The Language of Physics

Photon
A small bundle of electromagnetic energy that acts as a particle of light. The photon has zero rest mass and its energy and momentum are determined in terms of the wavelength and frequency of the light wave (p. 924).

Photoelectric effect
Light falling on a metallic surface produces electrical charges. The photoelectric effect cannot be explained by classical electromagnetic theory. Einstein used the quantum theory to successfully explain this effect and won the Nobel Prize in physics. He said that a photon of light collides with an electron and imparts enough energy to it to remove it from its position in the metal (p. 925).

Principle of complementarity
The wave theory of light and the quantum theory of light complement each other. In a specific case, light exhibits either a wave nature or a particle nature, but never both at the same time (p. 933).

Compton effect
Compton bombarded electrons with photons and found that the scattered photon has a different wavelength than the incident light. The photon lost energy to the electron in the collision (p. 934).

de Broglie relation
de Broglie assumed that the same wave-particle duality associated with electromagnetic waves should also apply to particles. Thus, particles should also act as waves. The wave was first called a pilot wave, and then a matter wave. Today, it is simply called the wave function (p. 938).

Heisenberg uncertainty principle
The position and momentum of a particle cannot both be measured simultaneously with perfect accuracy. There is always a fundamental uncertainty associated with any measurement. This uncertainty is not associated with the measuring instrument. It is a consequence of the wave-particle duality of matter (p. 944).

Virtual particles
Ghostlike particles that exist around true particles. They exist by borrowing energy from the true particle, and converting this energy into mass. The energy must, however, be paid back before the time Δt, determined by the uncertainty principle, elapses. The virtual particles supply the force necessary to keep protons and neutrons together in the nucleus (p. 949).

Summary of Important Equations

Planck's relation
$$E = nh\nu \tag{31.2}$$

Einstein's photoelectric equation
$$KE_{max} = h\nu - W_0 \tag{31.10}$$

The work function
$$W_0 = h\nu_0 \tag{31.11}$$

Properties of the photon

Rest mass
$$m_0 = 0 \tag{31.14}$$

Energy
$$E = h\nu \tag{31.6}$$

Relativistic mass
$$m = \frac{E}{c^2} = \frac{h\nu}{c^2} \tag{31.16}$$

Momentum
$$p = \frac{E}{c} = \frac{h\nu}{c} = \frac{h}{\lambda} \tag{31.21}$$

Momentum of any particle
$$p = \frac{\sqrt{E^2 - E_0^2}}{c} \tag{31.19}$$

Compton scattering formula
$$\lambda' - \lambda = \frac{h}{m_0 c}(1 - \cos\phi) \tag{31.28}$$

de Broglie relation
$$\lambda = \frac{h}{p} \tag{31.29}$$

The uncertainty principle
$$\Delta p\,\Delta x \geq \hbar \tag{31.44}$$
$$\Delta\theta\,\Delta L \geq \hbar \tag{31.51}$$
$$\Delta E\,\Delta t \geq \hbar \tag{31.55}$$

Angular momentum of a particle
$$L = rp\sin\theta \tag{31.48}$$
$$L = rp = rmv \tag{31.47}$$

Payback time for a virtual particle
$$\Delta t = \frac{\hbar}{(\Delta m)c^2} \tag{31.57}$$

Gravitational red shift
$$\nu_f = \nu_g\left(1 - \frac{gy}{c^2}\right) \tag{31.63}$$

$$T_f = T_g\left(1 + \frac{gy}{c^2}\right) \tag{31.64}$$

Slowing down of a clock in a gravitational field
$$\Delta t_f = \Delta t_g\left(1 + \frac{gy}{c^2}\right) \tag{31.65}$$

Slowing down of an accelerated clock
$$\Delta t_f = \Delta t_a\left(1 + \frac{ay}{c^2}\right) \tag{31.66}$$
$$\Delta t = \frac{\Delta t_a}{\sqrt{1 - v^2/c^2}} \tag{31.70}$$

Length contraction in a gravitational field
$$\lambda_f = \left(1 + \frac{gy}{c^2}\right)\lambda_g \tag{31.73}$$

Length contraction in an acceleration
$$\lambda_0 = \left(1 + \frac{ay}{c^2}\right)\lambda_a \tag{31.74}$$
$$L = L_0\sqrt{1 - v^2/c^2} \tag{31.77}$$

Questions for Chapter 31

†**1.** How would the world appear if Planck's constant h were very large? Describe some common occurrences and how they would be affected by the quantization of energy.

2. When light shines on a surface, is momentum transferred to the surface?

3. Could photons be used to power a spaceship through interplanetary space?

4. Should the concept of the cessation of all molecular motion at absolute zero be modified in view of the uncertainty principle?

5. Which photon, red, green, or blue, carries the most (a) energy and (b) momentum?

6. Discuss the entire wave-particle duality. That is, is light a wave or a particle, and is an electron a particle or a wave?

†**7.** Discuss the concept of determinism in terms of the uncertainty principle.

†**8.** Why isn't the photoelectric effect observed in all metals?

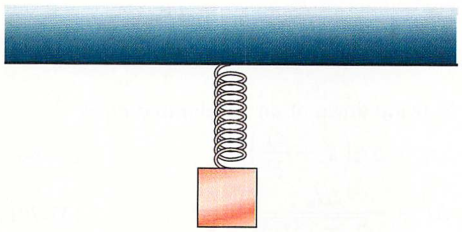
9. Ultraviolet light has a higher frequency than infrared light. What does this say about the energy of each type of light?

†**10.** Why can red light be used in a photographic dark room when developing pictures, but a blue or white light cannot?

Problems for Chapter 31

31.2 Blackbody Radiation

1. A weightless spring has a spring constant of 18.5 N/m. A 500-g mass is attached to the spring. It is then displaced 10.0 cm and released. Find (a) the total energy of the mass, (b) the frequency of the vibration, (c) the quantum number n associated with this energy, and (d) the energy change when the oscillator changes its quantum state by one value.



2. Find the energy of a photon of light of 400.0-nm wavelength.

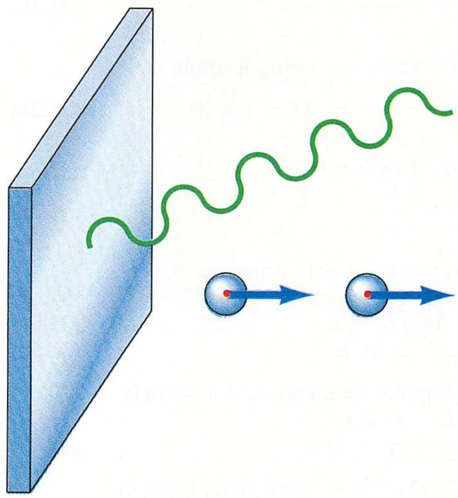
3. A radio station broadcasts at 92.4 MHz. What is the energy of a photon of this electromagnetic wave?

31.3 The Photoelectric Effect

4. The work function of a material is 4.52 eV. What is the threshold wavelength for photoelectronic emission?

5. The threshold wavelength for photoelectronic emission for a particular material is 518 nm. Find the work function for this material.

†**6.** Light of 546.0-nm wavelength is incident on a cesium surface that has a work function of 1.91 eV. Find (a) the frequency of the incident light, (b) the energy of the incident photon, (c) the maximum kinetic energy of the photoelectron, (d) the stopping potential, and (e) the threshold wavelength.



31.4 The Properties of the Photon

7. A photon has an energy of 5.00 eV. What is its frequency and wavelength?

8. Find the mass of a photon of light of 500.0-nm wavelength.

9. Find the momentum of a photon of light of 500.0-nm wavelength.

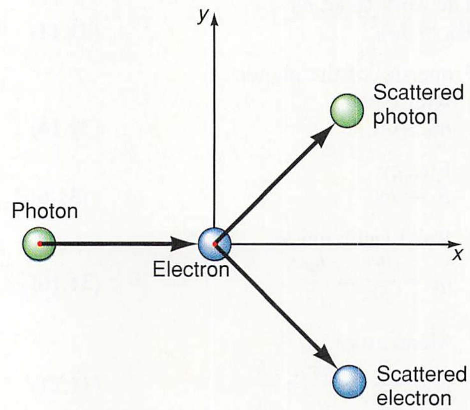
10. Find the wavelength of a photon whose energy is 500 MeV.

11. What is the energy of a 650 nm photon?

31.5 The Compton Effect

12. An 80.0-KeV X ray is fired at a carbon target and Compton scattering occurs. Find the wavelength of the incident photon and the wavelength of the scattered photon for an angle of 40.0°.

13. If an incident photon has a wavelength of 0.0140 nm, and is found to be scattered at an angle of 50.0° in Compton scattering, find the energy of the recoiling electron.



14. In a Compton scattering experiment, 400-nm photons are scattered by the target, yielding 769-nm photons. What is the angle at which the 769-nm photons are scattered?

31.6 The Wave Nature of Particles

15. Find the wavelength of a 4.60×10^{-2} kg golf ball moving at a speed of 60.0 m/s.

16. Find the wavelength of a proton moving at 10.0% of the speed of light.

17. Find the wavelength of an electron moving at 10.0% of the speed of light.

18. Find the wavelength of a 5.00-KeV electron.

19. Find the wavelength of an oxygen molecule at room temperature.

20. What is the frequency of the matter wave representing an electron moving at a speed of $2c/3$?

21. (a) Find the total energy of a proton moving at a speed of $c/2$. (b) Compute the wavelength of this proton.

31.8 The Heisenberg Uncertainty Principle

22. A 4.6×10^{-2} kg golf ball is in motion along the x-axis. If it is located at the position $x = 1.00$ m, with an uncertainty of 0.005 m, find the uncertainty in the determination of the momentum and velocity of the golf ball.

23. Find the minimum uncertainty in the determination of the momentum and speed of a 1300-kg car if the position of the car is to be known to a value of 10 nm.

24. The uncertainty in the position of a proton is 100 nm. Find the uncertainty in the kinetic energy of the proton.

31.9 Different Forms of the Uncertainty Principle

†25. The lifetime of an electron in an excited state of an atom is 10^{-8} s. From the uncertainty in the energy of the electron, determine the width of the spectral line centered about 550 nm.

Additional Problems

26. Approximately 5.00% of a 100-W incandescent lamp falls in the visible portion of the electromagnetic spectrum. How many photons of light are emitted from the bulb per second, assuming that the wavelength of the average photon is 550 nm?

Interactive Tutorials

27. The photoelectric effect. Light of wavelength $\lambda = 577.0$ nm is incident on a cesium surface. Photoelectrons are observed to flow when the applied voltage $V_0 = 0.250$ V. Find (a) the frequency ν of the incident photon, (b) the initial energy E of the incident photon, (c) the maximum kinetic energy KE_{max} of the photoelectrons, (d) the work function W_0 of cesium, (e) the threshold frequency ν_0, and (f) the corresponding threshold wavelength λ_0.

28. Light of wavelength $\lambda = 460$ nm is incident on a cesium surface. The work function of cesium is $W_0 = 3.42 \times 10^{-19}$ J. Find (a) the frequency ν of the incident photon, (b) the initial energy E of the incident photon, (c) the maximum kinetic energy KE_{max} of the emitted photoelectrons, (d) the maximum speed v of the electron, (e) the threshold frequency ν_0, and (f) the corresponding longest wavelength λ_0 that will eject electrons from the metal.

29. Properties of a photon. A photon of light has a wavelength $\lambda = 420.0$ nm, find (a) the frequency ν of the photon, (b) the energy E of the photon, (c) the mass m of the photon, and (d) the momentum p of the photon.

30. The Compton effect. An x-ray photon of energy $E = 90.0$ KeV is fired at a carbon target and Compton scattering occurs at an angle $\phi = 30.0°$. Find (a) the frequency ν of the incident photon, (b) the wavelength λ of the incident photon, and (c) the wavelength λ' of the scattered photon.

31. Using the concept of wave particle duality, calculate the wavelength λ of a golf ball whose mass $m = 4.60 \times 10^{-2}$ kg and is traveling at a speed $v = 60.0$ m/s.

Additional Problems

34. Find the velocity of an electron in a 5.29×10^{-11} m radius orbit by (a) the Rutherford model and (b) the Bohr model of the hydrogen atom.

35. In what quantum state must an orbital electron be such that its orbital angular momentum is 4.719×10^{-34} J s (i.e., find l, the orbital angular momentum quantum number).

†36. Determine the angular momentum of the moon about the earth. (a) Use Bohr's postulate of quantization of angular momentum and determine the quantum number associated with this orbit. (b) If the quantum number n increases by 1, what is the new angular momentum of the moon? (c) What is the change in the orbital radius of the moon for this change in the quantum number? (d) Is it reasonable to neglect quantization of angular momentum for classical orbits?

37. From the frame of reference of the electron in the hydrogen atom, the proton is in an orbit about the electron and constitutes a current loop. Determine the magnitude of the magnetic field produced by the proton when the electron is in the $2p$ state.

†38. Using the results of problem 37, (a) determine the additional potential energy of an electron caused by the spin-orbit interaction. (b) Find the change in energy when electrons drop from the $2p$ state back to the ground state. (c) Find the frequencies of the emitted photons. (d) Find the wavelengths of the emitted photons.

Interactive Tutorials

39. Bohr theory of the atom. An electron is in a Bohr orbit with a principal quantum number $n_i = 3$, and then jumps to a final orbit for the final value $n_f = 1$, find (a) the radius of the nth orbit, (b) the speed of the electron in the nth orbit, (c) the energy of the electron in the initial n_i orbit, (d) the energy of the electron in the final n_f orbit, (e) the energy given up by the electron as it jumps to the lower orbit, (f) the frequency, and (g) the wavelength of the spectral line associated with the transition from the initial $n_i = 3$ state to the final $n_f = 1$ state.