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Atom-interferometric determination of the dc-Stark shift of the Mg-intercombination line

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The dc-Stark shift of the magnesium $3s^2(^1S_0)$–$3s3p(^3P_1)$ line is measured by subjecting both arms of an atom interferometer to a constant electric field. In this interferometer based on Ramsey's method of separated oscillating fields each arm is uniquely associated with either the upper or lower state of the intercombination transition, so that the Stark energy perturbation provides two different potentials in the two arms of the interferometer. The resulting relative phase shift corresponds to a difference of $-(8.0\pm1.0)$ kHz $(\mathrm{kV/cm})^{-2}$ in the polarizabilities of the $^1S_0$ and the $^3P_1(|m|=1)$ states, in agreement with a theoretical calculation.

1. Introduction

Atom interferometry is fast becoming a powerful method for studying fundamental effects of physics. (For a recent overview see ref. [1].) The main advantages of atom interferometers compared to light and other matter-wave interferometers are a consequence of the rich internal structure and the higher rest mass of atoms. Energy shifts of the atomic levels caused by electromagnetic interactions can lead to potentials that influence the motion of the separated wave packets, thus causing fringe shifts in the interferometer signals, e.g., the ac-Stark shift of the atomic ground state caused by a non-resonant laser field has been measured in this way [2,3].

One interferometer type particularly suited to make full use of all the advantages of atom interferometry is the Ramsey Interferometer [2,3]. In sec. 2 a short review of its properties will be given. We have used our Mg Ramsey Interferometer to measure the dc-Stark shift of the Mg intercombination line. This experiment is described in sec. 3. The experimental result is compared with theoretical calculations. After taking into account the theoretical results for the ground state polarizability it yields an accurate value for the polarizability of the $3s3p(^3P_1)$ excited state.

The relevance of this work with respect to an optical frequency standard based on the Mg intercombination transition and for other interferometric experiments, particularly effects of the Aharonov–Bohm type [4,5], will be explained in sec. 4.

2. The magnesium Ramsey interferometer

In the experiment described here a thermal Mg atomic beam is crossed perpendicularly by two pairs of travelling laser beams. This setup, which has been used for optical Ramsey spectroscopy for quite some time [6], was recently recognized as an atom interferometer [7]. A detailed explanation is given elsewhere [2].

In brief, each interaction zone between laser and atomic beams acts as a beam splitter for the atomic wave. The atom either absorbs or stimulatedly emits a photon with a given excitation probability (e.g. 50% for a $\pi/2$ pulse), gaining or loosing the corresponding photon momentum. This process splits and later recombines the atomic wave function coherently. As shown in fig. 1, two different closed trapezoidal paths are possible. They correspond to the blue (A) and the red (B) recoil components of the spectroscopic signal.

Introducing a potential V into one arm of the interferometer influences the motion of the corresponding atomic wave packet, e.g., in a potential val-

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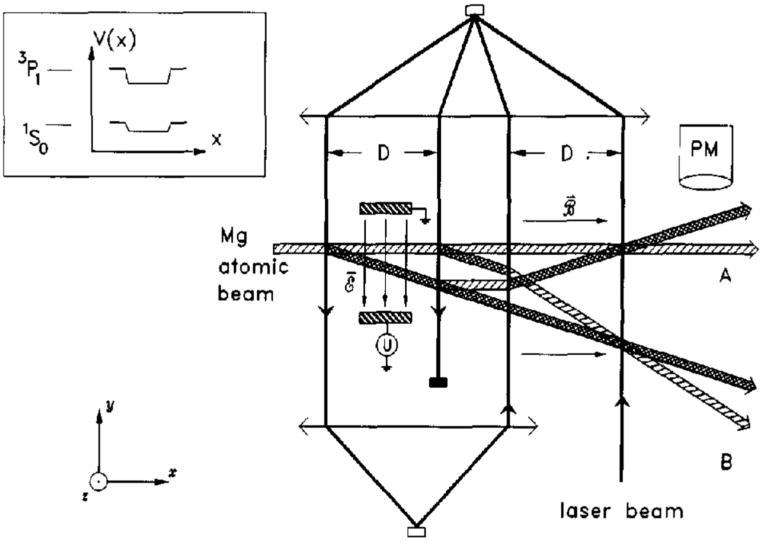

Fig. 1. Experimental setup. The interaction between the laser beams and the atomic beam creates two Mach–Zehnder type interferometers, A and B. The population in one exit port is measured by counting the fluorescence of the excited state (cross-hatched) with a photo multiplier (PM). A magnetic field B helps to select the $m_x=0$ sublevel. The Stark effect leads to a potential $V(x)$ for the atomic wave packets in the region between the capacitor plates.

ley the wave packet will be accelerated towards the minimum and then decelerated on the way out. This leads to a longitudinal advance Δx_V of this part of the wave packet compared to that in the other arm of the interferometer. Using Ehrenfest's theorem in the approximation that V is small compared to the total energy E of the atom, Δx_V can be calculated to yield:

$$\Delta x_V = -\frac{1}{2E}\int V(x)\,\mathrm{d}x\,. \qquad (1)$$

This leads to a phase shift in the interference pattern. More significant, however, is the fact that Δx_V is generally much larger than the coherence length of the thermal atomic beam. Thus at the exit port interference is lost. As explained in ref. [2], a detuning of the laser frequency results in a relative spatial displacement between the wave packets in the two arms of the interferometer, which allows the displacement caused by the potential to be compensated. Maximum contrast of the interference signal can be restored by changing the laser frequency by an amount $\Delta\nu$ given by $\Delta\nu = -\Delta x_V E/hD$ [2]. D denotes the separation between co-propagating laser beams as shown in fig. 1, h is Planck's constant. The potential V and the frequency shift $\Delta\nu$ are related by

$$\Delta\nu = \frac{1}{2hD}\int V(x)\,\mathrm{d}x\,. \qquad (2)$$

The shift $\Delta\nu$ is the averaged line shift along the path of the atom.

3. Measurement of the dc-Stark shift

3.1. Experiment

Applying an electric field $\mathscr{E}$ to the arms of the Ramsey Interferometer influences the internal energy of the atoms through the dipole interaction $er\mathscr{E}$. Since the atom enters the electric field slowly compared to its internal time scale this leads – analogous to the Born–Oppenheimer approximation – to a potential V for the external motion. For the Stark effect, V is given through the atomic polarizability α:

$$V(x) = -\tfrac{1}{2}\alpha\,\mathscr{E}(x)^2\,. \qquad (3)$$

We have placed a capacitor between two co-propagating laser beams as shown in fig. 1. In addition to the electric field there is a magnetic field parallel to the atomic beam direction across the interferometer region. It serves to separate the magnetic sublevels of the excited state. With the polarization of the laser beams parallel to the magnetic field, the interferometer is only utilizing the $\Delta m_x = 0$ transition. Note that with regard to the perpendicular electric field in the y-direction, the atoms in the excited state are in a coherent superposition of $m_y = \pm 1$ states.

The capacitor has a length of 5.0 mm in the direction of the atomic beam, and the separation between the two plates is 1.9 mm. The distance D between the laser beams is 8.6 mm. The electric field extends across both arms of the interferometer. Since the separated atomic wave packets are in different internal states in this part of the Ramsey Interferometer, they experience different Stark shifts. The resulting potential difference leads to a relative spatial shift of the wave packets which in turn – as explained in the previous section – causes the envelope of the Ramsey fringes to shift in frequency space. Figure 2 shows typical examples for both Ramsey fringes of the uninfluenced interferometer (top curve) and shifted fringes with a voltage U of 1.4 kV across the capacitor plates (bottom curve). Each fringe pattern is a combination of the two recoil components separated by 79.5 kHz. The recoil components show about 1.5 fringes whose periodicity of 50 kHz is determined by the distance D between the laser beams and the mean atomic velocity [8]. Each data point was taken with an integration time of 1.4 s.

The fringe pattern with the voltage applied is shifted by an amount $\Delta\nu = 82$ kHz, which is more than two fringe periods. There is a slight reduction of fringe amplitude noticeable in the bottom curve of fig. 2. This is due to the fact that with the laser detuned 82 kHz from resonance the excitation probability is reduced. In terms of interferometry this means that the beam splitting ratio of the lasers has become worse.

We have measured frequency shifts for several voltage settings including both polarities on the capacitor plates. The results are presented in fig. 3. We have numerically calculated the electric field distribution of the capacitor including fringe fields and performed the integration of the potential in the re-

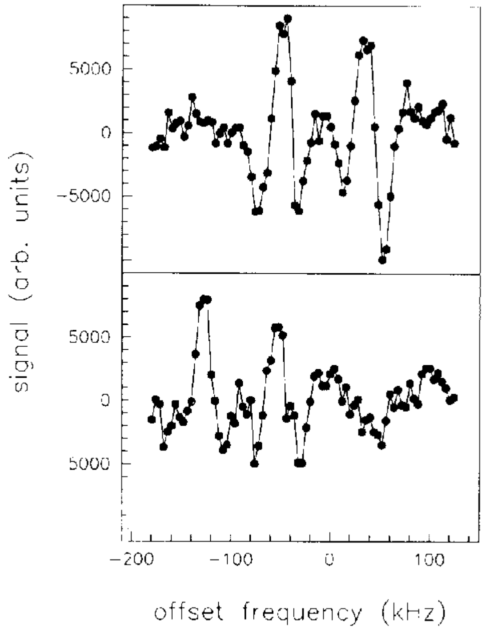

Fig. 2. Interference fringes with (bottom) and without (top) a voltage of $U = 1.4$ kV on the capacitor plates. The signal of the photomultiplier is shown with the incoherent background (Lamb dip) subtracted. The line connects the data points.

gion between the two laser beams (eq. (2)). A numerical evaluation of the electric field is important since the rather small ratio of length to distance of our capacitor increases the total field integral by roughly 20% compared to the case with no fringe fields. We thus deduce a difference in the polarizabilities of the $3s^2(^1S_0)$ and the $3s3p(^3P_1, |m|=1)$ states of

$$\alpha(^3P_1) - \alpha(^1S_0) = 8.0 \pm 1.0 \text{ kHz } (\text{kV/cm})^{-2} . \quad (4)$$

The main contributions to the error are statistical uncertainties in the fitting of our data as in fig. 3 (10%), plus our incomplete knowledge of the field distribution (5%). Systematic errors caused by any residual drift of the laser have been minimized by taking data at each laser frequency consecutively with and without the electric field. Misalignement of the electric and magnetic fields is estimated to be less than 5° corresponding to a maximum error of less than 1%.

A related experiment has been performed by Haun and Zacharias [9]. They used Ramsey's original method of two separated oscillating rf-fields to mea-

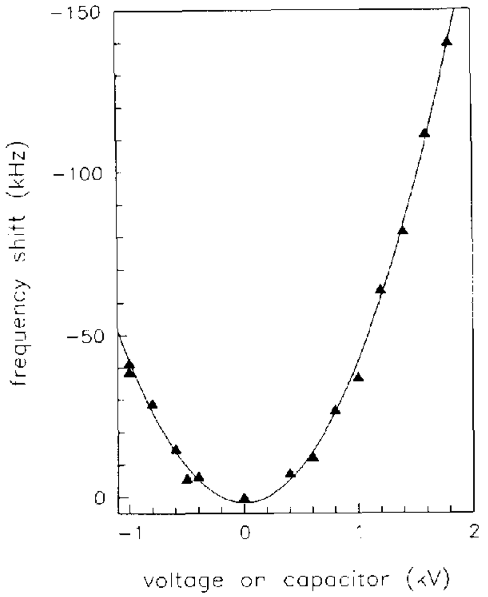

Fig. 3. Frequency shift of the interference pattern versus voltage across the capacitor. The line is a parabolic fit whose linear and constant coefficients are zero within our experimental accuracy.

sure the Stark effect on the cesium-133 hyperfine structure.

3.2. Theoretical discussion

To our knowledge no previous measurements for magnesium of either polarizabilities or line shifts due to electric fields have been reported in the literature. There are several theoretical calculations of the polarizability of the ground state, the most accurate yielding $\alpha(^1S_0)=(17.7\pm0.4)$ kHz $(kV/cm)^{-2}$ [10]. Bava et al. [11] have performed a summation of oscillator strengths both within the singlet and triplet system to estimate the effect of black-body radiation on the intercombination line and on sub-mm transitions within the ^3P fine structure multiplet. For the intercombination transition their claimed accuracy was only to the order of magnitude, because the underlying data sets of oscillator strengths came from different sources and could not be expected to agree.

We have repeated those calculations, using the same data for the oscillator strengths [12] and taking into account the fact that in the experiment described here the $^3P_1$-state is in $m=\pm1$ sublevels. We calculate a polarizability of $\alpha(^3P_1, m=\pm1)=24\pm2$ kHz $(kV/cm)^{-2}$. Together with the value for $\alpha(^1S_0)$ we thus arrive at a theoretical estimate for the difference in polarizabilities of 6.3 ± 2.0 kHz $(kV/cm)^{-2}$, which is to be compared with the experimental value (eq. (4)).

The two results agree within their estimated errors. We have thus established a connection between empirical values for the singlet and the triplet system and validated the result of Bava et al. If one accepts the theoretical result for the ground state polarizability as fairly accurate, this measurement can be used to derive a value of polarizability of the $^3P_1$ $(m=\pm1)$ excited state or the corresponding element of the polarizability tensor. The value is $\alpha(^3P_1, m=\pm1)=25.7\pm1.1$ kHz $(kV/cm)^{-2}$, with the error resulting from the uncertainties in the theoretical and the experimental value.

4. Applications for a possible Mg optical frequency standard and atom interferometry

Due to the highly sensitive dependence of the Ramsey Interferometer fringes on the laser frequency this setup is being investigated as a candidate for an optical frequency standard [13,2]. In this context stray electric fields would degrade the quality of the frequency reference. From our measurement of the Stark effect of the Mg intercombination transition we can deduce that the influence of electric fields can easily be suppressed to values negligible for ultra high precision spectroscopy. This holds true even for experiments using trapped atoms, where a linewidth of a few ten Hertz is expected [14]. For instance, stray electric fields with a magnitude of 1 V/cm would lead to frequency shifts of 4 mHz.

Several authors have pointed out the intriguing possibility of measuring the Aharonov–Casher effect (ACE) with an atom interferometer [15,16,1]. Such an experiment requires placing an electric field across the arms of the interferometer, too. For the Ramsey interferometer one has to consider the large fringe shifts associated with the Stark effect in addition to ACE phases. From our result, one can estimate that for thermal velocities and moderate to high field strength the ACE results in a phase shift that is at least one million times smaller than the Stark phase shift. One possible solution is to extend the electric field into the interaction regions with the laser beams. In this case the ACE would be detectable as a fringe shift relative to the dc-Stark shifted incoherent background.

Futhermore, with the setup of fig. 1 the Stark effect can be used advantageously to perform a scalar Aharonov–Bohm experiment similar to the one performed by Allman et al. [17] with neutrons. Localized and velocity selected wave packets can be created using pulsed excitation. Applying a voltage to the capacitor only while such an atomic wave packet is present between the electrodes is expected to result in a dispersion-free phase shift of the interference signal. We plan to conduct a corresponding experiment.

5. Summary

We have reported an atom-interferometric measurement of the Stark shift of the Mg intercombination transition. This is a new application of atom interferometry for measuring internal atomic quantities. Introducing electric fields into an atom interferometer is a very simple way to bring about phase changes. Also it allows directionally sensitive, i.e. vector interactions to be studied. We were able to prepare the atoms, so that the $m \pm 1$ part of the polarizability of the excited state could be measured. Other components of the polarizability tensor can be measured in the future.

From our measurement we can deduce that stray electric fields and black-body radiation will not have a significant effect on the quality of an optical frequency standard based on the Mg intercombination transition. The relevance of this work towards Aharonov–Bohm type experiments has been pointed out.

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