

### 29.1 Quantization of Energy

- The first indication that energy is sometimes quantized came from blackbody radiation, which is the emission of EM radiation by an object with an emissivity of 1.
- Planck recognized that the energy levels of the emitting atoms and molecules were quantized, with only the allowed values of  $E = \left(n + \frac{1}{2}\right)hf$ , where  $n$  is any non-negative integer (0, 1, 2, 3, ...).
- $h$  is Planck's constant, whose value is  $h = 6.626 \times 10^{-34} \text{ J} \cdot \text{s}$ .
- Thus, the oscillatory absorption and emission energies of atoms and molecules in a blackbody could increase or decrease only in steps of size  $\Delta E = hf$  where  $f$  is the frequency of the oscillatory nature of the absorption and emission of EM radiation.
- Another indication of energy levels being quantized in atoms and molecules comes from the lines in atomic spectra, which are the EM emissions of individual atoms and molecules.

### 29.2 The Photoelectric Effect

- The photoelectric effect is the process in which EM radiation ejects electrons from a material.
- Einstein proposed photons to be quanta of EM radiation having energy  $E = hf$ , where  $f$  is the frequency of the radiation.
- All EM radiation is composed of photons. As Einstein explained, all characteristics of the photoelectric effect are due to the interaction of individual photons with individual electrons.
- The maximum kinetic energy  $\text{KE}_e$  of ejected electrons (photoelectrons) is given by  $\text{KE}_e = hf - \text{BE}$ , where  $hf$  is the photon energy and BE is the binding energy (or work function) of the electron to the particular material.

### 29.3 Photon Energies and the Electromagnetic Spectrum

- Photon energy is responsible for many characteristics of EM radiation, being particularly noticeable at high frequencies.
- Photons have both wave and particle characteristics.

### 29.4 Photon Momentum

- Photons have momentum, given by  $p = \frac{h}{\lambda}$ , where  $\lambda$  is the photon wavelength.
- Photon energy and momentum are related by  $p = \frac{E}{c}$ , where  $E = hf = hc/\lambda$  for a photon.

### 29.5 The Particle-Wave Duality

- EM radiation can behave like either a particle or a wave.
- This is termed particle-wave duality.

### 29.6 The Wave Nature of Matter

- Particles of matter also have a wavelength, called the de Broglie wavelength, given by  $\lambda = \frac{h}{p}$ , where  $p$  is momentum.

- Matter is found to have the same *interference characteristics* as any other wave.

### 29.7 Probability: The Heisenberg Uncertainty Principle

- Matter is found to have the same interference characteristics as any other wave.
- There is now a probability distribution for the location of a particle rather than a definite position.
- Another consequence of the wave character of all particles is the Heisenberg uncertainty principle, which limits the precision with which certain physical quantities can be known simultaneously. For position and momentum, the uncertainty principle is  $\Delta x \Delta p \geq \frac{h}{4\pi}$ , where  $\Delta x$  is the uncertainty in position and  $\Delta p$  is the uncertainty in momentum.
- For energy and time, the uncertainty principle is  $\Delta E \Delta t \geq \frac{h}{4\pi}$  where  $\Delta E$  is the uncertainty in energy and  $\Delta t$  is the uncertainty in time.
- These small limits are fundamentally important on the quantum-mechanical scale.

### 29.8 The Particle-Wave Duality Reviewed

- The particle-wave duality refers to the fact that all particles—those with mass and those without mass—have wave characteristics.
- This is a further connection between mass and energy.