“Bose-Einstein condensation of lithium molecules and studies of a strongly interacting Fermi gas”

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Workshop on Ultracold Fermi Gases, Levico
Quantum degenerate Na$_2$ molecules

Takashi Mukaiyama, Kaiwen Xu, Jamil Abo-Shaeer, Jit Kee Chin, Daniel Miller, W.K.
The new cold frontier: molecules

Molecule

Two atoms

Magnetic field

Feshbach resonance

E

atoms

cells

molecules
Zero energy of the condensate

Feshbach resonance

Zeeman tuning a bound molecular state to zero energy!

Energy

0

Bound molecular states

Theory:
Stwalley 1976
Verhaar 1993

Exp:
MIT, Texas 1998
molecule atoms

E Feshbach resonance

molecule atoms

Bosons: Boulder, Garching, Innsbruck, MIT
Fermions: Boulder, Rice, Paris, Innsbruck, MIT
Na condensate in a single beam optical dipole trap

$|F=1, m=1>$

$N \sim 3 \times 10^6$

$n \sim 4 \times 10^{14} \text{ cm}^{-3}$

$\omega_{\text{trap}} \sim 2\pi \times (290 \text{ Hz}, 290 \text{ Hz}, 2.5 \text{ Hz})$

Trap depth $\sim 1.4 \mu\text{K}$

$B_{\text{FB}} \sim 907 \text{ Gauss}$

$\Delta B \sim 1.0 \text{ Gauss}$
Atom-Molecule Collision

\[ \frac{\dot{N}_m}{N_m} = -K_{am} \cdot n_a \]

\[ K_{am} = 6.4 \times 10^{-11} \text{ cm}^3 / \text{sec} \]

\[ \tau \sim 92 \mu\text{sec} \]
Molecules with phase-space density of $20!$ is critical phase-space density for BEC.

Conversion of gas of coherent atoms into a gas of coherent molecules.
$\delta E = \tau_p \times \Delta \mu \dot{B}$

($\tau_p$ : predissociation time)
\[ \delta E = \tau_p \times \Delta \mu \dot{B} \]

(\( \tau_p \): predissociation time)

However:

\[ \tau_p \propto \sqrt{\delta E} \]

Wigner threshold law
Quantum degeneracy in fermions
Quantum Degenerate Gases

- non-interacting fermions: Pauli blocking
- interacting fermions: BCS-like superfluidity
- mixtures of Bose and Fermi gases
Quantum degenerate fermions

Potassium $^{40}$K
Boulder
Florence

Lithium $^6$Li
Rice
Paris
Duke
MIT
Innsbruck

Lots of work in progress: chromium, strontium
Sodium - Lithium Mixture

Na $F = 2$ condensate as refrigerator
cool Li $F = 3/2$ (state $|6\rangle$) in a magnetic trap -
20s forced evaporation

$10^7$ atoms in BEC (w/o Li)  
50 $10^6$ Li atoms at $\frac{T}{T_F} < 0.3$

Preparation of an interacting $^6$Li system

Setup:

Optical trapping:
9 W @ 1064 nm

$\omega = 2\pi \times (16,16, 0.19)\ kHz$

$E_{\text{trap}} = 800\ \mu K$
Interacting Fermions

Spin-mixture of Spin $\hat{\mathcal{I}}$ and $\mathcal{D}$

Without interaction:

$$a = 0$$
Interacting Fermions

Spin-mixture of Spin $\uparrow$ and $\downarrow$

With attractive interaction:
\[ a < 0 \]

BCS-Transition
Condensation of long-range Cooper pairs

\[ T_C \approx 0.5 T_F e^{-\frac{2k_F \pi}{|a|}} \]

We want a large and negative scattering length

Promising candidate: $^6$Li, $a_T = -2100 a_0$
Interacting Fermions

Spin-mixture of Spin $\uparrow$ and $\downarrow$

With repulsive interaction:

\[ a > 0 \]

A bound state appears!

\[ E_B = -\frac{\hbar^2}{2ma^2} \]

per atom
Interacting Fermions

Spin-mixture of Spin $\uparrow$ and $\downarrow$

With repulsive interaction: $a > 0$

BEC-Transition
Condensation of tightly bound Fermion pairs

$$T_C = 0.91 \, \hbar \omega \, N_{\text{mol}}^{1/3}$$
$$= 0.5 \, T_F$$

$$E_B = -\frac{\hbar^2}{2ma^2}$$

per atom

A bound state appears!
The BEC-BCS Crossover

BEC of Molecules: Condensation of tightly bound fermion pairs
BCS-limit: Condensation of long-range Cooper pairs

\[ a > 0 \quad a < 0 \]

Energy
Magnetic Field
Molecules
Atoms

\[ B_0 \]
Direct evaporation of $^6\text{Li}$ molecules

**Long lifetime** of Lithium molecules! (ENS, Rice)

- Directly evaporate at large and positive $a$
- Form molecules by three-body recombination when $kT \lesssim E_B$

$$a > 0$$

$$E_B = -\frac{\hbar^2}{2ma^2}$$
Direct evaporation of $^6\text{Li}$ molecules

Long lifetime of Lithium molecules! (ENS, Rice)

\[ \dot{\gamma} \text{ Directly evaporate at large and positive } a \]

\[ \dot{\gamma} \text{ Form molecules by three-body recombination when } kT \lesssim E_B \]

\[ a > 0 \]

Cool further
\[ \Rightarrow \text{BEC of molecules!} \]

\[ E_B = -\frac{\hbar^2}{2ma^2} \]
BEC of Molecules

Up to 3 million condensed molecules

Also: Boulder, Innsbruck, Paris

B = 745G
N_C/N = 45%

B = 797G
N_C/N = 87%
Direct Imaging of Molecules

Large size $R$ of the molecules:

Excited state line-splitting: $\propto \hbar \Gamma (\lambda/R)^3$

For $R > \lambda = 100 \text{ nm}$ absorbs light resonant with the atomic transition:

Observations:
Around 770G 100% signal strength at 650G it is 50%
Lifetime of the Molecular BEC

tau1: 850 ms
tau2: 10 s
\[ a \sim 22 / m \varepsilon = 22 / m R_e \sim e R \]

\[ \sim \hbar^2 / m R_e^2 \]

\[ \varepsilon_0 = \hbar^2 / ma^2 \]
Momentum of each atom $\frac{\hbar}{a}$

Relative wave function of the two blue atoms $\psi(r) \approx \sin(kr) \approx \sin(r/a)$

Probability to form molecule with size $R_e \approx |\psi(R_e)|^2 \approx (R_e/a)^2$

D. S. Petrov, C. Salomon, and G. V. Shlyapnikov, preprint cond-mat/0309010
Crossover from a Degenerate Fermi Gas to a BEC of molecules

Recent results of the last two months:
• Innsbruck
• Boulder
• MIT
• Paris
Locating the Feshbach Resonance by Molecule Dissociation

\[ B_0 = 822 \pm 3 \text{ G} \]

Dissociate Molecules after 10 ms time of flight in a 4 ms ramp (100 G/ms).

\[ B_0 = 822 \pm 3 \text{ G} \]
Locating the Feshbach Resonance by Molecule Dissociation

$B_0 = 822 \pm 3 \text{ G}$

12.5 G/ms

100 G/ms

30 G/µs

$B_0 = 822 \pm 3 \text{ G}$
Strong Coupling Between Atoms and Molecules

- Produce Fermi Sea at 870 G
- Switch off magnetic field after different times of flight.
- Assuming Landau-Zener-model

\[ e^{-c n \frac{n}{B}} \]

\[ c = \frac{\pi \hbar}{2 \Delta \mu} |V|^2 \]

\[ \dot{B} = 30 \text{ G/\mu s} \]

\[ \Omega_R = \sqrt{|V|^2} \quad n = 6 \text{ MHz} \]
Crossover from a BEC to a DFG …and back
Produce Fermi sea at 920G and ramp in 500ms to final field

T = 0 Fermi cloud:

T = 0 BEC:

Innsbruck
Paris
How to detect Condensates of Pairs of Fermions?

\[ a > 0 \quad a < 0 \]

Molecule \hspace{2cm} Long-range pair

\[ \uparrow \quad \downarrow \]

Idea: Quickly ramp over resonance to rapidly transfer fermionic atom pairs into molecules

Is the ramp fast enough to neglect collisions or other dynamics?

Limitation:
Probably works only for next neighbors
Can only detect “molecular” pairs, not long-range Cooper pairs
Observation of Condensates!

Starting field: 900 G

Initial temperature: $T / T_F = 0.2$  $T / T_F = 0.1$  $T / T_F = 0.05$


Pair condensation above the Feshbach resonance

Claim for Cooper pair condensation

Condensate Fraction vs. hold time

$k_F|a| > 1$ from 720 G on
Condensate Fraction vs. temperature
„Phase diagram“ for pair condensation

Condensate Fraction at 820 G

Magnetic Field [G]

$k_F|a| > 1$

$T/T_F$
What’s going on?

Tentative interpretation:
High condensate fraction implies pre-existing molecules above the two-body resonance position – stabilized by the Fermi sea

Simple model, neglecting interactions

[Diagram with two inverted triangles, one filled with blue dots and the other with red dots]
What's going on?

Tentative interpretation:
High condensate fraction implies pre-existing molecules above the two-body resonance position – stabilized by the Fermi sea

Simple model, neglecting interactions

At \( T/T_F = 0.05 \): Pauli blocking factor \( 10^{-16} \)
What’s going on?

Tentative interpretation:
High condensate fraction implies pre-existing molecules above the two-body resonance position – stabilized by the Fermi sea

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BEC-BCS transition only occurs when
\[ E_{\text{Mol}} \leq 2E_F \] or equivalently \( k_F |a| \leq 1 \)

Simple model, neglecting interactions.

Also: H. T. C. Stoof, preprint cond-mat/0402xxx
Prediction

Fermi sea "leaks" into molecule BEC:
\( \tilde{\gamma} \) \( k_F \) is reduced, cloud shrinks!
• None of the experimental results are inconsistent with the existence of a molecular condensate above the Feshbach resonance
• None of the experiments has conclusively identified any feature characteristic for the BCS regime, e.g. delocalization of pairs
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The Lithium Team

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