Chapter 1

The Monochromator and Photomultiplier

1.1 Introduction

A monochromator is a device used to isolate a small wavelength interval of a spectrum. It consists of an entrance slit, a dispersive element (*e.g.* a grating), and an exit slit which allows only a selected portion of the spectrum to pass to a detector. The photon detector in this lab is a photomultiplier tube. The instrument can be used to study the wavelengths and intensities of spectral lines emitted by a source.

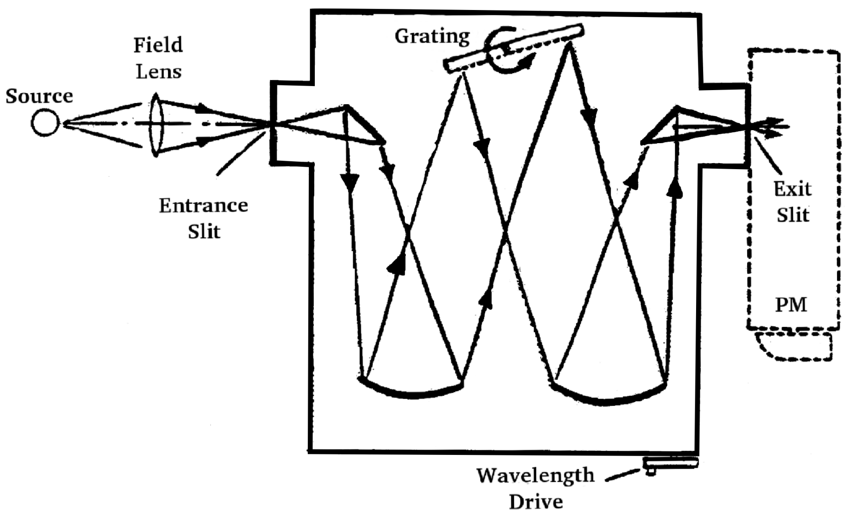

Figure 1.1: The Czerny-Turner Monochromator (the field lens is optional).

1.2 The Czerny-Turner Monochromator

Although the particular model of monochromator used here is small, the design and operation is identical to that of larger models. This particular arrangement of mirrors, slits, and grating is referred to as the Czerny-Turner arrangement. The dispersive element is a diffraction grating.

The light path through the instrument is shown in Fig. 1.1. The light from the source falls on the entrance slit. If necessary the light intensity can be increased with a field lens. A spherical mirror then collimates the beam of light and illuminates the grating. The grating disperses different wavelengths at different angles and one of these wavelengths is focussed onto the exit slit by the other spherical mirror. Since the slits are very narrow (typically 0.1mm or less), only a small range of wavelengths emerges from the exit slit. The instrument width of this monochromator is approximately 1nm, but for more expensive instruments a width of 10^{-2}nm is easily achievable.

1.3 The RCA 931A Photomultiplier Tube

The photomultiplier tube is a vacuum tube device used in industry to measure light signals, especially those from transient light sources. (A transient light source is one which only emits for a short period of time, such as a spark). The active element of a PM is the photo-cathode, which liberates electrons when struck by light. These electrons form a current pulse, which is amplified by a series of dynodes. Because the photon energy depends on the colour of the light, the energy (and number) of liberated electrons will also. This changes the dynode avalanche amplification which results in a current pulse amplitude dependent on the colour of the light. The last dynode is called the anode and is connected by an anode resistor to ground (see Fig. 1.2). A voltage is therefore developed across the anode resistor which, in the ideal case, is proportional to the intensity of the incident light. The schematic construction and operation of the photomultiplier tube is shown in Fig. 1.2.

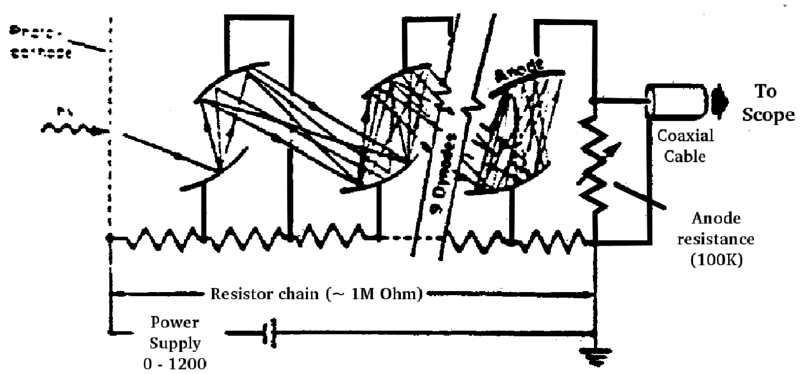

Figure 1.2: Schematic of the RCA 931 Photomultiplier Tube.

1.4 Linearity of the Photomultiplier

The linearity of the PM response must be established before accurate intensity measurements can be made. This is done by plotting the amplitude of the PM signal as a function of the intensity of the incident light. Ideally the graph should be linear, but at large signals a deviation from linearity is usually observed.

The experimental arrangement to measure the response curve is shown in Fig. 1.3. A slit assembly is mounted in front of the photomultiplier. Directly behind the slit is located a neutral-density step wedge which is used to change the intensity of light striking the PM. The light source is a tungsten lamp connected to a DC power supply. The light from the lamp is "chopped" by a motor-driven chopper (a standard procedure for converting the steady light to light pulses which are more easily measured by the photomultiplier). In our case the chopper is an enclosed fan.

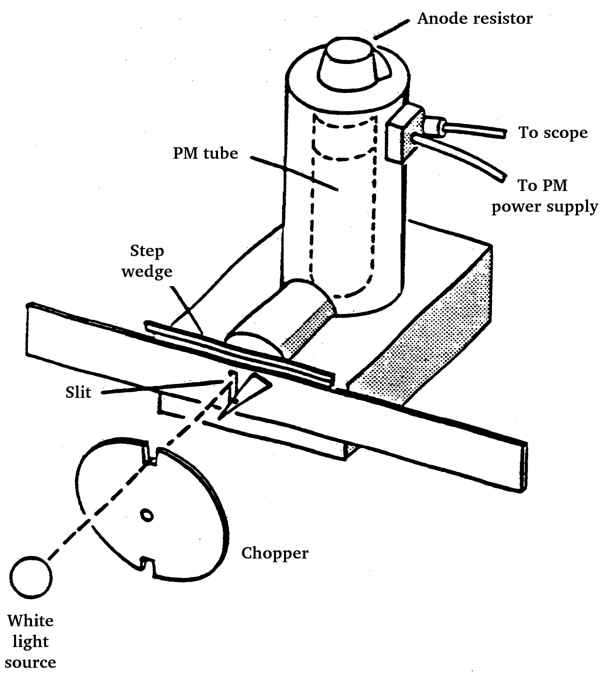

Figure 1.3: Experimental arrangement for measuring the linearity of the PM

WARNING: THE POWER SUPPLY TO THE PHOTOMULTIPLIER MUST NEVER BE TURNED ON WHEN IT IS EXPOSED TO ROOM LIGHT!

1.4.1 Procedure

Set up the apparatus as shown in Fig. 1.3, with the lamp approximately 2 feet from the slit. The chopper can be located anywhere in between. Connect the oscilloscope and use the measurement function soft key to measure the signal from the PM. Position the step wedge so that the darkest step is behind the slit. (This is a precautionary step to prevent damage from occurring to the PM).

Adjust the oscilloscope to the most sensitive setting, and turn on the PM power supply (1200 volts). Set the potentiometer on the PM to approximately halfway, and turn on the lamp and light chopper. Adjust the lamp position laterally to get a maximum signal.

Measure the voltage output of the PM for the different steps in the filter, and plot this voltage against the relative intensity of the light. The relation of the density of the step to the intensity of the transmitted light is

$$D_N = -\log_{10} T_N \tag{1.1}$$

where $T_N = I_t/I_0$ is the transmission of the step wedge. The voltage reading will be highest for the lightest part of the step wedge. Do not let the voltage rise above about 20V. Observe the pulse shape at high light intensities and comment on what occurs.

1.5 Wavelength Calibration of the Monochromator

The wavelength drive of the monochromator is reasonably accurate, but sometimes it has a zero error produced by cranking the wavelength drive beyond its limits. The zero error and the constant of proportionality are established by comparing the measured locations of lines of the helium spectrum with their known wavelengths. The zero error may be as much as 10nm.

1.5.1 Important note on monochromator alignment

The transmission through the monochromator is highly dependent on the angle of the light with respect to the monochromator. To line up the monochromator, first make sure the gain and the supply voltage on the PMT are set to ZERO and remove it from the monochromator. Set the monochromator to 500 nm and then take the slits out the front and back and look in through the back of the monochromator (i.e. put your eye where the PMT would normally be). Move the light source around until you can see light through the monochromator and then put in the first slit and optimize the position of the lamp with this first slit in place. Put in the second slit and repeat the above step. When you are done, put the PMT back in place and turn the supply on and adjust the gain setting until you get a measurable signal (about 1V). The supply voltage to the PMT can be increased if more gain is needed, but do not exceed 1.2 kV. While you can use the voltmeter to measure the voltage output of the PMT, in most cases where the PMT output noise is high and you want a reliable measurement, you will need to use a fan to chop the light going to the monochromator, and you will use the oscilloscope to measure the PMT response to the dark and light periods.

1.5.2 Procedure

Using the above alignment procedure, align a helium Geissler tube through the monochromator. Then transfer the PMT to the mount on the exit slit of the monochromator, and with the voltmeter set on its most sensitive scale, determine the positions of the various helium emission lines on the wavelength drive. Plot a graph of measured location versus known wavelength to obtain a wavelength calibration graph.

1.6 Spectral Response of the PM-Monochromator Combination

It was pointed out in Section 1.3 that the photomultiplier does not respond equally to light of different wavelengths; neither does the monochromator. The combination of the two is very wavelength sensitive. For many experiments involving comparison of intensity measurements at various portions of the spectrum, it is necessary to know the spectral response of the system.

To measure this response, light from a continuum source is passed through the system and the PMT signal, $S(\lambda)$, is measured at many wavelengths over the complete spectrum. If the intensity of the source, $I_w(\lambda, T)$ at a temperature of T, is known as a function of wavelength, λ, then the response of the system as a function of wavelength is given by,

$$R(\lambda) = \frac{S(\lambda)}{I_w(\lambda, T)} \tag{1.2}$$

Once the response function is known, the intensity of any other source at wavelength λ may be determined by measuring $S_2(\lambda)$ and dividing by $R(\lambda)$.

A perfect black body radiator emits power per unit area per unit wavelength interval per unit solid angle (*i.e.* irradiance per unit wavelength interval per unit solid angle) according to the Planck function:

$$I(\lambda, T) = 2c^2 h\lambda^{-5}\left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]^{-1} \text{watts}\cdot\text{m}^{-3}\cdot\text{steradian}^{-1}$$

$$= A\lambda^{-5}\left[exp\left(\frac{B}{\lambda T}\right) - 1\right]^{-1} \tag{1.3}$$

Where λ is in meters, $A = 2c^2h = 1.19 \times 10^{-16}\text{watts}\cdot\text{m}^2\cdot\text{steradian}^{-1}$, and $B = 1.44 \times 10^{-2}\text{m}\cdot\text{K}$.

Most radiators are not perfect so that equation 1.3 must be modified by multiplying by a factor which characterizes the particular radiating surface. This factor is called the emissivity, $\epsilon(\lambda, T)$ and it varies with temperature and wavelength. Thus, for tungsten;

$$I_w(\lambda, T) = \epsilon_w(\lambda, T) I(\lambda, T)$$

Emissivity curves for tungsten are shown in Fig. 1.4

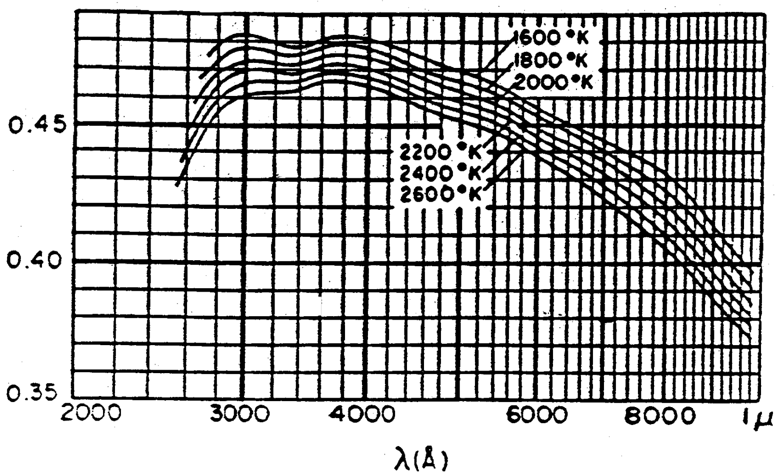

Figure 1.4: Emissivity curves of Tungsten (Devos, Physics 20, 690, in reading room. See the class website for an updated, electronic version)

1.6.1 Procedure

You will measure the response of your system to a tungsten lamp, but please remember to NOT leave the lamp on at high intensity for an extended period of time or else you will burn it out. The experimental arrangement is shown in Fig. 1.5 The photomultiplier should be covered with a black cloth to shield it from room light leaking around the housing.

Adjust the tungsten filament D.C. supply voltage for near maximum brightness. Measure the brightness temperature, T_b, of the filament using the disappearing-filament pyrometer. For this measurement, the pyrometer needs to be more than 1m away from the lamp in order to get a good reading. Also, the trigger to light the pyrometer is a lever underneath the temperature scale, and there are lenses on the front and back which will need to be adjusted.

The pyrometer will read true temperature only if the source is a perfect radiator. For the tungsten radiator a correction temperature must be added to the brightness temperature to obtain the true temperature, T_t. A correction curve is supplied. Finally, *DO NOT FORGET TO CONVERT T_t TO KELVIN.* Make sure that this temperature and a second one 300° lower are both on the correction graph, and on the emissivity plot (Fig. 1.4).

Set the wavelength drive at about 500nm. Adjust the lateral position of the source for maximum signal on the scope using the automatic measuring function (at least 500mV). Take readings of $S(\lambda)$ at intervals of 25nm from 300 to 700nm.

Decrease the temperature of the filament by about 300K and repeat the above measurements.

Finally, with the lamp off, obtain a background spectrum and subtract this from each of the above spectra.

Produce values of I_w from the curves in Fig. 1.4 and values of $I(\lambda, T)$ cal-

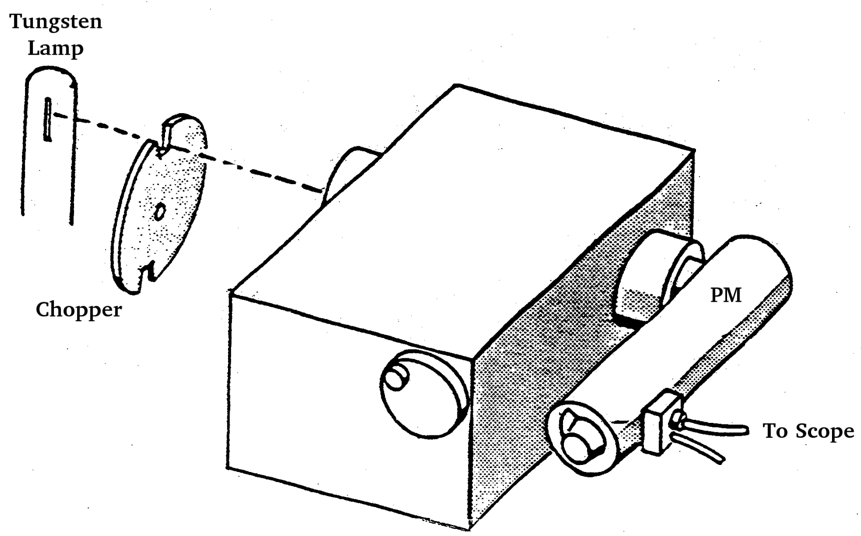

Figure 1.5: Experimental arrangement for measuring the wavelength response

culated from (1.3). Calculate and plot the response function $R(\lambda)$ for both temperatures. Since we are only interested in relative values, $R(\lambda)$ can be plotted on a scale with 1.0 as the maximum value. Because of the tedious nature of the calculations, you are asked to calculate only two separate values of I_w and $R(\lambda)$ by hand, to demonstrate that you understand how these values are obtained. The remainder of the I_w and normalized $R(\lambda)$ values may be computed using a program. Be sure to calculate uncertainties in order to evaluate results properly.

The normalized response function should be independent of temperature. Is it? If not, why not?

1.7 Relative Intensities of Helium Lines

Having determined $R(\lambda)$, you can now use the instrument to measure the spectrum of other light sources. As an example, you can measure the relative intensities of the lines emitted by a Helium Geissler tube.

1.7.1 Procedure

This part of the experiment should be done without the light chopper. Find the helium line giving the largest signal and arrange the Geissler tube so that the PM is not saturated for this line. Measure the signals and find the relative line strengths normalized to 1.0 for the strongest lines (see equation 1.2). Compare your results with other measurements.[1]

[1]www.hbcpnetbase.com; Section 10: Atomic, Molecular, and Optical Physics; Line Spectra of the Elements

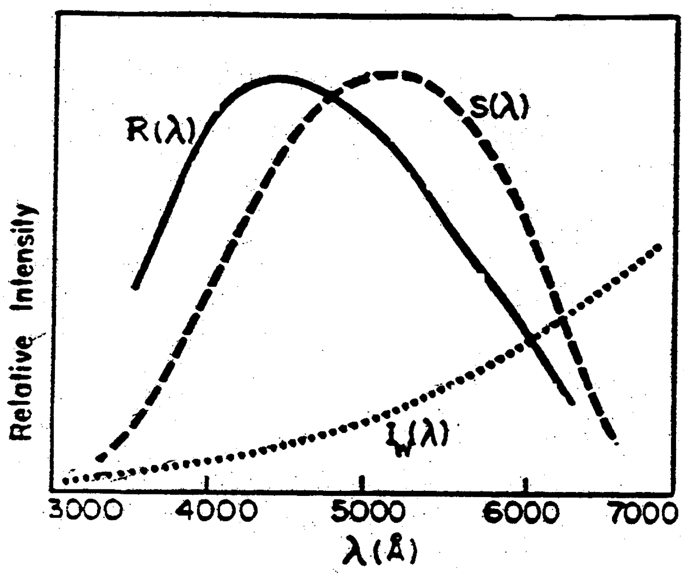

Figure 1.6: Intensity, Signal and Response Curves