Ultra cold Fermi and Bose gases: playing with Feshbach resonances

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Summary

- Ultra-cold Bose and Fermi gases
  Search for BCS pairing
- Cooling of fermions
- Experimental setup

Results:
- Observation of Fermi pressure
- 1D Bose condensate in Fermi sea
- Matter-wave bright soliton

Perspectives
Bose-Einstein Condensation

Bose-Einstein condensate

Bose enhancement

\[ T_c = \frac{\hbar \omega}{k_B} (0.83 \, \text{N})^{1/3} \]

1995 Cornell / Wieman, Ketterle

Rb, Na, Li, H, \(^*\)He, K

Sodium

Rbodium

Rubidium
Bosons and fermions at very low temperature

**Bose-Einstein condensate**

\[ T_c = \frac{\hbar \omega}{k_B} (0.83 N)^{1/3} \]

- 1995 Cornell / Wieman, Ketterle
- Rb, Na, Li, H, *He, K
- Interesting physics:
  - coherence
  - atom laser
  - Cold molecules
  - vortex and superfluidity
  - Cold collisions

**Fermi sea**

\[ T << T_F = \frac{\hbar \omega}{k_B} (6 N)^{1/3} \]

- 1999 at JILA with $^{40}$K
- 2001 Rice, ENS, Duke, MIT
- Interesting physics:
  - Fermi pressure,
  - Mixture of quantum gases
  - Pair formation: BCS transition
  - Light scattering
Condensation of fermion pairs?

Search for BCS transition

Mixture of states $\uparrow$ and $\downarrow$ with attractive interaction: $\alpha < 0$

Condensation of Cooper pairs at

$$T_{BCS} = T_F e^{-\frac{2k_F}{a}}$$

For $|k_F|a \ll 1$: $T_{BCS} \sim 2.5\% T_F$

Near Feshbach resonance: $T_{BCS} = 0.5 T_F$

Lithium 6: $a_t = -110$ nm & Feshbach resonance at 820 Gauss
**Evaporative Cooling**

- **Evaporative cooling** is today the only known method to date to reach quantum degeneracy:
  - Remove hot atoms
  - Use elastic collisions for rethermalization
Cooling of fermions: sympathetic cooling

Problem: anti-symmetrization for fermions

In a collision between two identical fermions, in the scattering cross-section only odd partial waves are allowed:

Anti-symmetry of the total wave function under exchange of the two particles.

Scattering in $p, t$... waves.

But at very low temperature, these contributions become negligible.

Solution:

Sympathetic cooling of distinguishable particles: mixtures

fermions in two different spin states:

- fermions-bosons: two isotopes of the same atom: Li7, Li6, ENS, Rice
- fermions-bosons: different elements: ex: K, Rb,

JILA, Duke

LENS, MIT, JILA
The scattering length: $a$

- At very low temperatures one parameter is sufficient to describe atomic interactions: the scattering length $a$.

- Scattering cross section: $\sigma = 4\pi a^2$ (for non identical particles).

- Mean field of a gas with density $n$:
  $$U = \frac{4\pi \hbar^2 n a}{m}$$

- Example: BEC in dependence of mean field:
  - Ideal gas: $a=0$
  - Repulsive: $a>0$
  - Attractive: $a<0$

3D gas

1D gas

Gaussian

Parabola

Collapse (for $N>N_{\text{crit}}$)

Soliton
Fermionic Lithium ($^6$Li)

<table>
<thead>
<tr>
<th>State</th>
<th>$a_e$</th>
<th>$\mu_e$</th>
<th>$\mu_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>3/2, +3/2\rangle$</td>
<td>$+2.1$ nm</td>
<td>$1 \mu_b$</td>
</tr>
<tr>
<td>$</td>
<td>1/2, -1/2\rangle$</td>
<td>$+2.0$ nm</td>
<td>$1/3 \mu_b$</td>
</tr>
</tbody>
</table>

Bosonic Lithium ($^7$Li)

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<tr>
<th>State</th>
<th>$a_e$</th>
<th>$\mu_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>2, +2\rangle$</td>
<td>$-1.4$ nm</td>
</tr>
<tr>
<td>$</td>
<td>1, -1\rangle$</td>
<td>$+0.27$ nm</td>
</tr>
<tr>
<td>$</td>
<td>1, +1\rangle$</td>
<td>$+\infty$ nm</td>
</tr>
</tbody>
</table>

Lithium isotopes
Set-up

MOT beams

Differential pumping

Lithium oven at 500 °C

Slower beam

pump

Glass cell for MOT and magnetic trap

Zeeman slower

$V_{cap} = 1000 \text{ m/s}$

$F_{lux} \approx 2 \times 10^9 \text{ s}^{-1}$

Li
Two isotope magneto-optical trap

<table>
<thead>
<tr>
<th>Number</th>
<th>Li7</th>
<th>Li6</th>
<th>Li7</th>
</tr>
</thead>
<tbody>
<tr>
<td>T [µT]</td>
<td>1000</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

M.O. Mewes et al., PR A 61, 011403R (2001)
Magnetic elevator
Strongly confining trap: 4 Ioffe bars with $3 \times 800$ A current.
Switch-off time: $30 \mu s$

Two pinch coils for axial confinement.

Oscillation frequency: $f_{\text{rad}} = 8 \text{ kHz}$, $f_{\text{ax}} = 200 \text{ Hz}$ for a bias field of 2 Gauss.
Results in higher hyperfine states
Sympathetic cooling of Lithium 6

$^{6}\text{Li}$

$^{7}\text{Li}$ alone

$^{7}\text{Li}$

F. Schreck et al., PR A 64, 011402R (2001)

$N_{\text{init}}^{6} = 2 \times 10^{6}$

$N_{\text{init}}^{7} = 3 \times 10^{8}$
Observation of Fermi pressure

Simultaneous measurement of thermalized fermionic and bosonic distributions

$^7\text{Li}$ Bosons
$^6\text{Li}$ Fermions

Optical density [arb]

Axial distance [mm]

$2.7 \times 10^4$ Bosons at $T=0.94 \, \mu \text{K} = T_F$

$8.1 \times 10^4$ Fermions with $T_F=4.38 \, \mu \text{K}$
Observation of Fermi pressure

Simultaneous measurement of thermalized fermionic and bosonic distributions

$^{6}\text{Li}$ Fermions

\(T=0\)

Optical density [arb]

Axial distance [mm]

0.6 mm

2.7 x 10^4 Bosons at \(T=0.94\ \mu K = T_c\)

8.1 x 10^4 Fermions with \(T_F=4.38\ \mu K\)
Observation of Fermi pressure

- Simultaneous measurement of thermalized fermionic and bosonic distributions

- Measurement of the degeneracy:
  - thermalized mixture: $^6T = ^7T$
  - $T_F$ calculated with $^6N$ and known potential

\[
\frac{T}{T_F} = 0.25(5)
\]
Results in the lower hyperfine states
Lithium Energy levels

\[ |\frac{3}{2}, \frac{3}{2}\rangle \]
\[ |\frac{1}{2}, -\frac{1}{2}\rangle \]
\[ |\frac{1}{2}, \frac{1}{2}\rangle \]

6 Li

27 G

\[ a_{\frac{3}{2}} = +40 a_0 \]
\[ \mu = 1 \mu_0 \]

\[ a_{\frac{1}{2}} = +38 a_0 \]
\[ \mu = \frac{1}{3} \mu_0 \]

7 Li

140 G

\[ |\frac{1}{2}, +\frac{1}{2}\rangle \]
\[ |\frac{1}{2}, -\frac{1}{2}\rangle \]
\[ |\frac{1}{2}, +\frac{1}{2}\rangle \]

\[ a_{\frac{1}{2}} = +5.1 a_0 \]
\[ \mu = \frac{1}{2} \mu_0 \]
Bose Einstein condensate and Fermi sea

F. Schreck, L. Khaykovich, K. Corwin, G. Ferrari, T. Bourdel, J. Cubizolles, C. Salomon
PRL, 87, 080403, August 2001
Temperature of Fermi gas?

$^7$Li BEC  $^6$Li Fermi sea

$N_B = 3 \times 10^4$
$N_0 = 8 \times 10^3$
$T = 1.7 \, \mu K$
$= 0.87 \, T_C$
$v_{rad} = 5 \, kHz$
$v_{ax} = 83 \, Hz$

$N_F = 2.5 \times 10^4$
$T/T_F = 0.6$
$v_{rad} = 4.4 \, kHz$
$v_{ax} = 74 \, Hz$

Difficult to measure the temperature of a Fermi gas below $T_F$

The position distribution of trapped Bose gas has a double structure
Thomas–Fermi profile for condensate and thermal cloud.
Fit on $N_0$, $N_B$, $T$
Quasi-pure condensate in Fermi sea

\[ \text{Below this temperature, the thermal fraction of } ^7\text{Li becomes undetectable} \]

\[ N_F = 4 \times 10^3 \quad \text{T/T}_F = 0.2(1) \]

\[ N_B = 10^4 \quad N_0/N_B = 0.77 \quad T = 0.28 \mu K = 0.2(1) T_C \]
A 1D condensate

Radial size:
\[ \sigma = 1.03 \sigma_0 = 1 \mu m \]

Axial size:
\[ \sigma_0 = 28 \mu m \]

\[ R = 7 \sigma_0 = 28 \mu m \]

\[ \mu = 0.45 \frac{\text{Hz}}{\text{m}^2} \]

Expansion of the radial harmonic oscillator ground state

Thomas-Fermi

Time of flight [ms]

[\omega^2]_0
The crossed dipole trap

Two YAG beams with 5W and waist of 38 µm
Lithium 6 in optical dipole trap in |3/2, 3/2 >

\[ ^6\text{Li}(1/2, 1/2) + ^6\text{Li}(1/2, -1/2); T = 1\text{mK} \]

4 \times 10^4 \text{ atoms at } 10 \, \mu\text{K}
Experiments with Li 7 in the absolute ground state
Lithium 7

Bosonic Lithium \(^7\)Li

\[ a = -1.4 \text{ nm} \]
\[ \mu = 1 \mu_B \]

\[ |2, +2\rangle \]

\[ |1, -1\rangle \]

\[ |1, +1\rangle \]

\[ a = +\infty \ldots -\infty \text{ nm} \]
\[ \mu = -1/2 \mu_B \]

E

B

140 G
Feshbach resonance in $^7\text{Li}$ $|F = 1, m_F = 1\rangle$

L. Venturi and C. Williams

Scattering length [nm]

B [Gauss]

Evaporation
Ideal gas
Scattering length $a < 0$

[Graph showing data points and trend lines]
$^7\text{Li}$ Condensate with adjustable $a$

- Evaporation to 10 $\mu$K in magnetic trap
- Transfer atoms into dipole trap
- Transfer from $|2,2\rangle$ to $|1,1\rangle$
- Evaporation to BEC with $a = 2.5$ nm by reducing trap depth by $x20$ in 250 ms !!!
- Time of flight picture:

![Graph of integrated optical density vs. axial distance](image)

$N_c = 2 \times 10^4$

At $T = T_c / 2$
Cut axial confinement and observe expansion in 1D optical waveguide.

Solution production
Ideal gas in 1D waveguide
Ideal gas versus Soliton

Soliton $a = -0.21$ nm

Ideal gas $a \approx 0$ nm
Matter wave soliton

- Dispersion of matter wave: \( E = \frac{\hbar^2 k^2}{2m} \)
- Non linear interaction due to mean field
  
  \[
  1D \text{ GPE:} \quad \mu \dot{\psi}(z) = -\frac{\hbar^2}{2m} \frac{d^2 \psi(z)}{dz^2} + \left( \frac{1}{2} m \omega_z^2 z^2 + N g_{1D} |\psi(z)|^2 \right) \psi(z); \quad g_{1D} = 2a \left( \hbar \omega_{rad} \right)
  \]

- Dark solitons created in BEC in Hannover, NIST and Harvard

Here: bright Solitons

\[
\Psi(z) = \frac{1}{(2l)^{1/2}} \frac{1}{\cosh(z/l)}
\]

With \( l = -\frac{\sigma_{ho}^2}{Na} \) For 1D condition

\[
N_{max} = -\sqrt{2} \frac{\sigma_{ho}}{\alpha}
\]
Stability diagram of the soliton: 3D GP equation

\[ E_{GP} / \hbar \omega_\perp \]

\[ E_{GP} / \hbar \omega_\perp \]

Expected: \( 4.2 \times 10^3 \leq N_{at} \leq 5.2 \times 10^3 \), \( l_z = 1.7 \mu m \)

For \( a = -0.21 \) nm and \( \omega_z / \omega_\perp = i \times 70 / 710 \)

Measured: \( N_{at} = 6(2) \times 10^3 \)
Solitons

Dispersion counterbalanced by non-linear interaction

Discovered 1834 by Scott Russell in water

Used in optical fibers for telecommunications
Soliton of marathon runners
Perspectives

- Studies with bosonic lithium
  - Soliton
    - collision between two solitons
  - Condensate with tunable $a$
    - very large $a$
    - 1D condensate
- Studies with boson/fermion mixtures
  - Phase separation
  - Find limit of $T/T_F$
  - Better thermometry using collisional relaxation
  - Influence of losses
- Studies with fermionic lithium
  - Feshbach resonance
  - Role of losses
  - BCS transition?
  - Fermions in optical lattices
Lithium Energy levels

\[ |3/2, +3/2\> \quad \begin{cases} a_{6,7} = +40 a_o \\ \mu = 1 \mu_b \end{cases} \]

\[ |1/2, -1/2\> \quad \begin{cases} a_{6,7} = +38 a_o \\ \mu = 1/3 \mu_b \end{cases} \]

\[ |1/2, +1/2\> \quad \begin{cases} a_{6,7} = +10 a_o \\ \mu = 1/2 \mu_b \end{cases} \]

\[ |2, +2\> \quad \begin{cases} a = -27 a_o \\ \mu = 1 \mu_b \end{cases} \]

\[ |1, -1\> \quad \begin{cases} a = +5.1 a_o \\ \mu = 1/2 \mu_b \end{cases} \]

\[ |1, +1\> \quad \begin{cases} a = +1.5 a_o \\ \mu = 1 \mu_b \end{cases} \]
Sympathetic cooling of Lithium 6

$^6\text{Li}$

$^7\text{Li}$

$^7\text{Li}$ alone

F. Schreck et al., PRA, 86, 011402R (2001)

$N_{\text{init}}^6 = 2 \times 10^6$

$N_{\text{init}}^7 = 3 \times 10^8$
The two isotopes see the same trapping potential.

Thermal equilibrium at $T = 0.94 \mu K$. $N_B = 2.7 \times 10^4$, $N_F = 8.1 \times 10^4$

Fermi temperature calculated from $N_F$, $\omega_{\text{rad}}$, $\omega_{\text{ax}}$: $T_F = 4.38 \mu K$

$T/T_F = 0.22(5)$

Also:

$T/T_F = 0.36(5)$

with $T_F = 11 \mu K = 3 T_{\text{recoil}}$
Lithium Energy levels

\[ |3/2, +3/2\rangle \]
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\[ a = +5.1 a_0 \]
\[ \mu = 1/2 \mu_B \]

27 G

140 G

E

B

6\_Lithium

7\_Lithium
Perspectives:
Condensates: rapid development
Beyond mean field. Superfluid-insulator Mott transition (München)
Applications: Atom interferometry; high precision inertial sensors
higher flux of coherent matter wave required

Fermi gases
Study of mixture: Fermi gas - Condensate
Find limit of $T/T_F$,
Influence of losses
Better thermometry using collisional relaxation

Light scattering by Fermi gas
Modification of spontaneous emission rate

Search for BCS transition in optical dipole trap.
Very rich physics!!
Influence of losses on Fermi degeneracy

E. Timmermans, cond-mat/0110098, (2001)

Different from classical gas and condensates
Cooling and losses

Model:
- Fermions in a box
- Condensate at $k = 0$
- Cooling dynamics
- Decrease of $E_F$
- Decrease of condensate atom number

Probability of finding a fermion on sphere of radius $k$:

$$\frac{\partial P(k)}{\partial t} = + \sum_k \gamma(k' \rightarrow k) P(k') (1 - P(k))$$

$$- \sum_k \gamma(k \rightarrow k') P(k) (1 - P(k')) P(k)$$

$$\Phi P(k)$$
Influence of losses on temperature

T. Bourdel

Important parameter: \( \Phi = \frac{\Phi}{\Gamma} \) = loss rate / fermion-boson collision rate

\[ \Gamma = 4\pi a_{6,7}^2 n_B v_F \]

Conclusion: for going to \( T_F/100 \)

\[ \frac{\tilde{\Phi}}{\Gamma} = 10^{-4} \]
Phase separation?

Calc. for T=0 (analogous to K. Mottner).

Without BEC

\[ N_B = 10^4 \]
\[ N_f = 10^4 \]
\[ U_{B,C} = 0.5 \mu K \]
\[ T_F = 2 \mu K \]

With BEC

\[ N_B = 10^3 \]
\[ N_f = 1 \mu K \]
\[ U_{B,C} = 0.5 \mu K \]
\[ T_F = 1 \mu K \]