# Modern Physics Lab

**Blackbody Radiation** **9/04**

## Purpose of the experiment

- Use blackbody radiation to determine the temperature of an object.

# Background Information

In this experiment, you will learn how to measure an object's temperature by examining its blackbody spectrum. The object you will be examining is a 300 W incandescent, tungsten filament light bulb.

An incandescent light source that emits light through a small cavity is a "perfect" emitter". By definition, a perfect emitter is one that emits light in an infinite number of wavelengths in the visible and invisible electromagnetic spectrum. When light from the blackbody is cast through a prism, the observed spectrum is continuous and no overlapping of the spectral lines occurs.

For this lab, parallel light rays travel through the collimating lens, which allows the light rays to remain parallel. Passing through the prism, the light rays refract and project in front of the aperture slit over the light sensor. The light sensor detects and records the light intensity as voltage. (See Figure 1 below.)

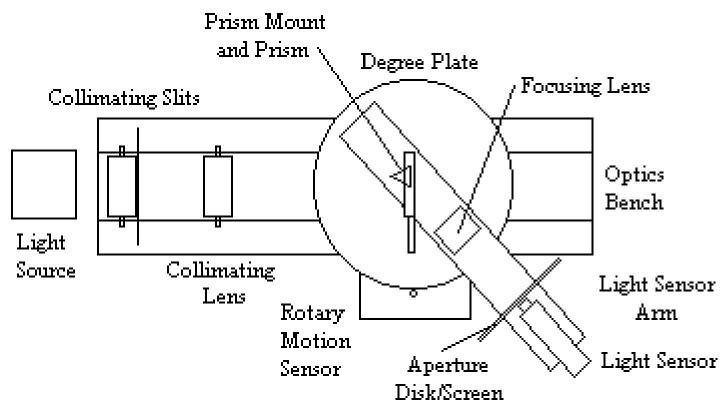


Figure 1: Set up of spectrophotometer.

Unlike other light sources, changes in light intensity from an incandescent blackbody is solely dependent on temperature. Increasing the temperature of the blackbody light source increases the light intensity. For any given temperature, there appears to be an optimal wavelength for reaching a maximum light intensity. You will be exploiting this relationship between intensity and wavelength to determine the light bulb's temperature.

The angle of the emitted light depends upon the refraction index of the prism and the wavelength of the light. Shorter wavelengths show more bend than longer wavelengths and therefore exhibit higher indices of refraction. It will be necessary for you to determine the relationship between the wavelength and refraction angle in order to complete this lab.

# Prelab

- The intensity of blackbody radiation is a function of both temperature and wavelength:

$$I(\lambda,T)=\frac{2\pi hc^2}{\lambda^5\left(e^{hc/\lambda kT}-1\right)} \qquad \text{(Equation 1)}$$

  Plot I vs. λ for 500 K, 1000 K and 2000 K. For each case, show graphically that Wien's Law gives you the wavelength where the maximum value of I occurs.

- The Cauchy equation gives the relationship between wavelength and index of refraction:

$$n=\frac{A}{\lambda^2}+B \qquad \text{(Equation 2)}$$

  where A and B depend on the type of glass for the prism. Using a computer curve fitting program and the following data, find the constants A and B.

| Wavelength (nm) | Refraction Index |
|---|---|
| 404.7 | 1.776 |
| 435.8 | 1.762 |
| 480.0 | 1.748 |
| 486.1 | 1.746 |
| 546.1 | 1.734 |
| 587.6 | 1.728 |
| 643.8 | 1.722 |
| 656.3 | 1.721 |
| 706.5 | 1.717 |
| 852.1 | 1.709 |
| 1014.0 | 1.703 |

- Consider the following diagram:

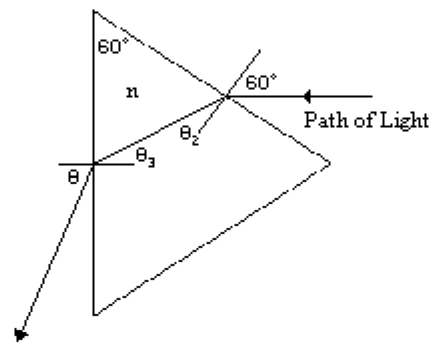


Figure 2: Path of light through prism.

The light beam passes from air to glass and then from glass back to air. Write down Snell's Law for each interface, assuming that the index of refraction for air is exactly 1. This gives you two equations. Since the prism angle is 60 degrees, it can be shown that $\theta_2 + \theta_3 = 60^O$. This gives you a third equation. Eliminate $\theta_2$ and $\theta_3$ from these three equations to show that:

$$n = \sqrt{\left(\frac{2}{\sqrt{3}}\sin\theta + \frac{1}{2}\right)^2 + \frac{3}{4}} \qquad \text{(Equation 3)}$$

- Combine Equations 2 and 3 to find $\lambda(\theta)$.

# Set Up

This lab exercise is fairly involved. Be sure to perform the set up for this experiment accurately. Doing so will save you a lot of time while doing the lab.

> Warning! The black body light source can get very hot. Do not let the bulb touch anything while it is on.

> Caution! Handle all optics carefully. Handle the lenses only by their plastic parts. Also, avoid touching the prism *except by the metal prism mount.*

Please refer to the Figure 1 above as needed when setting up this experiment:

## Computer/ULI Start Up

- Be sure that the power cord for the light source is plugged into a different outlet than the one used for the computer.
- Boot up the computer and turn on the ULI interface box (there is a red switch on the back of the box).
    - Notice that the light sensor and rotary motion sensor are already plugged into the appropriate ports on the ULI box and power supply. DO NOT adjust these. Be sure both sides of the power supply are at 12 V.
- From the desktop, start the *Logger Pro* software.
- Once the program starts, it will need to scan for the ULI interface box. From the dialog box that comes up, select “Modem Port” from the drop down menu and press the “Scan” button.
- After a second, the dialog box will say it found the “ULI2 Rev. 1.40” interface. Press OK.

Using the exact ratio of the degree plate to the small pinion post will improve the accuracy of measurement. The ratio is approximately 60 to 1, meaning that the pinion rotates 60 times for 1 revolution of the degree plate. To determine the exact ratio, perform the following calibration:

- Remove the prism mount from the degree plate. DO NOT touch the prism itself. Only touch the metal portions of the prism mount. Place the prism carefully out of the way where it will not be damaged.

- Remove the light sensor arm from the degree plate by unscrewing the two small thumbscrews. (Store the thumbscrews in the empty holes on the light sensor arm. DO NOT lose these!!)

- Turn the degree plate so the zero degree mark is exactly lined up with the index mark on the arm.

- In the *Logger Pro* software, select File | Open to load the file "Rotary Calibration".

- On the *Logger Pro* toolbar, press the Collect button to start taking data. Rotate the degree plate slowly and continuously through exactly one revolution while taking data. When you are done, press the Stop button.

    - If the small pinion slips rather than turns, make sure that the thumbscrews that hold the rotary motion sensor onto the hinge are tight. You may need to loosen the screws and then push the rotary motion sensor so it is as close to the base as possible before re-tightening the screws.

- On the toolbar, press the "x = ?" (value of the function at x) button. Move the cursor to the maximum value of the data. This value is the ratio of the radii of the degree plate to the pinion. It should be around 60. Record this value.

- Replace the light sensor arm, but do not replace the prism mount yet.

## Masking the Spectrophotometer

- Using the black cloth and binder clips provided, mask off the spectrophotometer so that the only light that reaches it from the light source comes through the collimating slit. (The light source you will be using is a 300 W light bulb with a tungsten filament.) The black cloth should be clipped to the collimating slits (see Figure 1).
    - Make sure the inner and outer slits on the collimating slits are aligned.
    - For this lab, you will need to use the same number slit on the collimating slits as you use on the aperture disk. For example, if you use the number 4 slit on the aperture disk, you must also use the number 4 slit on the collimating slits.
    - Using the ring stand clamps, adjust the level of the optics bench such that it is at the same level as the light source.

## Positioning the Collimating Slits and Lens

The focal length of the collimating lens is about 10 cm, so the lens should be positioned about 10 cm from the slits. Use the following procedure to position the lens more precisely:

- Darken the room.
- Set up the blackbody light source at one end of the optics rail and mask off the spectrophotometer using the procedure outlined above (see Masking the Spectrophotometer). Make sure the light from the source passes through one of the slits on the collimating slits and then through the collimating lens.
    - Play with both the level of the optics bench and the alignment of the light source with the slits until you get the brightest light beam possible passing through the collimating lens. This is <u>critical</u> to getting good data. When you are looking from where the prism will be, make sure you can see the tungsten filament through the collimating slits. <u>Failure to do so will result in bad data!!!</u>
- Rotate the light sensor arm so the aperture bracket and light sensor are out of the way and the beam of light can shine onto a distant vertical surface such as a wall.

- Adjust the distance between the collimating slits and the collimating lens so that the beam of light is neither converging nor diverging. The beam of light should stay about the same width all the way to the distant vertical surface. Hold a piece of paper in the light beam's path at various distances along the beam's path. Check to see that the light beam's with is about the same at each distance. Note that the light may not be in focus during this process.

- Adjust the collimating slits until the light beam is vertical.

- Replace the prism mount. Do not screw the grating mount down all the way, the degree plate needs to be free to rotate. Also, attach the grating to the grating mounts using the magnets such that the glass side of the grating faces the light source.

    - With the degree plate set a zero, be sure that the prism mount is aligned exactly along the 0 – 180 degree line on the degree plate.

## Mounting and Positioning the Focusing Lens

The degree plate has markings on either side of the light sensor arm that indicate the approximate position in which to place the focusing lens. The focusing lens has two small magnets in its base that hold it in place on top of the light sensor arm. Place the focusing lens on the light sensor arm between the grating mount and the high sensitivity light sensor.

The focusing lens focal length is about 10 cm, so the lens should be positioned on the light sensor arm about 10 cm in front of the aperture disk.

- With the room dark, set up the optics bench such that the light from the collimating slits and collimating lens shines through the prism and focusing lens. (Do not readjust your collimating slits and collimating lens since they should already be in place.)

- Move the light sensor arm so the white central ray of light is centered on the slit at the bottom of the aperture disk. You will not be able to see the visible part of the spectrum as it will be too far away to shine on the aperture screen.

- Adjust the position of the focusing lens until the central ray is sharply focused.

- In the *Logger Pro* software, select File | Open to load the file “Blackbody”.
    - While the sensors will already be configured, little else has been done for you within *Logger Pro*. All of the measurements are left for you to make.
    - Be sure you are plotting Intensity vs. Angle on the displayed graph.
- You are now ready to start the laboratory exercise.

# The Lab

**The goal**: To measure the temperature of a light bulb using its blackbody spectrum.

**Remember to include the uncertainty in your measurement and the units**

### Data Collection

Consider the following when performing this experiment:

- There are five slits on the collimating slits slide and six slits on the aperture disk. You can select wider slits in order to increase the amount of light that passes through the grating and into the light sensor, but this will make a wider spectral pattern and decrease the accuracy of your measurements.

  - Remember, you will need to use the same number slit on the collimating slits as you use on the aperture disk. For example, if you use the number 4 slit on the aperture disk, you must also use the number 4 slit on the collimating slits.

- Again, play with both the level of the optics bench and the alignment of the light source with the slits until you get the brightest light beam possible passing through the collimating lens. This is critical to getting good data. When you are looking from where the prism will be, make sure you can see the tungsten filament through the collimating slits. Failure to do so will result in bad data!!!

- The prism mount and prism must remain fixed at all times. If not, your data will be in error. If the prism mount rotates at any time during the scanning, discard the data, recalibrate, and take another reading.

- The high sensitivity light sensor has a GAIN select switch on top with three settings (1, 10, and 100). When you measure the spectrum, you will need to determine which one(s) to use.

- You will need to measure the angle to the white light that passes directly through the spectrophotometer and under the prism. This angle is subtracted from all angles, so that all angles are referenced from the parallel beams that are incident on the spectrophotometer (see the angle θ in Figure 2).

- The bulb is connected to a variable voltage supply. Varying the voltage will change the temperature of the bulb. Get blackbody curves (Intensity vs. Wavelength, NOT Intensity vs. Angle) for several values of temperature.

- When taking data in *Logger Pro*, you will be measuring the voltage given off by the light sensor and the angle registered by the rotary motion sensor. However, you will also be interested in other quantities that can be derived from the data from these two sensors. These include light intensity, wavelength, and angular position. You can have the computer calculate these quantities by doing the following:

    - Select Data | New Column… | Formula… from the menu bar.

    - Click the Options tab. This will allow you to enter information for a new data column that can be plotted. Fill in the fields of Long Name, Short Name, and Units.

    - Click on the Definition tab. Enter an equation definition here that the computer will use to calculate a new quantity.

        - You need to have the computer calculate λ for every value of θ. To do so, enter the following equation EXACTLY in the definition tab:

          | |
          |---|
          | sqrt(A/(((1.1547*sin("Angle"*2*"pi"/360)+0.5)^2+0.75)^0.5-B)) |

          where "Angle" is defined under a separate column definition as:

          | |
          |---|
          | "Position"*(360/Ratio of Radii)+70-(Angle of White Light) |

          replacing A, B, Ratio of Radii and Angle of White Light with the numbers you measured or calculated.

- When performing a scan, you will need to do the following:

    - Turn out the lights and turn down the brightness on the computer monitor if necessary.

    - Begin by placing the stop against the angle indicator on the spectro-photometer table. This is at about 70 degrees. Keep in mind that the rotary motion sensor always starts at zero. You will need to compensate for this by entering the above equations into the Definition Tab.

- Before starting a scan, block the light source by placing your hand between the collimating slits and the light source. While the light is blocked, press the TARE button on the light sensor to zero the sensor. Remove your hand to unblock the light and start recording data by pressing the Collect button on the *Logger Pro* toolbar. (Note: To avoid measurement drift, you must tare the light sensor before each scan through the spectrum.)

- You will be scanning from 70 degrees and moving toward zero degrees. When taking data, you will want to slowly and continuously scan the spectrum in one direction only. You will need to determine where to stop. When you are done, press the Stop button on the *Logger Pro* toolbar.

- The angular resolution of the rotary motion sensor is 1440 divisions per rotation. One rotation of the pinion is 6 degrees on the degree plate.

- It is a good practice to save any data you wish to keep to disk. In any case, you will need to print the spectra for your lab write up.

## Shut Down

- Turn off the light source.
- Be sure you have saved any data to disk that you want to keep.
- Exit *Logger Pro* and shut down the computer.
- Turn off the ULI box.
- Make sure all equipment is accounted for and in place.
- [FYI]

[FYI] Los Angeles, California is further east than Reno, Nevada.