Class: B. Tech (Unit IV)

I have taken all course materials for Unit IV from Book Concept of Modern Physics by Arthur Besier, Shobhit Mahajan & S. Rai Choudhury (McGraw Hill Education).

Students can download this book form given web address;

Web Address : **https://b-ok.cc/book/2700591/864ac0**

Some topics (mainly LASER) of unit IV (Laser and Fiber Optics) have been taken from **Chapter4** from above said book (**https://b-ok.cc/book/2700591/864ac0**). I am sending pdf file of Chapter 4 which have **LASER** notes.

UNIT-IV: LASER & FIBER OPTICS

Introduction; Absorption and Emission, Einstein's coefficients & equations; Metastable states, Population inversion, Pumping (three and four level laser schemes), Basic parts of a Laser, Characteristics of Laser Radiations; Classification of Lasers, Ruby Laser, He-Ne Laser, GaAs Laser; Applications of lasers in holography

Basics of optical fiber, Total Internal Reflection, Acceptance angle, Numerical Aperture; Modes of Propagation, Single Mode Step Index Optical Fiber, Multimode Step Index Optical Fiber, Graded Index Fiber, Losses, Dispersion in Optical Fiber, Intermodal and intramodal dispersion, Applications of optical fiber; Problems.

where m is the electron mass. From Eq. (4.23) the energy levels of a positronium "atom" are

$$E_n' = \left(\frac{m'}{m}\right)\frac{E_1}{n^2} = \frac{E_1}{2n^2}$$

This means that the Rydberg constant—the constant term in Eq. (4.18)—for positronium is half as large as it is for ordinary hydrogen. As a result the wavelengths in the positronium spectral lines are all twice those of the corresponding lines in the hydrogen spectrum.

Example 4.7

A **muon** is an unstable elementary particle whose mass is $207m_e$ and whose charge is either $+e$ or $-e$. A negative muon (μ^-) can be captured by a nucleus to form a muonic atom. (*a*) A proton captures a μ^-. Find the radius of the first Bohr orbit of this atom. (*b*) Find the ionization energy of the atom.

Solution

(*a*) Here $m = 207m_e$ and $M = 1836m_e$, so the reduced mass is

$$m' = \frac{mM}{m + M} = \frac{(207m_e)(1836m_e)}{207m_e + 1836m_e} = 186m_e$$

According to Eq. (4.13) the orbit radius corresponding to $n = 1$ is

$$r_1 = \frac{h^2\epsilon_0}{\pi m_e e^2}$$

where $r_1 = a_0 = 5.29 \times 10^{-11}$ m. Hence the radius r' that corresponds to the reduced mass m' is

$$r_1' = \left(\frac{m}{m'}\right)r_1 = \left(\frac{m_e}{186m_e}\right)a_0 = 2.85 \times 10^{-13}\ \text{m}$$

The muon is 186 times closer to the proton than an electron would be, so a muonic hydrogen atom is much smaller than an ordinary hydrogen atom.

(*b*) From Eq. (4.23) we have, with $n = 1$ and $E_1 = -13.6$ eV,

$$E_1' = \left(\frac{m'}{m}\right)E_1 = 186E_1 = -2.53 \times 10^3\ \text{eV} = -2.53\ \text{keV}$$

The ionization energy is therefore 2.53 keV, 186 times that for an ordinary hydrogen atom.

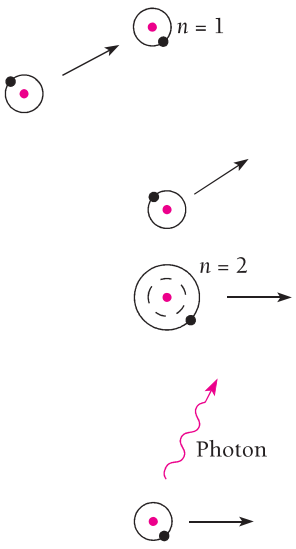


Figure 4.18 Excitation by collision. Some of the available energy is absorbed by one of the atoms, which goes into an excited energy state. The atom then emits a photon in returning to its ground (normal) state.

4.8 ATOMIC EXCITATION

How atoms absorb and emit energy

There are two main ways in which an atom can be excited to an energy above its ground state and thereby become able to radiate. One of these ways is by a collision with another particle in which part of their joint kinetic energy is absorbed by the atom. Such an excited atom will return to its ground state in an average of 10^{-8} s by emitting one or more photons (Fig. 4.18).

To produce a luminous discharge in a rarefied gas, an electric field is established that accelerates electrons and atomic ions until their kinetic energies are sufficient to

Auroras are caused by streams of fast protons and electrons from the sun that excite atoms in the upper atmosphere. The green hues of an auroral display come from oxygen, and the reds originate in both oxygen and nitrogen. This aurora occurred in Alaska.

excite atoms they collide with. Because energy transfer is a maximum when the colliding particles have the same mass (see Fig. 12.22), the electrons in such a discharge are more effective than the ions in providing energy to atomic electrons. Neon signs and mercury-vapor lamps are familiar examples of how a strong electric field applied between electrodes in a gas-filled tube leads to the emission of the characteristic spectral radiation of that gas, which happens to be reddish light in the case of neon and bluish light in the case of mercury vapor.

Another excitation mechanism is involved when an atom absorbs a photon of light whose energy is just the right amount to raise the atom to a higher energy level. For example, a photon of wavelength 121.7 nm is emitted when a hydrogen atom in the $n = 2$ state drops to the $n = 1$ state. Absorbing a photon of wavelength 121.7 nm by a hydrogen atom initially in the $n = 1$ state will therefore bring it up to the $n = 2$ state (Fig. 4.19). This process explains the origin of absorption spectra.

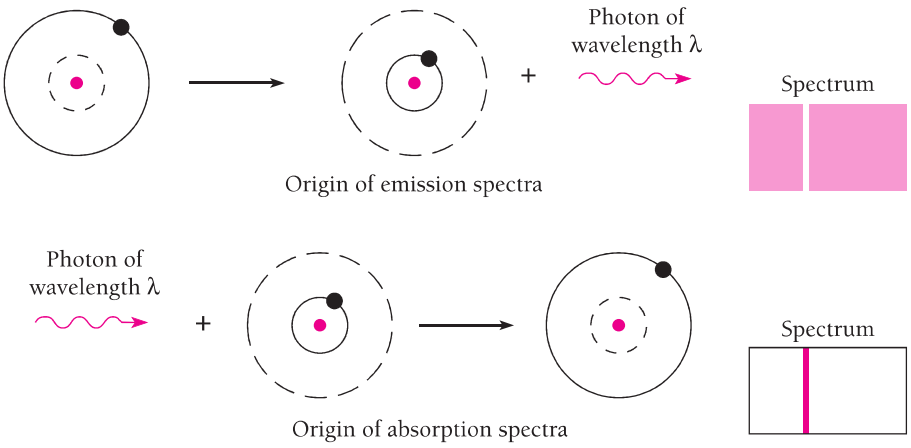


Figure 4.19 How emission and absorption spectral lines originate.

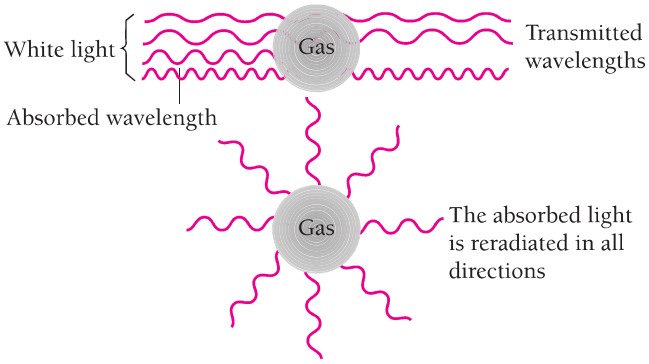


Figure 4.20 The dark lines in an absorption spectrum are never totally dark.

When white light, which contains all wavelengths, is passed through hydrogen gas, photons of those wavelengths that correspond to transitions between energy levels are absorbed. The resulting excited hydrogen atoms reradiate their excitation energy almost at once, but these photons come off in random directions with only a few in the same direction as the original beam of white light (Fig. 4.20). The dark lines in an absorption spectrum are therefore never completely black but only appear so by contrast with the bright background. We expect the lines in the absorption spectrum of any element to coincide with those in its emission spectrum that represent transitions to the ground state, which agrees with observation (see Fig. 4.9).

Franck-Hertz Experiment

Atomic spectra are not the only way to investigate energy levels inside atoms. A series of experiments based on excitation by collision was performed by James Franck and Gustav Hertz (a nephew of Heinrich Hertz) starting in 1914. These experiments demonstrated that atomic energy levels indeed exist and, furthermore, that the ones found in this way are the same as those suggested by line spectra.

Franck and Hertz bombarded the vapors of various elements with electrons of known energy, using an apparatus like that shown in Fig. 4.21. A small potential difference V_0 between the grid and collecting plate prevents electrons having energies less than a certain minimum from contributing to the current I through the ammeter. As the accelerating potential V is increased, more and more electrons arrive at the plate and I rises (Fig. 4.22).

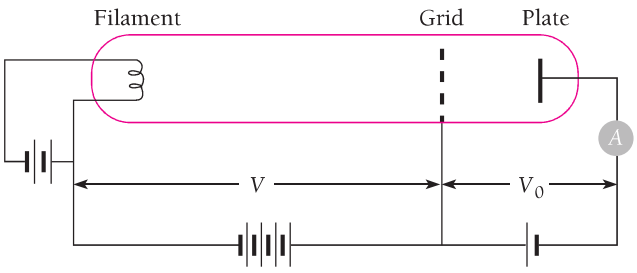


Figure 4.21 Apparatus for the Franck-Hertz experiment.

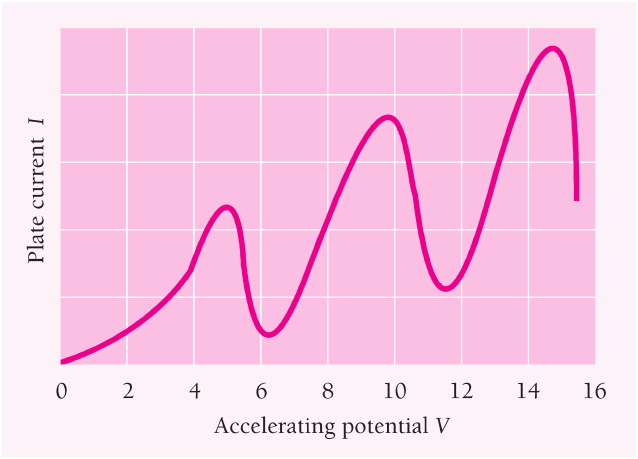


Figure 4.22 Results of the Franck-Hertz experiment, showing critical potentials in mercury vapor.

If KE is conserved when an electron collides with one of the atoms in the vapor, the electron merely bounces off in a new direction. Because an atom is much heavier than an electron, the electron loses almost no KE in the process. After a certain critical energy is reached, however, the plate current drops abruptly. This suggests that an electron colliding with one of the atoms gives up some or all of its KE to excite the atom to an energy level above its ground state. Such a collision is called inelastic, in contrast to an elastic collision in which KE is conserved. The critical electron energy equals the energy needed to raise the atom to its lowest excited state.

Then, as the accelerating potential V is raised further, the plate current again increases, since the electrons now have enough energy left to reach the plate after undergoing an inelastic collision on the way. Eventually another sharp drop in plate current occurs, which arises from the excitation of the same energy level in other atoms by the electrons. As Fig. 4.22 shows, a series of critical potentials for a given atomic vapor is obtained. Thus the higher potentials result from two or more inelastic collisions and are multiples of the lowest one.

To check that the critical potentials were due to atomic energy levels, Franck and Hertz observed the emission spectra of vapors during electron bombardment. In the case of mercury vapor, for example, they found that a minimum electron energy of 4.9 eV was required to excite the 253.6-nm spectral line of mercury—and a photon of 253.6-nm light has an energy of just 4.9 eV. The Franck-Hertz experiments were performed shortly after Bohr announced his theory of the hydrogen atom, and they independently confirmed his basic ideas.

4.9 THE LASER

How to produce light waves all in step

The **laser** is a device that produces a light beam with some remarkable properties:

1 The light is very nearly monochromatic.
2 The light is coherent, with the waves all exactly in phase with one another (Fig.4.23).

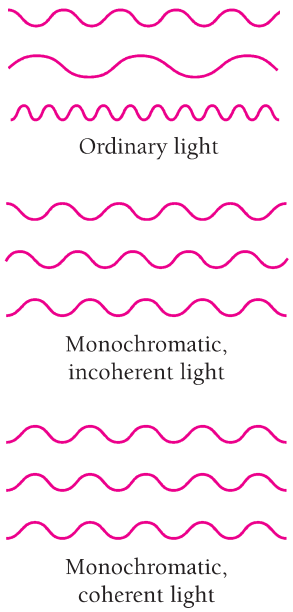


Figure 4.23 A laser produces a beam of light whose waves all have the same frequency (monochromatic) and are in phase with one another (coherent). The beam is also well collimated and so spreads out very little, even over long distances.

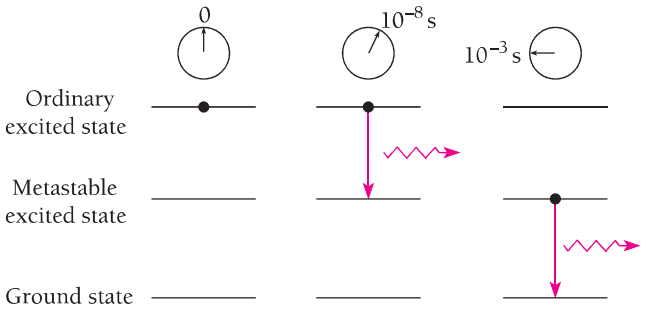


Figure 4.24 An atom can exist in a metastable energy level for a longer time before radiating than it can in an ordinary energy level.

3 A laser beam diverges hardly at all. Such a beam sent from the earth to a mirror left on the moon by the Apollo 11 expedition remained narrow enough to be detected on its return to the earth, a total distance of over three-quarters of a million kilometers. A light beam produced by any other means would have spread out too much for this to be done.
4 The beam is extremly intense, more intense by far than the light from any other source. To achieve an energy density equal to that in some laser beams, a hot object would have to be at a temperature of 10^{30} K.

The last two of these properties follow from the second of them.

The term *laser* stands for *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation. The key to the laser is the presence in many atoms of one or more excited energy levels whose lifetimes may be 10^{-3} s or more instead of the usual 10^{-8} s. Such relatively long-lived states are called **metastable** (temporarily stable); see Fig. 4.24.

Three kinds of transition involving electromagnetic radiation are possible between two energy levels, E_0 and E_1, in an atom (Fig. 4.25). If the atom is initially in the lower state E_0, it can be raised to E_1 by absorbing a photon of energy $E_1 - E_0 = h\nu$. This process is called **stimulated absorption.** If the atom is initially in the upper state E_1, it can drop to E_0 by emitting a photon of energy $h\nu$. This is **spontaneous emission.**

Einstein, in 1917, was the first to point out a third possibility, **stimulated emission**, in which an incident photon of energy $h\nu$ causes a transition from E_1 to E_0. In stimulated emission, the radiated light waves are exactly in phase with the incident ones, so the result is an enhanced beam of coherent light. Einstein showed that stimulated emission has the same probability as stimulated absorption (see Sec. 9.7). That is, a photon of energy $h\nu$ incident on an atom in the upper

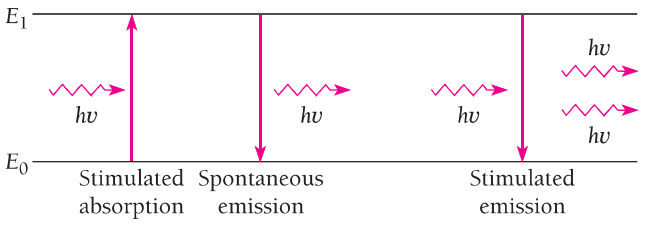


Figure 4.25 Transitions between two energy levels in an atom can occur by stimulated absorption, spontaneous emission, and stimulated emission.

Charles H. Townes (1915–) was born in Greenville, South Carolina, and attended Furman University there. After graduate study at Duke University and the California Institute of Technology, he spent 1939 to 1947 at the Bell Telephone Laboratories designing radar-controlled bombing systems. Townes then joined the physics department of Columbia University. In 1951, while sitting on a park bench, the idea for the **maser** (*m*icrowave *a*mplification by *s*timulated *e*mission of *r*adiation) occurred to him as a way to produce high-intensity microwaves, and in 1953 the first maser began operating. In this device ammonia (NH_3) molecules were raised to an excited vibrational state and then fed into a resonant cavity where, as in a laser, stimulated emission produced a cascade of photons of identical wavelength, here 1.25 cm in the microwave part of the spectrum. "Atomic clocks" of great accuracy are based on this concept, and solid-state maser amplifiers are used in such applications as radioastronomy.

In 1958 Townes and Arthur Schawlow attracted much attention with a paper showing that a similar scheme ought to be possible at optical wavelengths. Slightly earlier Gordon Gould, then a graduate student at Columbia, had come to the same conclusion, but did not publish his calculations at once since that would prevent securing a patent. Gould tried to develop the laser—his term—in private industry, but the Defense Department classified as secret the project (and his original notebooks) and denied him clearance to work on it. Finally, twenty years later, Gould succeeded in establishing his priority and received two patents on the laser, and still later, a third. The first working laser was built by Theodore Maiman at Hughes Research Laboratories in 1960. In 1964 Townes, along with two Russian laser pioneers, Aleksander Prokhorov and Nikolai Basov, was awarded a Nobel Prize. In 1981 Schawlow shared a Nobel Prize for precision spectroscopy using lasers.

Soon after its invention, the laser was spoken of as a "solution looking for a problem" because few applications were then known for it. Today, of course, lasers are widely employed for a variety of purposes.

state E_1 has the same likelihood of causing the emission of another photon of energy $h\nu$ as its likelihood of being absorbed if it is incident on an atom in the lower state E_0.

Stimulated emission involves no novel concepts. An analogy is a harmonic oscillator, for instance a pendulum, which has a sinusoidal force applied to it whose period is the same as its natural period of vibration. If the applied force is exactly in phase with the pendulum swings, the amplitude of the swings increases. This corresponds to stimulated absorption. However, if the applied force is 180° out of phase with the pendulum swings, the amplitude of the swings *decreases*. This corresponds to stimulated emission.

A **three-level laser,** the simplest kind, uses an assembly of atoms (or molecules) that have a metastable state $h\nu$ in energy above the ground state and a still higher excited state that decays to the metastable state (Fig. 4.26). What we want is more atoms in the metastable state than in the ground state. If we can arrange this and then shine light of frequency ν on the assembly, there will be more stimulated emissions from atoms in the metastable state than stimulated absorptions by atoms in the ground state. The result will be an amplification of the original light. This is the concept that underlies the operation of the laser.

The term **population inversion** describes an assembly of atoms in which the majority are in energy levels above the ground state; normally the ground state is occupied to the greatest extent.

A number of ways exist to produce a population inversion. One of them, called **optical pumping,** is illustrated in Fig. 4.27. Here an external light source is used some of whose photons have the right frequency to raise ground-state atoms to the excited state that decays spontaneously to the desired metastable state.

Why are three levels needed? Suppose there are only two levels, a metastable state $h\nu$ above the ground state. The more photons of frequency ν we pump into the assembly

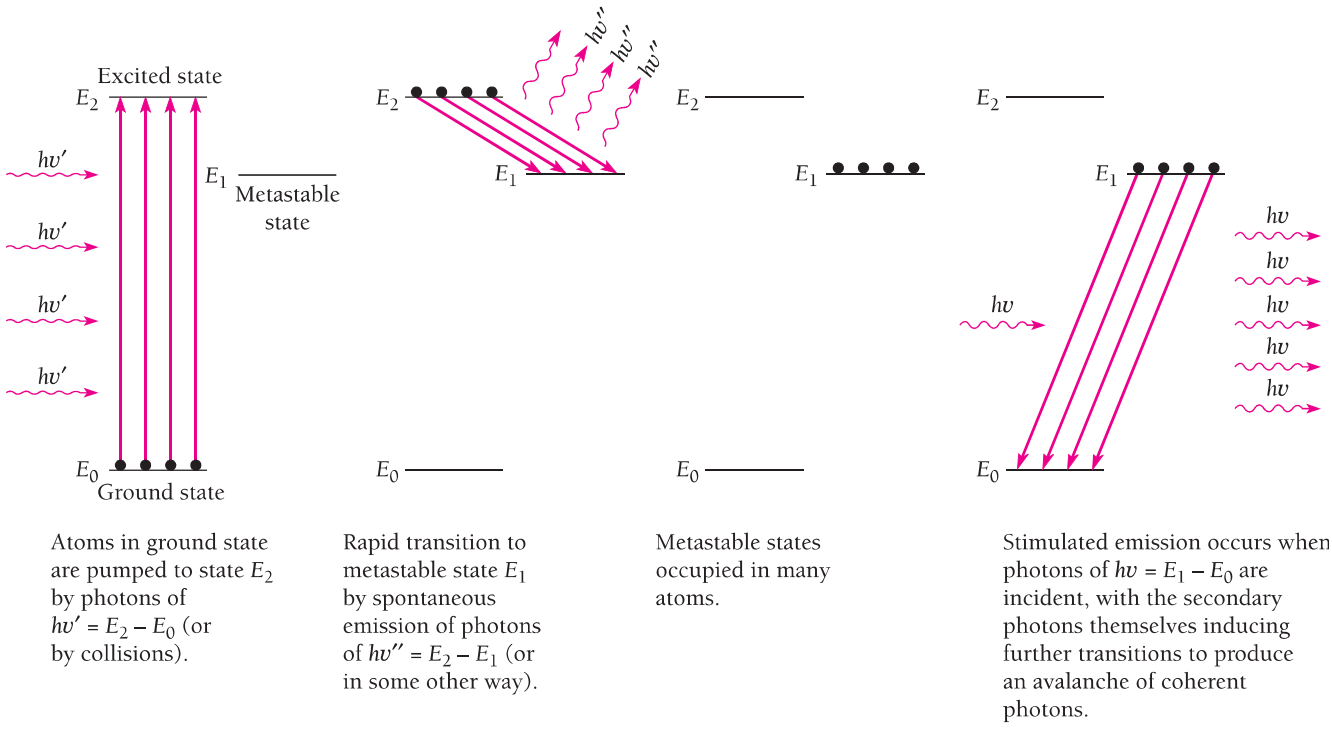


Figure 4.26 The principle of the laser.

of atoms, the more upward transitions there will be from the ground state to the metastable state. However, at the same time the pumping will stimulate downward transitions from the metastable state to the ground state. When half the atoms are in each state, the rate of stimulated emissions will equal the rate of stimulated absorptions, so the assembly cannot ever have more than half its atoms in the metastable state. In this situation laser amplification cannot occur. A population inversion is only possible when the stimulated absorptions are to a higher energy level than the metastable one from which the stimulated emission takes place, which prevents the pumping from depopulating the metastable state.

In a three-level laser, more than half the atoms must be in the metastable state for stimulated induced emission to predominate. This is not the case for a **four-level laser.**

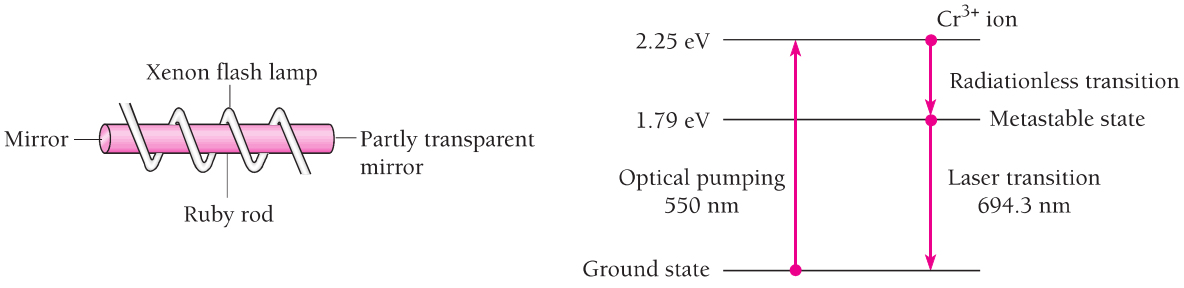


Figure 4.27 The ruby laser. In order for stimulated emission to exceed stimulated absorption, more than half the Cr^{3+} ions in the ruby rod must be in the metastable state. This laser produces a pulse of red light after each flash of the lamp.

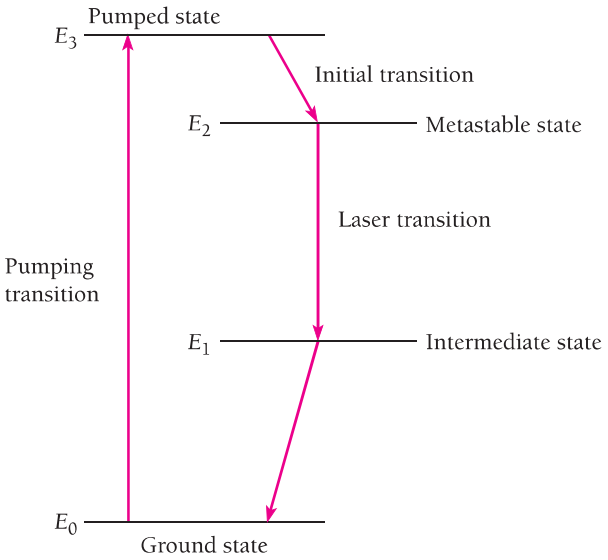
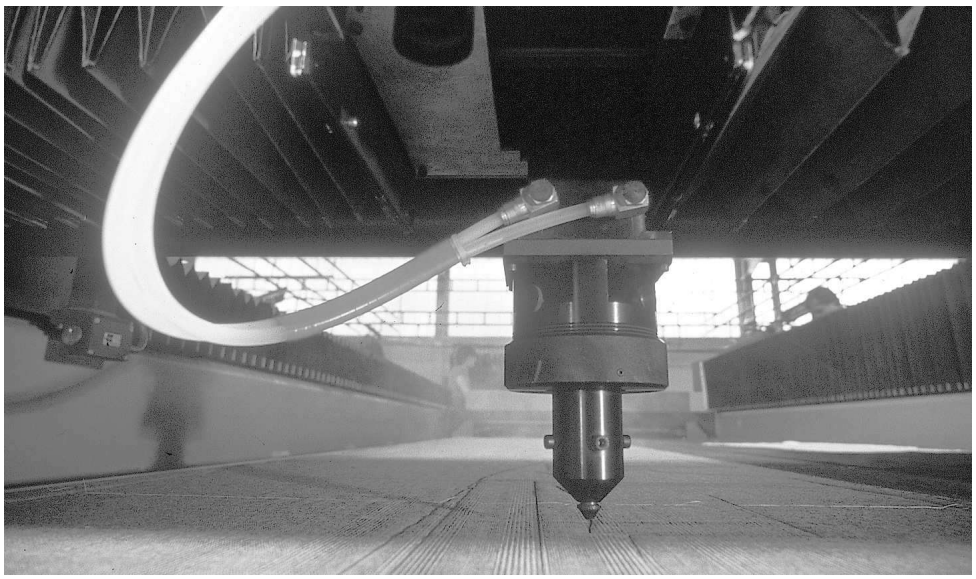


Figure 4.28 A four-level laser.

As in Fig. 4.28, the laser transition from the metastable state ends at an unstable intermediate state rather than at the ground state. Because the intermediate state decays rapidly to the ground state, very few atoms are in the intermediate state. Hence even a modest amount of pumping is enough to populate the metastable state to a greater extent than the intermediate state, as required for laser amplification.

Practical Lasers

The first successful laser, the **ruby laser**, is based on the three energy levels in the chromium ion Cr^{3+} shown in Fig. 4.27. A ruby is a crystal of aluminum oxide, Al_2O_3,



A robot arm carries a laser for cutting fabric in a clothing factory.

in which some of the Al^{3+} ions are replaced by Cr^{3+} ions, which are responsible for the red color. A Cr^{3+} ion has a metastable level whose lifetime is about 0.003 s. In the ruby laser, a xenon flash lamp excites the Cr^{3+} ions to a level of higher energy from which they fall to the metastable level by losing energy to other ions in the crystal. Photons from the spontaneous decay of some Cr^{3+} ions are reflected back and forth between the mirrored ends of the ruby rod, stimulating other excited Cr^{3+} ions to radiate. After a few microseconds the result is a large pulse of monochromatic, coherent red light from the partly transparent end of the rod.

The rod's length is made precisely an integral number of half-wavelengths long, so the radiation trapped in it forms an optical standing wave. Since the stimulated emissions are induced by the standing wave, their waves are all in step with it.

The common **helium-neon gas laser** achieves a population inversion in a different way. A mixture of about 10 parts of helium and 1 part of neon at a low pressure (~1 torr) is placed in a glass tube that has parallel mirrors, one of them partly transparent, at both ends. The spacing of the mirrors is again (as in all lasers) equal to an integral number of half-wavelengths of the laser light. An electric discharge is produced in the gas by means of electrodes outside the tube connected to a source of high-frequency alternating current, and collisions with electrons from the discharge excite He and Ne atoms to metastable states respectively 20.61 and 20.66 eV above their ground states (Fig. 4.29). Some of the excited He atoms transfer their energy to ground-state Ne atoms in collisions, with the 0.05 eV of additional energy being provided by the kinetic energy of the atoms. The purpose of the He atoms is thus to help achieve a population inversion in the Ne atoms.

The laser transition in Ne is from the metastable state at 20.66 eV to an excited state at 18.70 eV, with the emission of a 632.8-nm photon. Then another photon is spontaneously emitted in a transition to a lower metastable state; this transition yields only incoherent light. The remaining excitation energy is lost in collisions with the tube walls. Because the electron impacts that excite the He and Ne atoms occur all the time, unlike the pulsed excitation from the xenon flash lamp in a ruby laser, a He-Ne laser operates continuously. This is the laser whose narrow red beam is used in supermarkets to read bar codes. In a He-Ne laser, only a tiny

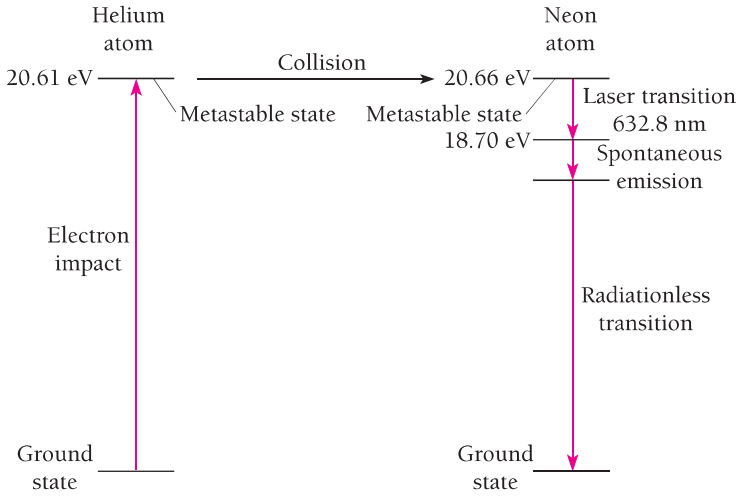


Figure 4.29 The helium-neon laser. In a four-level laser such as this, continuous operation is possible. Helium-neon lasers are commonly used to read bar codes.

Chirped Pulse Amplification

The most powerful lasers are pulsed, which produces phenomenal outputs for very short periods. The petawatt (10^{15} W) threshold was crossed in 1996 with pulses less than a trillionth of a second long—not all that much energy per pulse, but at a rate of delivery over 1000 times that of the entire electrical grid of the United States. An ingenious method called chirped pulse amplification made this possible without the laser apparatus itself being destroyed in the process. What was done was to start with a low-power laser pulse that was quite short, only 0.1 picosecond (10^{-13} s). Because the pulse was short, it consisted of a large span of wavelengths, as discussed in Sec. 3.7 (see Figs. 3.13 and 3.14). A diffraction grating then spread out the light into different paths according to wavelength, which stretched the pulse to 3 nanoseconds (3×10^{-9} s), 30,000 times longer. The result was to decrease the peak power so that laser amplifiers could boost the energy of each beam. Finally the amplified beams, each of slightly different wavelength, were recombined by another grating to produce a pulse less than 0.5 picoseconds long whose power was 1.3 petawatts.

fraction (one in millions) of the atoms present participates in the laser process at any moment.

Many other types of laser have been devised. A number of them employ molecules rather than atoms. **Chemical lasers** are based on the production by chemical reactions of molecules in metastable excited states. Such lasers are efficient and can be very powerful: one chemical laser, in which hydrogen and fluorine combine to form hydrogen fluoride, has generated an infrared beam of over 2 MW. **Dye lasers** use dye molecules whose energy levels are so close together that they can "lase" over a virtually continuous range of wavelengths (see Sec. 8.7). A dye laser can be tuned to any desired wavelength in its range. **Nd:YAG lasers,** which use the glassy solid yttrium aluminum garnet with neodymium as an impurity, are helpful in surgery because they seal small blood vessels while cutting through tissue by vaporizing water in the path of their beams. Powerful **carbon dioxide gas lasers** with outputs up to many kilowatts are used industrially for the precise cutting of almost any material, including steel, and for welding.

Tiny **semiconductor lasers** by the million process and transmit information today. (How such lasers work is described in Chap. 10.) In a compact disk player, a semiconductor laser beam is focused to a spot a micrometer (10^{-6} m) across to read data coded as pits that appear as dark spots on a reflective disk 12 cm in diameter. A compact disk can store over 600 megabytes of digital data, about 1000 times as much as the floppy disks used in personal computers. If the stored data is digitized music, the playing time can be over an hour.

Semiconductor lasers are ideal for fiber-optic transmission lines in which the electric signals that would normally be sent along copper wires are first converted into a series of pulses according to a standard code. Lasers then turn the pulses into flashes of infrared light that travel along thin (5–50 μm diameter) glass fibers and at the other end are changed back into electric signals. Over a million telephone conversations can be carried by a single fiber; by contrast, no more than 32 conversations can be carried at the same time by a pair of wires. Telephone fiber-optic systems today link many cities and exchanges within cities everywhere, and fiber-optic cables span the world's seas and oceans.