Magneto-optical trapping of silver atoms

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The realization of a magneto-optical trap (MOT) for silver atoms is reported. Trapping light at 328 nm was used and the trap was loaded directly from a thermal beam to store over 10^6 atoms with storage times of up to 16 s. Evidence of branching from the $^2P_{3/2}$ excited state to the metastable $^2D_{5/2}$ level was found and its decay rate determined. The temperature of the atoms is estimated to be 300(90) μK by measuring the mechanical properties of the MOT through observation of trap center oscillations.

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I. INTRODUCTION

The remarkable capabilities of laser cooling and trapping techniques for neutral atoms have led to great advances in the field of neutral atom-based frequency standards [1]. The preparation of cold atomic samples with high densities and low kinetic energies permits extremely high-resolution experiments, both in the microwave and the optical-frequency domains. There are several atomic systems affording excellent prospects of high stability and accuracy in the optical region, with the intercombination lines of the alkaline-earth-metal atoms being among the most investigated [2].

Among the other possible systems, especially those with transitions of ultralow natural linewidth of the order of 1 Hz [3,4], the silver atom is regarded as one of the most promising candidates for an optical frequency standard. First proposed in 1976 by Bender *et al.* [5], the Ag I $4d^{10}5s\,^2S_{1/2}$–$4d^9 5s^2\,^2D_{5/2}$ transition (see Fig. 1) provides an attractive reference frequency for the following reasons: The $^2D_{5/2}$ metastable level, which decays by emission of electric quadrupole radiation at 330.6 nm, has an estimated lifetime of 0.2 s [6], corresponding to a natural linewidth of only 0.8 Hz. In contrast to the alkaline-earth-metal atoms, it is thus possible to operate the future frequency standard on a transition with a natural linewidth narrow enough for it to benefit from the long interaction time in an atomic fountain setup [4]. Furthermore, the long-lived state is accessible with a two-photon transition at 661.2 nm, providing a first-order Doppler-free interaction with atoms of all velocities. As an important technical aspect, the frequency needed to drive the clock transition can be provided by a small and efficient diode laser system. Third, laser cooling is made possible by using the D_2 resonance line at 328 nm, which connects the ground state with the $5p\,^2P_{3/2}$ level. Due to the degenerate ground state, sub-Doppler cooling mechanisms may lead to low temperatures and narrow transverse velocity distributions to keep the fountain atoms spatially together and provide the necessary flux of slow atoms.

The clock transition in silver has hitherto not been directly observed. An indirect measurement of the transition frequency was made by Larkins and Hannaford [7], who measured the emission wavelengths from a hollow-cathode discharge of two lines that link the $5s\,^2S_{1/2}$ ground state to the $^2D_{5/2}$ metastable level via the $6p\,^2P_{3/2}$ level. The main difficulty in observing the weak clock transition is the detection of the atoms excited to the long-lived $^2D_{5/2}$ state. Optical detection can be achieved by using a second laser at 547 nm which will drive the atom from the metastable state to the $6p\,^2P_{3/2}$ level, from which it decays to the ground state. A group at CNAM in Paris is pursuing this option in a thermal atomic beam experiment [8]. In our group, the aim is to excite the clock transition in a sample of trapped and cooled silver atoms. The proposed detection scheme is based on the shelving technique first applied to trapped ion spectroscopy [9], where the strong cooling transition is used to monitor the number of atoms in the trap. Excitation to the metastable level will then be seen as an additional trap loss mechanism, i.e., reduced trap fluorescence [10]. So not only is the use of cooled and trapped atoms essential to provide the extended interaction time needed in a future subkilohertz spectroscopy experiment, it also provides an efficient detection mechanism for the two-photon transition.

Reports in the literature of elements that have been stored in a magneto-optical trap (MOT) have mostly been limited to alkali-metal, alkaline-earth-metal, and rare-gas atoms [11]. There are two main difficulties in setting up a MOT for silver atoms. One is associated with its level structure as depicted in Fig. 1. The $5s\,^2S_{1/2}$ $(F=1)$–$5p\,^2P_{3/2}$ $(F=2)$ transition, which can be used for cooling, has a wavelength of 328.16 nm and a natural linewidth of $\Gamma/2\pi = 23$ MHz [12]. The

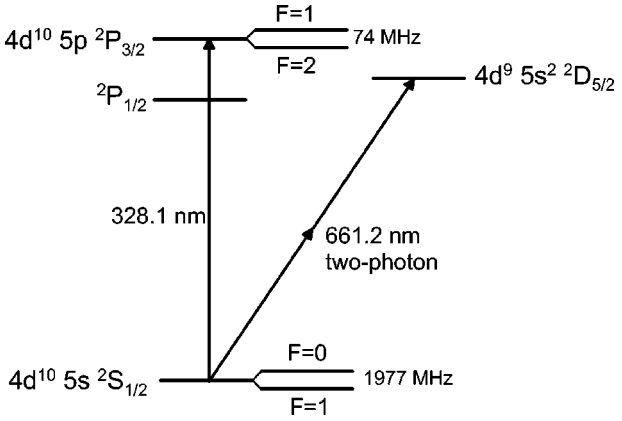

FIG. 1. Partial energy-level diagram for ^{109}Ag, showing the transitions relevant to this work.

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high saturation intensity of 87 mW/cm^2 obliges one to generate relatively high laser power in the uv for full saturation of the transition. In addition, because of nonzero nuclear spin ($I=\frac{1}{2}$) and the comparatively small hyperfine splitting of the upper cooling level (74 MHz for ^{109}Ag), the atom will undergo optical pumping into the $F=0$ hyperfine level of the ground state. This problem—similar to the case of the alkali metals—must be overcome by applying a repumper detuned about 1.9 GHz. The second difficulty arising in preparing a silver MOT is the very low vapor pressure, which inhibits the use of the simplest method of loading atoms into the trap: catching the slow atoms from the background in a vapor cell [13] would require temperatures of about 500 °C and is therefore impractical.

II. EXPERIMENTAL SETUP

The required uv power is obtained by using a Coherent 899-21 ring dye laser with DCM dye to generate light at 656 nm. This is transmitted into an optical enhancement cavity for frequency doubling with a 10-mm-long LBO crystal cut at Brewster's angle. With about 500 mW of fundamental input, as much as 40 mW of frequency-doubled laser light at 328 nm was produced. The frequency of the dye laser is locked to the atomic transition by splitting off a small part of the laser light, which is then directed to a well-collimated silver atomic beam at a right angle. Recording of the Doppler-free fluorescence lines gives the signal to stabilize the laser.

The light necessary for repumping is generated by a diode laser system at 656 nm that consists of an extended-cavity diode laser (ECDL) and a tapered amplifier. The frequency of the ECDL is stabilized relatively to the frequency of the dye laser by recording the beat note between the two lasers. Its output of roughly 5 mW is increased in the tapered amplifier to about 100 mW and frequency-doubled in a second enhancement cavity with a $LiIO_3$ crystal. The repumping light with a few milliwatts of power is superimposed by the trapping laser (1.86 GHz detuning) and then divided into three parts to form the trapping beams of the MOT.

The vacuum system consists of two chambers. The first one contains an oven in the form of a ceramic crucible resistively heated by a tantalum wire to produce an effusive atomic beam. The background pressure is measured to be 2×10^{-9} mbar and the oven is typically operated at a temperature of 1200 K. The beam is collimated by two apertures and passes through an interaction zone for spectroscopy as well as laser locking. It then enters the second chamber through a small aperture to guarantee differential pumping. A turbomolecular pump keeps the pressure below 5×10^{-10} mbar. The distance between the oven and the trap center is 0.5 m. Because of the low laser power available and the complexity of the laser system, it was decided to load the trap directly from the thermal atomic beam without any further beam slowing. In addition, a second oven located only 3 cm from the center of the trapping region can be used. This silver source consists of a small filament made of 25-μm-thin rhenium wire to which a small droplet of molten silver is applied. We use resistive heating with a dc current of 2.1 A to evaporate the silver atoms. Because of its small size, the source can be placed very close to the MOT to achieve a large filling rate due to the wide solid angle. During operation, the background pressure did not change within the sensitivity of our pressure gauge. The only disadvantage of the source is the low capacity compared with the large-quantity evaporation with crucibles.

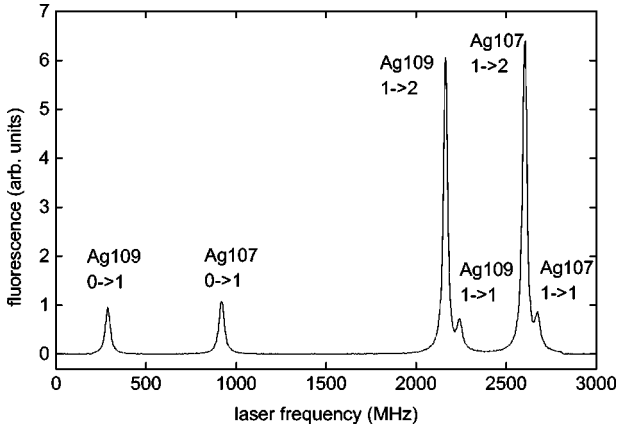

FIG. 2. The $^2S_{1/2}$–$^2P_{3/2}$ spectrum, obtained with a frequency-doubled diode laser aligned perpendicular to the thermal atomic beam.

The set of anti-Helmholtz coils that generate the spherical quadrupole field for the MOT must be switched off very fast for future spectroscopic investigations. It is therefore of compact design and is placed inside the ultrahigh-vacuum chamber. At a maximum current of 10 A, the coils give an axial gradient of about 50 G/cm in the z direction. The MOT is operated in the standard six-beam σ^+-σ^- configuration [14]. The three laser beams of equal intensity have a radius of 3 mm. A photomultiplier is used to monitor the trap fluorescence and an intensified CCD camera allows measurement of the spatial extent of the atomic cloud.

III. RESULTS

The atomic beam was used to make a spectroscopic measurement of the $5s\,^2S_{1/2}$–$5p\,^2P_{3/2}$ cooling transition of the silver atom. Figure 2 shows the spectrum obtained with three allowed hyperfine transitions for each of the two isotopes. The probing diode laser with a frequency stability better than 500 kHz was transmitted to the well-collimated atomic beam at a right angle. Since the laser intensity was kept far below the saturation intensity, the observed transitions are Doppler-free with a linewidth given by the natural linewidth of the upper cooling level. By means of the known hyperfine splitting [15], the center-of-mass isotope shift was determined to be $\Delta\nu=476\pm10$ MHz with the ^{109}Ag state above the ^{107}Ag state. The measuring accuracy was limited by the piezononlinearity of the laser scan.

We succeeded in observing the MOT for both silver isotopes, ^{107}Ag and ^{109}Ag, with the ratio of the observed signal intensities reflecting the natural abundances of 52% and 48%, respectively. The number of trapped atoms was determined by estimating the rate at which an individual atom scatters photons at a given laser intensity and detuning and

by measuring the total fluorescence intensity of the atomic cloud with the photomultiplier detector. The light-to-signal conversion ratio and the light collection efficiency were obtained by transmission measurements on our collection optics. By filling the MOT from the thermal atomic beam generated by the filament close to the trap center, up to 3×10^6 silver atoms could be stored. The cloud extent was of Gaussian shape with diameters of about 300 μm and corresponding densities of 10^9 atoms/cm^3. The number of trapped atoms was found to be quite sensitive to the laser detuning. Due to the relatively low laser power available (saturation parameter below 1), the maximum number was reached at detuning of about $-1\,\Gamma$, and no atoms could be stored with detuning larger than $2.5\,\Gamma$ below resonance. The frequency difference of the repumping laser relative to the main trapping component was set at 1.88 GHz.

In our present setup, the maximum particle number in the trap is determined by two dominant trap depopulation mechanisms. One is the trap loss resulting from collisions of stored particles with fast silver atoms from the atomic beam. By studying the filling of the MOT after abrupt switch-on of the trapping beams [16], we observed storage times of about 1–5 sec, with decreasing values for higher temperatures of the atomic oven. Longer accumulation times and hence higher equilibrium particle numbers could be achieved by introducing a shield to protect the MOT from collisions with the hot atoms from the thermal beam. The decay of the trap due to collisions with background gases is negligible at a pressure smaller than 5×10^{-10} mbar. The other loss mechanism limiting the storage time is due to leakage of the population from the cooling transition. This is similar to strontium or calcium traps employing analogous transitions [10], but with trap lifetimes in the silver case that are two orders of magnitude larger. The D_2 transition in silver is not a closed transition, since a small part of the $^2P_{3/2}$ population spills to the $^2D_{5/2}$ metastable level, which lies 230 cm^{-1} below the $2P_{3/2}$ state (Fig. 1). Because of the long lifetime of the metastable level, atoms that have decayed to the $^2D_{5/2}$ state will cease to interact with the trapping lasers and escape from the trap. The trap lifetime will thus depend on the excitation probability of the atom.

The storage time of the trap was determined as a function of the laser power in the trapping beams by interrupting the trap loading and observing the decay of the trap fluorescence. With fixed detuning and varying laser intensities, decay curves were measured by monitoring the fluorescence signal after the atomic beam had been blocked by a mechanical shutter. To determine the trapping lifetime, each of the data sets was fitted with a decaying exponential. Two of the curves are shown as examples in the inset of Fig. 3. For any power level of the trapping beams used in the experiment, the measured fluorescence could be described by a single exponential decay, showing that decay due to light-assisted collisions or other density-dependent mechanisms has no effect.

The storage time as a function of the laser power shows the expected decrease with increasing laser power (Fig. 3). If all the atoms that decay to the $^2D_{5/2}$ state escape from the trap, the trap lifetime τ can be modeled by $\tau=(f\gamma_{P\text{-}D})^{-1}$,

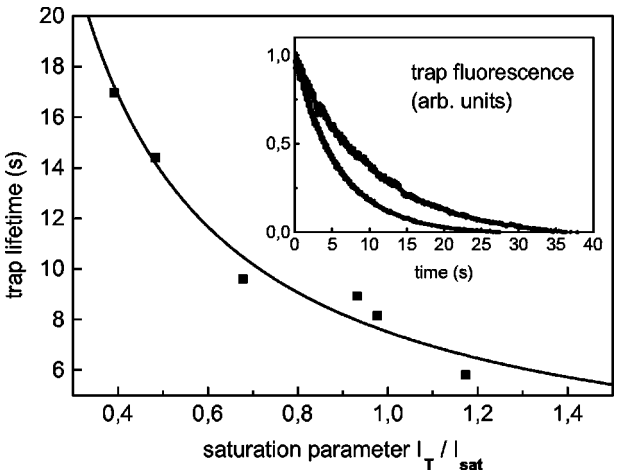

FIG. 3. Trapping lifetime versus laser intensity for fixed detuning of -1Γ. The solid line is a fit as explained in the text. The inset shows the normalized trap fluorescence as a function of time after blocking the atomic beam for two different total intensities ($I_T/I_{sat}=0.9$ and 1.1).

where f is the excitation probability to the $^2P_{3/2}$ state [17] and $\gamma_{P\text{-}D}$ is the decay rate from the $^2P_{3/2}$ state to the $^2D_{5/2}$ level. We can estimate the excited-state fraction f, which depends on the mean laser intensity and detuning, and fit the above equation with the measured values of the trap lifetime (solid line in Fig. 3). This gives $\gamma_{P\text{-}D}=1.6\pm0.6$ s [18], where the errors in the determination of f are the dominant source of uncertainty in our measurement of the decay rate to the metastable state.

To obtain an estimate of the temperature of the stored atoms, we made preliminary measurements of the mechanical properties of the MOT by exciting a coherent oscillation of the trapped cloud. The method is explained in detail in [19,20]. The oscillation of the trapped atomic sample is obtained by superimposing an additional ac magnetic field (maximum amplitudes below 200 mG) on the MOT mag-

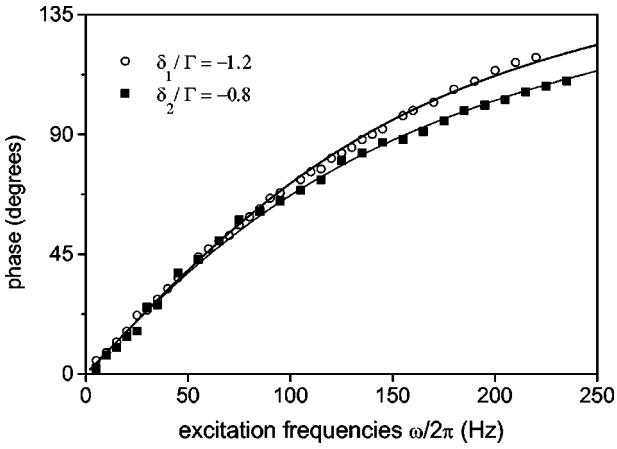

FIG. 4. Frequency response of $\phi(\omega)$ for the trap oscillation in the radial direction of the MOT quadrupole field for two different detunings δ_1, δ_2 of the trapping lasers. The solid lines are fitted curves based on the overdamped harmonic motion of the atoms in the trap.

netic field, which yields a periodic motion of the center point of the spherical quadrupole field. The phase shift between the MOT oscillation and the external periodic excitation is then recorded by imaging the trap fluorescence onto the photomultiplier. If a razor blade is positioned in front of the PMT, the position change of the MOT is converted into an ac signal and the phase shift ϕ can be measured with a lock-in amplifier. Figure 4 shows typical curves of the frequency response $\phi(\omega)$ for two different laser detunings.

Fitting the theoretical phase lag of a driven overdamped harmonic oscillator [19] to the data (solid lines in Fig. 4) allows determination of the friction coefficient α and spring constant κ of the trap. To give an example, for the two data sets δ_1 and δ_2 in Fig. 4 we observed values for the spring constant in the radial direction of $\kappa = 1.6(2) \times 10^{-19}$ N/m and $2.1(2) \times 10^{-19}$ N/m, respectively. Finally, the temperature can be deduced via the equipartition theorem $k_B T = \kappa \sigma^2$, where σ is given by the rms radius of the Gaussian density distribution of the trap. We therefore measured the spatial extent of the MOT with a CCD camera as a function of the laser detuning. The lowest temperature obtained is $T = 300(90)$ μK for detuning of roughly -1Γ, which is below the Doppler limit given by $T_D = \hbar\Gamma/2k_B = 560$ μK.

In conclusion, we made a spectroscopic measurement on the D_2 line in Ag I and determined the ^{107}Ag-^{109}Ag isotope shift of the transition involved. It was possible to confine silver atoms in a magneto-optical trap. About 10^6 atoms were stored with trap lifetimes of up to 16 s and mean atomic velocities with values smaller than 20 cm/s. Our MOT thus provides an excellent starting point for a future spectroscopy experiment to observe the narrow two-photon transition of the silver atom.

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