THE THERMAL LENS EFFECT

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I. INTRODUCTION

When a narrow laser beam shines through a nearly transparent liquid, a small amount of the incident energy is locally absorbed by the sample along the laser beam. When this local heating occurs, the refractive index of the medium also changes locally along the beam, and the entire medium acts as a lens. This effect is called thermal lensing or thermal blooming. For very pure liquids such as water or the various alcohols, the length of sample necessary to attenuate the beam to a tenth of its original intensity can be many meters. The thermal lens effect allows the measurement of this attenuation length in laboratory-sized samples centimeters long. In this experiment, the attenuation properties of carbon tetrachloride (CCl_4) are measured using the thermal lens effect. This write-up is organized into four parts. The basic physical ideas are outlined in the first part. The second part displays the basic equations that govern the effect. They are to be found in an article by Joel Harris, "Thermal Lens Effect ", in the series *Chemical Analysis,* Vol. 87, *Analytical Applications of Lasers,* E. H. Peipmeier, Ed., that you can consult in the library for more detail (the volume is on reserve in the E&S library, call number 543.085 A532). The third part of this write-up describes the experiments you must do, and the fourth part provides detailed instructions and hints about making the measurements described in the third part.

The use of the thermal lens and related effects in analytical chemistry is becoming remarkably widespread, particularly in the determination of trace amounts of chemicals in solvents. Variations of the thermal lensing effect are also used in condensed matter physics. Thermal blooming must also be dealt with when propagating a laser beam through the air over long distances. Students interested in the range of applications can consult the article by Imasaka and Ishibashi in Progress in Quantum Electronics, Vol. **14,** 1990. See particularly sections 4.3 through 4.7.

II. THE BASIC PHYSICS

Before you can understand thermal lensing, you need to review the behavior of simple thin lenses. Get an introductory physics text and review reflection and refraction at planar interfaces and how convex (converging) and concave (diverging) lenses bend light rays. Answer the following questions in your notebook:

A. Sketch the light rays as a parallel beam passes through a converging lens.

B. Sketch the light rays as a parallel beam passes through a diverging lens with a very long focal length. If a screen is placed some distance after the lens, how does the size of the spot on the screen vary as the focal length becomes shorter, i.e. the lens becomes "stronger".

C. Now consider the set up you have in this experiment: a parallel beam passing through a converging lens followed by a weak diverging lens and then hitting a screen. Use simple ray tracing to show: (1) the size of the beam spot on the screen decreases when the diverging lens is inserted between the converging lens and its focal point; and (2) the size of the beam spot on the screen increases when the diverging lens is inserted beyond the focal point of the converging lens.

The amount of expansion can be expressed in terms of the focal length of the induced lens. The shorter its focal length, the greater the beam expansion. Since the effect is small for moderate laser power and a slightly attenuating sample, the first approximation is to assume that the effect is linear in laser power, and that the lens can be treated by the "parabolic lens approximation". Then we expect that the magnitude of the induced (negative) focal length will depend on laser power P and on the rate at which energy is deposited, PA, where A is the sample absorbance. The temperature rise and temperature profile in the sample near the beam depends on the rate at which the deposited heat is conducted away from the region of the beam, which is determined by the thermal conductivity, k, of the sample. One expects that the larger k, the smaller the induced effect. So the strength of the induced lens can be expected to be inversely proportional to k.

It is a curious feature that the steady state induced lens strength depends only on the above quantities, and the wavelength of light. But other properties of the liquid govern how rapidly the lens is developed. The conversion of absorbed energy to temperature rise is determined by the combination ρC_p , where ρ is the density and C_p is the heat capacity at constant pressure of the fluid. The time scale is also inversely proportional to the thermal conductivity, and depends on the diameter of the beam in the sample.

Note that the thermal lensing effect is a *nonlinear* optical phenomenon, i.e. the light effects the refracting properties of the medium and these altered properties in turn effect the distribution of the light in the medium. Also note that while we normally think of a lens as an object with curved sides and a constant internal index of refraction, here we have the same lensing effect from an object with parallel sides but an index of refraction which varies within the object

III. THE EQUATIONS

There is one basic equation that governs both essential aspects of the thermal lens effect: the sample's position dependence, and its time dependence. There are also several equations that define and relate some of the variables and constants that appear in this basic equation. The fundamental measurement ought to be the expansion or contraction of the beam as the thermal lens develops. Rather than making that difficult (and expensive) measurement, it is sufficient to measure the intensity of the center of the beam at a large distance away from the sample. If the beam expands, the intensity of the laser light at the beam's center will drop. It is important to recognize that this decrease is *NOT* due to the absorption of energy in the sample, which is unmeasurably small. Similarly, we expect that if the beam's diameter contracts, the intensity at the center of the beam will rise. That intensity is sensed by a photo-transistor that looks at the beam through a 100μm hole. There is also a narrow-band optical filter in front of the photodetector that lets through only light of the He-Ne laser's wavelength, λ, which is 632.8 nm. The filter allows the experiment to be conducted in room light. Figure 1 shows a block diagram of the apparatus.

We call the intensity at beam center as a function of time *I(t)*. To avoid proliferation of notation, we will use *I(t)* to indicate the voltage recorded on the digital storage oscilloscope after amplification of the photo-transistor's signal. That is to say that *V(t)* is taken to be *I(t)*. The basic equation, then, is:

$$I(t) = I(0)\left[1 + \frac{\theta}{\left(1+\frac{t_c}{2t}\right)}\left(\frac{2\gamma}{1+\gamma^2}\right) + \frac{\theta^2}{\left(1+\frac{t_c}{2t}\right)^2}\left(\frac{1}{1+\gamma^2}\right)\right]^{-1} \tag{1}$$

In equation (1), θ is defined as:

$$\theta = 2.303\left(-\frac{dn}{dT}\right)\frac{PA}{\lambda k} \tag{2}$$

where dn/dT appears with a negative sign because for most liquids at most temperatures dn/dT is negative (water near 0°C is an exception) and θ must be >0. In your lab book, verify that θ is a dimensionless number. For H_2O at room temperature: the thermal conductivity k = .606 W m^{-1} K^{-1}, C_p = 4.184 J gm^{-1} K^{-1}, ρ = 977.8 kg m^{-3}, and dn/dT = -2.25 x $10^{-5}K^{-1}$.
Also in equation (1), γ is the reduced sample position, given by:

$$\gamma = \frac{Z}{Z_c} \tag{3}$$

where Z is the position of the sample relative to the focal plane of the positive lens (see the discussion of the position measurement for a more precise definition), and Z_c is the confocal length, defined later in equation (6).
Also from equation (1), t_c is the characteristic time for the development of the thermal lens in the sample, given by:

$$t_c = \frac{\omega_1^2 \rho C_p}{4k} \tag{4}$$

where ω_1 is the beam radius in the sample. See the brief discussion below of Gaussian beams for the physical meaning of "beam radius" and the associated concept, the beam waist.

The beam radius seen in equation (4) is dependent on the sample position as given by:

$$\omega_1^2 = \omega_0^2\left[1+\left(\frac{Z\lambda}{3\pi\omega_0^2}\right)^2\right] \tag{5}$$

where ω_0 is the "beam waist radius". Equation (5) does not describe the beam behavior in the *geometric* optics limit, but rather describes the propagation of a highly coherent, Gaussian laser beam. The confocal length, Z_c, from Gaussian optics is given by:

$$Z_c = \frac{3\pi\omega_0^2}{\lambda} \tag{6}$$

Warning: textbooks discussing Gaussian optics do not have the factor of 3 in the definition of confocal length. It appears here out of convenience, as an artifact of the theory of the modified parabolic lens approximation that produced equation (1).

Gaussian beams are produced by lasers that operate in what is known as the TEM_{00} mode. The 20 milliwatt Helium-Neon laser used in the lab is supposed to be a TEM_{00} laser. Unfortunately, the beam is contaminated by other modes, and as a result some of the measurements you make will seem to contradict the requirement of the theory that the beam be Gaussian. The beam waist spot size, ω_0, and the confocal distance (or Rayleigh length), Z_c, are both important parameters in this experiment. If the mode is indeed a TEM_{00} mode, then the beam intensity in the radial direction obeys this equation:

$$I(r) = \left[\frac{2P}{\pi\omega_0^2}\right]\exp\left(\frac{-2r^2}{\omega_0^2}\right)$$

where r is the distance in the radial direction. The equation is unnumbered because you won't be using it, but it serves to define ω_0. Note that at $r = \omega_0$ the intensity is down by a factor of e^{-2} from the intensity at r = 0.

IV. MEASUREMENTS

You will make two basic kinds of measurements: position measurements and time measurements. The time measurements will be compared to equation (1) for particular values of γ, but before that comparison can be done, you must have some idea of the magnitudes of the parameters Z_c and θ. To get estimates of these variables, you need to make rather careful position measurements - essentially the magnitude of the effect as a function of the position of the sample.

(a) Position measurements.

The last equation we need is derived from the basic equation. You should derive (and show the derivation in your laboratory notebook) that the quantity $\Delta I/I = [I(0)-I(\infty)]/I(\infty)$ can be obtained from equation (1) to get:

$$\frac{\Delta I}{I} = \theta\left(\frac{2\gamma}{1+\gamma^2}\right) + \theta^2\left(\frac{1}{1+\gamma^2}\right) \tag{7}$$

The position of the sample is to be read from the vernier scale on the rail on which the sample is mounted. Your measurements of *ΔI/I* as a function of position will allow you to determine the parameters θ and Z_c. It is not important to pay attention to any of the time dependence (even t_c) while doing the position measurements.

Assume θ is small, let's say 0.1. Now analyze equation (7) to first order in θ. Record answers to these questions in your notebook: Where is *ΔI/I* zero? Where is it a maximum, a minimum? What happens at large values of γ? Sketch the function in your notebook. What effect does the second order term have on the aspects of the curve listed above?

It is important to know what, exactly, Z is measuring. As stated earlier, Z is the distance from the focal plane of the positive lens to the position of the sample. We read the position of the sample off of the scale at the base of the sample holder in units of cm from about 30 to 60. It is important to note that these numbers ARE NOT values of Z! They are, rather, measurements of some other position variable we'll call X. There is some position in X which corresponds to the location of the focal plane of the positive lens, which we'll call X_0. In order to get Z, we need to subtract the value of X from the value of X_0; in other words, $Z = X_0 - X$. X_0 will be somewhere near 42 on the track. Subtracting X from this value will make it so that the negative values of Z are closer to the positive lens (i.e., $\gamma < 0$ in that direction) and positive values of Z are farther away from the positive lens (i.e., $\gamma > 0$ in the other direction). Then from equation (7), for values of $X < X_0$, $\gamma > 0$, making $\Delta I/I > 0$ and $I(0) > I(\infty)$. This implies that the thermal lens trace will have a *downward* swing to it in time. One can expect basically the opposite for positions on the track $X > X_0$.

We don't know right away the location X_0 better than to say that it is near 42.5 on the scale, but that's OK. When one is estimating the value of θ, one only needs the vertical value of the maximum and minimum of the $\Delta I/I$ vs. position curve. This means that one can plot $\Delta I/I$ vs. X (instead of Z) to get this result. Later, when we want to try to fit our results to equation (7), we need to translate X into Z, and so we need to know X_0. One way to find the approximate value of X_0 (which you should do for yourself to prove that it is near 42.5) is to move the sample holder back and forth along the track until the beam spot on the face of the cuvette appears to be smallest. This point is approximately X_0. Another, perhaps better way to do this is by fitting the $\Delta I/I$ curve.

(b) Time measurements.

Equation (1) gives the time dependence of I(t). The unknown parameters of the equation are t_c, θ, and Z_c. You will need the results of the position measurements in order to provide a value of Z_c (and consequently γ). You will make the time measurements in the vicinity of $\gamma = \pm 1$. The quantity I(0) can be determined with sufficient accuracy as long as the time per division is short enough to give a reasonable measure of this amplitude. You will know from your preliminary studies and from having done the position measurements how short that time is. The total sweep time may not be enough to get a reasonable approximation of $I(\infty)$, but that is not needed and can be ignored. The major time dependence of the signal occurs within a few multiples of the characteristic time, t_c, so best practice is to use a sweep time that does not last a very large multiple of t_c, as was done for the position measurements. More detailed instructions are given below.

V. EXPERIMENTAL PROCEDURES.

LASER SAFETY

IF THE LASER BEAM OR THE SPECULAR REFLECTION FROM ANY SURFACE STRIKES YOUR EYE, SERIOUS EYE DAMAGE WILL RESULT. THE RULES FOR USE OF THE LASER ARE POSTED ON THE WALL. READ AND THEM AND DISCUSS THEM WITH THE INSTRUCTOR BEFORE YOU BEGIN THE EXPERIMENT. THESE ARE A FEW KEY POINTS:

WHETHER THE BEAM IS ON OR OFF, DO NOT LOOK ALONG THE BEAM PATH.

DO NOT PLACE ANYTHING INTO THE LASER BEAM UNLESS THE BEAM SHUTTER IS CLOSED.

IF YOU NOTICE ANY STRAY REFLECTION - I.E. A SPOT OF RED LIGHT APPEARING ON ANY SURFACE OTHER THAN THE APPROPRIATE OPTICAL ELEMENTS, IMMEDIATELY CLOSE THE SHUTTER TO THE LASER AND INFORM THE INSTRUCTOR.

DO NOT SIT IN A CHAIR WHICH PUTS YOUR EYES AT BEAM LEVEL DURING THE EXPERIMENT.

ASK THE INSTRUCTOR TO MAKE BEAM ALIGNMENT ADJUSTMENTS WHEN YOU ARE READY TO MAKE OBSERVATIONS OF THE THERMAL LENS EFFECT. DO NOT ATTEMPT TO MAKE YOURSELVES.

Electronics

The digital scope has some characteristics and some limitations that one must understand and work around in developing measurement techniques for this experiment. Each display screen is obtained by the instrument by sampling the incoming signal 500 times. Consequently one cannot see temporal features that last less than 1/500 of the total sweep time, or 1/50 of the sweep time per division. This limitation has consequences when trying to measure both $1(0)$ and $I(\infty)$ on the same sweep.

Since for this experiment both $1(0)$ and $I(\infty)$ are represented by signals at the one volt level, and they differ by the order of 100 mV at most, in order to display the signal on the screen with, say, 20 mV/division sensitivity, it is necessary to set the offset to about 900 millivolts. Since each trace is initiated by opening the shutter so that the initial signal goes from zero to 900 mV or so, it is sometimes useful to trigger at a low level. That can be done by putting the signal into another channel, say channel 2, and triggering on a positive-going edge of the signal into channel 2. Since one is not observing this signal, no offset is needed, and the trigger level can be set to any level desired.

Noise, Other Sources of Error, and Time Scales.

Note: Throughout the description of the procedures, we have suggested choices for the time and voltage offsets and sensitivities. These are only suggestions and the best settings change as the apparatus drifts and is realigned. Think about what you are trying to characterize of measure and you choose the best settings.

Before proceeding with quantitative measurements, it is necessary to understand the nature of the noise and other systematic errors involved in this experiment and the techniques you need to reduce them as much as possible. In this section of the experiment, you will investigate a number of phenomena which will serve to confound your results throughout the experiment. Understanding their nature and how to best avoid confusing their effects with the thermal lens effect is crucial to gleaning any physics from the experiment. For each of the following sections, spend a brief amount of time (*no more than 5 to 10 minutes or so for each effect*) studying the effects of the difficulties and understanding how to avoid them.

The first source of error is background effects. Remove the sample from the beam, open the shutter and examine the signal on either the analog scope *(ac* coupled, at least 100 mv/division gain setting) or the digital scope, set to auto trigger (ac coupled, 100 or less mV/division). Both scopes should have a time sweep of about 10 ms/division. You *MAY* see a fairly large signal (20-50 mV or more) that has a frequency component near (but not exactly at) 60 Hz. This signal is probably caused by the "rumbling" of the air conditioning system. The optical system is sensitive to "microphonics" because if a mirror has a piece of dust on it, that dust scatters light that interferes with the main beam. As optical elements vibrate, the interference fringes move relative to the pinhole, and the fluctuations in the detected light occur. If the problem is at all noticeable, blow dust off all the mirrors gently with the "air can". If the effect is not visible, you may proceed.

With the signal is as quiet as possible and the sample still out of the beam, observe the effects of banging on the table with your hand, loud talking, and ambient air currents. You can stir up the air near the beam by waving a hand or a piece of paper near the beam. These observations should help you establish the conditions necessary to maximize the signal to noise in this experiment.

The second source of error is laser power drift. Observe fluctuations caused by changes in the laser power. A 1% fluctuation in laser power, which is within specifications for this laser, would produce a 35 mv signal out of 3.5 volts DC signal. That much change is readily seen in this experiment, and represents a source of noise that is not readily accounted for by the standard statistical analyses of the individual runs. If it occurs on a typical time scale of tens of seconds, it does not usually disturb individual measurements significantly. Observe the signal on a time scale of 1 sec/division.

The third of these sources of error is the phenomenon of convection inside the sample cuvette. This phenomenon has a nasty habit of throwing off results and making certain experimental measurements not reproducible. However, these convective processes can be suppressed if the proper measures are taken. Herein, we seek to qualitatively observe the convection phenomenon and make a pseudo-quantitative estimate of the time at which the phenomenon sets in.

1. Put the sample back in the beam.

2. Open the shutter and aim the beam such that it is basically focused on the vertical center of the sample in the cuvette. Do not worry about the oscilloscope readout just yet.

3. Move the sample holder such that the small vernier scale on the base of the sample holder coincides with a value on the track somewhere in the vicinity of 45.5 cm (this need not be exact, but the sample should be between 43 and 47 cm on the track). You should notice that the beam spot is comparatively small on the cuvette face.

4. Close the shutter and wait a few minutes before proceeding. This allows the convection effects that have been occurring while aligning the sample properly to settle out.

5. While waiting, set the oscilloscope to 1 sec/div, 0 ms delay, 20 mV/div, 950.0 mV offset, and auto trigger.

6. Once you have waited the proper amount of time, open the shutter and watch the oscilloscope trace. If the trace is not on the screen, the offset needs to be adjusted up or down according to whether a bright green line traces on the top or bottom edge of the screen. When you find it, you should notice that the trace will begin sort of level and then begin to pseudo- systematically wander up and down as time passes. This wandering will persist across multiple full sweeps across the oscilloscope screen. This signal wandering about is due to the convection effects that are occurring in the cuvette.

7. When you have finished observing this effect, close the iris and wait another few minutes. Set the oscilloscope to 100 ms/div, triggered trigger (not auto), but leave the other settings the same.

8. When the proper amount of time has elapsed, open the iris and watch the trace appear on the screen. You will notice that it has a definite upswing in the first part of the trace. The trace should then begin to level off. However, after some characteristic time, the trace will begin to spread in vertical width and wander as it did previously. This characteristic time marks the onset of the convection processes. Determine, roughly, this time. You should note that measurements taken after the iris has been open for this amount of time will not be reliable, as shown in the previous part of this excursion!

Another way to observe the effects of convection are to take a 'snapshot' of the effect and then quickly take another snapshot. That is, don't wait for the convection effects to settle out and then try to take data. You will see the difficulty in doing this type of procedure.

To be safe, it is good technique to keep the shutter closed as much as possible, and leave it open only during measurements. If no convective instabilities develop, then the sample can be expected to recover in the absence of the beam in several tens or hundreds of time constants t_c. Since that time is never more than 200 ms for the positions Z used in the experiment, in the absence of convective instabilities the experiment can be repeated fairly rapidly. But one should use caution and be aware of the traps and errors that can be induced by too rapid repetition of the experiment when taking quantitative data.

The third source of error is setting up interference fringes between direct and reflected beams. Move the sample to about 45 on the track. Open the shutter and aim the beam that is reflected from the second face of the cuvette back along the direct beam. You should see the reflected spot appearing on the rear face of the iris. Set the oscilloscope to 5 ms/division, -5 ms delay, 50 mV/division, and about 950 mV offset. Close the shutter and briefly wait for convection effects to settle. Open the shutter and observe the signal. If the reflected beam is pointing back along the direct beam's path, you should have a terribly noisy signal. Repeat the close/open shutter bit a few more times to satisfy yourself it wasn't simply a poor data set.

When you are satisfied it was not simply a single data set that was bad, open the shutter again. Now aim the reflected beam to the side (left or right) of the hole in the iris so that you can see the beam spot on the black part of the iris. Now try the close/open shutter bit again. You should see a nice, clean thermal lensing signal. Naturally, you want to avoid that interference etalon effect at all costs.

Another source of error is the measurement of I(0). To investigate the small time behavior of the apparatus, set the digital scope to the time scale of 200 μs/division. Set the delay to -200 μs, the trigger level to about a half a volt (you should verify that the level is not critical), and the trigger to be enabled with a positive-going edge. The sample should be in the beam, with the beam going through the top of the sample for this part of the experiment.

The vertical scale should be set to 100 mV/div, and the offset to somewhere in the vicinity of 900mV. Set the trigger mode to triggered (not "auto"), and press the "single" button, the second from the left in the top row of buttons. The scope should indicate it is awaiting trigger. Close the shutter if you have not already done so. The scope should not trigger since closing the shutter generates a negative going edge, and the scope should be set to trigger off a positive going edge. Wait a minute, then open the shutter. Note the initial wavy motion of the oscilloscope trace up and down. This is due to the interference effects associated with the edge of the shutter running past the beam. Also note the time scale on the scope over which the signal is essentially constant. You should repeat these observations several times.

Now lengthen the sweep time to 5 ms/division, delay -500 μs. Then each sample is 0.1 ms, and the sampling occurs at an uncontrollable (by the experimenter) time during that interval. Repeat observations several times, paying attention to the level of the first sample data point. Remember, this level is going to be used for your I(0) measurement in the position data. The purpose of these observations is to make you aware of the uncertainties, and occasional outright and obvious inaccuracies, in the measurement of I(0).

Remember, if the sweep time allowed to be too many t_c's, not only will long term drift (very low frequency noise) be more likely to contaminate the run, but the very first data point will be averaged over an interval that could be a significant fraction of t_c. So compromises must be made. As an aid, graphs for two values of θ and γ of $\Delta I(t)/I(\infty)$ are attached (see figures 2-4). They essentially plot the signal shape, normalized to $I(\infty)$, out to 100 t_c. In using these one can estimate the possible systematic error in your measurements, since you measure "$I(\infty)$" at a finite time. Don't forget, using the graph for γ=l, θ=0.24 as an example, that your entire signal's amplitude at t = 0 is only $1+\theta+\theta^2/2=1.2688$. The graphs will help you to determine the possible systematic error in your measured value of $I(\infty)$ for the time at which the sweep ends.

Measurement Procedures

Common to both the position and time measurements is the need to know the laser power, P, since the value of θ will vary directly with the power. It will also be needed to eventually convert the measured quantity θ into the sample absorbance, *A*. θ depends on P but A does not. Thus, as you make measurements, values of A are unaffected by drift of P while values of θ are. You should monitor P at each time and position measurements.

Measure the power of the beam with the power meter sensor positioned both before and after the sample cell. Since the sensitivity of the meter varies across its face, you will increase your precision (it not necessarily your accuracy) by making sure you position the power meter consistently both laterally and along the track.. The measurements before and after the sample will differ by a quite noticeable amount. Why?. Write your answer in your notebook. Does it make sense given that about 4% of the light is reflected out of the beam at the front air/glass interface and another 4% at the rear glass/air interface? Convince yourself that the power of the beam in the sample is approximately the average of these two readings. (Be sure the meter is calibrated for the He-Ne wavelength. See the instructor.)

Procedure for the position measurement

The object is to measure the quantity ΔI/I as a function of the sample position, Z. Begin by determining experimentally the position at which ΔI/I ~ *0.* Then determine with a quick series of observations where ΔI/I is roughly maximum, both positive and negative. Use a sweep rate of 20 to 50 ms/division for these measurements. The confocal distance Z_c is approximately half the distance between the positive and negative maxima. You next want to carefully measure *ΔI/I* from outside γ = -1 to outside γ = +1, taking special care and extra data points near γ = ±1. Determine and record $I(\infty)$, I(0), and ΔI (in voltage units) by using the ΔV/Δt markers on the digital scope.

You need to establish the uncertainty on your measurements. You have now seen that there are fluctuations of the measured values of I on the time scale of a single measurement, on the scale of the time between individual measurements, on the scale of the time needed to make an entire position sweep, and day to day variations. How will you handle these complex fluctuations and drifts to determine valid uncertainties to be used in curve fitting and uncertainties in your final reported values of parameters? Should you be seeking uncertainties in I(∞), I(0), or ΔI when you make multiple measurements at fixed Z? How might they be related? How fast do you need to sweep though Z values as opposed to making multiple measurements at a single Z before moving on to another Z value? Will you be able to compare I values measured on different days? But the values of the absorption in the sample does not drift from day to day. How can you get the most precise value for the absorption and give your measured value a justified uncertainty? This is one of the more complex parts of this experiment. Come up with ideas and then discuss things with the instructor.

Detailed suggestions about making the measurements follow:

The Δt option is to be disabled.

Trigger: Trig'd (shutter closed)

ΔV: Always use the same one for *I(0)* (Vmarker2) and the other for *I(∞)* (Vmarker1). The difference in voltage (displayed at the bottom of the oscilloscope screen along with the two actual voltages) is Vmarker2 - Vmarker1 (which is I(0) - I(∞), or ΔI). The object is to record the voltages corresponding to *1(0)* and *I(∞),* and the difference between them.

Push the button marked 'Single' (check for message "awaiting trigger").

Open the shutter by pressing and releasing the shutter control button. The shutter should be set so that it is open for a set amount of time and then closes automatically. If it does not close, try pressing and releasing the shutter control button again. On the other hand, if it does not stay open long enough to get a full sweep on the screen, adjust the dial on the side of the shutter toward the lens to a smaller number.

Select the V(0) marker and adjust it to lie on the first point or an appropriate extrapolation of the curve to t=0. Use care and judgment here and record in your lab book how you chose V(0).

Select the V(∞) marker and adjust it to lie on the average of the presumably constant points (except for noise) at the end of the trace.

Record *V(0), V(∞),* and ΔV and repeat for the next measurement.

Take at least four or five measurements for each sample position Z.

Plot the values of ΔV/V as you take the data. Plotting will help you decide where in Z you will need to take more data and when to repeat measurements.

When you have finished taking data, you should have a curve which has a minimum, a zero, and then a maximum. It is not necessary to get too much data past the two extrema in the curve, as the distant points mostly show the decay of the effect at large Z. You should convince yourself that this is true by taking at least a few points at large Z of, say, 55 and 35 on the Vernier scale.

Once you have your plot, the value of θ is quite easily found.

Is the small θ approximation limit you made earlier reasonable? Can you see the impact of the θ^2 term? Now that you have located the positions of $\gamma=\pm1$, go back and make careful measurements of the $\Delta V/V(\infty)$ and the laser power. From these measurements determine a value and uncertainty for A as measured from the maximum and the minimum. Are they the same? If not, there must be something wrong with the model. Discuss with the instructor how these results can still be useful.

A is the fraction of power absorbed in the sample. Is it big? Does your answer make sense in light of the color of the sample? If this fraction of the power is absorbed in a 1 cm sample, and the fraction of power absorbed depends on the sample length, L, as $A = 1 - \exp(-\alpha L)$, how long would the sample have to be to absorb 10% of the light? Determine α, the absorption length of water. α is the fundamental quantity since it is a property of the material and not the specific sample being measured.

Next, you may determine a value for the confocal length, Z_c, by deducing that when $\Delta I/I$ is a maximum or minimum:

$$Z_c \approx Z_0 \tag{8}$$

Once you get Z_c**,** you can then find the beam waist radius of the laser from equation (6).

Procedure for the time measurement

From your position data, select the points Z for which you estimate that $\gamma = 1$ and $\gamma = -1$. You will take the time-dependent data only at those points. Set the digital scope as in the position measurement, except the time scale and delay should be smaller. Try perhaps 10ms/division, with -10ms delay. You might want to experiment with shorter or longer sweeps as well. If one measures the intensity at a time $t_L=0.5t_c$, the ratio of the intensity $I(t_L) = I(0)/B$, where B is given by:

$$B = 1 \pm \frac{1}{2}\theta + \frac{1}{8}\theta^2 \text{ at } \gamma = \pm 1 \tag{9}$$

Then if we measure I(0) and divide it by B, we get $I(t_L)$. The object is to then look at a given trace and find the time at which the intensity has risen (or fallen) to $I(t_L)$. This time is t_L, which we multiply by 2 to get t_c. You should make at least 5 measurements of t_L at both $\gamma = \pm1$, but don't be afraid to take more than that. You should feel confident that your value of t_c is not wavering considerably with time (i.e. the value of t_c should probably not agree with, say, 0).

From the value of t_c and knowing that $Z = Z_c$ at $\gamma = \pm1$, we find that the beam waist radius can be found from combining equations (4) and (5) as:

$$\omega_0 = \sqrt{\frac{2kt_c}{\rho C_p}} \tag{10}$$

We can calculate ω_0 from equation (10) and then compare with our previously found value of the beam waist radius. How do these two values compare? Are they both the same order of magnitude?

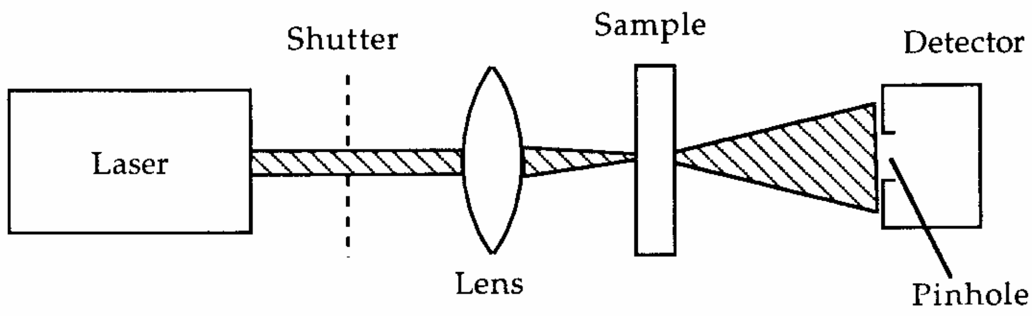

Figure 1 Block diagram of apparatus

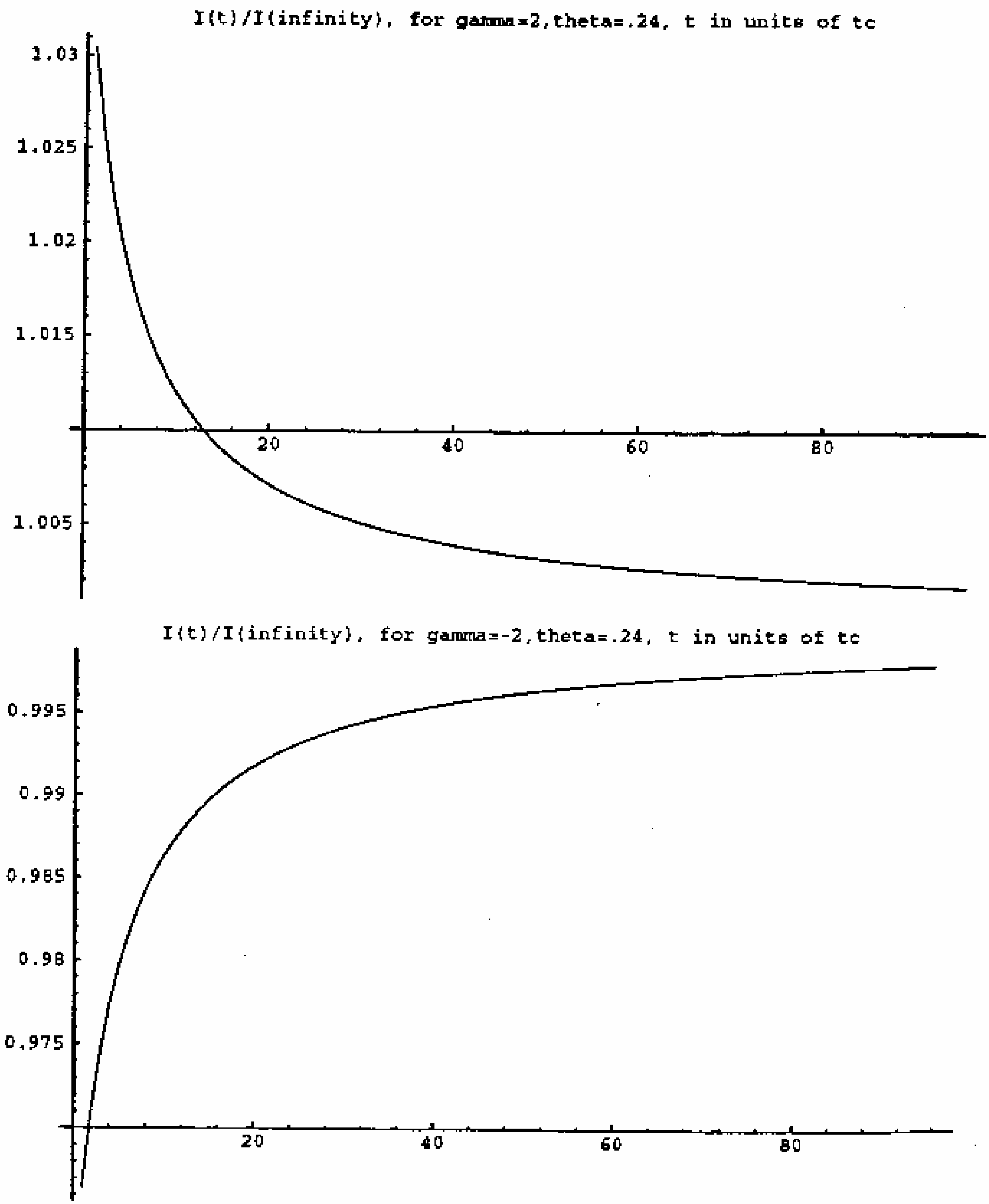
I(t)/I(infinity), for gamma=2,theta=.24, t in units of tc
1.03
1.025
1.02
1.015
1.005
20
40
60
80
I(t)/I(infinity), for gamma=-2,theta=.24, t in units of tc
0.995
0.99
0.985
0.98
0.975
20
40
60
80

Fig 2

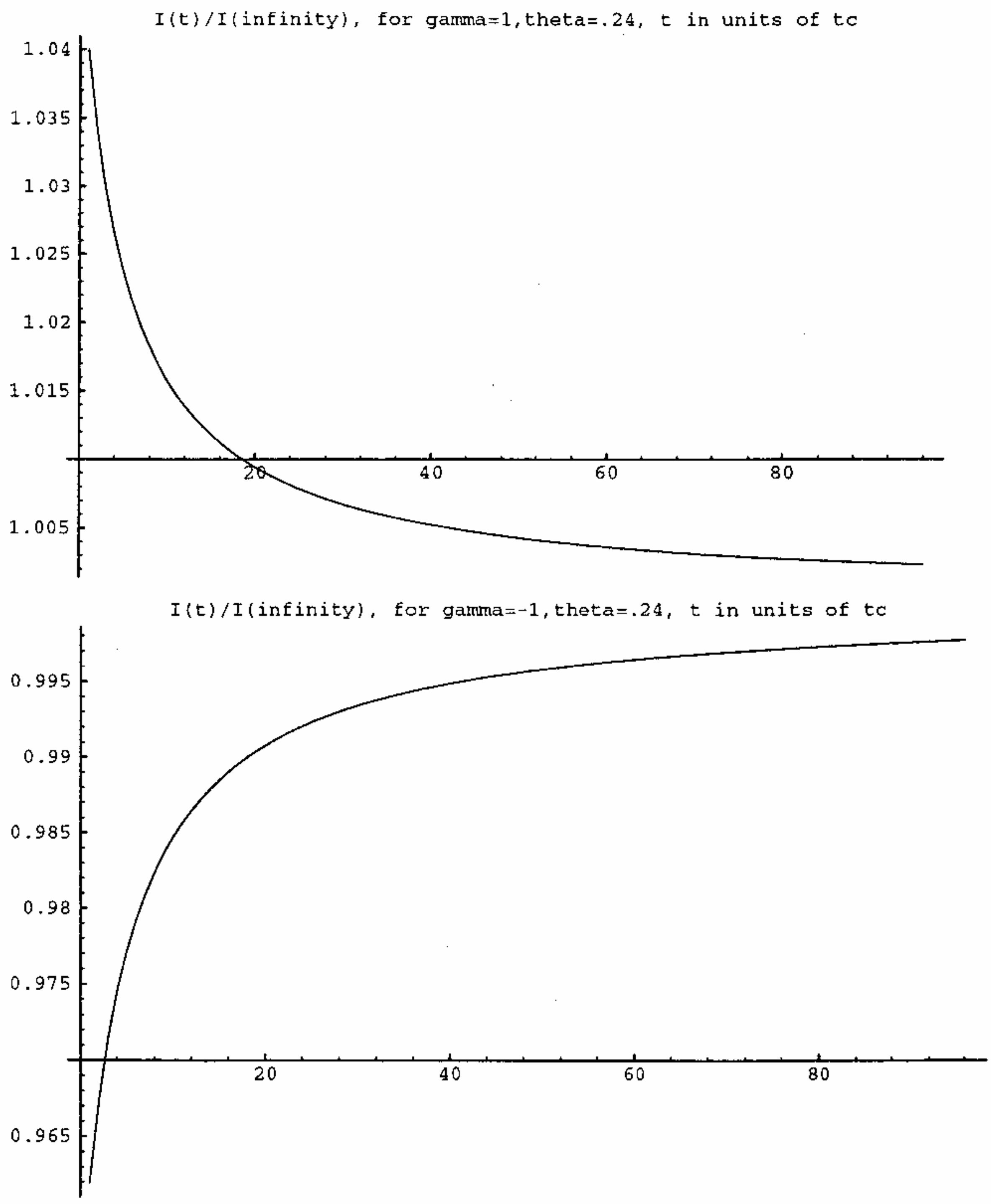
I(t)/I(infinity), for gamma=1,theta=.24, t in units of tc
1.04
1.035
1.03
1.025
1.02
1.015
1.005
20
40
60
80
I(t)/I(infinity), for gamma=-1,theta=.24, t in units of tc
0.995
0.99
0.985
0.98
0.975
0.965
20
40
60
80

Fig 3

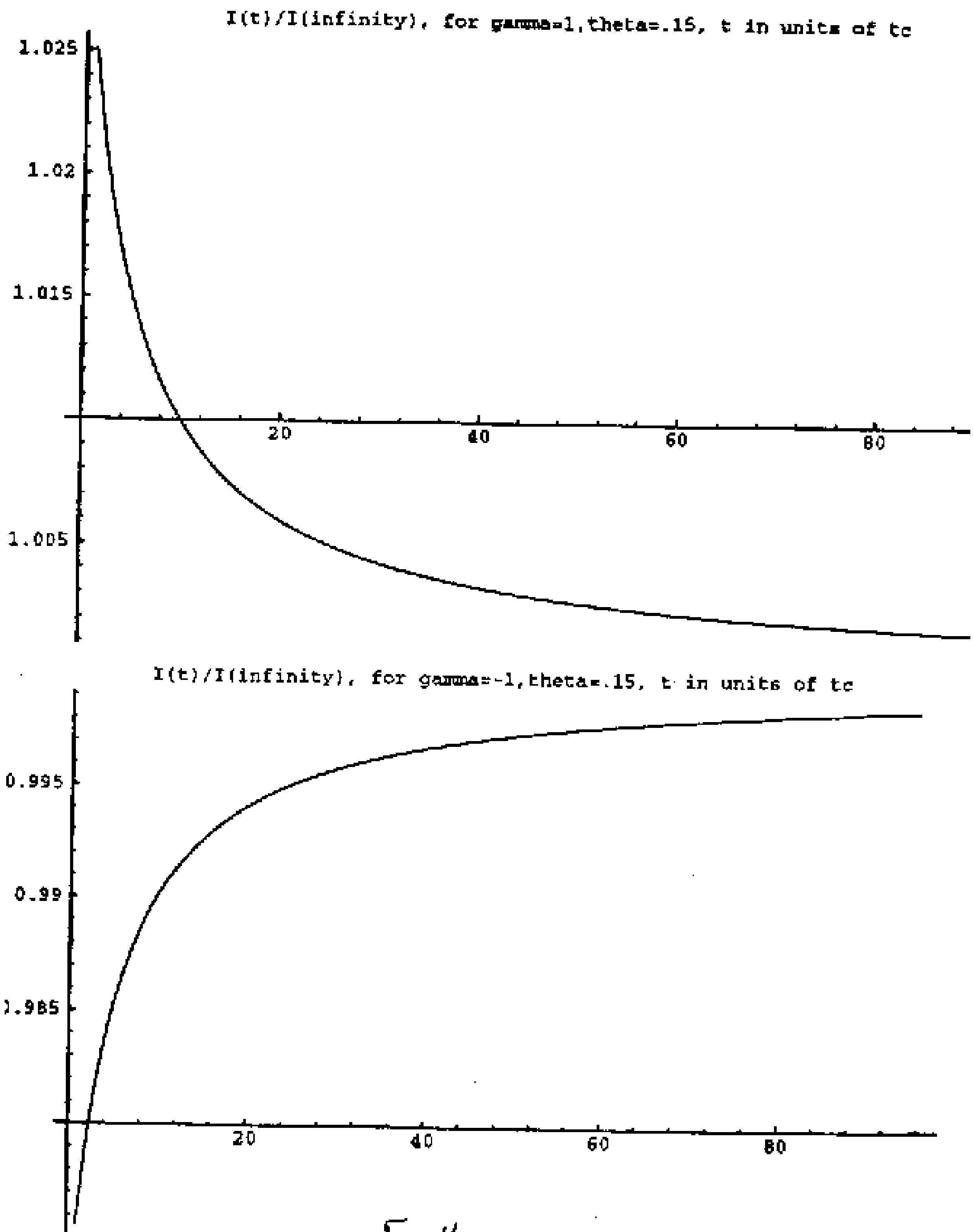
I(t)/I(infinity), for gamma=1,theta=.15, t in units of tc
1.025
1.02
1.015
1.005
20
40
60
80
I(t)/I(infinity), for gamma=-1,theta=.15, t in units of tc
0.995
0.99
0.985
20
40
60
80

Fig 4