SPECTROMETER ALIGNMENT

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BASIC APPROACH

Suppose a diffraction grating with line spacing *d* is situated in the *y-z* plane, with the rulings in the *y* direction, as shown in Figure 1.

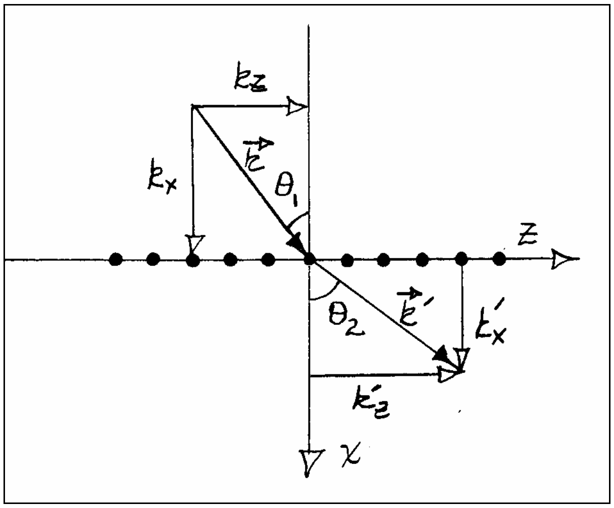

Figure 1. The basic geometry of a transmission grating.

A plane wave with wavelength λ and wave vector **k** is incident upon the grating, and a plane wave of wave vector **k′** is diffracted. The general diffraction conditions are as follows:

$$\begin{aligned} &k \equiv |\mathbf{k}| \quad k' \equiv |\mathbf{k}'| \\ &k = k' = 2\pi / \lambda \\ &k'_y = k_y \\ &k'_z = k_z \pm 2\pi m / d \quad m = 0, 1, 2, \ldots \end{aligned} \tag{1}$$

The first equation defines the magnitude of the wave vectors. The second equation expresses conservation of energy: the photon is elastically diffracted, so there is no change in wavelength. The third equation tells us that there is no change in the component of wave vector along the direction of the grating rulings. The fourth equation, which is the most important, tells us that the wave vector component in the z-direction must change by an integer multiple of $2\pi / d$. These equations are very general, and can be further generalized to three-dimensional periodic structures, which is the basis for x-ray diffraction.

Our spectrometer is set up so that $k_y = k'_y = 0$.[1] If we then define $\sin\theta_1 \equiv k_z / k$ and $\sin\theta_2 \equiv k'_z / k$, it is easy to derive the familiar diffraction equation in terms of angles:

$$\sin(\theta_2) - \sin(\theta_1) = \pm m\lambda / d \qquad (2)$$

For precision spectroscopy, we want θ_1 and θ_2 to be sharply defined. The traditional method for making θ_1 well defined is to place a narrow vertical entrance slit near the light source. The slit is followed by a focusing lens of focal length f, placed at a distance f downstream from the slit. The rays emerging from the lens will be parallel (collimated), and thus their directions will be sharply defined. This slit-lens combination is called a *collimator*. Similarly, θ_2 is well defined if rays at a diffracted angle θ_2 are focused by a *telescope* onto cross-hairs (the reticle) for subsequent viewing with an eyepiece.

It is also helpful, but not necessary, to set up the apparatus so that θ_1 is fixed and is equal to zero. That is, the incident rays are normal to the grating. Our grating equation then is trivial:

$$\boxed{\begin{aligned}&\sin(\theta_2) = m\lambda / d\\ &\lambda = (d/m)\sin(\theta_2)\end{aligned}} \qquad (3)$$

This configuration, with $\theta_1 = 0$, is shown in Figure 2 on the next page.

The basic approach, therefore, is to have a collimator fixed in space whose optical axis is perpendicular to the plane of a fixed diffraction grating. The diffracted light is then observed through a telescope that can be rotated about a vertical axis passing through the grating. Thus, the classic spectrometer consists of a fixed collimator; a table upon which the grating rotates (to set it once and for all to 0 degrees), and a rotating telescope arm.

MECHANICAL CONFIGURATION

Collimator: The collimator and slit assembly are rigidly attached to the main body of the spectrometer. The only adjustment of the collimator consists of the focusing knob, whose purpose is to render light from the slit parallel.

Telescope: The telescope may be freely rotated relative to the collimator by unlocking the clamping screw (just under the telescope). When the telescope is near its desired position, tighten the clamping screw and perform a fine adjustment with the fine adjust screw (also just under the telescope). Note that the fine adjustment screw will have no effect if the clamping screw is not tightened.

Grating table: There are several possible adjustments of the grating table, two of which are somewhat redundant. The rotation of the *table* about a vertical axis may be accomplished in three ways:

1. To the left of the collimator and near the base, there is a locking screw and a fine adjustment screw. With the locking screw loose, the grating table may be rotated

[1] Some spectrometers deliberately tilt the grating so that this condition is not satisfied. The spectrometer used in Physics 135 is an example of this, in the so-called Littrow geometry.

by hand. With the locking screw tight, the grating table may be rotated by adjusting the fine adjustment screw. *Note: both of these actions will change the vernier reading*.

2. You may coarsely adjust the grating table, without disturbing the vernier reading, by unclamping the table with the screw just under the grating table.

Finally, three vertical thumb screws may be used to tilt the grating table.

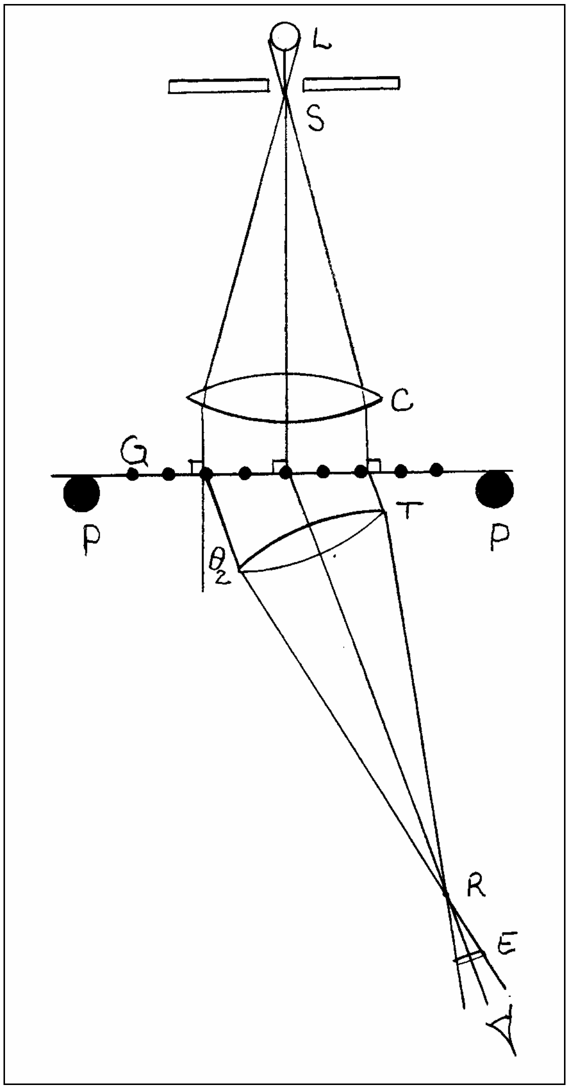

Figure 2. The optimal spectrometer configuration, with incident light normal to the grating. L is the light source, S is the entrance slit, C is the collimator lens, G is the grating, P are the locating posts, T is the telescope lens, R is the reticle, and E is the eyepiece.

Vernier indicator: The vernier scales measure the relative angle between the telescope and the grating. However, you may wish to set the vernier scales to a known value when, say, the grating is exactly perpendicular to both the collimator and the telescope.

ALIGNMENT OBJECTIVES
(See next section for alignment procedure)

Once you have become familiar with the general principles of operation and the various adjustment screws, you will need to align the spectrometer. Tracing the light from the source to your eye, a well-aligned spectrometer will have the following properties:

1. Collimator focus: Light rays entering the entrance slit (near the source) will be rendered parallel (collimated) by the collimator.
2. Grating normal (1): The grating *normal* should be perpendicular to the rotational axes of the spectrometer; *i.e.* it should lie in the horizontal plane.
3. Grating normal (2): Ideally, but not necessarily, the grating normal should be parallel to the axis of the input collimator; *i.e.* the plane of the grating should be perpendicular to the axis of the collimator. This ensures that the incidence angle, θ_1, equals zero degrees exactly, which greatly simplifies the analysis.
4. Grating rulings: The grating rulings should be vertical; *i.e.* parallel to the rotational axes of the spectrometer.
5. Telescope focus: Parallel rays entering the objective of the receiving telescope should be focused on the reticle of the telescope.
6. Telescope eyepiece: The telescope eyepiece should be adjusted so that the reticle is in focus when viewed by the observer.

ALIGNMENT PROCEDURE

Remove grating or mirror: The grating and the mirror are stored in plastic boxes at your bench. Always store the grating with the label on top; and always store the mirror with the front surface on top.

Set up light source: Remove the grating or the mirror from the grating holder. Plug a mercury Geissler tube into the tube holder, which in turn is connected to a variable transformer (variac). Set the variac to zero volts, and then turn the variac and tube switch on, and increase the voltage until the tube lights. It is best to turn it a little above this threshold, say 10 volts above, for the stability of operation. Place the collimator slit near, but not touching, the Geissler tube. It will also be helpful if you place a mask between the tube and the slit, to block stray light.

Unlock the telescope adjustment clamp (under the telescope), and rotate the telescope by hand until it is roughly parallel with the collimator. Once you are close enough, you will be able to see the direct beam from the slit. It may be blurry because one or both of the collimator/telescope combination may be out of focus, but you should still be able to see it and center the telescope crosshairs reasonably close to it.

Focus the telescope eyepiece on the crosshairs: Focus the telescope *eyepiece* on the reticle cross-hairs by moving the eyepiece slightly in or out of its sleeve until the crosshairs appear sharp to your eyes. We recommend aligning the cross hairs as an ($\times$) rather than as a (+) . This ensures a sharper definition of the horizontal position of the image, and hence a sharper definition of θ_2.

Preliminary focus of the collimator: Adjust the *collimator focus* (not the telescope focus) until you see a sharp image of the slit.[2]

Align the telescope parallel to the collimator: You should now adjust the telescope axis so that the cross hairs are in a fixed position relative to the luminous image of the slit. This is accomplished by locking the telescope adjustment screw and using the fine adjustment. You will notice that the entrance slit consists of a fixed blade and an adjustable blade.

Final focus of the telescope: A properly focused telescope renders incident parallel rays to be focused on the reticle (cross hairs). To accomplish this we will use the method of *autocollimation*.

Suppose, as a thought experiment, the reticle cross hairs were luminous. Light could travel forward from them, through the eyepiece, and you would see luminous cross hairs. Light could also travel backward from them, through the telescope main lens, and toward a mirror located at the grating holder, whereupon they would be reflected back through the telescope. If the telescope is focused at infinity, which is the desired outcome, the light rays falling on the mirror will be collimated (parallel); hence the reflected rays will be parallel and thus focused on the (luminous) cross hairs. The result will be that if the telescope is focused at infinity, as it should be, one will see two sharply focused images of the cross hairs: the primary light, and the reflected light. Furthermore, if the two images exactly overlap, then the mirror is exactly perpendicular to the axis of the telescope.

1. *Procedure:* Install the mirror into the sample holder, with the front surface of the mirror against the two precision vertical posts.
2. Connect the autocollimator lamp leads to the 12 volt battery.
3. Unlock the grating holder clamp (just below the grating holder), and rotate the mirror until you see the reflected image of the crosshairs, along with the primary image of the crosshairs.
4. Adjust the telescope focus until the reflected image of the crosshairs is sharp.
5. After this step, *never* readjust the telescope focus; it should now be focused at infinity and there is never a need to change it.

Adjust the normal to the mirror: The mirror is held in place by spring clips that push the mirror against a pair of precision-ground posts (see the final notes at the end). Adjusting the mirror, in turn, adjusts the grating when it replaces the mirror. Ultimately, we would like the normal to the grating (mirror) to be parallel to the rays emerging from the collimator. Since the telescope axis is now accurately parallel to the collimator axis, it will be sufficient to align the mirror to the axis of the telescope rather than to the collimator. This will require both a table tilt adjustment, and a careful adjustment of the rotational axis of the mirror.

[2] This step will be refined later. At this point it only ensures that the combination of collimator focus and telescope focus gives a sharp image. At this stage it does not guarantee that the beam is collimated at the grating holder.

The first step is to set the vernier to a convenient value. To accomplish this, unlock the fine control clamp (lower left, toward the rear) and rotate the grating table by hand until the vernier is near the desired value (90 degrees, 270 degrees, or some other convenient value). Then lock the fine control clamp and adjust the fine control screw (also lower left, toward the rear) until the vernier reads exactly the desired number.

Now, loosen the grating table upper clamp and rotate the grating table until the two pairs of crosshairs horizontally overlap. Carefully re-clamp the grating table. Note that re-clamping the table may disturb the setting, so this step may need to be repeated several times.

The forward-backward tilt of the mirror is accomplished by adjusting the leveling screws on the grating holder to tilt the mirror so that the cross hairs vertically overlap.

You may have to repeat these two steps a couple of times until the cross hairs precisely overlap. Note that the table tilt adjustment is not as critical as the rotation adjustment. When these two steps are successfully completed, the two cross-hairs should be accurately coincident and the vernier scale should read a standard number (say 90 or 270 degrees). You should now disconnect one lead of the autocollimator lamp from the battery.

Final focus of the collimator: In an earlier step we made a preliminary adjustment of the collimator focus. Now that the telescope is focused at infinity, you may *gently* (see below) remove the mirror, and adjust the focus of the *collimator* (*not* the telescope) to obtain a sharp image of the Geissler tube.

Final notes:

1. You will notice that the grating table, which is supported by three spring-loaded thumb screws, is the least solid component of the spectrometer. As a consequence, you need to be very delicate when you swap the mirror for the grating, and vice versa. You are advised to repeat the alignment steps from time to time, to make sure that the grating table has not been bumped out of alignment. Once you are familiar with the procedures, realignment will not take too long.
2. The grating is clamped between a pair of vertical posts and a pair of spring clips. The table should be oriented so that the posts are on the downstream (telescope) side of the grating. This ensures that the plane of the rulings passes through the vertical axis of the spectrometer.
3. The grating design constant $1/d$ is actually 7500 lines per inch (they were made in England). For some bizarre reason, the manufacturer labeled the gratings as $1/d$ = 300 lines per millimeter, which is off by about a percent. *Caveat emptor*!