Two-photon Photoassociation Spectroscopy of CsYb

Alex Guttridge
Outline

• Motivation
• Trapping and cooling of Cs and Yb
• One-photon photoassociation of Cs*Yb molecules
• Two-photon photoassociation and scattering lengths
• Outlook
• Summary
Why Cs and Yb?

Cs
- High Mass Alkali
- Rich Feshbach Structure
- 1 Valence Electron

CsYb
- Heteronuclear
- Ground state EDM
- Unpaired Electron – Magnetic Dipole Moment
- Reduced Mass Tuning
- Fermi-Bose and Bose-Bose Mixtures

Yb
- 7 Isotopes
- 2 Fermions and 5 Bosons
- 2 Valence Electrons

Alex Guttridge
QSUM Annual Meeting – 2nd July 2018
Producing ground state molecules

- Follow successful method used in RbCs

Ultracold mixture in dipole trap/lattice

- To prepare the scatteri

- Prediction of Feshbach resonances for magnetoassociation requires knowledge of bound state binding energies

- Measurement of the CsYb binding energies using photoassociation can determine the interspecies scattering lengths and enable the prediction of Feshbach resonances
Dual-Species Apparatus
Cs and Yb BECs

- Can independently produce $^{133}\text{Cs}$, $^{174}\text{Yb}$ and $^{170}\text{Yb}$ BEC’s
- Efficient evaporative cooling of $^{174}\text{Yb}$ allows for all optical production of large BECs with \( N > 4 \times 10^5 \) atoms
Degenerate Fermi Gas of $^{173}$Yb

- Working with fermionic Yb allows realisation of Bose-Fermi mixtures and production of fermionic molecules
- We can produce a degenerate Fermi gas of $^{173}$Yb in a six spin mixture ($I=5/2$)
- Temperature is limited by Pauli blocking but may be overcome by sympathetic cooling with Cs (in a suitable trap)
Thermalisation

- Prepare mixture of Cs and Yb in dipole trap

- Observe the thermalisation of Cs with $^{174}\text{Yb}$ or $^{170}\text{Yb}$ in the dimple trap

• Use a rate equation model to extract interspecies collision cross sections and scattering lengths

\[
\sigma_{\text{Cs}^{174}\text{Yb}} = (5 \pm 2) \times 10^{-13} \text{ cm}^2 \\
\sigma_{\text{Cs}^{170}\text{Yb}} = (18 \pm 8) \times 10^{-13} \text{ cm}^2 \\
\alpha_{\text{Cs}^{174}\text{Yb}} = -60 \pm 9 \, \text{a}_0 \\
\alpha_{\text{Cs}^{170}\text{Yb}} = 90 \pm 2 \, \text{a}_0
\]
Photoassociation of CsYb molecules
Photoassociation

- **One-photon photoassociation takes place with a mixture of Cs atoms in $F=3$, $m_F=+3$ state and Yb in $^1S_0$ state
- **Photoassociation takes place below the Cs $D_{1}$ transition
- PA is the process where a colliding atom pair is excited into an excited molecular state

![Diagram showing energy levels and transitions involving Cs and Yb atoms.](image-url)
Experimental Setup

- Photoassociation takes place in dipole trap containing $8 \times 10^5 \text{ Yb}$ and $7 \times 10^4 \text{ Cs}$
- The trap is formed by two beams which are focused to a $33 \pm 2 \, \mu\text{m}$ and $75 \pm 2 \, \mu\text{m}$ waist and crossed at an angle of 40°
- Photoassociation light is counter propagated along one arm of dimple using a dichroic mirror
- PA waist $\sim 100 \, \mu\text{m}$
CsYb Spectra

- Illuminate the mixture with PA light ($I = 0.2 - 100 \text{ W/cm}^2$) for 50 ms
- Detect the creation of Cs*Yb molecules by loss of Cs atoms
- Typical FWHM is 5 - 10 MHz ($\Gamma_{D1} = 2\pi \times 4.6 \text{ MHz}$)
- Check if CsYb by removing Yb with a pulse of 399 nm light just before PA

CsYb Spectra

- For each vibrational level we observe two features corresponding to the hyperfine splitting of the $D_1$ line
- PA creates molecules in high vibrational levels which are described as ‘physicists molecules’ where the properties of the molecules are dictated by the behaviour of two free atoms

Hyperfine Splitting

- Hyperfine splitting of PA lines decreases with the binding energy of the vibrational level
- R-dependence of hyperfine coupling constant due to perturbation of atomic wavefunction in a collision with Yb
- Same effect predicted to produce Feshbach resonances in the ground state

Le Roy-Bernstein Analysis

- Photoassociation measurements performed on Cs$^{174}$Yb, Cs$^{173}$Yb, Cs$^{172}$Yb and Cs$^{170}$Yb molecules.
- Mass scaled LRB analysis constrains the number of bound states to be 154 or 155.

2-photon photoassociation

- Extension of the one photon scheme where an additional laser drives a transition between the electronically excited molecular state and the ground electronic state
2-photon Spectra

- First identify features with ATS spectroscopy (“loss of loss”)
- Creation of electronically excited Cs*Yb is suppressed by light shift when 2\textsuperscript{nd} photon is resonant with bound-bound transition

A. Guttridge et al., arXiv:1806.00295
2-photon Spectra

- Can verify the 3 level nature of this system by observation of EIT
- On 2-photon resonance a dark state is created between two free atoms (Cs+Yb) and a ground state molecule (CsYb)

A. Guttridge et al., arXiv:1806.00295
2-photon Spectra

- For accurate measurements of the binding energy $E_{b1}$ we use Raman spectroscopy
- The loss feature signifies the production of ground state CsYb molecules
- Data is fitted by a Fano profile

$\Delta_{FB} = -15 \text{ MHz}$

$\Delta_{2\gamma} = \Delta_{BB} - \Delta_{FB}$

A. Guttridge et al., arXiv:1806.00295
## Binding energies

<table>
<thead>
<tr>
<th>Yb Isotope</th>
<th>(n')</th>
<th>(n'')</th>
<th>(E_{b1}/\hbar) (MHz)</th>
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<tr>
<td>170</td>
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</table>

- Binding energies of vibrational levels are calculated from the frequency difference between the two PA lasers on 2-photon resonance
- AC Stark shifts and thermal shifts of photoassociation line must be accounted for in measurements

A. Guttridge et al., arXiv:1806.00295
Fitting of an interaction potential to the measured binding energies was performed by Frye and Hutson. The resulting interaction potential allows the calculation of scattering lengths and prediction of Feshbach resonances. All scattering lengths are between $-2\hbar a$ and $+2\hbar a$ with the exception of $\text{Cs}^+ \text{Yb}^{176}$. 

A. Guttridge et al., arXiv:1806.00295
Cs+Yb Scattering properties

- Extracted scattering lengths are in good agreement with thermalisation measurements
- All mixtures except Cs+\(^{176}\)Yb are miscible at 22 G, the Efimov minimum in the Cs three-body rate
- Large scattering length of Cs+\(^{176}\)Yb enhances FR width
- Cs+\(^{171}\)Yb scattering length is promising for the production of Bose-Fermi mixtures

A. Guttridge et al., arXiv:1806.00295
Outlook
Towards degenerate mixtures

• Currently, large difference in polarisability limits the sympathetic cooling of Cs
• Large Cs three-body loss rate means a weaker Cs trap is desirable
• Large difference in trap frequencies leads to differential gravitational sag

<table>
<thead>
<tr>
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<th>Polarisability</th>
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<tr>
<td>1070 nm (a_0^3)</td>
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<tr>
<td>Yb</td>
<td>158.0</td>
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<tr>
<td>Cs</td>
<td>1136.5</td>
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</table>
Towards degenerate mixtures

- Introduce bichromatic trap (532 + 1070 nm) to reduce Cs heating due to tight confinement

- Enables controllable overlap of clouds which can mitigate gravitational sag and enhance sympathetic cooling

- 532 nm laser has been installed in the setup and Yb atoms have been loaded into the trap
Bose-Bose mixtures

\[ g_{ij} = 2\pi \hbar^2 a_{ij} \left( \frac{m_i + m_j}{m_i m_j} \right) \]

\[ \Delta = \frac{g_{CsCs} g_{YbYb}}{g_{CsYb}^2} - 1 \]

- The tunability of the Cs scattering length at low magnetic fields allows the exploration of the miscible-immiscible phase transition
- The negative interspecies scattering length of Cs\(^+\)\(^{174}\)Yb allows the formation of mass imbalanced quantum droplets

C. R. Cabrera et al., Science 359, 301 (2018)
Feshbach resonances

- Fitted interaction potential from photoassociation measurements may be used to predict Feshbach resonance positions and widths for all isotopologs.
- Knowledge of scattering length allows us to identify which mixtures are most promising for magnetoassociation.
- Feshbach resonances between alkali and closed shell atoms have recently been observed in RbSr.

V. Barbé et al., Nature Physics (2018) DOI: 10.1038/s41567-018-0169-x
Summary

- Creation of an ultracold mixture of Cs and Yb
- Production of ultracold CsYb molecules through one- and two-photon photoassociation
- Calculated scattering lengths are promising for the realisation of a double-degeneracy in a bichromatic trap
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