Ultracold dipolar bosonic molecules

Workshop on Quantum Simulations with Ultracold Atoms
ICTP Trieste
Tetsu Takekoshi, 20.07.12
• RbCs motivation – a toy for artificial condensed matter systems: novel many-body states, quantum phase transitions, strong correlations, many-body transport, etc.
• we have rovibhyper ground state RbCs
• ground state RbCs from a double Mott insulator soon.
Why degenerate dipolar gases?

\[ \Sigma \] rigid rotor

\[ \hat{H}_{\text{rot}} = B \hat{J}^2 \]
\[ \hat{H} = \hat{H}_{\text{rot}} - \hat{d} \cdot E = \hat{H}_{\text{rot}} - dE \cos \theta \]
\[ E = E e_z \]

Review articles:
Why degenerate dipolar gases?

87RbCs lowest rotational level

![Diagram showing the relationship between dipole moment (Debye) and field (V/cm).]
Why degenerate dipolar gases?

\[ U_{dd}(r) = \frac{C_{dd}}{4\pi} \frac{1 - 3\cos^2\theta}{r^3} \]

\[ C_{dd} = \frac{d^2}{\varepsilon_0} \]

\[ C_{dd} = \mu_0\mu^2 \]

\[ \frac{\mu_0\mu^2}{d^2/\varepsilon_0} \sim \alpha^2 \sim 10^{-4} \]

Review articles:

\[ a_{dd} \equiv \frac{C_{dd}m}{12\pi\hbar^2} \]

\[ \varepsilon_{dd} \equiv \frac{a_{dd}}{a} = \frac{C_{dd}}{3g} \]
Why degenerate dipolar gases?

\[
a_{dd} = \frac{md^2}{4\pi\varepsilon_0\hbar^2}
\]

dipolar gases

\[
\varepsilon_{dd} \equiv \frac{a_{dd}}{a} = \frac{C_{dd}}{3g}
\]

dipole moment (debye)

characteristic range (bohr)

optical lattice spacing

typical experimental atomic scattering lengths

Colorado

Innsbruck

Stuttgart

Urbana / Stanford

stadium
Why degenerate dipolar gases?

\[ a_{dd} = \frac{md^2}{4\pi\varepsilon_0 \hbar^2} \]

dipole moment (debye)

\[ \varepsilon_{dd} \equiv \frac{a_{dd}}{a} = \frac{C_{dd}}{3g} \]

dipole moment (debye)

characteristic range (bohr)

Innsbruck in progress...

optical lattice spacing

typical experimental atomic scattering lengths

d

\[ d \]

dipole moment (debye)

characteristic range (bohr)

\[ a_{dd} = \frac{md^2}{4\pi\varepsilon_0 \hbar^2} \]

dipole moment (debye)

\[ \varepsilon_{dd} \equiv \frac{a_{dd}}{a} = \frac{C_{dd}}{3g} \]

dipole moment (debye)

characteristic range (bohr)
Why degenerate dipolar gases?

Novel effects appear – NOT contact interaction!

- Identical fermions interact
- exotic quantum phases
- novel spectrum of excitations
- geometry-dependent interaction

B. Capogrosso-Sansone et al.,
Why degenerate dipolar gases?

- Quantum degeneracy
- Coherent state transfer
- Enhanced PA?
- Laser cooling?
- Sympathetic cooling?
- Evaporative cooling?
- Buffer-gas cooling
- Stark, magnetic, optical deceleration
- Photo-association

Carr DeMille Krems and Ye, NJP 11, 055049 (2009).
Why degenerate dipolar gases?

- Quantum degeneracy
- Coherent state transfer
- Enhanced PA?
- Laser cooling?
- Sympathetic cooling?
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- Stark, magnetic, optical deceleration

Carr DeMille Krems and Ye, NJP 11, 055049 (2009).
Recipe for high phase-space density dimer gas

degenerate atomic gas(es) $\rightarrow$ Feshbach molecules $\rightarrow$ coherent ground state transfer

- high phase space density almost guaranteed
- high experimental complexity
- limited to "boring" molecules, i.e. dimers
- successfully applied thus far to $\text{KRb, Cs}_2, \text{Rb}_2 (^3\Sigma), \ldots \text{RbCs}$
The colliding BEC method
Coupled channel model

model includes LIF-FFT spectroscopic data from Riga, Rio de Janeiro
Coupled channel model

Coupled channel model

Data for model – Feshbach molecule binding energies through magnetic field modulation

The source of much trouble...

Coupled channel model

Cs $|3,3\rangle + ^{87}\text{Rb} |1,1\rangle$

Coupled channel model

Cs |3,3⟩ + $^{87}$Rb |1,1⟩

Johann Danzl (now "Dr.") Russell Hart (Rice)

The colliding BEC method

Typically 60k Cs + 150k Rb gives 4000 RbCs (we detect only atoms)
Ground state transfer

Hamiltonian: \[
H(t) = \frac{\hbar}{2} \begin{bmatrix}
0 & \Omega_1 & 0 \\
\Omega_1 & 0 & \Omega_2 \\
0 & \Omega_2 & 0
\end{bmatrix}
\]

Eigenstates with light on:
\[
| \Theta \rangle = \frac{\Omega_1}{\Omega_2} 
\]
\[
| a^\rightarrow \rangle = \sin \Theta \cos \Phi | 1 \rangle - \sin \Theta | 2 \rangle + \cos \Theta \cos \Phi | 3 \rangle 
\]
\[
| a^\leftarrow \rangle = \sin \Theta \cos \Phi | 1 \rangle - \sin \Phi | 2 \rangle + \cos \Theta \cos \Phi | 3 \rangle 
\]
\[
\frac{\tan \Theta}{\text{dark state}} = \frac{\Omega_1}{\Omega_2}
\]

\[
\Theta \text{ goes from 0 to } \Pi \text{ adiabatically}
\]

Hamiltonian:

\[ H(t) = \frac{\hbar}{2} \begin{bmatrix} 0 & \Omega_1 & 0 \\ \Omega_1 & 0 & \Omega_2 \\ 0 & \Omega_2 & 0 \end{bmatrix} \]

Eigenstates with light on:

\[ |a^+\rangle = \sin \Theta \sin \Phi |1\rangle + \cos \Phi |2\rangle + \cos \Theta \sin \Phi |3\rangle \]

\[ |a^0\rangle = \cos \Theta |1\rangle - \sin \Theta |3\rangle \text{ dark state} \]

\[ |a^-\rangle = \sin \Theta \cos \Phi |1\rangle - \sin \Phi |2\rangle + \cos \Theta \cos \Phi |3\rangle \]

\[ \tan \Theta = \frac{\Omega_1}{\Omega_2} \]

\[ \Theta \text{ goes from } 0 \text{ to } \pi \text{ adiabatically} \]

Energies and rotational constants agree well with Docenko et al., PRA 81 042511 (2010). (Riga, Rio de Janeiro)

\[ S = 1, \Sigma = -1, 0, 1 \]
\[ \Lambda = 1 \]
\[ \Omega = \Lambda + \Sigma = 0, 1, 2 \]

At ground state transfer, suggested Bergeman et al., PRA 67 050501 (2003). (Riga, Rio de Janiero)

\[ A^1\Sigma^+ - b^3\Pi_{0+} \]

Spin-orbit mixing \( \Delta \Omega = 0, \Delta J = 0 \)

Feshbach molecule absorption

Hund’s case (a)

Dark states (projection)
Ground state transfer

Suggested Bergeman et al., PRA 67 050501 (2003). (Riga, Rio de Janiero)

$S = 1, \Sigma = -1,0,1$

$\Omega = \Lambda + \Sigma = 0,1,2$

$\Lambda = 1$

$A^{1}\Sigma^{+} - b^{3}\Pi_{0+}$

spin-orbit mixing $\Delta \Omega = 0, \Delta J = 0$

Feshbach molecule absorption

Energies and rotational constants agree well with Docenko et al., PRA 81 042511 (2010). (Riga, Rio de Janiero)
RbCs two-photon STIRAP to $v=0$, $J=0$.

(on a thermal RbCs sample at 200-300 nK trapped in an optical lattice)

single-pass transfer efficiency $\approx 87\%$

- we detect only atoms
- STIRAP references -- two optical cavities locked to Cs atomic reference laser
- estimated relative laser linewidth: 5-10kHz
Cs |3,3⟩ + ^{87}\text{Rb} |1,1⟩ in incoming s-wave collision has $M_F=4$, therefore, Feshbach molecules also have $M_F=4$.

Ground state transfer all accessible directly through STIRAP (in theory)

where are we ?!!

$87\text{Rb}^{133}\text{Cs}$

dominant terms – scalar nuclear dipole-dipole, nuclear Zeeman
J. Aldegunde (Salamanca) and Jeremy M. Hutson (Durham)
Excited state model
(help from Romain Vexieu, Anne Crubelier, Oliver Dulieu)

\[ A^1\Sigma^+ \rightarrow b^3\Pi_0^+ \]

FIG. 3: \( 217\text{GHz} \) Feshbach \( \rightarrow b^3\Pi_1 \) \( \nu' = 29, J' = 1 \) horizontal laser polarization. Red lines indicate calculated transition strengths.

Ground state transfer

\[ b \Pi \]

Parameter fit to effective Hamiltonian:
\[ H = H_{\text{rotation}} + H_{\text{Zeeman}} + H_{\text{hf}} \]
\[ H_{\text{hf}} = a_{\text{Rb}} \mathbf{i}_{\text{Rb}} \cdot \mathbf{L} + a_{\text{Cs}} \mathbf{i}_{\text{Cs}} \cdot \mathbf{L} \]

Overall frequency shift

(1st unambiguous observation of orbital hyperfine in bialkalis)
FIG. 4: 182G $Feshbach \rightarrow b^3\Pi_1 v' = 29, J' = 1$ vertical laser polarization. The lowest-frequency peak here (STIRAP 1) is currently used for STIRAP. Green lines indicate calculated transition strengths.

TABLE II: 182G $b^3\Pi_1 v' = 29, J' = 1$ expectation values. (Green lines from left to right in Fig. 4.)

| $\langle \hat{n}_{i_{in}} \rangle$ | 1.45827 | 1.10556 | 0.79239 | -0.21970 | 0.64279 | 1.21344 |
| $\langle \hat{n}_{i_{ex}} \rangle$ | 3.46557 | 2.80281 | 3.1212 | 3.25451 | 2.43313 | 1.91451 |
| $\langle \hat{n}_{i} \rangle$ | -0.92384 | 0.09163 | 0.08642 | 0.06519 | 0.92408 | 0.87205 |
| $\langle M \rangle$ | 4 | 4 | 4 | 4 | 4 | 4 |
| $\langle \hat{P}(\delta) \rangle$ | 0.92671 | 0.06771 | 0.00303 | 0.00199 | 0.00130 | 0.00268 |
| $\langle \hat{P}(\epsilon) \rangle$ | 0.04354 | 0.23208 | 0.57762 | 0.03066 | 0.08868 | 0.02533 |
| $\langle \hat{P}(\zeta) \rangle$ | 0.03590 | 0.51521 | 0.31557 | 0.00686 | 0.00002 | 0.12472 |
| $\langle \hat{P}(\theta) \rangle$ | 0.00089 | 0.02827 | 0.07226 | 0.07094 | 0.16983 | 0.11726 |
| $\langle \hat{P}(\iota) \rangle$ | 0.00201 | 0.00986 | 0.00123 | 0.22829 | 0.40066 | 0.25803 |
| $\langle \hat{P}(\kappa) \rangle$ | 0.00065 | 0.04539 | 0.02830 | 0.02986 | 0.32579 | 0.56525 |

$\delta$ denotes projection onto $m_{j'} = -1, m_{i_{in}} = \frac{1}{2}, m_{i_{ex}} = \frac{1}{2}$,
$\epsilon$ denotes projection onto $m_{j'} = 0, m_{i_{in}} = \frac{1}{2}, m_{i_{ex}} = \frac{1}{2}$,
$\zeta$ denotes projection onto $m_{j'} = 1, m_{i_{in}} = \frac{1}{2}, m_{i_{ex}} = -\frac{1}{2}$,
$\theta$ denotes projection onto $m_{j'} = 1, m_{i_{in}} = -\frac{1}{2}, m_{i_{ex}} = \frac{1}{2}$,
$\iota$ denotes projection onto $m_{j'} = 1, m_{i_{in}} = \frac{1}{2}, m_{i_{ex}} = \frac{1}{2}$,
$\kappa$ denotes projection onto $m_{j'} = 1, m_{i_{in}} = -\frac{1}{2}, m_{i_{ex}} = -\frac{1}{2}$.
Ground state transfer

Table IV: Lowest ten 182G $X^1\Sigma^+ v'' = 0, j'' = 0$ states from Fig. 12 calculated using our model. "Ground range" is the range of magnetic fields over which the given state has the lowest energy.

<table>
<thead>
<tr>
<th>Energy ($\hbar$Hz)</th>
<th>M</th>
<th>Ground range</th>
<th>Spin state</th>
</tr>
</thead>
<tbody>
<tr>
<td>-44076</td>
<td>5</td>
<td>&gt;90G</td>
<td></td>
</tr>
<tr>
<td>-57992</td>
<td>4</td>
<td>72-90G</td>
<td></td>
</tr>
<tr>
<td>-34104</td>
<td>3</td>
<td>52-72G</td>
<td></td>
</tr>
<tr>
<td>-43876</td>
<td>4</td>
<td>&lt;52G</td>
<td></td>
</tr>
<tr>
<td>-43803</td>
<td>2</td>
<td>&lt;39G</td>
<td></td>
</tr>
<tr>
<td>-65070</td>
<td>1</td>
<td>&lt;19G</td>
<td></td>
</tr>
<tr>
<td>-45897</td>
<td>3</td>
<td>&lt;18G</td>
<td></td>
</tr>
<tr>
<td>-25186</td>
<td>0</td>
<td>&lt;15G</td>
<td></td>
</tr>
<tr>
<td>-27298</td>
<td>2</td>
<td>&lt;12G</td>
<td></td>
</tr>
<tr>
<td>-29460</td>
<td>3</td>
<td>&lt;8G</td>
<td></td>
</tr>
</tbody>
</table>

Ground state model

reproduced from
Aldegunde et al., PRA 78 033434 (2008).

182G is intermediate Zeeman regime.

Stark shifts added for future dipolar expts.
Cs |3,3> + $^{87}$Rb |1,1> in incoming s-wave collision has $M_F=4$, therefore, Feshbach molecules also have $M_F=4$

dominant terms – scalar nuclear dipole-dipole, nuclear Zeeman

J. Aldegunde (Salamanca) and Jeremy M. Hutson (Durham)
Cs $|3,3\rangle$ + $^{87}\text{Rb} |1,1\rangle$ in incoming s-wave collision has $M_F=4$, therefore, Feshbach molecules also have $M_F=4$.

Ground state transfer all accessible directly through STIRAP (in theory)
VH polarization 182G, excited state $M_F=4$. 

Three parameter fit: $\Omega_1, \Omega_2$, relative laser linewidth. ($\Omega_1$ agrees with direct measurement and \textit{ab initio} calculation.)

Feshbach $\rightarrow$ ground 87%
VV polarization 182G, excited state M=4

Prediction from previous fit results

Inappropriate ramps used. Data must be retaken.
Ground state transfer

87RbCs lowest rotational level
Our current estimated phase-space density ~0.01?
A new method is necessary to get us to 1.
We really want something like this! (atom pairs)

Noah Bray-Ali and Carl Williams
preliminary calculations

J. Freericks
numerical simulations starting
RbCs from a double Mott insulator

\[ \hat{H} = -J \sum_{\langle ij \rangle} \hat{a}_i^\dagger \hat{a}_j - \sum_i \mu \hat{n}_i + \sum_i \frac{U}{2} \hat{n}_i (\hat{n}_i - 1) \]

\[ U \propto \frac{4\pi \hbar^2 a}{m} \]

\[ a_{CsCs} = 1700 \ a_0 \]

\[ a_{RbRb} = 100 \ a_0 \]

\[ a_{RbCs} = \text{tunable} \]

(0.2 G wide Feshbach resonance)

\[ U_0^{RbRb}/J_{Rb} \ll 35 \quad U_0^{CsCs}/J_{Cs} \ll 35 \]

2 superfluids
RbCs from a double Mott insulator

\[ \hat{H} = -J \sum_{\langle ij \rangle} \hat{a}_i^{\dagger} \hat{a}_j - \sum_i \mu \hat{n}_i + \sum_i \frac{U}{2} \hat{n}_i (\hat{n}_i - 1) \]

\[ U_{RbRb} \sim +k_B \times 15 \text{ nK} (h \times 300 \text{ Hz}) \]
\[ U_{CsCs} \sim +k_B \times 400 \text{ nK} (h \times 8000 \text{ Hz}) \]
\[ U_{RbCs} = \text{tunable, make negative?} \]

Need to prevent site occupation by:

Rb   Rb   Cs
→ three body loss

want \[ U_{RbRb} + U_{RbCs} > 0 \]

\[ \frac{U_0^{RbRb}}{J_{Rb}} = 2500 \quad U_0^{CsCs} / J_{Cs} = 4.3 \]

- Freeze out Cs
- Rb superfluid flows onto Cs
- Use onsite interactions \( U \) to prevent 3 particles per lattice site

\[ \frac{\Delta a_{RbCs}}{\Delta B} = \frac{a_{RbCs} \text{ background}}{\Delta} = \frac{649a_0}{0.2 \text{ G}} = 3.3 \frac{a_0}{mG} \]

5–10 mG noise measured in lab \[ \rightarrow \Delta a_{RbCs} = 17-33a_0 \]
Mean-field phase diagram of Rb atoms in an optical lattice resonantly interacting with a Cs Mott insulator. $J/h$ is the Rb tunneling rate. (Noah Bray-Ali, Carl Williams)
Now make Feschbach molecules, and do STIRAP (Much simpler version works for Rb₂, Cs₂) Lower lattice adiabatically for molecular superfluid
Dual species SF-MI: same lattice but not yet overlapped

Rb

Cs

$V_0 = 14 \, E_r$

$V_0 = 30 \, E_r$

final lattice power
What if this is not enough for degeneracy?
(KRb currently at $1.5T_F$, PSD 0.1)
What if this is not enough for degeneracy?
3D Evaporative cooling of ground state RbCs with no electric field?

Three body loss?

- Spin changing collisions driven by collision anisotropy
- Centrifugal barrier $\sim \mu^{-3/2} C_6^{-1/2}$

$C_6 = 140000 a_o$ calculated for RbCs

Piotr S. Zuchowski and Jeremy M. Hutson PRA 81, 060703 (2010).

Kotochigova NJP 12, 073041 (2010).
Evaporative cooling of molecules: ground state molecules are precious. Perhaps one can use atoms instead?

Dimer-monomer collisions: one will be forbidden.

Use Cs atoms as a coolant

\[
\begin{align*}
\text{Cs}_2 &: v = 0, \quad 183 \text{ cm}^{-1} \\
\text{RbCs} &: v = 0, \quad 154 \text{ cm}^{-1} \\
\text{Rb}_2 &:
\end{align*}
\]

- Requires high Cs-Cs, RbCs-Cs thermalization rates.
- Requires low Cs-Cs-Cs, RbCs-RbCs-Cs, RbCs-RbCs-Cs, RbCs-Cs-Cs-Cs three body recombination rates (may need to goto 20G!)
• we have rovibhyper ground state RbCs (PSD 0.01)
• our toy is almost finished!

Coming soon
• RbCs from a double Mott insulator
• The fun stuff...
Conference on Cold and Ultracold Molecules

November 18-23, 2012
University Center Obergurgl (“near” Innsbruck)

- Direct and indirect cooling techniques
- Controlled quantum chemistry
- Ultracold molecules for tests of quantum physics
- Molecular quantum gases
- Frontiers in molecular quantum control
- …

Organizers: Guido Pupillo (chair), Francesca Ferlaino, Hanns-Christoph Nägerl

More to come...
http://www.esf.org/index.php?id=9144
Production of a dual-species Bose-Einstein condensate of Rb and Cs atoms
A.D. Leecher, T. Takekoshi, M. Debatin, B. Schuster, R. Rameshan, F. Ferlaino, R. Grimm, and H.-C. Nägerl

Molecular spectroscopy for ground-state transfer of ultracold RbCs molecules
Markus Debatin, Tetsu Takekoshi, Raffael Rameshan, Lukas Reichsöllner, Francesca Ferlaino, Rudolf Grimm, Romain Vexiau, Nadia Bouloufa, Olivier Dulieu, and Hanns-Christoph Nägerl

Towards the production of ultracold ground-state RbCs molecules: Feshbach resonances, weakly bound states, and the coupled-channel model
Tetsu Takekoshi, Markus Debatin, Raffael Rameshan, Francesca Ferlaino, Rudolf Grimm, Hanns-Christoph Nägerl, C. Ruth Le Sueur, Jeremy M. Hutson, Paul S. Julienne, Svetlana Kotochigova, and Eberhard Tiemann

PHYSICAL REVIEW A 85, 032506 (2012)
Cs BEC requires optical traps.
Optical BEC of Rb makes dual species apparatus simpler.

Cs $|3,3\rangle$ or $^{87}\text{Rb} |1,1\rangle$
Cs BEC requires optical traps.
Optical BEC of Rb makes dual species apparatus simpler.

Our dream:
like $^{87}$Rb $^{85}$Rb mixture

The colliding BEC method

Making Feshbach molecules requires a high phase space density mixture.

mixture problems bad, but not insurmountable

really bad mixture problems

Rb + Cs
Starting point: all-optical Cs BEC
Making Feshbach molecules requires a high phase space density mixture

mixture problems bad, but not insurmountable

really bad mixture problems

Evap.

atom number in dimple

Cs MOT size

Rb

Cs
Important for Rb-Cs mixtures:

Traps are deeper for Rb than for Cs. (evaporative heat load mostly on Rb)

high Rb/Cs thermalization

Bad for simultaneous evaporation
Good for Cs cooling! (efficient)

Bad luck #1
Traps are deeper for Rb than for Cs. (evaporative heat load mostly on Rb)

Large interspecies background scattering length \(a_{\text{RbCs}} \approx 649a_0\) from coupled channel model

Ratio of “good” to “bad” collisions
\[ = \frac{4\pi a_{\text{RbCs}}^2}{(K_{\text{RbRbCs}} n_{\text{Rb}})} \]

Large three-body recombination rates
For example \(K_{\text{RbRbCs}} \sim |a_{\text{RbCs}}|^4 \approx 10^{-24} \text{ cm}^6 \text{s}^{-1}\) (measured)

high Rb/Cs thermalization

Bad for simultaneous evaporation
Good for Cs cooling! (efficient)

The colliding BEC method

Important for Rb-Cs mixtures:

Bad luck #2
The colliding BEC method

- Raman cooling
- reservoir (spin filter)
- separate dimples
The colliding BEC method

- Cs |3,3⟩
- Rb |1,1⟩

Integrated density

20,000 atoms

100,000 atoms

dimple power

57.4 mW
29.4 mW
5.0 mW
2.5 mW
The colliding BEC method

Combine and magnetoassociate quickly

\[ a_{RbRb} - a_{CsCs} = 1 > 0 \text{ miscible} \]


Durham group PRA 84 011603 (2011).
RbCs from a double Mott insulator

Rb superfluid-Mott insulator transition

Image after expansion – matter wave interference

Superfluid state $J \gg U$

- delocalised
- poissonian distribution
- phase coherence
- interference pattern
RbCs from a double Mott insulator

Rb superfluid-Mott insulator transition

Mott insulator state $J \ll U$

- localized atoms
- no phase coherence
- no interference pattern
- fixed atom number per site
RbCs from a double Mott insulator

Rb superfluid-Mott insulator transition
Coupled channel model

Data for model – Feshbach resonances

Atoms remaining vs. B (Gauss) for Cs and Rb.
RbCs from a double Mott insulator

Increasing the lattice depth

**Phase transition**
from the superfluid BEC
to a localized **Mott-insulator** state

Proposal: P. Zoller et al., 1998

This should also work the other way round!!!

Reduction of lattice depth:

**Phase transition**
from a localized **Mott-insulator** state of molecules
to a molecular **BEC („mBEC“)**

Proposal: P. Zoller et al., 2002
Ground state transfer

Romain Vexieu, Nadia Bouloufa, Oliver Dulieu

1/1064 nm = 9398 cm$^{-1}$

"Rb" + "Cs"

"RbCs"

magic wavelength

Luck!!
Coupled channel model

Initial medium range potential taken from Fourier transform spectroscopy study (Riga) O. Docenko et al., PRA 83, 052519 (2011). Level energies accurate to ~ 1GHz x h

C. Ruth LeSueur, Jeremy M. Hutson (Durham) Paul S. Julienne (JQI, NIST, UMD) Svetlana Kotochigova (Temple) Eberhard Tiemann (Hannover)

Initial medium range potential taken from Fourier transform spectroscopy study (Riga) O. Docenko et al., PRA 83, 052519 (2011). Level energies accurate to ~ 1GHz x h

| TABLE III: Parameters of the fitted potential. [12 Aug 2011] |
|-----------------------------------------------|------------------|------------------|------------------|
| | fitted value | 95% confidence limit | sensitivity | |
| | | | | |
| $B_S^{SR} (E_h)$ | 147.675 | 0.49177 | 0.00007 |
| $B_S^{LR} (E_h)$ | 428.9211 | 0.86538 | 0.00003 |
| $A_{2SO}^{LR}$ | 0.0001350 | 0.0000006 | 0.0000136 |
| $C_6 (E_h a_0^6)$ | 5694.8300 | 0.3108 | 0.0005 |
| $C_8 (E_h a_0^8)$ | 80198.08 | 8750.1 | 0.3 |
| derived parameters | value | uncertainty | |
| $a_S$ (bohr) | 993 | 6.9 |
| $a_T$ (bohr) | 512.4 | 1.4 |
FIG. 10: [Color online.] RbCs scattering length at the \( |1, 1\rangle + |3, 3\rangle \) threshold at fields above 560 G, calculated using the final fitted potential at \( E = 160 \) nK. Resonance positions are marked by vertical lines, with the value of \( M_F \) of the corresponding bound state indicated using the same color scheme as in Fig. 7.
**Ground state transfer**

Ground state transfer

\[
\Omega_1 = \left( \frac{\Gamma}{\tau_{irr}} \right)^{1/2} = \frac{\mu \cdot E}{\hbar}
\]

broader than expected from calculations (Vexieau, Bouloufa, Dulieu)
Ground state transfer

Ground state spectroscopy:

\[ H(t) = \frac{\hbar}{2} \begin{bmatrix} 0 & \Omega_1 & 0 \\ \Omega_1 & 0 & \Omega_2 \\ 0 & \Omega_2 & 0 \end{bmatrix} \]

Eigenstates with light on:

\[ |a^+\rangle = \sin \Theta \sin \Phi |1\rangle + \cos \Phi |2\rangle + \cos \Theta \sin \Phi |3\rangle \]
\[ |a^0\rangle = \cos \Theta |1\rangle - \sin \Theta |3\rangle \]
\[ |a^-\rangle = \sin \Theta \cos \Phi |1\rangle - \sin \Phi |2\rangle + \cos \Theta \cos \Phi |3\rangle \]

\[ \tan \Theta = \frac{\Omega_1}{\Omega_2} \]

\[ \text{spont. em.} \]

Ground state transfer

Ground state spectroscopy:

\[ H(t) = \frac{\hbar}{2} \begin{bmatrix} 0 & \Omega_1 & 0 \\ \Omega_1 & 0 & \Omega_2 \\ 0 & \Omega_2 & 0 \end{bmatrix} \]

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\[ |a^-\rangle = \sin \Theta \cos \Phi |1\rangle - \sin \Phi |2\rangle + \cos \Theta \cos \Phi |3\rangle \]

\[ \tan \Theta = \frac{\Omega_1}{\Omega_2} \]

Ground state transfer

Ground state spectroscopy:

$$H(t) = \frac{\hbar}{2} \begin{bmatrix} 0 & \Omega_1 & 0 \\ \Omega_1 & 0 & \Omega_2 \\ 0 & \Omega_2 & 0 \end{bmatrix}$$

Eigenstates with light on:

$$|a^+\rangle = \sin \Theta \sin \Phi |1\rangle + \cos \Phi |2\rangle + \cos \Theta \sin \Phi |3\rangle$$

$$|a^0\rangle = \cos \Theta |1\rangle - \sin \Theta |3\rangle$$

$$|a^-\rangle = \sin \Theta \cos \Phi |1\rangle - \sin \Phi |2\rangle + \cos \Theta \cos \Phi |3\rangle$$

$$\tan \Theta = \frac{\Omega_1}{\Omega_2}$$

projection $\cos \Theta$ onto $|1\rangle$:

$$P_{1\rightarrow a^0\rightarrow 1} = P_{1\rightarrow a^0} P_{a^0\rightarrow 1} = \cos^4 \Theta = \frac{\Omega_1^4}{(\Omega_1^2 + \Omega_2^2)^2}$$

Ground state spectroscopy:

\[ H(t) = \frac{\hbar}{2} \begin{bmatrix} 0 & \Omega_1 & 0 \\ \Omega_1 & 2\Delta_1 & \Omega_2 \\ 0 & \Omega_2 & 2(\Delta_1 - \Delta_2) \end{bmatrix} \]

Ground state transfer

\[ \Delta_1 \quad \text{spont. em.} \quad \Delta_2 \]

![Diagram of energy levels and transitions](image)
Ground state transfer

Ground state spectroscopy:

\[ H(t) = \frac{\hbar}{2} \begin{bmatrix} 0 & \Omega_1 & 0 \\ \Omega_1 & 2\Delta_1 & \Omega_2 \\ 0 & \Omega_2 & 2(\Delta_1 - \Delta_2) \end{bmatrix} \]

- Have mapped out ground state \( v=0 \ N=0,2 \).
- Rotational constants agree very well with Fourier transform spectroscopy experiments.
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Supercavities!

- sub-Hz laser stabilities possible (cavities themselves are the reference)
- limited by acoustics
- finesse ~200000
- narrow linewidth diode lasers also being built