Observation of light-induced coherence loss in a caesium atomic fountain

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Abstract. We report on an experimental measurement of the phase shifts associated with the AC Stark effect. The optically induced light shift was measured using a Ramsey fringe technique and we have made detailed studies of the potential sources of coherence loss that can occur for an atomic sample manipulated by light. We investigated the loss of coherence due to the light shifts induced by using a non-uniform laser beam and the effects of scattered light. These measurements have implications for experiments which use optical techniques for manipulating atomic wavepackets in atom optics and atom interferometry.

1. Introduction

Experiments that directly measure or are sensitive to the phase of atomic wavepackets have created much interest recently. Atomic frequency standards [1], atom interferometers [2] and Bose–Einstein condensation [3] are several examples where the atomic phase plays an integral role in the experiments. Often light fields are used to manipulate the atoms in such experiments, inducing Stark shifts and changing the phase of the atomic wavepackets. To date there has been very little in depth experimental investigation of the way in which the AC Stark effect can influence these experiments. The Stark shift has been seen as a problem to be eliminated, with great efforts made to reduce it, but little attention paid to the precise diagnosis of its effects.

We have constructed a caesium atom interferometer in which optical adiabatic transfer pulses [4] are applied to separate the wavepackets spatially. Thus it is crucial to understand the effect the light has on the coherence between the states and also the phase shifts that it induces. This experiment closely resembles an atomic fountain clock and so it presents an ideal opportunity for measuring how the coherence established by the microwaves is affected by perturbations from the light or other fields.

2. Experimental details

The design of our atom interferometer uses a basic caesium clock as its foundation. A microwave transition between the hyperfine ground levels forms a coherent superposition of two states and the technique of adiabatic transfer is used to manipulate the momentum of the atomic wavepackets coherently. The essential idea behind the interferometer experiment has been described in detail elsewhere [5], so here we provide only a brief overview and a description of the apparatus.
Figure 1. Schematic diagram of the apparatus. The atoms were launched through the microwave cavity where they interacted with the first microwave pulse. Above the cavity they experienced the light pulse and then returned due to gravity to experience the second microwave pulse. The number of atoms in the $F = 4$ state was detected with a time-of-flight beam.

Adiabatic transfer involves the coherent transfer of atomic population from one state to another with the use of a series of laser pulses. In our adiabatic transfer experiments these pulses were of different polarisations, allowing transfer of population from the $m_F = 0$ state to the stretched state. The appropriate choice of beam directions meant that momentum was imparted to the atoms from the light during the transfer. In the complete interferometer we apply a $\frac{\pi}{2}$ pulse of microwaves to create an equal superposition of the $F = 3$ and $F = 4, m_F = 0$ states. The $F = 4$ component of the superposition is then manipulated with the adiabatic transfer, and finally the superposition is recombined again with a second $\frac{\pi}{2}$ microwave pulse.

The work described in this paper used a simplified version of the above experiment where the adiabatic transfer was replaced by a light field of constant linear polarisation, a schematic of which is shown in figure 1. In these experiments a cloud of cold caesium atoms from a magneto-optical trap (MOT) were launched upwards using a moving molasses technique. Optical pumping was then used to prepare the atoms in the $F = 3, m_F = 0$ state before they passed through a microwave cavity located approximately 20 cm above the trapping region. In this they received a $\frac{\pi}{2}$ pulse of microwaves to create a superposition of the $F = 3$ and 4, $m_F = 0$ states. After reaching a maximum height 2 cm above the cavity the atoms fell back down and were exposed to a second $\frac{\pi}{2}$ microwave pulse. These two microwave interactions performed the role of the separated fields in a Ramsey experiment, so that by scanning the microwave frequency and detecting the population of the $F = 4$ level a Ramsey fringe pattern was observed.

In between the two microwave interactions it was possible to apply a single pulse of linearly polarised light tuned to the $F = 4$ to $F' = 4$, D2 transition ($6^2S_{1/2} - 6^2P_{1/2}$). The forbidden nature of this transition between the $m_F = 0$ states makes it an excellent tool for the investigation of the different types of loss associated with light used to manipulate atoms. In particular it mimics some of the effects of adiabatic transfer which may be used as a beam splitter for the atomic wavepacket. During adiabatic transfer there are no resonant excitations which is also the case for the linearly polarised light. The need for precise alignment of the electric field to avoid loss means that defects in the polarisation can be studied which is another critical factor for achieving efficient adiabatic transfer. The AC Stark effect can be investigated as the phase shifts caused by this effect can easily be measured. With the Ramsey fringes the nature of the interactions which occur in between
Observation of light-induced coherence loss

Figure 2. The phase shifts of the Ramsey fringes as a function of the pulse length of the linearly polarised light. The different detunings used were $\delta = -135$ MHz, $\delta = -126$ MHz and $\delta = -45$ MHz. The lines are linear fits to the data.

The linearly polarised beam produces significant light shifts because of the off-resonant interactions with the $F' = 3$ and $F' = 5$ levels which have non-zero dipole matrix elements for this polarisation. These light shifts can also lead to a loss of coherence across the atomic sample with the use of a non-uniform beam. The beam used was located about 2 cm above the microwave cavity, had an approximate diameter of 3 cm and a total power of about 12 mW. A bias field of 10 mG was applied along the $z$ direction, which was also the direction of the polarisation.

3. Results

The phase shifts induced on the Ramsey fringes caused by exposing the atoms to a pulse of linearly polarised light between the two microwave interactions are shown in figure 2. The magnitude of the Ramsey fringe phase shift produced by the AC Stark effect was determined by the detuning and intensity of the light.

We note that the results agree well with the calculated phase shift which may be approximated to

$$\phi = \Omega^2 \left( \frac{C_{43}^2}{\delta_3} + \frac{C_{45}^2}{\delta_5} \right) T, \quad (1)$$

where $\Omega$ is the Rabi frequency normalised on a transition with Clebsch–Gordon coefficient one, $C_{43}$ is the Clebsch–Gordon coefficient for the $F = 4$ to $F' = 3$ transition and $C_{45}$ the Clebsch–Gordon coefficient for the $F = 4$ to $F' = 5$ transition, $\delta_3$ and $\delta_5$ the detunings of the light from the $F' = 3$ and $F' = 5$ transitions respectively and $T$ represents the length of time for which the light is applied.

It is possible to eliminate the phase shift by choosing the detuning of the laser such that the phase shifts from the $F' = 3$ and $F' = 5$ levels cancel. Calculation of the detuning at which this occurs gives a frequency 126 MHz below the $F = 4$ to $F' = 4$ transition and results at this detuning are shown in figure 2. Very little phase shift is observed with the light at a
detuning 126 MHz below the $F = 4$ to $F' = 4$ transition and the magnitude and sign of the phase shifts vary as expected as the detuning is changed from this value. Unfortunately it is not possible to perform adiabatic transfer at such a large detuning from a transition as this would require large powers to achieve appropriate Rabi frequencies. Accurate comparison between the experimental phase shift results and theoretical predictions was difficult due to uncertainties in the intensity of the light used, arising from the non-uniform beam profile. Qualitatively the results do confirm this mechanism for the phase shifts.

The phase shift introduced by the light would not be such a problem if every atom experienced the same shift, however the magnitude of the shift depends upon the intensity of the laser field. Because we used truncated Gaussian laser beams which have a non-uniform intensity distribution the phase shift varied across the atomic sample, leading to a washing out of the Ramsey fringes as seen in figure 3. A plot of visibility as a function of pulse length (figure 4) clearly shows this loss of contrast. Experimentally some variation in intensity across the beam is inevitable, hence an understanding of the way in which the light affects the atoms is very important.

It is interesting to compare the washing out of the fringes due to the non-uniform beam profile with the effect observed when the atoms are exposed to various amounts of scattered light, as seen in figure 5. In this case the main loss mechanism was loss of population due to excitation from the $F = 4$ level. The fringes again disappeared as the pulse length was increased, however the mean value did not remain the same as it does in figure 3. Instead the troughs of the fringes maintained a value independent of the pulse length and therefore the visibility remained approximately one, in contrast to the effect observed with linearly polarised light (figure 4).

4. Discussion

The observations of the changes in the Ramsey fringes are signatures that the phenomena causing the loss occur due to different processes. In the former case the reduction in fringe contrast arises because of a loss of coherence of the atomic ensemble. The light causes
the phase of an individual atom to change to a value dependent upon its position in the laser beam. A distribution of phases across the atomic distribution will clearly reduce the visibility. In the second case, the unpolarised scattered light causes the $F = 4, m_F = 0$ population to be pumped into other states that do not interact with the microwaves. This does cause some loss of coherence but the overiding feature is the population loss which acts to reduce the amplitude of the Ramsey fringes. Confirmation of these mechanisms has been provided by modelling the system, the results of which can be seen in figure 6.
5. Theory

Calculations to model the microwave interactions and loss of coherence and population have been performed and were based on a simple two state Bloch model for the transition between the $F = 3, m_F = 0$ and $F = 4, m_F = 0$ states. The introduction of decoherence and population loss between the two Ramsey $\pi$ microwave pulses has been studied in an attempt to model the loss mechanisms encountered in the experiment.

Using the standard Bloch vector given in equation (2), we represented the interaction of the atoms with the microwave radiation by matrix $m_{rad}$, and the free propagation in time by matrix $m_{free}$. These matrices $\Delta$ represents the detuning of the microwaves from resonance and $\Omega$ is the Rabi frequency. In solving the time-dependent Schrödinger equation for this system one finds that the interactions may be represented by the matrix exponentials of $m_{rad}$ and $m_{free}$ acting on the Bloch vector as indicated in equation (5).

\[
\mathbf{s} = \begin{pmatrix} \rho_{12} + \rho_{21} \\ i(\rho_{12} - \rho_{21}) \\ \rho_{22} - \rho_{11} \end{pmatrix}
\]

\[
m_{rad} = \begin{pmatrix} 0 & \Delta & 0 \\ -\Delta & 0 & \Omega \\ 0 & -\Omega & 0 \end{pmatrix},
\]

\[
m_{free} = \begin{pmatrix} 0 & \Delta & 0 \\ -\Delta & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}.
\]

With an initial Bloch vector $s_i$, then the final state, $s_f$, is given by

\[
s_f = e^{m_{rad}\tau} e^{m_{free}T} e^{m_{rad}\tau} s_i
\]

where $\tau$ is the pulse length of the interaction with the microwave radiation and $T$ is the propagation time between the microwave pulses.

Loss of coherence and loss of population were introduced by manipulating the Bloch vector in the middle of the free propagation time. This was achieved with additional matrices given in equations (6) and (7), multiplied together as in equations (8) and (9). $l_c$ represents the matrix used to simulate coherence loss where $\alpha$ is the fraction of the coherence left and $l_p$ and $v_p$ were used to simulate population loss, $\beta$ being the fraction of the upper state
Observation of light-induced coherence loss

population left.

\[ l_c = \begin{pmatrix} \alpha & 0 & 0 \\ 0 & \alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad (6) \]

\[ l_p = \begin{pmatrix} \sqrt{\beta} & 0 & 0 \\ 0 & \sqrt{\beta} & 0 \\ 0 & 0 & (1 + \beta)/2 \end{pmatrix}, \quad v_p = \begin{pmatrix} 0 \\ 0 \\ (\beta - 1)/2 \end{pmatrix}, \quad (7) \]

\[ s_l = e^{m_{\text{rad}} \tau} e^{m_{\text{mic}} T/2} l_c e^{m_{\text{mic}} T/2} e^{m_{\text{rad}} \tau} s_l \]

\[ s_l = e^{m_{\text{rad}} \tau} e^{m_{\text{mic}} T/2} (l_p e^{m_{\text{mic}} T/2} e^{m_{\text{rad}} \tau} s_l + v_p). \quad (9) \]

It was seen in section 3, that the non-uniformity of the laser beam used to induce the phase shifts lead to a loss of coherence of the atomic ensemble. This was modelled through the reduction of the diagonal elements of the density matrix using \( l_c \). This leads to the same results as performing a summation over different density matrices which have experienced different phase shifts due to the non-uniform beam profile.

Results of these calculations can be seen in figure 6. These clearly demonstrate the differences between the loss mechanisms as seen in the experimental results.

6. Conclusion

In summary we have observed the phase shifts introduced to an atomic sample through the AC Stark shifts using a combination of light and microwave fields. This has clearly shown the power of this technique for studying the decohering effects in an interferometer by using the microwave established coherence. Loss of coherence of the atomic ensemble has been observed and attributed to a non-uniform beam profile. Particular attention should be given to achieving uniform light beams and small atomic clouds if a uniform phase is to be maintained across the cloud in any atomic interference experiment. Population loss due to scattered light has also been observed. Such loss manifests itself in a different way to coherence loss as has been shown both experimentally and theoretically.

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References