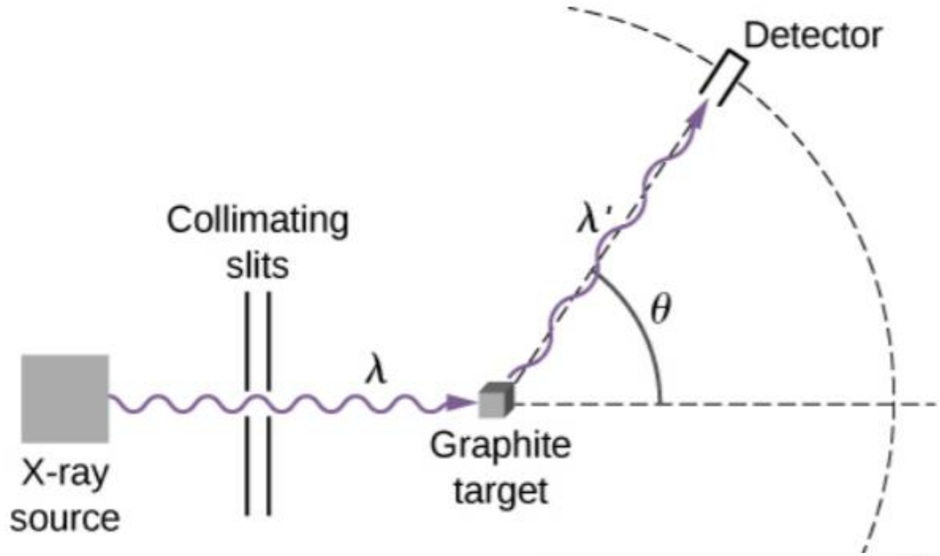
Compton Effect: confirmation of the particle model of e. m. radiation

- Compton Effect was discovered by Arthur Holly Compton in 1923 and for this discovery he was awarded by the Nobel Prize in Physics in 1927.
- According to classical theory of scattering, the wavelength of X-ray would not be changing (Thomson scattering) after interaction with the electrons, however Compton did find a change in wavelength in experiment. Then Compton Effect was explained on the basis of the quantum theory (particle "photon" model) of light.
- This Effect convinced remaining doubters of the existence of photons. It constitutes very strong evidence in support of the Quantum Theory of radiation.

Compton Effect: confirmation of the particle model of e. m. radiation

- The Compton effect (also called Compton scattering) is the result of a high-energy photon colliding with a target, which releases loosely bound electrons from the outer shell of the atom or molecule.
- The scattered radiation experiences a wavelength shift that cannot be explained in terms of classical wave theory, thus lending support to Einstein's photon theory.
- The effect is important because it demonstrates that light cannot be explained purely as a wave phenomenon.
- **Compton effect is the decrease in energy (increase in wavelength) of an X-ray or gamma ray photon, when it interacts with matter. Because of the change in photon energy, it is an inelastic scattering process.**
- Compton used a combination of three fundamental formulas representing the various aspects of classical and modern physics, combining them to describe the quantum behavior of light:
- Light as a particle, as noted in the photoelectric effect
- Relativistic dynamics: special theory of relativity
- Trigonometry: law of cosines

Experimental demonstration of the Compton Effect



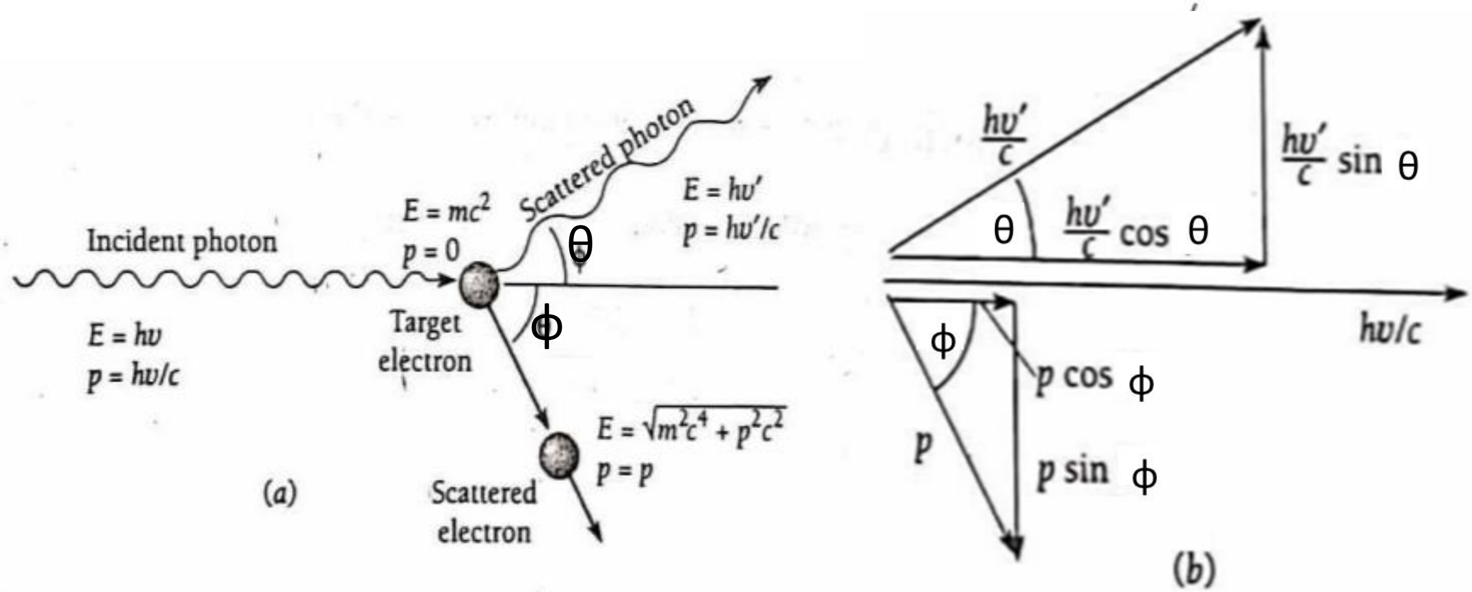


Figure 2.22 (*a*) The scattering of a photon by an electron is called the Compton effect. Energy and momentum are conserved in such an event, and as a result the scattered photon has less energy (longer wavelength) than the incident photon. (*b*) Vector diagram of the momenta and their components of the incident and scattered photons and the scattered electron.

Mathematical description of Compton Effect

We can think of the photon as losing an amount of energy in the collision that is the same as the kinetic energy (KE) gained by the electron, although actually separate photons are involved. If the initial photon has the frequency ν associated with it, the scattered photon has the lower frequency ν', where

Loss in photon energy = gain in electron energy

$$h\nu - h\nu' = KE \qquad (1)$$

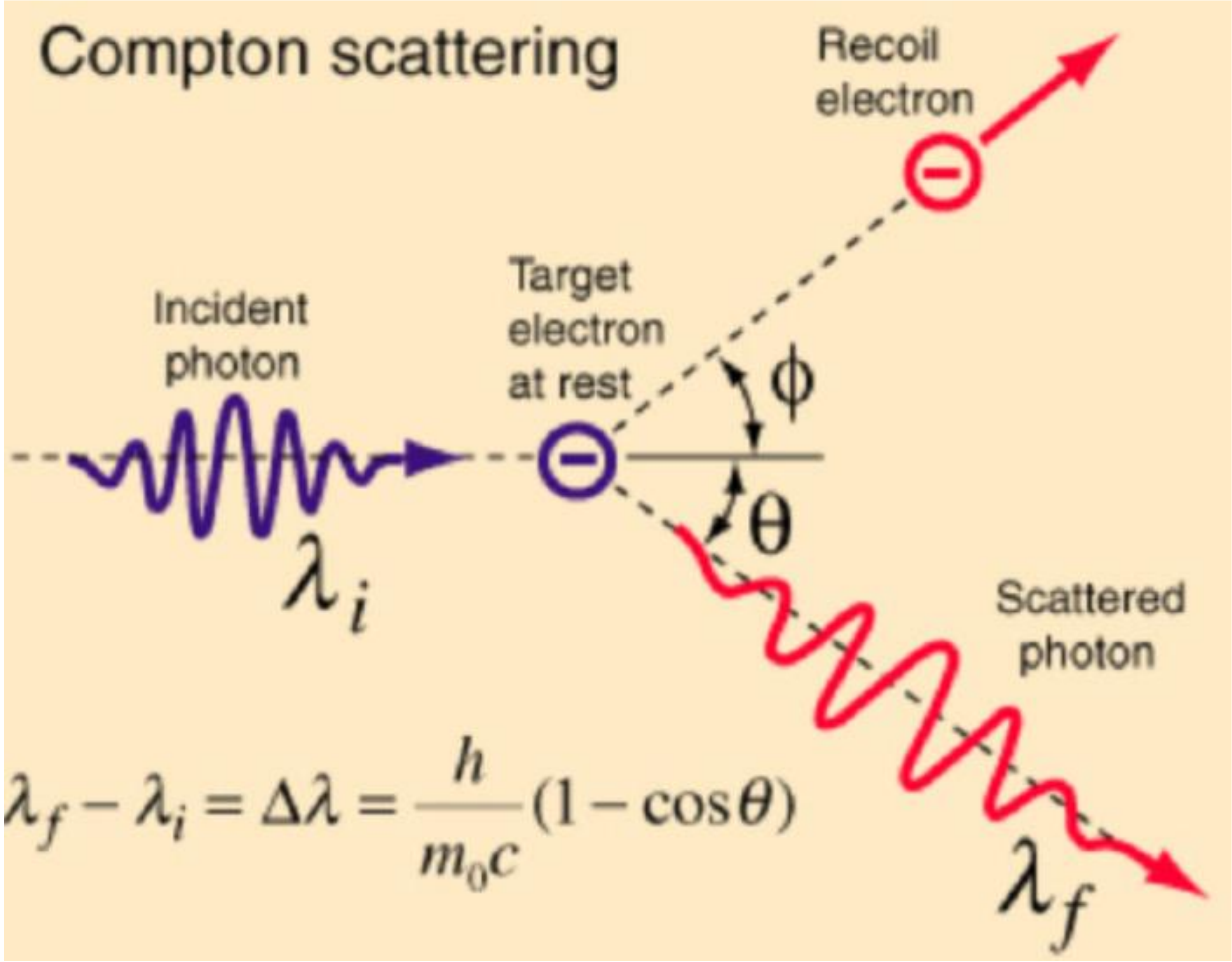
and the momentum of a massless particle is related to its energy by the formula

$$E = pc \qquad (2)$$

Since the energy of a photon is $h\nu$ its momentum is

$$p = \frac{E}{c} = \frac{h\nu}{c} \qquad (3)$$

Momentum, unlike energy is a vector quantity that incorporates direction as well as magnitude, and in the collision momentum must be conserved in each of two mutually perpendicular directions (when more than two bodies participate in a collision, momentum must be conserved in each of three mutually perpendicular directions). The directions we choose here are that of the original photon and one perpendicular to it in the plane containing the electron and the scattered photon (fig)



Initial momentum = final momentum

$$h\nu/c + 0 = (h\nu'/c)\cos\theta + p\cos\phi \qquad (4)$$

and perpendicular to this direction
Initial momentum= final momentum

$$0 = (h\nu'/c)\sin\theta - p\sin\phi \qquad (5)$$

From Equation (1)(4)(5), we can find a formula that relates the wavelength difference between initial and scattered photons with the angle θ between their directions, both of which are readily measurable quantities (unlike the energy and momentum of the recoil electron).

The first step is to multiply Eqs (4)(5) by c and rewrite them as

$$(pc)\cos\phi = h\nu - (h\nu')\cos\theta \qquad (6)$$

$$(pc)\sin\phi = (h\nu')\sin\theta \qquad (7)$$

By squaring each of these equations and adding the new ones together, the angle φ is eliminated, leaving

$$p^2 c^2 = (h\nu)^2 - 2(h\nu)(h\nu')\cos\theta + (h\nu')^2 \qquad (8)$$

Next we equate the two expressions for the total energy of a particle

$$E = KE + mc^2 \qquad (9)$$

$$E = \sqrt{m^2c^4 + p^2c^2} \qquad (10)$$

From equation(1), we have

$$p^2 c^2 = (h\nu)^2 - 2(h\nu)(h\nu') + (h\nu')^2 + 2mc^2(h\nu - h\nu') \qquad (11)$$

Substituting this value of p^2c^2 in Eq.(8), we finally obtain

$$2mc^2(h\nu - h\nu') = 2(h\nu)(h\nu')(1 - \cos\theta) \qquad (12)$$

This relationship is simpler when expressed in terms of wavelength λ .Dividing Eq.(12) by $2h^2c^2$

$$mc/h(\nu/c - \nu'/c) = (\nu/c)(\nu'/c)(1 - \cos\theta) \tag{13}$$

and so, since $\nu/c=1/\lambda$ and $\nu'/c=1/\lambda'$

$$mc/h(1/\lambda - 1/\lambda') = (1 - \cos\theta)/\lambda\lambda' \tag{14}$$

$$\lambda - \lambda' = h/mc(1 - \cos\theta) \tag{15}$$

Equation(15) gives the change in wavelength expected for a photon that is scattered through the angle θ by a particle mass m . This change is independent of the wavelength λ of incident photon. The quantity

$$\lambda_c = \frac{h}{mc} \tag{16}$$

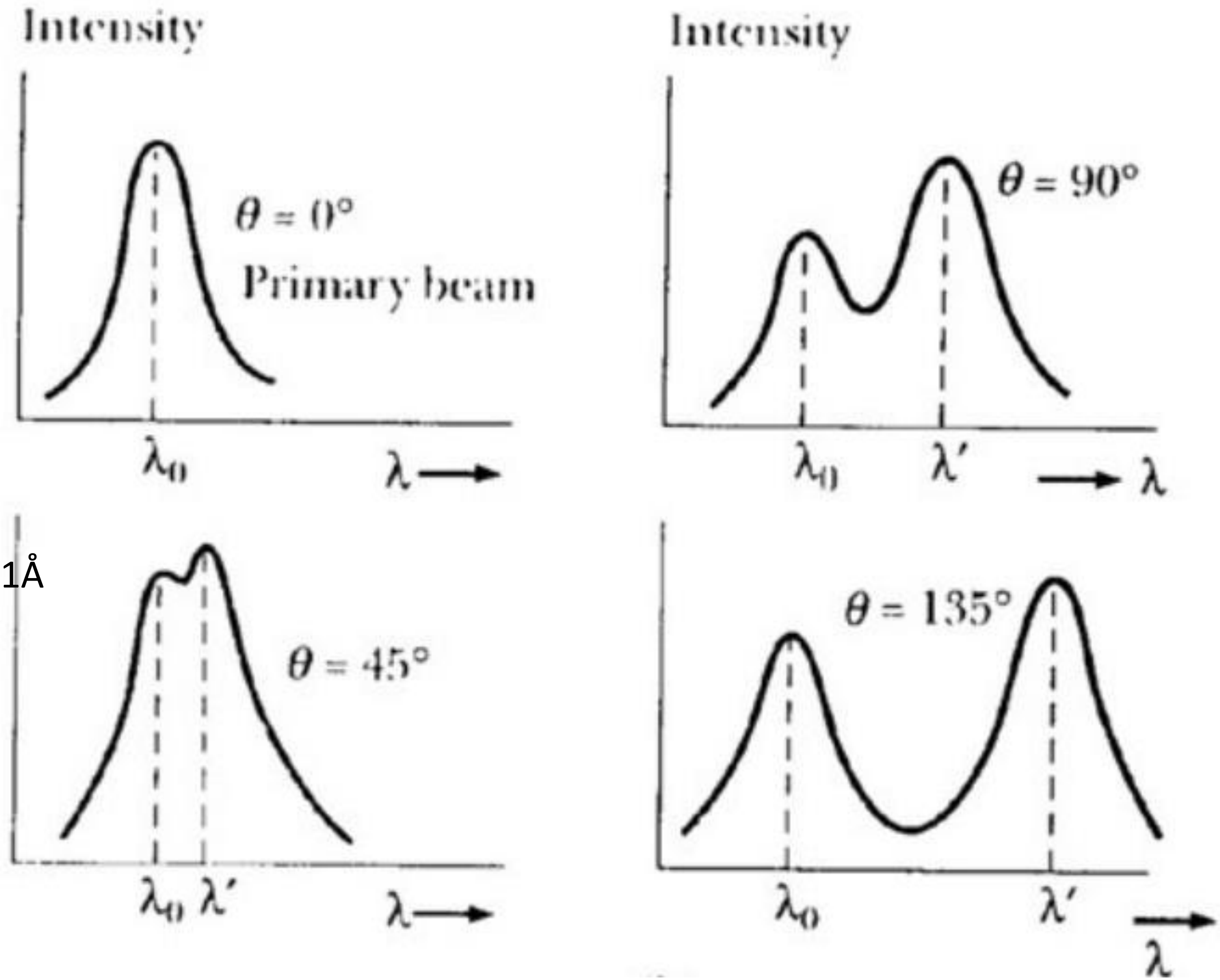
is called the Compton wavelength of the scattering particle. For an electron $\lambda_c=2.426\times10^{-12}$m . In terms of λ_c , Eq.(15) becomes

$$\lambda - \lambda' = \lambda_c(1 - \cos\theta) \tag{17}$$

(iii) $\theta = 90^o$, $\Delta\lambda = 0.0242$Å

(i) $\theta = 0^o$, $\Delta\lambda = 0$

(ii) $\theta = 45^o$, $\Delta\lambda = 0.0071$Å



TYPES OF INTERACTIONS WITH MATTER

- Photoelectric Absorption
- Compton Scattering
- Pair Production

PAIR PRODUCTION

Introduction:-

- Pair production is a process in which the energy of a photon is converted into rest mass.
- In this process, the photon disappears as an electron (negatron) and positron pair is created.

HISTORY OF PAIR PRODUCTION

- The pair production phenomena was first predicted by a British physicist P.A.M. Dirac in 1925.
- His work suggested the existence of a sea of particles below physical matter which remains unobservable.
- Dirac's concept which predicted the positron, the anti electron, was rather than two separate particles being produced, an electron is released from an infinite sea of particles below empty space.
- In removing a particle from sea, the remaining particle would act as the antiparticle.

- In the process of pair production the energy carried by a photon is completely converted into matter, resulting in the creation of an electron positron pair.
- Except for its charge, a positron is identical in all ways to an electron. Since the charge of the system was initially zero, two oppositely charged particles must be produced in order to conserve charge.
- In order to produce a pair, the incident photon must have an energy at least equal to the rest energy of the pair; any excess energy of the photon appears as kinetic energy of the particles.

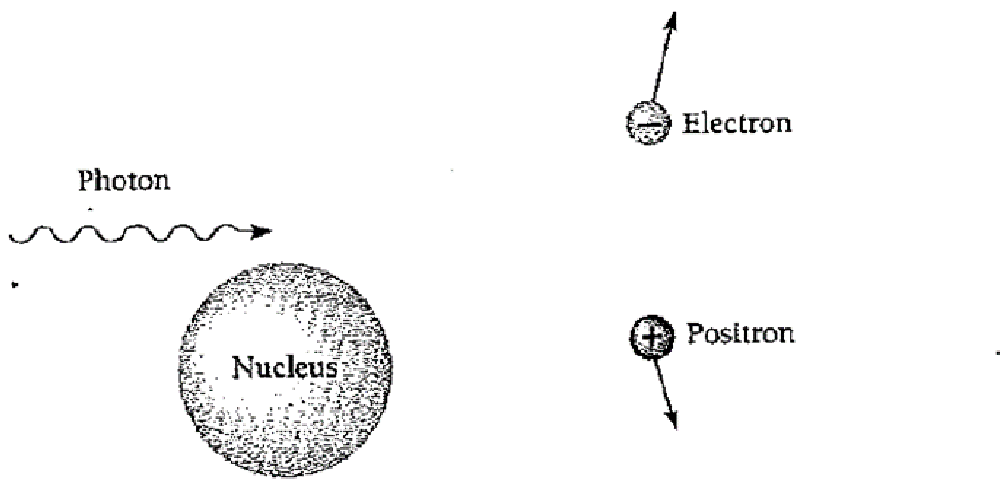


Figure 2.25 In the process of pair production, a photon of sufficient energy materializes into an electron and a positron.