

Answer to Essential Question 27.6: The fact that Planck's constant is tiny means that the uncertainty principle is important for objects around the size of an atom or less. If Planck's constant was a great deal larger, such as 1 J s, the uncertainty principle (and the de Broglie wavelength) would be relevant for all objects we deal with on an everyday basis. The world would be a much stranger place than it already is. Cars would diffract from tunnels, batters in baseball would have to deal with the wave nature of the baseball, etc.

Chapter Summary

Essential Idea: The Quantum World.

The quantum world deals with interactions between very small particles like electrons, protons, and atoms. Because of the tiny value of Planck's constant ($h = 6.626 \times 10^{-34}$ J s), the behavior of such particles is very different from the behavior of everyday objects. Among other things, these tiny objects exhibit both a wave nature and a particle nature.

Black body radiation

Black body radiation is the radiation, in the form of electromagnetic waves, which emanates from a warm object. An example is the red-orange glow given off by a toaster element. Black body radiation is historically significant, because Max Planck explained it in terms of quantized energy levels, the first time quantized energy levels had been used.

The Photoelectric effect

When light is incident on a metal, electrons can be emitted from the metal, in a process known as the photoelectric effect. Electrons are emitted only if the frequency of the light is larger than a particular threshold frequency that depends on the metal. Increasing the intensity of the incident light does not change the maximum kinetic energy of the emitted electrons. The photoelectric effect cannot be explained in terms of light acting as a wave. Instead, it is explained in terms of light being made up of particles, which we call photons, with the electrons being emitted because of single photon – single electron interactions.

$$E = hf, \quad (\text{Equation 27.2: Energy of a photon})$$

where f is the frequency of the electromagnetic wave corresponding to the photon.

$$K_{\max} = hf - W_0, \quad (\text{Equation 27.3: The photoelectric effect})$$

where K_{\max} is the maximum kinetic energy of the electrons and W_0 is the work function.

The Compton effect

Despite having no mass, photons carry momentum, given by

$$p = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda}. \quad (\text{Equation 27.6: Momentum of a photon})$$

The fact that photons have momentum is demonstrated by the Compton effect, a single photon – single electron collision in which both momentum and energy are conserved.

$$\Delta\lambda = \lambda' - \lambda = \frac{h}{m_e c} (1 - \cos\theta), \quad (\text{Equation 27.7: The Compton Effect})$$

where m_e is the mass of the electron, and the quantity $h/(m_e c) = 2.43 \times 10^{-12}$ m is the Compton wavelength. θ is the angle between the directions of the incident and outgoing photons, while λ' is the wavelength of the outgoing photon and λ is the wavelength of the incident photon.

Wave-particle duality

Light is not the only thing that exhibits both a wave nature and a particle nature – everything exhibits such wave-particle duality. The wavelength of an object is inversely proportional to its momentum.

$$\lambda = \frac{h}{p} = \frac{h}{mv} . \quad (\text{Equation 27.8: the de Broglie wavelength})$$

To explain the results of a particular experiment, usually either the wave nature or the particle nature is used.

Heisenberg's uncertainty principle

Quantum physics actually puts a limit on how accurately we can know something. More specifically, the uncertainties in two related quantities, such as the position and momentum of an object, are related in such a way that the smaller the uncertainty in one of the quantities, the larger the uncertainty has to be in the other quantity.

$$\Delta x \Delta p \geq \frac{h}{4\pi} = 5.273 \times 10^{-35} \text{ J s} . \quad (\text{Equation 27.9: Heisenberg's uncertainty principle})$$

End-of-Chapter Exercises

Exercises 1 – 12 are conceptual questions that are designed to see if you have understood the main concepts of the chapter.

1. Astronomers can determine the temperature at the surface of a star by looking at the star's color. Explain how the color of a star corresponds to its temperature, and comment on whether a blue star has a higher surface temperature than does a red star, or vice versa.
2. An incandescent light bulb gives off a bright yellow-white glow when it is connected to a wall socket. If the potential difference across the bulb is reduced, however, not only does the bulb get dimmer, the emitted light takes on a distinct orange hue. Explain this.
3. With a particular metal plate, shining a beam of blue light on the metal causes electrons to be emitted via the photoelectric effect. If we reduce the intensity of the light shining on the metal, without changing its wavelength, what happens? Explain your answer.
4. The work functions of gold, aluminum, and cesium are 5.1 eV, 4.1 eV, and 2.1 eV, respectively. If light of a particular frequency causes photoelectrons to be emitted when the light is incident on an aluminum surface, explain if we know whether this means that photoelectrons are emitted from a gold surface or a cesium surface when the light is incident on those surfaces.
5. With a particular metal plate, shining a beam of green light on the metal causes electrons to be emitted. (a) If we replace the green light by blue light, do we know that electrons will be emitted? (b) If the two beams have the same intensity and are incident on equal areas of the plate, do we get the same number of electrons emitted per second in the two cases? Assume that the probability that a photon will cause an electron to be emitted is the same in both cases (e.g., for every two photons incident on the plate, one electron is emitted).