Strongly Interacting Regimes in the Lithium-Ytterbium System

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UW INT Workshop, 12th May 2014
Dilute Quantum Degenerate Gases
Ground State

Energy [MHz]

\[ E = -\frac{Ze^2}{2\epsilon} \]

B field [Gauss]

\(|1\rangle\)
\(|2\rangle\)
\(|3\rangle\)
\(|4\rangle\)
\(|5\rangle\)
\(|6\rangle\)

Magnetic Feshbach Resonance

S-wave \( a_{s1} (a_0) \)

Magnetic field [Gauss]

\(|1\rangle\)
\(|2\rangle\)

Strongly interacting fermions
BEC of molecules
Fermi superfluid
Ytterbium: Heavy, 2-Electron Atom

Precision expts, Atomic clock on $^1S_0 \rightarrow ^3P_0$. Yb fermions for quantum simulation [SU(N)].

+ Li: Coolant, heavy-light mix, Fermi bath/probe, $^2\Sigma$ molecule.
Strongly Interacting Regime I

Magnetic field [Gauss]

Feshbach Resonance between 2 spin states of $^6$Lithium

Real part $a_{21}$ ($a_0$)

Questions of 3 particle stability
Can modify/probe resonance
Coolant/Thermometry
Strongly Interacting Regime II

Feshbach Resonance between Li and Yb.

Efimov Trimers
Heavy/light combinations
Bose/Fermi combinations

Paramagnetic Polar Molecule
Spin-controlled chemistry
Quantum Simulation, spins on lattice
Li-Yb Apparatus
Combining Ground State $^6$Li-$^{174}$Yb

Combined optical dipole trap at 1064nm

It's stable!

Extract $|a| = (13 \pm 3) a_0$ ($\sim 0.7$nm)

Other Yb isotopes + Li: similar weak interactions

V. Ivanov et al.
PRL 106, 053201 (2011)
Quantum Degenerate Li-Yb mixture

$^6\text{Li} \ T = 0.2 \ T_F$
TOF = 0.5 ms

$^174\text{Yb} \ \text{BEC}$
TOF = 10 ms

0.1 $T_F$ with further cooling

Evaporative cooling of Yb
Sympathetic cooling of Li

Similar results in Kyoto group (2011)

A. Hansen et al.
PRA 84, 011606(R) (2011)
Yb+Li1+Li2 near Li Feshbach

Magnetic field [Gauss]

Yb

Stability/reactivity of FB molecules
Yb as a bath or probe

Magnetic Feshbach Resonance

s-wave $a_{21}(a_0)$

Magnetic field [Gauss]

0 500 1000 1500 2000

-4000 0 2000 4000
Collisional Stability near Li Feshbach

“Loss” Spectrum

Li Fraction remaining after 500 ms

600 650 700 750 800 850 900 950

Magnetic Field (Gauss)

Li only (T_F/2)

ka = 1

Faster dimer formation (a^6)

Increased dimer stability (a^{-3.3})

Theory: Petrov, Shlyapnikov, Salomon, Kokkelmans, Chin, Grimm, Ho, others
Collisional Stability near Li Feshbach

“Loss” Spectrum

Li Fraction remaining after 500 ms

Magnetic Field (Gauss)

$a^6$ $\text{Li}|1\rangle + \text{Li}|2\rangle + \text{Li} \quad \Rightarrow \quad \text{Li}_2^g + \text{Li} \quad (+\epsilon_B) \quad (I)$

$a^3.3$ $\text{Li}_2^g + \text{Li} \quad \rightarrow \quad \text{Li}_2^d + \text{Li} \quad (+\epsilon_D) \quad (II)$

$a^4$ $\text{Li}|1\rangle + \text{Li}|2\rangle + \text{Yb} \quad \Rightarrow \quad \text{Li}_2^g + \text{Yb} \quad (+\epsilon_B) \quad (III)$

$a^{-1}$ $\text{Li}_2^g + \text{Yb} \quad \rightarrow \quad \text{Li}_2^d + \text{Yb} \quad (+\epsilon_D) \quad (IV)$

$a^2$ $\text{Li}|1\rangle + \text{Li}|2\rangle + \text{Yb} \quad \rightarrow \quad \text{Li}_2^d + \text{Yb} \quad (+\epsilon_D) \quad (V)$

Stable Region (at unitarity)

Lossy Region

Magnetic Field (Gauss)

$a \rightarrow \infty$
Scaling to Other Fields

Scaling from rate constant measurements at 710 G

Scaling laws: Petrov/Shlyapnikov, D’Incao/Esry, others (2003 onwards)
Evolution at unitarity
(810 G, ka=+6)

Good collisional stability with Yb
Clear inter-species thermalization.

A. Khramov et al
PRA 86, 032705 (2012)

Related work in Innsbruck on K-Li: PRL 103, 223203 (2009)
Feshbach Resonance in Li-Yb?

Collisions in a bi-alkali system.
Supports strong Feshbach resonances

Collisions in a spin-zero+alkali system.
“Usual” Feshbach resonance not supported

No resonances seen yet in expts with spin-zero +alkalis

Coupling through Li hyp const and Yb nuclear spin.
Predicted width of ~ 1 \( \mu \)mG at > 1kG

Brue and Hutson, PRL 108, 043201 (2012)
Feshbach Resonance in Li-Yb?

(Too?) Narrow Feshbach resonance with *ground* Yb

\[ \text{Li} \ + \]

\[ \begin{align*}
\text{\( ^1S_0 \) (6s²) Ytterbium} \\
\text{\( ^3P_0 \)} & \text{ (6s6p)} \\
\text{\( ^3P_1 \) (6s6p)} & \text{ (666nm)} \\
\text{\( \lambda = 399\text{nm} \)} & \text{ (666nm)} \\
\text{\( \Gamma/2\pi = 29\text{ MHz} \)} & \text{ (666nm)} \\
\text{\( ^3P_2 \)} & \text{ (6s6p)} \\
\text{\( \lambda = 556\text{nm} \)} & \text{ (6s6p)} \\
\text{\( \Gamma/2\pi = 182\text{ kHz} \)} & \text{ (6s6p)}
\end{align*} \]
Feshbach Resonance in Li-Yb?

(Possible) broad Feshbach resonance with *metastable* Yb*

Resonances in Yb+Yb*: Takahashi group - PRL 110, 173201 (2013)
Coupling through anisotropic interactions: S. Kotochigova group - PRL 109, 103002 (2012)
Feshbach Resonance in Li-Yb*

Broad Feshbach resonances with \textit{metastable} Yb* (Kotochigova; Hutson)

These resonances can also be lossy.

Parallel calculations in S. Kotochigova group
Preparing and Monitoring the $^3P_2$ State

(6s7s) $\rightarrow ^3S_1$

(6s6p) $\rightarrow ^1P_1$

(6s6p) $\rightarrow ^3D_2 (6s5d)$

$^3S_1$

$^3D_2 (6s5d)$

$^3P_2$

$^3P_1$

$^3P_0 (6s6p)$

399nm

Laser Cooling Yb

556nm
Preparing and Monitoring the $^3P_2$ State

Prior $1S_0 \to 3D_2$ work: Bowers et al PRA 59, 3513 (1999), Yamaguchi et al PRL (2008)
Preparing and Monitoring the $^3P_2$ State

Preparing and Monitoring the $^3P_2$ State

Detecting $^3P_2$

$^1S_0$ → $^3P_2$

$^3D_2$ → $^3S_1$

$^1P_1$ → $^3P_2$

770nm

649nm

399nm
Combining Ground Li and Excited Yb* Atoms

\[ \frac{\dot{n}_{Yb^*}}{n_{Li} n_{Yb^*}} = -K_2 n_{Li} - K_2 n_{Yb^*}^2, \]
\[ \frac{\dot{n}_{Li}}{n_{Li} n_{Yb^*}} = -K_2' n_{Li} n_{Yb^*}, \]

Yb*-Yb* 2 body decay constant \( K_2 = 2.5 \times 10^{-11} \text{ cm}^3/\text{s} \)

Yb*-Li 2 body decay constant \( K_2' < 3 \times 10^{-12} \text{ cm}^3/\text{s} \)

A. Khramov et al. PRL 112, 033201 (2014)
Li-Yb* Field dependent losses

[Graphs showing atom number versus time for different magnetic field strengths (100G and 270G) with error bars and trend lines.]
Loss Spectroscopy of Li and Yb*

(Preliminary)

Initial peak densities: \( n_{Yb(Li)} = 0.8(2.2) \times 10^{12}/\text{cm}^3 \). Temp \( \sim 1.6\mu\text{K} \).
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Yb as a bath or probe with strongly-interacting Lithium fermions

Li+Yb* system inelastics: different spin states 2 vs 3-body evolution LiYb molecules

Optical Lattice