Atom Interferometry using Bose-Einstein Condensates

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Research Talk
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Outline

• Condensate interferometry

• Making BEC

• Our interferometer

• Polarizability measurement
What is atom interferometry?

Just like optical interferometry:

Gratings can split and recombine waves - whether from Maxwell or Schrodinger equations
Differences between atoms and light:

**Light:**
- Easy to manipulate
  - beams in air
  - mirrors, beamsplitters
- High flux ($10^{16}$ photons/s)

**Atoms (thermal beam):**
- Hard to manipulate
  - atoms in vacuum
  - gratings
  - small deflection angles
- Low flux ($10^9$ atoms/s)
Differences between atoms and light:

**Light:**
- Easy to manipulate
  - beams in air
  - mirrors, beamsplitters
- High flux \(10^{16} \text{ photons/s}\)
- Weak interactions with environment

\[
\phi = \frac{2\pi n}{\lambda} \Delta d
\]
- path length difference \(\Delta d\)
- index of refraction \(n\)

**Atoms (thermal beam):**
- Hard to manipulate
  - atoms in vacuum
  - gratings
  - small deflection angles
- Low flux \(10^9 \text{ atoms/s}\)
- Strong interactions with environment

\[
\phi = \frac{t}{\hbar} \Delta E
\]
- energy difference \(\Delta E\)
- interaction time \(t\)
Applications

Can measure anything that changes energy of an atom:
- All kinds of EM fields (external or collisions)
- Gravity

Also inertial effects:
- Acceleration and rotation

Light also sensitive to inertial effects
  but atoms more sensitive by $mc^2/\hbar \omega \sim 10^{10}$
Applications

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Potential uses:
- Fine-structure constant
- Atomic properties
- Surface characterization
- Quantum light detection
- Magnetometry
- Inertial navigation
- Geophysics
- Oil exploration

Many already realized with thermal atom interferometers
Making an interferometer

First need to make a condensate!

BEC happens when \( \Lambda \approx \ell \)
   deBroglie wavelength \( \approx \) interparticle spacing

In air: \( \Lambda = 10^{-11} \text{ m} \), \( \ell = 10^{-9} \text{ m} \)
   \( \Lambda \sim T^{-1/2} \), so could cool air to 30 mK
      - but gases freeze first

Need to use dilute gas to avoid making solid or liquid
   \( \Rightarrow \) Get much colder
Making BEC

Use $^{87}\text{Rb}$ atoms

Aim for $T \sim 100 \text{ nK}$, $n \sim 10^{13} \text{ cm}^{-3}$ (about $10^{-6} \ n_{\text{air}}$)

Achieve with 3 steps:
1. Laser cooling
2. Magnetic trapping
3. Evaporative cooling

Discuss briefly
Laser Cooling

Start with gas of rubidium atoms

Shine lasers from all directions tuned below atomic resonance

Doppler shift:
- moving atoms scatter light from beam opposing motion

Atoms slow down = cool

Get sample of cold atoms:

\[ N \approx 4 \times 10^9 \text{ atoms} \quad T \approx 250 \mu\text{K} \quad n \approx 3 \times 10^{11} \text{ cm}^{-3} \]

\[ n\Lambda^3 \approx 5 \times 10^{-7} \quad \rightarrow \quad \text{Limited by opacity of cloud} \]
Magnetic Trap

Can’t get much colder or denser with laser cooling

Transfer to magnetic trap:

Rb atoms have one unpaired electron

Get energy shift in field due to magnetic moment

\[ V = 2\mu_B B m_S \]

\( \mu_B = \) Bohr magneton = 58 \( \mu \)eV/T = 67 \( \mu \)K/G

\( m_S = \) spin quantum number = \( \pm \frac{1}{2} \)

For \( m_S = +\frac{1}{2} \) state, have \( V = \mu_B B \)

energy high when \( B \) high

\[ \Rightarrow \text{atom attracted to region of low } B \]
So atoms trapped near minimum in \( B \)

Easy way to achieve: two opposed coils
   Get \( B = 0 \) in center
   Can’t get lower than that!

Switch off lasers, turn on magnets

Good isolation from environment:
   - Lifetime about 100 s
   - Negligible heating

Gives linear potential
   (We actually make it harmonic)
So atoms trapped near minimum in $B$

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Evaporative Cooling

How to get colder? Take away hot atoms

Drive transition $m_S = +\frac{1}{2} \rightarrow -\frac{1}{2}$ using rf field

Only resonant if $\hbar \omega_{\text{rf}} = 2 \mu_B B$

Tune $\omega_{\text{rf}}$ above trap bottom:
- only energetic atoms ejected

Take away more than average energy
- remaining atoms colder

Continue to BEC
- $N \approx 2 \times 10^4$ atoms
- $T \approx 200 \text{ nK}$
Condensate Production

Just before condensation:
evaporate to 2.95MHz

Initiate condensate formation:
evaporate to 2.90MHz

Mostly condensate:
evaporate to 2.77MHz

Absorption images:
Shine laser on atoms, observe shadow
Interferometry

So we got a condensate… yay!

Want to make an interferometer:
   Split wave function apart and later recombine

Hard to do in trap:
   - packets can’t move very far apart

But if we turn off trap, atoms fall in gravity
   - hard to deal with

Our solution: put atoms in magnetic waveguide
Atom Guide

Two dimensional trap
- like optical fiber for atoms

Send atoms wherever we want

Basic design:
four wire, linear quadrupole

Line with $B = 0$ at center of rods
Confines atoms to axis

Again gives linear potential...
use tricks to make harmonic
Waveguide Construction

Copper rods provide fields
Rod spacing ~ 1 cm

All inside vacuum chamber at $P \sim 10^{-11}$ torr
Make BEC inside guide structure
Interferometry

Basic scheme:
- Split into two packets
- Packets fly apart
- Turn around via reflection
- Packets come back together
- Apply splitting operation again
Interferometry

Basic scheme:
- Split into two packets
- Packets fly apart
- Turn around via reflection
- Packets come back together
- Apply splitting operation again

Quantum operations are reversible:
- If $\psi$ unchanged, atoms brought back to rest
But if packets have phase shift $e^{i\phi}$, $\psi$ is not the same
  - Atoms keep moving
Probability to come to rest $\sim \cos^2\phi$
Splitting

Implement with standing wave laser beam

Intensity: 

Laser tuned far from resonance
- no absorption

But do get energy shift $\propto$ intensity

$$V_{\text{laser}} = \beta \cos^2(kz)$$

(atoms are dielectrics: field induces dipole moment $p \propto E$, get energy $pE \propto E^2 \propto I$)
Two pictures:

1) Atom wave diffracts from light potential just like light diffracts from grating

±1 diffraction orders
move at \( v_0 = \frac{2\hbar k}{M} = 1.2 \text{ cm/s} \)
(from grating spacing \( \lambda/2 \))

2) Atoms absorb photon from one beam, emit into other

Net momentum transfer \( 2\hbar k \)

Reverse process gives \(-2\hbar k\)
Interferometer experiment

Atoms make full oscillation:

(split) reflect reflect split

\( T \)

(Trap gradients cancel out in 2\textsuperscript{nd} half)
\[
\frac{N_0}{N} = \frac{1}{2} (1 + \cos \phi)
\]

0 phase  \hspace{1cm} \pi/2 phase  \hspace{1cm} \pi phase
Interference!

![Graph showing interference pattern with Applied Phase on the x-axis and $N_0/N$ on the y-axis. The graph features a red curve with data points and error bars.](image)
Interferometer visibility

Visibility vs. Total interferometer time [ms]

- Data points
- Model curve
Arm Separation

Get interferometer time \(~80\) ms

… competitive with non-condensate techniques

Have record for \textit{arm separation} \(~0.4\) mm

- Useful for putting different arms in different environments
- Allows measurement of more different phenomena

Example: interactions with surface
- need one packet to hit surface, other not
- easier if packets well separated

Also, neat to make “macroscopic” quantum states
Our atoms separate for time $T/4 = 18$ ms

Picture of split packets:

Separation = 0.42 mm
= 4 sheets of paper

In most other experiments, separation $\sim 10$ µm, if at all

Get literal picture of distinct atomic waves that are quantum coherent
Applied interferometer to first measurement:
Electric Polarizability

\[ \alpha \text{ defined by } U = -\frac{1}{2} \alpha \langle \vec{E}^2 \rangle \]

Related to:
- Index of refraction
- Electron and ion scattering
- Van der Waals interactions
- Rayleigh scattering
- Casimir-Polder effect

Proof of importance: it’s in the CRC
Measure at optical frequencies:

Apply intensity $I$ for time $\tau$

Measure phase $\phi \propto \alpha I \tau$
Polarizability Results

\[ \alpha_{\text{exp}} = (8.37 \pm 0.24) \times 10^{-25} \text{ m}^{-3} \]

\[ \alpha_{\text{th}} = 8.67 \times 10^{-25} \text{ m}^{-3} \]

\[ \alpha_{\text{exp}} = (9.48 \pm 0.25) \times 10^{-28} \text{ m}^{-3} \]

\[ \alpha_{\text{th}} = 9.14 \times 10^{-28} \text{ m}^{-3} \]

Most accurate measurement to date
Polarizability for resonant light:

Get dispersion shape, like index of refraction
Next big measurement:
Measure dc polarizability

Apply static field instead of laser

\[ V \]

Should work much better:
Laser beams noisy, hard to calibrate

With dc measurement, hope to get $10^{-3}$, $10^{-4}$ precision

Makes sensitive test of atomic structure theories
Special motivation: atomic clocks

SI second currently defined by Cs hyperfine transition freq

But Cs atoms don’t work well at low temperatures:
- Rb atoms give better performance
  Rb being considered as new standard

One limitation: black-body shift
  Transition shifted by thermal radiation
  effect $\sim \alpha_{dc}$
  Need to account for this, but $\alpha$ not known well enough

Better measurement would help resolve problem
Conclusions

Condensate interferometry has good prospects for precision measurements.

Demonstrated 80 ms coherence time and 0.4 mm arm separation
- biggest for any atom interferometer

Used to measure ac polarizability

Plan to measure dc polarizability next

Credits...
Group members

Ben Deissler, Ofir Garcia, CAS, Eun Oh, Jeramy Hughes, John Burke

Funding:

[NSF logo]
[GBECi logo]
[DARPA logo]
Loading Guide

- BEC formed in center of guide
- Gradually decrease 3D trap, Increase linear quadrupole

Get adiabatic transfer to guide
no losses observed

Linear trap is very weak
Residual confinement from leads:
\[ \omega/2\pi \sim 1 \text{ Hz} \]

Adiabatic expansion:
Cool to below 1 nK
Measurement

Let moving atoms propagate, then take picture:

Measure $N_0/N = \text{fraction of atoms ending at rest}$
Results

Clear interference for $T$ up to 44 ms

Adjust $\phi$ by shifting phase of standing wave before final split

Visibility = $\frac{\text{max} - \text{min}}{\text{max} + \text{min}}$

$= 0.45 \pm 0.1$
For large $T$, output fluctuates from run to run.
- interferometer is noisy.
How does 44 ms compare?

Similar experiment demonstrated at Univ. Colorado:


Coherence time limited to 10 ms

Other BEC methods encounter similar limits:

Saba et al., *Science* 307, 1945 (2005) ~ 1 ms

For a while, we held record, but then…

Jo et al., cond-mat/0608585 (MIT) ~ 200 ms

Note, non-condensate interferometers now up to

$T \sim 400$ ms… some work to do!
Difficulties

Interference limited by many effects:
- Environmental B fields
- Trap field fluctuations
- Mechanical vibrations
- Stability of laser
- Residual condensate motion
- Atomic interactions

JILA experiment: interactions were main problem
Olshanii and Dunjko, cond-mat/0505358
Interactions

Atom in BEC repel each other

JILA experiment:
\[ N \approx 5000 \text{ atoms} \]
\[ \omega_{\perp} \approx 2\pi \times 100 \text{ Hz} \]
\[ \omega_z \approx 2\pi \times 5 \text{ Hz} \]

Interaction energy \( \approx 160 \text{ Hz/atom} \) (~3 rad in 3 ms sep. time)

Extra phase for green
Extra phase for blue

Position dependent phase degrades contrast
Our solution: use lower density

\[ N \approx 5000 \text{ atoms} \]

\[ \omega_\perp \approx 2\pi \times 4 \text{ Hz} \]

\[ \omega_z \approx 2\pi \times 1 \text{ Hz} \]

Interaction energy \( \approx 10 \text{ Hz/atom} \)

- reduces separation phase to \( \sim 0.2 \text{ rad} \)

We developed special techniques for weak confinement

- seems to work

Recent MIT experiment works differently

- but also at limit of interaction noise

We should be able to get up to \( T \sim 1 \text{ s} \)
Technical problems

Identified two problems
1) Atoms were moving in trap

Plot \((x,y)\) position of condensate for several runs:

- Position varies by \(\sim 100 \, \mu\text{m}\)

In 1-Hz harmonic oscillator, corresponds to \(v \sim \omega y \sim 0.5 \, \text{mm/s}\)

- Large enough error to spoil laser pulses
Atom motion seemed random

But try synchronizing experiment to 60 Hz:

Why does 60 Hz matter?

When loading atoms into guide, \( \omega \) passes through 60 Hz

\[ \rightarrow \text{Stray fields excite motion} \]

Fix by doing all evaporation with \( \omega/2\pi < 60 \) Hz

Problem seems fixed!
Second problem: splitting effectiveness varied from run to run.

Seemed like intensity variation in light, but laser power was stable, beam profile uniform.

Monitor setup:
- camera or photodiode
- vacuum chamber
- glass windows
Pictures looked OK:

Then looked at beam reflected from mirror:

Horrible noise:
Noise from interference in glass windows
- very sensitive to position of chamber, beam

Got new chamber with anti-reflection coated windows,
looks much better

Getting ready to install… hope to see much improvement
Next steps

Want to use interferometer to make a real measurement

Electric polarizability:
In electric field $E$, energy shifts by $-\frac{1}{2} \alpha E^2$

Polarizability $\alpha$ related to many atomic properties

Last measured for Rb in 1974, with 1% precision
Modern measurements for Li, Na, Cs: $10^{-3}$ precision
With condensate interferometer, aiming for $10^{-4}$
(even with existing performance)
Measurement method

- Put condensate between two plates
Measurement method

- Put condensate between two plates
- Separate as before
Measurement method

- Put condensate between two plates
- Separate as before
- Apply voltage pulse to one side
Measurement method

- Put condensate between two plates
- Separate as before
- Apply voltage pulse to one side
- Recombine and measure $\phi$