Physics 566 – Quantum Optics

Problem Set #2 – Solutions

Problem 1

Two level atom. In RWA (in rotating frame)

$$\hat{H}_{eff} = -\frac{\hbar\Delta}{2}\hat{\sigma}_z - \frac{\hbar\Omega}{2}\hat{\sigma}_x = -\frac{\hbar}{2}\vec{\Omega}\cdot\hat{\vec{\sigma}}$$

$$\vec{\Omega} = \Delta\vec{e}_z + \Omega\vec{e}_x = \tilde{\Omega}\,\vec{e}_n$$

$$\tilde{\Omega} = \sqrt{\Omega^2+\Delta^2} \qquad \vec{e}_n = \cos\theta\,\vec{e}_z + \sin\theta\,\vec{e}_x \qquad \cos\theta = \frac{\Delta}{\tilde{\Omega}}$$

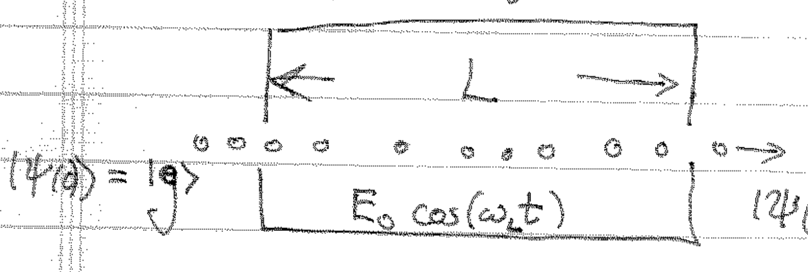
$$\sin\theta = \Omega/\tilde{\Omega}$$

Unitary evolution (in rotating frame)

$$\hat{U}(t) = e^{-i\hat{H}_{eff}t/\hbar} = e^{i\frac{\tilde{\Omega}t}{2}\hat{\sigma}_n} = \cos\left(\frac{\tilde{\Omega}t}{2}\right)\hat{\mathbb{1}} + i\sin\left(\frac{\tilde{\Omega}t}{2}\right)\hat{\sigma}_n$$

$$= \cos\left(\frac{\tilde{\Omega}t}{2}\right)\hat{\mathbb{1}} + i\sin\frac{\tilde{\Omega}t}{2}\left(\cos\theta\,\hat{\sigma}_z + \sin\theta\,\hat{\sigma}_x\right)$$

(i) Rabi geometry



$$\Omega = d_{eg}E_0/\hbar$$

(a) Mono-energic beam with velocity v, length chosen such that $\Omega\frac{L}{v} = \pi$ (i.e. π-pulse for atoms on resonance)

Now we have the Rabi solution:

$$|\psi(t)\rangle = \hat{U}(t)\,|g\rangle =$$

$$= \left(\cos\left(\frac{\tilde{\Omega} t}{2}\right) - i\cos\theta\,\sin\left(\frac{\tilde{\Omega} t}{2}\right)\right)|g\rangle + i\sin\theta\,\sin\frac{\tilde{\Omega} t}{2}\,|e\rangle$$

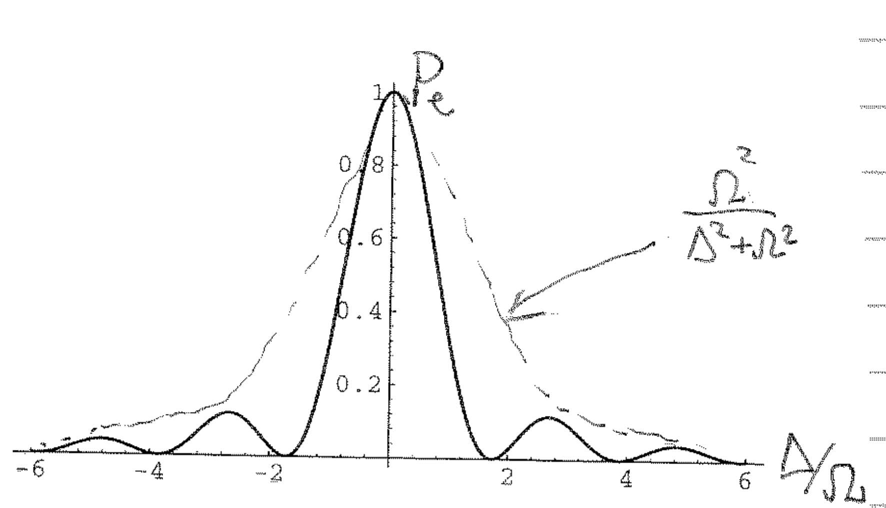
Thus the probability to be in the excited state after a time $t = \frac{L}{v}$ is

$$P_e = \sin^2\theta\,\sin^2\left(\frac{\tilde{\Omega} L}{2v}\right) = \frac{\Omega^2}{\Delta^2 + \Omega^2}\,\sin^2\left(\frac{\sqrt{\Omega^2+\Delta^2}\,L}{2v}\right)$$

$$\Rightarrow \boxed{P_e = \frac{1}{1+\left(\frac{\Delta}{\Omega}\right)^2}\,\sin^2\left(\left(1+\frac{\Delta^2}{\Omega^2}\right)^{1/2}\frac{\pi}{4}\right)}$$

(where I used $\Omega L/v = \pi$

Plot of P_e as a function of $\Delta = \omega_L - \omega_{eg}$ in units of Ω



Linewidth $\Delta\omega \sim \Omega = \frac{\pi}{T}$ where $T = \frac{L}{v}$

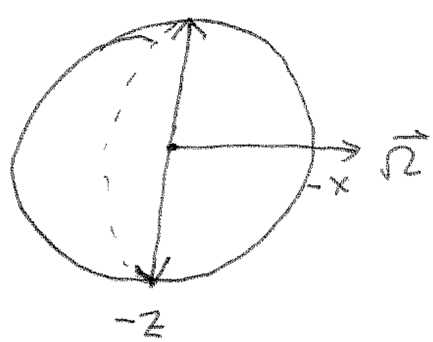
(d) Continued

We see that the linewidth is on the order

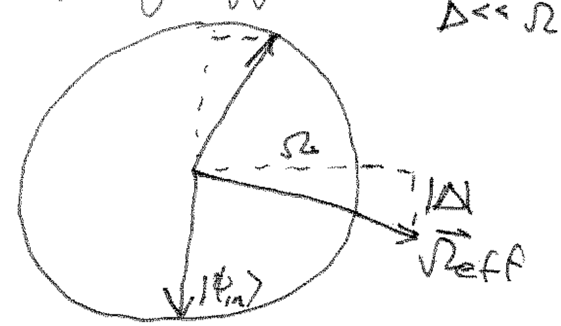
$$\Delta\omega \cong \Omega = \frac{\pi}{T} \quad \text{where} \quad T = \frac{L}{v} = \text{interaction t}$$

On the Bloch-sphere

Resonance $\Delta = 0$



Slightly off-resonance $\Delta \ll \Omega$



$$\vec{\Omega}_{eff} = \Omega \vec{e}_x + \Delta \vec{e}_z$$

From simple geometry we see that $P_e = \left| \frac{\Omega}{\sqrt{\Delta^2 + \Omega^2}} \right|^2$ (for $\tilde{\Omega} T = \pi$)

It is clear from these sketches that when Δ is on the order of Ω population transfer to the excited state decreases substantially. Since we have fixed $\Omega T = \pi$ we get the most sensity to Δ by making T longer and thus Ω smaller

(b) Now suppose the atoms have a distribution of velocities characteristic of thermal beams

$$f(v) = 2\frac{v^3}{v_0^4} e^{-\frac{v^2}{v_0^2}} \quad \text{where} \quad v_0 = \sqrt{\frac{2k_BT}{m}}$$

Note: for this distribution

- Most probable velocity: $v_p = 1.22\, v_0$
- Average velocity: $\bar{v} = 1.33\, v_0$
- rms velocity: $\sqrt{\Delta v^2} = 1.42\, v_2$

We have for a fixed velocity and detuning

$$P_e(\Delta, v) = \frac{1}{1+\left(\frac{\Delta}{\Omega}\right)^2} \sin^2\left(\left(1+\frac{\Delta^2}{\Omega^2}\right)^{1/2}\frac{\Omega L}{2v}\right)$$

At zero detuning (on resonance): $P_e(0,v) = \sin^2\left(\frac{L\Omega}{2v}\right)$

Now we must average over the velocity distribution:

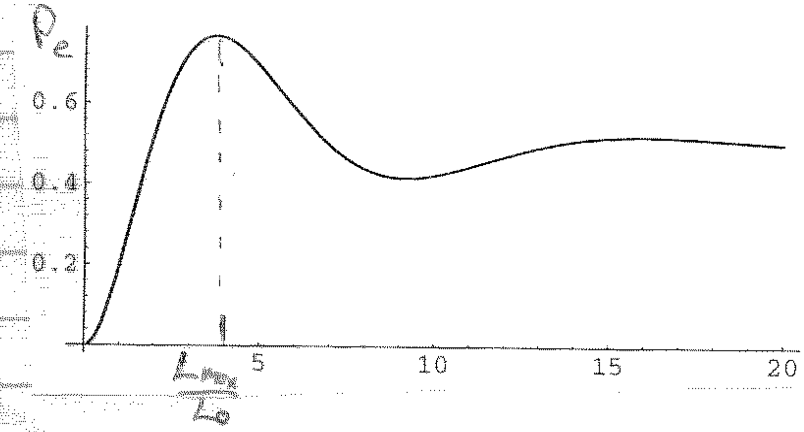
$$P_e = \int_0^\infty dv\, f(v)\, P_e(0,v) = \int_0^\infty dx\, f(x)\, \sin^2\left(\frac{\theta_0}{2x}\right)$$

where $x \equiv \frac{v}{v_0}$ (dimensionless velocity)

and $\theta_0 \equiv \frac{\Omega L}{v_0}$ (Angle turned by the Bloch vector for atoms traveling at v_0 and ω_L on resonance)

Note: Always reëxpress in terms of dimensionless variables

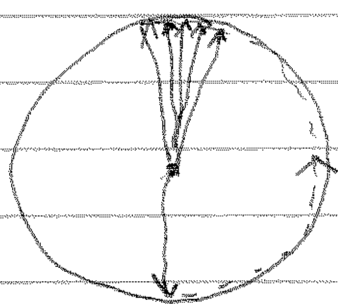
Plot (calculated with Mathematica)



$\frac{L}{L_0}$ $\left(L_0 = \frac{v_0}{\Omega_L}\right)$

The maximum P_e occurs at $\Theta_0 = \frac{\Omega_L L_{max}}{v_0} \approx 3.77$ or $\frac{\Omega_L L_{max}}{v_0} \approx 1.20\pi$. We can understand this from the fact that the most probable speed is $v_p \cong 1.2\, v_0 \Rightarrow \frac{\Omega_L L_{max}}{v_p} \approx \pi$

~~Also~~ On the Bloch-sphere:



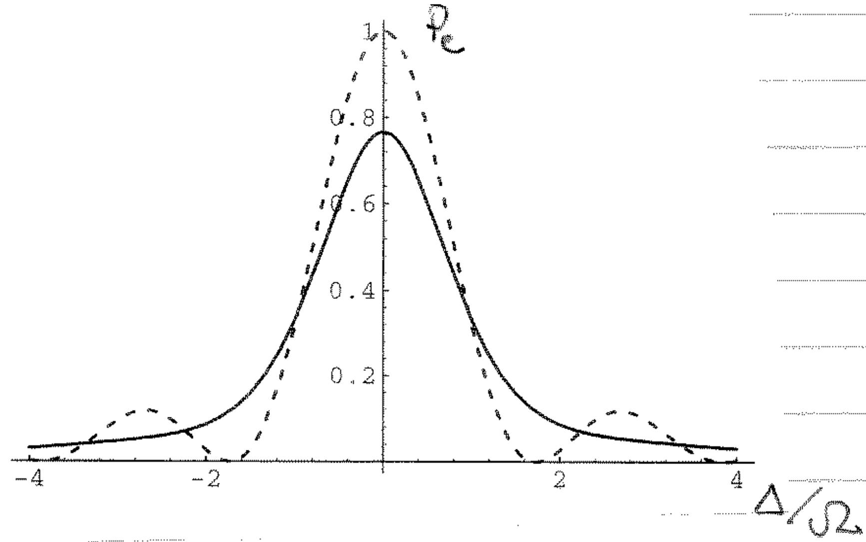
Distribution of velocities
⇒ Distribution of interaction times
⇒ Distribution of rotation angles

This is an example of "inhomogeneous" broadening. The "damped" Rabi oscillations plotted above are not due to dissipation. Rather they are due to the spread in rotation angle due to an inhomogeneity in the sample (here velocity).

Now set $\theta_0 = 1.2\pi \approx 3.8$, and $\Delta \neq 0$

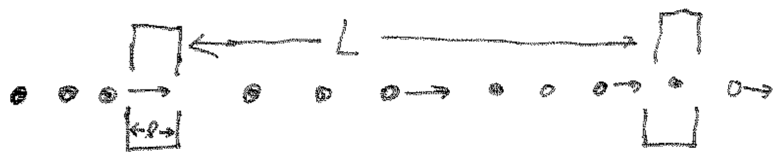
$$\Rightarrow P_e = \frac{1}{1+\left(\frac{\Delta}{\Omega}\right)^2} \int_0^\infty \sin^2\left(\left(1+\frac{\Delta^2}{\Omega^2}\right)^{1/2} \frac{\theta_0}{2} \frac{1}{x}\right) \left(2x^3 e^{-x^2}\right) dx$$

Plot as a function of Δ/Ω with $L = L_{max}$
(Solid curve)



For reference I have added the curve for mono-energetic atom (dashed curve). We see that the spread in velocities leads to a broadening of the resonance lineshape.

(ii) Ramsey separated zone method



(c) Given $|\psi(0)\rangle = |g\rangle$ and $|\Delta| \ll \Omega$

In the interaction regions: $\tilde{\Omega} \cong \Omega \qquad \Theta \approx \pi/2$

$$\hat{U}_{int}(t) \cong \cos\left(\frac{\Omega t}{2}\right)\hat{\mathbb{1}} + i\sin\left(\frac{\Omega t}{2}\right)\hat{\sigma}_x = e^{i\frac{\Omega t}{2}\hat{\sigma}_x}$$

In the free zone: $\tilde{\Omega} = \Delta \qquad \Theta = 0$

$$\hat{U}_{free}(t) = \cos\left(\frac{\Delta t}{2}\right)\hat{\mathbb{1}} + i\sin\frac{\Delta t}{2}\,\hat{\sigma}_z = e^{i\Delta t/2\,\hat{\sigma}_z}$$

(free precession about $-\vec{e}_z$ axis with frequency Δ (in the rotating frame)

$$\therefore\ |\psi(\tau = \tfrac{\ell}{v})\rangle = \cos\left(\frac{\Omega\tau}{2}\right)|g\rangle + i\sin\left(\frac{\Omega\tau}{2}\right)|e\rangle$$

$$= \frac{1}{\sqrt{2}}\left(|g\rangle + i|e\rangle\right)$$

$T = \frac{L}{v}$ $$|\psi(\tau + T)\rangle = \hat{U}_{free}(T)\,|\psi(\tau)\rangle = \frac{1}{\sqrt{2}}\left(e^{-i\Delta T/2}|g\rangle + ie^{i\Delta T/2}|e\rangle\right)$$

$$= \frac{1}{\sqrt{2}}\left(e^{-i\frac{\Delta L}{2v}}|g\rangle + ie^{i\frac{\Delta L}{2v}}|e\rangle\right)$$

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$$|\psi(2\tau+T)\rangle = \hat{U}_{int}(\tau)\,|\psi(\tau+T)\rangle$$

$$= \frac{1}{\sqrt{2}}\left(e^{-i\frac{\Delta L}{2v}}\,\hat{U}_{int}(\tau)|g\rangle + i e^{i\frac{\Delta L}{2v}}\,\hat{U}_{int}(\tau)|e\rangle\right)$$

$$= \frac{1}{\sqrt{2}}\left(e^{-i\frac{\Delta L}{2v}}\frac{1}{\sqrt{2}}(|g\rangle + i|e\rangle) + i\frac{e^{i\frac{\Delta L}{2v}}}{\sqrt{2}}(|e\rangle + i|g\rangle)\right)$$

$$= \frac{1}{2}\left(e^{-i\frac{\Delta L}{2v}} - e^{i\frac{\Delta L}{2v}}\right)|g\rangle + \frac{i}{2}\left(e^{i\frac{\Delta L}{2v}} + e^{-i\frac{\Delta L}{2v}}\right)|e\rangle$$

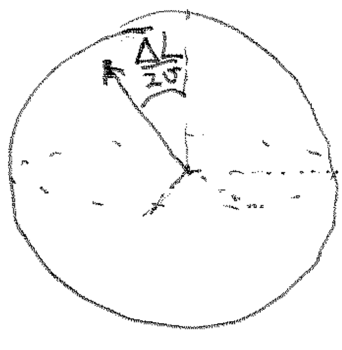
$$\Rightarrow \boxed{|\psi(2\tau+T)\rangle = -i\sin\left(\frac{\Delta L}{2v}\right)|g\rangle + i\cos\left(\frac{\Delta L}{2v}\right)|e\rangle}$$

Bloch sphere in Rotating Frame

$|\psi(0)\rangle$ $\qquad$ $|\psi(\tau)\rangle$ $\qquad$ $|\psi(\tau+T)\rangle$

angle of precession $\Delta \cdot T$

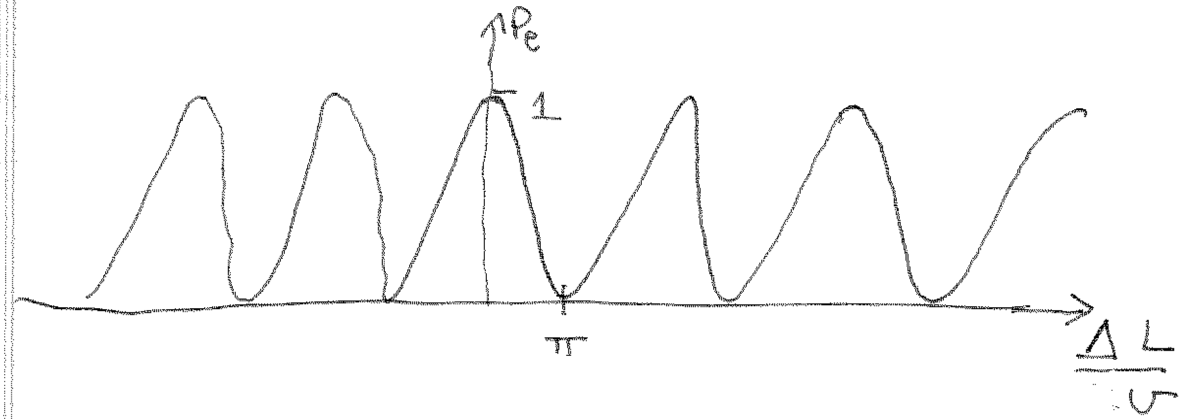
$\Longrightarrow$ Final zone



$|\psi(2\tau+T)\rangle$

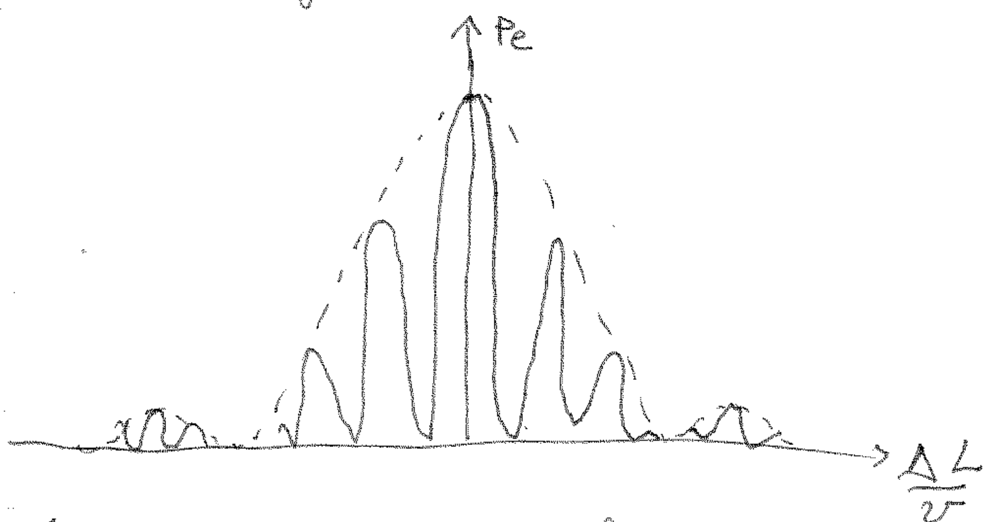
Final vector rotated towards north-pole. Final angle $\theta = \pi - \frac{\Delta L}{2v}$

(d) $P_e(t_{Final}) = \cos^2\left(\frac{\Delta L}{2v}\right)$



This is known as "Ramsey fringes"

<u>Note</u>: We have assumed $\Delta \ll \Omega$. For the general solution we would have

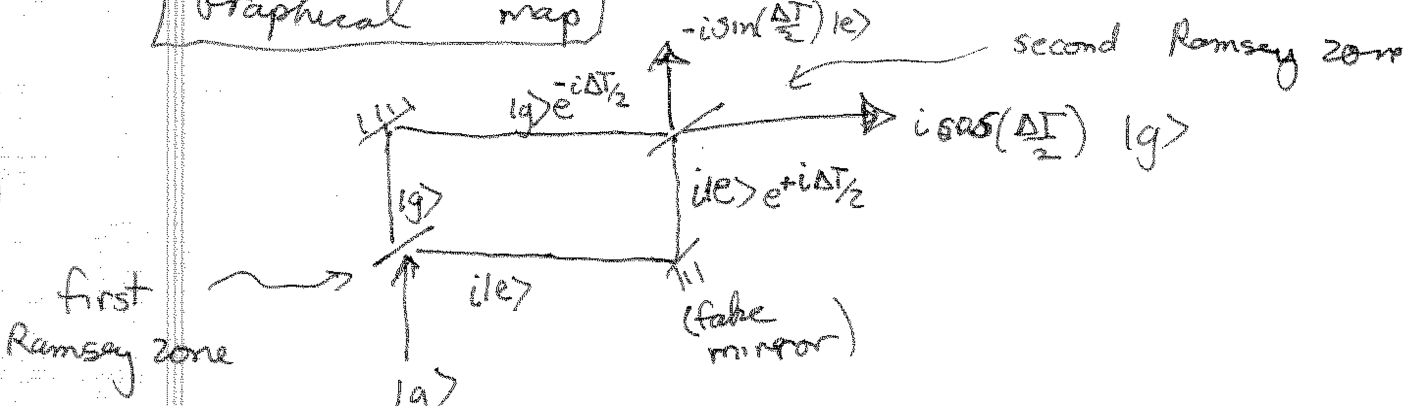


The envelope of the fringe pattern is the Rabi pattern of part (a) due to the transit time brodening of width $\Delta\omega \sim \frac{v}{l}$

The fringes themselves have a width on the order $\Delta\omega \sim \frac{v}{L}$ which can be much smaller

(e) It is clear from the plots of part (d) the the Ramsey geometry results in a kind of interference pattern. We can think of the two "branches" of the wavefunction, $|e\rangle$ or $|g\rangle$, as the two "arms" of an interferometer. The Ramsey zones produce $\pi/2$ pulse are like "beam splitters". In the free interaction zone the two branches of the interferometer pick up a relative phase of ΔT.

$\boxed{\text{Graphical map}}$



The key to the Ramsey ~~meath~~ meathod is to make T as big as possible. Then we can measure extremely small detunings Δ because a measurable phase will accumulate (shown in the third mapping on the Bloch sphere) This is the basic physics behind the atomic clock. The idea is to lock a "local oscillator" to to the natural oscillation of a two level atom (Two hyperfine levels of cesium). When the frequency of the oscillator is on resonance we're there!

Physics 566

Problem 2: Spin Precession in a magnetic field (10 points)

Consider a spin 1/2 particle such as an electron. It possesses an intrinsic magnetic moment described by the operator

$$\hat{\vec{\mu}} = \gamma_s \hat{\vec{S}}$$

where γ_s is "gyromagnetic ratio", and $\hat{\vec{S}}$ is the spin angular momentum operator. When placed in a magnetic field, the interaction Hamiltonian is given by

$$\hat{H} = -\hat{\vec{\mu}} \cdot \vec{B} = -\gamma_s \vec{B} \cdot \hat{\vec{S}} = -\gamma_s \sum_{j=1}^{3} B_j \hat{S}_j$$

(a) Let us consider the dynamics in the Heisenberg picture. The equation of motion for the i^{th} component of spin is:

$$\frac{d}{dt}\hat{S}_i = \frac{1}{i\hbar}[\hat{S}_i, \hat{H}] = \frac{1}{i\hbar}\left[\hat{S}_i, -\gamma_s \sum_{j=1}^{3} B_j \hat{S}_j\right]$$

$$\underset{\text{Linearity}}{=} -\frac{\gamma_s}{i\hbar}\sum_{j=1}^{3} B_j \underbrace{[\hat{S}_i, \hat{S}_j]}_{\sum_{k=1}^{3} i\hbar\epsilon_{ijk}\hat{S}_k} = -\sum_{j,k=1}^{3} \gamma_s \underset{\epsilon_{ijk}}{B_j} \hat{S}_k$$

Aside

Recall rule: $(\vec{A}\times\vec{B})_i = \sum_{j,k=1}^{3} \epsilon_{ijk} A_j B_k$

$$\Rightarrow \boxed{\frac{d}{dt}\hat{\vec{S}} = -\vec{\Omega}\times\hat{\vec{S}}} \quad \text{where } \boxed{\vec{\Omega} = \gamma_s \vec{B}}$$

Problem 2

(b) In spherical basis:

$$\hat{H} = -\gamma_S \vec{B}\cdot\hat{\vec{S}} = -\frac{\hbar\gamma_S}{2}\vec{B}\cdot\hat{\vec{\sigma}} = -\frac{\hbar\vec{\Omega}}{2}\cdot\hat{\vec{\sigma}}$$

$$= -\frac{\hbar}{2}\left(\Omega_- \hat{\sigma}_+ + \Omega_+ \hat{\sigma}_- + \Omega_z \hat{\sigma}_z\right)$$

where $\Omega_\pm \equiv \Omega_x \pm i\Omega_y \qquad \hat{\sigma}_\pm = \frac{\hat{\sigma}_x \pm i\hat{\sigma}_y}{2}$

Commutation relations $[\hat{\sigma}_z, \hat{\sigma}_\pm] = \pm 2\hat{\sigma}_\pm$

$[\hat{\sigma}_+, \hat{\sigma}_-] = \hat{\sigma}_z$

Heisenberg equations of motion:

$$\boxed{\dot{\hat{\sigma}}_z = -\frac{i}{\hbar}[\hat{\sigma}_z, \hat{H}] = i(\Omega_- \hat{\sigma}_+ - \Omega_+ \hat{\sigma}_-)}$$

$$\dot{\hat{\sigma}}_+ = -\frac{i}{\hbar}[\hat{\sigma}_+, \hat{H}] = \frac{i}{2}\left([\hat{\sigma}_+, \hat{\sigma}_-]\Omega_+ + [\hat{\sigma}_+, \hat{\sigma}_z]\Omega_z\right)$$

$$\boxed{\dot{\hat{\sigma}}_+ = \frac{i}{2}\Omega_+ \hat{\sigma}_z - i\Omega_z \hat{\sigma}_+}$$

Note: In the standard RWA Hamiltonian

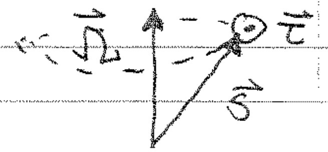
$\Omega_+ = \Omega_- = \Omega$ (Rabi freq) $\qquad \Omega_z = -\Delta$ (detuning

$$\Rightarrow \dot{\hat{\sigma}}_z = i\Omega(\hat{\sigma}_+ - \hat{\sigma}_-) \Rightarrow \langle\hat{\sigma}_z\rangle = w(t)$$

$$\dot{\hat{\sigma}}_+ = i\frac{\Omega}{2}\hat{\sigma}_z + i\Delta\hat{\sigma}_+ \Rightarrow \langle\hat{\sigma}_+\rangle = u(t) + iv(t)$$

Physically: If $\hat{\vec{S}}$ were interpreted as a classical angular momentum vector then

$$\frac{d}{dt}\vec{S} = \vec{\tau} = \text{torque} = -\vec{\Omega} \times \vec{S}$$



Since $\vec{\tau} \perp \vec{S}$, $\vec{S}$ does not change length but instead, direction $\Rightarrow$ $\vec{S}$ presesses about $-\vec{\Omega}$

Classically, this is what we expect for a classical magnetic moment in a static $\vec{B}$ field. In that case the torque is $\vec{\tau} = \vec{\mu} \times \vec{B} = \gamma \vec{L} \times \vec{B}$

$$\Rightarrow \frac{d\vec{L}}{dt} = \vec{\tau} = \vec{\mu} \times \vec{B} = \gamma \vec{L} \times \vec{B} = -\gamma \vec{B} \times \vec{L} = -\vec{\Omega} \times \vec{L}$$

The precession frequency $\Omega = \gamma B$ is known as the Larmor frequency

(6) Solving for $\hat{\vec{S}}(t)$: Take second derivative assuming static $\vec{B}$ field

$$\frac{d^2}{dt^2}\hat{\vec{S}} = -\vec{\Omega} \times \frac{d\hat{\vec{S}}}{dt} = \vec{\Omega} \times (\vec{\Omega} \times \frac{d\hat{\vec{S}}}{dt}) = \vec{\Omega}(\vec{\Omega} \cdot \vec{S}) - \Omega^2 \vec{S}$$

For the case $\vec{\Omega} = \Omega \vec{e}_z$ (magnetic field in z-direction)

$$\frac{d\hat{S}_x}{dt} = -\Omega \hat{S}_y \qquad \frac{d\hat{S}_y}{dt} = \Omega \hat{S}_x \qquad \frac{d\hat{S}_z}{dt} = 0$$

$$\frac{d^2\hat{S}_x}{dt^2} = -\Omega^2 \hat{S}_x \qquad \frac{d^2\hat{S}_y}{dt^2} = -\Omega^2 \hat{S}_y$$

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Thus $\hat{S}_x$ and $\hat{S}_y$ satisfy the SHO equation and $\hat{S}_z$ is unchanged

$$\Rightarrow \boxed{\hat{S}_z(t) = \hat{S}_z(0)}$$

$$\hat{S}_x(t) = \hat{S}_x(0)\cos\Omega t + \frac{1}{\Omega}\left.\frac{d\hat{S}_x}{dt}\right|_0 \sin\Omega t$$

$$\Rightarrow \boxed{\hat{S}_x(t) = \hat{S}_x(0)\cos\Omega t + \hat{S}_y(0)\sin\Omega t}$$

$$\hat{S}_y(t) = \hat{S}_y(0)\cos\Omega t + \frac{1}{\Omega}\frac{d\hat{S}_y}{dt}\sin\Omega t$$

$$\Rightarrow \boxed{\hat{S}_y(t) = \hat{S}_y(0)\cos\Omega t - \hat{S}_x(0)\sin\Omega t}$$

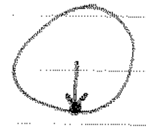
Bloch vector $\vec{Q}(t) = \langle \hat{\vec{\sigma}}(t) \rangle$

in Heisenberg state $|\psi\rangle = |-_z\rangle$ (time independent)

$$\Rightarrow Q_z(t) = \langle \sigma_z(t) \rangle = \langle -_z | \sigma_z(0) | -_z \rangle = -1$$

$$Q_x(t) = \langle \sigma_x(t) \rangle = \cos\Omega t \cancelto{0}{\langle -_z | \sigma_x(0) | -_z \rangle} + \sin\Omega t \cancelto{0}{\langle -_z | \sigma_y(0) | -_z \rangle}$$

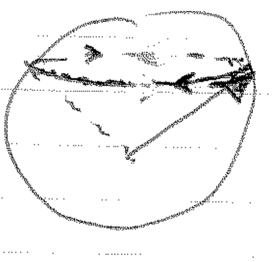
$$= 0$$

Similarly $Q_y(t) = 0 \Rightarrow$  Bloch sphere

Eigenstate $\Rightarrow$ No motion

If we started in an arbitrary state

$$|+_n\rangle = \cos\frac{\theta}{2}|+_z\rangle + e^{i\phi}\sin\frac{\theta}{2}|-_z\rangle$$

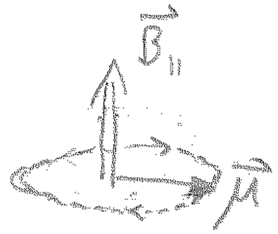


Bloch vector

Larmor precesses about $-\hat{e}_z$ with frequency Ω

Problem 3: Inhomogeneous broadening

(a) "Free induction" = free processing of the Bloch vector in x-y plane



$$\Omega_{\parallel} = \gamma |\vec{B}_{\parallel}|$$

Larmor procession ~~frequency~~

In the absence of dissipation, and for a fixed $\vec{B}_{\parallel}$, given $|\psi(0)\rangle = |+_x\rangle$

$$\langle \hat{\sigma}_x \rangle = \cos \Omega_{\parallel} t = \cos(\gamma B_{\parallel} t)$$

(i) Now we must average over the distribution of $B_{\parallel}$

$$\langle \hat{\sigma}_x \rangle = \int_{-\infty}^{\infty} dB_{\parallel} \cos(\gamma B_{\parallel} t)\, P(B_{\parallel})$$

$$= \text{Re}\underbrace{\left[\int_{-\infty}^{\infty} dB_{\parallel}\, e^{-i(\gamma B_{\parallel})t}\, P(B_{\parallel})\right]}_{\text{Fourier transform of } P(B_{\parallel})}$$

Gaussian distribution $P(B_{\parallel}) = \frac{1}{\sqrt{2\pi \Delta B_{\parallel}^2}}\, e^{-(B_{\parallel}-B_0)^2/2\Delta B_{\parallel}^2}$

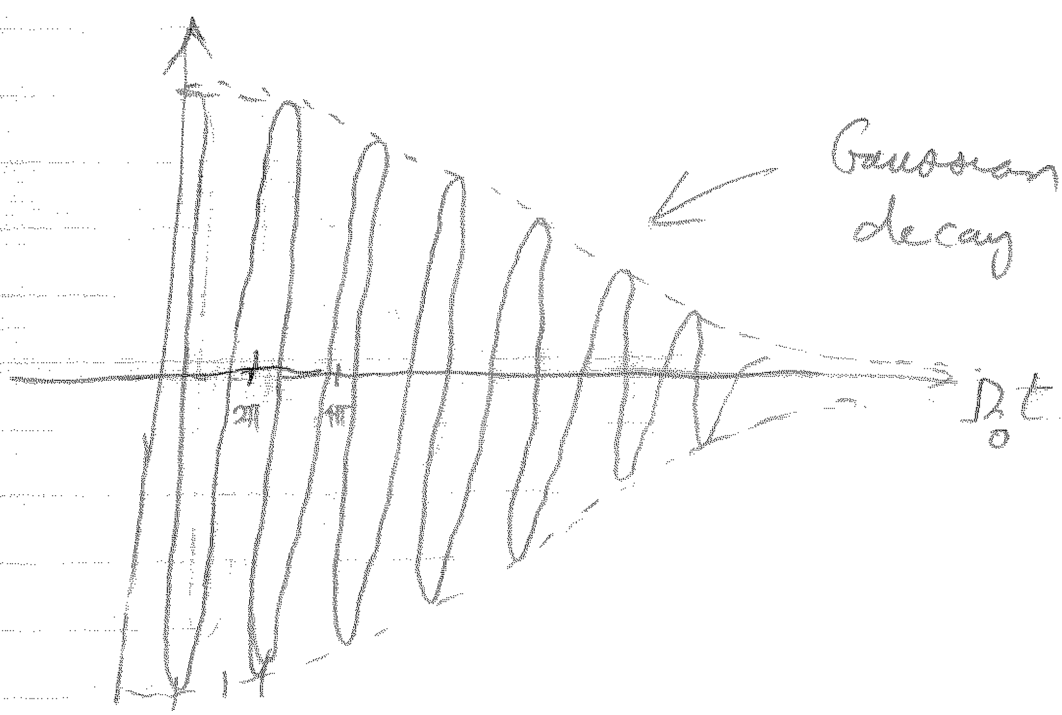
with $\Delta B_{\parallel} \ll B_0$

Change variables $\Omega = \gamma B_{\parallel}$

$$\Rightarrow \; P(\Omega) = \frac{1}{\sqrt{2\pi\,\Delta\Omega^2}}\, e^{-(\Omega-\Omega_0)^2/2\Delta\Omega^2}$$

$$\int_{-\infty}^{\infty} d\Omega\, e^{-i\Omega t}\, P(\Omega) \underset{\substack{\Uparrow \\ \text{shift origin}}}{=} e^{-i\Omega_0 t} \underbrace{\left(\int_{-\infty}^{\infty} d\bar{\Omega}\, e^{-i\bar{\Omega} t}\, \frac{e^{-\bar{\Omega}^2/2\Delta\Omega^2}}{\sqrt{2\pi\,\Delta\Omega^2}} \right)}_{e^{-(\Delta\Omega\, t)^2/2}\sqrt{\frac{\Delta\Omega^2}{2\pi}}}$$

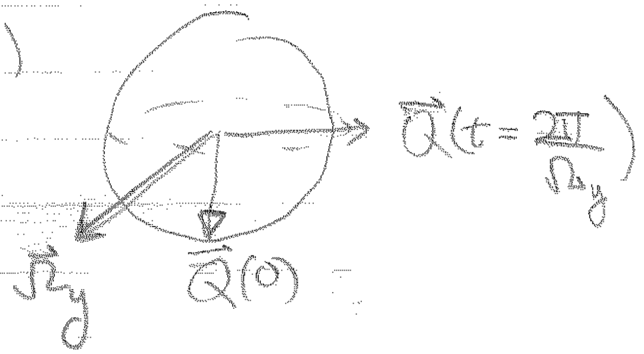
$$\Rightarrow \langle \hat{\sigma}_x(t) \rangle = \frac{e^{-\frac{(\Delta\Omega t)^2}{2}}}{\sqrt{2\pi/\Delta\Omega^2}} \cos(\gamma B_0 t)$$



(ii) The decay here is due sole to the different spin getting out of phase. The characteristic decay time is set by the width of the spectral distribution.

$$\boxed{T_2^* \sim \frac{1}{\Delta\Omega} = \frac{1}{\gamma \Delta B_{\parallel}}}$$

(iii)



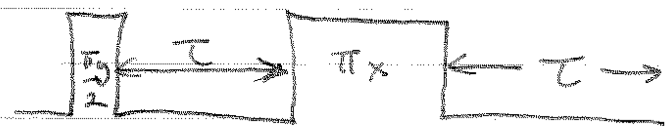
By apply a pulse with $\vec{\Omega}$ along $\vec{e}_y$ such that $\Omega_y T = \pi/2$ we rotate the spin to be along $\vec{e}_x$.

The problem is that Ω_y is not well defined because of the inhomogenity. However, the effect of inhomogeneity is cause the different spins do get out of phase. So, if the time of the pulse $T << T_2^*$ everything basically stays in phase. Thus we must have

$$\frac{\pi}{2\Omega_y} << T_2^* \Rightarrow \boxed{\Omega_y >> \frac{\pi}{2T_2^*}}$$

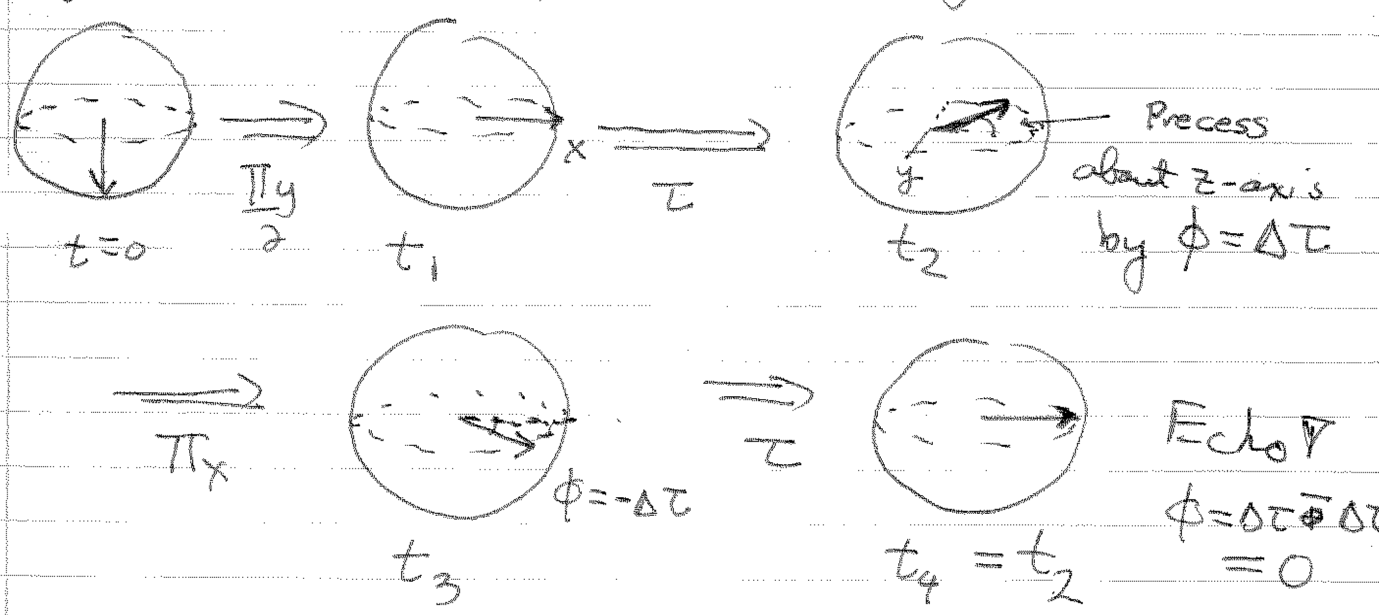
(b) Spin echo

Consider the following pulse sequence



Let us consider a single spin with resonance frequency detuned Δ from resonance of carrier. Thus pulse is assume to be sufficiently broad-band to bring the spin into x-y plane, independent of Δ

Sequence on Bloch-sphere (in rotating frame



During the time intervals τ, the spin precesses at frequency Δ (in rotating frame) about z-axis. The π_x pulse effectly puts the spin "behind the starting line" by an amount exactly equal the amount it precessed. Thus after the second free precession period τ the spin returns to the x-axis

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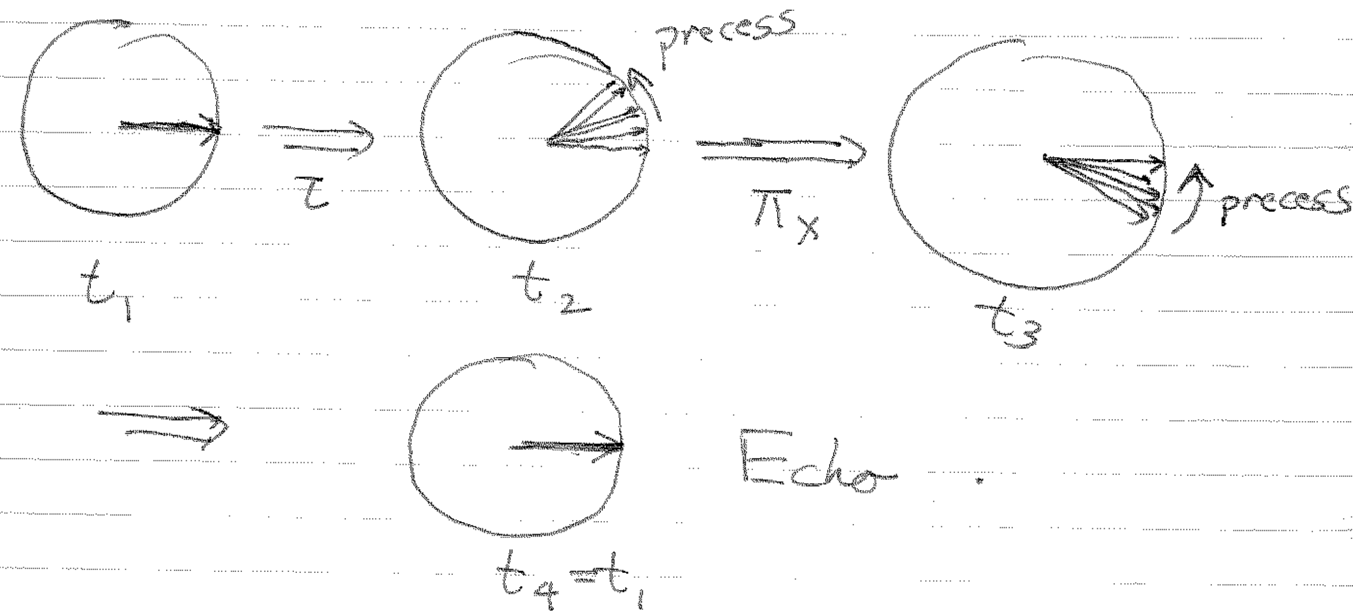
Let us now consider an ensemble of spins with a spread in Δ, $\Delta\omega_{inh}$.

Looking in the x-y plane at time-slices t_1, t_2, t_3, t_4



The dephasing is reversed by the π_x pulse.

After the second time τ the spins rephase and an echo signal will be seen.