Chapter 4

LIGHT--THE PARTICLE--
and
A LITTLE BIT OF STELLAR EVOLUTION

A.) The Photoelectric Effect:

1.) We have talked about light as a wave. It turns out that in certain instances, it can also act like a particle. This chapter is mostly devoted to those situations.

2.) In 1905, Einstein published three papers.

a.) One was on molecular theory and Brownian motion in which he proved the existence of atoms.

b.) A second was on his Special Theory of Relativity.

c.) And a third was on the quantum theory of light. It was in this last paper that he explained what was called the *photoelectric effect*, and for which he received a Nobel Prize in 1921.

The *photoelectric effect* is what we are interested in here.

3.) Photoelectric Effect:

a.) Due to Young's experiment, scientists believed light was a wave until the early 1900's when a phenomenon called the *photoelectric effect* was observed.

b.) In the *photoelectric effect*, light directed at the right kind of metal is found to liberate electrons from the metal (this liberation is observed as a current). What is unusual about this is that there are very specific criteria required before the effect will show itself. Specifically:

i.) High frequency blue light liberates electrons immediately, no matter how intense the source. That is, just a tiny bit of blue light will do the trick.

ii.) Lower frequency red light liberates no electrons, no matter how intense the light (bright, bright red light does nothing).

iii.) There seems to be a cut-off frequency above which the effect works even at low intensity, and below which nothing happens, no matter how intense the light.

c.) None of this makes sense from a wave-theory perspective. That is, although it takes a minimum amount of energy to excite an atom to the point where it literally throws out an electron from its atomic structure, there is no reason why blue light should work while red light does not.

The rationale for this follows:

i.) The only difference between red-light electromagnetic radiation and blue light electromagnetic radiation is the wavelength of each (blue light is shorter wavelength, higher frequency, whereas red light is long wavelength, low frequency).

ii.) In both cases, the energy carried by the waves *is assumed to be spread out across each wave front.*

iii.) Even if a red light wave is somehow associated with *less energy* than a blue light wave, there should still be some relatively short period of time by which enough *low-energy red-light waves* have washed over the metal's atoms to transfer the energy required to start the effect. That doesn't happen.

d.) Einstein solved the dilemma by using an idea borrowed from Maxwell Planck.

i.) Planck suggested that the energy E wrapped up in the light of a particular frequency ν was *proportional to the frequency*. Mathematically speaking, he said:

$$E = h\nu,$$

where again, E is this energy quantity, ν is the frequency in question, and h is a proportionality constant called Planck's constant.

ii.) Einstein went one step further. He maintained that light could act like a wave in some cases but could also act like a BUNDLE OF ENERGY--a particle--in other cases. (As you have learned, particles of light are now called *photons*).

iii.) When acting like a *wave*, light's characterizing parameter is its *frequency*. When acting like a *particle*, light's characterizing parameter is its *energy* (the energy wrapped up in the particle). The link between the two characterizations is $E = h\nu$. (This should all be review at this point.)

e.) Using Einstein's theory, the photoelectric effect becomes understandable:

i.) Blue light has a higher frequency than does red light. That means a blue-light photon has more energy associated with it than does a red-light photon.

ii.) An atom must absorb a certain amount of energy before it can kick an electron out of its structure.

iii.) When red light is shone on a photoelectric metal, it is as though *particles of energy* (photons) are raining down on the metal. If it takes more energy to shake an electron free than is wrapped up in a single red-light photon, an atom absorbing a red-light photon will take the photon's energy into itself but will not as a consequence kick an electron out.

As the odds of two photons hitting a single atom in rapid succession are nil (i.e., rapid enough to provide the minimum energy for liberation), red-light does not precipitate the photoelectric effect.

iv.) When absorbed by an atom, a single blue-light photon *does* have enough energy to kick an electron loose. So when blue-light photons begin to rain down on a photosensitive metal, electrons are liberated immediately, no matter how dim the blue light.

f.) It all makes perfect sense if you understand how atoms and light work.

4.) After Einstein's explanation of the photoelectric effect, scientists had to accept what is now called *the dual nature of light*. Light can act like a particle sometimes doing things that only particles can do, and light can act like a wave sometimes doing things that only waves can do. It is just the way light is build.

B.) The Atom and the Production of Light:

1.) An interesting question arises, "What is the mechanism that produces light in today's world." After all, photons were created during the big bang, but that situation is long gone. When you flip the light switch in your room, you get light immediately. How so?

2.) It turns out that the production of light is intimately related to the way atoms are built.

3.) Let's assume some things about atomic structure. Specifically:

a.) Assume that electrons move around the nucleus in circular paths (they don't, but for now, assume they do).

b.) Assume that when an electron is in an orbit whose distance is r_o units away from the atom's center, it is in its lowest energy state (this is called the *ground level*). Also assume that when in this state, the electron's potential energy content is E_o.

c.) Assume that the orbitals and energy states are "quantized" in the sense that electrons can only reside in certain specific ones *and no others.*

d.) Assume that the farther out an electron's orbits, the greater the electron's potential energy content.

e.) Having defined the radius and energy of the ground state to be r_o and E_o respectively, assume that the radius of the electron when in what is called the *first excited state* is r_1, and that its energy in that state is E_1. Follow similar reasoning for the second excited state, the third excited state, etc.

Note: I realize that this is mildly confusing, but some books identify the ground state as E_1 and the first excited state as E_2. I'm obviously not doing it this way, but you should be aware of the discrepancy should you ever study the subject from another text.

4.) Having made all of these assumptions, let's take the simplest atom possible--hydrogen--and see what kinds of things we might expect of it. We will start by assuming that its one electron spends most of its time in the atom's least energetic state, which is to say *the ground level*.

a.) Let's try to kick the electron out of the atom. We can do that by having the atom absorb a small jolt of energy. Assume we try this and find that the electron doesn't release. Being still bound, we evidently haven't added enough energy to do the job.

b) Systems in nature tend to migrate toward *least energy states*. Electrons are no different. If the previous blast of energy has pushed the electron into one of its excited states, it will take only a short period of time before it transitions back down into its unagitated ground level. We will wait a short time, then give the atom a little larger jolt of energy.

Let's assume we do so and the electron still doesn't get kicked out of the atom.

c.) We continue to do this until we find that minimum energy that will eject our electron. In doing so, we have determined the *binding energy* of an electron residing in a hydrogen's ground level.

d.) If we did this for real, we would find that the magnitude of the ground state binding energy for an electron in a hydrogen atom is approximately 13.7 electron-volts.

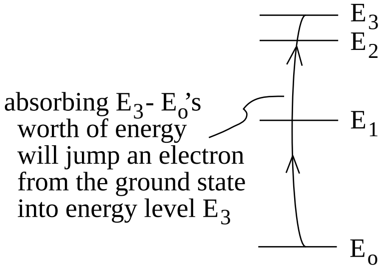
Note 1: The *electron-volt*, whose short-hand notation is *eV*, is a very small unit of energy. It is equivalent to $1.6\text{x}10^{-19}$ joules of energy.

e.) Although *the why* might not be immediately obvious (though is should be clearer within the next few sentences), energies associated with bound states are always denoted as *negative* numbers. The ground state energy for an electron in a hydrogen atom is, therefore, formally written as *-13.7 eV*.

i.) The negative sign is meant to denote that the electron *lacks* that amount of energy if it is to be free.

ii.) Put a little differently, when the electron becomes free, there will be *zero* system energy associated with it. The negative number tells you that you would have to add to the system 13.7 eV if the electron was to be free (i.e., was to get to the *zero* net system energy state).

5.) From above, we have determined the ground state energy E_o for the electron in a hydrogen atom. Let's now assume that somehow, our hydrogen atom absorbs energy in the amount of $E_3 - E_o$ (remember, E_3 is the amount of energy it will have when in the third excited state). This energy absorption allows the electron to transit from its ground state to the *third excited state*. Put a little differently, it motivates the electron to move from an orbit of radius r_o to an orbit of radius r_3.

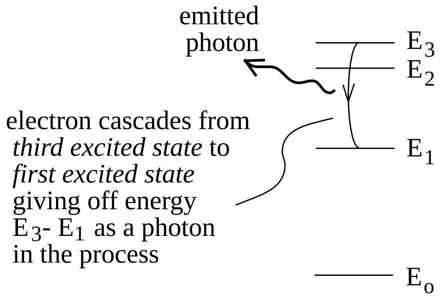


What happens next?

a.) In a relatively short period of time, our electron will dump some of its energy and transit down into a lower energy level. (Remember, systems in nature tend to migrate to lower energy states.)

b.) For the sake of argument, let's assume that our particular electron transits from energy level E_3 to energy level E_1.

c.) In doing so, it must shed energy in the amount $E_3 - E_1$.



d.) What happens to that shed energy?
IT LEAVES AS A PHOTON--a bundle of light energy.

6.) We know that the relationship between the energy in a light photon and the frequency of electromagnetic wave associated with that bundle is $E = h\nu$.

a.) What this means is that in this case of our transiting electron, the *frequency* of emitted light will be related to the energy levels associated with each orbit as

$$E_3 - E_1 = h\nu_{3to1}.$$

where ν_{3to1} is the frequency of light given off when the electron moves from energy level *3* to energy level *1*.

7.) In other words, by measuring the frequency of light coming out of the atom, we can determine the *difference* in energy between the fourth excited state and the second excited state.

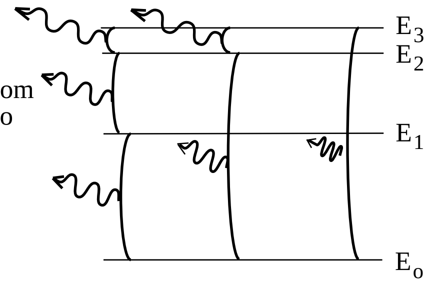
8.) What's more, sooner or later the electron will dump more energy and transit down into a still lower energy state.

a.) When it makes this jump, it will eject another photon whose energy and frequency will be different from the first.

b.) This process will continue until the electron is, once again, back in its ground state.

9.) The bottom line to all of this is that if you have a gas in which billions and billions of hydrogen atoms are being excited, you are going to have more than billions and billions of electrons transitions as a consequence. And as that happens, you are going to see coming out of the gas a superposition of very specific frequencies of light, all of which will be generated by very specific energy bundles (in fact, all of the possible energy bundle combinations for an electron starting in the third excited state are shown in the sketch.

This is how optical light is created inside an atom.



all of the ways an electron can cascade from the *third excited state* to *ground state*--note that the high frequency photons have shorter wavelengths . . .

10.) So how *do* we determine the frequencies coming out of the hydrogen atom? Enter the *spectroscope*.

a.) When light passes through a prism, the angle of refraction differs depending upon the frequency of the light interacting with the structure. In other words, different frequencies will deviate differently. This, in turn, means that a prism can be used to split light up into its component frequencies.

Note: Another device that will also split light up into its component frequencies is the diffraction grating I talked about in the last chapter.

b.) A spectroscope is a device that used a prism or diffraction grating to split light from an excited gas into its characteristic frequencies, then allows the user to take data that will allow for the determination of those frequencies. The sketch shows the general layout.

11.) Although we haven't approached this in a traditional way, the model we have been dancing around is called the *Bohr model* of the atom. It is a highly limited model in the sense that it completely ignores the fact that electron motion is three dimensional, not two dimensional, and that the orbitals that electrons frequent are rarely circular (or spherical) in nature. Still, it does do a nice job of animating what, in general, happens when light is produced in an atom.

D.) Minor Note: How *does* one excite atoms or molecules in a gas?

1.) There are a number of ways to excite gas molecules.

a.) In most cases, gasses are comprised of aggregates of atoms that make up molecules.

b.) One way or another, something has to do *work* on these molecules, putting energy into the system in the process. In many cases, that is done through atomic collisions. How so?

2.) An example: A fluorescent tube is a long, enclosed tube filled with gas. At each end, there are electrodes that can be connected to a power supply.

a.) When power is provided to the tube, a very high voltage sets up an electric field that accelerates free electrons between the electrodes. The acceleration gives the electrons *kinetic energy*. As these free electrons hurtle through the gas, they randomly strike individual gas atoms and molecules giving up *kinetic energy* with each hit. That energy loss is absorbing as an energy gain by the molecule.

As a consequence, *the gas glows* giving off a very light, metallic blue color.

b.) After each collision, the free electrons re-accelerate. They are, after all, still in the electric field set up by the electrodes. Once up to speed, they are ready to deliver another hit.

c.) There are billions and billions of these collisions going on continuously as long as the electric field is on.

3.) A second example: A standard, incandescent light bulb is comprised of a metal wire filament supported by two posts located inside a partially evacuated glass container (in my country, we call this container *a bulb*).

a.) When a light bulb is screwed into a socket the wires of which are plugged into the wall, the bulb lights up when the switch is thrown and power is applied. But why?

b.) From covalently bonded structures, outermost electrons are bound to their atom or, at the very least, to its atom's surrounding neighbors. Contrary to this, metallically bonded structures have the peculiar property of allowing their outermost "valence" electrons to wander freely throughout the metallic structure.

c.) When the switch is thrown, the power supply sets up an electric field. That electric field accelerates the outer shell "valence" electrons along the length of the wire.

d.) The valence electrons pick up kinetic energy as they move under the influence of the electric field, and as they do so they inevitably collide with molecules that are fixed in the lattice of the metallic structure.

e.) These molecules absorb the energy in two ways.

i.) Molecular motion in the form of vibration increases. This is observable as a *heat up* of the metal as the current passes through the wire.

ii.) Atoms making up the molecular structure throw inner shell electrons up into a higher energy level.

f.) It is this latter option that creates the situation in which an electron can transit from a higher energy level to a lower energy level, giving off light in the process.

E.) Emission and Absorption Spectra

1.) When a gas is excited and gives off light as outlined above, very specific frequencies of light are emitted. That light is called the *emission spectra* for the gas.

2.) Because the emission spectra for, say, hydrogen is unique, we have come to know what that spectra looks like through experimentation and the use of a spectroscope.

3.) So let's say we have an unknown gas that, unbeknownst to us, is made up of hydrogen, helium, and lithium. We can identify each of the unknown elements in the gas by exciting the gas, then using a spectroscope to see the what its composite emission spectra looks like. The characteristic lines for each of the elements will show themselves, and in doing so we are able to identify the presence of that gas in the sample.

4.) What is interesting and useful is that if you pass white light through, say, hydrogen gas, the frequencies in the white light that match the frequencies of the emission spectra for hydrogen will individually excite hydrogen atoms as they pass through the hydrogen and, being absorbed, will be re-emitted in random directions. If we then pass that light through a spectroscope, we will find all of the frequencies of white light *except* the frequencies that had been absorbed. That is, there will be all of the colors of the rainbow (i.e., all of the colors that make up white light) with black lines interspersed throughout indicating absorbed frequencies. This is called the *absorption spectra* of a gas.

5.) What is interesting is that the spectral pattern from the emission spectra from, say, hydrogen, will look exactly like the spectral pattern from the absorption pattern of white light passing *through* hydrogen. The same would be the case if the gas had been helium or lithium or whatever.

6.) How is this useful? Put the light from a star through a spectroscope and what will you see? You will see all of the frequencies of white light *except* the absorption spectra of *all of the elements that actively absorb out light from the sample.* In other words, we can determine a lot about a star by its absorption spectra. In fact, as all stars have hydrogen in them, we can tell a lot about the star's temperature by how much of hydrogen's absorption spectra is present (at higher temperatures, that spectra disappears--we'll talk about this more later.)

7.) But there's more!

F.) Back to the Doppler Shift

1.) If you will remember from a chapter ago, when light is emitted from an object that is traveling away from you, the wavelength of that light is Doppler Shifted. This turns out to be a very useful phenomenon in astronomy.

2.) You train your telescope on a star.

a.) You capture its light and send it through a spectroscope to get the composite absorption spectra for the star.

b.) You look to see if there is hydrogen's absorption spectra in the incoming light.

i.) How do you know what hydrogen's absorption spectra looks like? Here on earth you have already sent the light from excited hydrogen gas through a spectroscope to see what hydrogen's *emission spectra* looks like. Knowing the one, you know the other.

c.) Not all stars will show hydrogen spectra. The temperature of the star determines this. Nevertheless, let's assume that you find the characteristic pattern of hydrogen's spectra in a star you are looking at. You could then use a spectroscope to determine the frequency of each spectral line.

d.) You know what the frequencies are when you are not moving, relative to the sample. With the frequencies determined using the absorption spectra, you can determine by how much the frequency has been shifted.

e.) With a determination of the shift, you can determine the radial speed of the star relative to earth.

3.) It is through this kind of analysis that it has been concluded that *everything* outside our own local group of stars is moving *away from* the earth.

4.) Does this mean that we are at the center of all things, that the Big Bang happened *right here*? Nope. Not even close. How so?

a.) Let's assume the Big Bang happened on top of the number at the bottom of this page. For a star *right now* to be, say, a third of the way up the page, it would have to have some velocity.

b.) For a star to be two-thirds of the way up the page, *it* would have to have *twice* the velocity.

c.) And for a star to be at the top of the page, *it* would have to have *three times* the velocity.

d.) So let's assume we are the star that is two-thirds up the page.

i.) When we look at the star at the top of the page, it will be moving away from us because it will have a larger velocity than us.

ii.) But when we look at the star a third up the page, we will be moving faster than it, so we will be moving *away* from it. OR, from our perspective, it will seem as though *it* is moving away from us.

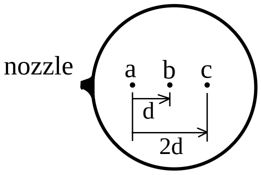
e.) In all cases, no matter where we look (and assuming we aren't looking at objects in our local star group), celestial objects will appear to be moving away from us. It just can't be concluded that we are the center of all things.

5.) Were the relative velocities imparted in the beginning with the Big Bang? The answer to that is *yes* and *no*. In other words, there are two ways to look at it, depending upon the situation.

6.) For situations in which the observed stellar object is close to us (i.e., within our galaxy), the relative velocities that produce red shift can be thought of as physical velocity differences between us and the object in question. That is, the observed stellar object really is moving away from us in the same way a speeding car moves away from a slower car.

7.) For situations in which the observed stellar object is far away (i.e., in another galaxy), the relative velocities that produce red shift is due to the expansion of the universe. This seemingly bizarre claim is best seen with an analogy.

a.) Consider a partially blown up balloon with three dots labeled *a*, *b*, and *c* on it. Assume the initial distance between *dot a* and *dot b* is distance *d*, and the distance between *dot a* and *dot c* is distance *2d*. This is all shown on the sketch.

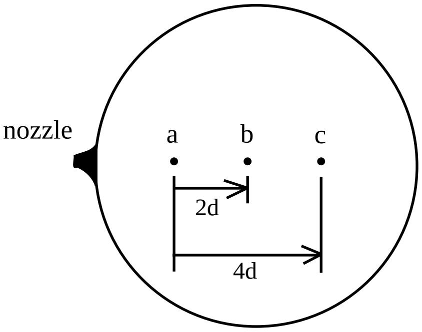


b.) Let's now blow the balloon up so that the new distance between *dot a* and *dot b* is distance *2d*. From the second sketch, you can see that the new distance between *dot a* and *dot c* is now *4d*.

c.) If *dot a* was the earth and *dots b* and *c* were stellar objects, it would look as though *dot c* was moving away from the earth faster than *dot b*.

i.) That is, the stellar object at *dot b* started a distance *d* units from the earth and moved to a position *2d units* away--a net displacement of *d units*.

ii.) *IN THE SAME AMOUNT OF TIME*, the stellar object at *dot c* moved from its initial position *2d* units from the earth to its new position *4d units* out--a net displacement of *2d units*.



iii.) As the time of motion was the same for both, *dot c* must be moving faster, relative to the earth, than *dot b*.

d.) The moral of the story? In an expanding universe, objects that are far apart experience a larger separation speed than do object that are close together. In other words, the relative velocity differences that produce red shifts, at least when dealing with object far apart, are produced by *the universe expanding*.

PHYSICS EXAM SUMMARY
2004-2005

1.) When did Einstein publish his three papers?
2.) What, generally, is the *photoelectric effect*? What was Einstein's explanation for it? What did Einstein's explanation tell us about light?
3.) Why does *blue light* elicit a response from a photoelectric surface whereas *red light* doesn't?
4.) What is the relationship between the energy of a photon of a particular color light, and the frequency of that light if viewed as a wave?
5.) If I give you an energy level diagram, complete with the energy of each orbital, you should be able to determine what wavelength of light would be given off if an electron were to jump from one level to another. You should also be able to determine how much energy would have to be imparted to the atom to excite the atom from one energy state to another.
6.) What are *emission spectra*? What are *absorption spectra*?
7.) How do we determine the emission spectra for a particular gas?
8.) How does knowing the emission spectra for a particular gas help us in astronomy?
9.) What does the red shifting of light from a star tell us?
10.) When dealing with a star close to the earth (i.e., within our galaxy), what is the cause of any measured red shift that might exist within the star's spectrum?
11.) When dealing with a stellar object that is far from earth (i.e., from outside our galaxy), what is the cause of any measured red shift that might exist within the stellar object's spectrum?
12.) In Hewitt, pages 538-551 pretty much talks about the geometric optics already highlighted above (i.e., reflection, ray tracing, mirages, etc.). You don't need to worry about *lenses*, *fiber optics*, or *binoculars* in that chapter.
13.) In Hewitt, pages 563-575 pretty much talks about waves already highlighted (i.e., refraction, diffraction, etc.). You don't need to worry about *thin films* in that section.
14.) What is the difference between the origin of red shift