Feshbach resonances in a Fermionic Mixture of Lithium and Potassium

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Outline

Heteronuclear Fermi-Fermi mixtures

The machine

Feshbach resonances in $^6$Li – $^{40}$K
Ultracold alkali fermions

$^6\text{Li}$

$^{40}\text{K}$
Ultracold alkali fermions

$^6\text{Li}$ & $^40\text{K}$
**control knobs** *(single species)*

- **interaction strength**
- **BEC-BCS crossover physics**
  - Innsbruck, JILA, MIT, Duke, ENS, Rice

- **trap parameters:**
  - anisotropy, ellipticity etc. (very flexible!)

- **physics of polarized Fermi gases**
  - Rice
  - MIT
new possibilities in FF mixtures

control of mass ratio

fermion pairing with unequal masses, stable heteronuclear molecules, novel quantum phases ...

independent control of optical potentials

pairing with unequal Fermi surfaces
e.g., small trap of $^{40}$K in a large trap of $^{6}$Li
or optical lattice for $^{87}$Sr in a bath of $^{6}$Li ...
The machine
The Lithium-Potassium-Strontium Machine
The all-optical way

\[ ^{6}\text{Li} \text{ MOT: } N \sim 10^9 \quad T \sim 300\mu K \]

Dipole trap (100W 1075nm laser):
- \( U \sim k_B 1\) mK
- \( w \sim 30\) µm
$^6\text{Li}_2$ molecular Bose condensation

After 10ms time of flight: PURE BEC!

in dipole trap

<table>
<thead>
<tr>
<th>Time of Evaporation</th>
<th>Image</th>
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<tr>
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absorption images of $^6$Li and $^{40}$K atoms after 3 s of forced evaporative cooling at 750G

26 µK trap depths 55 µK
temperature ~ 4µK
numbers ~ $10^5$

heteronuclear Fermi–Fermi mixture
Feshbach resonances
scattering length

s-wave scattering length $a$ determined by last bound level
scattering length

- Bound state
- Closed channel
- Incident channel

U(r) vs. r
Feshbach resonance

$U(r)$ as a function of magnetic field $B$

- Bound state
- Closed channel
- Incident channel
- Coupling

Magnetic moment of closed channel differs from the magnetic moment of the incident channel

$s$-wave scattering length $a$ as a function of magnetic field $B$

$m_B$
Forming molecules

Three body collision:
(Fulfills energy and momentum conservation)
How do we know where they are?

Molecules form at resonance
Decay to lower state in 3-body collision leads to atom/molecule loss:

→ Measure loss in dependence of magnetic field!
Feshbach resonances

prepare mixture of Li\textmid1\textket{} and K\textmid1,2\textket{} in IR trap and evaporative cooling at 760 G
wait 10 s losses occur 
capture to MOT and observe remaining fluorescence

Prepare stable mixture

state change with RF

Remove unwanted states
and observe remaining fluorescence

state change with RF

Remove unwanted states

Li\textmid1\textket{} + K\textmid1\textket{}

Li\textmid1\textket{} + K\textmid2\textket{}

Li\textmid1\textket{} + K\textmid3\textket{}

RF sweep resonant laser

\[ B \ [G] \]

\[ 760 \]
Li\(1\) > K\(2\) scan
Interspecies Feshbach resonances

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<tr>
<th>channel</th>
<th>position [G]</th>
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Interpret data using several methods:

1) New, simple „asymptotic bound state“ model by S. Kokkelmans, T. Tiecke and J. Walraven
2) Coupled channels calculation by P. Julienne, E. Tiesinga
3) Coupled channels calculation by E. Tiemann

All models: only two free parameters fit model to data:
position of last bound state in singlet (↑↑) and triplet (↑↑↑) potential (= a_S and a_T)
What do we learn?

- $p$-wave molecules
- $s$-wave molecules
- Individual atoms

Graph showing $K$ fluorescence (arb. units) versus $B$ (mT) with $E/h$ (GHz) as the y-axis.
What do we learn?

- $U(r)$
- bound state
- closed channel
- coupling
- incident channel
- $p$-wave molecules
- $s$-wave molecules
- individual atoms
- $r$
**Simple Model**

\[
H = H^{hf} + H^{Z} + H^{rel}
\]

Replace by singlet or triplet binding energy.

Diagonalize H.

\[
H^{hf} = \frac{a_{hf}^{Li}}{\hbar^2} s_1 \cdot i_1 + \frac{a_{hf}^{K}}{\hbar^2} s_2 \cdot i_2
\]

\[
H^{Z} = \gamma_e S \cdot B - \gamma_{n1} i_1 \cdot B - \gamma_{n2} i_2 \cdot B
\]

\[
H^{rel} = -\frac{1}{2\mu} \left( p_r^2 + \frac{L^2}{r^2} \right) + \sum_{S=0,1} V_S(r) P_S
\]
Simple Model

- $p$-wave molecules
- $s$-wave molecules
- Individual atoms
From s- to p-wave resonances

- Long range potential known from literature
- Fit short range \textit{s-wave} potential such that \( E_s \) and \( E_t \) correct
From s- to p-wave resonances

- Long range potential known from literature
- Fit short range s-wave potential such that $E_s$ and $E_t$ correct
- Add centrifugal barrier to obtain $E_s$ and $E_t$ for p-wave potential
From s- to p-wave resonances

Individual atoms

p-wave molecules

s-wave molecules
Predicted s-wave resonances

All predicted s-wave Feshbach resonances:

Results from simple „asymptotic bound state“ model by S. Kokkelmans, T. Tiecke and J. Walraven
Predicted s-wave resonances

s-wave Feshbach resonances for stable mixtures:

Results from simple „asymptotic bound state“ model by S. Kokkelmans, T. Tiecke and J. Walraven
\( \text{Li}\,|1\rangle \, K\,|2\rangle \, \text{scattering length} \)

Coupled channels calculation by Eite Tiesinga and Paul Julienne

interaction tuning!

heteronuclear molecules!
Kai Dieckmanns group

\[
\sigma_p \left(10^{-18} \text{ cm}^2\right) \\
B (\text{mT})
\]

singlet scattering length \( a_s = 52.1 \ a_0 \)

triplet scattering length \( a_t = 63.5 \ a_0 \)
Stable Molecules

Same mechanism responsible for molecule formation and decay to lower state: 3-atom collision

Why can molecules form and then remain stable?

3-atom collision needs 3 atoms closer than size of endstate

In 2 fermion mixture Pauli principle inhibits two of the three atoms to get close

Big Feshbach molecules can still be formed, but decay to tight last bound state highly suppressed!

Molecules of Fermions much more stable than molecules of bosons!

PRL, 93, 090404
Stable Molecules

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PRL, 93, 090404
Li\textsuperscript{1}>Li\textsuperscript{2}>K\textsuperscript{1}> mixture

Atom numbers after 1 second hold:

Stable around resonance!

\begin{itemize}
  \item \textsuperscript{6}Li: \( \frac{T}{T_F} \sim 0.2 \) \quad \text{N} \sim 10^5 \\
  \item \textsuperscript{40}K: \( \frac{T}{T_F} \sim 0.5 \) \quad \text{N} \sim 10^4
\end{itemize}

(Preliminary)
**Li|1>Li|2>K|1> mixture**

Atom numbers after 1 second hold:

- Stable around resonance!

K probe for Li BEC-BCS Crossover!

### Graph

- **x-axis:** Magnetic field (G)
- **y-axis:** Number of atoms (arb. units)

- **Li Feshbach resonance**

### Data

- **6Li:** \( T/T_F \sim 0.2 \) \( N \sim 10^5 \) (Preliminary)
- **40K:** \( T/T_F \sim 0.5 \) \( N \sim 10^4 \)
Why is that?

Yet another suppression mechanism:

3 atoms close to each other:
increased kinetic energy due to Heisenberg uncertainty principle

2 or 3 resonant interactions:
Interaction wins, molecule unstable
(Efimov physics)

Only 1 resonant interaction:
Kinetic energy wins: molecule stable

Suppression of Molecular Decay in Ultracold Gases without Fermi Statistics

Seen in RbK|1> + K|2> mixture: PRL 100, 143201 (2008)
Future

Next steps:
• heteronuclear molecules
• study heteronuclear BEC-BCS crossover
New project: Sr BEC

Strontium

- metastable state
- intercombination line
- weak magnetic moment

Possibilities:
- Optical Feshbach resonances
- Subwavelength optical lattices (proposals by Zoller group)
- State specific optical potential
- Storage of quantum information in nuclear spin

possibilities for quantum simulation and computation
The team
<table>
<thead>
<tr>
<th>System</th>
<th>Team</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs-Rb GOST</td>
<td>RG</td>
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