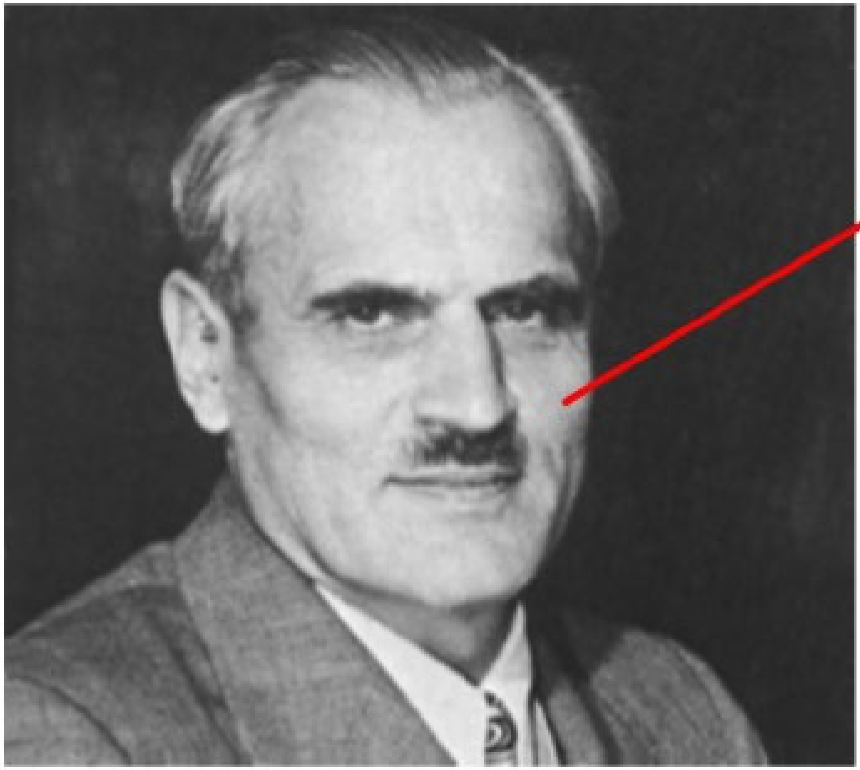
Physics 30 Unit C - EMR

The Compton Effect



Hey Kids! Learn about my effect!

Lesson 9

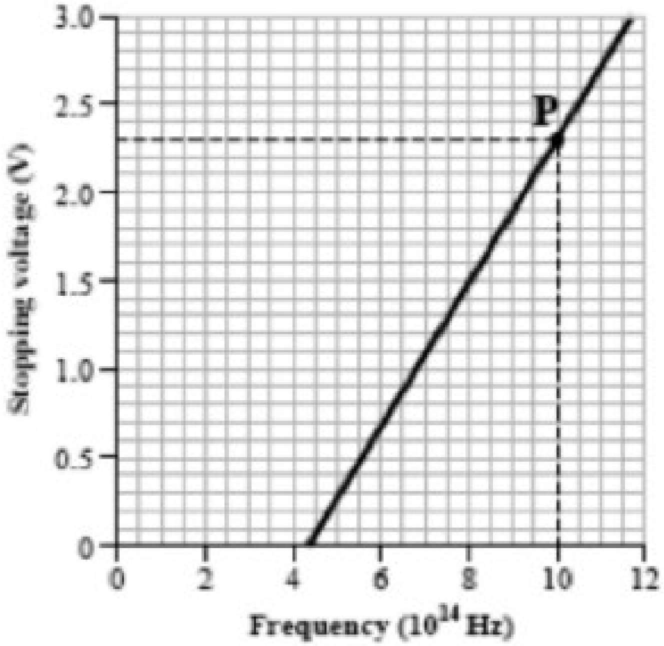
Objective

- **Explain, qualitatively and quantitatively, how the Compton effect is an example of wave particle duality, applying the laws of mechanics and conservation of momentum and energy to photons**

Diploma Question Alert!

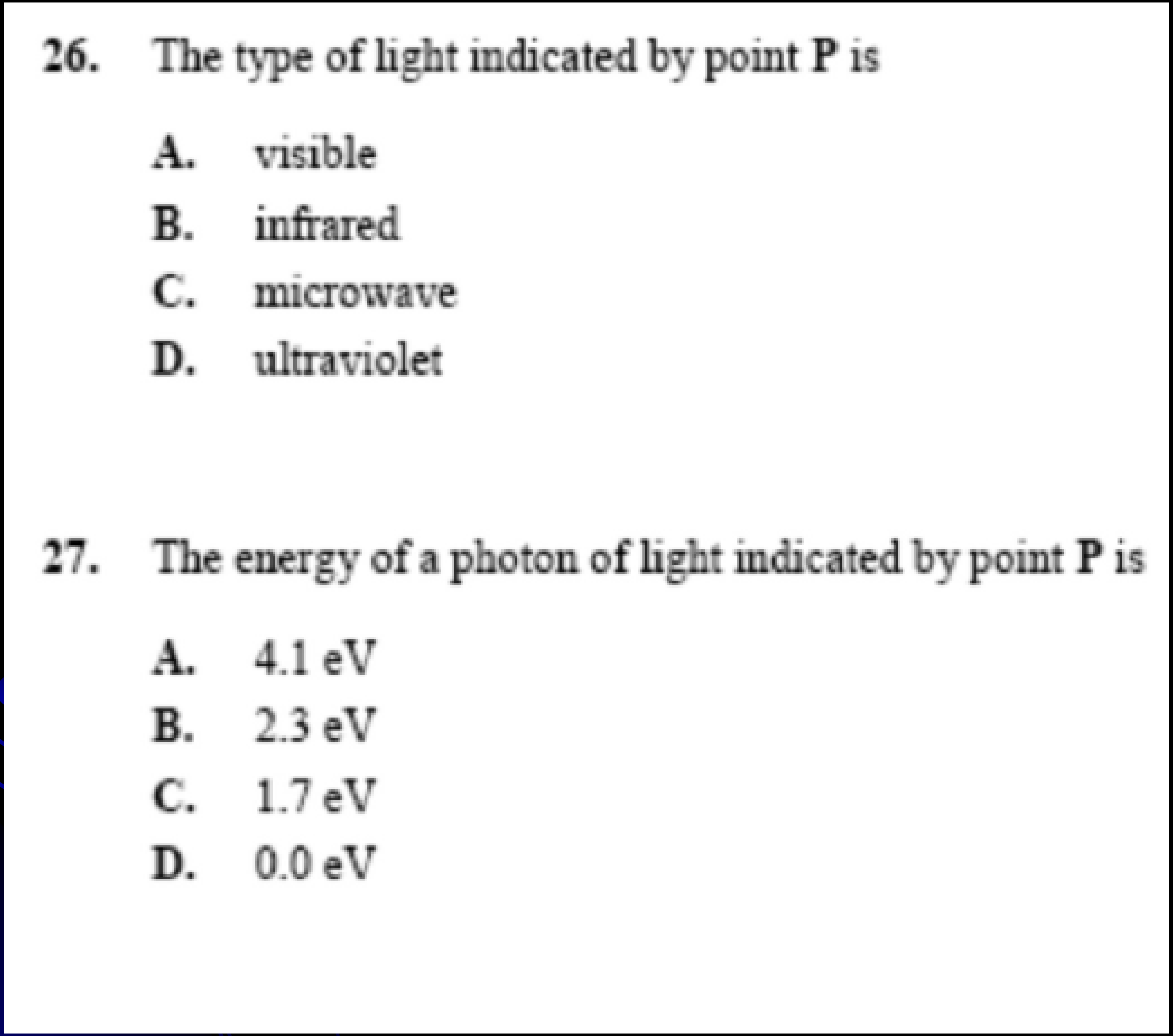
Use the following information to answer the next three questions.

A graph of data obtained from a photoelectric effect experiment is shown below.



Stopping Voltage as a Function of the Frequency of Incident Light on a Cesium Plate

Point **P** corresponds to a trial using light at the frequency indicated.

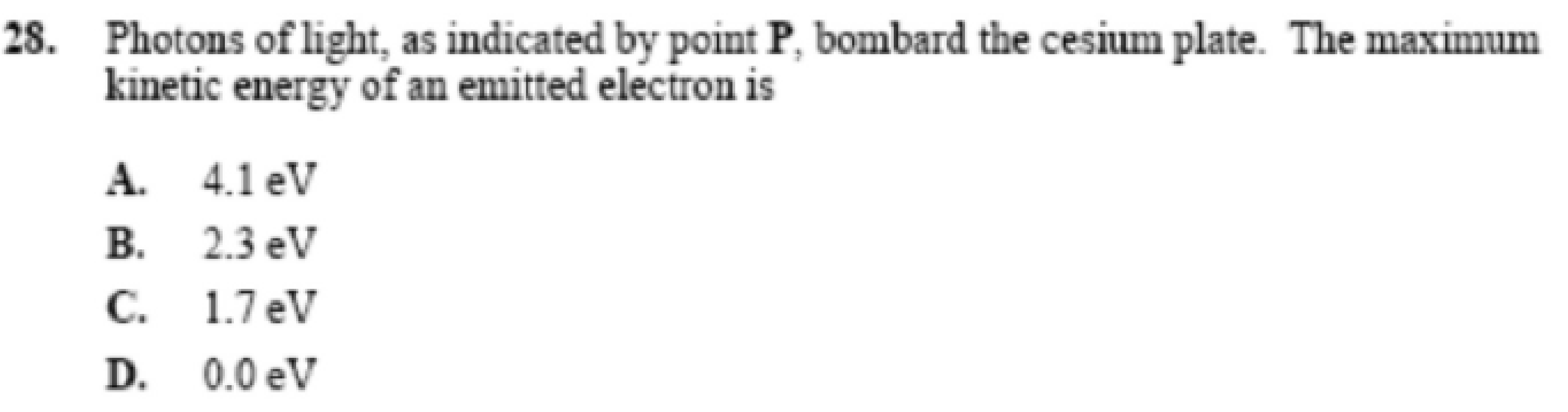


26. The type of light indicated by point **P** is

- A. visible
- B. infrared
- C. microwave
- D. ultraviolet

27. The energy of a photon of light indicated by point **P** is

- A. 4.1 eV
- B. 2.3 eV
- C. 1.7 eV
- D. 0.0 eV



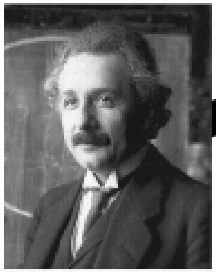
28. Photons of light, as indicated by point **P**, bombard the cesium plate. The maximum kinetic energy of an emitted electron is

A. 4.1 eV

B. 2.3 eV

C. 1.7 eV

D. 0.0 eV



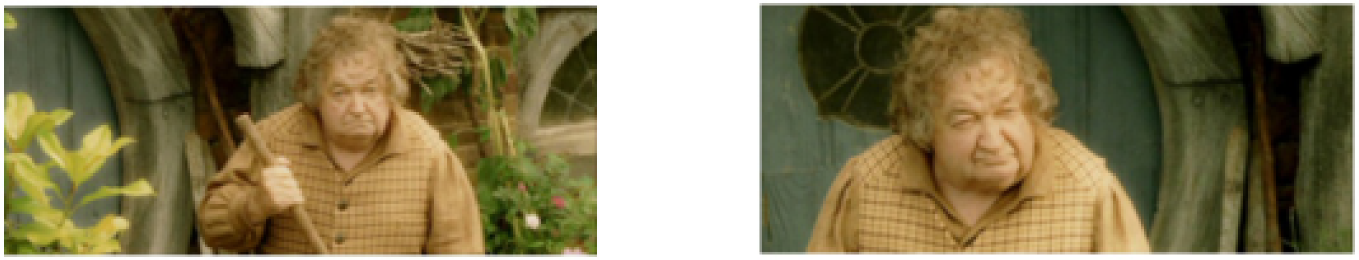
1905

The year 1905 will forever be known to physicists as Einstein's Wonderful Year. In the period of 12 months, he released papers on:

- **the photoelectric effect and the photon theory of light**
- **Brownian motion, supporting Atomic Theory (Nobel Prize)**
- **Special Relativity (c is upper limit, length contraction, time dilation, lack of simultaneity, death of aether)**
- **Mass-Energy equivalence: $E = mc^2$**

Q: What have you done this year? (Just asking)

The photoelectric effect was a huge proof that light behaved like a particle, but the entire scientific community still wasn't convinced.



So, what other particle like properties could light also have?

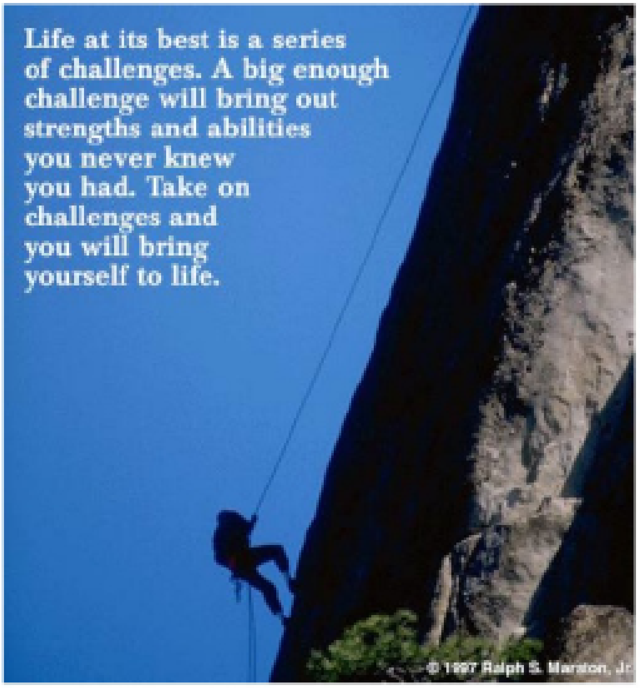
Unit

Hint: A

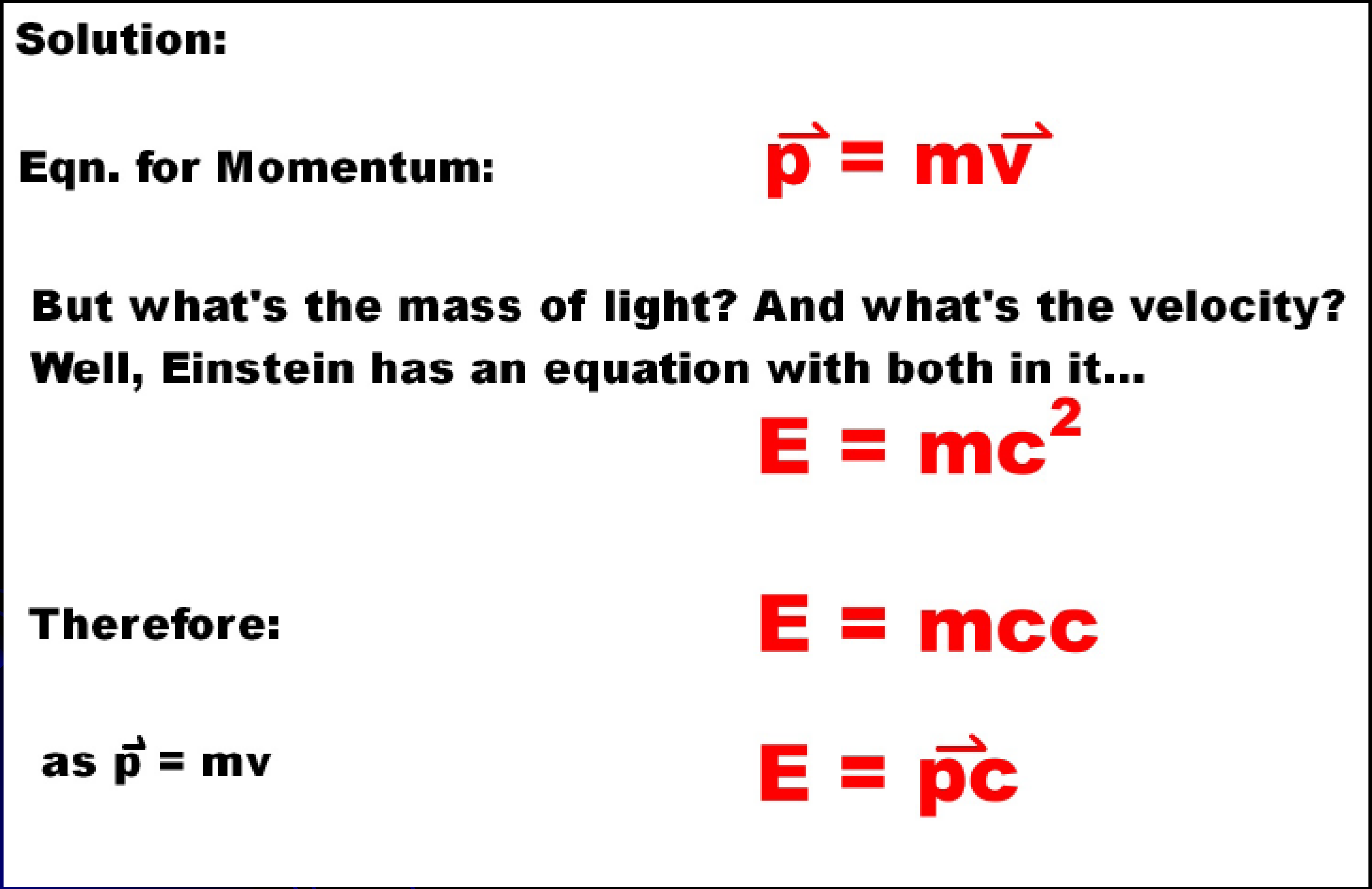
Momentum

If light is really a particle, it must have momentum. In his mass-energy equivalence paper, Einstein theorized that photons must have momentum.

Challenge: Derive a formula for the momentum of a photon.



Crappy Motivational Poster



Solution:

Eqn. for Momentum: $\vec{p} = m\vec{v}$

But what's the mass of light? And what's the velocity? Well, Einstein has an equation with both in it...

$$E = mc^2$$

Therefore: $E = mcc$

as $\vec{p} = mv$ $E = \vec{p}c$

$$E = \vec{p}c$$

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

$$\frac{hc}{\lambda} = \vec{p}c$$

Therefore:

$$\vec{p} = \frac{h}{\lambda}$$

momentum of light

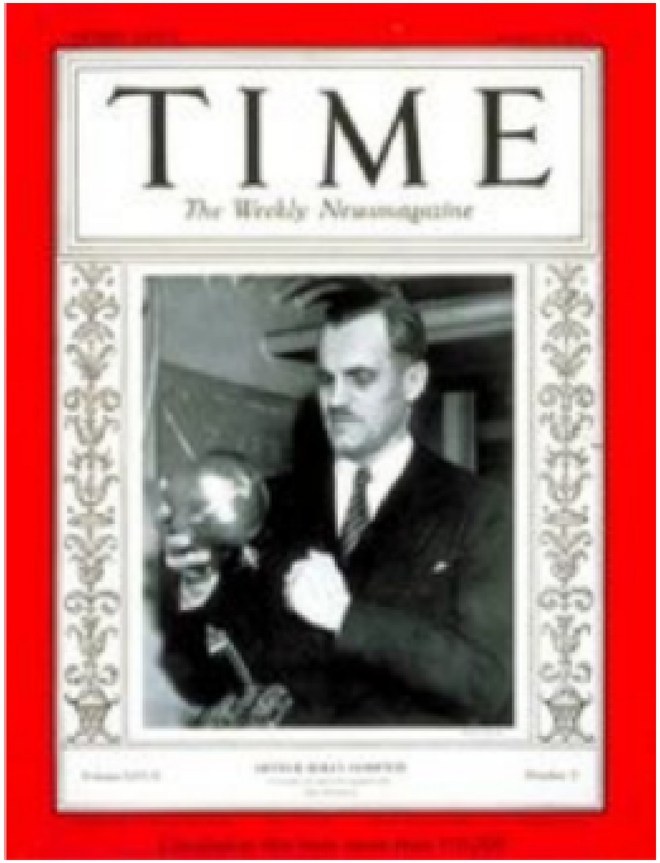
h = Planck's Constant

λ = wavelength of light

This is a mathematical expression that shows light has momentum. But without proof, it's little more than some interesting math...

Proof = Arthur Compton

In 1923, 18 years after Einstein's Wonderful Year (and after all his other theories from that year had been proven), American Arthur Compton devised an experiment to show photons have momentum.

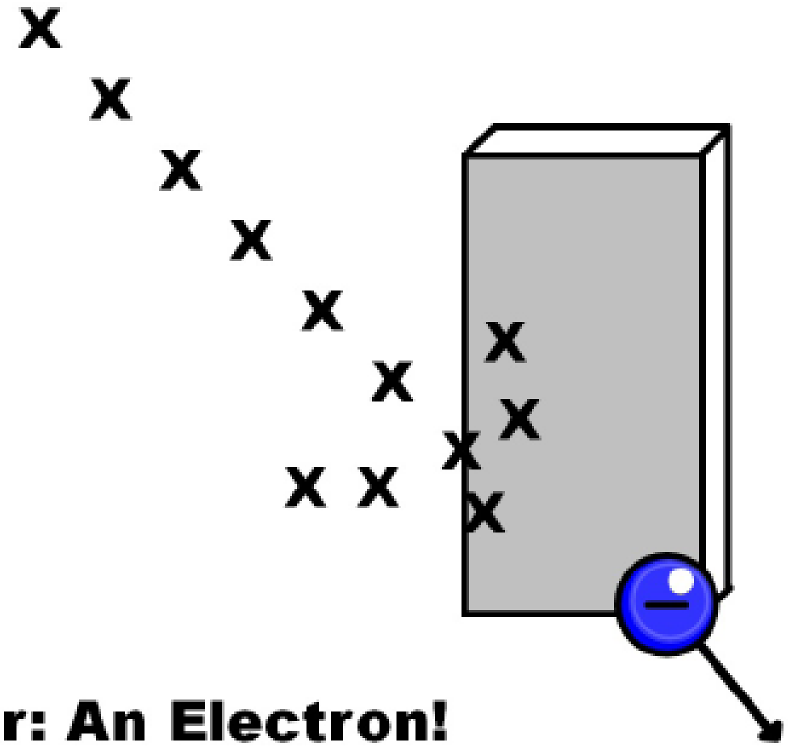


Use of X-Rays

Compton had made his career out of shooting X-rays at things.

One day he shot an X-ray at a metal plate.

What do you think this produced?

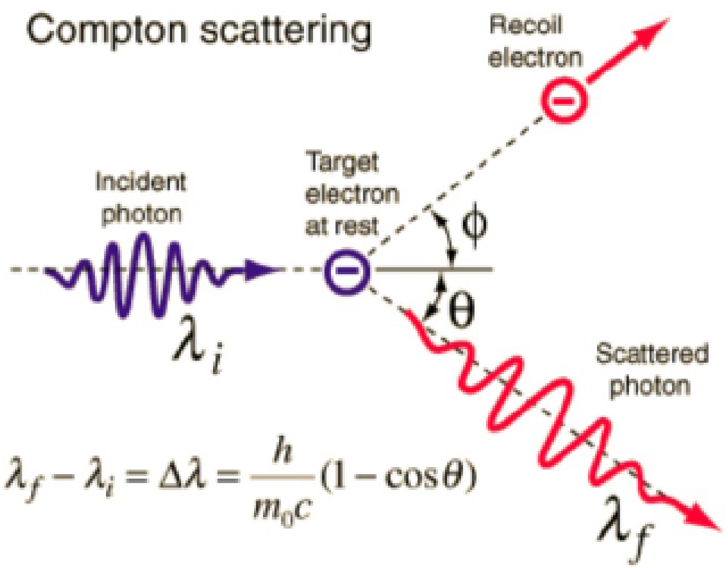


Answer: An Electron!

The Experiment

- **In 1923 Compton sent a beam of X-rays with a known frequency at a block of graphite. When they hit the graphite, he noticed that the frequency of the rebounding x-ray was lower than the incident x-ray and an electron was emitted.**

Now, the interesting bit…



Compton noticed something else happening here as well: not only was an electron produced, but some of the X-ray also deflected, or scattered, after hitting the electron. This was later called Compton Scattering.

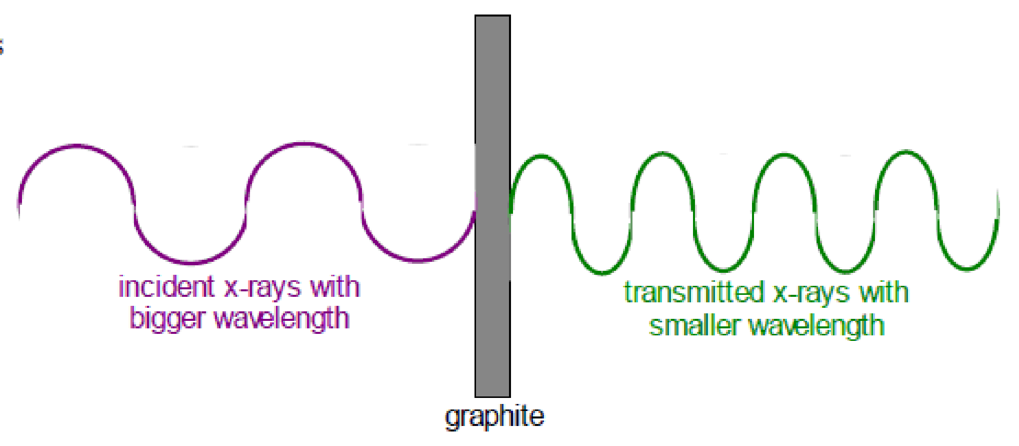
The incident X-ray had a different wavelength than the scattered X-ray. This was later named the Compton Effect.

The Experiment

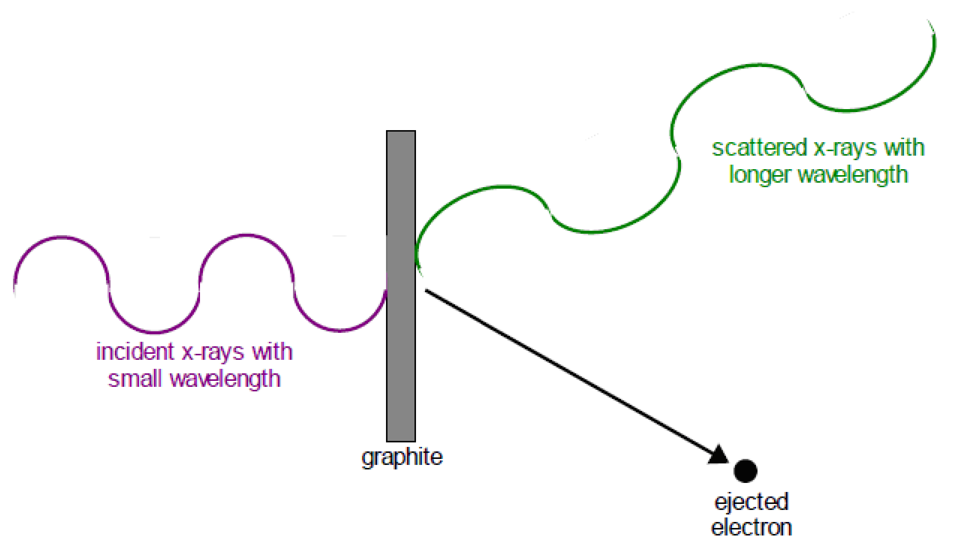
- **The results could not be explained using EMR wave theory. In classical EMR theory, if light was a wave without mass, the light should pass through the graphite with a smaller wavelength (squished like bouncing a ball) and an unchanged (or at least not smaller) frequency!**

Expected vs. Actual Results

Expected



Actual



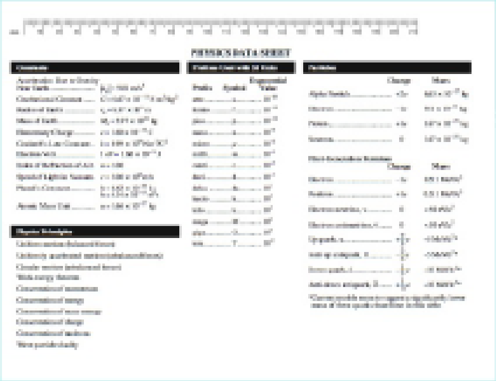
Interpretation

- **According to Planck, energy is carried in the frequency of EMR. A lower frequency meant that energy was lost.**
- **The direction of the ejected electron and deflected EMR indicated a collision.**
- **A fundamental principle of physics is the conservation of momentum in ANY collision.**

Compton applied two of the big principals in physics to this situation:

Conservation of Momentum: the total momentum of the X-ray and electron before collision must equal the total momentum of the X-ray and electron after collision.

Conservation of Energy: the total energy of the X-ray and electron before collision must equal the total of the energy of the X-ray and electron after collision.



These physics principles show up on your formula sheet for your NR's!

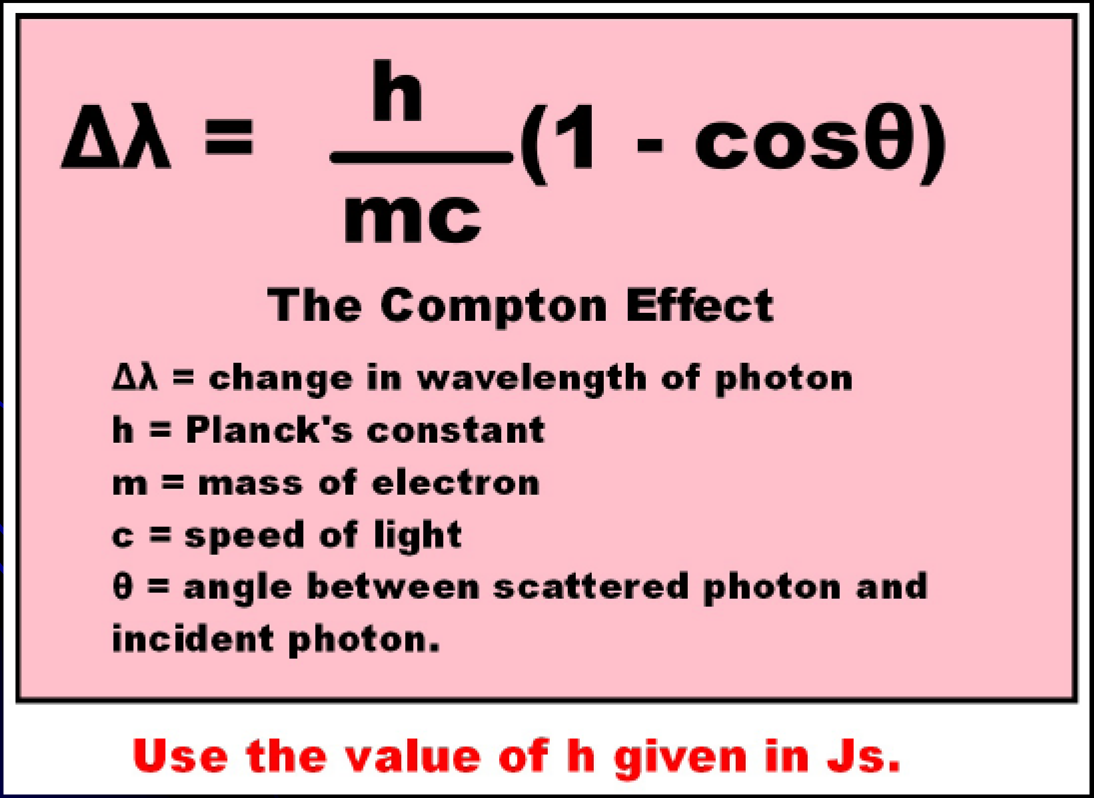
Interpretation

- **He used Einstein’s equation $E=mc^2$ to produce an expression for this momentum of an EMR particle (photon).**

$$p=E/c = h/\lambda$$

Equation for Compton Effect

- **Compton derived an equation that considered x-rays as a particle. Using Einstein’s relativity theory, conservation of momentum, conservation of energy, and some complicated algebra he came up with**



$$\Delta\lambda = \frac{h}{mc}(1 - \cos\theta)$$

The Compton Effect

$\Delta\lambda$ = change in wavelength of photon
h = Planck's constant
m = mass of electron
c = speed of light
θ = angle between scattered photon and incident photon.

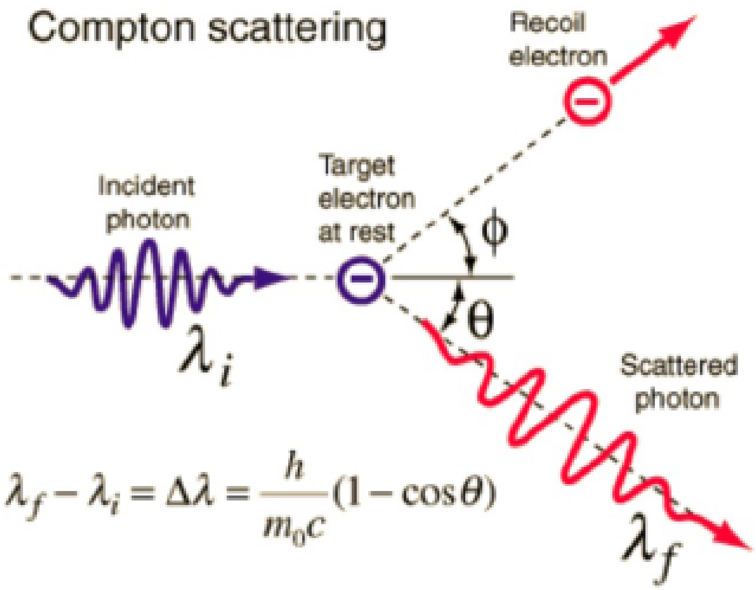
Use the value of h given in Js.

Summary

- **In the photoelectric and in the Compton experiment the results were interpreted as being consistent with particle behavior.**
- **In fact, his calculations proved an almost 100% conservation of momentum. The particle model of light (photons) MUST be correct**
- **This was a turning point in the particle theory of light, when the majority of physicists started to believe that the wave-particle duality of light was probably correct.**

Variables

- Where:
- $\Delta\lambda$ is the change in the wavelength of the incident EMR. ($\lambda_f - \lambda_i$)
- h/m_ec is known as the Compton wavelength of the electron.
- Cosθ is the scattering angle of the EMR.
- Example: x-rays of 2.00×10^{-10} m are scattered by some material. The scattered EMR is detected at 45.0° to the incident beam. Calculate their wavelength.



$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c}(1 - \cos\theta)$$

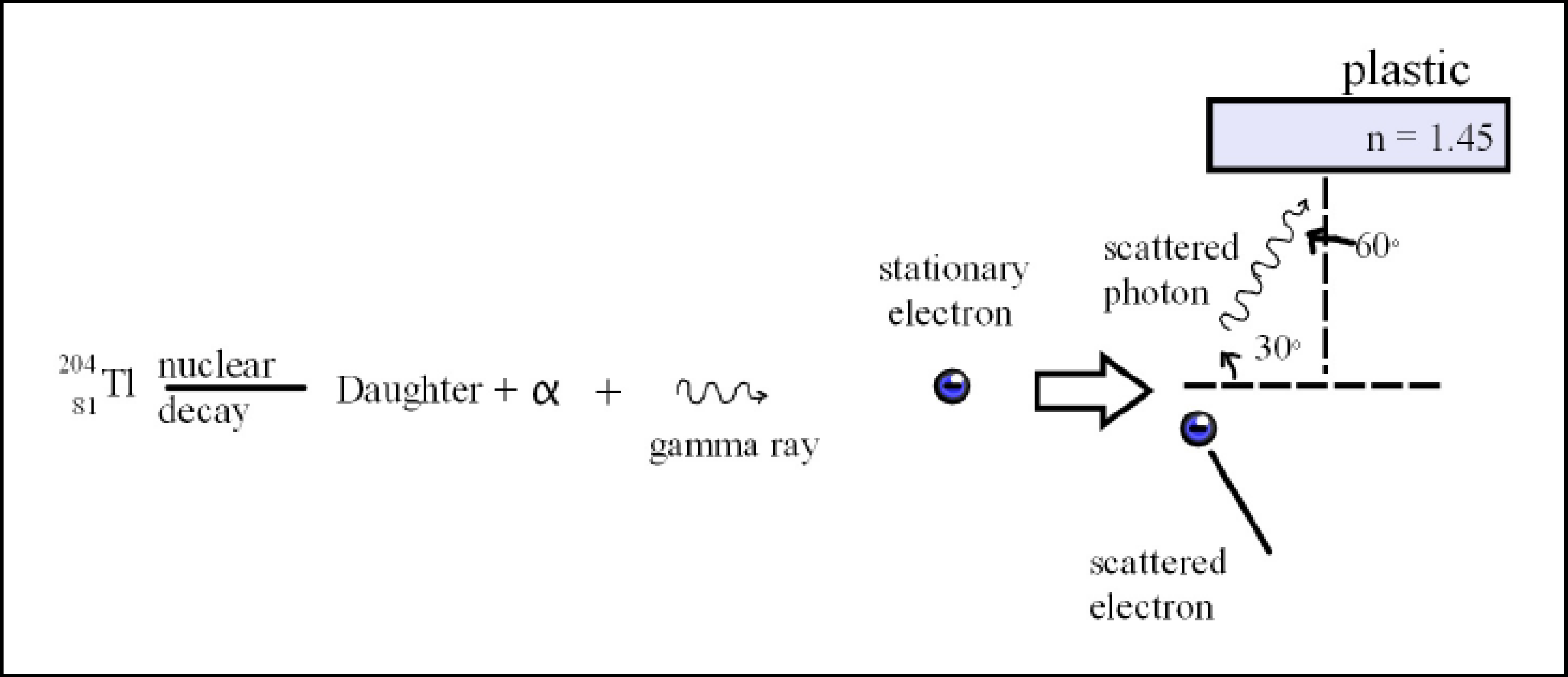
Note, the angle is the angle between the scattered photon and incident photon.

ex) In the diagram above, the incident photon scatters at an angle of 25°, what is the change in wavelength?

ex) (pg 723) What is the maximum change in wavelength that a 0.010 nm X-ray can undergo by Compton scattering with an electron?

Hint: maximum wavelength change occurs at maximum scattering angle. What is the max scattering angle?

Hint: this is called <u>back scattering.</u>



- Ex: If the incident wavelength of the gamma ray is 3.5 x 10^{-13} m, what is the wavelength of the scattered photon when it enters (refracts in) the plastic?

Momentum Example

- In a Compton scattering event, the incident frequency of an X-ray photon is 4.50×10^{17} Hz. The scattered photon has a wavelength of 7.0×10^{-10} m and is scattered at an angle of 38º NofE. What is the velocity of the electron that was released in the collision?

Examples

1. Calculate the energy and momentum of blue light with a wavelength of 400 nm.
2. Calculate the momentum of an x-ray having a frequency of 3.00 x 10^{18} Hz.