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Magnetic field calibration using a single barium ion

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A single atom as a probe of an external magnetic field can provide both high resolution as well as precision. In this article the use of a single trapped and laser cooled ion as a probe of magnetic field magnitude as well as direction is discussed. We show that the highest precision can be obtained by Zeeman shift measurements involving dipole forbidden transition, however zero field calibration can be done with moderate precision involving fast dipole transitions.

Keywords: Laser cooled ion, Zeeman shift, Dipole transitions.

1 Introduction

Trapped and laser cooled ions are the forerunners in the field of precision measurements, clocks, quantum simulator, quantum computation and quantum communication [1-6]. A single ion trapped in a Paul trap and laser cooled to the Doppler limit, provides a clean system whose interactions with external fields are very well characterized. Therefore, it is well suited for measuring certain fields generated by external sources at the position of the ion. Since the position of the ion is governed by the minimum of the applied harmonic potential, it is a controllable parameter. Therefore, the measured field can be mapped over a certain region with high precision. Among the fields that can be measured by a single ion varies from magnetic to force-field [7-8] to electric field gradients [9]. However, magnetic field measurements performed by SQUIDS are robust as well as accurate. On the contrary, neutral atoms provide another platform to measure magnetic fields with even higher precision but with restricted applications [10]. Single ions may provide options for both high precision as well as robustness at the expense of higher experimental complexity. In this article the measurements are far imprecise as compared to those obtained by the *State-of-the-Art* magnetic field sensors like SQUIDS.

In this article, the main intention is to show two completely different approaches to measure the magnetic field vector at the position of the ion. The first approach relies on a dipole forbidden transition making it experimentally challenging but provides high precision. The second approach is based on magnetically driven Electromagnetically Induced Transparency (EIT). While the first approach is rather well known, the second, to the best of our knowledge, is new. In the case of the second approach the experiment is rather robust but less precise. The article in organized in the following manner. First, a short theoretical introduction will be provided for both the approaches followed by the experimental setup for implementing both the methods. The results obtained will be discussed and compared while wrapping up with concluding remarks.

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2 Methods of measuring magnetic field with high precision

A Dipole forbidden transitions

Throughout this article we will restrict ourselves to simple atomic level scheme as shown in Fig 1 for hydrogenic atoms and ions. In particular singly charged barium ion is used in the experiment, however the physics holds for any hydrogenic ion. In absence of magnetic field the magnetic sub-levels are degenerate. The degeneracy is lifted by application of a magnetic field. In case of a low magnetic field strength, the energy shifts of the magnetic sub-levels are proportional to the strength of the applied magnetic field. Therefore, measuring the level shift of a magnetic sub-level directly provides the strength of the magnetic field at the position of the ion. However, it is essential to calibrate the field prior to any measurement. The level shift of a magnetic sub-level m_j as a function of the change in magnetic field strength ΔB is given by

$$\Delta E_{m_j} = \mu_B m_j g_j \Delta B; \tag{1}$$

where μ_B is the Bohr magneton, m_j and g_j denotes the magnetic quantum number and the Landé-g factors of the level respectively. It is, therefore, straightforward to anticipate that the precision on the magnetic field determination is proportional to the precision on the frequency determination. In case of dipole transitions such as $S-P$, the precision is limited by the lifetime of the P state which is about 5 – 6 ns implying ≈ 20 MHz width. On the contrary, if measurements are performed on the dipole forbidden $S-D$ transitions, the sensitivity as well as precision is only limited by the linewidth of laser. As an example the life-time of the $D_{5/2}$ level of Ba^+ is about 30s corresponding to a natural linewidth of ≈5 mHz and hence a life-time limited magnetic field sensitivity of about 70 fT. However, in reality, laser phase noise would dominate as compared to the natural linewidth.

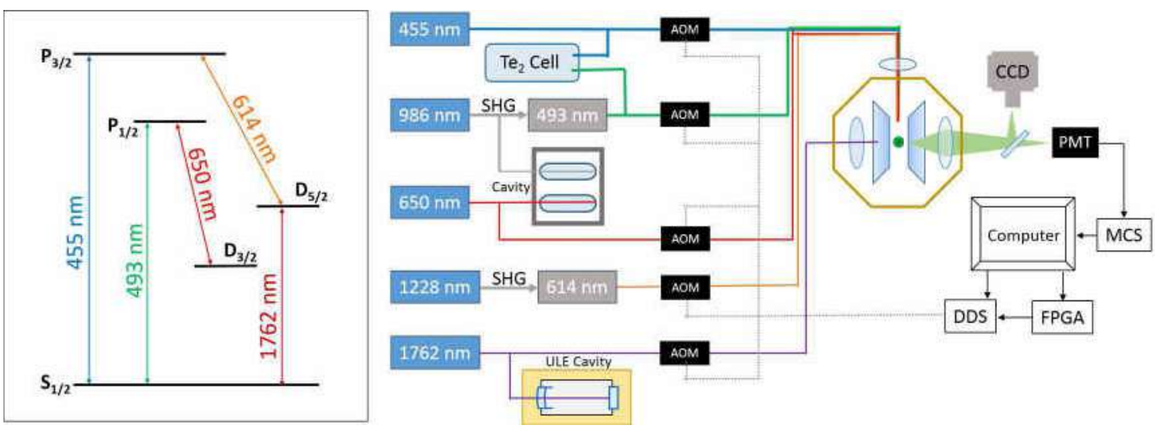

Fig 1. Left : Energy level structure of Ba+ ion. Right : Schematic diagram of the experimental setup. The laser frequency and amplitudes are controlled by a computer. All the laser frequencies are monitored by a wavemeter.

B Dipole transitions and EIT

The magnetic field measurement using dipole forbidden transition suffers from the stringent requirement of the narrow linewidth laser to probe the transition [11-14]. An alternative approach is to use dipole allowed transition but in a regime where narrow electromagnetically induced transparency [15] can be employed to overcome the issue of broad linewidth. Consider the energy level diagram as shown in Fig 1. It is possible to continuously excite the $P_{3/2}$ using a laser at 455 nm. However, since the ion decays into the meta-stable D-state, continuous observation of fluorescence is only possible if re-pumping lasers at 650 nm and 614 nm are simultaneously applied. In case of zero magnetic field the Zeeman sub-levels are degenerate, therefore there are 2 possible superposition states in the $D_{5/2}$ level which are dark and cannot be excited by any laser polarization exciting the $P - D$ transition [16]. This makes the ion transparent to the excitation light at 455 nm. The only way to bring the ion back to the fluoresce cycle is to either modulate the polarization of the re-pump lasers or to lift the degeneracy up.

Here we propose to lift the degeneracy up by varying the magnetic field such that fluorescence is observed. Since the narrow resonance is caused by the coherence of the magnetic levels, the width depends on the probe laser combined linewidth. Therefore, the magnetic field at the position of the ion can be extracted by nullifying fluorescence level using calibrated magnetic field coils. The theory is based on the principles of the Hanle effect with the additional complexity of using narrow bandwidth laser for excitation rather than broad bandwidth ones [17].

C Experimental setup

The overall setup for both the experiments are the same with only difference of applied lasers. Therefore, in the following a brief overview of the experimental setup is provided followed by specific differences between the two experiments. More detailed description of the setup can be found in Fig 1. The Paul trap used in this experiment is a linear Paul trap with blade like structure for better optical access. The trap is operated at a frequency of 16 MHz with an RF power of about 3 – 5W leading to radial secular frequencies of about a few MHz. The axial frequency is usually kept at 1MHz. The operating parameters however differ for linear chain of ions which are not a subject of discussion here. A single ion produced in a hot barium oven is resonantly ionized by a single diode laser at 413 nm addressing an inter-combination line of neutral barium before it is excited to continuum. Once trapped, the ion is then laser cooled by the dipole excitation laser at 493 nm in combination with re-pump laser at 650 nm. The ion is also detected by photons emitted at 493 nm with an overall efficiency of about 0.1%. This leads to a photon collection rate which is more than 3000 counts/10ms. The overall setup is schematically shown in Fig 1. The emitted fluorescence photons from a single ion can either be detected by an Electron multiplier charged coupled device (EMCCD) from *Andor Luca* or by a photo multiplier tube (PMT) from *Hamamatsu*.

, In the first part of the experiment we employ a narrow linewidth diode laser at 1760 nm [13] to address the dipole forbidden quadrupole transition between the $S - D$ states. The laser is phase locked to an ultra low expansion (ULE) cavity by Pound-Drever-Hall technique. The measured linewidth of the laser after locking to the ULE cavity is found to be less then 300 Hz [13]. This is only estimated from the spectral data of the single ion $S - D$ transition and hence mostly likely limited by the magnetic field fluctuations. Three pairs of coils are used in anti-Helmholtz configuration to generate a constant magnetic field at the center of the trap. The ion after being laser cooled to the Doppler limit has a measured mean radial phonon number of about 5 – 7 depending the strength of the radial confinement. This assures negligible Doppler broadening. Two pairs of compensation rods placed parallel to the blade electrodes are used to compensate any residual micro-motion of the trapped ion. In detail discussion about the setup can be found in [20, 21].

In the case of the second experiment the $S - P_{3/2}$ transition is excited by a diode laser at 455 nm. In order to avoid population trapping in the D-states, two repump diode lasers are applied at 650 nm and 614 nm, respectively. In this experiment the observable is the photon count at 455 nm instead of the usual 493 nm. We use interference filters with narrow bandwidth to observe only the required wavelength at the PMT. The 455 and 493nm lasers are frequency locked to a molecular resonance line of Te_2 molecule in a hot cell [18, 19]. The repump laser 650 is passively locked to a reference cavity while the frequency doubled 614 nm laser is not locked. The linewidth of the 455 nm laser is estimated to be about 400 kHz.

3 Results

In order to obtain the Zeeman shift of the magnetic sub-level in $D_{3/2}$ level, the 1760 nm laser is applied to drive the $S_{1/2}$ ($m = \pm 1/2$) to $D_{3/2}$ ($m = \pm 5/2$) transition. The spectra is obtained by measuring the transition probability as a function of frequency of the laser. In order to have efficient transfer the pulse duration of the excitation is always kept at measured *PI*-time of the transition for a given power of the laser. The configuration of the laser polarization, magnetic field and the direction of propagation dictates the transition probability. In this experiment, only Δm = 2 transition is allowed. In order to calibrate a pair of magnetic field coils, the other two pairs of coils are kept constant. The residual magnetic field, in this case the resultant of the Earth's magnetic field and the field due to the other coils, is then measured by changing the coil current only in one pair. As an example the current applied to the vertical pair of magnetic field coils are varied; Fig 2. The measured width of each resonance is Fourier limited to about 1 kHz as governed by the pulse width of the applied 1760 nm laser. As the current is varied the center of resonance shifts linearly and is independent of the direction of the magnetic field. Therefore, on extrapolation as shown in the inset of Fig 2, the two curves intersects at a coil current of 23.65(1.0) mA where the uncertainty is mainly due to the precision of the coil current supply. Therefore, any unknown magnetic field at the position of the ion can be determined by null measurement and the calibration plot of the magnetic field coils, provided the coils are orthogonal to each other. In our experiment, the non-orthogonality is negligible within the measurement uncertainties.

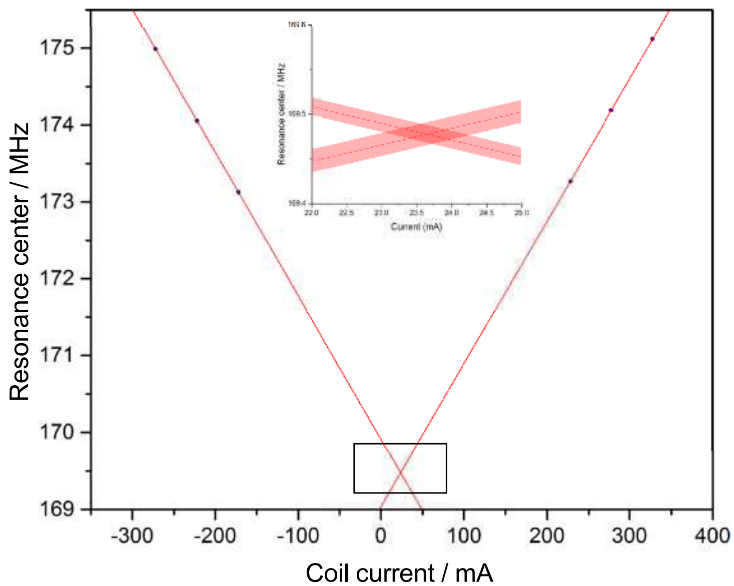

Fig 2. S-D transition resonance frequency of a single barium ion as a function of the applied magentic field. The upward and downward magentic fields strength are independently fitted to a linear model and the intersection is shown by a box. The inset shows the zoomed view of the boxed part of the curve.

As discussed earlier, the Zeeman shift measurement requires ultra stable laser, therefore to avoid the complexity, here we discuss another method of obtaining the magnetic field strength with lesser precision by technically much simpler.

In this experiment, we apply the 455 nm, 614 nm and 650 nm lasers with polarizations of all the lasers perpendicular to both the magnetic field vector and the propagation direction. The steady state fluorescence count is measured along the incident light polarization direction as a function of the magnetic field strength. The behaviour is shown in Fig 3. In order to understand the experimentally obtained curve we have solved the 16-level optical Bloch equation with all relevant experimental parameters which matches well the curve. The most interesting feature is the narrow dip close to the zero magnetic field. This can be understood, by considering the case when the magnetic field is zero. The *D*-state Zeeman sub-levels are degenerate leading to dark superposition states in the Zeeman manifold. These states cannot be pumped out to the fluorescence cycle by only σ polarization light field. However, with the application of a small magnetic field the degeneracy is lifted and the fluorescence level is retrieved back. In order words the phenomena is similar to EIT, where the atom is transferred to the dark D-state without populating the P-state in absence of the magnetic field. The width of this narrow dip is governed mainly by the coherence of the applied laser fields. In our case it is mainly limited by the re-pump laser drift. A closer look at the Fig 3 allows the zero point of the magnetic field to be measured within an uncertainty of 1×10^{-4} Gauss. The experimentally obtained width of the central narrow peak is around 1.3 ± 0.06 Gauss.

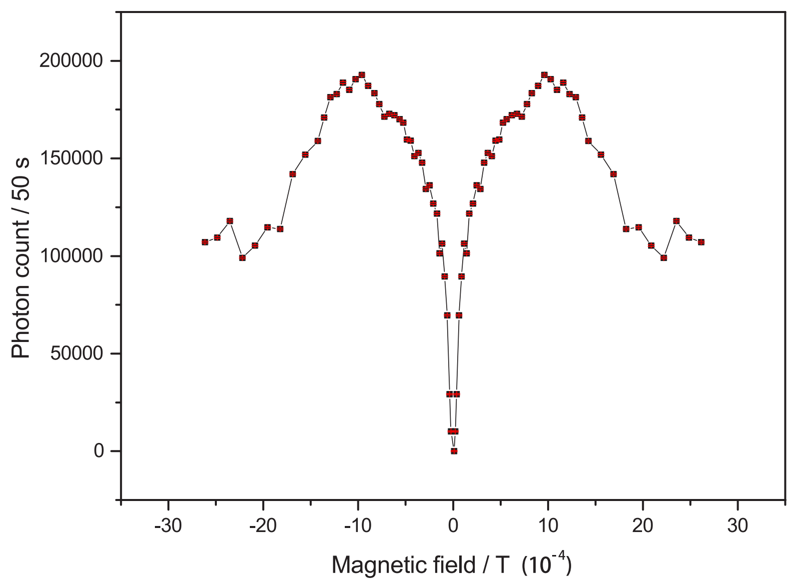

Fig 3. The photon counts of S-P fluorescence at 455 nm per 50s of accumulation is plotted as a function of applied magnetic field strength. The line is only to guide the eye. The features for high magnetic field is due to optical nutation and not important for this work.

4 Conclusion

In conclusion, we show that using only two dipole allowed transitions it is possible to measure the vector magnetic field with high spatial resolution. The resolution is achieved by confinement of a single ion and laser cooling it while the sensitivity of the magnetic field determination is obtained by coherent population trapping into Zeeman sub-levels.

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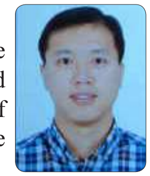

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