Volume or white-light holograms do not require a laser to see the image, but can be viewed with ordinary white light (preferably a nearly point source, such as the Sun or a clear bulb with a small bright filament). Such holograms must be made, however, with a laser. They are made not on thin film, but on a *thick* emulsion. The interference pattern in the film emulsion can be thought of as an array of bands or ribbons where constructive interference occurred. This array, and the reconstruction of the image, can be compared to Bragg scattering of X-rays from the atoms in a crystal (see Section 25–11). White light can reconstruct the image because the Bragg condition ($m\lambda = 2d \sin \theta$) selects out the appropriate single wavelength. If the hologram is originally produced by lasers emitting the three additive primary colors (red, green, and blue), the three-dimensional image can be seen in full color when viewed with white light.

Summary

In 1925, Schrödinger and Heisenberg separately worked out a new theory, **quantum mechanics**, which is now considered to be the fundamental theory at the atomic level. It is a statistical theory rather than a deterministic one.

An important aspect of quantum mechanics is the Heisenberg **uncertainty principle**. It results from the wave–particle duality and the unavoidable interaction between an observed object and the observer.

One form of the uncertainty principle states that the position x and momentum p_x of an object cannot both be measured precisely at the same time. The products of the uncertainties, $(\Delta x)(\Delta p_x)$, can be no less than $\hbar (= h/2\pi)$:

$$(\Delta p_x)(\Delta x) \gtrsim \hbar.$$
 (28–1)

Another form of the uncertainty principle states that the energy can be uncertain (or nonconserved) by an amount ΔE for a time Δt , where

$$(\Delta E)(\Delta t) \gtrsim \hbar.$$
 (28-2)

According to quantum mechanics, the state of an electron in an atom is specified by four **quantum numbers**: n, ℓ, m_{ℓ} , and m_s :

- *n*, the principal quantum number, can take on any integer value (1, 2, 3, ···) and corresponds to the quantum number of the old Bohr model;
- (2) ℓ , the orbital quantum number, can take on values from 0 up to n 1;
- (3) m_{ℓ} , the magnetic quantum number, can take on integer values from $-\ell$ to $+\ell$;
- (4) m_s , the spin quantum number, can be $+\frac{1}{2}$ or $-\frac{1}{2}$.

The energy levels in the hydrogen atom depend on n, whereas in other atoms they depend on n and ℓ .

The orbital angular momentum of an atom has magnitude $L = \sqrt{\ell(\ell + 1)} \hbar$ and z component $L_z = m_\ell \hbar$.

When an external magnetic field is applied, the spectral lines are split (the **Zeeman effect**), indicating that the energy depends also on m_l in this case.

Even in the absence of a magnetic field, precise measurements of spectral lines show a tiny splitting of the lines called **fine structure**, whose explanation is that the energy depends very slightly on m_{ℓ} and m_s .

Transitions between states that obey the selection rule $\Delta \ell = \pm 1$ are far more probable than other so-called forbidden transitions.

The arrangement of electrons in multi-electron atoms is governed by the Pauli **exclusion principle**, which states that no two electrons can occupy the same quantum state—that is, they cannot have the same set of quantum numbers n, ℓ , m_{ℓ} , and m_s .

As a result, electrons in multi-electron atoms are grouped into **shells** (according to the value of n) and **subshells** (according to ℓ).

Electron configurations are specified using the numerical values of *n*, and using letters for ℓ : *s*, *p*, *d*, *f*, etc., for $\ell = 0, 1, 2, 3$, and so on, plus a superscript for the number of electrons in that subshell. Thus, the ground state of hydrogen is $1s^1$, whereas that for oxygen is $1s^22s^22p^4$.

In the **Periodic Table**, the elements are arranged in horizontal rows according to increasing **atomic number** (= number of electrons in the neutral atom). The shell structure gives rise to a periodicity in the properties of the elements, so that each vertical column can contain elements with similar chemical properties.

X-rays, which are a form of electromagnetic radiation of very short wavelength, are produced when high-speed electrons strike a target. The spectrum of X-rays so produced consists of two parts, a *continuous* spectrum produced when the electrons are decelerated by atoms of the target, and *peaks* representing photons emitted by atoms of the target after being excited by collision with the high-speed electrons. Measurement of these peaks allows determination of inner energy levels of atoms and determination of atomic number *Z*.

[*Fluorescence occurs when absorbed UV photons are followed by emission of visible light, due to the special arrangement of energy levels of atoms of the material. **Phosphorescent** materials have **metastable** states (long-lived) that emit light seconds or minutes after absorption of light.]

Lasers produce a narrow beam of monochromatic coherent light (light waves *in phase*).

[*Holograms are images with a 3-dimensional quality, formed by interference of laser light.]