Atom Optics with Frequency-Chirped Laser Pulses

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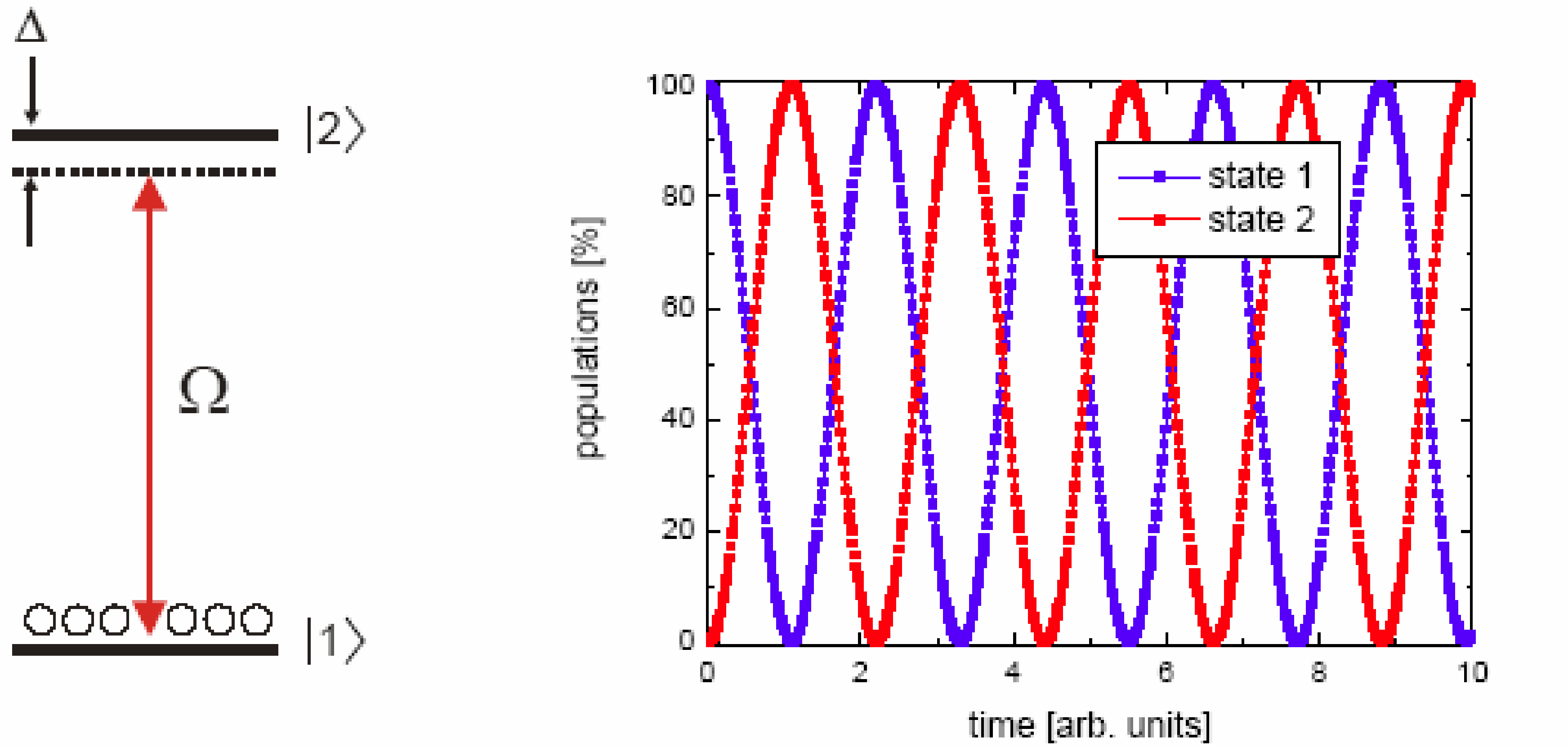
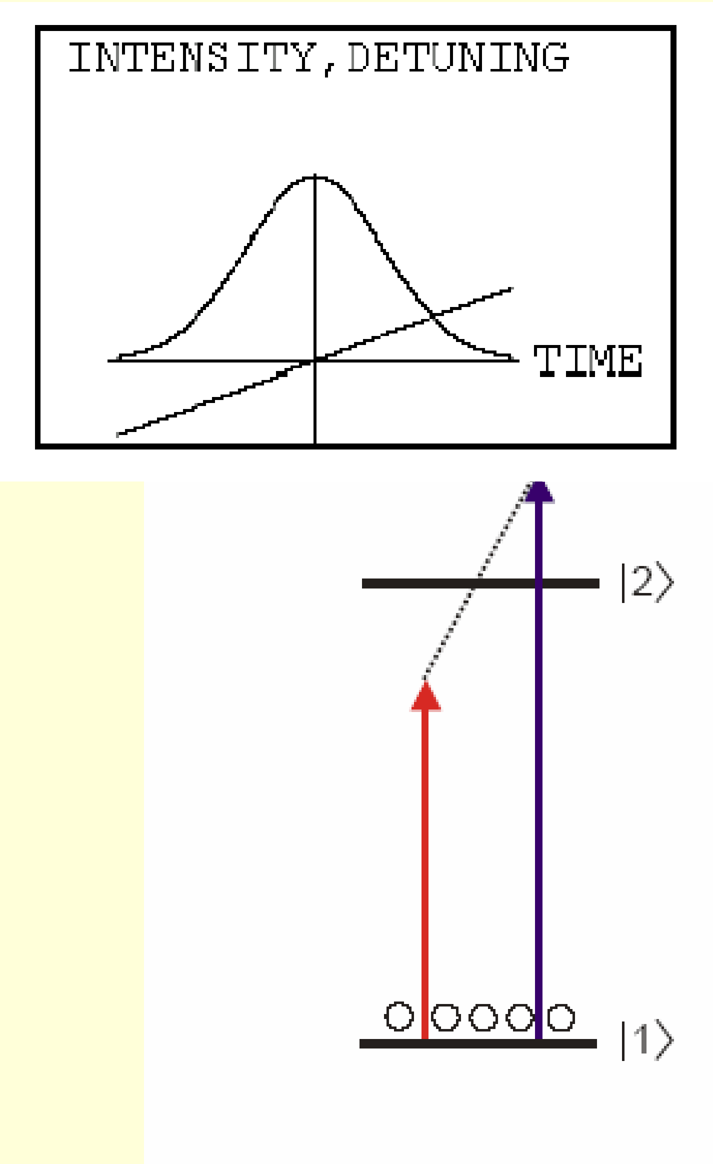
- Motivation:

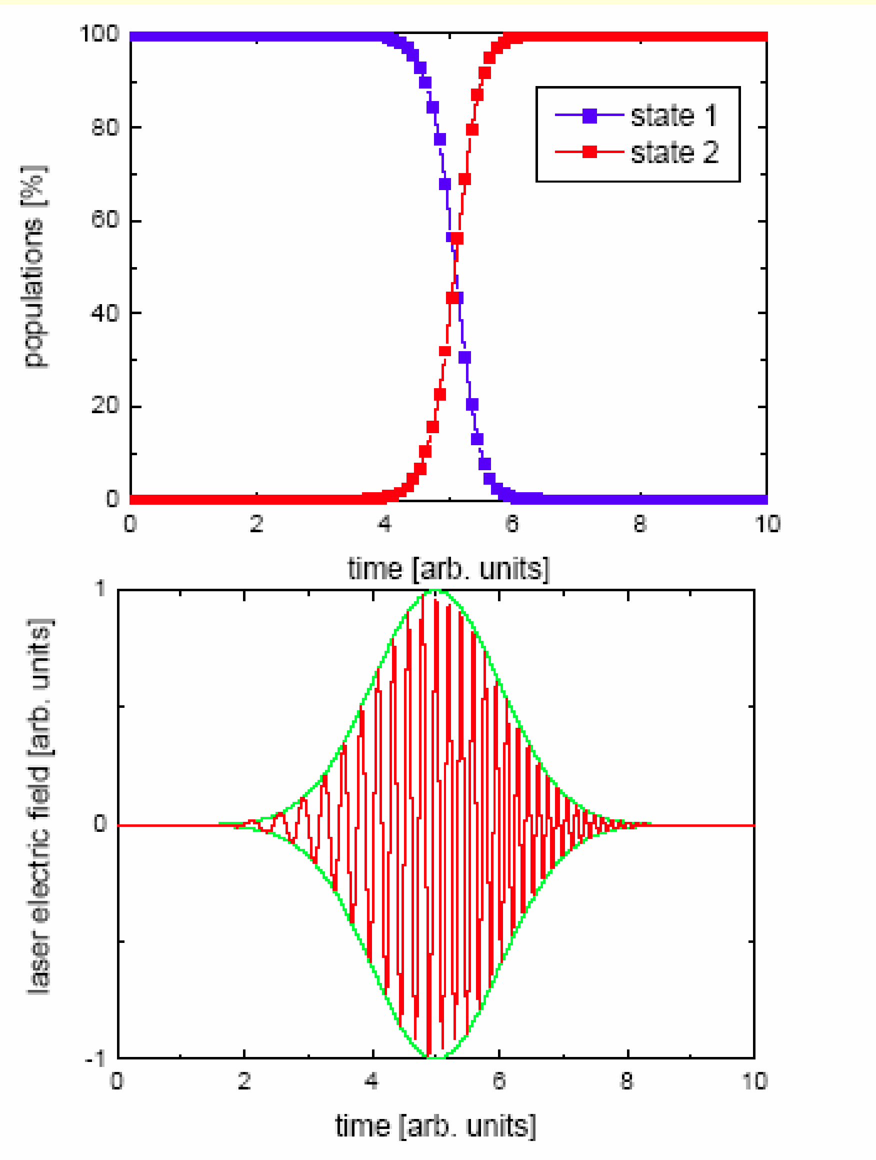
  Applications in quantum chemistry, *Quantum computing; Slowing down and stopping of light pulses; Information writing in collective spin coherences and populations of metastable states; Nonlinear optical processes in coherently prepared media; Coherent manipulation and splitting of atomic beams; Atomic interferometry, and others.*
- Effect of interaction of frequency-chirped laser pulses with two- and multi-level quantum systems: The physical basis.
- Manipulation of inner quantum states by frequency-chirped pulses:
- - *Coherent population transfer to a target quantum state and “on demand” creation of coherent superposition of metastable states*
- *- Optical information writing and storage in populations of meta-stable atomic states.*
- Manipulation of translational quantum states by frequency-chirped laser pulses:
- *-Mechanical momentum transfer to atoms by separated and/or partially overlapping counter-propagating pulse pairs.*
- Experiments with atoms cooled and trapped in MOT.

Action of a laser pulse with area $A = \int \Omega(t)\,dt = 5\pi$



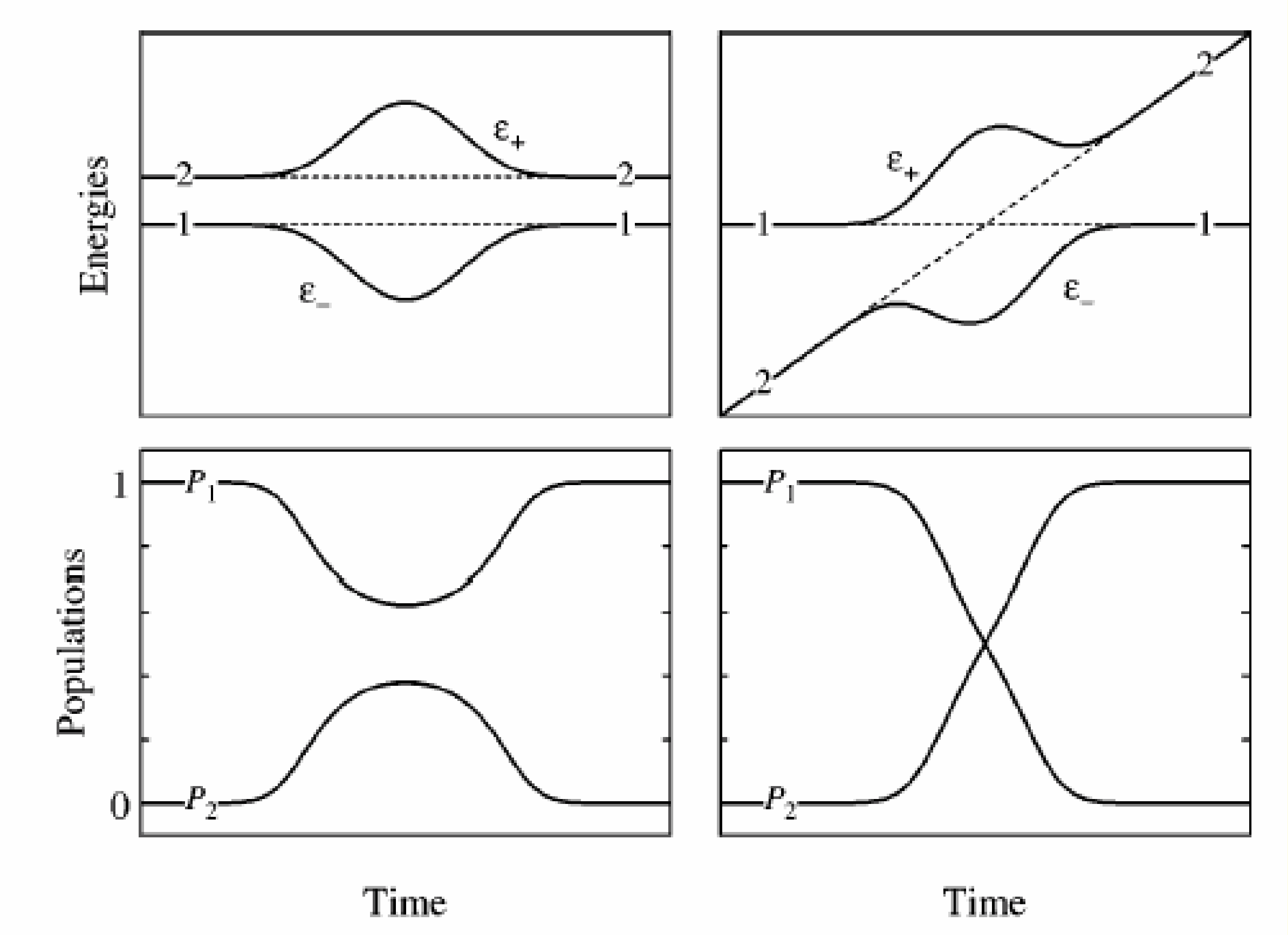
Action of a frequency chirped laser pulse on a two-level atom in the adiabatic passage regime





Dressed (adiabatic) states picture: quasienergies and populations

$$\hat{H}(t)\vec{b} = w(t)\vec{b}$$



Chirped pulses: the Vector Model

$$\partial\vec{R}/\partial t = \vec{\Omega}\times\vec{R};$$

$$\vec{R}(t) = \vec{e}_1 X + \vec{e}_2 Y + \vec{e}_3 Z;$$

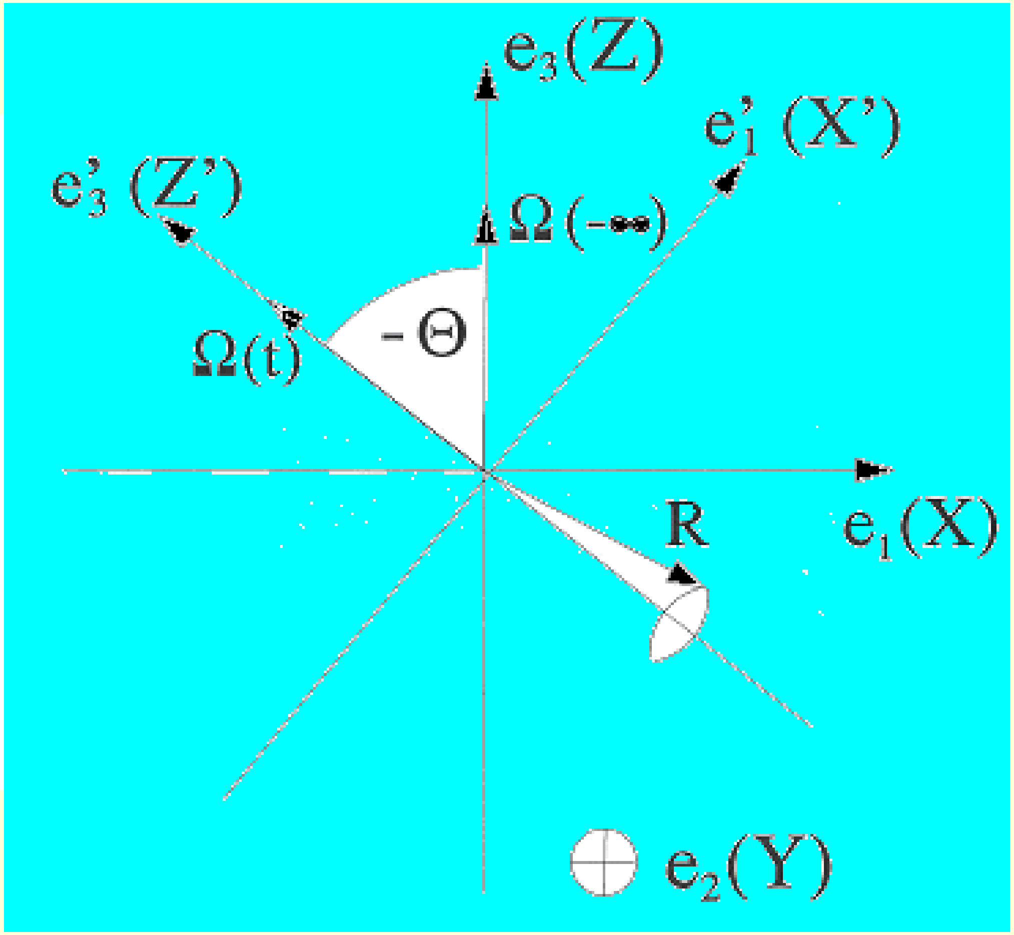
$$\vec{\Omega} = -\vec{e}_1\Omega_R(t) + \vec{e}_3\varepsilon(t);$$

$$\Omega^2(t) = \Omega_R^2(t) + \varepsilon^2(t);$$

$$X(t) = \rho_{ab} + \rho_{ba}; Y(t) = i[\rho_{ab} - \rho_{ba}];$$

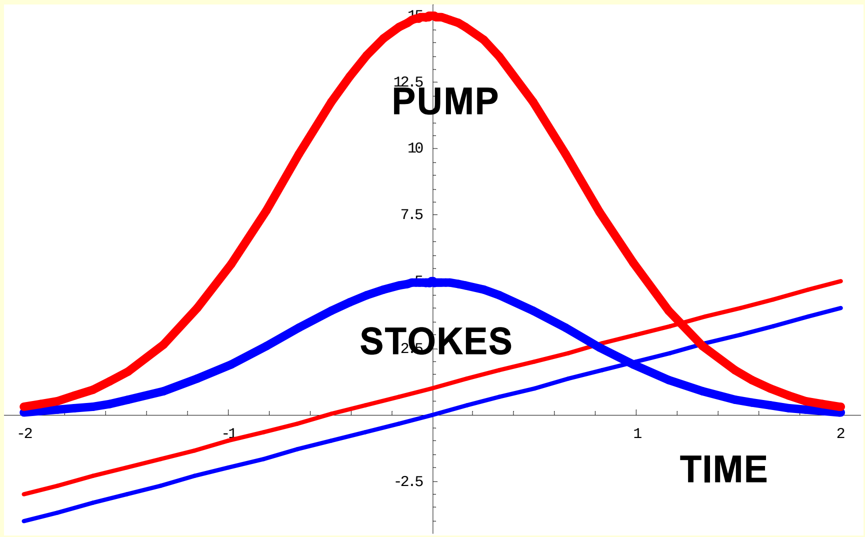
$$Z(t) = \rho_{bb} - \rho_{aa};$$

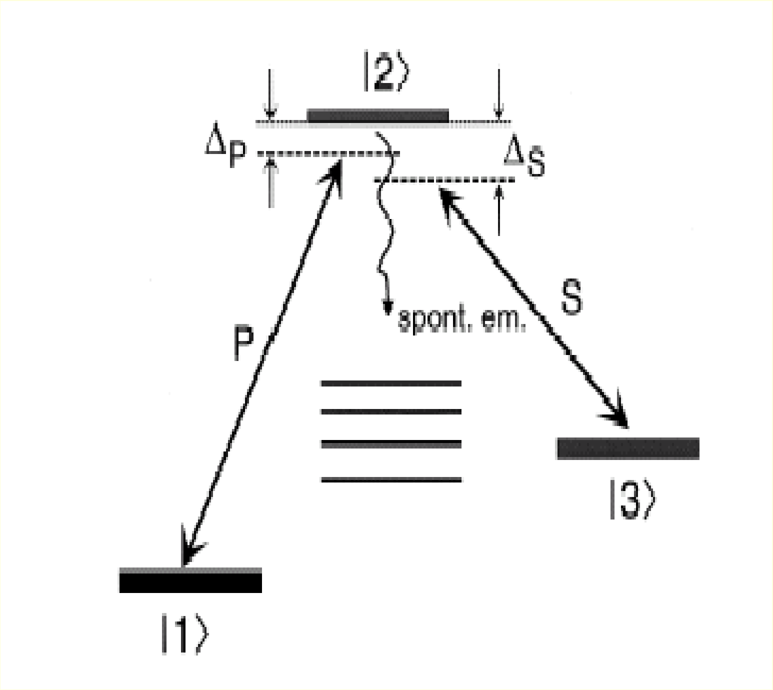
$$\varepsilon(t) = \omega_{12} - \omega; \omega = \omega_L + \partial\Phi/\partial t$$



$$\frac{1}{2}\left|\partial\Omega_R/\partial t\varepsilon - \Omega_R\partial\varepsilon/\partial t\right| << (\Omega_R^2 + \varepsilon^2)^{3/2}$$

A bi-chromatic frequency-chirped laser pulse & a model Λ-atom





Raman resonance when $\Delta_p = \Delta_s$

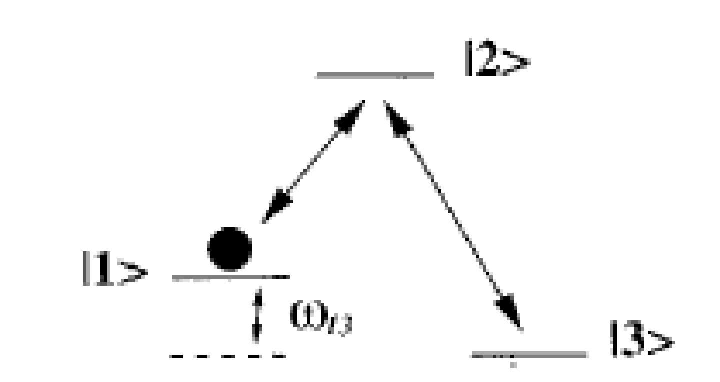
Interaction of Λ-atom with bi-chromatic frequency chirped laser pulses at Raman resonance: Dark and bright superposition of the ground states

$$\frac{d}{dt} g_b = iF(t)e; \frac{d}{dt} e - i\varepsilon(t)e = iF(t)g_b$$

,

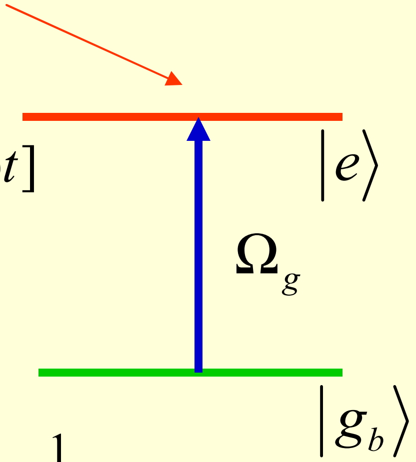
$$\frac{d}{dt} g_d = 0 \qquad F(t) = \Omega_g = f(t)\sqrt{|W_1|^2 + |W_2|^2}$$

;



$$\omega_L(t) = \omega_{L0} + \beta t$$

$$g_b(t) = [W_1^* a_1(t) + W_2^* a_3(t)] / \sqrt{|W_1|^2 + |W_2|^2}\,; e(t) \equiv a_2(t)\exp[i\varepsilon(t)t]$$

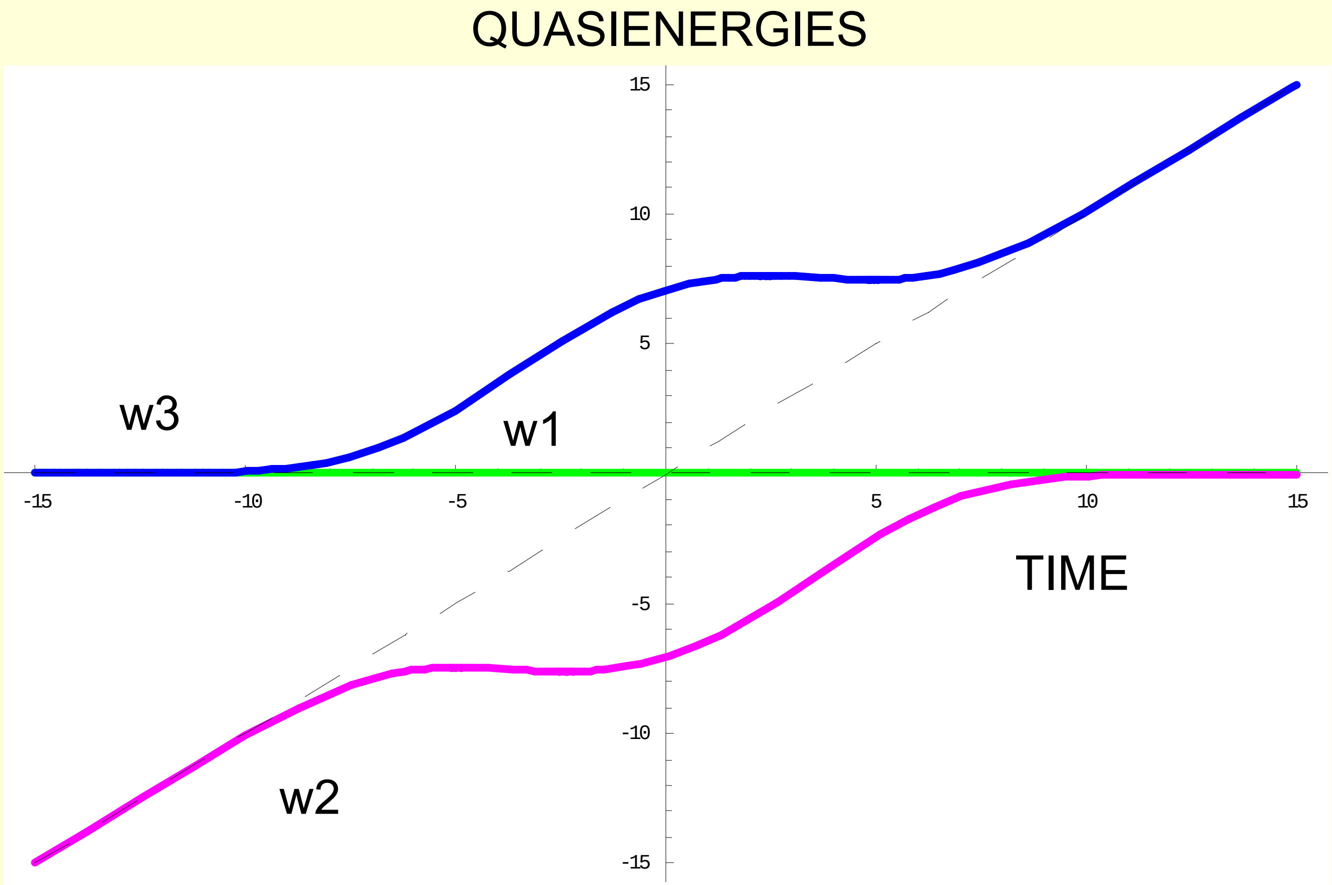


$$g_d(t) \equiv [W_2 a_1(t) - W_1 a_3(t)] / \sqrt{|W_1|^2 + |W_2|^2}$$

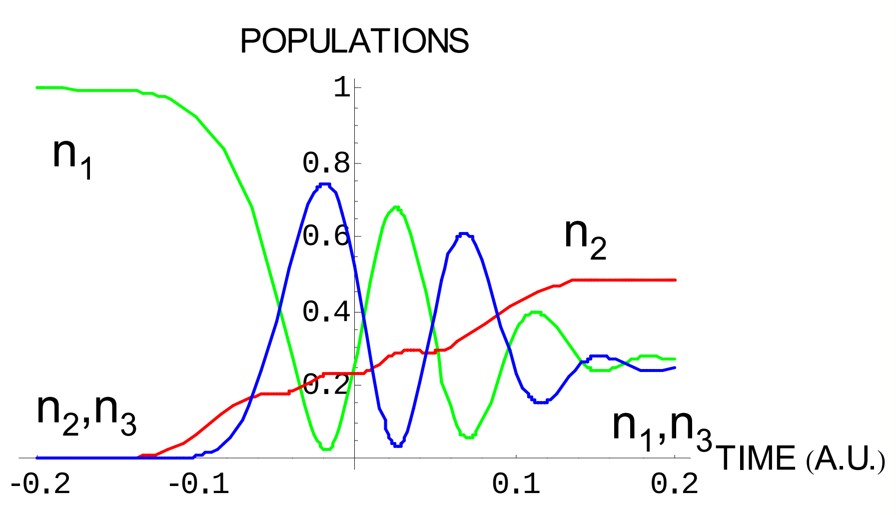
.

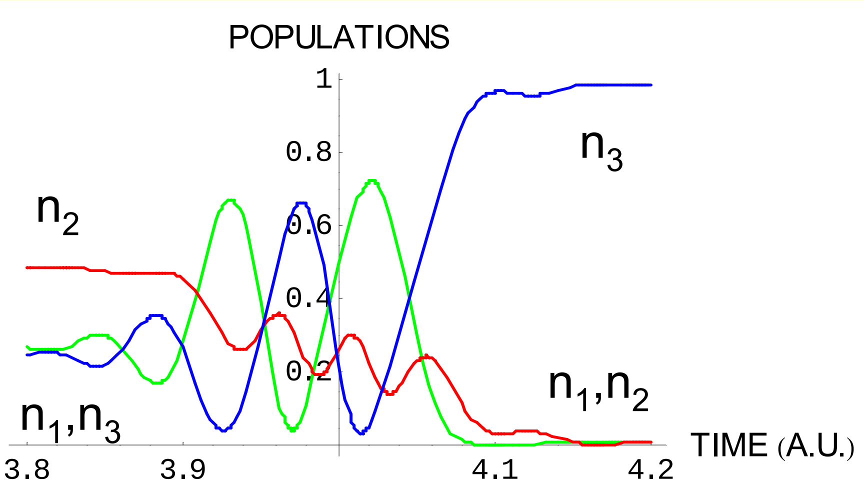
$$\Omega_1 = \Omega_{12} = \Omega_{21}{}^* = f(t)W_1 = \frac{1}{2\bar{h}} d_{12} A(t);\ \Omega_2 = \Omega_{23} = \Omega_{32}{}^* = f(t)W_2 = \frac{1}{2\bar{h}} d_{23} A(t)$$

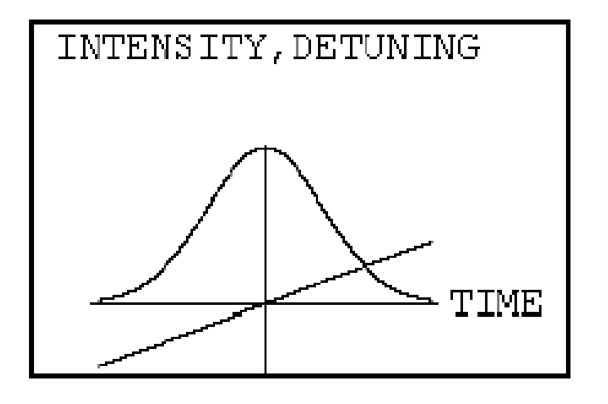
Evolution of the quasi-energies at Raman resonance: an equivalent two-level atom



An example: Λ-atom in the field of bi-chromatic frequency-chirped laser pulse at Raman resonace: an effective two-level atom



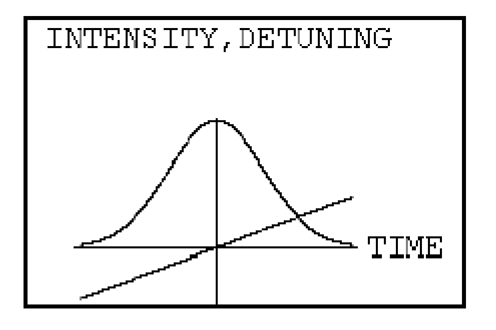


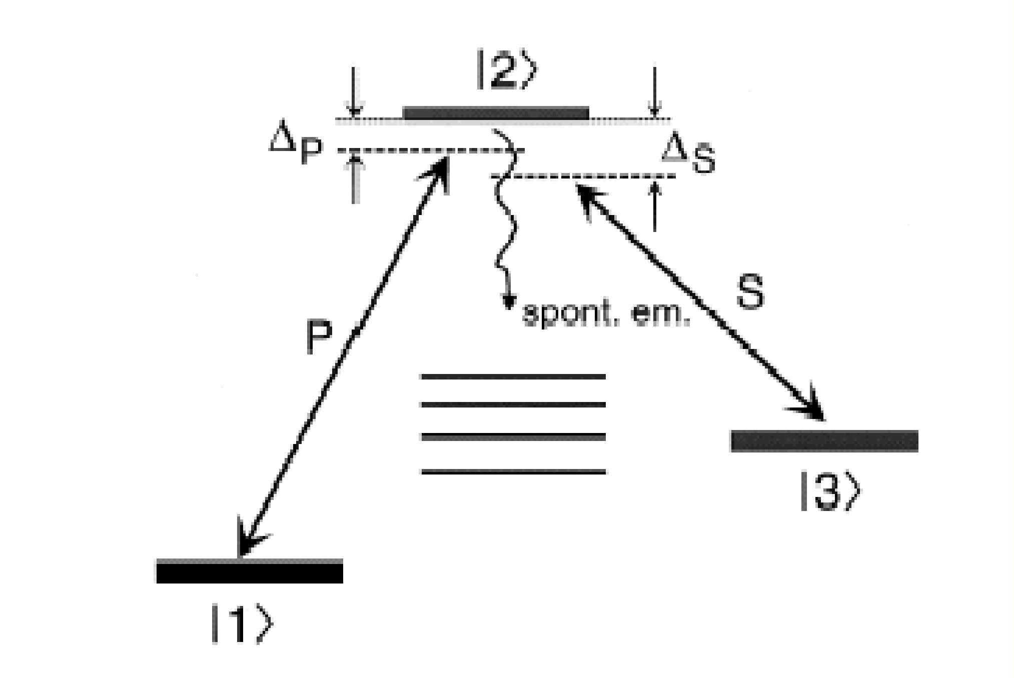


Interaction of a bi-chromatic laser pulse with Λ–atom in the case of nonzero Raman detuning:

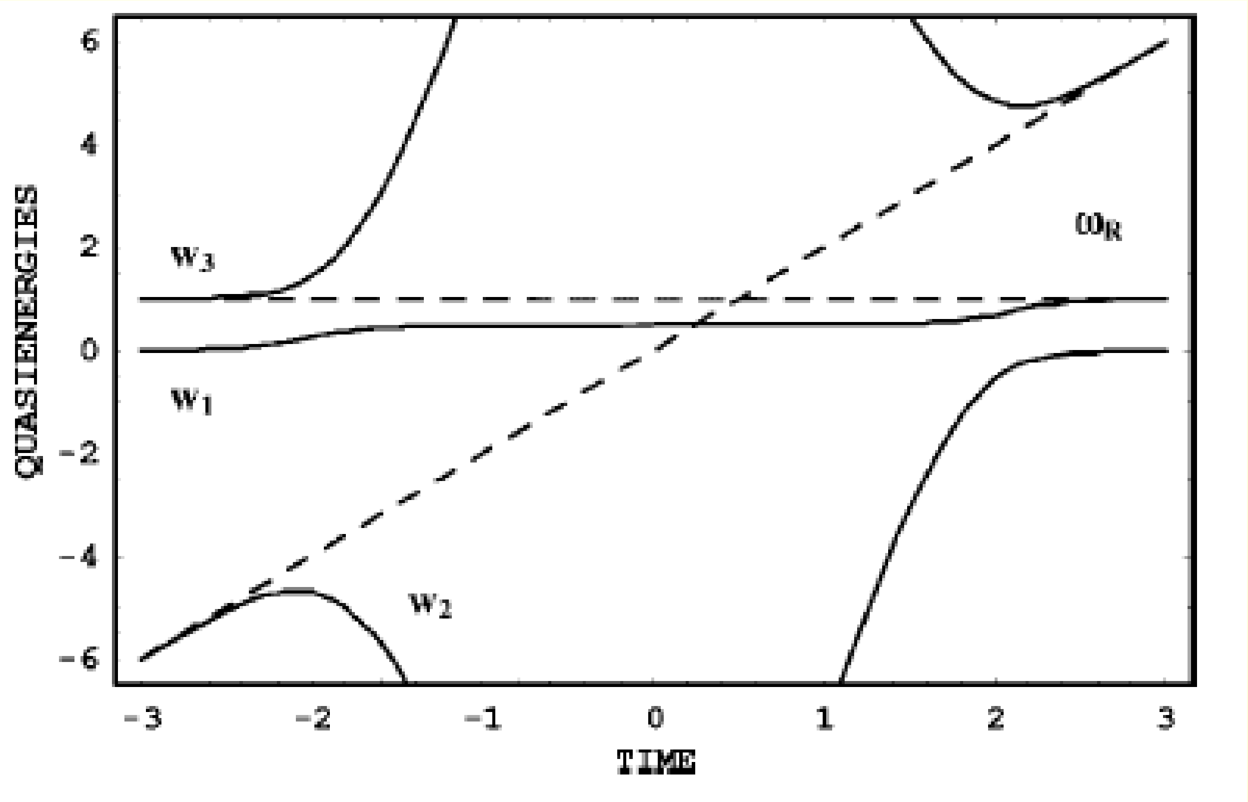
Coherent population transfer to a target state without excitation of the atom

$$\Delta_p - \Delta_s = w_R \neq 0$$





Evolution of the quasi-energies at nonzero Raman detuning



Suppression of the excitation

$$b_2^{(1)} / b_1^{(1)} = \frac{w_1}{\Omega_{12}}$$

$$b_3^{(1)} / b_1^{(1)} = \frac{\Omega_{32} w_1}{\Omega_{12}(w_1 - w_R)}$$

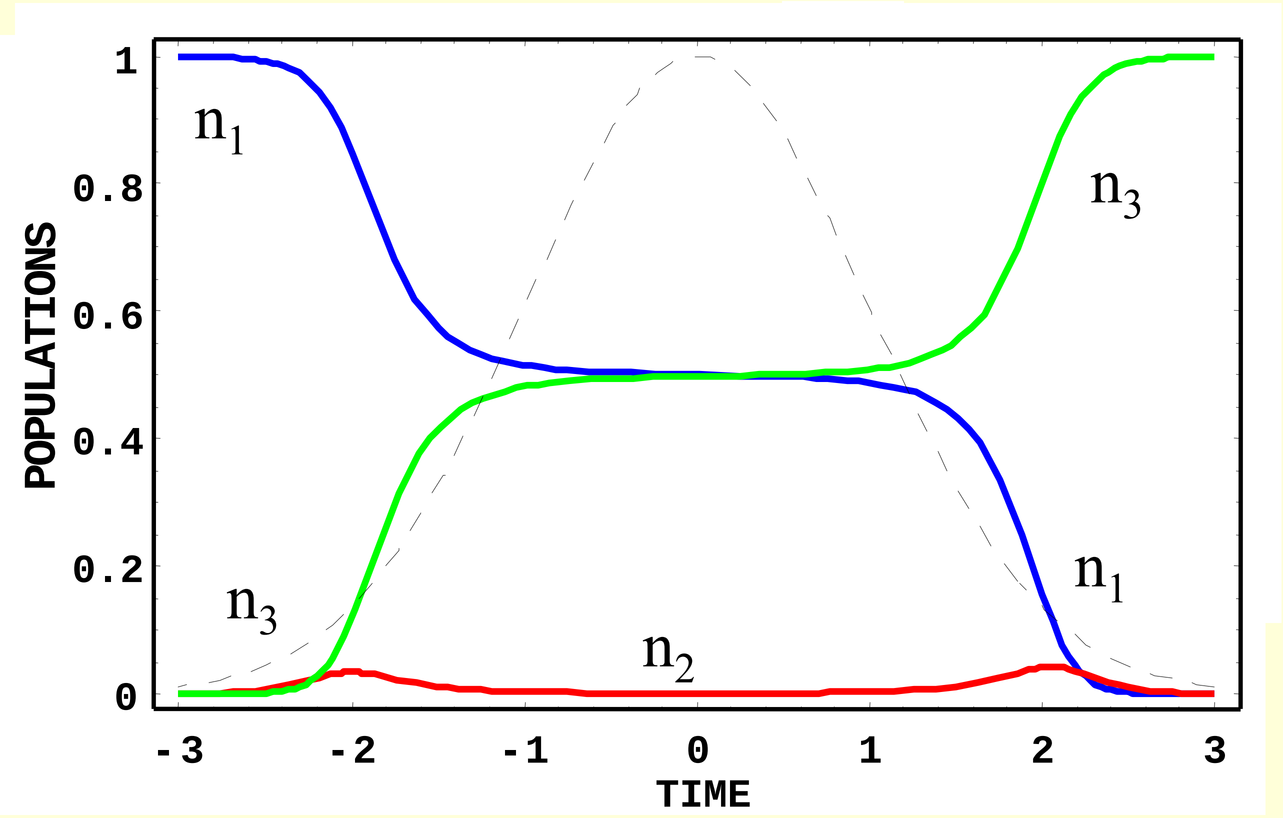
$$0 \le w_1 \le w_R$$

$$\left| b_2^{(1)} / b_1^{(1)} \right| \le \left| \frac{w_R}{\Omega_{12}} \right|$$

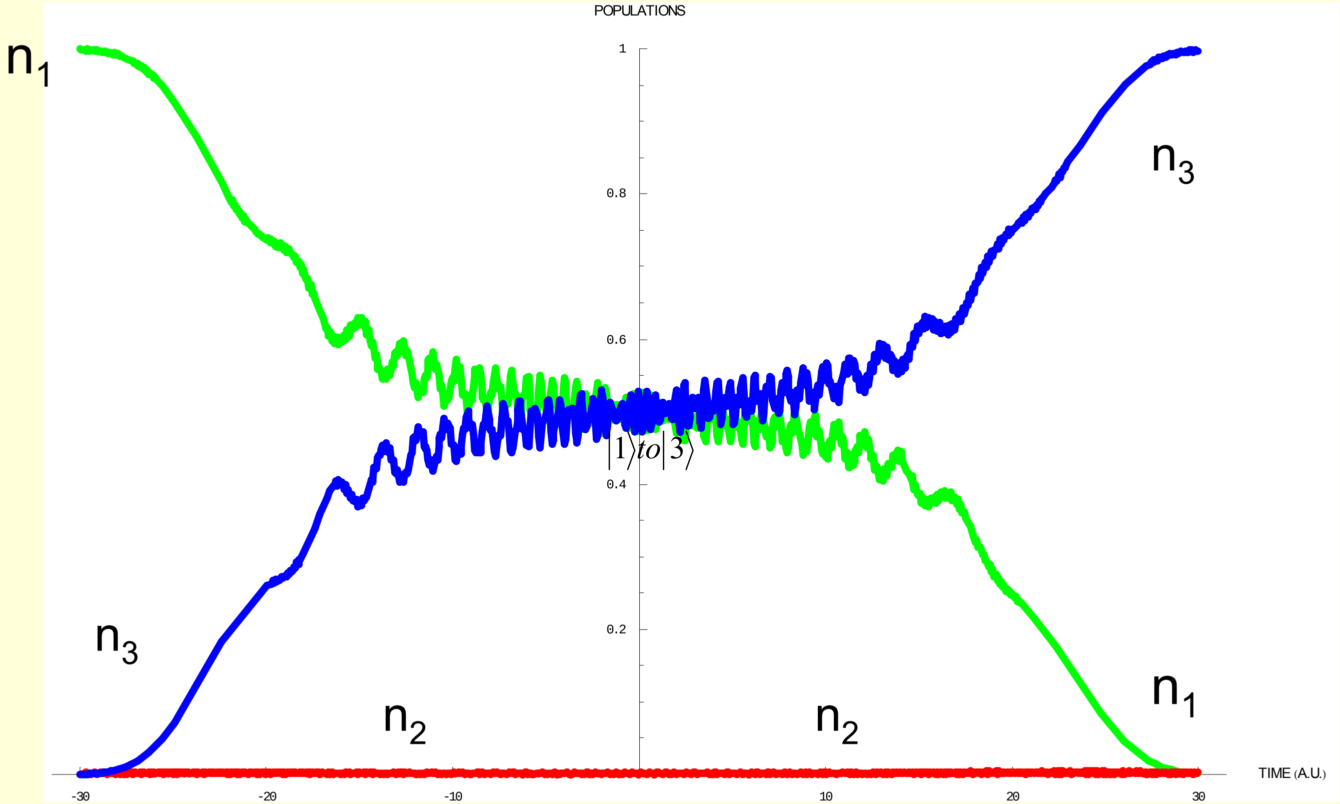
$$\left|\Omega_{12}\right|^2 + \left|\Omega_{23}\right|^2 >> \varepsilon_{12} w_R$$

$$\left|\Omega_{12}\right| >> w_R$$

Dynamics of the populations of the Λ-atom (the dressed state approximation)



Dynamics of the populations of the Λ-atom (result of an exact numerical simulation)



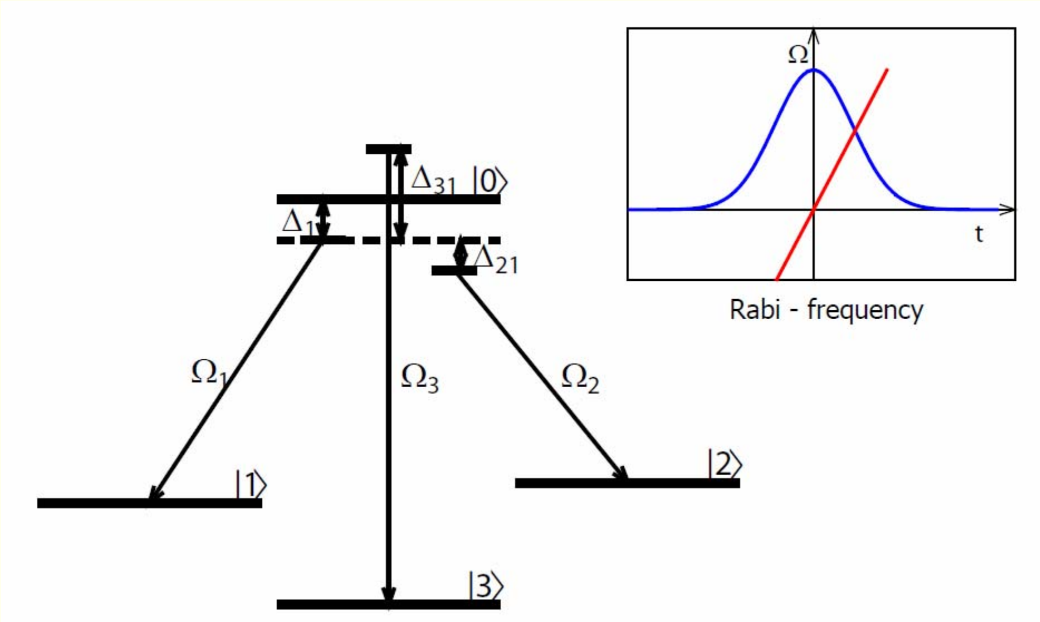
The coherent superposition of ground states is created only during the laser pulse. It vanishes at the end because of complete transfer of the atomic population from one ground state to the other one.

Creation of Coherent Superposition States

Applications:

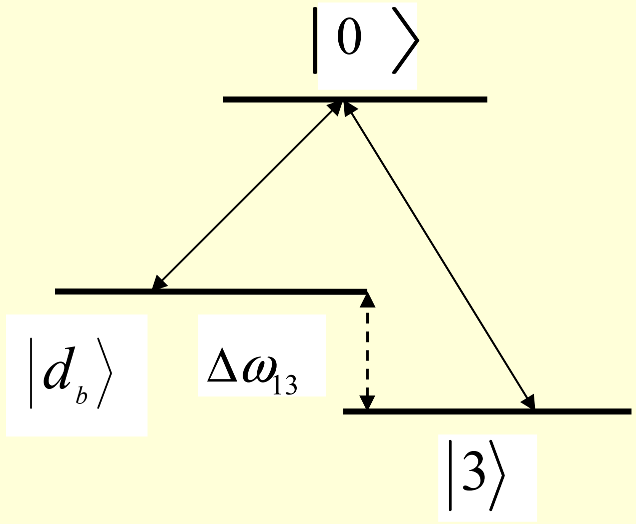
Quantum computing; Slowing down and stopping of light pulses; Information writing in collective spin coherencs; nonlinear optical processes in coherently prepared media

Creation of coherent superposition states without excitation of the atom: Tripod-like atoms in the field of frequency-chirped laser pulses



Tripod-atom reduced to Λ-atom at Raman resonance: $\Delta_{21} = 0$

$$\left| d_b \right\rangle = \frac{1}{\sqrt{1+\beta_{21}^2}} \left(\left| 1 \right\rangle + \beta_{21} \left| 2 \right\rangle \right)$$



$$\beta_{21} = \Omega_{02} / \Omega_{01}$$

The Mathematical Formalism

$$i\hbar \frac{d}{dt} \underline{a} = \hat{H} \, \underline{a}$$

$$= -\hbar \begin{bmatrix} \varepsilon_1(t) + t \, d\varepsilon_1(t)/dt & \Omega_{10}/2 & \Omega_{20}/2 & \Omega_{30}/2 \\ \Omega_{01}/2 & 0 & 0 & 0 \\ \Omega_{02}/2 & 0 & 0 & 0 \\ \Omega_{30}/2 & 0 & 0 & -\Delta\omega_{31} \end{bmatrix}$$

Dressed States Representation

$$\hat{H}_b \underline{b}^{(k)} = w_k \underline{b}^{(k)}$$

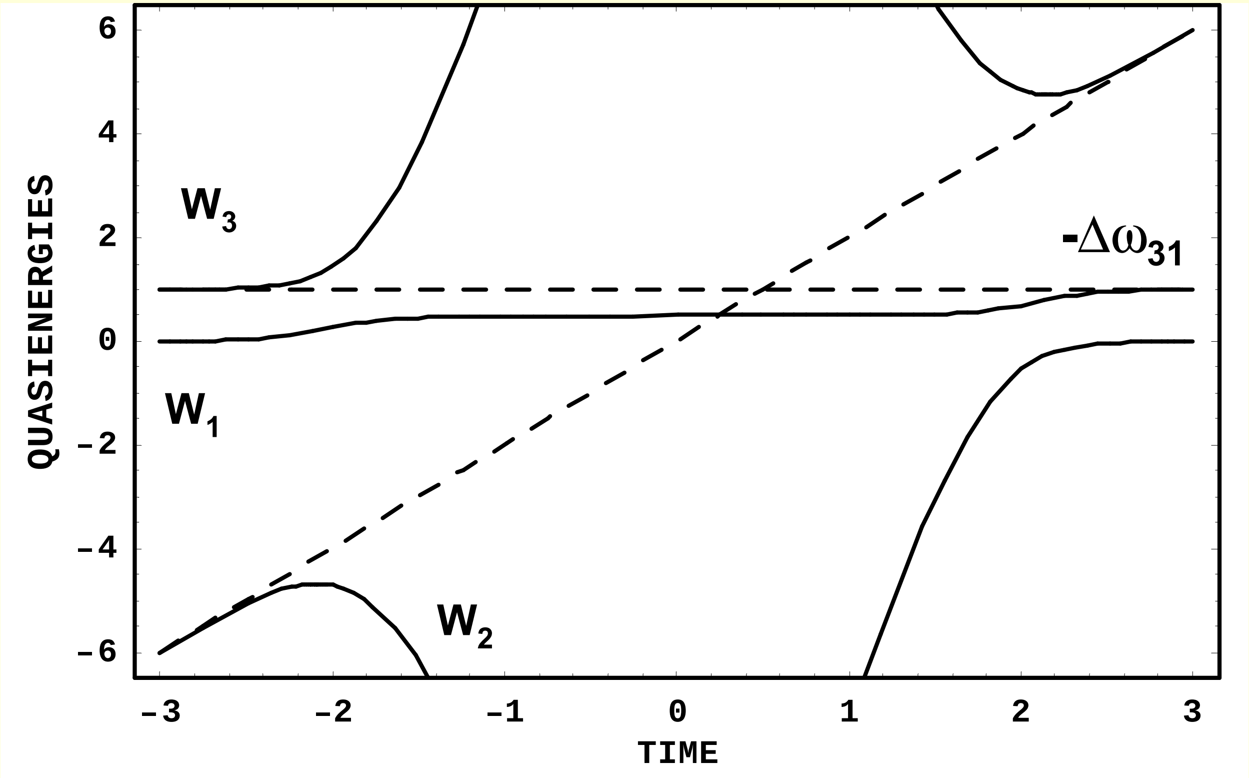
$$w^3 + w^2(\Delta\omega_{31} - \varepsilon_1) - w[\varepsilon_1 \Delta\omega_{31} + (|F_1|^2 + |F_2|^2)] - |F_1|^2 \Delta\omega_{31} = 0$$

$$b_1^{(k)} = \frac{F_1(w_k + \Delta\omega_{31})}{\sqrt{N}}, \qquad b_2^{(k)} = \frac{w_k(w_k + \Delta\omega_{31})}{\sqrt{N}}, \qquad b_3^{(k)} = \frac{F_2 w_k}{\sqrt{N}},$$

$$N = F_1^2(w_k + \Delta\omega_{31})^2 + w_k^2(w_k + \Delta\omega_{31})^2 + F_2^2 w_k^2$$

Quasi-energies of the dressed states

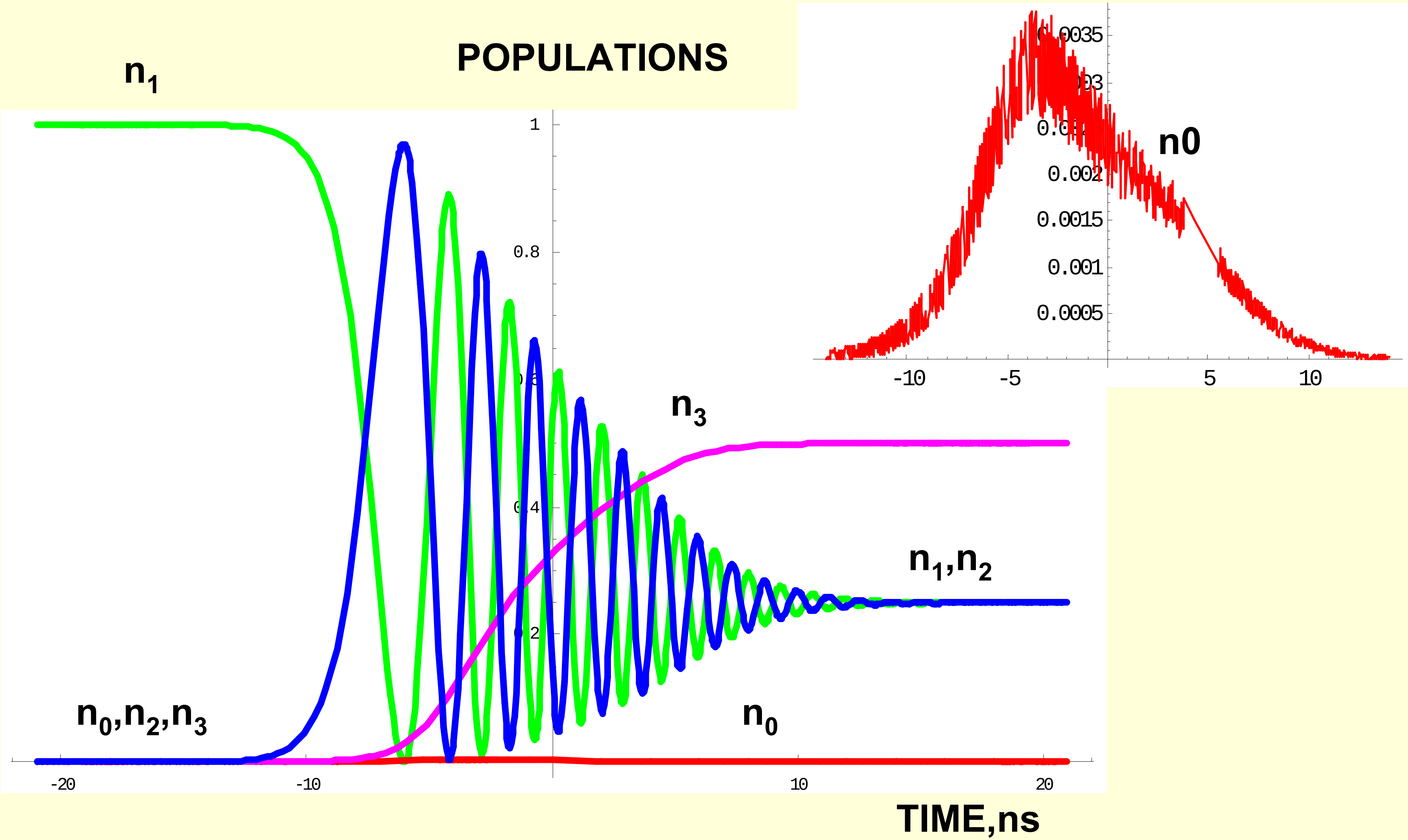
There is a negligibly small contribution of the excited state into the dressed state corresponding to the quasienergy w_1



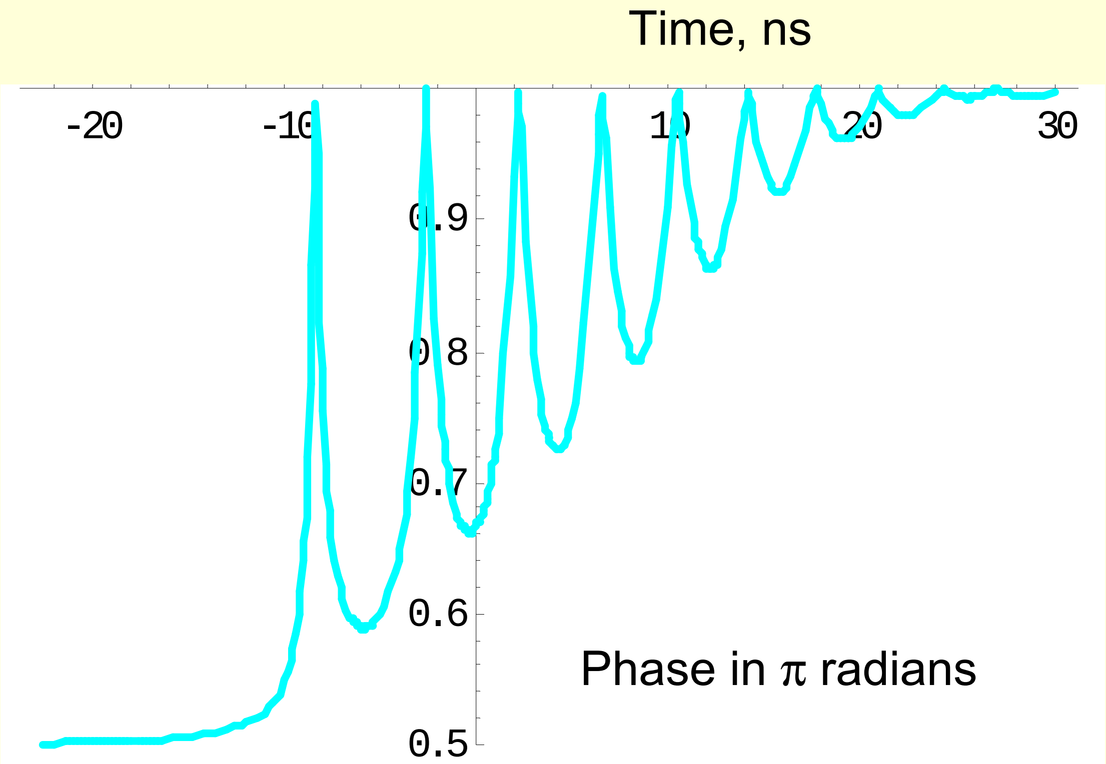
$$0 \leq w_1 \leq \left|\Delta\omega_{31}\right|$$

$$\left|b_2^{(1)} / b_1^{(1)}\right| \leq \left(\frac{\Delta\omega_{31}}{F_1}\right) << 1$$

Population dynamics: Equal dipole moments of the transitions



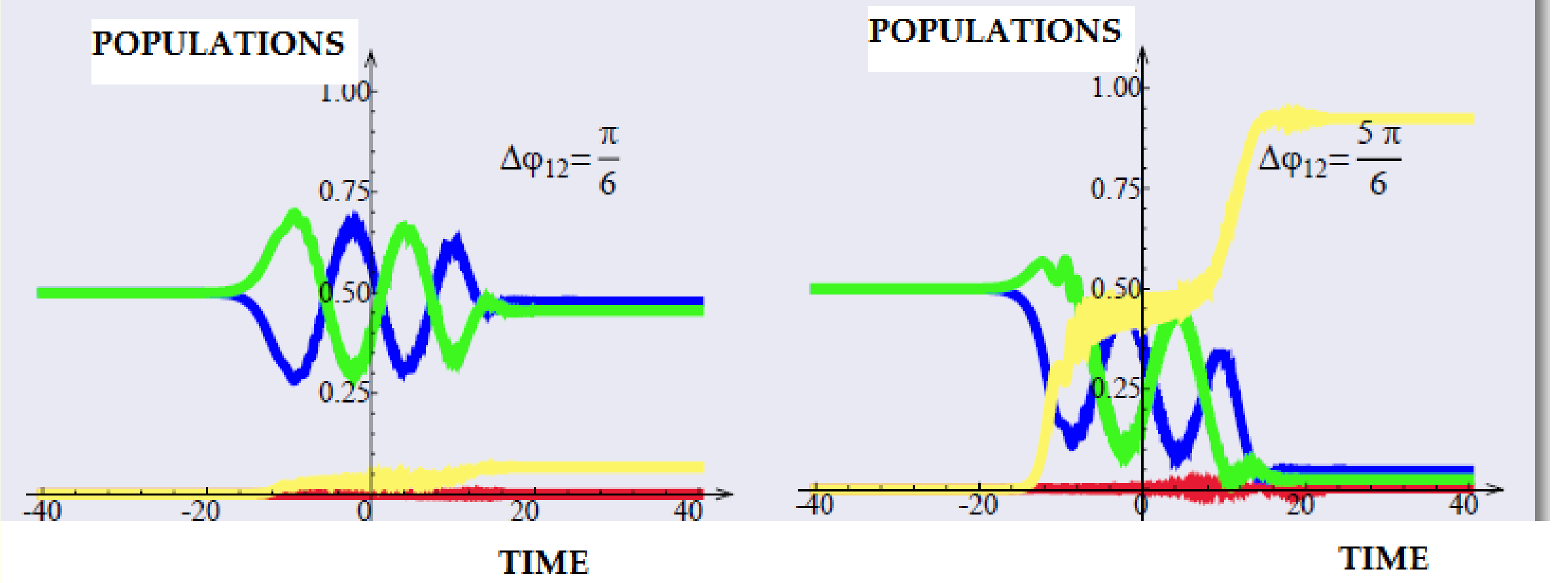
The phase of the Raman Coherence



The main advantage of using tripod-atom for creation of the coherent superposition is that there is no excitation of the atom and the superposition is maintained after the action of the laser pulse.

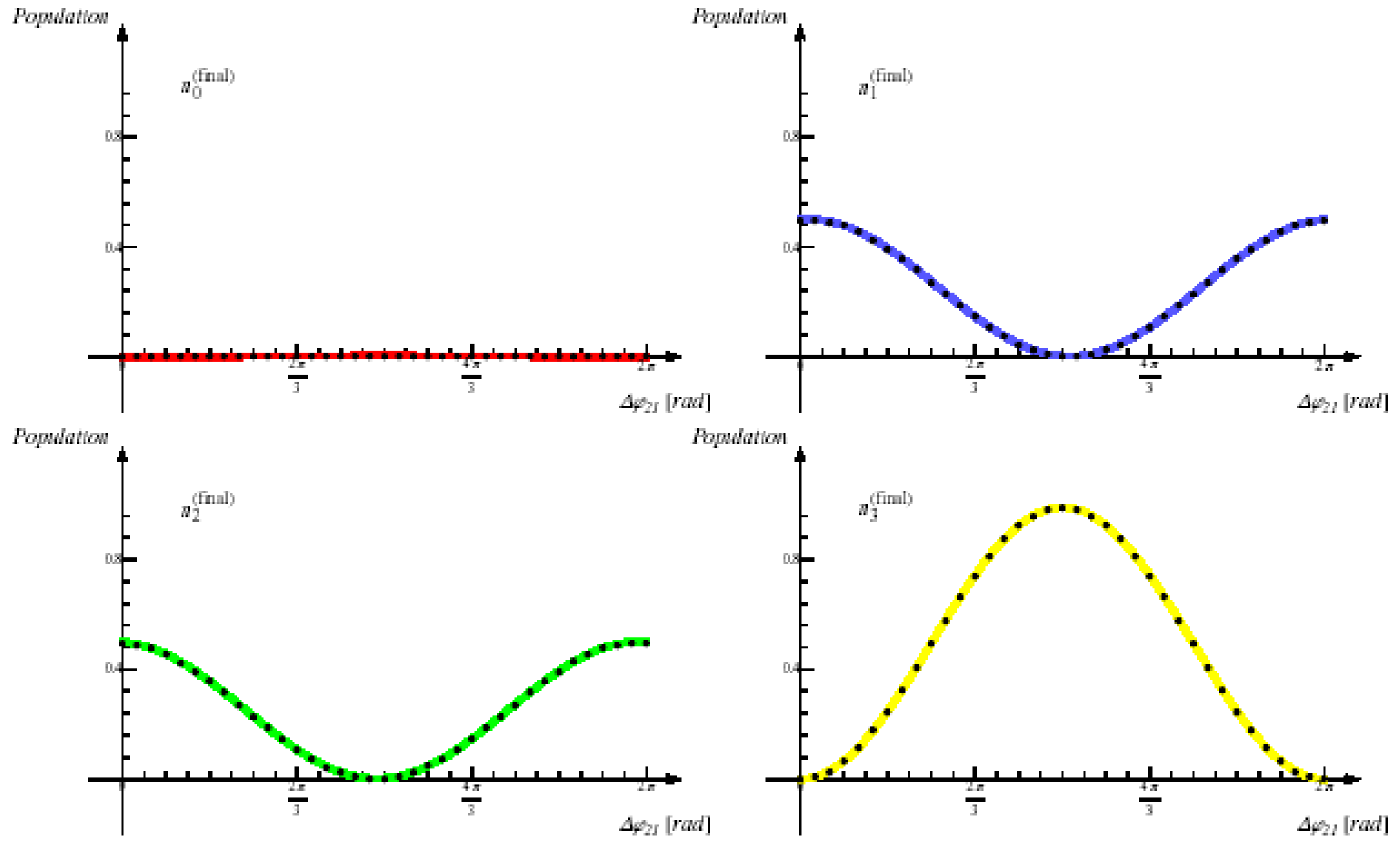
Optical information writing and storage in *populations* of meta-stable atomic states: The final populations depend on relative phase

$$\Omega_k = |\mathcal{R}_k| \exp\left(-\left[\left(\tfrac{t}{\tau}\right)^2\right]\right) \exp\left(\Delta\varphi_{12}\right)$$

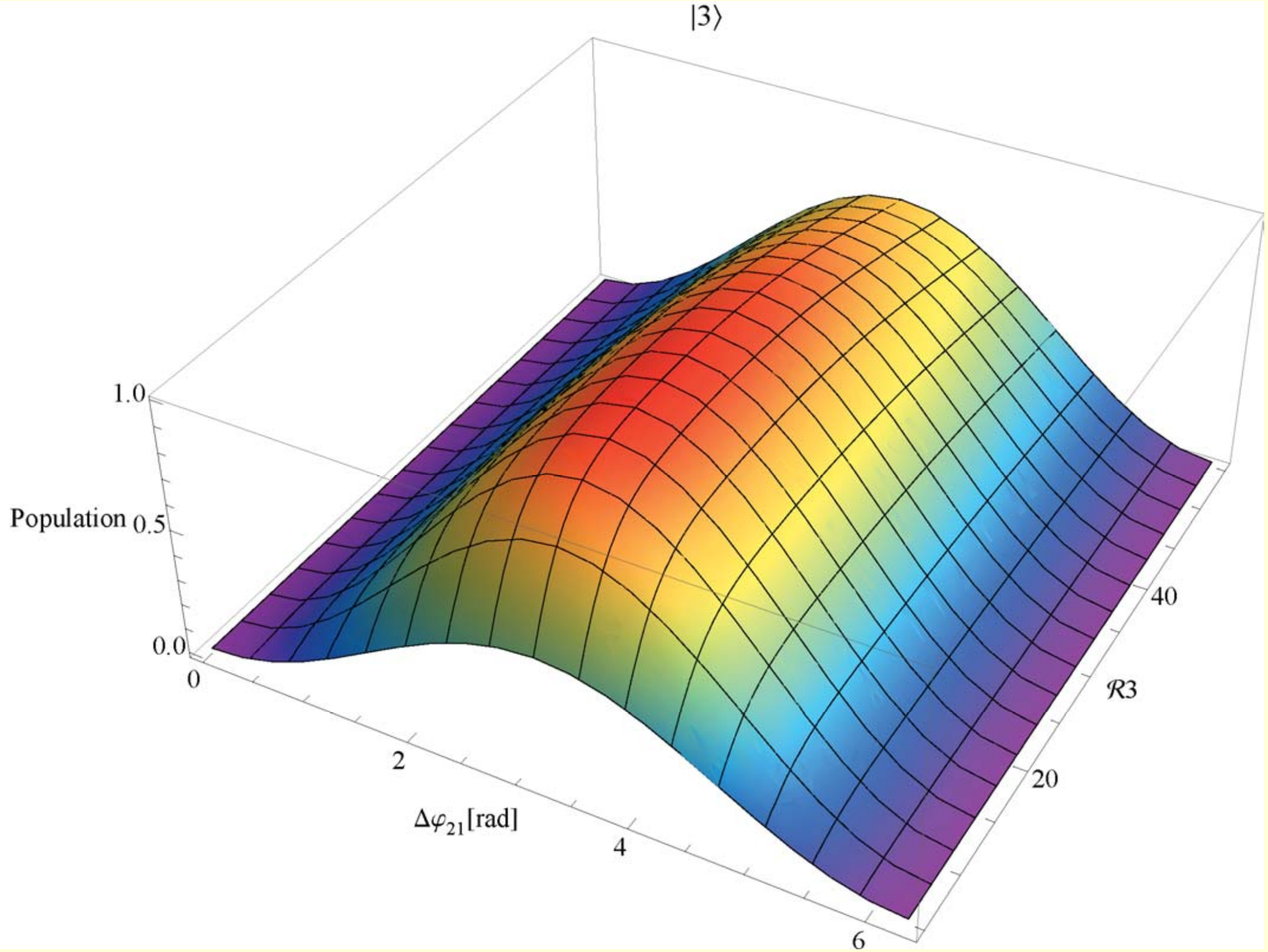


Dependence of final atomic populations on the relative phase $\Delta\varphi_{12}$ of the pulses in Raman resonance

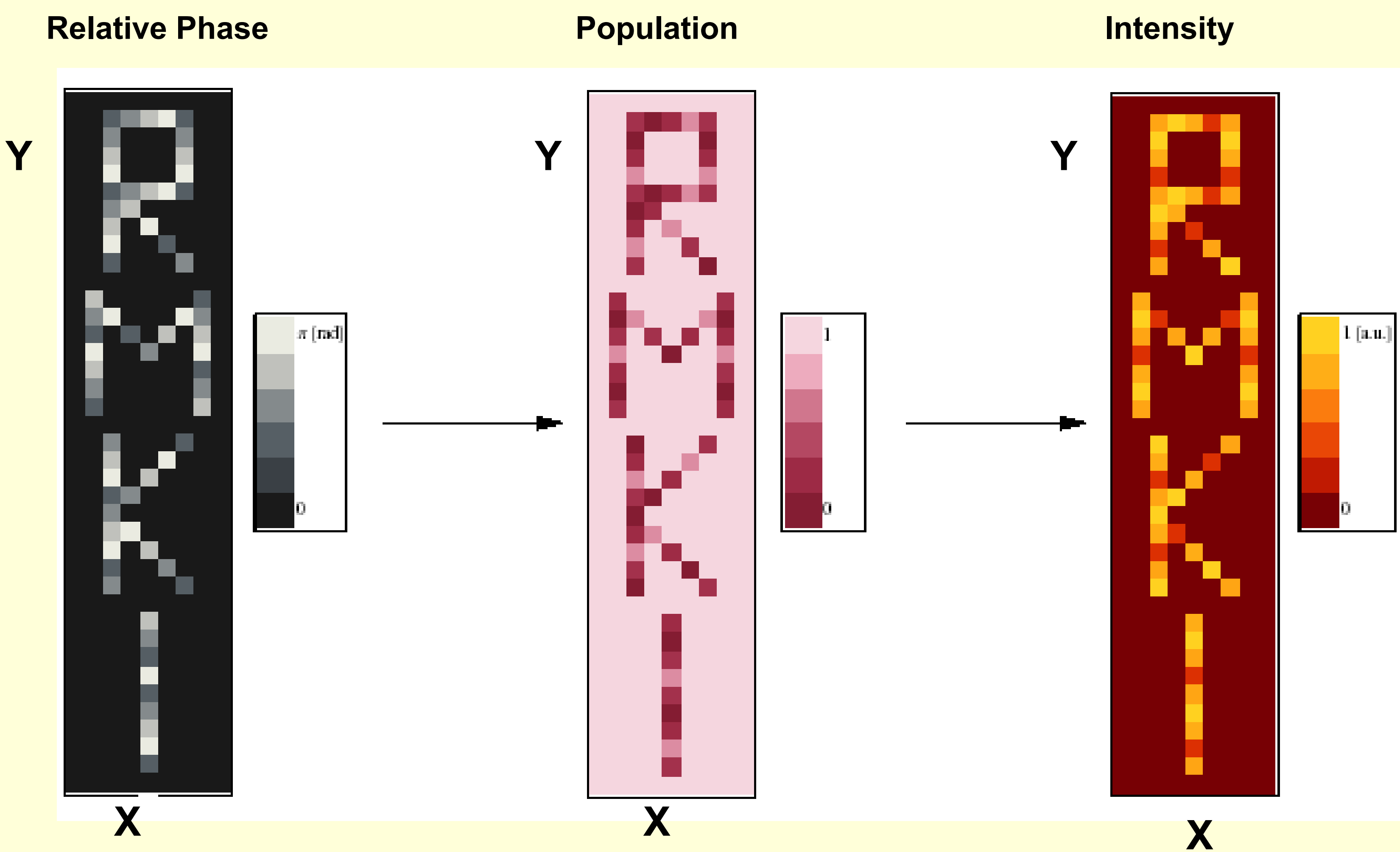
$$P(\Delta\varphi_{12}) = A \cdot \sin^2\left[\tfrac{1}{2}(\Delta\varphi_{12} - \phi_c)\right] + c$$



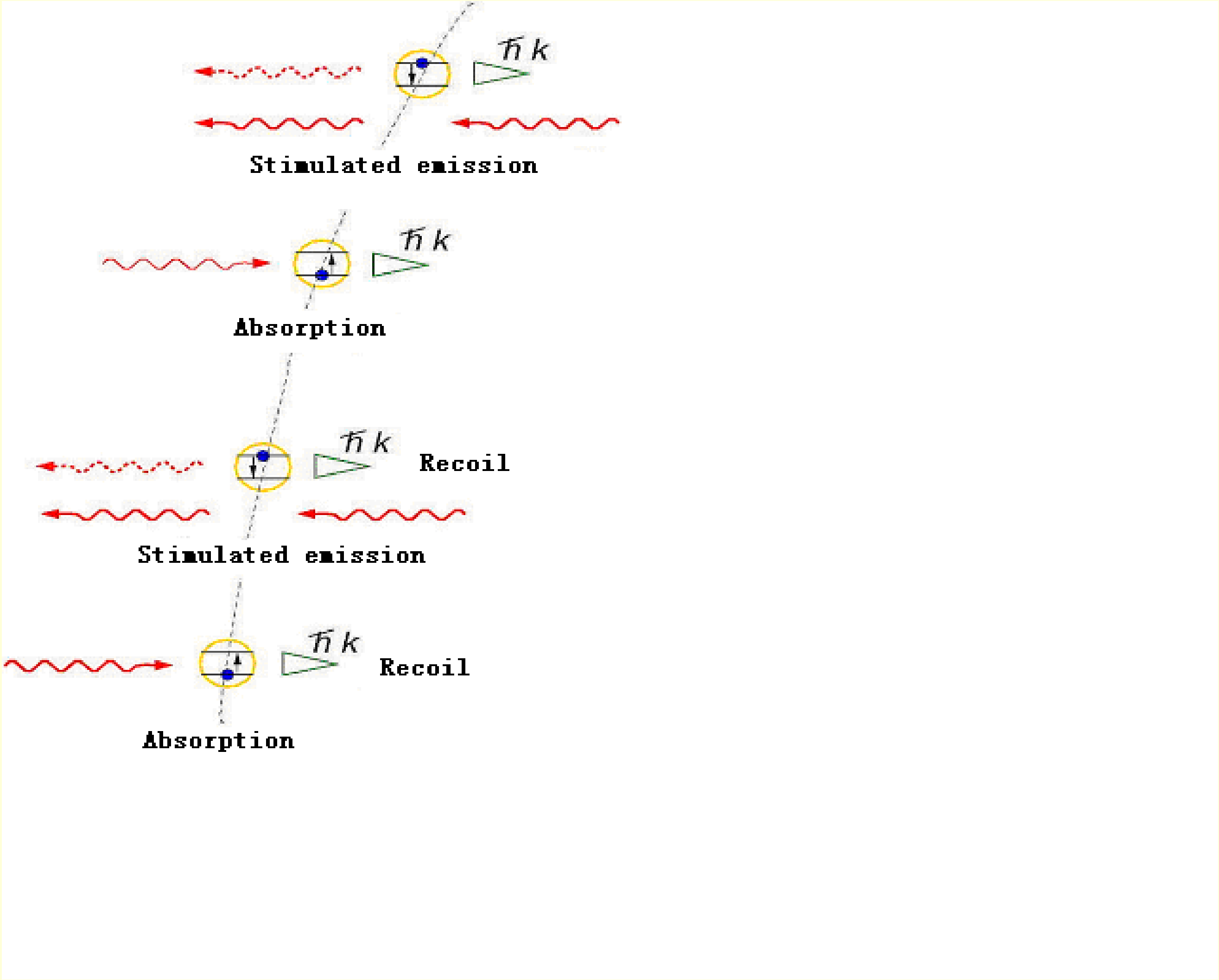
Robustness of the phase information writing



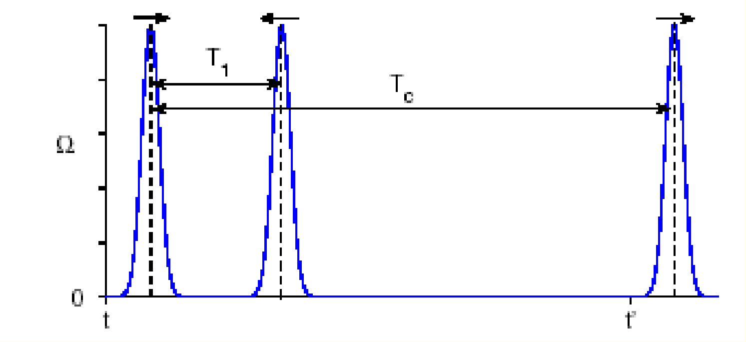
The schematic of the phase information writing in and reading out from the populations of the meta-stable states

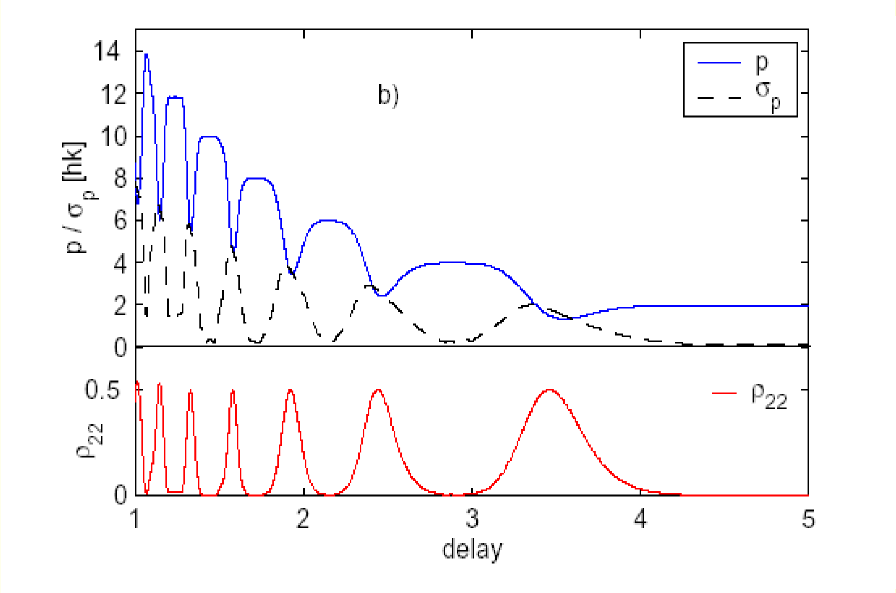


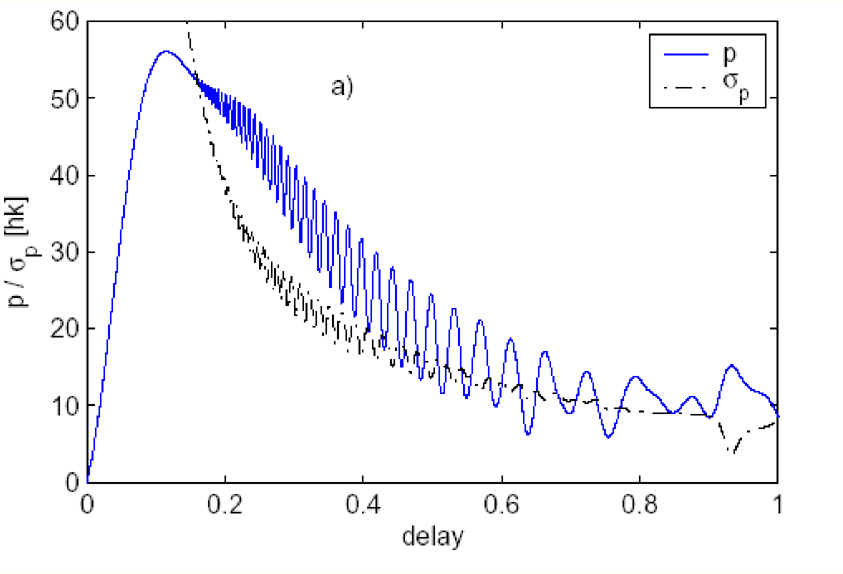
Using frequency-chirped pulses in manipulation of translational states of atoms



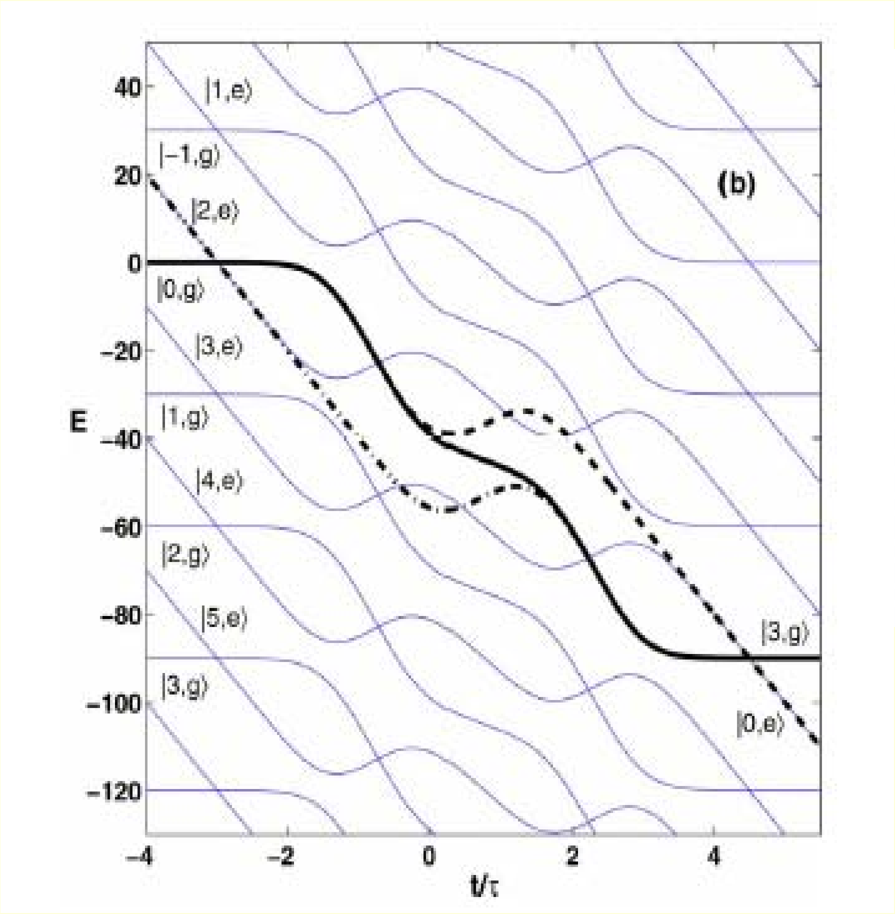
Mechanical momentum transfer from counter-propagating and partially overlapping frequency chirped pulses

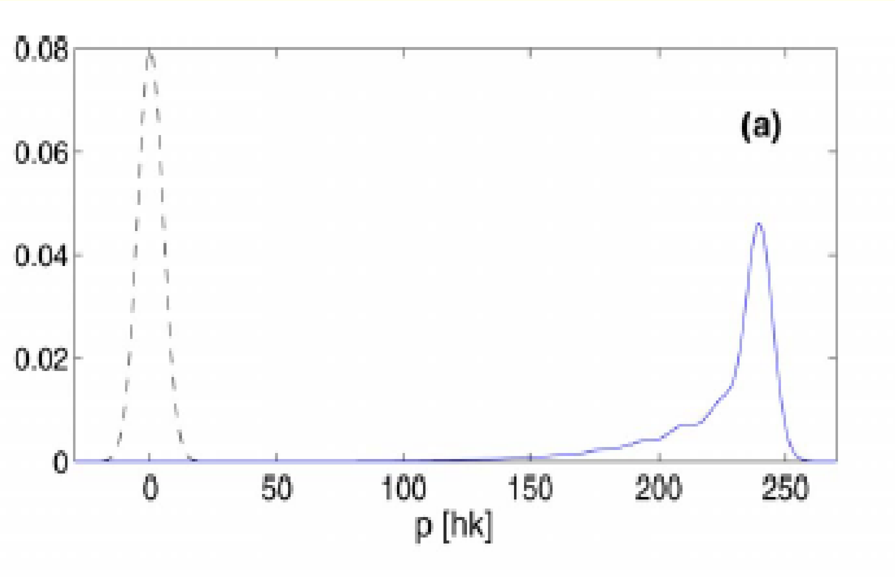






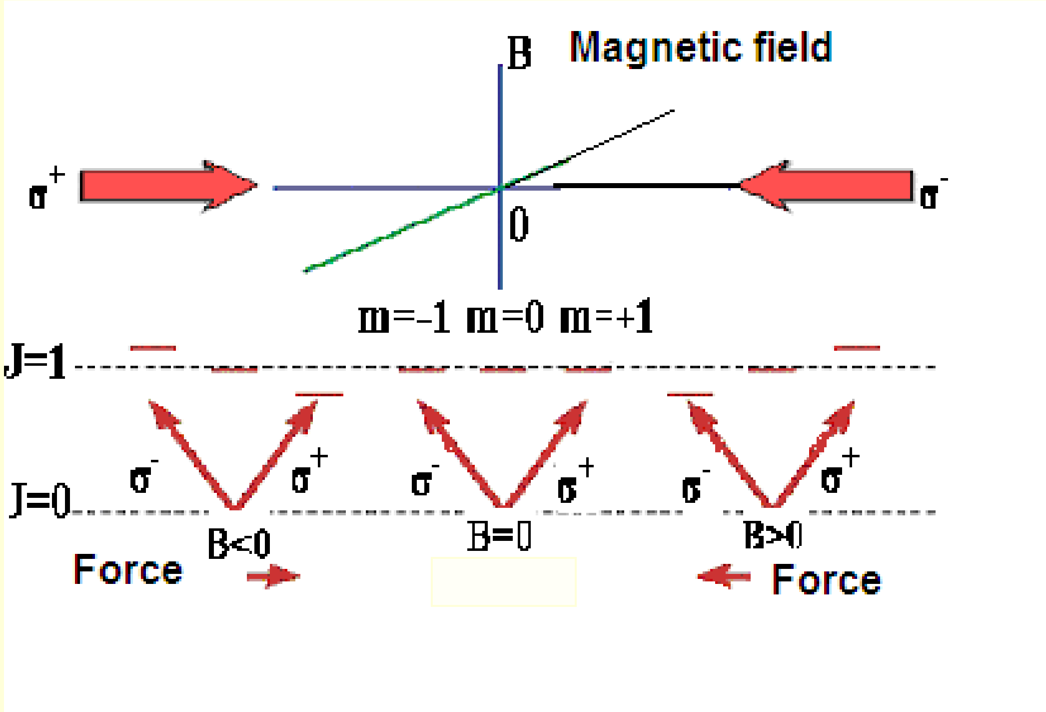
Floquet states and atomic momentum distribution

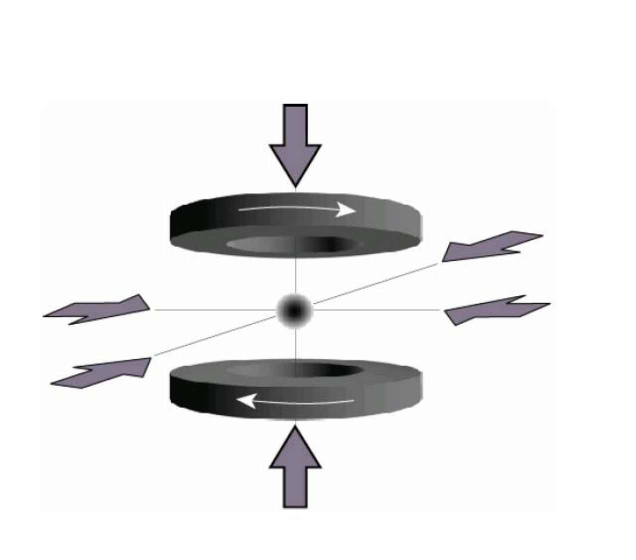




Momentum-space distribution functions before (dashed curve) and after (solid curve) the interaction with 30 pairs of overlapping frequency-chirped laser pulses.

Magneto Optical Trap





$$\mathbf{F} = \mathrm{F}^+ + \mathrm{F}^- = -\beta\,\mathbf{v} - \kappa\,\mathbf{r},$$

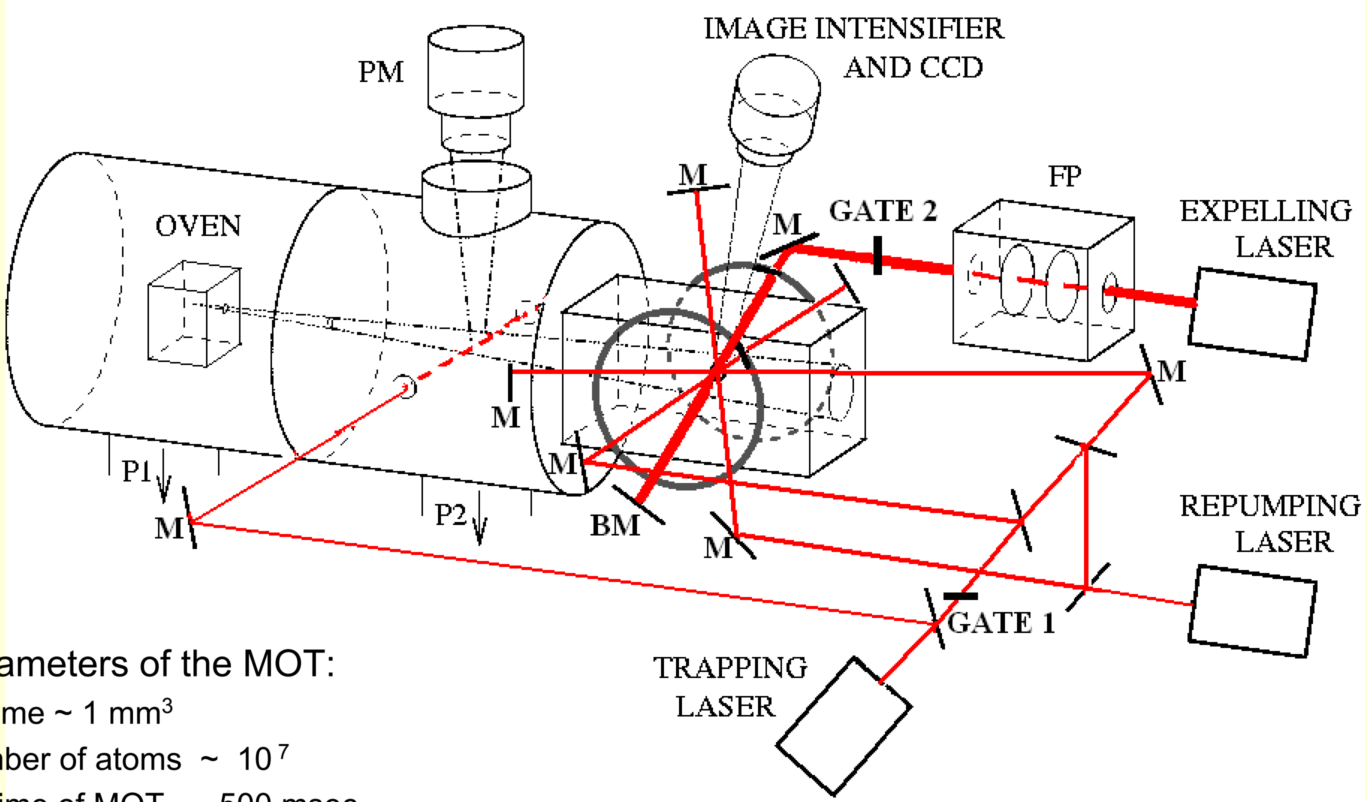
$$\kappa = \mu' A\beta/\hbar k$$

$$\delta\pm = \delta \mp \mathbf{kv} \pm \mu' B/\hbar$$

$$\Gamma_{MOT} = \beta/M$$

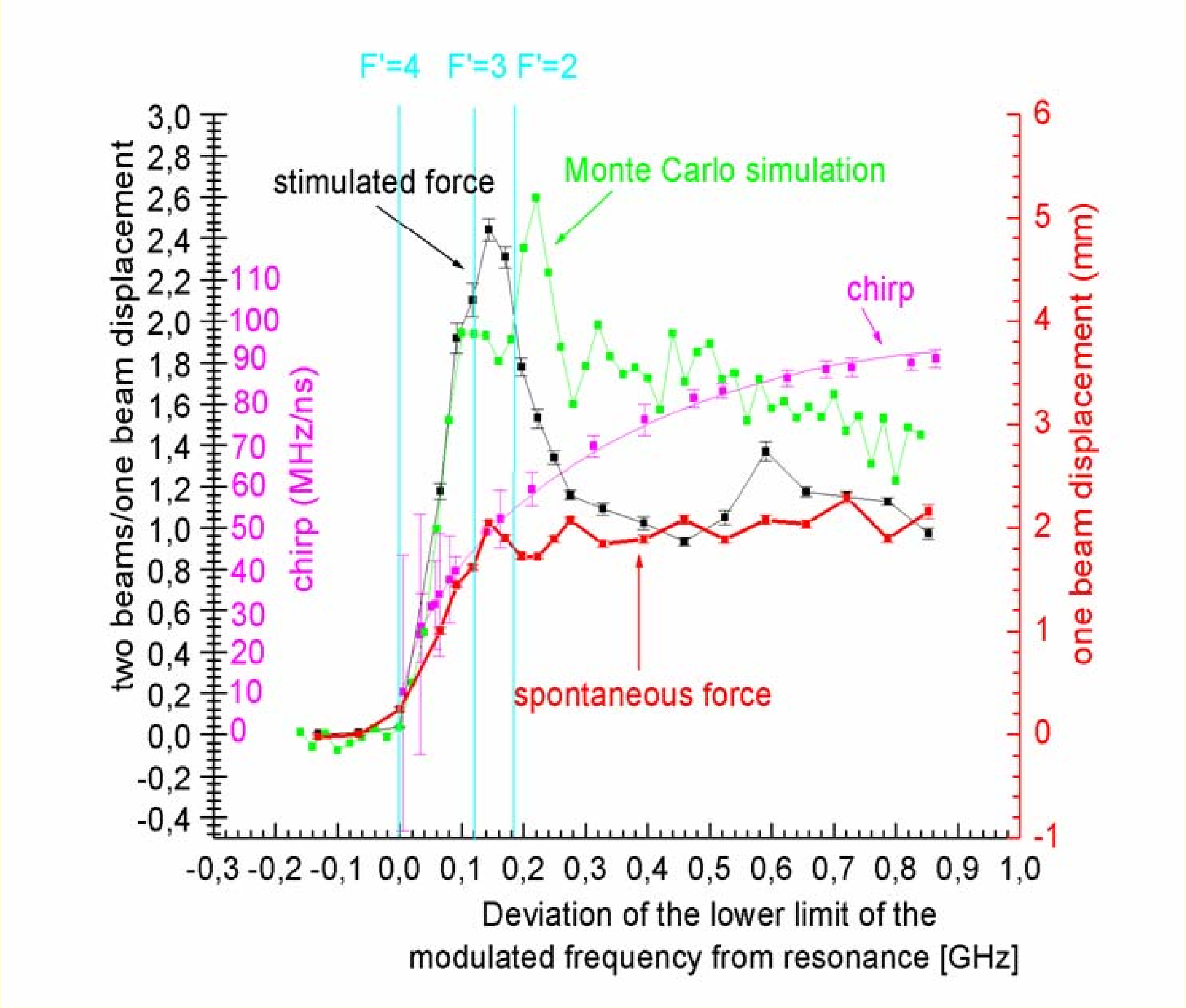
$$\omega_{MOT} = (\kappa/M)^{1/2}$$

Experimental Setup



- Parameters of the MOT:
- Volume ~ 1 mm^3
- Number of atoms ~ 10^7
- Lifetime of MOT ~ 500 msec
- Temperature ~ 10 -100 μK

Momentum transfer to Rb atoms by partially overlapping laser pulses



Conclusions

Frequency-chirped laser pulses may be successfully utilized in different fields of science and technology including

-atom optics (coherent manipulation of the quantum translational states, atom interferometers, etc.),

-nonlinear quantum optics (preparation of nonlinear media in coherent superposition states without excitation of quantum systems),

-quantum and classical information technologies (information writing and storage and processing using populations of long-living meta-stable states or (and) atomic spin coherences).

Due to the frequency chirp, such interactions are efficient both in homogeneously and inhomogeneously broadened media. The last is especially important for solid-state media.

Because the excitation of the atoms may be avoided in such systems, the interacting pulses may propagate loss-less in the media that provides high efficiency of the nonlinear optical processes in optically thick media.