

ABSTRACT

Title of thesis: TRANSMISSION SPECTRA OF ^{87}Rb
ATOMS NEAR AN OPTICAL NANOFIBER.

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Master of Science, 2016

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We present measurements of the transmission spectra of ^{87}Rb atoms at 780 nm in the vicinity of a nanofiber. A uniform distribution of fixed atoms around a nanofiber should produce a spectrum that is broadened towards the red due to shifts from the van der Waals potential. If the atoms are free, this also produces an attractive force that accelerates them until they collide with the fiber which depletes the steady-state density of near-surface atoms. It is for this reason that measurements of the van der Waals interaction are sparse. We confirm this by measuring the spectrum cold atoms from a magneto-optical trap around the fiber, revealing a symmetric line shape with nearly the natural linewidth of the transition. When we use an auxiliary 750 nm laser we are able to controllably desorb a steady flux of atoms from the fiber that reside near the surface (less than 50 nm) long enough to feel the van der Waals interaction and produce an asymmetric spectrum. We quantify the spectral asymmetry as a function of 750 nm laser power and find a maximum. Our model, which takes into account the change in the density distribution, qualitatively explains the observations. In the future this can be used as a tool to more comprehensively study atom-surface interactions.

TRANSMISSION SPECTRA OF ^{87}Rb ATOMS NEAR AN
OPTICAL NANOFIBER.

by

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Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park in partial fulfillment
of the requirements for the degree of
Master of Science
2016

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Dedication

To the family I was given and the family I chose,
and especially those who are both.

Acknowledgments

This work was supported by the National Science Foundation.

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Chapter 1: Introduction

Optical nanofibers (ONF) are becoming a new platform for experimental realizations in spectroscopy, sensing, and cold atom physics [1–5]. Particularly interesting are their application in quantum optics and quantum information [6–10]. The small mode area of the evanescent field around the ONF waist leads to strong coupling between the ONF guided mode and atoms near its surface [11]. Unlike other strong coupling platforms like optical cavities, an ONF does not require stabilization and provides very easy integration and readout.

Optical nanofibers have been used to study atomic spectra near surfaces [5, 12, 13], magneto-optical trap (MOT) size, lifetime [14], and temperature [15–17]. The basic system is sketched in Fig. 1. In this thesis we want to look at the transmission spectrum of the atoms in the vicinity of the nanofiber by sending a resonant probe laser beam with intensity I_{in} through the fundamental mode of the fiber and measuring the transmitted intensity I_{out} .

Sagué *et al.* [5] measured the absorption spectra of Cs atoms near a nanofiber finding a symmetric lineshape. They showed with numerical simulations that the presence of the nanofiber caused a significant decrease in the density of atoms near the surface because of the van der Waals attractive potential. Nayak *et al* [13] have

studied the fluorescence of atoms around a fiber by exciting the atoms from the side and collecting the fluorescence that couples through the mode of the nanofiber and performing a heterodyne photon counting measurement that after processing gives the spectrum of the fluorescence. They do see significant asymmetries in the fluorescence and relate that to the desorption of atoms from the fiber. They explicitly produced atoms with a UV laser shining on the fiber causing light induced desorption [18], but also other mechanisms of desorption. The shifts observed, in excess of 100MHz, come from atoms in a bound state of the van der Waals potential. As such, the measurements they present are not of near-surface atoms *per se*, but rather of atoms *on* the surface. Their work qualitatively shows the asymmetry but does not quantify it by comparison to a model.

The absorption spectra can give information about the local potentials felt by the atoms that can produce broadening mechanisms present in the system. Recently Lee *et al.* studied the inhomogenous broadening of the absorption line for Rb atoms trapped near (about 150 nm away) a nanofiber [19]. The main mechanism for the broadening there was the position dependent AC Stark shift on the ground and excited states caused by the lasers creating the dipole trap: a blue detuned laser to repel the atoms from the fiber and a red detuned laser to attract the atoms to the fiber such that there is a potential minimum around 150 nm away from the fiber. Recent work in Cs atoms show spectral insensitivity, but that is possible thought the existence of specific wavelengths for the red and blue lasers that cancel the radial dependence of the shift while keeping the ground state trap [20]. Here we probe free atoms that can be much closer to the nanofiber than in the trap. We

use atoms from a ^{87}Rb MOT. We also desorb atoms from the ONF surface and can control their density and, indirectly, their temperature by changing the power of an auxiliary blue detuned laser coupled to the fundamental mode of the nanofiber. The time scales for the desorption are short (milliseconds or less). We focus on a narrow resonance, with a natural linewidth of 6.07 MHz, in the cycling transition of the D_2 line to carefully study the modifications on the linewidth.

The thesis is organized as follows. After this introduction, section 1.1 outlines the nanofiber mode structure, probability of absorption, coupling efficiency, potential shifts, and model developed by Russell *et al.* [12]. Chapter 2 provides a general overview of the apparatus, the way we control the desorption, intensity-intensity correlations and briefly discusses the theoretical considerations for calculating and simulating them. Chapter 2 presents the experimentally measured spectra and the extracted asymmetries from the surface interaction. This is followed by a concluding chapter.

1.1 The system

The experiment relies on two main parts: an ONF and a source of cold ^{87}Rb atoms. A MOT provides a source of slowly moving atoms. The atoms can couple to the evanescent part of the fundamental guided mode of the ONF. The nanofiber guides the light, including spontaneous emission from the atoms. The light also can modify the local potential for the atoms, which move with typical velocities on the order of $10 \text{ cm} \cdot \text{s}^{-1}$.

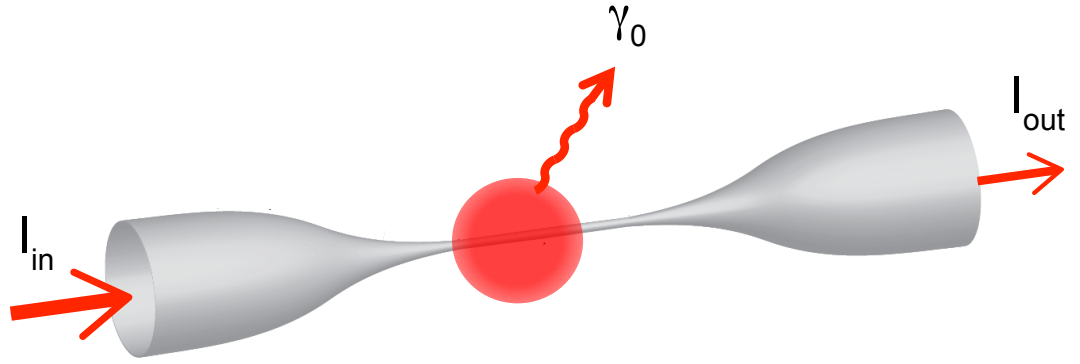


Figure 1.1: Experimental schematic. A MOT is spatially-overlapped with a nanofiber. We probe atoms in the vicinity of the nanofiber, in the evanescent mode, by looking at the change in the transmitted intensity I_{out} of a weak 780nm laser I_{in} scanned across resonance. Some of the light goes out as spontaneous emission at a rate γ_0 .

A standard optical fiber consists of a core of refractive index n_{core} and radius a , surrounded by a cladding with lower refractive index n_{clad} and radius R . In our ONFs, R is reduced to subwavelength dimensions by a flame-brush technique [21]. At these dimensions, the ONF can be considered as a simple dielectric of index $n_{\text{ONF}} = n_{\text{clad}}$, surrounded by $n = 1$, as the original fiber core becomes negligible. The tapers connecting the standard fiber on the input and output side to the ONF waist have milliradian angles for adiabatic propagation [22].

1.2 Nanofiber mode structure

Our single-mode nanofiber is a fiber pulled to a small enough diameter that all higher-order modes are cut off. The mode (HE_{11}) of such an ONF has an intensity profile outside of the fiber given by [23]

$$|\mathbf{E}(r)|^2 = \mathcal{E}^2 [K_0^2(qr) + uK_1^2(qr) + wK_2^2(qr)] , \quad (1.1)$$

where $\mathcal{E}^2$ is proportional to the intensity at the fiber surface; K_i is the modified Bessel function of the second kind of order i ; u and w are constants obtained from Maxwell's equations; r is the distance from the center of the fiber; and $q = \sqrt{\beta^2 - k^2}$ is the transverse component of the wavevector, where β is the field propagation constant in the nanofiber, and $k = 2\pi/\lambda$ is the free-space wavevector. The parameter q describes the decay of the field in the radial direction.

Figure 1.2 presents the intensity of the HE_{11} mode of the optical nanofiber normalized to the largest value of the intensity at the glass-vacuum interface. This calculation assumes circularly polarized light and serves to show the fast decay of

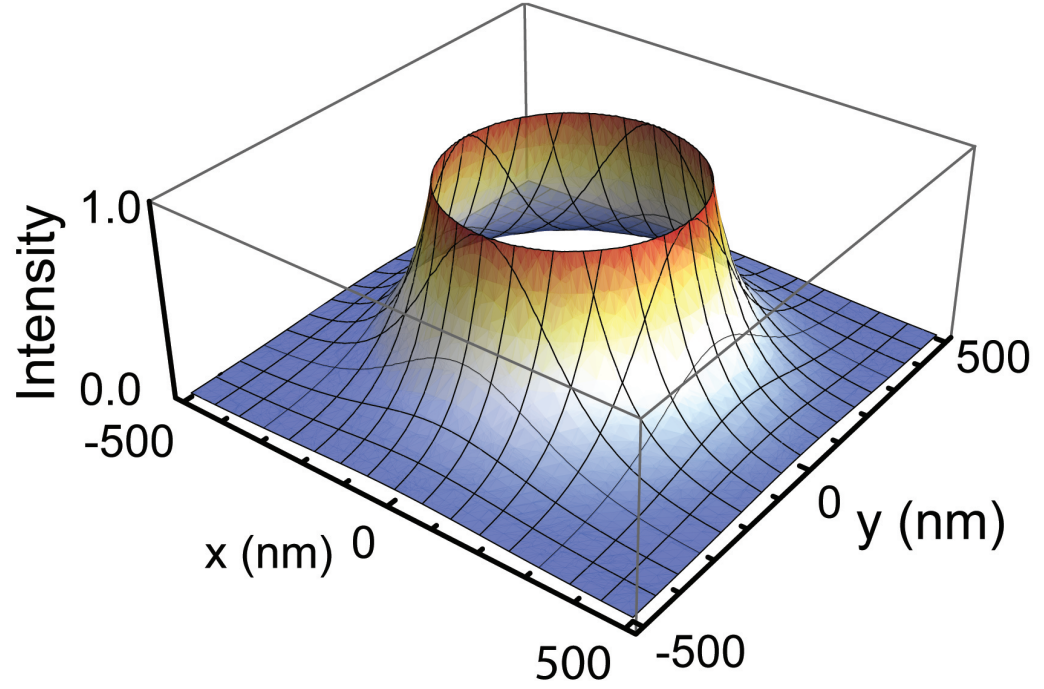


Figure 1.2: Intensity of the evanescent HE_{11} evanescent part of the nanofiber mode from Eq.1.1 for circularly polarized light, normalized to the largest value of the intensity at the glass-vacuum interface.

the mode (of order $\lambda/2\pi$) in the outside. About 40% of the intensity is outside the glass. The atoms that contribute to the absorption spectra will reside in this region, but are subject to further forces from the surface potentials (Van der Waals), significantly changing the distribution of atoms as will be seen later in sections.

We make a series of approximations to the model of the mode structure. The factors u and w in Eq. 1.1 are small for the fiber radius of 265 nm and wavelength of 780.24 nm (calculated to be 0.166 and 0.00875, respectively), so we neglect them and keep only the first term, which is proportional to K_0^2 . As a further simplifying approximation we also take the asymptotic form of K_0 [24],

$$K_0(z) \sim \sqrt{\frac{\pi}{2z}} e^{-z}, \quad (1.2)$$

which is valid in our case. This yields an intensity around the nanofiber proportional to $\exp[-2qr]/2qr$. Defining an effective index of refraction, $n_{\text{eff}} = \beta/k$, we can rewrite the propagation constant so that the radial decay parameter becomes $q = k\sqrt{n_{\text{eff}}^2 - 1}$, which is $0.66k$ for our nanofiber.

1.3 Probability of resonant absorption of light

The atom-surface potential shifts the atomic levels dependent on position. The shifts produce a spatially-varying absorption spectra, where the probability of absorption p_{abs} is:

$$p_{\text{abs}}(r) = \frac{\Gamma}{2} \frac{s}{1 + s + 4 \left(\frac{d\omega(r) + \delta}{\Gamma} \right)^2}, \quad (1.3)$$

where r is the position of the atom, $s = I/I_{\text{sat}}$ is the saturation parameter ($I_{\text{sat}} = 3.58 \text{ mW} \cdot \text{cm}^{-2}$ for a uniform sublevel population distribution [25]), $\delta = \omega_L - \omega_0$

is the detuning of the driving (i.e. probe) from atomic resonance and $d\omega(r) = (U_e(r) - U_g(r)) / \hbar$ is the atom-surface shift assuming a two-level atom with contributions from the excited U_e and ground U_g levels.

1.4 Coupling efficiency

The coupling efficiency of an atom to the ONF is the rate of spontaneous emission that couples into the one-dimensional mode of the fiber divided by the total spontaneous emission rate [11, 26],

$$\eta(r) = \Gamma_{1D}(r) / \Gamma_{\text{tot}}(r) . \quad (1.4)$$

Fermi's golden rule determines the form of $\eta(r)$, which follows the spatial variation of Eq. 1.1.

Photon detection at the end of the fiber is governed by Beer's law. The transmitted intensity, for low atomic number, in the experiment is proportional to one minus the probability of absorption of a photon from the nanofiber mode, which is mathematically described by the product of the photon absorption rate in Eq. 1.3 and the coupling efficiency in Eq. 1.4. The position-dependence of this joint probability allows us to obtain information about the atomic interaction with the surface.

The modifications to spontaneous emission (rate enhancement, guided mode coupling, etc.) are position-dependent relative to the nanofiber surface, so we need to know the spatial distribution of atoms over which to average these effects. We consider free cold atoms and desorbed atoms that are moving in the evanescent

mode using a thermal distribution.

1.5 Surface potentials

Ref. [27] provides a theoretical treatment of the problem of the modifications to the atomic spectra due to the nanofiber, based on quantum-mechanical scattering of atoms off of the surface potential. Here we focus on a simpler classical approach and a thermodynamic derivation of the population distribution.

The potential an atom sees arises from a van der Waals interaction between the silica surface of the fiber and the atom, mediated by virtual photon pair exchange between two dipoles. We approximate the nanofiber as an infinite dielectric plane when calculating the van der Waals potential [28–30]. The infinite-plane approximation is accurate to within 20% for atom-fiber distances less than 200 nm [23], a distance comparable to the decay length of the evanescent field ($q^{-1} \approx 188$ nm). We have seen effects of the finite radius of the nanofiber on the spontaneous emission decay rate, which is modified on average about $\pm 10\%$ depending on the alignment of the dipole with respect to the ONF [31].

At larger distances from the fiber, the van der Waals interaction transitions to a Casimir-Polder interaction, which takes into account retardation effects in the virtual photon exchange. An approximate way to smoothly connect these two regions is to use a phenomenological potential given by [12, 27]

$$U(r) = -\frac{hC_4}{r^3(r + C_4/C_3)}, \quad (1.5)$$

where h is Plank’s constant, r is the radial distance of the atom from the fiber

surface, and $C_3 = 746 \text{ Hz} \cdot \mu\text{m}^3$ and $C_4 = 67 \text{ Hz} \cdot \mu\text{m}^4$ are the van der Waals and Casimir-Polder coefficients for ^{87}Rb and fused silica, respectively. For a more detailed discussion see Ref. [17].

The attractive potential given by Eq. 1.5 accelerates atoms as they approach the fiber. As a result of the increased speed of atoms near the surface, the atomic density of untrapped atoms decreases near the fiber. Consider a flux of atoms, Φ moving with an average velocity v in the x -direction. Then the density of atoms is given by Φ/v , so that the density is inversely proportional to their speed.

1.6 Atomic density near the ONF surface

In order to quantify the effect of the potential on the density, consider the ideal gas law:

$$PV = Nk_{\text{B}}T, \quad (1.6)$$

where P is the pressure, V is the volume, N is the number of atoms, k_{B} is Boltzmann's constant, and T is the temperature. Assuming constant pressure, any change in thermal kinetic energy $k_{\text{B}}T$ must be balanced by an opposite change in the local atomic density $\rho = N/V$. Denoting the total energy of an atom by E , we can write it as a sum of the potential and kinetic energy in the system, $E = 3k_{\text{B}}T/2 + U(r)$, with $U(r)$ being the surface potential in Eq. 1.5. Then Eq. 1.6 can be recast as

$$P = \frac{3}{2}\rho(E - U(r)). \quad (1.7)$$

We now solve for the density, and normalize it such that it equals one at large distance – we can safely assume that the MOT cloud density is constant far away

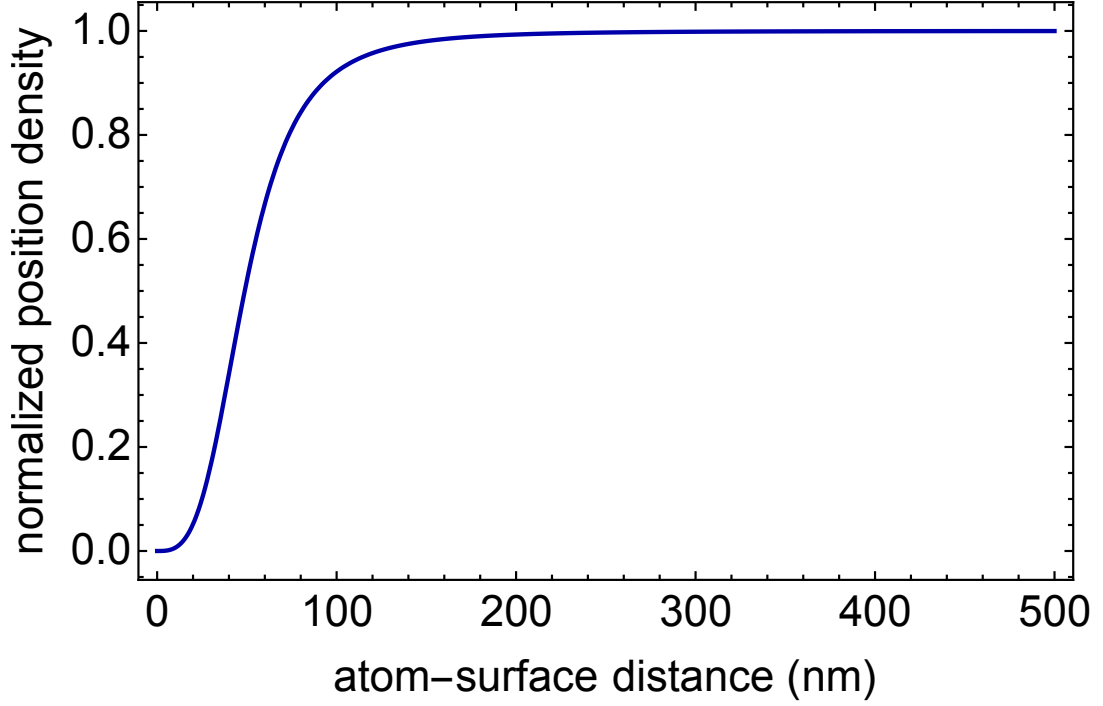


Figure 1.3: Predicted normalized position density $\tilde{\rho}$ of thermal rubidium atoms ($T = 200 \mu\text{K}$) as a function of atom-surface distance d from a fused silica surface. Figure from [32].

from the fiber surface, as its size ($\sim\text{mm}$) is much larger than length scale over which the atom-fiber coupling is appreciable ($< \mu\text{m}$). This yields

$$\tilde{\rho}(r) = \frac{1}{1 - U(r)/E}, \quad (1.8)$$

where $\tilde{\rho}(r)$ is the normalized position density.

Figure 1.3 displays a plot of Eq. 1.8 for an atom temperature of $200 \mu\text{K}$. We see there is a sharp decrease in density near the surface, as expected. This result is in agreement with the numerical calculations of Sagué *et al.* in Ref. [5].

Figure 1.6 shows the distribution of atoms that contribute to the absorption signal. We convolve the predicted normalized position density from Fig. 1.3 with the HE_{11} evanescent mode from Eq. 1.1 and Eq. 1.2 and plotted in Fig. 1.2. The resulting probability distribution has a very close resemblance to a log-normal distribution which is a continuous probability distribution of a random variable whose logarithm is normally distributed. A log-normal process is the statistical realization of the multiplicative product of many independent random variables, each of which is positive. This is the case in the nanofiber as the atoms can not be inside the glass and will have a bias (positive value) on the position in space.

1.7 Expected linewidth

The ideal spectrum of a collection of N atoms undergoing only spontaneous emission is the Fourier transform of the exponential decay with time constant τ . However, when measuring in the frequency domain, other broadening mechanisms can be present, such as the effects of the van der Waals potential explained in the previous section.

The measured linewidth will be an average of the position-dependent rates calculated above, weighted by the population density of the atoms. Writing this average yields

$$\frac{\gamma'}{\gamma_0} = \frac{\int dr (\gamma_{1D} + \gamma_{\text{rad}}) \eta(r) \tilde{\rho}(r) p_{\text{abs}}(r)}{\int dr \gamma_0 \eta(r) \tilde{\rho}(r) p_{\text{abs}}(r)}, \quad (1.9)$$

where $\eta(r) = \gamma_{1D}(r)/\gamma_{\text{tot}}(r)$ defines the coupling efficiency into the guided mode, and $p_{\text{abs}}(r)$ is the probability for an atom to absorb a photon from the probe. This

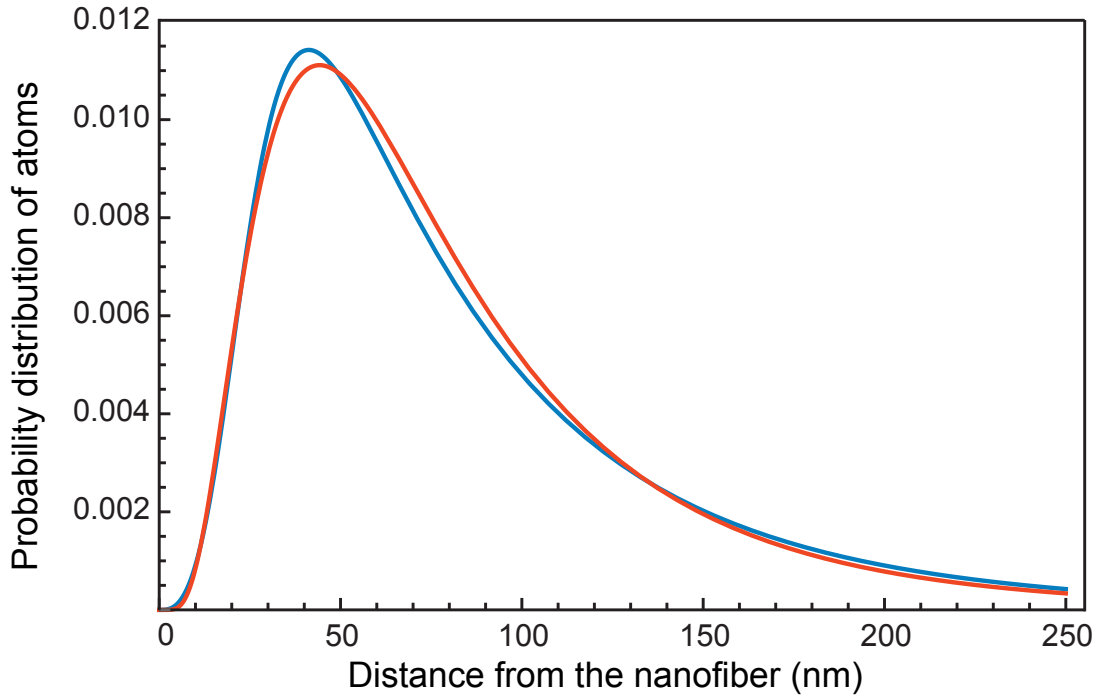


Figure 1.4: Probability of atoms that contribute to the signal taking into account the mode distribution. Red numerical integration Blue best fit to a log-normal distribution.

absorption probability depends on the atom-fiber separation, as the van der Waals interaction shifts the atomic levels out of resonance with the driving beam (see Sec. 1.3).

1.8 Spectra calculation

Russell *et al.* [12] analyze the lineshape of the fluorescence emitted by a cloud of optically excited cold atoms and coupled into an ONF. They describe the asymmetry of the lineshape caused by the red shifts arising from both the van der Waals and Casimir Polder interaction of the atoms with the surface of the ONF. They show that the lineshape of the fluorescence coupled into an ONF is influenced by the van der Waals interaction and is characterized by a long tail on the red side of the spectrum.

Their calculation of the fluorescence spectrum is a good guideline for us to see what to expect on the absorption spectra that we are measuring. Their model assumes the two-level atoms placed around the ONF are spatially broad. In principle, every atom could be excited by the laser field and, subsequently, would be able to emit fluorescent light. However, the resonance condition restricts the spatial position of atoms which can, in reality, emit fluorescence. When the resonance condition occurs at short distances, i.e. in the case of the van der Waals interaction, the atoms are essentially excited at a mean radial position, occupying a cylindrical shell coaxially located around the ONF.

The spatial width, δr , of the cylindrical shell containing excited atoms is de-

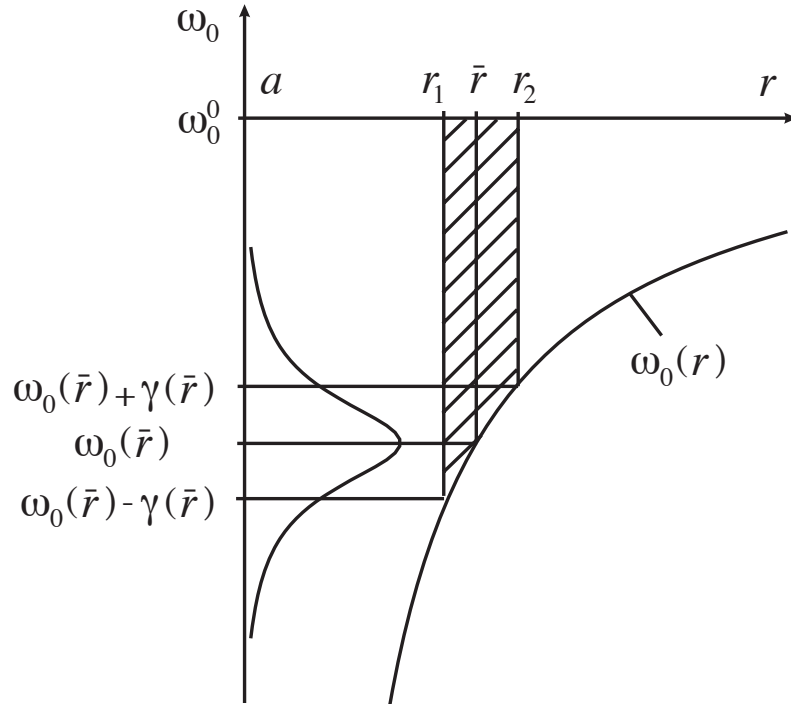


Figure 1.5: Position-dependent optical absorption line. The shaded area indicates the position of the cylindrical shell containing the excited atoms. (Adapted from Fig. 3 of Russell *et al.* [12])

fined by a position-dependent frequency width, of an optical resonance. Assuming that, at the edges of the shell the probability of atomic excitation is half of that at the center of the shell, one can evaluate the radii of the shell edges, r_1 and r_2 . The spatial width of the cylindrical shell containing excited atoms is given by $\delta r = r_2 - r_1$. (See Fig. 1.5). Their model predicts an asymmetry in the line shape, with the red side broader than the blue side. The group of Hakuta has also studied in detail this problem. See their experimental paper and the references therein [13].

1.9 Model

We present here a refined model of the spectral asymmetry to better understand the physics and be able to quantify the data. The density model is similar to those presented in Section 2.5, and is still classical, meaning we consider the atoms having classical trajectories. The classical nature of the simulations is justified because the smallest angular momenta present in the system are still ~ 100 times larger than $\hbar$. The spectral model, which still assumes two level atoms, is similar to Eq. 1.9, but this only accounts for effects due to atomic resonance and must be modified to extend to an ensemble in an evanescent field. To find the probability of a guided photon being absorbed by an atom in the cloud, Eq. 1.9 must be weighted by the coupling strength η (Eq. 1.4) and the cloud density $\tilde{\rho}$ (Eq. 1.8). These quantities are both radially dependent, and their combined effect is shown in Fig. 1.6.

$$P_{abs}(r, \omega) = \eta(r) \tilde{\rho}(r) p_{abs}(r, \omega) \quad (1.10)$$

To turn this into a complete absorption spectrum, we follow a process schematically shown in Fig. 1.5. For every fixed ω , P_{abs} is integrated in r ,

$$P_{abs}(\omega) = \int dr \eta(r) \tilde{\rho}(r) p_{abs}(r, \omega), \quad (1.11)$$

which accurately captures the spectrum for the steady-state density distribution $\tilde{\rho}(r)$. The normalization is excluded for ease of interpretation. Since this requires numerical integration anyway, it can be extended to arbitrary density distributions without any extra effort. In order to model the desorption process, $\tilde{\rho}$ is replaced with

$$\rho_{tot} = \tilde{\rho}(r) + u(r), \quad (1.12)$$

$$u(r) = u_0 \frac{r_0}{r_0 + r}, \quad (1.13)$$

where $u(r)$ is the density distribution of desorbed atoms u_0 is a scaling parameter, and r_0 is the fiber radius. The 1D simulation described in Sec. 2.5 shows that the radial density distribution is essentially flat beyond 1 nm from the fiber, and is essentially flat everywhere at temperatures that can achieve desorption. In 2D (r and Φ) the density integrated over a solid angle is constant in r , so the density of atoms in a shell surrounding the fiber is reduced by the ratio of the source radius (the fiber) to the shell radius. Implicit in 1.12 is the assumption that the desorption process does not affect (and is not affected by) the MOT-only density distribution $\tilde{\rho}$. High-vacuum intuition makes this seem like a safe assumption, and it appears to

be valid based on the results.

Figure 2.6 shows the density distribution $\rho_{tot}(r)$ extracted by fitting our model to the spectrum measured with 40 μ W of heating power during a short desorption cycle. It is a sum of the MOT-only density distribution, $\tilde{\rho}$, and the distribution of desorbed atoms, $u(r)$. With $\tilde{\rho}(r)$ known (or bounded), the only free parameter that directly affects this distribution is u_0 . It is important to understand that the only the relative proportion of the desorption distribution and MOT-only distribution affects the asymmetry. A uniform change of the density will only affect the OD. This is how a spectrum from the short desorption cycle, where the MOT was thinned by a resonant “depumping” laser, can exhibit a higher degree of asymmetry than one from the long desorption cycle, which is able to produce a much higher desorption flux and does not use a depumping laser.

For the purposes of fitting, every uncertain parameter in the model is exposed, some constants are absorbed into a scaling parameter, and translation parameters are introduced:

$$P_{abs}(\omega)[\omega_0, \Gamma_0, u_0, T_{MOT}, I_0, O] = \quad (1.14)$$

$$O - I_0 \int dr \eta(r) (\tilde{\rho}(r, T_{MOT}) + u_0 \frac{r_0}{r_0 + r}) p_{abs}(r, \omega - \omega_0, \Gamma_0).$$

The transformations (I_0, O, ω_0) are standard fare for fits, and quantifying the effect u_0 has on the spectrum was the motivation for the model in the first place. The role of parameters Γ_0 and T_{MOT} , however, is more subtle. Γ_0 represents the atomic linewidth, and enters in p_{abs} , the resonant absorption component of the

model. Variations in this parameter are significant to the goodness-of-fit, but do not couple to the asymmetry estimate. The parameter was first estimated by fitting to a minimally-asymmetric spectrum, which agreed with a simple Lorentzian fit. After verifying that Γ_0 did not change as a free parameter for the asymmetric datasets, it was constrained to a small range around 8 MHz. We do not yet understand its significant deviation from the natural linewidth. Recent modeling indicates that this broadening is consistent with the Purcell enhancement of the spontaneous emission decay rate. Long range dipole interactions mediated by the fiber may also contribute.

The temperature of the MOT, T_{MOT} , affects the steady-state component of the the atomic distribution, $\tilde{\rho}$. Decreasing the the temperature extends the low-density region, and increasing it brings the distribution closer to the fiber. The parameter is negligible for high-asymmetry spectra because the distribution is dominated by the desorption component, but is very sensitive at minimum asymmetry. In an indirect way, this allowed us to use van der Waals to measure the temperature of the MOT to be 332 μK . We did not separately verify this number, but it is consistent with our most recent recent time-of-flight measurements.

It is important to note that the influence of parameters Γ_0 and T_{MOT} is distinct enough that they do not interfere. They converge to their true values when both are left as free parameters, and when either is fixed.

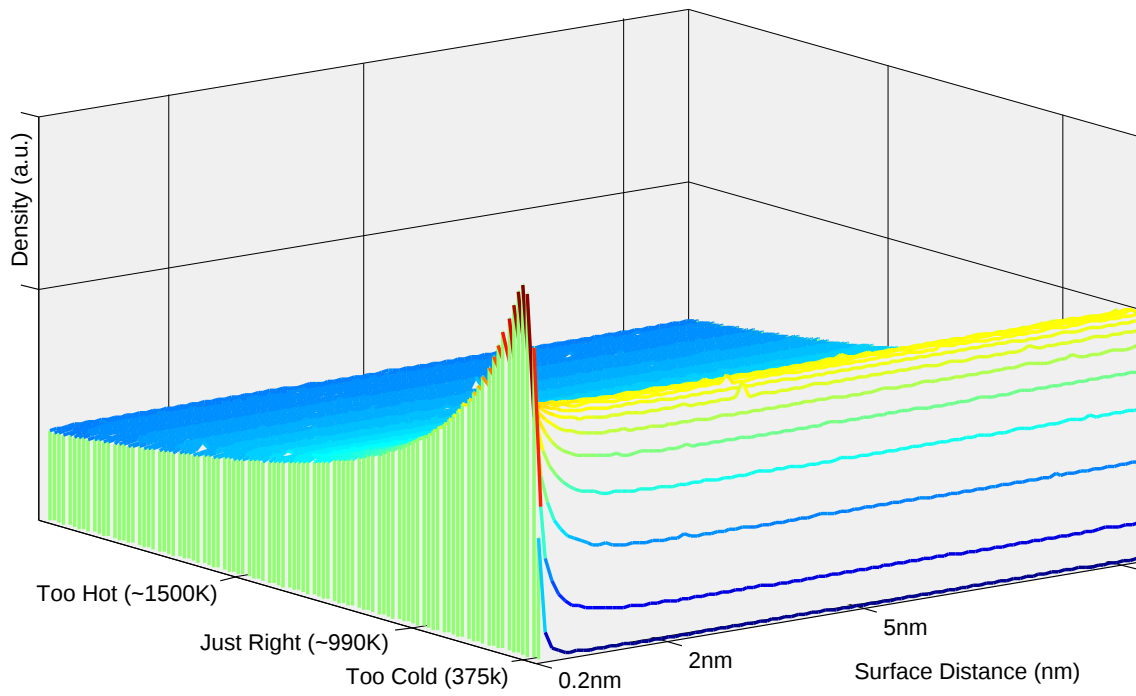


Figure 1.6: Density of thermal atoms desorbed from the fiber, from a numerical simulation

Chapter 2: Experiment and results

2.1 Apparatus

The optical nanofiber (ONF) is produced via the flame brushing technique [33, 34]. A hydrogen-oxygen flame acts as a local heat source to soften 125 μm -diameter, single-mode fiber (Fibercore SM800) whose ends are pulled with computer-controlled linear motors. This method reliably produces fibers of subwavelength diameters with transmission of the fundamental mode above 99% and as high as 99.95%, allowing them to sustain powers of hundreds of milliwatts in high vacuum [33]. We estimate the diameter of our ONF to be 530 ± 50 nm, with a 1% uniformity over a length of 7 mm. This fiber diameter with the stated uncertainty accepts only one guided mode, described by Eq. 1.1, at the experimentally relevant wavelength of 780 nm.

Rubidium atoms can coat the fiber surface and reduce transmission under operating pressures, but applying a 750 nm through-fiber heating beam with a power of more than a few μW is sufficient to desorb the atoms within a few hundred μs .

We briefly review here the MOT system. For a detailed description please see the PhD Thesis of J. A. Grover [32]. Our system consists of the main science chamber with an antechamber equipped with a precision vacuum manipulator (VG Scienta

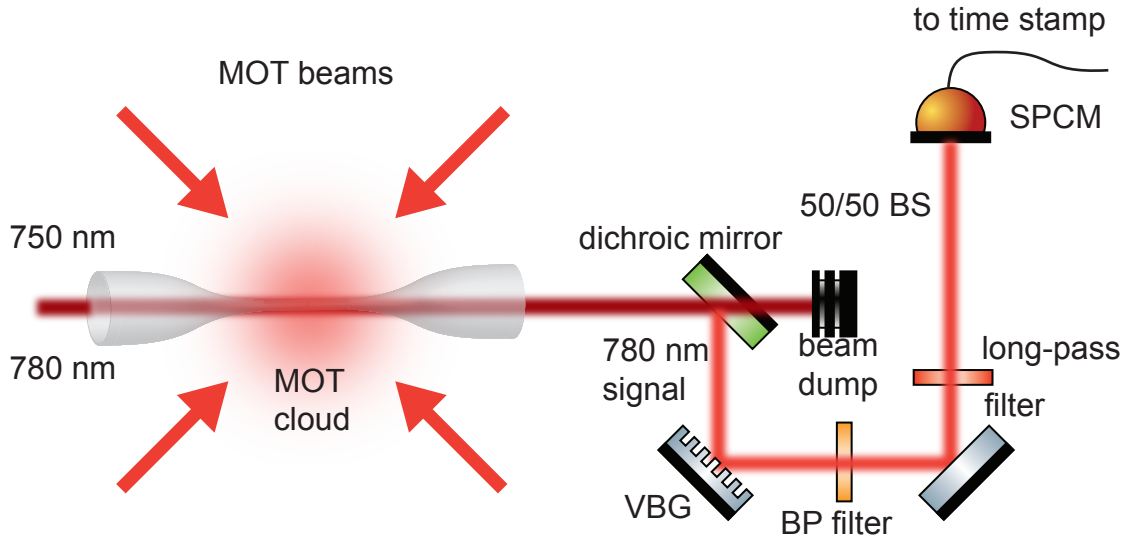


Figure 2.1: Experimental schematic. A 780 nm resonant probe beam launched through the nanofiber scans across the atomic resonance, and an SPCM measures the transmitted light. A 750 nm laser also launched through the nanofiber heats it. The MOT forms around the nanofiber. The transmitted photons are filtered by a volume Bragg grating (VBG), bandpass (BP) filter, and long-pass filter before being sent to an SPCM which are then time stamped for processing.

Transax) . The science chamber maintains a pressure of better than 10^{-9} mbar with two ion pumps (50 L s^{-1}). The ONF is epoxied onto a titanium alloy fiber holder which is held on the vacuum manipulator rod at the antechamber and is transferred to the science chamber. The mounted ONF is extended to the out-of- vacuum patch-cord single-mode fiber via a Teflon ferrule fiber feedthrough with a Swagelok connector. An ^{87}Rb magneto-optical trap (MOT) loaded from a background vapor of ^{87}Rb generated by SAES dispensers produces a cloud of $\approx 10^8$ atoms in a gradient magnetic field that can vary between 5 G/cm and 15 G/cm, achieving temperatures between tens of μK and hundreds of μK [17].

A Toptica TA Pro generates the trapping laser light. A Pound-Drever-Hall based lock [35] on saturation spectroscopy of Rb provides a stable reference for the frequency. The lasers are coupled to single mode polarization preserving fibers to provide the three beams that, with retroflection, form the trapping beams. We derive from this laser a depumping beam by the appropriate use of double-passed acoustic optical modulators (AOMs) to move population into the $5S_{1/2}, F = 1$ ground state that is invisible to the trap beam that operates in the $5S_{1/2}, F = 2 \rightarrow 5P_{3/2}, F = 3$ cycling transition. The resonant beam, frequency-scanned through a double-pass AOM, is also intensity stabilized. A SIM960 PID controller provides realtime feedback through the RF power of the AOM driver. These measures limit systematic power fluctuations in the $\pm 25 \text{ MHz}$ scan to less than 1%. A Toptica DL Pro provides the repumping light necessary for operation of the MOT.

We overlap the cloud with the ONF waist using magnetic field shim coils and the vacuum manipulator with 2D manual translation stages. Two orthogonal

imaging systems ensure alignment.

A 750 nm wavelength laser (Coherent Ti:Sa 899) provides the heating of the fiber but has been used as the repulsive component of the dipole trap in the nanofiber [19]. This laser is not locked in frequency, it can vary some tens of MHz in minutes, but an AOM controls its amplitude. We have available a 1064 nm wavelength beam (JDSU NPRO) that has been used to provide the attractive potential, but can also heat the fiber.

We measure atomic absorption with a weak, near-resonance beam (780 nm) coupled through the ONF, counting transmitted photons with avalanche photodiodes (APD, Laser Components COUNT-250C-FC) operating in Geiger mode. Because light levels near 10 pW saturate the APDs, great care must be taken to filter stray light and maintain low probe power. We use linearly or circularly polarized light at the entrance of the fiber but we are unsure of the state of polarizations that the atoms feel as the fiber can have significant birefringence. Three narrow-line volume Bragg gratings (VBG OptiGrate BP-785, 0.18 nm spectral bandwidth at 785 nm) filter amplified spontaneous emission from the Ti:Sapphire laser near 780 nm before the fiber. A VBG at the output of the nanofiber serves as a mirror to direct signal to the APDs and as another filter to block in-fiber background induced by the blue trapping beam. This light due to either fluorescence or Raman scattering is the main source of background in the experiment. Two more bandpass filters further reduce background counts, and finally long-pass color filters (Thorlabs, FGL645) directly in front of the APD fiber couplers reduce short-wavelength background from stray light. A series of differing neutral optical density (OD) filters before and after

the nanofiber allow us to vary the probe intensity while keeping light levels within the dynamic range of the APDs. TTL pulses from the APDs are counted with a PC time-stamp card (Becker and Hickl DPC-230) for recording detection times with 164 ps resolution, with on-line processing of the signal with software.

The light intensity of the probe is kept to less than one tenth of the saturation intensity for the transition (3.58 mW/cm^2) to make sure there is no power broadening. Given the mode area of the field, the intensity reaches saturation with even tens of pW of power. Since we are interested in near-surface effects, and the evanescent field intensity changes quickly as a function of radius, the power corresponding to saturation intensity is not well defined. Characterizing an effective area by integrating over the mode gives 200 pW. Background counts from all sources (ambient light, incomplete MOT turnoff, etc) are negligibly low, with one notable exception. We notice a count rate correlated to the 750 nm heating beam that exceeds the extinction efficiency of our filter array, but we have yet to explain the mechanism. We initially suspected fluorescence of proprietary fiber dopants, but we did not observe a spectral response over a scan of several nanometers. Our working hypothesis is that these counts are the result of thermal blackbody radiation coupling to the guided mode, due to the very high temperatures that the fiber can reach, but the results so far are inconclusive. Our usual counting rates are $7 \times 10^4 \text{ s}^{-1}$, well below saturation of the APDs and corresponds to a probe power of 19 pW

2.2 Atoms from MOT and from controlled desorption from the fiber

We load the MOT from the low-velocity tail of a background vapor of ^{87}Rb atoms produced by a dispenser. Our temperature measurements [17] show quantitative agreement with a model that incorporates the density of atoms that is flat except near the nanofiber, see Fig. 1.3. Under normal conditions, the transmission spectrum of MOT atoms coupled to the fiber is symmetric due to the low density of atoms near the fiber surface as seen in Fig. 1.3 above.

The fiber itself can be used as a dispenser of atoms by using a 750 nm laser collinear with the probe 780 nm laser to heat the fiber and free physisorbed atoms in the surface, creating a more even distribution than the one seen in Fig. 1.6. This is a different approach to that taken by Nayak *et al.* in Ref. [13] where they use a UV laser from the side to increase the desorption. We know the fiber is hot by looking with a commercial infra red (IR) viewer into the vacuum chamber and seeing the glowing of the fiber for many seconds after the 750 nm light is off. When attempting to see similar heating with 1060 nm, we have been unable to see similar glowing with the IR viewer. Attempts to see any blackbody photons as background on the APD over a narrow bandwidth around 780 nm have not been conclusive. The heating process should have little effect on the chemisorbed atoms on the surface. Fig. 2.2 shows the degree to which a coated fiber attenuates the 780 nm probe, and the dramatic increase in transmission as atoms are thermally desorbed. An interesting feature of this process is the characteristic amount of time it takes for desorption to begin, ranging from several ms at low power to less than μs at high power. Atoms

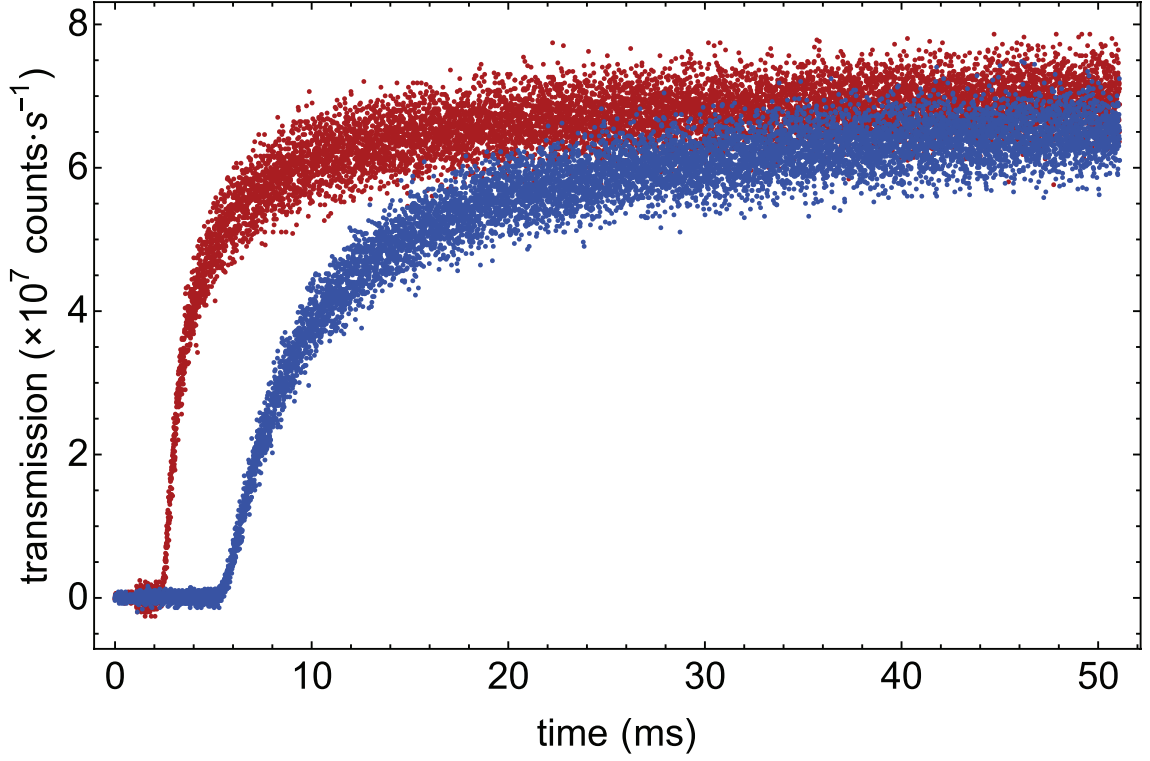


Figure 2.2: Probe transmission as atoms are thermally desorbed from the fiber. Red shows a heating power of $480 \mu\text{W}$, and blue shows $120 \mu\text{W}$ at 780 nm . Figure from [32]

on the surface have a negligible thermal capacity compared to the energy deposited during this period, so this seems to suggest that some of the atoms are trapped in a bound state.

Atoms close to the nanofiber should reveal a red-biased asymmetry and shift due to van-der-Waals as predicted by Russell *et al.* [12].

2.3 Data and fitting

For this experiment, the MOT beams are turned off during data acquisition, but we do not switch any of the magnetic fields. We verify by changing the value of the magnetic field that the MOT does not move much (less than 1 mm) so that the magnetic field seen by the atoms is small and does not cause much of a magnetic shift or broadening. We do not have control of the probe polarization, as stated above, and we do not have a clear quantization axis.

Figure 2.3 shows the basic timing of the detection cycle. We control the number of atoms desorbed from the fiber by the amount of power and the length of the desorption pulse from the 750 nm laser. We control the number of atoms from the MOT using the depumping beam that moves the atoms to the $F = 1$ hyperfine manifold of the ground state while the probe frequency scans approximately ± 25 MHz using a double passed AOM whose frequency is time-controlled and synchronized with the cycle, so we know the probe frequency at all times. The heating beam is cycled according to the two schemes shown in Figure 2.3. The short desorption process applies heat only while probing. This is sufficient to achieve the high temperatures required for desorption, due to the fibers very small thermal mass, but begins to introduce noticeable light shifts at powers exceeding $40 \mu\text{W}$. The long desorption process, shown second in Figure 2.3, inverts the duty cycle to heat the fiber while not probing. The fiber maintains temperature during the short probing period, so desorbed atoms can be very energetic without being subject to light shifts. In both cases, the period of the collection cycle is lower than the thermalization time of

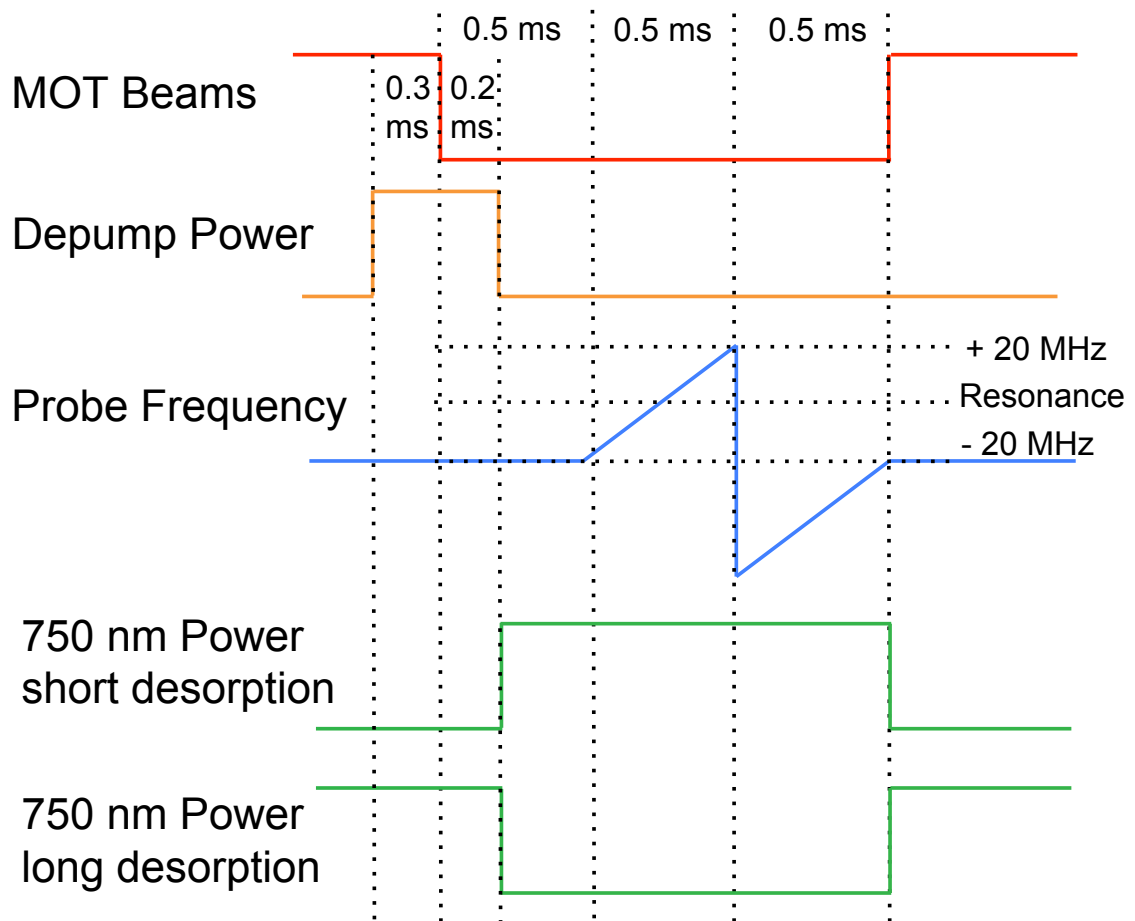


Figure 2.3: Simplified timing of the measurement. This cycle repeats itself every 30ms. The green lines give the two methods used to control desorption: long and short injection of 750 nm light.

the fiber, which occurs mostly due to radiation [36]. Because of this the fiber is always hot, so we assume that a monolayer never has time to form and the power transfer from the heating beam is roughly constant. It is important to note that this desorption process is purely thermal, in contrast to Ref. [13] where they rely on UV light. In our experiment, the combination of the 750 nm laser and 780 nm probe cannot produce two-photon ionization.

We can increase the density of near-surface atoms by increasing the length of the heating cycle, producing a significantly higher optical depth. However, this is limited by the deposition rate of atoms onto the fiber, so we can improve the density and enhance the asymmetry by increasing the accumulation time.

2.4 Measured spectra

Figures 2.4 and 2.5 show examples of the transmitted spectra through the ONF showing optical absorption on the $5S_{1/2}, F = 2 \rightarrow 7P_{3/2}, F = 3$ transition of ^{87}Rb . Given the small optical attenuations caused by the small number of atoms, the difference between $\exp(\alpha l)$ and $1 - \alpha l$ is negligible so we assume that the spectrum of absorption is linear in the transmission from the approximation. Our total accumulation time for a spectrum is about 400 seconds, less a total of 23 seconds of dead time in between our 17 second sub-cycles. This corresponds to roughly 19,000 data-collection periods.

During this time the dispenser current runs at a constant current of about 4.2 A, and variations in the current do not seem to influence the number of available

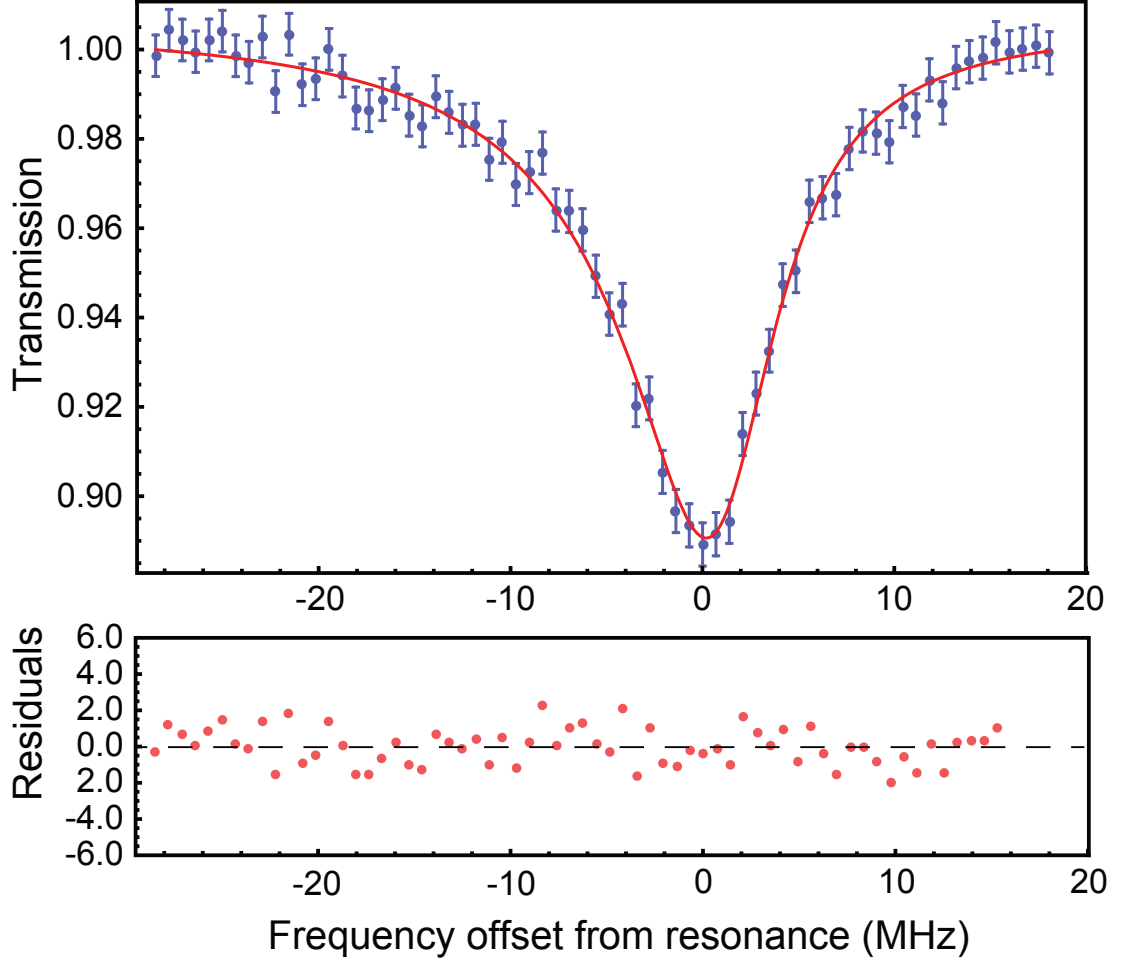


Figure 2.4: Transmission spectrum through the nanofiber with no heating ($0 \mu\text{W}$ of 750 nm power). This is the nearly-symmetric case, which we observe when no atoms have been desorbed. The error bars are statistical. The red line is the fit to the model above showing the normalized residuals. The reduced χ^2 is 1.11.

atoms near or far from the fiber, in contrast to the observations in Ref. [13]

Figure 2.4 comes from MOT atoms only. The distribution has very little asymmetry and a linewidth of 8.9 MHz. The broadening from the natural value of 6.06 MHz is symmetric and will not be relevant for the discussion. This may be due to dipole interactions between distant atoms mediated by the fiber, which would be an interesting experiment of its own. In Fig. 2.5, the fiber is heated by a 40 μ W 750 nm laser pulse, and clearly shows a long tail on the red side of resonance. The exact location of the resonance is subject to change due to uncontrolled offsets that arise when re-locking the probe laser.

It is interesting to note that the asymmetry in Fig. 2.4 is small but not zero. Thus, the spectrum is sensitive to the density distribution of atoms around the fiber, providing yet another way to measure the temperature of the MOT [17]. Fitting our numerical model to the spectrum predicts a temperature of 332 ± 17 μ K.

To compensate for systematic fluctuations and slow drifts of the probe power, each spectrum is processed from two independent datasets. A “signal” set collected with the MOT active, and a “background” set collected with the MOT turned off. We calculate the absorption spectrum by taking the ratio of the two datasets. This has the potential to reduce the measured atomic OD if background levels are sufficiently high, but it does not affect the measured asymmetry. We note that the OD is low for all the measurements.

The fitting parameters are tabulated in Table 2.1, with the exception of the vertical offset and scaling. The desorption density parameter u_0 is shown as $1/(1 + u_0)$, which scales with *symmetry*. We chose this form because it saturates to 1 with

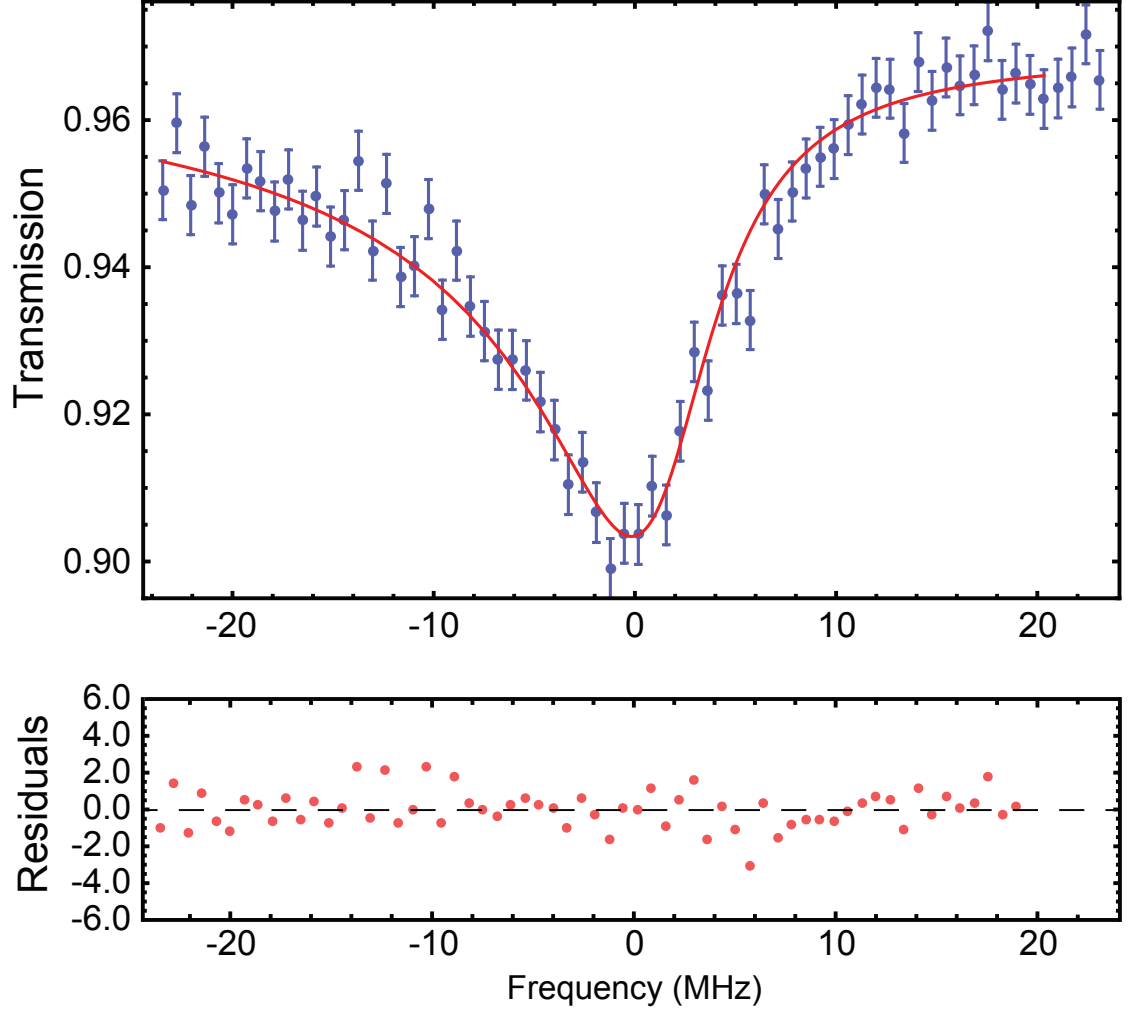


Figure 2.5: Transmission spectrum through the heated nanofiber ($250 \mu\text{W}$ of 750 nm power). This is the asymmetric case, which we observe in the presence of desorbed atoms. The error bars are statistical. The reduced χ^2 is 1.32.

no desorbed atoms, and it goes to 0 when the desorption density is very high. Since the asymmetry depends on the relative proportion of desorbed atoms to cold atoms, asymmetry becomes visible in the $u_0 < 1$ range, as seen in Fig 2.6. At higher values ($u_0 > 5$), the distribution quickly becomes dominated by $u(r)$. In this regime, the spectral asymmetry begins to saturate, and is only weakly sensitive to increasing in u_0 . Because of this, values of u_0 can become very large ($u_0 > 1000$) at high desorption rates. Γ_0 was allowed to vary for the latter three datasets to investigate the possibility of broadening due to the significant Purcell enhancement experienced by very-near surface atoms, as well as potential dynamic effects. The reduced χ^2 of the $120\mu\text{W}$ dataset is high compared to the rest. We suspect that there are effects at high desorption densities that we have not accounted for, which result in increased near-surface density. We do not observe any dynamic changes in density on this time scale.

Power	$\omega_0/2\pi$	$\Gamma_0/2\pi$	T_{MOT}	$1/(1 + u_0)$	A_{calc}	χ^2/ν
(μ W)	(MHz)	(MHz)	(μ K)			
0 (s)	5.9 ± 0.2	8.1 ± 0.3	332 ± 17	1	0.13	1.11
40 (s)	3.7 ± 0.2	8.2 ± 0.4	332 (f)	$8.1 \pm 1.5(10^{-4})$	0.24	1.15
40	0.7 ± 0.1	8.1 (f)	336 ± 23	0.84 ± 0.07	0.15	1.16
120	1.0 ± 0.2	9.2 ± 1.0	332 (f)	$1.4 \pm 0.1(10^{-4})$	0.34	1.91
250	0.9 ± 0.3	8.4 ± 0.9	332 (f)	$1.7 \pm 0.2(10^{-4})$	0.27	1.32
350	0.8 ± 0.2	9.5 ± 2.4	332 (f)	0.90 ± 0.09	0.14	1.29

Table 2.1: Best-fit parameters for each of the measured spectra. Fixed parameters are indicated with an (f), and the short desorption cycle is indicated with an (s). The fact that the 0μ W dataset was taken in the short desorption cycle is not relevant because the heating beam was disabled.

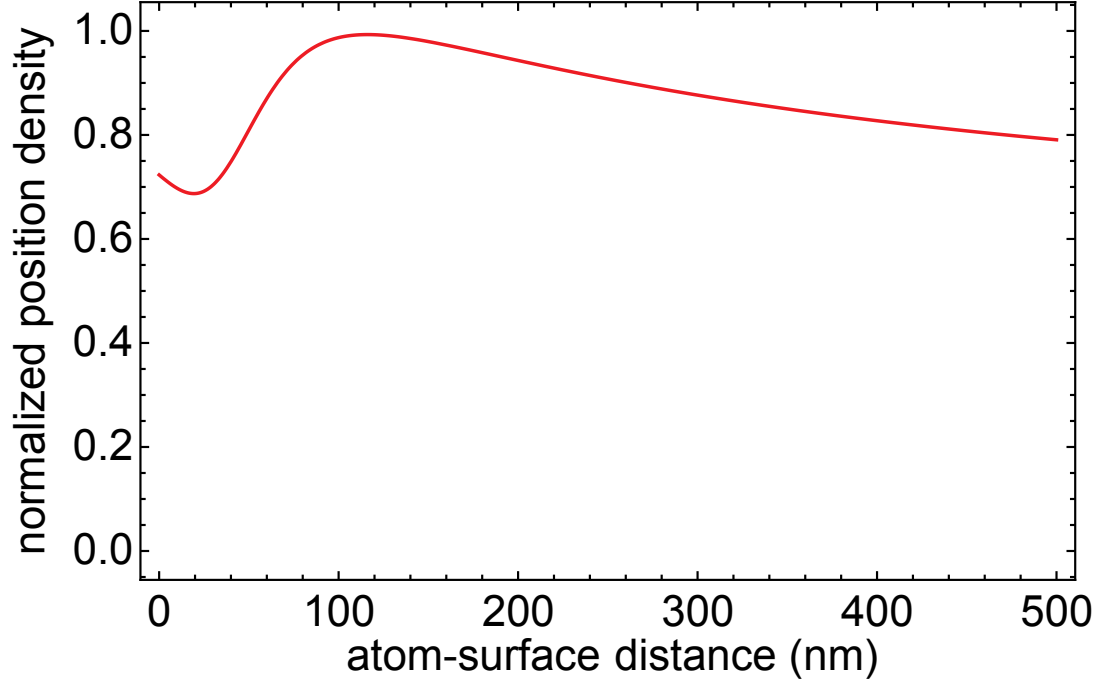


Figure 2.6: The density distribution of atoms around the fiber with $40 \mu\text{W}$ of short-cycle heating power, normalized to it's maximum.

2.5 Asymmetry measurement

We calculate the spectral asymmetry by first finding the point of maximum absorption, then summing all the counts on the blue side of resonance up to a given point in frequency that defines a frequency maximum. This gives us a quantity that we call R , and then we sum points on the red side of resonance over the same width, giving us L . This is shown in Fig. 2.7. The asymmetry parameter A is then:

$$A = \frac{L - R}{L + R} \quad (2.1)$$

This function is zero for a symmetric scan and can increase (decrease) to a maximum (minimum) of $+(-)$ 1. Because van der Waals produces red-biased shifts, we expect this number to be strictly positive. After fitting the numerical model, we evaluate the same parameter by integrating over the regions rather than calculating a discrete sum, also shown in Fig. 2.7.

The errors in the figure are dominated by the uncertainty in determining the center of the resonance. We vary the position by plus and minus one bin (about 500 kHz) and recalculate the value of A to set the limits of the error. The uncertainty due to the counting statistics is negligible on this scale. The point at zero power exhibits minimal (but nonzero) asymmetry, which we expect based on the tails of the MOT-only atom density distribution (see Fig. 1.3).

Adding a 5 ms accumulation period to the long desorption cycle has a negligible impact on the degree of asymmetry, as indicated by the overlapping 250 μ W points, which indicates that the accumulation and desorption processes reach some kind of steady state in this regime. When we repeated the measurement at 40 μ W using the long desorption cycle illustrated in Fig. 2.3, we obtained different values but statistically consistent results. This is because the long desorption process produces densities high enough to measure without reducing the MOT density with the depump beam. Detuning due to van der Waals biases the depumping process towards atoms far from the fiber, which slightly exaggerates the asymmetry.

By measuring the asymmetry induced by van der Waals, we can see that the density of desorbed atoms depends on the temperature of the fiber that is transferred to the atoms, shown in Fig. 2.8. If the atoms are too cold (no 750 nm power) they

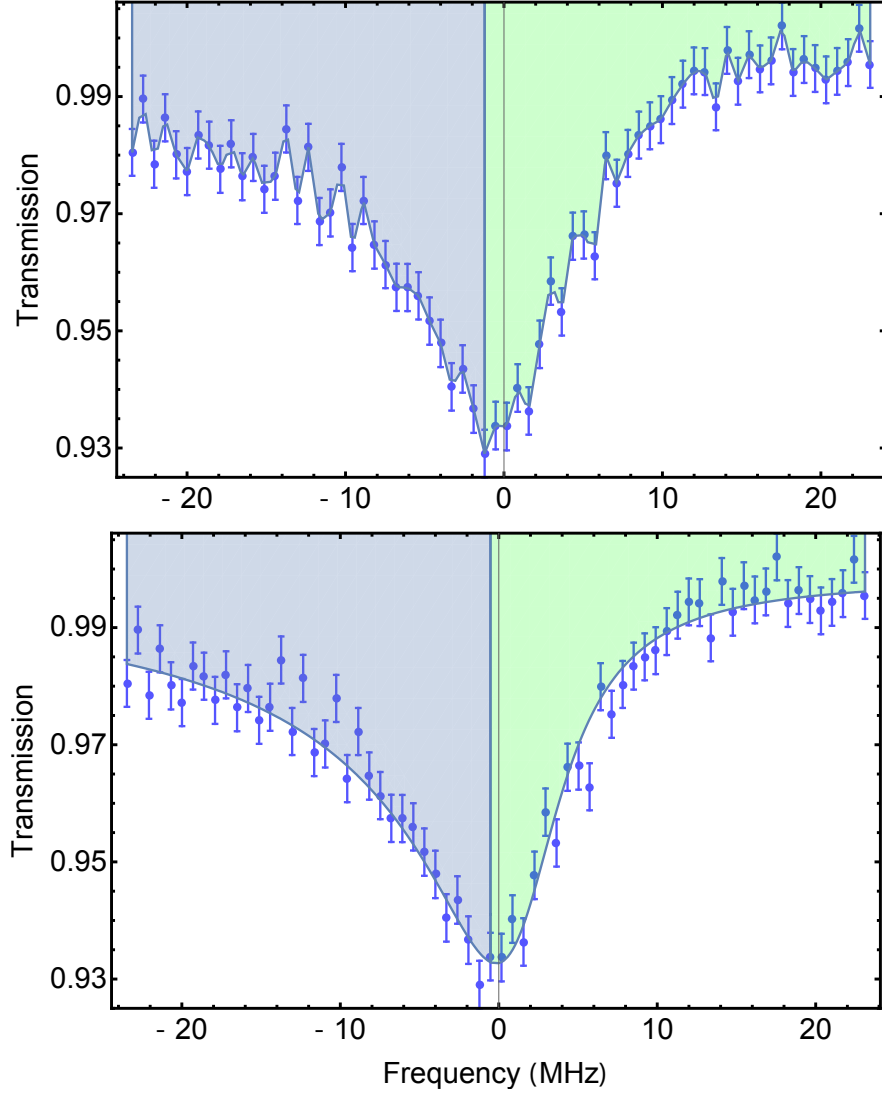


Figure 2.7: Graphic illustration of how we calculate asymmetry from raw data (above), and the fitted model (below). For spectra that are not centered, the integration area is reduced to the distance between the center and the nearest edge. To the extent done in our analysis, shrinking the regions has a negligible impact on A .

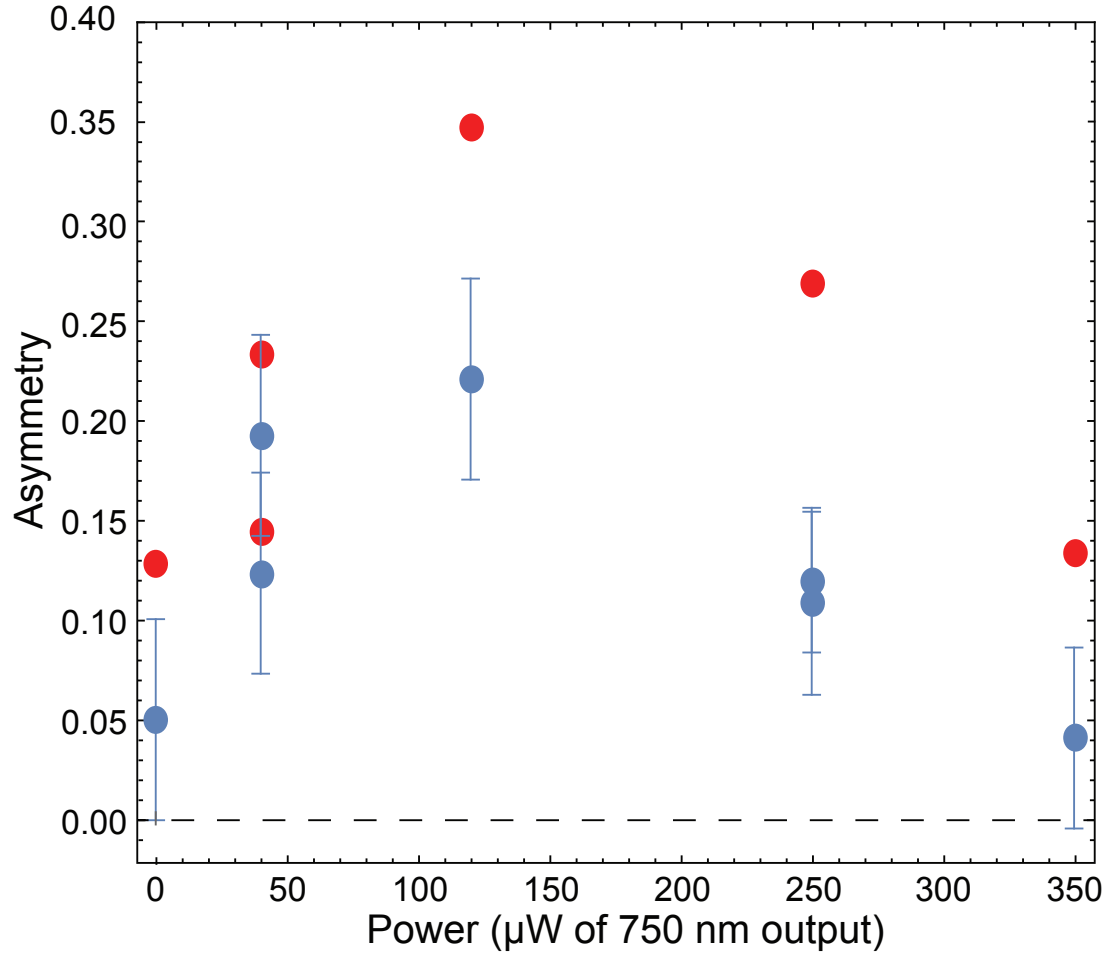


Figure 2.8: Lineshape asymmetry A as a function of the power in the 750 nm desorbing laser. Blue points are calculated directly from data, and red points are calculated from the model. See Table 2.1 for fitting parameters

do not have the kinetic energy sufficient to overcome van-der-Waals. Too hot and they fly away before they can interact (high 750 nm power). There is a power that maximizes the asymmetry, balancing a high desorption flux with a sufficiently long interaction time. In our configuration, we found that this power is roughly $120\ \mu\text{W}$. It is difficult to directly relate this power to a temperature because we do not know all the dissipation mechanisms, if the heating is localized, or what percent of the heating beam is lost at the waist vs. at the free space coupler. With that said, we can estimate that it is in the range of 750-1200K. The simulation using our model predicts maximum density around 990K falling off towards 1500K. Our intuition is further advised by the glowing visible with an IR viewer at $1.3\ \mu\text{m}$. We have actually managed to form a small MOT from just atoms desorbed from the fiber (after a long weekend with the dispensers turned off). For the purpose of comparison, an SAES Rb getter begins to reach vapor pressures sufficient to yield atoms for a weak MOT around 3A, or 800 K.

Chapter 3: Conclusions

We have presented absorption spectra of ^{87}Rb atoms around an optical nanofiber. When using a cloud of cold atoms from a MOT the spectra are nearly symmetric indicating that the atoms are too far from the surface of the nanofiber to feel either the van der Waals or the Casimir-Polder interactions. By carefully using a desorption protocol of the atoms deposited on the surface of the nanofiber it is possible to observe the van der Waals asymmetry in the spectra, quantify it, and extract the density distribution.

Something interesting to do in the future is to try to see if changing the alignment of the atomic dipoles with respect to the fiber, as we have done on the lifetime measurements [31], can cause a difference in the asymmetry. Also ways to control the polarization of the probe and the preparation of the atoms in a particular magnetic sublevel could show more subtle changes.

Extending the range of the scan may also reveal vdW bound states, which would be of great interest to study, and potentially of great value to manipulate.

Use of this desorption technique should enable future work probing the properties of the atom-nanofiber interaction, and open a new parameter space for applications that operate in the very near surface regime.

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