Engineering of correlated photon pairs via interaction between Rydberg atoms during the storage of slow light

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Rydberg atoms

Rydberg atom

A Rydberg atom is an excited atom with an electron in a state with a very high principal quantum number $n \geq 50$. 
Distinctive properties of Rydberg states:

- an enhanced response to electric and magnetic field
- long decay times
- electron wavepackets move along classical orbits
- excited electron experiences Coulomb electric potential
- radius of an orbit scales as $n^2$
- energy level spacing decreases as $1/n^3$
Interactions between Rydberg atoms

- Transition dipole moment to nearby states scales as $n^2$
- **Strong** dipole-dipole interactions
- The interaction strength rapidly increases with $n$;
- The strength of interactions for $n \gtrsim 100$ can be comparable to the strength of the Coulomb interaction between ions.
- Can be used for engineering of desired many-particle states.
Dipole blockade

- If one atom is excited into the Rydberg state
  - strong interaction shifts the resonance frequencies of all the surrounding atoms
  - suppressing their excitation.
- Rydberg blockade can be applied in
  - quantum information processing
  - non-linear quantum optics using Rydberg EIT
Cycling at the speed of light?
Three level Λ system

Probe beam: $\Omega_p = \mu_{ge} E_p$
Control beam: $\Omega_c = \mu_{ge} E_c$
Three level $\Lambda$ system

- **Dark state**
  \[ |D\rangle \sim \Omega_c |g\rangle - \Omega_p |s\rangle \]

- Transitions $g \rightarrow e$ and $s \rightarrow e$ interfere destructively
- Cancelation of absorption
- **Electromagnetically induced transparency**—EIT
- Very fragile
- Very narrow transparency window

![Diagram of three level $\Lambda$ system with levels $g$, $e$, and $s$ connected by $\Omega_c$ and $\Omega_p$.]
- Narrow transparency window: $\Delta\omega \sim 1\, \text{MHz}$
- Very dispersive medium
- Small group velocity — slow light
EIT → atom-light interactions without absorption
Rydberg states → strong long-range atom-atom interactions
As a result → photon-photon interactions.
For a single incident probe photon

- the control field induces a transparency in a narrow spectral window via EIT
- probe photon is coupled to Rydberg excitation forming a combined quasiparticle — Rydberg polariton
- Rydberg polariton propagates at a reduced speed $\ll c$
When two probe photons propagate in the Rydberg medium

- strong interaction between two Rydberg atoms tunes the transition out of the resonance
- destroying the transparency and leading to absorption.
Experimental realization of quantum nonlinear optics


$46 \leq n \leq 100$
Disadvantage of Rydberg EIT

Only one photon propagates without absorption in the Rydberg blockade region. All additional photons are absorbed leading to losses.

Our proposal
To use atom-atom interactions during light storage.
Storing of slow light

Hau et al., Nature, 2001
Storing of slow light

- Dark state

\[ |D\rangle \sim |g\rangle - \frac{\Omega_p}{\Omega_c} |s\rangle \]

- Information on probe beam is contained in the atomic coherence

- Storing of light — switching off control beam; information about light is retained in the atomic coherence

- Releasing — switch on control beam
Ladder scheme with the Rydberg state \( s \)

Storing procedure:
1. Probe field is stored in a coherence between ground state \( g \) and Rydberg state \( s \)
2. \( \pi/2 \) pulse is applied converting the Rydberg state \( |s\rangle \) to a supperposition of \( s \) and \( p \) Rydberg states

\[
|+\rangle = \frac{1}{\sqrt{2}} (|s\rangle + |p\rangle)
\]
- Resonance dipole-dipole interaction between Rydberg atoms $V$
- Exchange of the $s$ and $p$ Rydberg states.
- During the storage correlated pairs of atoms are created in the initially not populated state

\[ |- \rangle = \frac{1}{\sqrt{2}} (|s\rangle - |p\rangle) \]
State of atoms at the end of storage period

- Atom in state $g$
- Atom in state $+$
- Atom in state $-$
At the end of the storage a second $\pi/2$ pulse is applied, converting the state $|−\rangle$ into Rydberg state $|s\rangle$ and state $|+\rangle$ into state $|p\rangle$.

Excitations in the $s$ state are converted into the probe photons,

$p$ state excitations remain in the medium.
Consequences

- No regenerated slow light without interaction between the atoms
- Restored probe beam contains correlated pairs of photons
Second-order correlation function:

\[ g^{(2)}(\tau) = \frac{\langle \mathcal{E}^\dagger(t)\mathcal{E}^\dagger(t + \tau)\mathcal{E}(t + \tau)\mathcal{E}(t) \rangle}{\langle \mathcal{E}^\dagger(t)\mathcal{E}(t) \rangle \langle \mathcal{E}^\dagger(t + \tau)\mathcal{E}(t + \tau) \rangle} \]

Can be measured using the Hanbury-Brown and Twiss detection scheme
Second-order correlation function of the restored light

We assume

\[ r_c \lesssim r_{\text{Ry}} , \]

where

- \( r_c \) is a characteristic interaction distance: \( V(r_c)T = 1 \)
- \( r_{\text{Ry}} \) is a mean distance between Rydberg atoms

Second order correlation function of the restored light

\[ g_{\text{out}}^{(2)}(\tau) \sim 1 - \cos[V(v_{g0}\tau)T] \]

For small storage time \( T \)

\[ g_{\text{out}}^{(2)}(\tau) \sim [V(v_{g0}\tau)T]^2 \]
Second-order correlation function of the restored light

\[ g^{(2)}_{\text{out}}(\tau) \sim [V(v_{g0}\tau)T]^2 \]

- Allows to measure interaction potential
- Corrections due to the finite spectral width of EIT (see red dashed curve)
Influence of slow light losses

The restored light acquires a finite spectral width $\Delta \omega_{\text{out}} \sim v_{g0}/r_c$, which leads to a finite life-time of the Rydberg polariton, $\tau_{\text{pol}}^{-1} = 2\Gamma(\Delta \omega_{\text{out}}/\Omega_c)^2$. This distorts short time behaviour of $g^{(2)}_{\text{out}}(\tau)$. 

![Graph showing the behavior of $g^{(2)}_{\text{out}}(\tau)$](image)
Two-photon states can be created by properly **storing and retrieving** the slow light in the medium of Rydberg atoms.

The second-order correlation function of the restored light is determined by the **atom-atom interactions** during the storage.

Measurement of the restored light allows one to **probe** interactions in many-body systems using optical means.

Sensitivity of such measurements can be increased by increasing the storage time.
Thank you for your attention!