Laser stabilization via saturated absorption spectroscopy of iodine for applications in laser cooling and Bose-Einstein condensate creation

Motivation

In general, the wavelength produced by a given laser will drift over time. Changes in local temperature can occur from room-level fluctuations, power supplies, heating ovens for various optical devices, or the researchers themselves. Further, movement either of laser parts, lubrication, or even the entire enclosure can also cause a laser's output to shift over time.[1]

However, any high-precision measurement will naturally require tight control over all of its components. Additionally, if one wishes to excite a specific atomic or molecular transition, the light used for such an excitation must be held similarly tightly to that transition's characteristic wavelength. Therefore, it is desirable for general purposes to have a laser which is stabilized to output a specified wavelength.

In particular, the Ultracold Atoms group at the University of Washington – Seattle currently uses feedback to lock their lasers to certain transition wavelengths of an ytterbium cell (atomic and molecular transitions are highly insensitive to most external effects – see Background, section V). This cell is quite bulky, however, with low visibility and difficult maintenance. More importantly, however, this cell must be heated to 400°C in order to produce enough gaseous ytterbium for the laser lock to function, but this can produce air currents and distortion in nearby optics. For these reasons, a glass cell containing molecular iodine has been investigated as an alternative to the ytterbium cell. This would eliminate abnormal heat currents and optical distortion produced by the heated ytterbium cell while retaining

[1] Newport

similar wavelength precision. Additionally, a laser locked to this frequency would be of use for many experiments involving ytterbium transitions, such as for the measurement of time standards or other ultracold ytterbium traps.[2]

Background

This work was carried out in order to achieve a high-precision laser lock for use in Bose-Einstein condensate ytterbium-atom interferometry, without the need for a heated cell. Therefore, the background portion of the paper will discuss (1) laser cooling, the process by which hot atoms are cooled to near-absolute-zero temperatures; (2) Bose-Einstein condensates (BECs), a macrostate wherein a large number of bosons simultaneously occupy an identical ground state; (3) interferometry, both in general and as conducted using BECs; (4) α, the fine structure constant which determines the coupling strength between charges and electromagnetic effects, and the determination of a precise value for which constant serves as a primary motivation for this work; and finally (5) saturated absorption spectroscopy, a process which allows for the measurement of highly precise atomic or molecular transition frequencies to which a laser can be locked.

I. Laser cooling

This section describes each of three successive elements of the laser cooling process used by Gupta *et al.* to cool ytterbium atoms into the BEC state: a Zeeman slower, a magneto-optical trap (MOT), and an optical dipole trap (ODT) which also utilizes evaporative cooling.

[2] Jayakumar 1

First, solid ytterbium is heated to 400°C, which causes gaseous ytterbium to leave the solid at high speeds. This gaseous ytterbium is then collimated using multiple screens to form a beam with a nearly 1-dimensional velocity distribution. A slightly red-detuned laser is then shone directly opposite the direction of the atom beam; since the atoms are moving quickly toward the light source, the light is blueshifted in their frame and the atoms are resonant with the light. This allows the laser to impart a momentum kick to the atoms, which then re-emit light in a random direction, for a net decrease of forward momentum. Pervading the beam environment is a magnetic field, which increases dramatically as the atoms move closer to the ultimate trap location. This spreads the transitions via the Zeeman effect, causing the moving atoms to stay in resonance with the laser even as the Doppler shift they observe decreases with their momentum. The Zeeman slower is essentially used to allow the MOT to "catch" the atoms – the magneto-optical trap begins just after the Zeeman slower, once the atoms have been slowed enough to be efficiently trapped.[3]

The magneto-optical trap (MOT) consists of three circularly-polarized lasers, each reflected to create a pair of oppositely-polarized, opposite-direction, collinear beams, and a set of anti-aligned Helmholtz coils (see fig. 1). The coils produce a quadrupolar magnetic field, and the circular polarization of the light reverses the position of the atoms' magnetic moments relative to the field. When an atom is traveling toward the source of one of the beams, the atom observes the Doppler-shifted wavelength to be on-resonance, which pushes the atom back

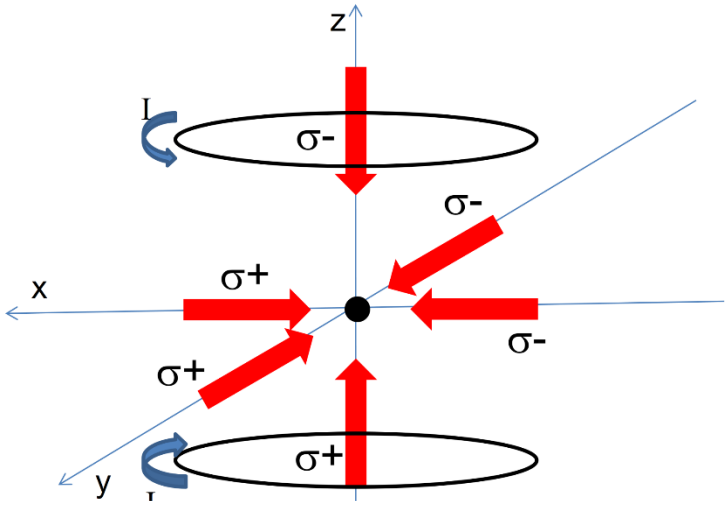

Fig. 1 – Diagram of a MOT. Red arrows represent red-detuned laser beams and black circles represent Helmholtz coils.

[3] Jamison 9-12, Laser

toward the center of the trap. The spin carried by the photon reverses the direction of the electron's spin and causes the interaction with the magnetic field to reverse as well, also pushing the atom back into the center. This results in a non-conservative trap which lowers the atoms' energy over time.[4]

The second trapping stage, the optical dipole trap (ODT), utilized in this laser setup which uses far-off-resonance light to attract atoms to the focus of the beam, and unlike the MOT, the ODT is conservative. The light used is far-detuned from resonance to avoid large interactions with the atoms. The electric field generated by incoming light alters the energy levels in the atom, i.e. induces an oscillatory dipole moment in the atom. This induced dipole moment then feels a force pushing it toward the area of minimum potential, which also occurs at the location of highest intensity. According to Grimm *et al.*, the relation is the following:

$$U_{dip} = -\frac{1}{2\epsilon_0 c} Re(\alpha) I,$$

where $Re(\alpha)$ is the real portion of the complex polarizability α and I is the beam intensity.[5] From this relation, it can be easily seen that not only does the laser's focus (location of highest intensity) determine the location of the trap, the intensity at its focus determines the depth of the trap and therefore the atom energies it is capable of holding. This latter fact is exploited in evaporative cooling.[6]

Since the ODT is a conservative trap, atoms will oscillate inside according to the shape of the potential well and their energies. Therefore, for a given distribution of atom velocities, there is also a corresponding distribution of oscillation amplitudes. By lowering the intensity of the ODT beam, high-

[4] Jamison 12-14, Magneto-Optical
[5] Grimm 3
[6] Jamison 20-21, Optical

energy atoms' oscillation amplitudes will exceed the height of the potential well, and these atoms will fall out of the trap. This allows the remaining trapped atoms to reach a new, lower thermal equilibrium.[7]

II. Bose-Einstein condensates

As a cloud of bosonic atoms cools progressively, each atom also becomes progressively less distinguishable from any other. Eventually, all atoms will "condense" into identical ground states, allowing the entire cloud to be described by a single wavefunction – this is a Bose-Einstein condensate. Since all atoms share a wavefunction, the coherence of a beam formed by this cloud is much higher than other atom beams or low-temperature fermion beams. Further, the large size of this cloud relative to a single atom allows quantum effects to be greatly amplified for precise observation. This high coherence and amplification make BECs highly useful for many applications similar to those of lasers (hence BECs are sometimes referred to as "atom lasers").[8]

III. Interferometry

An interferometer uses, as its name suggests, the interference pattern of two superimposed waves to determine a phase difference between the two. To start, a single wave source is divided in two, each beam made to undergo some treatment, and then the beams are recombined. At the location of recombination, an interference pattern forms – if both treatments are identical, no phase change will be measured and the waves will interfere only constructively. However, if the treatments are not completely identical, the two beams may be out of phase and recombine to form some other waveform. The waveform resulting from the interference of the two beams is called a contrast signal and can be used to determine the phase difference between the two waves. Phase difference is always measured modulo 2π; the advantage, however, is that the precision to which the *difference* is measured is also the precision

[7] Jamison 17-21
[8] Jamison 22-27

for the entirety of the accrued phase. This allows for exceedingly high relative precision when the amount of total accrued phase is very high (e.g. the LIGO experiment).[9]

In the case of atoms, the initial trapped cloud is allowed to expand, then pulsed with a standing wave of light. This splits the cloud into three momentum groups based on what type of pulse each observed: those that felt a momentum kick in the positive direction, those that received it in the negative direction, and those that felt no kick at all. The two "kicked" populations now have different momenta than the third, which causes them to accrue phase more quickly. After some amount of time, a second pulse reverses the effects of the original, and after an identical intermediary time step, a final "readout" pulse is used to obtain an interference pattern between the kicked paths and the unkicked path.[10]

It is important to remember that since this interferometer utilizes quantum phenomena (versus macroscopic, continuous effects), the three populations here are not separate; rather, the wavefunction of the cloud is altered to contain a superposition of positively kicked, negatively kicked, and non-kicked states. The readout pulse is the first observation made and as such, these two "extra" wavefunctions exist only in momentum, not spatial location.[11]

The final phase difference can be used to obtain a value for ω_{rec}, which is roughly a measure of the recoil in the atom from the interaction with the light. ω_{rec} can then be used to calculate $\frac{h}{m}$ via the following relation:

$$\omega_{rec} = \frac{h}{m}\frac{k^2}{4\pi},$$

where k is the wavevector of the light and m the mass of the atom. This $\frac{h}{m}$ value is used in the equation

[9] Jamison 30-35
[10] Jamison 57-59
[11] Jamison 59

$$\alpha^2 = \frac{2R_\infty}{c}\frac{m}{m_e}\frac{h}{m},$$

where R_∞ is the Rydberg constant and m_e is the mass of an electron, to obtain a value for α, the fine structure constant.[12]

IV. α, the fine structure constant

The fine structure constant α was initially conceived as part of an explanation for the fine structure in hydrogen spectral lines.[13] Now, more succinctly, it is often thought of as a highly fundamental constant which "characterizes the strength of the electromagnetic interaction".[14] Bouchendira *et al.*, source of the previous quotation, currently hold the most precise direct measurement of α^{-1} – 137.035999037(91).[15] QED calculations using the g-2 measurement appear to agree with this value, despite being highly involved and theoretical.[16] In this way, a direct measurement of α serves as a test for the validity of QED theory.[17]

While Bouchendira *et al.* used an interferometer to determine $\frac{h}{m}$ for rubidium, Gupta *et al.* seek to leverage the relatively large coherence length of a BEC.[18] This should allow for much greater scaling of precision as the three superimposed wavefunctions are allowed to evolve over longer timescales.

V. Saturated Absorption Spectroscopy

Doppler broadening presents the primary difficulty in measuring transition wavelengths in iodine gas. Given a single laser beam, passing through the iodine cell and sweeping up and down in wavelength across the target transition, one would expect a sharp increase in absorption at the transition. However, since the iodine gas behaves as a thermal cloud, the molecules have a distribution of velocities according

[12] Jamison 49
[13] National
[14] Bouchendira 1
[15] Ibid.
[16] Ibid.
[17] Ibid.
[18] Bouchendira 2, Jamison 22-27

to their temperature. Each molecule then observes the incoming laser beam as shifted according to its velocity, which results in a significantly broader range of increased absorption; whereas a natural linewidth might be on the order of kHz to tens of MHz, observed Doppler widths for this work were on the order of GHz (see fig. 2).[19]

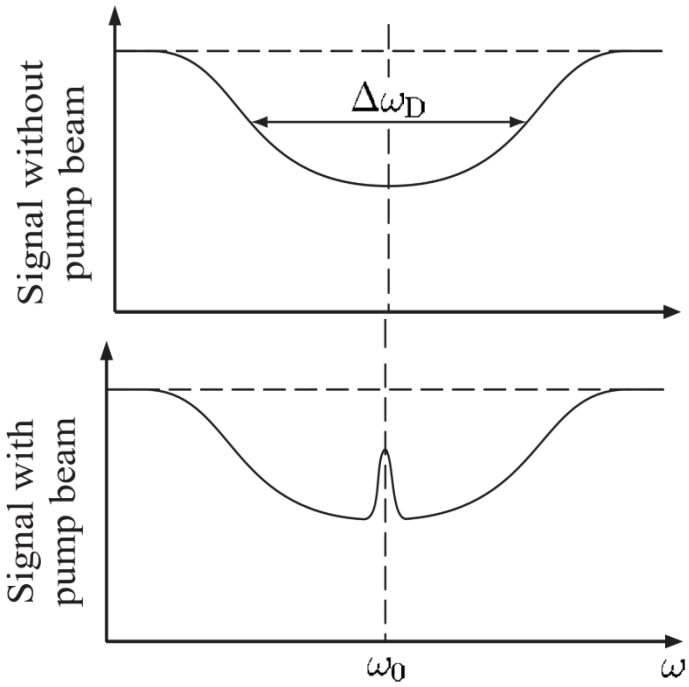

Fig. 2 – Top, a simple Doppler-broadened transition. Bottom, the same transition with the addition of a strong pump beam.

Saturated absorption spectroscopy avoids this difficulty by splitting off most of the initial light (henceforth referred to as the probe beam) into a second beam (the pump beam). This second beam is then redirected back through the opposite side of the cell, collinear and antiparallel to the probe beam (see fig. 3).[20]

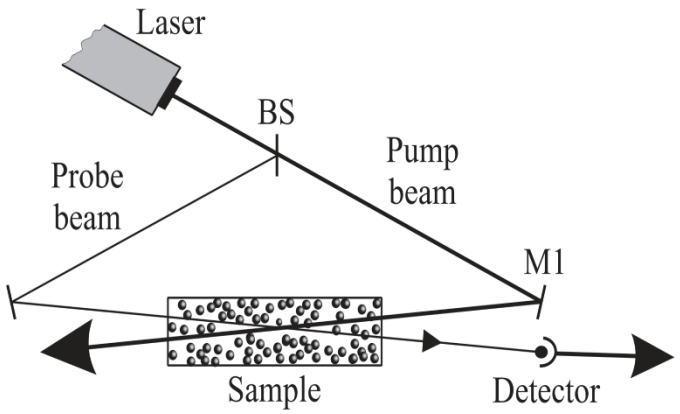

Fig. 3 – Diagram of a typical saturated absorption setup. Note that for a practical setup, the pump and probe beams are collinear, and the pump must entirely overlap the probe.

As the laser scans through off-resonance wavelengths, both pump and probe beams address different velocity classes, and the typical Doppler-broadened absorption profile is observed. However, when both beams are on-resonance, the pump beam's high power excites all or nearly all of the molecules in its path. The

[19] Foot 152
[20] Foot 156

probe, then, observes no absorption, since for all the molecules it *could* have excited, the pump has already done so. As can be seen in the bottom graph of Fig. 2, the addition of a pump beam creates a sharp peak – a system to supply feedback to the laser can then be set up using this peak as a reference point.[21]

Progress and observations

This summer brought with it three major results, all of which couple roughly to a particular change in the setup.

First, a basic absorption setup was replicated on an optics table – essentially the saturated absorption design from above, but without the split-off pump beam (albeit with additional lenses for collimation and mirrors for greater alignment sensitivity). This allowed the data previously obtained from a compilation of iodine absorption lines to be compared to the observed data (see fig. 4).

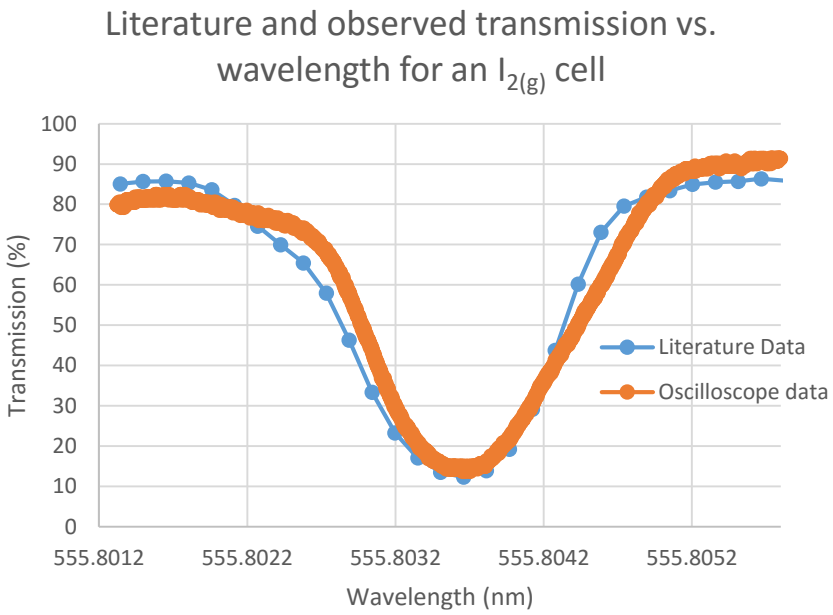

Fig. 4 – Literature and observed data for the iodine transitions (3 transitions fits these data optimally). Note: observed data has been shifted and rescaled for clarity.

Second, the full saturated absorption design from above was constructed and a second, un-pumped probe split off from the first. This allowed the "baseline" signal to be subtracted from the pumped

[21] Foot 156-159

probe, theoretically increasing sensitivity. However, it quickly became apparent that the amount of intensity required to fully saturate this iodine transition was exceptionally high, exceeding that of the atomic transition by many orders of magnitude. The beam size in the cell was diminished by way of a number of lenses and the power was increased in order to combat this difficulty, for an intensity change from the initial 25 mW/cm^2 to the final peak of 3000 mW/cm^2.

Finally, Foot's basic setup was altered further to include a double-pass through an acousto-optical modulator (AOM). The AOM is comprised of a crystal and a piezoelectric transducer – the signal passed to the AOM creates phonons which then mix with the light in the crystal, boosting the frequency of the light by that of the phonon. A dither was then introduced into this boosting frequency (essentially a superimposition of a low-amplitude, low-frequency oscillation onto the base AOM signal); the resulting photodiode signal was fed into a lock-in amplifier along with the dither, and the final output from the lock-in amplifier is the derivative of the original signal (see fig. 5). This signal will be used for the eventual laser stabilization (in this context however, the term "error signal" is used), but also greatly increases the sensitivity to small spikes.

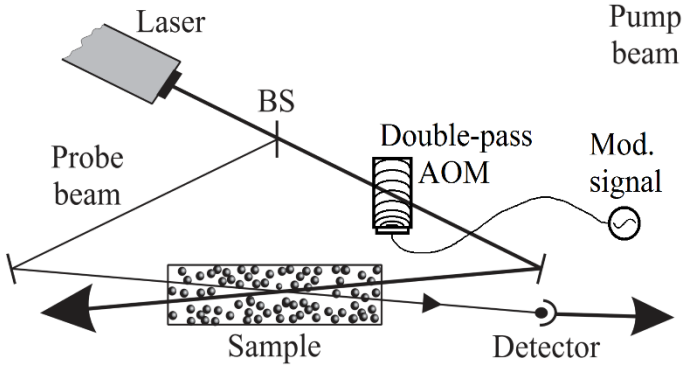

Fig. 5 – A simplistic illustration of the final setup used for this work.

Future work

The primary bottleneck in terms of pump intensity was the doubling crystal used to convert the laser's output at 1012 nm into 556 nm light for use with ytterbium. This periodically-poled lithium niobate crystal (PPLN) essentially combines two photons into one, halving the wavelength. However, the maximum input power that had previously been used with this crystal was only 80 mW, whereas the laser itself can put out up to 1 W of power in infrared. Because this group ordered it from an external source,

it was unclear exactly what the maximum input power for the crystal was, and therefore erring on the side of caution seemed pragmatic. That being said, further correspondence with the manufacturer of this crystal would lead to greater understanding of the crystal itself, and could possibly allow the pump power to be increased significantly.

Another bottleneck in this experiment was divergence of laser beams. Since a laser diverges more quickly with decreased waist size, it is difficult to decrease the pump beam size by large factors without also making the beam very large at some point within the cell. However, the beam size *can* be improved somewhat upon the current size; this could also be aided by the addition of an iris to the probe beam, limiting its size and reducing any concerns about coverage (the pump must entirely cover the probe beam to be effective).

Furthermore, the width of the saturated absorption peak could become an issue assuming sufficient power. One way to combat this might be to purposely pressure-broaden the signal by heating the cell with a Peltier thermoelectric cooler (TEC). This would also increase the saturation intensity, however. Alternately, a significant decrease in the total laser scan size (not to be confused with the AOM boost or modulation), coupled with a further-zoomed scope, would help to reveal very sharp peaks.

Finally, it is also possible to use light from a different laser, either for proof-of-concept or a permanent fix. Carrying over ~1W of green laser light would almost certainly be effective in saturating the transition, although it would also likely prove unsatisfying and certainly work intensive – assuming the current laser can be increased in power, this would require minimal adjustment of optics as compared to bringing over external light.

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Works Cited

Note: in addition to the sources cited here, much of the information contained above also came from conversations with and questions asked of those in the University of Washington – Seattle's Ultracold Atoms group – Deep, Katie, Dan, Ben, Alaina, Ricky, and Ryan, in no particular order.

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