Fabrication of One-Dimensional Single-Atom Arrays with Tunable Spacing and Their Application to the Study of Atomic Collective Effects

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Abstract

Research on coupled interatomic interactions and multi-atom collective effects constitutes an important topic in contemporary cold atom physics. When the interatomic distance is at the subwavelength scale, coherent radiation between atoms can profoundly modify the overall optical response of the atomic system, manifesting as: frequency shifts of atomic energy levels; significant shortening or extension of excited-state lifetimes; pronounced directionality of atomic radiation in space, etc. Such atomic systems exhibit collective behavior rather than individual atomic behavior, a phenomenon referred to as collective radiation effects. For cesium atoms in low-lying excited states, realizing dipole-dipole interactions between atoms requires minimizing the interatomic spacing, and the atomic system displays different collective effects under various atomic separations. Therefore, the research focus of this work is to design a one-dimensional dipole trap array that realizes a one-dimensional single-atom array with tunable spacing less than half a wavelength, and to investigate the characteristics of atomic collective effects using this platform.

The main work of this paper includes: the design, construction, and debugging of a one-dimensional blue-detuned dipole trap array with tunable spacing, and the trapping of a one-dimensional single-atom array. Based on this experimental setup, theoretical studies were conducted on dipole-dipole interactions between two atoms and multiple atoms, as well as the collective radiation characteristics of atomic arrays. Additionally, we theoretically investigated the influence of atomic temperature on the collective radiation of the array using Monte Carlo simulations.

Full Text

Abstract

The dipole-dipole interaction between atoms and collective effects in atomic ensembles are currently important topics in cold atom physics research. When the distance between atoms is on the subwavelength scale, coherent radiation between atoms dramatically modifies the optical response of the atomic system as a whole, manifesting as frequency shifts in atomic energy levels, significantly shortened or extended lifetimes of excited states, and pronounced directionality in atomic radiation in space. Such atomic systems exhibit collective behavior rather than individual atomic properties, a phenomenon referred to as collective radiation effects. For cesium atoms in lower excited states, achieving dipole-dipole interaction requires minimizing the interatomic distance. Different atomic spacings lead to different collective effects in the atomic system. Therefore, designing a one-dimensional dipole trap array that can realize a tunable-spacing one-dimensional single-atom array with spacing less than half a wavelength, and using it to investigate the characteristics of atomic collective effects, constitutes the main focus of this thesis.

The primary work of this thesis includes: the design, construction, and debugging of a spacing-tunable one-dimensional blue-detuned dipole trap array, and the capture of a one-dimensional single-atom array. Based on this experimental apparatus, we theoretically investigate dipole-dipole interactions between two atoms and multiple atoms, as well as the collective radiation characteristics of atomic arrays. Additionally, we theoretically simulate the influence of atomic temperature on the collective radiation of the array using Monte Carlo methods.

Keywords: dipole-dipole interaction; single atomic chain; collective effect; quantum optics

Chapter 1 Introduction

1.1 Introduction to Cold Atom Manipulation

Optical dipole traps, also known as optical tweezers, are widely applied in biomedical research, nanoscience, quantum physics, and numerous other fields. In cold atom physics experiments, optical dipole traps are essential tools for trapping neutral atoms. By designing the spatial dimensions of the dipole trap, one can capture single atoms, multiple atoms, or even thousands of atoms. In the earliest experiments observing optical trapping of atomic clouds [22], the optical tweezers used consisted of a strongly focused Gaussian beam with a detuning of approximately 10^4 atomic natural linewidths, successfully trapping about 500 sodium atoms in a molasses at 10^-3 K.

1.2 Development History and Research Progress of Single-Atom Physics

[FIGURE:2.3] shows a schematic diagram of the principle of atomic capture in an optical dipole trap [44]. Considering the simplest case of a dipole trap formed by a focused Gaussian beam, if the atomic temperature is lower than the trap depth, the atom will be captured in the trap. The captured atom still possesses temperature and experiences a harmonic potential in both the radial direction r and axial direction z within the dipole trap:

$$U = -U_0 + U(r, z) \approx U_0 \left(-1 + \frac{r^2}{w_0^2} + \frac{z^2}{z_R^2} \right) \tag{2.1}$$

where w_0 is the waist of the Gaussian beam, $z_R = \frac{\pi w_0^2}{\lambda}$ is the Rayleigh length, λ is the wavelength of the dipole trap laser, ω_r and ω_z are the oscillation frequencies in the radial and axial directions respectively.

1.3 Structure of This Thesis

The development of single-atom physics has progressed significantly since the first observations of optical trapping. The ability to isolate and manipulate individual atoms has opened new avenues for quantum information processing, precision measurement, and fundamental physics studies. This thesis focuses on extending these capabilities to create tunable one-dimensional atomic arrays for investigating collective effects.

Chapter 2 Experimental Preparation of Cold Atoms and Single-Atom Capture

2.1 Magneto-Optical Trap

The magneto-optical trap (MOT) is a standard technique for pre-cooling and trapping neutral atoms using spatially varying magnetic fields and counter-propagating laser beams. Our implementation follows established designs with careful consideration of geometric constraints imposed by the blue-detuned lattice apparatus.

2.2 Optical Dipole Trap

The optical dipole trap utilizes the AC Stark shift to create a conservative potential for neutral atoms. The trap depth is proportional to the laser intensity and inversely proportional to the detuning from atomic resonance. For blue-detuned traps, the potential is repulsive, requiring hollow beam geometries to create trapping regions.

2.4 Single-Atom Capture in Blue-Detuned Dipole Trap

Capturing single atoms in blue-detuned dipole traps presents unique challenges compared to red-detuned traps. The repulsive nature of the potential necessitates precise control over trap geometry and atomic density. Our approach combines a one-dimensional optical lattice formed by two-beam interference with a transverse hollow beam to create an array of bottle traps.

Chapter 3 Collective Emission in Sub-Wavelength Atomic Chain

3.1 Atomic Dipole Moment

The atomic dipole moment induced by an external field is fundamental to understanding dipole-dipole interactions. For a two-level atom interacting with a near-resonant field, the induced dipole moment can be expressed as:

$$\mathbf{p} = \alpha(\omega)\mathbf{E}$$

where $\alpha(\omega)$ is the complex polarizability and $\mathbf{E}$ is the electric field amplitude.

3.3 Theoretical Analysis of Collective Emission in 1D Atomic Chain

The collective emission from a one-dimensional atomic chain depends critically on the interatomic spacing relative to the transition wavelength. When atoms are separated by less than $\lambda/2$, the dipole-dipole interaction leads to collective eigenmodes with superradiant and subradiant characteristics. The theoretical framework considers the coupled dynamics of atomic dipoles through the electromagnetic field, leading to modified decay rates and frequency shifts.

The electric field at position z due to other atoms in the chain can be expressed as:

$$E(z) = E_0 e^{ikz} + \sum_{j \neq i} \frac{k^2}{4\pi\epsilon_0} \frac{e^{ik|z-z_j|}}{|z-z_j|} p_j \tag{3.10}$$

Further considering that each atom experiences radiation from other atoms in both positive and negative directions along the z-axis, this can be written more specifically as [38]:

$$E(z) = E_0 e^{ikz} + \sum_{j \neq i} \frac{k^2}{4\pi\epsilon_0} \frac{e^{ik|z-z_j|}}{|z-z_j|} p_j \mathcal{D}(z-z_j) \tag{3.11}$$

where $\mathcal{D}(z-z_j)$ accounts for the directional dependence of the dipole radiation pattern.

Chapter 4 Design and Loading of 1D Blue-Detuned Lattice

4.1 Overall Design Concept

In the previous chapter, we introduced the fundamental principles of dipole-dipole interactions and clarified the influence of atomic spacing on interaction strength. This chapter focuses on the design scheme for a one-dimensional dipole trap array with tunable atomic spacing. The overall structure is shown in [Figure 4: see original paper].1.

The blue-detuned one-dimensional dipole trap array consists of two main components. First, inspired by the mechanical structure of a compass, we use multiple polarizing beam splitters (PBS) and wave plates to divide an incident beam into two beams with identical polarization that are symmetric about the lens center. These beams then interfere in the vacuum system to create a blue-detuned optical lattice that divides the atomic cloud into multiple slices. By adjusting the position of the incident light, we can control the separation between the two beams, thereby changing the spacing of the interference fringes. Second, we introduce a hollow beam through a vortex phase plate from the side, creating a series of closed blue-detuned bottle traps in three-dimensional space, as illustrated in [Figure 4: see original paper].2.

4.2 Gaussian Beam Interference Analysis

Gaussian beams are the most common optical resource in quantum optics, with electric field amplitude distribution satisfying:

$$E = A_0 \frac{w_0}{w(z)} e^{-\frac{r^2}{w(z)^2}} e^{-i\left(kz - \arctan(z/z_R) + \frac{kr^2}{2R(z)}\right)} \tag{4.1}$$

where r is the position vector in the field, $w(z)$ is the beam radius, w_0 is the waist size, and A_0 is the amplitude.

In our experimental setup, the incident light coupling head has a focal length of 4.51 mm, corresponding to a waist of $w_0 = 447.90\,\mu$m and Rayleigh length of $z_R = 808$ mm. The power is 350 mW at a wavelength of 780 nm, with the fiber output face positioned 18 cm from our custom high-numerical-aperture lens assembly [56]. By adjusting two quarter-wave plates, we ensure equal power in the two beams after the PBS, each with 160 mW. In the apparatus, the D-shaped mirror is approximately $l = 1$ cm from the small PBS, which has a side length of $a = 1$ cm. Considering the half-wave loss from the mirror, the phase difference between the two beams is:

$$\Delta l = 2(l + a) \tag{4.2}$$

$$\Delta\phi = 2\pi \frac{\Delta l}{\lambda} + \pi \tag{4.3}$$

The beam radii before the high-NA lens assembly are $w_1 = 9.75\,\mu$m and $w_2 = 9.64\,\mu$m.

When a Gaussian beam passes non-paraxially through a lens, both its propagation direction and waist size change. Assuming the Gaussian beam propagates along the y-axis before the lens and deflects along the x-direction after passing through the lens ([Figure 4: see original paper].3), the electric field distributions of the two beams after coordinate transformation are:

$$E_1 = A_1 \frac{w_0}{w(z)} e^{-\frac{(x-d/2)^2+y^2}{w(z)^2}} e^{-i(kz-\arctan(z/z_R)+\frac{k[(x-d/2)^2+y^2]}{2R(z)})} e^{ikx\sin\theta} \tag{4.4}$$

$$E_2 = A_2 \frac{w_0}{w(z)} e^{-\frac{(x+d/2)^2+y^2}{w(z)^2}} e^{-i(kz-\arctan(z/z_R)+\frac{k[(x+d/2)^2+y^2]}{2R(z)})} e^{-ikx\sin\theta} \tag{4.5}$$

where $\theta = \tan^{-1}(d/2f)$, d is the separation between the two beams, and f is the focal length of the high-NA lens assembly. The intensity distribution at any position in the x-y plane from two-beam interference is:

$$I = |E_1|^2 + |E_2|^2 + E_{1E}2^* + E_{2E}1^* \tag{4.6}$$

For $d = 18$ mm, the calculated interference pattern at the focal plane matches our experimental observations with a standard CCD.

Based on equation (2.6), we calculated the trap depth distribution of the two-beam interference pattern in both x and y directions, shown in [Figure 4: see original paper].5. Assuming an atomic cloud temperature of 500 µK and $d = 18$ mm, we can trap 13 single atoms with 660.66 nm spacing. The oscillation frequency in the x-direction is 500-600 kHz, while the y-direction frequency is primarily determined by the hollow beam dimensions.

4.3 Hypergeometric Gaussian Mode and Vortex Beam

The other major component forming the one-dimensional blue-detuned dipole trap array is the hollow beam that confines the interference fringes. In our experiment, we use a vortex phase plate with topological charge 1 to generate a first-order Laguerre-Gaussian mode for the hollow beam. The topological charge refers to the ratio of the phase rotation after passing through the vortex plate to 2π. The phase plate shape and corresponding Laguerre-Gaussian modes for different topological charges are shown in [Figure 4: see original paper].6.

Mathematically, hollow beams can be described by Hypergeometric-Gaussian modes:

$$u_{p,m}^{HG} = \sqrt{\frac{2^{p+|m|+2}}{\pi\Gamma(p+|m|+1)}}\frac{1}{\Gamma\left(1+|m|+\frac{p}{2}\right)}\Gamma(|m|+1)\times i^{|m|+1}Z^{\frac{p}{2}}(Z+i)^{-1-|m|-\frac{p}{2}}\rho^{|m|}e^{-\frac{\rho^2}{Z+i}}e^{im\phi}\times{}_{1F}1\left(-\frac{p}{2},|m|+1\right. \tag{4.7}$$

where $\rho = r/w_0$ is the normalized radial coordinate, $Z = z/z_R$ is the normalized axial coordinate, m is the topological charge, and ${}_{1F}1(a,b;x)$ is the confluent hypergeometric function. The key to solving the hypergeometric Gaussian mode lies in solving the confluent hypergeometric function, which can be obtained from Kummer’ s equation:

$$z\frac{d^{2w}}{dz^2} + (b-z)\frac{dw}{dz} - aw = 0 \tag{4.8}$$

The general solution is:

$$M(a,b,z) = {}_{1F}1(a,b;z) = \sum_{n=0}^{\infty}\frac{a^{(n)}z^n}{b^{(n)}n!} \tag{4.9}$$

where $a^{(0)} = 1$ and $a^{(n)} = a(a+1)(a+2)\cdots(a+n-1)$ is the rising factorial.

In our experimental setup, the incident coupling head has a focal length of 15.29 mm and power of 570 mW. After passing through the 34.35 mm high-NA lens assembly, the trap depth distribution of the hollow beam with topological charge 1 at the waist position is shown in [Figure 4: see original paper].7. The inner full width at half maximum (FWHM) is 3.84 µm, the outer FWHM is 12.97 µm, and the central oscillation frequency is 61.14 kHz.

In a subsequent design using a custom lens assembly with $f = 55$ mm and NA = 0.12, the incident coupling head uses a 75 mm focal length lens. The corresponding trap depth distribution at the waist is shown in [Figure 4: see original paper].8, with inner FWHM of 1.24 µm, outer FWHM of 4.24 µm, and central oscillation frequency of 303.89 kHz.

4.4 Scheme of Magneto-Optical Trap

In our experiment, the vacuum system window is cell-shaped with 5 mm wall thickness and 20 mm inner side length. When designing the MOT structure, we inject two pairs of beams in the horizontal plane of the platform and one pair in the vertical direction, as shown in [Figure 4: see original paper].9. When designing the angles of the two horizontal beams, multiple factors including incident angle and beam size must be considered. On one hand, to minimize the spacing of the blue-detuned dipole trap array, the focal length of the high-NA objective used for the two-beam interference should be as small as possible, requiring the MOT center to be as close as possible to the front surface of the cell. On the other hand, the MOT beams must preserve access for the side hollow beam while considering its geometric positioning.

Considering the Gaussian beam size, let the beam waist be w, the distance from the atomic cloud to the outer front surface of the cell be d, the refractive index of the cell wall be n, the incident angle be θ, the refraction angle be ϕ, the distance from the incident point to the outer front surface be x_1, the projected size of the incident beam on the cell surface be x_2, the offset during propagation along the side wall be x_3, and the horizontal distance from the refraction exit point to the MOT center be x_4. The geometric relationships yield:

$$x_2 = \frac{w}{\cos\theta} \tag{4.10}$$

$$x_3 = 5\text{mm} \cdot \tan\phi \tag{4.11}$$

$$x_4 = 10\text{mm} \cdot \tan\theta \tag{4.12}$$

$$\sin\theta = n \cdot \sin\phi \tag{4.13}$$

$$x_1 + x_2 + x_3 + x_4 = d \tag{4.14}$$

To avoid scattering from the cell adhesive areas, we must restrict the incident beam position. Considering the 33 mm outer diameter of the lens assembly used for the side hollow beam, we obtain:

$$x_1 \geq 5\text{mm} \tag{4.15}$$

$$x_3 + x_4 + (f - 15\text{mm})\tan\theta - \omega \geq [\text{constraint}] \tag{4.16}$$

The MOT beams exit through a single-mode polarization-maintaining fiber with core diameter $w_0 = 2.5\,\mu$m and coupling head. According to the Gaussian beam waist transformation formula, when the coupling head lens has focal length f, the MOT beam waist is:

$$w = \frac{\lambda f}{\pi w_0} \tag{4.17}$$

When the high-NA lens assembly for the two-beam interference is 1 mm from the cell front surface, we obtain the relationship between the available range of θ and f, shown in [Figure 4: see original paper].10. After comprehensive consideration, we select the scheme with $\theta = 34^\circ$ and $f = 15.36$ mm. The corresponding MOT parameters are listed in .1.

.1 Basic parameters of MOT beams - Waist: 1.67 mm - MOT position (from front side): [value] - Angle of two horizontal beams: 34° - Cooling beam power: 1.2 mW - Repumping beam power: 0.3 mW

In actual single-atom capture experiments, we found that regardless of how we optimized the atomic cloud state and dipole trap position, the MOT light introduced stray signals two orders of magnitude stronger than the single-atom signal, completely drowning out the desired signal. Therefore, we needed to analyze the mechanism of stray signal introduction and eliminate it to improve the signal-to-noise ratio.

Through further analysis of beam propagation in the cell, we discovered that when the angle between the two horizontal MOT beams is large, a small fraction of MOT light reflects from the cell' s inner surface to the front port and is collected by the high-NA lens assembly, as shown in [Figure 4: see original paper].11. By analyzing the cell surface coating properties, we found that optimizing θ so that the horizontal MOT light undergoes two reflections inside the cell before exiting through the front port can reduce stray light by at least three orders of magnitude.

From [Figure 4: see original paper].11, the condition for two reflections of the horizontal MOT light on the cell inner surface is:

$$d - 5\text{mm} \geq 3x_4 \tag{4.18}$$

This also determines the upper limit of θ. Due to space constraints, we readjusted d to 10 mm and replaced the side lens assembly with a custom design of $f = 55$ mm and NA $= 0.12$. Considering the size of the side lens assembly, θ must also satisfy equation (4.16).

After comprehensive consideration, the final θ is selected as 18°. The MOT image captured is shown in [Figure 4: see original paper].12.

4.5 EMCCD Imaging System Design

Beyond the MOT and dipole traps, we need "eyes" to observe whether atoms are captured and to perform subsequent experimental operations. These "eyes" refer to electron-multiplying CCD cameras (EMCCD), which can detect single photons and are widely used in biology, chemistry, physics, and astronomy.

Our imaging system design is shown in [Figure 4: see original paper].13, operating on the same principle as a telescope with 11× magnification. The EMCCD sensor has a minimum pixel size of 16 μm, corresponding to an image plane resolution of 1.4 μm.

4.6 System Parameters and Performance

The overall structure of the dipole trap apparatus is shown in [Figure 4: see original paper].14. Our design targets are:

1. Tunable spacing of the dipole trap array from less than half a wavelength to several micrometers
2. Capability to capture more than 5 single atoms
3. Trap oscillation frequencies suitable for subsequent sub-Doppler cooling

Based on the above design and practical considerations, we evaluated the basic performance of the dipole trap apparatus. The beam separation in the two-beam interference can be varied from 2 mm to 18 mm, yielding a tunable dipole trap spacing range of 660.66 nm to 5.8 µm. The primary factor limiting the minimum spacing is the inner dimension of the quarter-wave plate mounts before the two small PBSs.

In actual experiments, after polarization gradient cooling, the atomic temperature is on the order of 10 µK. We evaluated the number of atoms that can be captured under a dipole trap power of 320 mW, as shown in [Figure 4: see original paper].15. At minimum dipole trap spacing, the system can capture up to 29 atoms, with central oscillation frequencies ranging from 188.40 kHz to 663.94 kHz, all satisfying the requirements for sideband cooling. At maximum spacing, the system can capture 3 atoms with frequencies between 56.55 kHz and 60.70 kHz. For our collective effect studies, an atomic array with 5.8 µm spacing has limited practical significance, but the trap number can be increased by raising the dipole trap power when necessary.

Overall, our design meets and significantly exceeds the initial requirements, enabling further experimental work.

4.7 Loading of 1D Single Atomic Chain

Compared to red-detuned dipole traps, blue-detuned dipole traps present a repulsive potential, making atom capture more challenging. Considering future sideband cooling requirements, the smaller trap volume creates significant difficulties for direct single-atom array capture. To determine feasibility, we estimated the trap volume and MOT atomic density.

During atom loading, we adjust the interference fringe spacing to approximately 3 µm to increase trap volume:

$$V_{\text{trap}} = \pi r_1^2 r_2 \approx 30\,\mu\text{m}^3 \tag{4.19}$$

where r_1 and r_2 are the inner FWHM of the hollow beam and the two-beam interference fringe spacing, respectively. The minimum atomic density required to capture one atom in this volume is:

$$\rho_{\min} = \frac{1}{V_{\text{trap}}} \approx 3 \times 10^{13}\,\text{cm}^{-3} \tag{4.20}$$

For the MOT, we can use the fluorescence collection port to measure the fluorescence signal N_{fluo} under specific Probe light conditions and calculate the atom number N_{MOT} [50]:

$$N_{\text{MOT}} = \frac{8\pi}{\eta_{\text{det}}\Omega t_{\text{bin}}\Gamma}\left(1 + 4\frac{\Delta^2}{\Gamma^2} + 6\frac{I}{I_{\text{sat}}}\right) N_{\text{fluo}} \tag{4.21}$$

where Δ is the Probe detuning, Γ is the natural linewidth, I is the Probe intensity, I_{sat} is the saturation intensity, t_{bin} is the collection time bin, η_{det} is the detection efficiency, and Ω is the collection solid angle:

$$\Omega = 4\pi \sin^2 \frac{\theta}{2} = 2\pi(1 - \cos\theta) \tag{4.22}$$

Here θ is the planar collection angle of the lens assembly ([Figure 4: see original paper].16). The numerical aperture relates to θ by:

$$\mathrm{NA} = n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{4.23}$$

Our lens assembly with NA = 0.12 corresponds to $\Omega = 0.11$. With Probe power of 1.2 mW, 10 MHz detuning, 1.67 mm waist, $N_{\mathrm{fluo}} = 8000$, $\eta_{\mathrm{det}} \approx 0.1$, and $t_{\mathrm{bin}} = 50$ ms, we obtain $N_{\mathrm{MOT}} = 13.372$.

To determine MOT density, we calculate the collection volume corresponding to the solid angle. Under cylindrical approximation:

$$V_{\mathrm{col}} = \pi w^2 \mathrm{DOF} \tag{4.24}$$

where DOF is the depth of field, given empirically by:

$$\mathrm{DOF} = \frac{\lambda}{2\,\mathrm{NA}^2} \tag{4.25}$$

For cesium fluorescence at 852 nm, the collection volume is 0.304 mm^3, yielding a MOT density of $4.40 \times 10^7\ \mathrm{cm}^{-3}$—six orders of magnitude lower than required for single-atom capture! Given laser power and MOT size limitations, we must consider alternative approaches to increase atomic density.

We added a high-power, large-volume 1064 nm red-detuned dipole trap to the original apparatus. The integrated system is shown in [Figure 4: see original paper].17. The 1064 nm dipole trap attracts atoms from the MOT, significantly increasing atomic density. Its spatial potential distribution is shown in [Figure 4: see original paper].18.

In experiments, we first capture atoms in the MOT, perform 10 ms polarization gradient cooling to reach ~100 µK, then turn on the 1064 nm red dipole trap. Atoms in the dipole trap are observed on the EMCCD ([Figure 4: see original paper].19). After additional 5 ms polarization gradient cooling to ~10 µK, we finally activate the blue-detuned dipole trap array. We successfully captured a one-dimensional single-atom array ([Figure 4: see original paper].20).

Although we observed the single-atom array signal, the loading efficiency remains low for further experimental needs, primarily due to insufficient atomic density. Future improvements include: (1) increasing the 1064 nm dipole trap power while reducing its size to increase trap depth; (2) appropriately increasing the hollow beam size to reduce the required atomic density for blue-detuned traps; (3) adding an electrically tunable lens to the hollow beam path for dynamic size adjustment.

Chapter 5 Qualitative Analysis of Temperature Effects on Collective Radiation

5.1 Theoretical Framework

After successfully capturing the one-dimensional single-atom array, we analyze experimental factors affecting collective radiation. Theoretically treating interatomic interactions in atomic arrays requires writing the system's density matrix and dissipation, then solving the master equation for steady states. Analyzing collective radiation further requires considering each atom' s polarization direction and spatial position to calculate interactions, making it extremely complex and currently impractical for large systems. Therefore, we qualitatively discuss how atomic motion at different temperatures affects experiments, providing intuitive guidance for future specific experiments.

In Chapter 3, we analyzed collective effects under ideal conditions of 100% loading efficiency and zero temperature. In real experiments, loading efficiency cannot reach 100%, though additional techniques can rearrange atoms to achieve effectively perfect arrays [29-31]. Atomic temperature directly determines atomic motion, affecting array geometry and interatomic phases. Additionally, due to anisotropic radiation patterns, each atom experiences a different radiation field, leading to varying scattering cross-sections and different sensitivities to specific light field directions.

For atoms trapped in a dipole trap, their motion can be treated as harmonic oscillation:

$$x = A\sin(\omega t + \phi_0) \tag{5.1}$$

where A is the atomic motion range in the trap (obtainable from Chapter 4 for given temperatures), ω is the oscillation frequency, and ϕ_0 is the initial phase. The atomic velocity is:

$$v = \dot{x} = A\omega\cos(\omega t + \phi_0) \tag{5.2}$$

Assuming $\phi_0 = 0$, the maximum velocity at $t = 0$ follows the Maxwell-Boltzmann distribution:

$$f(v) = \sqrt{\frac{m}{2\pi k_B T}}\exp\left(-\frac{mv^2}{2k_B T}\right) \tag{5.3}$$

The distribution of oscillation frequencies is:

$$f(\omega) = \frac{A}{\omega^2}\sqrt{\frac{m}{2\pi k_B T}}\exp\left(-\frac{mA^2}{2k_B T\omega^2}\right) \tag{5.4}$$

The atomic scattering cross-section is:

$$\sigma = \frac{\sigma_0}{1 + 4\frac{\delta^2}{\Gamma^2} + \frac{I}{I_{\text{sat}}}} \tag{5.5}$$

where $\sigma_0 = \frac{3\lambda^2}{2\pi}$ is the resonant cross-section, δ is the field detuning, and I is the power density of the atomic radiation field at the spatial position.

5.2 Monte Carlo Simulation of Collective Emission at Different Temperatures

Based on equations (5.1)-(5.4), we first simulated the motion of five single atoms in a one-dimensional array at different temperatures ([Figure 5: see original paper].1). We then analyzed dipole-dipole interactions between any two atoms using equation (3.6), calculated interatomic distances, and obtained the radiation pattern of two atoms in free space. Using equation (5.5), we calculated scattering cross-sections for all other atoms and checked whether they fall within the radiation pattern of the first two atoms. If so, we calculated the three-atom radiation pattern using equation (3.12), recalculated scattering cross-sections, and iterated this process to obtain collective radiation characteristics for different spatial distributions.

We performed 2000 simulations each for temperatures $T = 1\,\mu$K, $10\,\mu$K, $100\,\mu$K, and $1000\,\mu$K. Results are shown in [Figure 5: see original paper].2, where blue, red, yellow, and gray represent cases with 5, 4, 3, and 2 atoms participating in collective effects, respectively.

Extending to 10,000 simulations, statistical distributions are shown in [Figure 5: see original paper].3. Analysis reveals that lower temperatures produce smaller position fluctuations, narrower radiation divergence angles, and higher probabilities of atoms sensing each other’ s radiation. Consequently, more atoms participate in collective effects, and dipole-dipole interactions become stronger.

Chapter 6 Conclusion and Outlook

Neutral atoms, ions, and superconducting circuits are the three most promising platforms for quantum computing. Neutral atoms have demonstrated unique advantages in spatial scalability, holding the record for largest spatial scale, and attracting significant scientific interest. Beyond quantum computing, neutral atom arrays are crucial for investigating fundamental physical laws, such as collective effects and the microscopic nature of dipole-dipole interactions. Most published experiments use standing-wave fields to trap one-dimensional atomic arrays, rarely exploring the atomic spacing degree of freedom—arguably the most critical parameter for studying collective effects. This thesis presents a design for a spacing-tunable dipole trap apparatus, demonstrates single-atom capture, and provides preliminary simulations of collective radiation characteristics.

Although we have achieved single-atom capture in a one-dimensional blue-detuned dipole trap array, challenges remain in loading efficiency and atomic temperature. To improve loading efficiency, we must increase the 1064 nm red-detuned dipole trap depth to raise atomic density by 4-6 orders of magnitude, or adjust the 780 nm hollow beam to increase blue-detuned trap volume. Additionally, we need to implement sideband cooling or more compact gray molasses cooling to further reduce temperature and achieve "identical" atoms.

With this system, we can investigate fundamental physics questions. By designing appropriate temperature and spacing, we can achieve in-phase coupling where the atomic system emits photons in pairs within specific spatial ranges, providing a platform for generating squeezed vacuum states. With sideband cooling to nK temperatures, the probability of all atoms participating in collective radiation exceeds 99%, producing strongly anisotropic fluorescence with photon number equal to atom number—ideal for generating non-classical states like Fock and N00N states. Combined with our spatial correlation measurement techniques [58], this enables multi-dimensional quantum state investigation. For few-atom systems, exact theoretical solutions exist, allowing precise experimental design. For large atom numbers, no universal theory exists, enabling experimental exploration of strongly coupled multi-atom systems.

In quantum computing, this array can implement controlled single-atom entanglement by tuning temperature and spacing, enabling quantum encoding, memory, and logic gates. Combining with our group' s "magic wavelength" scheme [59] can further improve coherence times. Additionally, exciting atoms to Rydberg states dramatically increases interaction strength, facilitating non-classical state preparation and quantum computation via free-space strong interactions.

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Publications During Degree

1. Tiancai Zhang, Wei Wu, Pengfei Yang, etc., High-finesse micro-optical Fabry–Pérot cavity and its applications in strongly coupled Cavity QED, Acta Optica Sinica (Invited Review) (in press)
2. Shaokang Li, Gang Li, Wei Wu, etc., High-numerical-aperture and long-working-distance objectives for single-atom experiments, Review of Scientific Instruments, 91, 043104
3. Gang Li*, Yali Tian*, Wei Wu, etc., Triply magic conditions for microwave transitions of optically trapped alkali-metal atoms, Physical Review Letters, 123, 253602
4. Yali Tian, Pengfei Yang, Wei Wu, etc., Precision measurement of cesium 6S–7S two-photon spectroscopy with single trapped atoms, Japanese Journal of Applied Physics, 58, 4
5. Jinkai Cao, Pengfei Yang, Yali Tian, Wei Wu, etc., Measurement of high order coherence of light field based on enhanced CCD, Acta Optica Sinica, 39, 7

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