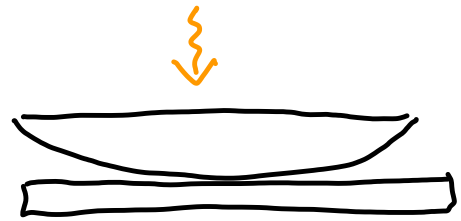
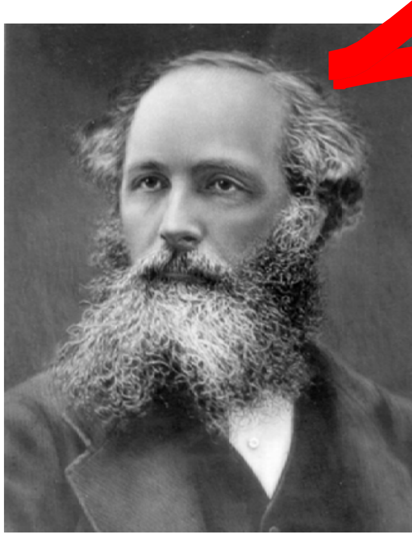
Physics 123 - March 27, 2013

Note Location!

- Exam 2 – Thursday, April 11, 0800
  Dewey 1101
- No Lectures in Hoyt next week
  Lectures will be posted (PDF + mp3)
  Email questions



Light is a wave !!

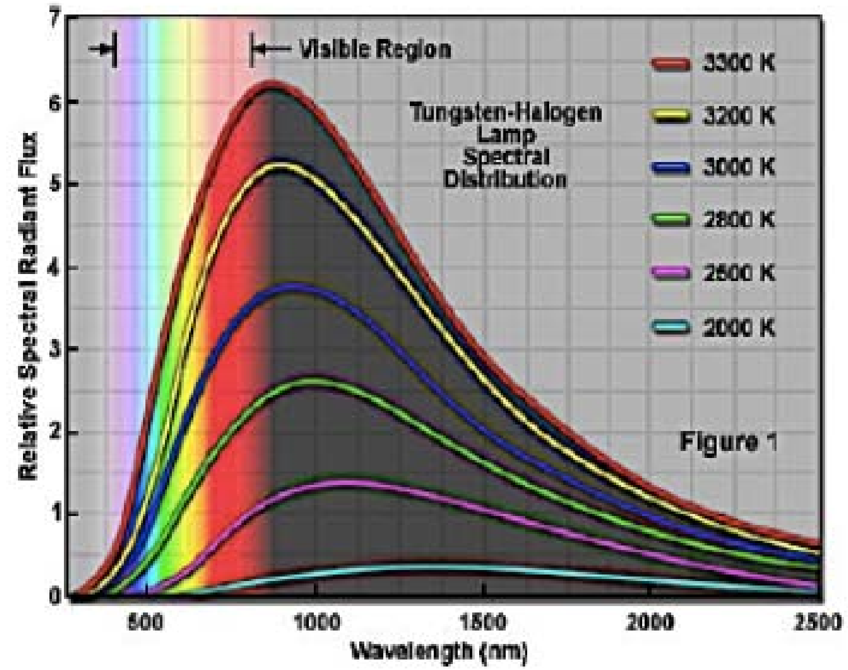


James Clerk Maxwell

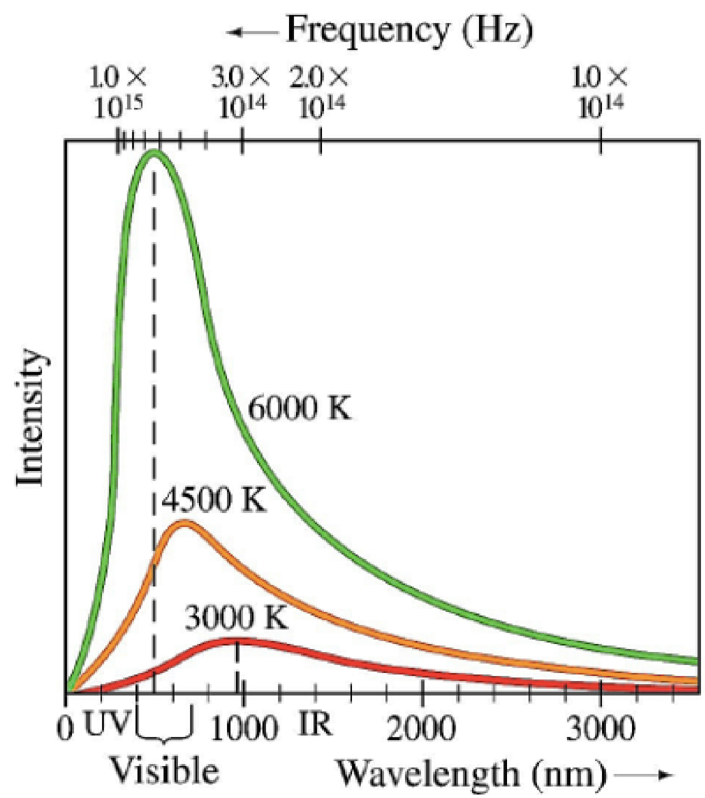
Wave equations
diffraction
interference
refraction
...

Black Body Radiation

"Blackbody" radiation (emitted by object)

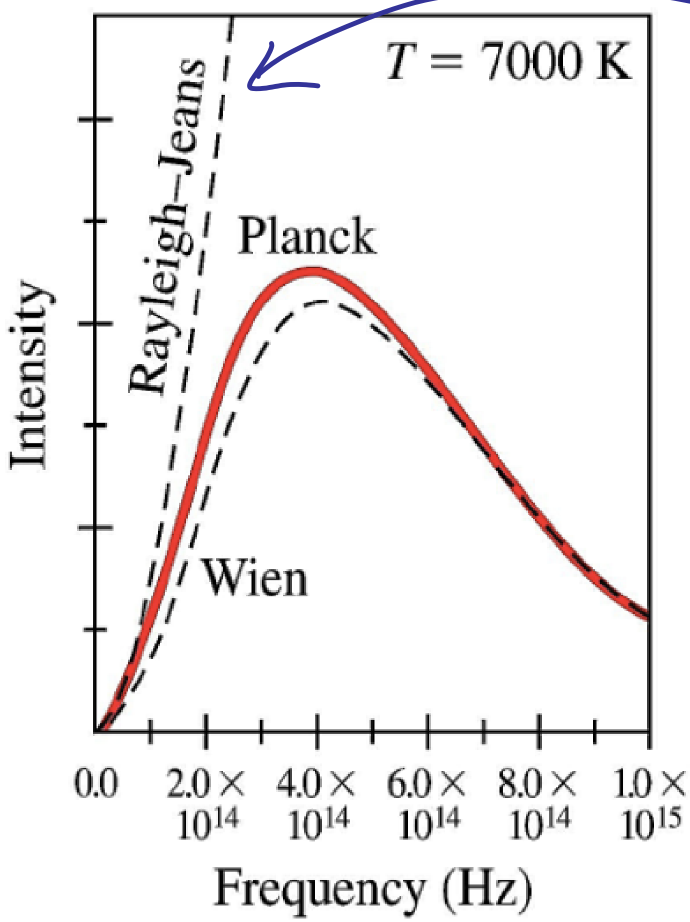


"Blackbody" radiation (emitted by object)



Wien's law:

$$\lambda_{max} T = 2.90 \times 10^{-3}\ \mathrm{m \cdot K}$$



go to high ν

Ultraviolet catastrophe

http://www-history.mcs.st-andrews.ac.uk/Mathematicians/Planck.html

Max Planck
1858-1947
German national
1918 Nobel Prize
Blackbody radiation hypothesis in 1900

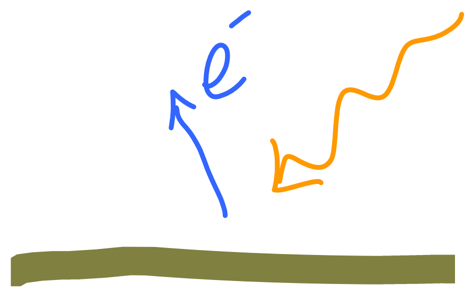
$$I(\lambda, T) = \frac{2\pi hc^2\lambda^{-5}}{e^{hc/\lambda k_B T} - 1}$$

$E(\nu) \sim 0, h\nu, 2h\nu, 3h\nu$

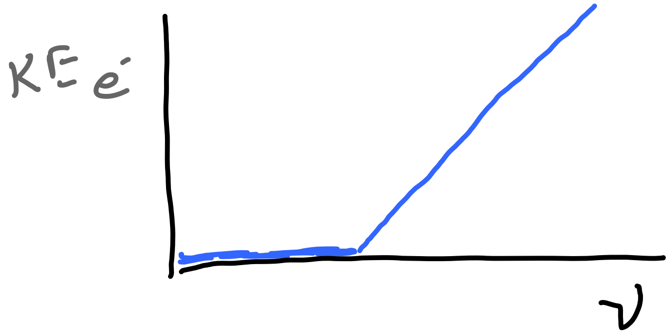
$h \equiv$ Planck's constant
6.626×10^{-34} J·S

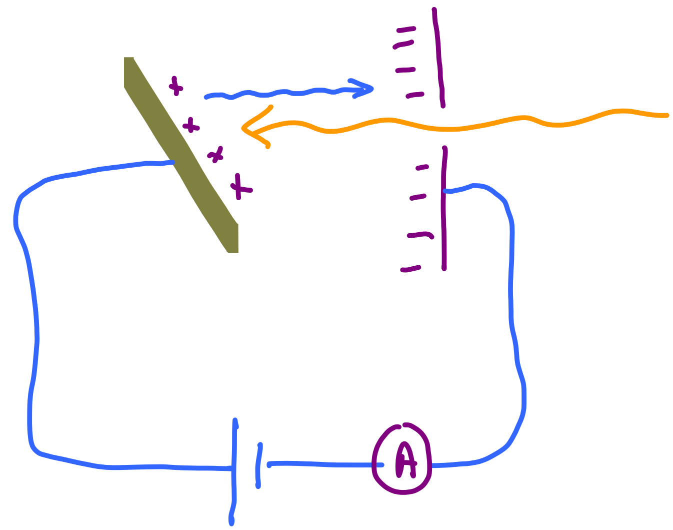
$k_B \equiv$ Botzman's constant
1.38×10^{-23} J/K

Photoelectric Effect

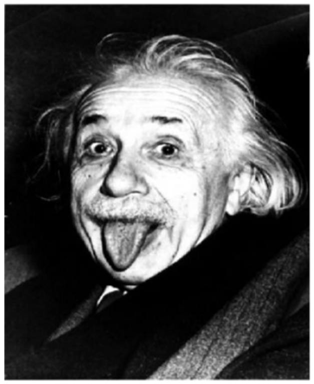


What is seen





NO light intensity dependence

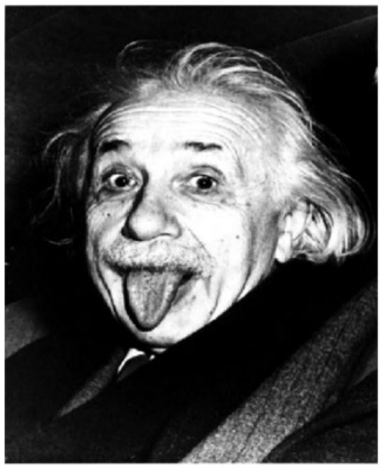


1905

$$KE_e = E_{light} - W$$

E_{light}: $h\nu$

W ← work function (Binding energy of e^- in metal)

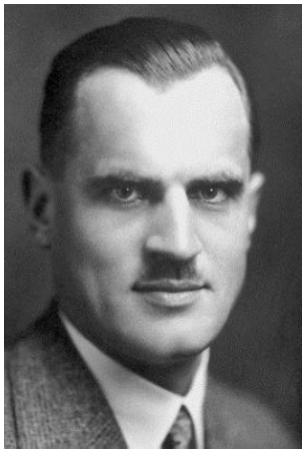


1905

"Annus Mirabilis"
Extraordinary Year

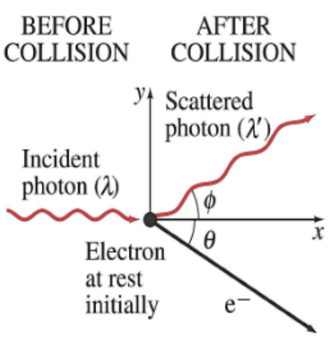
4 papers in Annelen der Physik

- Photoelectric effect
- Brownian Motion
- Special Relativity
- Mass-Energy equivalence

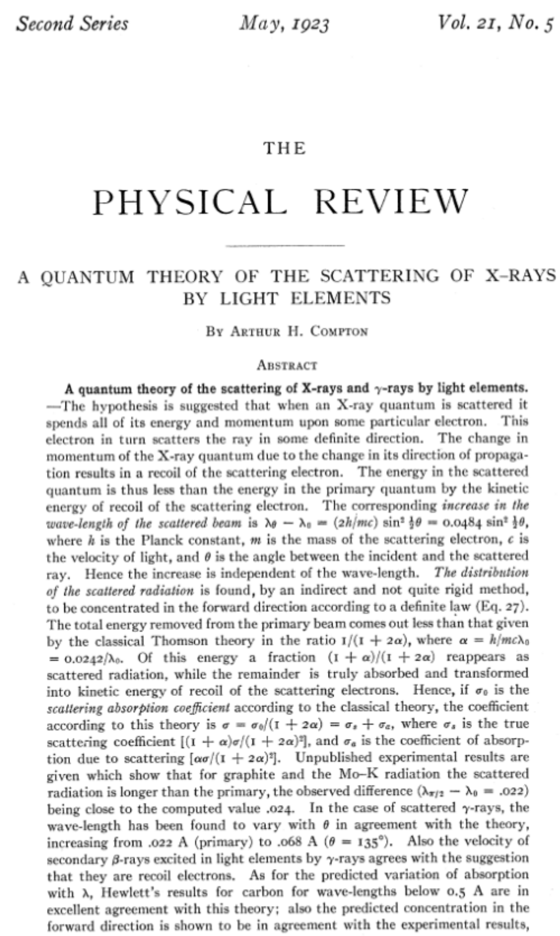


Arthur Compton
Washington Univ.
1892-1962

Compton Scattering



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



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THE

PHYSICAL REVIEW

A QUANTUM THEORY OF THE SCATTERING OF X-RAYS BY LIGHT ELEMENTS

By Arthur H. Compton

Abstract

A quantum theory of the scattering of X-rays and γ-rays by light elements. —The hypothesis is suggested that when an X-ray quantum is scattered it spends all of its energy and momentum upon some particular electron. This electron in turn scatters the ray in some definite direction. The change in momentum of the X-ray quantum due to the change in its direction of propagation results in a recoil of the scattering electron. The energy in the scattered quantum is thus less than the energy in the primary quantum by the kinetic energy of recoil of the scattering electron. The corresponding *increase in the wave-length of the scattered beam* is $\lambda_\theta - \lambda_0 = (2h/mc)\sin^2\frac{1}{2}\theta = 0.0484\sin^2\frac{1}{2}\theta$, where h is the Planck constant, m is the mass of the scattering electron, c is the velocity of light, and θ is the angle between the incident and the scattered ray. Hence the increase is independent of the wave-length. *The distribution of the scattered radiation* is found, by an indirect and not quite rigid method, to be concentrated in the forward direction according to a definite law (Eq. 27). The total energy removed from the primary beam comes out less than that given by the classical Thomson theory in the ratio $1/(1+2\alpha)$, where $\alpha = h/mc\lambda_0 = 0.0242/\lambda_0$. Of this energy a fraction $(1+\alpha)/(1+2\alpha)$ reappears as scattered radiation, while the remainder is truly absorbed and transformed into kinetic energy of recoil of the scattering electrons. Hence, if σ_0 is the *scattering absorption coefficient* according to the classical theory, the coefficient according to this theory is $\sigma = \sigma_0/(1+2\alpha) = \sigma_s + \sigma_a$, where σ_s is the true scattering coefficient $[(1+\alpha)\sigma/(1+2\alpha)^2]$, and σ_a is the coefficient of absorption due to scattering $[\alpha\sigma/(1+2\alpha)^2]$. Unpublished experimental results are given which show that for graphite and the Mo–K radiation the scattered radiation is longer than the primary, the observed difference ($\lambda_{\pi/2} - \lambda_0 = .022$) being close to the computed value .024. In the case of scattered γ-rays, the wave-length has been found to vary with θ in agreement with the theory, increasing from .022 A (primary) to .068 A ($\theta = 135°$). Also the velocity of secondary β-rays excited in light elements by γ-rays agrees with the suggestion that they are recoil electrons. As for the predicted variation of absorption with λ, Hewlett's results for carbon for wave-lengths below 0.5 A are in excellent agreement with this theory; also the predicted concentration in the forward direction is shown to be in agreement with the experimental results,

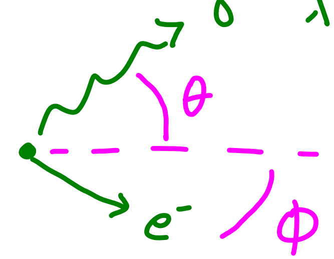
Compton Scattering

initial state

photon
λ
$h\nu = E_\gamma$

Free, at rest

Final State



γ λ', $h\nu' = E'$

$E^2 = p^2c^2 + m^2c^4$ ($m^2c^4 \to 0$ for photon) ⤳ $\frac{E_\gamma}{c} = p_\gamma$

Momentum cons. in transverse direction

$$p_{e'} \sin\phi = p_{\gamma'} \sin\theta$$

$$\sin\phi = \frac{E_{\gamma'}}{c\, p_{e'}} \sin\theta$$

momentum cons. in the longitudinal direction

$$p_\gamma = \frac{E_\gamma}{c} = p_{\gamma'}\cos\theta + p_{e'}\cos\phi$$

$p_{\gamma'} \rightarrow \frac{E_{\gamma'}}{c}$; $\cos\phi = (1 - \sin^2\phi)^{1/2} = \left[1 - \left(\frac{E_{\gamma'}\sin\theta}{p_{e'}c}\right)^2\right]^{1/2}$

$$\left(\frac{E_\gamma}{c} - \frac{E_{\gamma'}}{c}\cos\theta\right)^2 = p_{e'}^2\left[1 - \left(\frac{E_{\gamma'}}{p_{e'}c}\sin\theta\right)^2\right]$$

mult. by c^2, regroup

$$p_{e'}^2c^2 = (E_\gamma - E_{\gamma'}\cos\theta)^2 + E_{\gamma'}^2\sin^2\theta = E_\gamma^2 - 2E_\gamma E_{\gamma'}\cos\theta + E_\gamma^2$$

Conservation of Energy

$$E_\gamma + m_e c^2 = E_{\gamma'} + \sqrt{m_e c^4 + p_{e'}^2 c^2}$$

$$E_\gamma^2 - 2E_\gamma E_{\gamma'} \cos\theta + E_{\gamma'}^2$$

$$E_\gamma + m_e c^2 = E_{\gamma'} + \sqrt{m_e c^4 + E_\gamma^2 - 2E_\gamma E_{\gamma'} \cos\theta + E_{\gamma'}^2}$$

solve for $E_{\gamma'}$

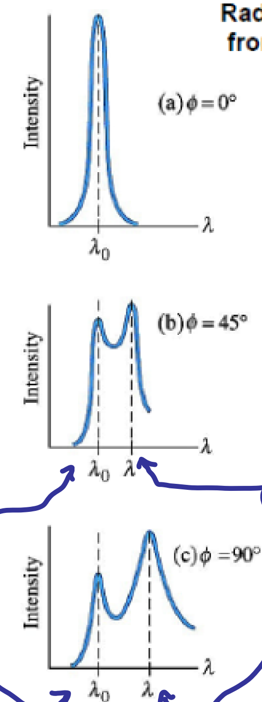
$$E_{\gamma'} = \frac{1}{\frac{1-\cos\theta}{m_e c^2} + \frac{1}{E_\gamma}}$$

$$E_\gamma = h\frac{c}{\lambda} \qquad E_{\gamma'} = h\frac{c}{\lambda'}$$

uses $E = h\nu$

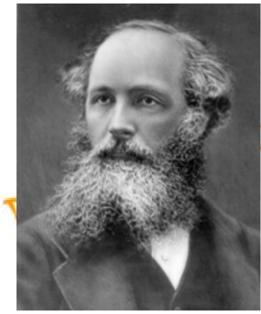
$$\lambda' = \lambda + \frac{h}{mc}(1 - \cos\theta)$$

Radiation scattered from a target such as graphite



free electrons

bound electrons

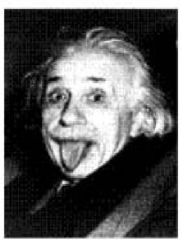


Maxwell's equations
interference
diffraction
Refraction
dispersion
⋮

light is a wave!

Planck

Blackbody Radiation



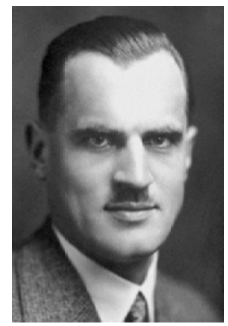
Einstein

Photoelectric effect

1905

light comes in little packets with energy $E = h\nu$

light is a particle!



?

Compton

Compton Scattering

Louis Victor Pierre Raymond 7th duc de Broglie

1892 - 1987

France

1924 Thesis → Research on the Theory of the Quanta

1929 Nobel Prize in physics

Matter can have wave characteristics

perhaps the same relationship holds for matter?

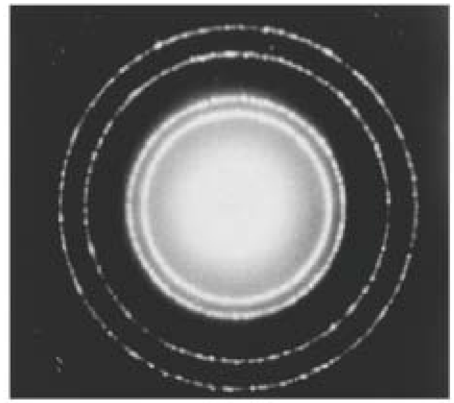
wavelength $\lambda = \frac{h}{p}$

$E = \sqrt{p^2c^2 + m^2c^4}$ → 0 photon → $E = pc$

$E = h\nu$ → $v = \lambda\nu$ → $E = \frac{hc}{\lambda}$ → $\frac{h}{\lambda} = \frac{E}{c}$

$\frac{h}{\lambda} = \frac{pc}{c}$

$\lambda = h/p$



Diffraction pattern of electrons scattered from Al foil.

George Paget Thomson
1892-1975
son of J.J. Thomson
Aberdeen Univ.
independent discovery of same phenomenon

Clinton Davisson and Lester Germer
Experimental confirmation of the wavelike nature of electrons - 1927 - Bell Labs

Davisson and Thomson won the Nobel Prized in Physics in 1937 "for their experimenta discovery of the diffraction of electrons by crystals"