Laser Absorption Spectroscopy on Pressure-Broadened Rubidium D1 Line

Emma Goldberg

Introduction

Motivation

A series of experiments run at the Stanford Linear Accelerator Center and in progress at the Thomas Jefferson National Accelerator Facility are investigating the spin structure of the neutron. In these experiments, a beam of polarized electrons is scattered by a target of polarized helium-3 gas. The ^{3}He is polarized by spin-exchange collisions with optically pumped rubidium vapor, and the target polarization is measured with nuclear magnetic resonance (NMR) or electron resonance polarimetry (EPR). Because the signal size in each of these methods is proportional to the total number of polarized nuclei, to determine the percent target polarization it is essential to know the density of ^{3}He in the target cell. The goal of my project is to develop a system to measure this density.

One way to measure the ^{3}He density is to look at the broadening of the D1 spectral line of the Rb in the target cell. The main factor in the broadening of the line is collisions with other atoms— each collision spreads the energy levels a bit more, so the more ^{3}He there is in the cell, the broader the spectral lines. To measure the linewidth, laser light of the appropriate wavelength (about 795 nm) is shone into the cell, and the transmitted intensity is recorded as the wavelength is scanned around the resonance.

In this paper, I will describe the experimental apparatus I used for this laser absorption spectroscopy, the spectra I obtained, and the analysis. I will also mention previous work done in this field and directions for future work.

Previous Work

This kind of density measurement on target cells has been made by groups at TRIUMF [6] and Princeton University [9].

The TRIUMF group looked at four target cells whose densities were presumed known, based on the pressure measured when the cells were tipped off. To measure the linewidth, a cell was entirely enclosed in an oven (temperature variations of less than 3 K over the surface of the cell), light from a Ti:sapphire laser, pumped by an Ar$^+$ ion laser, was sent in to the cell, and the transmitted intensity was measured with a photodiode. In their analysis, the spectra were fit with a Lorentzian plus a "convenient" exponential asymmetry term:

$$\ln \frac{I(0)}{I(x)} = \sigma(\nu)[\mathrm{Rb}]x$$

	Ring Laser	Diode Laser	Ti:sapph
frequency stable to:	100 kHz	$<$ 50 MHz	~2 GHz
bandwidth of:	500 kHz	$<$ 300 kHz	$<$ 40 GHz
power:	few mW, stable	~5 mW, stable to 2.5%	to 3.25 W, stable to 3%
tunability:	finely (adjust cavity)	finely (adjust current or temp.)	roughly (adjust birefringent filter)

Table 1: laser characteristics

where

$$\sigma(\delta\nu) = \frac{A\,\Gamma}{(\delta\nu)^2 + (\Gamma/2)^2} + \frac{b\delta\nu}{\Gamma} e^{|\delta\nu|/\Gamma_a}$$

$I(0)$ is the incident intensity, $I(x)$ is the transmitted intensity, $\sigma(\nu)$ is the absorption cross-section as a function of frequency, [Rb] is the rubidium number density, x is the optical depth, Γ is the linewidth, $\delta\nu = \nu - \nu_0(p)$, and b and Γ_a are asymmetry parameters. The linewidth was found to increase linearly with pressure, $\Gamma = 20.0\,p$, where p is the pressure at 273 K. Reproducing their fit, I find:

$$\Gamma[\mathrm{GHz}] = (20.96 \pm 0.36)\ \mathrm{p[atm]} \tag{1}$$

The Princeton group used a cell in which the pressure of the ^{3}He could be measured and varied. The laser was a Ti:sapphire ring laser. The asymmetry in the lineshape was derived from the inter-atomic van der Waals interaction. The asymmetry was small, so the spectra were fit to the first order approximation:

$$\sigma(\nu) = \frac{A\,[1 + C(\delta\nu)]}{(\delta\nu)^2 + (\Gamma/2)^2} + B \tag{2}$$

Their result was a linear dependence of linewidth on density:

$$\Gamma = (18.7 \pm 0.7)\ \mathrm{GHz/amg} \tag{3}$$

My Goal

The fundamental goal of my project is to produce independent measurements of the ^{3}He density of the most recent target cells. Currently, the density is determined at Princeton, where the cells are made, but the results are not checked elsewhere. Because knowing the density is so crucial, it is essential that other groups be able to measure it as well. It is not sufficient simply to measure the density of ^{3}He when the cells are made: the cells are cryogenically cooled and a torch is used to tip them off of a manifold, so a pressure measurement made at the base of the manifold is subject to the uncertainties inherent in this procedure (*e.g.* temperature gradients or leakage). In addition, there is the possibility that target cells slowly leak, so it is useful to be able to measure the ^{3}He density at a later time.

As originally stated, the goal of my project was to demonstrate that spectra of high precision could be obtained by using a laser diode as the light source. The Princeton group uses a Ti:sapphire ring laser, and the TRIUMF group used a straight Ti:sapphire laser. The characteristics of these lasers are compared in Table 1. The main advantage of using a ring laser is the stability and tunability of its output light, and the main disadvantage is cost and unreliability— they are very complicated and tend to break. The output of a diode laser is practically just as good, and though

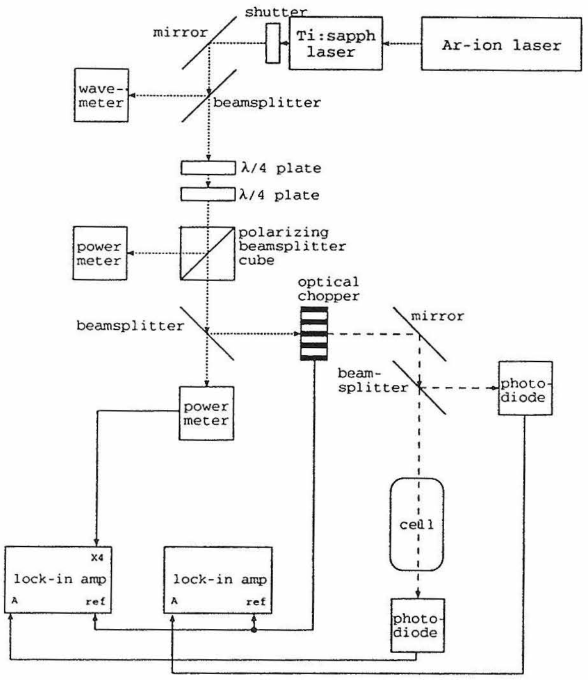

Figure 1: Experimental Setup

they may be tricky to get working at first, they are much less expensive and fairly straightforward to use.

The characteristics of the light from the Ti:sapph lasers in our lab did not seem stable or sensitive enough to produce spectra of the precision required. However, I started taking spectra with one of these lasers while I was getting everything else set up and waiting for the laser diodes and controllers to arrive. As I worked to get the electronics functioning and eliminate various systematic problems, though, it became clear that spectra of sufficient quality could be obtained with this Ti:sapph laser. Because of this development, along with developments in the availability of the diode laser, the focus of the project was shifted: instead of trying to produce spectra with a diode laser (though see the section on Work in Progress), I have been working to obtain good spectra with the Ti:sapph and to develop the analysis and reference system necessary to extract precise values for target cell densities. When the diode laser becomes available this summer, I will be able to transfer much of my work to that system.

Experimental Apparatus

The most recent version of the experimental apparatus is shown schematically in Figure 1. The various components are described here.

Lasers

The light source used was a Spectra Physics Model 3900S Ti:sapphire laser pumped by a Model 2040E Ar^+-ion laser. The Ar^+-ion laser contains a plasma tube with argon gas, which is excited by an electric discharge. The visible transitions in the four-level energy scheme occur at about

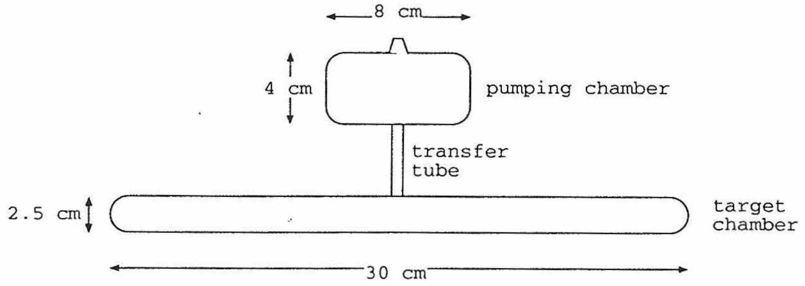

Figure 2: Target Cell

480 nm, and the laser can be operated with output powers between 5.5 and 20 W.

The Ti:sapph laser contains a solid-state laser medium of titanium-doped (Ti_2O_3) sapphire (Al_2O_3). The lasing medium is in a four-mirror folded cavity, and population inversion is achieved with the Ar^+-ion pump beam. A birefringent filter before the output coupler allows wavelength tuning. When a screw on the laser cover is turned, the filter rotates slightly, transmitting linearly polarized light of a certain (multiple of) frequency— it acts as a half-wave plate at variable wavelength. The other wavelengths passing through emerge elliptically polarized and are attenuated to below the lasing threshold by multiple reflections at Brewster's angle. The output power of the Ti:sapph laser is about 15% of the pump power. The beam emerges linearly polarized and with a diameter of about 1 mm and, in this case, with a wavelength of about 795 nm.

Because of occasionally-prohibitive power fluctuations, an attempt was made at finding the optimal power settings for the lasers. The Ar^+-ion laser's output is equally stable at any power, though there was concern that running at lower powers would shorten the lifetime of the tube. The stability of the modes in the Ti:sapph, though, depends on the pumping power and the cooling temperature. Various combinations of settings were tried, but no clearly optimal combination was found. Typically, the output of the Ar^+-ion was 6 W and the Ti:sapph chiller was kept at 18°C.

The wavelength was measured with an ILX OMH-6730B wavemeter, on the slow response time setting, to a precision of ±0.01 nm. This also appeared to be just about the limit of the Ti:sapph's wavelength stability, so a more precise wavemeter was not attempted, though a design consisting of an interferometer and CCD array was considered.

Target Cell

A diagram of a typical target cell is shown in Figure 2. The cell is blown of Corning 1720 glass. This material is difficult to work with, but its high density is necessary to prevent leakage of the helium. There is still the possibility that the cells might leak over long periods of time, which is something my project would discover.

In the real experiments, the electron beam passes through the lower target chamber, and circularly polarized laser light is shone into the rubidium-containing upper pumping chamber which is enclosed in an oven so that the rubidium can be heated and vaporized. For my original measurements, I used one of these ovens. It is a plastic (torlon) box with viewing windows on the sides and optical windows on the front and rear faces. Its two sections are assembled around the cell, and the joints are sealed with high temperature rubber and silicon goo (Dow Corning RTV 732).

Due to concerns about the effects of having only part of the target cell heated (see the section on Temperature Gradients), a second oven was designed and built. It is an aluminum box

(12"×12"×16") with optical windows on the front and rear and holes in one side for air and RTD wires in and out. It is insulated on the inside with pieces of water-heater blanket wrapped in aluminum foil. The cell is suspended by the neck on a wooden stand.

The oven is heated with a stream of hot air. Air at a pressure of about 20 psi is passed through a HotWatt 750 W heater into the oven, and then allowed to leave through an exit hole. An RTD coming through the side of the oven reads out the temperature, and its resistance is used in a feedback circuit which controls the power to the heater. This system keeps the oven's air temperature stable to about a degree at a specified set point temperature. In the large oven, by adjusting the airflow at various temperatures, the temperature over the entire cell can be kept uniform to within a degree.

Optics

All the optics used are coated for 795 nm. The mirrors are intended for 45°, and the beamsplitters were found to reflect about 7% of the incident power. Two quarter-wave plates are used together as a half-wave plate— in combination with a cross-polarized beamsplitter cube, the laser power incident on the cell can be regulated mostly-independent of the laser settings. By rotating one of the wave plates, the amount of light passed by the cube can be varied from nearly 0 to nearly 100% of the light coming out of the laser.

Power Measurements

The photodiodes used for the first spectra were Newport 818-SL with a home-made circuit to provide the reverse bias. After a lot of trouble with these (the response was often confused or non-existent, and generally not reliable or sensitive enough), they were replaced with New Focus 2301 photodiodes. These are usually run on their lowest gain setting, and work well. A Spectra Physics 405 power meter is used as a second reference and beam stop.

Electronics

The optical chopper (New Focus 3501, 42/30 wheel) is a pinwheel which spins at a specified frequency (2 kHz used here), modulating the light which passes through it— what goes in is a continuous beam and what emerges is a square wave. The modulating frequency and the output powers of the photodiodes are sent to a lock-in amplifier (Stanford Research Systems SR 530) which extracts only the portion of the input signal (from the photodiodes) which is modulated at the reference frequency (from the chopper). This allows extraneous noise to be filtered out and increases the sensitivity tremendously, which is essential in regions of low transmission.

While taking data, the signals from the photodiodes are monitored on an oscilloscope. At first, the power levels were just read off of the scope, but the uncertainties associated with this procedure were rather large, as the signal jumped around a bit and the transmitted and reference powers couldn't be read simultaneously.

So instead, a computerized averaging system was set up. The output of the lock-in amps are sent by GPIB to a computer, and a program written in LabView reads the lock-in outputs several times (alternating between the transmitted and reference powers), averages the results, and writes the average and standard deviation to a file. There were some serious difficulties in getting LabView to communicate with the lock-ins; sometimes a nonsense value would be returned. The program includes a step to filter out most of these bad values, and the data are also displayed graphically so the bad runs can be removed manually.

Acquiring a Spectrum

Taking a spectrum involves the following steps: While the oven is coming up to temperature, the laser alignment and electronics connections are checked. The laser wavelength is scanned quickly, and the transmitted intensity is watched on the oscilloscope to check that the light is really passing though the cell. The reference power is checked to make sure the laser output power is reasonably stable. If everything looks okay (about 2/3 of the time), the data file is opened and the acquisition begins.

The spectra are acquired with the room and shutter-indicator lights off, since their reflections badly disturb the measured powers. For each point, the wavelength is adjusted by about 0.1 nm, the lock-in sensitivity is adjusted as needed, and readings from the photodiodes and power meter are taken and averaged. If there are no apparent electronic malfunctions, the values are saved and the process begins again. The wavelength is generally swept a couple times back and forth across the resonance. When things work, each spectrum takes about an hour to complete.

Theoretical Lineshape

The spectra obtained with this setup are shown in later sections. Here I will describe the function used there to fit the data; it is a convolution of several broadening effects.

Natural Broadening

In an atomic transition from state n to state n', the photon emitted or absorbed is not of precisely the same energy each time; that is, the width of the resonance is not infinitely small. An excited state of an atom has a natural lifetime, and an electron in a higher energy state n will decay on its own to a lower energy state n'. Applying the form of the Heisenberg uncertainty principle

$$\Delta E\,\Delta t \simeq \hbar$$

to the state with lifetime Δt gives the spread in energy, ΔE, of the state.

The profile of the spectral line [the function describing the radiated energy at each frequency, $\phi(\omega)$] is proportional to the norm-squared of the Fourier transform of the radiated electric field.[1] The electric field can be written as:

$$E(t) = \begin{cases} 0 & \text{from } t = -\infty \text{ to } t = 0 \\ E_0 e^{-\gamma t/2} \cos \omega_0 t & \text{from } t = 0 \text{ to } t = +\infty \end{cases}$$

The harmonic wave is damped exponentially because the rate of spontaneous decay depends on the number of atoms in states n and n' at each instant. So

$$\begin{aligned} \hat{E}(\omega) &= \textstyle\int_{-\infty}^{\infty} E(t)\, e^{i\omega t}\, dt \\ &= \tfrac{E_0}{2}\left[\tfrac{\gamma}{2} - i(\omega + \omega_0)\right]^{-1} + \tfrac{E_0}{2}\left[\tfrac{\gamma}{2} - i(\omega - \omega_0)\right]^{-1} \end{aligned}$$

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[1] This is derived quantum mechanically in [2], and semi-classically in [10].

This distribution has peaks at $\pm\omega_0$, but for optical frequencies, $\omega_0 \gg \gamma$ and the distribution centered at $+\omega_0$ can be considered separately. The spectral line then looks like

$$\phi(\omega) \propto \left|\hat{E}(\omega)\right|^2 \propto \frac{\gamma/2}{(\omega-\omega_0)^2 + (\gamma/2)^2}, \tag{4}$$

which is the Lorentz profile.

For a typical light-producing electron transition, $\Delta t = 1/\gamma \sim 10^{-8}$ s,[2] so the FWHM of a naturally broadened spectral line is about 0.1 GHz.

Doppler Broadening

As an atom moves with velocity v along the line of sight, its change in frequency is given (to first order) by

$$\nu - \nu_0 = \frac{\nu_0 v}{c}, \tag{5}$$

where ν_0 is the rest frame frequency.

The number of atoms with velocity between v and dv is given by the Maxwell velocity distribution:

$$P(v) = 4\pi\left(\frac{m}{2\pi kT}\right)^{3/2} v^2 e^{-\frac{mv^2}{2kT}}\, dv \tag{6}$$

where m is the mass of an atom and T is the temperature.

Substituting from (5) into (6) (see [10]), the profile function is:

$$\phi(\nu) \propto P(v) \propto \tfrac{1}{\Delta\nu_D} e^{-\frac{(\nu-\nu_0)^2}{\Delta\nu_D}},$$
$$\Delta\nu_D = \tfrac{\nu_0}{c}\sqrt{\tfrac{2kT}{m}}$$

For my measurements, the Doppler width is approximately

$$\Delta\nu_D = \frac{1}{2(795\ \text{nm})}\sqrt{\frac{2k(400\ \text{K})}{(85.5\ \text{g/mol})/N_A}} = 0.2\ \text{GHz},$$

which is comparable to the natural broadening.

Collisional Broadening

If an atom emits light at frequency ω_0 and the radiation is not interrupted, the time-dependence of the electric field amplitude will be

$$E(t) = E_0 \cos(\omega_0 t)$$

The wave train of the radiation can be interrupted, though, by collisions with other atoms. If the time between two collisions is τ, then the emitted radiation is described by

$$E(t) = E_0 \cos(\omega_0 t)\, \Theta(\tau - |2t|),$$

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[2] [3], p. 309

where Θ is the Heaviside function. The line profile is then:

$$\phi(\omega) \propto |\mathcal{F}[E(t)]|^2 \propto \left(\frac{\sin[(\omega-\omega_0)\tau/2]}{(\omega-\omega_0)/2}\right)^2 \tag{7}$$

But all the wave trains do not have the same length and phase. Lorentz's distribution for the probability that the time since the last collision is between τ and $\tau + d\tau$ is (see [1])

$$P(\tau)\, d\tau = e^{-\tau/\tau_c} \frac{d\tau}{\tau_c} \tag{8}$$

where τ_c is the mean time between collisions. Averaging the spectrum (7) with the probability weighting (8) gives

$$\phi(\omega) \propto \int_0^\infty \left(\frac{\sin[(\omega-\omega_0)\tau/2]}{(\omega-\omega_0)/2}\right)^2 e^{-\tau/\tau_c}\, d\tau$$

which evaluates to the Lorentz profile:

$$\phi(\omega) \propto \frac{1}{(\omega-\omega_0)^2 + (1/\tau_c)^2} \tag{9}$$

For these high-pressure cells, collisional broadening is the dominant factor in determining the lineshape, and the spectral line is essentially Lorentzian.[3]

Instrumental Broadening

The measured width of the spectral line depends not only on the actual atomic linewidth but also on the spectral width of the laser used to probe the line. In the case of the ring laser, the laser linewidth is about 500 kHz, which is negligible when compared to typical spectral linewidths of greater than 100 GHz. For the regular Ti:sapphire laser, though, the laser linewidth is on the order of tens of GHz and should not be disregarded, as it was in [6].

The function to which the data should be fit is the convolution of a Lorentzian (for the shape of the atomic spectral line),

$$L(\omega, \Gamma) = \frac{\Gamma/2}{\omega^2 + (\Gamma/2)^2},$$

and a Gaussian (for the shape of the laser line),

$$G(\omega, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-\omega^2}{2\sigma^2}}.$$

The convolution is defined as:

$$L * G(\omega) = \int_{-\infty}^{\infty} L(\eta)\, G(\omega - \eta)\, d\eta$$

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[3] This would be the case even including the natural width (Eqn. 4), as the convolution of two Lorentzians is still a Lorentzian. If the Doppler broadening were significant, its Gaussian form could be included as is done in the following section for the instrumental broadening.

The integral can be evaluated by taking the Fourier transforms of L and G and applying the Fourier Convolution theorem:

$$L * G(\omega) = \mathcal{F}\left(\mathcal{F}^{-1}[L]\,\mathcal{F}^{-1}[G]\right) = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{-\frac{\Gamma}{2}|x|}\, e^{-\frac{\sigma^2}{2}x^2}\, e^{i\omega x}\, dx$$

Then break the integral into positive and negative parts and evaluate each by completing the square in the exponent. The convolved lineshape is then

$$L * G(\omega) \propto \Re e\left\{e^{\frac{\Gamma/2 - i\omega}{2\sigma^2}}\left[1 - Erf\left(\frac{\Gamma/2 - i\omega}{\sqrt{2}\sigma}\right)\right]\right\}, \tag{10}$$

where the complex error function is $Erf(z) = e^{-z^2}\left(1 + \frac{2i}{\sqrt{\pi}}\int_0^z e^{-t^2}\,dt\right)$. This is the Voigt profile.

Looking at the spectra taken, a Lorentzian fit is very good— the Gaussian effects of the laser are not obvious, indicating that the laser linewidth is significantly less than the quoted upper limit of 40 GHz. Based on numerical simulations, I estimate that the width is less than 20 GHz.

It is not easy to fit data to (10) because the function is not straightforwardly differentiable. I tried several different fitting programs, as well as various forms of the function. The closest I could come to a fittable form was using a method outlined in [4], but I was still not able to get a sufficiently close fit on both the wings and the peak, and error propagation would not be feasible.

Because the spectra really do look Lorentzian (I tried fitting with the Voigt function by hand and could not significantly improve the goodness of the fit), I have fit them with Lorentzians in the following sections. To account for the laser linewidth, I will measure σ and then use a numerical relation between the full width and the true Lorentzian component. For example, for $\sigma = 20$ GHz,

$$\Gamma_{full} = 49.27 + 0.4752\Gamma_{lor} + 0.00295\Gamma_{lor}^2 - 6.68 \times 10^{-6}\Gamma_{lor} \tag{11}$$

where Γ_{full} is measured and Γ_{lor} is the true spectral linewidth.

Asymmetry

In many of the spectra taken, the lineshape appears slightly asymmetric. This shows up especially well in the difference plots. In [8], the Van der Waals inter-atomic potential is modeled, and to first order the effect is expressed by the parameter $C = 0.664\, 2\pi T_d$, where T_d is the collision time, in (2). I have included this asymmetry in my fits: its value is consistent from spectrum to spectrum. However, the expected temperature dependence of

$$C \propto v_{th}^{-6/5} \propto T^{-3/5}$$

is not observed, so I am not absolutely sure that it is the Van der Waals interaction which is being seen.

Results— Small Oven

One of many, many spectra accumulated is shown in Figure 3. The reference normalization is clearly necessary. The asymmetric Lorentzian fit works very well— the Gaussian effects of the laser linewidth are not severe. The large error bars near the resonance are due mainly to the inclusion of the errors in wavelength (±0.01 nm), which have been iterated into errors in power. Blindly

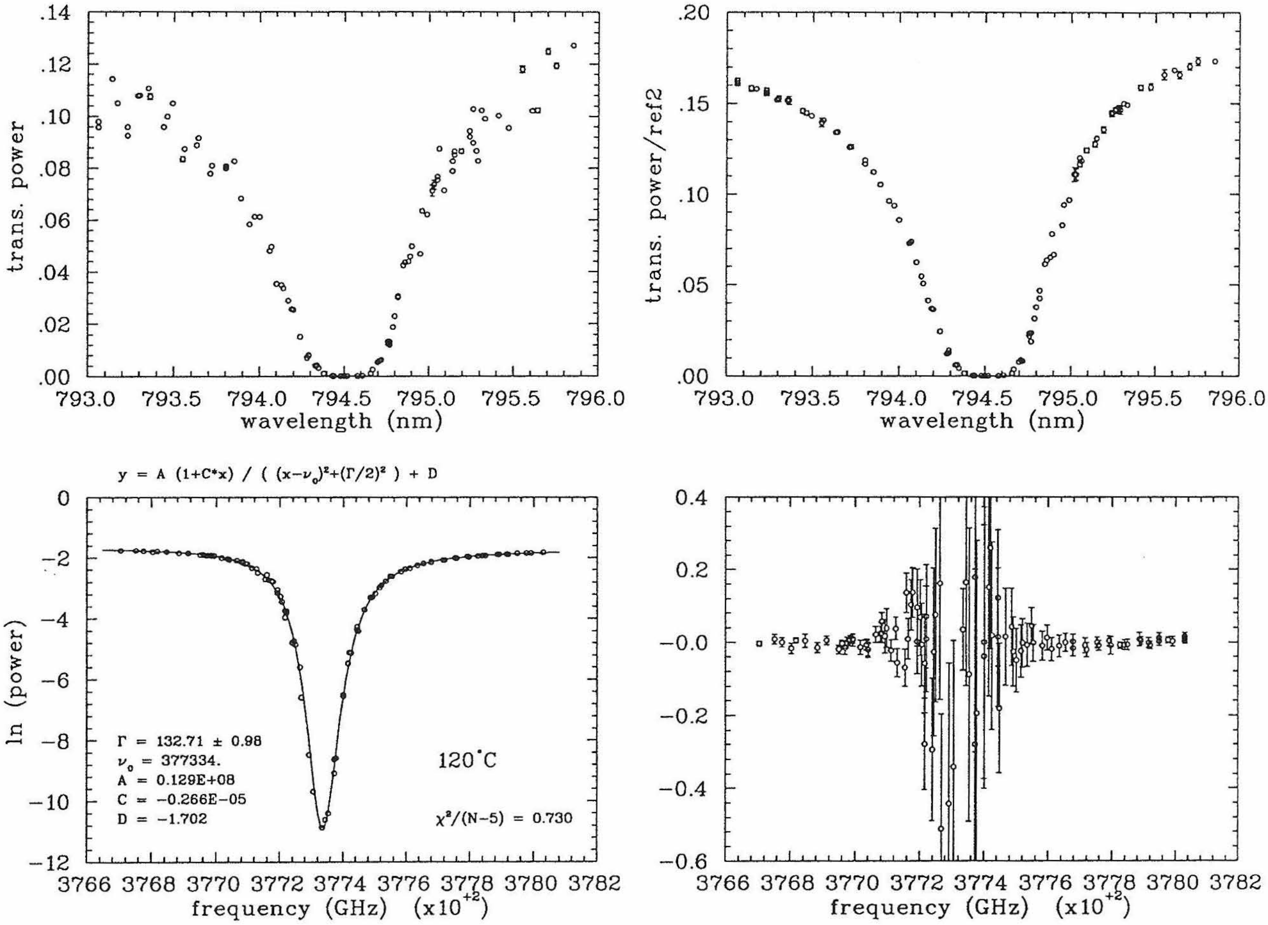

Figure 3: Shown are the raw data, normalization with reference power, an asymmetric Lorentzian fit to the data, and the difference plot of the fit.

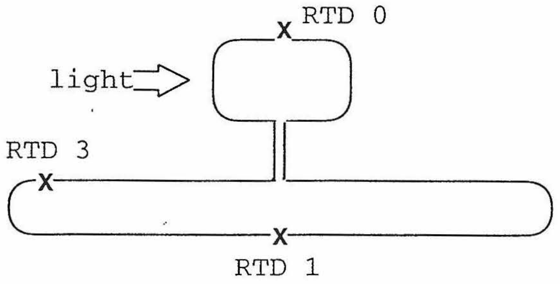

Figure 4: RTD placement

applying the result (3) to the width of $\Gamma = 132.7 \pm 1.0$ GHz gives a ^{3}He density of 7.06 ± 0.12 amg. At 23°C, this is 7.67 ± 0.13 atm, which almost reasonably close to [7]'s quoted value of 8.44 atm.

Spectra were taken at 80°C, 100°C, 120°C, and 140°C. At lower temperatures, the Rb vapor pressure was low enough that the difference between the baseline and minimum was significantly blurred by noise. At higher temperatures, the Rb vapor pressure was high enough that there was zero transmission near the resonance and the negative peak was cut off. These effects could be mitigated somewhat by changing the incident intensity; the best-looking results were for an oven temperature of 100°C and an incident power of about 0.3 mW.

Temperature Corrections

But these spectra, taken with the cell heated by the small oven, cannot directly be translated into a value for pressure. With only the upper chamber of the cell enclosed in the oven, the temperature gradients throughout the whole cell cause density gradients in the gas inside. The ^{3}He density measured is that in the pumping chamber, and a correction is necessary before a total helium density can be quoted.

To monitor the temperature of the cell, RTDs were taped to the cell's outer walls on both the upper pumping chamber and the lower target chamber (see Figure 4). As seen by [9], where an RTD was mounted to the inside of a reference cell, the air inside the cell quickly reaches the temperature of the glass. As the oven was heated, these temperatures were monitored: it was found that the glass of the pumping chamber reached equilibrium with the surrounding air temperature after about 20 minutes.

The density correction can be calculated from the ideal gas law. The pumping chamber of the cell has volume V_p and temperature T_p, and the target chamber has volume V_t and temperature T_t. The number of atoms in the pumping chamber is $m_p = n_p V_p$, in the target cell $m_t = n_t V_t$, and for the entire cell $m_0 = m_p + m_t = n_0 V_0 = n_0(V_p + V_t)$. Since the two chambers are connected, they are at equal pressures:

$$P_p = \frac{m_p R T_p}{V_p} = P_t = \frac{m_t R T_t}{V_t} \Rightarrow \frac{m_0}{V_p + V_t} = \frac{m_p}{V_p}\frac{T_p V_t + T_t V_p}{T_t(V_p + V_t)}$$

$$n_0 = A\, n_p,\ A = \frac{T_p V_t + T_t V_p}{T_t V_0} \tag{12}$$

The values obtained from this relation and operating temperatures are listed in Table 2. These

	nominal temperature (°C)			
	80	100	120	140
oven air	79.5 – 81.4	99.0 – 101.5	117.8 – 120.5	138.0 – 140.9
RTD 0	84.6 – 84.7	105.5 – 105.8	125.2 – 125.5	145.6 – 146.1
RTD 1	44.3 – 44.4	49.7 – 49.8	54.5	60.2
RTD 3	43.3	47.9 – 48.0	52.9 – 53.0	58.3 – 58.4
T_p	84.7 ± 1	105.7 ± 2	125.4 ± 2	145.9 ± 3
T_t	43.8 ± 2	48.9 ± 2	55.0 ± 2	59.3 ± 2
A [from (12)]	1.07 ± 0.02	1.10 ± 0.02	1.12 ± 0.02	1.15 ± 0.02

Table 2: cell temperatures

measurements were made on Minnehaha, for which [7] quotes:

$$V_p = 70.4 \pm 3.2\,\mathrm{cm}^3,\ \mathrm{V_t} = 94.0 \pm 3.2\,\mathrm{cm}^3,\ \mathrm{V_0} = 164.4 \pm 0.3\,\mathrm{cm}^3$$

Though this is a reasonable attempt at a theoretical correction of the temperature gradient, it detracts significantly from the final precision and leaves some conceerns. Much better than trying to model the density gradient is to remove the gradient altogether. This was the purpose of building the large oven, which can contain and heat the entire cell uniformly. Though this would not be a feasible heating option for the experiments being run in beam, it is a good idea for the spectra being taken in lab. The results from the large oven (presented in the next section) indicate that this correction is fairly good: at 120°C, a width of 132.71±0.98 GHz becomes 148.6±2.9, which is in agreement with but not as precise as the later measurements.

Results— Large Oven

Normalized, fit spectra at different temperatures are shown in Figure 5. I had expected to see a temperature dependence of the width, since at higher temperatures the atoms are moving faster and collide with each other more often. However, the length of the collisions is then shortened, and the effects seem to balance out. [9] also noticed essentially no temperature dependence in the D1 width. For the width $\Gamma = 146.0 \pm 1.6$ and (3), Minnehaha's density comes to 7.81±0.15 amg, or 8.50±0.17 atm at 23°C. Comparing with 8.44 atm, this is right on. Or assuming a laser linewidth of 20 GHz and applying (11), $\Gamma = 140$ GHz, for a pressure of 8.15 atm, which is still within reason.

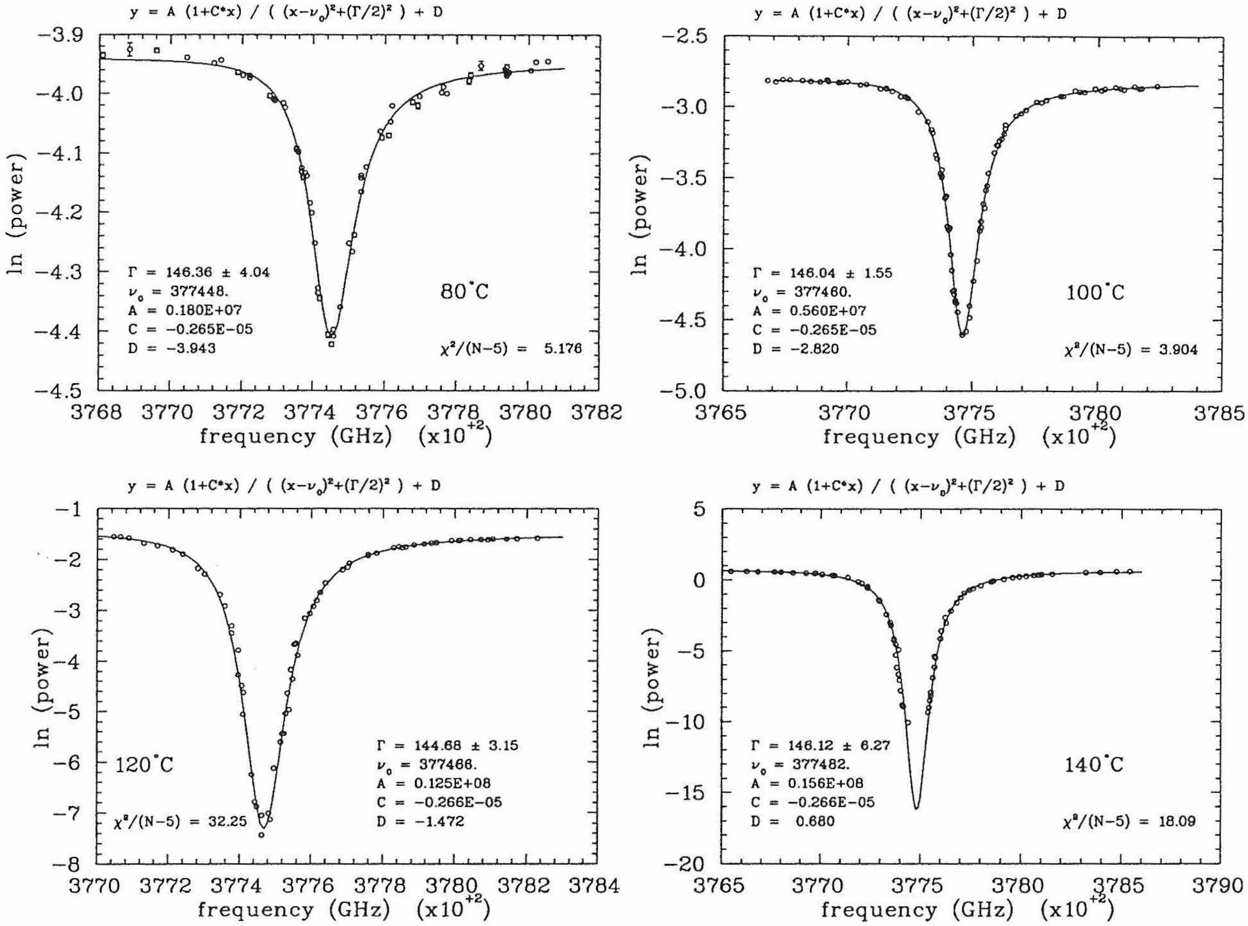

Figure 5: Spectra taken with the large oven.

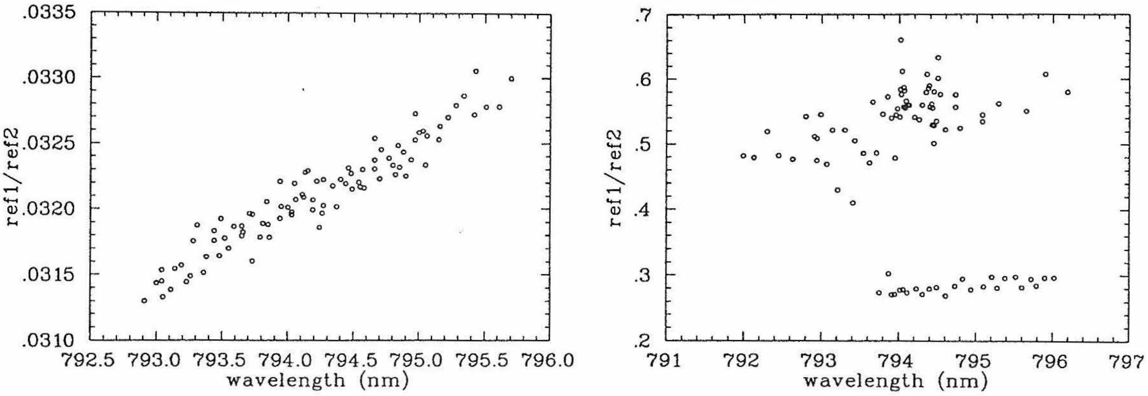

Figure 6: ratio of reference powers (photodiode/power meter) as a function of wavelength for two spectra taken at 140°C

Work in Progress

There is still a bit of work to be done before this project will be complete. Here I will describe where the remaining work stands at the moment. I will continuing working in this lab through the summer and into next year, so it will eventually be done.

Laser Linewidth

Because of the difficulties in fitting the Voigt function, it is very important to measure the laser linewidth. I think I can do this with a good diffraction grating simply by looking at the spread in the interference pattern. I would also like to find or write a program to fit the function and see how the results agree.

Reference Power

As shown in Figure 1, both a power meter and a photodiode were used to measure the power incident on the cell at the times the transmitted power was measured. Ideally, normalization by each of these devices would work equally well, but this was not always observed. For some spectra normalization by the power meter was better, and for others the photodiode gave a smoother result. Generally, the two devices did not exactly agree with each other; particularly bad cases are shown in Figure 6. The first case shows a wavelength dependence in one of the devices, and the second shows a discontinuity I am not able to explain.

Because it is important that the reference measurement used for normalization be reliable, I would like to alter the experimental setup to use one photodiode to measure both the transmitted and the reference powers simultaneously. This can be achieved by redirecting the laser beam and using the second ring on the chopper wheel so that the transmitted and reference powers are chopped at different frequencies. The signal from the photodiode can then be sent to the two lock-ins, referenced to the two different frequencies, and the two signals can be extracted. This method should remove concerns of variations in response among devices and hopefully give a more reliable normalization.

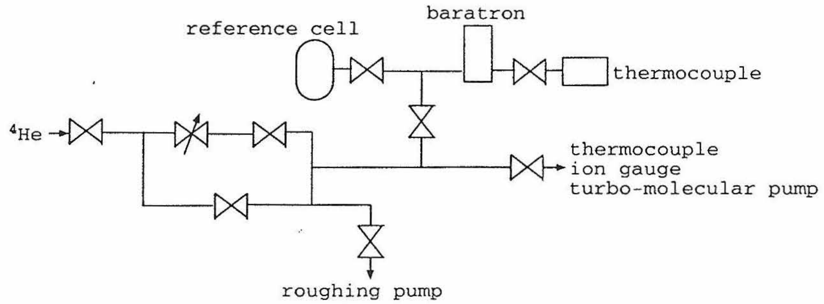

Figure 7: Gas System

Reference Cell

Rather than trusting the linewidth-density relation (3) from [9], which was made with different equipment, I want to make a reference cell with which to do a calibration. This cell would be filled to a known density and a spectrum taken, and then the procedure would be repeated at other densities.

I currently have the gas system and glass cell prepared. The reference cell is a single cylinder, 4.5 in long and blown from pyrex. It is attached to the gas system shown in Figure 7. The roughing pump is used to bring the pressure in the system down to $\sim 10^{-3}$ torr, and the turbo-molecular pump reduces the pressure to $\sim 7 \times 10^{-6}$ torr. The thermocouples and ion gauge read out the level of the vacuum. Once the entire system was evaculated, the ampoule containing the Rb (inside the cell manifold) was broken open, the Rb was chased with a methane torch into the cell, and the ampoule was tipped off.

The cell is currently ready to be filled with ^{4}He. Beginning with lower pressures (due to safety and filling considerations), it will be filled with gas, the pressure will be read with the high-pressure baratron, the cell will be removed at the valve and sealed in the oven, and spectra will be taken at various temperatures. The procedure will be repeated for several different pressures, and the results should give a reliable linewidth–pressure relation.

Laser Diode

I currently have a laser diode, mount, and control unit, which should be operational very soon. However, Jefferson Lab will be giving us a complete New Focus 6312 diode laser at the beginning of the summer, so it was decided to hold off on this part of the project, focusing on the aspects described above, until then. This laser's output light will have better stability and a far narrowed linewidth than the Ti:sapph being used now, so it should not be difficult to incorporate it into the current system. The wavelength is controlled through GPIB; the laser cavity is adjusted by means of motors and PZTs. The spectra produced with this laser should give insight into those from the Ti:sapph, and most importantly provide a simple and mobile [4] system for measuring ^{3}He pressure in target cells.

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[4] After it became clear that pressures could be measured well here, the cell Jin was to be mailed here for spectra to be taken. This cell was used in the most recent experiment at Jefferson Lab, and there was concern that its quoted density was not accurate. Unfortunately, the cell exploded while being shipped. It is therefore hoped that our system can be moved to the lab to carry out these measurements in the future.

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