**Key Ideas**

**Two Principles of Relativity:**
- The laws of physics are the same for all uniformly moving observers.
- The speed of light is the same for all observers.

**Consequences:**
- Different observers measure different times, lengths, and masses.
- Only spacetime is observer-independent.

**Important Concepts**

\[
E = mc^2 \\
t = T\sqrt{1 - \left(\frac{v}{c}\right)^2} \\
l = L\sqrt{1 - \left(\frac{v}{c}\right)^2} \\
m = m_0\sqrt{1 - \frac{v^2}{c^2}} \\
KE = mc^2 - m_0c^2 = m_0c^2\sqrt{1 - \frac{v^2}{c^2}} - m_0c^2
\]

**Chapter 27**

**Quantum Physics**

- Photoelectric Effect
- Compton Effect
- Photon Theory of Light
- Wave Nature of Matter
- Wave-Particle Duality
- Wave Function
- Uncertainty Principle

**Ideas of quantum theory were developed when classical physics could not explain a handful of physical phenomena observed in beginning of the 20th century**
Planck's quantum hypothesis

Planck's model required that the energy in the atomic vibrations of frequency \( f \) was some integer times a small, minimum, discrete energy,

\[
E_{\text{min}} = hf
\]

where \( h \) is a constant, now known as Planck's constant,

\[
h = 6.626176 \times 10^{-34} \text{ J\cdot s}
\]

Planck's proposal then requires that all the energy in the atomic vibrations with frequency \( f \) can be written as

\[
E = nhf
\]

where \( n \) is an integer, \( n = 1, 2, 3, \ldots \) No other values of the energy were allowed.

The energy is quantized!

Planck did not realize how radical and far-reaching his proposals were. He viewed his strange assumptions as mathematical constructions to provide a formula that fit the experimental data. It was not until later, when Einstein used very similar ideas to explain the Photoelectric Effect in 1905, that it was realized that these assumptions described "real physics" and were much more than mathematical constructions to provide the right formula.

The Photoelectric Effect

Heinrich Hertz first observed this photoelectric effect in 1887. This, too, was one of a few phenomena that Classical Physics could not explain. Light falling on a metal can cause electrons to be ejected from the metal. This is known as the photoelectric effect:

Photon Theory of Light

In 1905 Albert Einstein provided a daring extension of Planck's quantum hypothesis and proposed that the energy of the light is contained in "packets" or quanta each with energy of

\[
E = hf
\]

where again \( h \) is Planck's constant and \( f \) is the frequency of the light. All of the energy in one quantum -- now called a photon -- is given to one electron.

For light with a frequency \( f \) greater than some particular threshold frequency, there would be enough energy and the electron would be ejected. From the conservation of energy, we would expect the electron to leave with kinetic energy \( KE \) given by

\[
hf = KE + W \quad \text{or} \quad KE = hf - W
\]

where \( W \) is the amount of work that must be done to separate an electron from the metal. For the least strongly bound electrons this amount of work is known as the "work function" and is labeled \( W_0 \). These electrons will leave with the greatest kinetic energy \( KE_{\text{max}} \) which is given by

\[
hf = KE_{\text{max}} + W_0 \quad \text{or} \quad KE_{\text{max}} = hf - W_0
\]

\( W_0 \) is the minimum energy needed to remove an electron from a surface.
Photoelectron energy increases with frequency of incident light 
\( KE_{\text{max}} = h f - W_o \)

An increase in the intensity of the light only means an increase in the number of photons so more electrons will be ejected. But there will be no increase in the maximum energy of the electrons.

Kinetic Energy can never be negative so this equation defines a threshold frequency, \( f_0 \), from
\[ h f_0 = W_o \]

If the frequency of the light is below this threshold frequency \( f_0 \) there will be no photoelectrons ejected from the metal.

In 1913 and 1914 Robert A Millikan carried out careful experiments and measured precisely what Einstein's new theory predicted.

Question: Photoelectrons are emitted by a metal surface only when the light directed at it exceeds a certain minimum
(a) wavelength
(b) frequency
(c) speed
(d) charge

Answer: b

Question: When light is directed on a metal surface, the energies of the emitted electrons
(a) vary with the intensity of the light
(b) vary with the frequency of the light
(c) vary with the speed of the light
(d) are random

Answer: b

Compton Effect

\[ h f - h f' = KE \]

Photon momentum \( p=hf/c \) [i.e., \( m_p c=(hf/c^2)c \)]

After a collision between a photon and electron
\[ 1/f - 1/f' = (h/m_0 c^2)(1-\cos\phi) \]

The greater the scattering angle, the greater should be the change in frequency
Compton effect verifies that photons do indeed possess the momentum $p=hf/c$ and do indeed behave like particles in collisions: the quantum nature of light with ordinary conservation of momentum and energy.

However, Young's famous double slit experiment had shown conclusively that light was a wave, not a particle.

Wave-Particle Duality

de Broglie proposed that electrons, too, have a wave nature and a wavelength and that all material objects have a wave nature. In particular, de Broglie proposed that the wavelength of a body could be found from

$$\lambda = h/p = h/mv$$

This wave is often called its de Broglie wave. Planck's constant $h$ has such an extremely small value that the wavelength associated with any ordinary object is far too small to be experimentally detected.

The wave and particle aspects of matter complement one another

- One must be aware of both the particle and wave aspects in order to have an understanding of matter.
- One must also recognize that a visual picture of a wave-particle is not possible
- Which aspect is most significant depends on how the object's de Broglie wavelength compares with the dimension of whatever it interacts with

Example: Compare the de Broglie wavelength of 54-eV electrons with spacing of atomic planes in a crystal, which is $0.91\times10^{-10}$ m.

Solution: KE of a 54-eV electron is

$$KE=(54eV)(1.6\times10^{-19} \text{ J/eV})=8.6\times10^{-18} \text{ J}$$

$$KE=1/2 \ m v^2, \ mv=(2mKE)^{1/2}$$

$$\lambda = h/mv = h/(2mKE)^{1/2} = 1.7\times10^{-10} \text{ m}$$

Comparable to the spacing of the atomic planes, so diffraction occurs

Example: Find the de Broglie wavelength of a 1500-kg car whose speed is 30 m/s.

Solution: The car's wavelength is

$$\lambda = h/mv = 6.63\times10^{-34} \text{ J} \cdot s/(1.5\times10^3)(30\text{ m/s})$$

$$= 1.5\times10^{-38} \text{ m}$$

The wavelength is so small compared to the car's dimension that no wave behavior is to be expected.

Question: Modern physical theories indicate that

(a) all particles exhibit wave behavior
(b) only moving particles exhibit wave behavior
(c) only charged particles exhibit wave behavior
(d) only unchanged particles exhibit wave behavior

Answer: b
### Question:
Why do we say that light has wave properties? Why do we say that light has particle properties?

**Answer:**

*Evidence for wave behavior:*
Interference, polarization, and diffraction

*Evidence for particle behavior:*  
Photoelectric effect, Compton effect, pair production

### Question:
If an electron and a proton travel at the same speed, which has the shorter wavelength?

**Answer:**  
\[ \lambda = \frac{h}{mv} \], a proton's mass is about 2000 times an electron's mass, so  
\[ \frac{\lambda_p}{\lambda_e} = \frac{m_e v_e}{m_p v_p} = \frac{m_e}{m_p} = 1/2000 < 1 \]

### Question:
UV light causes sunburn, whereas visible light does not. Why?

**Answer:**  
UV light has higher frequencies than visible light, so the energy of each UV photon is larger than that of a visible light photon (E=hf). A UV photon has enough energy for certain chemical reaction to occur, whereas a visible light photon does not.

### Question:
In both the photoelectric effect and in the Compton effect we have a photon colliding with an electron causing the electron to fly off. What then is the difference between the two processes?

**Answer:**

*Photoelectric effect:* a photon may knock an electron out of an atom and in the process itself disappear  
*Compton effect:* a photon can be scattered off an electron and in the process loss some energy.

### Question:
What is the difference between a photon and an electron?

**Answer:**
1. An electron has a mass, but a photon does not;  
2. An electron has an electric charge, but a photon does not;  
3. An electron has \( v < c \), but a photon has \( v = c \)

### Particles and Waves

*On the microscopic level, a wave-particle duality replaces the distinction between waves and particles so evident on macroscopic level.*  
*This duality is the key to understanding the structure of atoms and why they behave as they do.*