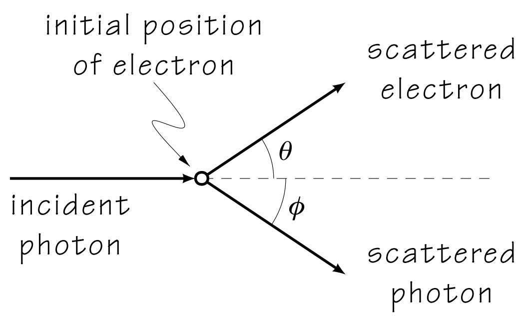
PHYSNET

MISN-0-219

THE COMPTON EFFECT



Project PHYSNET Physics Bldg. Michigan State University East Lansing, MI

THE COMPTON EFFECT

by

Michael Brandl

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Input Skills:

1. Familiarity with the properties of photons (MISN-0-212).
2. Some familiarity with the properties of electromagnetic waves (MISN-0-210 and MISN-0-211) is helpful, but not absolutely necessary.
3. Solve two-particle collision problems using conservation of linear momentum (MISN-0-15) and conservation of energy (MISN-0-21).
4. Given a particle's rests mass and velocity, calculate its relativistic energy and momentum (MISN-0-24).

Output Skills (Knowledge):

K1. Derive the equation for the wave length shift caused by the Compton effect. Start from fundamental conservation laws. Define all terms and justify each step.

K2. State how the results of the Compton experiment contradict the classical electromagnetic wave picture and support the photon theory of light.

K3. Describe how two properties of the photon allow it, at high densities, to give the appearance of an electromagnetic wave.

Output Skills (Problem Solving):

P1. Given the necessary data about a collision between a photon and an electron, use the Compton shift equation and conservation laws to find either the electron's or photon's final momentum, kinetic energy and wavelength.

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New authors, reviewers and field testers are welcome.

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1. Introduction

1a. The Nature of Light. On the macroscopic, everyday-world scale, all of the properties exhibited by light are wave properties: refraction, reflection, diffraction, and interference. Maxwell's equations predict the existence of electromagnetic waves produced by oscillating charges and seem to be a perfect way to describe light and other forms of electromagnetic radiation, at least on the macroscopic level.[1]

1b. Microscopic Description of Light. On the microscopic level, however, electromagnetic radiation exhibits an entirely different set of properties. The photoelectric effect showed that light is granular rather than smooth in nature on this level and that it carries its energy in discrete bundles called photons.[2] The interaction between electromagnetic radiation and matter on the microscopic scale must be described in terms of the interactions between individual particles and individual photons.

The Compton effect gives us more information about the properties of photons. Not only does each photon carry a specific amount of energy, it also carries a specific amount of momentum. Certain types of scattering of electromagnetic radiation from matter can therefore be described in terms of collisions between individual particles and individual photons. The standard rules of relativistic kinematics apply to such collisions, and can be used to determine the properties of the scattered photons, which combine to give the measurable properties of the scattered radiation. The Compton effect shows that, in these collisions, photons act precisely like particles which have a rest mass of zero. On the microscopic scale, therefore, electromagnetic radiation is essentially composed of streams of particles.

[1] See "The Derivation of the Electromagnetic Wave Equation from Maxwell's Equations" (MISN-0-210).

[2] See "The Photoelectric Effect" (MISN-0-213).

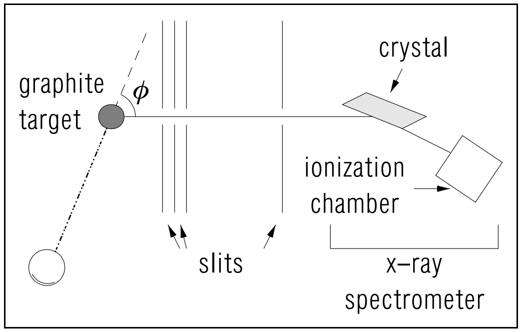

Figure 1. Compton's Experimental Apparatus.

2. The Experimental Evidence

2a. 1923: Possible Scattering of Secondary X-Rays. When A.H. Compton performed his now-famous experiment in 1923, it had already been known for some time that a material illuminated by x-rays gave off what were called secondary rays. Compton was attempting to show that these secondary rays were primarily the result of scattering of the incident x-rays from electrons in the material.

2b. Wavelength Shift: Dependent on Angle. The scattering of x-rays from free electrons was explainable in terms of the classical electromagnetic-wave theory of radiation; the details had been worked out by Sir J.J. Thomson. J.A. Gray observed, and Compton verified, that the scattered x-rays had the same polarization and roughly the same intensity as were predicted by Thomson's scattering theory, but that the scattered rays were absorbed more readily than the incident x-rays would be. It occurred to Compton that this increased absorbability could be explained if one assumed that the wavelength of the scattered rays was slightly higher than the original wavelength of the incident x-rays. His measurements of the absorbability of the scattered x-rays over a wide range of incident wavelengths indicated that the increase in wavelength of the scattered x-rays was consistently on the order of 0.03 Å. Compton decided to check for this wavelength increase directly, using an x-ray spectrometer. He also checked to see if the wavelength shift depended upon the angle through which the x-rays were scattered.

2c. Compton's Apparatus. Compton's experimental setup is shown schematically in Fig. 1. X-rays of known wavelength were produced in an x-ray tube and allowed to strike a graphite target. A series of slits allowed only those scattered x-rays which left the target in a direction making an angle ϕ with the direction of the beam of incident x-rays to enter the

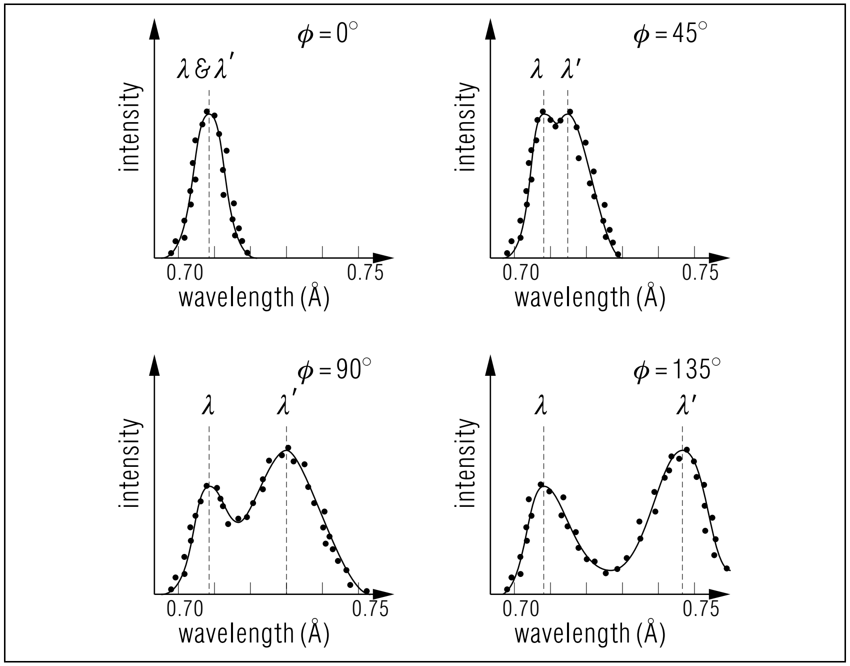

Figure 2. Results of Compton's Experiment.

spectrometer. This angle ϕ is the angle through which these particular x-rays had been scattered; its value could be varied by moving the x-ray source. The x-rays spectrometer consisted of a crystal from which the x-rays were reflected and an ionization chamber which detected the x-rays. The wavelength of the scattered x-rays could be determined from the angle at which they were reflected from the crystal with maximum intensity (a well-known interference effect). The output of the spectrometer was essentially an indication of the intensity of the scattered x-rays as a function of wavelength.

2d. Results of Compton's Experiment. The output of the spectrometer for several values of the scattering angle ϕ is shown in Fig. 2. The x-rays incident on the graphite target have a wavelength of $\lambda = 0.707\,\text{Å}$. When $\phi = 0°$, the x-rays being detected in the spectrometer are essentially those which have undergone no scattering, so it is not surprising that the spectrometer's output is a single peak centered around $\lambda = 0.707\,\text{Å}$. As the value of ϕ is increased, however, that single peak splits up into two peaks, one at the original value of $\lambda = 0.707\,\text{Å}$, and the other at the

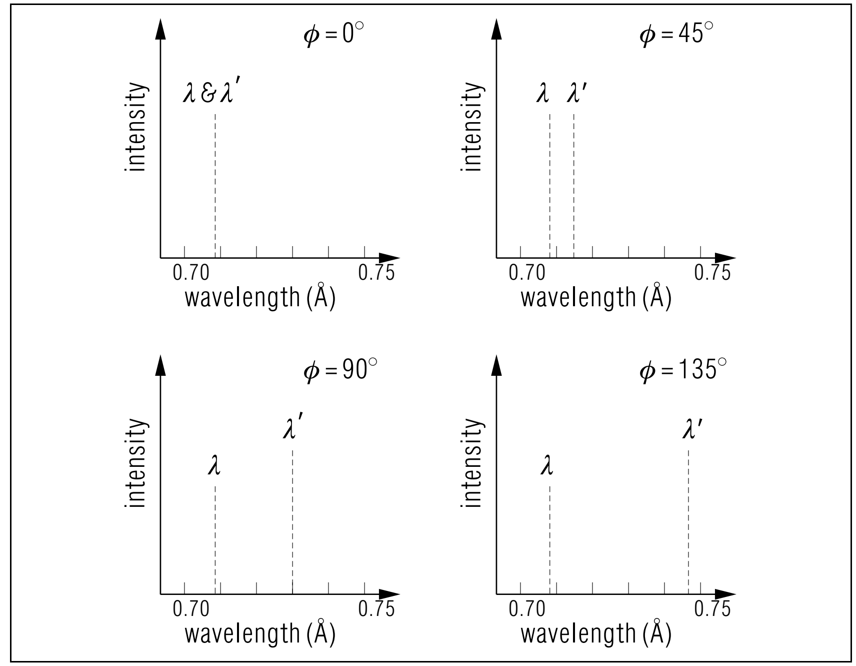

Figure 3. Idealized Results of Compton's Experiment.

increased wavelength λ', whose value depends upon the value of ϕ.

2e. Compton's Empirical Formula. Compton had shown that at least some of the scattered x-rays had their wavelengths changed in the scattering process - an observation that is at odds with the classical electromagnetic-wave theory's explanation of scattering, as we shall see below. Furthermore, it was evident that the amount by which the wavelength of a scattered x-ray changed was directly related to the angle ϕ through which it had been scattered. Later experiments developed the empirical relationship for the shifted peak's position:

$$\lambda' - \lambda = \lambda_c (1 - \cos\phi) \tag{1}$$

where λ' is the wavelength of scattered x-rays, λ is the wavelength of incident x-rays, $\lambda_c = 2.426 \times 10^{-12}\,\text{m} = 2.426 \times 10^{-2}\,\text{Å}$, a constant, and ϕ is the angle through which x-rays are scattered.

2f. Target Independence. The basic experiment can be repeated using a variety of different materials as targets, and the above relationship will be found each time. This implies that the phenomenon being observed is a property of basic constituents of all matter, rather than of any specific substance.

Equation (1) is a useful tool—any theory of x-ray scattering from matter will have to predict the same relationship before it can be accepted as realistic.

3. Electromagnetic-Wave Explanation

3a. Overview. In the classical picture, x-rays are simply electromagnetic waves having short wavelengths and hence high frequencies. The mechanisms by which an electromagnetic wave "scatters" from an electron or any other charged particle is easily understood; it is shown pictorially in Fig. 4.

3b. Scattering as a Driven Oscillator. An electromagnetic wave consists of a time-varying and spatially-varied electric field $\vec{E}$ and magnetic field $\vec{B}$. If we were to sample such a wave at a stationary point, we would see an oscillating electric field and an oscillating magnetic field. An electron struck by an electromagnetic wave of frequency ν would therefore see the wave as an electric field $\vec{E}$ and a magnetic field $\vec{B}$, each oscillating with the frequency ν. If the electron is initially at rest and is not accelerated to a high velocity, the effects of the magnetic field upon it will be negligible. However, the varying electric field causes the electron to be accelerated up and down, forcing it to oscillate at the same frequency ν at which the field itself oscillates. The oscillating electron now acts as a source of new electromagnetic waves which head out in all directions, each one having the same frequency ν with which the electron is oscillating.

3c. Summary of the 2-step Process. The process by which x-rays scatter from electrons in the classical electromagnetic-wave picture therefore has two steps: (1) the incident x-ray forces the electron to oscillate; and (2) the oscillating electron produces the scattered x-rays.

3d. Polarization and Intensity vs. Angle: Good. The details of the above process can be worked out using Newtonian kinematics to determine the characteristics of the scattered radiation produced by that motion, as was done by Sir J. J. Thomson. This gives some specific information about the scattered radiation—its polarization (direction in which the electric field vector points) is the same as that of the incident radiation, and its intensity is a well-defined function of the direction at which it comes out relative to the direction of the incident radiation. These

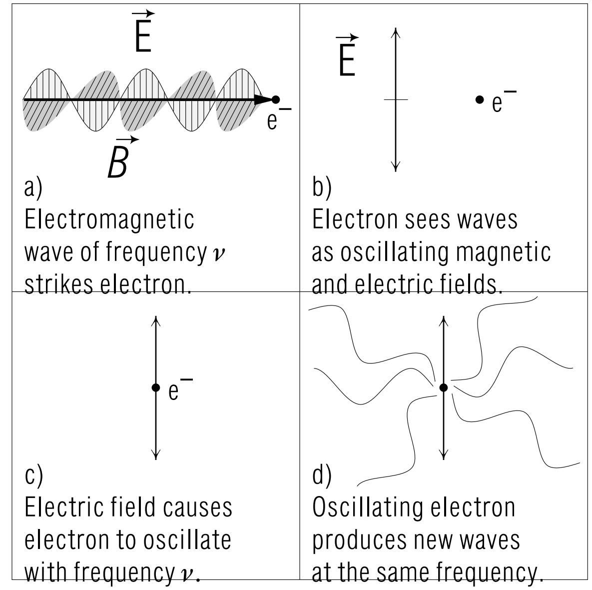

Figure 4. Electromagnetic wave "scattering" from an electron.

predictions were borne out fairly well by Compton's earlier experiments.

3e. Sharp Shifted Peak: Failure. The classical theory does, however, make one specific prediction which is flatly contradicted by the results of Compton's experiment. The electron is forced to oscillate at the same frequency as the incident radiation, and the scattered radiation produced by that oscillation must in turn have the same frequency.[3] Therefore, the wavelengths of the incident and scattered x-rays must be identical. Yet Compton's experiment showed that at least some of the scattered x-rays have longer wavelengths than the incident x-rays. We must therefore conclude that the classical theory does not give a valid description of the phenomenon.

[3] The frequency of the scattered radiation is spread out into a range centered on the frequency of incident wave. This phenomenon is called "radiation reaction."

4. The Photon Explanation

4a. Kinematics is Necessary. Since the electromagnetic-wave theory of radiation is unable to explain the Compton effect, we must look to the photon theory for help. But how do we deal with photons? We have to know how to treat them kinematically before we can determine how they scatter from particles.

4b. Fairly Well Localized. The photoelectric effect tells us something about photons. They are the discrete bundles of energy that make up electromagnetic radiation. The photoelectric effect shows that each photon interacts only with a single electron,[4] so photons must be fairly localized objects. Therefore, it is only natural to think of photons as particles.

4c. Correspondence with Waves. In order to look like an electromagnetic wave when there is a huge density of them, photons must be a very special class of particles. First, like the electromagnetic wave, they have to travel at the speed of light. This is something that, according to relativity, ordinary particles with mass cannot do. Second, any electromagnetic wave which carries an amount of energy E must also carry along with it an amount of momentum $p = E/c$.[5] The photon satisfies both of these criteria because it is massless, so relativity allows it to travel at the speed of light, and each photon obeys the momentum/energy relation:

$$p_{ph} = E_{ph}/c\,, \tag{2}$$

where p_{ph} is the photon's momentum, E_{ph} is the photon's energy.

We can now examine the way in which photons scatter from electrons and other massive particles. We simply consider a photon as a massless particle with momentum $p_{ph} = h/\lambda$, and energy $E_{ph} = p_{ph}c = h\nu$, and proceed to work out the (relativistic) kinematics of the collision between such a particle and an electron.

4d. Collision Between Photon and Electron. Let us look at the collision in a frame in which the electron is initially at rest, as is shown in Fig. 5. Primed quantities are those existing after the collision. The incoming photon is part of a beam of incident radiation of wavelength λ, so the magnitude of its momentum is

$$p_{ph} = \frac{h}{\lambda} \tag{3}$$

[4] See "The Photoelectric Effect" (MISN-0-213).
[5] See "Energy and Momentum in Electromagnetic Waves" (MISN-0-211).

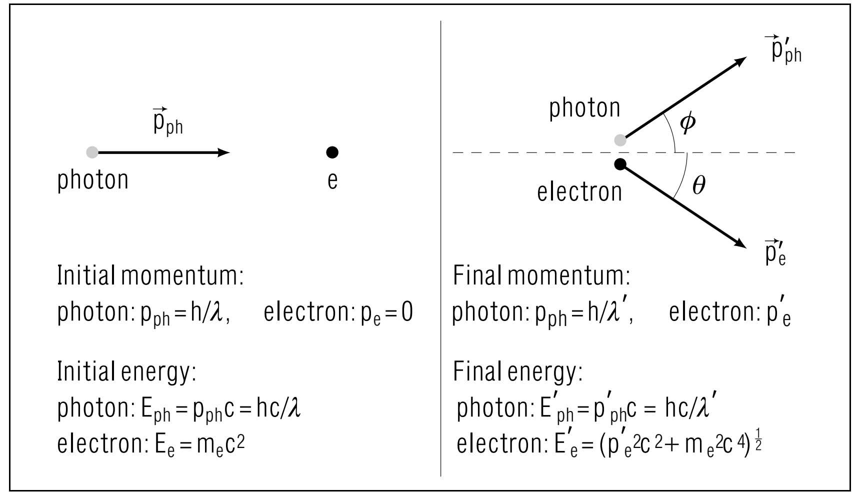

Figure 5. Collision between a photon and an electron.

and its energy is

$$E_{ph} = p_{ph}c\,. \tag{4}$$

The outgoing photon, coming out at an angle ϕ relative to the direction of the incident photon, is part of the beam of scattered radiation going out at that angle, whose wavelength is designated λ'. Its momentum is therefore

$$p'_{ph} = \frac{h}{\lambda'} \tag{5}$$

and its energy is

$$E'_{ph} = p'_{ph}c\,. \tag{6}$$

The electron is initially at rest, so its momentum is

$$p_e = 0\,. \tag{7}$$

The initial energy of the electron is

$$E_e = m_e c^2\,, \tag{8}$$

which is, of course, just the rest energy of the electron due to its mass. The outgoing electron, coming out at an angle θ relative to the direction of the incident photon, has momentum p'_e. The energy of the outgoing electron is

$$E'_e = \left({p'_e}^2 c^2 + m_e^2 c^4\right)^{1/2}\,, \tag{9}$$

which is the sum of its relativistic kinetic energy and its rest energy.

5. Deriving Compton's Formula

5a. The General Approach. What we would like to end up with is an expression that we can check against the empirical relationship given in Eq. (1). It must involve λ (or p_{ph}), λ' (or p'_{ph}), and ϕ. We therefore want to eliminate the unnecessary elements like the electron's final momentum, p'_e, and the angle θ at which the electron comes out. In order to eliminate the electron's kinematical variables, we must solve for them in terms of the photon's variables. The electron and photon variables are connected by the laws of conservation of momentum and energy so those are what we use.

5b. Applying Conservation of Momentum. First we write down the equation for conservation of momentum in the collision,

$$\vec{p}_{ph} + (\vec{p}_e = 0) = \vec{p}\prime_{ph} + \vec{p}\prime_e\,, \qquad (10)$$

solve it for $\vec{p}\prime_e$,

$$\vec{p}\prime_e = \vec{p}_{ph} - \vec{p}\prime_{ph}\,, \qquad (11)$$

and square it:

$$p_e'^{\,2} = p_{ph}{}^2 + p_{ph}'^{\,2} - 2\vec{p}_{ph}\cdot\vec{p}'_{ph}\,. \qquad (12)$$

Since ϕ is the angle between the ingoing and outgoing photon direction, $\vec{p}_{ph}\cdot\vec{p}'_{ph} = p_{ph}p'_{ph}\cos\phi$, and so:

$$p_e'^{\,2} = p_{ph}{}^2 + p_{ph}'^{\,2} - 2p_{ph}p'_{ph}\cos\phi\,. \qquad (13)$$

5c. Applying Conservation of Energy. We now write down the equation for conservation of energy in the collision:

$$E_{ph} + E_e = E'_{ph} + E'_e\,, \qquad (14)$$

solve it for E'_e,

$$E'_e = E_{ph} - E'_{ph} + E_e\,, \qquad (15)$$

and square it:

$$E_e'^{\,2} = E_{ph}{}^2 + E_{ph}'^{\,2} - 2E_{ph}E'_{ph} + 2(E_{ph} - E'_{ph})E_e + E_e{}^2\,. \qquad (16)$$

Eqs. (4), (6), (8), and (9) give the energies involved in terms of the momenta and the electron's rest mass. Substituting these into Eq. (16) yields:

$$p_e'^{\,2}c^2 + m_e^2c^4 = p_{ph}{}^2c^2 + p_{ph}'^{\,2}c^2 - 2p_{ph}p'_{ph}c^2 + 2(p_{ph} - p'_{ph})m_ec^3 + m_e^2c^4\,. \qquad (17)$$

Solving this for $p_e'^{\,2}$ gives:

$$p_e'^{\,2} = p_{ph}{}^2 + p_{ph}'^{\,2} - 2p_{ph}p'_{ph} + 2(p_{ph} - p'_{ph})m_ec\,. \qquad (18)$$

5d. The Compton Formula. Equating the right side of Eqs. (13) and (18) gives an expression involving only p_{ph}, p'_ph, ϕ, and the constants m_e and c:

$$p_{ph}p'_{ph}\cos\phi = p_{ph}p'_{ph} - (p_{ph} - p'_{ph})m_ec\,, \qquad (19)$$

or, equivalently,

$$(p_{ph} - p'_{ph})m_ec = p_{ph}p'_{ph}(1 - \cos\phi)\,. \qquad (20)$$

Dividing through by $p_{ph}p'_{ph}$ gives

$$\left(\frac{1}{p'_{ph}} - \frac{1}{p_{ph}}\right)m_ec = (1 - \cos\phi)\,. \qquad (21)$$

Equations (3) and (5) give the ingoing and outgoing photon momenta in terms of the incident and scattered wavelengths λ and λ'. Substituting these in yields:

$$\left(\frac{\lambda'}{h} - \frac{\lambda}{h}\right)m_ec = (1 - \cos\phi)\,, \qquad (22)$$

or

$$\lambda' - \lambda = \frac{h}{m_ec}(1 - \cos\phi)\,. \qquad (23)$$

This is the famous (infamous) Compton shift equation. It was assumed implicitly in the derivation that the electron involved was free, rather than being bound to an atom. Had the electron been bound, the situation would have been quite different, since the atom would then also have been involved in the collision (more on this below).

The "free electron" requirement needs qualification; we really need only require that the amount of energy by which the electron is bound to its atom (or to the material itself, in the case of a conductor) should be much less than the amount of kinetic energy involved in the collision (which is, roughly, the energy of the photon involved). Since an x-ray photon, for instance, has a very high energy (on the order of 10^2 to 10^5 eV), any electron bound to its atom or material by only a few eV can be considered to be essentially free in a collision with such a photon.

5e. Summary. If we allow a beam of x-rays of wavelength λ to strike a target, some of the photons in the beam will interact with the (essentially) free electrons in the material. Those photons which, after scattering, come out at an angle ϕ relative to the incident beam direction "add up" to form the scattered beam of x-rays observed at that angle, whose wavelength λ' is given by Eqs. (1) and (23).

6. Identifying the Peaks

6a. Identification of the Shifted Peak. Equation (1) is the empirical relationship found between the wavelength shift of a scattered beam of x-rays and the angle through which the x-rays have been scattered. Equation (23) is the theoretical relationship between the same two quantities. Compare the two equations. In both cases the wavelength shift is proportional to $(1-\cos\phi)$; the photon theory predicts the proper angular dependence. The constant involved in Eq. (23) is:

$$\frac{h}{m_e c} = \frac{6.6262\times10^{-34}\,\mathrm{J\,s}}{(9.1096\times10^{-31}\,\mathrm{kg})(2.9979\times10^{8}\,\mathrm{m/s})} = 2.4263\times10^{-12}\,\mathrm{m}\,,$$

which matches the experimentally discovered constant in Eq. (1), $\lambda_c = 2.426\times10^{-12}$ m.

6b. Shifted and Unshifted Peaks. We have now successfully accounted for part of the experimental results by showing that those x-rays whose wavelengths have been changed in the scattering process have scattered from free electrons in the target material. We have explained the occurrence of the shifted peak in Figs. 2 and 3. But what about the unshifted peak that shows up in the same figures? These x-rays have also been scattered through some angle, and so must have collided with something in the target, but their wavelengths have not been measurably changed in the process.

6c. Identification of the Unshifted Peak. The obvious conclusion is that these x-rays have scattered from something other than free electrons in the material. An x-ray photon passing through a graphite target could strike either a lightly bound ("free") electron, an electron bound tightly to its carbon atom, or conceivably even the nucleus of a carbon atom. In the last two cases, the photon would be colliding with the entire carbon atom, whose mass is considerably greater than the mass of a single electron. The kinematics of such a collision are identical to those of

a collision between a photon and a free electron. Some wavelength shift would be predicted in this case; its form would be identical to that of Eq. (23), but with the electron mass m_e being replaced by the mass of the carbon atom, $m_C = 2\times10^4\, m_e$. The wavelength shift caused by x-rays scattering from carbon atoms in a graphite target is therefore about four orders of magnitude smaller than the shift caused by scattering from free electrons in the same target. The maximum shift due to scattering from free electrons is about 4×10^{-2} Å, which can be measured. The maximum shift due to scattering from carbon atoms, however, is only about 2×10^{-6} Å. This shift is too small to measure, so any x-rays which scatter from atoms in a target will seem to come out with the same wavelength they had when they struck the target, no matter how large the angle through which they have been scattered.

Acknowledgments

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PROBLEM SUPPLEMENT

$$m_e = 511\,\text{KeV/c}^2; \qquad hc = 1.24\,\text{KeV nm}$$

1. What is the ratio of Compton wavelength shift for radiation scattered at 120° to that scattered at 60°?
2. X-rays of wavelength 100 pm are scattered from a carbon block. What is the observed shift in the wavelength for radiation leaving the block at an angle of 60° from the direction of the incident beam?
3. What is the Compton scattering angle for gamma rays which have a wavelength of 10.00 pm after scattering, 9.67 pm before?
4. For 30° Compton scattering, which is larger: $\Delta\lambda$ for $\lambda = 0.15$ nm or $\Delta\lambda$ for $\lambda = 0.10$ nm?
5. What is the scattering angle for the Compton wavelength shift to be at a maximum value?
6. After an elastic collision with a free electron, a photon is observed to have a momentum equal to 134 KeV/c and to be traveling in a direction 13.6° away from its direction before the collision. Calculate the wavelength of the incident photon if the electron was originally at rest.
7. The Compton shift for an x-ray photon is found to be 0.70 pm. If the photon collided with an electron initially at rest, giving it a kinetic energy $E_k = 673$ KeV, find the initial momentum and energy of the x-ray. *Help: [S-1]*

Brief Answers:

5. $(2n+1)\pi$; n is any integer
1. 3:1
4. They are the same; $\Delta\lambda = \lambda_c(1-\cos\phi)$ which is constant, not depending on λ.
6. $\lambda = 9.18$ pm
7. $p_\gamma = 1.48\,\text{MeV}/c$; $E_\gamma = pc = 1.48$ MeV
2. $\Delta\lambda = 1.21$ pm
3. 29.9°

SPECIAL ASSISTANCE SUPPLEMENT

S-1 *(from PS, problem 7)*

Given: $E_{electron}$, $\Delta\lambda_\gamma$

Find: E_γ, P_γ

Method: $\Delta E_\gamma = E_{electron}$; $\Delta E_\gamma = E_\lambda - E_{\lambda'} = \dfrac{hc}{\lambda} - \dfrac{hc}{\lambda'}$

but: $\lambda' = \lambda + \Delta\lambda$

So: $E_e = hc\left(\dfrac{1}{\lambda} - \dfrac{1}{\lambda'}\right) = hc\left(\dfrac{1}{\lambda} - \dfrac{1}{\lambda + \Delta\lambda}\right)$

$$\frac{E_e}{hc} = \frac{1}{\lambda} - \frac{1}{\lambda + \Delta\lambda} = \frac{\Delta\lambda}{\lambda(\lambda + \Delta\lambda)}$$

Let: $a \equiv \dfrac{E_e}{hc\Delta\lambda} = \dfrac{1}{\lambda(\lambda + \Delta\lambda)}$

$\Longrightarrow \quad \lambda^2(a) + \lambda(a\Delta\lambda) - 1 = 0$

quadratic equation: solve by quadratic formula

$a = 0.77535\,\text{pm}^{-2}$

$a\Delta\lambda = 0.54275\,\text{pm}^{-1}$

$\lambda = 0.83838\,\text{pm}$

$E_\gamma = \dfrac{hc}{\lambda} = \dfrac{1.24\,\text{MeV pm}}{0.83838\,\text{pm}}$

MODEL EXAM

Compton Formula: $\lambda' - \lambda = \dfrac{h}{m_e c}(1 - \cos\phi)\,.$

$hc = 1.24\,\text{KeV nm}$

$m_e c^2 = 0.51\,\text{MeV}$

1. See Output Skill K1 in this module's *ID Sheet*.
2. A γ-ray with an initial wavelength of 1.19×10^{-3} nm is observed to be scattered through an angle of 37° upon collision with a free electron. If the electron is initially at rest, find its kinetic energy after the collision.

Brief Answers:

1. See this module's *text*
2. $E_{electron} = 304\,\text{KeV}$