takes place. Five main interactions can occur:

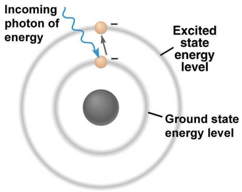
3. *A photon may emerge with less energy and momentum after freeing an electron. After this interaction with matter, the photon still travels at the speed of light but with less energy and a lower frequency. This is the* ***Compton effect****.*



Photon Interactions

In both the photoelectric effect and the Compton effect, when a photon comes into contact with matter, an interaction takes place. Five main interactions can occur:

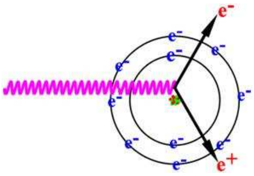
4. *A photon may be* ***absorbed*** *by an individual atom and elevate an electron to a higher energy level within the atom. The electron remains within the atom but is in an* ***excited state****.*



Photon Interactions

In both the photoelectric effect and the Compton effect, when a photon comes into contact with matter, an interaction takes place. Five main interactions can occur:

5. *A photon can undergo* ***pair creation****, where it becomes converted into two particles with mass. This process conserves energy and momentum because all the energy of the photon becomes converted into the kinetic energy of the new particles and their rest mass energy.*



Photon Interactions

PHOTON INTERACTIONS

- when a photon comes into contact with matter, five main interactions can occur:
  ① reflection
  ② photoelectric effect
  ③ Compton effect
  ④ absorbed (electron in excited state)
  ⑤ pair creation

✔ Check Your Learning

TEXTBOOK

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