

$|g_2, N_1, N_2+1\rangle$

$|g_1, N_1+1, N_2\rangle$

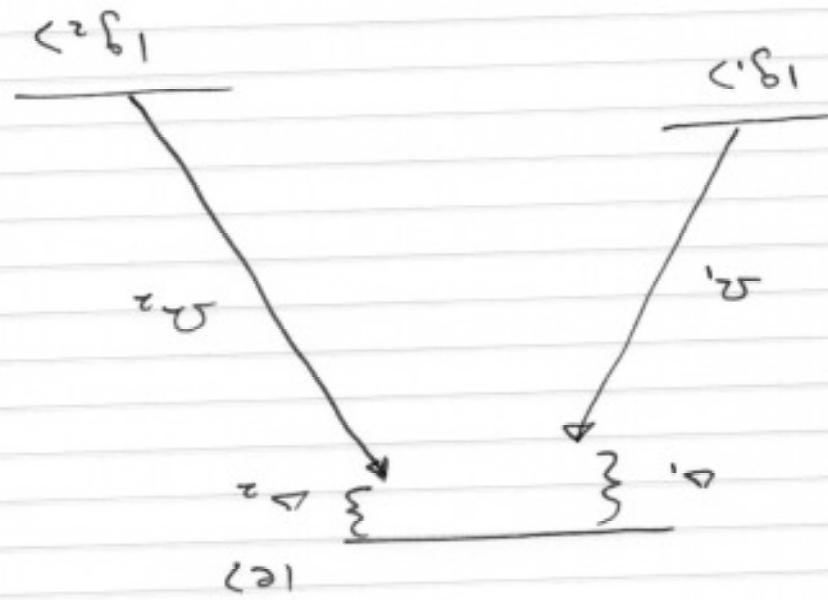
$|e, N_1, N_2\rangle$

the dressed picture

(perturbatives)

and vice-versa (polarization or different

- assume  $\omega_1$  does not couple  $|g_2\rangle; |e\rangle$



3-LEVEL ATOMS, CPT  $\neq$  EIT

so we can now write the matrix:

$$= \Delta_1 - \Delta_2$$

$$\Delta E_{(g_1, g_2)} = \omega_{(a)}^2 + \omega_b^2 - \omega_1^2 = \omega_b^2 - \omega_b^2 - \Delta_2^2 + \omega_2^2 - \omega_1^2$$

$$\Delta E_{(g_1, g_2)} = \omega_b^2 - \omega_{(a)}^2 - \omega_2^2 \equiv \Delta_2$$

$$\Delta E_{(g_1, g_2)} = \omega_b^2 - \omega_1^2 \equiv \Delta_1$$

$|g_1, N_1+1, N_2\rangle$  is the other states:

so we can define energy differences between

$|e, N_1, N_2\rangle$  has to  $\omega_0$

energy of state  $|g_2\rangle$

$|g_2, N_1, N_2+1\rangle$  has  $\hbar\omega_{(a)} + \hbar\omega_2$

then  $|g_1, N_1, N_2\rangle$  has  $\hbar\omega_1$

- assume  $|g_1\rangle$  is  $a + E = 0$

we need the energies in the basis:

to write the dressed atom Hamiltonian matrix.

$$\text{or } \omega(\omega^2 + Aw + B) = 0$$

$$\omega^3 + Aw^2 + B\omega = 0$$

is

- then  $C = 0$  and the secular eq.

$$\text{resonance } \Delta_2 = \Delta_1$$

- now consider the case of Z-photon (Raman)

$$C = (\Delta_1 - \Delta_2)^{\frac{1}{2}} \Delta_1^2$$

$$B = \Delta_1 (\Delta_1 - \Delta_2) - \Delta_1^2 - \Delta_2^2$$

$$\text{where } A = -(2\Delta_1 - \Delta_2)$$

$$\omega^3 + Aw^2 + B\omega + C = 0$$

The secular equation can be written as:

Find the new eigenvalues.

we can solve the secular equation to

$$\begin{pmatrix} 0 & \Delta_2/2 & \Delta_1 - \Delta_2 \\ \Delta_2/2 & \Delta_1 & \Delta_2/2 \\ 0 & \Delta_1/2 & 0 \end{pmatrix} = H$$

(3)

$$\frac{\sqrt{a_1^2 + a_2^2}}{a_2(1g_1) - a_1(1g_2)} = \langle \alpha \rangle$$

we find

using 2) and normalization ( $a_1^2 + a_2^2 = 1$ )

$$(0=9) \quad 0 = 9^2 \cdot 0 \quad (3)$$

$$2) \quad a^{1/2} \cdot a + a^{1/2} \cdot c = 0$$

$$0 = 9 \iff 0 = 9^{\frac{1}{2}} \cdot b \quad (1)$$

plus 3 eqs.

$$(a|g_1\rangle + b|g_2\rangle + c|g_3\rangle) = 0 = \begin{pmatrix} c \\ b \\ a \end{pmatrix} \begin{pmatrix} 0 & a^{1/2} & 0 \\ a^{1/2} & 0 & b^{1/2} \\ 0 & b^{1/2} & 0 \end{pmatrix}$$

and solve for the eigenvector

Let's first consider the state with no light shift

$$\omega_{\text{ex}} = \frac{1}{2} \Delta_1 = \sqrt{\Delta_1^2 + a_1^2 + a_2^2}$$

$$\omega = 0$$

so the 3 states are

(4)

$\Rightarrow$  a "dark" state  
final state.

the excitation of the 2 states to the same  
- there is a quantum interference between

$$|\alpha\rangle = |4^{\text{NC}}\rangle$$

The state is not coupled to the excited state

$$O = \frac{\underbrace{\gamma_{22} + \gamma_{21}}_{\gamma_{12}}}{\gamma_{11}} - \frac{\underbrace{\gamma_{21} + \gamma_{12}}_{\gamma_{22}}}{\gamma_{22}}$$

$$= \langle e | \gamma \cdot E_1 | \gamma_{22} | g_1 \rangle + \langle e | \gamma \cdot E_2 | \gamma_{21} | g_2 \rangle$$

$$= \langle e | \gamma \cdot E_1 | \alpha \rangle + \langle e | \gamma \cdot E_2 | \alpha \rangle$$

$$\langle e | \gamma \cdot E_1 + E_2 | \alpha \rangle$$

calculate the excitation rate of  $|e\rangle$ :

⑤

combinations of  $|g_1\rangle$ ;  $|g_2\rangle$ .

- We have found symmetric; anti-symmetric

a different basis than  $|g_1\rangle, |g_2\rangle, |e\rangle$ .

- we are just viewing the atom from

is strongly coupled to the excited state.

$|A_e\rangle$  is the other ground state, which

$$\underbrace{|g_1\rangle + |g_2\rangle}_{|A_e\rangle} = |A_e\rangle \approx |g_1\rangle + |g_2\rangle$$

$$|B_e\rangle \approx |e\rangle$$

dimin. ( $\omega \ll \Delta$ ), we find

expressions, but in the low excited state

other 2 states. They yield more complicated

we can solve for the eigenvectors of the

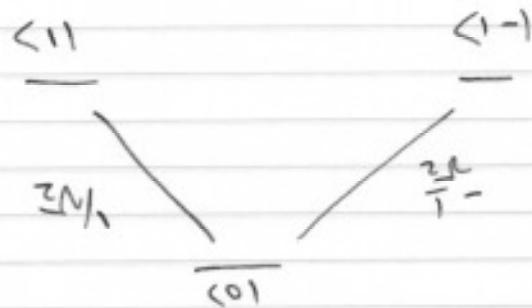


Since the C-G configuration have opposite site signs.

$$\{ \langle 1-1 + 11 \rangle \} \stackrel{\frac{1}{2}}{=} |4_{\text{NC}} \rangle$$

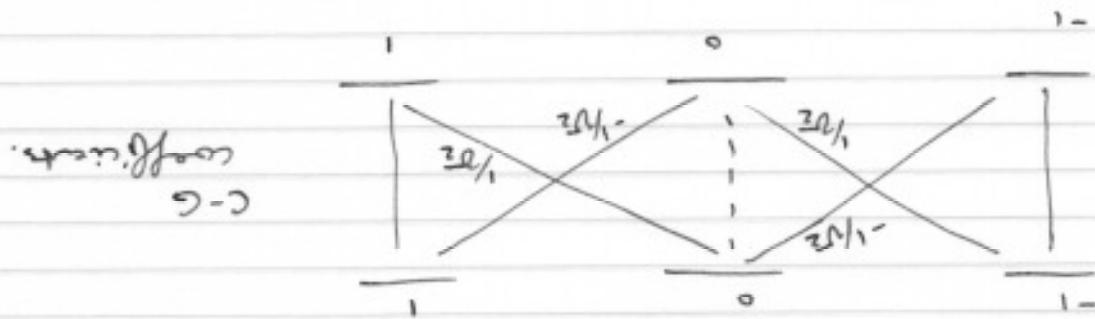
then we can clearly write

$$\text{if we assume } \sigma^+ = \sigma^-$$



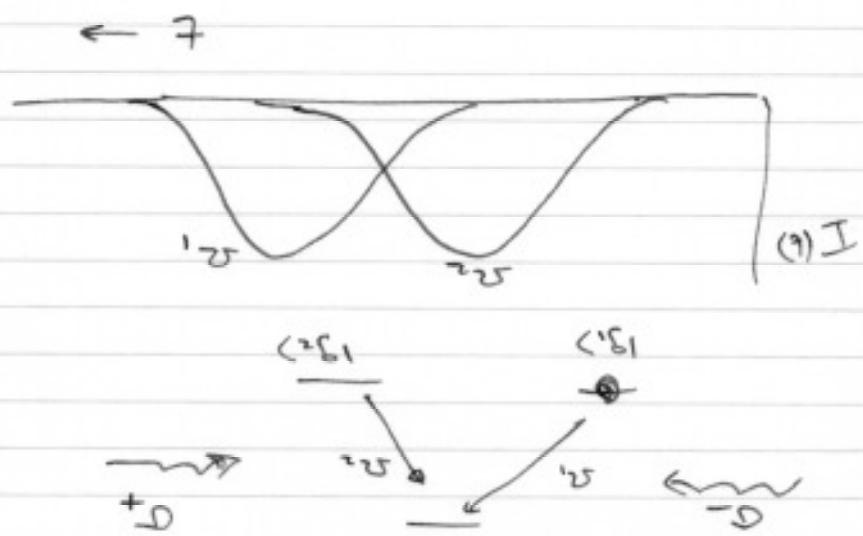
Reduces to a 3-level problem

if we apply only  $\sigma^+$  or  $\sigma^-$  operator



as an example, consider a  $\sigma^z = 1 \leftrightarrow \sigma^z = -1$  transition

II



resonant:

- can be used to adiabatic transfer

(CPT)

$\Rightarrow$  coherent population trapping

coherently pump d.c.

these 2 lasers with  $\Delta_1 = \Delta_2$ , the atom will

emission. So if we subject an atom to

if it is pumped there through spontaneous

this implies that the atom will stay there in  $|4\alpha\rangle$

which is equivalent to the excited state,

- since the non-coupled state has the



- see Goldner, et al. PRL 72 997 (1994).  
⇒ Photon redistribution

changed by  $k_2 - k_1 = 2k$  for counter-prop.

so not only did state change, but momentum

$$|g_1, N_1+1, N_2\rangle \leftrightarrow |g_2, N_1, N_2+1\rangle$$

including momentum

so atom is transferred.

$$|\psi_{NC}(t=\infty)\rangle = |\beta_2\rangle$$

in  $|\psi_{NC}\rangle$  throughout, and  $|\psi_{NC}(t=-\infty)\rangle = |\beta_1\rangle$

if the process is adiabatic, atom will stay

and finally turn off  $\Delta_1$   
then slowly turn off  $\Delta_2$

then slowly turn on  $\Delta_1$

$$|\psi_{NC}\rangle \propto \Delta_2 |g_1\rangle - \Delta_1 |g_2\rangle = |\beta_1\rangle \text{ if } \Delta_1 = 0$$

turn on  $\Delta_2$  (counter-intrusive pulse sequence)  
slowly

population initially in  $|g_1\rangle$

adiabatic transfer:



sufficient separation of the eigenvalues.

unless  $\omega_1 \neq 0$ , by which point there is

since the character of  $|4_{NC}\rangle$  does not change

so  $|4_{NC}\rangle = 0$ , and we can be adiabatic

$$|g_1\rangle = |g_1\rangle \text{ (since } \omega_1 = 0)$$

$$\sqrt{\omega_2^2 + \omega_1^2}$$

$$|\psi\rangle = \omega_2 |g_1\rangle - \omega_1 |g_2\rangle \text{ at beginning of pulse}$$

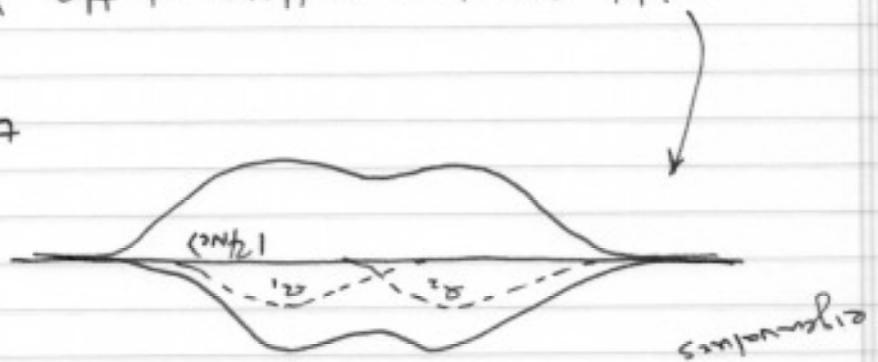
$$\langle e^* | e^* \rangle \ll \frac{\hbar}{\epsilon_3 - \epsilon_2}$$

recall adiabatic condition:

there is very little separation between eigenvalues.

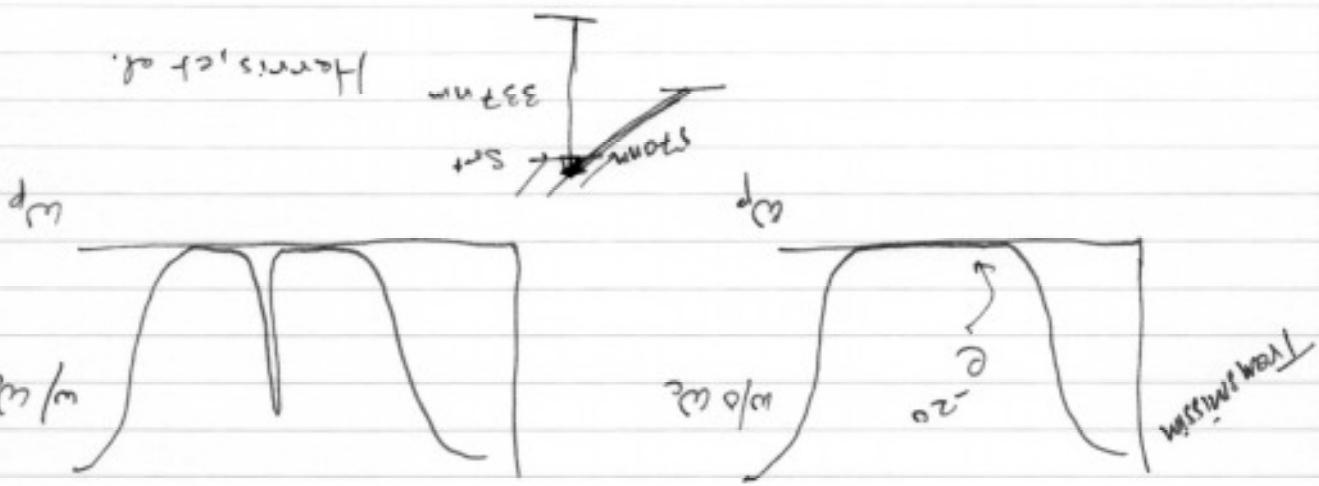
might expect a problem at the beginning where

$\omega_1$

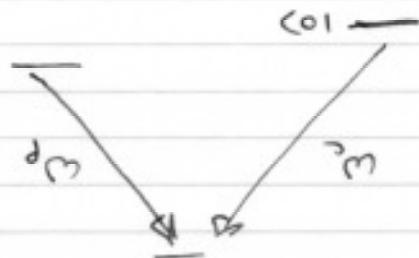
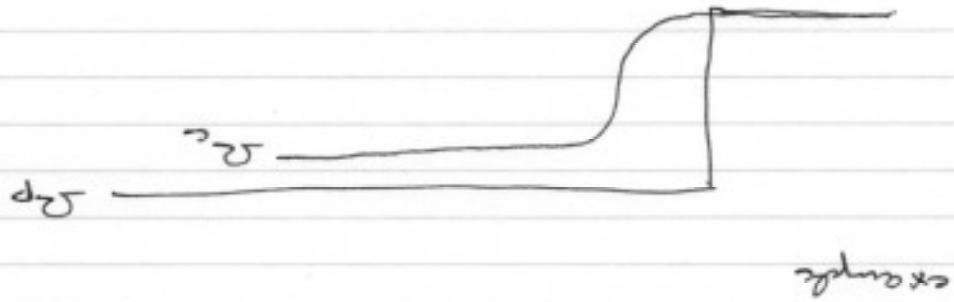


How do we know if each be adiabatic?





will put other into dark state.  
- then adiabatically turn on  $\omega_1$ , which  
turn on  $\omega_2$  (when in state 1)



(EIT)

Electromagnetically-Induced Transparency



$$v_p = \frac{1}{\Delta t} = \frac{c}{n}$$

$$k\Delta z = \omega \Delta t$$

constant phase more  $\Delta z$  in  $\Delta t$ , given by

the pulse is  $\phi = kz - \omega t$ , so points of

points of constant phase more

define grain velocity as the velocity at which

$$\text{where } k = n\omega/c$$

$$E(z, t) = A e^{i(kz - \omega t)} + \text{c.c.}$$

with refractive index  $n$

consider an EM wave propagating in a medium

- a reminder about pulse propagation:

modifying the "velocity" of light.

EIT has found another use in terms of

(in UV, VUV regime in particular).

original idea of EIT was to reduce absorption



$$v_g = c/n$$

$$v_g = n \frac{dp}{dn}$$

we can derive a group index

$$\frac{u + \frac{dp}{dn}}{c} = v_g = \text{group velocity}$$

$$t = z \left( \frac{u}{c} + \frac{dp}{dn} \right)$$

$$0 = t - \frac{z}{c} + \frac{dp}{dn} \left( \frac{u}{c} \right) \Leftarrow$$

$$\phi = \frac{mp}{\phi p} = \frac{u}{c} - ct, \text{ we want } \phi = 0$$

the pulse moves.

add in phase, which we want to be stable at

The peak of the pulse is where the Fourier components

it must be composed of a spread in frequency.

If we consider a pulse propagating in a medium,



$$\frac{\omega}{\omega_{\max}} - 1 \leftarrow$$



$$\left[ \left( \frac{\omega}{\omega_0} - \frac{(\omega_0 + \omega)}{2\omega_0} \right)^2 + \frac{\omega^2}{\omega_0^2} \right]^{-1/2} = 1 + 2 \sin \left[ \frac{\omega}{\omega_0} \right]$$

$$n = n_0 + \frac{\omega^2}{\omega_0^2}$$

thus the group index can be written as:

where  $\omega_{\max} \propto D.P.$  ( $\propto$   $\omega_0$  directly)

$$\text{and the imaginary part } K = \omega_{\max} \frac{\omega^2}{(\omega_0 - \omega)^2 + \omega^2}$$

$$\text{the real part } n = 1 + \frac{\omega_{\max}^2}{2} \frac{(\omega_0 - \omega)^2}{(\omega_0 - \omega)^2 + \omega^2}$$

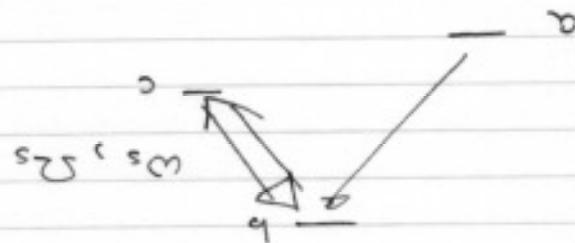
and imaginary parts of the index of refraction.

recall for a single resonance, we get real

as Hau et al. Nature 397, 594 (1999).

$$n_g = \frac{8\pi \omega N D_{ab}^2}{\pi R_s^2}$$

size of 3-layer eggs, yields:



— enter EIT, which can remove absorption.

But absorption coefficient  $\alpha \sim 10^4 \text{ cm}^{-1}$

$$n_{abs} = 50000 \quad \leftarrow$$

$$1 - S = 10^{-6}$$

$$S_{abs} = 0.1$$

$$1 - S = 5 \times 10^{-6}$$

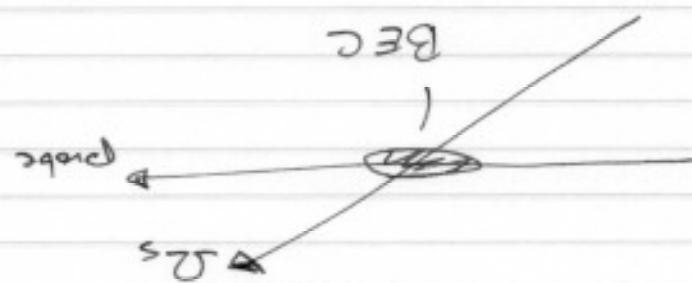
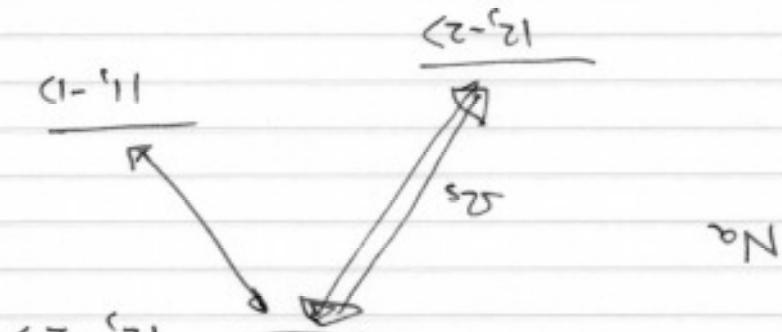
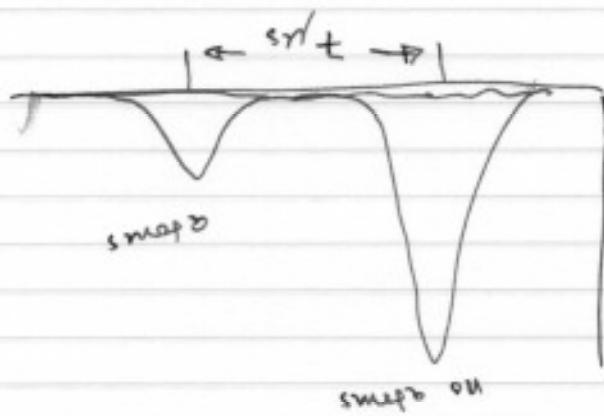
typical values



in the medium by  $c/\sqrt{\gamma}$   
 Note: this also compresses the pulse

$$v_g = \sqrt{\gamma} c \approx 33 \text{ m/s}$$

in  $230 \mu\text{s}$  long cloud



vapor  
 in thermal  
 co-propagation  
 due  
 can be  
 problems  
 avoid Doppler  
 BEC &  
 use of

- just stopped in the others.
- the light was not stopped - it was of the 2 atomic levels.
- information is stored in the coherence photons have disappeared, and the who can, up to simulated environment
- what has happened?

and the light can be extracted.  
turning back on  $\Sigma_2$ 's reherses coupling

- then  $U_2 = C$  and light is "stopped"
- 3) when completely coupled in medium,
- 2) set in weak pulse field pulse
- 1) same form as strong  $\Sigma_2$

recall  $U_2 \propto \Sigma_2^2$

Hau, et al. Nature 409 490 (2000).

: "stopped" light,



- shopping bags + may be useful for quantum information storage.

dark-light  
- consequence to a mixture of photons  
of atomic polarization, governed by

- eigenstates of the Hawaiian with  
dark-light polarizations

see Fischauer; Lekin PRL 84 5094(2000).

- a nice viewpoint - polaritons

