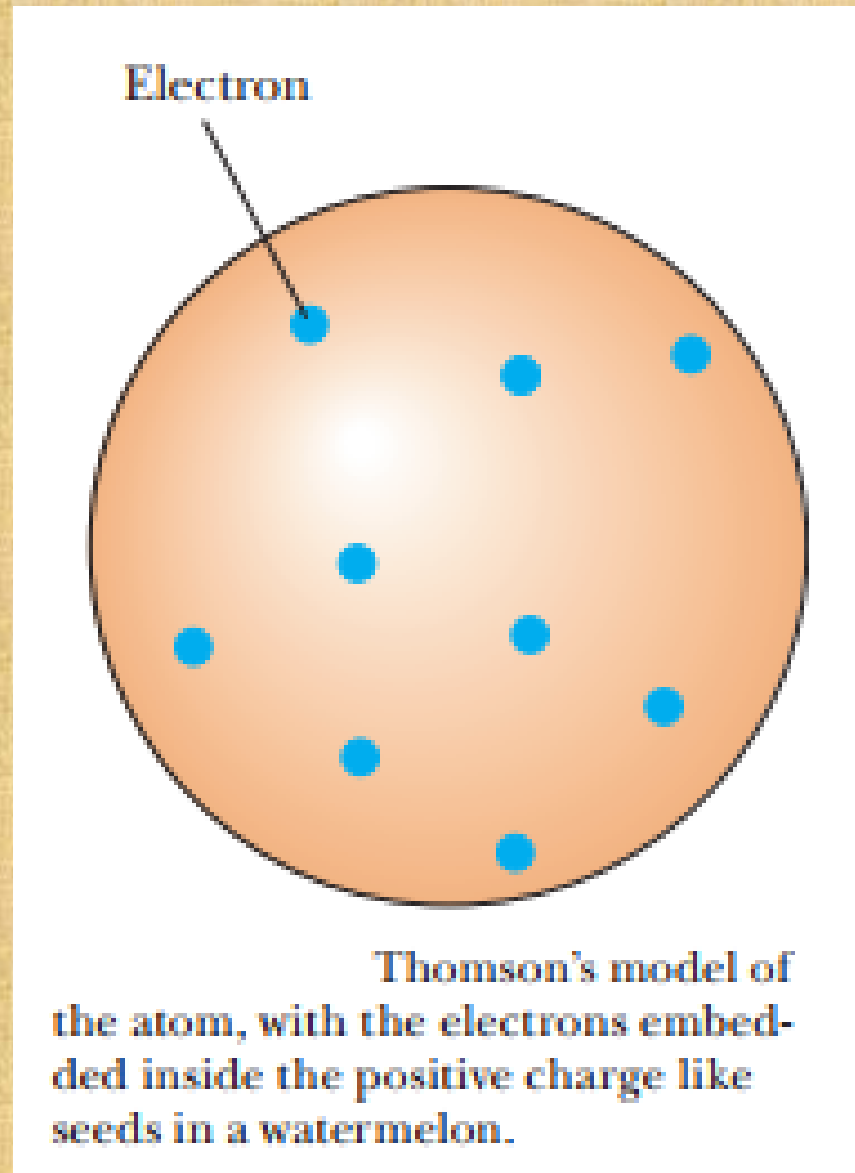# Atomic Physics

By

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Early Models of the Atom

Electron

Thomson's model of the atom, with the electrons embedded inside the positive charge like seeds in a watermelon.

Early Models of the Atom

(a) Geiger and Marsden's technique for observing the scattering of alpha particles from a thin foil target. The source is a naturally occurring radioactive substance, such as radium. (b) Rutherford's planetary model of the atom.
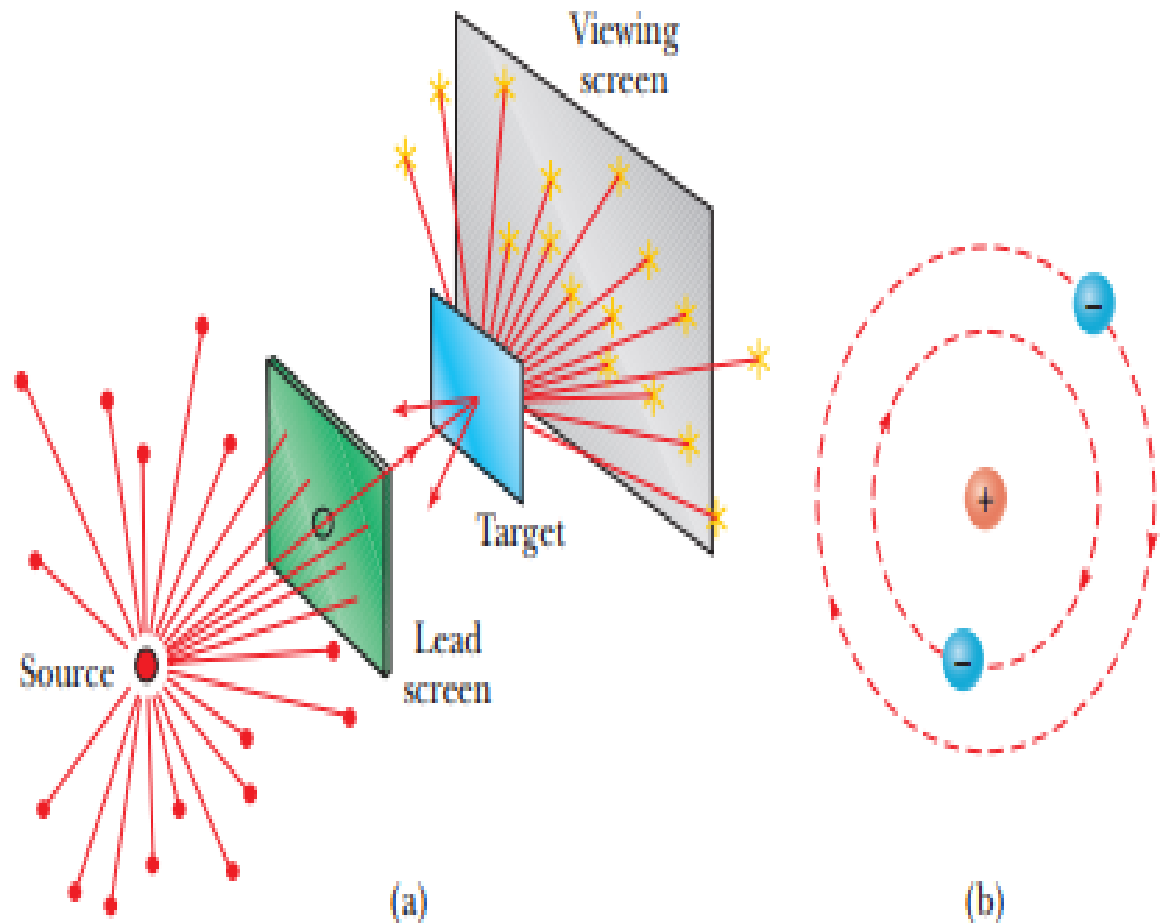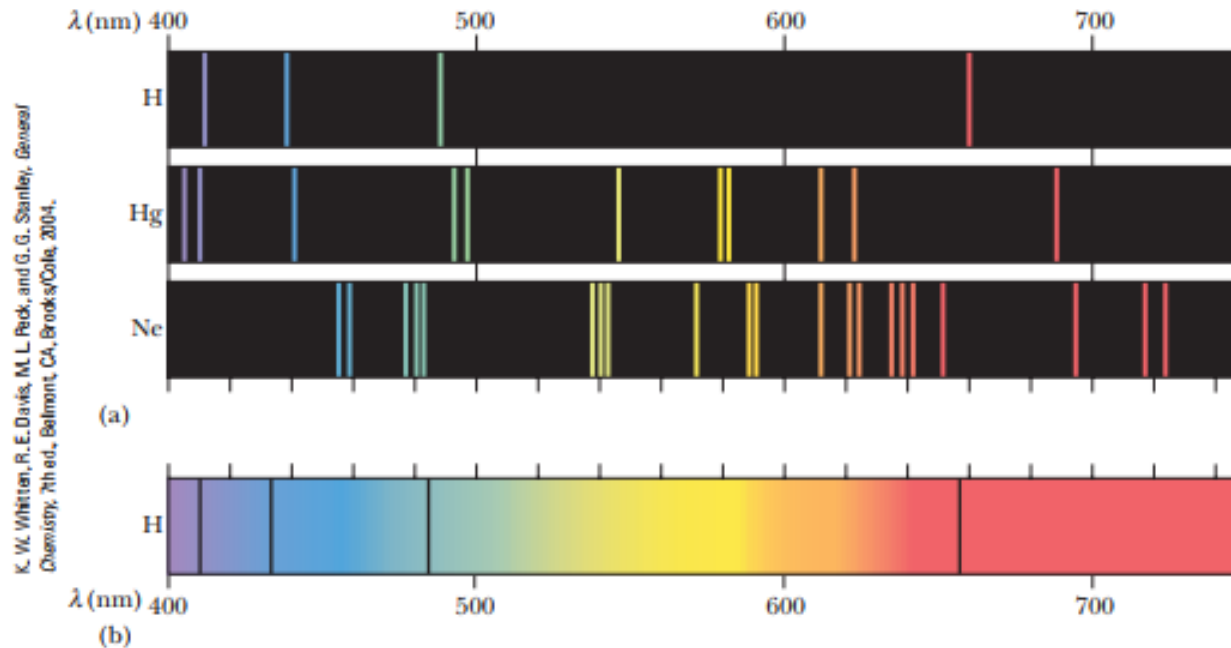
Atomic Spectra

Balmer series →

$$\frac{1}{\lambda} = R_{\mathrm{H}}\left(\frac{1}{2^2} - \frac{1}{n^2}\right)$$

where n may have integral values of 3, 4, 5, . . . , and R_{H} is a constant, called the **Rydberg constant**. If the wavelength is in meters, then R_{H} has the value

Rydberg constant →

$$R_{\mathrm{H}} = 1.097\ 373\ 2 \times 10^7\ \mathrm{m}^{-1}$$

Atomic Spectra

λ (nm) 400   500   600   700

H

Hg

Ne

(a)

H

λ (nm) 400   500   600   700

(b)

K. W. Whitten, R. E. Davis, M. L. Peck, and G. G. Stanley, *General Chemistry*, 7th ed, Belmont CA, Brooks/Cole, 2004.

Visible spectra.
(a) Line spectra produced by emission in the visible range for the elements hydrogen, mercury, and neon.
(b) The absorption spectrum for hydrogen. The dark absorption lines occur at the same wavelengths as the emission lines for hydrogen shown in (a).

λ (nm)   486.1   656.3

364.6   410.2   434.1
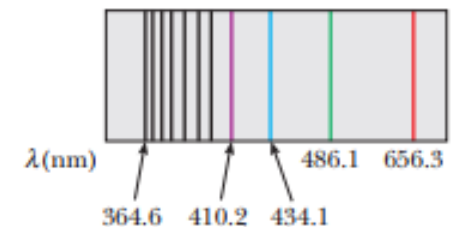
The Balmer series of spectral lines for atomic hydrogen, with several lines marked with the wavelength in nanometers. The line labeled 364.6 is the shortest-wavelength line and is in the ultra-violet region of the electromagnetic spectrum. The other labeled lines are in the visible region.

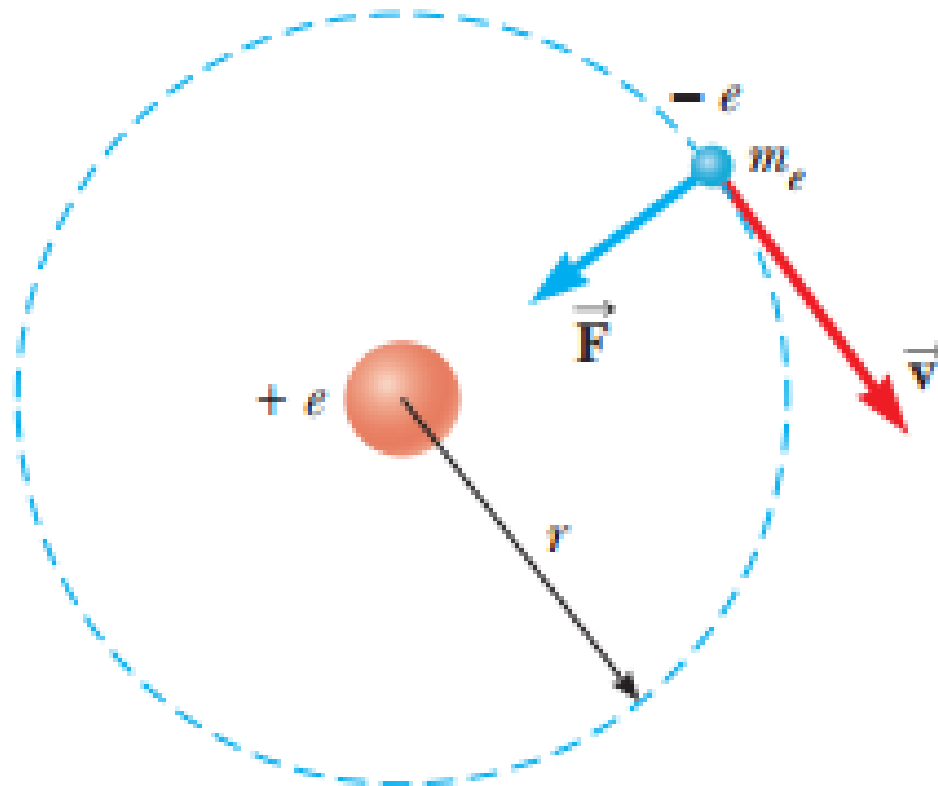# Bohr's model of the hydrogen atom

Diagram representing Bohr's model of the hydrogen atom. The orbiting electron is allowed only in specific orbits of discrete radii.

Bohr's model of the hydrogen atom

1. The electron moves in circular orbits about the proton under the influence of the Coulomb force of attraction, as in Figure. The Coulomb force produces the electron's centripetal acceleration.

2. Only certain electron orbits are stable and allowed. In these orbits no energy in the form of electromagnetic radiation is emitted, so the total energy of the atom remains constant.
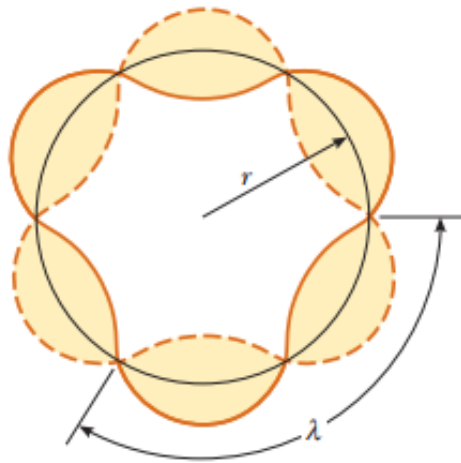
Bohr's model of the hydrogen atom

3. Radiation is emitted by the hydrogen atom when the electron "jumps" from a more energetic initial state to a less energetic state. The "jump" can't be visualized or treated classically. The frequency f of the radiation emitted in the jump is related to the change in the atom's energy, given by

$$Ei-Ef=hf$$

Standing-wave pattern for an electron wave in a stable orbit of hydrogen. There are three full wavelengths in this orbit.

4. The circumference of an electron's orbit must contain an integral number of de Broglie wavelengths,

$$2\pi r = n\lambda \qquad n = 1, 2, 3, \ldots$$

(See Fig. 28.6.) Because the de Broglie wavelength of an electron is $\lambda = h/m_e v$, we can write the preceding equation as

$$m_e v r = n\hbar \qquad n = 1, 2, 3, \ldots$$

where $\hbar = h/2\pi$.

With these four assumptions, we can calculate the allowed energies and emission wavelengths of the hydrogen atom using the model pictured in Figure 28.5, in which the electron travels in a circular orbit of radius r with an orbital speed v. The electrical potential energy of the atom is

$$PE = k_e \frac{q_1 q_2}{r} = k_e \frac{(-e)(e)}{r} = -k_e \frac{e^2}{r}$$

where k_e is the Coulomb constant. Assuming the nucleus is at rest, the total energy E of the atom is the sum of the kinetic and potential energy:

$$E = KE + PE = \tfrac{1}{2}m_e v^2 - k_e \frac{e^2}{r}$$

By Newton's second law, the electric force of attraction on the electron, $k_e e^2/r^2$, must equal $m_e a_r$, where $a_r = v^2/r$ is the centripetal acceleration of the electron, so

$$m_e \frac{v^2}{r} = k_e \frac{e^2}{r^2}$$

Multiply both sides of this equation by $r/2$ to get an expression for the kinetic energy:

$$\tfrac{1}{2}m_e v^2 = \frac{k_e e^2}{2r}$$

Combining this result with Equation 28.6 gives an expression for the energy of the atom,

$$E = -\frac{k_e e^2}{2r}$$

where the negative value of the energy indicates that the electron is bound to the proton.

Bohr's model of the hydrogen atom

$$v^2 = \frac{n^2\hbar}{m_e^2 r^2} = \frac{k_e e^2}{m_e r}$$

$$r_n = \frac{n^2\hbar^2}{m_e k_e e^2} \qquad n = 1, 2, 3, \ldots$$

This equation is based on the assumption that the **electron can exist only in certain allowed orbits determined by the integer n.**

The orbit with the smallest radius, called the **Bohr radius**, a_0, corresponds to $n = 1$ and has the value

$$a_0 = \frac{\hbar^2}{m k_e e^2} = 0.052\,9 \text{ nm}$$

A general expression for the radius of any orbit in the hydrogen atom is obtained by substituting Equation 28.11 into Equation 28.10:

$$r_n = n^2 a_0 = n^2(0.052\,9 \text{ nm})$$

The first three Bohr orbits for hydrogen are shown in Active Figure 28.7.

Equation 28.10 can then be substituted into Equation 28.9 to give the following expression for the energies of the quantum states:

$$E_n = -\frac{m_e k_e^2 e^4}{2\hbar^2}\left(\frac{1}{n^2}\right) \qquad n = 1, 2, 3, \ldots$$
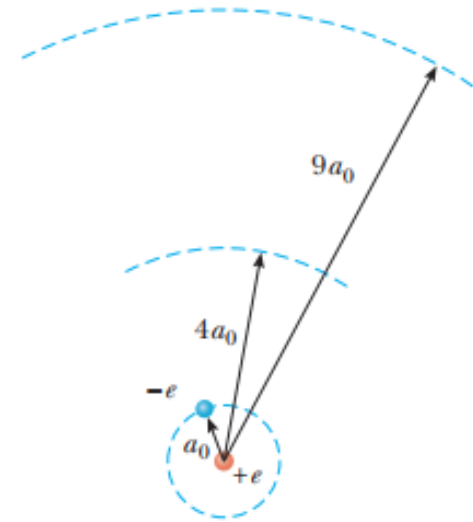
ACTIVE FIGURE 28.7
The first three circular orbits predicted by the Bohr model of the hydrogen atom.

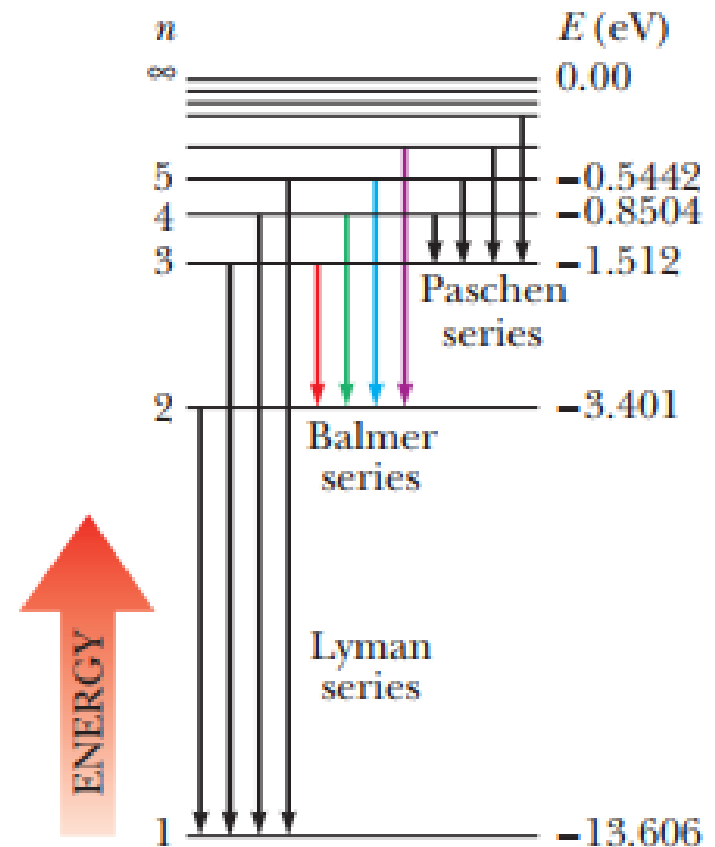# Bohr's model of the hydrogen atom

If we substitute numerical values into Equation 28.13, we obtain

$$E_n = -\frac{13.6}{n^2} \text{ eV}$$

The lowest-energy state, or **ground state**, corresponds to $n = 1$ and has an energy $E_1 = -m_e k_e^2 e^4 / 2\hbar^2 = -13.6$ eV. The next state, corresponding to $n = 2$, has an energy $E_2 = E_1/4 = -3.40$ eV, and so on. An energy level diagram showing the

Bohr's model of the hydrogen atom

An energy level diagram for hydrogen. Quantum numbers are given on the left, and energies (in electron volts) are given on the right. Vertical arrows represent the four lowest-energy transitions for each of the spectral series shown. The colored arrows for the Balmer series indicate that this series results in visible light.

Bohr's model of the hydrogen atom

$$f = \frac{E_i - E_f}{\hbar} = \frac{m_e k_e^2 e^4}{4\pi\,\hbar^3}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

where $n_f < n_i$.

To convert this equation into one analogous to the Rydberg equation, substitute $f = c/\lambda$ and divide both sides by c, obtaining

$$\frac{1}{\lambda} = R_{\mathrm{H}}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

where

$$R_{\mathrm{H}} = \frac{m_e k_e^2 e^4}{4\pi\,c\hbar^3}$$

Hydrogen-like Atoms

The analysis used in the Bohr theory is also successful when applied to *hydrogen-like* atoms. An atom is said to be hydrogen-like when it contains only one electron. Examples are singly ionized helium, doubly ionized lithium, and triply ionized beryllium. The results of the Bohr theory for hydrogen can be extended to hydrogen-like atoms by substituting Ze^2 for e^2 in the hydrogen equations, where Z is the atomic number of the element. For example, Equations 28.13 and 28.16 through 28.17 become

$$E_n = -\frac{m_e k_e^2 Z^2 e^4}{2\hbar^2}\left(\frac{1}{n^2}\right) \qquad n = 1, 2, 3, \ldots$$

and

$$\frac{1}{\lambda} = \frac{m_e k_e^2 Z^2 e^4}{4\pi c \hbar^3}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

Although many attempts were made to extend the Bohr theory to more complex, multi-electron atoms, the results were unsuccessful. Even today, only approximate methods are available for treating multi-electron atoms.

Three Quantum Numbers for the Hydrogen Atom

Quantum Number	Name	Allowed Values	Number of Allowed States
n	Principal quantum number	$1, 2, 3, \ldots$	Any number
ℓ	Orbital quantum number	$0, 1, 2, \ldots, n-1$	n
m_ℓ	Orbital magnetic quantum number	$-\ell, -\ell+1, \ldots,$ $0, \ldots, \ell-1, \ell$	$2\ell+1$

Shell and Subshell Notation

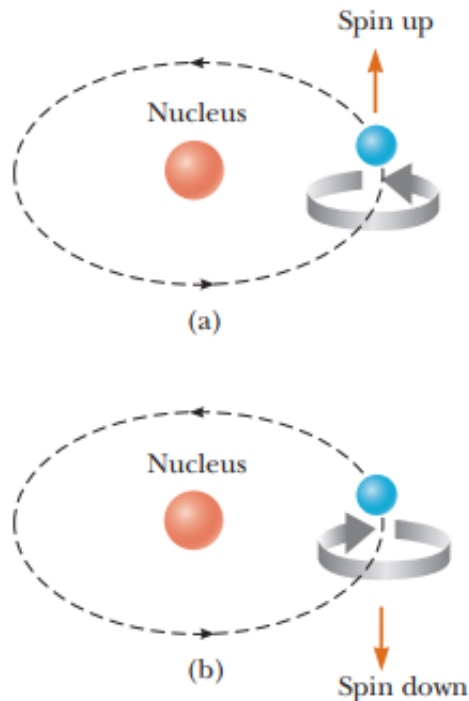| n	Shell Symbol	ℓ	Subshell Symbol
1	K	0	s
2	L	1	p
3	M	2	d
4	N	3	f
5	O	4	g
6	P	5	h
. . .		. . .	

For example, if $n = 1$, there is only 1 value of ℓ, $\ell = 0$. Because $2\ell + 1 = 2 \cdot 0 + 1 = 1$, there is only one value of m_ℓ, which is $m_\ell = 0$. If $n = 2$, the value of ℓ may be 0 or 1; if $\ell = 0$, then $m_\ell = 0$; but if $\ell = 1$, then m_ℓ may be 1, 0, or -1. Table 28.1 summarizes the rules for determining the allowed values of ℓ and m_ℓ for a given value of n.

For historical reasons, **all states with the same principal quantum number n are said to form a shell**. Shells are identified by the letters K, L, M, . . . , which designate the states for which $n = 1, 2, 3$, and so forth. **The states with given values of n and ℓ are said to form a subshell**. The letters $s, p, d, f, g, \ldots$ are used to designate the states for which $\ell = 0, 1, 2, 3, 4, \ldots$. These notations are summarized in Table 28.2.

States that violate the rules given in Table 28.1 can't exist. One state that cannot exist, for example, is the $2d$ state, which would have $n = 2$ and $\ell = 2$. This state is not allowed because the highest allowed value of ℓ is $n - 1$, or 1 in this case. So for $n = 2$, $2s$ and $2p$ are allowed states, but $2d, 2f, \ldots$ are not. For $n = 3$, the allowed states are $3s, 3p$, and $3d$.

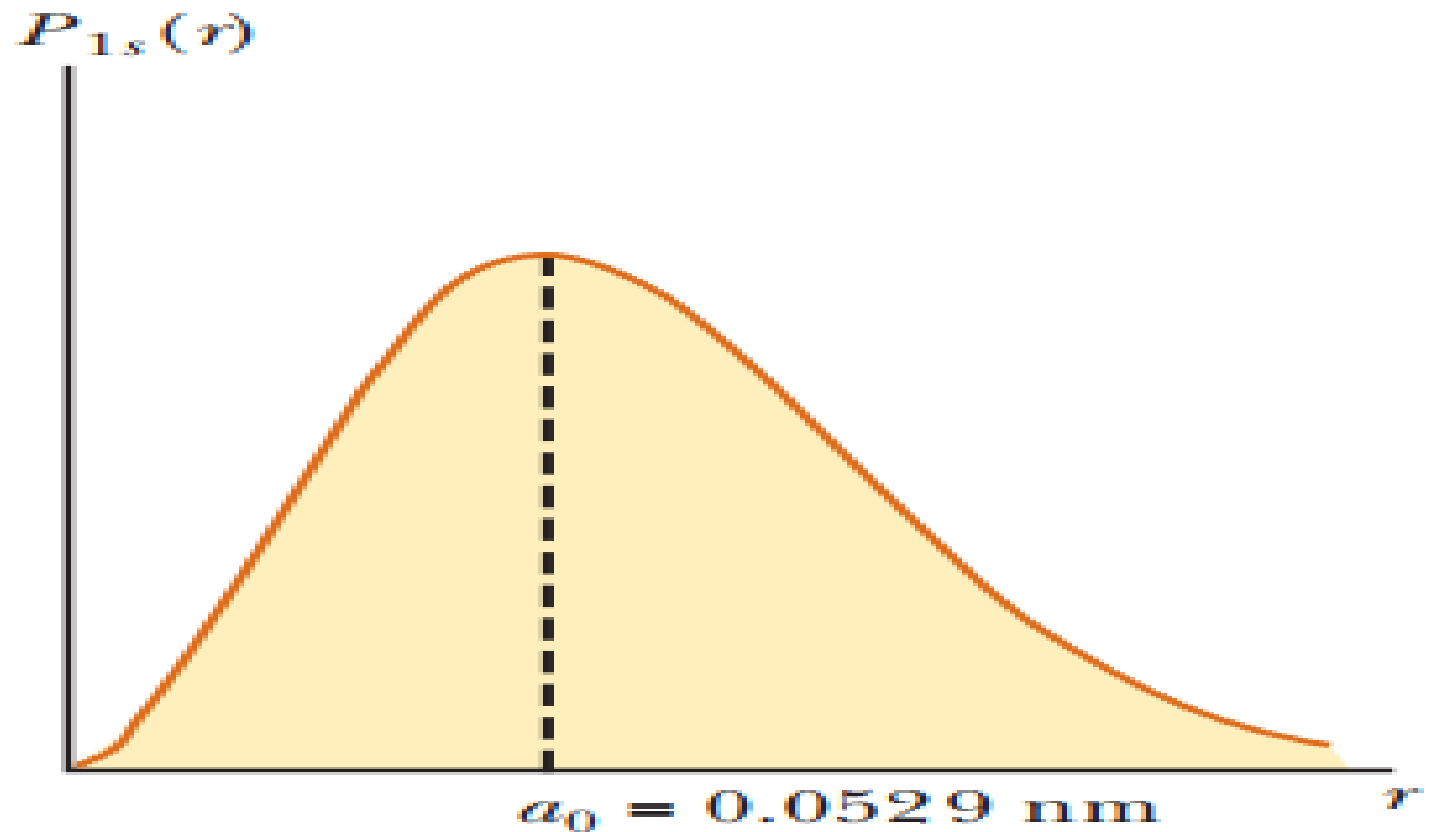In general, for a given value of n, there are n^2 states with distinct pairs of values of ℓ and m_ℓ.

Spin

In high-resolution spectrometers, close examination of one of the prominent lines of sodium vapor shows that it is, in fact, two very closely spaced lines. The wavelengths of these lines occur in the yellow region of the spectrum, at 589.0 nm and 589.6 nm. This kind of splitting is referred to as **fine structure**. In 1925, when this doublet was first noticed, atomic theory couldn't explain it, so Samuel Goudsmit and George Uhlenbeck, following a suggestion by Austrian physicist Wolfgang Pauli, proposed the introduction of a fourth quantum number to describe atomic energy levels, m_s, called the **spin magnetic quantum number**. Spin isn't found in the solutions of Schrödinger's equations; rather, it naturally arises in the Dirac equation, derived in 1927 by Paul Dirac. This equation is important in relativistic quantum theory.

In describing the spin quantum number, it's convenient (but technically incorrect) to think of the electron as spinning on its axis as it orbits the nucleus, just as Earth spins on its axis as it orbits the Sun. Unlike the spin of a world, however, there are only two ways in which the electron can spin as it orbits the nucleus, as shown in Figure 28.11. If the direction of spin is as shown in Figure 28.11a, the electron is said to have "spin up." If the direction of spin is reversed as in Figure 28.11b, the electron is said to have "spin down." The energy of the electron is slightly different for the two spin directions, and this energy difference accounts for the sodium doublet. The quantum numbers associated with electron spin are

As an electron moves in its orbit about the nucleus, its spin can be either (a) up or (b) down.

Electron Clouds

$P_{1s}(r)$

$a_0 = 0.0529$ nm

The probability per unit length of finding the electron versus distance from the nucleus for the hydrogen atom in the 1s (ground) state. Note that the graph has its maximum value when r equals the first Bohr radius, a_0.

Electron Clouds
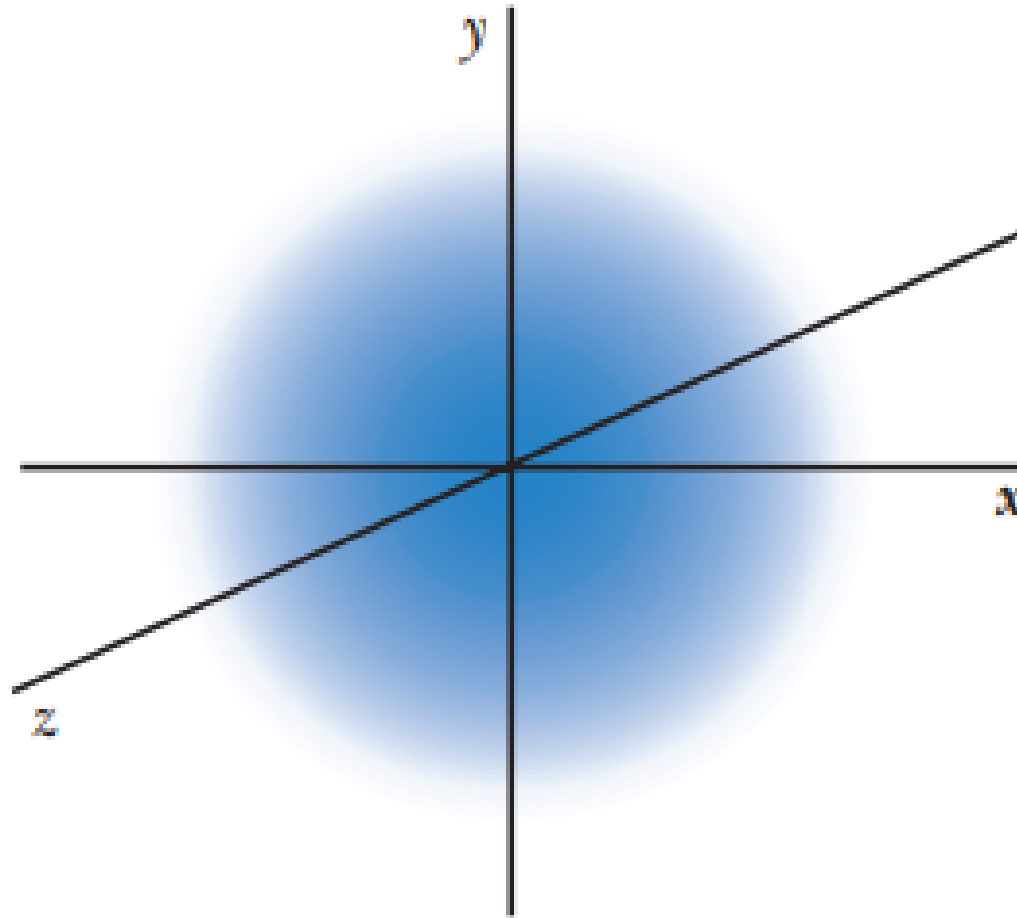
The spherical electron cloud for the hydrogen atom in its 1s state.

Pauli exclusion principle

"No two electrons in an atom can ever have the same

set of values for the set of quantum numbers n, l, m_l,

and m_s".

Pauli exclusion principle

Number of Electrons in Filled Subshells and Shells

Shell	Subshell	Number of Electrons in Filled Subshell	Number of Electrons in Filled Shell
K ($n = 1$)	$s(\ell = 0)$	2	2
L ($n = 2$)	$s(\ell = 0)$	2	8
	$p(\ell = 1)$	6	
M ($n = 3$)	$s(\ell = 0)$	2	18
	$p(\ell = 1)$	6	
	$d(\ell = 2)$	10	
N ($n = 4$)	$s(\ell = 0)$	2	32
	$p(\ell = 1)$	6	
	$d(\ell = 2)$	10	
	$f(\ell = 3)$	14	

Dr. Khokon Hossen

Pauli exclusion principle

Electronic Configurations of Some Elements

Z	Symbol	Ground-State Configuration		Ionization Energy (eV)	Z	Symbol	Ground-State Configuration		Ionization Energy (eV)
1	H		$1s^1$	13.595	19	K	[Ar]	$4s^1$	4.339
2	He		$1s^2$	24.581	20	Ca		$4s^2$	6.111
					21	Sc		$3d4s^2$	6.54
3	Li	[He]	$2s^1$	5.390	22	Ti		$3d^24s^2$	6.83
4	Be		$2s^2$	9.320	23	V		$3d^34s^2$	6.74
5	B		$2s^22p^1$	8.296	24	Cr		$3d^54s^1$	6.76
6	C		$2s^22p^2$	11.256	25	Mn		$3d^54s^2$	7.432
7	N		$2s^22p^3$	14.545	26	Fe		$3d^64s^2$	7.87
8	O		$2s^22p^4$	13.614	27	Co		$3d^74s^2$	7.86
9	F		$2s^22p^5$	17.418	28	Ni		$3d^84s^2$	7.633
10	Ne		$2s^22p^6$	21.559	29	Cu		$3d^{10}4s^1$	7.724
					30	Zn		$3d^{10}4s^2$	9.391
11	Na	[Ne]	$3s^1$	5.138	31	Ga		$3d^{10}4s^24p^1$	6.00
12	Mg		$3s^2$	7.644	32	Ge		$3d^{10}4s^24p^2$	7.88
13	Al		$3s^23p^1$	5.984	33	As		$3d^{10}4s^24p^3$	9.81
14	Si		$3s^23p^2$	8.149	34	Se		$3d^{10}4s^24p^4$	9.75
15	P		$3s^23p^3$	10.484	35	Br		$3d^{10}4s^24p^5$	11.84
16	S		$3s^23p^4$	10.357	36	Kr		$3d^{10}4s^24p^6$	13.996
17	Cl		$3s^23p^5$	13.01					
18	Ar		$3s^23p^6$	15.755					

Note: The bracket notation is used as a shorthand method to avoid repetition in indicating inner-shell electrons. Thus, [He] represents $1s^2$, [Ne] represents $1s^22s^22p^6$, [Ar] represents $1s^22s^22p^63s^23p^6$, and so on.

Characteristic x-rays

Characteristic X-rays are emitted when outer-shell electrons fill a vacancy in the inner shell of an atom, releasing X-rays in a pattern that is "characteristic" to each element.

Characteristic X-Ray Production

- Outgoing projectile electron (lower energy)
- M Shell
- Target atom
- L Shell
- K shell
- W
- Incoming projectile electron (high energy)
- K X-ray
- L X-ray
- Characteristic X-ray emission
- Ejected electron ionizes atom
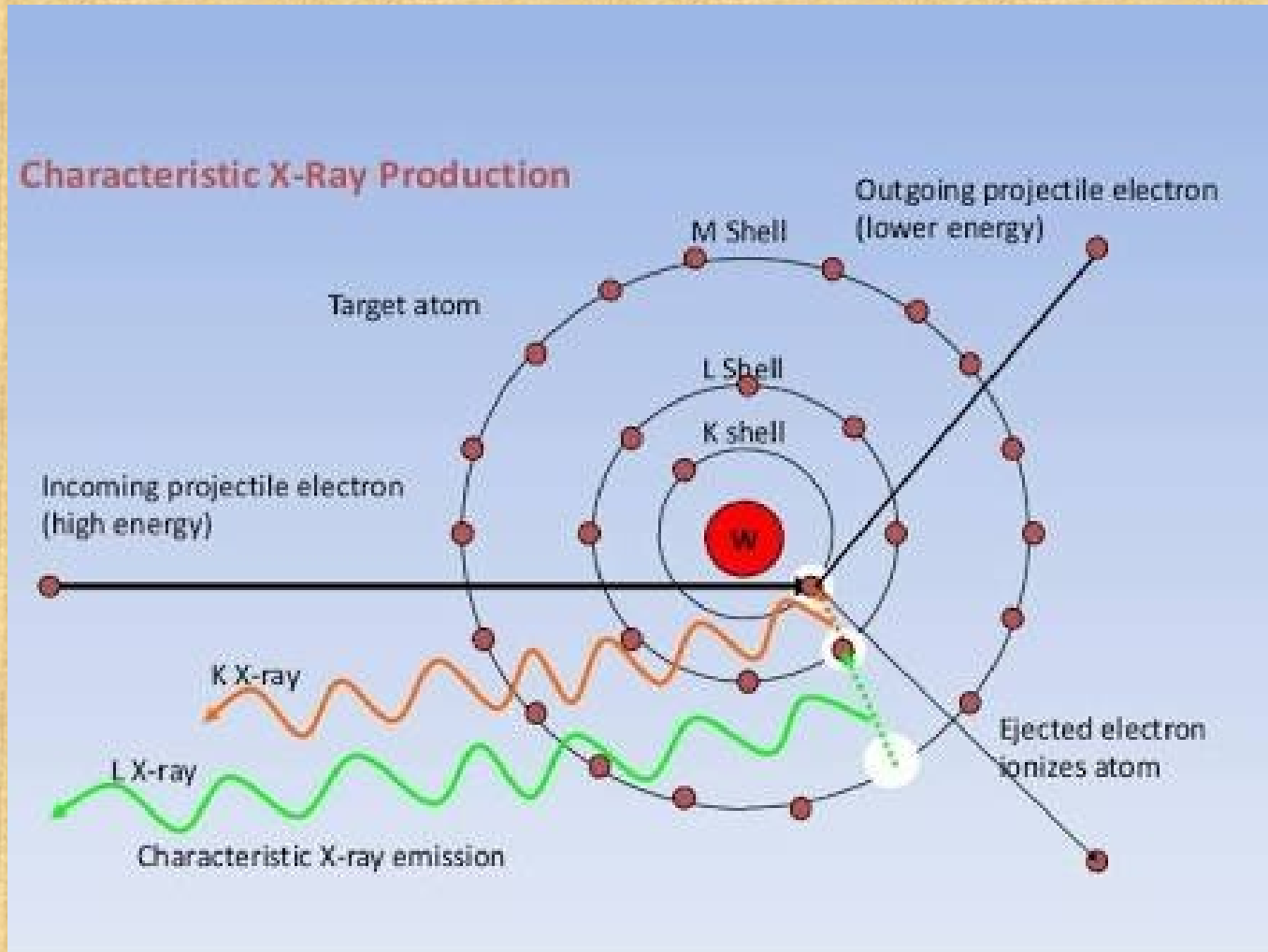
Characteristic x-rays

The first step in the production of characteristic x-rays occurs when a bombarding electron collides with an electron in an inner shell of a target atom with sufficient energy to remove the electron from the atom.

The vacancy created in the shell is filled when an electron in a higher level drops down into the lower-energy level containing the vacancy.

Characteristic x-rays

The time it takes for that to happen is very short, less than 10^{-9} s. The transition is accompanied by the emission of a photon with energy equaling the difference in energy between the two levels.

Typically, the energy of such transitions is greater than 1000 eV, and the emitted x-ray photons have wavelengths in the range of 0.01 nm to 1 nm.

Characteristic x-rays
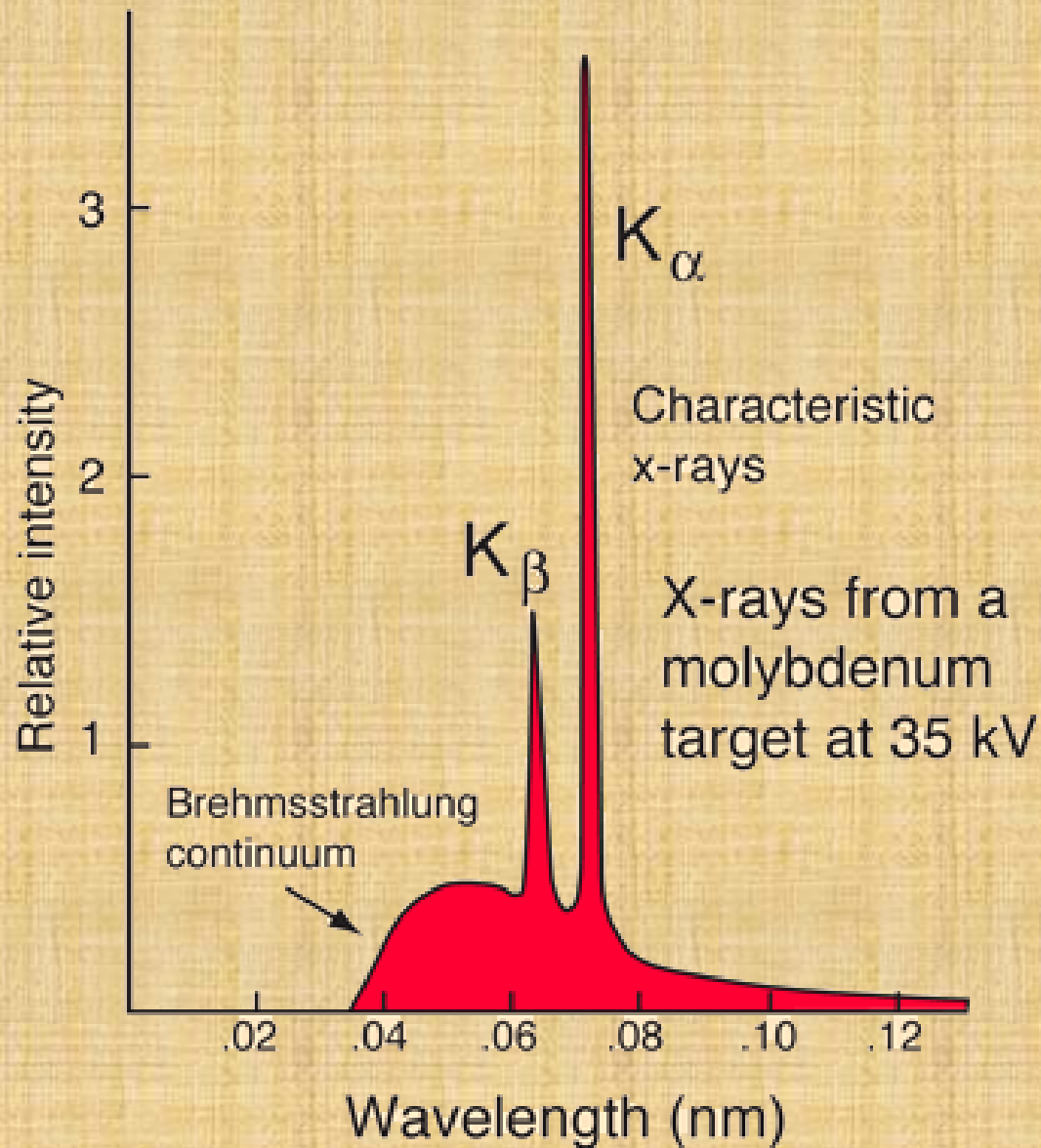
ATOMIC TRANSITIONS AND LASERS

E_4 ——————————————

E_3 ——————————————

E_2 ——————————————

E_1 ——————————————
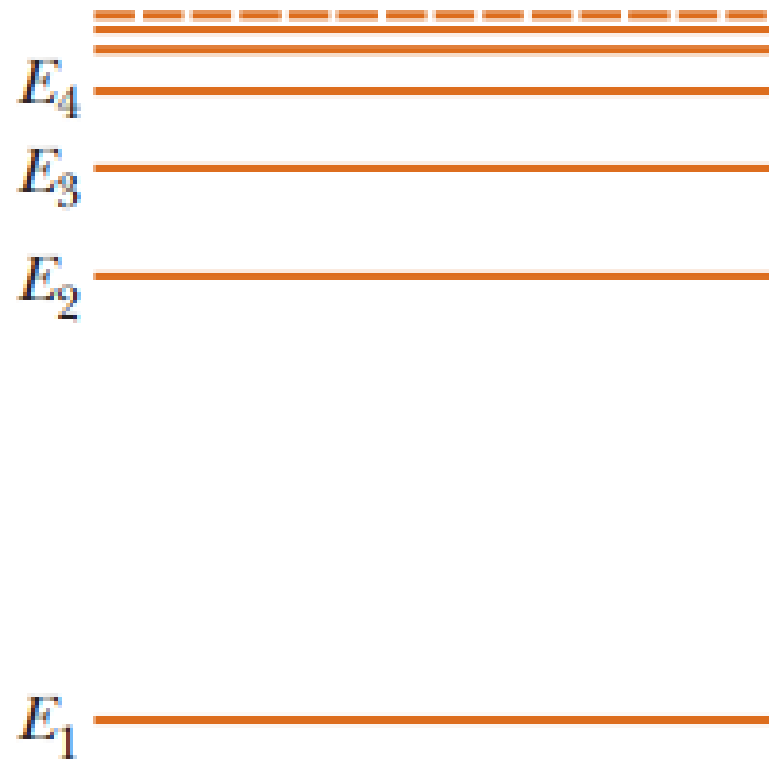
Energy level diagram of an atom with various allowed states. The lowest-energy state, E_1, is the ground state. All others are excited states.

ATOMIC TRANSITIONS AND LASERS

A laser is produces a very narrow beam of light that is useful in many technologies and instruments. The letters in the word laser stand for Light Amplification by Stimulated Emission of Radiation.

The letters in the word laser stand for Light Amplification by Stimulated Emission of Radiation. A laser is an unusual light source. It is quite different from a light bulb or a flash light. Lasers produce a very narrow beam of light. This type of light is useful for lots of technologies and instruments—even some that you might use at home!

Atom in ground state | Atom in excited state

E_2 | E_2

hf

ΔE

E_1 | E_1

Before | After
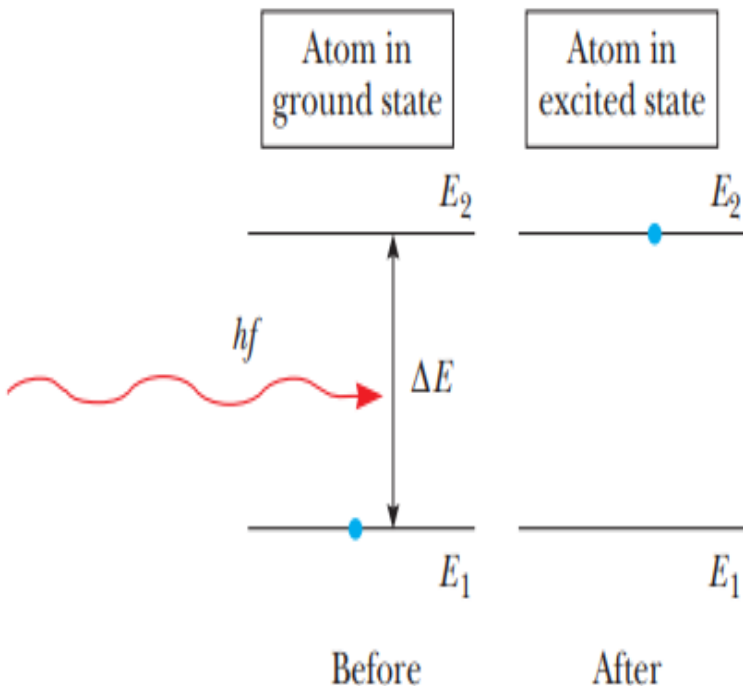
Diagram representing the process of *stimulated absorption* of a photon by an atom. The blue dot represents an electron. The electron is transferred from the ground state to the excited state when the atom absorbs a photon of energy $hf = E_2 - E_1$.

Atom in excited state | Atom in ground state

E_2 | E_2

$hf = \Delta E$

ΔE

E_1 | E_1

Before | After
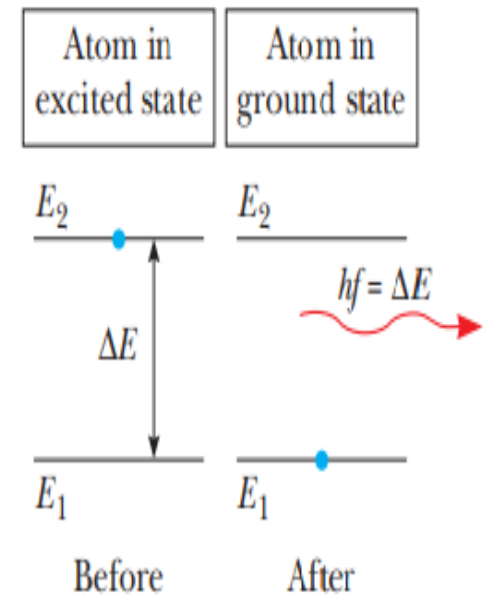
Diagram representing the process of *spontaneous emission* of a photon by an atom that is initially in the excited state E_2. When the electron falls to the ground state, the atom emits a photon of energy $hf = E_2 - E_1$.

ATOMIC TRANSITIONS AND LASERS
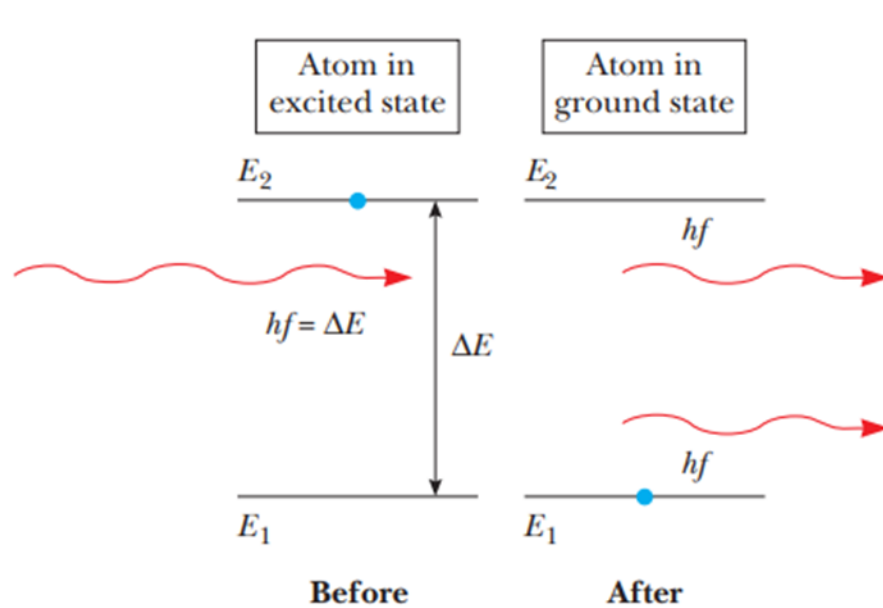
Diagram representing the process of *stimulated emission* of a photon by an incoming photon of energy *hf*. Initially, the atom is in the excited state. The incoming photon stimulates the atom to emit a second photon of energy $hf = E_2 - E_1$.
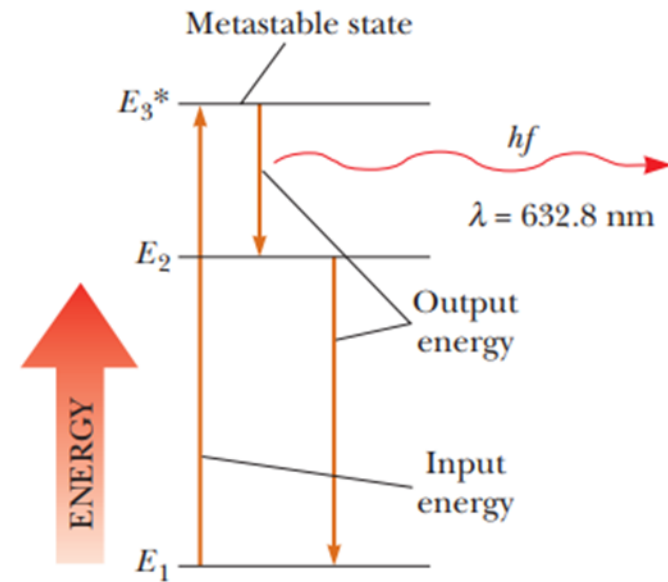
Energy level diagram for the neon atom in a helium–neon laser. The atom emits 632.8-nm photons through stimulated emission in the transition $E_3^* \rightarrow E_2$. This transition is the source of coherent light in the laser.

ATOMIC TRANSITIONS AND LASERS

Lasers that cover wavelengths in the infrared, visible, and ultraviolet regions of the spectrum are now available.

Applications include the surgical "welding" of detached retinas, "lasik" surgery, precision surveying and length measurement, a potential source for inducing nuclear fusion reactions, precision cutting of metals and other materials, and telephone communication along optical fibers.

ATOMIC TRANSITIONS AND LASERS
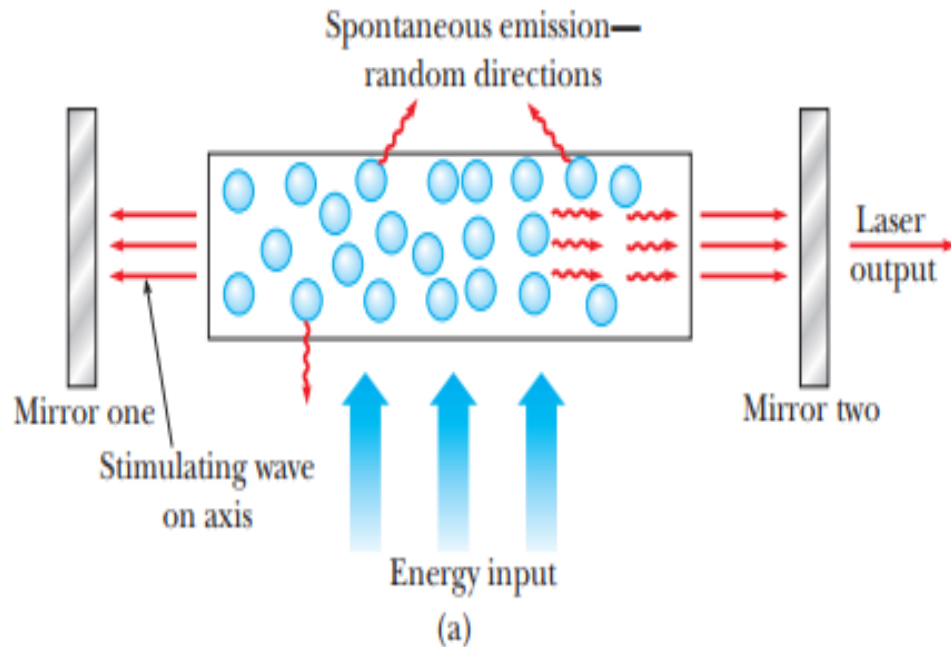
(a) Steps in the production of a laser beam. The tube contains atoms, which represent the active medium. An external source of energy (optical, electrical, etc.) is needed to "pump" the atoms to excited energy states. The parallel end mirrors provide the feedback of the stimulating wave. (b) Photograph of the first ruby laser, showing the flash lamp surrounding the ruby rod.

Thanks a lot!

Optics

Colors swirl on a soap bubble as it drifts through the air on a summer day, and vivid rainbows reflect from the filth of oil films in the puddles of a dirty city street.

Beachgoers, covered with thin layers of oil, wear their coated sunglasses that absorb half the incoming light.

In laboratories scientists determine the precise composition of materials by analyzing the light they give off when hot, and in observatories around the world, telescopes gather light from distant galaxies, filtering out individual wavelengths in bands and thereby determining the speed of expansion of the Universe.

Optics

Understanding how these rainbows are made and how certain scientific instruments can determine wavelengths is the domain of wave optics.

Light can be viewed as either a particle or a wave. Geometric optics, the subject of the previous chapter, depends on the particle nature of light.

Wave optics depends on the wave nature of light. The three primary topics we examine in this chapter are interference, diffraction, and polarization. These phenomena can't be adequately explained with ray optics, but can be understood if light is viewed as a wave.

Optics

Conditions for interference:

In our discussion of interference of mechanical waves, we found that two waves could add together either constructively or destructively. In constructive interference the amplitude of the resultant wave is greater than that of either of the individual waves, whereas in destructive interference, the resultant amplitude is less than that of either individual wave. Light waves also interfere with one another. Fundamentally, all interference associated with light waves arises when the electromagnetic fields that constitute the individual waves combine.

Optics

Conditions for interference:

Interference effects in light waves aren't easy to observe because of the short wavelengths involved (about 4×10^{-7} m to about 7×10^{-7} m). The following two conditions, however, facilitate the observation of interference between two sources of light:

Optics

Conditions for interference:

1. The sources are coherent, which means that the waves they emit

    must maintain a constant phase with respect to one another.

2. The waves have identical wavelengths.

Optics

Young's double-slit experiment:
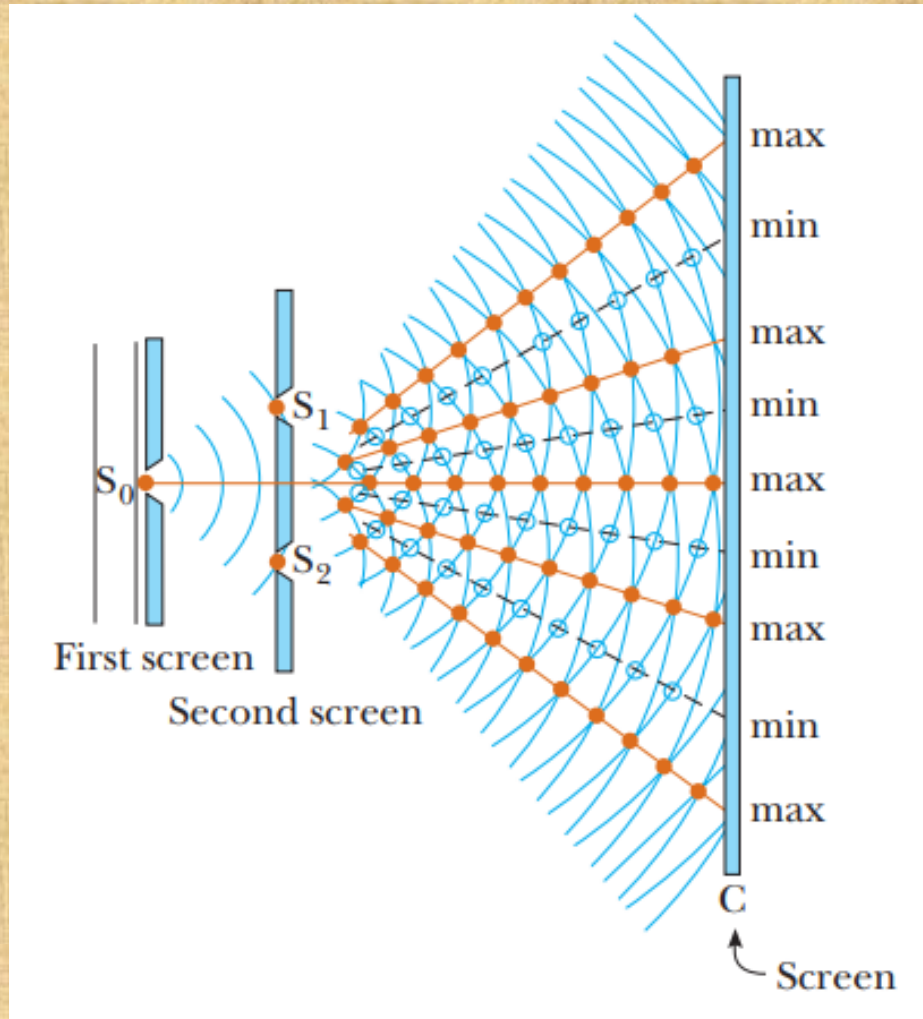
A diagram of Young's double slit experiment. The narrow slits act as sources of waves. Slits S_1 and S_2 behave as coherent sources that produce an interference pattern on screen C. (The drawing is not to scale.)

Young's double-slit experiment:

$$\delta = r_2 - r_1 = d \sin \theta$$

Equation 24.1 assumes the two waves travel in parallel lines, which is approximately true because L is much greater than d. As noted earlier, the value of this path difference determines whether the two waves are in phase when they arrive at P. If the path difference is either zero or some integral multiple of the wavelength, the two waves are in phase at P and constructive interference results. Therefore, the condition for bright fringes, or **constructive interference**, at P is

Condition for constructive interference (two slits) →

$$\delta = d \sin \theta_{\text{bright}} = m\lambda \qquad m = 0, \pm 1, \pm 2, \ldots$$

(a)   (b)   (c)
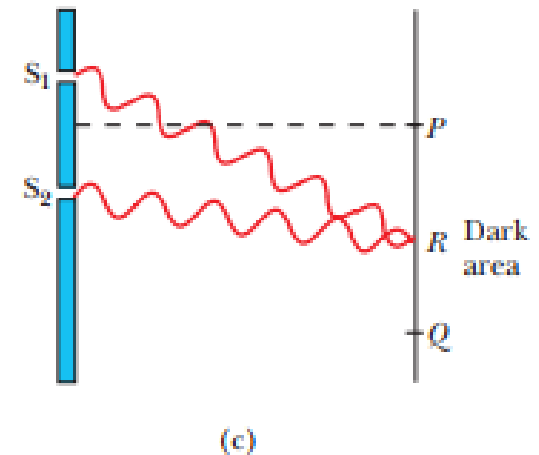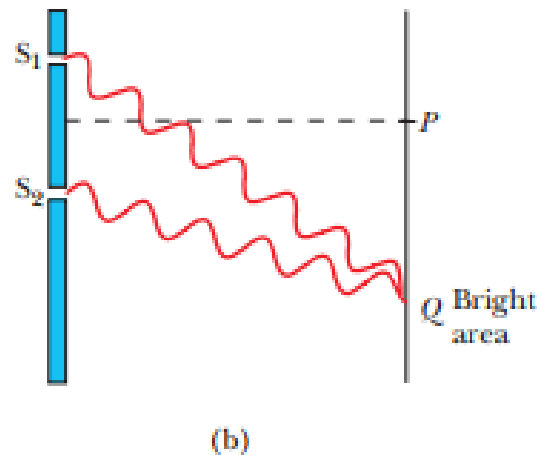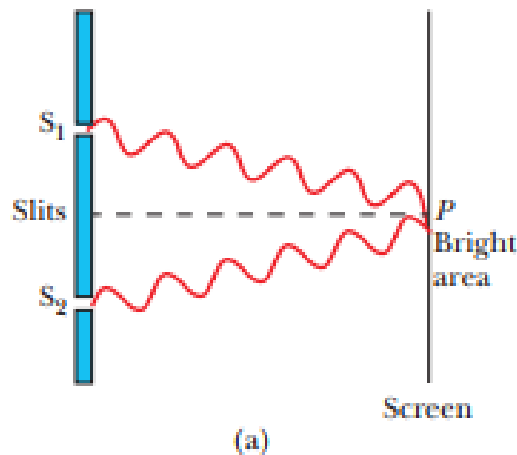
(a) Constructive interference occurs at P when the waves combine. (b) Constructive interference also occurs at Q. (c) Destructive interference occurs at R when the wave from the upper slit falls half a wavelength behind the wave from the lower slit. (These figures are not drawn to scale.)

Young's double-slit experiment:
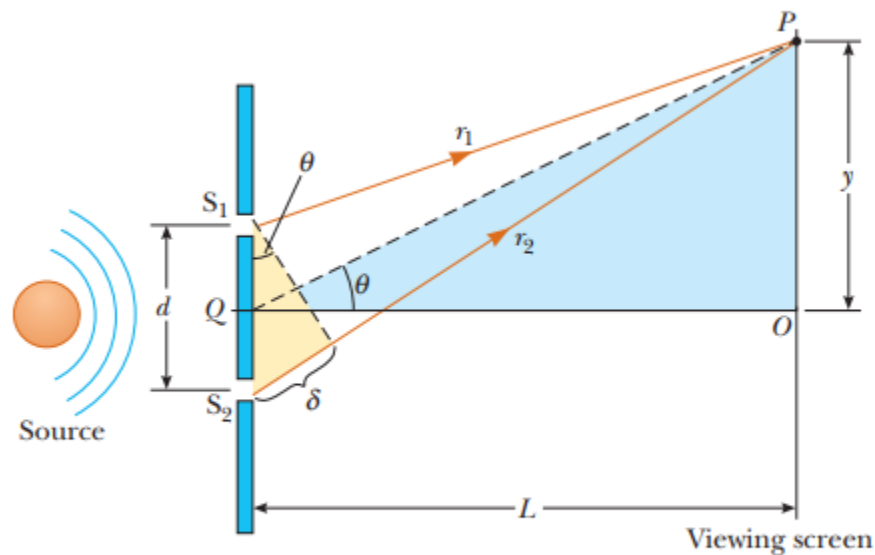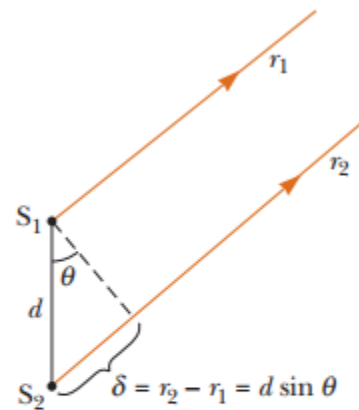
A geometric construction that describes Young's double-slit experiment. The path difference between the two rays is $\delta = r_2 - r_1 = d \sin \theta$. (This figure is not drawn to scale.)

$\delta = r_2 - r_1 = d \sin \theta$

(a)

(b)

Young's double-slit experiment:

$$\delta = d \sin \theta_{dark} = (m + \tfrac{1}{2})\lambda \qquad m = 0, \pm 1, \pm 2, \ldots$$

If $m = 0$ in this equation, the path difference is $\delta = \lambda/2$, which is the condition for the location of the first dark fringe on either side of the central (bright) maximum. Likewise, if $m = 1$, the path difference is $\delta = 3\lambda/2$, which is the condition for the second dark fringe on each side, and so forth.

It's useful to obtain expressions for the positions of the bright and dark fringes measured vertically from O to P. In addition to our assumption that $L \gg d$, we assume $d \gg \lambda$. These assumptions can be valid because, in practice, L is often on the order of 1 m, d is a fraction of a millimeter, and λ is a fraction of a micrometer for visible light. Under these conditions θ is small, so we can use the approximation $\sin \theta \cong \tan \theta$. Then, from triangle OPQ in Figure 24.4, we see that

$$y = L \tan \theta \approx L \sin \theta$$

Solving Equation 24.2 for $\sin \theta$ and substituting the result into Equation 24.4, we find that the positions of the *bright fringes*, measured from O, are

$$y_{bright} = \frac{\lambda L}{d} m \qquad m = 0, \pm 1, \pm 2, \ldots$$

Using Equations 24.3 and 24.4, we find that the *dark fringes* are located at

$$y_{dark} = \frac{\lambda L}{d}(m + \tfrac{1}{2}) \qquad m = 0, \pm 1, \pm 2, \ldots$$
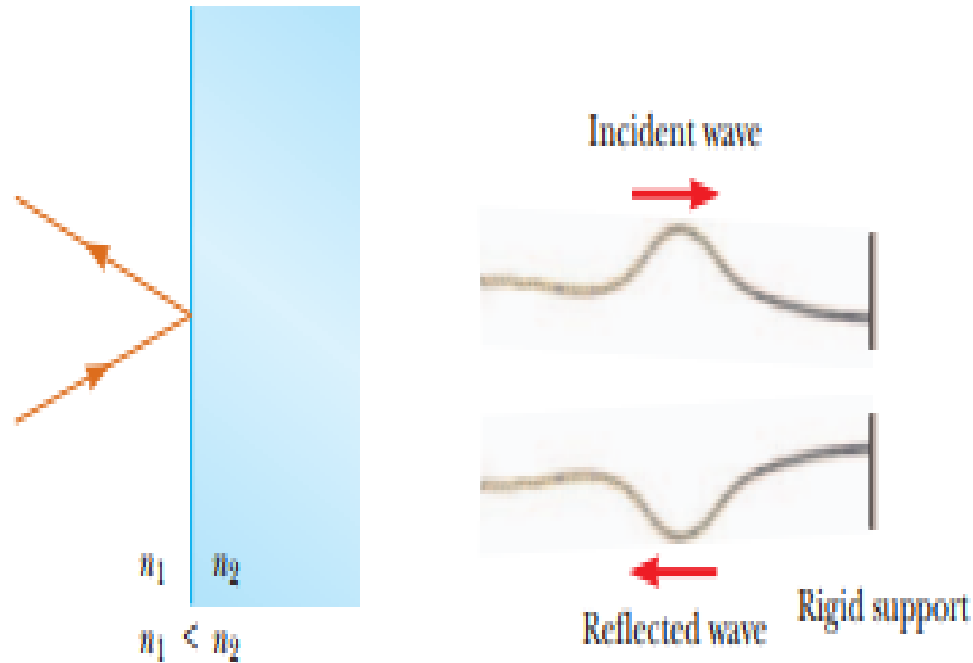
Change of Phase due to reflection
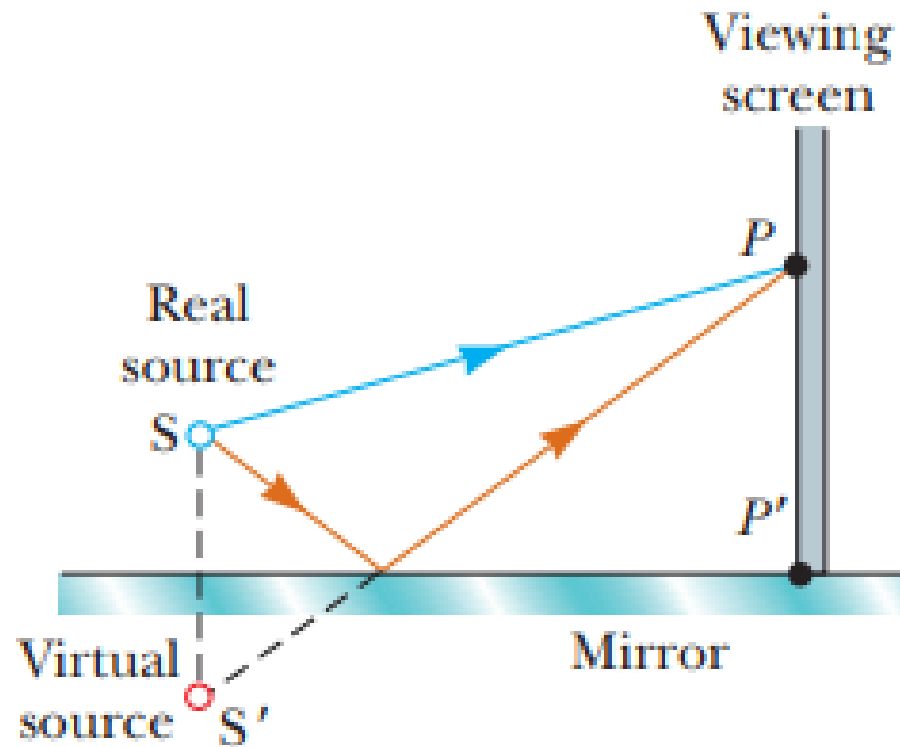
Lloyd's mirror. An interference pattern is produced on a screen at *P* as a result of the combination of the direct ray (blue) and the reflected ray (brown). The reflected ray undergoes a phase change of 180°.
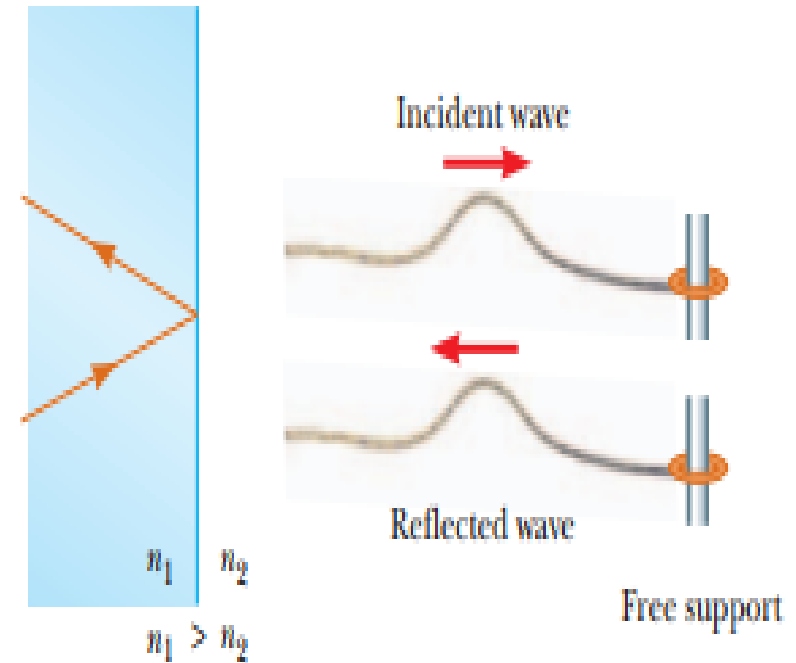
# Change of Phase due to reflection

180° phase change

No phase change

Incident wave

Incident wave

n_1 n_2

$n_1 < n_2$

Reflected wave   Rigid support

(a)

n_1 n_2

$n_1 > n_2$

Reflected wave

Free support

(b)

(a) A ray reflecting from a medium of higher refractive index undergoes a 180° phase change. The right side shows the analogy with a reflected pulse on a string. (b) A ray reflecting from a medium of lower refractive index undergoes no phase change.

Interference in thin films

180° phase change

No phase change

1

2

Air

Surface A

Film with index n

t

Surface B

Air
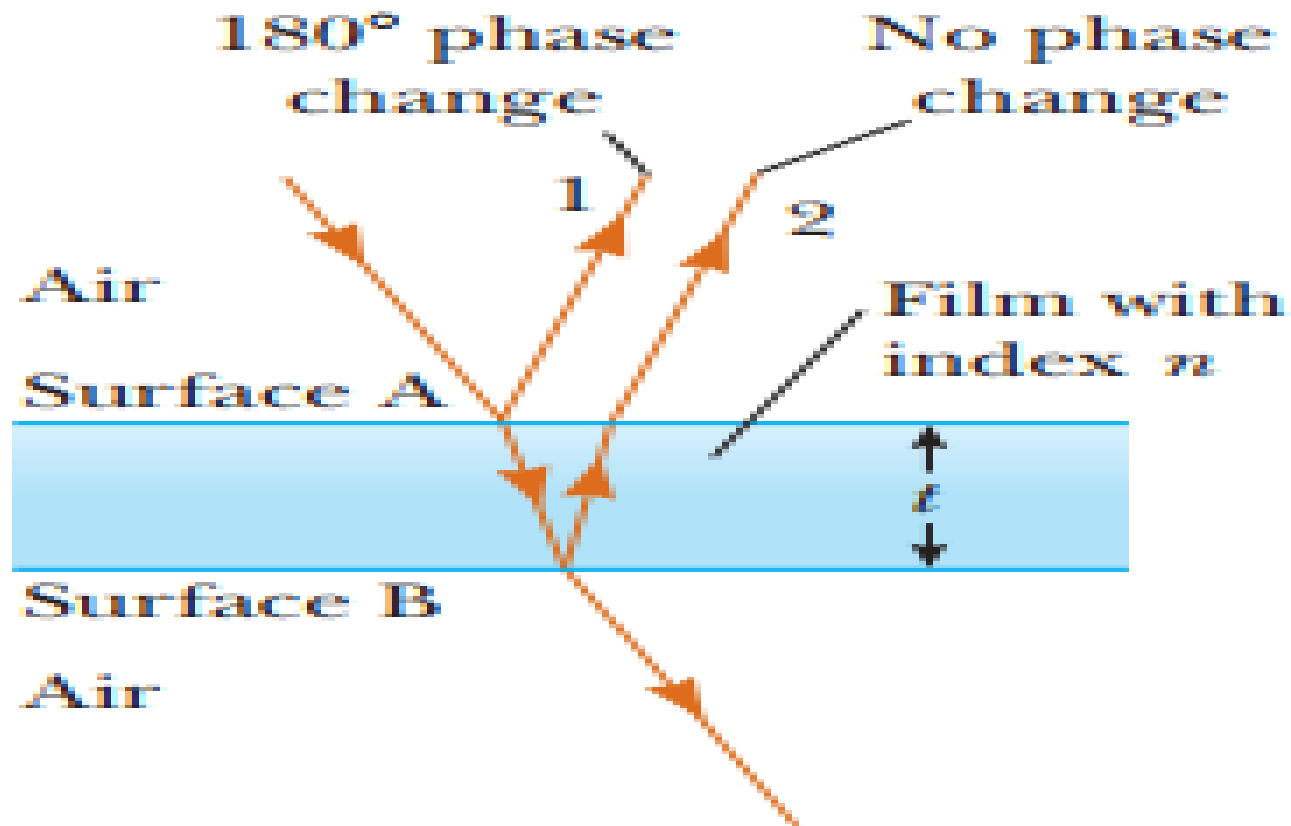
Interference observed in light reflected from a thin film is due to a combination of rays reflected from the upper and lower surfaces.

Newton's rings.

Another method for observing interference in light waves is to place a plano-convex lens on top of a flat glass surface, as in Figure. With this arrangement, the air film between the glass surfaces varies in thickness from zero at the point of contact to some value t at P.

If the radius of curvature R of the lens is much greater than the distance r and the system is viewed from above light of wavelength λ, a pattern of light and dark rings is observed. These circular fringes, discovered by Newton, are called Newton's rings.

Newton's rings.
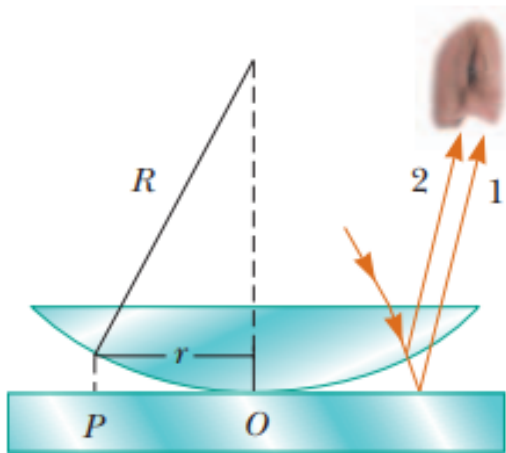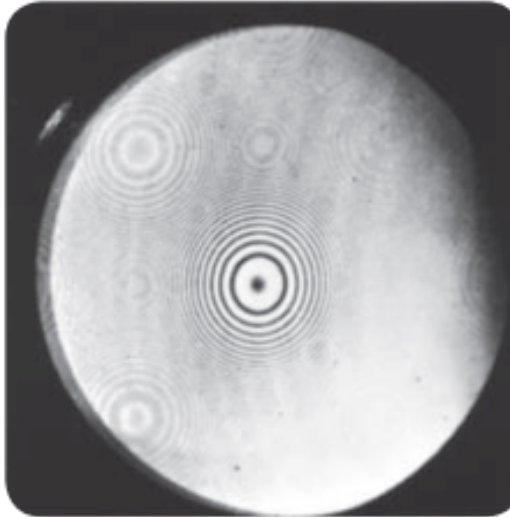
(a) The combination of rays reflected from the glass plate and the curved surface of the lens gives rise to an interference pattern known as Newton's rings. (b) A photograph of Newton's rings. (c) This asymmetric interference pattern indicates imperfections in the lens.
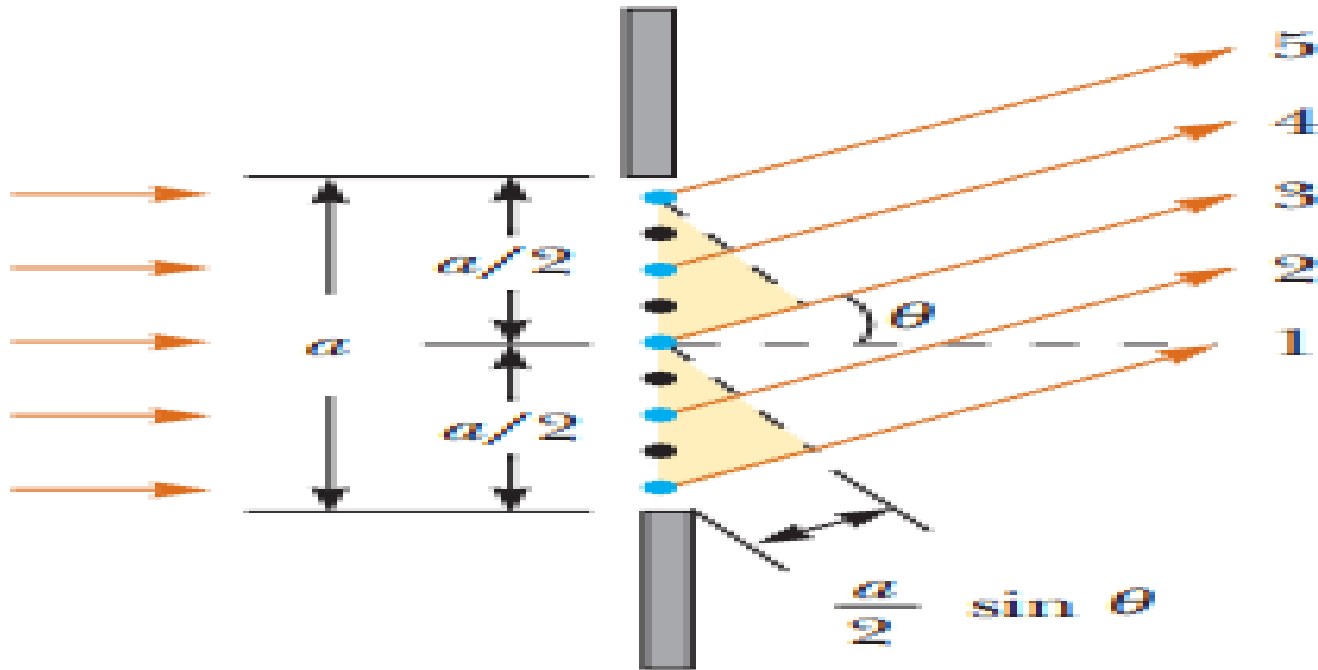
Diffraction

Suppose a light beam is incident on two slits, as in Young's double-slit experiment. If the light truly traveled in straight-line paths after passing through the slits, as in Figure, the waves wouldn't overlap and no interference pattern would be seen. Instead, Huygens' principle requires that the waves spread out from the slits, as shown in Figure. In other words, the light bends from a straight-line path and enters the region that would otherwise be shadowed. This spreading out of light from its initial line of travel is called diffraction.

Diffraction

(a) The Fraunhofer diffraction pattern of a single slit. The parallel rays are brought into focus on the screen with a converging lens. The pattern consists of a central bright region flanked by much weaker maxima. (This drawing is not to scale.) (b) A photograph of a single-slit Fraunhofer diffraction pattern.

Slit

Lens

θ

f

Incoming wave

Screen

(a)
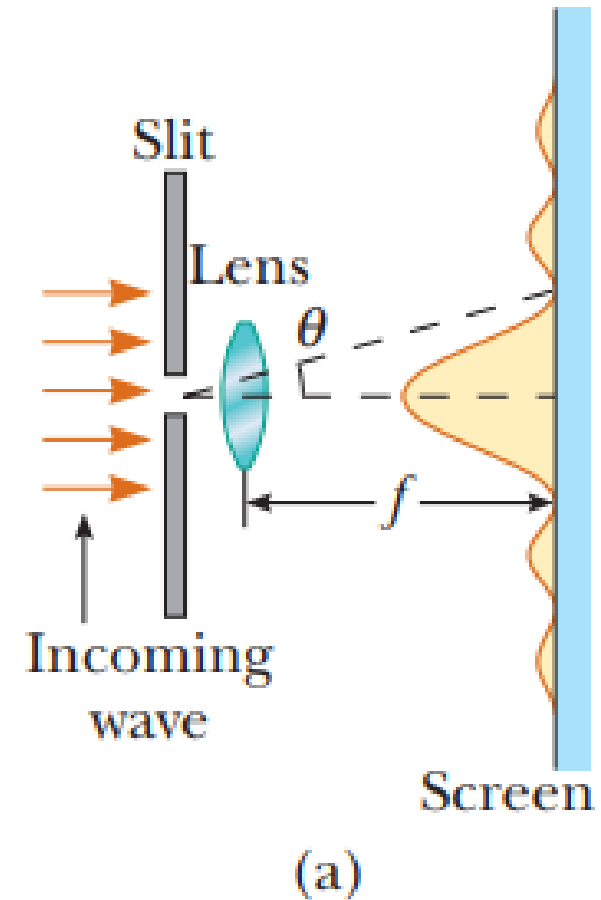
Single slit Diffraction

Diffraction of light by a narrow slit of width a. Each portion of the slit acts as a point source of waves. The path difference between waves 1 and 3 or between waves 2 and 4 is equal to $(a/2) \sin \theta$. (This drawing is not to scale, and the waves are assumed to converge at a distant point.)

Single slit Diffraction

$$\frac{a}{2} \sin \theta = \frac{\lambda}{2}$$

or when

$$\sin \theta = \frac{\lambda}{a}$$

If we divide the slit into four parts rather than two and use similar reasoning, we find that the screen is also dark when

$$\sin \theta = \frac{2\lambda}{a}$$

Continuing in this way, we can divide the slit into six parts and show that darkness occurs on the screen when

$$\sin \theta = \frac{3\lambda}{a}$$

Therefore, the general condition for **destructive interference** for a single slit of width a is

$$\sin \theta_{\text{dark}} = m\frac{\lambda}{a} \qquad m = \pm 1, \pm 2, \pm 3, \dots$$

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Single slit Diffraction

y_2 $\sin \theta_{\text{dark}} = 2\lambda/a$

y_1 $\sin \theta_{\text{dark}} = \lambda/a$

0

$-y_1$ $\sin \theta_{\text{dark}} = -\lambda/a$

$-y_2$ $\sin \theta_{\text{dark}} = -2\lambda/a$
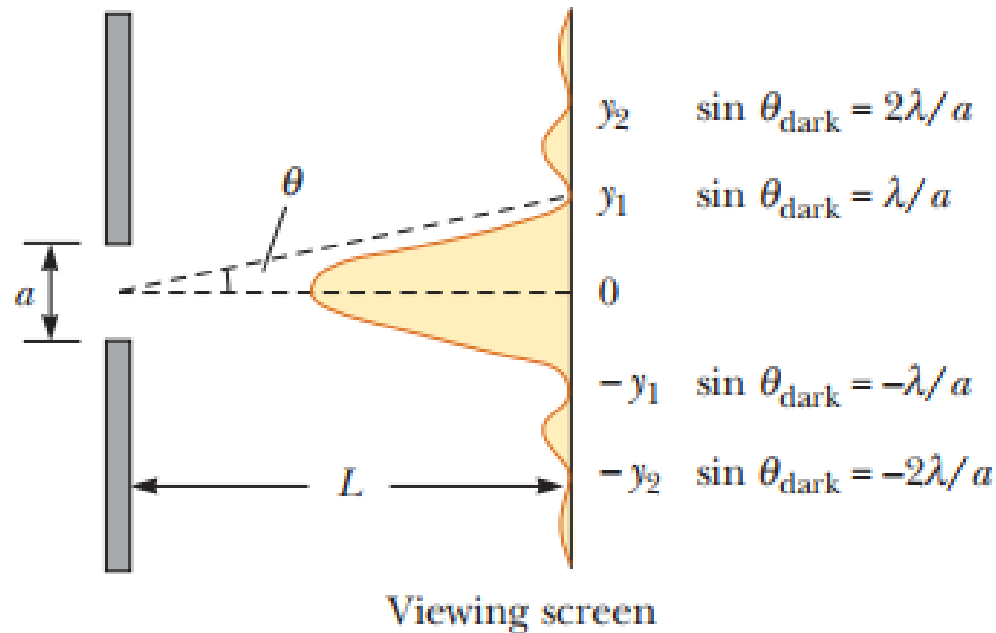
Positions of the minima for the Fraunhofer diffraction pattern of a single slit of width a. (This drawing is not to scale.)
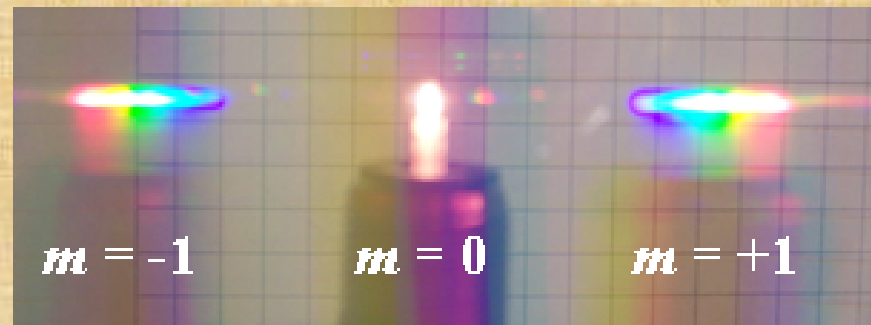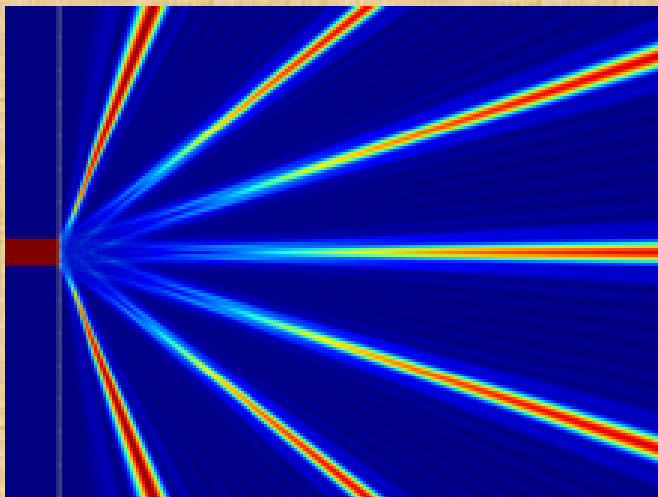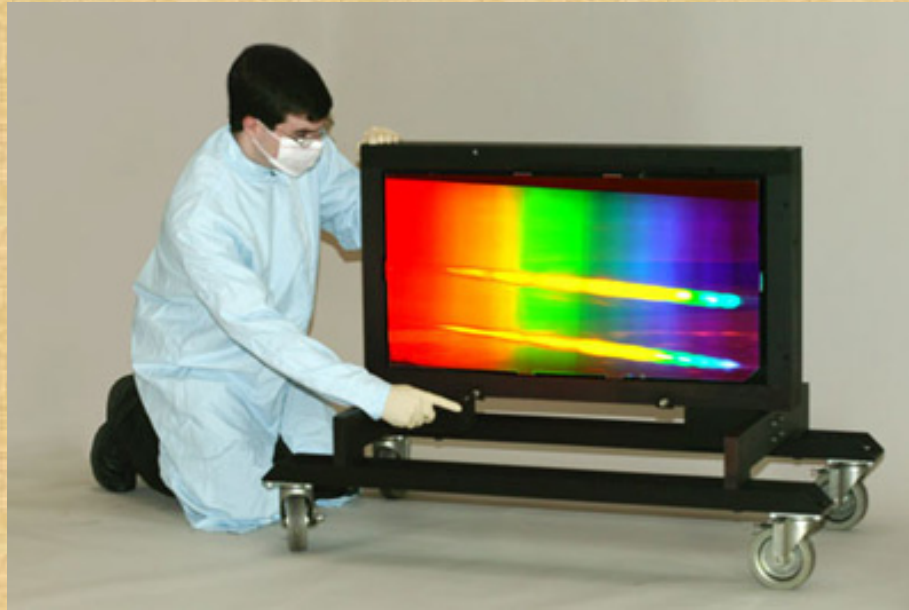
Viewing screen

Diffraction grating

In optics, a diffraction grating is an optical component with a periodic structure that splits and diffracts light into several beams travelling in different directions.
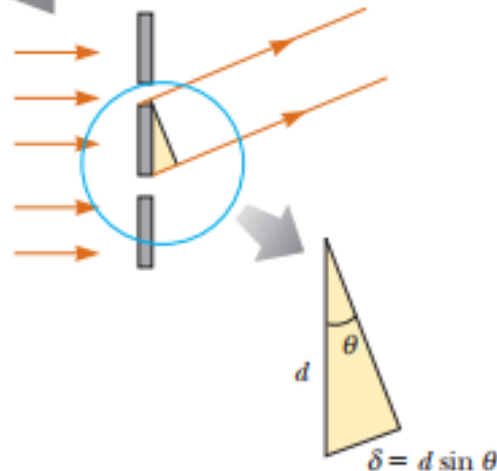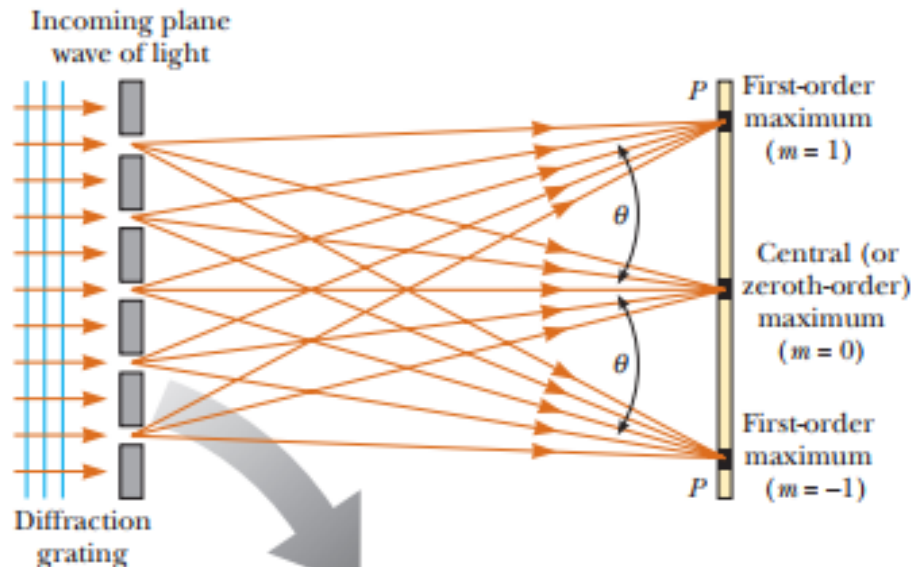
Diffraction
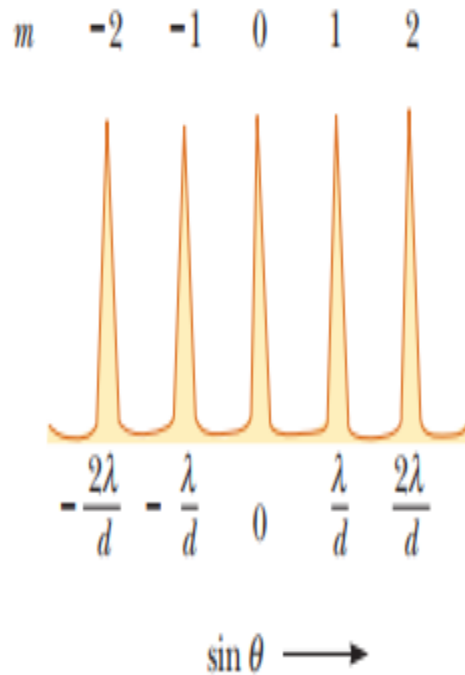

$m = -1$ $m = 0$ $m = +1$
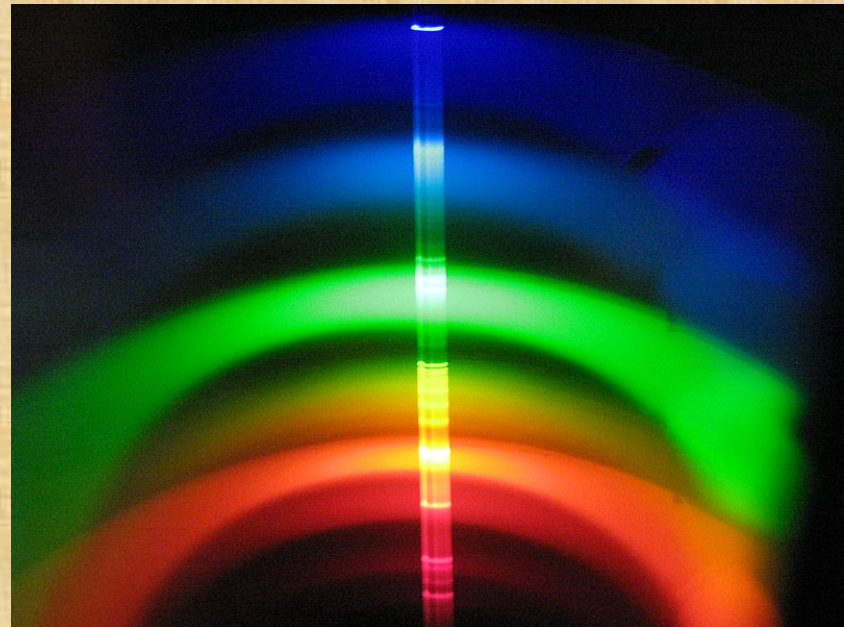
Diffraction

$$d \sin \theta_{bright} = m\lambda \qquad m = 0, \pm 1, \pm 2, \ldots$$

← Condition for maxima in the interference pattern of a diffraction grating

Incoming plane wave of light

Diffraction grating

P First-order maximum $(m = 1)$

Central (or zeroth-order) maximum $(m = 0)$

First-order maximum $(m = -1)$

P

d

θ

$\delta = d \sin \theta$

A side view of a diffraction grating. The slit separation is d, and the path difference between adjacent slits is $d \sin \theta$.

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Diffraction grating

| m | -2 | -1 | 0 | 1 | 2 |

$-\dfrac{2\lambda}{d}$ $-\dfrac{\lambda}{d}$ 0 $\dfrac{\lambda}{d}$ $\dfrac{2\lambda}{d}$

$\sin\theta \longrightarrow$

Intensity versus $\sin\theta$ for the diffraction grating. The zeroth-, first-, and second-order principal maxima are shown.

Collimator

Telescope

Slit

θ

Source
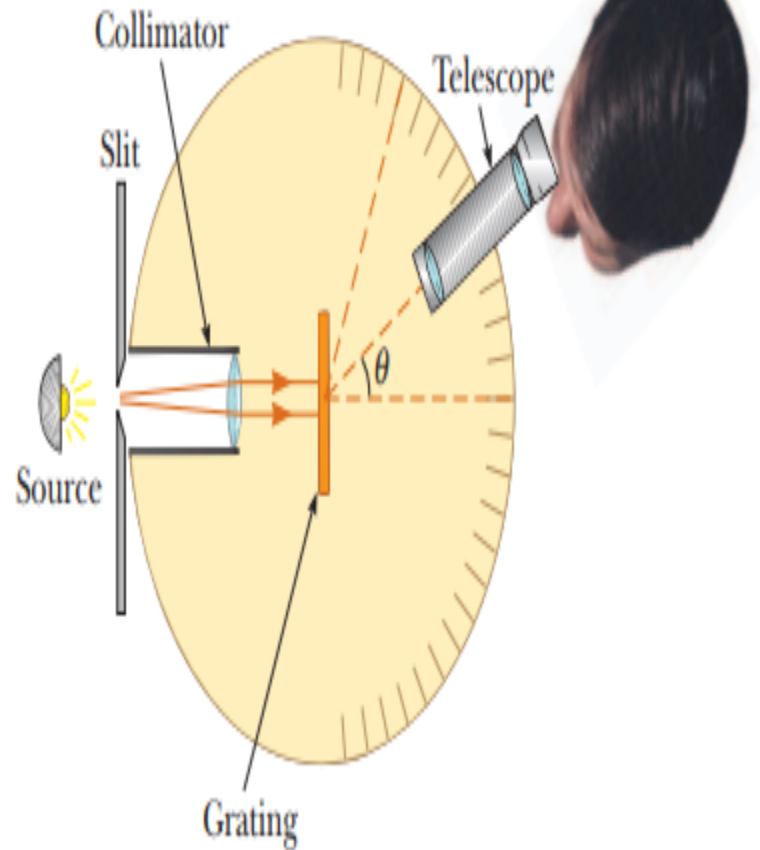
Grating

A diagram of a diffraction grating spectrometer. The collimated beam incident on the grating is diffracted into the various orders at the angles θ that satisfy the equation $d\sin\theta = m\lambda$, where $m = 0, \pm1, \pm2, \ldots$

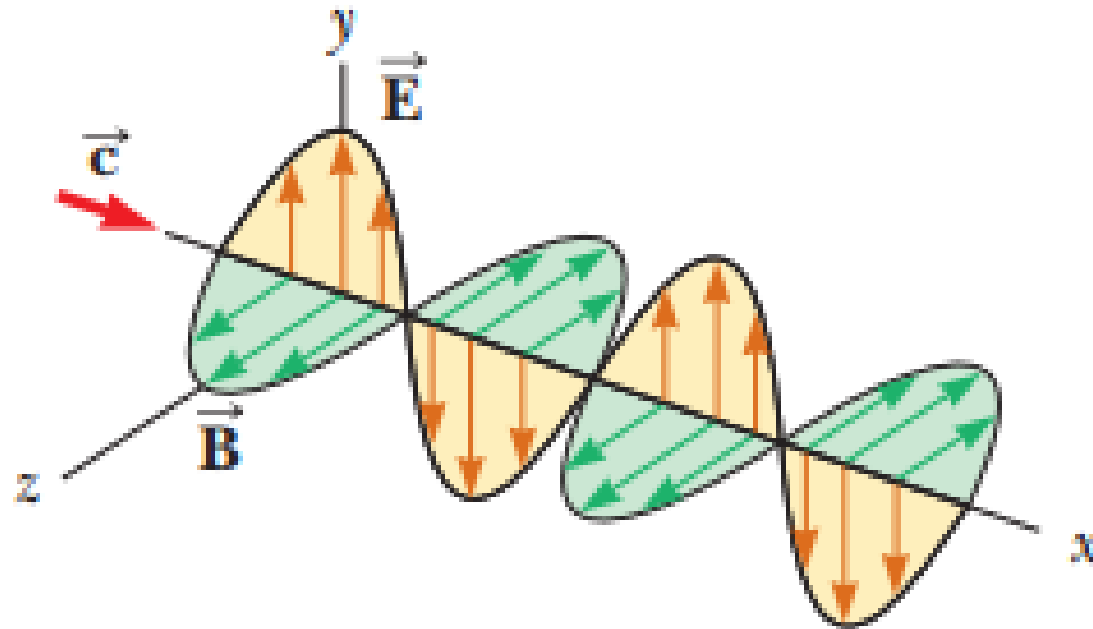Dr. Khokon Hossen

Polarization

Polarization is the property of wave that can oscillate with more than one orientation. A light wave is vibrating in more than one plane is referred to as unpolarised light. The process of transforming unpolarized light into polarized light is known as the polarization of light
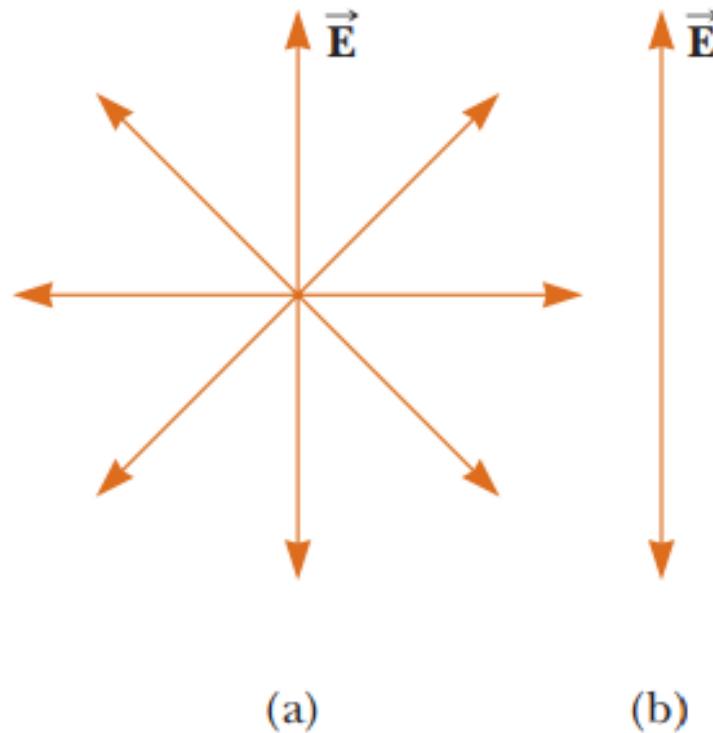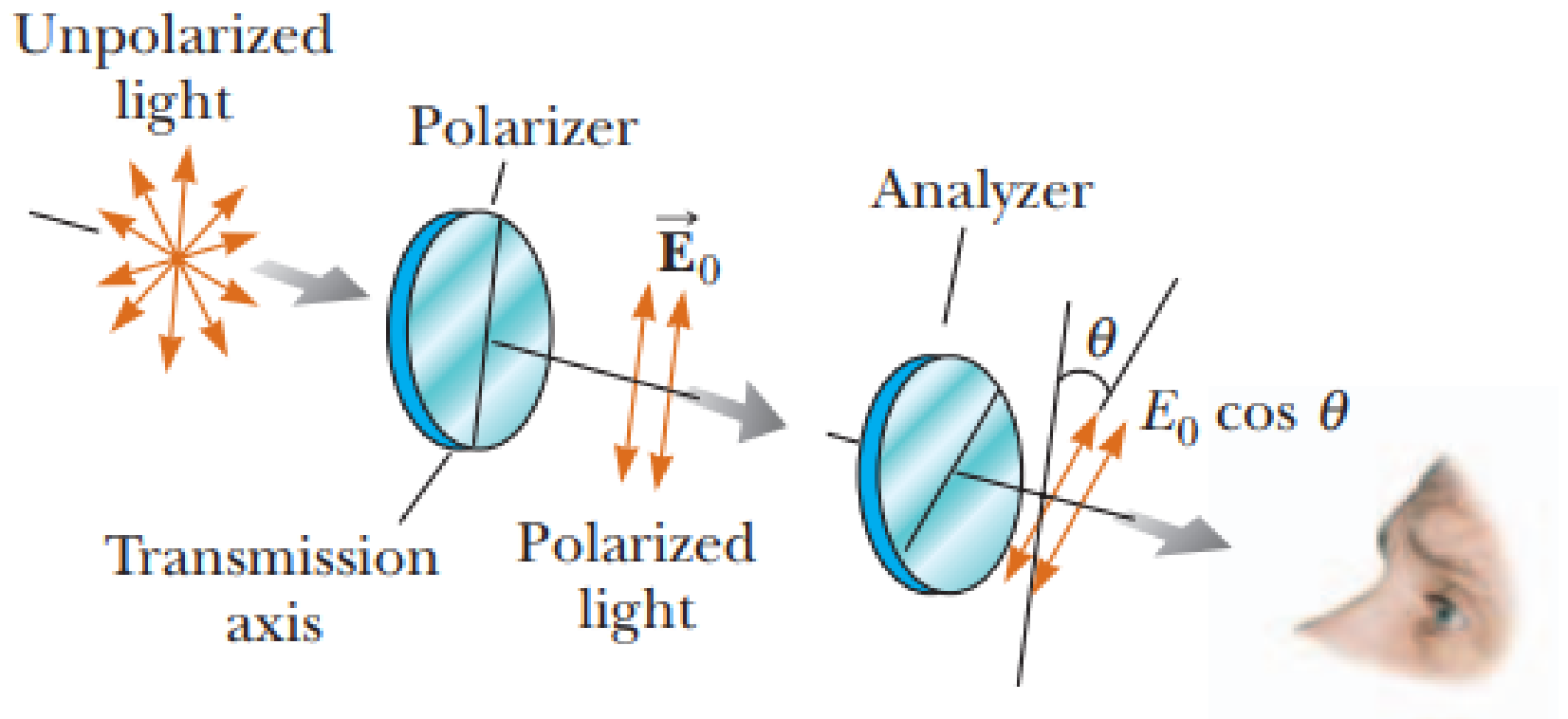
Polarization
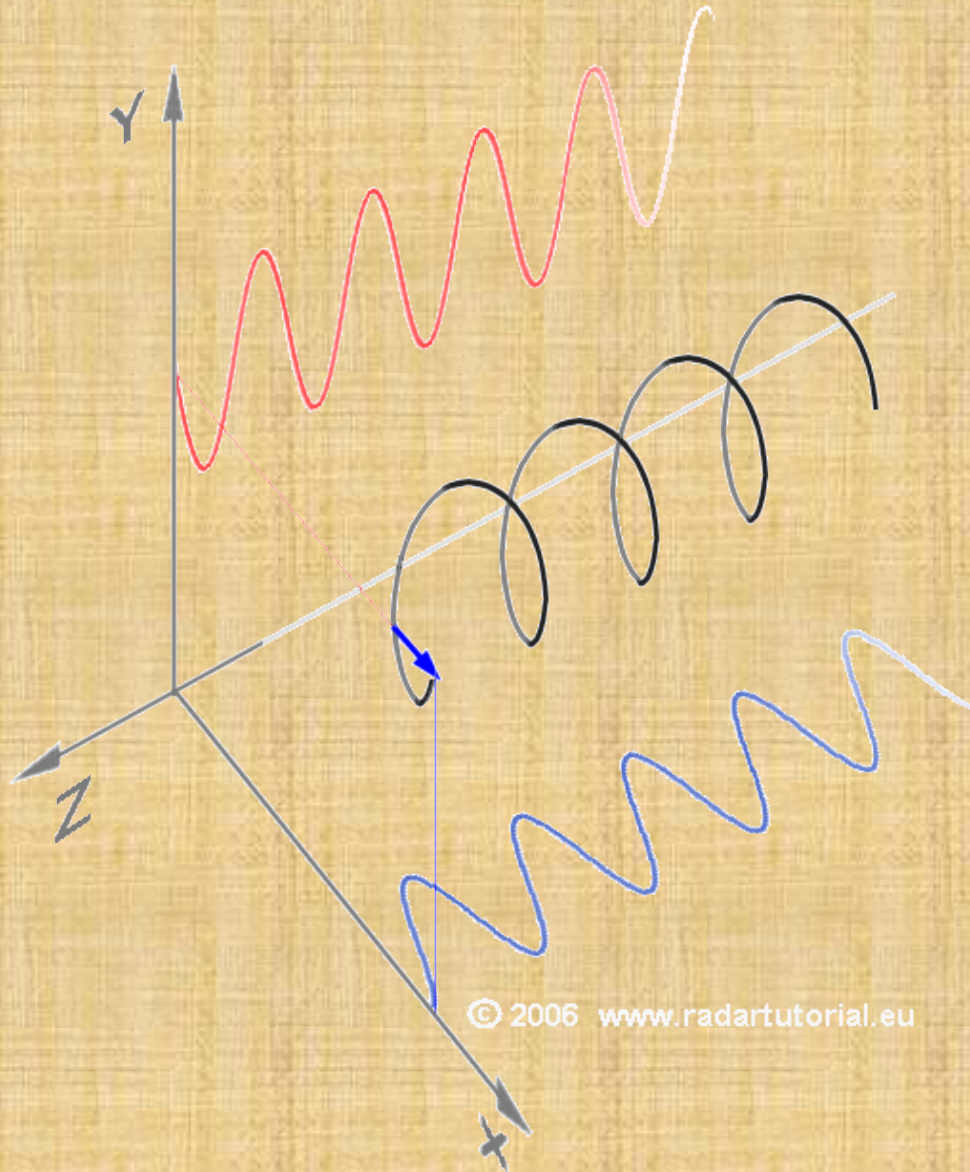
Polarization

A schematic diagram of a polarized electromagnetic wave propagating in the x-direction. The electric field vector $\vec{E}$ vibrates in the xy-plane, whereas the magnetic field vector $\vec{B}$ vibrates in the xz-plane.

Polarization

(a) An unpolarized light beam viewed along the direction of propagation (perpendicular to the page). The transverse electric field vector can vibrate in any direction with equal probability. (b) A linearly polarized light beam with the electric field vector vibrating in the vertical direction.

Polarization by Selective Absorption

Unpolarized light

Polarizer

$\vec{E}_0$

Analyzer

Transmission axis

Polarized light

θ

$E_0 \cos \theta$

Two polarizing sheets whose transmission axes make an angle θ with each other. Only a fraction of the polarized light incident on the analyzer is transmitted.

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Polarization by Selective Absorption

The intensity of light transmitted through two polarizers depends on the relative orientations of their transmission axes. (a) The transmitted light has *maximum* intensity when the transmission axes are *aligned* with each other. (b) The transmitted light intensity diminishes when the transmission axes are at an angle of 45° with each other. (c) The transmitted light intensity is a *mini-mum* when the transmission axes are at *right angles* to each other.

(a) (b) (c)
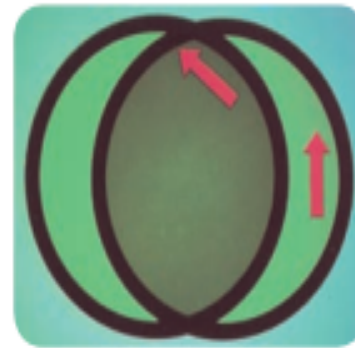
square of its amplitude E, we conclude that the intensity of the (polarized) beam transmitted through the analyzer varies as

Malus's law →

$$I = I_0 \cos^2 \theta$$

where I_0 is the intensity of the polarized wave incident on the analyzer. This expression, known as **Malus's law**, applies to any two polarizing materials having transmission axes at an angle of θ to each other. Note from Equation 24.13 that the transmitted intensity is a maximum when the transmission axes are parallel ($\theta = 0$ or 180°) and is a minimum (complete absorption by the analyzer) when the transmission axes are perpendicular to each other. This variation in transmitted intensity through a pair of polarizing sheets is illustrated in Figure 24.27.

When unpolarized light of intensity I_0 is sent through a single ideal polarizer, the transmitted linearly polarized light has intensity $I_0/2$. This fact follows from Malus's law because the average value of $\cos^2 \theta$ is one-half.

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Polarization by Reflection

(a)

(b)
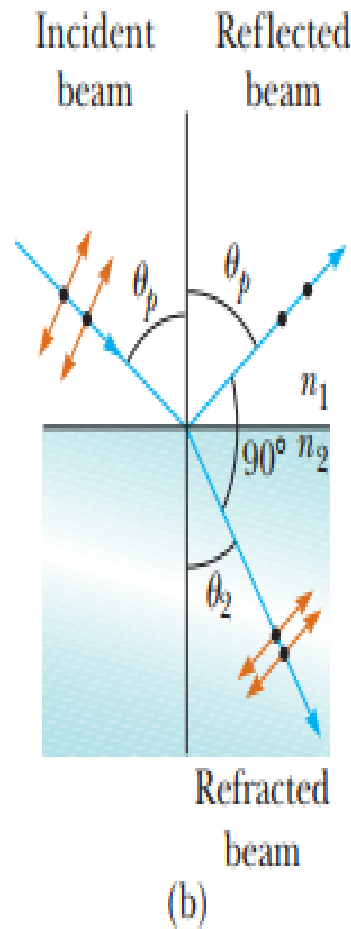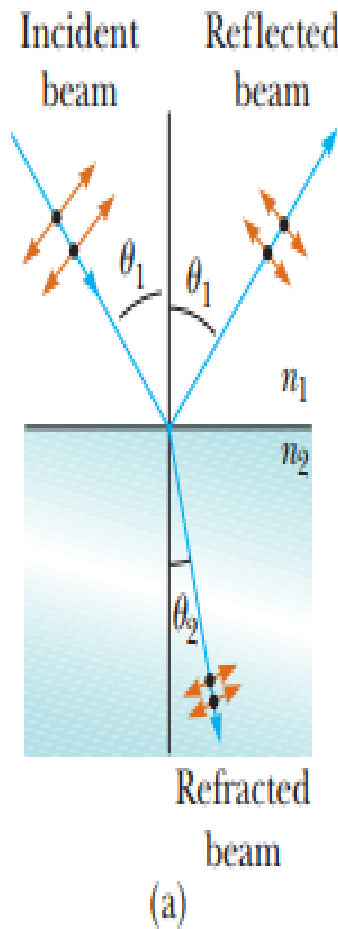
(a) When unpolarized light is incident on a reflecting surface, the reflected and refracted beams are partially polarized.
(b) The reflected beam is completely polarized when the angle of incidence equals the polarizing angle θ_p, satisfying the equation $n = \tan\theta_p$.

we see that at the polarizing angle, $\theta_p + 90° + \theta_2 = 180°$, so $\theta_2 = 90° - \theta_p$. Using Snell's law and taking $n_1 = n_{air} = 1.00$ and $n_2 = n$ yields

$$n = \frac{\sin \theta_1}{\sin \theta_2} = \frac{\sin \theta_p}{\sin \theta_2}$$

Because $\sin \theta_2 = \sin(90° - \theta_p) = \cos \theta_p$, the expression for n can be written

$$n = \frac{\sin \theta_p}{\cos \theta_p} = \tan \theta_p$$

Equation 24.14 is called **Brewster's law**, and the polarizing angle θ_p is sometimes called **Brewster's angle** after its discoverer, Sir David Brewster (1781–1868). For example, Brewster's angle for crown glass (where $n = 1.52$) has the value $\theta_p = \tan^{-1}(1.52) = 56.7°$. Because n varies with wavelength for a given substance, Brewster's angle is also a function of wavelength.

Polarization by reflection is a common phenomenon. Sunlight reflected from water, glass, or snow is partially polarized. If the surface is horizontal, the electric field vector of the reflected light has a strong horizontal component. Sunglasses made of polarizing material reduce the glare, which *is* the reflected light. The transmission axes of the lenses are oriented vertically to absorb the strong horizontal component of the reflected light. Because the reflected light is mostly polarized, most of the glare can be eliminated without removing most of the normal light.
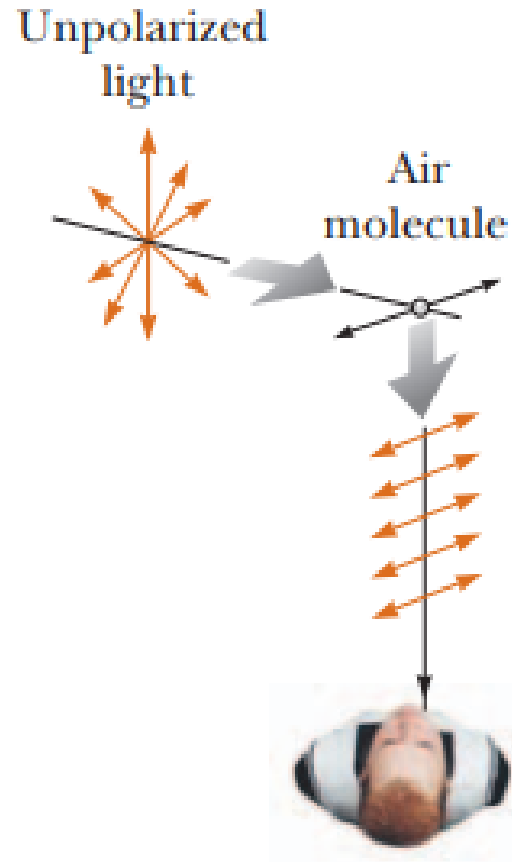
Polarization by Scattering

When light is incident on a system of particles, such as a gas, the electrons in the medium can absorb and reradiate part of the light. The absorption and reradiation of light by the medium, called **scattering**, is what causes sunlight reaching an observer on Earth from straight overhead to be polarized. You can observe this effect by looking directly up through a pair of sunglasses made of polarizing glass. Less light passes through at certain orientations of the lenses than at others.

Figure 24.29 illustrates how the sunlight becomes polarized. The left side of the figure shows an incident unpolarized beam of sunlight on the verge of striking an air molecule. When the beam strikes the air molecule, it sets the electrons of the molecule into vibration. These vibrating charges act like those in an antenna except that they vibrate in a complicated pattern. The horizontal part of the electric field vector in the incident wave causes the charges to vibrate horizontally, and the vertical part of the vector simultaneously causes them to vibrate vertically. A horizontally polarized wave is emitted by the electrons as a result of their horizontal motion, and a vertically polarized wave is emitted parallel to Earth as a result of their vertical motion.

Scientists have found that bees and homing pigeons use the polarization of sunlight as a navigational aid.

Polarization by Reflection
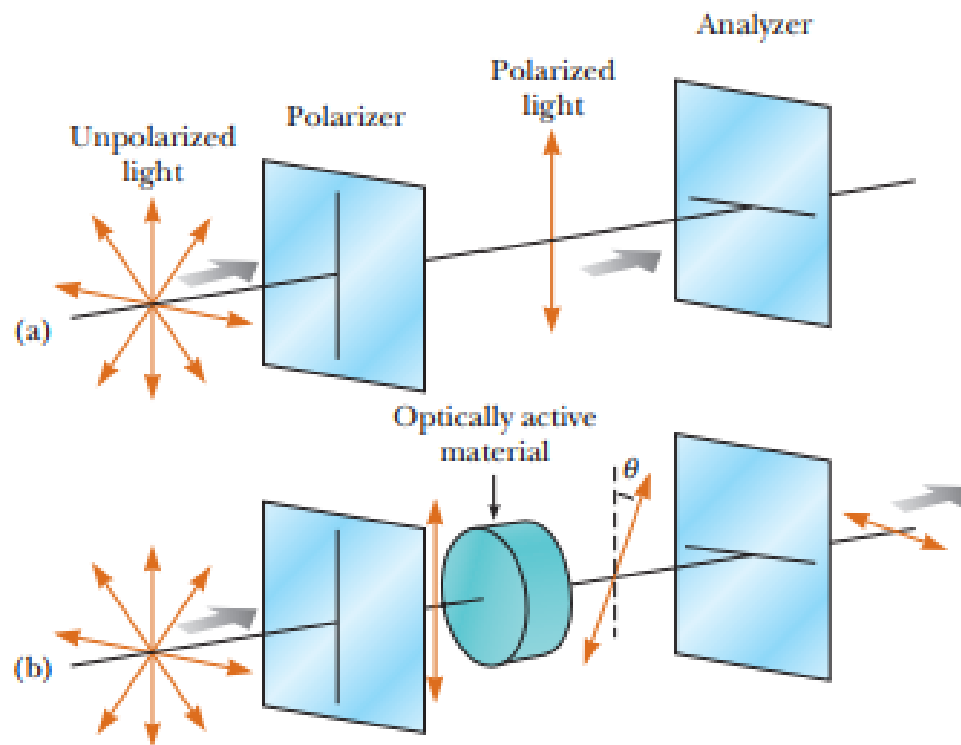

Unpolarized light

Air molecule

The scattering of unpolarized sunlight by air molecules. The light observed at right angles is linearly polarized because the vibrating molecule has a horizontal component of vibration.

Optical Activity

Many important practical applications of polarized light involve the use of certain materials that display the property of **optical activity**. A substance is said to be optically active if it rotates the plane of polarization of transmitted light. Suppose unpolarized light is incident on a polarizer from the left, as in Figure 24.30a. The transmitted light is polarized vertically, as shown. If this light is then incident on an analyzer with its axis perpendicular to that of the polarizer, no light emerges from it. If an optically active material is placed between the polarizer and analyzer, as in Figure 24.30b, the material causes the direction of the polarized beam to rotate through the angle θ. As a result, some light is able to pass through the analyzer. The angle through which the light is rotated by the material can be found by rotating the polarizer until the light is again extinguished. It is found that the angle of rotation depends on the length of the sample and, if the substance is in solution,

(a) When crossed polarizers are used, none of the polarized light can pass through the analyzer. (b) An optically active material rotates the direction of polarization through the angle θ, enabling some of the polarized light to pass through the analyzer.

# Liquid Crystals

Liquid Crystals

An effect similar to rotation of the plane of polarization is used to create the familiar displays on pocket calculators, wristwatches, notebook computers, and so forth. The properties of a unique substance called a liquid crystal make these displays (called LCDs, for *liquid crystal displays*) possible. As its name implies, a **liquid crystal** is a substance with properties intermediate between those of a crystalline solid and those of a liquid; that is, the molecules of the substance are more orderly than those in a liquid, but less orderly than those in a pure crystalline solid. The forces
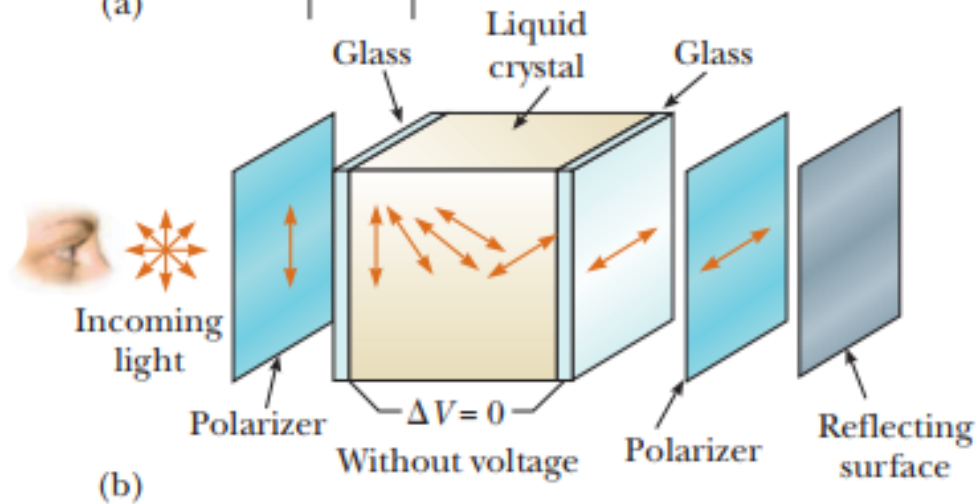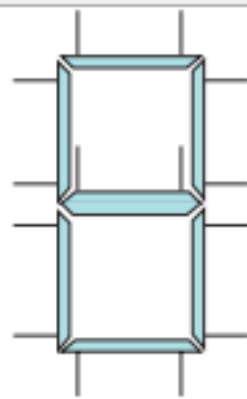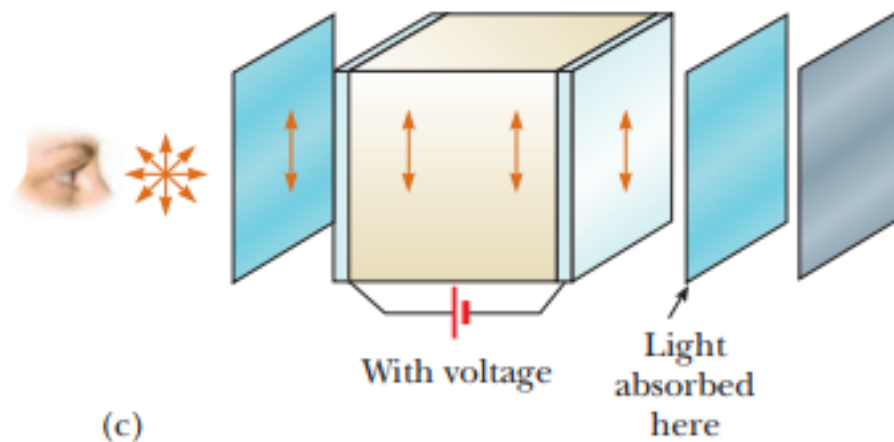
(a)

(b)

APPLICATION

Liquid Crystal Displays (LCDs)
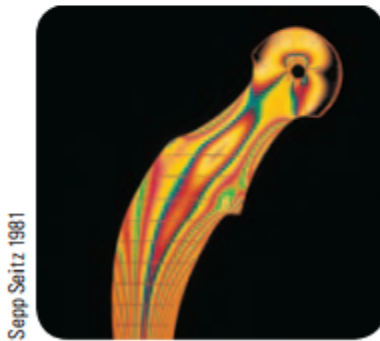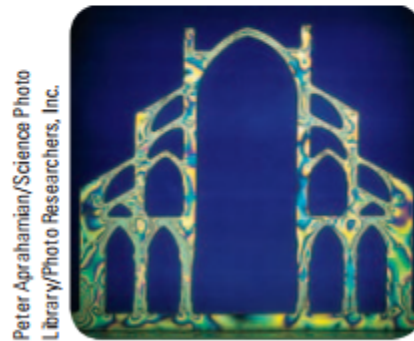
(a) Strain distribution in a plastic model of a replacement hip used in a medical research laboratory. The pattern is produced when the model is placed between a polarizer and an analyzer oriented perpendicular to each other. (b) A plastic model of an arch structure under load conditions observed between perpendicular polarizers. Such patterns are useful in the optimum design of architectural components.

(a)

Glass   Liquid crystal   Glass

Incoming light

Polarizer $\Delta V = 0$ Polarizer   Reflecting surface
Without voltage

(b)

With voltage   Light absorbed here

(c)

(a) The light-segment pattern of a liquid crystal display. (b) Rotation of a polarized light beam by a liquid crystal when the applied voltage is zero. (c) Molecules of the liquid crystal align with the electric field when a voltage is applied.

Optics   Dr. Khokon Hossen

Thanks a lot for your attention!

Assignment

"Separate hydrogen and oxygen from water through electrolysis and hence hydrogen fuelled electricity generation"

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