Nonlinear quantum optics for spinor slow light

Julius Ruseckas[1] Viačeslav Kudriašov[1] Algirdas Mekys[1] Tomas Andrijauskas[1] Ite A. Yu[2,3] Gediminas Juzeliūnas[1]

[1]Institute of Theoretical Physics and Astronomy, Vilnius University, Lithuania
[2]Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
[3]Center for Quantum Technology, Hsinchu, Taiwan

Abstract

We investigate quantum nonlinear effects at a level of individual quanta in a double tripod atom-light coupling scheme involving two atomic Rydberg states [1]. In such a scheme the slow light coherently coupled to strongly interacting Rydberg states represents a two-component or spinor light [2]. The scheme provides additional possibilities for the control and manipulation of light quanta. A distinctive feature of the proposed setup is that it combines the spin-orbit coupling for the spinor slow light with an interaction between the photons, enabling generation of the second probe beam even when two-photon detuning is zero. Furthermore, the interaction between the photons can become repulsive if the one-photon detunings have opposite signs. This is different from a single ladder atom-light coupling scheme [3], in which the interaction between the photons is attractive for both positive and negative detunings, as long as the Rabi frequency of the control beam is not too large.

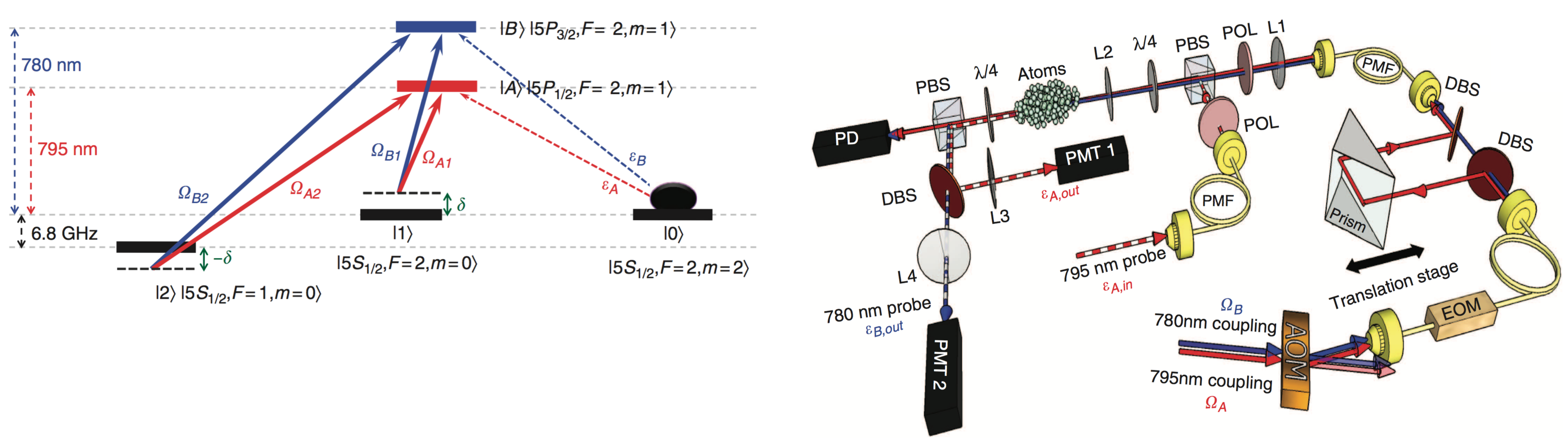
[1] J. Ruseckas, V. Kudriašov, A. Mekys, T. Andrijauskas, Ite A. Yu, and G. Juzeliūnas, arXiv:1805.00144 [quant-ph]; accepted for publication in Phys. Rev. A (2018).

[2] M.-J. Lee, J. Ruseckas, Ch.-Y. Lee, V. Kudriašov, K.-F. Chang, H.-W. Cho, G. Juzeliūnas, and I. A. Yu, Nat. Commun. **5**, 5542 (2014).

[3] O. Firstenberg, T. Peyronel, Q.-Y. Liang, A. V. Gorshkov, M. D. Lukin, and V. Vuletić, Nature **502**, 71 (2013).

Spinor slow light

M.-J. Lee, J. Ruseckas, *et al*, Nat. Commun. **5**, 5542 (2014).



Matrix representation — Spinor slow light:

$$\mathcal{E} = \begin{pmatrix} \mathcal{E}_1 \\ \mathcal{E}_2 \end{pmatrix}, \qquad \hat{\Omega} = \begin{pmatrix} \Omega_{11} & \Omega_{12} \\ \Omega_{21} & \Omega_{22} \end{pmatrix}, \qquad \hat{\delta} = \begin{pmatrix} \delta_1 & 0 \\ 0 & \delta_2 \end{pmatrix}$$

δ_1 and δ_2 are the detunings from two-photon resonance.
Equation for two-component probe field in the atomic cloud:

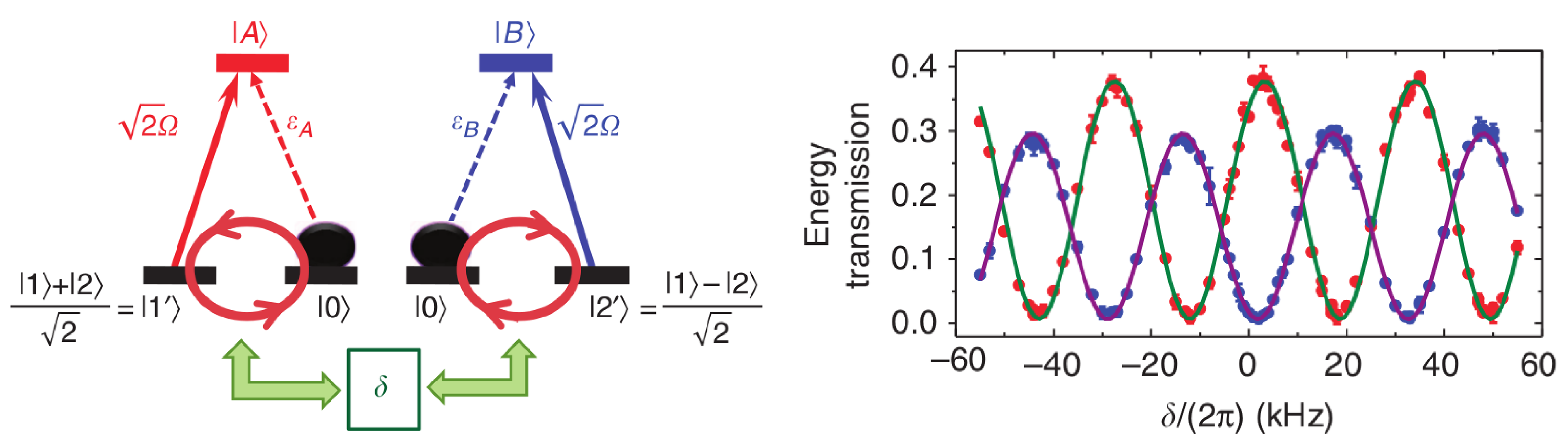
$$(c^{-1} + \hat{v}^{-1})\frac{\partial}{\partial t}\mathcal{E} + \frac{\partial}{\partial z}\mathcal{E} + \mathrm{i}\hat{v}^{-1}\hat{D}\mathcal{E} = 0$$

Similar to the equation for probe field in Λ scheme, only with matrices.
$\hat{D} = \hat{\Omega}\hat{\delta}\hat{\Omega}^{-1}$ is a matrix due to two-photon detuning,

$$\hat{v} = \frac{c}{g^2}\hat{\Omega}\hat{\Omega}^{\dagger}$$

is a matrix of group velocity (not necessarily diagonal).

Two-photon detuning causes oscillations in the intensities of transmitted probe fields

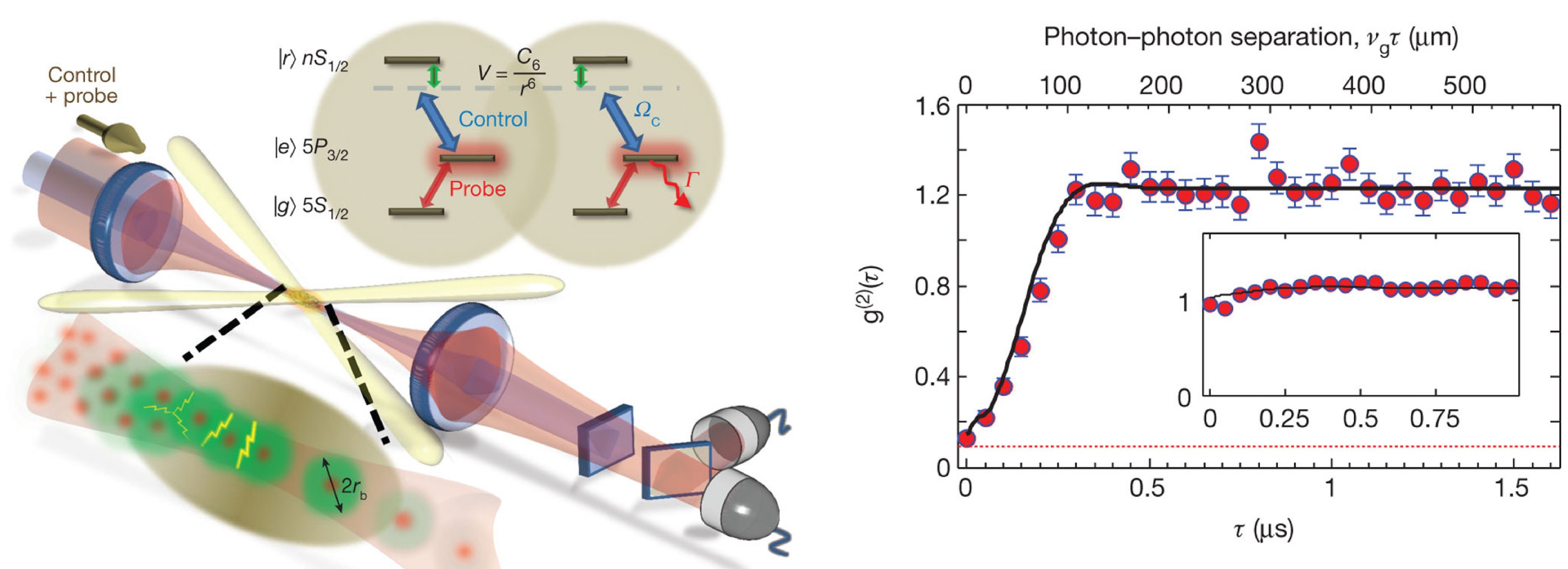


Detuning can be caused by the interaction. For example: generation of correlated two-photon states due interaction between Rydberg atoms

J. Ruseckas, I. A. Yu, G. Juzelinas, Phys. Rev. A **95**, 023807 (2017).

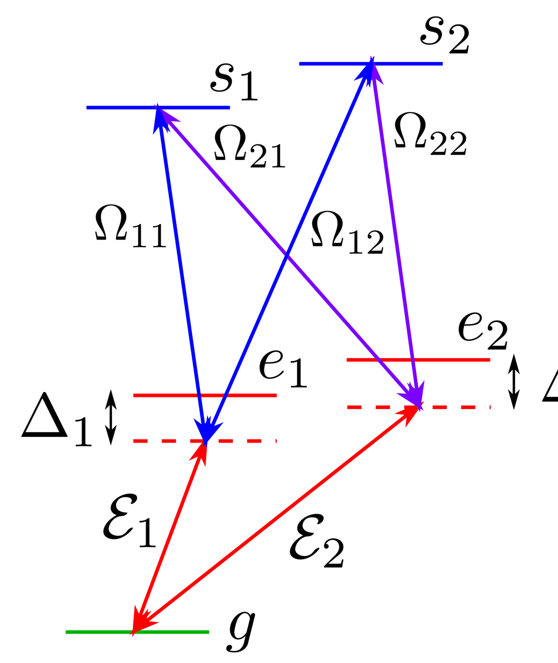
Quantum nonlinear optics using Rydberg atoms

A. V. Gorshkov *et al*, Phys. Rev. Lett. **107**, 133602 (2011).
T. Peyronel *et al*, Nature **488**, 57 (2012).

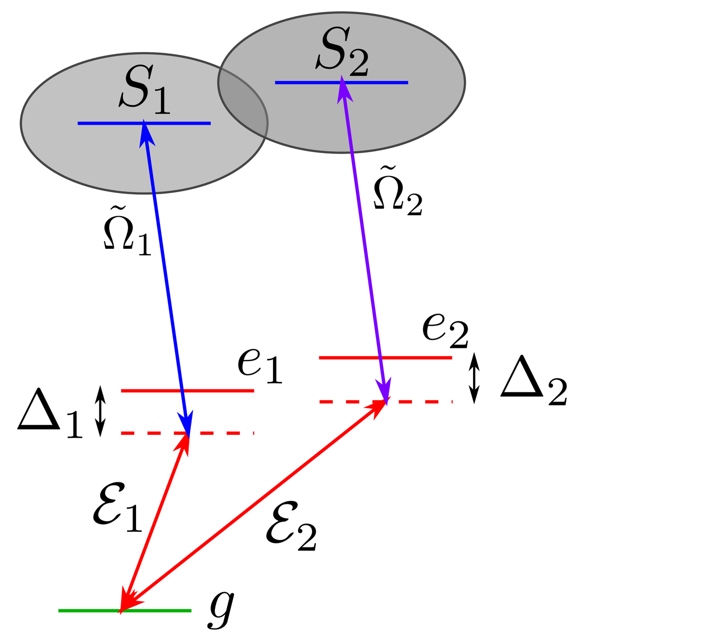


Double tripod scheme with Rydberg levels

J. Ruseckas *et al*, arXiv:1805.00144 [quant-ph]; accepted in Phys. Rev. A (2018).



Double tripod atom-light coupling scheme involving the Rydberg levels s_1 and s_2.



$|S_1\rangle \sim \Omega_{11}|s_1\rangle + \Omega_{12}|s_2\rangle\,, \quad |S_2\rangle \sim \Omega_{21}|s_1\rangle + \Omega_{22}|s_2\rangle$

Probe fields $\mathcal{E}_1$ and $\mathcal{E}_2$ are coupled via atomic coherences if $\langle S_1|S_2\rangle \neq 0$

The probe fields are assumed to be sufficiently weak at the input, so that the contribution due to more than two photons is not important.

Equal one-photon detunings

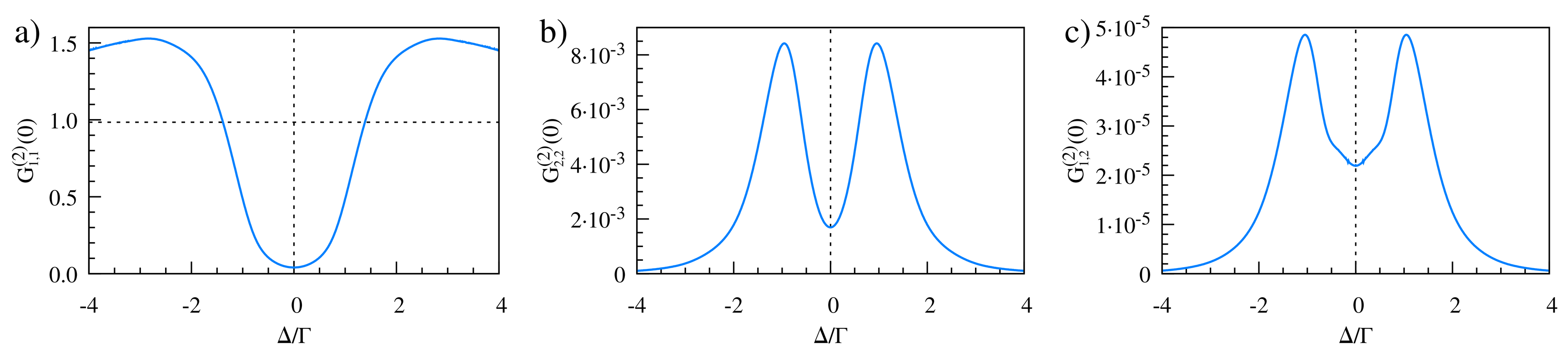
Approximate closed equation for two-photon amplitudes $\Phi_{\mathcal{E}_j\mathcal{E}_l}$:

$$\mathrm{i}\partial_R\Phi_{\mathcal{E}_j\mathcal{E}_l} = -4L_{\mathrm{abs}}\frac{\tilde{\Delta}}{\Gamma}\partial_r^2\Phi_{\mathcal{E}_j\mathcal{E}_l} + \frac{\mathrm{i}}{\bar{v} - L_{\mathrm{abs}}\frac{\tilde{\Delta}}{\Gamma}V(r)}\sum_m(v_{l,m}\partial_r\Phi_{\mathcal{E}_j\mathcal{E}_m} - v_{j,m}\partial_r\Phi_{\mathcal{E}_m\mathcal{E}_l}) + \frac{V(r)}{\bar{v} - L_{\mathrm{abs}}\frac{\tilde{\Delta}}{\Gamma}V(r)}\sum_{m,n}A_{jl,mn}\Phi_{\mathcal{E}_m\mathcal{E}_n}$$

spin-orbit coupling

interaction

Here $R = \frac{1}{2}(z + z')$, $r = z - z'$, $\bar{v} = \frac{1}{2}(v_{1,1} + v_{2,2})$, $\tilde{\Delta} = 2\Delta - \mathrm{i}\Gamma$



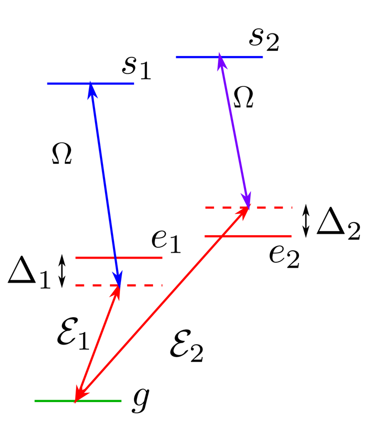
Only the first probe beam with the amplitude a is incident on the atom cloud; $v_{1,2}/v_{1,1} = 1/2$.
Second-order correlation functions normalized to the intensity of the incident probe beam

$$G^{(2)}_{j,l}(0) = \frac{1}{a^4}|\Phi_{\mathcal{E}_j\mathcal{E}_l}(R = L, r = 0)|^2$$

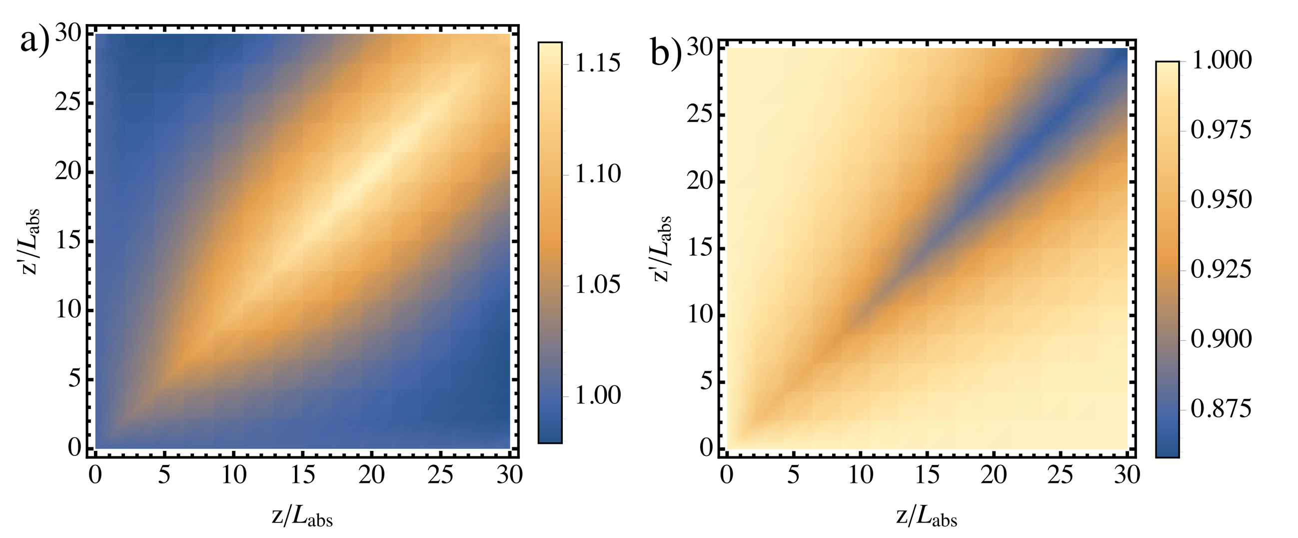
Photons are transferred from the first to the second probe beam even in the case of zero two-photon detuning.

Opposite signs of one-photon detunings

The approximations leading to the single closed equation are not valid when detunings are different.



No transfer of photons between probe beams.



Square of the absolute value of the two-photon wave function a) $|\Phi_{\mathcal{E}_1\mathcal{E}_1}|^2$ and b) $|\Phi_{\mathcal{E}_1\mathcal{E}_2}|^2$, when one-photon detunings have opposite signs; $\Delta/\Gamma = 2.5$

The decrease of the second-order correlation function $G^{(2)}_{1,2}(0)$ represnts an effective repulsion between the photons from different probe beams

Acknowledgements
The work was supported by the project TAP LLT-2/2016 of the Research Council of Lithuania and the Ministry of Science and Technology of Taiwan under Grant Nos. 104-2119-M-007-004 and 105-2923-M-007-002-MY3.

julius.ruseckas@tfai.vu.lt http://web.vu.lt/tfai/j.ruseckas