One and two-colour photoassociation spectroscopy of $^{40}$Ca

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Outline

Our group focused on bosonic\textsuperscript{40}Ca

- Atomic interaction in quantum gases

- Methods for manipulation of interaction
  - Optical Feshbach resonances (OFR)
  - Theoretical description

- Measurement of weakly bound levels in ground and excited state potentials by one and two-colour photoassociation spectroscopy

- Outlook for optical Feshbach resonances with Calcium
Interaction / scattering length

Potential energy of two atoms as function of their nuclear distance $R$

Scattering length as a description for the scattering behaviour of the atoms

Interaction / scattering length

The interaction in cold quantum gases can be described by a single quantity - the scattering length

Scattering length as a description for the scattering behaviour of the atoms

Feshbach resonances

Feshbach Resonance: Coupling of the ground scattering state to a bound molecular state. Influence on scattering behaviour!

Magnetic Feshbach resonances

Optical Feshbach resonances
### Comparison between magnetic and optical Feshbach resonances

<table>
<thead>
<tr>
<th>Magnetic Feshbach resonances</th>
<th>Optical Feshbach resonances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field B</td>
<td>Laser frequency $\nu$</td>
</tr>
<tr>
<td>Coupling due to short-range spin-dependent interaction</td>
<td>Coupling due to long-range photoassociation</td>
</tr>
<tr>
<td>Different spin component</td>
<td>Many vibrational levels of same closed-channel molecular state</td>
</tr>
</tbody>
</table>

**Advantages**
- The close channel state does not break down
- Well investigated and widespread

**Advantages**
- High spatial resolution depending on focusing of laser light
- Very fast switching of laser light

The MFR and OFR can be treated by the same resonance scattering formalism when the spontaneous emission is taken into account.
Narrow line optical Feshbach resonances

- “Narrow line can help” / predictions for alkaline-earth elements
  
  Ciurylo et al., PRA 71, 030701(R) (2005)

  ✓ \(^{172}\)Yb, \(\Gamma_{\text{\(^{3}\)P\(-\text{\(^{1}\)S\(_{0}\)}}\)}} = 181 \text{ kHz}, \) Enomoto et al., PRL 101 203201 (2008)

  ✓ \(^{88}\)Sr, \(\Gamma_{\text{\(^{3}\)P\(-\text{\(^{1}\)S\(_{0}\)}}\)}} = 7.5 \text{ kHz}, \) Yan et al., PRL 110 123201 (2013)

- \(^{40}\)Calcium has very narrow line width 374 Hz of transition \(^{3}\)P\(_{1}\) – \(^{1}\)S\(_{0}\) 657 nm
Photoassociation at $^3\text{P}_1+^1\text{S}_0$

1. Two ground state atoms collide in a laser field (s-wave scattering).

2. At the proper distance a pair of atoms can be excited to a bound molecule.

3. The photoassociation lines are detected via loss of atoms.
Cooling scheme

4s4p \(^1P_1\)

1. stage MOT (423 nm)

2. stage MOT (657 nm)

dipole trap

1 s

0.3 s

1.5 s

4s4s \(^1S_0\)

657 nm 370 Hz

423 nm 34 MHz

After evaporation:

N \sim 150\,000

T \sim 1\,\mu K

\rho \sim 10^{13}\,\text{cm}^{-3}
Photoassociation

Thermal broadening

Photoassociation at $^3P_1+^1S_0$ / Line frequencies

Measured curves for two different trap depths and temperatures

$$T = 0.5 \, \mu \text{K}$$
$$U_{\text{tr}} = 1/2 \, U_0$$

$$T = 1 \, \mu \text{K}$$
$$U_{\text{tr}} = U_0$$

6 measured photoassociation lines of bound vibration states in the two excited ungerade potentials $^3\Pi_u$ and $^3\Sigma^+_u$

<table>
<thead>
<tr>
<th>level $v'$</th>
<th>$\Delta_b^{\text{calc}}$ GHz</th>
<th>$\Delta_b^{\exp}$ GHz</th>
<th>$\delta$ kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1 0</td>
<td>-0.308672</td>
<td>-0.308670 (7)</td>
<td>2</td>
</tr>
<tr>
<td>-1 1</td>
<td>-0.982995</td>
<td>-0.982994 (6)</td>
<td>1</td>
</tr>
<tr>
<td>-2 0</td>
<td>-4.649199</td>
<td>-4.649203 (22)</td>
<td>-4</td>
</tr>
<tr>
<td>-2 1</td>
<td>-7.411944</td>
<td>-7.411946 (12)</td>
<td>-2</td>
</tr>
<tr>
<td>-3 0</td>
<td>-17.857274</td>
<td>-17.857274 (7)</td>
<td>0</td>
</tr>
<tr>
<td>-3 1</td>
<td>-24.539446</td>
<td>-24.539446 (7)</td>
<td>0</td>
</tr>
</tbody>
</table>

Kahmann et al, PRA, 89, 023413 (2014)
Nonlinear Zeemann effect

Nonlinear Zeemann effect even at low fields of few mT amounts to several kHz

Tiemann et al., PRA, 92, 023419 (2015)
Isolated resonance theory of optical Feshbach resonance

The bosonic $^{88}\text{Sr}$ has narrow line width 7 kHz of transition $^{3}\text{P}_{1} \rightarrow ^{1}\text{S}_{0}$. Compared to $^{88}\text{Sr}$ the natural line width of $^{40}\text{Ca}$ is 20 times narrower.

The photoassociation resonances of $^{40}\text{Ca}$ can be treated as isolated.

Pic: Nicholson et al., PRA, 92, 022709 (2015)
Isolated resonance theory of optical Feshbach resonance

Stimulated width due to laser light

\[ \Gamma_{\text{stim}} = 2l_{\text{opt}} k_{\text{col}} \Gamma_{\text{mol}} \]

\[ l_{\text{opt}} = \frac{\hbar^3 \cdot |\langle \Psi_e | \Psi_g \rangle|^2 \cdot I}{16\pi \epsilon k_{\text{col}}} \]

Inelastic loss coefficient

\[ \frac{d\rho}{dt} = -K_{\text{inel}} \rho^2 \]

\[ K_{\text{inel}} = \frac{2\pi\hbar}{\mu} \frac{l_{\text{opt}} \Gamma_{\text{mol}}^2}{\Delta^2 + (\Gamma_{\text{mol}} + \Gamma_{\text{stim}})^2 / 4} \]

Change of scattering length

\[ a = a_{\text{bg}} + a_{\text{opt}} = a_{\text{bg}} + \frac{l_{\text{opt}} \Gamma_{\text{mol}} \Delta}{\Delta^2 + \Gamma_{\text{mol}}^2 / 4} \]

First measurement at high intensities

Stimulated width

$$\Gamma_{\text{stim}} = 2l_{\text{opt}} k_{\text{col}} \Gamma_{\text{mol}} \quad l_{\text{opt}} = \frac{\lambda^3 \cdot FCD \cdot I}{16 \pi c k_{\text{col}}}$$

Other main broadening mechanisms:
- Doppler broadening
- Thermal broadening

expected: \( \Gamma / 2\pi = 70 \text{ kHz} \)
measured: \( \Gamma / 2\pi = 220 \text{ kHz} \)

First trial to observe optical Feshbach resonances was not successful because of this unexpectedly high power broadening.
Saturation of one colour photoassociation

Measurement indicates saturation of broadening and of the corresponding loss.
Isolated resonance theory of optical Feshbach resonance

Stimulated width due to laser light

\[ \Gamma_{\text{stim}} = 2l_{\text{opt}} k_{\text{col}} \Gamma_{\text{mol}} \]

\[ l_{\text{opt}} = \frac{\lambda^3 \cdot |\langle \Psi_e | \Psi_g \rangle|^2 \cdot I}{16 \pi c k_{\text{col}}} \]

Inelastic loss coefficient \( \frac{d \rho}{dt} = -K_{\text{inel}} \rho^2 \)

\[ K_{\text{inel}} = \frac{2 \pi h}{\mu} \frac{l_{\text{opt}} \Gamma_{\text{mol}}^2}{\Delta^2 + (\Gamma_{\text{mol}} + \Gamma_{\text{stim}})^2 / 4} \]

Change of scattering length

\[ a = a_{\text{bg}} + a_{\text{opt}} = a_{\text{bg}} + \frac{l_{\text{opt}} \Gamma_{\text{mol}} \Delta}{\Delta^2 + \Gamma_{\text{mol}}^2 / 4} \]

Measurement of vibrational levels in ground state potential

Two colour photoassociation spectroscopy:

$L_1$, $L_2$ detuned from intermediate state → losses if $v_1 - v_2 = v_{binding}$

Requires an additional photoassociation laser $L_2$
Additional photoassociation laser

- Stability comparable to the ultra stable laser width line width of about 10 Hz
- Tuning range until 40 GHz
- Power of slaves about 100 mW
Additional photoassociation laser

Beat between the both masters shows 88% of power in central carrier peak
The position of the unperturbed state was determined by correcting of light shifts of the two photoassociation lasers and the dipole trap laser.

<table>
<thead>
<tr>
<th>$v$</th>
<th>$J$</th>
<th>$\nu_{binding}$ in MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>0</td>
<td>-1387.442(9)</td>
</tr>
<tr>
<td>39</td>
<td>2</td>
<td>-1005.366(6)</td>
</tr>
<tr>
<td>40</td>
<td>0</td>
<td>-1.601(7)</td>
</tr>
</tbody>
</table>
Improved ground state potential $X \, ^1\Sigma^+_g$ of calcium dimer

Including the inner part of the ground state potential $X \, ^1\Sigma^+_g$ the whole potential was obtained by fitting of the long range $C_6$, $C_8$ coefficients and dissociation energy $D_e$ to reproduce the energies of the measured PA lines.

$$V_{X \, ^1\Sigma^+_g} (R) = D_e - \frac{C_6}{R^6} - \frac{C_8}{R^8}$$

$D_e = 1102.074 \, \text{cm}^{-1}$

$C_6 = 1.02609 \times 10^7 \, \text{cm}^{-1}\text{Å}^6$

$C_8 = 3.540 \times 10^8 \, \text{cm}^{-1}\text{Å}^8$

Improved background scattering length of $^{40}$Ca

<table>
<thead>
<tr>
<th>scattering length</th>
<th>publication</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 - 300 $a_{\text{Bohr}}$</td>
<td>C. Degenhardt et al., PRA 67, 043408(2003)</td>
</tr>
<tr>
<td>$\approx$ 440 $a_{\text{Bohr}}$</td>
<td>S. Kraft et al., PRL 103, 130401(2009)</td>
</tr>
</tbody>
</table>

Filtered Laser Excitation + Laser Induced Fluorescence
One Colour Photoassociation on $^1S_0 - ^1P_1$ transition
Estimated from chemical Potential in BEC

\[ a_{bg} = (308 \pm 20) \cdot a_{\text{Bohr}} \]
Expected losses and scattering length in $^{40}$Ca

Initial parameters:

- $T = 1 \mu K$
- $I = 1000 \text{ Wcm}^{-2}$
- $N_0 = 170 000$
- $\rho_0 = 3 \cdot 10^{13} \text{ cm}^{-3}$

\[ a_{\text{bg}} = 308 \ a_{\text{Bohr}} \]

\[ a_{\text{opt}} \propto \frac{l_{\text{opt}}}{\Delta} \quad \text{and} \quad K_{\text{inel}} \propto \frac{l_{\text{opt}}}{\Delta^2} \]

\[ \Gamma / 2\pi = (250_{\text{Broadening}} + 30_{\text{stim}}) \text{ kHz} \]

<table>
<thead>
<tr>
<th>Detuning $\Delta$</th>
<th>$a_{\text{opt}}$</th>
<th>losses in the trap after 50 ms irradiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MHz</td>
<td>32 $a_{\text{Bohr}}$</td>
<td>2 %</td>
</tr>
<tr>
<td>500 kHz</td>
<td>65 $a_{\text{Bohr}}$</td>
<td>7 %</td>
</tr>
<tr>
<td>250 kHz</td>
<td>130 $a_{\text{Bohr}}$</td>
<td>22 %</td>
</tr>
<tr>
<td>125 kHz</td>
<td>259 $a_{\text{Bohr}}$</td>
<td>44 %</td>
</tr>
</tbody>
</table>

Significant changing of the scattering length and small losses near molecular resonance
Conclusions

- The six weakest bound vibrational states of the two excited ungerade potentials (c $^3\Pi_u$ and a $^3\Sigma^+_u$) in $^{40}$Ca with very high (kHz) accuracy by one colour photoassociation spectroscopy

- Building of additional off-set locked diode laser

- Measurement of three weakly bound vibrational v = -2 state (J=0, 2) in the ground potential $^1\Sigma^+_g$ by two colour photoassociation spectroscopy

- Improved scattering length 308(20)$a_{\text{Bohr}}$

Outlook

- Measurement of one colour photoassociation lines at very high intensities using improved

- Feasibility of optical Feshbach resonance with $^{40}$Ca
Thank you for attention