30 Light Emission

Photo openers show three physics-educator friends, George Curtis, University of Hawaii at Hilo, Neil de Grasse Tyson, Hayden Planetarium in New York, and Evan Jones, Sierra College in California. Evan is a big advocate of LEDs for home and industrial lighting, and contributed to their treatment in this chapter. The laser show is by friends at Lund University in Sweden.

The profile is Neil de Grasse Tyson, who wonderfully brings good science to the public.

This chapter begins by treating the Bohr model of the atom with simplified energy levels to explain light emission, whether by a gas discharge tube, incandescent or fluorescent lamp, phosphorescent mineral, or a laser.

Excitation between the various simplified energy levels of the Bohr model of the atom is used in this chapter to explain the emission of light. Note that this is quite a different model of light emission compared to the oscillator model we introduced in Chapters 26 and 27. Subtle oscillations of the electron shells underscore light being reflected or transmitted. Excitation is not subtle, and is a different process—electrons make transitions from one electron shell to another. There are two different models of behavior here. One suits the processes of reflection and transmission of light, and the other suits the way light is emitted from a light source to begin with. Neither of the two atomic models presented is intended to convey a picture of what atoms are "really like," but instead are simplified representations that are useful for conceptualizing how atoms behave. You may comment on the nature of a model in physics here; namely that a model is not "right" or "wrong," but "useful" or "nonuseful." No scientific models are carved in stone.

Arbor Scientific has a Spectrum Analysis kit composed of a power supply and gas tube holder, with seven gas spectrum tubes about 26 cm long. Power supply (P2-9500), analysis set (P2-9501), and discharge tubes (P2-9500 09-15). Arbor also supplies the RSpec-Explorer (P2-9505) for studying spectra. Check out their RSpec demo video on their internet site ArborSci.com. For low-cost hand-held classroom spectrum viewers check out *Elements, Mixtures and Molecules Spectrum Viewer* at www.hermograph.com/spectrumviewers.

Students are quite familiar with glow-in-the-dark strips used as head gear or necklaces, popular in dance spots. Or glow-in-the-dark key rings, activated by light. For the record, these phosphorescent materials contain calcium sulfide, activated by bismuth, with additional traces of copper, silver, or lead. These materials are harmless, and very different from the old zinc sulfide materials impregnated with trace amounts of radium to supply alpha particles for stimulation.

The treatment of lasers in this book is very elementary. Lasers today, though operating on the principles treated in the text, do much more than the applications cited in the book. Amplification techniques now find lasers cutting through materials better than was done by torches and saws in the past. The applications of lasers, from dental and medical tools to military weapons, seems endless.

This chapter is a necessary background for the following two chapters. If you are not going to lecture on the quantum physics of Chapters 31 and 32, then this chapter fits very well when sandwiched between Chapters 26 and 27. Then the nature of light (Chapter 26) is followed by how light is emitted. Color (Chapter 27) picks up the sequence. Another advantage is an earlier treatment of the laser, which is likely part of your demo equipment for Chapter 28.

If you don't provide small diffraction gratings to your class, consider using a large demonstration grating for showing spectral lines of gas discharge tubes. Holographic diffraction grating film sheets 6" by 12" are available from Edmund Scientific Company. Sandwich a sheet between a couple of pieces of glass and you've got a first-rate demonstration grating. Arbor Scientific has bright holographic inexpensive gratings P33-0980.

Next-Time Questions:
- Absorption Spectra

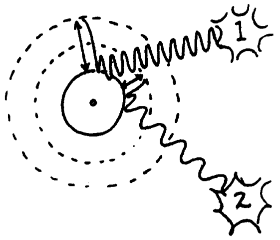
Hewitt-Drew-It! Screencasts: •*Atomic Excitation* •*Atomic Spectra* •*Emission of Light* •*Lamps* •*Laser Light*

SUGGESTED LECTURE PRESENTATION

Excitation

Begin by holding a book above the lecture table and dropping it. Then hold it higher and drop it again. State that the potential energy you supplied to the book was converted to kinetic energy and then to sound energy. State that the higher you boost the book before dropping it, the louder the sound. State that a similar thing happens in the case of atoms. Parallel your book example and consider the case of an electron being boosted to a higher orbit in an atom. Just as a screen door that is pushed open against a spring snaps back and produces sound, the displaced electron snaps back to its ground state and produces light. It emits a throbbing spark of light we call a *photon*. Show that when it is boosted to higher levels, it emits a higher frequency photon upon de-excitation. Introduce the relationship $E \sim f$ for the resulting photons. Then to $E = hf$. Discuss the variety of energy-level jumps for a simple atom.

> CHECK QUESTION: Two photons are emitted as a result of the transitions shown on the board. If one photon is red and the other blue, which is which? [Be sure to draw the shorter wavelength for the greater transition, from the second level to ground state, and the longer wavelength for the smaller transition from level one to ground.]



Emission Spectra

> DEMONSTRATION: Show the spectra of gas discharge tubes. Either use a large diffraction grating that you hold in front of the tube, or pass small gratings among the class, so the spectral lines can be observed.

Cite examples of the uses of spectrometers—how very minute quantities of materials are needed for chemical analysis—how tiny samples of ores are sparked in carbon arcs and the light directed through prisms or diffraction gratings to yield precise chemical composition—note their use in fields as diverse as chemistry and criminology.

Absorption Spectra

Distinguish between emission and absorption spectra. Cite that a century ago, the chemical composition of the stars were thought to be forever beyond the knowledge of humankind—and now today we know as much about their composition as we do the Earth's. (Figure 30.9, by the way, is exaggerated in that it shows an absorption line matching every emission line rather than the actual principle emission lines.)

Incandescence

Emphasize the discreteness of the lines from atoms in the gaseous state. Then lead into the idea of excitation in an incandescent lamp, where the atoms are in the solid state. State how in the crowded condition the energy levels interact with one another and produce a distribution of frequencies rather than discrete frequencies that characterize the gaseous state. Sketch a bell-shaped curve and label the peak of the curve as the frequency proportional to the absolute temperature of the source. Be sure to clear up any misconceptions that $f \sim T$ means that the frequency of light is proportional to the temperature of light (light can impart temperature, but doesn't have a temperature of its own. T is the temperature of the source).

Lamps

Compare the prospects of lighting via CFLs and LEDs, both in the near future and further down the road. CFLs have cause a lot of "green" excitement and the public has taken to them. The mercury in them, however, is of some concern. The development of LED bulbs has quickly progressed to bulbs that can be screwed into sockets as incandescent bulbs have always been.

Incandescence

> CHECK QUESTION: Hold up an obviously broken light bulb and ask if it is presently emitting electromagnetic energy. [Sure is, as is everything—its temperature is simply too low for the corresponding frequency to trigger the light receptors of our retinas.]

Get into the idea of the infrared part of the spectrum. Show in a sequence of radiation curves on the board how an increase in temperature brings the curve "sloshing over" into the lower frequency portion of the visible spectrum—hence the red hotness of a hot poker. Show how an increase in temperature brings the curve into the visible spectrum producing white light. Show why a hot poker does not become green hot, and how sharp the curve would have to be to produce green without sloshing into the other frequencies which result in white light. If you have discussed the treatment of overlapping distribution curves (back in Chapter 17 page 176 in this manual), you might make reference to this and quip that only narrow-minded people would expect that a hot poker could glow green-hot.

Fluorescence

Show some fluorescent materials in the room light. Explain the role of photons in the room lighting that excite the molecules in the material that produces not only reflection, but emission—hence the term *day-glow* that sometimes describes fluorescent paints.

> CHECK QUESTION: Would higher-frequency light produce more glowing, and why? [Yep, more energy per photon!]
>
> DEMONSTRATION: Show fluorescent materials illuminated with a black light. Discuss the observations with the black light still on, and then extinguish the light so the room is totally dark. Ask what is happening (have some phosphorescent materials in your display).

Phosphorescence

> DEMONSTRATION: Call attention to the glowing of your phosphorescent materials while the lights are off. Compare this to swinging a screen door open when you walk out of the house and hearing it slam about a minute or so later. The screen door and the excited electrons become "stuck" for a while.

Cite common examples—watch and clock faces, light switches, even party jewelry. Acknowledge watch faces activated by radioactive minerals. Discuss also the phenomena of bioluminescence. It turns out that even the deepest depths of the ocean there is a background of bioluminescence that is the subject of much study. Photo detectors at great depths sense light when objects suddenly move in water.

Lasers

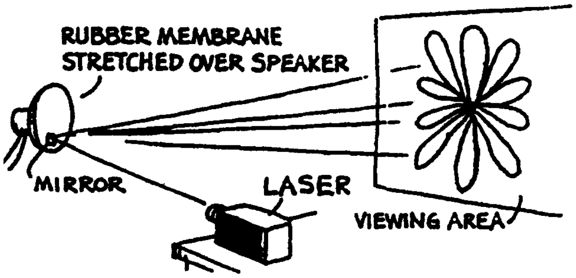
William J. Beaty reminds us that laser light travels in straight lines like any other light, and to clear up the possible misconception that laser light travels in wiggly paths as suggested by Figures 30.19 through 30.21. The common sine configuration represents the changing intensity of the electric field of light—a graph of intensity versus time or distance.

Another misconception is that laser light is always parallel light. While it's true that many lasers are designed to emit thin nonspreading beams, it is wrong to suppose this is a characteristic of laser light. Those in your supermarket check-out stand, for example, fan out. A common HeNe classroom laser contains a converging lens, a "parallelizing lens," to correct for the spreading that exists within the beam. Without it, the beam would spread. So although laser light can be *made* extremely parallel, it is not a characteristic of laser light in general.

Laser light is not necessarily brighter than other types of light. Your classroom laser puts out much less light than a flashlight bulb. A primary difference is that a laser provides a point source while an ordinary bulb is an extended source. Even weak light from a laser is concentrated by the lens of your eye to a blazing pinpoint on your retina. This is why even a weak laser is dangerous. Concentration is the factor, like the difference between looking at a frosted bulb and an unfrosted bulb of the same wattage. If a laser beam were of the same wattage of an ordinary house lamp, the beam would burn whatever it touched. A laser can concentrate light.

High-energy lasers are something else. The details of the simple helium-neon laser shown in Figure 30.22 in the text, nicely serves as a foundation for higher-energy lasers that followed. Medical applications are commonly known. Lasers are also used in cutting steel and other metals, in welding, brazing, bending materials, engraving or marking, cleaning, and as weapons, where they successfully destroy missiles. Whereas Figure 30.22 illustrates the rudiments of a laser, acknowledge the advancement of laser technology.

> DEMONSTRATION: Give a laser show. Sprinkle chalk dust or smoke in the beam, show diffraction through a thin slit and so forth. An unforgettable presentation is that of Think and Do 38 on page 388 in Chapter 20 wherein a laser beam is projected on a mirror fastened to a rubber membrane that is stretched over a radio loudspeaker. Do this to music and fill the darkened room with a display of dancing lissajous patterns on the walls.



Lasers

When Conceptual Physics made its advent back in 1971, lasers were the new physics application looking for problems. A first application was visible "chalk lines" for surveying; medical applications were still on the drawing boards. The current question is what devices have no lasers!

Answers and Solutions for Chapter 30

Reading Check Questions

1. At these high frequencies, ultraviolet light is emitted.
2. Discrete means unique, that other states don't overlap it.
3. Electrons in the outer electron shells have greater potential energy.
4. The atom de-excites and emits light.
5. They are equal.
6. The relationship is $E = hf$.
7. Blue light has both a greater frequency and energy per photon.
8. Atoms can be excited without limit.
9. The colors indicate the various atoms undergoing excitation.
10. A mercury-vapor lamp puts a greater part of its energy into light than an incandescent bulb lamp does.
11. A spectroscope is a device that measures frequencies of light in a beam of light.
12. In a gaseous phase, emitted light is from well-defined energy levels of outer electron shells in atoms. In the solid phase, smearing of light occurs due to mutual interactions among neighboring atoms in close contact.
13. The relationship is $f \sim T$ (covered also in Chapter 16.)
14. Where many lines appear in an emission spectrum, empty spaces appear in an absorption spectrum.
15. Fraunhofer lines are spectral absorption lines in the solar spectrum.
16. The Doppler effect causes a stretching of waves for receding stars and compressed waves for approaching stars.
17. There is more energy per photon in UV.
18. Phosphorescence is fluorescence with a time delay between excitation and de-excitation.
19. A metastable state is a prolonged state of excitation.
20. Air contains oxygen, which oxidizes the filament. Argon does not.
21. Primary excitation is by electron impact; secondary is by photon impact.
22. A CFL is longer lasting than an incandescent bulb.
23. A LED is even longer lasting than an incandescent bulb.
24. Monochromatic light is of photons having a single frequency;
25. Coherent light is of photons having a single frequency that are in phase with one another.
26. The photons from a laser are coherent.

Think and Do

27. Grandma has seen this progression of lamps!
28. Line and band spectra are nicely shown.

Think and Solve

29. (a) The B-to-A transition has twice the energy and twice the frequency of the C-to-B transition. Therefore it will have half the wavelength, or 300 nm. Reasoning: From $c = \lambda f$, $\lambda = c/f$. Wavelength is inversely proportional to frequency. Twice the frequency means half the wavelength.
    (b) The C-to-A transition has three times the energy and three times the frequency of the C-to-B transition. Therefore it will have one-third the wavelength, or 200 nm.

Think and Explain

30. In accord with $E = hf$, a gamma ray photon greater energy because it has a higher frequency.

31. The energy levels are different for the atoms and molecules of different materials, hence the different frequencies of radiation emitted when excitation occurs. Different colors correspond to different energy changes and frequencies.
32. Higher-frequency higher-energy blue light corresponds to a greater change of energy in the atom.

33. More energy is associated with each photon of ultraviolet light than with a photon of visible light. The higher-energy ultraviolet photon can cause sunburn-producing chemical changes in the skin that a visible photon cannot do.

34. Doubling the wavelength of light halves its frequency. Light of half frequency has half the energy per photon. Think in terms of the equation $c = f\lambda$. Since the speed of light c is constant, λ is inversely proportional to f.

35. A neon tube doesn’t “run out” of atoms to be excited because its atoms are re-excited over and over, without the need for “new” atoms.

36. Spectral lines are images of the slit in a spectroscope. If the slit were crescent shaped, the “lines” would also be crescent shaped.

37. Spectral “lines” would be round dots. Very nearby lines would be easier to discern than dots that might overlap. Also, if the diameter of the hole were made as small as the width of the slit, insufficient light would get through. Thus the slit images are superior.

38. Neon light is not monochromatic, so diffracted light from a neon tube produces a band of colors, most of which are various shades of red. Light from a helium-neon laser is of one color—monochromatic—showing only one of the spectral lines of neon.

39. When a spectrum of the Sun is compared with the spectrum of the element iron, the iron lines overlap and perfectly match certain Fraunhofer lines. This is evidence for the presence of iron in the Sun.

40. By comparing the absorption spectra of various nonsolar sources through Earth’s atmosphere, the lines due to Earth’s atmosphere can be established. Then when viewing solar spectra, extra lines and extra line intensities can be attributed to the atmosphere of the Sun.

41. Spectral-line patterns that appear in starlight also appear in the spectra of elements on Earth. Since the spectra of light from distant stars matches the spectra of elements on Earth, we conclude that we and the observable universe have the same “fingerprints” and are made of the same stuff.

42. The moving star will show a Doppler shift. Since the star is receding, it will be a red shift (to lower frequency and longer wavelength).

43. The stars are incandescent sources, where peak radiation frequency is proportional to stellar temperature. But light from gas discharge tubes is not a function of gas temperatures; it depends on the states of excitation in the gas. These states are not dependent on the temperature of the gas, and can occur whether the gas is hot or cool.

44. In accord with $E \sim f$, the higher frequency ultraviolet photon has more energy than a photon in the visible part of the spectrum, which in turn has more energy than a photon in the infrared part of the spectrum.

45. Atomic excitation occurs in solids, liquids, and gases. Because atoms in a solid are close packed, radiation from them (and liquids) is smeared into a broad distribution to produce a continuous spectrum, whereas radiation from widely-spaced atoms in a gas is in separate bunches that produce discrete “lines” when diffracted by a grating.

46. Atoms excited in high-pressure gas interfere with one another in a way similar to the way closely-packed atoms in a solid do, resulting in overlapping waves and smearing of light.

47. When tungsten atoms are close-packed in a solid, the otherwise well-defined energy levels of outer electron shells are smeared by mutual interactions among neighboring atoms. The result is an energy band composed of myriad separate levels very close together. Because there are about as many of these separate levels as there are atoms in the crystalline structure, the band cannot be distinguished from a continuous spread of energies.

48. The many spectral lines from the element hydrogen are the result of the many energy states the single electron can occupy when excited.

49. The light that is absorbed is part of a beam. The light that is indeed re-emitted goes in all directions, with very little along the direction of the illuminating beam. Hence those regions of the spectrum are dark.

50. The “missing” energy may appear as light of other colors or as invisible infrared light. If the atoms are closely packed, as in a solid, some of the “missing” energy may appear as heat. In that case, the illuminated substance warms.

51. (a) An “absorption spectrum” is observed, with certain dark lines in a background of continuous light. (b) The “emission spectrum” will contain a few bright lines, most of which will match the lines in the absorption spectrum.

52. Fluorescence is the process in which high-frequency (high energy) ultraviolet radiation converts to low-frequency (lower energy) visible radiation with some energy left over, perhaps appearing as heat. If your friend is suggesting that low-energy infrared radiation can be converted to higher-energy visible light, that is clearly a violation of the conservation of energy—a no-no! Now if your friend is suggesting that infrared radiation can cause the fluorescence of still lower-frequency infrared radiation, which is not seen as light, then your friend’s reasoning is well founded.

53. As in the previous exercise, fluorescence requires that the photons of light initiating the process have more energy than the photons of light emitted. If visible light is to be emitted, then lower-energy infrared photons cannot initiate the process.

54. Fabrics and other fluorescent materials produce bright colors in sunlight because they both reflect visible light and transform some of the Sun’s ultraviolet light into visible light. They literally glow when exposed to the combined visible and ultraviolet light of the Sun.

55. The different colors emitted by fluorescent minerals correspond to different molecules with different sets of energy states. Such minerals can therefore be visually distinguished.

56. Just as a time delay occurs with the opening and closing of a spring door, a similar time delay occurs between excitation and de-excitation in a phosphorescent material.

57. Illumination by the lower-frequency light doesn’t have sufficiently energetic photons to ionize the atoms in the material, but has photons of enough energy to excite the atoms. In contrast, illumination by ultraviolet light does have sufficient energy for ejecting the electrons, leaving atoms in the material ionized. Imparting different energies produces different results.

58. A CFL puts out less heat and more light. For the same wattage, the CFL would put out far less heat than an incandescent bulb. The chickens would be well lit, but cold.

59. LEDs have a longer life than CFLs and incandescent lamps, which lowers maintenance costs.

60. Red + green = yellow.

61. LEDs will likely predominate because they have longer lives and are mercury free.

62. The acronym says it: *m*icrowave *a*mplification by *s*timulated *e*mission of *r*adiation.

63. The photons from the photoflash tube must have at least as much energy as the photons they are intended to produce in the laser. Red photons have less energy than green photons, so wouldn’t be energetic enough to stimulate the emission of green photons. Energetic green photons can produce less-energetic red photons, but not the other way around.

64. Photons in the laser beam are coherent and move in the same direction; photons in light emitted by an incandescent lamp are incoherent and move in all directions.

65. If it weren’t relatively long-lived, there wouldn’t be enough accumulation of atoms in this excited state to produce the “population inversion” that is necessary for laser action.

66. When an excited helium atom collides with a neon atom in its ground state, energy given by the helium to the neon must match that of the metastable state of neon. If the match in energies isn’t close, boosting neon to a metastable state wouldn’t occur.

67. Your friend’s assertion violates the law of energy conservation. A laser or any device cannot put out more energy than is put into it. Power, on the other hand, is another story, as is treated in the following exercise.

68. No device can put out more energy than is put in. But if a device takes in energy at a certain rate and emits it in a shorter time interval, then it is capable of putting out higher bursts of power than it takes in.

69. *f* bar is the peak frequency of incandescent radiation—that is, the frequency at which the radiation is most intense. *T* is the Kelvin temperature of the emitter.

70. A lamp filament or any object emits radiation at all temperatures greater than absolute zero. The peak frequency of this radiation is proportional to the absolute temperature of the object. At room temperature this frequency is in the far infrared part of the spectrum and therefore can't normally be seen. When the temperature of the filament is increased, more of the radiation moves into the visible part of the spectrum and we have light.

71. Both radiate energy, but since temperatures are different, the hotter Sun emits higher frequencies of light than does Earth, and of much greater intensity.

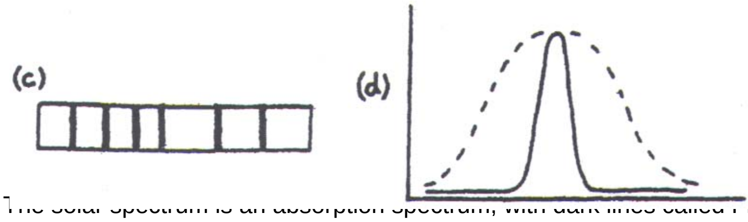
72. We can't see objects at room temperature in the dark simply because our eyes are not sensitive to the radiation the objects emit. If the temperature of the objects is increased sufficiently, then the radiation they emit is visible to us.

73. All bodies not only radiate energy, they absorb it. If radiation and absorption are at equal rates, no change in temperature occurs.

74. The metal is glowing at all temperatures, whether we can see the glow or not. As its temperature is increased, the glow reaches the visible part of the spectrum and is visible to human eyes—red. So the heated metal passes from infra-red (which we can't see) to visible red. It is red hot.

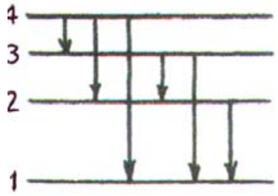
75. Star's relative temperatures—lowest for reddish; medium for whitish; and hottest for bluish.

76.



77. The solar spectrum is an absorption spectrum, with dark lines called Fraunhofer lines in honor of Joseph von Fraunhofer who d

78. Six transitions are possible, as shown. The highest-frequency transition is from quantum level 4 to level 1. The lowest-frequency transition is from quantum level 4 to level 3.



79. Energy is conserved, and frequency is proportional to a photon's energy. So the sum of the two frequencies is equal to the frequency of light emitted in the transition from quantum level 4 to the ground state, quantum level 1.

80. Yes, there is a relationship among the wavelengths, but it is not as simple as the relationship among frequencies. Because energies are additive, so are the frequencies. But since wavelength is inversely proportional to frequency, it is the inverses of the wavelengths that are additive. Thus,

$$\frac{1}{\lambda(4 \to 3)} + \frac{1}{\lambda(3 \to 1)} = \frac{1}{\lambda(4 \to 1)}$$

81. Only three, one from 4 to ground, one from 3 to ground, and one from 2 to ground. The transition from 4 to 3 would involve the same difference in energy and be indistinguishable from the transition from 3 to 2, or from 2 to ground.

Likewise, the transition from 4 to 2 would have the same change in energy as a transition from 3 to ground.

Think and Discuss

82. Its energy is very concentrated in comparison with that of a lamp.

83. Continued heating of a red-hot piece of metal will increase the peak frequency into the middle of the visible spectrum, and it will glow white hot (because all the visible frequencies are present). See the radiation curve in Figure 30.7. Continued heating will increase the peak frequency into the ultraviolet part of the spectrum, with part of it remaining in the blue and violet. So yes, we can heat a metal until it becomes blue-hot. (The reason you haven’t seen blue-hot metal is because metal will vaporize before it can glow blue hot. Many stars, however, are blue-hot.)

84. The radiation curve of an incandescent source (Figure 30.7) is wide, spanning a broad band of frequencies. A star that is red hot has its peak frequency in the infrared, with only some emitted light with frequencies in the lower part of the visible spectrum. If the star is hotter, emitted light may have frequencies spanning the visible spectrum, in which case the star appears white.

85. A star with peak frequency in the ultraviolet emits enough light in the higher-frequency part of the visible spectrum to appear “violet-hot.” As in the previous exercise, if it were cooler, all frequencies would be more balanced in intensity that would make it look whiter.

86. An incandescent source that peaks in the green part of the visible spectrum will also emit reds and blues, which would overlap to appear white. Our Sun is a good example. For green light and only green light to be emitted, we would have some other kind of a source, such as a laser, not an incandescent source. So “green-hot” stars are white.