Microwave Spectroscopy of Cold Rubidium Atoms

V.M. Entin and I.I. Ryabtsev

Institute of Semiconductor Physics, Siberian Division, Russian Academy of Sciences, Novosibirsk, 630090 Russia
(Dated: June 22, 2004)

The effect of microwave radiation on the resonance fluorescence of a cloud of cold $^{85}$Rb atoms in a magnetooptical trap is studied. The radiation frequency was tuned near the hyperfine splitting frequency of rubidium atoms in the $5S$ ground state. The microwave field induced magnetic dipole transitions between the magnetic sublevels of the $5S(F=2)$ and $5S(F=3)$ states, resulting in a change in the fluorescence signal. The resonance fluorescence spectra were recorded by tuning the microwave radiation frequency. The observed spectra were found to be substantially dependent on the transition under study and the frequency of a repump laser used in the cooling scheme.

PACS numbers: 32.60.+i, 39.25.+k, 39.30.+w, 42.50.Gy

The method of optical radiofrequency double resonance provides the basis for atomic frequency standards. Microwave radiation, resonant with transitions between the hyperfine levels of alkali metal atoms (for example, Rb and Cs), induces magnetic dipole transitions, resulting in a change in a resonance fluorescence or absorption signal at optical transitions from the ground state. In the first experiments, the effect of microwave fields on absorption and polarization of light from resonance lamps has been studied.

Before the advent of magnetooptical traps for laser cooling and capture of atoms, thermal atomic gases with a large Doppler broadening have been mainly studied. The first microwave spectroscopic experiments with cooled atoms have been performed in a magnetic trap with Na atoms. The fluorescence spectrum of Na atoms captured in a strong magnetic field ($\sim$2300 G) was studied in the presence of a probe laser field and probing microwave radiation. However, a strong magnetic field caused the broadening of resonances up to 200 MHz, which substantially exceeds the natural width of optical transitions.

Later, a microwave field was used to excite transitions between the hyperfine levels of the ground state of cesium atoms cooled in the optical molasses at the point of intersection of three standing light waves. The fluorescence signal from atoms, which have been preliminary cooled in the molasses, was studied after the shutdown of cooling laser beams. This allowed the observation of optically unperturbed microwave resonances of width as small as a few tens of hertz. The intensity of microwave radiation in these experiments did not exceed a few tens of nW/cm$^2$.

These studies have been further developed in experiments with so-called "atomic fountains" (see, for example, [6]). Narrowing of the atomic standard lines was achieved by the Ramsey fringes method during the roundtrip transit of cooled slow atoms in a microwave resonator. In addition, a microwave field was used in some papers instead of a repump laser to produce an optical/microwave magnetooptical trap.

The aim of the microwave spectroscopy of cooled atoms is, as a rule, the observation of ultranarrow resonances and the development of a precision atomic clock based on microwave transitions. However, microwave spectroscopy can be also used to study processes occurring in a cloud of cold atoms. For example, recently microwave spectroscopic experiments were performed with atoms loaded from a magnetooptical trap to an optical trap with a large frequency detuning. The authors of paper also observed narrow microwave resonances ($\sim$500 Hz and narrower) by switching off cooling lasers during measurements.

The aim of this work was to study the effect of a microwave field on a resonance fluorescence signal in a standard magnetooptical trap with Rb atoms and to estimate the possibility of using this effect for diagnostics of a cloud of cold atoms.

EXPERIMENTAL SETUP

The Rb atoms were cooled and captured in a magnetooptical trap using a laser setup containing two 780nm external resonator semiconductor lasers and a frequency-locking system based on saturated absorption in optical cells with Rb atoms.

Laser cooling was performed using a standard optical scheme consisting of three pairs of orthogonally polarized laser beams ($\sigma+$, $\sigma-$) crossing at the center of a quartz cell (Fig. 1), which was evacuated by ion pumps down to a pressure of $<1\times10^{-8}$ Torr. The source of Rb atoms was an ampoule containing a natural mixture of rubidium isotopes at room temperature.

The magnetic field gradient in the trap ($0\div15$ G/cm) was produced by a pair of anti-Helmholtz coils. Residual magnetic fields were compensated with the help of additional Helmholtz coils. The possibility of compen-
sation for residual magnetic fields and the accuracy of alignment of the laser beams were provided by using two CCD cameras placed from both sides of the cell.

The resonance fluorescence signal was detected with a calibrated twoelement photodiode equipped by a TV objective and a differential amplifier. The cloud image was projected by the objective on one of the elements of the photodiode, the second element being used to subtrack laser radiation scattered from the cell walls.

The Rb atoms were captured in the trap by locking the cooling laser frequency either to the slope of the saturated absorption (Fig. 2b) 5S_{1/2}(F=3)→5P_{3/2}(F=4) transition peak of ^85 Rb with the red 1±3Γ detuning from the resonance center (Fig. 2a) (Γ=6 MHz is the natural width of the D2 line of Rb) or to the slope of the fluorescence resonance of the trap. In the latter case, the so-called selfstabilized magnetooptical trap was realized [12]. As a result, the fluorescence signal had a more stable constant component corresponding to the equilibrium population of the trap.

The repump laser was tuned to the slope of the saturated absorption 5S_{1/2}(F=2)→5P_{3/2}(F=2 or 3) transition peak with the red 0±3Γ detuning (Fig. 2a) and was locked to the resonance using the Pound-Drever frequency modulation method [13, 14].

The output power of lasers was ~6 mW. Laser beams were expanded in front of the cell with the help of telescopes up to a diameter of 7±8 mm. The intensity of each of the laser beams incident on the cell was 2.6 mW/cm², while the calculated saturation intensity was 1.65 mW/cm². Figure 2c illustrates the measured dependence of the number of trapped atoms on the cooling laser frequency, the repump laser frequency being locked to the resonance at the 5S_{1/2}(F=2)→5P_{3/2}(F=2) transition. Figure 2d shows the dependence of the number of trapped atoms on the total power of the repump laser in the trap when the cooling laser was detuned by δ=9 MHz. It is seen that the saturation of trap population occurs even at 0.1 mW.

We obtained in the trap a cloud of cold atoms 0.6±2 mm in diameter, containing ≤2×10⁷ atoms, which corresponds to an atomic density ≤2×10¹⁰ cm⁻³. The cloud temperature equal to ~50μK was measured by the dynamics of a decrease in the number of atoms after a short (5±200 ms) switching off of the magnetic field gradient. The trap population decreased by a factor of e for the time t~30 ms. This means that a greater part of Rb atoms escaped from the region of interaction with laser radiation for the time 30 ms by flying the distance L=A/2≈3.5 mm (A is the beam aperture). In the Maxwell velocity distribution approximation, the expression for the average temperature of atoms can be written in the form [4]:

$$\langle T \rangle = \frac{M\langle v \rangle ^2}{3k_B}$$  \hspace{1cm} (1)$$

where \(\langle v \rangle = L/t\) is the average velocity of atoms, \(k_B\) is the Boltzmann constant, and \(M\) is the atom mass; and the temperature estimated from (1) is 50 μ.

In microwave spectroscopic experiments, we used a frequency synthesizer based on the first heterodyne of a S4-60 spectrum analyzer with a 20-dBm, 3-GHz (±300 MHz) power amplifier (Fig. 1). The width of the heterodyne line did not exceed 10 kHz. The frequency was continuously tuned with the help of a CAMAC digital-to-analog converter.

A weak change in the resonance fluorescence caused by magnetic dipole transitions in rubidium atoms was investigated by the lockin detection technique. For this
FIG. 2: (a) Scheme of transitions in $^{85}$Rb atoms; (b) saturated absorption spectrum of a reference cell; (c) the number of atoms in the trap as a function of the cooling laser frequency; (d) dependence of the number of atoms in the trap on the total output power of the repump laser.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 3a shows the dependence of the trap population on the microwave frequency for the case when the repump laser was detuned to the red with respect to the maximum of the $5S_{1/2}(F=2)\rightarrow5P_{3/2}(F=2)$ transition. The microwave spectrum was obtained after averaging over ten measurements. Noise and fluctuations were mainly caused by the photodetector noise. The position of the frequency 3035.732 MHz of the unperturbed microwave resonance for the magnetic dipole $5S_{1/2} (F=2) \leftrightarrow 5S_{1/2} (F=3)$ transition in $^{85}$Rb atoms is indicated by the dashed straight line. One can see that the fluorescence signal from the trap exhibits a dip near this frequency. The width of the microwave resonance was almost the same in different experiments and was $\sim$500 kHz.

The observed resonance is caused by the transfer of cold $^{85}$Rb atoms from the $5S_{1/2} (F=3)$ state to the $5S_{1/2} (F=2)$ state due to magnetic dipole transitions. In the case of exact tuning of the microwave frequency, the fluorescence intensity of the trap at the cooling $5S_{1/2}(F=3)\rightarrow5P_{3/2}(F=4)$ transition decreases because the number of atoms in the $5S_{1/2}(F=3)$ state decreases. The absence of the shift of the microwave resonance suggests that either the fluorescence signal is detected from the central part of a cloud of cooled
atoms, where the magnetic field is weak and the Zeeman shift of levels is negligible, or magnetic dipole transitions are excited between the central Zeeman components $5S_{1/2}(F=2,|m_F|=0)$ and $5S_{1/2}(F=3,|m_F|=0)$, which are not shifted. The latter assumption is unlikely because the magnetic moments of cold atoms have no definite orientation with respect to any arbitrary quantization axis in the trap, while the polarization of microwave radiation has not been especially selected. Therefore, the most probable reason for the absence of the shift of the microwave resonance is the detection of variations in the fluorescence intensity from the central part of the cloud. Such a behavior is observed only when the repump laser is tuned to the $5S_{1/2}(F=2)\rightarrow 5P_{3/2}(F=2)$ transition, at which a part of atoms at the trap center can be transferred to the dark states, which do not interact with laser radiation.

The decrease in the fluorescence intensity is most likely explained by the fact that microwave radiation transfers a part of atoms from the $5S_{1/2}(F=3)$ state to the local dark states, which are produced at the $5S_{1/2}(F=2)$ level by the repump laser. Because atoms in these states are not excited by the pump laser, they do not also interact with the radiation of the cooling laser, which results in the reduction of the fluorescence signal.

By analyzing the width of the observed resonance, note that the $5S_{1/2}(F=3)$ sublevel should experience the shift, broadening, and splitting under the action of radiation from the cooling laser due to the Autler-Townes effect. The level splitting and shift are determined by the position of the quasienergy levels

$$\omega_{\pm} = \delta/2 \pm \sqrt{\delta^2/4 + \Omega^2/4}, \quad (2)$$

where $\delta$ is the detuning from the optical resonance and $\Omega$ is the Rabi frequency. Note that the detuning and Rabi frequency in our experiment (in the case of saturation) are of the same order of magnitude as $\Gamma$. The magnetic-field gradient determines the variation of detunings on the cloud dimensions, therefore a microwave resonance should broaden up to a few megahertz. This conclusion is confirmed by recent paper in which the Autler-Townes effect was studied on optical transitions in cold Rb atoms and level shifts and splittings were observed.

However, the resonance width $\approx400$ kHz observed in our experiments is noticeably smaller than the above value and is virtually independent of the detuning of the cooling laser. This is probably explained by the fact that microwave radiation has induced transitions to the dark states, which do not interact with radiation. In this case, the resonance width was determined only by the inhomogeneity of the magnetic field at the trap center, where the dark states for degenerate levels can appear. This conclusion requires further experiments to study the features of the dark states produced at the trap center when the repump laser operates at the $5S_{1/2}(F=2)\rightarrow 5P_{3/2}(F=2)$ transition.

The resonance amplitude in Fig. 3a in different experiments was $(3\pm9) \times 10^3$ atoms. Its maximum value was determined by the strength of the magnetic component of the microwave field. At the same time, it was found that a rather large variation in the amplitude was caused by weak fluctuations in the detunings of laser frequencies from optical transition frequencies. The maximum amplitude was achieved when these detunings were identical, the central frequency of the resonance being invariable.

Quite a different picture was observed when the repump laser was tuned to the $5S_{1/2}(F=2)\rightarrow 5P_{3/2}(F=3)$ transition, for which the dark states are absent (Fig. 3b). The spectrum exhibits two peaks ($\pm \Delta f$), which are symmetrically split with respect to the center of the $5S_{1/2}(F=2)\rightarrow 5S_{1/2}(F=3)$ transition. It was assumed first
that these peaks appear due to the Antlter-Townes effect for the $5S_{1/2}(F=3)$ level in the field of the cooling laser because the shifts of resonances depended on the detuning of the cooling laser at the $5S_{1/2}(F=3)\rightarrow 5P_{3/2}(F=4)$ transition. However, one can see from Eq. (2) that the shifts of the quasienergy levels should be different in the case of the red detuning of the laser. Therefore, the shifts of the resonances in Fig. 3b should be also different, whereas we observe the symmetrical shifts and splitting.

The observed effect can be also interpreted in a different way. Because the frequencies of microwave resonances are shifted with respect to the central frequency, they are mainly caused by atoms located in the gradient magnetic field at the periphery of a cold cloud. As the red detuning of the cooling laser from the resonance with the $5S_{1/2}(F=3)\rightarrow 5P_{3/2}(F=4)$ transition increases, the temperature of atoms increases, resulting in an increase in the cloud size. Therefore, the shifts of microwave resonances increase due to the increase in the Zeeman splitting at the cloud periphery. The increase in the fluorescence signal in the region of resonances in Fig. 3b compared to its decrease in Fig. 3a is caused by the increase in the efficiency of the repump laser at the cloud periphery when microwave radiation is tuned to the resonance. The presence of two resonances in Fig. 3b suggests that magnetic dipole transitions are excited between the extreme Zeeman components of the $5S_{1/2}(F=2,|m_F|=\pm 2)$ and $5S_{1/2}(F=3,|m_F|=\pm 3)$ levels having the largest resonance shifts ($d\Delta_{\text{Zeeman}}/d\Delta B\approx 2.56 \text{ MHz/G}$). The frequency shifts shown in Fig. 4 correspond to the trap radius from 1 to 1.8 mm, in accordance with analysis of the TV image of the trap.

Although the main features of the spectra presented above were reproducible in different experiments, note that the signal noise and fluctuations were rather large. The signal/noise ratio was not substantially improved even in the case of lockin detection. This is related to a rather long loading time of the trap ($\sim 1 \text{ s}$), resulting in the suppression of the alternate component of the fluorescence signal. For this reason, the amplitude of resonances in our experiments did not exceed 0.01 of the total fluorescence intensity level.

At the same time, our experiments showed that the microwave spectroscopy of cold atoms allows one to study fluorescence signals from different regions of a cloud of cold atoms. The switching to the detection of one or another region of the cloud is achieved by a proper choice of one of the transitions for the repump laser. For example, when the $J\rightarrow J$ transition is used, a change in fluorescence from the central part of the cloud is detected, while in the case of the $J\rightarrow J+1$ transitions, fluorescence from the cloud periphery is analyzed. This is directly related to the presence of the “dark states” for the $J\rightarrow J$ transitions and their absence for the $J\rightarrow J+1$ transitions, as was already mentioned in [17]. These features can be used for the development of new methods for diagnostics of cold atoms.

We thank V.I. Yudin, A.V. Taichenachev, and O.N. Prudnikov for useful discussions. This work was supported by the Russian Foundation for Basic Research (project no. 020216332) and INTAS (grant no. 2001155).

[1] J. Vanier, C. Audoin, The quantum physics of atomic frequency standards. IoP Pub. (Bristol: ed. by A. Hilger), v.1-2 (1989).
[2] H. Kopferman, Kernmomente (Akademie, Frankfurt, 1956; Inostrannaya Literatura, Moscow, 1960).
[3] H. J. Metcalf, P. Van Der Straten, H. E. Stanley, Laser cooling and trapping. Springer, New York. (1999).
[4] A. G. Martin, K. Helmer, V. S. Bagnato et al. Phys.Rev.Lett. 61, 2431 (1988).
[5] D. W. Sesko, C. E. Wieman Opt. Lett. 14, 269 (1989).
[6] E. A. Donley, T. P. Crowley, T. P. Heavner et al. Proc. 2003 Joint Mtg. IEEE Intl. Freq. Cont. Symp. and EFTF Conf., p. 135 (2003).
[7] N. F. Ramsey, Molecular Beams (Clarendon Press, Oxford, 1956; Inostrannaya Literatura, Moscow, 1960).
[8] R. J. C. Spreeuw, C. Gerz, L. S. Goldner et al. Phys.Rev.Lett. 72, 3162 (1994).
[9] A. Kaplan, M. F. Andersen, N. Davidson Phys.Rev. A 66, 045401 (2002).
[10] V. M. Entin, A. E. Boguslavski, I. I. Ryabtsev, et al., Pisma Zh. Eksp. Teor. Fiz. 71, 257 (2000) [JETP Lett. 71, 175 (2000)].
[11] V. M. Entin, I. I. Ryabtsev, A. E. Boguslavsky et al. Opt.Commun. 207, 201 (2002).
[12] C. S. Fletcher, J. E. Lye, N. P. Robins et al. Opt.Commun. 212, 85 (2002).
[13] R. W. P. Drever, J. L. Hall, F. V. Kovalski et al. Appl.Phys. B 31, 97 (1983).
[14] G. C. Bjorklund, M. D. Levinson, W. Lenth et al. Appl.Phys B 32, 145 (1983).
[15] A. M. Tumaikin and V. I. Yudin, Zh. Eksp. Teor. Fiz. 98,
[16] S. H. Autler, C. H. Townes Phys.Rev. 100, 703 (1955).
[17] V. M. Akulin and N. V. Karlov, Intense Resonant Interactions in Quantum Electronics (Nauka, Moscow, 1987) [in Russian].

[18] B. K. Teo, D. Feldbaum, T. Cubel et al. Phys.Rev. A 68, 053407 (2003).
[19] S. R. Muniz, K. M. F. Magalhães, E. A. L. Henn et al. Opt.Commun. 235, 333 (2004).