Brune et al. 1996
Bertet et al. 2001

Haroche Expts (4/22/09)

Motivation: quantum measurement

- simple model (von Neumann): qubit A → system
  B → "meter," or meas. apparatus

  interaction: $\underbrace{(|0\rangle_A + |1\rangle_A)}_{\text{superposition}} \underset{\substack{\uparrow \\ \text{"meter ready"}}}{|0\rangle_B} \xrightarrow{\text{(unitary)}} \underset{\substack{\uparrow \\ \text{meter says } 0}}{|0\rangle_A|0_B\rangle} + \underset{\substack{\uparrow \\ \text{meter says } 1}}{|1\rangle_A|1\rangle_B}$

  - already reduced A to classical mixture:

    $\rho_A := \mathrm{Tr}_B(\rho_{AB}) = |0\rangle_A\langle 0|_A + |1\rangle_A\langle 1|_A$ $\boxed{\text{is this collapse?}}$

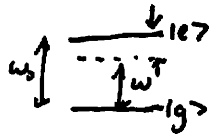
  - "measurement problem" → system ends up in $|0\rangle$ or $|1\rangle$, not classical mixture.
    - doesn't help to have observer measure meter: $|0\rangle_A|0\rangle_B|0\rangle_{obs} + |1\rangle_A|1\rangle_B|1\rangle_{obs}$ (von Neumann chain)
    - von Neumann: postulate that observer is classical, no superposition (⇒ collapse)
    - Bayesian: almost same, observer gets info, refines state (info) but never entangled (never physical unitary transformation)

- expts: see how simple measurements like this work (simple "meters")

Review: Two-Level Atom/System

Atom + laser/microwave
$\uparrow$ ω_0 $\uparrow$ ω

$\Delta := \omega - \omega_0 \rightarrow$ detuning



$H_A = \hbar\omega_0 |e\rangle\langle e|$

interaction $H_{AF} = -\vec{d}\cdot\vec{E}$ ($-e\vec{r}$, $\hat{\varepsilon}E_0\cos\omega t$)

$= -d_{eg}(\sigma+\sigma^\dagger)E_0(e^{i\omega t}+e^{-i\omega t})$

rotating-wave approx $\approx \frac{\hbar\Omega}{2}(\sigma e^{i\omega t}+\sigma^\dagger e^{-i\omega t})$

$\sigma := |g\rangle\langle e|$, $d_{eg} := \langle g|\hat{\varepsilon}\cdot\vec{d}|e\rangle$, $\Omega := -\frac{d_{eg}E_0}{\hbar}$ Rabi freq.

$\exists$ unitary transformation (like interaction picture)

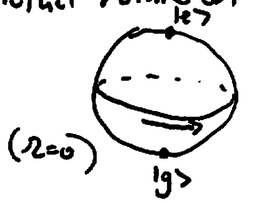
$\Rightarrow \tilde{H}_A = -\hbar\Delta|e\rangle\langle e|$, $\tilde{H}_{AF} = \frac{\hbar\Omega}{2}(\sigma+\sigma^\dagger)$

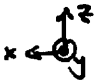
$\Rightarrow$ equiv to $\overset{\downarrow}{\underset{\uparrow\Delta}{=}}\ \begin{matrix}|g\rangle\\|e\rangle\end{matrix}$ + dc. interaction

or $\tilde{H}_A + \tilde{H}_{AF} = \begin{bmatrix} -\hbar\Delta & \hbar\Omega/2 \\ \hbar\Omega/2 & 0 \end{bmatrix}$

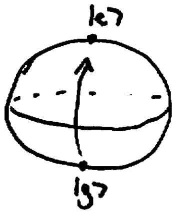
Recall: Δ causes azimuthal rotation on Bloch sphere (phase only) $\rightarrow$ Bloch, 1947 Feynman et al. 1957

(ang. freq. Δ)





Ω causes Rabi flopping $|g\rangle \rightarrow |e\rangle \rightarrow |g\rangle$
(ang. freq. Ω) $(\Delta=0)$



Qubit transformations via field:

"π pulse" $\rightarrow$ leave field on for $\frac{1}{2}$ period or $T = \frac{\pi}{\Omega}$

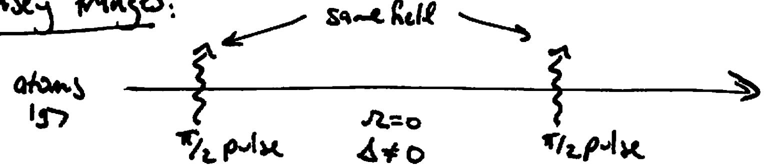
$|g\rangle \rightarrow |e\rangle$
$|e\rangle \rightarrow |g\rangle$

"$\frac{\pi}{2}$ pulse" $\rightarrow$ $\frac{1}{4}$ period or $T = \frac{\pi}{2\Omega}$

$|g\rangle \rightarrow |g\rangle - i|e\rangle$ (up to overall phases)
$|e\rangle \rightarrow |g\rangle + i|e\rangle$

$\boxed{\text{? unitarity}}$

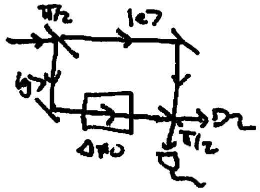
Ramsey fringes:



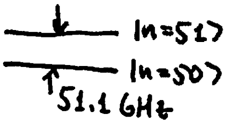
$\pi/2$ pulse $\quad \Omega=0 \quad$ $\pi/2$ pulse
$\Omega\neq0, \Delta\approx0 \quad \Delta\neq0 \quad \Omega\neq0, \Delta\approx0$

$|g\rangle \rightarrow |g\rangle - i|e\rangle \rightarrow |g\rangle - ie^{i\Delta t}|e\rangle$ $\hookrightarrow$ $|g\rangle - i|e\rangle \rightarrow |e\rangle$
$|g\rangle + i|e\rangle \rightarrow |g\rangle$
map phase onto population

like interferometer:



Experimental Apparatus (1996)



(circular states, max l, m)

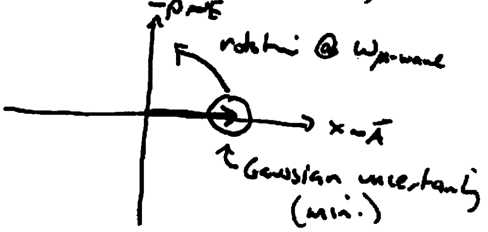
- Ramsey expt w/ Rydberg atoms (highly excited) → $\boxed{\text{why?}}$
  - advantages → - superconducting mirrors
    - microwave technology
    - large dipole moment (atom-field coupling) ~er
    - long lifetime (30 ms), $\Gamma \sim \omega_0^3$; cf 30 ns for optical
  - disadvantage → cryogenic
    - reduce blackbody μwave power (0.6K)
    - coupling to stray fields
- thermal beam from oven
- optically pump. atoms to Rydberg state only for right velocity (400±6 m/s), use Doppler effect + resonance.
- Ramsey $\frac{\pi}{2}$ pulses via μwave cavities
- detect final state via ionization (different ionization energies for $n=50, 51$)

Point: put extra cavity inside to "measure" state of atom

- cavity (single mode) → is harmonic oscillator in coherent state α $(n = \langle a^\dagger a\rangle = |\alpha|^2)$

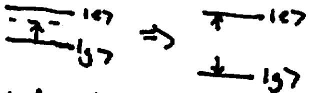
$$\alpha = \underset{\substack{\uparrow \\ \sim\sqrt{n},\ \text{field amplitude}}}{|\alpha|}\, e^{i\phi} \leftarrow \text{phase of oscillation}$$

$n = 9.5$ (significant uncertainty)



Dispersive measurement: cavity as "meter"

- Stark shift: atom + field

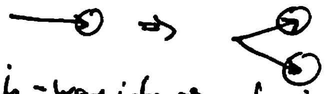


$\delta E \sim \pm \frac{\Omega^2}{\Delta}$

- analogous effect on field: phase shift (state-dependent), index of refraction due to 1 atom.

effectively:

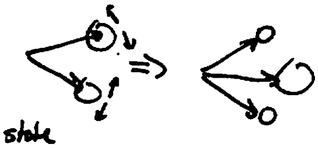
$$(|e\rangle+|g\rangle)|\alpha\rangle \rightarrow |e,\alpha e^{i\phi}\rangle + |g,\alpha e^{-i\phi}\rangle$$



if 2ϕ large enough to resolve states, then which-way info → no fringes (data) Figs 3, 4

larger ϕ → "more classical" meter

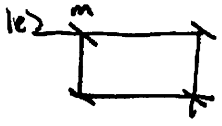
- two-atom correlation second atom after delay:



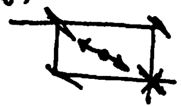
  - get fringes to probe coherence of field state
  - (data) Figs 5 watch coherence decay w/ time, faster if more classical.
    ↳ to statistical mixture
  - much shorter than cavity decay time for distinguishable

Eraser expt (2001)

- interferometer:



  - small m (quantum) → beamsplitter recoils, giving which-way info
  - large m (classical) → no recoil, interference
- eraser:



  - tie beamsplitters together about pivot point $\boxed{\text{fringes?}}$
  - second recoil "undoes" the first → no which-way info
- expt: use cavity as splitter, photon number like mass
  - atom changes photon # by 1, significant for small n, not for large n ($\sqrt{n}$ uncertainty)