Simulation of Dipole-Dipole Interactions With Ultracold Sr in an Optical Lattice

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***Abstract*—We theoretically study dipole-dipole interactions on $^3P_0$-$^3D_1$ with ultracold Sr atoms in a deep optical lattice. To prepare such a dense atomic sample, Bose-Einstein condensates (BEC) will be performed and subsequently are loaded into a Mott insulator by increasing the optical potential. Here, we calculate the important properties of Sr dipole-dipole interactions based on the coupled dipole model and also show the setup for the preparation of the Sr sample. Both simulation results and the feasibility of experiments indicate that lattice-based Sr atoms is an excellent candidate for studying dipole-dipole interactions.**

Keywords—Dipole-dipole interactions; Ultracold Sr atoms; Bose-Einstein condensates；Optical lattice

I. Introduction

As the development of laser cooling techniques, the exploration of many-body systems featuring dipole dipole interactions has been boosted and there have been intensive theoretical and experimental works [1-4]. The study on dipole dipole interactions is currently concentrated on Rydberg atoms[5-8], atoms with large magnetic dipole moment[9,10] or polar molecules[11]. Recently, the platform based on alkaline earth metal atoms has been proposed[12], where a weak laser is applied to couple atoms confined in a blue-detuned optical lattice. In the case of bosonic Sr, the transition of $^3P_0$-$^3D_1$ has a long wavelength 2.6 μm and the magic wavelength for it is 412.8 nm, which makes it easy to satisfy the condition of dense atomic sample by confining atoms in a deep optical lattice. Additionally, this transition has a large electronic dipole moment 4.03 D, which effectuates a strong resonant dipole-dipole interaction that extends over several lattice sites.

Here we theoretically study the dipole dipole interactions for Sr atoms in a 10×10 optical lattice. We did some simulations, based on the coupled dipole model, to see the properties, such as the frequency shifts, linewidth broadening and intensity suppression. We find that the properties of dipolar interactions become prominent while d is reduced to less than $3a$. We also see that the interatomic distance where the peak intensity occurs moves towards smaller values with the suppressed peak intensity as the laser frequency detuning increases.

Furthermore, we present a setup which will be used to prepare dense ultracold Sr atoms in the near future. The setup consists of MOT with both 461 nm blue beams and 689 nm red beams, optical dipole trap by crossed beams at 1064 nm, and two-dimensional optical lattice with the magic wavelength of 412.8 nm. After the red MOT cooling, we have got the cold atoms featuring the temperature of 1 μK and the atom number of 10^8. The BEC experiment is now smoothly ongoing. Our simulation results and the feasibility of experiments show that lattice-based Sr atoms provide another platform to study dipole dipole interactions.

II. Schematics of Setup

The setup is based on [13] shown in Fig. 1. To prepare ultracold dense sample, the pre-cooled atoms by MOT will be further cooled down to BEC in an optical dipole trap consisting of two crossed beams at 1064 nm. Once BEC is achieved, the ensemble will be transferred to a two-dimensional optical lattice, which is formed by 412.8 nm blue lasers, and finally trapped in Mott insulators with a spacing a. The 10×10 optical lattice is zoomed in shown in Fig. 1 (b). Each atom can be seen as a two-level system with ground state $^3P_0$ and excited state $^3D_1$. Atoms are coupled by dipole dipole interactions V. While the sample is prepared, a probe beam at 2.6 μm polarized along z axis will shine the ensemble to induce dipole dipole interactions which will be detected by a camera. The simplified level structure of Sr is shown in Fig. 1 (a). The two transitions of 461 nm and 689 nm are for MOT cooling. The laser at 698 nm will be used to pump atoms from ground state to $^3P_0$ state for the preparation of dipole dipole interactions. The probe laser at 2.6 μm is employed to drive the interactions between atoms.

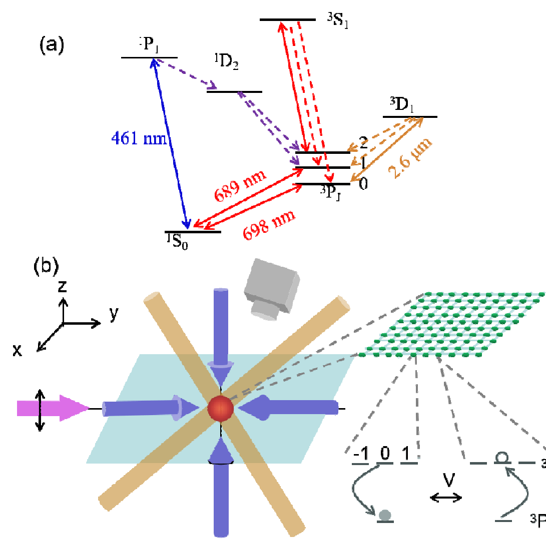

Fig. 1. (a) A simplified electronic level structure of Sr. Two transitions of 461 nm and 689 nm are for MOT; Dipole dipole interactions are induced at

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the transition of 2.6 μm. (b) Schematic of experimental setup. The atoms are trapped in an optical dipole trap consisting of 1064 nm crossed-beams (brown cylinders), and then transferred to a blue-detuned optical lattice (blue arrows). A probe beam at 2.6 μm (orchid) polarized along z axis is propagating along y axis to shine the ensemble. The ensemble is zoomed in to a 10×10 optical lattice. Each atom can be seen as a two-level system and they're coupled by dipole-dipole interactions *V*.

III. SIMULATION RESULTS

We use the coupled dipole model to govern the evolution of the density matrix ρ for an ensemble of N atoms. The master equation is given by $\dot{\rho} = -\frac{i}{\hbar}[H,\rho] + D(\rho)$, where $H = \hbar\omega_\alpha \sum_{i,\alpha} \hat{b}_i^{\alpha+} \cdot \hat{b}_i^{\alpha} + \hbar \sum_{i\neq k} \hat{b}_i^{\alpha+} \cdot \overline{V_{ik}} \cdot \hat{b}_k^{\alpha}$, $D(\rho) = \sum_{ik} \hat{b}_i^{\alpha} \cdot \overline{\Gamma_{ik}} \cdot \rho \hat{b}_k^{\alpha+} - \frac{1}{2}\{\hat{b}_i^{\alpha+} \cdot \overline{\Gamma_{ik}} \cdot \hat{b}_k^{\alpha}, \rho\}$. The corresponding steady-state solution is given by[4] $b_j^{\alpha} = \frac{\Omega^{\alpha}\delta_{\alpha,\gamma} e^{i\mathbf{k}_0\cdot\mathbf{r}_j}/2}{\Delta^{\alpha} + i\Gamma/2} + \sum_{n\neq j,\alpha'} \frac{G_{jn}^{\alpha\alpha'}}{\Delta^{\alpha} + i\Gamma/2} b_n^{\alpha'}$. The fluorescence intensity measured at ***rs*** can be obtained by $I(\mathbf{r}_s) \propto \sum_{jn} e^{-i\mathbf{k}_s\cdot\mathbf{r}_{jn}} \sum_{\alpha,\alpha'} (\delta_{\alpha,\alpha'} - \hat{\mathbf{r}}_s^{\alpha}\hat{\mathbf{r}}_s^{\alpha'}) b_j^{\alpha'} b_n^{\alpha*}$.

In the case of a 10×10 optical lattice, the scattered light intensity as a function of the interatomic distance for various laser frequency detunings is shown in Fig. 2. When the frequency detuning increases, the interatomic distance where the peak intensity occurs reduces and the peak intensity is suppressed. The results arise from the fact that, when the laser detuning increases, the atoms will be resonant with the laser at shorter interatomic distance; furthermore, the stronger dipolar interactions tend to further suppress the scattered intensity.

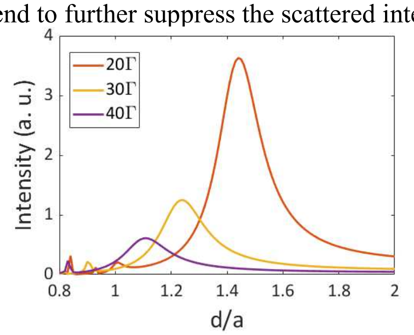

Fig. 2. The dependence of on-resonance scattered light on the interatomic distance for various laser detunings: 20Γ(red), 30Γ(orange), 40Γ(purple). The peak intensity occurs at shorter interatomic distance as the increase of laser detuning.

The collective optical response of the dense ensemble to the interatomic distance is investigated for a 10×10 optical lattice, which specifies the blue-detuned frequency shift, linewidth broadening and intensity decrease, shown in Fig. 3. The features of dipolar interactions are significantly obvious while d is less than $3a$. At $d=a$, the frequency shift reaches 50Γ and linewidth is broadened by a factor of 22.

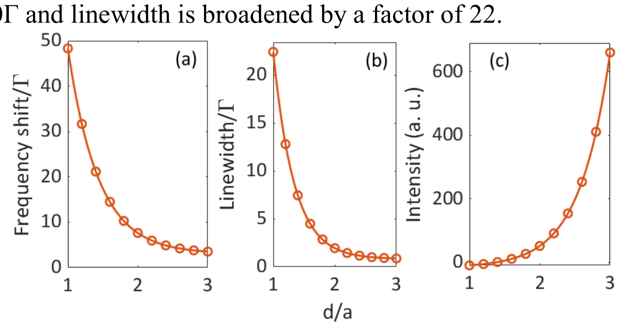

Fig. 3. The collective optical response of the ensemble to the interatomic distance. The dependence of frequency shift (a), linewidth (b) and on-resonance intensity (c) of scattered light on the interatomic distance.

Finally, we have calculated the spectrum as a function of the interatomic distance d and the laser frequency detuning and the result is shown in Fig. 4. The spectra at d=1.2a and 1.8a are shown. One observes the emergence of a number of narrow peaks belonging to long-lived subradiant states at d=1.2a.

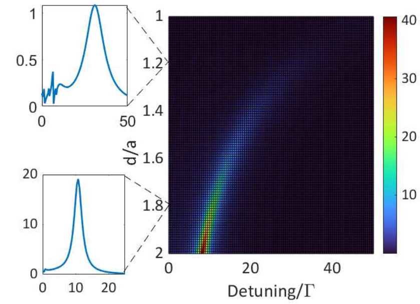

Fig. 4. The spectrum of fluorescence as a function of the interatomic distance and laser detuning. The spectra at d=1.2a and d=1.8a are shown.

IV. CONCLUSION

We theoretically study dipole dipole interactions on $^3P_0$-$^3D_1$ with ultracold Sr atoms in a 10×10 optical lattice. We calculate the frequency shift, linewidth and intensity, based on the coupled dipole model, under dipole dipole interactions of Sr atoms. We also show the setup to be employed to investigate the experiment in near future. The results predict that ultracold Sr atoms provide another platform for studying dipole dipole interactions.

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