Optics Communications 312 (2014) 192–198

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

All-optical trapping of strongly coupled ions

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ARTICLE INFO

Article history:
Received 15 July 2013
Received in revised form
7 September 2013
Accepted 16 September 2013
Available online 27 September 2013

Keywords:
Optical trap
Ion trap
Rectified gradient force
Coulomb clusters

ABSTRACT

We present and analyze a novel method of long-time ion trapping. This purely optical method is based on the action of rectified gradient forces on the ions in a 3D dissipative polychromatic optical superlattice which allows one to form super-deep potential wells for the ions. The ion trap presented ensures the possibility of long-time confinement both of single ions and small ordered ensembles of strongly coupled ions, i.e. ion (Coulomb) clusters. We demonstrate, by the numerical simulations of stochastic ion motion, the trapping of two-ion clusters for times exceeding several seconds.

1. Introduction

Ion traps have intensively been studied for many years. This interest is explained by their numerous important applications [1]. Many physical applications are associated with the possibility of forming long-lived ion (Coulomb) clusters in such traps [2].

Along with their undeniable advantages, conventional ion traps have a number of drawbacks due to there being unwanted types of ion motion: this is a radio-frequency driven micromotion in a Paul trap and a magnetron motion in a Penning trap [1].

Recent publications [3,4] have presented convincing evidence for the perspective development of purely optical methods of ion confinement which do not have the above-mentioned drawbacks. Moreover, in [3] an experiment was made where a single $^{24}Mg^{+}$ ion was confined in a monochromatic optical dipole trap (ODT) for several ms. In this experiment use is made of the gradient optical force [5] which was usually applied only for neutral particle trapping. The peculiarity of monochromatic ODT is a relatively shallow depth ΔW of light-induced potential wells. It is determined by the value of the light (Stark) shift of the atomic energy levels $\hbar\Delta_s$: $\Delta W \sim \hbar\Delta_s$. The depth ΔW which can usually be obtained in experiments with atoms in ODT is in the mK range. In the experiment in [3] owing to the laser field of high intensity ($>10^5$ W/cm^2) ΔW-value of 38 mK was achieved. The shallow depth of ODT can be a serious obstacle in using ODT for ion cluster trapping due to the strong Coulomb repulsion of the ions. For example, the Coulomb energy of two ions separated by the distance of 100 μm is approximately equal to 167 mK.

An alternative method for solving the problem of all-optical trapping, the confinement of ions in a so-called 3D polychromatic optical superlattice (OSL) [6,7] was suggested in [7]. The present paper is devoted to the theoretical substantiation and development of this idea. The action of the polychromatic OSL on ions is based on the effect of the gradient force rectification [8–10]. The rectified gradient force (RcGF) has the order of magnitude of the gradient force F_g in a monochromatic standing wave [5]: $F_g \sim 2\pi\hbar\Delta_s/\lambda$, but oscillates in space with the period L greatly exceeding the light wavelength λ: $L > \lambda$. Therefore, polychromatic OSL is capable of inducing 3D super-deep (as compared to ODT) potential wells [11,12] with the values of depth $\Delta W \sim \hbar\Delta_s L/\lambda \gg \hbar\Delta_s$. Moreover, the ions in such OSL are acted upon by considerable light-induced viscous friction force resulting in ion cooling.

We show that these properties of OSL allow long-time confinement of the strongly coupled ions in a single OSL cell. By numerical simulations of the light-induced dynamics of ions in OSL, we demonstrate the possibility of long-time confinement of a stable two-ion cluster during the time period exceeding a few seconds. Such a long-lived localized ion (Coulomb) cluster is observed under the following conditions (T and U_c are the effective temperature (in energy units) and energy of the Coulomb repulsion of the ions, respectively):

$$\frac{\Delta W}{T} \sim \frac{U_c}{T} \gg 1, \tag{1}$$

which are achieved at moderate optical field intensities ~ 1 W/cm^2.

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http://dx.doi.org/10.1016/j.optcom.2013.09.036

2. Model

2.1. Optical forces

We consider an ensemble of N identical ions with a tripod configuration of the energy levels which are located in the 3D polychromatic OSL [6,7]. The light field (with a complex amplitude $\mathbf{E}$) forming the OSL is a superposition of three color coherent "far-off-resonant" fields and a partially coherent (fluctuating) resonant field $\mathbf{E}'$ with the bandwidth Γ:

$$\mathbf{E}(\mathbf{r},t)=\sum_{j\in\{x,y,z\}}\mathbf{e}_j(E_{j1}(\mathbf{r})\exp[-i\Delta_j t]+E_j'(\mathbf{r},t)), \quad (2)$$

where $\mathbf{e}_j$ denotes the unit basis vectors of the Cartesian coordinate system, $j\in\{x,y,z\}$, $\omega_0\gg\Delta_j$, $E_j=(\mathbf{e}_j\mathbf{E}_j)$ which are subject to the conditions

$$\Delta_j,\ |\Delta_j-\Delta_i|\gg\Gamma\gg\frac{|\hat V_{j1}|^2}{\Delta_j},\ \frac{|\hat U_j|^2}{\Gamma},\ \gamma,\ ks. \quad (3)$$

Here, $\hat V_{j1}=dE_{j1}^*/\hbar$, $\hat U_j=dE_j^{'*}/\hbar$ are the Rabi frequencies, $d=\|d\|/\sqrt{3}$, $\|d\|$ is the reduced dipole transition matrix element, $k=\omega_0/c$ is the wave number, s is the thermal velocity of ions, $\gamma=\gamma'/3$, γ' is the rate of the spontaneous decay of an excited state. We assume that the light field drives the closed dipole transition $|F_b=0,M_b=\pm1\rangle\to|F_a=0,M_a=0\rangle$ where F_α and M_α are the full angular momentum and its projections for the ground ($\alpha=b$) and excited ($\alpha=a$) internal ionic states respectively. Since the light field is represented by superposition of linearly polarized waves (Eq. (2)), it is convenient to use the "Cartesian" basis states (of intra-ionic motions): $|x\rangle=(|1,-1\rangle-|1,1\rangle)/\sqrt{2}$, $|y\rangle=-i(|1,-1\rangle+|1,1\rangle)/\sqrt{2}$, $|z\rangle=|1,0\rangle$, $|a\rangle=|0,0\rangle$, for which the matrix elements of the dipole moment $\hat{\mathbf{d}}$ are directed along the unit vectors of Cartesian coordinate system [6,7]

$$\langle bj|\hat{\mathbf{d}}|a\rangle=\mathbf{e}_j d,\quad j\in\{x,y,z\}.$$

The relevant energy levels (in a tripod configuration) and coupling fields are shown in Fig. 1.

It comes from (3) that the coherent "far-off resonant" components of the field induce the light (Stark) shifts of the ionic energy levels, and the fluctuating field $\mathbf{E}'(\mathbf{r},t)$ provides incoherent excitation of the ions (their redistribution over the quantum states) [7]. The particular configurations of the fields E_{j1} and E_j' and the mechanism of the RcGF appearance are described in detail in [6,7]. Here, it is important to note the following key points.

The components E_j' of the partially coherent field fluctuate independently of each other (i.e. can be formed by different radiation sources).

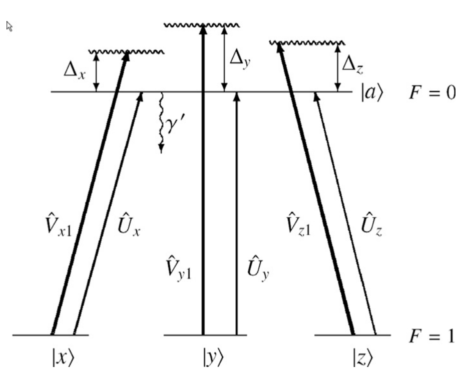

Fig. 1. Schematic diagram of a four-level tripod-type ion in a polychromatic field. The levels $|i\rangle$ and $|a\rangle$ (here and below $i\in\{x,y,z\}$) are coupled by the fields polarized along the i-axis. $\hat V_{i1}$ and $\hat U_i$ are the relevant Rabi frequencies for "far-off-resonant" and resonant field components, Δ_i are the detunings from the resonant frequency ω_0, γ' is the decay rate of an exited state $|a\rangle$.

According to the concept of the gradient force rectification [8,9] the fields E_{1j} and E_j' are non-uniform, i.e. include the plane-wave components capable of interfering with each other.

The frequency Ω_j' of the spatial modulation (along the j-axis) of the population differences (between the internal ionic states) induced by the field E_i' is close to the spatial frequencies $\Omega_j\sim\lambda^{-1}$ of the $|V_i(\mathbf{r})|^2\Delta_i$ oscillations[1]: $\delta\Omega_i=\Omega_j'-\Omega_j\ll\Omega_j',\Omega_j$ (where the index $j=y$ for $i=x$, $j=x$ for $i=z$, $j=z$ for $i=y$). The OSL periods L_j ($j\in\{x,y,z\}$) are determined by the spatial beat frequencies: $L_j=1/\delta\Omega_j$. Note that three spatial periods L_x, L_y, L_z can be controlled independently.

For the particular field configuration considered in [6,7] RcGFs can be presented by the following expressions:

$$\mathbf{F}_R=\mathbf{F}_{0R}+\mathbf{F}_{1R},\quad \mathbf{F}_{1R}=-m\sum_{j\in\{x,y,z\}}\varkappa_j(r_j)v_j\mathbf{e}_j,$$

$$\mathbf{F}_{0R}=-\nabla U_R,\quad U_R=-\sum_{j\in\{x,y,z\}}U_{jR}\cos\left(\frac{2\pi}{L_j}r_j\right),$$

$$U_{jR}=\hbar\gamma\frac{L_j}{\lambda}\frac{a_1G_i}{(1+b)}A(\chi),\quad A(\chi)=\frac{2\chi+1}{(4\chi+3)^2},$$

$$\varkappa_j(r)=\frac{2(6\chi^2+8\chi+3)}{(4\chi+3)^3\chi}\frac{a_1G_i}{(1+b)}\omega_R\left[b-\cos\left(\frac{2\pi}{L_j}r\right)\right], \quad (4)$$

where m is the ionic mass, $\omega_R=\hbar k^2/m$ is the recoil frequency $G_i=V_i^2/\Delta_i\gamma=I_i\gamma/I_s\Delta_i$, V_i are the amplitudes of the local Rabi frequencies $\hat V_i(r)$, I_i is the intensity of the light waves forming the field components $E_{i1}\mathbf{e}_i$, $I_s=\hbar\omega_0k^2\gamma/6\pi$ is the intensity of the optical radiation saturating the quantum transition, $r_j=(\mathbf{e}_j\mathbf{r})$, $v_j=(\mathbf{v}\mathbf{e}_j)$, $\mathbf{v}$ is the ion velocity, $\varkappa_j=\varkappa_j(r_j)$ are the friction coefficients, $\chi=R/\gamma$, $R\approx U^2/\Gamma$ is the rate of the transitions between the low-lying and excited ionic states, induced by the field $\mathbf{E}'$, U is the amplitude of the Rabi frequencies $\hat U_j$, b and $a_1<1$ are the independent parameters determined by relative amplitudes of the plane waves which form the field $\mathbf{E}'$ and characterize the spatial modulation of the population differences between internal ionic states. Eqs. (4) are valid in the semi-classical limit [5] and in the approximation of slow ions

$$ks<\gamma,\ \gamma\chi. \quad (5)$$

Thus, one can see from (4) that the force $\mathbf{F}_{0R}$ creates the periodic array of the potential wells (i.e. OSL) [7] and the force $\mathbf{F}_{1R}$ is the friction force (if the parameter $b>1$) and provides the ion cooling. The advantage of the considered model of the 3D OSL is the presence of numerous free parameters of the model which can be chosen independently: χ, G_i, L_i, $i\in\{x,y,z\}$, b. This allows modeling various modes of the RcGF action on ions. It is also worth noting that the action of the 3D OSL on the ions is equivalent to the action of three independent 1D OSLs.

For the correct modeling of the ion dynamics in OSL it is necessary that account should be taken of the fluctuations of the optical forces resulting in the ion velocity diffusion [5,12]. In the considered model of the dissipative OSL they can be described by the diffusion coefficients [7]

$$D_j=D_{s1}+D_1+D_{jR},\quad j\in\{x,y,z\},$$

$$D_{s1}=\left(\frac{\hbar k}{m}\right)^2\frac{\gamma\chi}{(4\chi+3)2},\quad D_1=\left(\frac{\hbar k}{m}\right)^2\gamma\frac{\chi(4\chi+2)}{(4\chi+3)4},$$

$$D_{jR}=\left(\frac{\hbar k}{m}\right)^2\gamma\frac{8\chi^3+16\chi^2+11\chi+3}{(4\chi+3)^3\chi}G_i^2, \quad (6)$$

where D_{s1} is the diffusion coefficient conditioned by the recoil at spontaneous transitions, D_1 is the coefficient of the diffusion connected with the action of the fluctuating field $\mathbf{E}'$ on the ions,

[1] The light (Stark) shifts are determined by the linear combinations of the functions $|V_i(\mathbf{r})|^2/\Delta_i$.