Decoherence and Control of Vibrational States of Atoms* in an Optical Lattice

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* – monatomic molecules

Coherent Control of Ultracold Molecular Processes
UBC ’07
DRAMATIS PERSONÆ

Toronto quantum optics & cold atoms group:

Postdocs: An-Ning Zhang (→ IQIS) Morgan Mitchell (→ ICFO)
(HIRING!) Matt Partlow (→ Energetiq) Marcelo Martinelli (→ USP)

Optics: Rob Adamson Kevin Resch (→ Wien → UQ → IQC)
Lynden (Krister) Shalm Jeff Lundeen (→ Oxford)
Xingxing Xing

Atoms: Jalani Fox (→ Imperial) Stefan Myrskog (→ BEC → ECE)
(SEARCHING!) Mirco Siercke (→ ...?) Ana Jofre (→ NIST → UNC)
Samansa Maneshi Chris Ellenor

UG’s: Ardavan Darabi, Nan Yang, Max Touzel, Michael Sitwell, Eugen Friesen

Some helpful theorists:
Pete Turner, Michael Spanner, H. Wiseman, J. Bergou, M. Mohseni, J. Sipe, Daniel James, Paul Brumer, ...
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Quantum Computer Scientists

The 3 quantum computer scientists:
see nothing (must avoid "collapse"!)
hear nothing (same story)
say nothing (if any one admits this thing is never going to work, that's the end of our funding!)
Something we were trying to do
  Preparing & tomographing quantum states in lattices
Something we didn’t anticipate [complicated plots]
  Pulse echo and a “fidelity freeze”
Pretty pictures in case I’ve already lost you
  Probing decoherence with 2D pump-probe spectro.
A completely different topic just to keep you on your toes (or because I’m indecisive)
  1-vs-2 coherent control of vibrational excitations

Summary
Quantum CAT scans
Tomography & control in Lattices

[Myrkog et al., PRA 72, 013615 (05)
Kanem et al., J. Opt. B7, S705 (05)]

Rb atom trapped in one of the quantum levels of a periodic potential formed by standing light field (30GHz detuning, c. 20 $\text{ER}$ in depth)

Goals:
How to fully characterize time-evolution due to lattice?
How to correct for “errors” (preserve coherence,...)?
How to convince the NSA that this is important for building quantum computers?
The workhorse: measuring state populations

Adiabatically lower the depth of the wells in the presence of gravity. Highest states become classically unbound and are lost. Measure ground state occupation.

Two Methods:
- Ramp down and hold. Observe population as a function of depth.

OR
- Ramp down very slowly and observe different states leave at distinct times.
Time-resolved quantum states
Aside: an unrelated interesting result

Fractional wavepacket revivals in a delta-kicked rotor experiment (fractional quantum resonances)

Kanem et al., PRL 98, 083004 (07)
Quantum state reconstruction

\[ Q(0,0) = \frac{1}{\pi} P_g \]
\[ W(0,0) = \frac{1}{\pi} \sum (-1)^n P_n \]

(former for HO only; latter requires only symmetry)

Cf. Poyatos, Walser, Cirac, Zoller, Blatt, PRA 53, 1966 ('96)
& Liebfried, Meekhof, King, Monroe, Itano, Wineland, PRL 77, 4281 ('96)
Recapturing atoms after setting them into oscillation...
...or failing to recapture them if you're too impatient
Oscillations in lattice wells

(Direct probe of centre-of-mass oscillations in 1µm wells; can be thought of as Ramsey fringes or Raman pump-probe exp’t.)
Husimi distribution of coherent state
Data: "W-like" $[P_g - P_e](x,p)$ for a mostly-excited incoherent mixture
Atomic state measurement
(for a 2-state lattice, with $c_0|0> + c_1|1>$)

Initial state:
- Left in ground band.
- Tunnels out during adiabatic lowering.
- (Escaped during preparation).

Displaced:
- $|c_0|^2$
- $|c_1|^2$

Delayed & displaced:
- $|c_0 + c_1|^2$
- $|c_0 + i c_1|^2$
Extracting a superoperator:
prepare a complete set of input states and measure each output

Operation:
Sitting in the lattice
for 1 period.

Likely sources of decoherence/dephasing:
Real photon scattering (100 ms; shouldn't be relevant in 150 μs period)
Inter-well tunneling (10s of ms; would love to see it)
Beam inhomogeneities (expected several ms, but are probably wrong)
Parametric heating (unlikely; no change in diagonals)
Other
Atom echoes
Towards bang-bang error-correction: pulse echo indicates $T_2 \approx 1 \text{ ms}$...

- Free-induction-decay signal for comparison
- Echo after “bang” at 800 $\mu$s
- Echo after “bang” at 1200 $\mu$s
- Echo after “bang” at 1600 $\mu$s

Coherence introduced by echo pulses themselves (since they are not perfect $\pi$-pulses)
Echo from compound pulse

Pulse 900 us after state preparation, and track oscillations

single-shift echo
(≈10% of initial oscillations)

double-shift echo
(≈20-30% of initial oscillations)

Ongoing: More parameters; find best pulse. E.g., combine amplitude & phase mod.

Also: optimize # of pulses.
Cf. Hannover experiment

Far smaller echo, but far better signal-to-noise ("classical" measurement of $<X>$)
Much shorter coherence time, but roughly same number of periods
– dominated by anharmonicity, irrelevant in our case.

Buchkremer, Dumke, Levsen, Birkl, and Ertmer, PRL 85, 3121 (2000).
Why does our echo decay?

Present best guess = finite bath memory time:

So far, our atoms are free to move in the directions transverse to our lattice. In 1 ms, they move far enough to see the oscillation frequency change by about 10%... which is about 1 kHz, and hence enough to dephase them.
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Except for one minor disturbing feature:

These data were first taken without the 3D lattice, and we don’t have the slightest idea what that plateau means. (Work with Daniel James to relate it to autocorrelation properties of our noise, but so far no understanding of why it’s as it is.)
Designing excitation pulses...

Pulses are consisted of time-dependent translations of the lattice (Combination of displacements and time delays)

Atoms are prepared in the lowest state (incoherent filling of the first band)

$U_0 = (18-20)E_R$

3 pulses:

- **Single-step pulse**
  - Displacement
  - Time evolution

- **Square pulse**
  - Time $\tau$

- **Gaussian pulse**
  - Time $\tau_{FWHM}$
Improved echo pulses

Square pulse

Coupling eff. of 3 pulse shapes versus shift
– Theory & Experiment (you guess which is which)

Loss from lattice
Single-step ~71%
Square ~70%
Gaussian ~55%

S. Maneshi et al., quant-ph/0706.3072
Going off the shallow end

The optimal coupling into $|1\rangle$ is $1/e$ in a harmonic oscillator, but rises to 67% (gaussian pulse) in a shallow lattice.

In our vertical configuration, we can’t go that far – have reached about 35% (square pulse).

Further thoughts on excitation pulses:
adiabatic rapid passage
AM + PM (later in this talk)
optimal control (GRAPE, etc)
(very shallow) horizontal lattice
Our thinking shows one-dimensionality
2D Fourier Transform Spectroscopy

2D spectroscopy is a technique to quantitatively distinguish multiple time scales: e.g., the homogeneous and inhomogeneous time scales, and the correlation time.

Method: apply $\omega_{\text{exc}}$ → detect $\omega_{\text{det}}$

inhomogeneous

$\Gamma_{\text{inhomogeneous}} >> \Gamma_{\text{homogeneous}}$

shape of the 2D spectrum

homogeneous
2D Spectrum of Modulation (in progress)

shaking the lattice at different frequencies by phase modulating one lattice beam

- modulation periods:
- modulating for 8 cycles
- amplitude of modulation:
- detected oscillations are Fourier transformed and the 2D spectrum is obtained.
Preliminary data on 2D Spectroscopy of Echo (in progress)

Modulation

Normalized Power Spectrum (Modulation alone)

Modulation + Echo square pulse

Normalized Power Spectrum (Modulation + Echo)
And finally, towards coherent control
One scheme for reducing leakage?

May expect loss $\propto \cos (\phi_{AM} - 2\phi_{PM} - \text{some phase})$

Classical explanation as “sideband engineering,” or something more?
Preliminary evidence for 1+2 coherent control
More preliminary data
(recent enough that we haven’t even agreed on conventions yet!)

EXP’T:

P₀p_vs_AMphase(PMphase=90)

GROUND

LOSS

SIM’S:

LOoss

1st EXC.

GROUND
Spurious phase-dependence of PM alone
Summary

1. We can prepare a variety of quantum states of vibration of atoms in lattice wells, and carry out quantum state & process tomography on them.

2. Decoherence occurs in 3-5 cycles due at least in part to inhomogeneous broadening.

3. Pulse echo can let us probe decoherence and/or the memory function of the inhomogeneities.
   We are surprised by the “fidelity freeze” in 1D and 3D lattices, and by the rapidity of the initial fidelity decay in the 3D case.

4. We have been able to excite as many as 70% of our atoms, and are continuing to work on optimizing pulses for control (& echo “error correction”).

5. We have apparently seem some 1-vs-2 coherent control, but have a lot more to understand.

6. There remain many other strategies to try, starting with ARP.