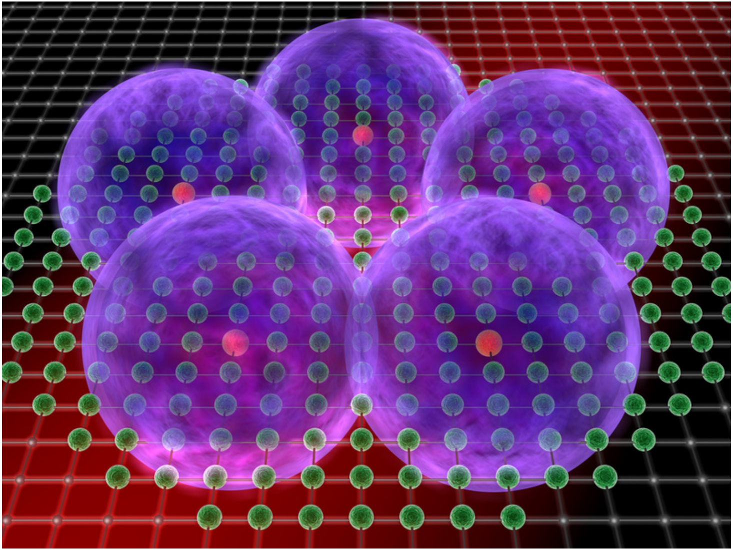
Engineering of correlated photon pairs via interaction between Rydberg atoms during the storage of slow light

Julius Ruseckas[1] Ite A. Yu[2] Gediminas Juzeliūnas[1]

[1]Institute of Theoretical Physics and Astronomy, Vilnius University, Lithuania
[2]National Tsing Hua University, Hsinchu, Taiwan

September 24, 2016

Rydberg atoms

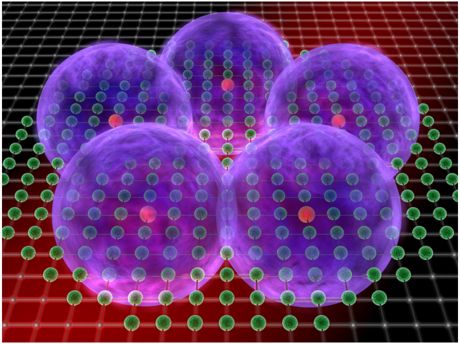


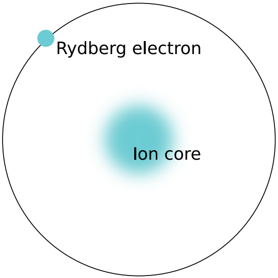
P. Schauß *et al*, Nature **491**, 87 (2012).

Rydberg atoms

Rydberg atom

A Rydberg atom is an excited atom with an electron in a state with a very high principal quantum number $n \gtrsim 50$.

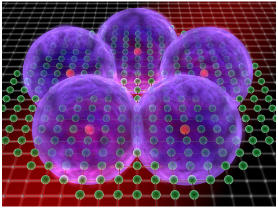




Rydberg atom

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.

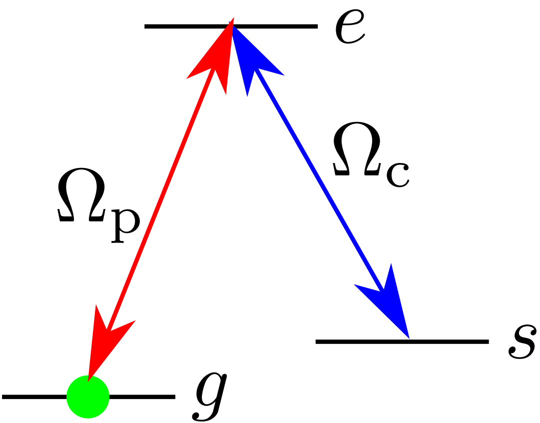
Dipole blockade

- 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

Slow light


18 February 1999
International weekly journal of science
nature
£5.45 € 7.59 FFr51 DM15 Lire 15000 A$16.50
www.nature.com
Cycling at the speed of light?

Three level Λ system



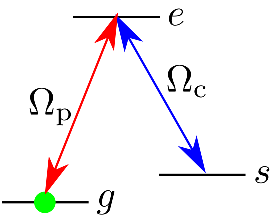
Probe beam: $\Omega_\mathrm{p} = \mu_{ge} E_\mathrm{p}$
Control beam: $\Omega_\mathrm{c} = \mu_{ge} E_\mathrm{c}$

Three level Λ system

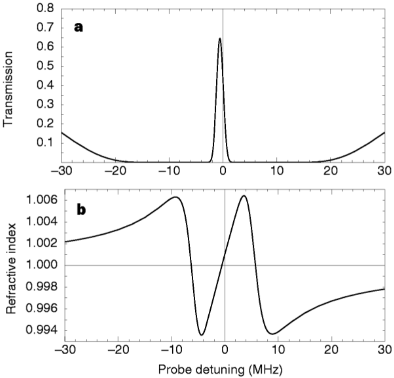
- Dark state

$$|D\rangle \sim \Omega_c|g\rangle - \Omega_p|s\rangle$$

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



Slow light



- Narrow transparency window $\Delta\omega \sim 1\,\mathrm{MHz}$
- Very dispersive medium
- Small group velocity — slow light

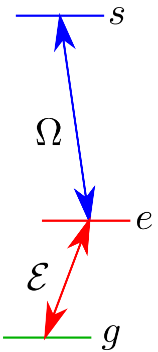
Rydberg EIT

- EIT $\rightarrow$ atom-light interactions without absorption
- Rydberg states $\rightarrow$ strong long-range atom-atom interactions
- As a result $\rightarrow$ photon-photon interactions.

Rydberg EIT

For a single incident probe photon

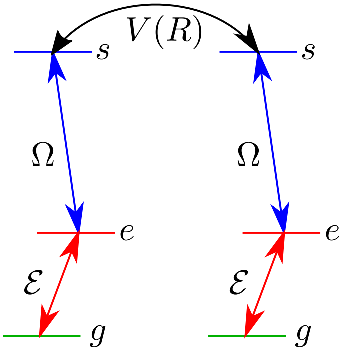
- the control field induces a transparency in a narrow spectral window via EIT
- probe photon is coupled to Rydberg excitation forming a combined quasiparticle — Rydberg polariton
- Rydberg polariton propagates at a reduced speed $\ll c$



Rydberg EIT

When two probe photons propagate in the Rydberg medium

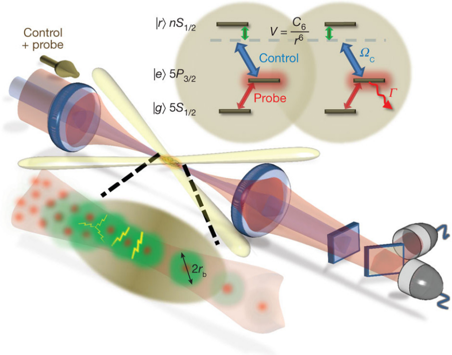
- strong interaction between two Rydberg atoms tunes the transition out of the resonance
- destroying the transparency and leading to absorption.

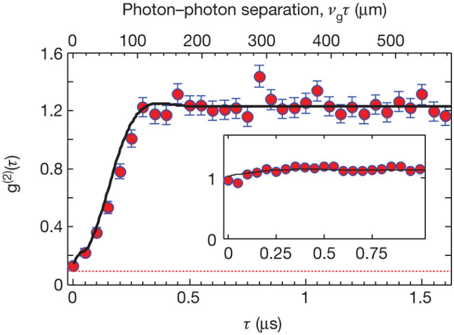


Experimental realization of quantum nonlinear optics

A. V. Gorshkov *et al*, Phys. Rev. Lett. **107**, 133602 (2011).

T. Peyronel *et al*, Nature **488**, 57 (2012).





$46 \leq n \leq 100$

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.

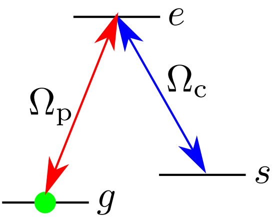
Storing of slow light

Hau *et al*, Nature, 2001

- Dark state

$$|D\rangle \sim |g\rangle - \frac{\Omega_{\mathrm{p}}}{\Omega_{\mathrm{c}}}|s\rangle$$

- 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

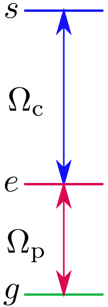


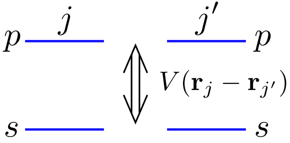
Storing slow light using two Rydberg states

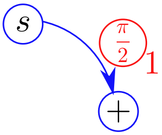
J. Ruseckas, I. A. Yu, and G. Juzeliūnas, arXiv:1606.00562

- 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

$$|+\rangle = \frac{1}{\sqrt{2}}(|s\rangle + |p\rangle)$$



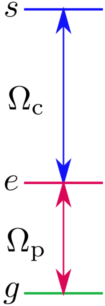


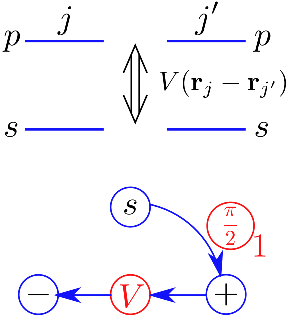


Stored Rydberg slow light

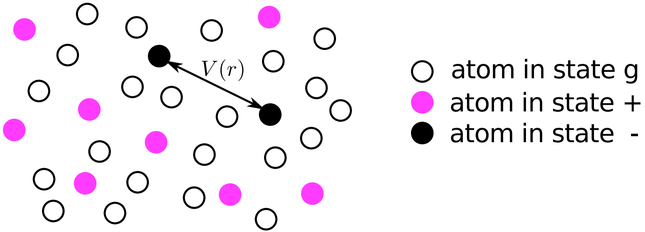
- Resonance dipole-dipole interaction between Rydberg atoms V
- Exchange of the s and p Rydberg states.
- During the storage correlated pairs of atoms are created in the initially not populated state

$$|-\rangle = \frac{1}{\sqrt{2}}(|s\rangle - |p\rangle)$$



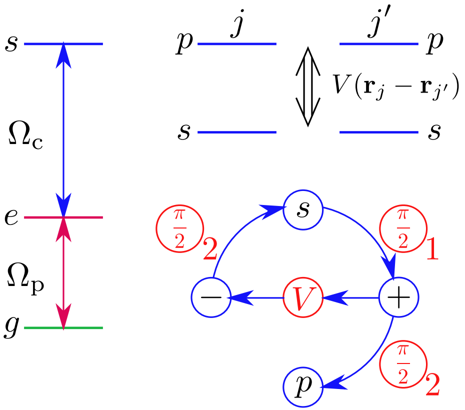


State of atoms at the end of storage period



Stored Rydberg slow light

- At the end of the sorage 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.



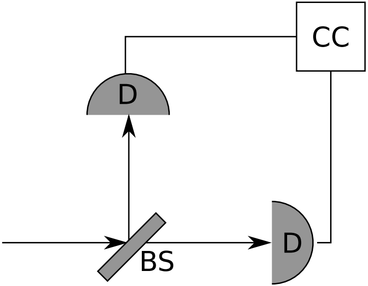
Consequences

- 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



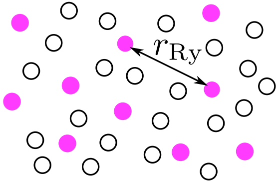
Second-order correlation function of the restored light

We assume

$$r_{\rm c} \lesssim r_{\rm Ry} \, ,$$

where

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



Second order correlation function of the restored light

$$g^{(2)}_{\rm out}(\tau) \sim 1 - \cos[V(v_{g0}\tau)T]$$

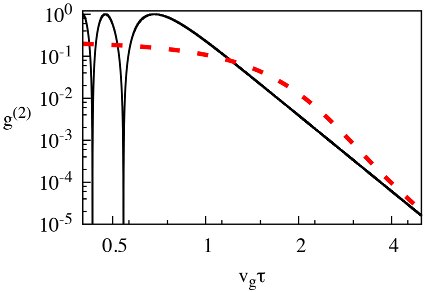
For small storage time T

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

Second-order correlation function of the restored light

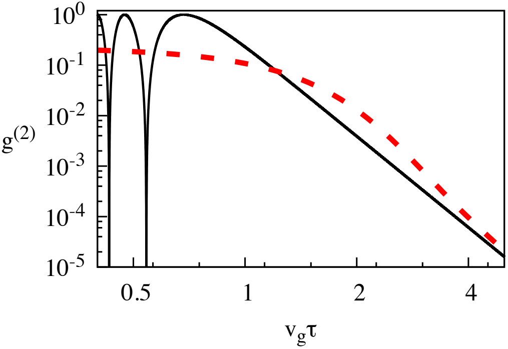
$$g^{(2)}_{\mathrm{out}}(\tau) \sim [V(v_{g0}\tau)T]^2$$

- 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 $\Delta\omega_{\mathrm{out}} \sim v_{g0}/r_{\mathrm{c}}$, which leads to a finite life-time of the Rydberg polariton, $\tau_{\mathrm{pol}}^{-1} = 2\Gamma(\Delta\omega_{\mathrm{out}}/\Omega_{\mathrm{c}})^2$. This distorts short time behaviour of $g_{\mathrm{out}}^{(2)}(\tau)$.



Summary

- 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!