Waves and Particles I: Electromagnetic Radiation behaving as Particles
Light is a wave
One source

http://www.falstad.com/mathphysics.html
Interference 2 sources

http://www.falstad.com/mathphysics.html
Six facts in favour of photons

- Photoelectric effect (Harris 72-75)
- Black body radiation (73)
- X-ray production (75-77)
- Compton effect (77-810)
- Pair production (83-84)
- Two-slit experiment with photons (87-90)
Six facts in favour of photons

- Photoelectric effect
Photoelectric effect

Weak negative voltage
Experimental results

Potassium
Tungsten

Stopping potential (V)

Frequency of light (s^{-1})
Six facts in favour of photons

- Photoelectric effect
- Black body radiation
Hot Steel and Pyrometer
Energy density low temperature

Photon energy [eV]

Spectral energy density $dE/df$

$P = 5.67 \times 10^{-8} T^4 \ [W/m^2]$

\[
\frac{dE_f}{df} = \frac{8\pi f^2}{c^3} \left( \frac{hf}{e^{hf/k_BT} - 1} \right)
\]
The energy of photons is quantized.

\[ E = hf = \hbar \omega \]

\[ \frac{dE_f}{df} = \frac{8\pi f^2}{c^3} \frac{hf}{e^{hf/k_BT} - 1} \]
Background blackbody radiation

\[ \frac{dE_f}{df} = \frac{8\pi f^2}{c^3} \frac{hf}{e^{\frac{hf}{k_B T}} - 1} \]

T = 2.726 K
Six facts in favour of photons

- Photoelectric effect
- Black body radiation
- X-ray production
Wilhelm Roentgen’ photographs

http://www.fh-wuerzburg.de/roentgen/
Modern X-ray tube

- Target
- Focus cup
- Tungsten filament
- Beryllium window
X-ray spectra

Intensity

Photon energy (keV)

Gold
Silver
Copper
Aluminum
Six facts in favour of photons

- Photoelectric effect
- Black body radiation
- X-ray production
- Compton effect
THE PHYSICAL REVIEW

THE SPECTRUM OF SCATTERED X-RAYS

By Arthur H. Compton

Abstract

The spectrum of molybdenum Ka rays scattered by graphite at 45°, 90° and 135° has been compared with the spectrum of the primary beam. A primary spectrum line when scattered is broken up into two lines, an "unmodified" line whose wave-length remains unchanged, and a "modified" line whose wave-length is greater than that of the primary spectrum line. Within a probable error of about 0.001 Å, the difference in the wave-lengths (λ - λₐ) increases with the angle θ between the primary and the scattered rays according to the quantum relation (λ - λₐ) = λ(1 - cos θ), where λ = ħ/me = 0.0242 Å. This wave-length change is confirmed also by absorption measurements. The modified ray does not seem to be as homogeneous as the unmodified ray; it is less intense at small angles and more intense at large angles than is the unmodified ray.

An x-ray tube of small diameter and with a water-cooled target is described, which is suitable for giving intense x-rays.

The writer has recently proposed a theory of the scattering of x-rays, based upon the postulate that each quantum of x-rays is scattered by an individual electron. The recoil of this scattering...
Compton effect

\[ \lambda' - \lambda = \frac{h}{m_e c} (1 - \cos \Theta) \]
Assumption: photon has momentum $h/\lambda$

\[
\begin{align*}
\frac{h}{\lambda} &= \frac{h}{\lambda'} \cos \Theta + \gamma m u \cos \varphi \\
\frac{h}{\lambda} &= \frac{h}{\lambda'} \sin \Theta - \gamma m u \sin \varphi \\
hc \frac{1}{\lambda} + mc^2 &= h \frac{1}{\lambda'} + \gamma mc^2
\end{align*}
\]

\[
\lambda' - \lambda = \frac{h}{m_e c} \left(1 - \cos \Theta \right)
\]
Six facts in favour of photons

- Photoelectric effect
- Black body radiation
- X-ray production
- Compton effect
- Pair production
The Positive Electron

Carl D. Anderson, California Institute of Technology, Pasadena, California
(Received February 28, 1933)

Out of a group of 1300 photographs of cosmic-ray tracks in a vertical Wilson chamber 15 tracks were of positive particles which could not have a mass as great as that of the proton. From an examination of the energy-loss and ionization produced it is concluded that the charge is less than twice, and is probably exactly equal to, that of the proton. If these particles carry unit positive charge the curvatures and ionizations produced require the mass to be less than twenty times the electron mass. These particles will be called positrons. Because they occur in groups associated with other tracks it is concluded that they must be secondary particles ejected from atomic nuclei.

Editor
Pair creation discovery
Bubble chamber
T = 100 MeV, L = 10 m.
Pair production

nucleus

photon

positron

electron
Six facts in favour of photons

- Photoelectric effect
- Black body radiation
- X-ray production
- Compton effect
- Pair production
- Two-slit experiment with photons
One narrow slit
One wide slit
2 narrow slits

http://www.falstad.com/mathphysics.html
Two-slit experiment with light
Six facts in favour of photons

- Photoelectric effect \( E = hf = \hbar \omega \)
- Black body radiation \( E = hf = \hbar \omega \)
- X-ray production \( E = hf = \hbar \omega \)
- Compton effect \( p = mv = \frac{h}{\lambda} = \hbar k \)
- Pair production \( E = hf = \hbar \omega \)
- Two-slit experiment

Single photon has still a wave character