Strongly interacting Fermi gases

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ultracold fermions: species

more candidates:
non-alkali species
fermion + fermion = boson
tunable $s$-wave interaction
fermionic pairing, many-body physics
$^6\text{Li}$ spin mixture

- **Feshbach resonance**
  - Prediction: Houbiers et al., PRA 57, R1497 (1998)
  - Precise characterization: Bartenstein et al., PRL 94, 103201 (2005)

- Weakly bound molecules

- Spin mixture of two lowest states
  - Stable against two-body decay

- Interaction control knob

Graph showing $^6\text{Li}$ ground state in a magnetic field.
optical trap for evaporative cooling
BEC of molecules

- partially condensed
- almost pure

**mBEC:**
- excellent starting point for studies on BEC-BCS crossover

- final trap power: 28mW
- number of molecules: 400,000
- temperature: 430nK
- condensate fraction: ~20%
two classes

Bosons
integer spin

Fermions
half-integer spin

trapped atoms at $T=0$

all in ground state: Bose-Einstein condensate

only one particle per state: degenerate Fermi gas

these two worlds are connected!
two classes

Bosons
integer spin

ever just one particle per state:
only in ground state:
Bose-Einstein condensate

Fermions
half-integer spin

“pairing“ is the key

all in ground state:
Bose-Einstein condensate

only one particle per state:
degenerate Fermi gas

trapped atoms at $T=0$
two classes

Bosons
integer spin

Fermions
half-integer spin

interaction control !!!

all in ground state:
Bose-Einstein condensate

only one particle per state:
degenerate Fermi gas

Feshbach resonance

ultracold.atoms
two classes

Bosons

integer spin

universal !!!

all in ground state:
Bose-Einstein condensate

Fermions

half-integer spin

universal !!!

only one particle per state:
degenerate Fermi gas

interaction control !!!
two classes

Bosons
integer spin

Fermions
half-integer spin

crossover gas
as a high-Tc superfluid

all in ground state:
Bose-Einstein condensate

only one particle per state:
degenerate Fermi gas
expt. milestones 2002-2005: is the crossover gas superfluid?

Duke, 2002

JILA, MIT 2004

pair condensation

hydrodynamic expansion

Innsbruck, 2004

collective modes

pairing gap

Duke, Innsbruck, 2004

heat capacity yes!

MIT, 2005

vortices

heat capacity yes!
collective oscillations

radial breathing mode

Innsbruck experiments
Bartenstein et al., PRL 92, 203201 (2004)
see also Altmeyer et al., cond-mat/0611285
Altmeyer et al., PRL 98, 0404401 (2007)

Duke Univ.
Kinast et al., PRL 92, 150402 (2004)
Kinast et al. PRA 70, 051401(R) (2004)
Kinast et al., PRL 94, 170404 (2005)

and many, many theory papers…
radial breathing mode

frequency
(normalized to sloshing mode)

damping

Bartenstein et al.,
PRL 92, 203201 (2004)

C. Chin et al.,

plausible explanation:
coupling of coll. osc. to pairing gap

hydrodynamic

collisionless

magnetic field (G)

600 800 1000 1200

\[ \frac{\Omega_r}{\omega_r} \]
radial breathing mode 2004 ultracold.atoms

exp. data from John Thomas group at Duke Kinast et al, PRA 70, 051401 (2004)

theory: mean field BCS à la Leggett, Nozières & Schmitt-Rink
Hu et al., PRL 93, 190403 (2004)
quantum Monte Carlo, Astrakharchik et al., PRL 95, 030404 (2005)
see also Manini and Salasnich, PRA 71, 033625 (2005)
Lee-Huang-Yang correction

leading correction is positive
→ upshift of collective-mode frequency in mBEC regime!
precision measurements

sloshing modes

beat reveals trap ellipticity of $\sim 6\%$

can be measured with $\sim 10^{-3}$ uncertainty

compression mode

accurate determination of frequency needs very low damping $\rightarrow$ optimized cooling!

anharmonicity effects in Gaussian trap potential $\sim 2\%$
suppressed to few $10^{-3}$ by normalization to sloshing mode
precision measurements

example for test of many-body theories with ultracold atoms!
slowly rotating Fermi gas

how to detect superfluidity?

vortices the only way?
slowly rotating Fermi gas

how to detect superfluidity?

both components hydrodynamic

superfluid angular momentum only with vortices

classical gas can carry angular momentum

idea: introduce slow rotation under conditions where no vortices are formed

observe quenching of the moment of inertia!
how to measure angular momentum

observe precession of quadrupole mode

(BEC work: ENS Paris, JILA, MIT)

angular momentum per atom

\[ L_z = 2 \Omega m r_{\text{rms}}^2 \]

works for any hydrodynamic system (superfluid or normal)
what the precession tells us

effective MOI \((L = \dot{\theta} \Omega)\)

\[
\Omega_{\text{prec}} = \frac{\dot{\theta}}{2\Theta_{\text{rig}}} \Omega
\]

MOI for rigid rotation

introduce dim.less „precession parameter“, just for convenience

\[
P = 2 \frac{\Omega_{\text{prec}}}{\Omega_{\text{trap}}} = \frac{\dot{\theta}}{\Theta_{\text{rig}}} \times \frac{\Omega}{\Omega_{\text{trap}}}
\]

\(P = 1\) for fully rotating non-superfluid cloud

superfluid quenching

incomplete class. rotation

if \(P < 1\) we have to separate these two effects!
evidence for quenching of the moment of inertia

\[ P = 1 \]

\[ T > T_c \]

\[ T < T_c \]

quenched MOI!

preliminary
superfluid transition temperature

$P = 1$

$T_c / T_F \approx 0.2$

general note: we do have a thermometry problem!

incomplete classical rotation

MOI quenching

full classical rotation (no superfluid)
creating a double-well potential
interference between two mBECs

700G: mBEC regime
second-sound modes?

out-of-phase oscillation of superfluid and non-superfluid part

how to excite?

how to detect?
Ultracold atoms join the fermion team

${}^6\text{Li}$
the fermion team

6$^{\text{Li}}-^{40}\text{K}$

Frederik Spiegelhalder
Andreas Trenkwalder
(RG)
(Eric Wille)
Florian Schreck
Devang Naik
fermion + fermion = boson

tunable s-wave interaction

fermionic pairing, many-body physics
two new twists

I. mass imbalance

very rich phases

Petrov et al., PRL 99, 130407 (2007)
crystalline phase

Iskin & Sá de Melo, PRL 97, 100404 (2006)

novel few-body phenomena

mediated interactions

three-body states
two new twists

II. trap imbalance

different resonance lines:
*species-specific optical potentials*

selective manipulation of one component!
species-specific optical lattice

optical potential seen by $^{40}$K, but not by $^{6}$Li

$^{6}$Li trapped by interaction with $^{40}$K
interaction properties of Li-K mixtures

completely unknown until 2007

do we have knobs (Feshbach resonances) for
  - interaction tuning
  - molecule formation
  - crossover physics

molecules

many-body pairs

interact.
tuning
Feshbach spectroscopy

Wille et al., PRL 100, 053201 (2008)
interspecies Feshbach resonances

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<th>width [G]</th>
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theory: T. Tiecke, J. Walraven, S. Kokkelmans & E. Tiesinga, P. Julienne

system essentially understood, but ....
they are all narrow!

closed-channel dominated Feshbach resonances!

1000 x wider:
entrance-channel dominated (ideal for crossover physics)
Fermi-Fermi $^{6}\text{Li}^{40}\text{K}$ molecules
association via 168G Feshbach resonance

$molecules$
$N \approx 2000$

$^{40}\text{K}$ line
$^{6}\text{Li}$ line

$free\ atoms$
$N_{Li} = 5 \times 10^4$
$N_{K} = 5 \times 10^3$

Important milestone for future experiments!
temperature measurement
a thermometer!
a thermometer!
thermalisation of K by Li

![Graph showing the thermalisation of K by Li](image)

- **1190 G**
thermalization at unitarity

$^{40}\text{K}$ good probe for strongly interacting Li!
fermion + fermion = boson
tunable s-wave interaction
fermionic pairing, many-body physics
ultracold expts. in Innsbruck (four PIs)

experiments in full operation

fermions
- single species ($^6$Li)
- mixtures ($^6$Li & $^{40}$K)

few-body physics ($\text{Cs}_2$, $\text{Cs}_3$, $\text{Cs}_4$)

tunable BEC (Cs) & homonucl. mols. ($\text{Cs}_2$)

heteronucl. mols. (RbCs)

two new adventures

quantum gases of Sr

strongly dipolar systems (Er)
thanks for your attention