Progress towards Collective Quantum Effects experiments on trapped neutral atom arrays

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HQAN Hybrid Quantum Architectures and Networks

NSF

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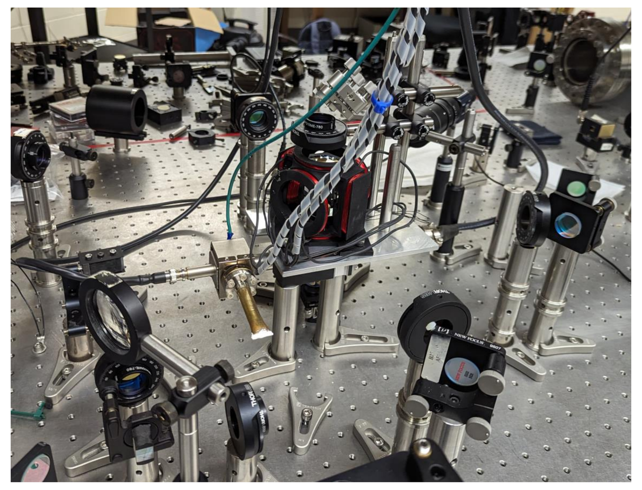
Overview

- Collective quantum effects have been extensively researched since the pioneering work of Dicke [1].
- Rate of spontaneous emission can be enhanced or decreased through the coherent interactions of quantum emitters [2].
- Collective constructive interference of the emissions are named superadiance and the destructive interference of these emitters are named subradiance [3,4].
- Previously these effects have been thought to be present in dense ensembles, however our group recently demonstrated that such effects are still present even in the dilute regime [5,6]. Specifically, a recent work from our lab have experimentally shown that the decay rates can be reduced due to subradiance as much as 20%, inside a dilute cloud at an optical depth of 10−2 or less [6].
- In a recent work [7], An and colleagues have predicted and experimentally demonstrated superabsorption, which can be viewed as the absorptive analog of superradiance. A very recent work from our lab reported the experimental absorptive analog of subradiance [8],
- Essentially, our goal in this work is to observe both super and subradiance and their absorptive counterparts in trapped atom arrays and observe the relationship of these effects to array spacing, array structure, loading rate and temperature.

Current Experimental Setup

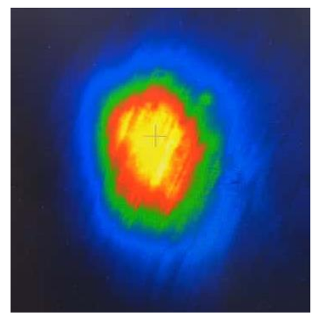
- To cool the ^{87}Rb atoms , we use the D2 line transitions $5^2S_{1/2} \rightarrow 5^2P_{3/2}$ for setting up the MOT in a glass cell. We are using two ECD Lasers, one being a $1.8\Gamma_a$ red detuned from F=2 → F'=3 transition cooling laser and the other being a closely red detuned F=1 → F'=2 repumper laser.
- We calculated our atom numbers to be around 2.000.000.

A picture of doppler cooled MOT from a CMOS camera



A photo of the setup

- To achieve sub-doppler cooling, the cooling beam is further red detuned by $10.72\Gamma_a$ from, F'=3 energy level . We measured the temperature of the Sisyphus cooled MOT to be around $30\mu K$.



A picture of Sisyphus cooled MOT from a EMCCD camera

Super/Sub Radiance Numerical Simulations

- The Hamiltonian of the dipole-dipole interaction and exchange processes is given below: ($\hbar = 1$) [9]

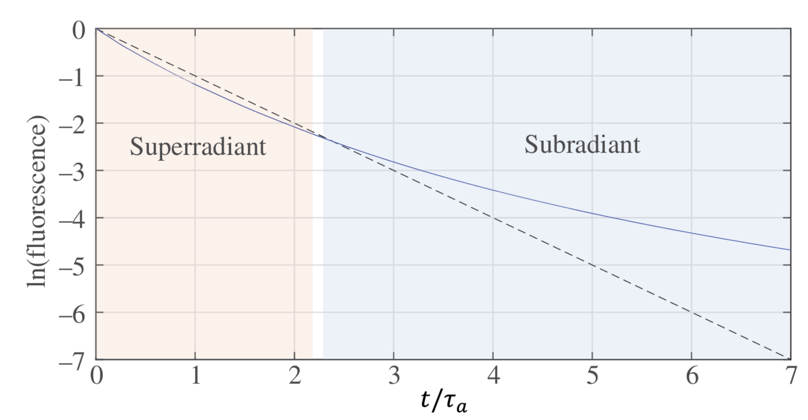
$$\hat{H} = \sum_{j=1}^{N} \frac{\omega_a \hat{\sigma}_z^j}{2} + \sum_{\vec{k},\vec{\epsilon}} \omega_{\vec{k},\vec{\epsilon}} \left(\hat{a}^{\dagger}_{\vec{k},\vec{\epsilon}} \hat{a}_{\vec{k},\vec{\epsilon}} + \frac{1}{2} \right) - \sum_{j=1}^{N} \sum_{\vec{k},\vec{\epsilon}} (g^{*}_{\vec{k},\vec{\epsilon}} e^{\vec{k}\cdot\vec{r}_j} \hat{\sigma}_+^j \hat{a}_{\vec{k},\vec{\epsilon}} + g_{\vec{k},\vec{\epsilon}} e^{-\vec{k}\cdot\vec{r}_j} \hat{\sigma}_-^j \hat{a}^{\dagger}_{\vec{k},\vec{\epsilon}})$$

- By applying the Born-Markov approximation and tracing out the radiation field one can reduce the Hamiltonian into an atomic-only exchange Hamiltonian.

$$\hat{H}_{eff} = \sum_j \sum_k \hat{H}^{jk} \qquad \hat{H}^{jk} = F_{jk} \hat{\sigma}_+^j \hat{\sigma}_-^k + F_{kj} \hat{\sigma}_-^i \hat{\sigma}_+^j \quad ,$$

$$F_{jk} = F_{kj} = -(i\frac{\Gamma}{2})(\frac{3}{8\pi}) \left[4\pi(1-\cos^2\theta_{jk}) \frac{\sin k_a r_{jk}}{k_a r_{jk}} + 4\pi(1-3\cos^2\theta_{jk}) (\frac{\cos k_a r_{jk}}{(k_a r_{jk})^2} - \frac{\sin k_a r_{jk}}{(k_a r_{jk})^3}) \right]$$

- The figure below show the norm of the wavefunction with respect to time. The dashed line is the exponential decay and the different color lines are for different initial positions for atoms. A numerical simulation plot from [6] can be seen below.



References

[1] R. H. Dicke, Coherence in Spontaneous Radiation Processes, Phys. Rev. 93, 99 (1954).
[2] M. Gross and S. Haroche, Superradiance: An Essay on the Theory of Collective Spontaneous Emission, Phys. Rep. 93, 301 (1982)
[3] N. Skribanowitz, I. P. Herman, J. C. MacGillivray, and M. S. Feld, Observation of Dicke Superradiance in Optically Pumped HF Gas, Phys. Rev. Lett. 30, 309 (1973).
[4] W. Guerin, M. O. Araujo, and R. Kaiser, Subradiance in a Large Cloud of Cold Atoms, Phys. Rev. Lett. 116, 083601 (2016)
[5] D. Das, B. Lemberger, and D. D. Yavuz, Subradiance and Superradiance-to-Subradiance Transition in Dilute Atomic Clouds, Phys. Rev. A 102, 043708 (2020).
[6] D. C. Gold, P. Huft, C. Young, A. Safari, T. G. Walker, M. Saffman, and D. D. Yavuz, Spatial Coherence of Light in Collective Spontaneous Emission, PRX Quantum 3, 010338 (2022)
[7] D. Yang, S. Oh, J. Han, G. Son, J. Kim, J. Kim, M. Lee, and K. An, Realization of Superabsorption by Time Reversal of Superradiance, Nature Photonics 15, 272 (2021).
[8] D. C. Gold, U. Saglam, S. Carpenter, A. Yadav, M. Beede, T. G. Walker, M. Saffman, and D. D. Yavuz, Experimental Observation of Subabsorption. Preprint (2025)
[9] D. D. Yavuz, A. Yadav, D. C. Gold, T. G. Walker, and M. Saffman, Numerical study of the spatial coherence of light in collective spontaneous emission, Phys. Rev. A 110, (2024).
[10] P. Huft, Y. Song, T. M. Graham, K. Jooya, S. Deshpande, C. Fang, M. Kats, and M. Saffman, Simple, passive design for large optical trap arrays for single atoms, Phys. Rev. A 105, (2022).

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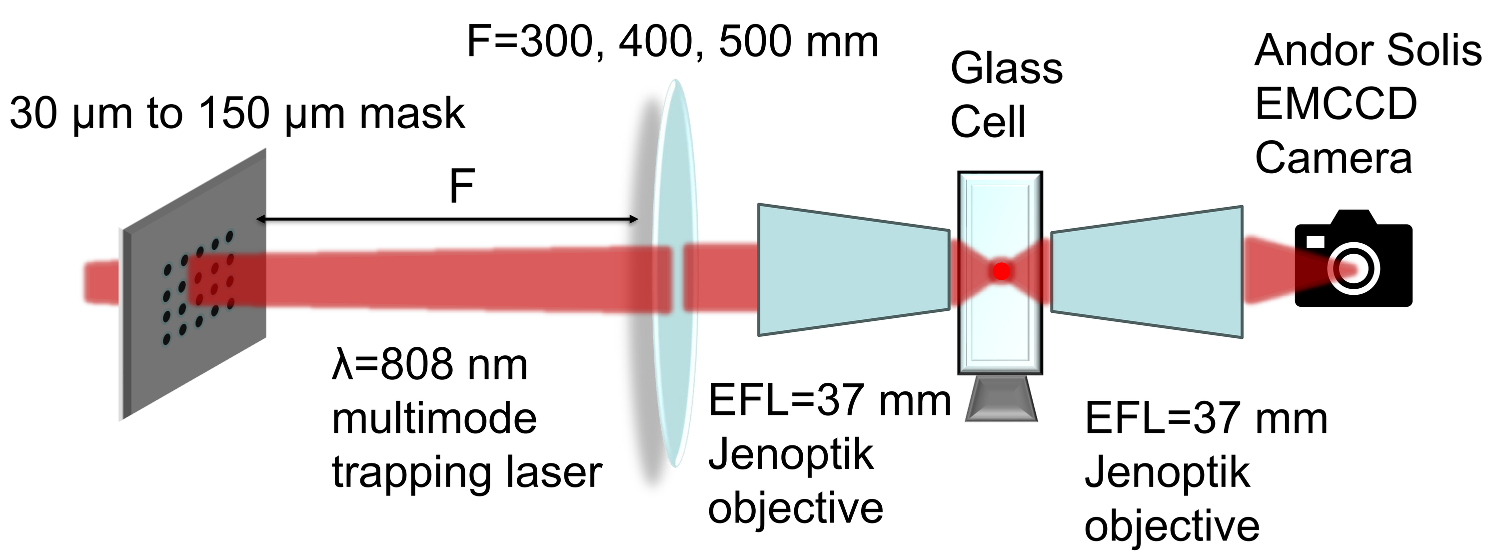
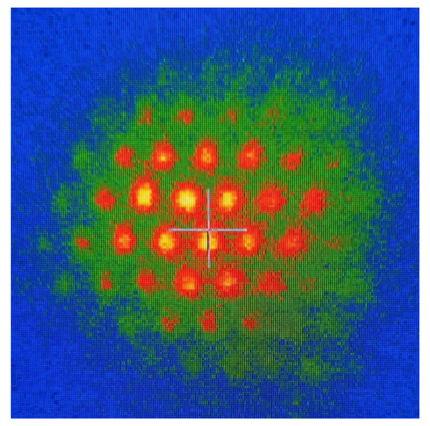
Passive optical trapping scheme and current challenges

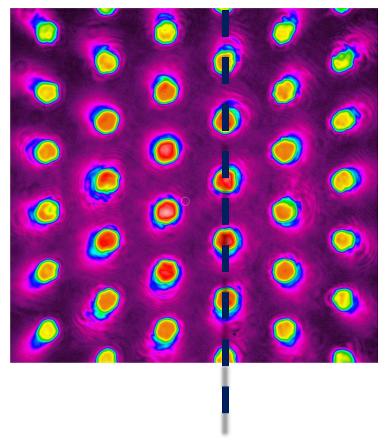


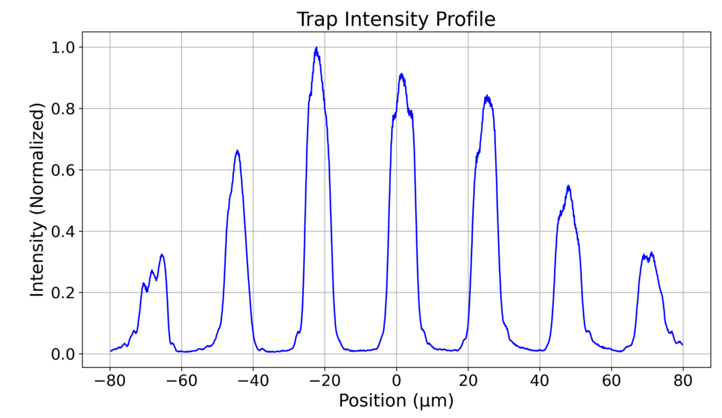
- Our array trapping scheme is based on [10] where the authors propose a passive optical setup where they use amplitude and phase masks to produce a trapping potential for atoms. In our scheme, we are using a λ=808 nm multimode trapping laser to from red detuned traps for Rb87 atoms.

24 µm spacing optical lattice ^{87}Rb traps with λ=808 nm trapping laser wavelength

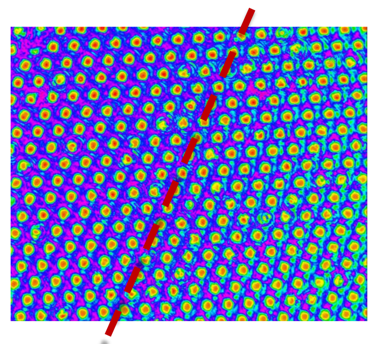


Intensity profile of 24 µm spacing traps

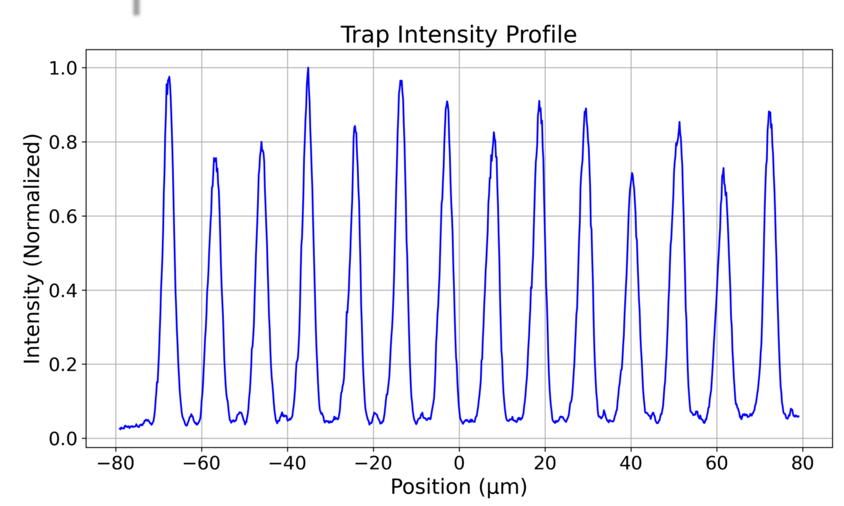




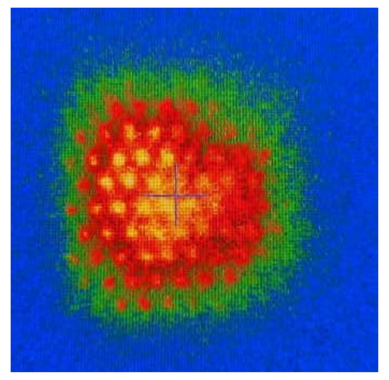
Intensity profile of 10 µm spacing traps



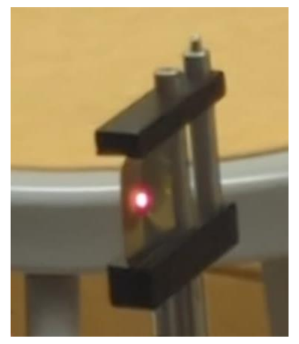
Cross section



14 µm spacing optical lattice ^{87}Rb traps with λ=808 nm trapping laser wavelength



A picture of one of the masks being hit by a 30W laser.

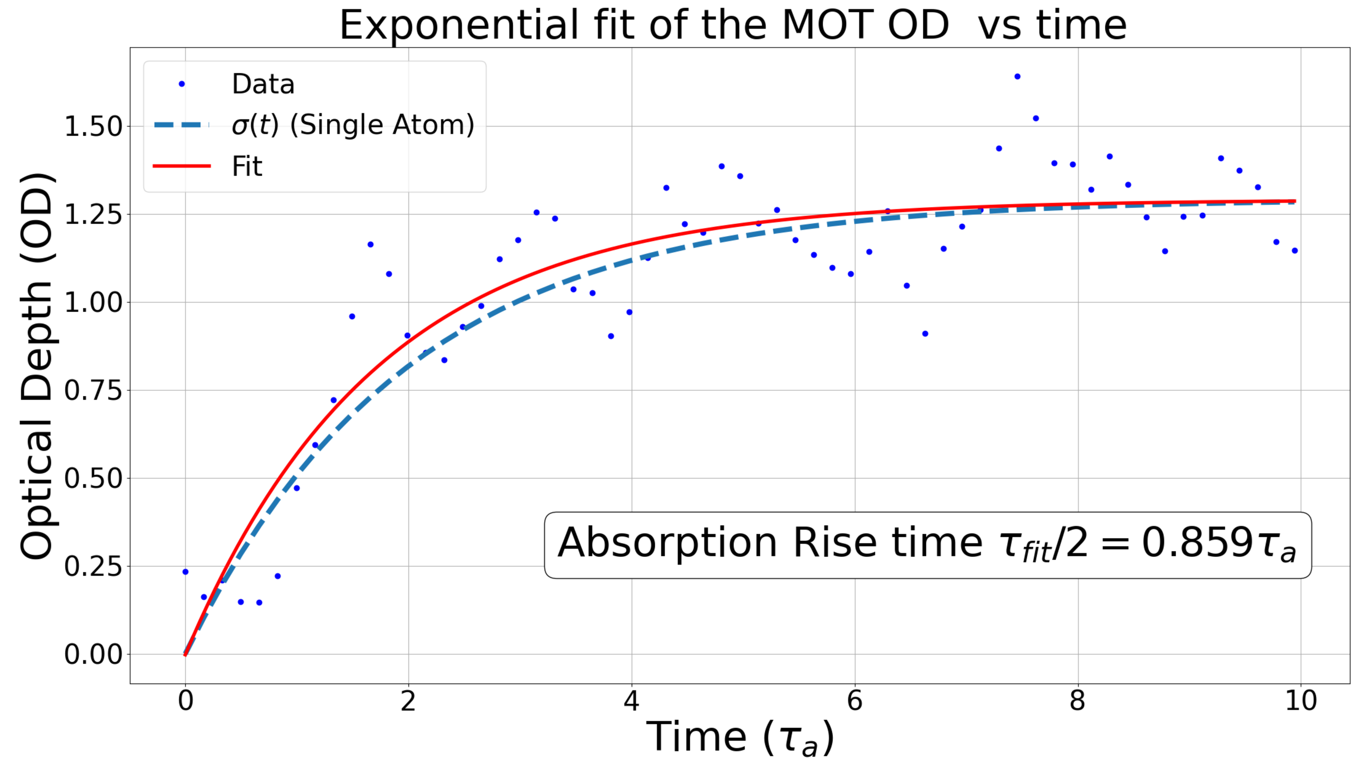


- The plot on the right shows the preliminary optical depth data of the Sisyphus cooled MOT.

$$I_{output}(t) = I_{input}(t) \exp[-\sigma(t)]$$

$$\sigma(t) = \sigma_{ss}\{1 - \exp[-t/(2\tau_a)]\}$$

Exponential fit of the MOT OD vs time



- Currently, we're close to replicate the measurements on refs. [6] and [8] on array structures.