Quantum nonlinear optics mediated by long-range interactions between Rydberg atoms

David Petrosyan

IESL-FORTH, GR

Outline

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- Conclusions

Interactions between Rydberg atoms

Rydberg Atoms

High principal quantum number

$$\boxed{n \gg 1}$$ (H-like)

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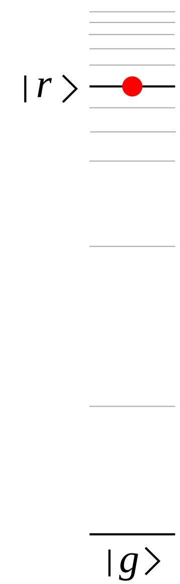

Energy $$\boxed{E_r = -\frac{\mathrm{Ry}}{n^{*2}}}$$

effective PQN $n^* = n - \delta_l$ (δ_l quantum defect)

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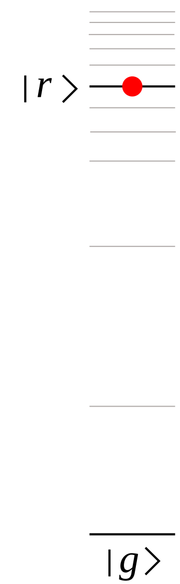
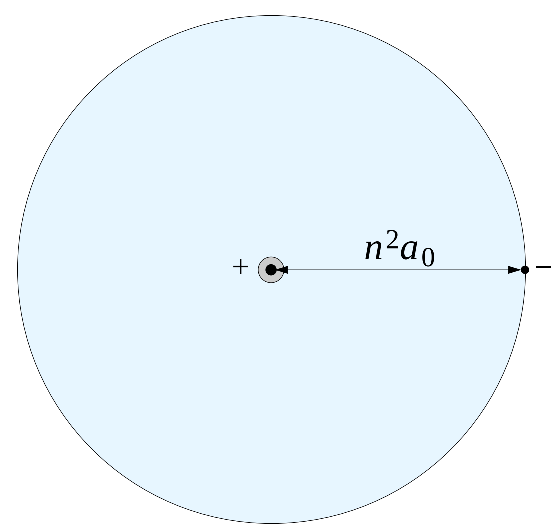


Energy $$\boxed{E_r = -\frac{\mathrm{Ry}}{n^{*2}}}$$

effective PQN $n^* = n - \delta_l$ (δ_l quantum defect)

Easily polarizable

Huge dipole moments $$\boxed{\wp \sim n^2 e a_0}$$



Gallagher, *Rydberg Atoms* (Cambridge 1994)

Dipole-Dipole Interactions

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$$D = \frac{\boldsymbol{\wp}_1 \cdot \boldsymbol{\wp}_2}{R^3} - 3\frac{(\boldsymbol{\wp}_1 \cdot \boldsymbol{R})(\boldsymbol{\wp}_2 \cdot \boldsymbol{R})}{R^5} \propto n^4$$

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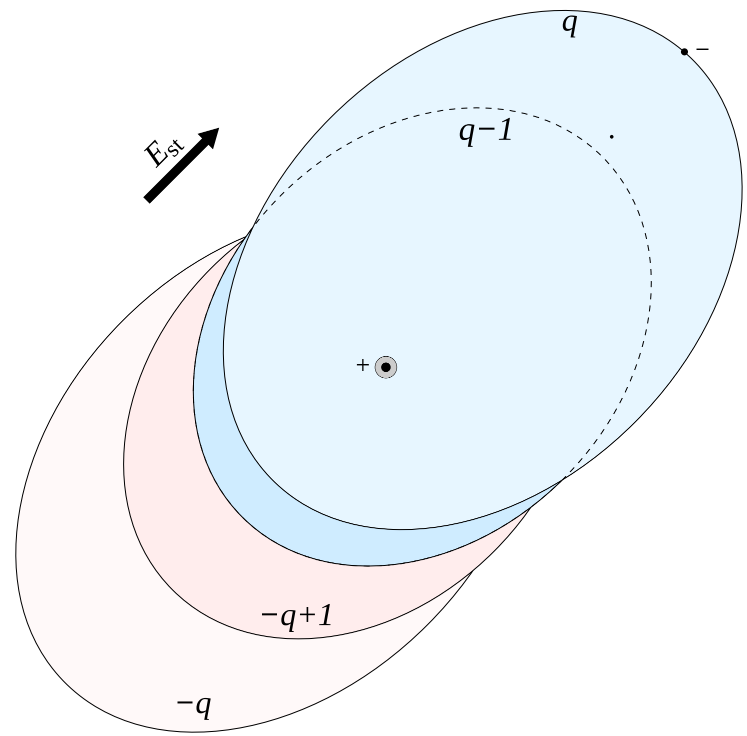
$\Rightarrow$ **Static DDI**

$\boldsymbol{E}_{\text{st}}$ induced Stark eigenstates

with permanent $\wp = \frac{3}{2} nqea_0$



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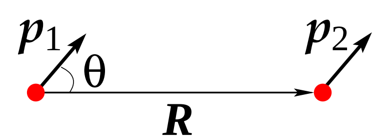

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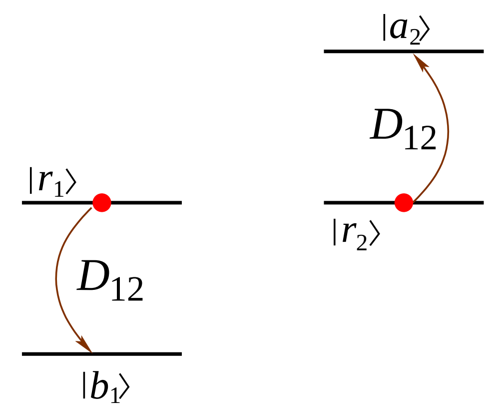
⇒ Resonant DDI

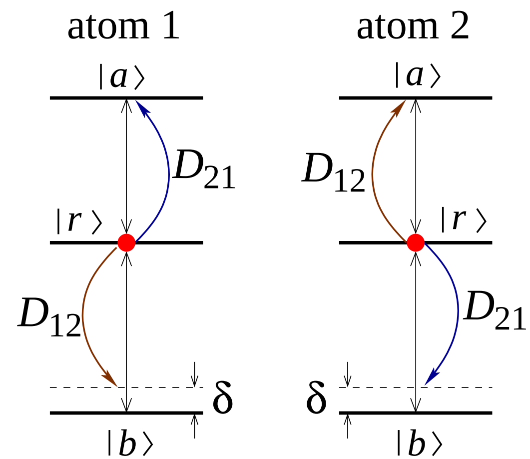
$$D = \frac{1}{R^3}\Big[\wp_{1+}\wp_{2-} + \wp_{1-}\wp_{2+} + \wp_{1z}\wp_{2z}(1 - 3\cos^2\theta)$$
$$-\frac{3}{2}\sin^2\theta(\wp_{1+}\wp_{2+} + \wp_{1+}\wp_{2-} + \wp_{1-}\wp_{2+} + \wp_{1-}\wp_{2-})$$
$$-\frac{3}{\sqrt{2}}\sin\theta\cos\theta(\wp_{1+}\wp_{2z} + \wp_{1-}\wp_{2z} + \wp_{1z}\wp_{2+} + \wp_{1z}\wp_{2-})\Big]$$



van der Waals Interaction

RDDI (Förster process)

$$D_{12} \equiv D(R) \propto \frac{\wp_{br}\wp_{ar}}{R^3} \propto n^4$$



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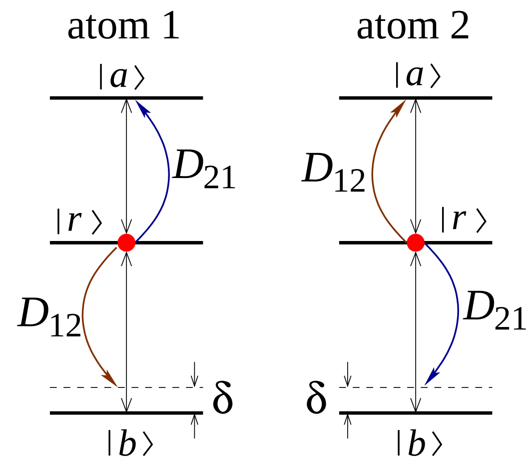
$(\delta \propto n^{-3})$



$\Rightarrow$ $|r_1\rangle\,|r_2\rangle \nrightarrow |a_{1,2}\rangle\,|b_{2,1}\rangle$: **Non-Resonant DDI** (Adiabatic elim. $|a_{1,2}\rangle\,|b_{2,1}\rangle$)

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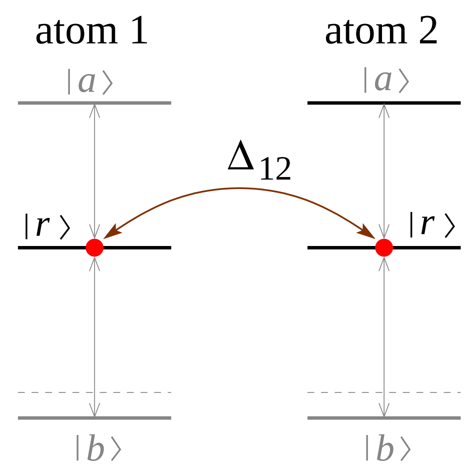

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⇒ Energy shift of $|r_1\rangle\,|r_2\rangle$ (2nd-order in D/δ)

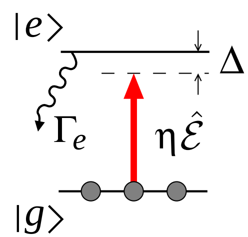
$$\mathcal{V}_{\mathrm{vdW}} = \hbar\hat{\sigma}^1_{rr}\Delta_{12}\hat{\sigma}^2_{rr}$$

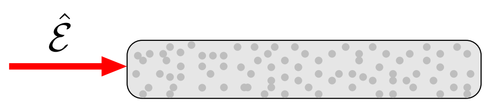
$\Delta_{12} \equiv \bar{\Delta}(R) = 2\frac{|D(R)|^2}{\delta} = \frac{C_6}{R^6} \propto n^{11}$ — vdWI strength

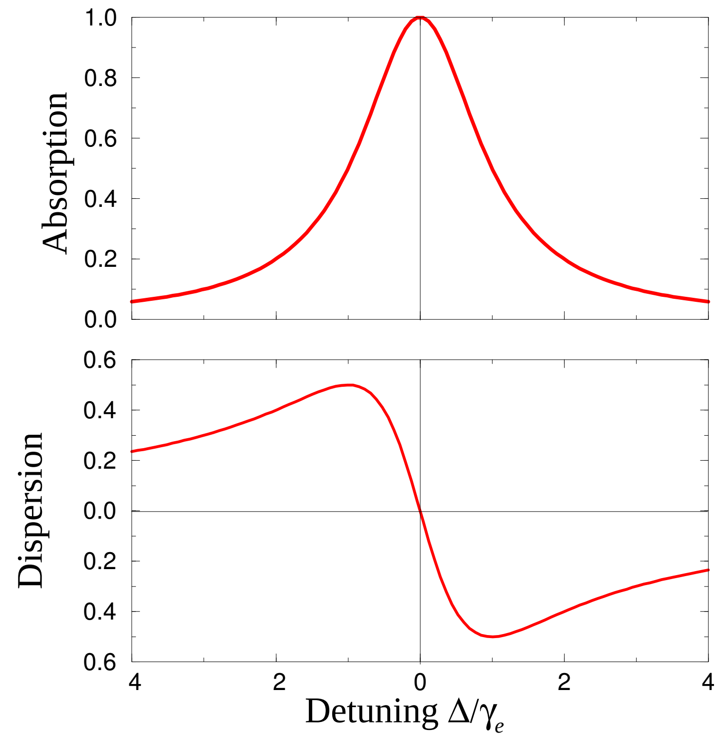
Saffman, Walker, Mølmer, RMP **82**, 2313 (2010)

Electromagnetically Induced Transparency in atomic medium

Electromagnetically Induced Transparency







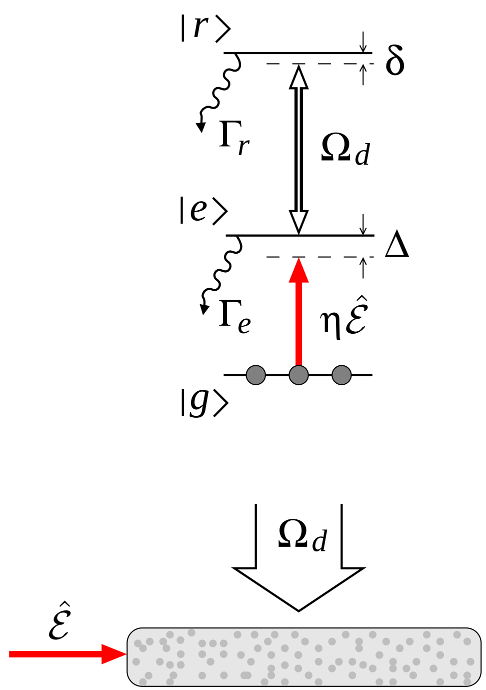
Stationary propagation

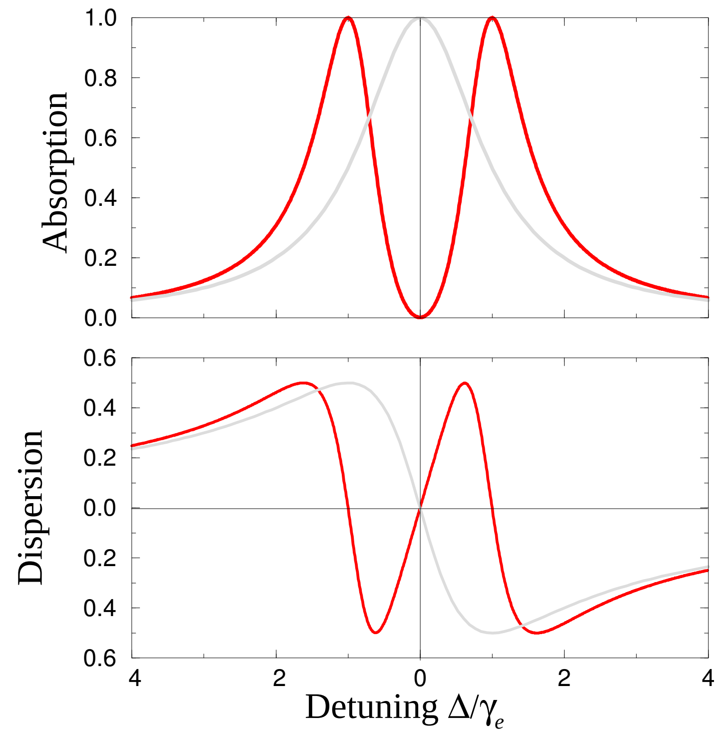
$$\partial_z \mathcal{E} = i\frac{\omega}{2c}\chi\mathcal{E}$$

2LA medium susceptibility

$$\chi = \frac{2}{\omega}\frac{i\eta^2 N}{\gamma_e - i\Delta} = \frac{i}{k}\frac{\sigma_0\bar{\rho}\Gamma_e}{\gamma_e - i\Delta}$$

Electromagnetically Induced Transparency





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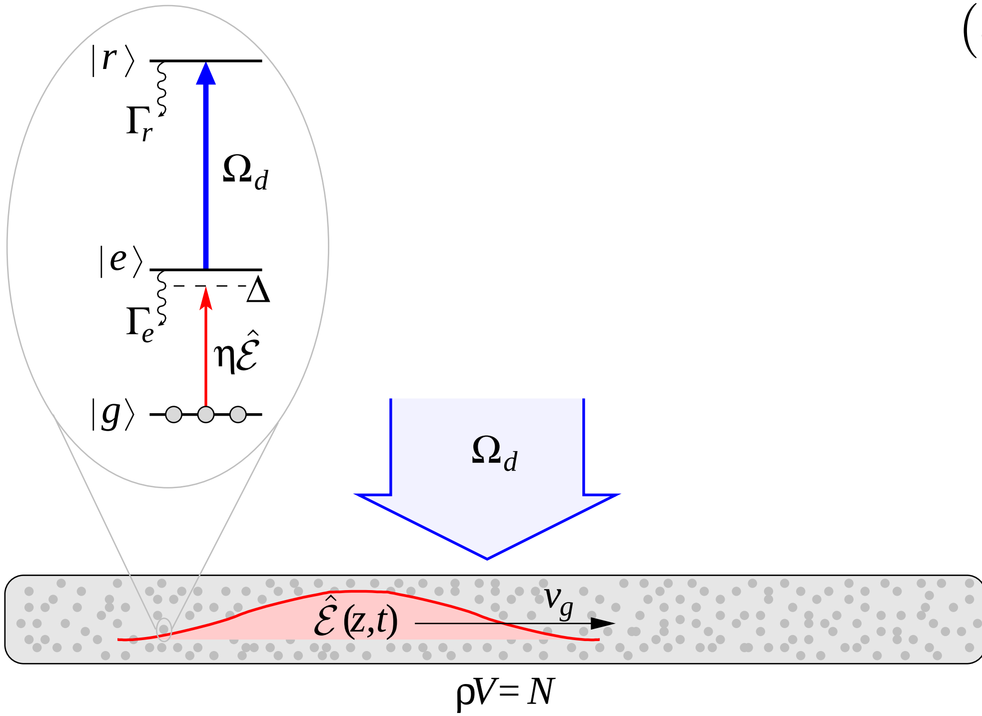
EIT (3LA) susceptibility

$$\chi = \frac{2}{\omega} \frac{i\eta^2 N}{\gamma_e - i\Delta + \frac{|\Omega_d|^2}{\gamma_r - i(\Delta+\delta)}}$$

Fleischhauer, Imamoglu, Marangos, RMP **77**, 633 (2005)

Pulse propagation in EIT medium



$$(\partial_t + v_g \partial_z)\hat{\mathcal{E}}(z,t) = i\frac{\omega}{2}\chi\,\hat{\mathcal{E}}(z,t)$$

with

$$v_g = \frac{c}{1+\frac{\omega}{2}\frac{\partial}{\partial\Delta}\mathrm{Re}\chi} \simeq c\frac{|\Omega_d|^2}{\eta^2 N} \ll c$$

$$\frac{\omega}{2}\chi \simeq \frac{\eta^2 N}{|\Omega_d|^2}(\Delta+\delta) \to 0$$

@ two-photon resonance

$$\boxed{\Delta \simeq -\delta \;\;\&\;\; |\gamma_e + i\delta|\gamma_r \ll |\Omega_d|^2}$$

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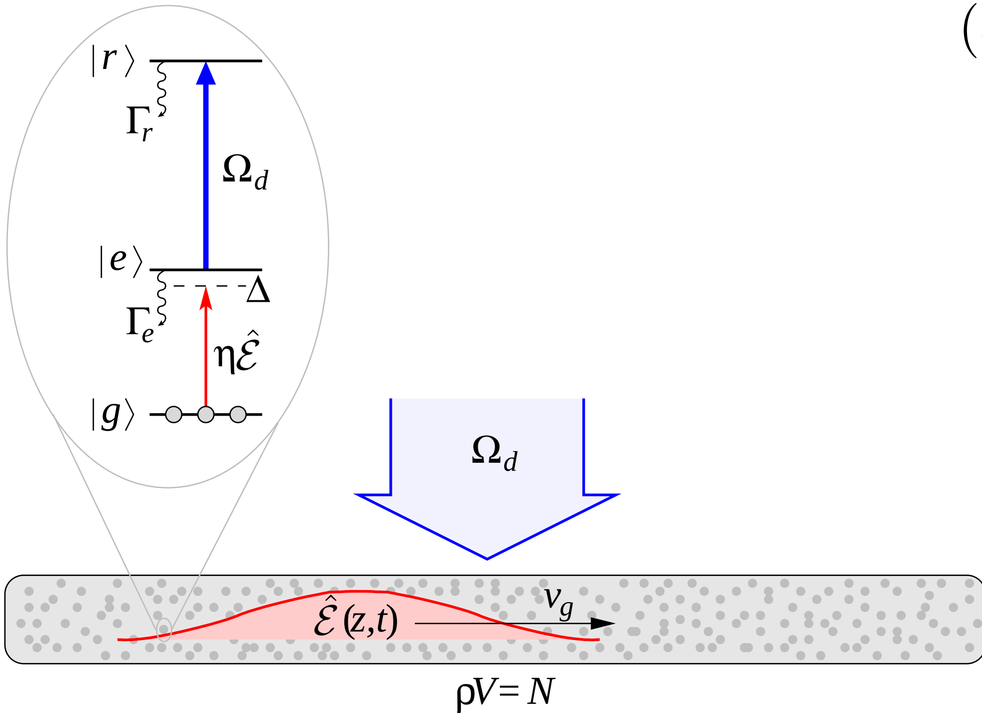

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Inside the medium ⇒ dark-state polariton

$$\hat{\mathcal{E}} \to \hat{\Psi} = \cos\Theta\hat{\mathcal{E}} - \sin\Theta\sqrt{N}\hat{\sigma}_{gr} \quad \text{with} \quad \tan^2\Theta = \frac{\eta^2 N}{|\Omega_d|^2} \gg 1 \qquad \left[\eta = \frac{\wp_{ge}}{\hbar}\sqrt{\frac{\hbar\omega}{2\epsilon_0 V}}\right]$$

Fleischhauer, Lukin, PRL **84**, 5094 (2000); PRA **65**, 022314 (2002)

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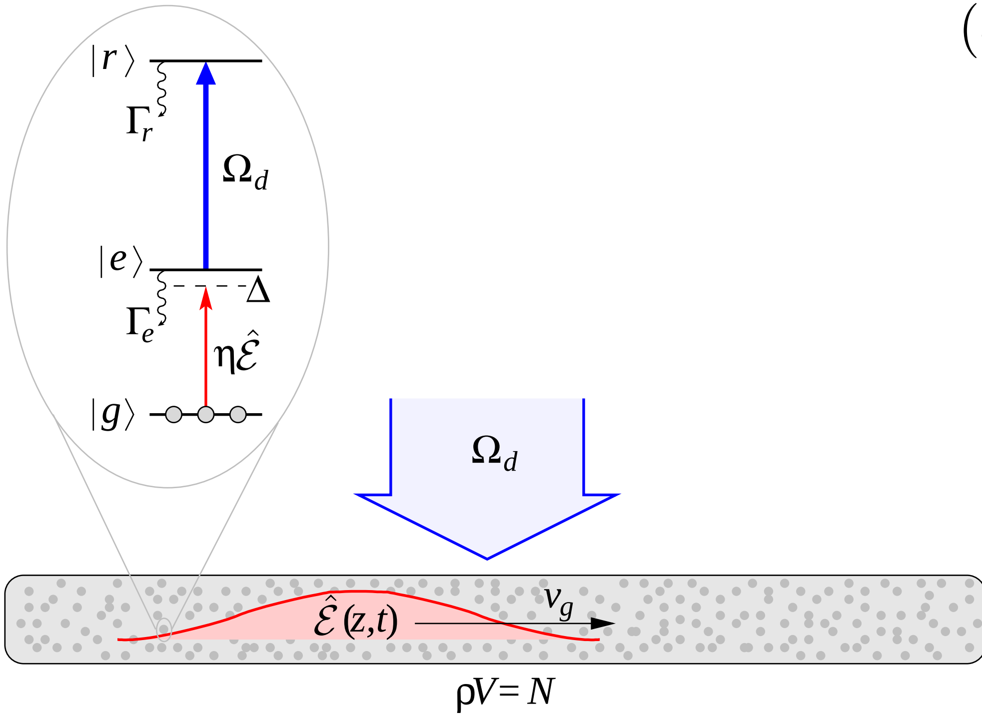

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Inside the medium $\Rightarrow$ dark-state polariton

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Photons are converted to atomic $|r\rangle$ excitations ($\cos\Theta \ll 1$) and propagate with slow (variable) group velocity $v_g(t) = c\cos^2\Theta(t) \ll c$:

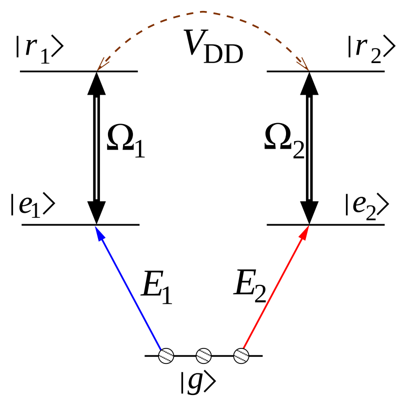
$$(\partial_t + v_g\partial_z)\hat{\Psi} = 0 \quad \Rightarrow \quad \hat{\Psi}(z,t) = \hat{\Psi}(z - \textstyle\int_0^t v_g(t')dt', 0)$$

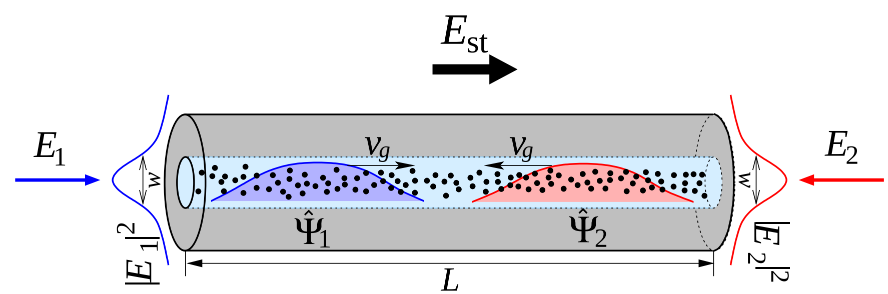
Fleischhauer, Lukin, PRL **84**, 5094 (2000); PRA **65**, 022314 (2002)

Giant cross-phase modulation:
Photonic phase gate

Friedler, Petrosyan, Fleischhauer, Kurizki, PRA **72**, 043803 (2005)
Shahmoon, Kurizki, Fleischhauer, Petrosyan PRA **83**, 033806 (2011)

Photon-Photon Interaction





Static $E_{\rm st}\mathbf{e}_z \Rightarrow$ Stark eigenstates $|r_j\rangle$ with SDMs $\wp_r \mathbf{e}_z = \frac{3}{2} n q e a_0 \mathbf{e}_z$

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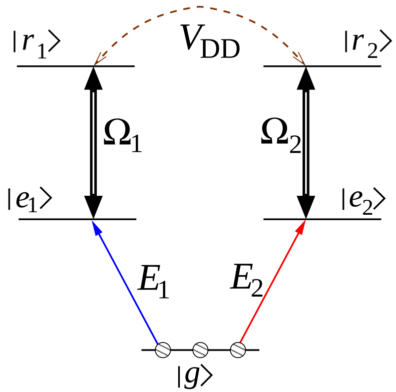

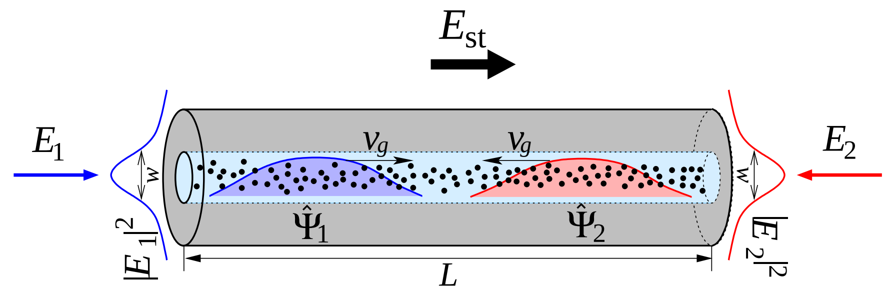

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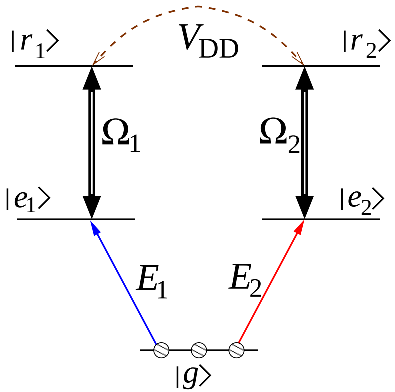

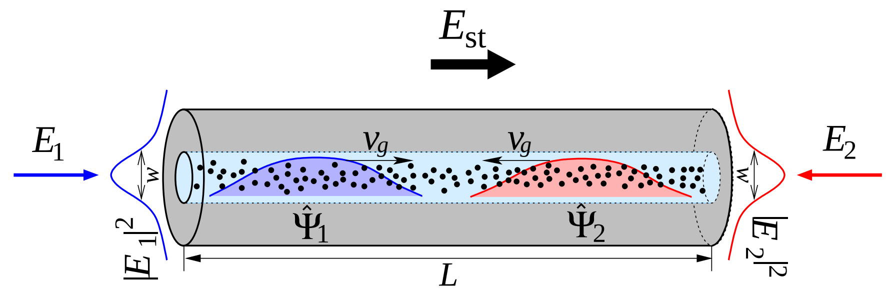

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Atomic components of $\hat{\Psi}_i$ interact via Static DDI $\Rightarrow$ induces XPM

$$V_{\rm DD} = \hbar \rho^2 \iint \mathrm{d}^3 r \, \mathrm{d}^3 r' \hat{\sigma}_{rr}(\mathbf{r}) D(\mathbf{r} - \mathbf{r}') \hat{\sigma}_{rr}(\mathbf{r}')$$

$$D(\mathbf{r} - \mathbf{r}') = C \frac{1 - 3\cos^2\theta}{|\mathbf{r} - \mathbf{r}'|^3} \quad \text{with} \quad C = \frac{\wp_{r_l} \wp_{r_{l'}}}{4\pi\epsilon_0 \hbar}$$

Resonant DDI (state mixing) is suppressed for $q = n - 1$, $m = 0$

Cross-Phase Modulation

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$$(\partial_t + v_g \partial_z)\hat{\Psi}_j(z,t) = -i \sin^2\Theta \hat{S}(z,t)\hat{\Psi}_j(z,t)$$

$$\boxed{\langle \hat{S}(z)\rangle < \delta\omega \simeq \frac{|\Omega_d|^2}{\gamma_e}}$$

$$\hat{S}(z,t) = \frac{1}{L}\int_0^L D(z-z')\sin^2\Theta[\hat{\mathcal{I}}_1(z',t) + \hat{\mathcal{I}}_2(z',t)]dz' \qquad \hat{\mathcal{I}}_j \equiv \hat{\Psi}_j^\dagger \hat{\Psi}_j$$

$$D(z-z') = \frac{1}{(\pi w^2)^2}\int d^2 r_\perp \int d^2 r'_\perp \, e^{-(r_\perp^2 + r'^2_\perp)/w^2} D(\mathbf{r}-\mathbf{r}')$$

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Input state: two single photons [$t = 0$, $z_1 = 0$ & $z_2 = L$]

$$|\Phi_{\text{in}}\rangle = |1_1\rangle |1_2\rangle \quad \left[|1_j\rangle = \frac{1}{L}\int dz f_j(z) \hat{\Psi}_j^\dagger(z) |0\rangle \right]$$

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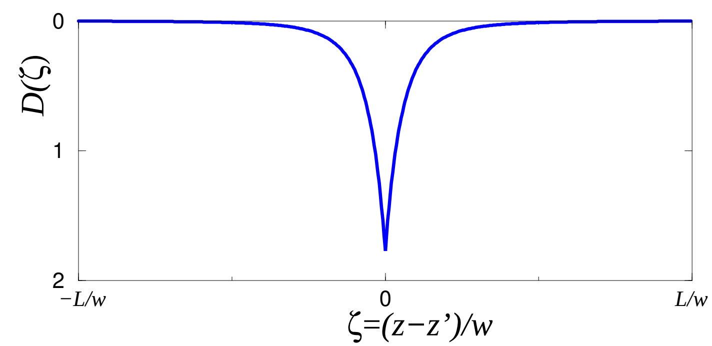
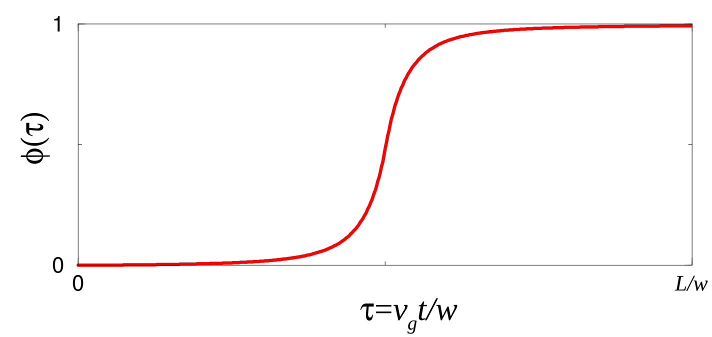
Evolution of two-photon wavefunction:

$$F_{12}(z_1,z_2,t) = \langle 0|\,\hat{\Psi}_1(z_1,t)\hat{\Psi}_2(z_2,t)\,|\Phi_{\text{in}}\rangle$$

$$= f_1(z_1 - vt) f_2(z_2 + vt) e^{i\phi(z_1,z_2,t)}$$

$$\phi(z_1,z_2,t) = -\sin^4\Theta \int_0^t dt' D(z_1 - z_2 - 2v_g(t-t'))$$





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$$D(z-z') = \frac{1}{(\pi w^2)^2}\int d^2 r_\perp \int d^2 r'_\perp e^{-(r_\perp^2 + r_\perp'^2)/w^2} D(\mathbf{r} - \mathbf{r}')$$

$$\Rightarrow \hat{\Psi}_j(z,t) = e^{-i\sin^2\Theta \int_0^t dt' \hat{S}(z \mp v_g(t-t'),t')} \hat{\Psi}_j(z \mp v_g t, 0)$$

Input state: two single photons [$t=0$, $z_1 = 0$ & $z_2 = L$]

$$|\Phi_{\text{in}}\rangle = |1_1\rangle |1_2\rangle \quad \left[|1_j\rangle = \frac{1}{L}\int dz f_j(z)\hat{\Psi}_j^\dagger(z)|0\rangle \right]$$

Output state: [$t = L/v_g$, $z_1 = L$ & $z_2 = 0$]

$$|\Phi_{\text{out}}\rangle = e^{i\phi}|1_1\rangle |1_2\rangle$$

$$\phi(L,0,L/v) = -\frac{\sin^4\Theta}{v_g}\int_0^L dz' D(2z'-L) = \frac{C}{v_g w^2}$$

Cross-Phase Modulation

$$(\partial_t + v_g \partial_z)\hat{\Psi}_j(z,t) = -i\sin^2\Theta \hat{S}(z,t)\hat{\Psi}_j(z,t)$$

$$\langle \hat{S}(z)\rangle < \delta\omega \simeq \frac{|\Omega_d|^2}{\gamma_e}$$

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Phase shift $\phi=\pi$ [spatially uniform!]

$\Rightarrow$ Universal CPHASE gate between SPh pulses $\hat{\mathcal{E}}_1$ & $\hat{\mathcal{E}}_2$

$$|x\rangle_1\,|y\rangle_2 \to (-1)^{xy}\,|x\rangle_1\,|y\rangle_2 \qquad (x,y\in[0,1])$$

Dissipative photonic interactions

Gorshkov et al., PRL **107**, 133602 (2011); Peyronel et al., Nature **488**, 57 (2012)
Pritchard et al., PRL **105**, 193603 (2010); Petrosyan et al., PRL **107**, 213601 (2011)
Ates et al. PRA **83**, 041802(R) (2011); Sevincli et al. PRL **107**, 153001 (2011)
Baur et al. PRL **112**, 073901 (2014); Gorniaczyk et al. PRL **113**, 053601 (2014)

Rydberg blockade of excitation

Atom in state $|R\rangle$ at position $\mathbf{r}'$

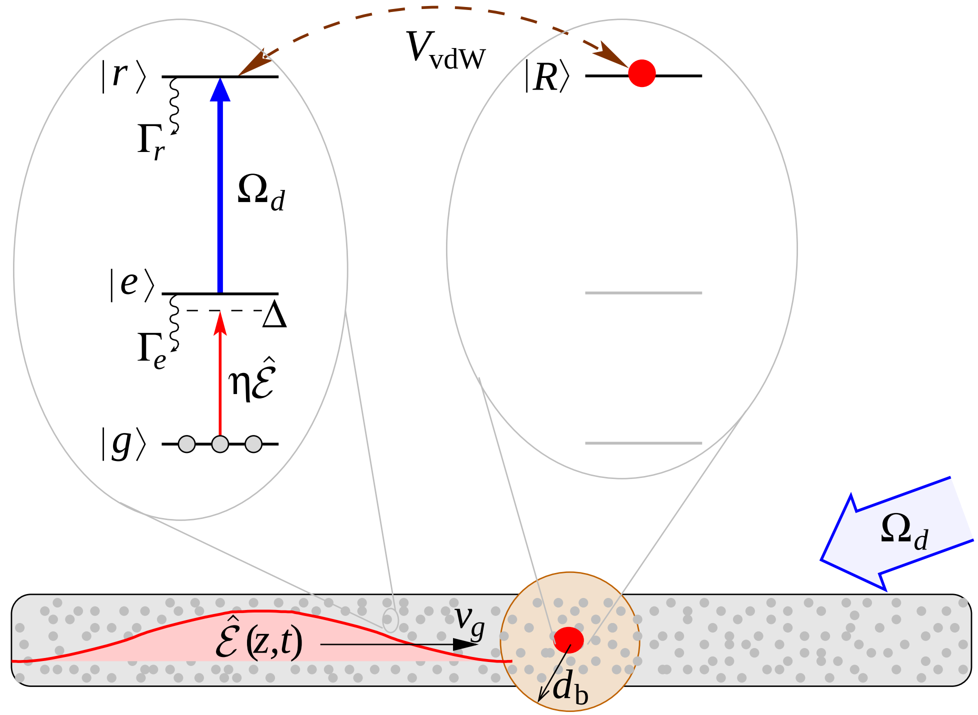
interacts with the medium

atoms via

$$V_{\rm vdW} = \sum_j \hat{\sigma}^j_{rr} \bar{\Delta}(\mathbf{r}_j - \mathbf{r}')\hat{\sigma}_{RR}$$

$$\boxed{\bar{\Delta}(\mathbf{r}_j - \mathbf{r}') = \frac{C_6}{|\mathbf{r}_j - \mathbf{r}'|^6}}$$

level shift of $|r\rangle$



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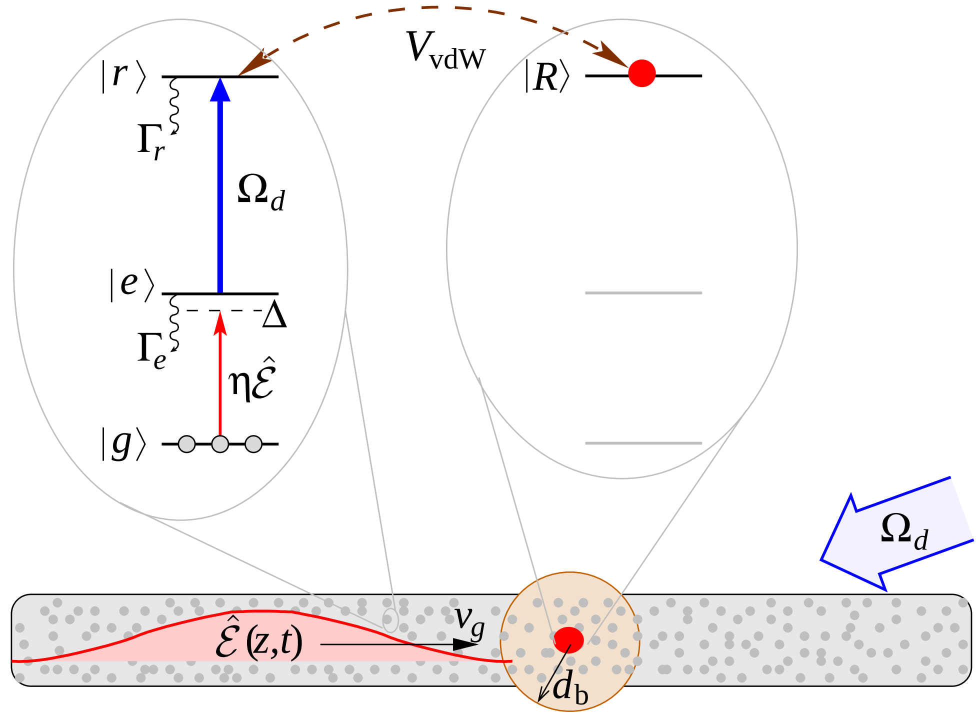

For $\bar{\Delta}(d) \gtrsim \delta\omega = \frac{|\Omega_d|^2}{\gamma_e}$

Rydberg excitation $|r\rangle$ is blocked $\Rightarrow$ Blockade distance $d_{\mathrm{b}} = \sqrt[6]{\frac{C_6}{\delta\omega}}$

Rydberg blockade of excitation

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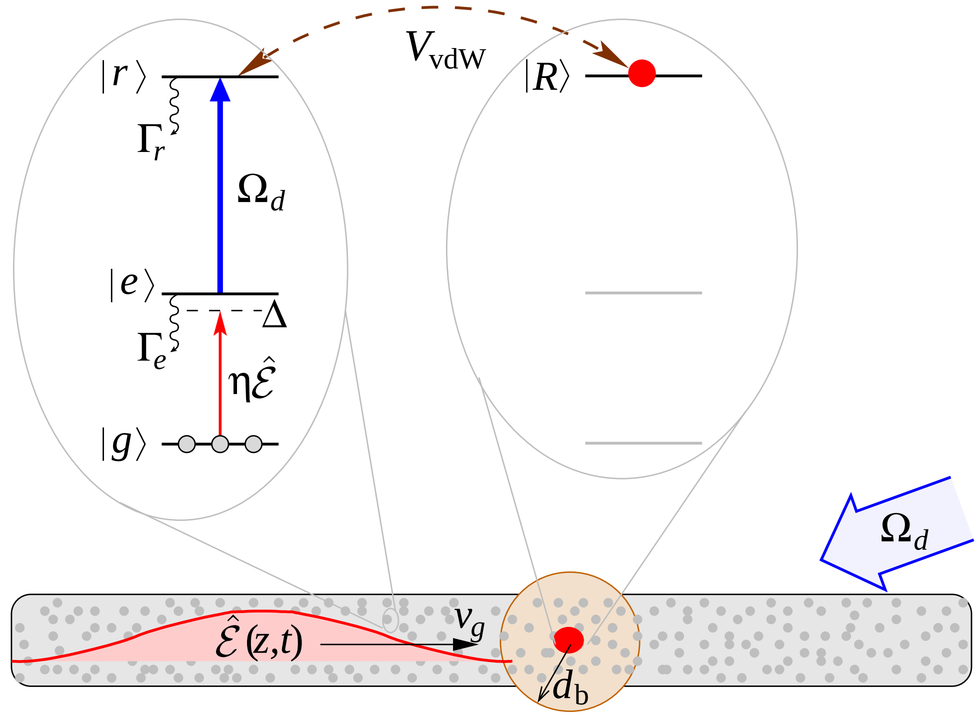

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1D $(w < d_{\mathrm{b}})$ propagation $\partial_z \mathcal{E} = i\frac{\omega}{2c}\chi\mathcal{E}$ with susceptibility

$$\chi(z) = \frac{2}{\omega}\frac{i\eta^2 N}{\gamma_e - i\Delta + \frac{|\Omega_d|^2}{\gamma_r - i(\Delta - \bar{\Delta}(z-z'))}} = \begin{cases} \frac{i}{k}\frac{\sigma_0\bar{\rho}\Gamma_e}{\gamma_e - i\Delta + \frac{|\Omega_d|^2}{\gamma_r - i\Delta}} & \text{if } (z-z') > d_{\mathrm{b}} \text{ (EIT)} \\ \frac{i}{k}\frac{\sigma_0\bar{\rho}\Gamma_e}{\gamma_e - i\Delta} & \text{if } (z-z') \leq d_{\mathrm{b}} \text{ (2LA)} \end{cases}$$

Photon transistor

Stored in $|R\rangle$ (photonic) excitation blocks the transmission of probe field

$\Rightarrow$ photons are (conditionally) absorbed in the blockade region by $\epsilon \simeq e^{-\mathrm{OD_b}}$

with $$\boxed{\mathrm{OD_b} = 4\sigma_0 \bar{\rho} d_\mathrm{b} > 1}$$

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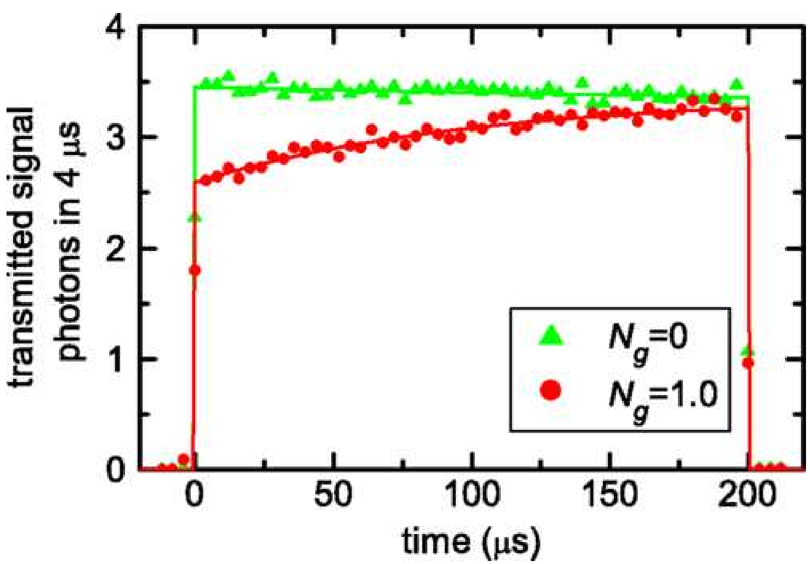
PRL **113,** 053602 (2014) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 1 AUGUST 2014

Single-Photon Transistor Using a Förster Resonance

Daniel Tiarks, Simon Baur, Katharina Schneider, Stephan Dürr, and Gerhard Rempe
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany



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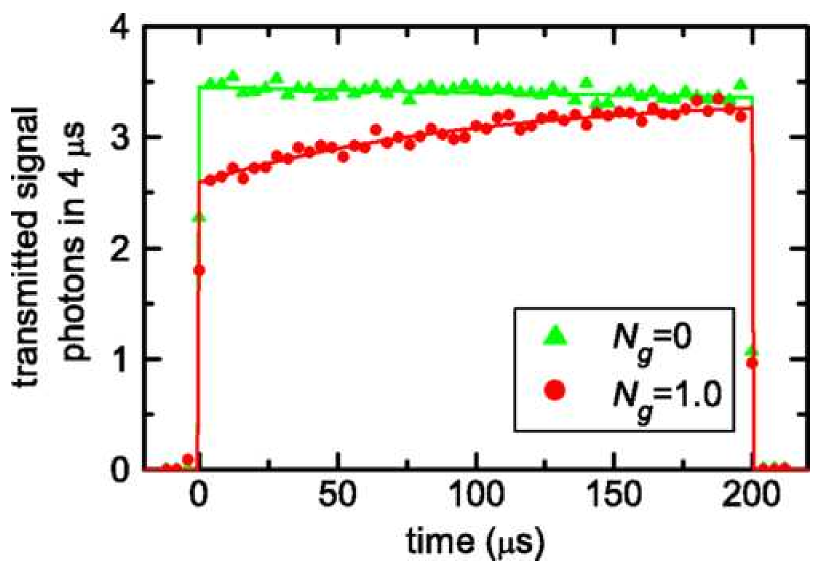
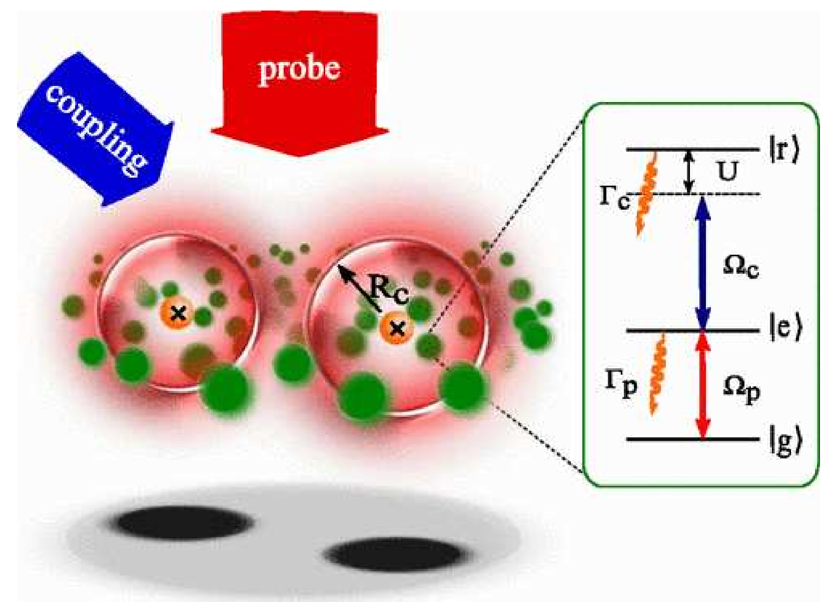


PRL 108, 013002 (2012) PHYSICAL REVIEW LETTERS 6 JANUARY 2012

Interaction Enhanced Imaging of Individual Rydberg Atoms in Dense Gases

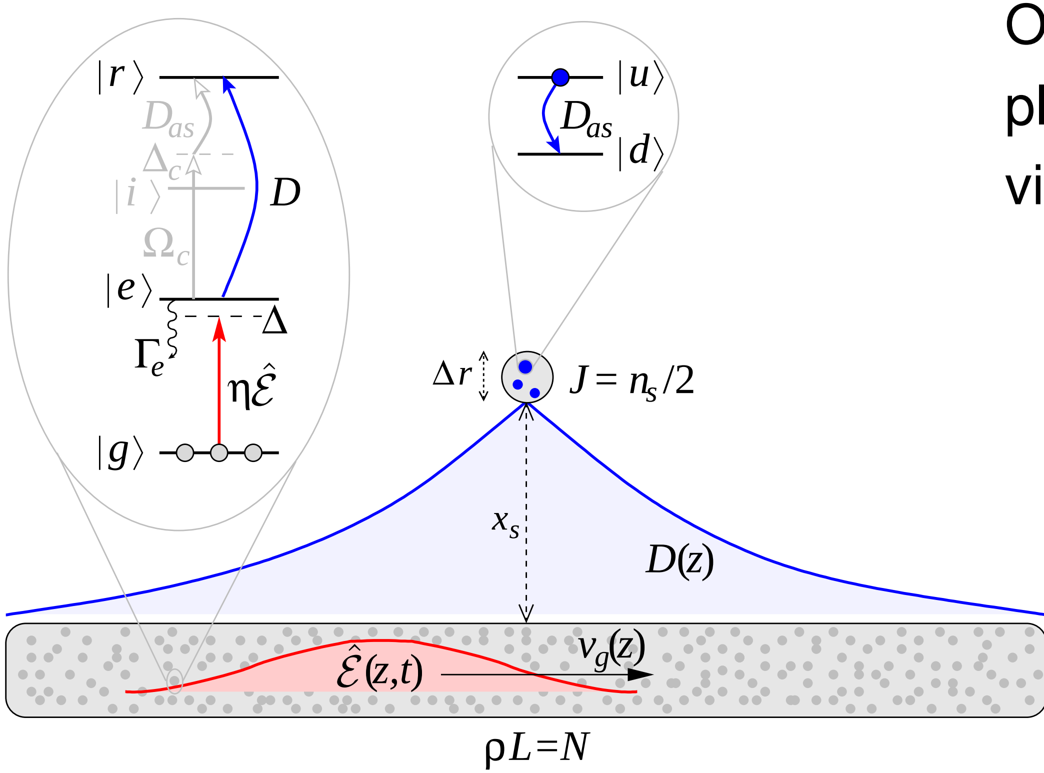
G. Günter, M. Robert-de-Saint-Vincent, H. Schempp, C. S. Hofmann, S. Whitlock,* and M. Weidemüller†
Physikalisches Institut, Universität Heidelberg, Philosophenweg 12, 69120 Heidelberg, Germany



Dipolar Exchange Induced Transparency with Rydberg atoms

Petrosyan, NJP **19**, 033001 (2017)

Dipolar-exchange induced transparency

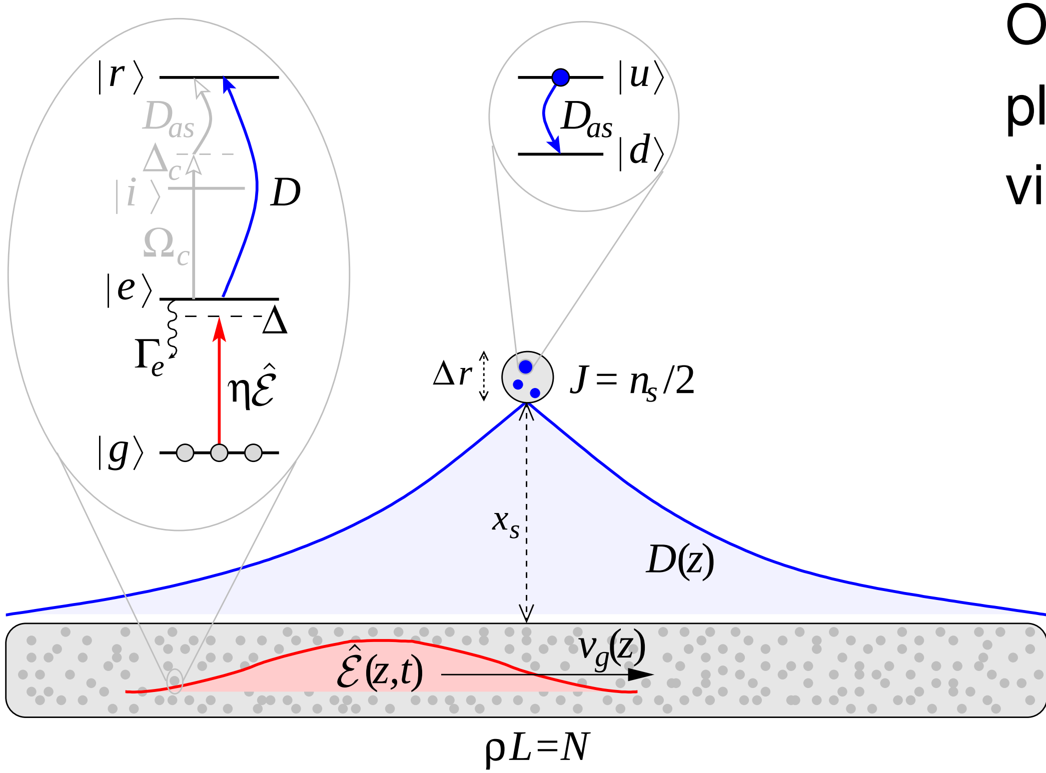


One or more spin atoms play the role of Ω_d via exchange interaction

$$\boxed{D(z)\,\hat{\sigma}_{re}(z) \otimes \hat{\sigma}_-}$$

$$D(z) = \frac{C_3 \Omega_c / \Delta_c}{|z\boldsymbol{e}_z - \boldsymbol{r}_j|^3}$$

Dipolar-exchange induced transparency



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Each probe photon in the medium attempts to create atomic $|r\rangle$ excitation with *simultaneous* flip of one spin atom $|u\rangle \to |d\rangle$ [$\hat{J}_- \equiv \sum_j^{n_s} \hat{\sigma}_-^j$ ($\Delta r \ll x_s$)]

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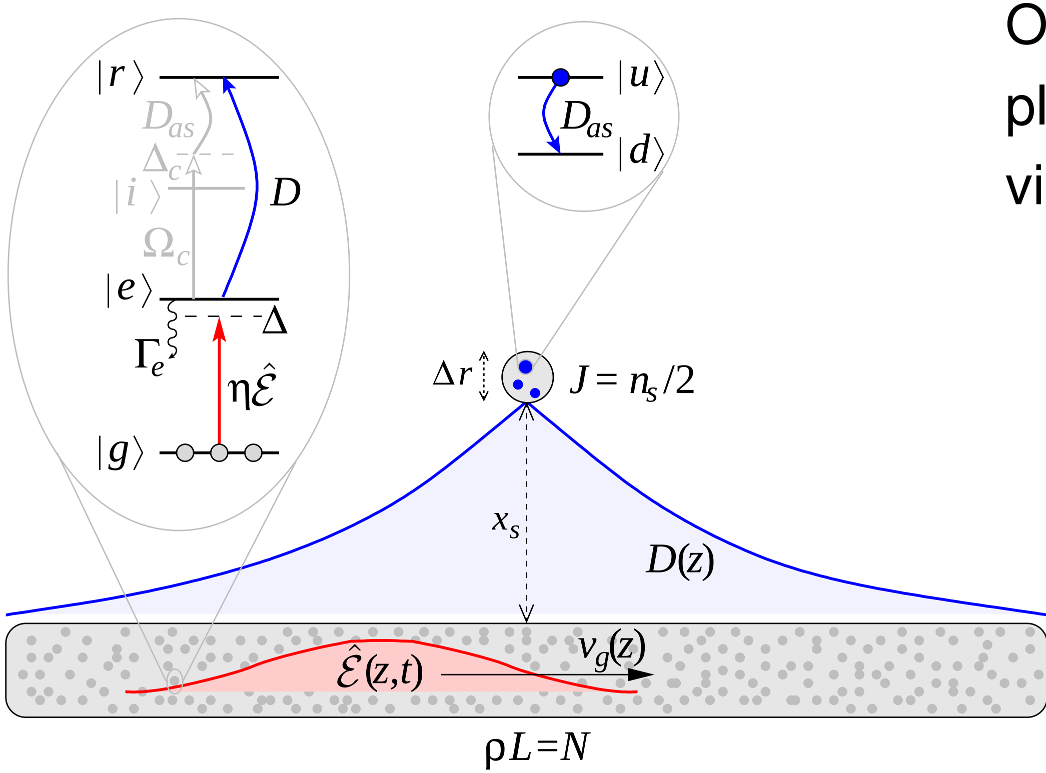

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⇒ DEIT exists for $n_p \leq n_s \equiv 2J$ photons ["spin" state $|J, J-n_p\rangle$]

⇒ $(n_p - n_s)$ photons are absorbed by resonant 2LA medium: OD$= 2\sigma_0 \bar{\rho} L > 1$

DEIT medium response

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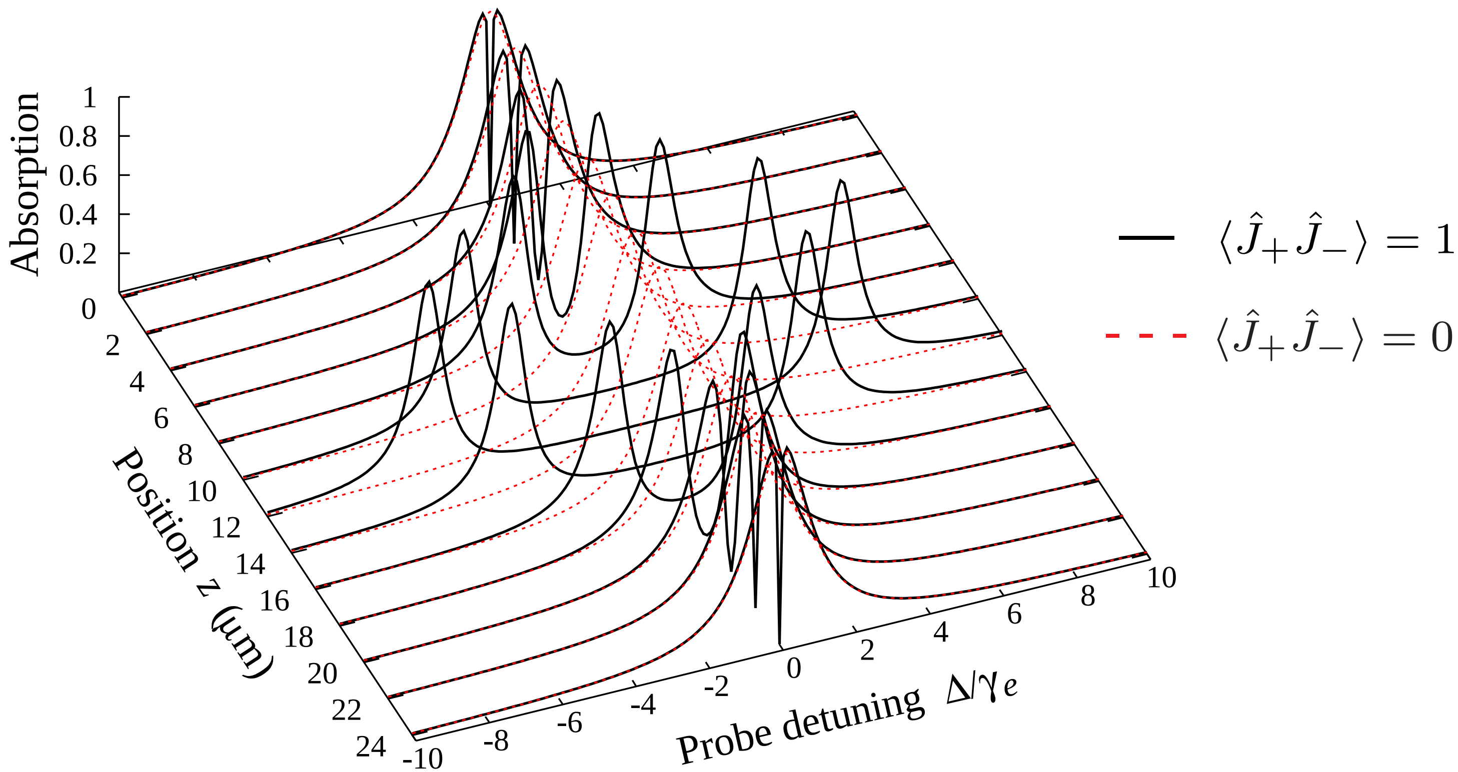

Susceptibility $\hat{\chi}(z,\Delta) = \frac{2}{\omega} \frac{i\eta^2 N}{\gamma_e - i\Delta + \frac{|D(z)|^2 \hat{J}_+ \hat{J}_-}{\gamma_r - i(\Delta+\delta)}}$ $\Rightarrow$ n_p-dependent

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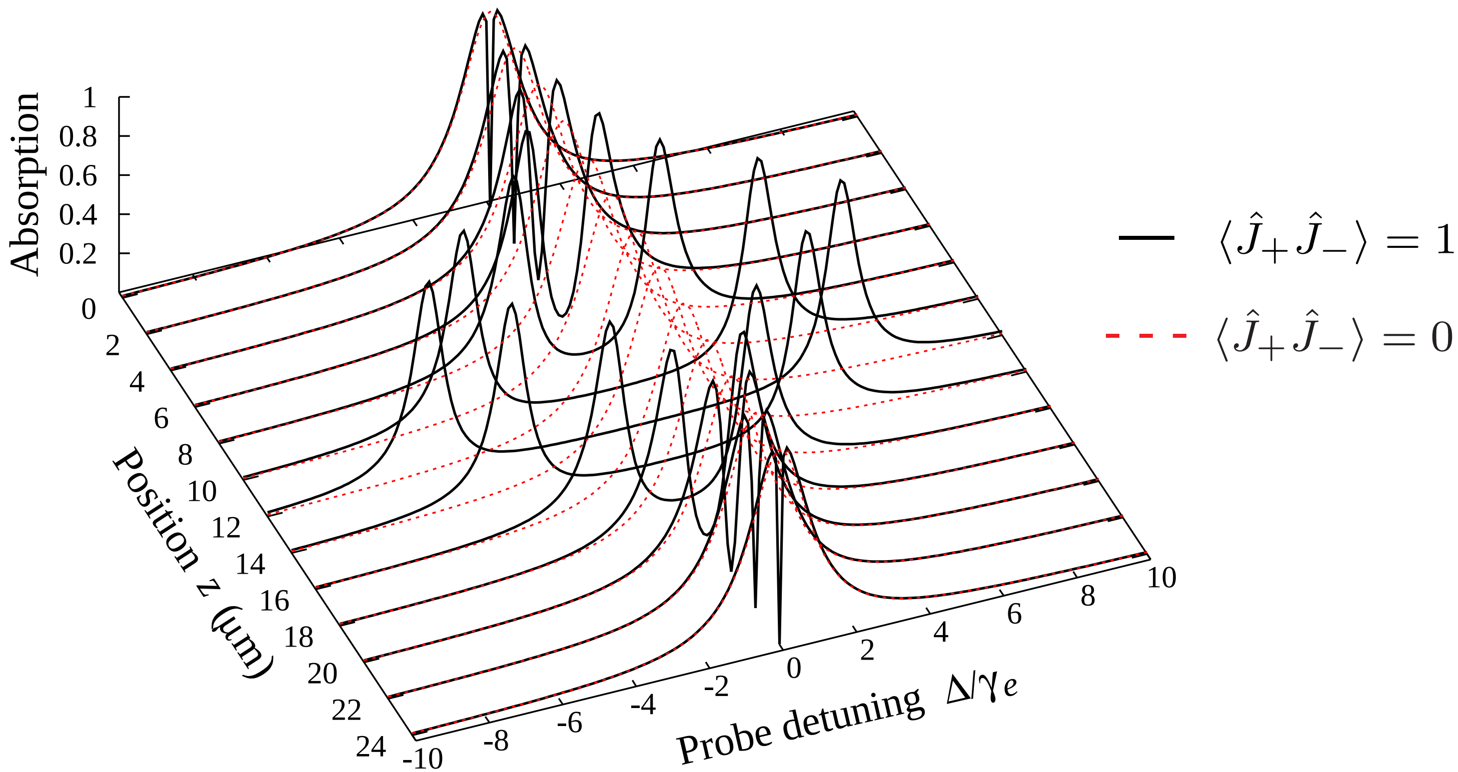

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group velocity @ $\Delta \simeq -\delta$

$\hat{v}_g(z) \simeq c \frac{|D(z)|^2 \hat{J}_+ \hat{J}_-}{\eta^2 N}$ $\Rightarrow$ $v_g^{(n_p+1)}(z) = c \frac{|D(z)|^2}{\eta^2 N} (n_s - n_p)(n_p + 1)$

Conclusions

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Reviews:

Murray & Pohl, Adv. Atom. Mol. Opt. Phys. **65**, 321 (2016)

Firstenberg, Adams, Hofferberth, J. Phys. B **49**, 152003 (2016)