BEC of $^6\text{Li}_2$ molecules: Exploring the BEC-BCS crossover

Johannes Hecker Denschlag
Institut für Experimentalphysik
Universität Innsbruck
The lithium team

Selim Jochim
Markus Bartenstein
Alexander Altmeyer
Stefan Riedl
Reece Geursen
Cheng Chin
Johannes Hecker Denschlag
Rudi Grimm
fermion + fermion = boson

boson

$\frac{1}{2}$

$\frac{1}{2}$
BEC – BCS crossover

molecules strong coupling crossover Cooper pairs weak coupling

interaction control via Feshbach resonance

degenerate Fermi gas

high $T_C$ superconductivity, neutron stars,
$^3$He superfluidity, nuclear physics
$^6\text{Li}$ in Innsbruck

Bose-Einstein Condensation of $^6\text{Li}_2$
- production of molecules
- cooling to condensation

Exploring the BEC-BCS cross-over
(varying particle interaction)
- studied cloud size
- excitation of collective oscillations
- pairing gap --- pairing of fermions

Location of the Feshbach resonance
- rf spectroscopy
Two Component Ultracold Li Atoms

- 50% - 50% mixture of $^6$Li atoms in the lowest two ground states

$^6$Li ground state in a magnetic field

Special features:
- Stable against two-body decay
- Feshbach resonance $\Rightarrow$ tunable interaction
Feshbach Resonance

- Weakly bound state (molecule)
- No bound state, only Fermi gas

Prediction:
M. Houbiers et al.,

834.1(1.5) G
in collab. with
A. Simoni,
E. Tiesinga,
C. Williams,
P. Julienne
$^{6}\text{Li}_2$ molecules

Binding energy at 764G $\sim k_B 2 \mu K$

Size of the molecules $\sim a$

10 billion times weaker than normal molecules
three-body recombination

molecules made by collisions

three atoms

three-body process

atom

molecule

$U(r)$

binding energy $E_b$
**molecule formation**

\[ B = 690 \, \text{G} : \]

mol. bind. energy \[ E_b = k_B \cdot 18 \mu K \] >> therm. energy \[ k_B T = k_B \cdot 2.5 \mu K \]

**Figure:**

![Graph](image)

- \( N_{\text{at}} + 2N_{\text{mol}} \)
- \( N_{\text{at}} \)
- \( 2N_{\text{mol}} \)

**Legend:**

- Blue dots: \( N_{\text{at}} + 2N_{\text{mol}} \)
- Red dots: \( N_{\text{at}} \)
- Black dots: \( 2N_{\text{mol}} \)

**Note:**

S. Jochim et al.

*PRL 91, 240402 (2003)*

**Remark:**

*Long lifetimes!!*
molecule-molecule collisions

U(r)

Feshbach molecule in last bound level

\( E_{\text{kin}} \)

short lifetimes ~ 1 ms for molecules from bosons
MIT (Na\(_2\)), MPQ (Rb\(_2\)), Ibk (Cs\(_2\))

long lifetimes (~ 10 s) for molecules from fermions

explanation (Petrov et al., cond-mat/0309010): Pauli blocking in inelastic molecule-molecule collisions
Get BEC with evaporative cooling !!!

precise control of laser power
10 W ➔ few 100µW

optical dipole trap

forced evaporation
Evaporative cooling
reduce trap depth in 2s by four orders of magnitude!

evaporation time

1.3 s 1.5 s 1.8 s 2.0 s

700 µm

density distribution

676G

final trap power
number of molecules
temperature
condensate fraction

3.8mW
200,000
few 10nK
>90%

excellent starting point for further experiments

lifetime 40s!

S. Jochim et al., Science '03
molecular BEC gallery

JILA, Jin et al.

MIT, Ketterle et al.

ENS Paris, Salomon et al.

Rice Univ., Hulet et al.
Bose-Einstein Condensation of $^6\text{Li}_2$

- Production of molecules
- Cooling to condensation

Exploring the BEC-BCS cross-over
(varying particle interaction)

- studied cloud size
- excitation of collective oscillations
- pairing gap --- pairing of fermions

Location of the Feshbach resonance

- rf spectroscopy
The BEC-BCS crossover
smooth! reversible! lossless!

Scattering length \[1000a_0\]

Molecules, strong coupling

BEC Superfluidity

Cross-over

Cooper pairs, weak coupling

BCS Superfluidity

Bartenstein et al.,
PRL 92, 120401
(2004)

BEC side

BCS side

"Cooper pairs"

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

our cigar-shaped trap

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

Bartenstein et al., PRL `04  similar work also by J. Kinast et al. PRL `04
Collective Quadrupolar Excitation

Axial Excitation

Radial Excitation

Theory: Stringari `97-`03, Vichi `01, Baranov `01, Heiselberg `04
Radio-frequency spectroscopy

Measurement of molecular binding energy in $^{40}$K

Radio-frequency spectroscopy of $^{6}$Li:

$m_I = -1, 0, 1$

High B-field

$m_F = 1/2, 3/2, 5/2, 7/2$

Energy (MHz)

Magnetic field (G)

$\sim 80$ MHz

$\sim 200$ Hz

}
radio-frequency spectroscopy

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

rf spectroscopy of $^6$Li:

~80MHz

$E_b/h$ binding energy
rf spectra in crossover regime

Evaporation at 764G, then ramp field to 720G

- No evaporation: $T >> T_c$
- Evaporation to $T \approx T_c$
- Evaporation to $T < 0.4 T_c$

Atoms only
Atom-molecule mixture
Pure molecular sample (BEC)

Chin et al., Science ‘04
rf spectra in crossover regime

evaporation at 764G, then ramp field into crossover

837 G:
\[ \approx \text{on resonance!} \]

\[ T \approx 0.2 \, T_F \]

double-peak structure: atoms and pairs

\[ T = 0.0? \, T_F \]

pairs only!

pair signal shifts with \( E_F \)!

many-body physics

Chin et al., Science '04
rf spectra in crossover regime

evaporation at 764G, then ramp field into crossover

large neg. sc. length

pairing gap in strongly interacting Fermi gas

Chin et al., Science ’04
temperature dependence of pairing

Kinnunen
Rodriguez
Törmä
*Science Express*
21 July 04

\[ T < 0.1 T_F \]

\[ \approx 0.5 T_F \]

\[ \approx 0.4 T_F \]

\[ \approx 0.2 T_F \]

\[ T < 0.1 T_F \]
temperature dependence of pairing
temperature dependence of pairing

(a) $T = 0.5T_F$

fractional loss in $|2>$

RF frequency offset (kHz)

paired

unpaired
temperature dependence of pairing

\[ T = 0.35T_F \]
temperature dependence of pairing

- $T = 0.2 T_F$

fractional loss in $|2>$ vs. RF frequency offset (kHz)
temperature dependence of pairing

\[ T \approx 0.05 T_F \]
Bose-Einstein Condensation of $^6\text{Li}_2$

- Production of molecules
- Cooling to condensation

Exploring the BEC-BCS cross-over

(varying particle interaction)

- studied cloud size
- excitation of collective oscillations
- pairing gap --- pairing of fermions

Location of the Feshbach resonance

- rf spectroscopy
Location of the Feshbach resonance

Magnetic field [G]

Molecular state

Fermi gas

continuum

binding energy [\mu K b]

Magnetic field [G]

high B-field

m = -1

m = 0

m = 1

~80 MHz

rf
bound-free dissociation spectra

720.13(4) G

694.83(4) G

binding energy 134(2) kHz

277(2) kHz

Free atoms transitions

lineshape of dissociation signal: C. Chin and P. Julienne cond-mat/0408254
rf spectroscopy on $^6\text{Li}_2$
bound-bound transition

exp. data → NIST theory group: multi-channel quantum scattering model

\[ a_s = 45.167(8) \, a_0 \]
\[ a_t = -2140(18) \, a_0 \]
s-wave scattering lengths

Bartenstein et al., cond-mat/0408673
conclusion

Precise determination of Feshbach position

BEC of $^6\text{Li}_2$ molecules
  • surprisingly simple to make it
  • essentially pure and very long lifetimes
  • excellent starting point

BEC-BCS cross-over
  • conversion into Fermi gas reversible
  • cloud size
  • collective excitation
  • pairing gap
  • universality scaling laws

... smoking gun for superfluidity?