Atoms and photons

Illustrations for Chapter 2

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October 12, 2022

Ramsey fringes

Cs microwave clock transition

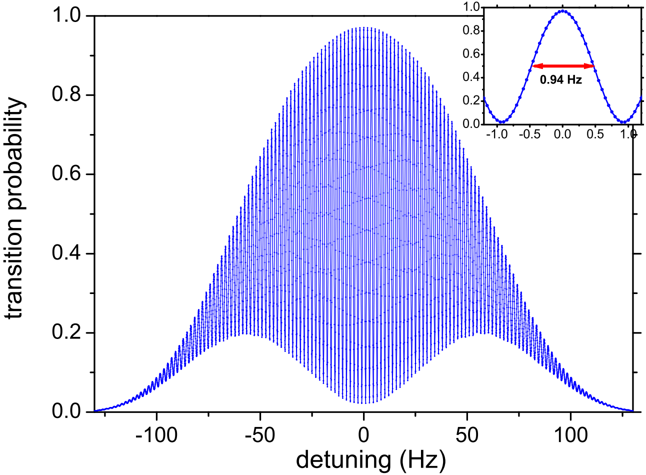
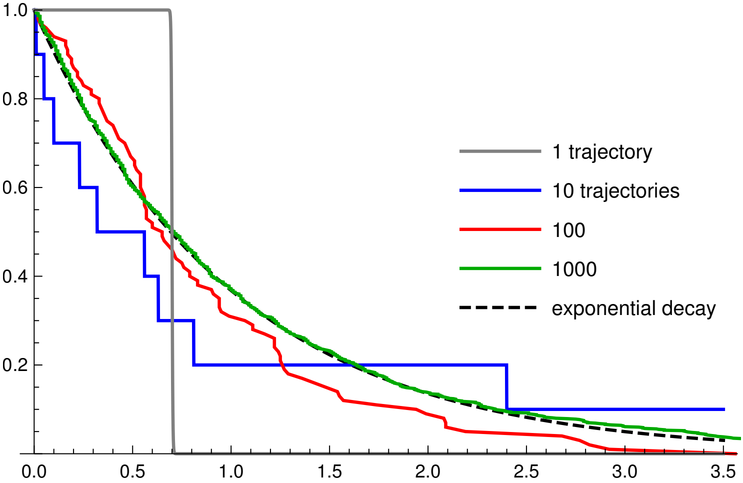


Figure from S. Bize et al., J. Phys. B: At. Mol. Opt. Phys. **38** S449 (2005)

Quantum Monte-Carlo simulation

Decay of an excited state



Optical Bloch equations

For X, Y, Z

OBE for the Bloch vector $\mathrm{r} = (X, Y, Z)$

$$\frac{dX}{dt} = \Delta Y - \Omega'' Z - \gamma' X \quad (1)$$

$$\frac{dY}{dt} = -\Delta X - \Omega' Z - \gamma' Y \quad (2)$$

$$\frac{dZ}{dt} = \Omega'' X + \Omega' Y - \Gamma(1 + Z) \quad (3)$$

Study of a useful case:

- Initial state $|g\rangle$: $Z(0) = -1$, $X(0) = Y(0) = 0$
- Ω real: $\Omega' = \Omega$, $\Omega'' = 0$
- On resonance $\Delta = 0$

$$\Rightarrow X(t) = 0$$

Rabi oscillations from Optical Bloch equations

Dynamics

- Equations for Z, Y:

$$\frac{dZ}{dt} = \Omega Y - \Gamma(1+Z) \quad (4)$$

$$\frac{dY}{dt} = -\Omega Z - \gamma' Y \quad (5)$$

- It follows that $\frac{dZ}{dt}(0) = 0$.
- Equation for Z:

$$\frac{d^2 Z}{dt^2} + (\Gamma + \gamma')\frac{dZ}{dt} + (\Omega^2 + \Gamma\gamma')Z = -\Gamma\gamma' \quad (6)$$

Rabi oscillations from Optical Bloch equations

Two regimes

$$\frac{d^2Z}{dt^2} + (\Gamma + \gamma')\frac{dZ}{dt} + (\Omega^2 + \Gamma\gamma')Z = -\Gamma\gamma'$$

- $\Omega > \frac{|\Gamma - \gamma'|}{2}$: Damped oscillations
  Oscillation frequency $\Omega' = \sqrt{\Omega^2 - \frac{(\Gamma - \gamma')^2}{4}}$
  Damping at $\Gamma'/2$ where $\Gamma' = \Gamma + \gamma'$
- $\Omega < \frac{|\Gamma - \gamma'|}{2}$: Exponential decay at

$$\Gamma_\pm = \frac{\Gamma'}{2} \pm \sqrt{\frac{(\Gamma - \gamma')^2}{4} - \Omega^2} \tag{7}$$

Rabi oscillations from Optical Bloch equations

Steady state

$$\frac{d^2Z}{dt^2} + (\Gamma + \gamma')\frac{dZ}{dt} + (\Omega^2 + \Gamma\gamma')Z = -\Gamma\gamma'$$

- Steady state:

$$Z_s = -\frac{\Gamma\gamma'}{\Omega^2 + \Gamma\gamma'} \quad (8)$$

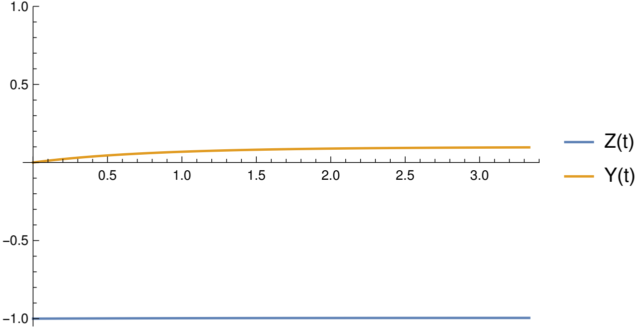
$$Y_s = \frac{\Omega\Gamma}{\Omega^2 + \Gamma\gamma'} \quad (9)$$

Rabi oscillations from Optical Bloch equations

Small coupling limit

We take $\gamma = 0$, $\gamma' = \Gamma/2$.

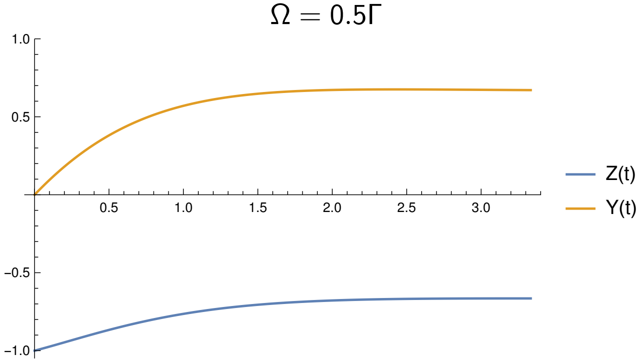
$\Omega = 0.05\Gamma$



Rabi oscillations from Optical Bloch equations

Close to critical coupling

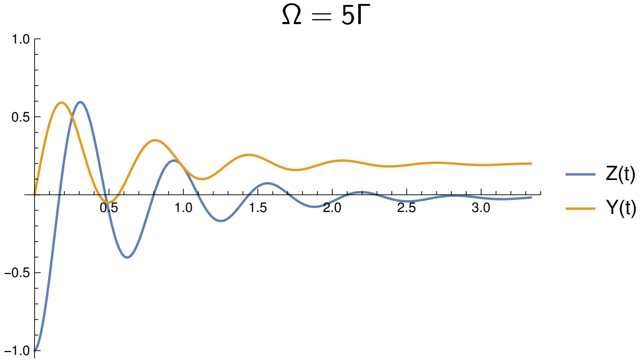
We take $\gamma = 0$, $\gamma' = \Gamma/2$.



Rabi oscillations from Optical Bloch equations

Medium coupling

We take $\gamma = 0$, $\gamma' = \Gamma/2$.

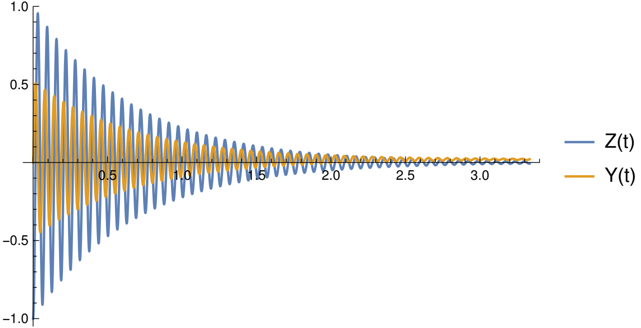


Rabi oscillations from Optical Bloch equations

Strong coupling limit

We take $\gamma = 0$, $\gamma' = \Gamma/2$.

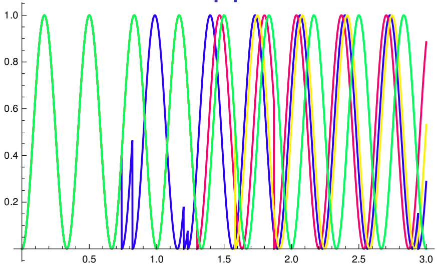
$\Omega = 50\Gamma$



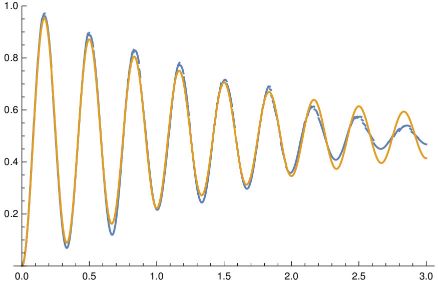
Damped Rabi oscillations from QMC approach

Link with quantum jumps:

5 trajectories

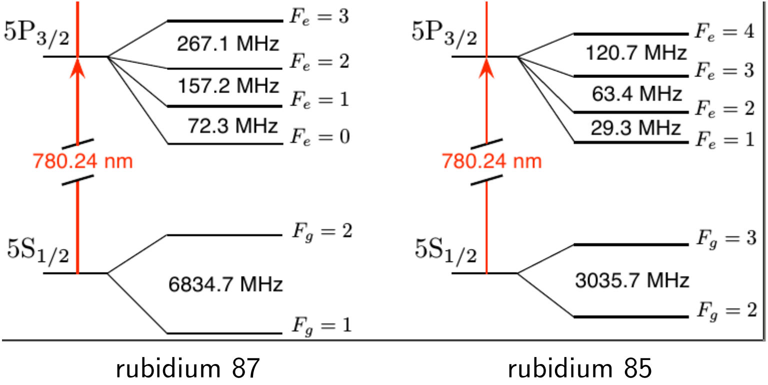


average over 100 trajectories



Saturated absorption spectroscopy

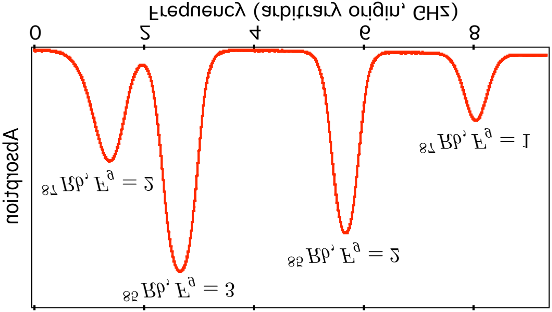
Level structure of rubidium



Saturated absorption spectroscopy

Linear spectrum (intensity on the detector)

Expected linewidth: $\dfrac{\Gamma}{2\pi} = 6$ MHz



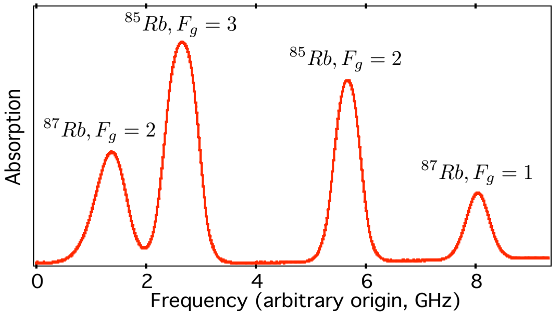
Doppler broadening: Gaussian with $\sigma_\nu = \frac{1}{\lambda}\sqrt{\frac{k_B T}{M}} = 217$ MHz

Figure from V. Jacques et al., Eur. J. Phys. **30**, 921 (2009).

Saturated absorption spectroscopy

Linear spectrum (relative absorption)

Expected linewidth: $\dfrac{\Gamma}{2\pi} = 6$ MHz

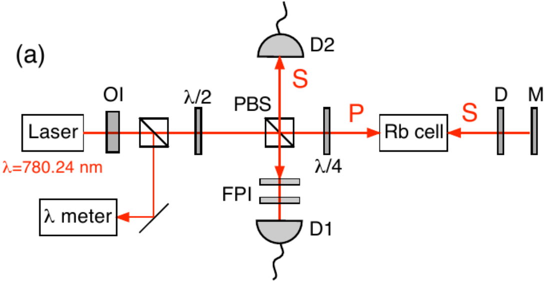


Doppler broadening: Gaussian with $\sigma_\nu = \frac{1}{\lambda}\sqrt{\frac{k_B T}{M}} = 217$ MHz

Figure from V. Jacques et al., Eur. J. Phys. **30**, 921 (2009).

Saturated absorption spectroscopy

Setup



Saturated absorption setup

Resonance for $\Delta = \pm kv$

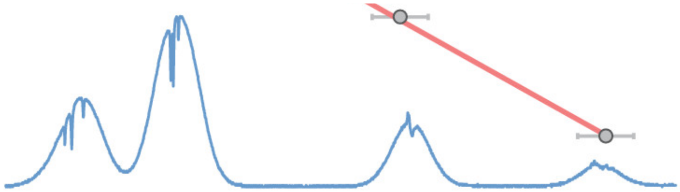
The velocity class $v = 0$ sees twice the intensity with respect to $v \neq 0$

$\Rightarrow$ reduced absorption for $\Delta = 0$

Figure from V. Jacques et al., Eur. J. Phys. **30**, 921 (2009).

Saturated absorption spectroscopy

Spectrum

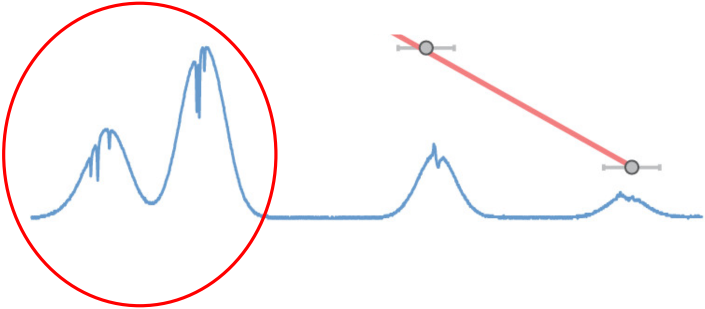


Saturated absorption spectroscopy: how many dips?

Figure from J. D. White and R. E. Scholten, Rev. Sci. Instr. **83**, 113104 (2012)

Saturated absorption spectroscopy

Spectrum

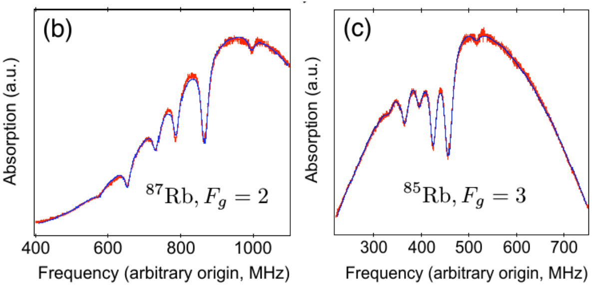


Saturated absorption spectroscopy: how many dips?

Figure from J. D. White and R. E. Scholten, Rev. Sci. Instr. **83**, 113104 (2012)

Saturated absorption spectroscopy

Spectrum: zoom on two lines



$^{87}Rb,\ F = 2 \rightarrow F'$ $\quad$ $^{85}Rb,\ F = 3 \rightarrow F'$

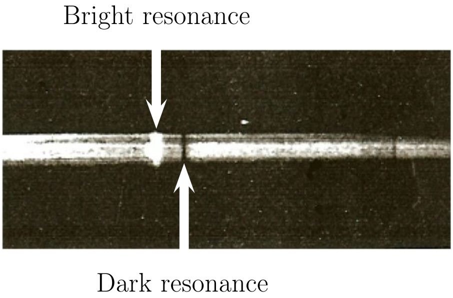
6 narrow lines for each main line!

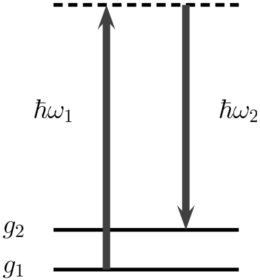
- $v = 0$: 3 dips for the 3 real lines
- $kv = \frac{\omega_1 + \omega_2}{2}$: a dip in between each pair of resonance lines

Figure from V. Jacques et al., Eur. J. Phys. **30**, 921 (2009).

Dark resonances

Observation in a sodium vapor

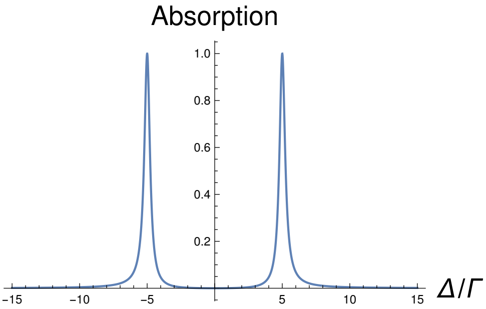




Arimondo/Allegrini group [Alzetta et al. 1976]

Electromagnetically Induced transparency (EIT)

Absorption spectrum at high power

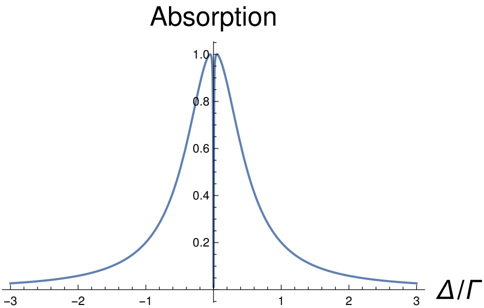


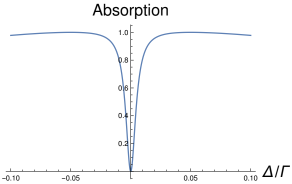
$$\Omega_2 = 10\ \Gamma$$

Autler-Townes splitting: two peaks split by Ω_2

Electromagnetically Induced transparency (EIT)

Absorption spectrum at low power





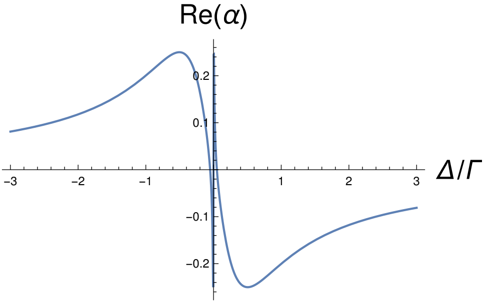
zoom

$$\Omega_2 = 0.1\ \Gamma$$

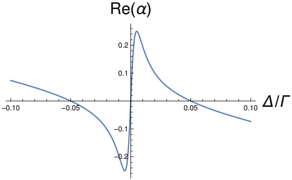
EIT: narrow dark window without absorption.

Electromagnetically Induced transparency (EIT)

Real part of polarizability



$\alpha'(\Delta)$



zoom

EIT: very large derivative of the real part of α.