# A Source of Correlated Photons and Atoms


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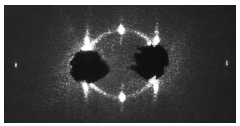
## Motivation

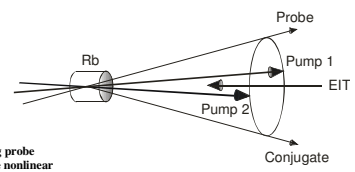
The emerging ability of laboratories to control matter at the quantum level has led to two technologies of interest to the Intelligence Community. The first is ***quantum computation***, which exploits quantum parallelism to mount strong attacks on conventional cryptographic schemes. The second is ***quantum cryptography***, which uses the principle of quantum entanglement to prevent undetected eavesdropping on encrypted communications.

Both technologies would benefit from techniques to generate robust entanglement between matter and light. I am working to construct a source of entangled, or "correlated" photons that is based on **four-wave mixing** in atomic vapors. These photons should be ideal for interacting with, and transferring entanglement to, samples of quantum degenerate atoms such as those in a **Bose-Einstein condensate (BEC)**.

## Two-beam-excited conical emission

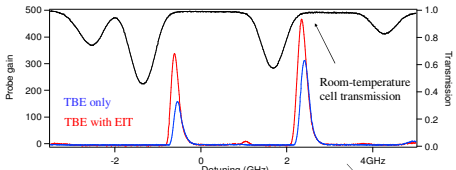
My initial scheme to produce correlated photons was based on two-beam-excited conical emission (TBE) in rubidium vapor. I combined TBE with electromagnetically induced transparency (EIT) to enhance nonlinear beam coupling. Unfortunately, spontaneous emission prevents this type of system from producing significant correlations.



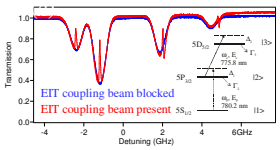



**ABOVE: TBE conical emission with stimulating probe and generated conjugate beams. Also visible are nonlinear Bragg diffraction spots. RIGHT: Experiment geometry.**

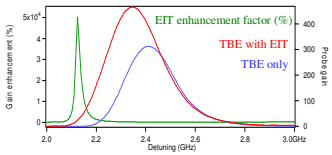
**RIGHT: TBE gain process without (blue) and with (red) EIT. BELOW: Ladder-scheme EIT, with a maximum absorption reduction of ~70%. BELOW RIGHT: TBE gain enhancement factor due to EIT, with a maximum of 50,000%.**




Temperature = 158C, Length = 8mm
EIT coupling beam @ 775.7741nm
Probe = 2 μW, Pump = 365 mW/beam

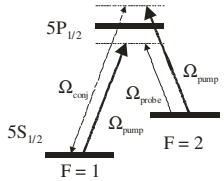



Temperature = 50C, Length = 8mm
EIT coupling beam @ 775.7760nm



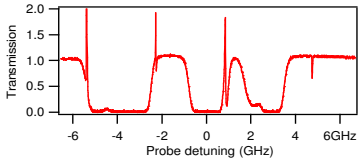

## Quantum coherence and dark states

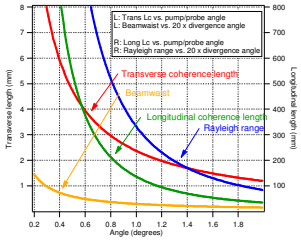
EIT helps reduce spontaneous emission by reducing the amount of time each atom spends in an excited state. With ideal EIT, the atom is placed into a perfect superposition of two long-lived ground states and never spontaneously decays.




Using a single pump and a copropagating probe beam, I have observed four-wave mixing based on a three-level system. The pump provides two photons, which induce gain on the probe and generate a copropagating conjugate beam.

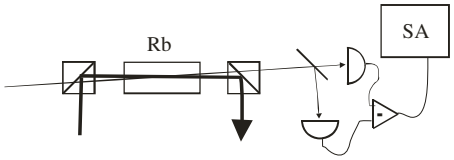
RIGHT: Probe scanned around D1 line or Rb with pump at -2 GHz. Gain at -5.5 GHz corresponds to the level scheme above, while for the gain at 1 GHz the roles of probe and conjugate are reversed.



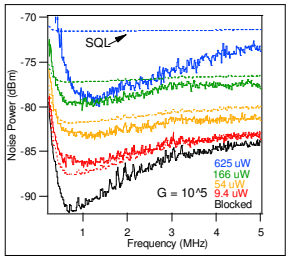

ABOVE: Phase-matching (momentum conservation) criteria for the lambda-scheme four-wave-mixing process. Both longitudinal and transverse phase-matching must be considered. Given realistic numbers, the vapor length cannot exceed ~ 10 cm. BELOW: The experimental setup, including the balanced photoreceivers and the spectrum analyzer (SA) used to detect relative intensity squeezing.

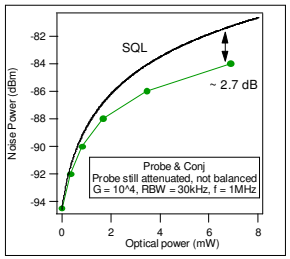
The gain in this nonlinear process depends strongly on pump intensity and the small angle between pump and probe. Because the atoms spend most of their time in the ground hyperfine levels, spontaneous emission is suppressed and the probe and conjugate are more likely to emerge from the near-resonant vapor without being rescattered by the atoms.



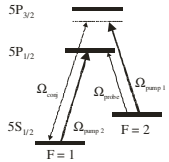
## Relative intensity squeezing

The probe and conjugate beams produced by this lambda-scheme four-wave mixing are bright (up to several mW) and thus any correlations between photons in the two beams should appear as a reduction in their relative intensity noise, i.e. relative intensity squeezing. To detect this I use a balanced photoreceiver calibrated to the standard quantum limit (SQL, a.k.a. shot noise) by an unamplified probe beam. For certain detunings, I observe up to several dB of squeezing below the SQL, evidence of **bright-beam photon correlations**.




ABOVE LEFT: Spectrum of relative intensity noise power for various total output optical powers. Dashed lines are the standard quantum limit (SQL). ABOVE RIGHT: Evidence of intensity squeezing at 1 MHz. LEFT: An alternate level scheme involving independent pump lasers which may provide even better squeezing and photon correlations.

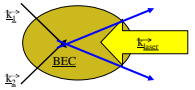



## Correlated atom lasers

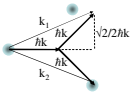
Our goal is to use this source for a **correlated Raman output coupler** for a BEC. Raman output coupling has already been used in our lab to produce an atom laser. A correlated Raman output coupler could produce correlated atom laser beams, for use in sub-shot-noise atom interferometry, quantum computation, Bell's inequality experiments, etc.

**Stimulated Raman transition**

Correlated photons in




Twin beams of atoms out




**Momentum transfer**

**NIST's Atom Laser:**
E. Hagley et al., Science **283**, 1706 (1999)

**Correlated atoms concept:**
P. Lett, J. Mod. Opt. **51**, 1817 (2004)