Spin-gradient thermometry and cooling in optical lattices

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Spin-gradient thermometry and cooling in optical lattices

+ Bragg scattering

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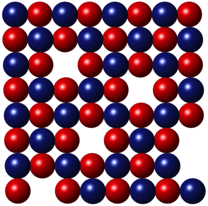
Outline

1. Motivation
2. Spin-gradient thermometry in optical lattices
3. Adiabatic demagnetization cooling
4. Bragg scattering from ultracold atoms in optical lattices

Condensed matter and dilute ultracold gases

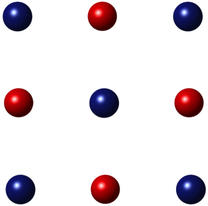
Normal matter (electrons in ionic lattice)

- Tightly packed atoms
- Complicated interactions
- Fixed parameters



"Artificial" matter (atoms in optical lattices)

- 10^8 times lower density
- Tunable interactions
- Controllable parameters



M. Lewenstein *et al.*, Adv. Phys. **56**, 243 (2007)

Condensed matter and dilute ultracold gases

Relative Scales

	YBCO	Rb in YAG lattice
Lattice Constant	10^{-9} m	5×10^{-7} m
Site Density	10^{21} cm^{-3}	10^{13} cm^{-3}
Interaction U	600 THz	700 Hz
Tunneling J	100 THz	20 Hz
Exchange J^2/U	1500 K	5×10^{-11} K
Néel temperature	300 K	2×10^{-10} K

B. Capogrosso-Sansone, S. Soyler, N. Prokof'ev, and B. Svistunov, Phys. Rev. A **81**, 053622 (2010)

Paths towards quantum magnetism

Anisotropic-XXZ Heisenberg Hamiltonian:

$$H = \sum_{\langle i,j \rangle} \left[\lambda_{\mu z} S_i^z S_j^z \pm \lambda_{\mu \perp} (S_i^x S_j^x + S_i^y S_j^y) \right] - B_z \sum_i S_i^z$$

- Fermions in harmonic traps
- Ultracold polar molecules in optical lattices
- Trapped ions
- Bosons in optical lattices (number or spin sector)

G. Jo *et al.*, Science, **325**, 1521 (2009)

A. V. Gorshkov *et al.*, Phys. Rev. Lett., **107**, 115301 (2011)

K. Kim *et al.*, Nature, **465**, 590 (2010)

J. Simon *et al.*, Nature, **472**, 307 (2011)

L. Duan, E. Demler, and M. Lukin, Phys. Rev. Lett., **91**, 090402 (2003)

Two component Mott insulator and quantum magnetism

Bose-Hubbard Hamiltonian for a two-component system:

$$H = -\sum_{\langle ij \rangle \sigma} \left(J_{\mu\sigma} a_{i\sigma}{}^{\dagger} a_{j\sigma} + H.c. \right) + \frac{1}{2} \sum_{i,\sigma} U_{\sigma} n_{i\sigma} (n_{i\sigma} - 1) + U_{\uparrow\downarrow} \sum_{i} n_{i\uparrow} n_{i\downarrow}$$

2CMI $\longrightarrow$ **anisotropic-XXZ Heisenberg Hamiltonian**:

$$H = \sum_{\langle i,j \rangle} \left[\lambda_{\mu z} S_i^z S_j^z \pm \lambda_{\mu\perp} (S_i^x S_j^x + S_i^y S_j^y) \right]$$

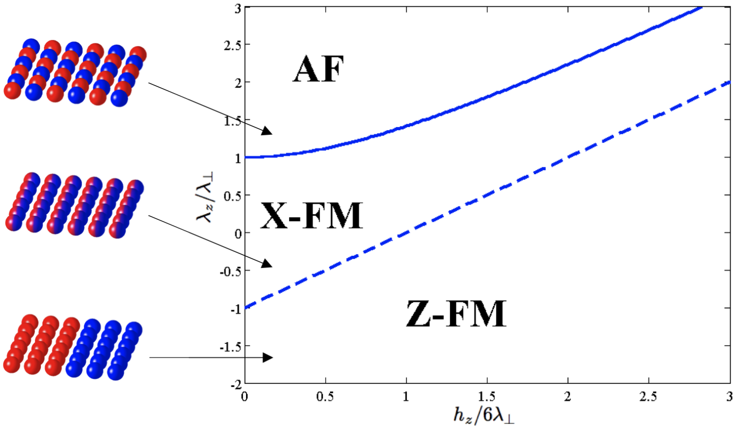
Tunable experimental parameters:

$$\lambda_{\mu z} = \frac{J_{\mu\uparrow}^2 + J_{\mu\downarrow}^2}{2 U_{\uparrow\downarrow}} - \frac{J_{\mu\uparrow}^2}{U_{\uparrow}} - \frac{J_{\mu\downarrow}^2}{U_{\downarrow}}$$

$$\lambda_{\mu\perp} = \frac{J_{\mu\uparrow} J_{\mu\downarrow}}{U_{\uparrow\downarrow}}$$

L. Duan, E. Demler, and M. Lukin, Phys. Rev. Lett., **91**, 090402 (2003)

Two component Mott insulator and quantum magnetism



L. Duan, E. Demler, and M. Lukin, Phys. Rev. Lett., **91**, 090402 (2003)

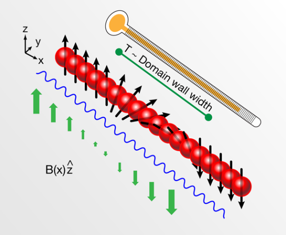
The necessary ingredients towards quantum magnetism

- Thermometry for the Mott state
- Reliable cooling
- Diagnostics of ordering
- Spin-interactions between nearest neighbors

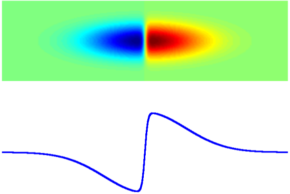
Spin-gradient thermometry in optical lattices-Theory

Mean spin $\langle s \rangle$ as a function of position x_i:

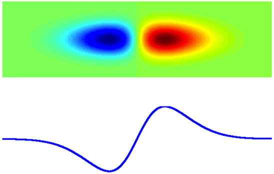
$$\langle s \rangle = tanh\left(-\frac{\Delta\mu_\sigma B(x_i)}{2k_B T}\right)$$



Low T



High T



D. M. Weld *et al.*, Phys. Rev. Lett., **103**, 245301 (2009)
A. M. Rey, Physics, **2**, 103 (2009)

Experimental procedure

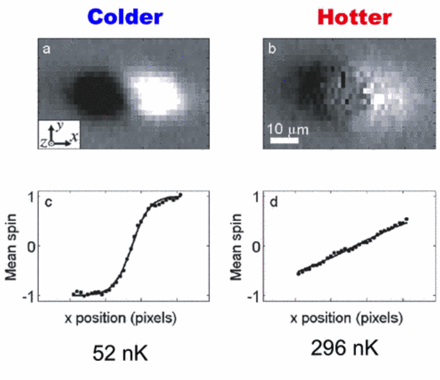
- Evaporate to BEC in optical trap
- Prepare $50\% - 50\%$ spin mixture with nonadiabatic sweep

Spin states for ^{87}Rb

We use ^{87}Rb in a quasi two-level scheme with $\nu = 6.834GHz$.
$|F = 1, m_F = -1\rangle \equiv |\uparrow\rangle$
and $|F = 2, m_F = -2\rangle \equiv |\downarrow\rangle$.

- Apply gradient and evaporate further
- Load atoms in a $3D$ lattice
- Image spin distribution in 2 shots

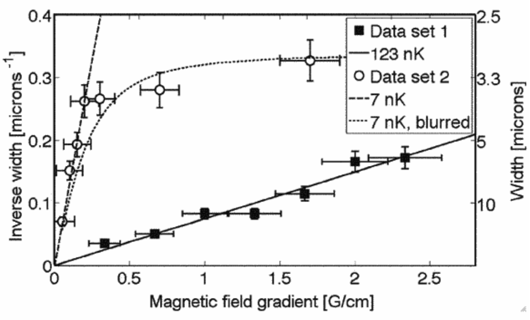
Spin-gradient thermometry in optical lattices-Experiment



- Large dynamic range from $500nK$ to $200pK$
- Works deep in the Mott insulator regime

D. M. Weld *et al.*, Phys. Rev. Lett., **103**, 245301 (2009)

Spin-gradient thermometry in optical lattices-Experiment



- Higher $\nabla|\vec{B}|$ leads to narrower mixed region
- The spin-mixed region shrinks for colder samples

Adiabatic demagnetization cooling-Theory

One each lattice site i -assuming that $J << U$ -the energy of the spin configuration will be:

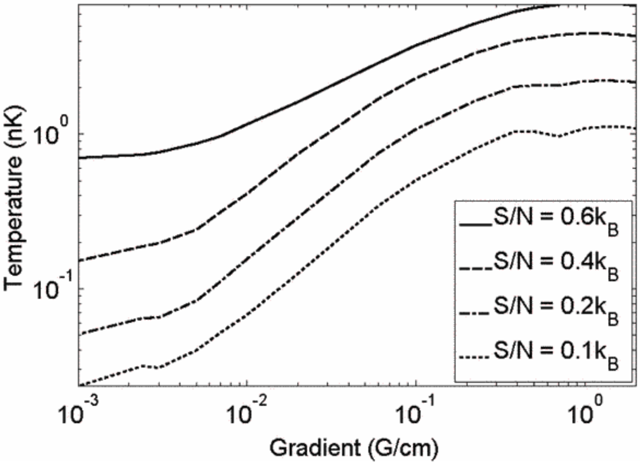
$$
\begin{aligned}
E_i\left(n_\uparrow, n_\downarrow, \nabla|\vec{B}|\right) =& p\nabla|\vec{B}|x_i\left(n_\uparrow - n_\downarrow\right) + \\
&+ \frac{1}{2}\sum_\sigma U_{\sigma\sigma} n_\sigma \left(n_\sigma - 1\right) + \\
&+ U_{\uparrow\downarrow} n_\uparrow n_\downarrow + \\
&+ V_i\left(n_\uparrow + n_\downarrow\right) + \\
&+ \left[-\mu_\uparrow n_\uparrow - \mu_\downarrow n_\downarrow\right]
\end{aligned}
$$

For zero magnetization

$$
\sum_i n_{\uparrow i} = \sum_i n_{\downarrow i} = \frac{N}{2}
$$

D. M. Weld *et al.*, Phys. Rev. A, **82**, 051603(R) (2010)

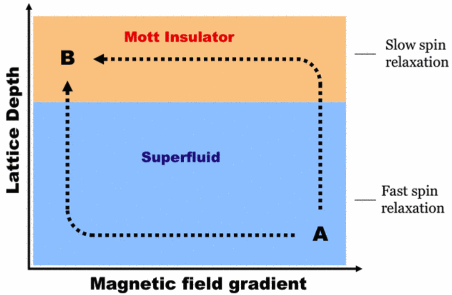
Adiabatic demagnetization cooling-Theory



- Isentropic/adiabatic demagnetization leads to cooling.
- Extremely low temperatures can be achieved

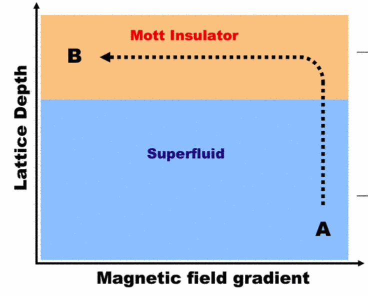
Experimental "phase space"

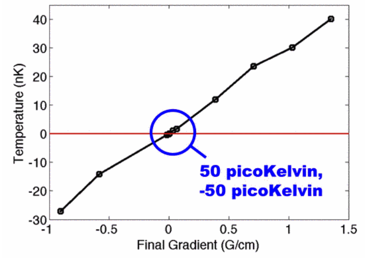
- Spin temperatures for slow spin relaxation
- Adiabatic demagnetization cooling for fast spin relaxation



P. Medley *et al.*, Phys. Rev. Lett., **106**, 195301 (2011)

Spin temperatures

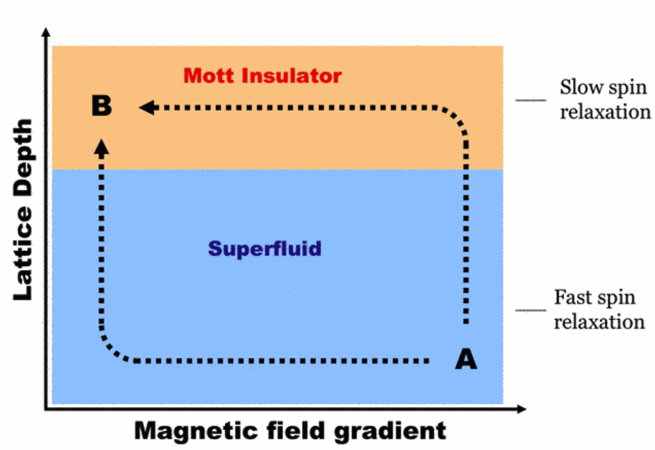




- For slow spin-relaxation times the spin profile is "frozen"
- The lowest/highest spin temperatures have been reached

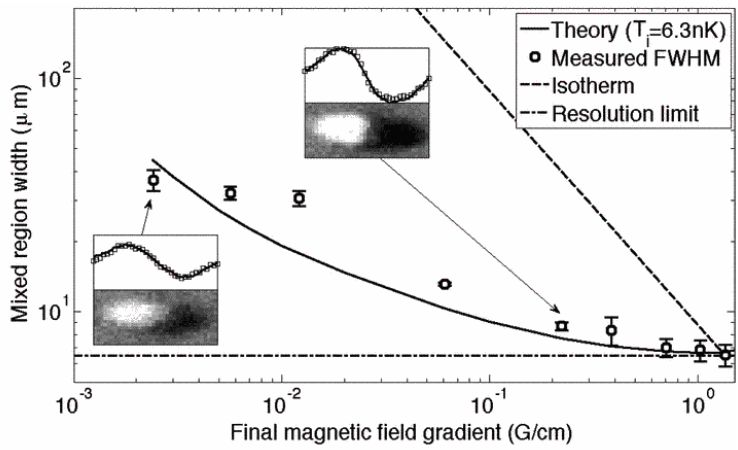
P. Medley *et al.*, Phys. Rev. Lett., **106**, 195301 (2011)

Adiabatic demagnetization cooling-Experiment



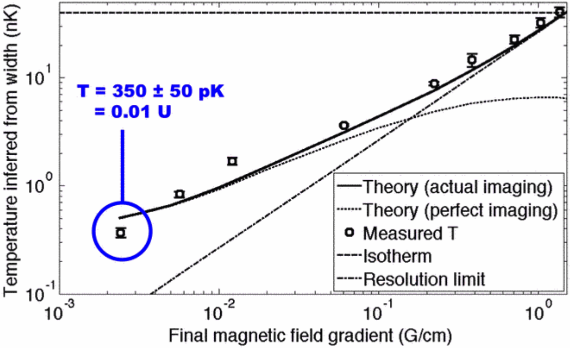
- Adiabatically "demagnetize" our sample by lowering $\nabla|\vec{B}|$
- Load the atoms in the lattice
- Cooling?

Adiabatic demagnetization cooling-Experiment



The width of $\langle s \rangle$ is always below the isotherm $T_i = 6.3nk$

Adiabatic demagnetization cooling-Experiment



- Record low temperatures for an equilibrated gas
- Entropy redistribution between spin and kinetic degrees of freedom leads to cooling

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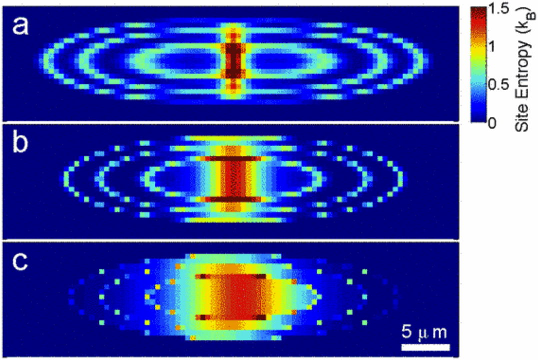
P. Medley *et al.*, Phys. Rev. Lett., **106**, 195301 (2011)

Cooling from the point of view of entropy redistribution

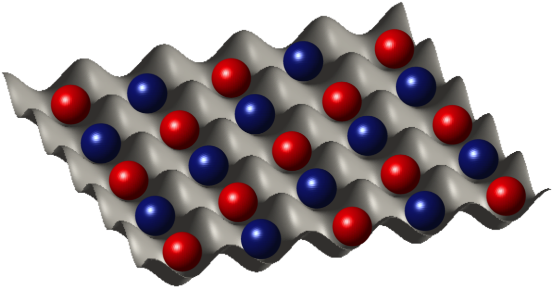


- Mixed-occupation numbers between Mott shells carry high entropy
- Adiabatic reversible "demagnetization" redistributes entropy to the spin-mixed region

D. M. Weld *et al.*, Phys. Rev. A, **82**, 051603(R) (2010)

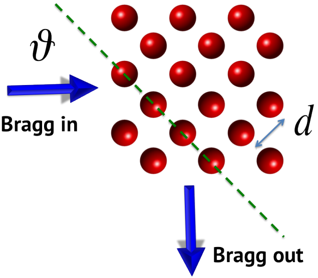
Bragg scattering from a crystal of ultracold atoms

Antiferromagnet



T. A. Corcovilos *et al.*, Phys. Rev. A, **81**, 013415 (2010)

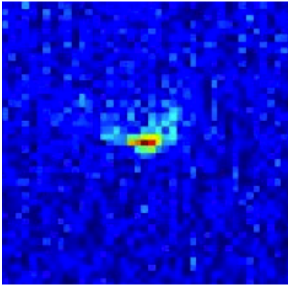
Bragg scattering from a crystal of ultracold atoms



$$n\lambda = 2dsin\theta$$

$$d = 532nm, \lambda = 780nm, \theta = 47^\circ$$

Bragg for $|F = 2, m_F = -2\rangle$



The atoms are in the lowest vibrational state

H. Miyake *et al.*, Phys. Rev. Lett., **107**, 175302 (2011)

Bragg as a probe of position spread

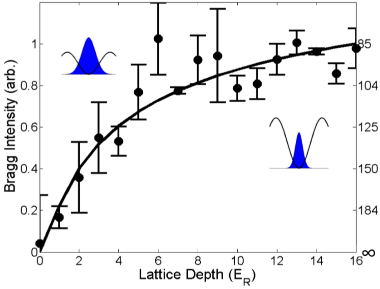
Debye-Waller factors:

$$\frac{d\sigma}{d\Omega} \propto \prod_{i=\{x,y,z\}} exp\left[-\frac{1}{2}(\Delta r_i)^2 \Delta K_i^2\right]$$

$$\Delta\vec{K} = \vec{k_{in}} - \vec{k_{out}}, \Delta r_i = \sqrt{\frac{\hbar}{m\omega_i}}$$

Bragg intensity I_{Bragg}:

$$I_{Bragg} \propto exp\left(-\frac{\lambda_L^2 K^2}{8\pi^2\sqrt{N_L}}\right)$$



Bragg as a probe of momentum spread

For the ground state of a harmonic oscillator:

$$(\Delta x(t))^2 = (\Delta x)^2 + \frac{(\Delta p)^2}{m^2} t^2,$$

Earlier experiments:

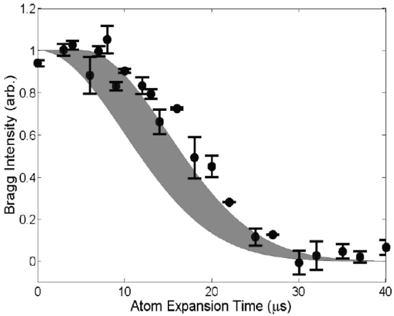
$$\frac{(\Delta p)^2}{m} = k_B T$$

But here:

$$(\Delta x)^2 (\Delta p)^2 = \hbar^2/4$$

Bragg intensity I_{Bragg}:

$$I_{Bragg} \propto exp(-\frac{(\Delta p)^2 K^2}{2m^2} t^2)$$



Heisenberg uncertainty limited wave functions

M. Weidemller *et al.*, Phys. Rev. Lett., **75**, 4583 (1995)
G. Birkl *et al.*, Phys. Rev. Lett., **75**, 2823 (1995)
H. Miyake *et al.*, Phys. Rev. Lett., **107**, 175302 (2011)

Atomic Talbot effect

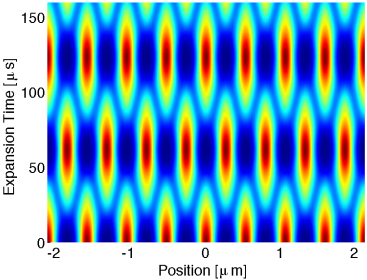
Bragg reflection: coherent light incident on periodically modulated atom density distribution. No need for atomic phase coherence.

What happens in the case of an evolving coherent matter wave?

$$\Psi(x,t) = \sum_{n=-\infty}^{n=+\infty} c_n exp\left[i\left(\frac{2\pi n}{\Lambda}x - \frac{2\pi^2 n^2 \hbar}{m\Lambda^2}t\right)\right], \Lambda = \frac{\lambda_L}{2}$$

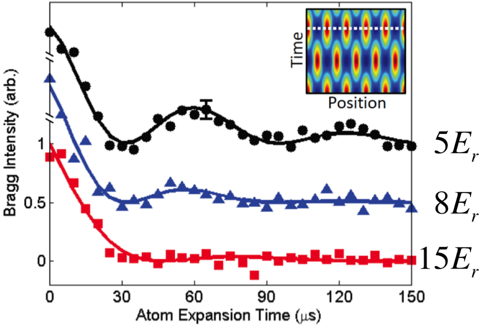
For $n = 1$ the **Talbot revivals** occur:

$$t_{revivals} = \frac{m\lambda^2}{2h} \approx 123\mu s$$



Bragg revivals and 3D Talbot effect

- Periodic matter waves lead to $3D$ atomic Talbot effect
- SF to MI transition leads to reduced revivals for higher E_r
- Decoherence mechanisms?

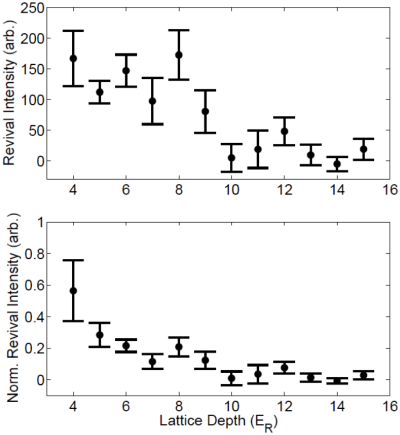


H. Miyake *et al.*, Phys. Rev. Lett., **107**, 175302 (2011)

Bragg superfluid to Mott insulator transition

- $SF \rightarrow MI \approx 13.5 E_r$
- Finite temperature
- Interaction effects

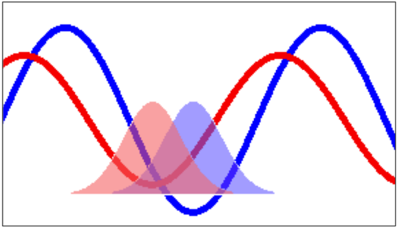
Bragg scattering can probe quantum phase transitions

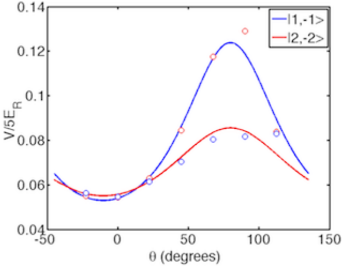


Spin-dependent lattices

Concept: Control $U_{\uparrow\downarrow}$ by splitting σ_+ and σ_- by $\Delta x = \theta\lambda_x/(2\pi)$.

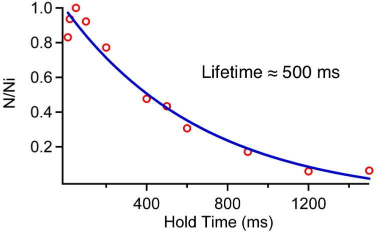
$$V_+(x,\theta) = V_0^+ cos^2(k_x x + \theta/2) \text{ and}$$
$$V_-(x,\theta) = V_0^- cos^2(k_x x - \theta/2)$$

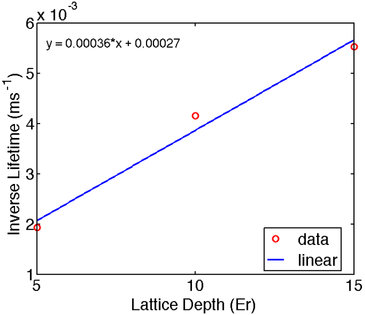




O. Mandel *et al.*, Phys. Rev. Lett., **91**, 010407 (2003)

Lifetime in spin-dependent lattices





- Atom lifetimes in the order of hundreds of ms
- Evidence that light scattering is responsible
- Adiabatic demagnetization cooling in SD lattices?

Aknowledgements

- Professors: Prof. Wolfgang Ketterle and Prof. David Pritchard
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