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Laser cooling of $^{171}Yb^{+}$ ions in a frequency-modulated field

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Abstract. **We have investigated the laser cooling of ytterbium ions in a radio-frequency trap by a frequency-modulated resonant laser field. It has been shown that the lowest laser cooling temperatures, close to the Doppler limit, can be reached at field modulation parameters $\mu \geqslant 0.1$. At lower μ values, the region of field parameters optimal for cooling shifts to higher intensities and the minimum possible laser cooling temperature increases.**

Keywords: *laser cooling, $^{171}Yb^{+}$ ion, radio-frequency trap, frequency-modulated field.*

1. Introduction

There are currently well-developed laser cooling methods, which are widely used for cooling and confining neutral atoms and ions in various areas of modern research: ultrahigh-resolution spectroscopy, fabrication of high-performance quantum sensors based on atom interferometers (gyroscopes and gravimeters) [1–3] and investigation of the fundamental properties of degenerate gases (Bose and Fermi condensates) [4, 5]. One of the most promising directions utilising cold atoms and ions is the development of modern optical frequency standards [6–9]. At present, frequency standards based on a single ytterbium ion confined in a radio-frequency (RF) Paul trap demonstrate the best relative uncertainty characteristics among ion standards [10], comparable to those of the best frequency standards based on neutral atoms (Sr and Yb) in optical lattices [9, 11].

The $^{171}Yb^{+}$ ion is a promising candidate for creating a new generation of optical frequency standards. Figure 1 shows a diagram of the low lying levels that are used for the laser cooling of this ion and clock transitions, as well as a schematic of an RF trap. The specific features of the energy level structure of the ytterbium ion allow the $^2S_{1/2}$ $(F = 0) \to {}^2D_{3/2}$ $(F = 2)$ quadrupole transition, with a wavelength of 436 nm and natural linewidth of 3.1 Hz, or the $^2S_{1/2}$ $(F = 0) \to {}^2F_{7/2}$ $(F = 3)$ octupole transition, with a wavelength of 467 nm and a natural lifetime of several years (Fig. 1a), to be used for designing an optical standard [12–14]. The possibility of employing compact diode lasers in ion cooling and clock transition detection schemes, along with the use of fibre systems for laser light delivery, makes the $^{171}Yb^{+}$ ion optimal for making an on-board optical frequency standard. Moreover, unlike ytterbium-172, the $^{171}Yb^{+}$ ion in its ground state, $^2S_{1/2}$, has a total angular momentum $F = 0$, which ensures low sensitivity of the standard to the magnetic field induced shifts in the frequency of clock transitions for lack of a linear Zeeman effect.

The specifics of $^{171}Yb^{+}$ cooling is that the ground and excited states of the $^2S_{1/2} \to {}^2P_{1/2}$ optical transition, which is used for laser cooling, each have two energy levels, with total angular momenta $F = 0$ and $F = 1$ (Fig. 1a). The hyperfine

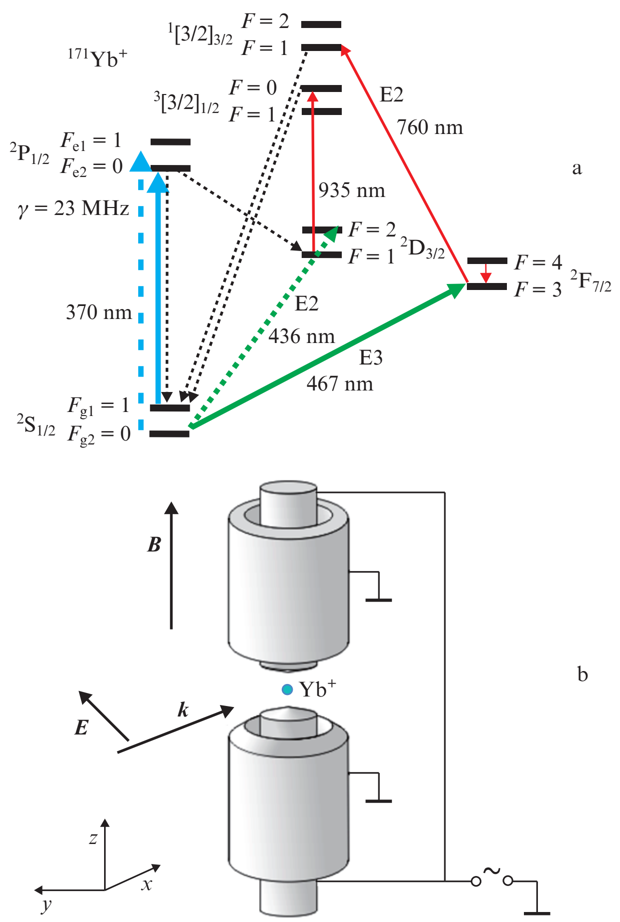

Figure 1. (a) Diagram of the low-lying levels of the $^{171}Yb^{+}$ ion that are used for laser cooling and (b) schematic of an RF trap.

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splitting is 12.6 GHz for the levels of the $^2S_{1/2}$ state and 2.1 GHz for the levels of the $^2P_{1/2}$ state.

For ion confinement in a trap in the Lamb–Dicke regime, use is made of Doppler laser cooling on the $^2S_{1/2}$ ($F = 0$) → $^2P_{1/2}$ ($F = 0$) transition, with a wavelength of 369.5 nm and natural linewidth γ = 23 MHz. As a result of nonresonant saturation of the $^2P_{1/2}$ ($F = 1$) level and a subsequent transition to the $^2S_{1/2}$ ($F = 0$) level, the ions stop interacting with the cooling monochromatic field. To depopulate the $^2S_{1/2}$ ($F = 0$) level and return the ion to the laser cooling process, the frequency of the cooling laser is sharply changed from one near the frequency between the hyperfine components of the $^2S_{1/2}$ ($F = 1$) → $^2P_{1/2}$ ($F = 0$) transition to a frequency that leads to saturation of the $^2S_{1/2}$ ($F = 0$) → $^2P_{1/2}$ ($F = 1$) optical transition and back again [15]. Another possibility is to use a frequency-modulated field in which the fundamental component near the resonance of the $^2S_{1/2}$ ($F = 1$) → $^2P_{1/2}$ ($F = 0$) optical transition ensures laser cooling and the sideband resonant with the $^2S_{1/2}$ ($F = 0$) → $^2P_{1/2}$ ($F = 1$) transition prevents optical pumping of the $^2S_{1/2}$ ($F = 0$) level [16]. There is also a decay channel from the $^2P_{1/2}$ ($F = 1$) level to the $^2D_{3/2}$ level (branching ratio $\alpha = 6.6\times10^{-2}$ [16]). The $^2D_{3/2}$ level is depopulated by pumping at a wavelength of 935.2 nm, in resonance with the $^2D_{3/2}$ – $^3[3/2]_{1/2}$ transition, followed by a spontaneous decay from the $^3[3/2]_{1/2}$ level to $^2S_{1/2}$ (Fig. 1a). In our experiment, the pump intensity is $I_p \approx 5$ W cm^{-2}, which leads to complete depopulation of the $^2D_{3/2}$ level.

Even though the laser cooling of ytterbium ions has been successfully demonstrated in experiments (see e.g. Refs [15–19]), in our opinion it is of theoretical interest to describe the laser cooling of ions in an RF trap and compare the results with those of a classic model for laser cooling in a monochromatic field.

Consider the problem of laser-cooling the $^{171}Yb^+$ ion in a frequency-modulated field:

$$\boldsymbol{E}(t) = E_0\boldsymbol{e}\exp(\mathrm{i}kx)\exp[-\mathrm{i}f(t)] + \mathrm{c.c.}, \qquad (1)$$

$$f(t) = \omega t + \mu\cos(\Delta\omega t),$$

where ω is the carrier frequency of the field; $\Delta\omega$ is the modulation frequency; μ is the modulation index; E_0 is the electromagnetic field amplitude; $\boldsymbol{e}$ is the complex polarisation unit vector; and $k = \omega/c$. The carrier frequency ω is near resonance with the $^2S_{1/2}$ ($F = 1$) → $^2P_{1/2}$ ($F = 0$) optical transition, and the modulation frequency is near resonance with the fundamental harmonic of the $^2S_{1/2}$ ($F = 0$) → $^2P_{1/2}$ ($F = 1$) optical transition, which should prevent accumulation of atoms in the $^2S_{1/2}$ ($F = 0$) state (Fig. 1a). Of particular interest in the problem under consideration is to find out how laser cooling parameters depend on optical field parameters (intensity, modulation frequency $\Delta\omega$ and frequency modulation index μ) and compare the results with those of a classic model for laser cooling on the $F = 1$ → $F = 0$ closed transition in a monochromatic field.

2. Methods and approaches

In our analysis, we will use the quasi-classical approximation, in which the recoil energy that an ion obtains in single events upon interaction with field photons is taken to be low compared to the radiation width of the excited-state level and the ratio of the width of the momentum distribution of atoms, Δp, to the photon momentum, $\hbar k/\Delta p \ll 1$, is taken to be sufficiently large [20–24]. Indeed, for the optical transition under consideration, these conditions are well satisfied in the case of the laser cooling of $^{171}Yb^+$ ions [$\hbar k^2/(2m\gamma) \approx 0.001$, where γ is the natural linewidth of the transition].

In the quasi-classical approach, the equation for the atomic density matrix $\hat{\rho}$,

$$\frac{\partial\hat{\rho}}{\partial t} = \frac{-\mathrm{i}}{\hbar}[\hat{H},\hat{\rho}] + \hat{\Gamma}\{\hat{\rho}\} \qquad (2)$$

(where $\hat{H}$ is the Hamiltonian of the system and $\hat{\Gamma}\{\hat{\rho}\}$ describes the relaxation of the atomic density matrix in spontaneous photon emission processes), can be reduced to the Fokker–Planck equation for the atomic distribution function in phase space, $W(r,p) = \mathrm{Tr}\{\hat{\rho}(r,p)\}$:

$$\left(\frac{\partial}{\partial t} + \frac{p}{M}\frac{\partial}{\partial r}\right)W = -\frac{\partial}{\partial p}F(r,p)\,W + \frac{\partial^2}{\partial p^2}D(r,p)\,W. \qquad (3)$$

Here F is the force acting on an atom; D is the diffusion coefficient; and M is the ion mass. This procedure and the applicability area of the quasi-classical approach are sufficiently well described in the literature [21, 22] for interaction of atoms with a monochromatic field. A distinctive feature of the problem under consideration is the presence of additional cooling-field harmonics, which requires that the procedure for deriving expressions for rate coefficients in the Fokker–Planck equation be modified. Let us describe the key points of this procedure. To this end, we consider a one-dimensional model for the motion of an ion in the potential of an ion trap,

$$U(x) = M\omega_{\mathrm{sec}}^2x^2/2, \qquad (4)$$

in the resonance laser field (1) in the presence of a magnetic field $\boldsymbol{B}$. The Hamiltonian of the system under consideration is,

$$\hat{H} = \hat{p}^2/(2M) + \hat{H}_0 + \hat{V} - \hat{\mu}\boldsymbol{B} + \hat{U}, \qquad (5)$$

where $\hat{V}$ is the operator of interaction with the laser field and $\hat{H}_0$ is the Hamiltonian of a free atom in a rotating basis (in energy pseudospin space) in matrix form:

$$\hat{H}_0 = [\varDelta_{\mathrm{e1e2}} + \varDelta_{\mathrm{g1g2}} - \delta - \mathrm{i}\mu\varphi(t)]\hat{\Pi}_{\mathrm{e1}}$$

$$+ [\varDelta_{\mathrm{g1g2}} - \delta - \mathrm{i}\mu\varphi(t)]\hat{\Pi}_{\mathrm{e2}} + \varDelta_{\mathrm{g1g2}}\hat{\Pi}_{\mathrm{g1}}. \qquad (6)$$

Here, $\delta = \omega - \omega_0$ is the detuning of the carrier frequency of field (1) from the frequency ω_0 of the $^2S_{1/2}$ ($F = 1$) → $^2P_{1/2}$ ($F = 0$) atomic transition; $\varDelta_{\mathrm{g1\,g2}}$ = 12.643 GHz and $\varDelta_{\mathrm{e1\,e2}}$ = 2.105 GHz are determined by the hyperfine splitting of the $^2S_{1/2}$ and $^2P_{1/2}$ levels; and $\varphi(t) = \Delta\omega \times [\exp(\mathrm{i}\Delta\omega t) - \exp(-\mathrm{i}\Delta\omega t)]/2$; $\hat{\Pi}_{\mathrm{e1}} = |^2P_{1/2}, F = 1\rangle\langle^2P_{1/2}, F = 1|$, $\hat{\Pi}_{\mathrm{e2}} = |^2P_{1/2}, F = 0\rangle\langle^2P_{1/2}, F = 0|$ and $\hat{\Pi}_{\mathrm{g1}} = |^2S_{1/2}, F = 1\rangle\langle^2S_{1/2}, F = 1|$ are the projectors on the states corresponding to the $|\mathrm{e1}\rangle = |^2P_{1/2}, F = 1\rangle$, $|\mathrm{e2}\rangle = |^2P_{1/2}, F = 0\rangle$ and $|\mathrm{g1}\rangle = |^2S_{1/2}, F = 1\rangle$ levels of the optical transition under consideration (Fig. 1a).

In the dipole approximation, the operator of interaction with field (1) has the form

$$\hat{V}^{\mathrm{e}_i\mathrm{g}_j} = \varOmega\sum_q \hat{T}_q^{\mathrm{e}_i\mathrm{g}_j}e^q, \qquad (7)$$

where $\Omega = \gamma\sqrt{I/(8I_{sat})}$ is the Rabi frequency $I_{sat} \approx$ 59.4 mW cm^{-2} is the saturation intensity for the $^2S_{1/2} \to {}^2P_{1/2}$ optical transition; e^q is the qth component of the field polarisation vector $\boldsymbol{e}$ in the circular basis; and

$$\hat{T}^{e_i g_j}_{q\mu,m} = \sqrt{(2J_{e_i}+1)(2F_{e_i}+1)}\begin{Bmatrix} J_{g_j} & J_{e_i} & 1 \\ F_{e_i} & J_{g_j} & I_s \end{Bmatrix} C^{F_{e_i,\mu}}_{g_j m;1,q} |e_i\rangle\langle g_j|$$

are the matrix elements ($\hat{T}^{e_i g_j}_q$ operators) expressed through Clebsch–Gordan coefficients and $6j$ symbols.

Like in the case of laser cooling in a monochromatic field, the expressions for the force and diffusion coefficient (3) can be written using the force operator $\hat{F}$ and matrix $\hat{\sigma}$ (see e.g. Refs [20–22]):

$$F(r,p) = \mathrm{Tr}\{\hat{F}\hat{\sigma}(r,p)\}, \qquad (8)$$

where the force operator is given by

$$F(r,p) = \mathrm{Tr}\{\hat{F}\hat{\sigma}(r,p)\},$$

and the $\hat{\sigma}$ matrix is a pseudostationary solution to the optical Bloch equation, i.e. to equation (2), with recoil effects neglected, which can formally be written in the form

$$v\frac{\partial\hat{\sigma}}{\partial z} = \hat{L}\{\hat{\sigma}\}, \qquad (9)$$

with the normalisation condition $\mathrm{Tr}\{\hat{\sigma}\} = 1$. Note that, in the case of the travelling wave (1) under consideration, the force acting on an ion is a spontaneous light pressure force, proportional to the total population of the $^2P_{1/2}$ ($F = 0$) and $^2P_{1/2}$ ($F = 1$) levels:

$$F = \gamma\hbar k\mathrm{Tr}\{(\hat{\Pi}_{e1} + \hat{\Pi}_{e2})\hat{\sigma}\}.$$

The diffusion coefficient

$$D = D^{(s)} + D^{(i)}$$

can be separated into contributions related to ion momentum fluctuations in spontaneous photon emission processes ($D^{(s)}$) and induced field photon absorption and emission processes ($D^{(i)}$). The spontaneous diffusion coefficient $D^{(s)}$ for the field configuration under consideration is proportional to the atomic population in the $^2P_{1/2}$ excited state:

$$D^{(s)} = \hbar^2 k^2 \mathrm{Tr}\{(\hat{\Pi}_{e1} + \hat{\Pi}_{e2})\hat{\sigma}\}/10. \qquad (10)$$

The induced diffusion coefficient is

$$D^{(i)} = -\mathrm{Tr}\{\hat{F}\hat{\eta}\}, \qquad (11)$$

where the $\hat{\eta}$ matrix is a solution to a modified Bloch equation with a source which is the anticommutator of the force fluctuation operator $\delta F = \hat{F} - F$ and matrix $\hat{\sigma}$,

$$v\frac{\partial\hat{\eta}}{\partial z} = \hat{L}\{\hat{\eta}\} - \frac{1}{2}\{\delta F, \hat{\sigma}\}, \qquad (12)$$

with the normalisation condition $\mathrm{Tr}\{\eta\} = 0$. Even though the expressions for the force and diffusion coefficients (8)–(12) are formally similar to those in the well-developed quasi-classical theory of laser cooling in a contribution field, there is a fundamental distinction in that the $\hat{L}$ operator is time-dependent [because so is the Hamiltonian $\hat{H}_0$ (6)], and this determines the time dependence of the solutions for the $\hat{\sigma}$ and $\hat{\eta}$ matrices. To find steady-state periodic solutions to Eqns (9) and (12), the $\hat{\sigma}$ and $\hat{\eta}$ matrices can be represented as a set of harmonics,

$$\hat{\sigma} = \sum_n \hat{\sigma}^{(n)}\exp(-\mathrm{i}\Delta\omega t), \quad \hat{\eta} = \sum_n \hat{\eta}^{(n)}\exp(-\mathrm{i}\Delta\omega t),$$

whose amplitudes can be found numerically by the method of continued fractions [23–25], which in turn allows us to find the light pressure force and diffusion coefficient for determining the distribution function of ions in the trap, $W(z,p)$ (3).

3. Calculation results

Figure 2 shows the light pressure force and diffusion coefficient as functions of the ion velocity in a trap. Note that, at zero velocity, there is a nonzero light pressure force, which shifts the ion from its equilibrium position in potential (4). A necessary condition for laser cooling is the presence of a magnetic field, which makes it possible to destroy dark (because of the coherent population trapping) states [26, 27] at the $|^2S_{1/2}, F = 1\rangle$ level. Figure 3 shows the distribution function of ions in the trap, W, at the field parameters represented in Fig. 2.

The momentum and coordinate distribution functions obtained here (Fig. 3) are well represented by Gaussians, $W(p) = A_p\exp[-p^2/(2\sigma_p^2)]$ and $W(x) = A_x\exp[-x^2/(2\sigma_x^2)]$, with σ_x = 0.05 μm and $\sigma_p = 29.6\hbar k$, which corresponds to an ion temperature in the trap $k_BT = 0.64\hbar\gamma$ ($T = 0.71$ mK).

Of particular interest for the laser cooling of ions is to optimise the parameters of the optical field (1) in order to obtain the lowest temperature and, hence, the smallest confinement region of atoms in the trap.

Figure 4 shows the laser cooling temperature as a function of the parameters Ω and δ for the $^{171}Yb^+$ ion in an RF trap at a varied modulation index μ. Minimum laser cooling temperatures $k_BT/(\hbar\gamma) = 1.8$ (at $\mu = 0.02$), $k_BT/(\hbar\gamma) = 3.9$ ($\mu = 0.05$) and $k_BT/(\hbar\gamma) = 1.2$ ($\mu = 0.1$) are ensured by the following optimal field parameters: $\Omega^*/\gamma = 19.5$ and $\delta^*/\gamma = -0.55$ (at μ = 0.02), $\Omega^*/\gamma = 19$ and $\delta^*/\gamma = -1.9$ ($\mu = 0.05$) and $\Omega^*/\gamma = 1.2$ and $\delta^*/\gamma = -0.6$ ($\mu = 0.1$).

Note that, at low μ values, the temperature reaches a minimum at higher optical field intensities. The minimum possible laser cooling temperature then exceeds the Doppler limit [$(k_BT_D/(\hbar\gamma) \approx 0.5$] by several times. At $\mu = 0.05$ or above, there is an additional region of field parameters (at low $\Omega \approx \gamma$ and detunings $\delta \approx -\gamma/2$), which contains an additional local minimum in ion temperature. For $\mu \geqslant 0.1$, the global minimum in laser cooling temperature is located in this region of field parameters and reaches values near the Doppler limit (Fig. 5a). Note that this region corresponds to the region of optimal parameters in the classic model for laser cooling in a monochromatic field resonant with the $F_g = 1 \to F_e = 0$ optical transition if we neglect optical pumping to neighbouring hyperfine splitting components (Fig. 5).

It follows from Fig. 5 that the optimal field parameters are $\Omega^*/\gamma = 1.1$, $\delta^*/\gamma = -0.55$ and $k_BT/(\hbar\gamma) = 0.62$ (at $\mu = 0.02$) (Fig. 5a) or $\Omega^*/\gamma = 1.1$, $\delta^*/\gamma = -0.52$ and $k_BT/(\hbar\gamma) = 0.58$ (Fig. 5b). The above analysis leads us to conclude that the cooling of the $^{171}Yb^+$ ion in a frequency-modulated field to

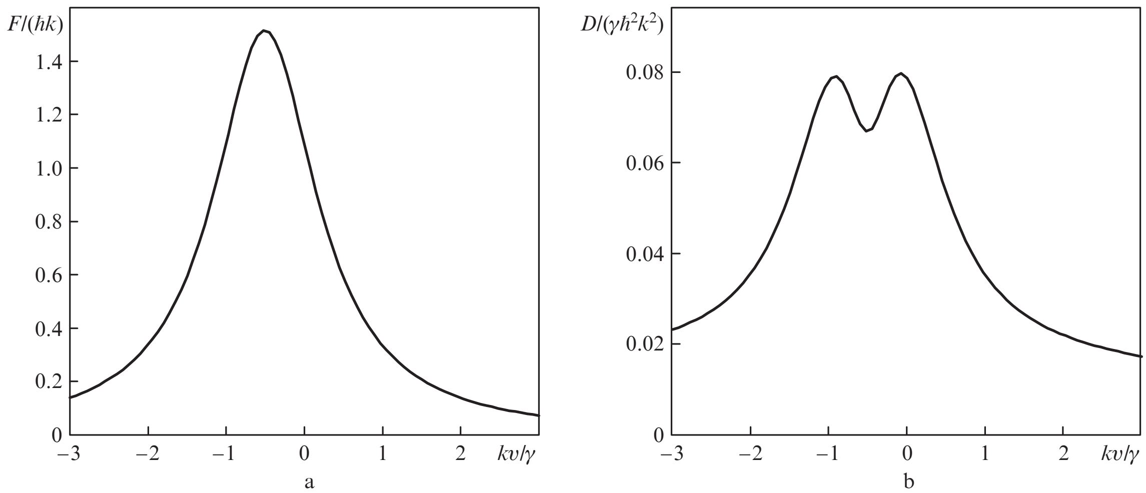

Figure 2. (a) Light pressure force and (b) diffusion coefficient as functions of the dimensionless velocity of the $^{171}Yb^+$ ion in a trap at a Rabi frequency $\Omega = 1\gamma$, frequency detuning $\delta = -\gamma/2$, modulation amplitude $\mu = 0.2$ and modulation frequency $\Delta\omega = \Delta_{g1\,g2} + \Delta_{e1\,e2}$. The magnetic field, H = 10 G, is directed vertically (Fig. 1b), and the electromagnetic field is linearly polarised at 45° to the magnetic field.

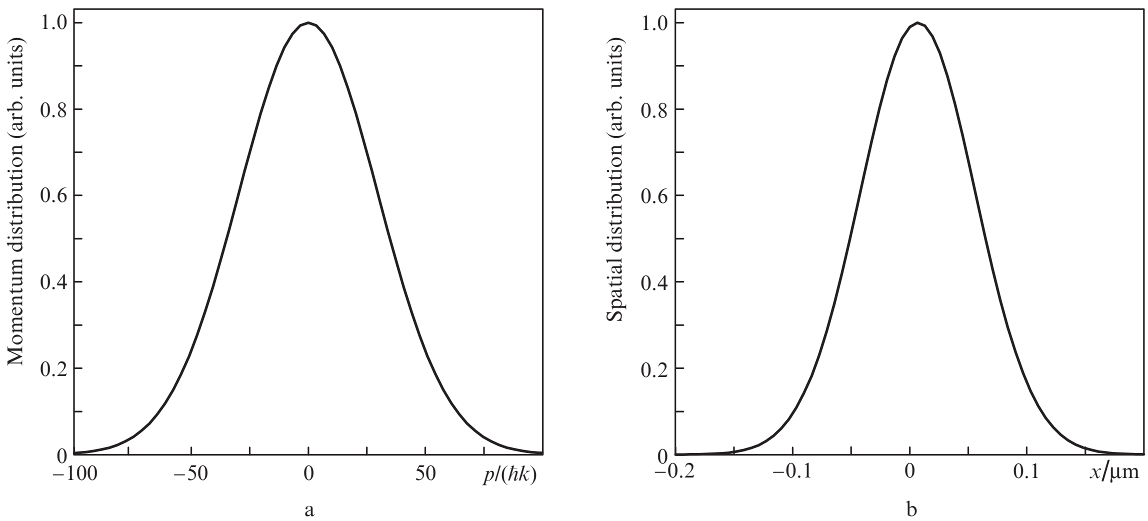

Figure 3. (a) Momentum and (b) coordinate distribution functions of the $^{171}Yb^+$ ion in a trap (ω_{sec} = 0.6 MHz). The field parameters correspond to Fig. 2.

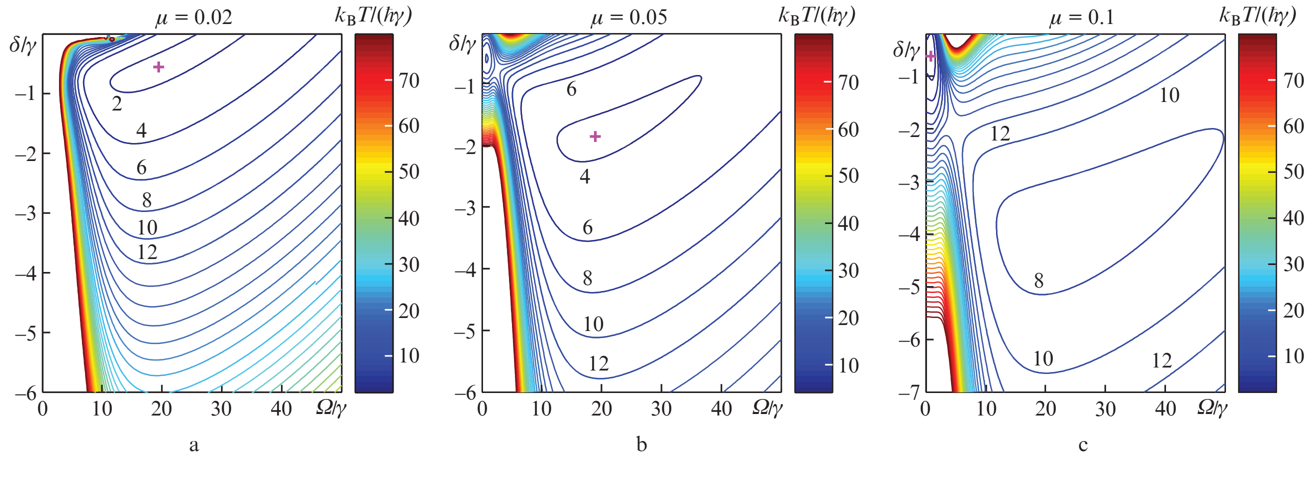

Figure 4. (Colour online) Contour plots of the ion temperature (in units of $\hbar\gamma$) vs. field parameters Ω and δ at different modulation indices μ (modulation frequency $\Delta\omega = \Delta_{g1\,g2} + \Delta_{e1\,e2}$). The magnetic field, H = 10 G, is directed vertically (Fig. 1b), and the electromagnetic field is linearly polarised at 45° to the magnetic field. The position of the global minima in the laser cooling temperature is marked by crosses.

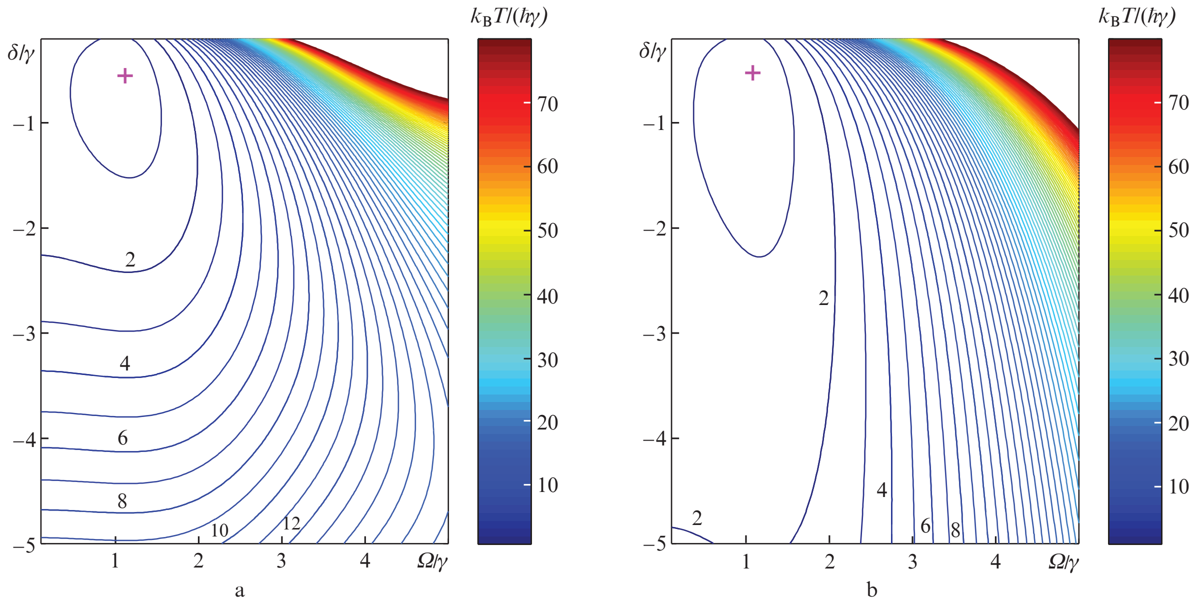

Figure 5. (Colour online) Contour plots of the ion temperature (in units of $\hbar\gamma$) vs. field parameters Ω and δ (a) at a large modulation index (μ = 0.2) (modulation frequency $\Delta\omega = \Delta_{\mathrm{g1\,g2}} + \Delta_{\mathrm{e1\,e2}}$) and (b) in a classic model for laser cooling in a monochromatic field resonant with the $F_g = 1 \to F_e = 0$ optical transition. The magnetic field, H = 10 G, is directed vertically (Fig. 1b), and the electromagnetic field is linearly polarised at 45° to the magnetic field. The position of the global minima in the laser cooling temperature is marked by crosses.

the Doppler limit temperature is possible for $\mu \geqslant 0.1$, where the population of the μ level is small. At lower $^2P_{1/2}$ (F = 0) values, the region of parameters at which the minimum laser cooling temperature can be reached shifts to higher intensities and the laser cooling temperature considerably increases.

4. Experimental

The fluorescence signal of cold atoms in a trap can be represented as the convolution of the population of excited states, $\pi_e = \mathrm{Tr}\{\hat{\Pi}_{e1}\hat{\sigma} + \hat{\Pi}_{e2}\hat{\sigma}\}$, and the velocity distribution function $W(v)$:

$$S(\delta) = A\int \pi_e(\delta, v)\, W(v)\,\mathrm{d}v + B, \tag{13}$$

where the coefficient A determines signal detection efficiency and B is the photodetector background signal.

The trapping and spatial confinement of single ions were ensured by an open RF quadrupole trap (endcap trap [28]), and a trapped ion was cooled using frequency-modulated light (1) at a wavelength of 369.5 nm, obtained as frequency-doubled radiation from a semiconductor laser operating at a wavelength of 739 nm [29]. The frequency was doubled using a $BiBO_3$ crystal inserted in a ring cavity (finesse $F_{\mathrm{fin}} \sim 400$; free spectral range FSR ~ 750 MHz), which also served as a reference cavity for laser frequency stabilisation. In addition, the output of the diode laser was modulated by an electro-optical modulator at a frequency of 14.75 GHz for the generation of spectral components capable of exciting a hyperfine component of the $^2S_{1/2}$ (F = 0) → $^2P_{1/2}$ (F = 1) cooling transition, which was not excited by the resonant cooling light. The free spectral range of the ring cavity was chosen such that the modulation and carrier frequencies were in resonance with its longitudinal modes. The fluorescence of the ytterbium ion (Fig. 6) induced by the cooling laser was projected by a multilens objective onto a photomultiplier and CCD camera [30]. The image in the camera was used to determine the number of trapped particles and monitor the ion position in the trap.

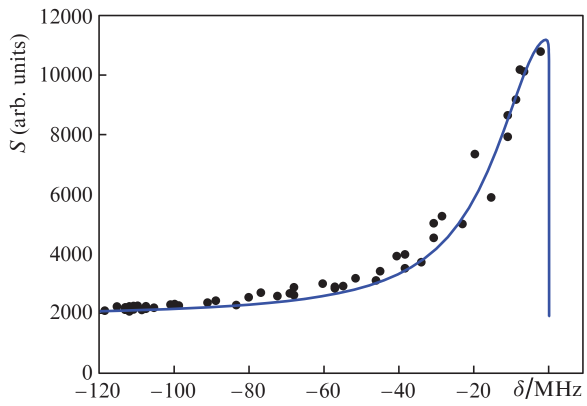

Figure 6. Photomultiplier signal as a function of frequency detuning at a cooling field power in the beam P = 15 μW. The solid line represents a fit to the theoretical model (12).

The laser beam diameter in the ion cooling region was ~40 μm. At the beam power chosen, P = 15 μW, the Rabi frequency is $\Omega \approx 0.8\gamma$, which is near the optimal optical field intensity for laser cooling. The sharp decay of the fluorescence signal near zero detuning is due to the increase in ion temperature and the impossibility of ion trapping and cooling for $\delta > 0$.

5. Conclusions

We have investigated the laser cooling of the $^{171}Yb^+$ ion in an RF trap under the effect of a frequency-modulated laser field resonant with the $^2S_{1/2} \to {}^2P_{1/2}$ optical transition (λ = 370 nm), which has hyperfine components. The fundamental frequency of the field is in resonance with the $^2S_{1/2}$ ($F = 1$) → $^2P_{1/2}$ ($F = 0$) optical transition, and the first sideband, with the $^2S_{1/2}$ ($F = 0$) → $^2P_{1/2}$ ($F = 1$) transition. The laser cooling temperature has been analysed as a function of optical field parameters. The results demonstrate that laser cooling temperatures close to the Doppler limit can be reached at field modulation parameters $\mu \geqslant 0.1$. At lower μ values, optical pumping of the $^2S_{1/2}$ ($F = 0$) level is significant, raising the minimum possible laser cooling temperature.

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