Multi-component slow light. Exchange of orbital angular momentum between slow light and cold atoms

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Quantum Optics Group

http://www.itpa.lt/quantumgroup/

Quantum Optics Group

at the Institute of Theoretical Physics and Astronomy, Vilnius University

- Main
- Members
- Research Area
- Collaboration
- Publications
- Media Coverage
- Links

The group is working on the theory of quantum optics at the Institute of Theoretical Physics and Astronomy of Vilnius University. Our main research interests are cold atomic gases, electromagnetically induced transparency, slow light, lefthanded light and effective gauge field theories.

The Quantum Optics group is headed by Professor Gediminas Juzeliūnas.

From left to right: Viktoras Pyragas, Simonas Grubinskas, Razmik Unanyan (University of Kaiserslautern), Gediminas Juzelūnas, Julius Ruseckas, Viačeslav Kudriašov, Algirdas Mekys

All group photos

Outline

1. Introduction
   - Slow light
   - Storing of slow light
2. Slow and stored light with orbital angular momentum
3. Multicomponent slow light
   - Neutrino-type oscillations for slow light
   - Dirac equation for slow light
   - Transfer of orbital angular momentum
4. Summary

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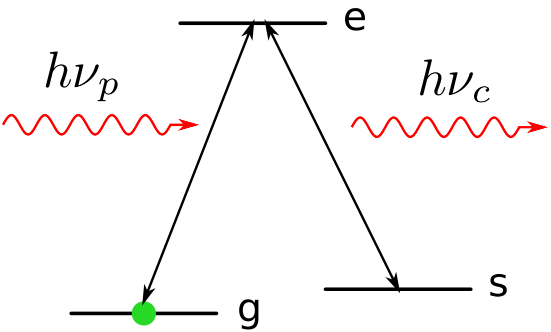
Slow light


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?



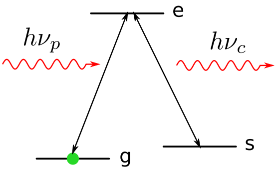
Probe beam: $\Omega_p = \mu_{13} E_p$
Control beam: $\Omega_c = \mu_{23} E_c$

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



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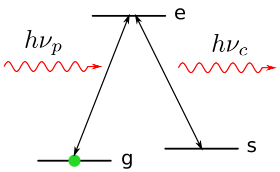

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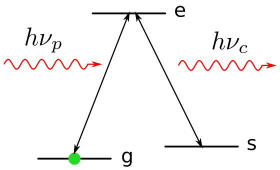

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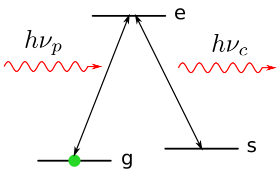

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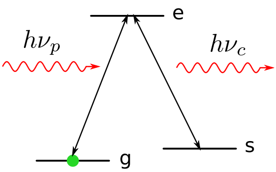

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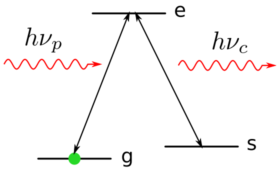
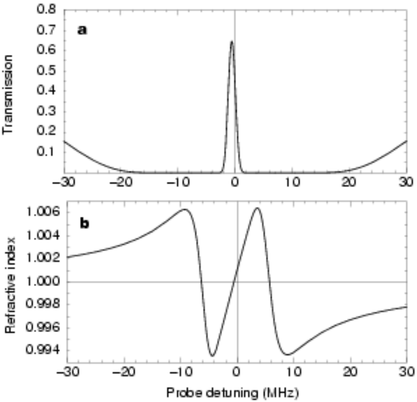


Slow light



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

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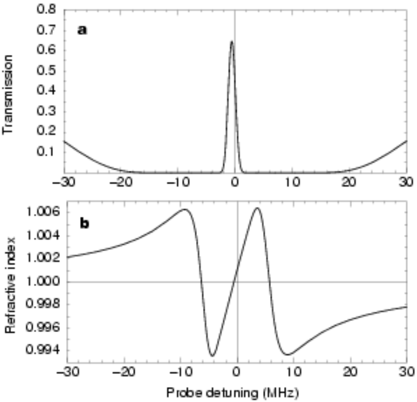

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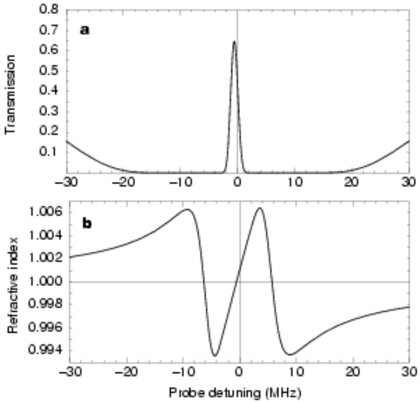

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Nature, Hau *et al*, 2001

Storing of slow light

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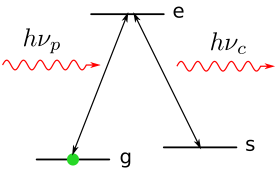
$$|D\rangle \sim |g\rangle - \frac{\Omega_p}{\Omega_c}|s\rangle$$

- Information on probe beam is contained in the atomic coherence
- Storing of light—switching off control beam; information in the atomic coherence is retained
- Releasing—switch on control beam



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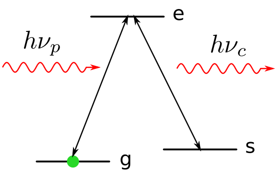

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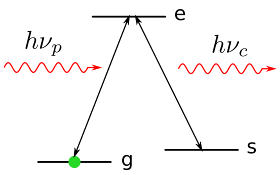

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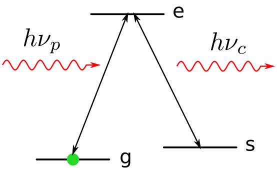

Storing of slow light

- Initial storage times (L. V. Hau *et al*, Nature 2001): 1 ms
- Recent improvement:
  - Storage time 240 ms:
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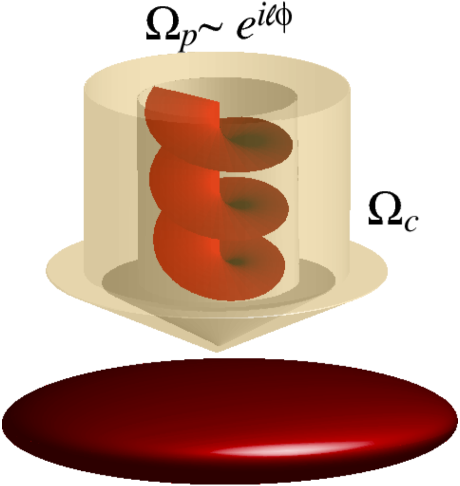
Light beams with OAM: Light Vortices



Light vortex

Light vortex — light beam with phase

$$e^{ikz+il\varphi},$$

where φ is azimuthal angle, l — winding number.

Light vortices have orbital angular momentum (OAM) along the propagation axis $M_z = \hbar l$.

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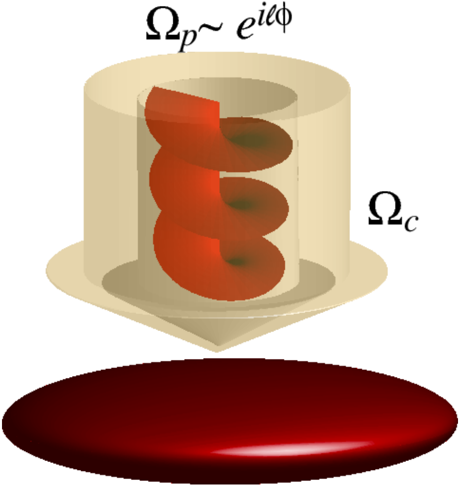

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Probe beam with OAM

Storage of optical vortices

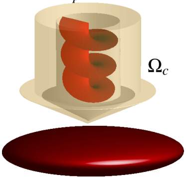
- Z. Dutton and J. Ruostekoski, Phys. Rev. Lett. **93**, 193602 (2004)
- R. Pugatch, M. Shuker, O. Firstenberg, A. Ron, and N. Davidson, Phys. Rev. Lett. **98**, 203601 (2007).

Control beam with OAM

What if

$$\Omega_c \sim \exp(i\ell\varphi) \quad ?$$

Transfer of the optical vortex from the control to probe beams during storage and retrieval



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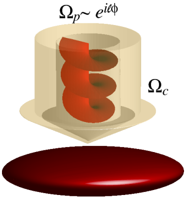

Control beam with OAM

Problem

Large absorption (non-adiabatic) losses at vortex core where Rabi frequency of control beam is 0

Solution

Use the tripod scheme.

Price: losses in the energy of the regenerated probe beam; a part of the stored probe beam remains frozen in the medium in the form of atomic spin excitations

- J. Ruseckas, A. Mekys, and G. Juzeliūnas, Opt. Spectrosc. **108**, 438 (2010).
- J. Ruseckas, A. Mekys, and G. Juzeliūnas, Phys. Rev. A **83**, 023812 (2011).
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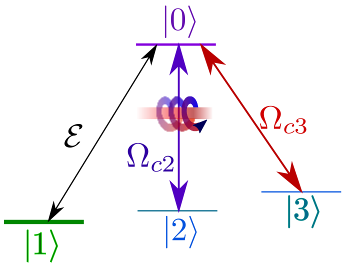
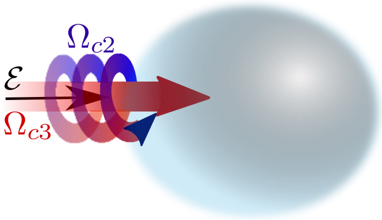
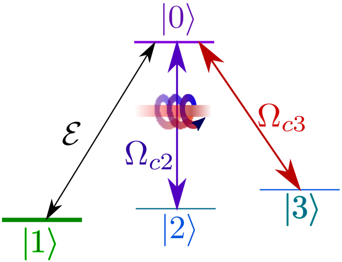
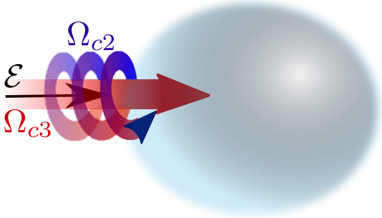




- Beam $\Omega_2 \sim \exp(i\ell\varphi)$ has zero intensity at the center
- Beam Ω_3 restores adiabaticity (non-zero intensity at the center)
- The optical vortex is transferred from Ω_2 to Ω_1 after regeneration

Control beam with OAM





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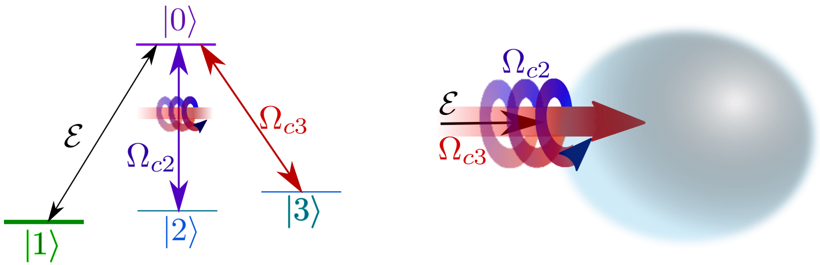

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Two possibilities

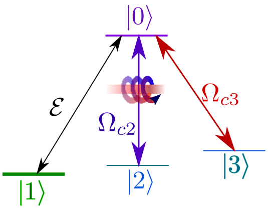
First case

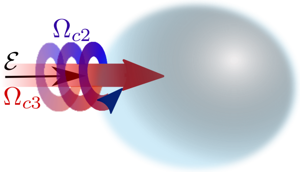
Ω_2 contains a vortex during retrieval stage

Second case

Ω_2 contains a vortex during storage stage.
Probe field acquires an opposite vorticity $\exp(-i\ell\varphi)$

Ω_3 is zero when Ω_2 does not contain a vortex.





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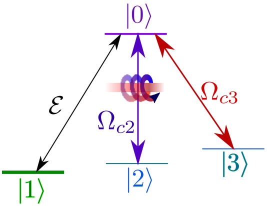
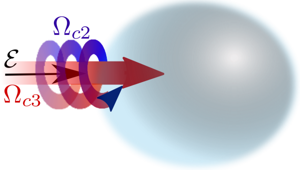
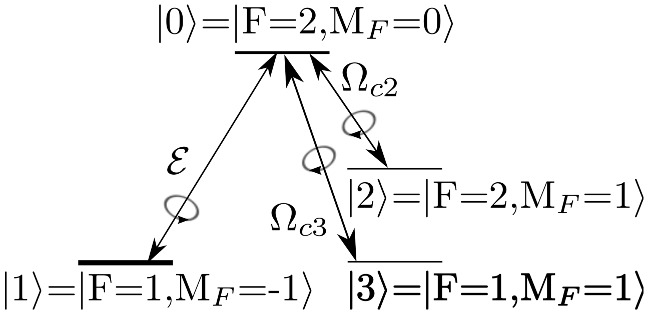




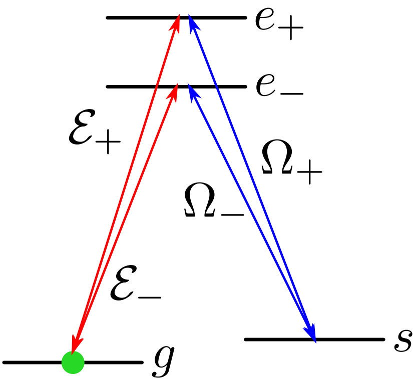
Possible experimental realization



- Atoms such as sodium or rubidium containing the hyperfine ground states with $F = 1$ and 2.
- Probe beam is σ^+ polarized, both control beams are σ^- polarized.

Slow light consisting of several connected fields?

First try: double Λ scheme



- An additional excited state
- An additional, counter-propagating control laser beam

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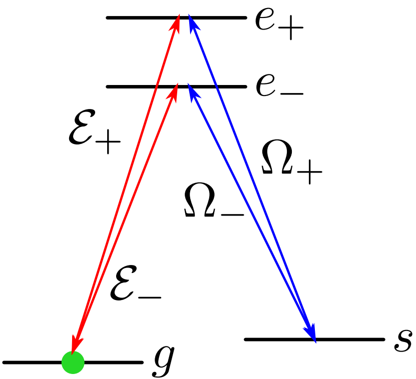

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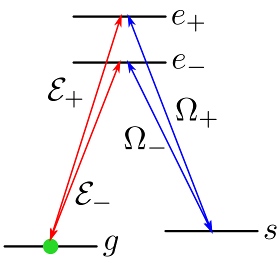
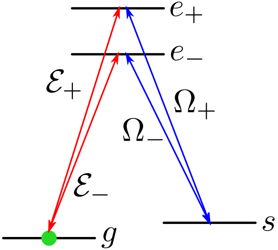
Double Λ scheme

- Used for stationary light
- Theory:
  - S. A. Moiseev and B. S. Ham, Phys. Rev. A **73**, 033812 (2006).
  - F. E. Zimmer *et al.*, Opt. Commun. **264**, 441 (2006).
  - M. Fleischhauer *et al.*, Phys. Rev. Lett. **101**, 163601 (2008).
- Experiment:
  - Y.-W. Lin *et al.*, I. A. Yu, Phys. Rev. Lett. **102**, 213601 (2009).



Double Λ scheme: bad for our purposes

- Only one dark state
- Only one dark state polariton (propagating without absorbtion)
- For multicomponent slow light we need to add more levels.



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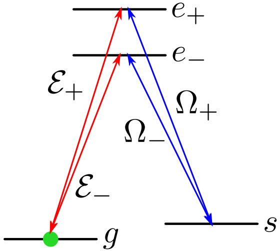

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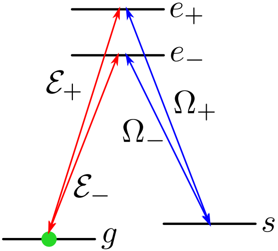

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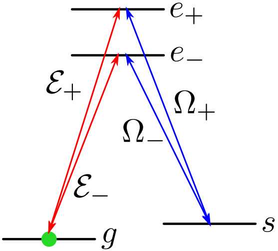


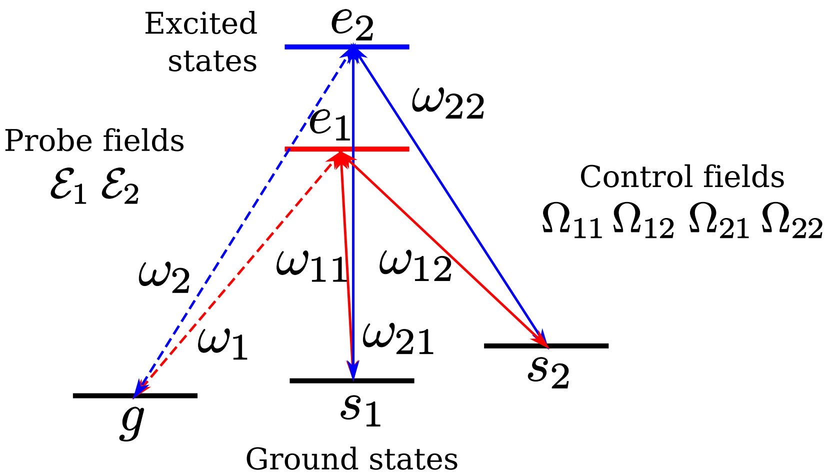
Multicomponent slow light

Solution

Use double tripod scheme

- R. G. Unanyan, J. Otterbach, M. Fleischhauer, J. Ruseckas, V. Kudriašov, G. Juzeliūnas, Phys. Rev. Lett. **105**, 173603 (2010).
- J. Ruseckas, V. Kudriašov, G. Juzeliūnas, R. G. Unanyan, J. Otterbach, M. Fleischhauer, arXiv:1103.5650v2 [quant-ph]. Submitted to Phys. Rev. A

Double tripod setup



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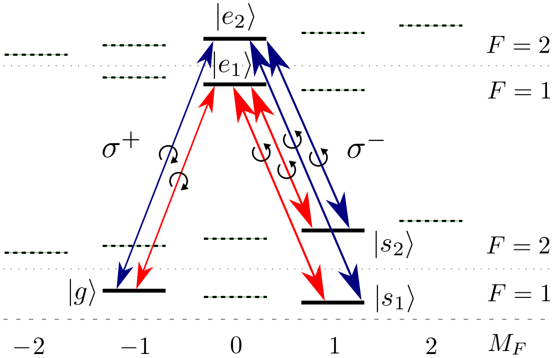
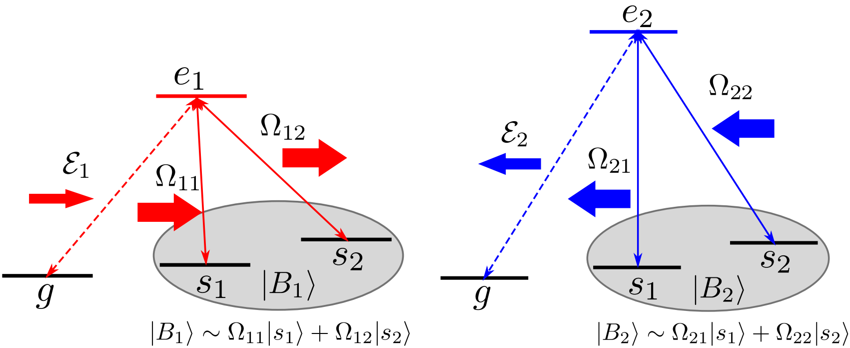


- Atoms like rubidium or sodium.
- Transitions between the magnetic states of two hyperfine levels with $F = 1$ and 2 for the ground and excited state manifolds.
- Both probe beams are circularly σ^+ polarized, all four control beams are circularly σ^- polarized.

Double tripod setup

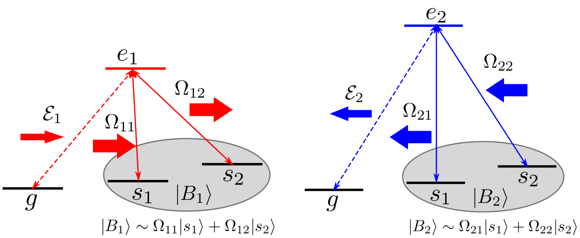


$\mathcal{E}_1$ and $\mathcal{E}_2$ drive different atomic transitions which are interconnected if $\langle B_1|B_2\rangle \neq 0$

Double tripod setup

Limiting cases:

- $\langle B_1|B_2\rangle = 0$ — two not connected tripods
- $\langle B_1|B_2\rangle = 1$ — double Lambda setup
- $0 < |\langle B_1|B_2\rangle| < 1$ — two connected tripods



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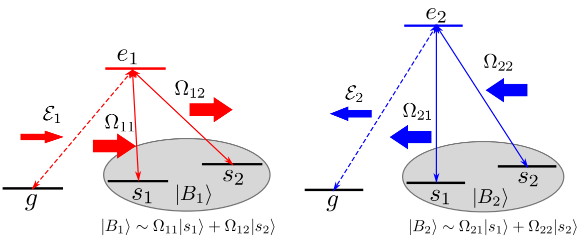

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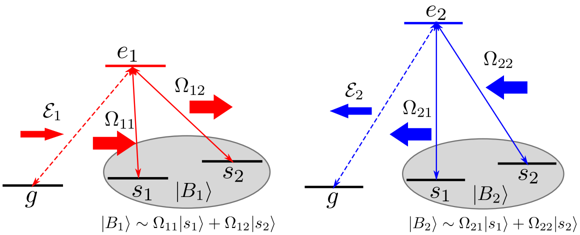

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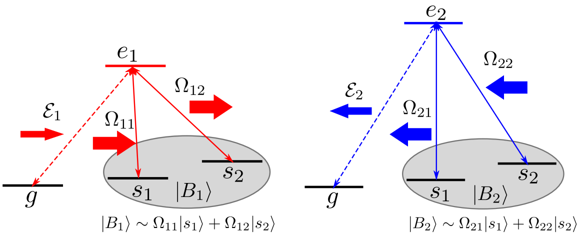

Propagation of slow light

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:

$$v^{-1}\frac{\partial}{\partial t}\mathcal{E} - \frac{i}{2k}\nabla^2\mathcal{E} - \frac{i}{2}k\mathcal{E} + i\left(v^{-1} - \frac{1}{c}\right)\hat{D}\mathcal{E} = 0$$

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,

$$v^{-1} = \frac{1}{c} + \frac{g^2 n}{c}(\hat{\Omega}^{\dagger})^{-1}\hat{\Omega}^{-1}$$

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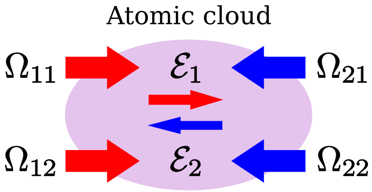
Neutrino-type oscillations for slow light

- The group velocity is a non-diagonal matrix
- Individual probe fields do not have a definite group velocity
- Only special combinations of both probe fields (normal modes) propagate in the atomic cloud with the definite (and different) velocities
- This difference in velocities causes interference between probe fields



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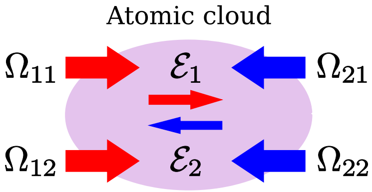

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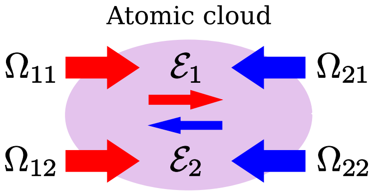

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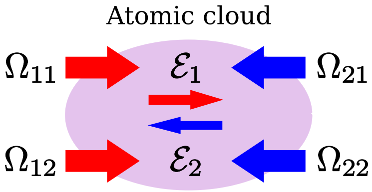

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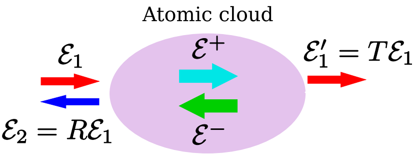

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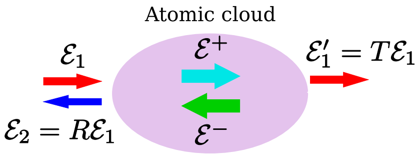

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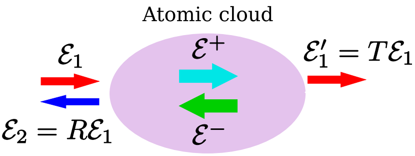

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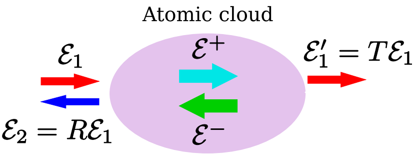

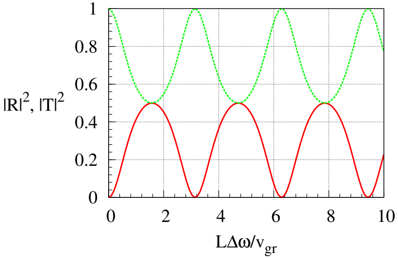

Dirac equation for two-component slow light

- Counter-propagating beams
- Non-zero two photon detuning $\delta_1 = -\delta_2 \equiv \delta \neq 0$
- A gap in dispersion ("electron-positron" type spectrum)
- Dirac type equation with non-zero mass for two component slow light:

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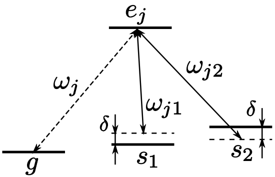

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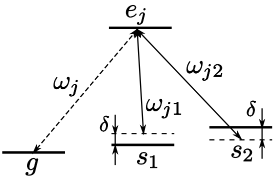

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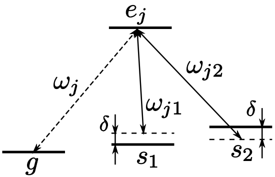

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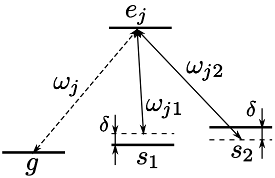

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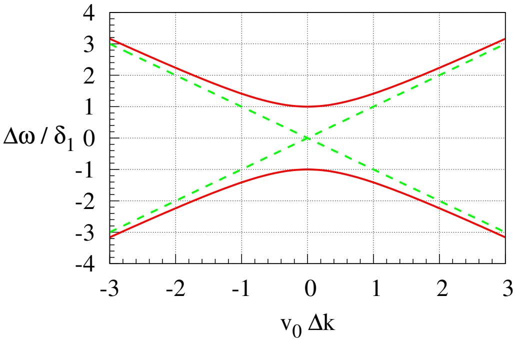

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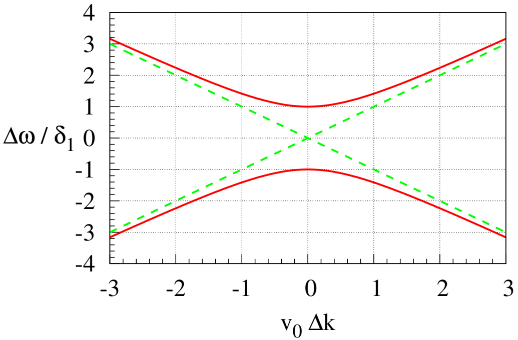

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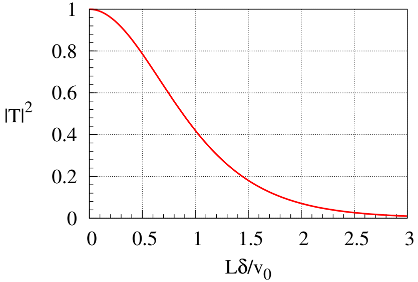

- Reflection and transmission coefficients at the gap center ($\Delta\omega = 0$):

$$T = \cosh^{-1}(L/\lambda_{\mathrm{C}}) \,, \quad R = \tanh(L/\lambda_{\mathrm{C}})$$

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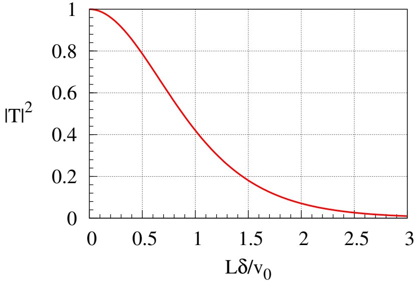

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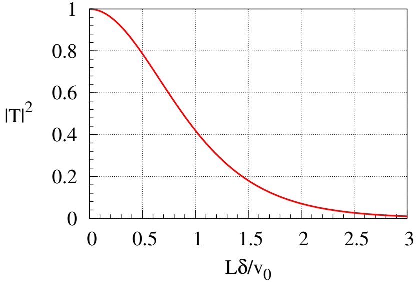

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Transfer of optical vortex to probe beams

- Co-propagating probe beams
- Control beams with Rabi frequencies $\Omega_{11} \sim e^{i\ell\varphi}$ and $\Omega_{22} \sim e^{-i\ell\varphi}$ have optical vortices with opposite vorticity
- Incident field $\mathcal{E}_1$ is without vortex
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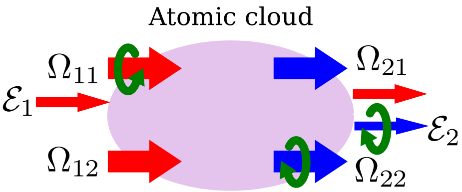

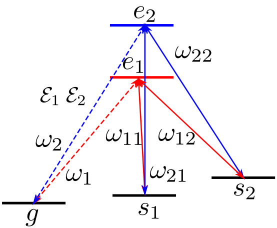

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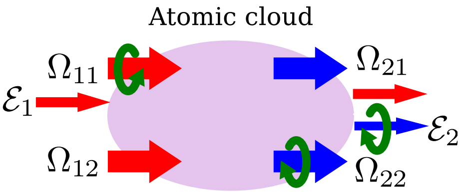

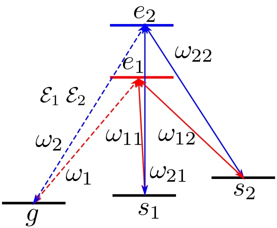

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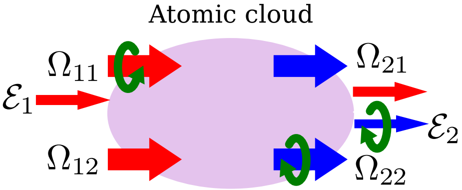

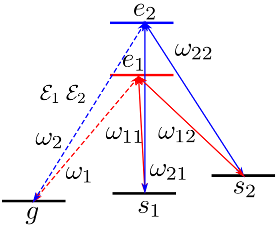

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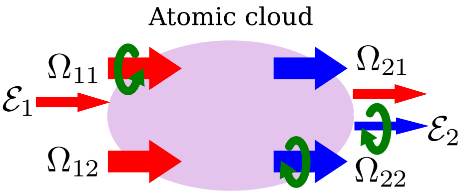

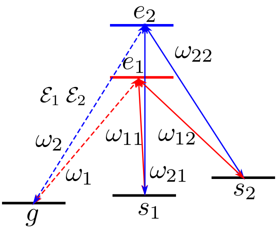

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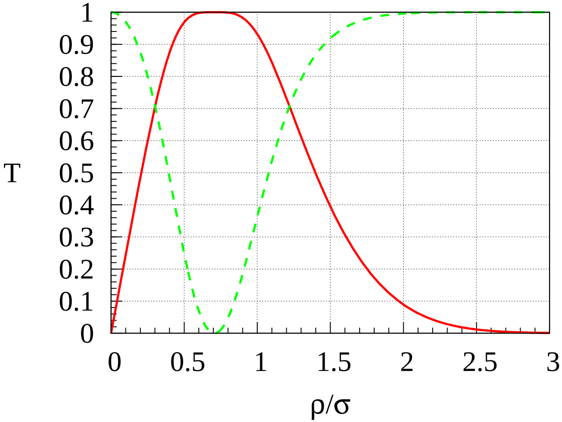

Transmission amplitudes for the second (solid red) and first (dashed green) probe beams.

Summary

- Two component slow and stationary light exhibits a number of distinct properties, such as the neutrino type oscillations between the components of light.
- Under certain conditions the slow light can be described by a relativistic equation of the Dirac-type for a particle of a finite mass, dispersion branches are separated by an energy gap.
- The corresponding Compton length determines the tunneling length of multicomponent light though the sample.
- Both tripod and double tripod schemes are applicable for transfer of optical vortex from the control beams to the the slow light.
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Thank you for your attention!