BEC and superfluidity in ultracold Fermi gases

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two classes

Bosons
integer spin

trapped atoms at $T=0$

all in ground state:
Bose-Einstein condensate

Fermions
half-integer spin

only one particle per state:
degenerate Fermi gas
two classes

Bosons
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all in ground state:
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trapped atoms
at $T=0$

only one particle per state:
degenerate Fermi gas
ultracold Fermi gases

1999: first degenerate Fermi gas ($^{40}$K)
Debbie Jin group at JILA, Boulder

degenerate Fermi gases now playing in nine labs:

$^{40}$K: JILA (1999)
Florence (2002)
Zurich (2004)

$^6$Li: Rice (2001)
ENS (2001)
Duke (2001)
MIT (2002)
Innsbruck (2003)

2003 – making molecules (bosons!)

BEC of molecules at Innsbruck, JILA, MIT, ENS Paris, Rice

2004 – BEC-BCS crossover, creation of fermionic superfluids
$^{6}$Li spin mixture

Feshbach resonance

$^{6}$Li ground state in a magnetic field

Prediction: (+1/2)

M. Houbiers et al., PRA 57, R1497 (1998).

weakly bound dimers: it's a kind of magic!

spin mixture of two lowest states stable against two-body decay

prediction: $|+3/2\rangle$

magnetic Field [G]

$0 250 500 750 1000 1250 1500$

$-4 -2 0 2 4$

$a (1000 \, \text{a}_0)$
three-body recombination

molecules made by collisions

three atoms

large positive scattering length and last bound level

\[ U(r) \]

\[ E_b = \frac{\hbar^2}{ma^2} \]

atom

\[ E_{\text{kin}} = 2E_b/3 \]

molecule

(binding energy \( E_b \))

three-body process

many states

\[ E_{\text{kin}} = E_b/3 \]
they are incredibly stable!
(when made of fermionic atoms)
expt.: Cubizolles et al., PRL 91, 240401 (2003)
Jochim et al., PRL 91, 240402 (2003)

„normal“ dimer
size ~1nm

weakly bound dimer
size ~100nm
optical trap for evaporative cooling

special feature #1
precise control of laser power
10 W $\rightarrow$ few 100µW

special feature #2: axial magnetic confinement
- spatial compression at very weak optical traps
- perfectly harmonic !!
- precisely known trap frequency for weak optical trap

$\nu_z = 24.5 \text{ Hz} @ 1\text{kG}$
Science (Aug 04):

The Chamber of Secrets
axial profiles \rightarrow phase transition

- partially condensed
- almost pure

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(a)</th>
<th>(b)</th>
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<tbody>
<tr>
<td>final trap power</td>
<td>28mW</td>
<td>3.8mW</td>
</tr>
<tr>
<td>number of molecules</td>
<td>400,000</td>
<td>200,000</td>
</tr>
<tr>
<td>temperature</td>
<td>430nK</td>
<td>few 10nK</td>
</tr>
<tr>
<td>condensate fraction</td>
<td>~20%</td>
<td>&gt;90%</td>
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</tbody>
</table>

excellent starting point for further experiments
molecular BEC gallery

JILA, Jin et al.

MIT, Ketterle et al.

ENS Paris, Salomon et al.

Rice Univ., Hulet et al.
the BEC-BCS crossover
two classes

**Bosons**
- integer spin
- trapped atoms at \( T=0 \)
- all in ground state: Bose-Einstein condensate

**Fermions**
- half-integer spin
- only one particle per state: degenerate Fermi gas

these two worlds are connected!
two classes

Bosons
integer spin

Fermions
half-integer spin

trapped atoms
at $T=0$

„pairing“ is the key

all in ground state:
Bose-Einstein condensate

only one particle per state:
degenerate Fermi gas
two classes

**Bosons**
- integer spin

**Fermions**
- half-integer spin

*Feshbach resonance*

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**interaction control !!!**

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all in ground state:
- Bose-Einstein condensate

only one particle per state:
- degenerate Fermi gas
two classes

Bosons
integer spin

Fermions
half-integer spin

all in ground state:
Bose-Einstein condensate

only one particle per state:
degenerate Fermi gas
two classes

Bosons
integer spin

Fermions
half-integer spin

all in ground state:
Bose-Einstein condensate

only one particle per state:
degenerate Fermi gas

neutron star

exotic states
of matter
exploring the crossover

molecular BEC

$na^3 = 0.04$
exploring the crossover

$na^3 = 0.28$

molecular BEC

$na^3 = 0.04$
exploring the crossover

Bosons

Fermions

\[ n_{a^3,kF} = \infty \]

\[ n_{a^3} = 0.28 \]

molecular BEC

\[ n_{a^3} = 0.04 \]

Scattering length (1000 \( a_0 \))

Magnetic field (G)

Ultracold atoms quantum gases
exploring the crossover

Bosons

Fermions

\( n_{a^3, k_F|a|} = \infty \)

\( n_{a^3} = 0.28 \)

\( k_F|a| = 6 \)

molecular BEC

\( n_{a^3} = 0.04 \)
exploring the crossover

Bosons

Fermions

fully reversible
no loss, no heating !!!
(isentropic)

molecular BEC

na³ = 0.04

na³ = 0.28

na³, k_F|a| = ∞

k_F|a| = 6

degenerate Fermi gas

Ultracold atoms quantum gases
cloud size $\rightarrow$ interaction energy

comparison with theory

BEC mean-field with $a_{\text{mol}} = 0.6a$

(Petrov et al. prediction)

quantum Monte Carlo

(Carlson et al. Astrakharchik et al.)

$\zeta_0 = 0.810(3)$

($\beta = \zeta_0^4 - 1$)

M. Bartenstein et al.
PRL 92, 120401 (2004); updated in Procs. ICAP-2004

normalized to non-interacting Fermi gas
collective modes in the BEC-BCS crossover

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

*interesting behavior of collective modes in the crossover* !!!

**our cigar-shaped trap**

\[ \nu_r = 755(10) \text{ Hz}, \; \nu_z \approx 22 \text{ Hz} \]
axial mode

M. Bartenstein et al., PRL 92, 203201 (2004), updated data analysis: PhD thesis M. Bartenstein

frequency (normalized to sloshing mode)

damping rate

hydrodynamic behavior
axial mode: resonance region

M. Bartenstein et al., PRL 92, 203201 (2004), updated data analysis: PhD thesis M. Bartenstein

frequency
(normalized to sloshing mode)

damping rate

**unitarity point:**

\[
\frac{\Omega_z}{\omega_z} = \sqrt{\frac{12}{5}}
\]

confirms equation of state

\[
\mu \propto n^{2/3}
\]

extremely weak damping in resonance region !!

superfluidity?
radial coll. excitation

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

frequency
(normalized to sloshing mode)

damping

\[ \frac{\Gamma_r}{\omega_r} \]

\[ \frac{\Omega_r}{\omega_r} \]

BEC limit

collisionless limit

hydrodynamic

collisionless

magnetic field (G)
comparison with theory

Hu et al., PRL 93, 190403 (2003) based on Leggett's mean-field model
Manini et al., cond-mat/0407039 based on Giorgini's qu.MC calculation

\[ \mu \sim n^{\gamma} \]
**Equation of state and collective frequencies of a trapped Fermi gas along the BEC-unitarity crossover**

cond-mat/0503618

G.E. Astrakharchik(a), R. Combescot(c), X. Leyronas(c) and S. Stringari(a,b)

- **how good is our experiment?**
  - **• axial trap very well known!**
  - **• radial trap freq. meas’d only in one direction:** ellipticity of laser beam ???
in progress: upgrade of apparatus

new possibilities
- precise studies of radial modes (compression and surface mode)
- rotating ellipse → stirring up vortices
measurement interpretation

something(\(B\)) \rightarrow something(\(1/k_Fa\))
something($B$) $\rightarrow$ something($1/k_Fa$)

precise knowledge of $a(B)$ through rf spectroscopy on ultracold molecules

Bartenstein et al., PRL 94, 103201 (2005)
(collaboration Innsbruck – NIST)
radio-frequency spectroscopy

meas. of mol. bind. energy in $^{40}$K

rf spectroscopy of $^6$Li:

~80MHz
\[ m_I = \begin{cases} 
-1 \\
0 \\
1 
\end{cases} \]

high B-field

rf frequency

loss signal

~200Hz
radio-frequency spectroscopy

- meas. of mol. bind. energy in $^{40}\text{K}$

- rf spectroscopy of $^{6}\text{Li}$:

- high B-field

- $m_I = -1, 0, 1$

- Breaking molecules costs energy
  $\rightarrow$

- Molecular signal up-shifted

- $\sim 80\text{MHz}$
radio-frequency spectroscopy

meas. of mol. bind. energy in $^{40}$K

rf spectroscopy of $^6$Li:

$\sim 80$ MHz

Atoms $m_f = -1, 0, 1$

molecules

High B-field

Fractional loss

720 G

rf offset (kHz)

$E_b/h$ binding energy
bound-free dissociation spectra

720.13(4) G

694.83(4) G

binding energy

134(2) kHz

277(2) kHz

lineshape of dissociation signal:
C. Chin and P. Julienne
PRA 71, 012713 (2005)
rf spectroscopy on $^6\text{Li}_2$
bound-bound transition

exp. data → multi-channel quantum scattering model

NIST theory group:

\[ \alpha_s = 45.167(8) \, \text{a}_0 \]
\[ \alpha_t = -2140(18) \, \text{a}_0 \]

second data point

83.2966(5) MHz
@ 676.09(3) G

83.6645(2) MHz
@ 661.44(2) G
s-wave scattering lengths

simple fit formulae available
rf spectroscopy in the strongly interacting Fermi gas

**observation of the pairing gap**

radio-frequency spectroscopy

meas. of mol. bind. energy in $^{40}$K

rf spectroscopy of $^{6}$Li:

~80MHz

rf

$m_f$ =
-1
0
1

breaking molecules costs energy
→
molecular signal up-shifted
two-body physics

high B-field
Radio-frequency spectroscopy

Meas. of mol. bind. energy in $^{40}$K

Rf spectroscopy of $^{6}$Li:

$\sim$80MHz

$m_f$ = -1 0 1

High B-field

Breaking pairs costs energy
→
Pair signal up-shifted

Many-body physics
rf spectra in molecular limit

evaporation at 764G, then ramp field to 720G

- no evaporation
- moderate evaporation
- deep evaporation

loss signal

- atoms only
- atom-molecule mixture
- pure molecular sample (BEC)
rf spectra in crossover regime

evaporation at 764G, then ramp field on resonance

\[ T \approx 0.2 T_F \]

double-peak structure: atoms and pairs

the pairing gap

\[ T = 0.0? T_F \]
pairs only!

shift decreases with Fermi energy
rf spectra in crossover regime

evaporation at 764G, then ramp field to *BCS side*

\[ T/T_F \approx 0.2 \]

\[ T/T_F \approx 0.0? \]
gap vs. coupling strength

\[ \frac{h \Delta \nu}{E_F} \propto \exp(-\frac{\pi}{2 k_F|a|}) \rightarrow \text{BCS} \]

\[ T_F = 3.6 \mu K \]

\[ 1.2 \mu K \]
gap vs. coupling strength

$molecular \ limit \ (two\text{-}body\ physics)$

radial osc. frequency

$T_F = 3.6\mu K$

$1.2\mu K$

$\rightarrow$ explanation for abrupt change!!

collective oscillation couples to pairs
temperature dependence

measured @ 837 G (unitarity)

controlled heating: same $T_F, N$

$T' \approx 0.8 T_F$

$\approx 0.75 T_F$

$\approx 0.45 T_F$

$< 0.2 T_F$

RF frequency offset (kHz)

"thermodynamics of interacting fermions"
Chen et al.
cond-mat/0411090
$T' \rightarrow T$
true temperature
temperature dependence

measured @ 837 G (unitarity)

controlled heating: same $T_F, N$

$T' \approx 0.3 \ T_F$

$\approx 0.28 \ T_F$

$\approx 0.22 \ T_F$

$< 0.1 \ T_F$

“thermodynamics of interacting fermions“
Chen et al.
cond-mat/0411090
$T' \rightarrow T$
true temperature
comparison with theory


T / T_F ≈ 0.22

T / T_F ≈ 0.28

T / T_F ≈ 0.30

T / T_F = 0.27

K. Levin, priv. comm.
phase diagram

\[ \frac{T}{T_F} \]

- **molecules**
  - \(^6\text{Li}\)
  - \(T_c\)

- **BEC**
  - \(^6\text{Li}\)

- **paired**
- **superfluid**
  - \(^6\text{Li}\)

- **BCS**

\[ -\frac{1}{k_F a} \]

Perali, Pieri, Pisani, Strinati


harmonic trap (inhomog. system)
conclusion

creation of a molecular BEC with $^6\text{Li}_2$

excellent starting point for further experiments
conclusion

creation of a molecular BEC with $^6\text{Li}_2$

excellent starting point for further experiments

studies on the BEC-BCS crossover

• cloud size
• collective modes
• pairing gap

\{ strong case for superfluidity \}

funding

\[ FWF \quad \text{Der Wissenschaftsfonds.} \quad \text{TMR network cold molecules} \]
ultracold.atoms

2D BEC in a surface trap
B. Engeser, K. Pilch, A. Jaakola, G. Hendl, H.-C. Nägerl

BEC of cesium, ultracold molecules
T. Kraemer, M. Mark, P. Waldburger, J. Herbig
C. Chin, H.-C. Nägerl

fermionic Li-6 & molecular BEC
A. Altmeyer, S. Riedl, M. Bartenstein, R. Geursen
S. Jochim, C. Chin, J. Hecker Denschlag

fermions

Cheng Chin
Lise-Meitner fellow

quantum matter in optical lattices
Johannes Hecker Denschlag
M. Theis, G. Thalhammer, K. Winkler, F. Lang,
S. Schmid

Li-K/Sr mixtures
E. Wille, G. Kerner, NN
Florian Schreck

Hanns-Christoph Nägerl
2nd generation cesium BEC
M. Gustavsson, P. Unterwaditzer, A. Flir

Innsbruck