Biphoton Polarization Entanglement Based on Cold Atom Ensemble

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Abstract

Distributed quantum computing networks promise to overcome the scalability limitations of individual quantum processors by connecting multiple quantum computers through entangled photon channels. We demonstrate a pathway toward such networks by generating momentum-entangled photons via spontaneous four-wave mixing and converting them to polarization-entangled states suitable for quantum communication protocols. Our system employs a 2D dark line MOT to produce entangled photon pairs with a narrow bandwidth (<50kHz) which is essential to interfacing with building blocks in quantum repeaters (quantum memories) and local quantum computers (atomic gates).

Background

Quantum networks are connections across potentially long physical distances between qubits. In this project, photon qubits are chosen because of the speed of information transport they offer and minimal interaction with their environment. Ionic qubits or neutral atom qubits are more difficult to transport over any distance. Using entanglement, quantum networking can share information over arbitrary distances in principle. However, photons experience loss in fiber cables, so quantum repeaters must be used to preserve quantum coherence. The 2D Dark Line MOT was chosen as the quantum repeater for its straightforward construction, reliable quantum memory, and repeatable photon emission using a Rydberg Blockade.

Quantum computing makes use of superposition and entanglement properties to execute some tasks exponentially faster than traditional computing. However, by increasing the number of qubits, the cost of creating a local quantum computer increases exponentially. Using a quantum network can realize distributed quantum computing with a decreased cost.

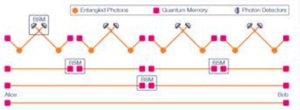

Figure 1: Quantum Network with quantum repeaters

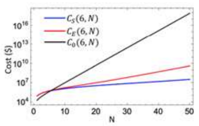

Figure 2: Cost in distributed versus local quantum computing

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, influenced by the Doppler effect and the Zeeman shift of the neutral atoms.

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

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

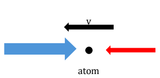

Figure 3: Visualization of laser cooling on a single atom.

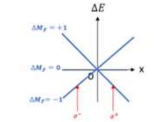

Figure 4: Visualization of the Zeeman shift as a function of position.

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).

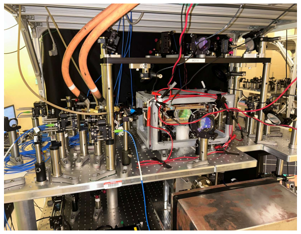

Figure 5: Setup of MOT

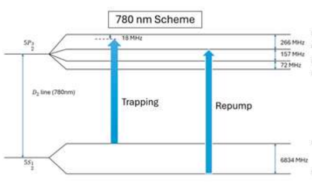

Figure 6: 780nm Energy Level Scheme

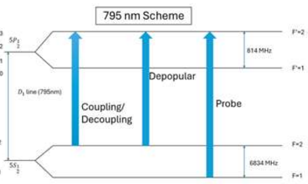

Figure 7: 795nm Energy Level Scheme

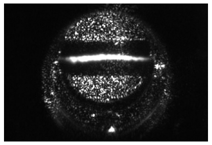

Figure 8: Image of 2D Dark Line MOT Fluorescence

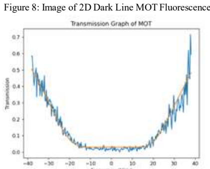

Figure 9: Optical Depth of 2D Dark Line MOT

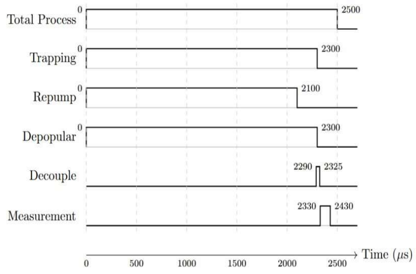

Figure 10: Timing Sequence for Dark Line 2D MOT

Biphoton Generation via SFWM

What are biphotons?
Biphotons mean entangled photon pairs.

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.

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

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

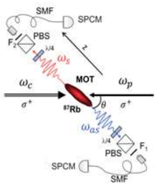

Figure 11: Biphoton-generation setup1

Biphotons Enhanced by High OD

Higher generation rate
High OD increases four-wave mixing efficiency through the collective effect.

Narrower bandwidth
High OD narrows the EIT window, yielding biphotons with longer coherence and reduced spectral width.

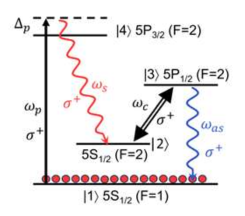

Figure 12: Level Diagram

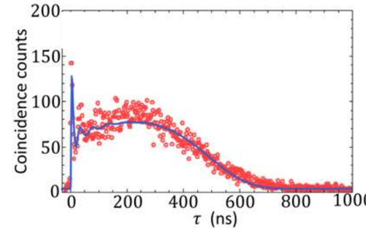

Figure 13: Coincidence Counts with 10min measurement time and 2ns time bin

Polarization Entanglement Biphoton

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.

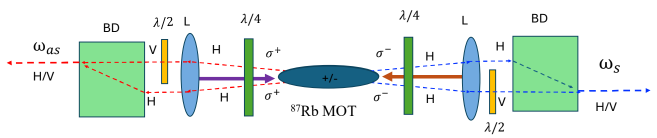

Figure 14: Polarization Entanglement Configuration

References:

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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).