Blue-detuned Optical Lattice for Sr Long-range Interactions

Shengnan Zhang*, Balsant Tiwari, Sandhya Ganesh, Preetam Ramchurn, Kai Bongs, Yeshpal Singh
Midlands Ultracold Atom Research Centre, School of Physics and Astronomy,
University of Birmingham,
Edgbaston, Birmingham B15 2TT, United Kingdom
E-mail: S.Zhang.3@bham.ac.uk

***Abstract*—Long-range interactions on the $5s5p^3P_0$-$5s4d^3D_1$ transition of Sr was first proposed [1] as the blue-detuned optical lattice allows the interatomic distance one order of magnitude shorter than the transition wavelength. We aim to create such an optical lattice at 412 nm of the magic wavelength in experiment to further study long-range interactions. Here we present the calculation of the atomic polarizabilities for $5s5p^3P_0$ and $5s4d^3D_1$ states. We also characterize the axial frequency on the lattice laser power and beam waist. The 412 nm lattice laser is frequency doubled from a Ti-Sapphire laser. Experimentally characterizing the optical lattice is still ongoing.**

Keywords—Optical lattice; long-range interactions; magic wavelength; trap frequency

I. INTRODUCTION

An optical lattice has become an essential tool, especially in optical clocks[2], lattice-based long-range interactions[1], since the idea was first proposed in 2001[3] as it allows effectively Stark-free confinements of atoms. It was proposed that deep lattice-trapped Sr atoms allow the study of long-range interactions on the $5s5p^3P_0$-$5s4d^3D_1$ transition due to its much shorter interatomic distance than the transition wavelength.

Here we calculated the polarizabilities for $5s5p^3P_0$ and $5s4d^3D_1$ states and found the magic wavelength at 412 nm for the blue-detuned optical lattice. It also shows that the magic wavelength exists at red detuning. We presented the characterization of trap frequency on the lattice power and beam waist. The lattice laser at 412 nm is frequency doubled from a Ti Sapphire laser with a total power of 1.5 W. Experimentally characterizing the optical lattice is still ongoing. We will further study long-range interactions with the lattice-based Sr atoms.

II. SCHEMATICS OF OPTICAL LATTICE

Fig. 1 shows the schematic of three-dimensional optical lattice. The experimental apparatus is the same as [4]. The lattice is composed of three pairs of counter-propagating beams at 412 nm along x, y and z directions. The polarization of beams in x and y is along z axis, and in z is along y axis. The probe beam at 2.6 μm is propagating along x to atoms. The lattice laser is from a frequency-doubled Ti Sapphire laser at 824 nm. The total power for 412 nm is around 1.5 W. Atoms are trapped in a blue magneto-optical trap (MOT) and subsequently red MOT before loading into the optical lattice. By increasing the lattice potential, atoms are confined in a Mott insulator with the interatomic distance 206 nm, one order of magnitude shorter than the transition wavelength 2.6 μm making it an ideal ensemble for studying long-range interactions.

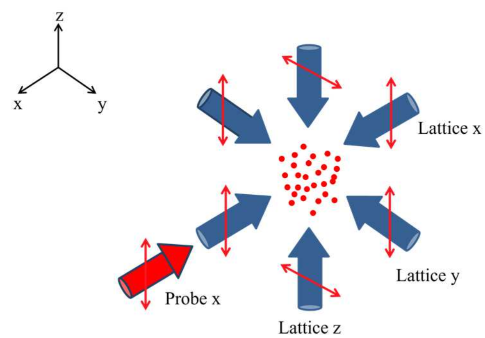


Fig. 1. Schematic of three-dimensional optical lattice. The blue arrows show the lattice laser beams; the red arrow shows the probe laser beam at 2.6 μm; the double-sided arrows show the laser polarizability.

III. ATOMIC POLARIZABILITY

To find out the magic wavelength for the optical lattice, we need to calculate the polarizability for the states of $5s5p^3P_0$ and $5s4d^3D_1$. The general expression of the dynamic polarizability is given by [5]

$$\alpha_a(\omega) = 6\pi\epsilon_0 c^3 \frac{\omega_{J_aJ_k}}{\omega_{cm}^3(\omega_{J_aJ_k}^2-\omega_L^2)} b_{J_aJ_k} b_{M_aM_k} \Gamma_{L_aL_k} \quad (1)$$

Where ω_{JaJk}, b_{JaJk}, b_{MaMk} and Γ_{JaJk} are the transition frequency, the branching ratio, the normalised magnetic branching ratio and the decay rate of J_a-J_b, respectively. For lineally polarized laser, b_{MaMk}=1 and hence be ignored. ω_{cm} is the centre-of-mass frequency, given by $\omega_{cm}^3 = \sum_{J_a} b_{J_aJ_k}\omega_{J_aJ_k}^3$.
The data for $5s5p^3P_0$ and $5s4d^3D_1$ are listed in the Table 1 [5,6]. The units for ω_{JaJk} and ω_{cm} are 10^{15} s^{-1}, for Γ_{JaJk} is 10^6 s^{-1}. The data for $5s4d^3D_1$ are just listed for $5snf^3F_2$, limited by the space.

Table 1 Parameters for calculation of the polarizability for $5s5p^3P_0$ and $5s4d^3D_1$.

state	level	λ(nm)	$\omega_{J_aJ_k}$	$\Gamma_{L_aL_k}$	$b_{J_aJ_k}$	ω_{cm}
$5s5p^3P_0$	$5s6s^3S_1$	679.289	2.773	74.58	1/9	2.701
	$5s7s^3S_1$	432.766	4.353	21.6	1/9	4.280
	$5s8s^3S_1$	378.160	4.981	8.22	1/9	4.909
	$5s9s^3S_1$	355.446	5.299	4.53	1/9	5.227
	$5s10s^3S_1$	343.525	5.453	2.77	1/9	5.411
	$5s4d^3D_1$	2603.13	0.7236	0.381	5/9	0.666
	$5s5d^3D_1$	483.339	3.897	61	5/9	3.880
	$5s6d^3D_1$	394.192	4.779	26.7	5/9	4.761

	$5s7d^3$D$_1$	363.018	5.189	14.2	5/9	5.171
	$5s8d^3$D$_1$	348.099	5.411	8.51	5/9	5.394
	$5s9d^3$D$_1$	339.326	5.551	5.51	5/9	5.534
	$5p^2$P$_1$	474.325	3.971	120	1/3	3.917
	$4d^{2\,3}$P$_1$	330.753	5.703	59	-	-
		316.309	5.955	9.77	1	5.955
	$5s9f^3$F$_2$	378.892	4.975	-	1	4.975
	$5s8f^3$F$_2$	384.333	4.904	-	1	4.904
$5s4d^3$D$_1$	$5s7f^3$F$_2$	392.587	4.801	-	1	4.801
	$5s6f^3$F$_2$	406.092	4.642	-	1	4.642
	$5s5f^3$F$_2$	430.811	4.375	-	1	4.375

The results of polarizabilities within the wavelength range of 390 nm to 440 nm for $5s5p^3$P$_0$ and $5s4d^3$D$_1$ are presented in Fig. 2. We find the magic wavelength for the blue-detuned optical lattice at 412 nm.

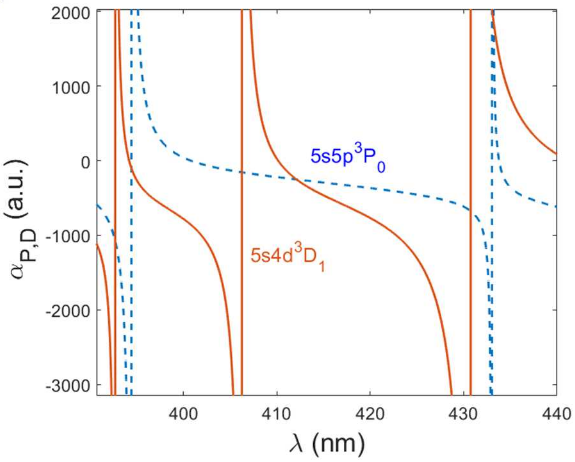


Fig. 2. The atomic polarizabilities of $5s5p^3$P$_0$ and $5s4d^3$D$_1$ from 390 nm to 440 nm. The magic wavelength is at 412 nm.

IV. CHARACTERIZATION OF OPTICAL LATTICE

To strictly confine atoms, we create a three-dimensional optical lattice. The optical potential when $\omega_x = \omega_y = \omega_z$ is expressed as

$$U\,(x, y, z) = U_0(\vec{e}_z coskx + \vec{e}_z cosky + \vec{e}_y coskz)^2 \qquad (2)$$

Where $U_0 = -\alpha_a \frac{4P}{\varepsilon_0 c\pi\omega^2}$, $\alpha_a = -760\, a.u.$. The trap frequency along x, y, z can be calculated by

$$\upsilon_x = \upsilon_y = \frac{2}{\lambda_L}\sqrt{\frac{|U_0|}{M}} \qquad (3)$$

$$\upsilon_z = \frac{1}{\lambda_L}\sqrt{\frac{2|U_0|}{M}} \qquad (4)$$

The trap frequency υ_z as a function of the lattice laser power and beam waist is shown in Fig. 3. The dependence of υ_z on the laser power for various beam waists are shown in Fig. 3(a). when the waist is 50 μm and power is 500 mW, the trap frequency in z can be 300 kHz. Fig. 3(b) shows the dependence of υ_z on the beam waist for various laser power. It decreases with the increase of waist.

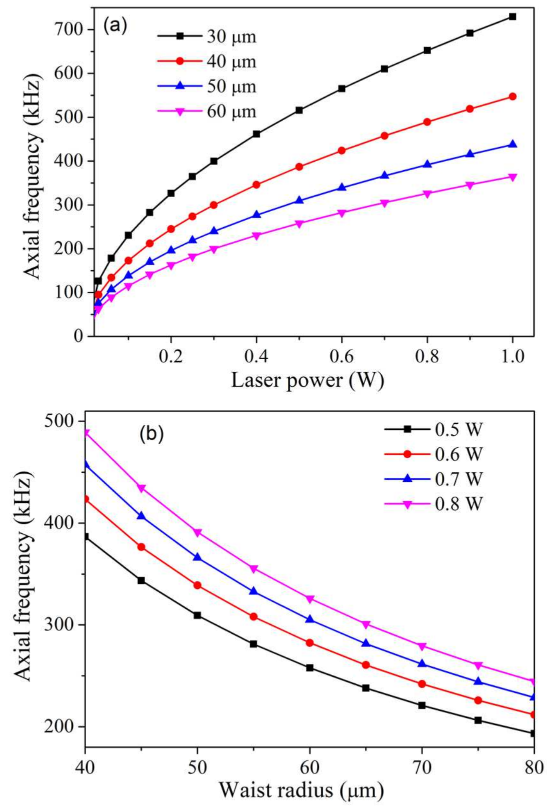
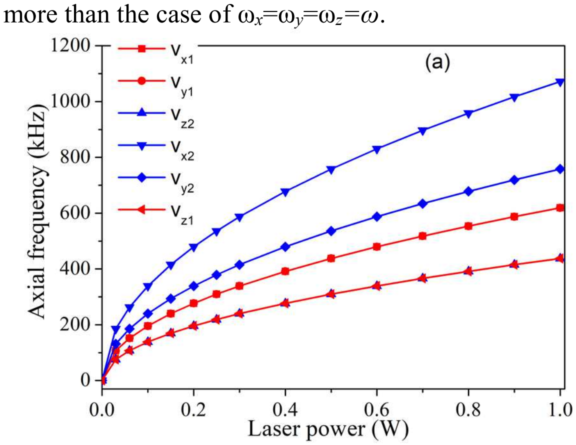


Fig. 3. (a) The trap frequency along z as a function of 412 nm laser power. (b) the trap frequency along z as a function of beam waist. Here $\omega_x=\omega_y=\omega_z$.

Furthermore, the trap frequency in the cases of $\omega_x=\omega_y=\omega_z=\omega$ and $\omega_y=\omega_z=2\omega_x=\omega$ has been studied as a function of laser power and beam waist. Fig. 4(a) shows the trap frequency *vs* laser power at ω=50 μm. The value of υ_z in the case of $\omega_x=\omega_y=\omega_z=\omega$ is the same as that of $\omega_y=\omega_z=2\omega_x=\omega$. The values of υ_x and υ_y are the same when $\omega_x=\omega_y=\omega_z=\omega$. Fig. 4(b) shows the trap frequency *vs* beam waist at P=1 W. The value of υ_x in the case of $\omega_y=\omega_z=2\omega_x=\omega$ is the maximum, which is $\sqrt{3}$ more than the case of $\omega_x=\omega_y=\omega_z=\omega$.



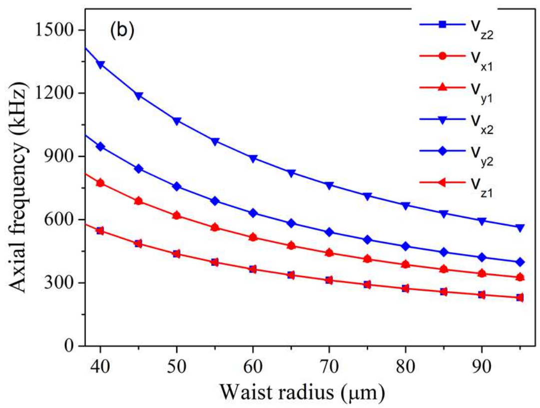


Fig. 4. (a) The trap frequency for all axes as a function of 412 nm laser power. (b) the trap frequency for all axes as a function of beam waist. Blue and red curves show $\omega_y=\omega_z=2\omega_x=\omega$ and $\omega_x=\omega_y=\omega_z=\omega$, respectively.

V. CONCLUSION

We have calculated the dynamic polarizabilities for $5s5p\,^3P_0$ and $5s4d\,^3D_1$ states, and found the magic wavelength at 412 nm for the blue-detuned optical lattice. We also characterized the axial frequency on the lattice laser power and beam waist in two different cases. We are still investigating the experimental characterization of the optical lattice. The atoms in a Mott insulator will be used to study long-range interactions.

ACKNOWLEDGMENT

The authors acknowledge funding from the UK Quantum Technology Hub Sensors and Timing (grant EP/T001046/1) and the European Union's Horizon 2020 research and innovation programme under grant agreement No 820404 (iqClock project).

REFERENCES

[1] B. Olmos, D. Yu, Y. Singh, F. Schreck, K. Bongs, and I. Lesanovsky, "Long-range interacting many-body systems with alkaline-earth-metal atoms," Phys. Rev. Lett., 110, 143602, 2013.

[2] M. Takamoto, F. -L. Hong, R. Higashi & H. Katori, "An optical lattice clock," Nature 435, pp.321-324, 2005.

[3] H. Katori, "Spectroscopy of strontium atoms in the Lamb-Dicke confinement," Proceedings of the 6th Symposium in Frequency Standards and Metrology, 323, 2001.

[4] S. Zhang, P. Ramchurn, M. Menchetti, Qasim Ubaid, Jonathan Jones, Kai Bongs, and Yeshpal Singh, "Novel repumping on $^3P_0\rightarrow{}^3D_1$ for Sr magneto-optical trap and Landé g factor measurement of $^3D_1$," J. Phys. B: At. Mol. Opt. Phys., 53, 235301, 2020.

[5] I. R. Hill, "Development of an apparatus for a strontium optical lattice optical frequency standard," PhD Thesis Imperial College London, 2012.

[6] J. E. Sansonetti, G. Nave, "Wavelengths, Transition probabilities, and energy levels for the spectrum of neutral strontium," J. Phys. Chem. Ref. Data 39, 033103, 2010.