Doing condensed matter physics with the ultracold atomic gases

Victor Gurarie

University of Wyoming, Feb 26 2010
Outline

• Condensed matter and atomic physics

• Early days: BEC (mid 90s)

• Big breakthrough: modeling condensed matter physics with cold atoms (1998-2003)

• Modern developments (2003 on)
Condesed Matter Physics
Condesed Matter Physics

- Solids, liquids, gases and phase transitions
- Liquid crystals
- Electron liquids and crystals (Fermi liquid, Wigner crystal, CDW)
- Superfluids, superconductors
- Magnets (FM, AFM)
- Insulators (Band, Mott, Anderson)
- Quantum dots and quantum chaos
- Luttinger liquids
- Quantum Hall Effect and topological states of matter
Atomic Physics (naive view of a condensed matter theorist)
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- precision spectroscopy
- atomic collisions
- molecules
- laser-atom interactions
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Dilute atomic gases

Density $\sim 10^{12} \text{ cm}^{-3} \leftrightarrow d \sim 10^4 \text{ Å}, \text{mfp} = 1/(n \sigma) \sim 10\text{cm}$

This is but an ideal gas...
Degenerate atomic gases

hot

classical ideal Boltzmann gas

\[ \lambda_{dB} \sim \frac{\hbar}{\sqrt{mT}} \]

cold

degenerate quantum gas
Degenerate atomic gases

classical ideal Boltzmann gas

degenerate quantum gas

$\lambda_{dB} \sim \frac{\hbar}{\sqrt{mT}}$

$\frac{\hbar}{\sqrt{mT_d}} \sim d$

Electron gas in a metal: $T_d \sim 10^4 \text{ K}$

Dilute atomic gas: $T_d \sim 10^{-6} \text{ K}$
Cooling of atomic gases

Steven Chu, Claude Cohen-Tannoudji, Bill Phillips

Nobel Prize 1997

For development of methods to trap and cool atoms with laser light
Cooling of atomic gases

Laser (Doppler) cooling

300 K to 1 mK
\sim 10^9 \text{ atoms}

Steven Chu, Claude Cohen-Tannoudji, Bill Phillips

Chu, Cohen-Tannoudji, Phillips

1997

Let Your Light Shine

University of Colorado

1876

T
Cooling of atomic gases

Evaporative cooling

1 mK to 1 µK
~$10^8 \rightarrow 10^6$ atoms

Laser (Doppler) cooling

300 K to 1 mK
~$10^9$ atoms

Steven Chu, Claude Cohen-Tannoudji, Bill Phillips

1997
Chu,
Cohen-Tannoudji,
Phillips
Imaging atomic gases

Time of flight measurements
Imaging atomic gases

Time of flight measurements
Imaging atomic gases

Time of flight measurements

probing w/ resonant laser

\[ n(r, t) \approx n_i (\hbar k = mr/t) \]
Degenerate (very) weakly interacting gases $T < T_d$
Degenerate (very) weakly interacting gases $T < T_d$

Bosons:
- Integer spin
- Symmetric wave function

Bose condensate

Bose  Einstein
Degenerate (very) weakly interacting gases $T < T_d$

Bosons:
- Integer spin
- Symmetric wave function
  
  Bose condensate

Fermions:
- Half-integer spin
- Antisymmetric wave function
  
  Degenerate Fermi gas: “Fermi condensate”

$E_F = k_B T_F$
(two iso-spin states)

Bose  
Einstein  
Fermi  
Dirac
First BEC ($^{87}$Rb)

June 1995 in $^{87}$Rb

September 1995 in $^{23}$Na

2001
Late 90s: “Dark ages” of cold atoms (various BEC experiments)

Ketterle ’97:
Will two ballistically expanding BECs interfere?
BEC experiments, late 90s

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Superfluid - Mott insulator transition

S. Doniach, 1981
Superfluid - Mott insulator transition
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S. Doniach, 1981
Superfluid - Mott insulator transition

Cold atom realization of the superconductor-Mott insulator transition

This transition can be observed if one puts some bosonic atoms on an optical lattice

Interfering laser beams

ac-Stark effect
(red-detuned, attractive)
Cold atom realization of the superconductor-Mott insulator transition

Experimental realization
M. Greiner, I. Bloch, T. Esslinger, T. Hansch (2001)
Cold atom realization of the superconductor-Mott insulator transition

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M. Greiner, I. Bloch, T. Esslinger, T. Hansch (2001)

Time of flight measurement
Degenerate Fermi gas

Degenerate Fermi gas


- Fermions do not interact at low T: difficult to cool
- Sympathetic cooling

\[ E_F = k_B T_F \]
(two iso-spin states)
Feshbach resonance (tunability of interactions)

Exploits the natural tendency of alkaline atoms to try to form molecules
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\[ U(r) \]

Closed channel

Open channel

Hyperfine interactions

Magnetic field
Feshbach resonance (tunability of interactions)

Exploits the natural tendency of alkaline atoms to try to form molecules
Feshbach resonance (tunability of interactions)

Exploits the natural tendency of alkaline atoms to try to form molecules

$U(r)$

$U_{\text{eff}}(r)$

Magnetic field
Feshbach resonance (tunability of interactions)

\[ U_{eff}(r) \sim a_b g \delta^3(r) \]

Ketterle (1998)
Feshbach resonance (tunability of interactions)

\[ U_{eff}(r) \sim a_{bg}\delta^3(r) \]

Ketterle (1998)

\[ a = a_{bg}(1 - \frac{\Delta B}{B-B_0}) \]
Feshbach resonance (tunability of interactions)

\[ U_{eff}(r) \sim a_{bg}\delta^3(r) \]

\[ a = a_{bg}(1 - \frac{\Delta B}{B-B_0}) \]

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Feshbach resonance (tunability of interactions)

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Modern developments

- Spinor condensates
- Confining atoms to 1D and creating Luttinger liquids
- Fermions on the lattice (modeling high Tc superconductors) - major project funded by DARPA
  - Modeling strongly paired superconductors
  - Modeling quantum magnetism
Attractively interacting Fermi gases

BCS-BEC crossover
(Eagles ’69, Leggett ’80)

Fermi gases with attractive interactions:

superconductors
Attractively interacting Fermi gases

BCS-BEC crossover
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Attractively interacting Fermi gases

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BCS superconductor

Bose-Einstein condensate of diatomic molecules

attraction strength
Attractively interacting Fermi gases

BCS-BEC crossover
(Eagles ’69, Leggett ’80)

BCS superconductor

Bose-Einstein condensate of diatomic molecules

Unitary point:
interactions are limited by unitarity $\delta_{\text{phaseshift}} = \frac{\pi}{2}$

Unitary point is universal:
interactions drop out from any physical quantity
Experimental observation of the crossover

D. Jin, M. Greiner, C. Regal, ‘03-04
RG picture of the BCS-BEC crossover

Molecular BEC   \[ \uparrow \]   BCS

Unitary critical point

Vacuum

Fermi liquid

\( \mu \)

Interaction strength

Noninteracting Fermi gas fixed point

Sachdev, ’06
Radzihovsky, ‘06

0

Fermi liquid

Noninteracting Fermi gas fixed point

Interaction strength

Vacuum

Unitary critical point

Molecular BEC   \[ \uparrow \]   BCS

Vacuum
RG picture of the BCS-BEC crossover

Molecular BEC

Crossover

BCS

Vacuum

Fermi liquid

Interaction strength

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Vacuum

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Interaction strength

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RG picture of the BCS-BEC crossover

Molecular BEC

Crossover

BCS

Fermi liquid

Interaction strength

Unitary critical point

Vacuum

Noninteracting Fermi gas fixed point

At unitarity $\mu = \frac{\xi (3\pi^2 n)^{2/3}}{2m}$

Universal critical amplitude

$\xi \approx 0.3 - 0.45$

Nicolić, Sachdev, ’07
Veillette, Sheehy, Radzihovsky, ‘07

Sachdev, ’06
Radzihovsky, ‘06
Exotic superconductors

Common superconductors: atoms in two different internal states form pairs. Pairs do not spin. “s-wave” superconductor
Exotic superconductors

Common superconductors: atoms in two different internal states form pairs. Pairs do not spin.
“s-wave” superconductor
**Exotic superconductors**

Common superconductors: atoms in two different internal states form pairs. Pairs do not spin.
“s-wave” superconductor

Exotic superconductors: atoms in identical internal states: pairs must spin.
“p-wave” superconductor
Exotic superconductors

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“s-wave” superconductor

Exotic superconductors: atoms in identical internal states: pairs must spin.
“p-wave” superconductor
p-wave superconductors in cold gases

• Take advantage of p-wave (angular momentum 1) Feshbach resonances

• Have a number of distinct phases, phase diagram has been worked out.

• One of the more common phases has topological order and particles with non-Abelian statistics.

VG, A. Andreev, L. Radzihovsky, 2005
Experiments

$p$-Wave Feshbach Molecules

J. P. Gaebler, * J. T. Stewart, J. L. Bohn, and D. S. Jin
JILA, Quantum Physics Division, National Institute of Standards and Technology
and Department of Physics, University of Colorado, Boulder, Colorado 80309-0440, USA
(Received 2 March 2007; published 16 May 2007)

Bottom line:
the molecules are unstable, with $\tau \sim 2\text{ms}$
Origin of instability: 3 body recombination

$Re \sim 25 - 50$ a.u.

$Re$ is the so-called van der Waals length (the typical interaction range)
Origin of instability: 3 body recombination

$R_e \sim 25 - 50 \text{ a.u.}$

$R_e$ is the so-called van der Waals length (the typical interaction range)

Protected by the Pauli principle
Origin of instability: 3 body recombination

By having opposite angular momenta, $p$-wave fermions beat the Pauli principle.

$R_e \sim 25 - 50 \text{ a.u.}$

$R_e$ is the so-called van der Waals length (the typical interaction range)

---

$s$-wave

Protected by the Pauli principle

$p$-wave

By having opposite angular momenta, $p$-wave fermions beat the Pauli principle
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Lifetime calculations

Interatomic distance

atomic mass

\[ \text{Lifetime} = \frac{mr^2}{\hbar} \frac{r}{R_e} \sim 20\text{ms} \]

van der Waals length

Probably, their life is too short!

J. Levinsen, N. Cooper, VG, 07-08
**Lifetime calculations**

Interatomic distance

Atomic mass

\[ \text{Lifetime} = \frac{mr^2}{\hbar} \frac{r}{R_e} \sim 20\text{ms} \]

Van der Waals length

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J. Levinsen, N. Cooper, VG, 07-08

Optical lattices may provide a way to overcome short lifetimes...

P. Zoller et al, 09
topological magnets
topological magnets

X.-G. Wen  F. Wilczek  A. Zee

1989
topological magnets

Heisenberg antiferromagnet

\[ H = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j \]

Nearest neighbors

Néel state
topological magnets

Heisenberg antiferromagnet

\[ H = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j \]

Nearest neighbors

Néel state

Chiral spin liquid (CSL)

Think of spin as attached to particles

spin-up spin-down

\[ H = J \sum_{\langle ij \rangle} f_{i,\alpha}^\dagger f_{i,\beta} f_{j,\beta}^\dagger f_{j,\alpha} \]

\( \langle ij \rangle, \alpha, \beta = \uparrow, \downarrow \)
topological magnets

Heisenberg antiferromagnet

\[ H = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j \]

Nearest neighbors

Néel state

Chiral spin liquid (CSL)

Think of spin as attached to particles

\[ f_{i,\uparrow}, f_{i,\downarrow}; f_{i,\downarrow}, f_{i,\uparrow} \]

spin-up spin-down

\[ H = J \sum_{\langle ij \rangle} f_{i,\alpha}^\dagger f_{i,\beta}^\dagger f_{j,\beta} f_{j,\alpha} \]

\[ <ij>, \alpha, \beta = \uparrow, \downarrow \]

\[ t_{ij} \]

What if \( \sum_{\alpha} \langle f_{i,\alpha}^\dagger f_{j,\alpha} \rangle = t_{ij} \)

\[ H = J \sum_{\langle ij \rangle, \beta} t_{ij} f_{i,\beta}^\dagger f_{j,\beta} + \ldots \]

"tight-binding Hamiltonian"
Nearest neighbors

Néel state

Heisenberg antiferromagnet

\[ H = J \sum_{<ij>} \vec{S}_i \cdot \vec{S}_j \]

Think of spin as attached to particles

\[ \uparrow \quad \downarrow \]

spin-up spin-down

Chiral spin liquid (CSL)

What if \[ \sum_{\alpha} \langle f^\dagger_{i,\alpha} f_{j,\alpha} \rangle = t_{ij} \]

\[ H = J \sum_{<ij>,\alpha,\beta=\uparrow,\downarrow} f^\dagger_{i,\alpha} f_{j,\beta} f^\dagger_{i,\beta} f_{j,\alpha} t_{ij} \]

“tight-binding Hamiltonian”

But what if \( t_{ij} \) correspond to a constant magnetic field?

This is CSL (or a topological magnet), by analogy with QHE
20 years and 552 citations later, nobody could still point out the Hamiltonian for which this scenario would work.
A proposal to generalize spin from SU(2) to SU(N)

Generalize the usual spin to SU(N) spin by using alkaline-earth atoms. Their nuclear spin does not interact and behaves like an electron spin, only larger.

The spin $I$ can be as large as $9/2$ (for $^{87}$Sr). Then $N=2I+1$ is as large as 10.

A.-M. Rey (2009)
SU(N) antiferromagnets in optical lattices

Interfering laser beams
SU(N) antiferromagnets in optical lattices

$^{87}\text{Sr}$ atoms
SU(N) antiferromagnets in optical lattices

Atom exchange leads to antiferromagnetic interactions (for nuclear spin).

$H = J \sum_{<ij>, \alpha, \beta=1, \ldots, N} f_{i,\alpha}^\dagger f_{i,\beta} f_{j,\beta}^\dagger f_{j,\alpha}$

$^{87}$Sr atoms
SU(N) antiferromagnets in optical lattices

Atom exchange leads to antiferromagnetic interactions (for nuclear spin).

\[ H = J \sum_{\langle ij \rangle, \alpha, \beta = 1, \ldots, N} f^\dagger_{i,\alpha} f_{i,\beta} f^\dagger_{j,\beta} f_{j,\alpha} \]

\(^{87}\)Sr atoms

Such SU(N) spins have a hard time ordering: too many directions nearby spins can point to while still being “opposite” to each other (minimize \( \vec{S}_i \cdot \vec{S}_j \))

M. Hermele (2009)
Topological SU(N) antiferromagnet

It turns out, for $N \geq 5$, the ground state is a chiral spin liquid (that is, a topological magnet), exactly of the type proposed by Wen, Wilczek and Zee.

M. Hermele, VG, A.-M. Rey, (2009)
Topological SU(N) antiferromagnet

It turns out, for \( N \geq 5 \), the ground state is a chiral spin liquid (that is, a topological magnet), exactly of the type proposed by Wen, Wilczek and Zee.

M. Hermele, VG, A.-M. Rey, (2009)

To show that, we employed the large N techniques:

\[
H = J \sum_{i,j} t_{ij} \left( f_{i,\alpha}^\dagger f_{j,\alpha} + hc \right) + \frac{N}{J} \sum_{<ij>} |t_{ij}|^2
\]

\[
S = N \operatorname{Tr} \log [S_{ij}] + \frac{N}{J} \sum_{<ij>} |t_{ij}|^2 + \text{saddle point in } t
\]
Anyons and non-Abelions

Lowering the potential at one site localizes a fractional or non-Abelian particle at that site.
Anyons and non-Abelions

Lowering the potential at one site localizes a fractional or non-Abelian particle at that site.

Experimental detection? Too soon to tell...
This is but the beginning...

We will see new remarkable experiments which will to build artificial “materials” with novel properties out of cold atoms...