

# **Closeout Memorandum for NRL Base Program 1U83: Rydberg Interactions for Quantum Information Science**

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## EXECUTIVE SUMMARY

This document satisfies the closeout requirements for NRL base program 1U83: Rydberg Interactions for Quantum Information Science. It provides an overview of the technical objectives of the program, technical progress, and dissemination of research findings through publications, reports, and presentations.

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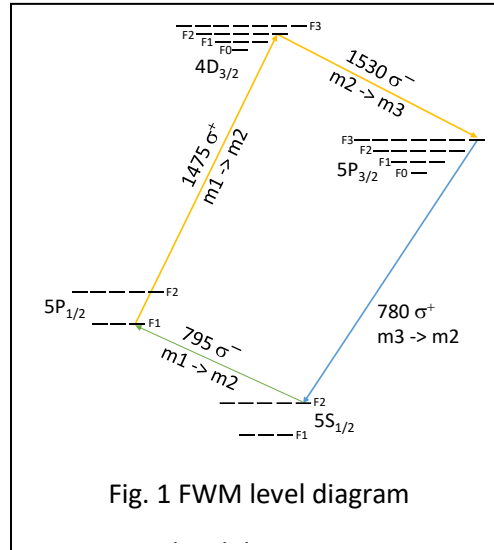
## Close out memo, 1U83: Rydberg Interactions for Quantum Information Science

### 1. PROGRAM DESCRIPTION

Rydberg interactions show great potential for quantum information science. The purpose of this program was to demonstrate unique properties of Rydberg states of neutral atoms such as Rydberg blockade mediated quantum gates and state preparation towards deterministic quantum repeaters. This research will pave the way to a long-sought goal of achieving a scalable quantum repeater for long-distance quantum communication, entanglement and teleportation by dramatically increasing the success probability of entanglement generation and swapping operations. Additional goal was to utilize four-wave-mixing FWM in atomic system to shift single photon frequency between atomic and telecom domains.

#### a. FWM

Quantum networks and quantum communication require quantum states to be transferred over large distances. This can be accomplished by conversion of atomic-wavelength photons to and from telecom wavelengths as fiber-based networks are a key element for propagation of quantum information and many proposed and demonstrated quantum memories or devices are based on photons created on atomic transitions. Previously, a conversion efficiency of 54% between atomic wavelengths and 1.3  $\mu\text{m}$  photons has been demonstrated in an ultra-dense cold atomic ensemble [1]. In this program we demonstrated a much simpler technique using four-wave mixing (FWM) in warm atomic vapor to frequency convert of 795nm photons at atomic wavelength to 1535nm photons at telecom wavelength for transmission in the fiber. Previously we demonstrated conversion of telecom frequency photons at 1530 nm to atomic frequency photons at 795nm [2]. In this program we demonstrated the inverse conversion process. Atoms in the warm Rb cell are initially optically pumped to  $F=2$ ,  $mF=2$  state to create a dense optical sample for the FWM process by judicious choice of pump and signal polarizations as well as atomic states and pulse durations. 795 nm photons (Rb  $5S_{1/2} \rightarrow 5P_{1/2}$  transition) are converted to 1530 nm (Rb  $4D_{3/2} \rightarrow 5P_{3/2}$ ) in the FWM process with pump beams at 1475 nm (Rb  $5P_{1/2} \rightarrow 4D_{3/2}$  transition) and 780 nm (Rb  $5S_{1/2} \rightarrow 5P_{3/2}$  transition), as depicted in Fig. 1. The intensities of both pump beams are chosen so that they have same the Rabi frequencies on their respective transitions. Converted 1530 nm photons are detected by single photon detector. We observe that for longer FWM pulses the conversion efficiency saturates at high Rabi frequencies. By time gating the measurement to the initial 20 ns of the pump pulse, the conversion reaches 6% at a pump Rabi frequency of  $2\pi$  250 MHz. The limiting factors for the conversion are the powers of the pump lasers and population redistribution in the magnetic sublevels of the ground state.



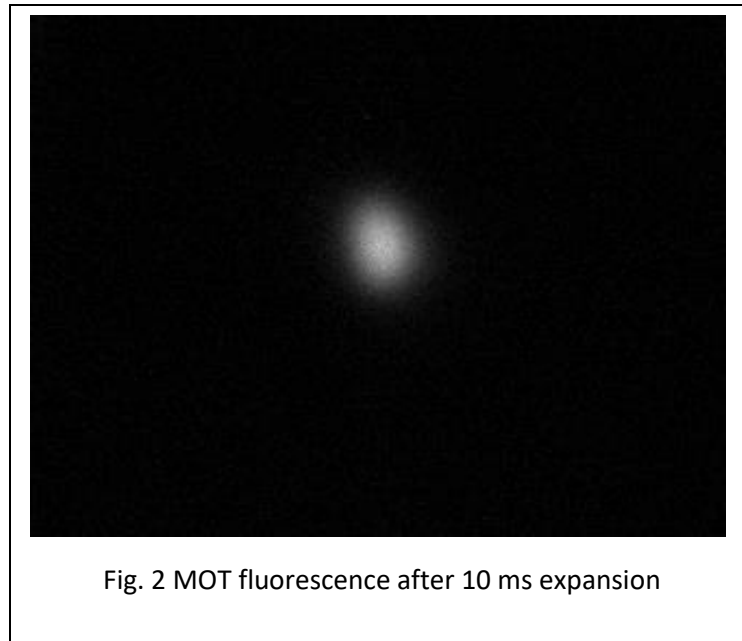
[1] A. G. Radnaev, Y.O. Dudin, R. Zhao, H. H. Jen, S. D. Jenkins, A. Kuzmich, and T. A. B. Kennedy, Quantum memory with telecom wavelength conversion, Nature Physics 6, 894 (2010).

[2] M. J. Piotrowicz, A. Black, and M. Bashkansky, "Conversion from Telecom to Atomic Photons by Four-Wave Mixing in a Warm Rb Cell," in Conference on Lasers and Electro-Optics, OSA Technical Digest (Optical Society of America, 2020), paper FW4C.4.

### b. MOT

Cooling and trapping atoms in a magneto optical trap (MOT) is the first step in this program. In order to accomplish this we assembled and stabilized laser systems to Rb transitions. This includes 780nm laser to cool and trap atoms in MOT, 795nm repump laser, 1475nm pump laser used for atomic-telecom wavelength conversion and frequency doubled 960nm laser at 480nm to address Rydberg states. All lasers were stabilized using optical frequency comb. We automated laser stabilization of 780 nm, 795 nm and 480 nm lasers, needed for MOT and for Rydberg states. This replaced complicated manual process with a push of a button. This also includes audio announcement of a fault condition.

We setup laser trapping and cooling of Rb in two-stage Cold Quanta MOT. The size of the MOT is  $\sim 1.2\text{mm}$  and we are collecting  $\sim 5 \times 10^7$  atoms per second. We measured temperature of atoms in the MOT of  $22\mu\text{K}$  in Horizontal and  $15\mu\text{K}$  in Vertical directions by extinguishing trapping fields and measuring expansion of trapped atoms in freefall. Figure 2 shows fluorescence from the atoms after expansion of 10ms.



#### c. Rydberg spectroscopy

We used ladder type electromagnetic induced transparency (EIT) in a warm Rb cell to determine correct high- $n$  Rydberg frequencies. We locked 780nm laser to a well-known  $5S_{1/2}$ - $5P_{3/2}$  transition and scanned 480 nm laser about  $n=57$   $D_{3/2}$  and  $D_{5/2}$  transitions and about  $n=100$   $D_{3/2}$  and  $D_{5/2}$  transitions. Reduced absorption of 780 light on resonance due to EIT allowed us to determine Rydberg transition frequencies. We compared our measured results with the calculations based on the public domain software alkali Rydberg calculations (ARC) and found discrepancies that are worse for higher  $n$  Rydberg levels.

#### d. Dipole trap

Quantum gates essential for quantum information science require very small size trapped atomic clouds. We accomplished this using optical dipole trap created by tightly focused single frequency 1.064nm crossed laser beams. We measured the sized of the dipole trapped atoms to be  $\sim 10 \times 20 \mu\text{m}$ . Figure 3 shows Rb87 atoms trapped in our crossed beams dipole trap. We imaged the dipole trapped atoms after approximately 50ms needed for the un-trapped Rb87 atoms to drop due to the gravity. We measured temperature of optical dipole trapped atoms of  $\sim 15\mu\text{K}$  in horizontal direction and  $\sim 50\mu\text{K}$  in vertical direction. This was done by measuring the cloud size during expansion without trapping fields. The weak probe beam must be aligned with the small optical dipole trapped atomic cloud. We demonstrated an alignment technique by pushing equal number of atoms into two legs of the crossed dipole beams by increasing power of the probe beam. Figure 4 illustrates this technique by showing fluorescence from the pushed atoms. Equal number of atoms in two legs signifies near perfect alignment.

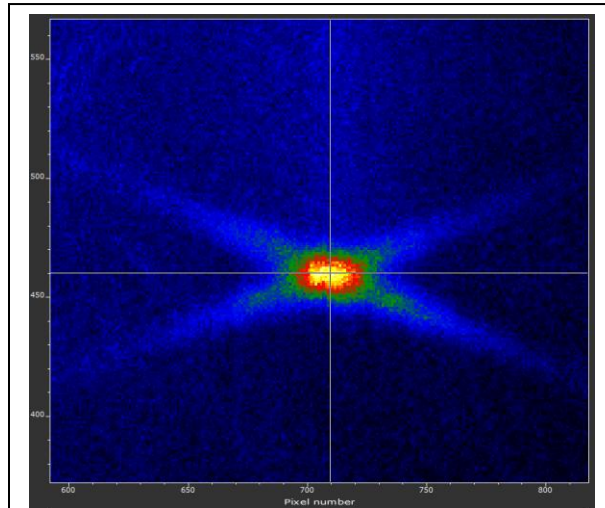


Fig. 3 Dipole trapped atoms (weak probe).

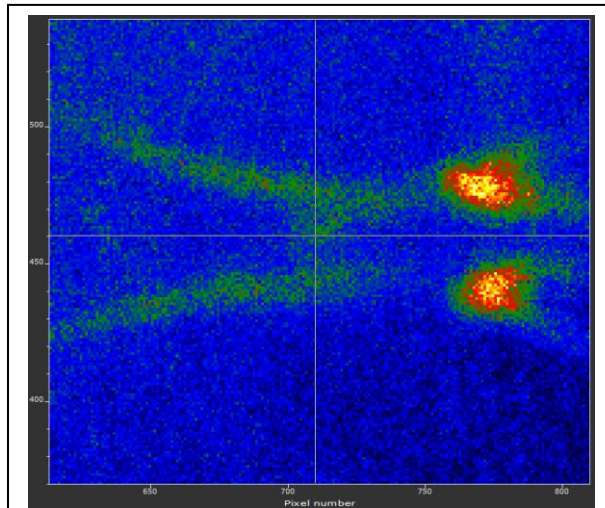
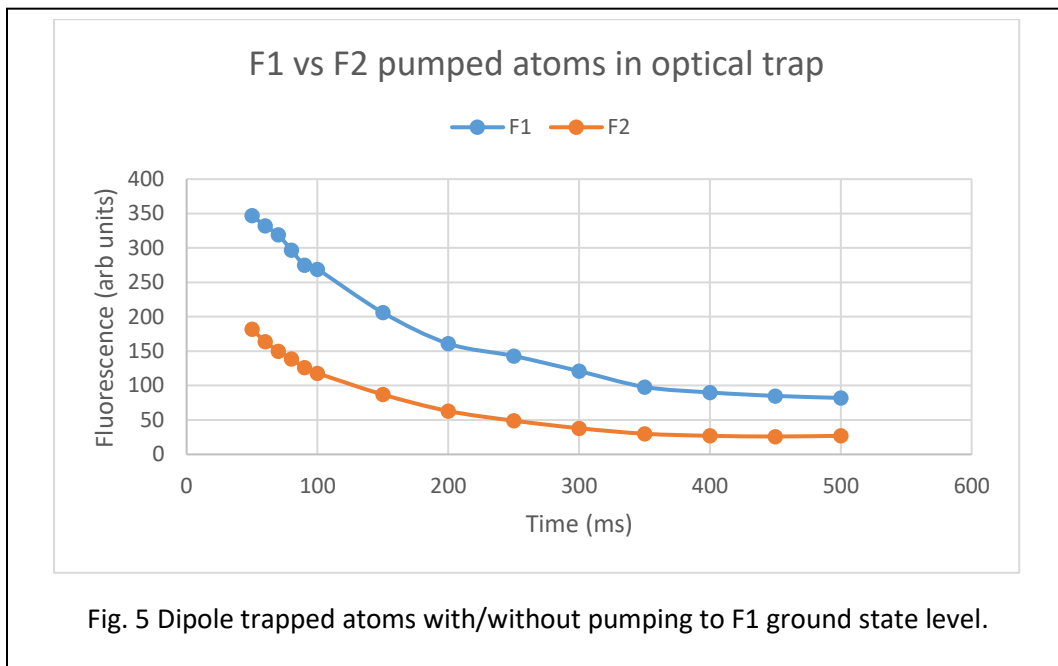


Fig. 4 Dipole trapped atoms (strong probe).

e. F1 pumping

After MOT stage Rb87 atoms are left in F2 upper ground state. Optically pumping atoms to the F2m2 dark state reduces atom heating as compared to pumping to any other state. However, atomic collisions in the upper F2 ground state in an optical dipole trap were previously demonstrated to reduce the number of atoms in the dipole trap by allowing them to escape from the trap by transitioning to the lower ground state [3]. To reduce this escape mechanism we pumped atoms to F1 ground state at the beginning of the adjustable wait period. At the end of the wait period we pumped trapped atoms back to the upper F2 ground state. By observing fluorescence for a very short time after pumping atoms back to F2 level and turning off dipole trapping beams we demonstrated doubling of the number of atoms in the trap. Figure 5 shows increase in the number of the trapped atoms after they are pumped to the F1 level during the wait time.



[3] Advances In Atomic, Molecular, and Optical Physics Volume 42. Series: Advances In Atomic, Molecular, and Optical Physics, ISBN: 9780120038428. Elsevier, vol. 42, pp. 95-170

f. Rydberg EIT

Ladder type electromagnetic induced transparency (EIT) using Rydberg states in optically trapped atoms is important for various effects such as nondestructive Rydberg excitation detection and deterministic single photon generation from the optical dipole trapped atoms. In order for EIT to be effective, significant absorption of the 780nm probe has to take place when control 480nm beam is not present. We demonstrated increased probe absorption in  $10\mu\text{m} \times 20\mu\text{m}$  dipole trapped atomic cloud (due to increase of trapped atoms) with pumping to F1 level as described above. Using increased number of dipole-trapped atoms we were able to

demonstrate EIT using  $n=57$  Rydberg state. Currently our focused probe beam at 780nm (but not 480nm control beam) is slightly larger than the trapped atomic cloud. Therefore, to demonstrate EIT, we allowed Rb87 cloud to expand by turning off dipole beams for  $\sim 125\mu\text{s}$ . By better focusing 780nm beam we expect to see significant improvement in EIT process and to enable use of higher Rydberg levels which is necessary for Rydberg blockade. Figure 6 demonstrates EIT effect by showing histograms of probe transmission in dipole trap with (EIT) and without (no EIT) control beam at 480nm present.

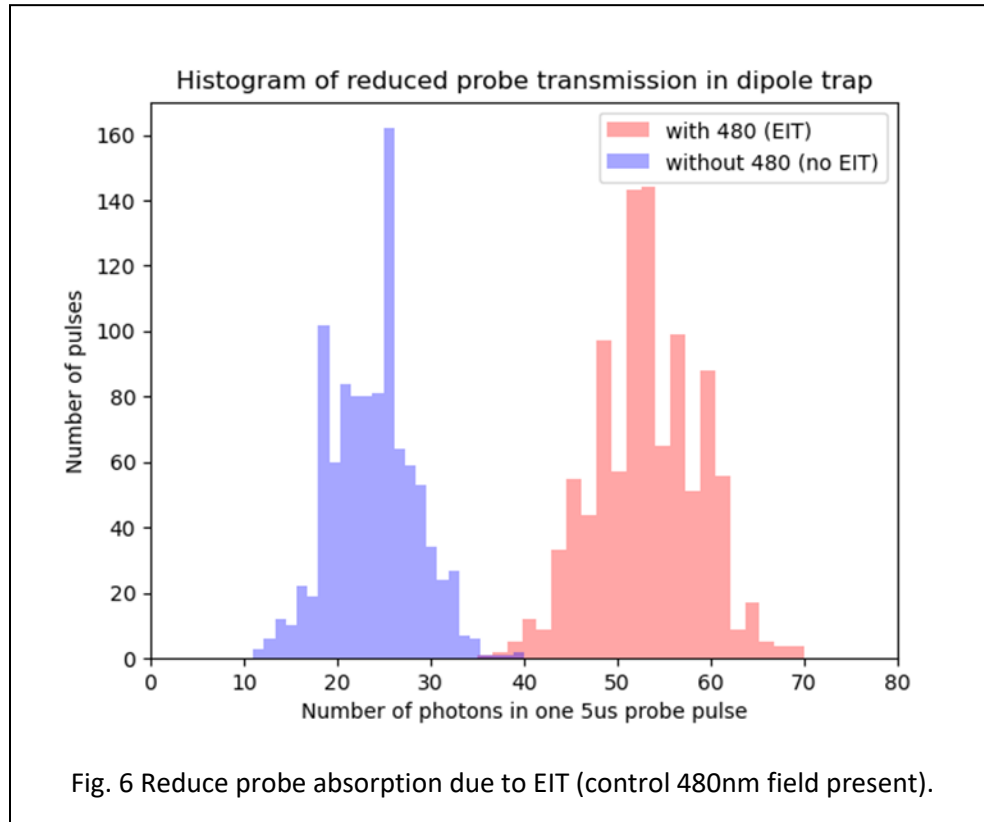


Fig. 6 Reduce probe absorption due to EIT (control 480nm field present).

## 2. DISSEMINATION

### g. Book chapter

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<https://onlinelibrary.wiley.com/doi/book/10.1002/047134608X>

#### h. Conference presentations

M. J. Piotrowicz, A. Black, and M. Bashkansky, "Conversion from Telecom to Atomic Photons by Four-Wave Mixing in a Warm Rb Cell," in Conference on Lasers and Electro-Optics, OSA Technical Digest (Optical Society of America, 2020), paper FW4C.4.

Jonathan Kwolek, Adam Black, and Mark Bashkansky, *Frontiers in Optics + Laser Science 2021 Technical Digest Series* (Optica Publishing Group, 2021), <https://doi.org/10.1364/FIO.2021.JTh5A.8>

J.M. Kwolek, A.T. Black, M. Bashkansky, "Conversion from atomic to telecom photons by four-wave mixing in optically pumped warm Rb", *FiO-LS*, Washington, DC United States, 2021 ISBN: 978-1-55752-308-2