Modern Physics

TOPIC 6

VOCABULARY

- absorption spectrum
- antimatter
- antiparticle
- antiquark
- atom
- atomic spectrum
- baryon
- bright-line spectrum
- emission spectrum
- energy level
- energy-level diagram
- excited state
- ground state
- hadron
- ionization potential
- lepton
- meson
- neutrino
- nuclear force
- nucleus
- photon
- Planck's constant
- positron
- quantized
- quantum
- quantum theory
- quark
- spectral line
- Standard Model of Particle Physics
- stationary state
- universal mass unit

Wave-Particle Duality of Energy and Matter

Earlier in this text, light, a form of electromagnetic radiation, was represented as a wave propagated by an interchange of energy between periodically varying electric and magnetic fields. Waves of electromagnetic energy are identified by their frequency, wavelength, amplitude, and velocity. In addition, electromagnetic radiation exhibits the phenomena of diffraction, interference, and the Doppler effect, which are readily explained by a wave model of light.

Waves Have a Particle Nature

The wave model of light, however, can not explain other phenomena such as interactions of light with matter. In these interactions, light—or other electromagnetic radiation—acts as if it is composed of particles possessing kinetic energy and momentum. For example, when light strikes matter, some of the light's momentum is transferred to the matter. Early in the last century it was discovered that light having a frequency above some minimum value and incident on certain metals caused electrons to be emitted from the metal. This phenomenon, called the photoelectric effect, could not be explained by a wave model of light. Albert Einstein explained the phenomenon using quantum theory developed by Max Planck.

Quantum Theory

Quantum theory assumes that electromagnetic energy is emitted from and absorbed by matter in discrete amounts or packets. Each packet of electromagnetic energy emitted or absorbed is called a **quantum** (plural, quanta) of energy. The amount of energy E of each quantum is directly proportional to the frequency f of the electromagnetic radiation. The proportionality constant between the energy of a quantum and its frequency is called **Planck's constant,** h. Thus, the energy of a quantum is given by this equation.

$$E = hf$$

E is in joules, f is in hertz, and h is a universal constant equal to 6.63×10^{-34} joule·second (J·s). The small energy values of quanta are often expressed in electronvolts, eV ($1 \text{ eV} = 1.60 \times 10^{-19}$ J).

The quantum, or basic unit, of electromagnetic energy is called a **photon.** Although a photon is a massless particle of light, it carries both energy and momentum. The energy of a photon can be found using the previous equation. For light in a vacuum, $f = c/\lambda$ (Topic 5), so the energy of a photon can also be described in this way.

$$E_{\text{photon}} = hf = \frac{hc}{\lambda}$$

The equation states that the energy of a photon is directly proportional to its frequency and inversely proportional to its wavelength.

SAMPLE PROBLEM

The energy of a photon is 2.11 electronvolts.
(a) Determine the energy of the photon in joules.
(b) Determine the frequency of the photon.
(c) Determine the color of light associated with the photon.

Solution: Identify the known and unknown values.

Known	*Unknown*
$E = 2.11$ eV	$E = ?$ J
$h = 6.63 \times 10^{-34}$ J·s	$f = ?$ Hz
	color = ?

(a) Convert electronvolts to joules using the relationship 1 eV = 1.60×10^{-19} J

$$2.11\ \text{eV}\left(\frac{1.60 \times 10^{-19}\ \text{J}}{1\ \text{eV}}\right) = 3.38 \times 10^{-19}\ \text{J}$$

(b) To find the frequency, solve the equation $E = hf$ for frequency f.

$$f = \frac{E}{h}$$

Substitute the known values and solve.

$$f = \frac{3.38 \times 10^{-19}\ \text{J}}{6.63 \times 10^{-34}\ \text{J}\cdot\text{s}} = 5.10 \times 10^{14}\ \text{Hz}$$

(c) According to the electromagnetic spectrum chart found in the *Reference Tables for Physical Setting/Physics*, a frequency of 5.10×10^{14} Hz corresponds to yellow light.

Photon-Particle Collisions

The photoelectric effect demonstrates that when a photon in the visible light range is incident on a metal surface, the photon's energy is completely absorbed and transferred to the emitted electron. However, when X-ray photons, which have much higher frequencies and energies than photons of visible light, strike a metal surface, not only are electrons ejected but electromagnetic radiation of lower frequency is also given off.

When an X-ray photon and an electron collide, some of the energy of the photon is transferred to the electron and the photon recoils with less energy. Less energy means that the photon has lower frequency. Figure 6-1 illustrates this phenomenon.

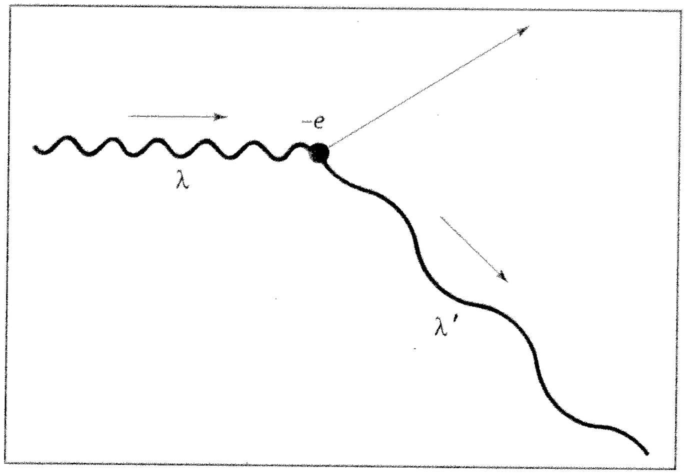


Figure 6-1. A collision of an X-ray photon and an electron in an atom: Besides the electron ejected from the atom, a photon of lower energy (longer wavelength) is also emitted (scattered) by the atom. The energy transferred to the electron equals the difference in energy between the incident photon and the scattered photon. The vector sum of the momentum of the electron and the scattered photon also equals the momentum of the incident photon.

Both energy, a scalar quantity, and momentum, a vector quantity, are conserved in this interaction, just as they are in collisions between particles. The incident photon loses energy and momentum, while the electron gains energy and momentum. Photons always travel at the speed of light. Thus, the momentum of a photon depends only on its wavelength or frequency.

Particles Have a Wave Nature

Just as radiation has both wave and particle characteristics, matter in motion has wave as well as particle characteristics. The wavelengths of the waves associated with the motion of ordinary objects, such as a thrown baseball, are too small to be detected. But the waves associated with the motion of particles of atomic or subatomic size, such as electrons, can produce diffraction and interference patterns that can be observed. Diffraction and interference phenomena provide evidence for the wave nature of particles.

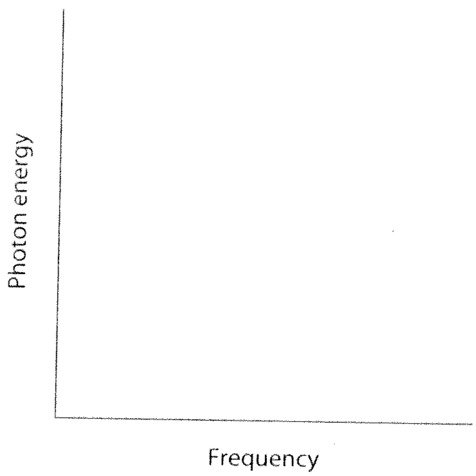
Review Questions

1. In which part of the electromagnetic spectrum does a photon have the least energy? (1) gamma rays (2) microwaves (3) visible light (4) ultraviolet

2. The energy of a photon varies inversely with its (1) frequency (2) momentum (3) speed (4) wavelength

3. Compared to a photon of red light, a photon of blue light has a (1) lower frequency and shorter wavelength (2) lower frequency and longer wavelength (3) higher frequency and shorter wavelength (4) higher frequency and longer wavelength

4. On the axes that follow, sketch a line to represent the relationship between photon energy and frequency for a series of photons.



5. A photon of green light has a frequency of approximately 6.0×10^{14} hertz. The energy associated with this photon is approximately (1) 1.1×10^{-48} J (2) 6.0×10^{-34} J (3) 5.0×10^{-7} J (4) 4.0×10^{-19} J

6. Determine the energy of a photon having a wavelength of 4.00×10^{-7} meter.

7. A photon has an energy of 8.0×10^{-19} joule. What is this energy expressed in electronvolts? (1) 5.0×10^{-38} eV (2) 1.6×10^{-19} eV (3) 8.0×10^{-19} eV (4) 5.0 eV

8. A gamma photon collides with an electron at rest. During the interaction, the momentum of the photon (1) decreases (2) increases (3) remains the same

9. An X-ray photon collides with an electron in an atom, ejecting the electron and emitting another photon. During the collision there is a conservation of (1) momentum only (2) energy only (3) both momentum and energy (4) neither momentum nor energy

10. Experiments performed with light indicate that light exhibits (1) particle properties only (2) wave properties only (3) both particle and wave properties (4) neither wave nor particle properties

11. According to the quantum theory of light, light energy is carried in discrete units called (1) protons (2) photons (3) photoelectrons (4) quarks

Early Models of the Atom

An **atom** is the smallest particle of an element that retains the characteristics of the element. Models for the structure of the atom have evolved over centuries as scientists have developed more sophisticated methods and equipment for studying particles that are too small to be detected by the unaided eye.

Thomson's Model

Just over 100 years ago, J. J. Thomson discovered that electrons are relatively low-mass, negatively charged particles present in atoms. Because he knew that atoms are electrically neutral, Thomson concluded that part of the atom must possess a positive charge equal to the total charge of the atom's electrons. Thomson proposed a model in which the atom consists of a uniform distribution of positive charge in which electrons are embedded, like raisins in plum pudding.

Rutherford's Model

Less than two decades later, Ernest Rutherford proposed a different model of the atom. He performed experiments in which he directed a beam of massive, positively charged particles, traveling at approximately one-tenth the speed of light, at extremely thin gold foil. Rutherford postulated that if an atom was like those described in Thomson's model, there would be only small net Coulomb forces on a positively charged particle as it passed through or near a gold atom in the foil, and the particle would pass through the foil relatively unaffected. However, he found that, although nearly all the positively charged particles were not deflected from a straight-line path through the gold foil, a small number of particles were scattered at large angles.

To explain the large angles of deflection of those few particles, Rutherford theorized that the massive, energetic, positively charged particles must have collided with other even more massive