Stop and Go Control of Light with Hot Atoms

Yuri Rostovtsev, Olga Kocharovskaya and M.O. Scully

Department of Physics,
Texas A&M University
College Station, TX 77843-4242

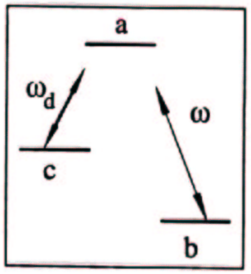
Slow group velocity of Light

- Observation of Slow light
  - in atomic vapors (cold and hot)
    L. V. Hau, et al., Nature (1999);
    M. Kash, et al., PRL (1999)
    D. Budker, et al., PRL (1999)
  - is solids
    A. V. Turukhin et al., PRL (2002)
- Applications
  - Nonlinear Optics, Phonons, Phasematching
    A.B. Matsko, et al., PRL (2000,2001)
  - New type of scattering
    S.E. Harris, PRL (2000)
  - A few photons level
    S.E. Harris, L. Hau, PRL (1999)
  - Stopping light [O. Kocharovskaya, PRL 2001], and Quantum Storage [L. Hau, et al., Nature 2001], [D. F. Phillips et al., PRL 2001]

Stopping Light

- stoping light via atomic motion (spatial dispersion)
  - Optical pumping scheme Kocharovskaya, PRL (2001)
  - Control propagation via additional fields (μwave, double Lambda scheme)
- stoping light via nonlinear interaction, Induced photonic crystal Rostovtsev et al., PRA (1999)

How slow is slow light?



$\tilde{v}_g \simeq 10 - 10^2$ m/s

L. V. Hau et al., Nature **397**, 594 (1999).

M. Kash et al., PRL **82**, 5229 (1999).

D. Budker et al., PRL **83**, 1767 (1999).

Temporal Dispersion

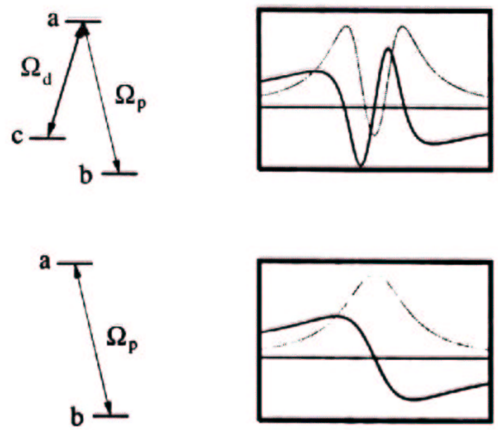
$$k = \frac{\omega}{c} n(\omega), \quad v_g = Re \frac{c}{n + \omega \frac{\partial n}{\partial \omega}}$$

S. E. Harris et al. Phys. Rev. **A46**, R29 (1992)

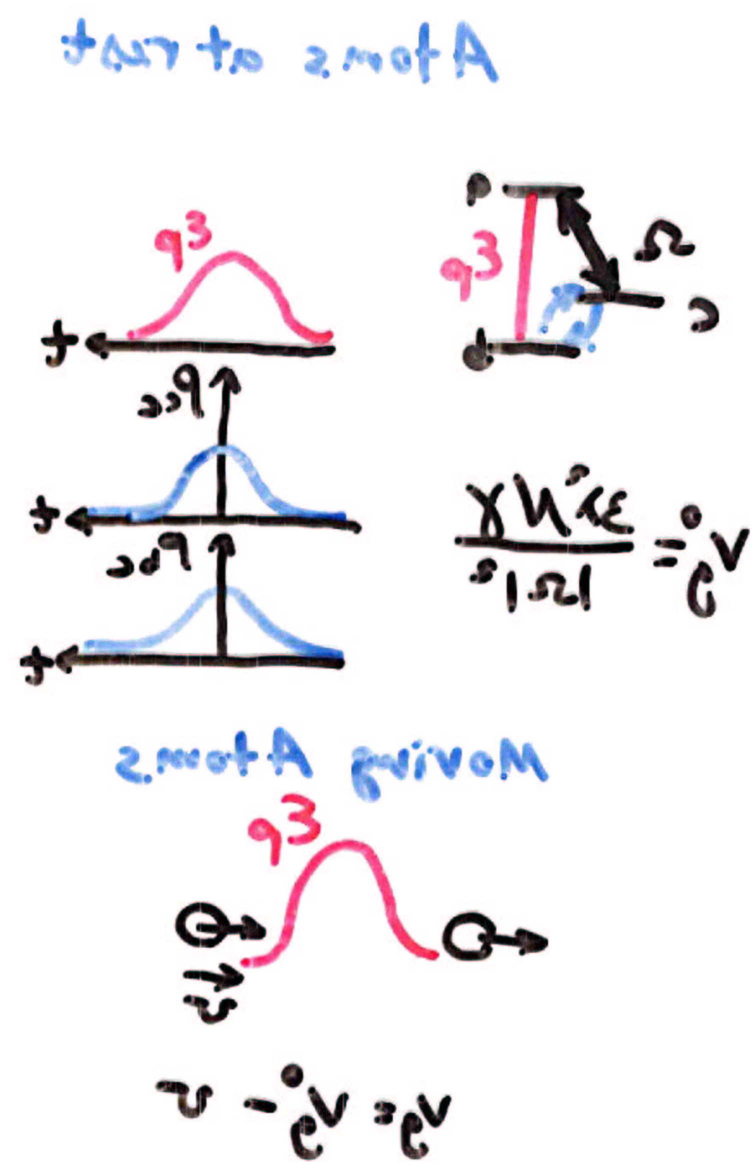
$$v_g = \frac{c}{1 + \frac{3c\lambda^2 N\gamma}{8\pi\Omega^2}}, \quad \Omega^2 \gg \gamma\gamma_{cb}$$

$$v_g > \frac{8\pi\gamma_{cb}}{3c\lambda^2 N}$$

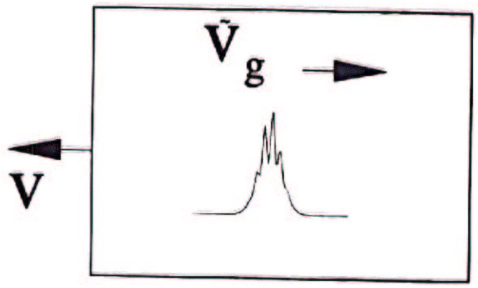
Three-level Λ system



$$\sigma_{ab} = \frac{-i\Omega_p}{\Gamma_{ab} + \frac{|\Omega|^2}{\Gamma_{cb}}}$$



Mono-velocity atoms



$$V_g = \tilde{V}_g - V$$

The Galilean transformation between laboratory and co-moving frames

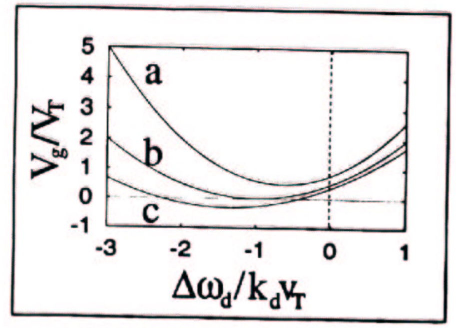
$$k = \tilde{k}, \quad \omega = \tilde{\omega} - \tilde{k}v,$$

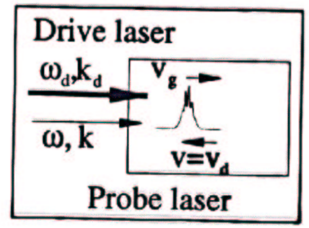
$$v_g = Re(d\omega/dk) = Re[d(\tilde{\omega} - \tilde{k}v)/d\tilde{k}] = \tilde{v}_g - v,$$

Spatial Dispersion

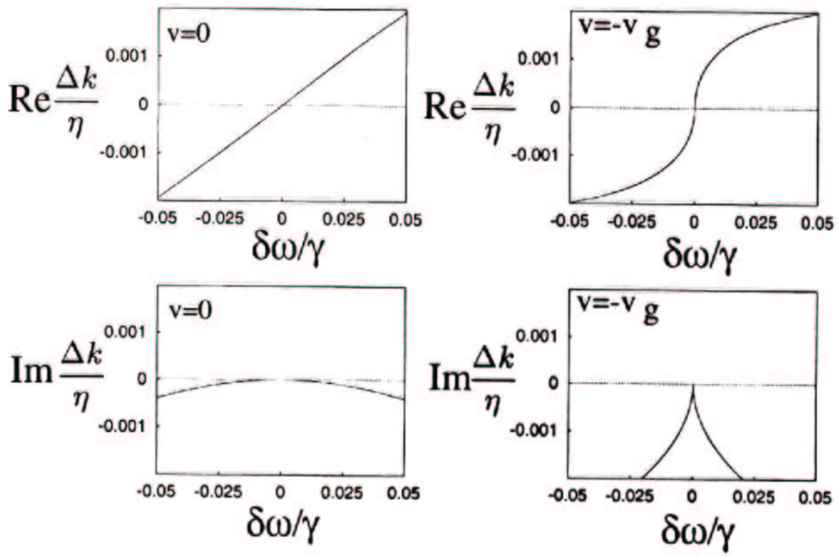
$$k = \frac{\omega}{c} n(\omega, k), \quad c = v_g\left(n + \omega\frac{\partial n}{\partial \omega}\right) + \omega\frac{\partial n}{\partial k}$$

$$v_g = Re\frac{c - \omega\frac{\partial n}{\partial k}}{n + \omega\frac{\partial n}{\partial \omega}} = \tilde{v}_g - v_s$$





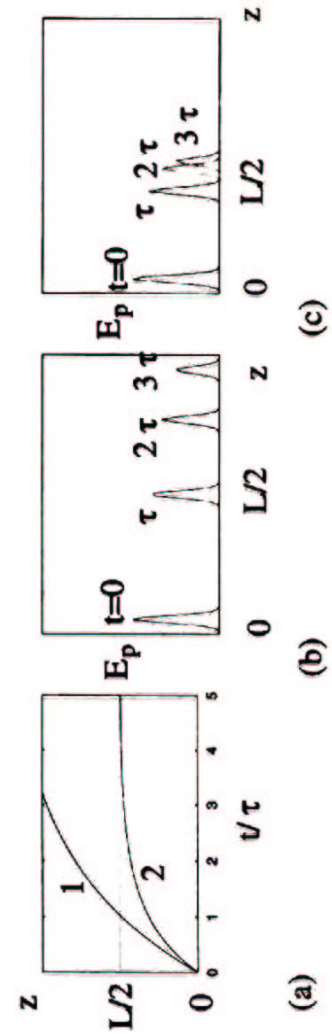
Laboratory Frame Physics



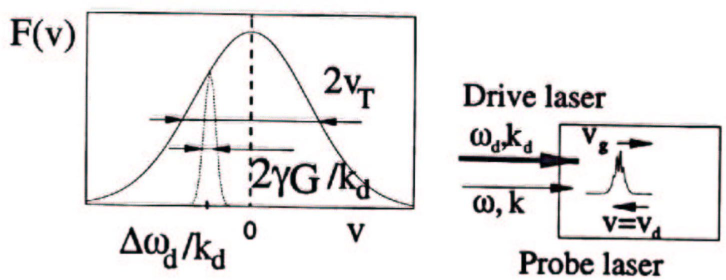
$$k = \frac{\nu}{c}(1 + \frac{1}{2}\chi) = k_0 + \Delta k$$

$$\eta = \frac{3\lambda^2 N}{8\pi}$$

$$\gamma = \frac{4\omega^3 \mathcal{P}^2}{3\epsilon_0 \hbar c^3}$$



Thermal velocity distribution



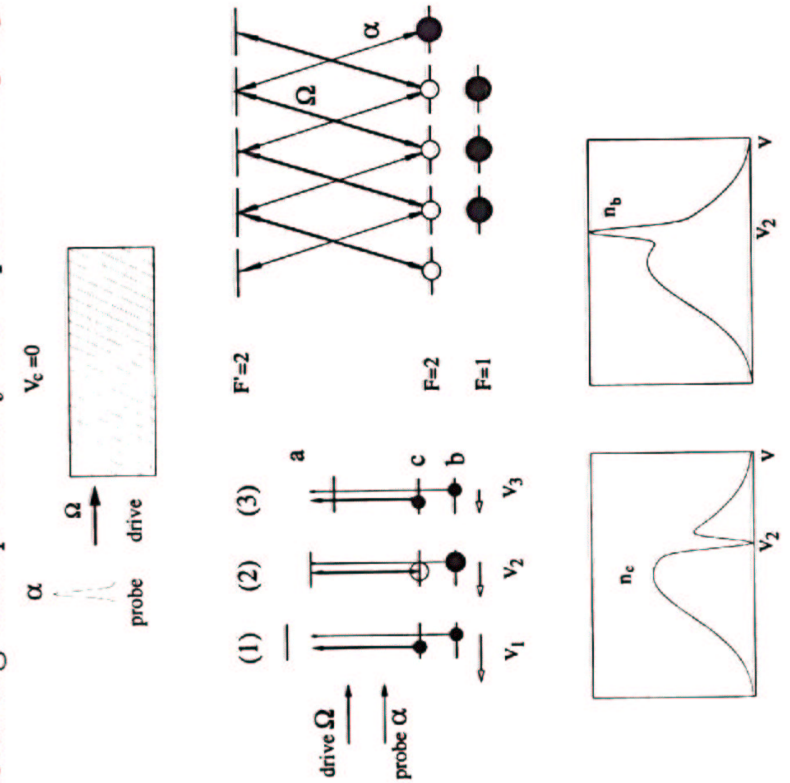
$$\Delta\omega_d = \omega_d - \omega_{ac} = kv_d$$

Necessary conditions:

$$\gamma \ll 2kv_T, \sqrt{\gamma_{cb}\gamma} < \Omega < kv_T\sqrt{\frac{\gamma_{cb}}{\gamma}}, \quad \left(\frac{\Omega^2\gamma}{kv_T} \ll \gamma_{cb}\right)$$

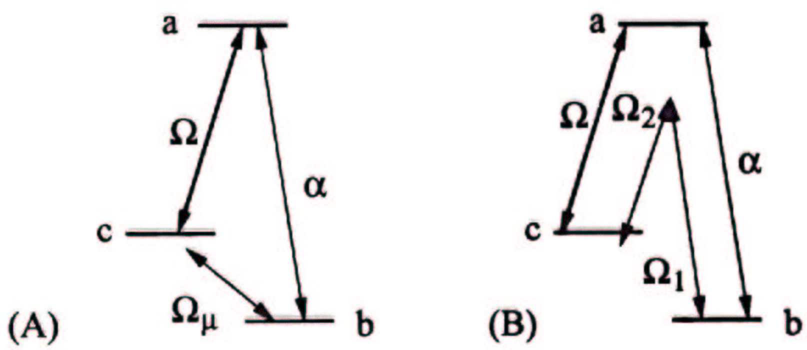
Otherwise all atoms are trapped. Width of the effective beam $k\Delta v \sim \Omega\sqrt{\frac{\gamma}{\gamma_{cb}}}$, $\left(\frac{\Omega^2\gamma}{\gamma^2+(kv_T)^2} \sim \gamma_{cb}\right)$

Slowing Group Velocity via Optical Pumping



$$|v - v_2| \le \sqrt{\frac{\gamma}{\gamma_{bc}}}\frac{|\Omega|}{k_d}$$

Control propagation via additional fields



The susceptibility $\chi(\nu)$ is obtained by solving density matrix equations of motion given by

$$\dot{\rho}_{ab} = -\Gamma_{ab}\rho_{ab} + i(\rho_{aa} - \rho_{bb})\alpha - i\Omega\rho_{cb} + i\Omega_\mu^*\rho_{ac}\exp(-i\delta\omega t),$$

$$\dot{\rho}_{cb} = -\Gamma_{cb}\rho_{cb} + i(\rho_{ca}\alpha - \rho_{ab}\Omega) + in_{cb}\Omega_\mu\exp(i\delta\omega t),$$

$$\dot{\rho}_{ca} = -\Gamma_{ca}\rho_{ca} + i(\rho_{cc} - \rho_{aa})\Omega + i\alpha\rho_{cb} - i\Omega_\mu^*\rho_{ba}\exp(-i\delta\omega t),$$

$$\dot{\rho}_{aa} = -(2\gamma + \gamma_0)\rho_{aa} - 2Im(\rho_{ab}\alpha^*) + 2Im(\rho_{ca}\Omega^*),$$

$$\dot{\rho}_{bb} = r_b - \gamma_0\rho_{bb} + \gamma\rho_{aa} + 2Im(\rho_{ab}\alpha^*) + 2Im(\rho_{cb}^*\Omega_\mu),$$

$$\dot{\rho}_{cc} = r_c - \gamma_0\rho_{bb} + \gamma\rho_{aa} - 2Im(\rho_{ca}\Omega^*) + 2Im(\rho_{cb}\Omega_\mu^*),$$

$$\chi(\nu, k) = \int \chi_v(\nu, kv)F_L(v)dv. \qquad (4)$$

where

$$F_L(v) = \frac{u_T}{\pi}\frac{1}{v^2 + u_T^2} \qquad (5)$$

$$\chi(\nu, k) = \qquad (6)$$

$$-\eta\int \frac{i}{\Gamma_{ab}\Gamma_{cb} + |\Omega|^2}\frac{1}{1+\xi}\left(\Gamma_{cb} + \frac{|\Omega|^2}{\Gamma_{ca}}\xi\right)\frac{u_T}{\pi}\frac{1}{v^2 + u_T^2}dv.$$

$$k_{cb}^2(\delta v)^2 = \gamma_{cb}^2 + \frac{4\Omega_\mu^2\gamma\gamma_{cb}}{\Omega^2 + 2\gamma\gamma_{cb}} \simeq \gamma_{cb}^2 + \frac{4\Omega_\mu^2\gamma\gamma_{cb}}{\Omega^2}$$

$$\chi(\nu, k) = \frac{\eta(\omega - i\gamma_{cb})}{\Omega^2} - \frac{\eta u_T\delta v}{2\Omega^2(u^2 + u_T^2)}(\omega + ku - i\gamma_{cb})$$

$$V_g = V_g^0\left(1 + \frac{u}{V_g^0}\frac{u_T\delta v}{2(u^2 + u_T^2)}\right) \qquad (7)$$

To stop light pulse we should meet the condition

$$4\delta v > V_g^0 \tag{8}$$

$$\gamma_{cb}^2 + 4\Omega_\mu^2 \gamma\gamma_{cb} > \frac{k_{cb}^2 \Omega^4}{4\eta} \tag{9}$$

or

$$\gamma_{cb}^2 + 4\Omega_\mu^2 \gamma\gamma_{cb} > \frac{k_{cb}^2 \Omega^2}{4\gamma} \tag{10}$$

For $\gamma_{cb} = 10^4$ s^{-1}, $\Omega = \gamma$ the inequality is correct..

The probe pulse can be represented as a sum of plane waves, in the form

$$E(t,z) = \sum_k E_k \exp(ikz - i\omega_k t). \tag{11}$$

Without a microwave field, the dispersion relation is given

$$\omega_k = V_g k, \tag{12}$$

Switching on the microwave field modifies the dispersion relation, $V_g = 0$, by

$$E(t,z) = \sum_k E_k \exp(ikz - i\omega_k t) = E(t = t_{on}, z).$$

The probe pulse is trapped at the position it has been at the time of switching t_{on}.