Biphoton Polarization Entanglement Based on Cold Atom Ensemble

PI: Shengwang Du
Presenter: Ian Jack
Graduate Students: Adi Bhatnagar, Stephen Wang, Xuanying Lai, Christopher Li

Abstract

This project aims to generate narrowband entangled photon sources as building blocks for quantum networks and quantum computing. We use spontaneous four-wave mixing (SFWM) in cold atomic ensembles to produce momentum-entangled photon pairs, which are later converted into polarization entanglement using waveplates and beam displacers. The SFWM process inherently features an embedded electromagnetically induced transparency (EIT) structure, which enhances nonlinear interaction efficiency, increases photon-pair generation rate, and enables narrow-bandwidth photon pairs.

A high optical depth (OD) atomic ensemble is crucial since both photon-pair generation rate and coherence time scale proportionally with OD. In our setup, a two-dimensional dark-line magneto-optical trap (MOT) cools and traps ^{87}Rb atoms, serving as the nonlinear medium. OD is determined by atomic density and ensemble length. By removing the magnetic field gradient along the z-axis, the atomic cloud elongates, increasing the interaction length and thus OD.

To raise atomic density, a dark-line repump beam is applied to reduce atom reheating caused by fluorescence scattering from the trapping beams. In addition, depopulation and decoupling optical pumping techniques efficiently transfer atoms to the desired ground state. With these optimizations, we achieve OD = 154, corresponding to more than 10^8 atoms within an ensemble of 1.7 cm length and 400 µm width, providing a high-quality medium for efficient, narrowband entangled photon generation.

MOT Principles

The magneto-optical trap (MOT) houses neutral atoms at micron-Kelvin (µK) and ultra-high vacuum conditions for a high optical depth (OD) system. High density of trapped neutral atom density corresponds to higher OD (exhibited by measurement of the wave equation [Equation 1]) , which is improved in 2D MOT setups relative to 3D MOTs by opening space along the zero-field line for trapping. An MOT configured effectively for EIT prefers high-OD due to increased strength of photon-atom coupling interactions in cold atoms. A combination of lasers and magnetic fields facilitates trapping and cooling by introducing a position-based restoring force along the x and y directions.

$$\frac{1}{\sqrt{N_A}}\sum_{k=1}^{N_A} e^{i(\mathbf{k}_w+\mathbf{k}_s)\mathbf{x}_k}|g_1\rangle_1|g_1\rangle_2\cdots|g_2\rangle_k\cdots|g_1\rangle_{N_A} \quad (1)$$

$$\gamma_p = \frac{s_0\frac{\gamma}{2}}{1+s_0+\left(2\frac{\delta+\omega_D+\omega_Z}{\gamma}\right)^2} \quad (2)$$

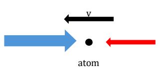

Figure 1: Visualization of laser cooling on a single atom.

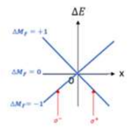

Figure 2: Visualization of the Zeeman shift as a function of position.

Biphoton Generation via SFWM

What is spontaneous four-wave mixing (SFWM)?
Four-wave mixing (FWM) is a third-order nonlinear process where two classical fields (coupling and pump) interact in a medium to generate two new fields (Stokes and anti-Stokes). In the spontaneous case, the generated photons arise spontaneous scattering.

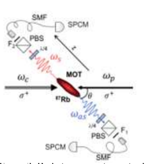

Figure 3: Biphoton-generation setup1

Where does entanglement come from?
Due to space and time symmetry system, we have momentum and energy conservation, which induces the phase matching condition:

$$(\vec{k}_c-\vec{k}_p+\vec{k}_s-\vec{k}_{as})\cdot\hat{z}=0 \qquad \omega_c+\omega_p-\omega_s-\omega_{as}=0$$

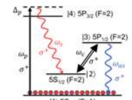

Figure 4: Level Diagram

2D Dark Line MOT Realization

To further increase trapped atom density, a dark line of the repump beam is imaged to the MOT center to prevent trapping beam fluorescence from disturbing the cooled and trapped atoms.

With the help of depopular and decouple to pump atoms from F=2 to F=1 ground state, we are able to realize OD = 154, which means more than10^8 atoms are trapped within the MOT (L = 1.7cm, W = 0.4cm).

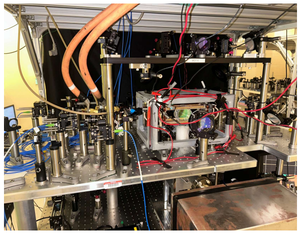

Figure 5: Setup of 2D MOT

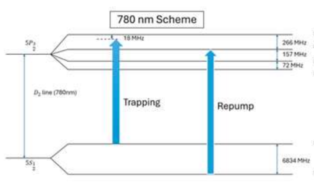

Figure 6: 780nm Energy Level Scheme

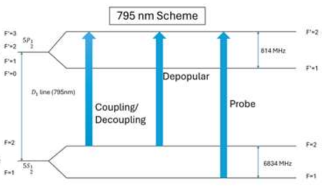

Figure 7: 795nm Energy Level Scheme

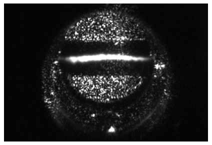

Figure 8: Image of 2D Dark Line MOT Fluorescence

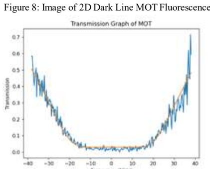

Figure 9: Optical Depth of 2D Dark Line MOT

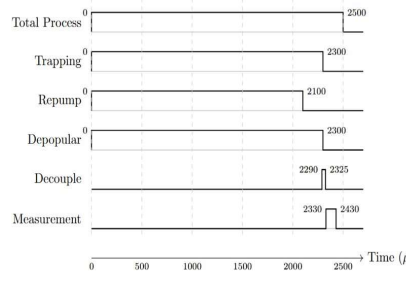

Figure 10: Timing Sequence for Dark Line 2D MOT

EIT Implementation

By strongly driving the $5P_{\frac{1}{2}}$ transition with a strong coupling beam, there is a much weaker interaction between the probe and trapped Rb atoms. When at the resonant frequency, the beam will pass through the MOT with a heavy refractive index. This creates a slow group velocity with high dispersion, inducing longer coherence times.

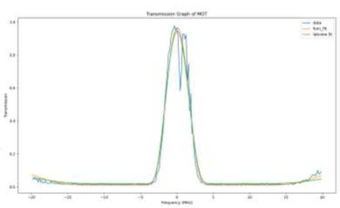

Figure 11: Fitting of Transmission Graph with EIT

$$\alpha+\beta e^{\frac{-OD*3*((\Delta-\delta p-\delta c)*(3*(\Delta-\delta p-\delta c)+\gamma_{12}*(\Delta-\delta p))+\gamma_{12}*(\frac{(\Omega_c^2)}{4}-(\Delta-\delta p*(\Delta-\delta p-\delta c+3*\gamma_{12}))))}{(\frac{(\Omega_c^2)}{4}-(\Delta-\delta p)*(\Delta-\delta p-\delta m+3*\gamma_{12})^2+(3*(\Delta-\delta p-\delta m)+\gamma_{12}*(\Delta-\delta p))^2}}$$

Polarization Entanglement Biphoton

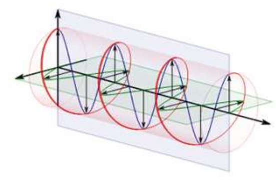

Figure 12: Illustration of Polarization in EM Waves

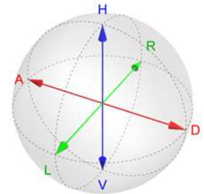

Figure 13: Bloch Sphere used for characterizing Polarization

Another entanglement? Why?
We choose to encode qubits using polarization entanglement because it allows straightforward implementation of single-qubit gates with simple optical elements such as waveplates.

How to convert momentum entanglement into polarization entanglement?
By the momentum-matching condition, the biphotons propagate in opposite directions. Using waveplates to manipulate polarization, lenses to collimate the beams, and a beam displacer to combine H and V polarizations, we generate a polarization-entangled state $\frac{1}{\sqrt{2}}(|HH\rangle+|VV\rangle)$.

How to evaluate the fidelity?
To evaluate the fidelity of the generated state, we perform quantum state tomography by projecting the biphotons onto different polarization bases. Using maximum likelihood estimation, we reconstruct the density matrix, from which the state fidelity can be calculated.

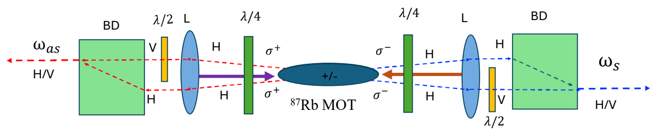

Figure 14: Polarization Entanglement Configuration

Next Steps

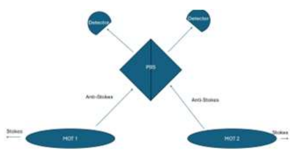

Figure 15: Polarization Swapping Configuration

- Verify polarization entanglement
- Demonstration entanglement swapping
- Verification using quantum tomography
- Characterization of loading time for a 2D MOT

References:
1. Xuanying Lai, Christopher Li, Alan Zanders, Yefeng Mei, and Shengwang Du, "Symmetry Protected Two-Photon Coherence Time," Phys. Rev. Lett. 133, 033601 (2024).
2. Luwei Zhao, Yumian Su, and Shengwang Du, "Narrowband biphoton generation in the group delay regime," Phys. Rev. A 93, 033815 (2016).
3. Shengwang Du, Jianming Wen, and Morton H. Rubin, "Narrowband biphoton generation near atomic resonance," J. Opt. Soc. Am. B 25, C98 (2008).
4. Shengwang Du, Yufei Ding, and Chunming Qiao, "S-QGPU: Shared quantum gate processing unit for distributed quantum computing," AVS Quantum Sci. 7, 013803 (2025).