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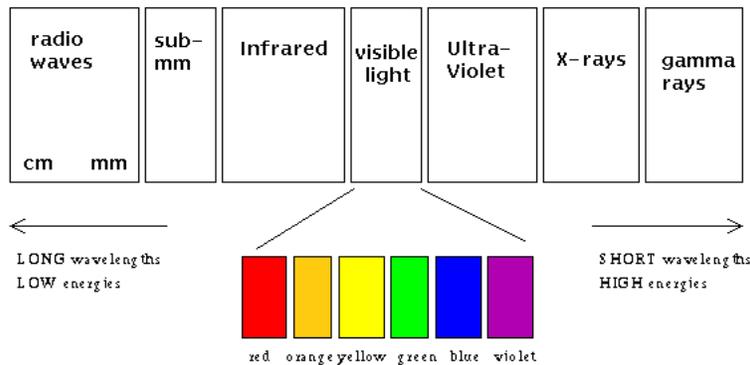
Section: \_\_\_\_\_

Date: \_\_\_\_\_

## PRELAB 5: SPECTRA LAB

### The Electromagnetic Spectrum

The word “light” in day-to-day speech usually refers to what we can see with our eyes, but visible light is only one small piece of the incredible electromagnetic spectrum. When we consider that light is just electromagnetic radiation, it is easy to recognize that the variety found in the spectrum corresponds to different properties of the same electromagnetic wave. For example, if we take visible light and “stretch it out,” so that it has a longer wavelength and less energy, it becomes an infrared wave or radio wave. Going the opposite direction and “squishing” the wave together, we gain the shorter wavelengths and higher energies of ultraviolet rays, x-rays, and gamma rays. Since frequency is inversely related to wavelength, we find that shorter wavelengths correspond to higher frequencies and longer wavelengths correspond to lower frequencies, as depicted in the chart below:



As we can see from the chart above, *color* is just a measurement of the energy contained in a particular electromagnetic wave. It can also be described as the amount of energy contained in one “piece” of light, called a *photon*. Photons are the mediators of the electromagnetic force; in this sense, light can be described as both a wave and a particle. When measuring energy, astronomers often use the unit *electronvolt* (eV). Take a look at the chart again: from it, we can see that a blue photon has more energy than an orange one. Apparently, the change in color corresponds to the different energies of the two individual photons.

Consider the following four statements describing a particular electromagnetic wave:

The light is yellow-green in color.

The photons of light have an energy of 2.25 eV.

The light has a wavelength of 550 nanometers.

The light has a frequency of  $5.45 \times 10^{14}$  Hz ( $1\text{Hz} = \frac{1}{\text{sec}}$ ).

*These statements are identical. The color, energy, frequency, and wavelength of light are all different ways to describe the same phenomenon.*

1. (1 point) UV light, x-rays, and gamma radiation are all harmful to humans, but radio waves pass through us all the time without consequence. Given the discussion about energy above, why is this true?

## Let There Be Light

To understand how most visible light is created, we must delve briefly into the realm of Quantum Mechanics. As a primary thought experiment, imagine you are leaning out of the window of a skyscraper. If you were to drop a bowling ball from the third floor, it would hit the ground with a certain amount of kinetic energy. If you dropped it from the 4th floor, it would hit the ground with even more energy. The higher the initial height, the more energy on impact.

The falling bowling ball is just a loose metaphor for what happens inside of an atom. We can model an atom as electrons confined to “levels” or “shells,” orbiting the nucleus. Just as the bowling ball gained kinetic energy on its fall, you may expect an electron “falling” closer to the nucleus to gain energy; however, that energy must be transitioned to a different form. Therefore, the excess energy is released as light.

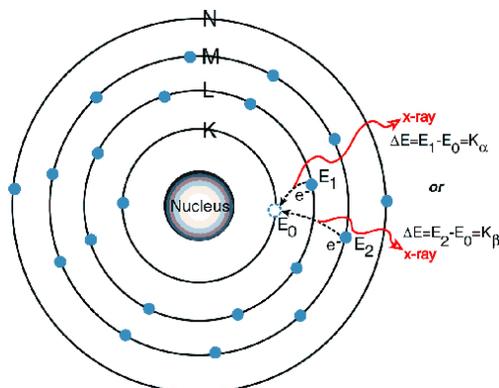


Figure 1: Light (electromagnetic radiation) is produced when a charged particle (ex. an electron) is accelerated, that is, when electrons get closer or “fall” towards the nucleus of an atom.

As electrons move into shells closer to the nucleus, they release specific amounts of energy corresponding to those shells. Because there are only certain wavelengths at which the atom can emit, the energy is said to be quantized. This means that if the wavelengths emitted are in the visible spectrum, only certain colors of light will be emitted; for example, the light generated from an electron falling from the second to the first shell might be very red, whereas the third to first shell transition may produce a yellow-green shade, and the fourth shell to first shell transition has enough energy to leave the visible spectrum and enter the ultraviolet region. This also means that a specific type of atom, such as Hydrogen or Helium, will only emit at specific colors of light; therefore, we can identify elements in a stellar spectrum based on the specific colors/wavelengths of light emitted and observed.

## Line Formation

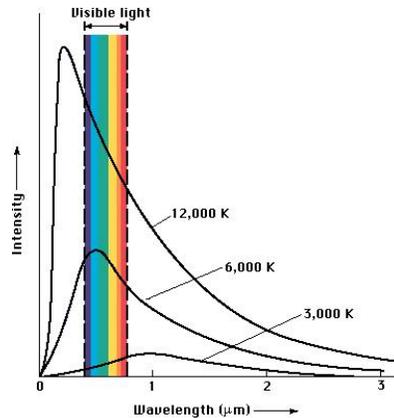
Just as an atom only emits at specific wavelengths, it can only absorb light at specific wavelengths as well. When a photon hits an atom, it will pass straight through it unless the energy of the photon is the perfect amount to knock one of the electrons into a higher shell. For example, if a photon passes through a gas formed from a certain element, the gas will absorb the colors of light that correspond to the energy level transitions specific to that element. After white light passes through the gas, an observer will notice that light of the absorbed color is missing from the emitted spectrum. That color has been *absorbed*. The lack of light at a specific color is called an *absorption line*. Absorption happens when light passes through a thick, cool material, which blocks out certain colors. This is typical in stars which are surrounded by atmospheres filled with hydrogen (H), helium (He), and other material.

If the gas is heated, the collisions of atoms can knock electrons into higher shells. When these electrons come back down, the atom releases photons. As there are only select energy photons the atom can emit, an observer will see light emitted from the atom at that color. This is called an *emission line*. Light that is re-emitted in a random direction is said to be *scattered*. Emission lines happen when a substance is heated. Hot, thin gases often will have emission lines.

2. (1 point) Consider a large box filled with a gas of a specific element that absorbs blue light. If you shined a mixture of red and blue light through the middle of the box, what color would the beam be when it reached the other side?
  
3. (2 points) White light is emitted from the Sun, yet our sky is blue. Why is this? (See “*Why is the Sky Blue*” in Ch. 7 of your textbook).
  
4. (1 point) If a star is surrounded by a thick, cool, dense cloud of helium, will we see helium emission lines or absorption lines? Why?
  
5. (1 point) If a star is surrounded by a hot, thin layer of hydrogen will we see hydrogen emission or absorption lines? Why?

### Blackbody Radiation and Wien’s Law

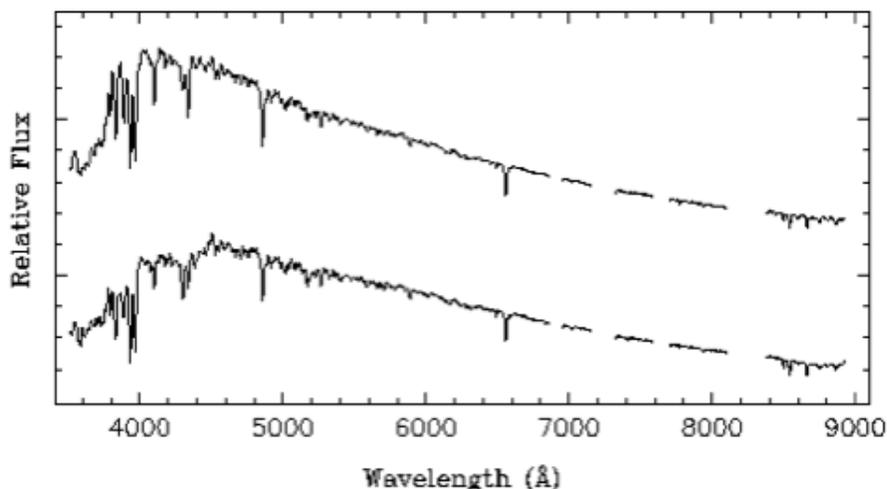
Every substance emits light; even our bodies glow in the infrared region of the electromagnetic spectrum! As energy is related to temperature, it is not hard to show that the hotter the object, the higher the energy of the emitted photons. For example, a star like the sun is about 6000 Kelvin (K), which peaks in the green-blue region of visible light. Hotter stars peak in the ultra-violet region, or even emit x-rays or gamma rays if their temperatures are high enough. On the other side of the spectrum, objects about the temperature of Earth largely emit infrared radiation. Note that even though an object may peak at a certain color/wavelength, it will still emit light at other colors.



The overall shape of these types of spectra are called *blackbody curves*. A *blackbody* is an object that only emits light (as opposed to reflecting it). A blackbody's emission is due to its temperature. Any object will produce a curve that looks roughly like the spectrum shown above. The real spectrum of a substance or object will contain other peaks and valleys, but the overall trend of the curve will be about the same. Given any spectrum, Wien's Law can be used to estimate the temperature of the star. Wien's Law states the temperature of the object (in Kelvin) is equal to  $2.9 \times 10^6$  divided by the wavelength of the brightest color light (in nm). This can also be written as:

$$\lambda_{max} = \frac{2.9 \times 10^6}{T}$$

6. (1 point) Some stars can have temperatures in excess of 100,000 K. Use the law above to calculate the brightest color of light emitted (your answer will be a wavelength, in nm). What color, or type of light do these stars primarily emit?
7. (2 points) Below are two examples of stellar spectra from the same star. The light from the star has been plotted as an absorption spectrum. Look at the dips in the spectrum (the absorption lines) and use them to identify which substances are in this star's atmosphere. Out of the listed choices, circle the lines present. Note that only one line needs to be seen for an element to be present in the stellar atmosphere.



Hydrogen lines: 6562 Å, 4865 Å  
 Helium lines: 3888 Å, 4471 Å, 5875 Å  
 Oxygen: 6870 Å  
 Mercury: 4360 Å, 5790 Å  
 Iron: 5170 Å

8. (1 point) Given a spectrum, Wien's Law can be used to estimate the temperature of the star. Estimate the temperature of the star in question 12 using Wien's Law. (Hint: of the wavelengths present in the spectrum, which is the brightest?) Remember  $1 \text{ Å} = 1 \times 10^{-10}$  meters.

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## LAB 5: SPECTRA LAB



Figure 2: Star-forming region Sh2-284, as captured by NASA's Wide-field Infrared Survey Explorer (WISE).

### 1 Introduction

In this lab, we will explore how photons interact with matter. Through examining how photons interact with a hydrogen atom, we will explore the phenomena of absorption, emission, and ionization. Then, the blackbody simulation will allow us to explore the relationship between wavelength and temperature, and to determine if there is an empirical relationship between an object's temperature and the light emitted.

Recall from the prelab that energy level transitions are responsible for the lines in a spectrum. If you observe a cool gas against a bright background such as a star's surface, the gas causes dark lines to appear in the spectrum, as photons are absorbed at specific wavelengths. This is called an *absorption spectrum*. On the other hand, if you observe a hot gas which is emitting light, it can produce a spectrum with bright *emission lines*. This is called an *emission spectrum*.

Finally, recall that Wien's Law states the temperature of the object (in Kelvin) is equal to  $2.9 \times 10^6$  divided by the wavelength of the brightest color light (in nm). This can also be written as:

$$\lambda_{max} = \frac{2.9 \times 10^6}{T}$$

### 2 Instructions

1. Open the NAAP Hydrogen Atom simulation. On the right-hand side of the screen, you should see an Event Log (make sure the dialogue box is blank). At the top-left of the screen, you should see a red circle with a p (representing the nucleus of the atom made of protons and neutrons), and a green circle with an e (representing electrons). The white rings gradually increase in spacing to the right of the screen, representing increasingly energetic energy levels, with the left-most empty ring being the

first excited state of the electron, the second empty ring is the second excited state, and so on. The electron is sitting in the ground state. This is a Bohr Model of a Hydrogen atom.

2. Click the  $P_\alpha$  button on the lower left of the screen. What happens to the electron when the photon is fired at the Hydrogen atom? What color is the photon? Check the event log and you'll see the energy of the fired photon as well as its interaction with the atom reported. Record this information, as well as your result, in the table on your worksheet. Clear the event log. Repeat this step for the  $H_\beta$  button as well.
3. Now click on the  $L_\alpha$  button towards the right side of the dialogue box. Watch carefully for the colors, and then record your observations after the simulation has finished. Record ALL energy level shifts in the table on your worksheet and clear the event log. Do the same for the  $L_\gamma$  button. Notice that if you hit the  $L_\gamma$  button again, you may not get the same interactions as you did the first time; therefore, if you miss something as you're watching the simulation, use the event log to fill in the blanks.
4. If you watch carefully, you'll notice that in the last step you have a second or so before the electron decays from a higher energy state to a lower one. Click the  $L_\beta$  button, but before the electron decays to a lower state, click the  $P_\alpha$  button. Record all your results in the table and clear the event log.
5. Repeat the last step using the  $L_\alpha$ , then  $H_\beta$  buttons. Make sure to record all your results.
6. Repeat the last step using the  $L_\gamma$ , then  $H_\beta$  buttons. Notice that the second incoming photon had enough energy to knock the electron away from the nucleus! This process is called *ionization*. Make sure to record all your results. No need to write down the "recombination" step.
7. Answer questions two and three on the lab worksheet.
8. Close the Hydrogen Atom simulation and open the PHET simulation entitled Blackbody Spectrum.
9. Set the temperature of the blackbody to 3000 K by typing the number into the dialogue box above the T (K) slider. This is the approximate temperature of a tungsten filament in an incandescent light bulb. Using the zoom tools, adjust the axes to read 3.16 on the y-axis (Intensity, the amount of light emitted) and 3 on the x-axis (wavelength). Answer questions 4-6 on the lab worksheet.
10. Set the temperature to 5800K. This is approximately the surface temperature of the sun. You'll need to zoom in on the horizontal axis and zoom out on the vertical axis. Answer questions 7-9 on the lab worksheet.
11. Now, let's explore the relationship between peak wavelength and temperature. For the temperatures listed in the chart in question 10 of your lab worksheet, determine the peak wavelength of each temperature. You may want to use the "ruler" tool in the program to help you line-up the peak with the x-axis. Be careful to record your wavelength in nanometers. Watch out for the changing scale on the x-axis!
12. Finish by answering the rest of the questions in your worksheet.



2. (1 point) Why do you think the  $H_{\beta}$  photon is sometimes absorbed, while other times it ionizes the electron it hits?
  
  
  
  
  
  
  
  
  
  
3. (1 point) Consider the  $L_{\beta}$  to  $P_{\alpha}$  experiment you conducted. Is the energy absorbed equal to the energy emitted? Does this agree with the Law of the Conservation of Energy?
  
  
  
  
  
  
  
  
  
  
4. (1 point) Based on the graph, does the light bulb produce visible light? Does it produce x-rays? How can you tell? (Hint: look at the area under the red curve!)
  
  
  
  
  
  
  
  
  
  
5. (1 point) In the spectrum made by the light bulb, which wavelength is most intense? How would you classify it?  
Wavelength: \_\_\_\_\_  
Type of Light: \_\_\_\_\_
  
  
  
  
  
  
  
  
  
  
6. (1 point) Given your answer to the question above, is an incandescent light bulb very good for its intended use? Why or why not?
  
  
  
  
  
  
  
  
  
  
7. (1 point) Compare the peak wavelength produced by the light bulb to the peak wavelength produced by the Sun.
  
  
  
  
  
  
  
  
  
  
8. (1 point) Look at the location of the visible spectrum “bar” and the blackbody curve on the graph in the simulation. Based on this pictorial representation, how is the radiation emitted by the Sun related to the visible spectrum?

9. (1 point) Is there evidence of the sun producing harmful ultraviolet radiation? Justify your answer.

10. (3 points) BLACKBODY SPECTRA

Temperature (K)	Peak Wavelength (nm)
600	
1200	
2500	
3500	
4500	
5500	

11. (2 points) Make a plot of Temperature (K) vs. Wavelength (nm) (y vs. x). What relationship do you see? Remember to label your axes!

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Picture Credits: Prelab, spectrum from old Spectra I PHYS 133 lab, energy shell diagram: [http://www.amptek.com/wp-content/uploads/2013/12/xrf\\_2.gif](http://www.amptek.com/wp-content/uploads/2013/12/xrf_2.gif), blackbody: [http://www.physics.umd.edu/courses/Phys401/bedaque07/blackbody\\_curves.jpg](http://www.physics.umd.edu/courses/Phys401/bedaque07/blackbody_curves.jpg), Lab, gas cloud: <http://www.jpl.nasa.gov/news/news.php?release=2011-066>. DISCLAIMER: This lab has been edited from the old PHYS 133 Spectra I and II labs and from Pennisi, Michael. "Blackbody Lab." *Blackbody Radiation and Wien's Law: For Teachers*. PHET, University of Colorado, 4 Nov. 2013. Web. 07 Sept. 2014. <http://phet.colorado.edu/en/contributions/view/3664>.