Control of atomic and molecular processes by designed external fields: From adiabatic to ultrafast strategies

S. Guérin

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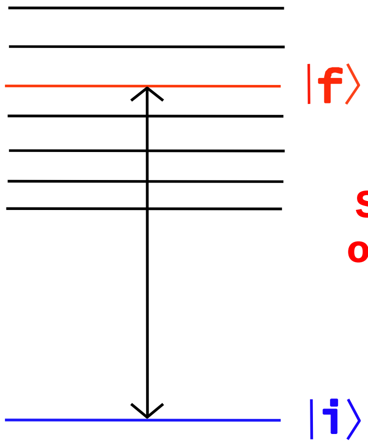
Marie-Curie Network (Fastquast)

Institut Carnot de Bourgogne, Dijon, France

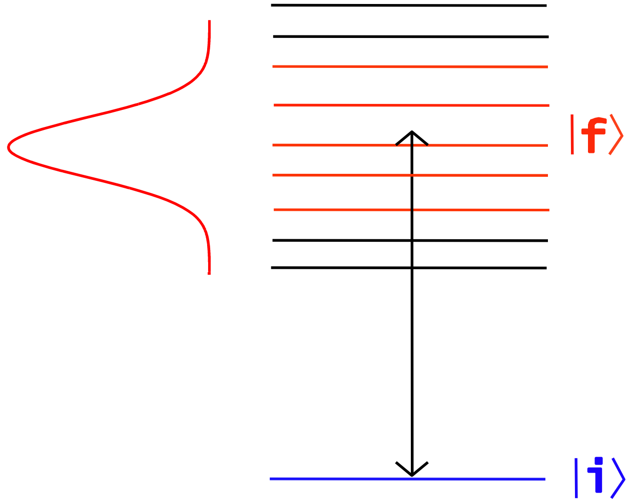
Cargese, August 2008

Strategies of control

Population transfer to a target state

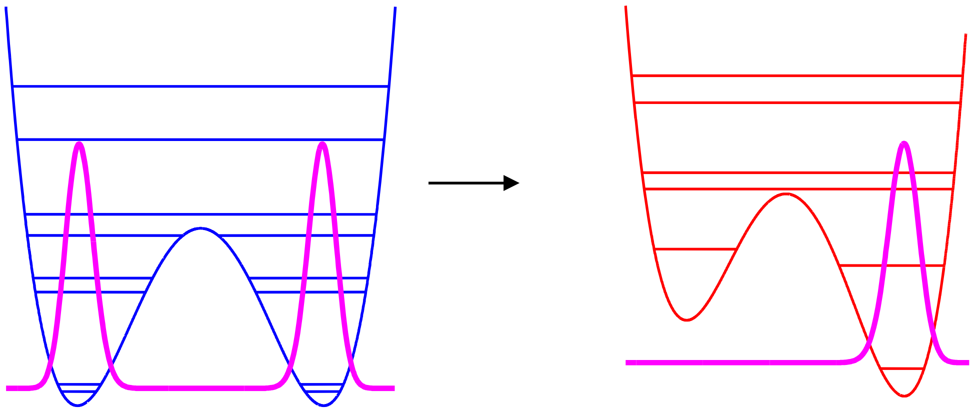


Adiabatic passage



Impulsive interaction

Dynamical adiabatic distortion of the effective potential



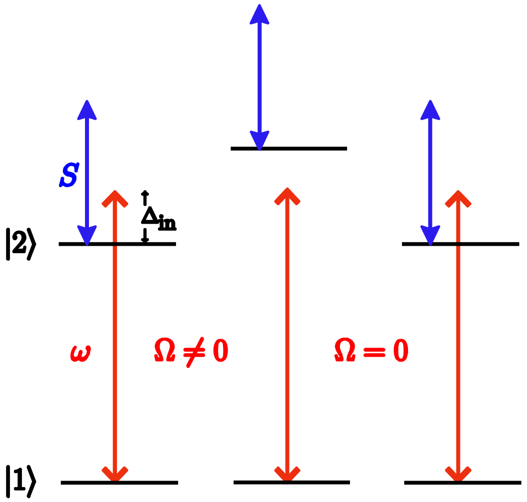
PRL 93, 223602 (2004)

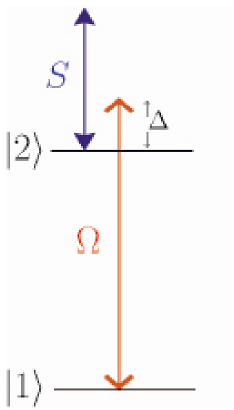
Dynamics of Chirped adiabatic passage

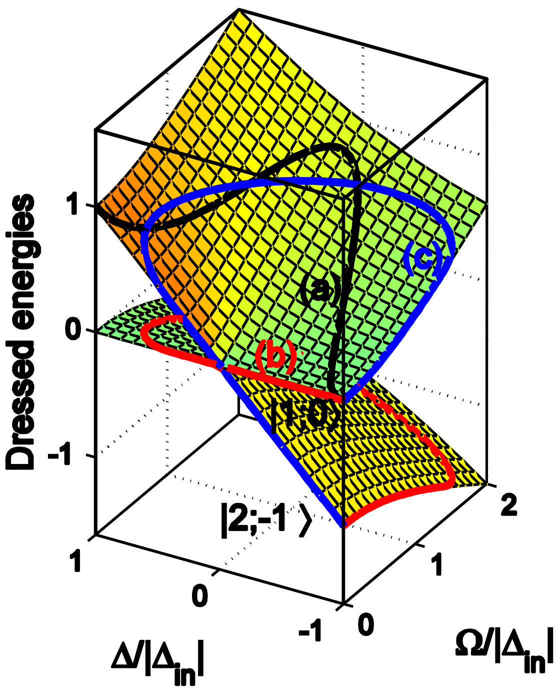
Phys. Rev. A 65, 043407 (2002)

$\Delta_{in} T \gg 1$

$$\mathrm{H}^{[\Omega(t),\Delta(t)]} = \frac{\hbar}{2} \begin{bmatrix} 0 & \Omega(t) \\ \Omega(t) & 2\Delta(t) \end{bmatrix}$$







Extension: Preparation of coherent superpositions of states
Phys. Rev. A 70, 013415 (2004)

Optimal chirped adiabatic passage: Level lines

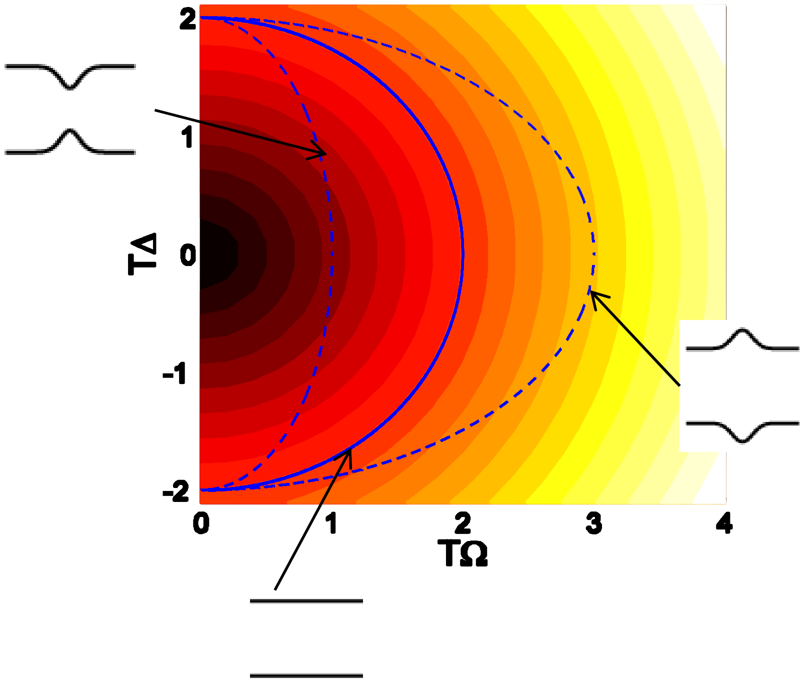
Phys. Rev. A 65, 023409 (2002)

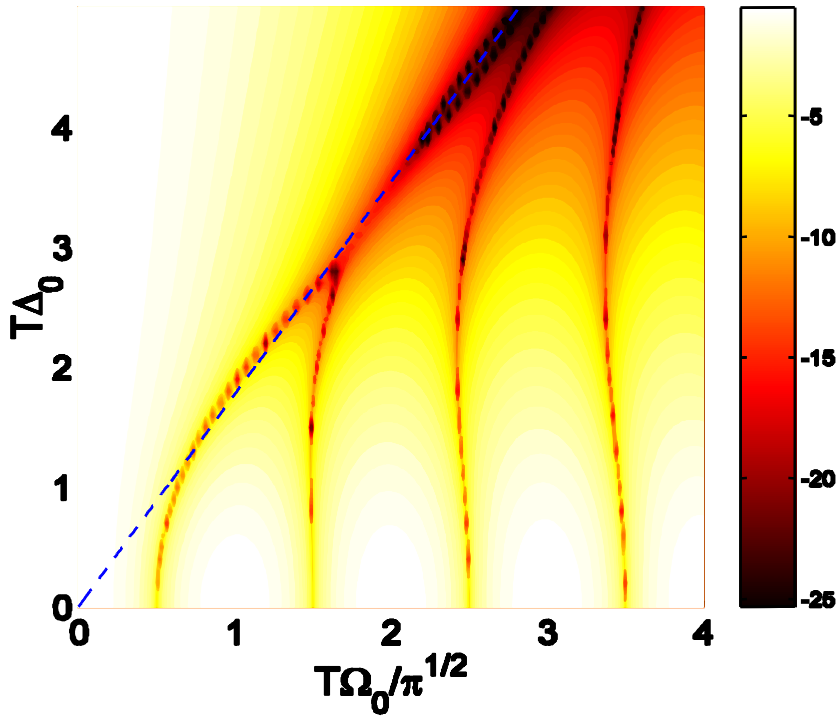
$$K_{\mathrm{eff}}^{[\Omega(t),\Delta(t)]} = T \begin{bmatrix} -\Delta(t) & \Omega(t) \\ \Omega(t) & \Delta(t) \end{bmatrix}$$

Eigenvalues: $\lambda_\pm = \pm\sqrt{\Delta(t)^2 + \Omega(t)^2}$

Level lines = Circles

Ellipses : $\begin{cases} \Omega(t) = \Omega_0 \exp\left(-t^2\right) \\ \Delta(t) = \Delta_0 \frac{|t|}{t} \sqrt{1 - \left[\frac{\Omega(t)}{\Omega_0}\right]^2} \end{cases}$





Lifting of degeneracy and coherent superposition of states

Phys. Rev. A 70, 43402 (2004)

The effective dressed Hamiltonian (quasi-resonant approximation or RWA)

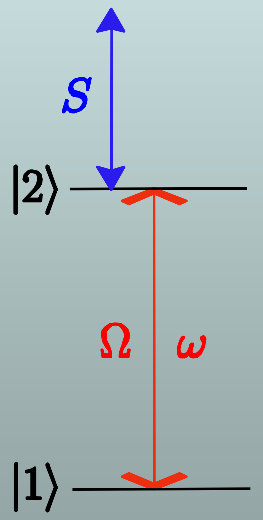
$$K_{\text{eff}}^{[\Omega(t),\Delta(t)]} = \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega(t) \\ \Omega(t) & 2\Delta(t) \end{bmatrix}$$

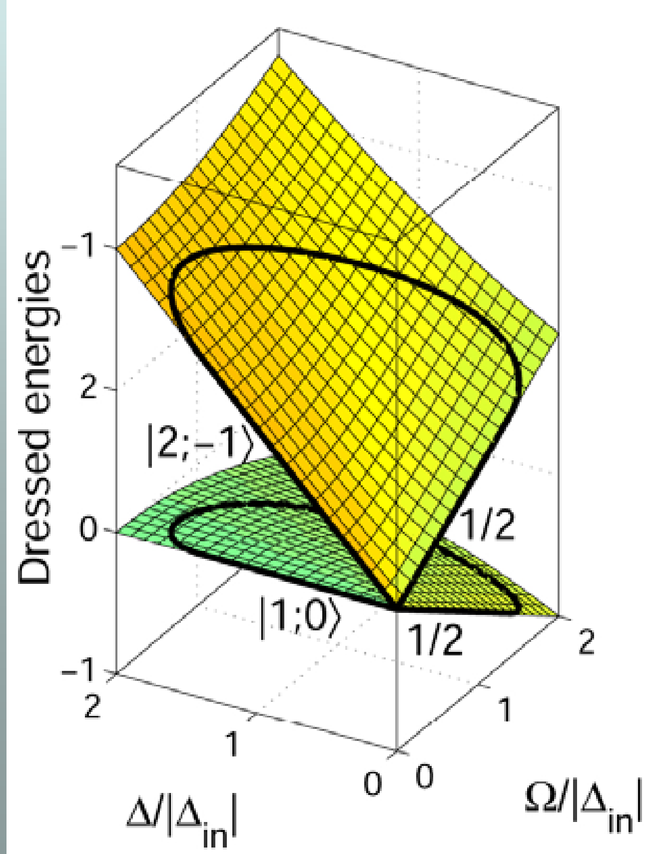
$$\Delta(t) = S(t)$$

One-photon: $\Omega(t) = \mu\mathcal{E}(t)/\hbar$

Stark field: $S(t) = \alpha\,[\mathcal{E}_S(t)]^2$

Resonant Stark chirp:





Adiabatic Floquet Theory: Interaction with a cavity field and a laser field

Adv. Chem. Phys. 125, 147 (2003)

Strong-field dressed Hamiltonian (Floquet Hamiltonian)

$$K = H_m - \mu\left[\mathcal{E}_C(a + a^\dagger) + \mathcal{E}_\ell \cos\theta\right] + \hbar\omega_C(aa^\dagger + 1/2) - i\hbar\omega_\ell \frac{\partial}{\partial\theta}$$

Interaction

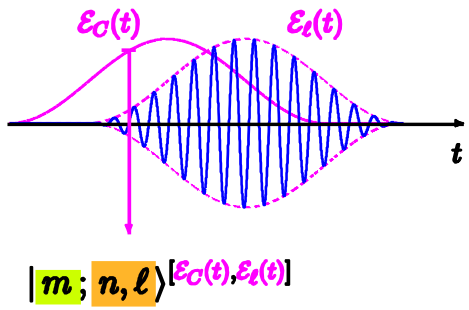
Photons

Classical fields:

$\theta \leftrightarrow \omega t$

Dressed states: $|\, m \;;\; n, \ell\,\rangle$

Adiabatic theorem:
the dynamics follows the instantaneous Floquet state which is continuously connected to the initial one.



$$t = 0:\ |1;0,0\rangle \xrightarrow[\text{Robustness}]{\text{Field parameters?}} |m;n,\ell\rangle$$

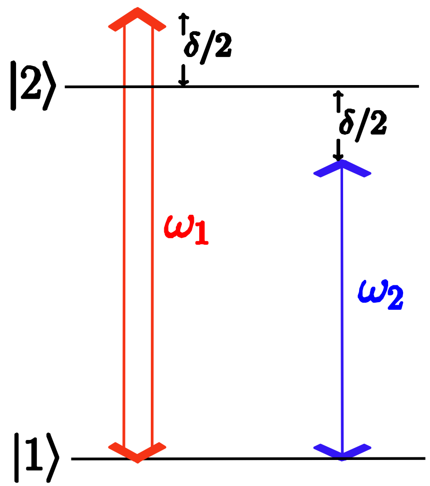
Multiphoton excitation in two-level systems

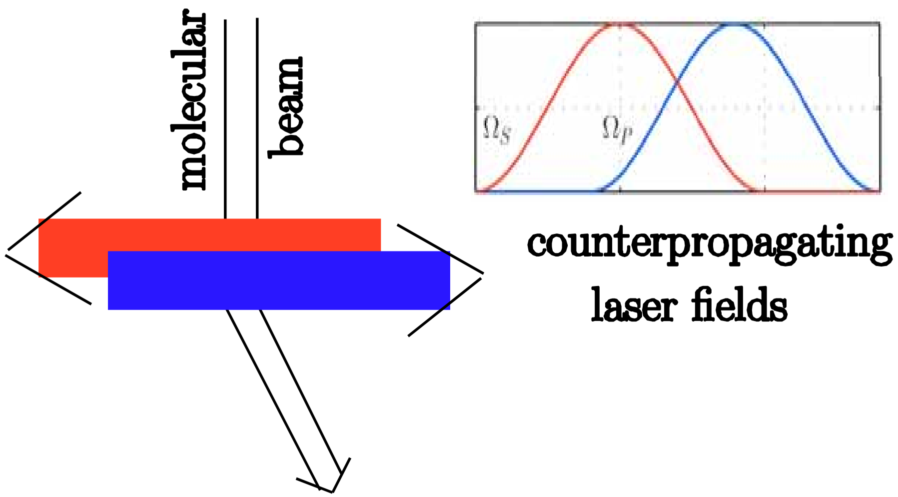
Phys. Rev. A 63, R031403 (2001)
Phys. Rev. A 68, 043405 (2003)

The effective dressed Hamiltonian

$$K_{eff}^{[\Omega_1(t),\Omega_2(t)]} = -i\hbar\delta\frac{\partial}{\partial\theta} + \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega_1(t) \\ \Omega_1(t) & -\delta \end{bmatrix} + \frac{\hbar\Omega_2(t)}{2}\begin{bmatrix} 0 & e^{-i\theta} \\ e^{i\theta} & 0 \end{bmatrix}$$

Effective photon: $\theta = \theta_1 - \theta_2$ of frequency $\delta = \omega_1 - \omega_2$

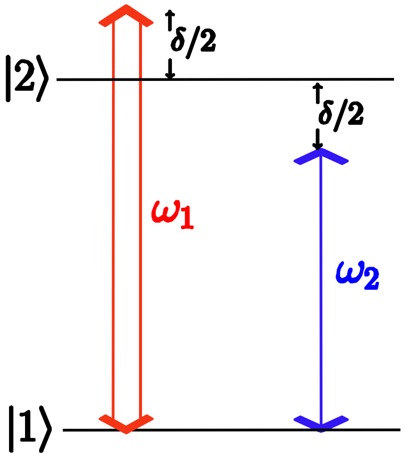




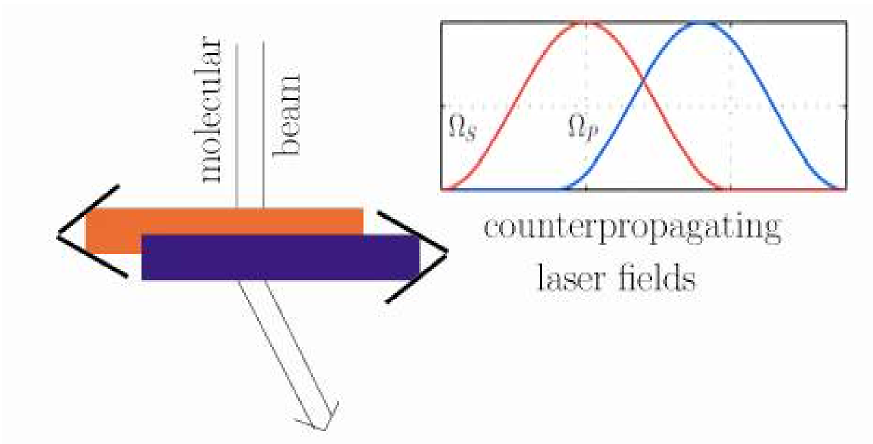
counterpropagating laser fields

Emission of k effective photons $\Longrightarrow$ Momentum deviation of $k\hbar(\omega_1+\omega_2)/c$.

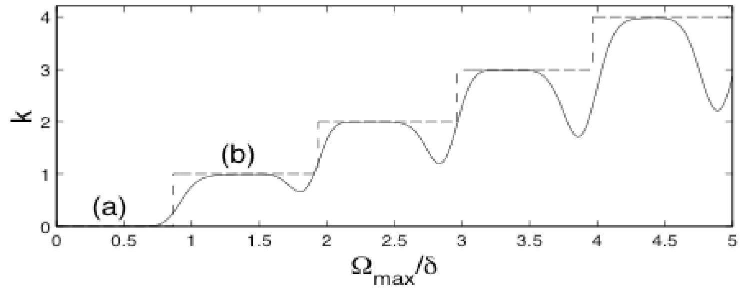
Experiments: K. Bergmann group (Kaiserslautern)



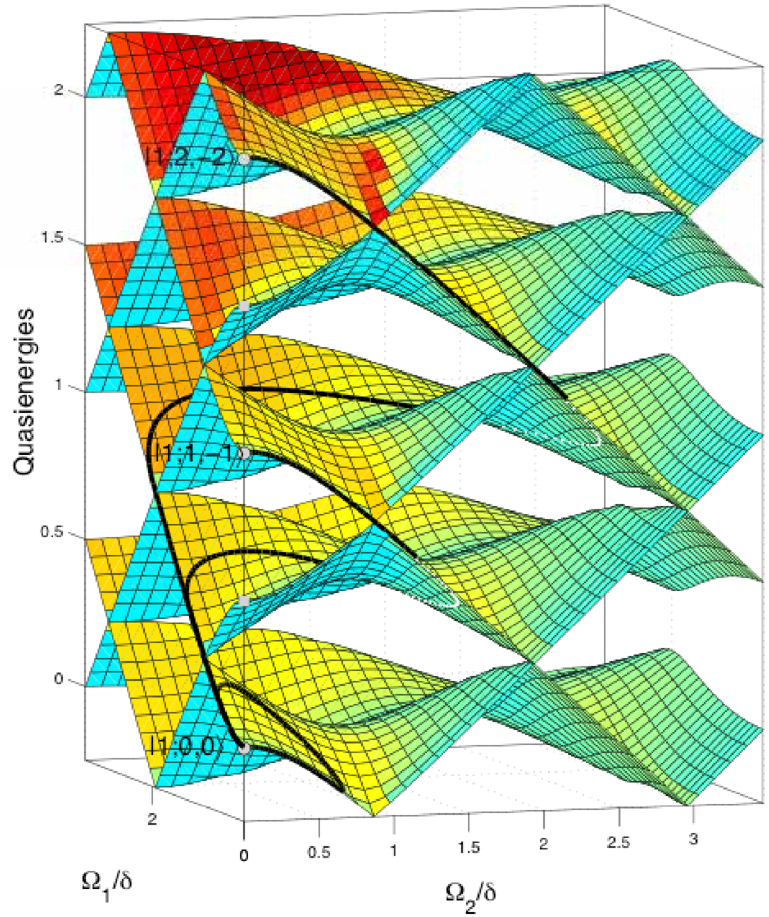
|2⟩
|1⟩
δ/2
δ/2
ω1
ω2



molecular
beam
Ωs
Ωp
counterpropagating
laser fields



k
(a)
(b)
Ωmax/δ
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5



Quasienergies
|1,2,−2⟩
|1,1,−1⟩
|1,0,0⟩
Ω1/δ
Ω2/δ

Adiabatic Passage
for Quantum Information

Elementary processes

- Generation of Fock states
- Entanglement
- Quantum Logical Gate for Computation
- Grover search

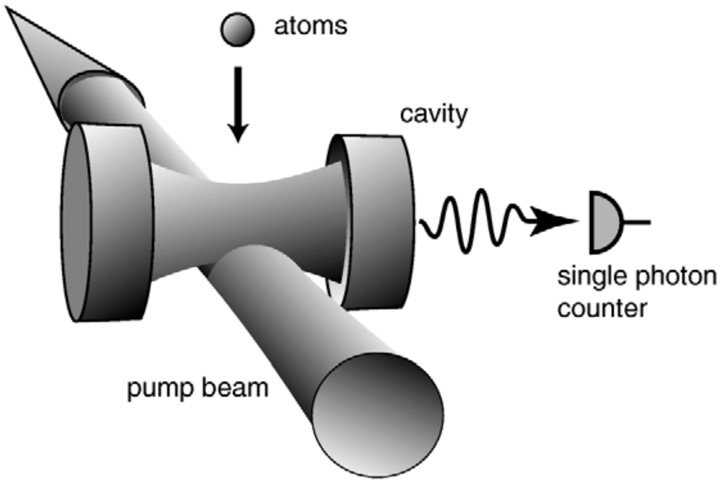
Quantum information in cavity-laser-atom systems

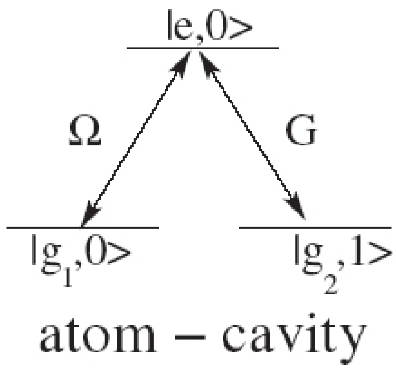
Source of photons on demand

Preparation of a single photon state:

A. Kuhn, G. Rempe group (Garching), Phys. Rev. Lett. **85**, 4872 (2000); **89**, 067901 (2002).

→ application to quantum cryptography, quantum networking.

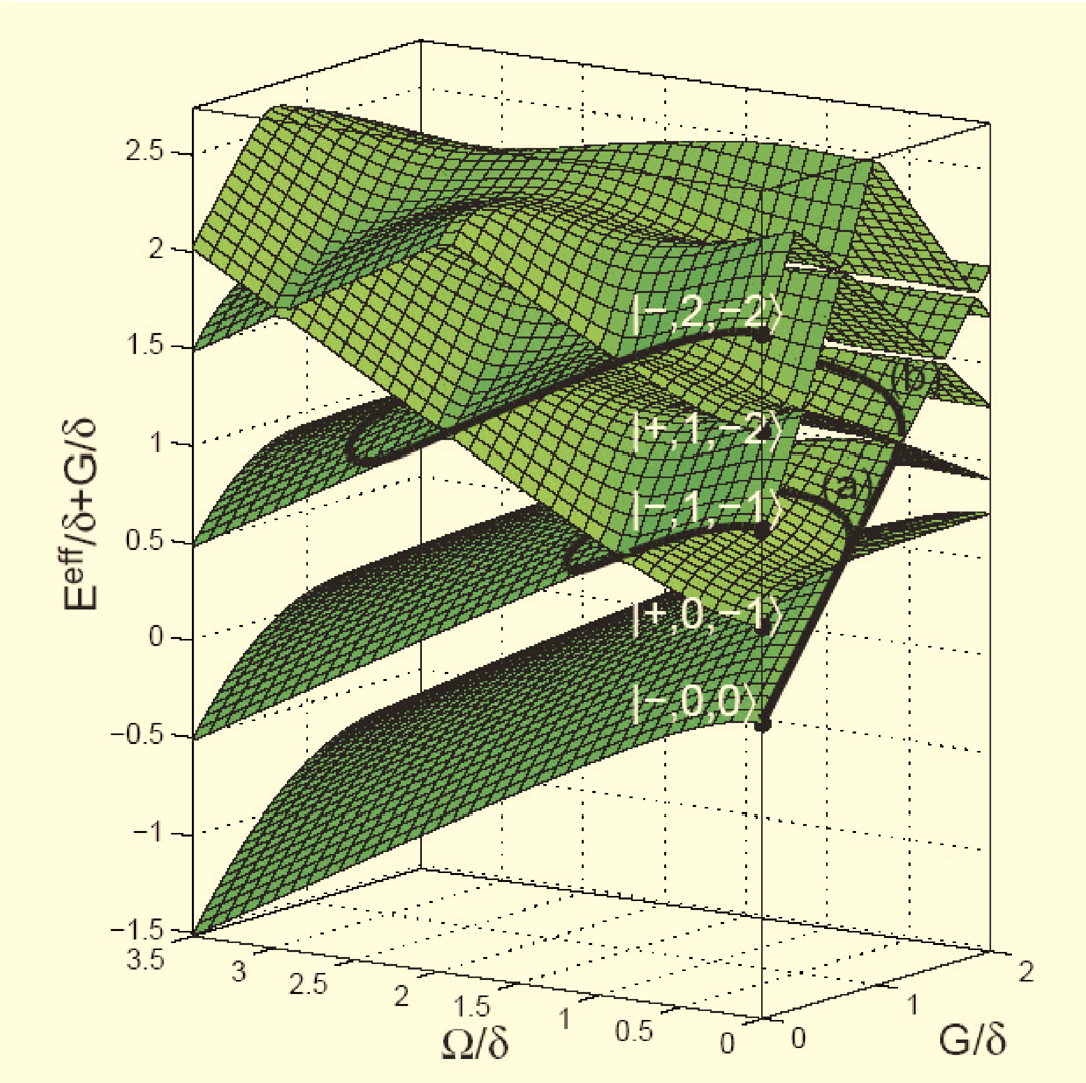


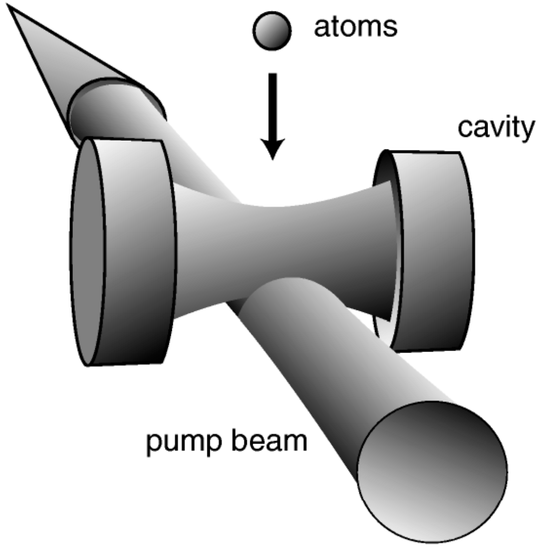


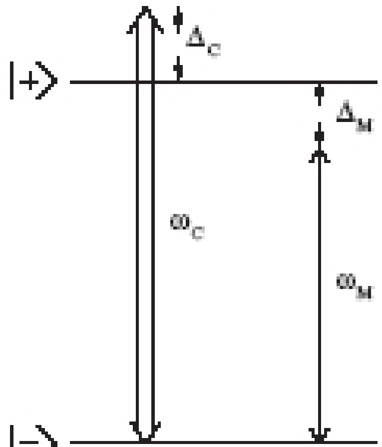
STIRAP with cavity + laser

Preparation of an arbitrary photon state

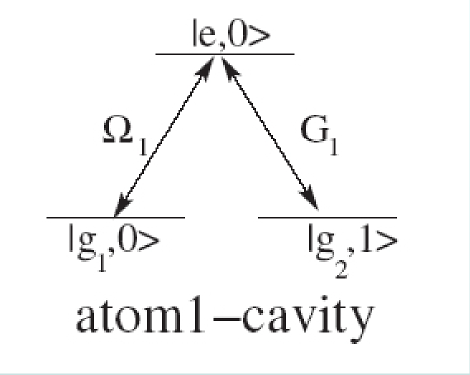
Phys. Rev. A 70, 013807 (2004)



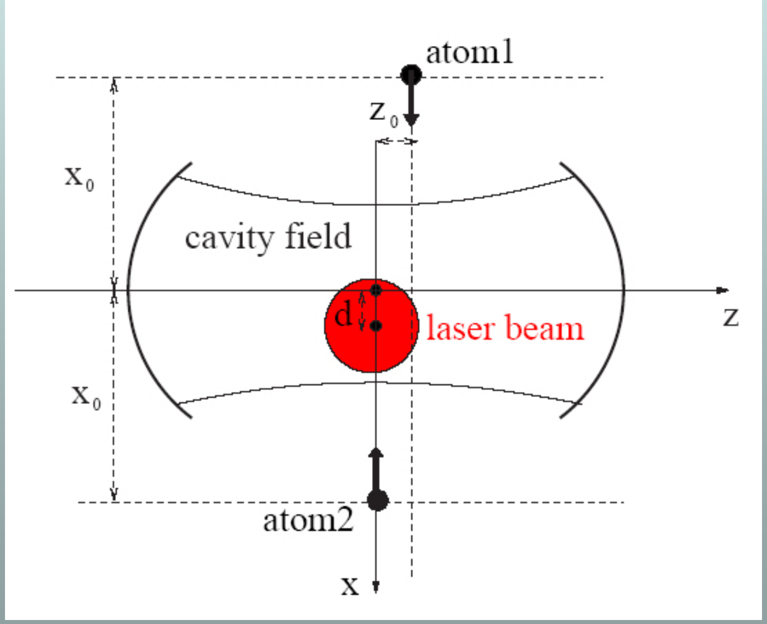


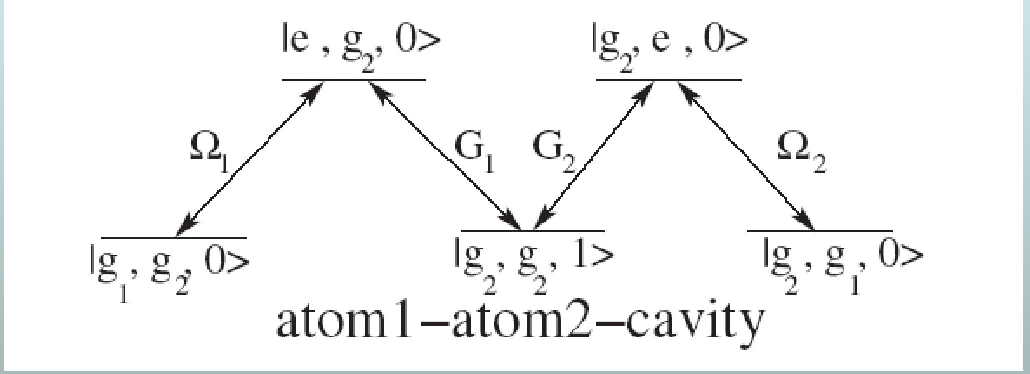


Quantum information in cavity-laser-atom systems: Atom-atom entanglement



$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|g_1, g_2\rangle + |g_2, g_1\rangle\right) \otimes |0\rangle$$





Dark State: Decoherence-free process

Phys. Rev. A 71 023805 (2005)
Phys. Rev. A 72 012339 (2005)

Single-qubit quantum gates by adiabatic passage

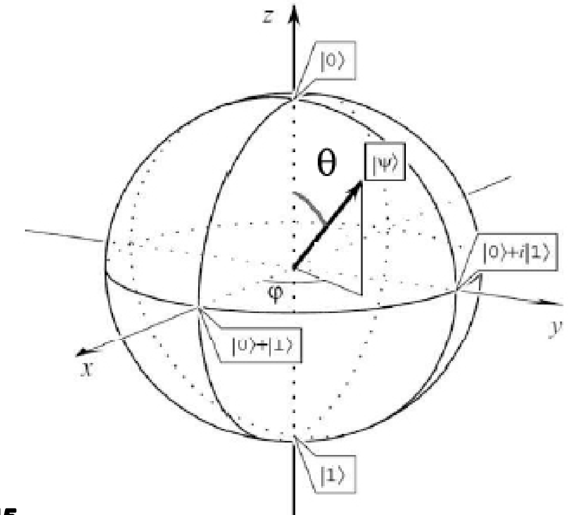
Kis - Renzoni Phys. Rev. A 65, 032318 (2002)
Optics Commun. 264, 362 (2006)

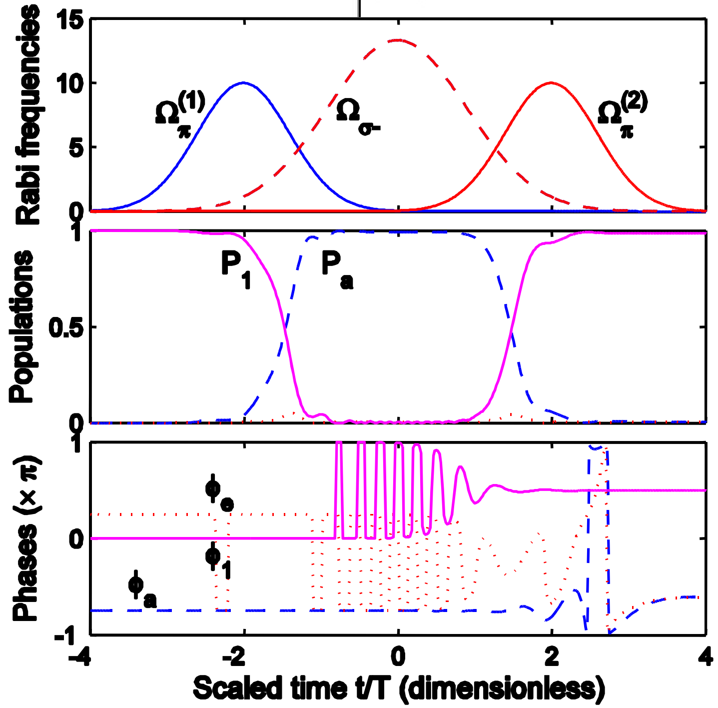
One-qubit gate:

implement a general unitary operation $U(\theta, \varphi)$

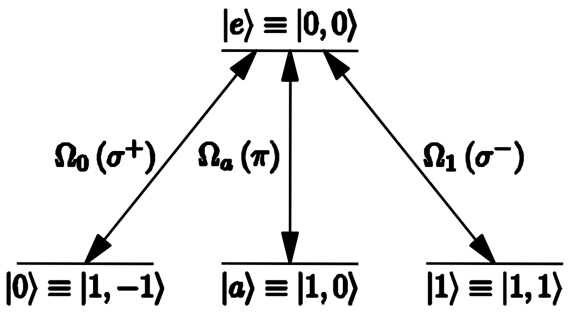
i.e. $\begin{cases} |0\rangle \;\rightarrow\; e^{-i\varphi}\cos\frac{\theta}{2}|0\rangle + \sin\frac{\theta}{2}|1\rangle \\ |1\rangle \;\rightarrow\; -\sin\frac{\theta}{2}|0\rangle + e^{i\varphi}\cos\frac{\theta}{2}|1\rangle \end{cases}$

Avoid non-robust dynamical phases,
geometrical phases
Use of static laser phases





Tripod system

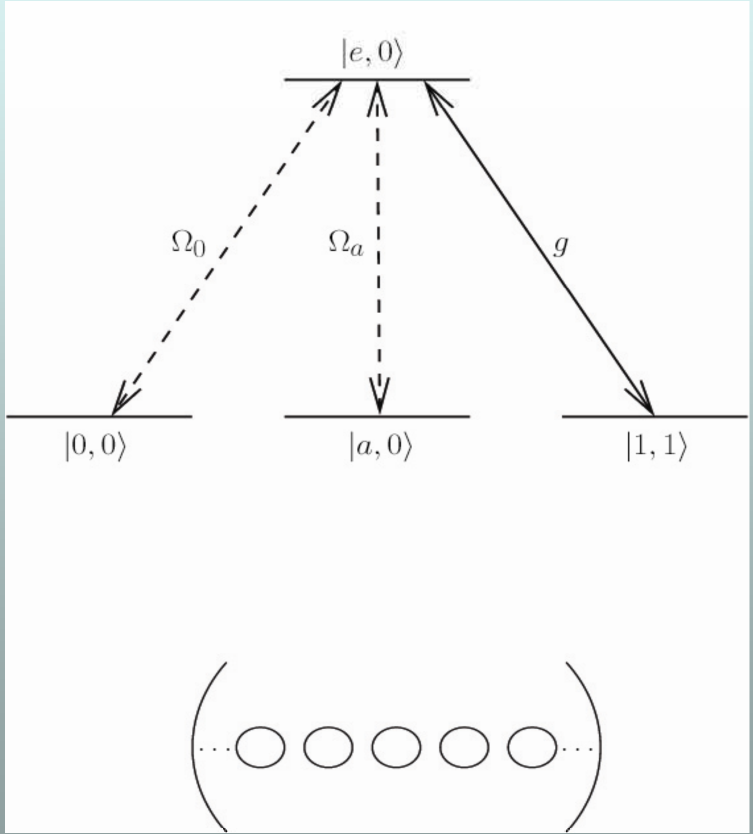


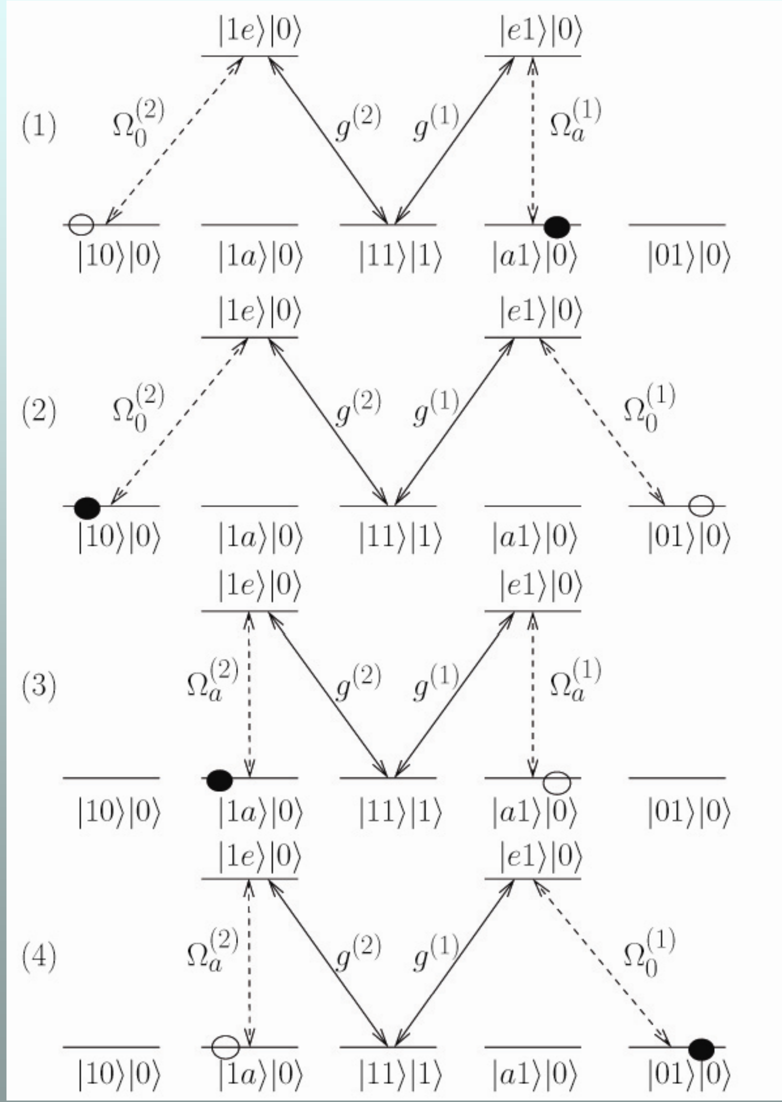
Quantum information in cavity-laser-atom systems: Quantum gates

SWAP gate

$$|\psi_i\rangle = \alpha|00\rangle|0\rangle + \beta|01\rangle|0\rangle + \gamma|10\rangle|0\rangle + \delta|11\rangle|0\rangle$$

$$|\psi_f\rangle = \alpha|00\rangle|0\rangle + \gamma|01\rangle|0\rangle + \beta|10\rangle|0\rangle + \delta|11\rangle|0\rangle$$





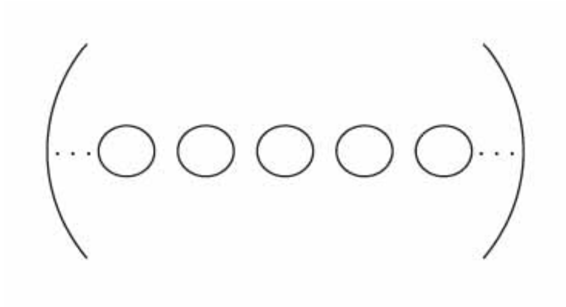
Phys. Rev. A 72, 062309 (2005)
Phys. Rev. A 73, 042321 (2006)

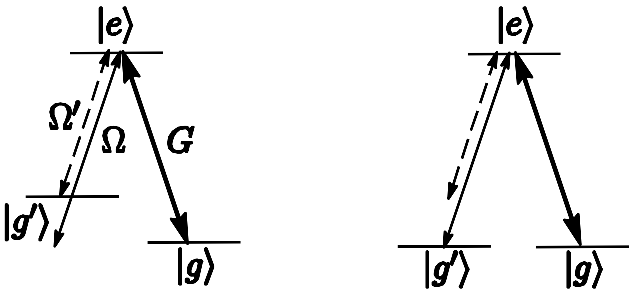
Adiabatic Grover quantum search

Phys. Rev. Lett. 99, 170503 (2007)

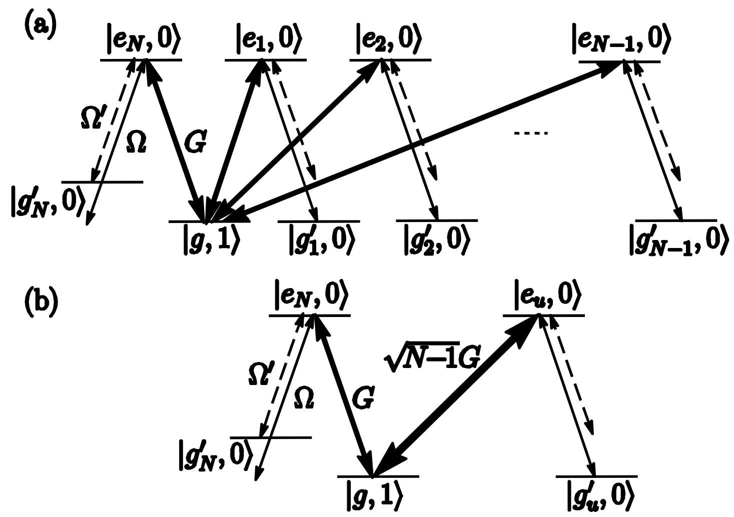
Continuous (analogic) version

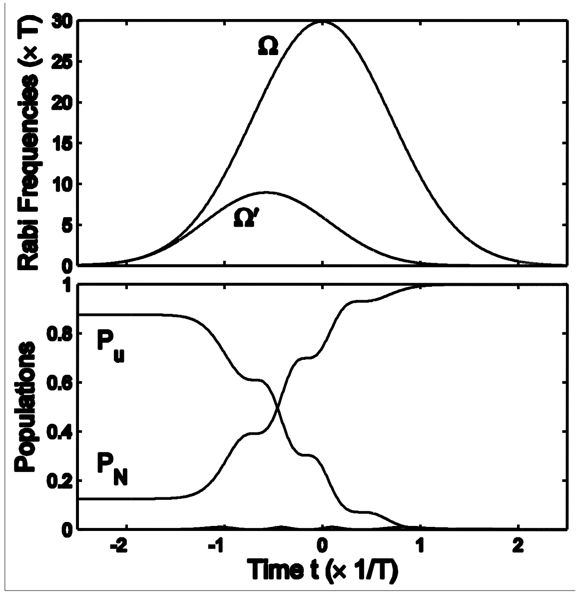
N atoms trapped in a cavity QED





Marked atom   Unmarked atom

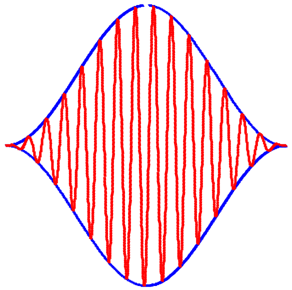




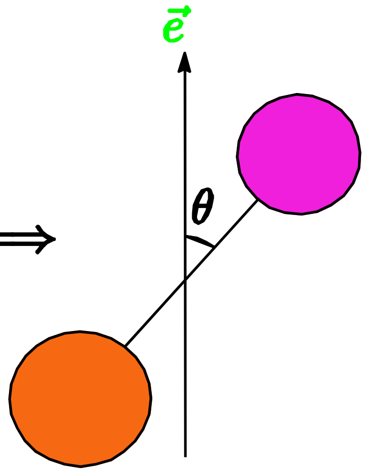
Search time grows as $(N)^{1/2}$!

Alignment and orientation

$\vec{e}\,\mathcal{E}\left(\frac{t}{\tau}\right)\cos\omega t$



$\Longrightarrow$



$$\text{Alignement}: \langle\cos^2\theta\rangle \longrightarrow 1$$

$$\text{Orientation}: \langle\cos\theta\rangle \longrightarrow \pm 1$$

Aligned (target) state in a rotational subspace
H_N={|J=0>,|J=1>,...,|J=N-1>}

$$\cos^2\theta_N|\Psi_{\mathbf{max}}\rangle = \lambda_{\mathbf{max}}|\Psi_{\mathbf{max}}\rangle$$

Adiabatic regime: $B_0\tau/\hbar \gg 1$
for nonresonant laser field

Phys. Rev. Lett. 88, 233601 (2002)

Impulsive regime: $B_0\tau/\hbar \ll 1$
for nonresonant laser field

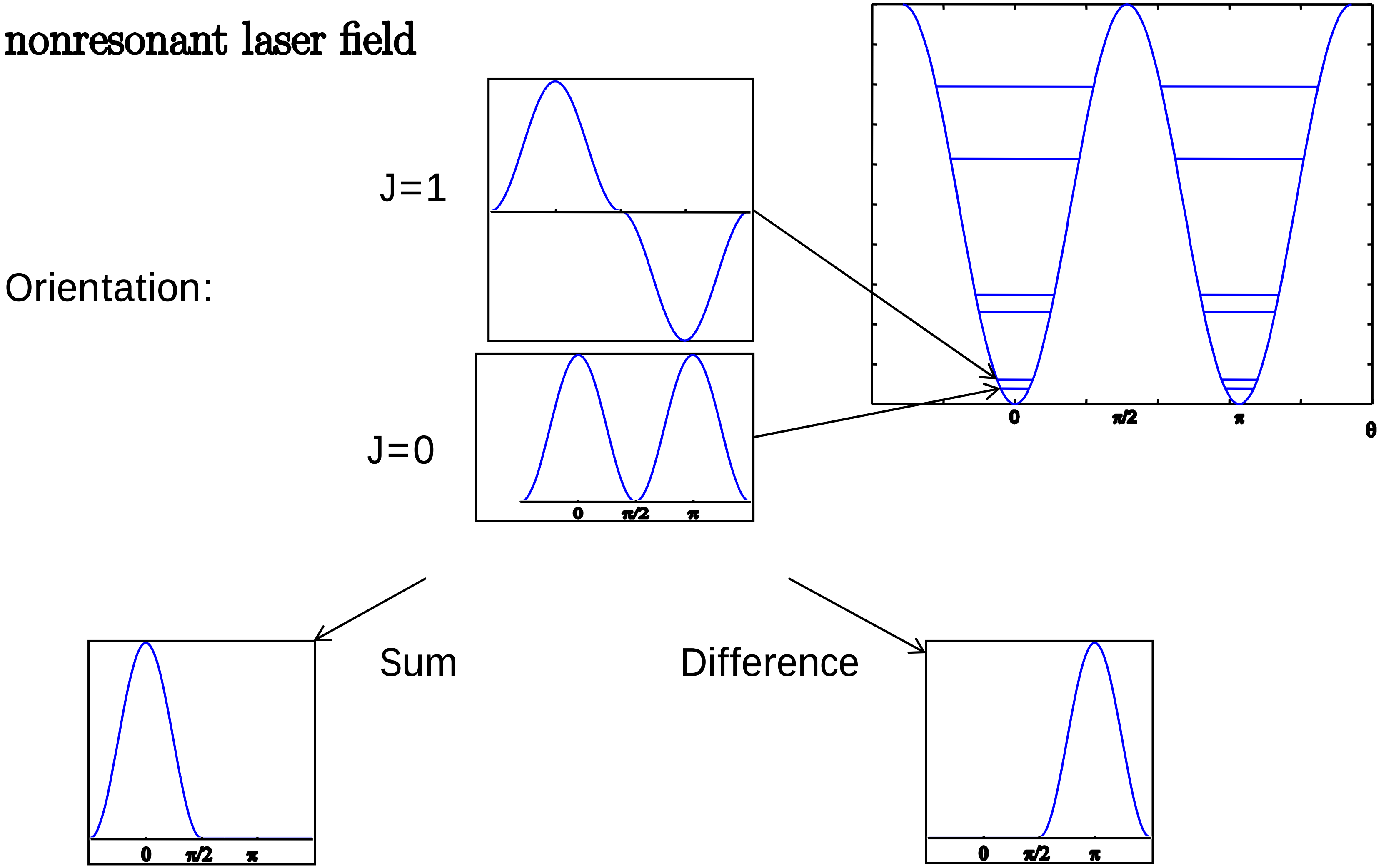
Phys. Rev. Lett. 94, 153003 (2005)

Alignment and orientation by adiabatic transport

Adiabatic regime: $B_0\tau/\hbar \gg 1$

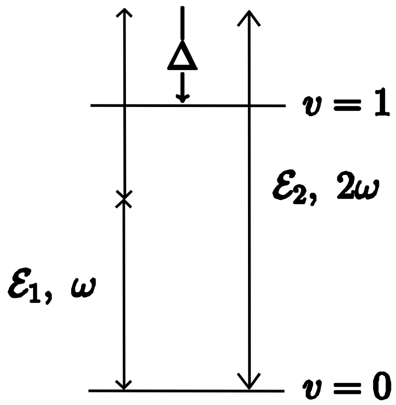
for nonresonant laser field

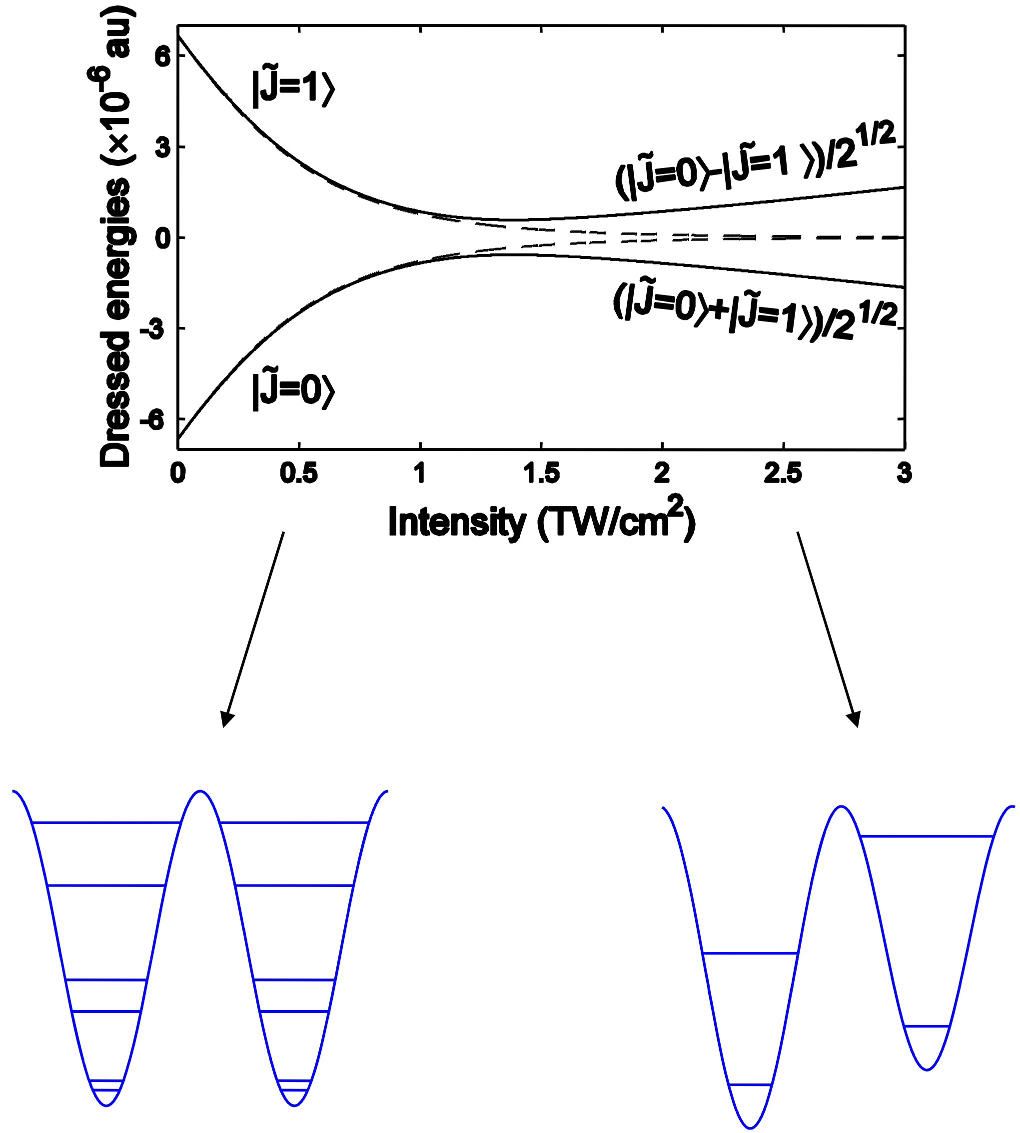
$$H = B\hat{J}^2 - \frac{1}{4}\mathcal{E}^2\Delta\alpha\cos^2\theta$$



Orientation by adiabatic passage: Mechanism

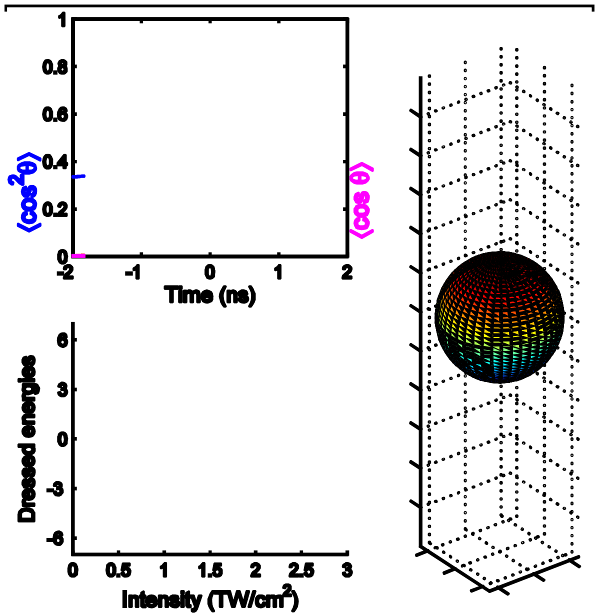
Phys. Rev. Lett. 88, 233601 (2002)



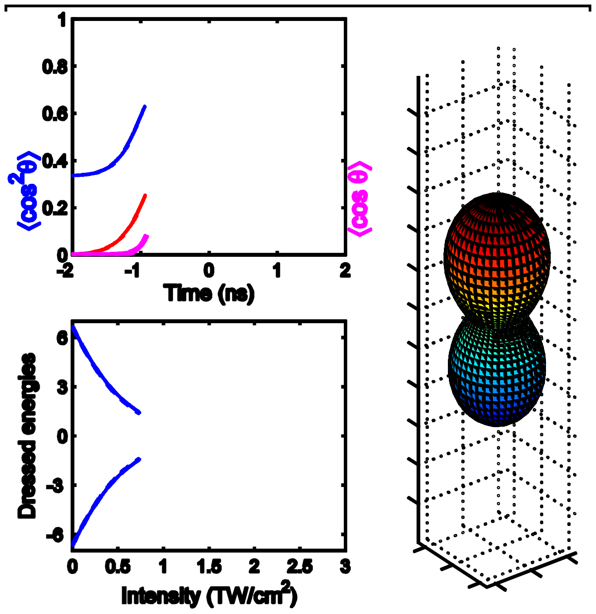


Orientation by adiabatic passage: Numerical simulations

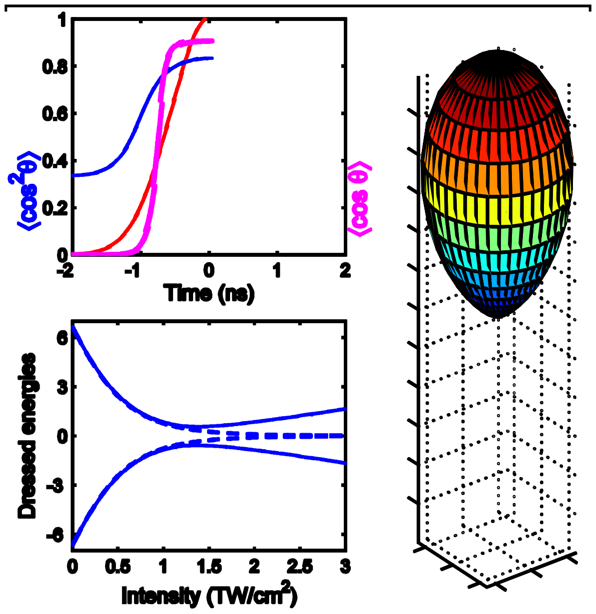
Phys. Rev. Lett. 88, 233601 (2002)



Isotropic initial angular distribution
of the molecular axis



Alignment before
the avoided crossing



Orientation after
the avoided crossing

Extension to the control of the tunneling effect: Phys. Rev. Lett. 93, 223602 (2004)

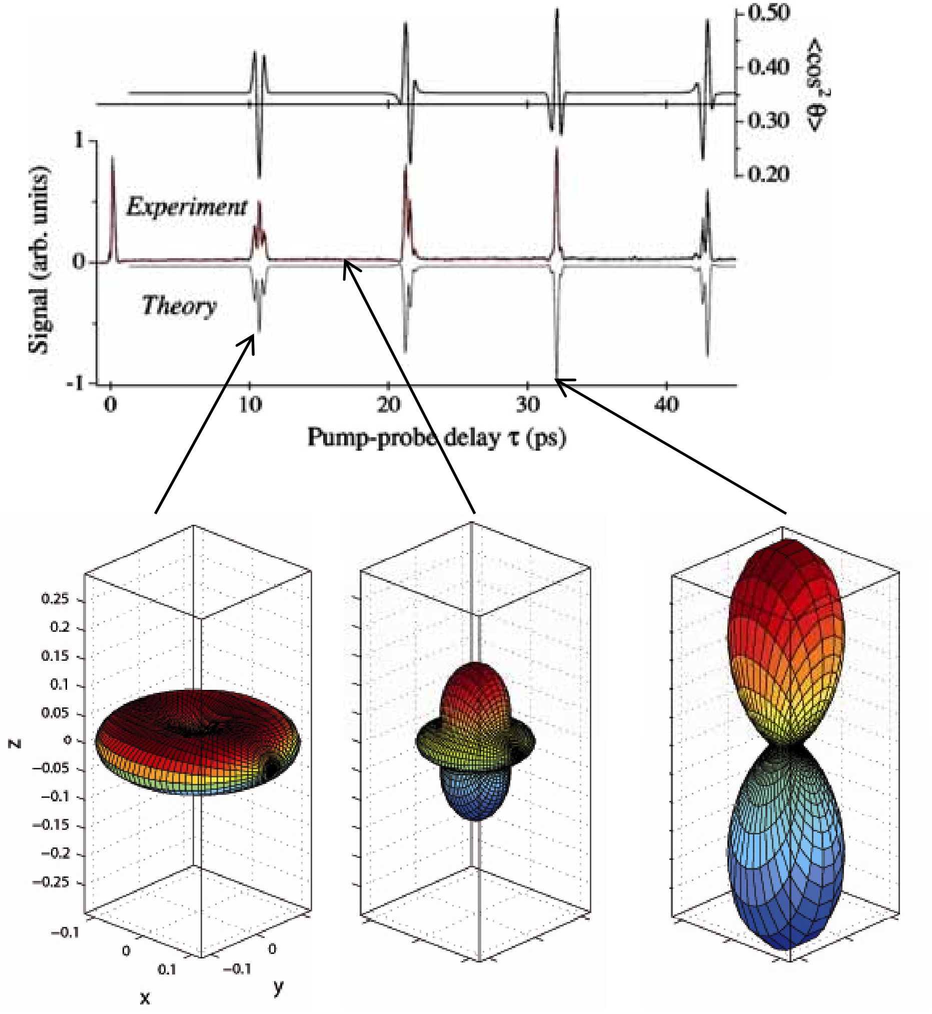
Postpulse alignment of molecules

Impulsive regime : $B_0\tau/\hbar \ll 1$
for nonresonant laser field

i.e. $\tau << T_{rot} = h/2B$

Non-intrusive measurement
of birefringence by
- polarization technique
- cross defocusing

CO_2 T=60K I_{kick}=40 TW/cm^2



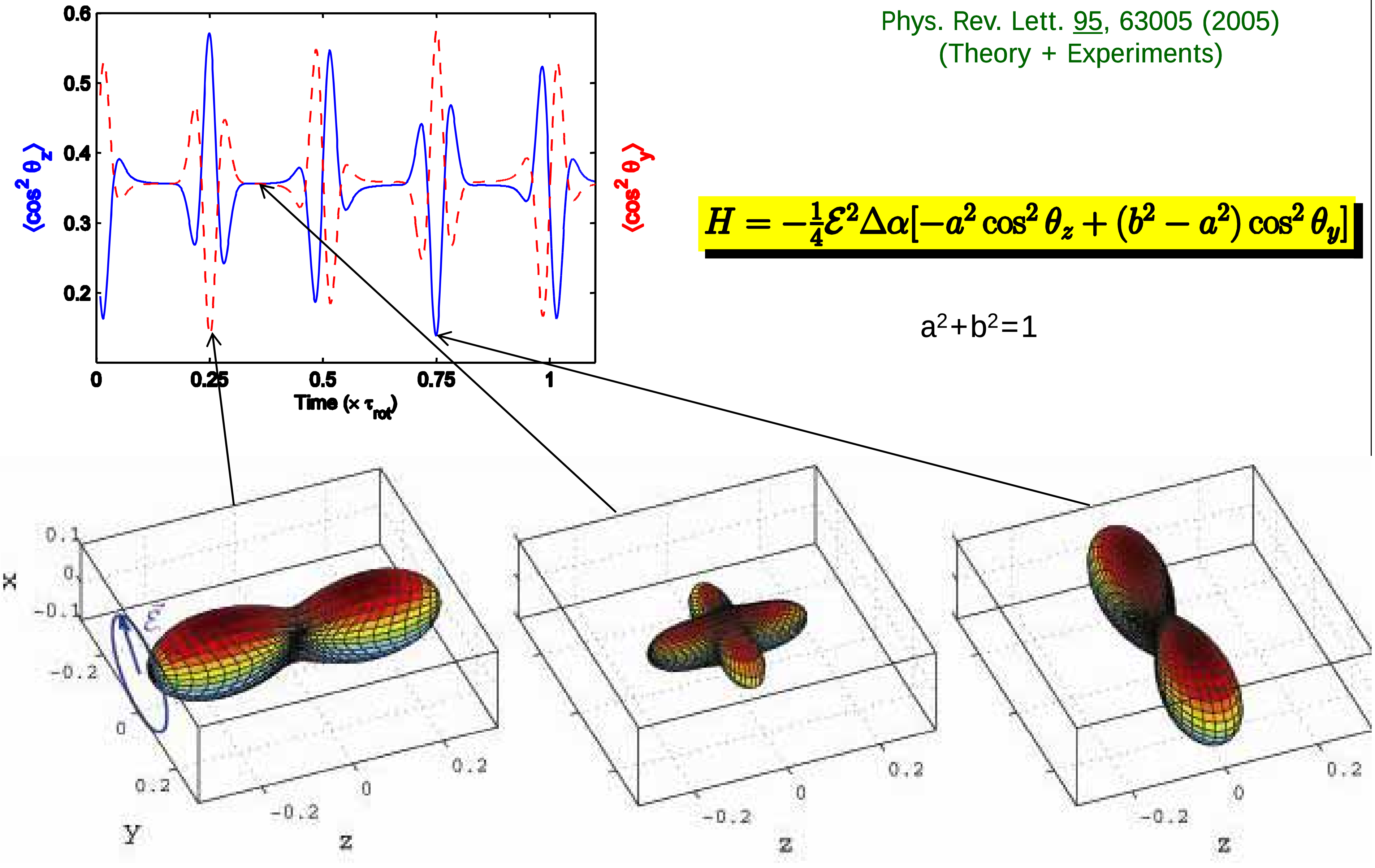
Phys. Rev. Lett. 90, 153601 (2003)

Field-free two-direction alignment alternation of molecules by elliptic laser pulses

Phys. Rev. Lett. 95, 63005 (2005)
(Theory + Experiments)

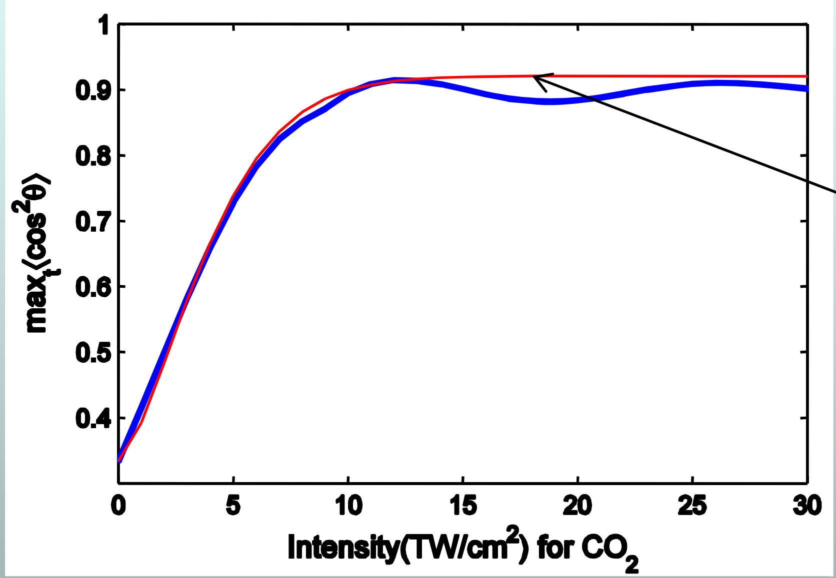
$$H = -\frac{1}{4}\mathcal{E}^2\Delta\alpha[-a^2\cos^2\theta_z + (b^2-a^2)\cos^2\theta_y]$$

$a^2+b^2=1$



Alignment in adiabatic versus impulsive regime

- Impulsive regime (laser kick): efficient but *saturates*



$$\max_t \langle \cos^2\theta \rangle_k \sim c_s - (c_s - 1/3)e^{-\zeta^{3/2}}$$

$$\zeta = \frac{\mathcal{E}_k^2 \Delta\alpha}{8\hbar} \int dt \Lambda(t)$$

-Adiabatic regime: postpulse alignment by sudden truncation (difficult to achieve experimentally): free of saturation but energetically *less efficient* -> destructive for high degree of alignment

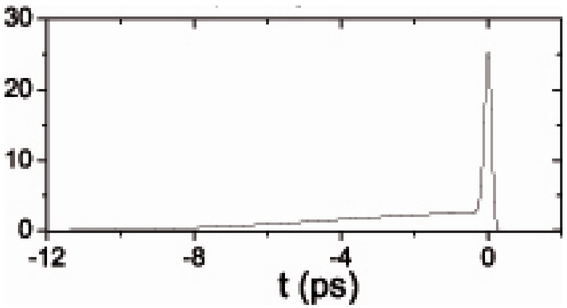
$$\max_t \langle \cos^2\theta \rangle_a \sim 1 - 1/\sqrt{\gamma}$$

$$\gamma = \mathcal{E}_a^2 \Delta\alpha / 4B$$

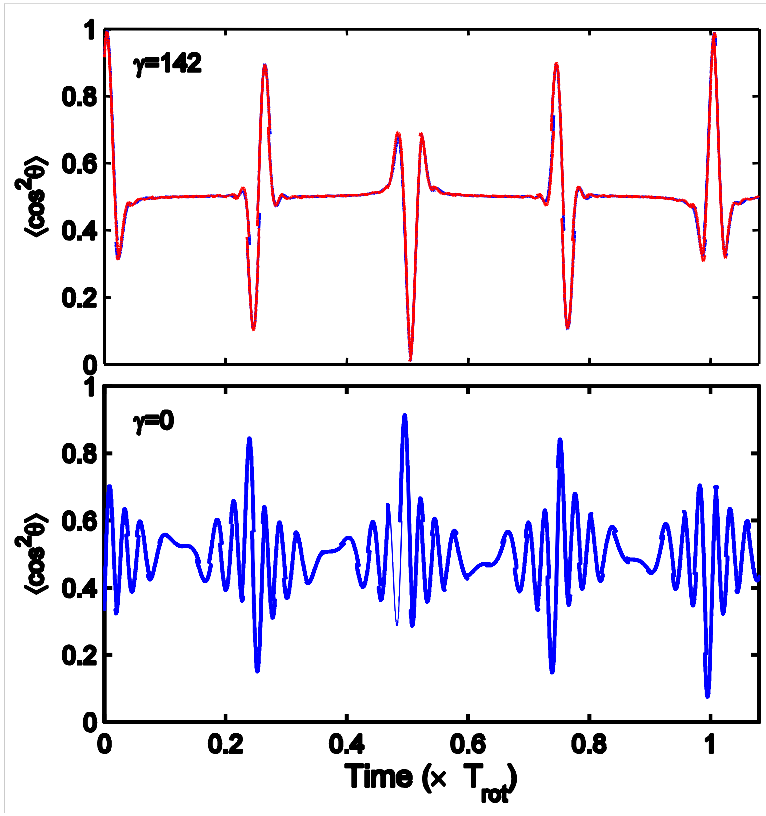
Alignment in combined adiabatic-impulsive regime

Phys. Rev. A 77, 041404(R) (2008)
Phys. Rev. A 75, 031403(R) (2007)

$$\gamma = \mathcal{E}_a^2 \Delta\alpha / 4B$$



$$\zeta = \frac{\mathcal{E}_k^2 \Delta\alpha}{8\hbar} \int dt \Lambda(t)$$



Adiabatic-impulsive (on the optimal line)

I_a=2.5 TW/cm^2 I_k=50 TW/cm^2

⟹ $\max_t \langle \cos^2\theta \rangle \approx 0.993$

Target state $|\langle \psi_{N=13} | \phi \rangle|^2 \approx 0.996$

Impulsive

I_a=0 I_k=50 TW/cm^2

Research projects of the theory team at UB

- Floquet adiabatic theory – Adiabatic passage for material and photonic states

- Alignment and orientation of molecules

- Adiabatic passage for quantum computation (X. Lacour, N. Sangouard, M. Amniat-Talab, S. Guérin)

- Control of dissipative systems (G. Dridi, M. Lapert, X. Lacour, D. Sugny, S. Guérin)

- Optimal control of quantum systems (C. Kontz, M. Lapert, D. Sugny)

- Manipulation of single photons (A. Gogyan, Y. Pashayan, Y. Malakyan, S. Guérin)

- Photoassociation of Bose-Einstein condensation (R. Sokhoyan, C. Leroy, A. Ishkhanyan)

Control in open quantum systems

Lindblad equation

$$\frac{d\rho}{dt} = -i[H,\rho] + \frac{1}{2}\Sigma_i\left([\Gamma_i,\rho\Gamma_i^\dagger] + [\Gamma_i\rho,\Gamma_i^\dagger]\right)$$

Lindbladien = linear operator $\mathcal{L}$

$$\frac{d\rho}{dt} = \mathcal{L}\rho$$

In the basis of the Pauli matrices $\{I_2, \sigma_x, \sigma_y, \sigma_z\}$

$$\mathcal{L} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & -\gamma/2-\Gamma & -\Delta & 0 \\ 0 & \Delta & -\gamma/2-\Gamma & -\Omega \\ -\gamma & 0 & \Omega & -\gamma \end{bmatrix}, \qquad H = \Delta\sigma_z/2 + \Omega\sigma_x/2$$

Γ: Dephasing rate

γ: Spontaneous emission rate

Control in open quantum systems

Phys. Rev. A 75, 033417 (2007)

Results for pure dephasing decoherence:

- Generalization of the Landau-Zener type formula

$$p = \frac{1-e^{-\eta}}{2} + e^{-\eta} p_0 \qquad \eta = \Gamma \int_{-\infty}^{\infty} dt \frac{\Omega^2}{\Delta^2 + \Omega^2}$$

Landau Zener: $p_0 = 1 - \exp\left[-\pi \Omega_0^2 T^2 / 2\right]$