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IMPROVED HIGH RESOLUTION SPECTROSCOPY WITH COLD MAGNESIUM ATOMS

A. Douillet, J. Keupp, T.E. Mehlstäubler, N. Rehbein, H. Wolff, E.M. Rasel and W. Ertmer
Institut für Quantenoptik - University of Hannover
Welfengarten 1, 30167 Hannover, Germany

Abstract - **We report on recent results in high precision spectroscopy with cold magnesium atoms. Resolutions as high as 290 Hz have been achieved with our Ramsey-Bordé interferometer tuned to the $3^1S_0 \rightarrow 3^3P_1$ intercombination line at 457.2 nm. The potential short-term stability inferred from the interference signal is 8 x 10^{-14} in 1 s. The residual atomic motion of the atoms, cooled to the Doppler limit, is identified as a main contribution to the contrast decay. In order to improve the performance of our interferometer, we are currently setting up a second experiment, where we can push the temperature limit to the µK-regime.**

I. INTRODUCTION

Throughout the past years, work in optical frequency standards has experienced an increasing interest, mainly due to two major developments. On one hand, the performance of optical clocks has become comparable to the state-of-the-art microwave standards [1,2]. On the other hand, the development of frequency comb generators [3, 4], which directly link microwave frequencies to the optical domain, simplifies the task of measuring optical frequencies.

Alkaline-earth atoms offer a rich spectrum of optical transitions reaching from very fast cycling transitions to extremely narrow lines between the two different spin systems. These intercombination lines can be used for high resolution spectroscopy in the optical domain. In ^{24}Mg, we use the fast $3^1S_0 \rightarrow 3^1P_1$ transition at 285 nm to trap and cool the atoms, which are then probed on the $3^1S_0 \rightarrow 3^3P_1$ transition at 457.2 nm. With our Ramsey-Bordé spectrometer we have achieved resolutions as high as 290Hz on this line. For longer interrogation times we are limited by the exponential decay of the contrast, due to the short-term line width of the spectrometer laser (γ=190 Hz) and the effect of residual motion of the atoms.(v_{rms} ~1m/s). In order to improve the short-term stability of our interferometer, we need to reduce the 3-D velocity of the atoms by further cooling. An interesting scheme can be to cool on a narrower frequency width transition. The clock transition itself is a promising candidate, and temperatures as low as 400 nK have been demonstrated in Sr, using such a scheme [5, 6]. However, in calcium or magnesium, the weak scattering rate of the intercombination line makes this direct cooling impossible. For these atoms, an interesting scheme appears to be quench-cooling [7, 8, 9], which we currently implement in our new magnesium apparatus. It consists in artificially enhancing the intercombination line width, by a repumper laser which de-excites atoms via an intermediate level.

II. EXPERIMENTAL SETUP AND SPECTROSCOPIC RESULTS

The spectroscopy is performed on a sample of cold magnesium atoms captured in a magneto-optical trap (MOT), as described in [10]. Here, we only give a rough description of our experimental setup and point out the major changes and improvements. Figure 1 sketches the apparatus.

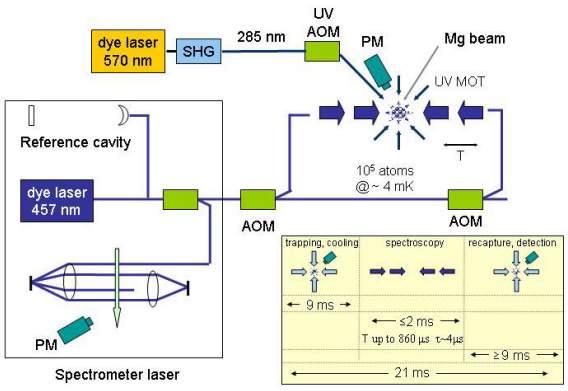

Fig. 1. Experimental setup. The magnesium atoms are trapped in a magneto-optical trap (MOT). The interferometer pulse sequence is generated by two acousto-optical modulators (AOM). PM: photo-multiplier. For clarity purpose, only one reference cavity is drawn.

The UV radiation at λ=285 nm, used to cool and trap the atoms, is generated by frequency doubling an iodine-stabilized Rhodamine dye laser (λ=570 nm), in an external cavity. For typical experimental parameters, optimized for atom interferometry, about 10^5 atoms are loaded from a thermal beam into a MOT

and cooled to temperatures of 3.8 mK, well above the Doppler limit of 2 mK. A re-designed beam pointing system, which is required for the transport of the UV-light between two optical tables across the laboratory, combined with a power stabilization reduce the fluctuations of the number of trapped atoms below 0.6%. The spectroscopy laser at λ=457.2 nm is based on a stilbene dye laser with an output power of 120 mW. A two-stage Pound-Drever-Hall (PDH) frequency stabilization scheme [11] reduces the laser line width below 200 Hz. The first PDH-stage is described in [12]. It uses a Zerodur cavity as a reference and reduces the laser line width to about 870 Hz. The performance is mainly limited by mechanical vibrations of the optical table. A further reduction of the line width is obtain by stabilizing the laser in a second step on an ULE cavity (finesse F=39000) reduces further the laser line width. This second resonator is inside a vacuum chamber and carried by a double-pendulum, which is damped by Eddy-currents. The granite platform holding this cavity is suspended with rubber-ropes at the laboratory ceiling. In order to compensate for residual drifts the laser is stabilized to the Ramsey signal of a magnesium beam interferometer. The time domain Ramsey-Bordé interferometer and the MOT are operated in cycles of 21 ms. We begin the measurement cycle with 9 ms of trapping, after that we turn off the trapping fields. Then the clock transition is probed with four blue pulses (Ramsey-Bordé type interferometer). The first pulse is applied 150 μs after the MOT coils are switched off, to allow the quadrupole field has vanished. The size of the interaction zone (beam waist of 3.38 mm) allows for an interrogation time of up to 2 ms before the atoms leave the interferometer. We detect the interference signal as an effective variation in the average MOT fluorescence using the electron shelving scheme [13]. Figure 2 shows experimental results we achieved.

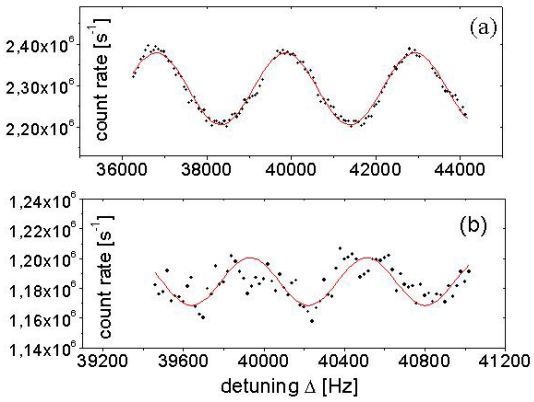

Fig. 2. Atom interferometry signal of a Ramsey-Bordé excitation scheme as a function of the laser detuning for resolutions of Δν=1530 Hz (a) and Δν=290 Hz (b).

For a moderate resolution of Δν=1530 Hz, given by Δν=1/(4T) where T is the time of free evolution, we achieve the highest signal to noise ratio (S/N) than reported so far for magnesium. The averaging time for one data point is t_m=1.05 s, corresponding to 50 interferometry cycles. We fit a cosine function with a fixed period given by the applied pulse sequence. The signal to noise ratio is calculated using the standard deviation of the difference between the data points and the fitted functions. The relative frequency stability of an atomic frequency standard for 1 s averaging time can be written as

$$\sigma_y(\tau = 1s) = \frac{1}{\pi\, Q\, S/N}\sqrt{\frac{t_m}{s}}$$

where Q is the experimental line quality factor.

For the resolution of Δν=1530 Hz the achieved S/N of 8.4 leads to a stability of $\sigma_y(\tau = 1s) = 8.9\times10^{-14}$. We could increase the resolution up to Δν=290 Hz with a free evolution time of T=860.8 μs (see curve (b) of fig. 2). A relative frequency stability $\sigma_y(\tau = 1s) = 7.8\times10^{-14}$ can be deduced from this measurement, with a quality factor $Q = 2.26\times10^{12}$ and S/N~2.

We measured the atom interferometry signal for different free evolution times, and deduced the corresponding frequency instability for this different resolutions. Down to Δν=1000 Hz the Allan variance is clearly decreasing with higher resolution and finally saturates near $\sigma_y(\tau = 1s) = 8\times10^{-14}$ because a degradation of the amplitude signal is balancing the increase in resolution. The atoms leaving the interrogation zone due to their residual motion and the phase fluctuations of the probe laser are the main contribution to the contrast decay. In order to estimate an upper limit for the spectroscopy laser line width we simulate the characteristic signal amplitude decay and extract the gaussian sigma σ_v of the velocity distribution and the center of mass. The Monte Carlo simulation evaluates the de-Broglie wave amplitudes at the interferometer ports for specific paths of individual atoms. We include the decay by spontaneous emission. For one signal amplitude data point we simulate the trajectories of 50.000 atoms and average the results. Figure 3 shows the variation of the measured signal as a function of the interrogation time on the curve (m) and the prediction of the model (a) for an amplitude decay due to atomic motion and spontaneous emission. A correction of the measured amplitude values by the simulated results yields a decaying function (b) that can be attributed to phase fluctuations of the spectroscopy laser.

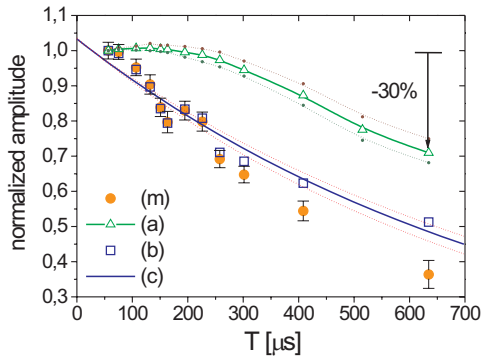

Fig. 3. Observed amplitude decay (m) in the interferometer signal with increasing time of free evolution T. curve (a) : Monte-Carlo simulation taking into account the atomic motion out of the interrogation zone and spontaneous emission. Curve (b) : corrected amplitude decay. Curve (c) exponential fit to estimate the laser line width.

Considering a white noise spectrum for the laser, the signal contrast decays exponentially with the laser line width. By fitting the corrected curve we estimate the width to be, at maximum, $\delta\nu \le (190 \pm 15)$ Hz.

III. THE NEW APPARATUS

We have identified the thermal expansion and residual motion of the atom cloud at a temperature of 3,8 mK in the Doppler regime as a major limitation for the resolution and stability in our atom interferometer. Since the non-magnetic ground state of ^{24}Mg hinders any standard sub-Doppler cooling mechanism, we will extend cooling and trapping to the ultra-narrow magnesium intercombination line by artificially broadening the line width with a quench laser. We developed a new setup which permits to test this new cooling scheme. As major improvements, the vacuum chamber allows optical access necessary for the different cooling stages, interferometry and storage of the atoms in a dipole trap. The polarisations of the cooling and quenching light is chosen in opposite helicity to optimize the excitation through the Zeeman sublevels of the $^3P_1$ state. Also, the MOT field coils are designed in such a way that linear part of the quadrupole field plays then role of a Zeeman-slower field combined with a UV slowing beam. In this configuration the number of trapped atoms can be increased to up to 10^7. The quench laser is a frequency doubled Titanium Sapphire laser operated at 924 nm. As non-linear crystal, we use a periodically-poled KTP crystal with a single pass conversion efficiency of $\Gamma = 1.5\times10^{-2}\,\mathrm{W/W^2}$ for a 15mm-long sample, which will be placed in a linear cavity. In that way, the fundamental waves pass twice through the crystal per round trip in the cavity. The second harmonic generation efficiency of this system is then equivalent as in a ring cavity with a crystal twice longer. To avoid destructive interference of the blue light created on the way forth and back, due to the phase shift at reflection on the highly reflective mirror and the length of the last domain of the poled crystal, the crystal is wedged [14]. We expect an output of approximately 400 mW of 462 nm light.

IV. CONCLUSION

We have performed precision spectroscopy of the 457 nm magnesium intercombination line with resolutions as high as 290 Hz. A two-stage locking scheme of the probe laser on ultra–stable resonators has reduced is line width to below 200 Hz. From the measured interference fringes, we infer a short-term stability of $\sigma_y(\tau = 1s) = 8\times10^{-14}$. We have reached the regime where the contribution of the kinetics of the atoms limits the interrogation time. Ramsey-Bordé interferometry on quench-cooled samples promises a significant increase in stability.

REFERENCES

[1] S. A. Diddams *et al.*, Science **293**, 825 (2001)
[2] S. Bize *et al.* , Proc. 6th Symp. on Frequency Standards and Metrology, ed. P. Gill (Singapore : World Scientific) p 53 (2002)
[3] Th. Udem, J. Reichert, R. Holzwarth, and T. W. Hänsch, Phys. Rev. Lett. **82**, 3568 (1999)
[4] D. J. Jones, S.A. Diddams, J. K. Ranka, A. Stentz, R. S. Windeler, J. L. Hall, and S. T. Cundiff, Science **228**, 635 (2000)
[5] H. Katori, T. Ido, Y. Isoya, and, M. Kuwata-Gonokami, Phys. Rev. Lett. **82**, 116 (1999)
[6] K. R. Vogel, T. P. Dinneen, A. Gallagher, and J. L. Hall, IEEE Trans. Instr. And Meas. **48**, 618 (1999)
[7] T. Binnewies, G. Wilpers, U. Sterr, F. Riehle, J. Helmcke, T.E. Mehlstäubler, E.M. Rasel and W. Ertmer, Phys. Rev. Lett. **87**, 123002 (2001).
[8] E. A. Curtis, C. W. Oates, L. Hollberg, Phys. Rev. A **64**, 031403 (2001).
[9] T.E. Mehlstäubler, J. Keupp, A. Douillet, N. Rehbein, E.M. Rasel and W. Ertmer, J. Opt. B : Quantum Semiclass. Opt. **5**, 183 (2003)
[10] K. Sengstock *et al*, Appl. Phys. B **59**, 99 (1994)
[11] R. W. P. Drever *et al*. App. Phys. B **31**, 97 (1983)
[12] F. Ruschewitz, J. L. Peng, H. Hinderthür, N. Schaffrarth, K. Sengstock, W. Ertmer, Phys. Rev. Lett. **80**, 3173 (1998)
[13] W. Nagourey, J. Sandberg, H. Demelt, Phys. Rev. Lett. **56**, 2797 (1986)
[14] G. Imeshev, M. Proctor, M. M. Fejer, Optics Letters, Vol. 23, No. 3 (1998)