

**Decoherence in trapped ions:  
unplanned and planned**

Frontiers of Quantum Decoherence - August 14, 2006  
Fields Institute, University of Toronto  
Brian King  
[http://physwww.mcmaster.ca/~kingb/King\\_B\\_h.html](http://physwww.mcmaster.ca/~kingb/King_B_h.html)

**Outline:**

- trapped ions
  - ion traps
  - degrees of freedom
  - state detection
  - interactions with lasers
- decoherence we'd like to remove
  - motional
  - spin
- decoherence we can cause
  - engineered reservoirs

**Linear ion traps:**

- axial confinement - static!

$$\Phi(z) = \left( \frac{m\omega_z^2}{2q} \right) \frac{z^2}{2}$$

$$\omega_z^2 = \frac{2\alpha q U_0}{m} \quad \alpha \sim 1 \text{ (geom.)}$$

- radial confinement -dynamic!

$$\Phi(r) = \frac{m}{2q} \left( \omega_r^2 - \frac{\omega_z^2}{2} \right) r^2$$

$$\omega_r^2 = \frac{q^2 V_0^2}{2m \Omega_{RF} \beta^4 r^4} \quad \beta \sim 1 \text{ (geom.)}$$

$\bullet \omega_r < \Omega_{RF}$

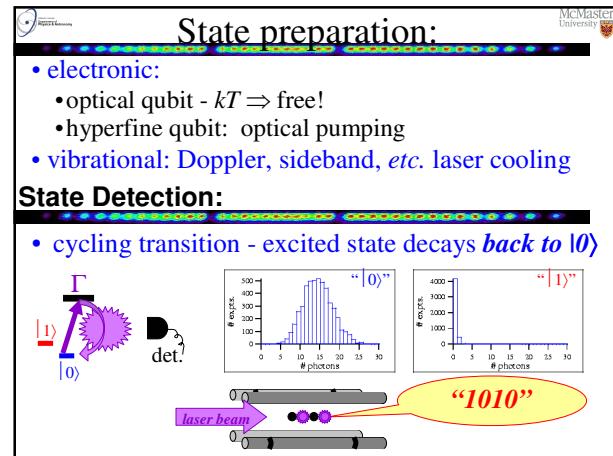
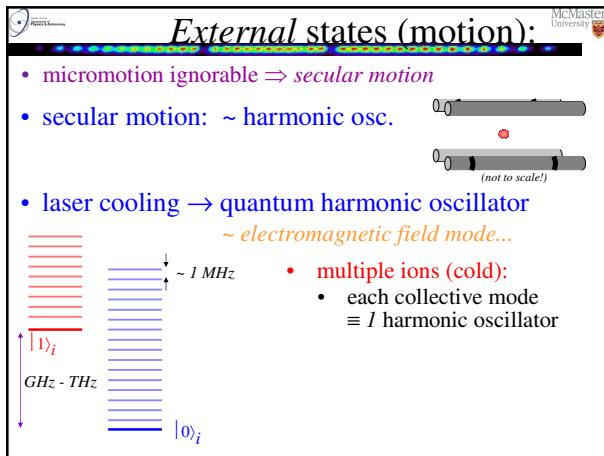
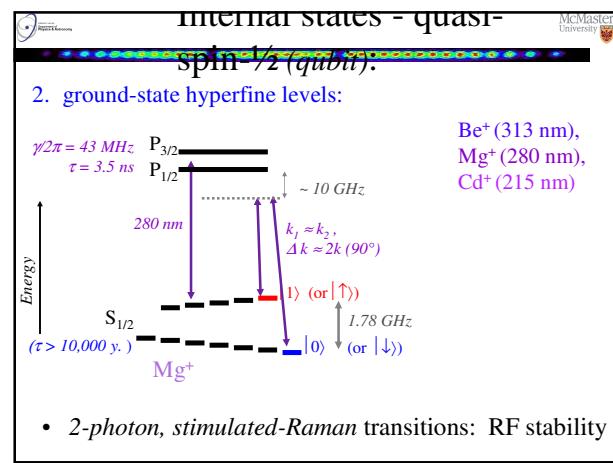
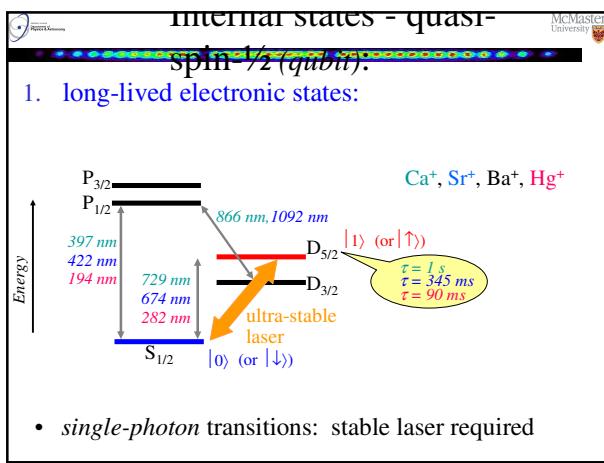
"micromotion"      "rotational" motion

- micromotion small, at different freq.

After D. Burkland, Rev. Sci. Inst. 75, 2858 (02)

**Ion traps *in situ*:**

- McMaster ion trap:  $^{25}\text{Mg}^+$



**Laser coupling:**

- $H_I \propto \mu \cdot E_0 e^{i(kz - \omega_i t)}$
- if ion vibrates, interaction strength modulated

$$H_I \propto \mu \cdot E_0 e^{i[k z_{\max} \cos(\omega_i t) - \omega_L t]}$$

Classically:  $\mu \cdot E_0 \sum_m i^m J_m(k z_{\max}) e^{im\omega_i t} e^{-i\omega_L t}$   
sidebands!

Quantum:  $H_I \propto \frac{1}{2} \mu E_0 (S_+ + S_-) e^{i[k z_0 (a + a^\dagger) - \omega_L t]}$   
 $= \Omega (S_+ + S_-) e^{i k z_0 (a + a^\dagger)} e^{-i \omega_L t}$

int. pic.:  $\Omega (S_+ e^{i \omega_i t} + H.C.) e^{i k z_0 (a e^{-i \omega_i t} + a^\dagger e^{i \omega_i t})} e^{-i \omega_L t}$

**Laser coupling:**

**1. Energy? detuning of laser(s) from resonance!**

$\omega_L = \omega_0$ : "carrier"  $- n_{0,i} \leftrightarrow n_{I,i}$   
 $\omega_L = \omega_0 + \omega_z$ : "blue sideband"  $- n_{0,i} \leftrightarrow n+1_{I,i}$   
 $\omega_L = \omega_0 - \omega_z$ : "red sideband"  $- n_{0,i} \leftrightarrow n-1_{I,i}$   
...etc. (higher sidebands...)

**coupling strength:**

$$\Omega_{n,n'} = \Omega \langle n | \hat{D}(i\eta) | n' \rangle$$

$$= \Omega e^{-\eta^2/2} \sqrt{\frac{n_{\leq}!}{n_{>}!}} \eta^{|n'-n|} L_{n \leq}^{|n'-n|}(\eta^2)$$

**Laser coupling:**

- coupling strength determined by **E gradients** (dipole!)

**2. momentum...**

- coupling strength  $\sim$  Lamb-Dicke parameter

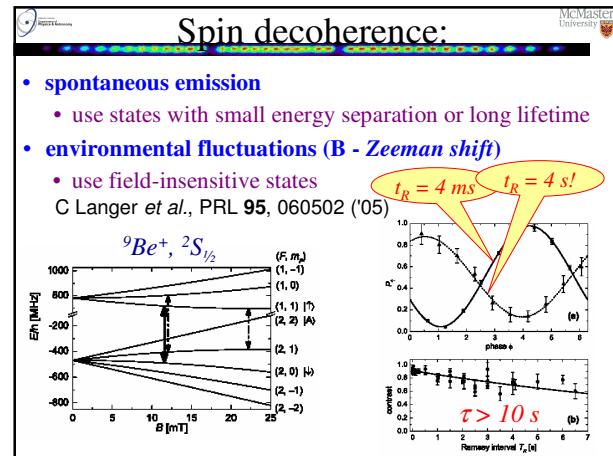
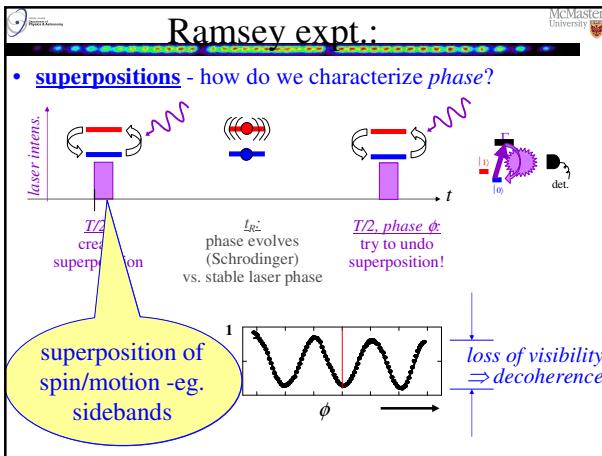
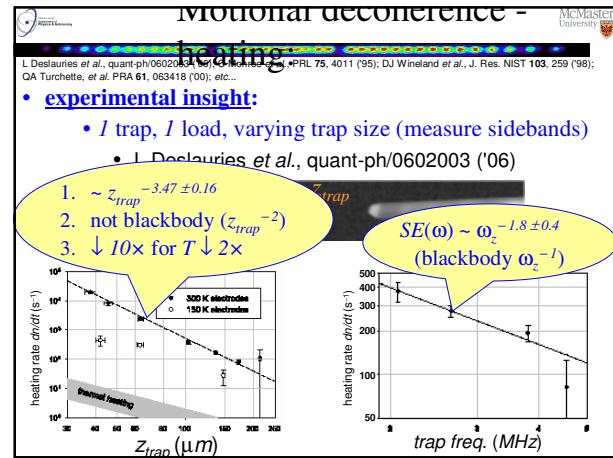
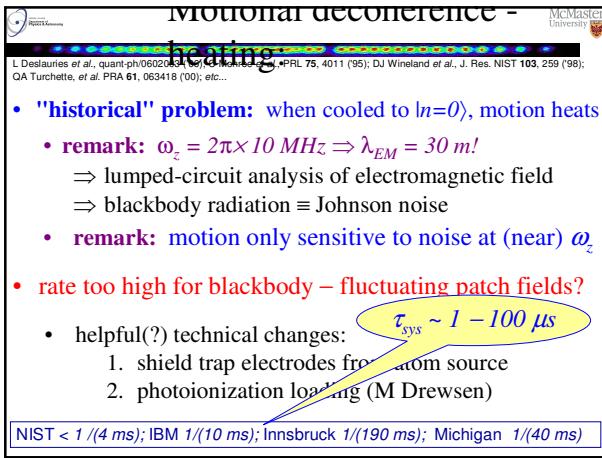
$$\eta = \frac{k \cdot z_0}{2p_0} = \frac{k \cdot \frac{\hbar}{2p_0}}{2p_0} = \eta = \frac{k \cdot z_0}{2p_0} = \frac{\hbar k}{2p_0}$$

- Lamb-Dicke parameter  $\sim p$  match to SHO
  - atom recoil vs. trap recoil!

**Coupling to only one motion:**

- ion is **charged**!:  $E \leftrightarrow$  force
- ion is **harmonically bound**: **resonance** ( $\omega_r$ )
  - classical force  $E_0 \sin(\omega t - \varphi) \rightarrow$  displacement  $\hat{D} \left( \frac{qE_0 z_0 e^{i\varphi}}{2\hbar} t \right)$
- alternative: co-propagating lasers, detuning  $\delta\omega$ 
  - "walking standing wave"
    - induces dipole moment
    - drives ion motion through dipole force

different dipole moment for  $|0\rangle, |I\rangle$ ?  
"cat state"  $|0,\alpha\rangle + |I,\beta\rangle$



**Spin deconherence - DESS+**

H Häffner, et al., Appl. Phys. B 81, 167 (2005); S Langer, et al., PRL 95, 060502 (06)

- encode 1 qubit/pseudospin in 2 (*with symmetry*):
  - prepare Bell states:  $\Psi_{\pm} = \frac{1}{\sqrt{2}} (\lvert 10 \rangle \pm \lvert 01 \rangle)$
  - $\lvert 10 \rangle$  and  $\lvert 01 \rangle$  are degenerate: insensitive to *global*  $\Delta B$

**NIST**

- hyperfine levels

**Innsbruck**

**Engineered reservoirs I:**

Myatt, et al., Nature 403, 269 (00); Turchette, et al., PRA 62, 053807 (00)

- amplitude reservoir (high-T):
 
$$\hat{H}_I = \hbar \sum_i (\Gamma_i \hat{b}_i \hat{a}^\dagger + \Gamma_i^\dagger \hat{b}_i^\dagger \hat{a})$$

$$\dot{\rho}(t) = \frac{\gamma}{2} (2\hat{a}\hat{\rho}\hat{a}^\dagger - \hat{a}^\dagger\hat{a}\rho - \rho\hat{a}^\dagger\hat{a}) + \frac{\gamma}{2}\bar{n} (2\hat{a}^\dagger\hat{\rho}\hat{a} - \hat{a}\hat{a}^\dagger\rho - \rho\hat{a}\hat{a}^\dagger)$$
  - 2.5 MHz Gaussian noise centred at 10.25 MHz ( $\approx v_z$ )

**cat state:** **background noise:** **sup. of number states:**

**Engineered reservoirs I:**

Myatt, et al., Nature 403, 269 (00); Turchette, et al., PRA 62, 053807 (00)

- phase reservoir (high-T):
 
$$\hat{H}_I = \hbar \sum_i (\Gamma_i \hat{b}_i \hat{a}^\dagger \hat{a} + \Gamma_i^\dagger \hat{b}_i^\dagger \hat{a}^\dagger \hat{a})$$

$$\dot{\rho}(t) = \frac{\kappa}{2} (2\hat{a}^\dagger\hat{a}\hat{\rho}\hat{a}^\dagger \hat{a} - (\hat{a}^\dagger\hat{a})^2\rho - \rho(\hat{a}^\dagger\hat{a})^2)$$
  - modulate trap strength with 2.5 MHz Gaussian 1-100 kHz
  - expt. ~ 1 ms  $\Rightarrow$  one phase/shot random shot to shot

**sup. of number states:**

**cat state:**

**Engineered reservoirs II:**

Poyatos, et al., PRL 77, 4728 (96); Myatt, et al., Nature 403, 269 (00); Turchette, et al., PRA 62, 053807 (00)

- zero-temperature reservoir: red sideband + spont. em.
  - ${}^9\text{Be}^+$  qubit:  $\lvert \uparrow \rangle \equiv \lvert 1 \rangle$  has lifetime  $\sim 10,000$  y
  - add laser resonant with  ${}^2P_{1/2}$  ( $\Gamma/2\pi = 19$  MHz), strength  $\Omega_D$

$\gamma_{\text{eff}} \sim \Omega_D^2/\Gamma$

**adjustable ratio  $\Omega_{rsb}, \gamma_{\text{eff}}$  of coherent to incoherent coupling**

