Some physics motivation for increasing sensitivity

Testing general relativity
- Equivalence principle
- Short range gravity/fifth forces
- Post-Newtonian effects

Gravitational wave astronomy
- Terrestrial and space detectors

Tests of QED
- Photon recoil (alpha measurements)

Tests of quantum mechanics
- Macroscopic superposition states
- Decay of coherence
Large wavepacket separation

- Long interferometer time (>2 seconds)
- Large momentum transfer beam splitters (>10 ℏk)

[Diagram showing particle paths and time intervals with 4 cm scale]

\[ m \quad \pi \quad \text{Time} \quad 0 \quad \pi \quad 2\pi \quad 2\pi \]
Light Pulse Atom Interferometry

- 1D (vertical) atomic fountain
- Atom is freely falling
- Lasers pulses are atom beamsplitters & mirrors (Raman or Bragg atom optics)
- \[ \frac{\pi}{2} - \pi - \frac{\pi}{2} \] pulse sequence
Apparatus

Ultracold atom source
- >10^6 atoms at 50 nK
- 3e5 at 3 nK

Optical Lattice Launch
- 13.1 m/s with 2372 photon recoils to 9 m

Atom Interferometry
- 2 cm 1/e² radial waist
- 500 mW total power
- Dynamic nrad control of laser angle with precision piezo-actuated stage

Detection
- Spatially-resolved fluorescence imaging
- Two CCD cameras on perpendicular lines of sight

Current demonstrated statistical resolution, ~5 ×10^{-13} g in 1 hr (^{87}\text{Rb})
Ultra-cold atom source

BEC source in TOP trap, then diabatic steps in strength of trap to further reduce velocity spread:

Atom cloud imaged after 2.6 seconds free-fall
No apparent heating from lattice launch
Interference at long interrogation time

Wavepacket separation at apex (this data 50 nK)

2T = 2.3 sec
Near full contrast
6.7×10^{-12} g/shot (inferred)

Interference (3 nK cloud)

LMT and Optical Lattice Acceleration
Large momentum transfer

**Need to transfer momentum to atoms**
- Large momentum transfer (LMT) beamsplitters enhance sensitivity: $k_{\text{eff}} = Nk$
- Launching atoms in fountains
- Generally moving atoms from one place to another

**General requirements**
- Efficient
- Coherent
- Fast
- Minimal phase errors (for interferometry)

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**Diabatic**
- Sequential Raman/Bragg
- Multi-photon Bragg

**Adiabatic**
- Optical lattice (Bloch oscillations)
- ARP Raman
Diabatic LMT processes

- Sequential Raman
  \[ |1, p + 2\hbar k\rangle \xrightarrow{(\text{flip})} |1, p + 4\hbar k\rangle \]

- N-Photon Bragg
  \[ |p + 2\hbar k\rangle \xrightarrow{\text{(flip)}} |p + 4\hbar k\rangle \]

- Sequential 2-Photon Bragg
  \[ |p\rangle \xrightarrow{\text{(flip)}} |p + 4\hbar k\rangle \]
Nearby levels limit the Rabi frequency for sequential Bragg.

Breakdown of the two-level Bragg picture

\[ \Omega = 0.01E_R \]
\[ \Omega = 4E_R \]
\[ \Omega = 8E_R \]

\[ \Omega \ll 8E_R \]

Optical lattice circumvents this speed limit by overlapping several Bragg transitions in time.
**Optical lattice**

**Optical lattice acceleration:**
- Adiabatic evolution of the ground state of the Bragg Hamiltonian
- Atom in a superposition of free space momentum eigenstates
- Fast, efficient momentum transfer

Effective Bragg Hamiltonian (with time dependent optical frequencies):

\[
H = \frac{\hat{p}^2}{2m} + \hbar \Omega \cos (2k(x - \xi(t)))
\]

\[
\xi(t) = \frac{1}{2k} (\Delta \omega_0 t + \frac{1}{2} \alpha t^2)
\]

“Standing wave” potential moving with velocity

\[
\dot{\xi}(t) = \frac{1}{2k} (\Delta \omega_0 + \alpha t)
\]
"Solid State" picture

\[
|\Psi_{\text{lab}}\rangle = \left( e^{-i\xi(t)\hat{p}} \right) \left( e^{i\int \frac{m}{2} \xi^2 dt} \right) |\Psi_{\text{ss}}\rangle
\]

\[
H_{\text{ss}} = \frac{(\hat{p} + q)^2}{2m} + \hbar \Omega \cos(2k\hat{x}) \quad q \equiv -m\ddot{\xi} = -m\frac{\Delta \omega_0 + \alpha t}{2k} (\text{quasimomentum})
\]

- Energy eigenvalues form band structure
- Adiabatic acceleration: atom stays in ground state as quasimomentum grows

\[ \hbar \Omega = 1.5 \ E_R \]

Lattice acceleration simulation

Lattice Ramp Up $\rightarrow$ Acceleration $\rightarrow$ Lattice Ramp Down

$\Omega = 20E_R$

$|0\hbar k\rangle$

$|\pm 2\hbar k\rangle$

$|\pm 4\hbar k\rangle$

$^{87}\text{Rb} \rightarrow \omega_R^{-1} \approx 40\,\mu s$
1) Landau-Zener tunneling
- Diabatic transition to higher band
- Atom tunnels out of lattice

Loss probability:
\[ P_{LZ} = \exp\left[-\frac{\pi \Omega_{bg}^2}{2 \alpha}\right] \]

\[ \Omega_{bg} \approx \Omega_{\text{eff}} = \frac{\Omega_1 \Omega_2}{2 \Delta} = \frac{\Gamma (I/I_{\text{sat}})}{2 (2\Delta/\Gamma)} \]

2) Spontaneous emission
- Absorption followed by incoherent scattering

Scattering rate:
\[ R_{sp} = R_{sp}^{(1)} + R_{sp}^{(2)} = \Gamma \frac{I/I_{\text{sat}}}{1 + (2\Delta/\Gamma)^2} \]

\[ (\text{both beams}) \]

*Can be mitigated using blue detuning*
Red vs blue detuning

Ground state lattice eigenstate overlap with laser intensity depends on sign of detuning:

Red detuning

Blue detuning

Atoms confined at intensity maxima

Light intensity

Wavefunction overlap with light decreases with increasing lattice depth
Optical lattice launch in the 10 m fountain

Small $1/e^2$ waist for high intensity:
- Lattice launch beams: 1.5 mm
- Atom optics beams: 2 cm

Off-axis beam delivery advantages:
- Higher lattice intensity
- No reflection lattice parasite
- Spontaneous emission suppression
  (for blue detuning)

6 m peak height
2.23 s drift time
11.1 m/s launch velocity
150 g acceleration

2.6 cm = (2.23 s)(2\(h\kappa/m\))

launch of 1950 photon recoils

launch of 1951 photon recoils
Measured launch performance

Lattice launch efficiency preliminary parametric study:

- Qualitative correspondence with loss theory (LZ tunneling, spontaneous emission)
- Blue detuning enhances performance

See also blue vs. red heating (theory): H. Pichler, PRA 82, 063605 (2010).
Delta Kick Cooling
Delta kick cooling in a harmonic trap

At the end of evaporation BEC:

- Atom number: $\sim 10^6$ atoms
- Cloud diameter: 10 -- 50 μm
- Temperature: $\sim 1$ μK (from chemical potential)

Harmonic Lens:

- $t = 0$
- $t < t_{\text{Lens}}$
- $t = t_{\text{Lens}}$
- $t = t_{\text{Lens}} + \varepsilon$

$$\frac{T_f}{T_i} = \left(\frac{\Delta x_i}{\Delta x_f}\right)^2$$

Ammann & Christensen, PRL 78, 1997
Magnetic lens in a harmonic trap

\[ \text{Position} \]

\[ \text{Time } [2\pi/\omega] \]

Trap turned off
Magnetic lens in a harmonic trap

![Graph showing position over time with the trap turned off at a specific point.](image)
Magnetic lens in a harmonic trap

Residual velocity is $x_0\omega$

$\frac{T_f}{T_i} = \left(\frac{\Delta x_i}{\Delta x_f}\right)^2$
Oscillations in a TOP trap

Absorptive images of atoms released into weak TOP potential (3.7 G & 25 G/cm)

Cloud width oscillations (breathing modes)

anisotropy
Isotropic turning points in a TOP trap

Tune radial and vertical trap frequencies of gravity + TOP trap using field gradient.

Absorptive images of atoms released into weak TOP potential (3.7 G & 22.9 G/cm)

Cloud width oscillations (breathing modes)

- Radial
- Vertical

TOP turn-off time
Another solution: optical lattice confinement

Lattice locks atoms vertically
Lattice Solution to Anisotropy

Another solution: optical lattice confinement

Radial (two-dimensional) expansion
Lattice Solution to Anisotropy

Another solution: optical lattice confinement

Lattice turns off  --  Expansion in three dimensions
Lattice Solution to Anisotropy

Another solution: optical lattice confinement

Turn off trap
Lattice-Aided Lens Cooling

Cloud launched to 9 meters

20x colder (50 nK)
Extending to colder temperatures

- Delta kick in micro gravity: weaker potential, more expansion
- Multiple lens sequences
- Apply additional kick at the fountain turning point
- Apply optical potential for radial delta kick (high power AI laser)
AC Stark Lens

Apply transient optical potential ("Lens beam") to collimate atom cloud in 2D

Lens beam parameters:
3 mm radial waist, ~3 Watts, 1 THz red detuned, ~30 ms duration (typical)
2D AC Stark Lens

No Lens  With Lens

North View  

West View  

Demonstrated refocusing in 2D

Atom cloud radius <200 microns (resolution limited) after 2.6 seconds drift!
Focusing atom cloud with AC Stark lens

**Vary effective focal length of AC Stark lens by changing lens pulse duration**

Collimating lens:

- Apply lens near top of fountain (~ 1 s TOF)
- With collimating lens, delta kick theory suggests temperature $< 100$ pK (!)

$$\frac{T_f}{T_i} = \left( \frac{\Delta x_i}{\Delta x_f} \right)^2$$

**Challenge:** Measure pK temperature when TOF expansion is small compared to size.

Work ongoing!
Initial application: Relaunch sequence

• Launched to 9.375 meters
• Relaunched to 6 meters
• 5 seconds total free fall time
• Not possible without lens
Collaborators

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