University of Groningen

Bachelor Thesis

Light Fields for Measuring Lightshifts in Ba\textsuperscript{+} Ions

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Abstract

Light shift of atomic levels induced by an intense off-resonant light field can be employed to measure properties of the atomic system. In particular it opens a path to measure atomic parity violation. This work focusses on creating an intense laser field and the overlapping of this field with a localized Ba$^+$ ion in a hyperbolic Paul trap. The design of the optical system is described and the procedure to align the focused laser beam with the ion is discussed. The successful alignment results in a detectable optical transition rate with a large detuning of 4 nm from the resonance. The optical signal from a single trapped Ba$^+$ ion was analysed in terms of frequency resolution which provides the sensitivity to the light induced shifts. The project was carried out at the Van Schwinderen Institute in the context of an experiment which aims at measurements of atomic parity violation in a single trapped Ba$^+$ and Ra$^+$ ion.
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### Abstract

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Chapter 1

Introduction

Atomic system placed in an intense light field experience a modification of energy levels, which is called the light shift. It is a sensitive probe for the atomic levels and the transition strength between them. Together with a good knowledge of the atomic structure in the form of wave functions for the levels and matrix elements for the transitions small effects like the weak interaction can be made measurable in atomic systems. This thesis was performed in the context of an experiment with trapped barium and radium ions where light shifts are used to observe atomic parity violation.

1.1 Atomic Parity Violation

The Standard Model is the currently prevailing theory of elementary particles. It describes all observed processes of particle physics, except gravity, using the properties and interactions of these elementary particles. Discrete symmetries are a part of the Standard Model. The discrete symmetries are charge conjugation, parity and time-reversal. Charge conjugation is an operation that changes a particle into its anti-particle. Parity describes a state under spatial reflection, $r \rightarrow r' = -r$, similar to a mirror. Time-reversal describes a state when it goes back in time. These symmetries are conserved by strong and electromagnetic interactions, but are violated by the weak interactions. Anyone interested in the weak interaction may try to investigate these discrete symmetries [1].

Testing parity in atoms, also called APV (Atomic Parity Violation), is one of the possible routes for exploring the weak interaction. But the weak interaction does not act on its own. The weak and electromagnetic interactions are unified in the electroweak interaction. The electroweak interaction was shown by Glashow, Salam and Weinberg in the 1960s.

A nice way to see the electroweak interaction is in Fig. 1.1. There are 3 terms: a purely electromagnetic, a purely weak and an electroweak interference term. The weak interaction is
significantly smaller than the electromagnetic interaction. The purely weak interaction term is therefore considered undetectable. The electromagnetic term and the electroweak interference term can be measured. In certain atoms these terms could be measured using the light shift or AC Stark shift.

Electric charge, $e$, is the coupling constant of the electromagnetic interaction. The coupling constant of the weak interaction is $g_W$. The Weinberg Angle $\theta_W$ relates the relative strength of these coupling constants. The ratio of these constants can be described by a function of the Weinberg Angle:

$$\sin^2(\theta_W) = \frac{e^2}{g_W^2} \quad (1.1)$$

It is not possible to measure $\theta_W$ directly. But it is possible to measure $\sin^2(\theta_W)$. In several experiments values of this function were measured, or to be measured. These experiments combined cover a large range of energy levels. The results of some experiments are shown in Fig. 1.2. The TRIµP group is working on an experiment related to APV. One goal is to use barium, in the form of $\text{Ba}^+$, and eventually radium, in the form of $\text{Ra}^+$, instead of cesium atoms.

Until now low energy experiments on APV have been performed with cesium atoms. Predictions have been made related to the strength of APV. It appears that the amount of APV is related to the atom. This is especially true for the amount of protons, atomic number $Z$, it contains. Bouchiat and Bouchiat derived that APV scales by an atomic number $Z$ cubed, $\text{APV} \propto Z^3$[7]. Since protons have charge, APV also scales with the electric charge of the nucleus in the same way. But APV actually increases faster than $Z^3$(Fig. 1.3). If we take $Z$ as the number of protons and if we take a relativistic factor $K_{\text{rel}}$, then $\text{APV} \propto K_{\text{rel}}Z^3$. Barium is heavier then cesium. So the amount of APV would be larger than for cesium. Radium is even heavier than barium. So the amount of APV is even larger. APV is predicted to be 50 times larger for radium as compared to cesium [3]. Aside from APV, one could also construct very accurate clocks with radium or barium ions [8–10].
Figure 1.2: The weak mixing angle $\theta_W$ shows an energy scale dependent behaviour. This could be explained by mainly screening up to 80.4 MeV and anti-screening for higher energies [3]. New experiments are planned at several energy levels. A theory exists that relates the mass of possible dark Z bosons to APV [4]. The figure is from [5]. A similar graph can be found in [6].

Figure 1.3: Scaling of the APV matrix element. In the alkali-earth elements it depends strongly on the number of protons, Z, in the atom. The lower (blue) line is if the APV matrix element would scale with $Z^3$. The higher (red) line is when certain relativistic corrections are applied. Ra$^+$ ions are very sensitive to APV. The figure is from [3].
1.2 Transitions and Matrix Elements

In order to find a physical description of an atom we first look at the hydrogen atom model. We use the hydrogen wave functions and then correct for differences between hydrogen and the other atom. With a model to describe the atom, we can try to find parameters of this model for a physical description, this includes transitions. These transitions can move electrons of the atom into a different state. The strength can be described by a transition matrix element

\[ M_{ij} = \langle \psi_i | H | \psi_j \rangle . \]  

(1.2)

The matrix element M contains the Hamiltonian H for the interaction that brings the particle from state i to state j. For a dipole transition the Hamiltonian becomes the electric dipole moment \( \vec{D} = e \vec{r} \). The dipole transition rate is related to the Einstein coefficients

\[ A_{ij} = \frac{g_j}{g_i} \frac{4\alpha}{3c^2} \omega^3 |M_{ij}|^2 \]  

(1.3)

were the factors \( g_i \) and \( g_j \) are the multiplicity of the states. Here \( \alpha \) is the fine structure constant, \( c \) is the speed of light and \( \omega \) is the transition frequency [11].

\( \text{Ba}^+ \) and \( \text{Ra}^+ \) ions both have one valence electron in an outer subshell. The inner shells can be corrected for. The correction is performed by a term dependent on the principal quantum number \( n \) [11]. Detailed calculations of these corrections can be performed for these ions see i.e. [12].

The outer shells of \( \text{Ba}^+ \) and \( \text{Ra}^+ \) are very similar, as can be seen in Fig. 1.4. The subshell structure is the same. This makes their description similar. The difference lies in the size of the atom. Radium is larger than Barium, and all subshells are one principle quantum number higher. This offers some explanation for the different wavelengths of the transitions.

An experimental determination of APV requires detailed knowledge of the structure of \( \text{Ra}^+ \) and \( \text{Ba}^+ \). It is desirable to obtain the matrix elements related to the pure electromagnetic term and the electroweak interference term. The electromagnetic contribution could be obtained through atomic spectroscopy of e.g. level energies, hyperfine structure, branching ratios or state lifetime and furthermore the measurement of an off-resonant light shift. The electroweak interference contribution might be obtained by using the light shift.
1.3 Light Shift

Apart from driving a transition between two states the presence of light modifies the energy levels. Either an electron makes a transition into another energy level or the energy levels themselves change. The first is an on-resonant transition. The light has a wavelength such that it drives a transition to a different state. The other is the light shift. The light creates a time dependent perturbation where the Hamiltonian $H_t$ is small compared to $H_0$, the unperturbed state of the particle. The light with detuning $\delta$ and intensity $I$ perturbs the dipole moment of a certain state [18]:

$$\Delta E^LS_g = \frac{2\pi \alpha I}{\delta} |\langle \psi_g | \epsilon \cdot r | \psi_e \rangle|^2.$$  \hspace{1cm} (1.4)

This perturbation is called the light shift. One could say the atom is squeezed and stretched by photons. In this case the light moves the relative energy levels of certain states, but does not change the state. The light shift works both on-resonant and off-resonant. It depends on the detuning $\delta$ (how far the light is off-resonant) by $1/\delta$. Light with a large detuning creates a smaller light shift than light with a small detuning. Furthermore it depends on the polarization of the laser beam with respect to the dipole moment of the ion. The explanation above was based on the semiclassical treatment of the light shift by Foot in ”Atomic Physics” [11]. The light shift is also explained in ”Laser cooling and trapping” by Metcalf and v. d. Straten [19].
Chapter 1. Introduction

For a given detuning, atom and state, the light shift scales with the light intensity. The light shift $\Delta$ and the intensity $I$ are related by factor $S_{\delta, \text{state}}$:

$$\Delta_{\delta, \text{state}, I} = S_{\delta, \text{state}} \ast I$$ (1.5)

An accurate determination of the intensity is crucial for the determination of the light shift related matrix elements.

1.4 Conclusion

Particle physics can be tested by making the particles and measuring them directly or measuring their decay products. There is also a different route in particle physics. This route consists of performing high precision measurements on atoms. This requires detailed knowledge of the atomic system under investigation. The Van Swinderen Institute has a project were they are trying to measure APV in Barium and/or Radium ions. Determining the APV matrix element requires a measurement strategy: good control of the system and a way to perform the measurements themselves. Ions well localized in a trap provide good control of the system, with great benefits for performing high precision measurements. Measurements on the ion can be done with light shifts.

This thesis analyses the design for far off-resonant light shift measurements with a high intensity laser beam. The focus mainly lies upon $\text{Ba}^+$ ions, but a similar method can applied to for $\text{Ra}^+$ ions.

Figure 1.5: An illustration of the light shift for a two level system. The ground state $|1\rangle$ and the excited state $|2\rangle$ are coupled through off-resonant light. The resonance frequency of the transition depends on the direction of detuning. The frequency of the resonance is reduced by blue detuned light and increased by red detuned light. The figure is from [2].
Chapter 2

Trapping and Controlling a Ba$^+$ Ion

2.1 Ion trap setup

How ions are trapped and controlled in the setup is crucial for performing high precision measurements. Here we provide information on the setup for ion trapping used during this work. A more detailed description can be found in [20].

2.1.1 Trapping a Single Ion

A single ion trap can be used to perform very precise measurements on an ion. This makes them attractive for measuring the light shift in ions. Ions are charged particles. Charged particles can be trapped by a hyperbolic Paul trap. The trap used in this work is described in [9]. The trap sits inside a vacuum chamber at a pressure of $< 10^{-10}$ mbar. This pressure allows for stable trapping of ions.

![Figure 2.1: Ion trap: a hyperbolic paul trap. A varying voltage $V_{RF}$ creates a field that directs a charged particle into the center of the trap. The figure is from [9].](image)

The setup is currently used to trap Ba$^+$. Depending on the circumstances this ion can be trapped for hours. This trap design has a relatively large volume and only requires one ion for measurements. The large volume was also chosen in order to trap rare radioactive materials, like Ra$^+$ ions [9, 20].
2.1.2 Vacuum Chamber

A precise measurement on an ion requires a fine control of the environment of the ion. Therefore a vacuum chamber is very important for the setup. A single ion can only be trapped and measured upon in a very low pressure. A higher pressure results in a higher probability for the ion to be kicked out of the trap, or be perturbed otherwise. It typically has a pressure between $10^{-9}$ and $10^{-11}$ mbar [21]. This pressure is sufficiently low for performing high precision measurements. It is reached by an ion getter pump and a Ti sublimation pump.

There are coils around the vacuum chamber to generate a magnetic field of 400 mG/A in any direction. This permits the compensation of local magnetic fields and the creation of a well known bias field. A typical current is 3 A. This results in a magnetic field of 1200 mG [21]. The magnetic field controls the orientation of the ion dipole with respect to the polarization of the light.

2.1.3 Lasers for Cooling and Detection

Near the main lab is a lab dedicated to lasers, a laser lab. It contains two lasers of interest: a laser that produces light with approximately a wavelength $\lambda = 650$ nm or red light, and a laser that produces light around $\lambda = 987$ nm or infrared light. The laser beams are transported with single-mode fibers to the Barium lab. In Fig. 2.3 they enter in the lower right corner.

The infrared laser light goes into a frequency doubling cavity. The frequency doubling is performed by a crystal at a certain temperature. This makes a blue laser light ($\lambda = 493$ nm) from an infrared laser light ($\lambda = 987$ nm). The laser beam are aligned and coupled into a fiber in "Box 1". The laser light is then brought to "Box 2".

The power of each seperate laser beam can be seen before the trap and after the trap. Photodiodes are used for that purpose. Two photodiodes in "Box 2" measure the power before the trap. The power before the trap gives information on the functioning of the lasers in the laser lab and the optical path until "Box 2". Two other photodiodes measure the power after the trap. The power after the trap is a good indication of the power in the trap. It also tells something about the alignment of the respective lasers. The blue and red laser beams enter the trap between the endcaps and the ring. The power of these laser beams can be up to 100 $\mu$W in the trap, their beam diameter is 120 $\mu$m.

There are two possible ways to perform spectroscopy. Either the blue laser is set to a certain frequency and one scans with the red laser. Or the red laser is set to a certain frequency and one scans with the blue laser.
2.1.4 EMCCD Camera and PMT

In order to see what happens after the ion(s) is/are trapped we need photon detectors. One such detector is an EMCCD: electron multiplied charge coupled device. It is a digital camera, but with the amount of electrons multiplied before charge collection in the CCD. This permits up to single photon detection. The EMCCD has a good spatial resolution especially when taking into account 16 times magnification, 512 x 512 pixels with 6/16 µm per pixel. Another detector is a PMT: photo multiplier tube. A PMT amplifies the initial photon signal more than $10^6$ times [22] before the electrical output signal is observed. The PMT is good at detecting single photons. In this experiment it is used in photon counting mode. Wavelength dependant filters are put in front of the EMCCD and the PMT in order to remove light that is not useful during the measurement.

During the trapping, the PMT is useful to see if there is any ion inside the trap. During the laser cooling the EMCCD can make clear wether there is one ion, or several, and wether they are well cooled. When the ion(s) is/are cooled, the PMT is used for performing measurements such as spectroscopy, see Fig. 2.2. It is also possible to infer dark states or shelved states from the PMT count rate. During such time the ion is in a state which is not resonant with any of the laser light frequencies.
2.1.5 Data Acquisition and Setup

The lab contains devices, e.g. an EMCCD camera, a PMT, several photodiodes, that provide large amounts of data related to the experiment. The data are transferred via some steps to a main control computer. This computer stores the data using ROOT, a program from CERN. Inside ROOT runs an algorithm called RaBogey, it is tailored to the specific needs of the lab. While the data are stored a real time copy is updated every second and shown live on screen. The real time information is used for running the experiment. The stored data are used for an in-depth analysis.

The computer also contains programs that allow for control over several parameters related to the experiment at a distance. These programs make it unnecessary to come close to the setup during a measurement. This in turn reduces disturbances of the trap and the optics surrounding the trap.

2.2 Light Shift Laser System

A second laser table contains a high power laser system that produces light at a wavelength of 589 nm. This light would induce the strongest light shift to the levels D_{3/2} and the P_{3/2}. The transition wavelength between these states is 585 nm.

The laser beam enters the main setup in Fig. 2.3 in the top right corner. Depending on the settings of the laser system and whether the beam is properly coupled into the fiber, the laser power after the fiber is up to 500 mW. The considerations for the optical elements in order to couple the light into the ion trap are discussed in Chapter 3. A shutter, which is computer controlled, can block the laser beam. The computer program allows to set a periodic function for the shutter. Typically it is set to 10 seconds on or not blocking and then 10 seconds off or blocking during a measurement. A variable attenuator is used when setting up optics along the beam. It reduces/attenuates the laser power. A 500 mW beam is quite dangerous for people and for certain equipment.

The light shift depends on the polarization of the yellow laser. A set of λ/2 and λ/4 waveplates can be used to select the polarization that is most suitable for measuring the light shift.

A 8:92 Reflection:Transmission pellicle beam splitter reflects a small part of the beam into a photo diode. The photodiode is used to measure the laser power after the fiber. It is important to calibrate the photo diode with a power meter. The power it reads is not always the same for the same amount of laser power. What the photodiode reads is related to the room temperature. A similar pellicle beam splitter is used to overlap an additional laser beam at wavelength with the yellow laser. This additional red laser beam makes it possible to align the ion with the laser beams.
Figure 2.3: The setup during a measurement using the laser light with $\lambda = 589 \text{ nm}$. The dotted lines represent ignored optical elements.

The beam is brought into a telescope and a final focussing lens $F_3$ with some mirrors. This includes a computer controlable piezo mounted mirror for very fine control of the beam. An aperture after the telescope is used to clean up the beam. Some part of the beam is split of with a pellicle beam splitter. This part is brought into a rotating slit beam profiler. The beam profiler sits roughly at the same distance from the pellicle beam splitter as the trap. The laser beam enters the trap through holes in the endcaps.

### 2.3 Single Ion Trapping

In this section we will describe how to prepare an ion in order to perform precise measurements. In this case the ion of interest is $\text{Ba}^+$, but the procedure is similar for $\text{Ra}^+$, except for the wavelengths. First we make ions inside the Paul trap who are subsequently trapped. If a single ion is trapped successfully, we cool its movement using laser cooling. The motion of the cooled ion eventually depends on the temperature and on the micro-motion. Trap imperfections, often caused by stray charges, can increase the movement of the ion. A more in-depth description on trapping can be found in [20].
Figure 2.4: A Grotrian diagram of a barium atom/ion. An ultraviolet-laser operating at $\lambda = 413.3584$ nm brings a barium atom, Ba I, from the 6s$^2$ 1S state into the 5d6p $^3$D state. After some time the same laser ionizes Ba I in the 5d6p $^3$D state into Ba II, a barium ion, in the $^2$S 6s state. The diagram is from [23]

2.3.1 Getting an Ion

Inside the vacuum chamber there is a small oven. Within the oven is a material containing barium. The oven is heated. When the temperature is high enough an atomic beam emerges and traverses the trap. An ultraviolet-laser operating at $\lambda = 413.3584$ nm is overlapped with the atomic beam inside the trap. The UV-laser is used to photo-ionize the Ba atoms into Ba$^+$ ions. In Fig. 2.4 Ba I is the barium atom and Ba II is the barium ion Ba$^+$. On a control computer the timing during the loading can be adjusted.

2.3.2 Trapping the Ion

The hyperbolic Paul trap "catches" the ion. It works by applying a varying rf-voltage upon it, resulting in a time varying quadrupole field. This field restricts the motion of the ion to within the trap. It results in a more or less circular macro-motion with a micro-motion on top, driven by the varying field. The chance to trap an ion increases with the trap volume. The ion trap in operation has a relatively large trap volume of more than 1 mm$^3$. The trap potential can be made deeper or shallower by changing the amplitude of the rf-voltage. A low rf-voltage gives a shallow potential. A high rf-voltage gives a deep potential. The optimal setting of the rf-voltage depends on the experiment.
2.3.3 Cooling the Ion

The macro-motion can be reduced by applying laser cooling. Two lasers in Fig. 2.2, the blue laser (around $\lambda = 493\,\text{nm}$) and the red laser (around $\lambda = 650\,\text{nm}$) perform this cooling for Ba$^+$. The lasers are red-detuned, this cools the ions. If the lasers are blue detuned, we heat up the ions. The lasers are called detuned with respect to the transitions to which they are closest. In order to cool an ion properly, we start with a large detuning. When the ion cools down the detuning can be reduced for even better cooling. In order to prevent heating of the ion the laser light frequencies are kept below the resonance. This results in a localization of an ion between 1 and 5 $\mu$m.

<table>
<thead>
<tr>
<th>Transition</th>
<th>$\lambda$(nm)</th>
<th>$A_{ij}(10^7$s$^{-1}$)</th>
<th>$I_s$(mW/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6p$^2$P$^1/2 - 6s^2$S$^1/2$</td>
<td>493</td>
<td>9.29(11)</td>
<td>16.1</td>
</tr>
<tr>
<td>6p$^2$P$^1/2 - 5d^2$D$^3/2$</td>
<td>650</td>
<td>3.34(11)</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Table 2.1: A table with parameters of two important dipole transitions in Ba$^+$. These transitions are used for cooling and probing the ion. Saturation intensity $I_s$ and wavelength $\lambda$ are from [20]. $I_s$ is defined in [11]. The Einstein coefficients $A_{ij}$ are from [3].

2.3.4 Shelving and Deshelving

The light at wavelength $\lambda = 589\,\text{nm}$ provides a small probability of driving D$^3/2 - P^3/2$ transition. The upper P$^3/2$ state has a probability to decay to the S$^1/2$ state and some probability to decay into the D$^5/2$ state. When the ion is in the D$^5/2$ state, it does not interact with the red/blue laser light. The ion is then called to be in the shelved state. It becomes invisible to
Figure 2.6: The Ba$^+$ ions are laser cooled. This is performed by two lasers: a red laser and a blue laser. Most cooling is performed by the blue laser, but some part is performed by the red laser.

Apart from the red, blue and yellow light, there are two LED’s, light emitting diodes, on the table. The LED light enters the trap along with the red and the blue laser beams as in Fig 2.2. One of the LED’s produces light at a wavelength around $\lambda = 617 \text{ nm}$. The light has a much broader spectrum than a laser, which means it is less coherent. However the intensity is sufficient to drive ion from the $D_{5/2}$ to the $P_{3/2}$ state and transfer it from the shelved state to the cooling cycle. It can be used to reduce the shelved time. We determined how much it reduces the time of the shelved state.

In order to test the desheling LED, we use a LED produces light with a similar broad spectrum, but now around a wavelength of $\lambda = 455 \text{ nm}$. It can shelve ions effectively. The measurement is presented in Chapter 4.3.
Chapter 2. Setup

2.4 Ba\(^+\) Ion Spectroscopy

Spectroscopy of Ba\(^+\) provides the information on the interaction with the light fields. An understanding of a spectrum provides insight into the sensitivity of light shift measurements. There are two main transitions in Ba\(^+\) of significant impact, one related to the blue laser and the other to the red laser. During a typical measurement one laser is kept at constant frequency, while the other laser is scanned over a range of frequencies. This yields a spectrum like in Fig. 2.8.

2.4.1 Scanning the blue laser

The measurements displayed in Fig. 2.8 show two spectra with different frequencies at wavelength 650 nm which were fixed and the blue frequency which was scanned. The difference was about 20 MHz. An additional feature in these spectra appears when the detuning of the two laser frequencies at wavelength 650 nm and 493 nm are equal. The observed scattering rate decreases at this point. This is the result of a two-photon interaction called the Raman transition resulting in a direct transition between the S\(_{1/2}\) and the D\(_{3/2}\) state. Then the ion spends less time in the P\(_{1/2}\) state, fewer photons from the decay of this state are observed by the PMT. Another feature is the lack of datapoints beyond a certain blue frequency. This is a result of the dual use of the blue laser. The blue laser is used for spectroscopy and it is used for cooling the ion. Above resonance the lasers do not cool the ion, but heat it up. Hence the ion is lost.

Figure 2.7: A Ba\(^+\) ion in the P\(_{3/2}\) mostly decays into the S\(_{1/2}\) state (purple) but also decays to the D\(_{5/2}\) and the D\(_{3/2}\) state (yellow). The D\(_{5/2}\) shelved state has a long lifetime, around 30 seconds [20], and is outside the cooling cycle (red and blue).
Chapter 2. Setup

The measurement was performed in 150 s. The magnetic field was approximately 4 G. The blue laser operates at an intensity $I_b = 1.6I_{s,b}$. When the red laser operates at the lower frequency it has an intensity $I_r = 3.3I_{s,r}$. When the red laser operates at the higher frequency it has an intensity $I_r = 2.3I_{s,r}$.

A fit of the model taking the Raman transition into account agrees well with the data, E.Dijck private communication and posters. It has been estimated that the frequency has resolution is about 0.2 MHz. Other uncertainties like blue and red laser linewidth, power broadening, and temperature of the ion can increase the absolute uncertainty to 1 MHz [20].

2.4.2 Effect of Polarization of Light

The measurements in Fig. 2.9 and 2.10 were done with equal laser settings but with a different orientation of the magnetic field. The cooling red laser frequency and the blue laser frequency were fixed. The probing red frequency was scanned. The blue laser operated at an intensity of $I_b = 0.7I_{s,b}$. When the red laser operates at the probing frequency it has an intensity $I_r = 2.2I_{s,r}$.

The measurement was taken beyond the resonance frequency of the red laser. The noise in the signal is quite consistent throughout the frequency range.

The large center resonance around -1190 MHz is caused by the red laser. The closer it gets to resonance, the more light is scattered from the ion. The resonance is broadened significantly by the red laser power. The dips in the Figures are Raman dips, caused by two-photon interactions by passing the $P_{3/2}$ state.

The difference between the graphs is a result of the orientation of the magnetic field with respect to the polarization of the blue laser. When magnetic field is parallel to the polarization...
Figure 2.9: A spectrum created by scanning the red probing frequency, but keeping the red cooling frequency and the blue frequency fixed. The spectrum is the sum of 2 measurements taking 225 s. The magnetic field was 4.5 G. The magnetic field is parallel to the polarization of the blue laser. The red laser is circularly polarized. The size of the magnetic field scales with the distance between the two Raman dips on both sides of the resonance: they result from Zeeman splitting.

Figure 2.10: A spectrum created with the same laser parameters as in Fig. 2.9. The spectrum is the average of 4 measurements taking 225 s. The magnetic field was 4 G. The important difference is the orientation of the magnetic field, it is orthogonal to the polarization of the blue laser light. If there is any Zeeman splitting, it is not easily discernable. Two linear fits were performed on the steep parts of the Raman dip. The slope is some indication of the sensitivity to a spectrum shift, like the light shift.
of the blue laser the Zeeman splitting of the Raman dips in Fig. 2.9 are discernable. The red laser is circularly polarized. There are various degeneracies lifted by the magnetic field, increasing the possible number of states from 3 to 8. Some of those specific transitions can now be observed. It could be used as a probe for measuring the magnetic field. Then the polarization could be changed, without changing the magnetic field. This would give precise information about the magnetic field in the orthogonal case as in Fig. 2.10. The size and orientation of the magnetic field might be the most important factors.

2.4.3 A Spectrum for Measuring the Light Shift

Fig. 2.10 is a very interesting spectrum for doing light shift measurements or any other high precision measurements. The central Raman dip is very deep and narrow. This could yield a good signal to noise ratio for frequency measurement. The sides provide steep slopes. An attempt is made to quantify how sensitive it is to a frequency change.

For a certain PMT count rate $R_x$ and a frequency $f_x$ we can get a derivative of these variables, which is the slope $dR_x/df_x$. The two red lines, one around the -1195 MHz beat note and the other around the -1185 MHz beat note, are the result of a linear fit. The line around the $f_a$ beat note and $R_a = 240 \text{ cps}$ has a slope of

$$\frac{dR_a}{df_a} = -67(3) \text{ cps/MHz} \quad (2.1)$$

The line around $f_b$ beat note and $R_b = 230 \text{ cps}$ has a slope of

$$\frac{dR_b}{df_b} = 59(3) \text{ cps/MHz}. \quad (2.2)$$

These two coefficients can in principle be determined with a much smaller uncertainty. The uncertainty in the count rate

$$\Delta R = \sqrt{\frac{R}{T}} \quad (2.3)$$

as a function of measurement time $T$ and rate $R$ has an influence on the uncertainty in frequency. The frequency uncertainty becomes

$$\Delta f = \Delta R \ast \frac{df}{dR}. \quad (2.4)$$

From the data in Fig 2.10 the measurement uncertainty in the frequency $f$ of the points a and b can be described by the figure of merit $\Delta f_{a,b}$, which is the frequency resolution.
Taking the rates at point a and b in 2.10 we get for point a

$$\Delta f_a = \sqrt{\frac{R_a}{\Delta T} \frac{df_a}{dR_a}} = -0.23 \frac{1}{\sqrt{\Delta T/s}} MHz$$ \hspace{1cm} (2.5)

and for point b

$$\Delta f_b = \sqrt{\frac{R_b}{\Delta T} \frac{df_b}{dR_b}} = 0.26 \frac{1}{\sqrt{\Delta T/s}} MHz$$ \hspace{1cm} (2.6)

if we extend the measurement time to $\Delta T$ seconds. We assume that the uncertainty of the measurement is given by the statistical uncertainty of the rate $R_a$ respectively $R_b$. A light shift of 200 kHz should be detectable with the measurement parameters in Fig. 2.10 at these slopes. The absolute value of the frequency resolution significantly below 100 kHz is achievable within 100 seconds of measurement time. The spectrum itself is fairly precise. But if there is any large systematic error, e.g. unstable lasers or lasers with a broad linewidth, the signal to noise ratio is reduced.
Chapter 3

Focussing High Power Laser Light

In order to create a detectable light shift a high power laser beam has to be focussed to a small spot. Considerations like aperture size or lens type are discussed because their influence is significant but they are often overlooked. Once the laser beam has been focussed to a small spot, it has to be overlapped with the ion. An additional red guiding laser beam is used for this purpose.

3.1 What is a Gaussian Beam?

This is a summary of some used Gaussian beam parameters. More in-depth treatment can be found in [24] and [25]. A beam is Gaussian if a cross section of its intensity profile can be described by a Gaussian. The radius of the focus is defined by the beam waist \( w_0 \). The definition of \( w_0 \) is the radius of the beam for which the intensity \( I = I_0 \cdot (e^{-2}) = 0.14I_0 \), \( I_0 \) is the peak intensity. The total power of the beam within the beam waist radius is 86% of the total beam power. A beam can be described relative to the location of the focus. Near the focus the beam is described by a plane wave, this is the near field. A perfect plane wave is also called collimated. A collimated beam is the part of the beam in the near field. This is closer to the focus than the Rayleigh range

\[
Z_R = \frac{\pi w_0^2}{\lambda}. \tag{3.1}
\]

The Rayleigh range has a distance from the focus such that the area of the beam is two times the area of the focus. Outside of the Rayleigh range the beam is described by a spherical (point source) wave, this is the far field. The far field has a constant divergence. The far field can be described by the far field angle \( \Theta \). 86 % of the beam power is contained within this angle.
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The beam waist and far field angle are related as follows

$$w_0 \ast \Theta = \frac{2\lambda}{\pi}$$

(3.2)

For a given laser beam the wavelength is constant. An increase in the beam waist gives a decrease in the far field angle, the reverse is also true. So the beam waist and the far field angle are inversely proportional.

Along the optical axis of a Gaussian beam at the focus the light intensity

$$I_0 = \frac{2P}{\pi w_0^2}$$

(3.3)

depends strongly on the beam waist $w_0$ and laser power $P$ [24].

The radial intensity profile in the focus

$$I = I_0 e^{-2r^2/w_0^2}$$

(3.4)

is a Gaussian distribution.

The size of the beam, spot size $w_s$, as a function of distance from the focus $Z$ is described by

$$w_s = w_0 \left(1 + \left(\frac{Z}{Z_R}\right)^2\right)^{1/2}.$$  

(3.5)

Eq. 3.5 defines the laser beam along the complete optical path, and Fig. 3.1 is a drawing of this function. The beam waist and the far field angle are only approximations. But the approximations are much easier to work with.

Figure 3.1: A Gaussian beam drawn along the optical axis.
We use two definitions of beam diameter. They are both related to the beam radius \( w_0 \). The small letter \( d_0 \) is the diameter of the beam for which \( I = I_0 \ast (e^{-2}) = 0.14I_0 \), so \( d_0 = 2w_0 \). This definition of beam diameter contains 86% of the total beam power. The capital \( D_0 \) is the diameter of the beam that contains 99% of the total beam power, \( D_0 = \pi w_0 \).

### 3.2 Sensitivity to the Light Shift

If the signal is so small that we are not sensitive enough to see this signal, it makes little sense to continue doing measurements. Therefore a first approximation to the size of the signal and some knowledge of the sensitivity to that signal is important.

From Eq. 3.4 we know the light shift scales with the light intensity. When we replace the light intensity with measurable parameters laser power \( P \) and beam waist radius \( w_0 \) using Eq. 1.5 we get:

\[
\Delta_{\delta,\text{state},P,w_0} = S_{\delta,\text{state}} \frac{2P}{\pi w^2_0} \tag{3.6}
\]

An accurate measurement of intensity depends on the measurement of laser power and waist size. An accurate determination of the intensity of the laser for light shifts is important for determining the light shift matrix element.

It has been calculated [26] that the \( D_{3/2} \) shifts by

\[
S_{(4 \text{ nm}, D_{3/2})} = 4.5 \ast 10^{-6} \frac{kHz \ m^2}{W}. \tag{3.7}
\]

Therefore the \( D_{3/2} \) state of \( \text{Ba}^+ \) is predicted to shift by about 2.7 MHz for a laser power of 2 W and and beam waist of 46 \( \mu m \). So for this setup the light shift is predicted to be:

\[
\Delta = 1.35 \frac{MHz}{W}. \tag{3.8}
\]

If we take 500 mW laser power, we get a light shift of 675 kHz. For a beam waist of 35 \( \mu m \) and 250 mW of power, we get a 583 kHz shift.

The frequency resolution for measuring the light shift for certain parts of the spectrum in Fig. 2.10 is quite good. The figure of merit tells us that a shift of more than 250 kHz could be detected in 1 s. As the predicted shift lies above 250 kHz, a light shift should be easily found. Such a spectrum is a good candidate for measuring a light shift.
This assumes that the polarization of the light is irrelevant. Polarization of the 589 nm laser might reduce the light shift significantly. Or it may alter how it affects certain specific transitions. The actual shift therefore can not be calculated precisely.

### 3.3 The use of a Beam Profiler

An important tool for setting up optics is a beam profiler. A beam profiler can be used to detect what shape or profile the beam has. A beam profiler can also be used to overlap two laser beams or to provide a precise location of the beam. Precise knowledge of the location of the beam can be used to overlap the beam with an ion. Be aware that the beam profiler should never look (directly) into a high power/intensity laser beam. The beam profiler will break when exposed to a certain intensity.

We use the BP209 beam profiler [27] to determine the beam diameter and location of the 589 nm laser beam. It is a double slit beam profiler, and is is used for determining a Gaussian beam profile. It is not the best option for determining the location of the beam. The slit is moving around so the intensity profile can jump around a bit if the profiler is not set to the right frequency. A CCD based beam profiler is more accurate in determining the beam location because it is stationary. Such a beam profiler is in "Box 2". It is used to provide the relative location of the red and the blue laser.

The error in the intensity depends on the error in the beam waist. So an accurate measurement of the beam waist is vital. The beam profiler can be used to determine the beam waist. The resolution of the beam profiler varies mainly depending on the scan rate and spot size. It is also possible to profile the beam only using the location of the beam. Determining the beam waist might be useful for optimizing the size and the location, along the optical axis, of the laser that creates the light shift. But the actual intensity might be more precisely determined with the shelving rate as in Section 4.2.2.

The beam waist can be determined by redirecting the beam using a pellicle beam splitter. The beam profiler can be put at the same distance from this splitter as the trap. The difference in this distance is smaller than 1 cm. This allows to measure the beam waist directly. The error in the beam profile is several $\mu m$. For a beam waist between 50 and 100 $\mu m$ the relative error is around 10 %. The beam profiler is useful for setting up the light shift laser. But it is not useful for a precise measurement of the intensity.
3.4 Focussing a Gaussian Beam

It is desirable to make a tight focus of the laser beam at the location of the ion. This is because the intensity increases quadratically with a decrease in the spot size, as was observed in the Eq. 3.6. Step by step we will create a set of lenses capable of focussing a Gaussian beam. This focus must be small because that creates a high intensity field. But not too small. The focus could become difficult to hit the ion with the beam. Or the uncertainty in the location of the ion could have a relatively large effect on the intensity. The explanation rests heavily on a book written on laser spectroscopy written by Demtröder, especially paragraph 5.9 [25]. The book on lasers written by Siegman, mainly Chapter 17, was similarly useful [24].

We will describe how to construct a set of lenses that focus a laserbeam. We will start with one lens focussing a collimated beam. Then we will use that concept to construct a system using more than one lens, resulting in a tighter focus. Of course this also means increased complexity. After that will come a short note on lens types. The knowledge will then be applied to the experimental stup.

3.4.1 Focussing a Collimated Beam using One Lens

A collimated Gaussian beam with spotsize $w_s$ falls into a lens of diameter $D = \pi w_s$. More than 99% of the incident energy on the lens passes through the lens. We use the focal spot size $d_0 = 2w_0$. This contains $1 - e^2 \approx 86\%$ of the beam energy. The focussing is performed by a lens with focal length $f$. The spot lies at a length $L = f$ from the lens. The spot is collimated.
within a distance of $Z_R$ from the focus. For these criteria Siegman argues the diameter of the focus is:

$$d_0 = 2w_0 \approx \frac{2f\lambda}{D_s}$$

Equation 3.9 shows that for a given wavelength the focus becomes smaller for a shorter focal length and/or a larger diameter. They are combined in the f-number or speed of the lens:

$$f^\# = \frac{f}{D_s}.$$ 

A fast lens, a lens with a low f-number, allows for a tight focus. The result is a high intensity for the same laser power. The tight focus also reduces the Rayleigh range $Z_R$, or depth of focus $= 2Z_R$. So the beam behaves like a plane wave for a small region.

All the multi-lens setups are basically ways of reducing the f-number. If we change the focal length of the focussing lens and/or the beam diameter, we change the f-number. By a focussing lens we mean a lens that changes a beam with a small divergence angle and a large spot size into a beam with a large divergence angle and a small (virtual) spot size.

### 3.4.2 Focussing a Collimated Beam using Two Lenses

In the two lens configuration, we reduce the f-number by reducing the focal length of the lens. Sadly the focus is not in the trap center anymore. This is solved by introducing a second lens that acts as a relay. There is a limit to the beam width, dictated by the size of the second lens. This lens is the limiting aperture. It dictates the minimum size of the beam waist at the focus. The aperture of optics close to the second lens should also be large enough.

The first lens, a diverging lens, focusses a collimated beam with diameter $D_s = \pi w_s$ into a virtual focus with diameter

$$d_v \approx \frac{2\lambda|f_1|}{D_s}.$$ 

It is a distance $f_1$ in front of the first lens. The second lens, acting as a relay, is put at a distance $L_1$ from the virtual focus. It is placed at a distance $L_1 - f_1$ from the diverging lens. It creates the final focus with diameter $d_0$ at distance $L_2$ with size:

$$d_0 = d_v \left( \frac{L_2 - f_2}{L_1 - f_2} \right)^{1/2}.$$ 

(3.12)
For $L_1 = L_2 = 2f_2$ we get $d_0 = d_v$. For other distances we need to make an approximation. We assume a perfect thin lens. For a thin lens

$$\frac{1}{f_2} = \frac{1}{L_1} + \frac{1}{L_2}$$

holds. We use it to eliminate $L_1$. From 3.13 we can say that

$$L_1 = \frac{f_2L_2}{L_2 - f_2}$$

(3.14)

When we put this back into 3.12 we can derive and simplify it into

$$d_0 \approx d_v \left( \frac{L_2}{f_2} - 1 \right)$$

(3.15)

This approximation only works for a thin lens and when $L_1$ and $L_4$ are close to $2f_2$.

The two lens setup looks a lot like a beam expander. If the distance between the lenses is the sum of their focal lengths, so $L_1 = f_2$, it actually is a beam expander. There are two beam expander types: Galilean and Keplerian. The difference lies in the first lens. The Galilean beam expander has a diverging first lens and a virtual beam focus. The Keplerian beam expander has a converging lens and a real beam focus. An aperture can be put in the real focus between the lenses to make the beam more Gaussian. An aperture could cut away higher modes. Because of the real focus it is not useful for high intensity lasers: it could interact with the air. A Galilean beam expander has a virtual focus, so this interaction is not possible. Another advantage of the Galilean beam expander is that it is two times the focal length of...
the first lens smaller. Because a high intensity laser is used it was decided to use a lens setup similar to a Galilean beam expander.

### 3.4.3 Focussing a Collimated Beam using Three Lenses

In a three lens configuration, we use the first two lenses to expand the beam, and the final lens to focus the beam into the trap. The first two lenses are placed as in a Galilean beam expander. The distance between the lenses is \( f_2 - f_1 \) so \( L_1 = f_2 \).

As previously, a beam with a diameter \( D_s = \pi w_s \) falls into a diverging lens. But now the lens is part of a Galilean beam expander. The beam expander enlarges or magnifies the beam. The magnification \( M \) is defined as:

\[
M \equiv \frac{f_2}{|f_1|} \quad (3.16)
\]

The magnification has two effects. It changes the (near field) beam diameter \( D \) and the far field angle \( \theta \). The angle and diameter are inversely proportional, so they are two sides of the same coin. The beam diameter changes into:

\[
D_e = MD_s \quad (3.17)
\]

And the far field angle changes into:

\[
\theta_e = \frac{\theta_s}{M} \quad (3.18)
\]
When the beam is magnified, the beam diameter increases. Consequently the collimation range $2Z_R$ increases. One could say the beam is more collimated. As an aside, if someone wants to reflect a laser from mirrors placed on the moon, one sends a beam with a diameter in the order of meters. We would like to place lens three, the final lens, near the middle of the collimation range. Because this range is quite large the focussing is less affected by distance $L_2$. The final lens focusses the beam into the trap at $L_3 = f_3$ resulting in a diameter

$$d_0 \approx \frac{2\lambda f_3}{D_e} = \frac{2\lambda f_3}{MD_s}$$

The focal length of $f_3$ probably does not equal its distance from the ion. In order to correct for this, the distance between the first two lenses can be adjusted such that the effective focal length of the final lens equals the distance to the ion. If the focal length is slightly shorter than the distance to the ion, one brings a slightly diverging beam into the final lens. If the focal length is longer, one uses a slightly converging beam.

The three lens design may be more complicated than the two lens design. But three lenses can produce a better focus than 2 lenses, simply because there are more degrees of freedom in the design.

### 3.4.4 Lens Type

When trying to focus light, it is not performed by an ideal lens. With an ideal lens one will get exactly the beam shown in the last sections. The lens is some approximation of the ideal, one tries to minimize optical aberrations depending on the application. The website of Newport maybe somewhat useful [28].

Bi-convex lenses are the best choice when the object and image distance are equal, 1:1 magnification. It minimizes spherical aberration, coma, distortion and chromatic aberration. This is approximately true up to a magnification between 1:5 and 5:1. This makes bi-convex lenses ideal for relaying a beam, like lens $f_2$ in Section 3.4.2.

When focussing or diverging a beam strongly, the magnification will be more significant. When the magnification is higher than 5:1 or lower than 1:5, there is an order of improvement when selecting a lens. The worst plan is to use a Bi-convex or Bi-concave lens. An improvement can be made by using a plano-concave or plano-convex (for beam expansion) lens. The flat surface should be pointing towards the side were the beam has the largest divergence angle. An even better option is an aspheric lens. In this case the most flat surface should point towards the smallest focus. All lenses described in Section 3.4.3 operate in such conditions.
It appears that the best option for anything is an achromatic doublet, two lenses combined and shaped to perfection. This perfection makes these lenses expensive though. This restricts their use only to the most crucial part of any similar experimental setup.

### 3.4.5 The Effects of an Aperture

An aperture truncates a part of a beam. When part of a Gaussian beam is truncated, besides that the total beam power is reduced, it is no longer a Gaussian after the aperture. The effects might be unnoticeable, and often the effects are negligible, but the effects should not be forgotten. It is important to remember that any optical element is an aperture. A piece of paper with a square shaped hole in it is just as much an aperture as a lens with a finite diameter. The effort of making a Gaussian beam, by moving it through an optical fiber, should not be lost in optics after the fiber. The book written by Siegman on Lasers is a good place to start, but the mathematics can be quite complicated [24].

The effects of an aperture are important when using optics to focus or broaden a beam. In the near field or Fresnel field, so within the Rayleigh range of the focus, the effects differ from the effect in the far field.

An example of an aperture is the circular aperture. It truncates the part of a Gaussian beam that lies outside its diameter. The effects of a circular aperture are described in Siegman’s Lasers Chapter 18 [24]. Another description of Gaussian beam truncation can be found in [29].

In the near field a circular aperture with diameter

\[
D \geq 4.6 \, w_0 = 2.3 \, d_0 
\]

has small effect on a Gaussian beam. This criterion is the advised diameter of an aperture. A smaller aperture should only be used if it is absolutely necessary. When the aperture is reduced to

\[
D = \pi \, w_0 
\]

the intensity is reduced by only 1%. The main trouble however are ripples in the intensity. These ripples would change the single spot beam into a many ring beam. Ripples make the beam almost unusable. A smaller aperture diameter makes the beam unpredictable at the center. This is clearly visible in Fig. 3.5.
Figure 3.5: Near-field intensity patterns for a circular aperture illuminated by a Gaussian plane wave. The implications of too small an aperture are quite significant. The ripples are about 20% in the beam except for the center. In the center the intensity variation is almost 100%. Taken from [24].

In the far field a circular aperture gives a different result. The actual diameter of the image spot is

\[ d_0 = K \ast \lambda \ast f\# \]  \hspace{1cm} (3.22)

were \( K \) is a factor dependent on truncation ratio \( T \) and the incoming illumination pattern. The truncation ratio

\[ T = \frac{D_b}{D_t} \]  \hspace{1cm} (3.23)

depends on incoming beam diameter \( D_b \) and aperture diameter \( D_t \). For a Gaussian beam \( K \) can be calculated at several intensity levels, relative to the maximum intensity, as a function of the truncation ratio \( T \). As visible in Fig. 3.6, an Airy function results when a beam is truncated strongly. Yet center beam intensity is conserved. When \( T \geq 2 \) the intensities are good within 1% and there is a minimal effect on the spot diameter. For \( T = 1 \) the beam power is reduced by 14% and the spot diameter is increased by 8%. If the aperture is a lens this truncation ratio could be used when beam power conservation is not too important. A smaller truncation ratio also means a lens aperture is used better, so its f-number is smaller.
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Figure 3.6: The spot profile becomes an Airy or Bessel function when an aperture is uniformly illuminated. It becomes a Gaussian when an aperture is illuminated by a Gaussian. Between these two extremes a combination of these profiles results. Whether an aperture has influence is determined by a $K$ factor. $K$ depends on the truncation ratio. Taken from [29]

3.4.6 Implementation of Focussing

During the light shift measurements two setups were implemented. At first the setup was as described in Section 3.4.2 and this is the telescope in Fig. 2.3. The addition of a third lens, $F_3$ in Fig. 2.3, gave different results. We pick a set of lenses. Then we make an estimate based on some parameters of the initial beam and the nominal values for the lenses. We try to find where the optimal lens position is for a minimal focus and what the resulting focus is. It is a starting point when setting up the optics. Finetuning has to be performed in the actual setup.

The beam has a wavelength $\lambda = 589 \text{ nm}$. The beam spot radius is approximately

$$w_s \approx 700 \mu \text{m}$$

resulting in a beam diameter at lens $f_1$ of

$$D_s = \pi \ast w_s \approx 2.2 \text{ mm}.$$  

The initial setup consisted mainly of two lenses. The setup is described in Section 3.4.2. Lens $F_1$ has a focal length of $f_1 = -75 \text{ mm}$ and can be moved relative to lens $F_2$. Lens $F_2$ has a focal length of $f_2 = 250 \text{ mm}$ and is fixed at roughly 1 m from the trap. The goal is to optimize the location lens $F_1$ such that a minimal focus is achieved 1 m from lens $F_2$. From formula 3.14 we can see that the focus must lie distance
Chapter 3. The 589 nm Laser Set Up

\[ L_1 = \frac{f_2 \cdot L_2}{L_2 - f_2} = \frac{1}{3} \text{ m} \]  

(3.26)

from the virtual focus created by lens \( F_1 \). The virtual focus lies 75 mm in front of lens \( F_1 \). This means the optimal distance between the two lenses is

\[ L_1 - f_1 = 258 \text{ mm} \]  

(3.27)

The initial lens creates a virtual focus of

\[ d_v \approx \frac{2\lambda |f_1|}{D_s} = 40 \mu \text{m} \]  

(3.28)

in front of it. The final lens gives a real focus diameter

\[ d_0 \approx d_v \left( \frac{L_2}{f_2} - 1 \right) = 120 \mu \text{m}. \]  

(3.29)

in the trap. This is only an approximation. A beam diameter of 92 \( \mu \text{m} \) at the same distance from the setup as the trap was measured with the beam profiler. The result is an intensity of \( 3.0(3) \times 10^7 \frac{W}{m^2} \). This intensity results in a light shift of 135 (14) kHz.

The second setup adds lens \( F_3 \) at 300 mm from the trap with focal length \( f_3 = 300 \text{ mm} \). The setup is described in Section 3.4.3. Lenses \( F_1 \) and \( F_2 \) have a distance of \( f_2 - f_1 = 175 \text{ mm} \) between them. The two lenses work as galilean beam expander, a telescope. They enlarge the beam with magnification

\[ M = \frac{f_2}{|f_1|} = 3.33 \]  

(3.30)

times. The beam diameter becomes

\[ d_0 \approx \frac{2\lambda f_3}{MD_s} = 48 \mu \text{m} \]  

(3.31)

in the trap. A beam diameter of 70 \( \mu \text{m} \) was measured with the beam profiler. The result is an intensity of \( 5.2(5) \times 10^7 \frac{W}{m^2} \). This intensity results in a light shift of 234 (23) kHz.

A smaller focus might be achievable by changing lenses \( F_1 \) and \( F_2 \). This can be performed by changing the ratio of the focal lengths and by setting the distance between them at a new \( f_2 - f_1 \). One has to be careful that the beam diameter does not go beyond the aperture of the employed optics as described in Section 3.4.5. The setup mainly contains optics with a
diameter of 25 mm. When a beam with a diameter of 2.2 mm is magnified 3.3 times the beam diameter becomes 7.3 mm. This is well within the margins of any aperture related problems.

### 3.5 Overlapping a Laser Beam Focus with a Trapped Ion

![Diagram of laser setup]

**Figure 3.7:** An additional red beam is aligned with the yellow laser by two mirrors and a pellicle beam splitter. This allows to overlap the yellow laser with the trapped ion(s).

Redirecting a cooling laser, and overlapping it with the light shift laser, is a method for making sure the ion is in the middle of the light shift laser beam. Some part of the red laser beam was split off, creating an additional red laser.

First the additional red laser is aligned with the yellow laser. After the alignment of the two beams, the yellow laser is shut off. Then the red laser is aligned such that it goes through the trap. After the the original red laser is shut off the ion is searched by moving the additional red beam around. The red laser has to be significantly below saturation intensity for a precise overlapping. Above saturation intensity the ion does not change its fluorescence as a function of location inside the beam. The movement is performed with very precise piezo mounted mirrors. If the additional red laser hits the ion, it cools the ion. This can be noticed from an increased count rate from the PMT and a visible blue dot in the EMCCD.

Because the yellow laser and the red laser are aligned, and because the red laser and the ion are aligned, the yellow laser and the ion are aligned. This could make it possible to measure a light shift with the yellow 589 nm laser.
Chapter 4

Results and Discussion

4.1 Results of Setting Up the Laser for Light Shifts

When setting up the Light Shift laser certain conditions must be met. Firstly the focus must be at the right location with respect to the ion. The location along the optical axis is important. But the overlap with ion is equally important, this is the location of the ion with respect to the optical axis. Secondly the beam waist of the focus should be minimized using a beam profiler and then measured by using the ion.

4.1.1 Focus of the Laser at the Correct Position on the Optical Axis

The beam profiler has been placed at the same distance $Z$ as the last pellicle beam splitter before the trap, see Fig. 2.3. Its location could vary by 10 mm. A beam with a beam waist of $w_0 = 35 \mu m$ and a wavelength of 589 nm has a Rayleigh range

$$Z_R = \frac{\pi w_0^2}{\lambda} = 6.5 \text{ mm}. \quad (4.1)$$

This means that the real intensity of the laser beam at the location of the ion can be more than 2 times smaller. A precise determination of the location of the beam is difficult. The intensity would be even further off with a smaller beam waist. When more precision or intensity is required the additional red laser might be used. It is possible to move around the first lens in the setup until the fluorescence with the additional red laser is maximal. The procedure would be similar to the overlapping procedure.
4.1.2 Overlapping the laser

The laser has been overlapped with a Ba$^+$ ion by moving a cooling beam, in this case a red laser with a wavelength of $\lambda = 650 \text{ nm}$. The PMT count rate depends linearly on the intensity of the red laser when the intensity does not exceed the saturation intensity of the 650 nm transition. A first search of the ion could be performed far above the saturation intensity, as this makes area of response of the ion to the beam larger. When the ion is found finer adjustments can be made by setting the maximum laser beam intensity below saturation intensity.

The beam was first aligned with the trap by hand. Then the actual overlapping was performed with piezo mounted mirrors. These mirrors could move the beam in steps of about 5 to 10 $\mu$m. We could be of the middle of the center of the beam by about this number. The beam diameter $d_0 = 70 \mu m$ is much larger than this. It takes 10-20 steps to move the beam across the ion.

If the ion is $r = 10 \mu m$ from the middle of the beam and the intensity in the center of the beam is $I_0$, the actual the intensity is:
\[ I = I_0 e^{-2r^2/w_0^2} = 0.85I_0. \] (4.2)

We could say \( r \) is the error caused by overlapping. The intensity reduced by up to 15\% due to the errors in overlapping the beam.

### 4.1.3 Determining the Beam Waist

The beam waist has been determined by the beam profiler. The initial 2 lens setup resulted in a beam diameter \( d_0 = 92(9) \) µm or beam waist \( w_0 = 46(5) \) µm. Because a light shift was not observed, an improvement was made with a third lens. This gave a beam diameter \( d_0 = 70(7) \) µm or beam waist \( w_0 = 35(4) \) µm. The resolution of the beam profiler is around 10\%. Be aware that a measurement on a high intensity laser beam should not be performed directly at full power. Either the power must be lowered significantly by setting the laser power lower. Or the power must be lowered by using for example a 8:92 Reflection:Transmission pellicle beam splitter.

If the beam waist is used for a precise measurement of the intensity a more precise method has to be used. The response of the ion fluorescence as a function of the beam profile, as with overlapping, could be used.

The additional red laser in combination with ion could also be used for determining the beam diameter of the light shift laser. We move the red beam around until the PMT gives less signal. It should be possible to derive the beam shape. This is difficult to do though. The red laser has to operate at quite a low power, well below the saturation intensity. If the laser is operated near the saturation intensity the fluorescence only changes near the edges of the beam. The ion is not cooled properly near the edges of the beam. Often the ion is lost during measurements.

Another option is to use the light shift laser instead of the red cooling laser, as was done by Koerber in his thesis [30]. He carried out a precise but somewhat tedious measurement using the light shift. Because the light shift depends on the intensity, it also depends on the intensity distribution. And the intensity distribution is related to the profile of the beam. Up to \( \mu \)m precision should be possible. But the method will only work if certain conditions are met. First of all the ion needs to be stable and well localized. This requires appropriate laser cooling and few stray potentials in the trap. A second requirement is an accurate knowledge of the location of the beam. The third condition is that the light shift for a certain frequency of the red and the blue laser light should be well known. This of course requires that the light shift is large enough.
4.1.4 The intensity of laser

Knowing the size of the beam waist makes it possible to derive the intensity of the laser beam along the optical axis. A beam waist \( w_0 = 35(3.5) \, \mu m \) and a nominal power \( P = 100 \, mW \) give an intensity

\[
I_0 = \frac{2P}{w_0^2} = 5.2(5) \times 10^7 \, \frac{W}{m^2}
\]  

(4.3)

in the center of the beam. Assuming a deviation of 10 \( \mu m \) the intensity is reduced by 15\%. If we include the error in the \( Z \), the intensity could be of by more than a factor two. The intensity could be deduced with a smaller error by measuring the shelving rate caused by the off-resonant laser.

4.2 Measurements Performed using the 589 nm Laser

Ba\(^+\) ion spectroscopy that used the 589 nm laser for measuring a light shift gave mixed results. The spectroscopy was performed with a fixed red laser frequency and a scan over the blue laser frequency. The light shift was not observed. But effects of the 589 nm laser were present.

4.2.1 Light Shift

From 3.7 and 4.3 we predict a light shift

\[
\Delta = S_{(4 \, nm, D_{3/2})}I = 234(23) \, kHz.
\]  

(4.4)

After several measurements, a discernable light shift has not been observed. A spectrum of a scan with the blue laser with the 589 nm laser on looks just like Fig. 2.8. Therefore the current setup needs improvements. This might be with regards to sensitivity of the setup to a shift. Or the laser beam does not have the right characteristics. For example the polarization of the beam might not be good. Or the intensity of the beam on the location of the ion is not high enough. A scan with the red laser could be more promising. With parameters of the setup such that they produce a spectrum similar to Fig. 2.10 a light shift might be more discernable.
Chapter 4. Results and Discussion

4.2.2 Shelving

Even though a light shift was not observed, another effect related to the light shift laser was observed: shelving. Shelving is in the tail of a Lorentzian distribution, with the top lying at the resonance. It changes with the detuning as $1/\delta^2$. It increases with intensity just like the light shift. Shelving however reduces the measurement time for light shift spectroscopy. Spectroscopy is impossible with a (temporarily) shelved ion. It is invisible to the EMCCD and PMT.

Near the Raman dip the ion is often in the D\textsubscript{3/2} state. This increases the shelving rate near the Raman dip. When scanning, the shelving rate seems to be higher near and in the Raman dip.

The ion can be shelved if the yellow laser is on and if it is not shelved already. In Fig. 4.2 the amount of time that the ion could be shelved is about 100 seconds. During these 100 seconds the ion is shelved around 7 times. Limited statistics result in a deviation of 3 counts. This results in a shelving rate $R_s$ of

$$R_s = 0.07(3) \text{ s}^{-1} \quad (4.5)$$

**Figure 4.2:** The blue line gives the PMT count rate, the yellow areas show when the yellow laser is active. The PMT count rate only goes to a very low, noise related, rate when the yellow laser is active. This is an effect of shelving the ion.
The shelving rate is an indication of the light intensity. A precise measurement on shelving could make it possible to disentangle the intensity of the yellow laser from other parameters that are related to the light shift. The shelving seems to be inherent to measuring a light shift. Therefore a shorter shelved lifetime is very desirable when measuring a light shift.

4.3 Measurements on the Deshelving LED

A reduction in the shelved lifetime of Ba$^+$ can be achieved with the deshelving LED. But before it is put to use the effectiveness has to be tested.

For this purpose we performed measurements using the shelving LED and the deshelving LED. It was decided to use several ions because it takes less time. A single ion experiment would be more precise, but takes more time. During the measurements, several ions were lost. But because there were multiple ions in the trap, the next measurement could continue. If there is only one ion and it is knocked out of the trap, a new ion has to be loaded. This can be quite time consuming. The LED at wavelength $\lambda = 617$ nm can be observed in the photodiode of the red laser after the trap. The LED at wavelength $\lambda = 455$ nm can be observed in the blue laser photodiode after the trap. A wavelength dependant filter could be used to remove this signal. This fact was used to analyze the data and put this into a diagram shown in Fig. 4.3.

Due to several complications and unknowns, a precise fit could not be calculated. When ions are shelved, they are not cooled. Because it takes some time to cool ions down the PMT count rate rises differently. The ions could be out of the cooling laser beams. This makes the cooling process more random. And if a part of the ions is shelved and the other part is deshelved, the shelved ions slow down the cooling of the deshelved ions. This is a disadvantage of using multiple ions.

A linear approximation in Fig. 4.3 shows the impact of the deshelving LED. It reduces the shelved lifetime by two to three times.
Figure 4.3: The slope with the deshelving LED on is noticeably steeper than the slope when the deshelving LED is off. The deshelving LED would make a noticeable difference in performing measurements on the light shift. During the measurements ions were lost. The experiments without the deshelving LED were performed with less ions than with the deshelving LED. The discrepancy in the number of maximum PMT counts comes from when the measurement was done. The downward trend in the "Signal with deshelving LED" after 43 seconds is a result of a new measurement, it can be ignored.
Chapter 5

Conclusion

In this thesis we have combined the single Ba\(^+\) ion trap setup with a strong focussed laser beam. This permits the observation of off-resonant light shifts of atomic states of Ba\(^+\) ions. Measurements of these light shifts provide information about the atomic wavefunctions which are relevant for the evaluation of atomic parity violation.

We use a high power laser at wavelength of 589 nm for inducing a light shift in Ba\(^+\). The designed imaging system permits the focussing of this laser beam to a diameter \(d_0 = 70(7) \mu m\), in the center of the trap, at the position of the ion. This yields for 100 mW total laser beam power a peak intensity \(I_0 = 5.2(5) \times 10^7 \text{W/m}^2\). The method of focussing a beam can be translated to other wavelengths without too much difficulty. The expected light shift is \(\Delta = 234(23) \text{kHz}\) in the D\(_{3/2}\) state of for laser beam with this intensity and wavelength. The light shift also depends on the polarization of light shift laser with respect to the magnetic field. Therefore the actual shift could be different.

The polarization of the red and blue laser with respect to the magnetic field influence measured spectra. The figures of merit of two sensitive points in a spectrum, Fig. 2.10, were calculated. This shows that the predicted light shift should produce a significant signal within a reasonable time, 100 seconds. Higher precision can be achieved with longer measurements and a larger light shift.

The uncertainty in the distance between the focus and the ion along the optical axis creates a large uncertainty in the intensity at the ion. Therefore the intensity of the laser beam at the ion cannot be accurately determined from the laser position. The position along the optical axis could be optimized by using a procedure similar to the overlapping of the light shift laser with the ion. This has not yet been performed. The beam center can be positioned with 10\(\mu m\) precision in relation to the ion. The overlapping was performed with an additional red cooling laser beam. This results in at most 15% intensity reduction. A beam profiler and a piezo mounted mirror make this possible.
Successful overlapping results in observed far off-resonant shelving to the D_{5/2} state. The shelving indicates that the intensity of this laser is high. With more data analyses the laser intensity could be derived from the shelving rate. The effects of off-resonant shelving can reduce the measurement time on the light shift resulting in less data. The shelved lifetime can be reduced significantly, up to three times, by applying a deshelving LED.

This system now permits the determination of the light shift in a single Ba^+. Measurements at several wavelengths provide for a stringent test of atomic structure as is required for the understanding of atomic parity violation in this system.
Bibliography


