Hauptseminar: Physik der kalten Gase, Rydberg atoms: Slow light

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Rydberg atoms: Slow light

Content

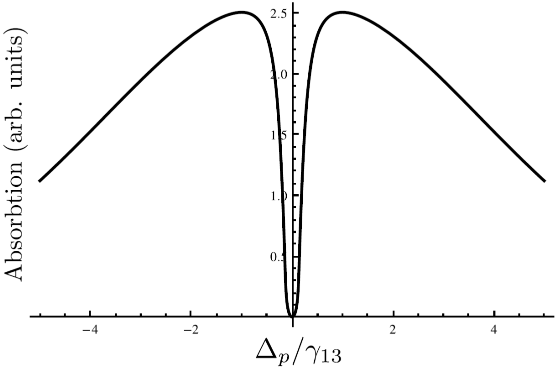
Introduction

Atom - light interaction

- Last week: Two level system
- Now: Three level system
- Basic effects like absorption still present
- New effect: Electromagnetically induced transparency

Introduction

EIT - Phenomenology

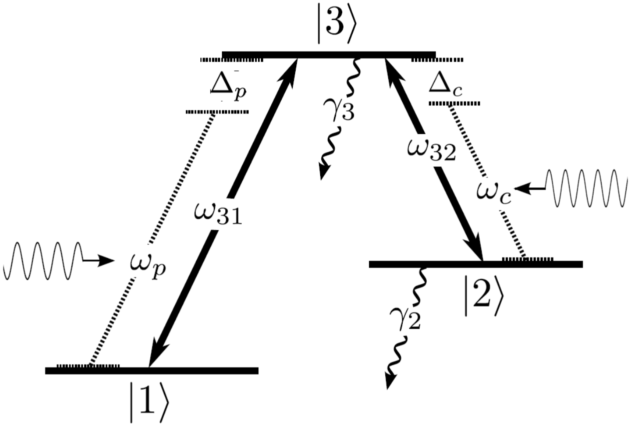


[1]

[1] W. W. Erickson, Electromagnetically Induced Transparency

Derivation

Level scheme



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[2]W. W. Erickson, Electromagnetically Induced Transparency

Derivation

Result

$$\chi = \frac{2N\left|d_{13}\right|\Omega_p}{E_p\epsilon_0}\frac{-2(\gamma_{21}+i(\Delta_c-\Delta_p))\Omega_p}{4(\gamma_{13}-i\Delta_p)(i\gamma_{12}-\Delta_c+\Delta_p)+i\Omega_c^2}$$

$$Re(\chi) = -\frac{2N\left|d_{13}\right|\Omega_p}{E_p\epsilon_0}$$

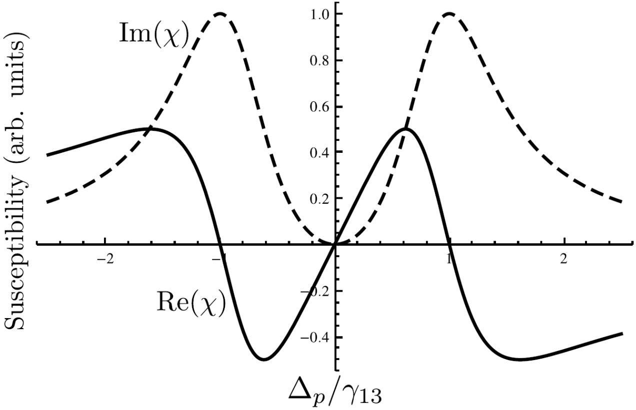
$$\cdot\frac{2(4(\gamma_{12}^2+(\Delta_c-\Delta_p)^2)\Delta_p+(\Delta_c-\Delta_p)\Omega_c^2)}{16(\gamma_{12}^2+(\Delta_c-\Delta_p)^2)(\gamma_{13}^2+\Delta_p^2)+8(\gamma_{12}\gamma_{13}+(\Delta_c-\Delta_p)\Delta_p)\Omega_c^2+\Omega_c^4}$$

$$Im(\chi) = \frac{2N\left|d_{13}\right|\Omega_p}{E_p\epsilon_0}$$

$$\cdot\frac{2(4\gamma_{13}(\gamma_{12}^2+(\Delta_c-\Delta_p)^2)+\gamma_{12}\Omega_c^2}{16(\gamma_{12}^2+(\Delta_c-\Delta_p)^2)(\gamma_{13}^2+\Delta_p^2)+8(\gamma_{12}\gamma_{13}+(\Delta_c-\Delta_p)\Delta_p)\Omega_c^2+\Omega_c^4}$$

Derivation

Result

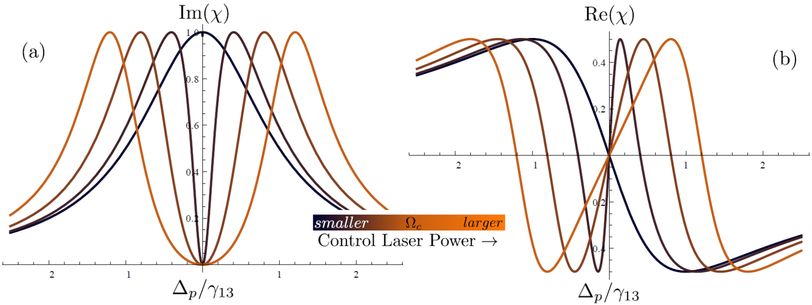


[3]

[3] W. W. Erickson, Electromagnetically Induced Transparency

Derivation

Dependency of Ω_c



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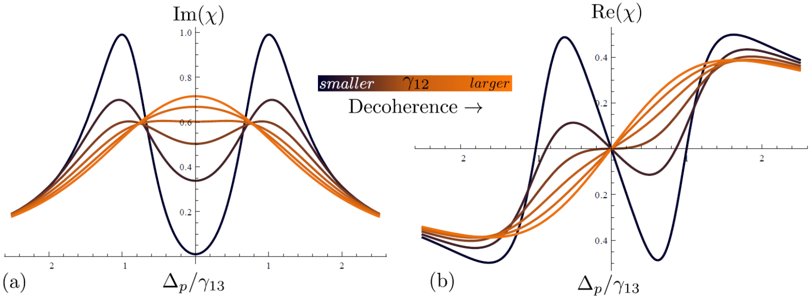
[4] W. W. Erickson, Electromagnetically Induced Transparency

Derivation

Dependency of γ_{12}



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[5] W. W. Erickson, Electromagnetically Induced Transparency

Slow light

- Dispersion relation

$$k = \frac{\omega}{v_{ph}} = \frac{\omega}{\frac{c_0}{n(\omega)}} \tag{1}$$

k wave number, ω frequency of the incoming light, v_{ph} phase velocity, c_0 speed of light in vacuum

- Group velocity

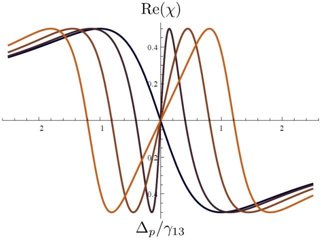
$$\frac{1}{v_g} = \frac{\partial k}{\partial \omega} = \frac{n(\omega) + \omega \frac{\partial}{\partial \omega} n(\omega)}{c_0} \tag{2}$$

$$v_g = \frac{c_0}{n(\omega) + \omega \frac{\partial}{\partial \omega} n(\omega)} \tag{3}$$

- Quick change in the refractive index over the frequency leads to a slow group velocity

Storage of light

- Apply probe pulse to medium (coupling: on)
- Lower down Ω_c by decreasing the coupling laser power
- $Re(\chi)$ becomes much steeper
- Group velocity becomes smaller
- "Stopping" resp. "saving" of photons
- To "read" the storage:
- Increase Ω_c
- Probe photon will be accellerated again.



[6]

[6] W. W. Erickson, Electromagnetically Induced Transparency

Population transfer

Aim: Transfering all atoms into state $|2\rangle$.

- Diagonalisation of Hamiltonian in rotational frame

$$\widetilde{H}_{EIT} = -\frac{\hbar}{2}\begin{bmatrix} 0 & 0 & \Omega_p \\ 0 & 2(\Delta_p - \Delta_c) & \Omega_c \\ \Omega_p & \Omega_c & 2\Delta_p \end{bmatrix} \tag{4}$$

- Eigenstates

$$\begin{aligned} |a^+\rangle &= \sin\Theta\sin\Phi\,|1\rangle + \cos\Phi\,|3\rangle + \cos\Theta\sin\Phi\,|2\rangle \\ |a^0\rangle &= \cos\Theta\,|1\rangle - \sin\Theta\,|2\rangle \\ |a^-\rangle &= \sin\Theta\cos\Phi\,|1\rangle - \sin\Phi\,|3\rangle + \cos\Theta\cos\Phi\,|2\rangle \end{aligned}$$

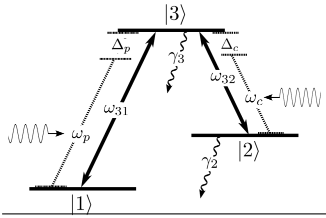
- $\tan\Theta = \frac{\Omega_p}{\Omega_c}$
- $\tan 2\Phi = \frac{\sqrt{\Omega_p^2 + \Omega_c^2}}{\Delta}$

Population transfer

$$|a^0\rangle = \cos\Theta\,|1\rangle - \sin\Theta\,|2\rangle\,, \qquad \tan\Theta = \frac{\Omega_p}{\Omega_c}$$

→ Varying of Ω_c and Ω_p

- Begin in state $|1\rangle$, i.e. $\Omega_c \gg \Omega_p$, adiabatically (slowly) change to $\Omega_p \gg \Omega_c$, i.e. atom is in state $|2\rangle$
- Lossless transfer, 100 % efficiency
- Counter-intuitive Pulses
- Stimulated Raman-adiabatic passage (STIRAP)



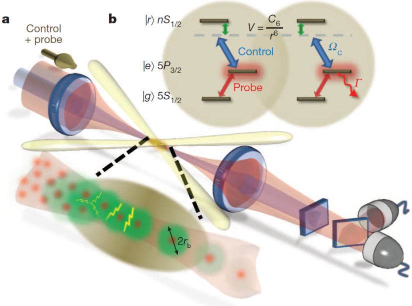
[7]

[7] W. W. Erickson, Electromagnetically Induced Transparency

Experiment: Interaction of slow photons

- Basic setup:
- Crossed dipole trap
- Beam waist: 4.5 μm
- Rydberg blockade radius: 3 – 13 μm

→ One-dimensional alignment of Rydberg atoms

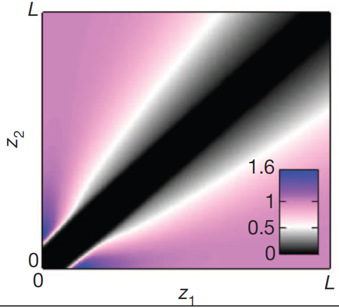


[8]

[8] T. Peyronel et al., Nature, Vol 488, 2 August 2012

Experiment: Interaction of slow photons

- Single photon is converted into a Rydberg polariton
- Second polarition cannot travel within a blockade radius of the first one
- Destruction of EIT
- Single photon source

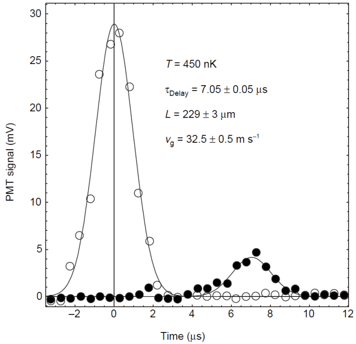


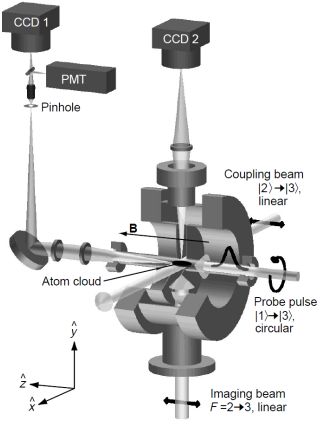
[9]

[9] T. Peyronel et al., Nature, Vol 488, 2 August 2012

Experiment: Measuring the group velocity

- Basic setup:
- Magneto-optical trap
- Measure time with and without atoms





[10]

[10] L. V. Hau et al., Nature, Vol 397, 18 February 1999

Conclusion

- Three level atom
- Electromagnetically induced transparency
- Small transparency window (large window: Autler-Townes splitting)
- Light speed reduction
- Population transfer

Future

- Optical transistor
- Light storage
- Single photon source

Thank you for your attention.

Questions?