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OPTICS
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Spectroscopy of Rubidium Atoms in a Femtosecond Pulsed Optical Dipole Trap

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The spectral properties of atoms localized in an optical dipole trap formed by femtosecond pulsed radiation are studied experimentally. It is shown that the shift of the absorption line of an atom due to the interaction of an atom with the field of localizing radiation coincides with the shift of the line of an atom localized in the field of cw laser radiation. Theoretical analysis shows that pulsed radiation with experimentally achievable average intensity and duration of a pulse makes it possible to implement an atom localization mode in which the line shift is absent.

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INTRODUCTION

Localization of neutral atoms is actively studied in view of fundamental problems of quantum mechanics and applications in quantum computer science and quantum sensors [1–3]. Optical dipole atomic traps can be used to localize cold atoms for times exceeding 300 s [4] and are a promising alternative to ion localization systems. Because cw lasers are available only in the visible and infrared regions, the creation of optical dipole traps is possible only for atoms and molecules that have spectral absorption lines in these spectral regions. The absence of ultraviolet narrowband laser sources prevents the use of the methods of laser cooling and atom trapping for the atoms most common in organic chemistry (hydrogen, carbon, oxygen, and nitrogen), as well as for atoms that are of technological interest (chromium, indium, silver, and aluminum) and whose resonant transitions are in the blue and ultraviolet regions. A possible solution to this problem is to use pulsed lasers that can generate high-power ultraviolet radiation. This is the reason for the considerable interest in pulsed dipole traps [5].

An important feature of optical dipole traps is that the optical field localizing the atom also shifts its energy levels (so-called light-induced shift) and thereby changes the frequency of the resonant transition between the energy levels of the atom. Various successful applications of trapped atoms are based on the possibility of eliminating these shifts or measuring and taking them into account with a high accuracy. There are several methods for measuring the spectrum of localized atoms using a probe laser field. These methods are based on the absorption of the probe laser radiation [6], fluorescence excited by absorbed radiation [7, 8], spectral-selective heating of atoms [9, 10], and their ionization from Rydberg states [11]. Some of these approaches can be combined with additional cooling cycles, which allows nondestructive spectral measurements of cold atoms [12]. Theoretical analysis [13] shows that the frequency shift of an atom absorption line in a pulsed periodic laser field differs from that in the case of the cw laser field. This allows discussing metrological applications of atoms localized by the pulsed field.

In this work, we experimentally and theoretically studied the spectral properties of rubidium atoms trapped in the field of periodic femtosecond laser pulses [14–16]. The method for measuring the spectral properties of rubidium atoms is based on measuring the loss of localized atoms in a trap when they are heated by a probe laser field [10]. This approach allows comparing the spectral properties of atoms localized in traps created by pulsed and cw laser radiation.

EXPERIMENT

To study the spectral properties of atoms localized in a pulsed dipole trap, we chosen the absorption line of the ^{85}Rb atom corresponding to the transition from the $F = 3$ level of the $5S_{1/2}$ ground state to the $F' = 4$ level of the $5P_{3/2}$ excited state. The experimental setup and structure of levels of the rubidium $D2$ line are shown in Fig. 1. To localize atoms, they were precooled in a magneto-optical trap (MOT) followed by sub-Doppler cooling to a temperature of about 80 μK. The dipole trap was created using a lens whose focal

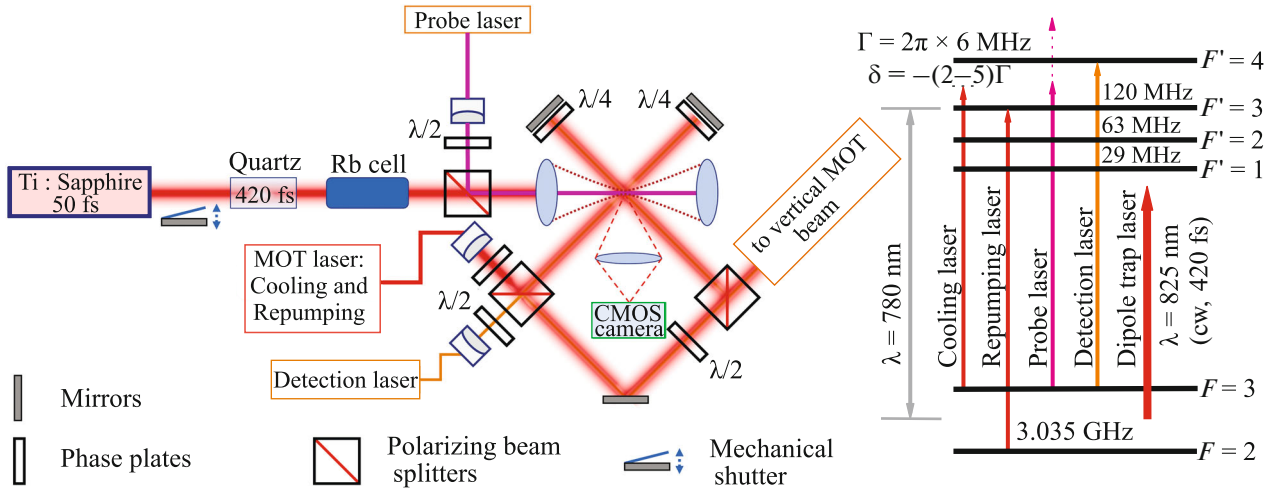

Fig. 1. (Color online) Experimental setup for studying the spectral properties of atoms localized in a pulsed dipole trap.

point was inside the MOT to capture the atoms. The laser used for creating the trap can operate both in continuous and pulsed generation modes with a pulse duration of 50 fs and a pulse repetition frequency of 80 MHz. This allowed comparing the spectral properties of atoms localized in traps created by both pulsed and cw radiation. The average radiation power in both cases was chosen the same and equal to 50 mW, which provided the same depth of the localization potentials created by pulse and cw radiation. When the radiation was focused into a spot with a radius of 8 μm, the depth of the optical potential was about 150 μK.

The laser radiation forming the dipole trap was passed through a spectral filter consisting of a cell with rubidium vapor. Such a cell can be heated to temperatures above 200°C and used in various experiments [17, 18]. The use of such a filter ensures filtering the spectral components of laser radiation resonant with the rubidium absorption lines, which significantly increases the lifetime of atoms in the optical potential in the pulse localization mode [19].

One of the factors limiting the lifetime of atoms in a dipole trap is fluctuations of the dipole force [20–22]. These fluctuations are particularly significant when atoms are localized by a femtosecond pulsed laser owing to the high peak intensity of the trapping field [16]. For this reason, pulsed radiation with a low average power (50 mW) was used in the experiment to localize the atoms. For the same reason (to reduce the peak intensity), laser radiation was passed through a 19.5-cm-long quartz glass, where the pulse duration was increased from 50 fs to $\tau_d = 420$ fs owing to the dispersion of the group velocity.

For the spectroscopy study of Rb atoms in the dipole trap, selective resonance heating was used [10]. This is the heating of atoms caused by the scattering of probe photons by them, and the magnitude of this heating depends on the frequency of the probe field. The measurements were made in two stages. At the first stage, the number of atoms N localized in the optical trap was measured without interaction with the probe field. The atoms were trapped by the dipole trap field for a time $\tau = 150$ ms, which is less than the lifetime of the atoms in the optical potential (1.2 s). At the second stage, a probe field was activated simultaneously with the localizing field. The interaction time of the atoms with the probe field was $\tau_p = 20$ ms, and the total trapping time was equal to the time τ of the first stage. After that, the number of atoms remaining in the optical trap N_p was measured using the fluorescence signal excited by probe laser radiation after switching off the probe and localizing fields. In the method of selective resonant heating, the measured quantity is the relative loss of atoms in the trap given by the expression

$$A = \frac{N - N_p}{N}, \quad (1)$$

where $N - N_p$ is the number of atoms leaving the trap owing to heating by the probe field and N is the total number of atoms in the trap. The measurement of the loss of atoms as a function of the frequency of probe field radiation completely determines the absorption line of localized atoms. A description of this method, as well as a detailed description of the experimental setup used, is given in [10].

Figure 2 shows the dependence of the relative loss of atoms on the frequency of the probe field measured for traps formed by both pulsed and cw radiation. The power of the probe radiation was 3 nW, which corresponded to the intensity $I_p = 1.5$ mW/cm^2 in the region of localization of atoms in the optical potential. The intensity of the probe field is comparable to the saturation intensity of the Rb atom equal to $I_{sat} = 2.5$ mW/cm^2. The experimental data were approximated using the Lorentz contour. As seen in Fig. 2, the

shift of the atom absorption line for both traps is the same and equal to 2 MHz. The broadening of the lines is 6 MHz, which is equal to the natural width of the absorption line of the studied transition.

DISCUSSION

To analyze the spectral properties of an atom in the pulsed radiation field, we considered the problem of interaction of a two-level atom with quasi-resonant radiation (probe field) in the presence of a strong pulsed field (trap field) with a large frequency detuning δ_d from the frequency of the $|g\rangle \rightarrow |e\rangle$ atomic transition. The average population $\langle\rho_{ee}\rangle$ of the excited state $|e\rangle$ was determined depending on the detuning δ_p of the probe field. The Rabi frequency of the probe field Ω_p was determined from the probe field intensity I_p = 1.5 mW/cm^2 used in the experiment. The Rabi frequency of the pulse field δ_d (which forms the dipole trap) has a time dependence determined by the time dependence of the laser pulse intensity. The duration of the laser pulse was τ_d = 420 fs [23].

The equations for the density matrix of such a system have the form

$$\begin{aligned}
&\rho_{gg}(t) + \rho_{ee}(t) = 1,\\
&\frac{d\rho_{ee}(t)}{dt} = i\Omega_p(\rho_{ge}(t)e^{-i\delta_p t} - \rho_{eg}(t)e^{i\delta_p t})\\
&+ i\Omega_d(t)(\rho_{ge}(t)e^{-i\delta_d t} - \rho_{eg}(t)e^{i\delta_d t}) - \rho_{11}\Gamma,\\
&\frac{d\rho_{ge}(t)}{dt} = i(\rho_{ee}(t) - \rho_{gg}(t))(\Omega_p e^{i\delta_p t}\\
&+ i\Omega_d(t)e^{i\delta_d t}) - \rho_{ge}\frac{\Gamma}{2},
\end{aligned} \tag{2}$$

where ρ_{gg}, ρ_{ee}, and ρ_{ge} are the elements of the density matrix and $\Gamma = 2\pi \times 6$ MHz is the natural width of the absorption line of the Rb atom. Numerical calculations were performed by analogy with the approach described in [13, 24, 25]. The pulse field interacts with the atoms only in short periods of time, determined by the pulse duration τ_d with a period of 12.5 ns corresponding to the repetition frequency of the pulsed laser of 80 MHz. Integrating the system of equations (2) over the time of the pulse duration gives the populations of the ground and excited states, as well as the off-diagonal matrix elements, at the end of the interaction of the atom with the field pulse. The values obtained are used as initial values for solving the problem of interaction of a two-level atom only with the probe field over a time interval equal to the period of pulse repetition, since interaction with the localizing pulse field between pulses can be ignored. The calculation process is repeated until the population of the excited state reaches a stationary value.

Figure 3a shows the map of the population $\langle\rho_{ee}\rangle$ of the excited state on the plane of two parameters: (i) the detuning δ_p of the probe field frequency from the atomic transition frequency of the atom at rest and (ii) the average intensity of the localizing pulse field. The dependence of the population of the excited state on the probe field frequency determines the absorption spectrum of the atom in the trap. It can be seen that the population $\langle\rho_{ee}\rangle$ of the excited state (and hence the absorption spectrum of the atom) depends on both parameters: when the intensity of the localizing field increases (which is equivalent to an increase in the depth of the trap), the absorption line of the probe laser radiation is blueshifted. At the same time, starting from a certain intensity of the laser field, two lines are observed in the absorption spectrum: one line in the blue region of the spectrum, the other in the red.

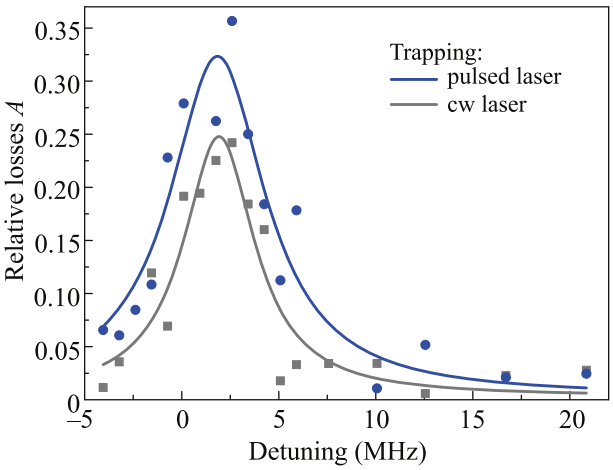

Fig. 2. (Color online) Spectrum of relative losses of atoms in optical dipole traps created by pulsed and cw laser fields.

Figures 3b–3e show the absorption spectra of the atom at various fixed average intensities of the localizing field. Figure 3e shows the absorption spectrum at zero field intensity. This case corresponds to a free atom at rest interacting with the probe laser field. As the intensity increases, the absorption line shifts (Fig. 3d) with subsequent splitting (Fig. 3c). The distance between the two split lines (Fig. 3c) is equal to the repetition frequency of the pulse field. Note that this splitting of the line was observed experimentally in [26].

The curve in Fig. 3d corresponds to the parameters used in our experiment. Figure 3f shows the same curve in units of the frequency detuning of the probe field, which corresponds to the parameters measured in the experiment. As can be seen, the line shift is 4.2 MHz and the line width is 7.6 MHz. The shift and width of the spectral line obtained in the calculation are in good agreement with the experimental data shown in Fig. 2. The differences are explained by the inaccuracy of determining the strength of the localizing and probe fields in the area of the atom traps.

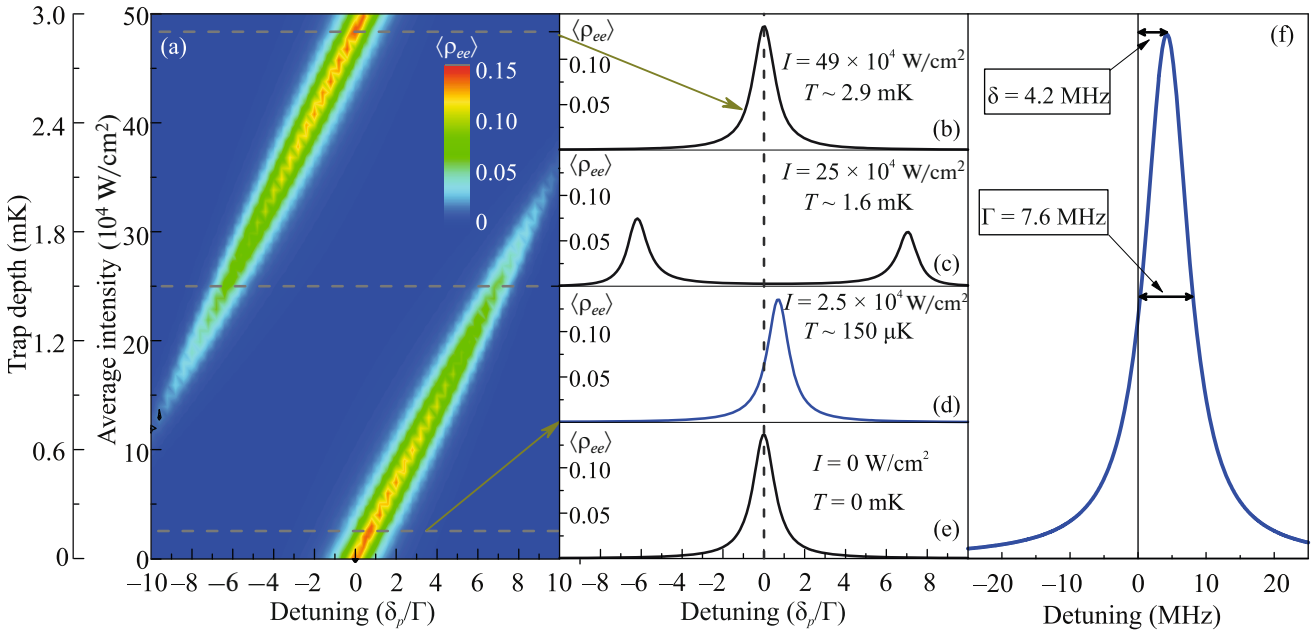

Fig. 3. (Color online) (a) Map of the excited state population $\langle \rho_{ee} \rangle$ on the plane of two parameters: (i) the detuning δ_p of the probe field frequency from the frequency of the atomic transition of the atom at rest and (ii) the average intensity of the localizing pulse field. (b–e) Cuts of the two-dimensional map (a) at fixed average intensities of the localizing pulse field. (f) Excitation spectrum of a two-level atom corresponding to the experimental conditions and parameters of the rubidium atom.

The results of the experiment (Fig. 2) and calculation (Fig. 3) show that the shift of the spectral line is observed in the pulse trap, although the atom does not interact with the laser field of the trap most of the time. The reason is that, when the atom interacts with a short pulse of the localizing field, the internal degrees of freedom of the atom are perturbed, and the relaxation time of the dipole moment induced by the field (~27 ns for the considered transition of the Rb atom) is comparable in magnitude to the period of laser pulses.

Note that the authors of [13] proposed a configuration of the localizing pulsed field where the shift of the atom absorption line is absent. This configuration corresponds to the strength of the localizing laser field, at which the phase shift of the atomic wavefunction is a multiple of 2π. This case corresponds to the curve in Fig. 3b, obtained at the average intensity of the localization field $I = 4.9 \times 10^5$ W/cm^2, which corresponds to the depth of the optical potential of 2.9 mK. It can be seen that the absorption line of the atom completely coincides with the absorption line of the free atom (Fig. 3e) obtained when the intensity of the localizing field is zero. It is important to note that similar calculations for the localization of atoms in the field of cw radiation with the intensity $I = 4.9 \times 10^5$ W/cm^2 give the shift of the spectral line equal to 14Γ, which qualitatively corresponds to the experimental data [12].

With the parameters of the localizing field accessible in this experiment (repetition frequency and pulse duration), it was not possible to study the case where the shift of the absorption line is absent. Splitting of the absorption line under pulsed perturbation of atoms was studied in [26] by the example of Cs atoms localized in a magneto-optical trap. The experimental dependence of the absorption spectrum obtained in this work is similar to the theoretical calculations shown in Fig. 3.

CONCLUSIONS

The absorption spectrum of Rb atoms localized in a pulsed optical dipole trap of femtosecond duration has been studied experimentally and theoretically. The experiment has demonstrated that the shift of the absorption line of atoms localized in the pulse trap is equal to the shift of the line in the trap formed by cw radiation with the same average radiation intensity.

Theoretical calculations have shown that there are parameters of the localizing pulsed periodic laser field in the trap at which the line shift is absent. For our experimental conditions, this mode requires average laser field intensity $I = 4.9 \times 10^5$ W/cm^2. Estimates show that this mode can be achieved by using periodic pulsed laser radiation with a pulse duration of 8 ps. The ability to create conditions for localization of atoms at which the spectral line shift is absent will expand the possibilities of using trapped atoms.

Note that the use of pulsed radiation for cooling and localization of atoms whose spectral lines are located in the ultraviolet part of the spectrum has attracted increasing attention in recent years [27–29].

The approach described in this work, together with the developed methods of laser cooling in the ultraviolet region of the spectrum, can be used in high-precision experiments to study the spectral properties of antihydrogen [30]. In addition, it opens opportunities to study the effects of atom scattering in the presence of pulsed interaction with laser fields [31].

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