Quantum-gas physics in orbit

prospects for microgravity Bose-Einstein condensates aboard ISS with NASA CAL (Cold Atom Laboratory)

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GUIDING QUESTIONS

➢ Can experiments on ultracold atoms shed light on fundamental physics issues?

➢ Can we use ultracold atoms to do something “useful”?

➢ How close to absolute zero can we get?
Portland, Maine has a 'snow dump' so tall that it's posing a hazard to aircraft.
Outline

➢ Bose-Einstein condensation refresher
➢ NASA CAL
➢ Tailored bubbles of quantum gas aboard CAL
➢ Tailored lattices for terrestrial BEC
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Given some local minimum in potential energy, how does a cloud of $N$ atoms in equilibrium at temperature $T$ (of order the energy-level spacing but not zero) distribute among the energy levels?

- Maxwell-Boltzmann statistics (distinguishable)
- Fermi-Dirac statistics
- Bose-Einstein statistics
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Startling pileup in the lowest-energy state at nonzero \( T \)!
"I maintain that, in this case, a number of molecules steadily growing with increasing density goes over in the first quantum state (which has zero kinetic energy) while the remaining molecules separate themselves … A separation is effected; one part 'condenses', the rest remains a saturated ideal gas."
I maintain that, in this case, a number of molecules steadily growing with increasing density goes over in the first quantum state (which has zero kinetic energy) while the remaining molecules separate themselves into two parts — one part...
20 years of BEC

MIT 1995 sodium; also 1998 hydrogen

(JILA 1995)


MPQ

JPL 2005
Early growth of a field

➢ ~30 ultracold labs in 2001, ~150 today?

➢ 1999: first degenerate Fermi gas (DFG)

➢ 1998-2002: early development of BECs in periodic potentials (“optical lattices”)

➢ 2002: observation of Mott-insulator/superfluid transition of a BEC in an optical lattice

➢ ultracold molecules at various stages…
Making BECs & terrestrial limitations

➢ Source: alkali (among many more now) vapors or beams

➢ Laser cooling to roughly sub-mK temps

➢ Transfer to conservative trap: optical or magnetic

➢ Evaporative cooling to nK regime

➢ Lower T... weaker trap? Collision rate limits equilibration (as does background vacuum pressure)

➢ $m g / k \ (\text{Rb}) = 0.1 \text{ mK / mm}$
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(trap sag)
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BEC physics in microgravity

➢ **NASA CAL:** BEC machine in (extended, orbital) microgravity.

*What does freefall give us?*

➢ Very *long* interrogation times of released clouds (opportunity for attempts at pK temperatures)

➢ Very *weak* traps without sag or dumping

➢ Symmetry: no more *mgz* preferential direction!
CAL mission architecture

Human Exploration and Operations Mission Directorate:
Space Life and Physical Sciences Division:
Physical Science Research Program
NRA: Research Opportunities in Fundamental Physics

Image courtesy NASA/JPL
Pressurized cargo vehicle aboard Dragon
EXPRESS rack
CAL in rack / Science Module
CAL in rack / Science Module
BEC as user facility?

➢ Single-mode fiber coupling
➢ Polarization control
➢ Optical alignment in general
➢ Laser or atomic source replacement?
New: Portable Ultracold Atom Lab
Roll your BEC or ultracold atom system to your desired location in your premises. The system consists of an ultra-high vacuum cell, complete physics package and all the required electronics, lasers, optics, and imaging equipment to create and image Bose-Einstein condensate and forms of ultracold atoms
NASA CAL science projects

➢ "Coherent magnon optics"

➢ "Atom interferometry with quantum gases in microgravity"

➢ "Zero-g Studies of few-body and many-body physics"

➢ "Microgravity dynamics of bubble-geometry BEC"

➢ "High-precision microwave spectroscopy of long-lived circular-state Rydberg atoms in microgravity"

➢ "Consortium for Ultracold Atoms in Space"

➢ "Development of Atom Interferometry Experiments for ISS CAL"
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Atom interferometry

➢ NIST F1 time standard (Cs fountain)
➢ Evolution time limited by gravity
➢ Can do interferometry with BECs…

Kasevich 2008

NIST

MIT
FIG. 1. Phase-space diagrams. (a) Upon release from a trap, the atoms have independent Gaussian distributions in position and momentum. (b) After a period of free expansion, position and momentum are partially correlated, leading to a tilted ellipse in phase space. (c) Application of a pulsed harmonic potential rotates the distribution onto the x axis, lowering the temperature of the cloud.

Myrskog 2000
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New BEC geometries

➢ History of the field has been an exploration of geometry, dimensionality and topology. 1D condensates, 2D condensates (BKT physics), toroidal condensates, box condensates, double-wells.

➢ Proposal: a bubble-geometry BEC system: i.e. local minimum of a potential at nonzero radial position (spherical or elliptical)

➢ Features: boundary-free system, new kinds of collective excitations, possibly interesting vortex behavior, expansion dynamics, 1D/2D crossover, neat dynamical engineering of potentials…
➢ Take levels with **opposite potential curvature** and apply some external coupling $\Omega$ (perhaps rf or microwave for ground-state Zeeman sublevels).

➢ Lower adiabatic potential used for evaporative cooling: upper one less used

➢ Theory straightforward...move to rotating frame w/ RWA, get the coupled/dressed/adiabatic potentials with LZ gap $\sim \Omega$

➢ Spatially-dependent spin superposition
Radiofrequency dressing

- Slice through 3D bubble potential

- Dressed gap increases with coupling, suppressing nonadiabatic losses

- Bubble radius increases with detuning

- Shell trap-frequency (controlling 1D vs 2D bubble) decreases with coupling
Why not terrestrial bubbles?

➢ “2D” slice with tilt: depending on bubble radius, BEC won’t live on shell

➢ Can maybe play with very strong traps, also light-shift gradient compensation: tough!

➢ Significant work done by Perrin group (Paris), Demarco (UIUC) creating 2D condensate held by gravity at bottom of a bubble potential. Also Foot (Oxford) similar work in a TAAP

➢ In this case folks deliberately use gravity: we are seeking to complete this shell/bubble!


White….DeMarco, PRA 74 023616 (2006)
Possible observations

➢ “Accordion” mode, “balloon” mode oscillations (match up w/ theory over parameter space)

➢ “Collapse” of shell in time-of-flight

➢ 2D-3D crossover (thick/thin shell)?

➢ Vortex dynamics on curved surface and on unbounded simply-connected surface (possibly more interesting on ellipsoidal shell- nonconstant curvature)

(vortices are repelled from regions of positive curvature and attracted to regions of negative curvature, independent of direction of circulation)

Lannert et al. unpublished

Lannert….Vishveshwara, PRA 75, 013611 (2007)
Challenges!

➢ Aspect ratio & geometry

Spherical likely impossible, but 2:1, 3:1... shouldn’t affect physics too much as long as initial condensate isn’t effective 1D (although worth exploring anyway)

➢ Heating?

Dressing needs to be very low-noise: phase-coherent sweeping, very stable trap...

➢ Uniformity?

Few nK shift, compare to chem. potential

Cause: wandering of angle of trap bias field...

➢ Adiabaticity?

Rabi frequency of rf coupling needs to be 10s of kHz otherwise system will just decay to lowest adiabatic potential (Landau-Zener problem, or Born-Oppenheimer failure)

Next steps

➢ Bates & JPL: building Bates-local mockup of CAL-chip BEC machine, study dressing process on machines as close to flight hardware as possible

➢ Focus on: adiabaticity, trap uniformity, heating and frequency stability, LZ losses, diagnostics & imaging, BEC thermometry, \( \Omega \) calibration...

➢ Theory work- excitations, dimensionality, trap shape and confinement, vortices, uniformity and chemical potential issues

➢ Development of dressed-state intuition with primary Bates BEC machine.

➢ Direct tests of current terrestrial sagged-bubble ideas and theory
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BEC research at Bates

➢ Solid-state analogues with BECs loaded into nonstandard optical lattices

➢ BEC machine: hybrid magnetic/optical trap: exploit trap volume & ease of magnetic trap and stable/spinor nature of optical trap

\[ T \approx 1800 \text{nK}, N \approx 3 \times 10^6 \]

\[ T \approx 400 \text{nK}, N \approx 1 \times 10^6 \]

\[ T < 100 \text{nK}, N \text{ BEC} \approx 2 \times 10^5 \]
Using a BEC to simulate solid-state physics

➢ Now what to do? Take the BEC and raise up a periodic potential!

ANALOGOUS to electrons moving in the crystal lattice of a solid

➢ NEED BEC: these sine potentials are weak, also want ground state

➢ can perform quantum simulation of particles in a crystal lattice
Optical lattice menagerie

- Solid-state simulation, arrays of neutral-atom qubits, dimensionality...

- Quantum phase transition from a superfluid to a Mott insulator in a gas of ultracold atoms

- Observation of a One-Dimensional Tonks-Girardeau Gas

- Imaging single atoms in a three-dimensional array

- Controlled exchange interaction between pairs of neutral atoms in an optical lattice

- Single-spin addressing in an atomic Mott insulator

- Time-Resolved Observation and Control of Superexchange Interactions with Ultracold Atoms in Optical Lattices

- Realization of the Hofstadter Hamiltonian with Ultracold Atoms in Optical Lattices
LIGHT FORCES

Laser light

Focused laser beams, RED or BLUE of resonance

$\alpha < 0, \alpha > 0$

Atomic polarizability:

$\alpha(\lambda)$

$U(r) = -\langle d \cdot E \rangle \propto -\alpha |E(r)|^2$

Intensity $\sim E^2$
Any intensity pattern yields a potential energy surface

\[
\mathcal{I}(x) \sim (\varepsilon_1 + \varepsilon_2) \cdot (\varepsilon_1^* + \varepsilon_2^*) = \mathcal{I}_1 + \mathcal{I}_2 + 2\sqrt{\mathcal{I}_1 \mathcal{I}_2} \cos\left(\frac{2\pi x}{\lambda/2}\right)
\]
OPTICAL LATTICES

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Red-detuning: attractive
Blue-detuning: repulsive

Any intensity pattern yields a potential energy surface
OPTICAL LATTICES

1D
2 beams: pile of wells
atoms form quasi-2D traps

2D
4 beams: bundle of long, skinny wells
atoms form quasi-1D systems

3D
6 beams: complete 3D lattice: simple cubic
“optical crystal” (minima every half-wavelength)

Detuning beams: atoms average over high frequency interference terms
➢ (Very) spin-dependent 1D optical lattice for $^{87}\text{Rb}$

➢ Circularly-polarized lattice beams at 790.06 nm (tune-out wavelength) between D1 and D2
Radiofrequency dressing

- (Very) spin-dependent 1D optical lattice for $^87\text{Rb}$
- Circularly-polarized lattice beams at 790.06 nm (tune-out wavelength) between D1 and D2
- dressed picture, with upper and lower adiabatic potentials
- which “bare” (lab-basis) spin state you’re in depends on where you are...
- real-time alteration of lattice properties (periodicity, tunnelling, interaction, etc.)
Radiofrequency dressing

\[ U(x,m) \quad U^*(x,m) \]
\[ \Omega, \hbar \omega \]

"bare"optical potential for \( m = -1 \)

\[ \mathcal{H}(\mathbf{r}) = \begin{pmatrix} U(x,-1) - \delta & \Omega/2 & 0 \\ \Omega/2 & U(x,0) & \Omega/2 \\ 0 & \Omega/2 & U(x, +1) + \delta + \delta' \end{pmatrix} \]

coupling
1D momentum-space data

➢ bare lattice
(orders spaced at twice lattice photon momentum)

➢ ramp up lattice, turn on rf off-resonance,
ramp B-field over few ms to dress the system
1D momentum-space data

➢ bare lattice
(orders spaced at twice lattice photon momentum)

➢ dressed near (not at) the $\lambda/4$ "sweet spot"

$2\hbar k$

components predicted from simple Bloch theory

$2\hbar k$

note +/- 4, 6, note "long tail"
Momentum-space distortion signature

Nonadiabatic losses

upper adiabatic pot'l

dressed wavefunctions

gap $\Omega^*$

“LZ” loss to high-momentum states of lower potentials

lower adiabatic pot'l

- These aren’t an issue at all for realistic parameters in magnetic traps (external or on-chip); nm length scale fuels the loss.

- Limiting factor in proof-of-principle 2D-lattice work at NIST in 2007
Nonadiabatic losses

\[ \text{gap } \Omega^* \]

Observed loss vs. model scaling for photon scattering.

- Loss rate (s\(^{-1}\))
- Coupling parameter \( \Omega^*/\omega^* \)

Graph showing observed loss data with error bars, model scaling, and photon scattering trends.

Lossy, SG

Stable

Lossy
Next...2D?
Next...2D?
Takeaways

➢ Quantum gases: almost twenty years of insights into quantum mechanics (single-particle and many-body), statistical physics & thermodynamics, precision measurements...

➢ NASA CAL: BEC machine in (extended, orbital) microgravity.

➢ Can tailor geometries for BEC with a diverse toolbox

➢ Can tailor geometries for BEC with optical-lattice interference and rf-dressing techniques.

➢ Can do BEC physics at an undergraduate institution!
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➢ NASA CAL collaborators

➢ Courtney Lannert (UMass / Smith College)

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➢ Bates group:

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  Spencer Goossens ‘15
  Tiago Correia ‘17

➢ New postdoc Tom Jarvis

➢ Recent work: Chris Guo (Stanford Mech. Eng.), Eddie Moan (UVA physics), Saad Ansari (physics TBA)

$:\textbf{NASA CAL}: \text{JPL RSA No. 1502172}$ \hspace{1cm} \textbf{also}: AFOSR , NSF MRI
Apply B-gradient during time-of-flight expansion to separate out lab-basis spin components.
Effects of coupling strength

- **LOSSY**
  - Energy levels increasing with coupling strength
  - $\Omega^* \simeq 0.3U_0$

- **STABLE**
  - Energy levels constant
  - $\Omega^* \simeq 1.8U_0$

Increasing coupling strength