A Quantum Degenerate Bose Mixture of $^{87}\text{Rb}$ and $^{133}\text{Cs}$ - Toward Ultracold Heteronuclear Molecules


Department of Physics
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Motivation

- Bialkali molecules in the ground state have a large permanent electric dipole moment ex. RbCs $d=1.25$ Debye

$$V_{int} = d^2 \frac{1 - 3\cos^2 \theta}{|r - r'|^3} + \frac{4\pi\hbar^2 a}{M} \delta(r - r')$$

Dipole-dipole interaction

Contact interaction

- Quantum computation with trapped polar molecules

- RbCs is one of the stability of quantum gases of alkali-metal dimers ex. $XY+XY \rightarrow X_2+Y_2$
  
  $XY+XY \rightarrow X+XY_2$ or $X_2Y+Y$

<table>
<thead>
<tr>
<th></th>
<th>Na</th>
<th>K</th>
<th>Rb</th>
<th>Cs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li</td>
<td>−328(2)</td>
<td>−533.9(3)</td>
<td>−618(200)</td>
<td>−415.38(2)</td>
</tr>
<tr>
<td>Na</td>
<td>74.3(3)</td>
<td>45.5(5)</td>
<td>236.75(20)</td>
<td>37.81(13)</td>
</tr>
<tr>
<td>K</td>
<td>−8.7(9)</td>
<td></td>
<td>29.1(1.5)</td>
<td></td>
</tr>
<tr>
<td>Rb</td>
<td></td>
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</table>

PRA, 81, 060703(R) (2010)
Cool Molecules

Directly:
Buffer gas cooling
Stark deceleration_Electric & Magnetic
Sympathetic cooling

Indirectly:
Atoms are pre-cooled by laser-cooling and then,
1) associated into ground state via photoassociation or
2) follow a two step scheme which is magneto-association using a Feshbach resonance and STIRAP

Nature Physics, 6, 265-270 (2010)
Magnetic deceleration

CsYb molecules via magneto-association and STIRAP

Theory of ultracold molecule formation, cooling molecules to microkelvin using the theory of ultracold collisions to make sympathetic cooling work

Buffer gas cooling, electric deceleration, and sympathetic cooling.

Photostop
Introduction

Atoms in which laser cooling has been demonstrated:\(^1\):

<table>
<thead>
<tr>
<th>Alkali metals</th>
<th>Alkaline earth metals</th>
<th>Noble Gases</th>
<th>Lanthanide</th>
<th>Others</th>
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<tbody>
<tr>
<td>Li</td>
<td>Mg</td>
<td>He</td>
<td>Dy</td>
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<tr>
<td>Na</td>
<td>Ca</td>
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<td>K</td>
<td>Sr</td>
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<td>Hg</td>
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<tr>
<td>Cs</td>
<td>Ba</td>
<td>Xe</td>
<td></td>
<td>Al</td>
</tr>
<tr>
<td>Fr</td>
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</tbody>
</table>

Species | Dipole Moment |
<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>(^6)Li(^{23})Na</td>
<td>0.53 D(^4)</td>
</tr>
<tr>
<td>(^40)K(^{87})Rb</td>
<td>0.57 D(^2)</td>
</tr>
<tr>
<td>(^{87})Rb(^{133})Cs</td>
<td>1.25 D(^3)</td>
</tr>
<tr>
<td>(^6)Li(^40)K</td>
<td>3.5 D(^4)</td>
</tr>
<tr>
<td>(^6)Li(^{87})Rb</td>
<td>4.1 D(^4)</td>
</tr>
<tr>
<td>(^6)Li(^{133})Cs</td>
<td>5.48 D(^4)</td>
</tr>
</tbody>
</table>

Mixed species Feshbach molecules:
- \(^6\)Li + \(^{23}\)Na  
  (Stan et al., Phys. Rev. Lett. 93, 143001 (2004))
- \(^40\)K + \(^{87}\)Rb  
- \(^6\)Li + \(^{40}\)K  
- \(^6\)Li + \(^{87}\)Rb  
  (Deh et al., Phys. Rev. A 77, 010701(R) (2008))
- \(^7\)Li + \(^{87}\)Rb  
- \(^{87}\)Rb + \(^{133}\)Cs  

\(^1\)(Steele, J. Vac. Sci. Technol. B 28, C6F1 (2010))
\(^2\)(Ni et al., Science 322, 231 (2008))
\(^4\)(Igel-Mann et al., J. Chem. Phys. 84, 5007 (1986) theor.)
Outline

• Bose-Einstein condensation of $^{87}$Rb BEC
  - in a combined magnetic and optical trap
  - in a levitated crossed dipole trap

• Bose-Einstein condensation of $^{133}$Cs
  - a new method for the production of $^{133}$Cs BEC
  - demonstrate the creation of Cs$_2$ molecules via magneto-association on the 4g(4)

• A quantum degenerate Bose Mixture of $^{87}$Rb and $^{133}$Cs
  - observe a striking phase separation of the two species
  - observation of an interspecies Feshbach resonance at 181.7(5) G

• Stimulate Raman adiabatic passage (STIRAP)
  - a two-photon transition can used to transfer the Feshbach molecules into the rovibrational ground state or a more deeply bound state

• Conclusion
- Cold-atomic beams source is created by Pyramid MOT.
- \( \geq 9 \times 10^8 \) \(^{87}\)Rb & \( 4 \times 10^8 \) \(^{133}\)Cs can be obtained by science MOT.
- The optical potential is produced by two laser beams with waists of ~60 \( \mu \)m and wavelength 1550nm from a 30 Watt IPG ELR-30-LP-SF
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Rb BEC in a combined trap

\[ P = 502 \text{ mW} \]
\[ \text{Waist} = 62 \mu \text{m} \]
\[ U = 7.0 \mu \text{K} \]
\[ \omega_z = 25.8 \text{ Hz} \]
\[ \omega_\rho = 136.8 \text{ Hz} \]
\[ T_{\text{Mean}} = 0.371 \mu \text{K} \]
\[ N = 1.11 \times 10^6 \]
\[ n_0 = 4.41 \times 10^{13} \text{ cm}^{-3} \]
\[ \text{PSD} = 1.06 \]

\[ P = 389 \text{ mW} \]
\[ \text{Waist} = 62 \mu \text{m} \]
\[ U = 5.3 \mu \text{K} \]
\[ \omega_z = 25.8 \text{ Hz} \]
\[ \omega_\rho = 120.7 \text{ Hz} \]
\[ T_{\text{Mean}} = 0.252 \mu \text{K} \]
\[ N = 7.01 \times 10^5 \]
\[ n_0/N = 14.6 \% \]
\[ \text{PSD} = 1.51 \]

\[ P = 252 \text{ mW} \]
\[ \text{Waist} = 62 \mu \text{m} \]
\[ U = 3.3 \mu \text{K} \]
\[ \omega_z = 25.8 \text{ Hz} \]
\[ \omega_\rho = 97.8 \text{ Hz} \]
\[ N = 1.93 \times 10^5 \]
\[ n_0 = 2.26 \times 10^{14} \text{ cm}^{-3} \]
AtMol
Durham Atomic & Molecular Physics

• Atoms in the weak-field seeking |1,-1> state are loaded into the hybrid trap, a cross-dipole trap and quadrupole trap, after a pre-cooling using RF evaporation in quadrupole trap.

• The levitated crossed dipole trap is formed by two laser beams and a levitation field. The contour plots results the trapping potential including gravity for $^{87}$Rb in the |1, +1> state. Both 150 mW beams are focussed to ~60 µm and the magnetic filed contents a magnetic field gradient 29 G/cm and a bias field of 22.4 G along z axial.

$$\Delta U_{\text{gravity}} = mg (\Delta z)$$

$$\Delta E = \mu g F_m \Delta B_z$$

• The loading trap is performed at a power of 6 W in each beam with a gradient of 29 G/cm.
**87**Rb BEC in a levitated crossed dipole trap

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• A 26 x 26 mm square coil of 3 turns are driven to create an RF Filed at 1.5 MHz. A bias field of 22.4 G is then switched on to cross the RF Zeeman resonance at 2.1 G.

$$P_{ad} = 1 - \exp\left(\frac{-\pi \omega_i^2}{2|\alpha|}\right)$$

$$\omega_i^2 \gg |\alpha| = \left|\frac{d}{dt}\omega_0 - \omega_r\right|$$

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\]


\[
\begin{align*}
\text{Atom Number} \times 10^6
\end{align*}
\]

\[
\begin{align*}
\text{RF Power (dBm)}
\end{align*}
\]
The phase-space density trajectory to BEC of $^{87}$Rb ($|1,+1>$) in the cross dipole trap. $N_{\text{BEC}} = 1 \times 10^6$

Control the depth of the levitated crossed dipole trap by manipulating the magnetic field gradient. C. Chin, Phys. Rev. A, 78, 011604(R), 2008

Sympathetic cooling of different spin states in the levitated cross dipole trap by a tilting potential. The inset shows the vertical cross-section through the potential minimum for a beam power of 0.45 W and a magnetic field gradient of 13 G/cm.

Application of the experiment to sympathetic cooling of $^{133}$Cs. The dipole trap potential corresponds to 100 mW in each beam, a magnetic field gradient of 38 G/cm and a bias field of 22.4 G.
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• Conclusion
\[^{133}\text{Cs BEC in the cross-dipole trap}\]

Why \(^{87}\text{Rb}\)?

Why \(^{133}\text{Cs}\)?
Cs BEC in the cross-dipole trap

Why $^{87}$Rb?

Why $^{133}$Cs?
133Cs BEC in the cross-dipole trap

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

$^{133}\text{Cs BEC in the cross-dipole trap}$

$^{87}\text{Rb} \approx 100a_0$
133Cs BEC in the cross-dipole trap

Why $^{87}\text{Rb}$?

Why $^{133}\text{Cs}$?

$$\Gamma_{El} = \langle n \rangle \sigma \langle v_R \rangle \propto \sigma = \frac{8\pi a^2}{1 + k^2 a^2}, \quad k = \frac{m\langle v_R \rangle}{\hbar}$$
Why $^{87}\text{Rb}$?

Why $^{133}\text{Cs}$?

$$\Gamma_{El} = \langle n \rangle \sigma \langle \nu_R \rangle \propto \sigma = \frac{8\pi a^2}{1 + k^2 a^2}, \quad k = \frac{m \langle \nu_R \rangle}{\hbar}$$

$$\frac{\dot{N}}{N} = -L\langle n^2 \rangle, \quad L_3 = n_l C \frac{\hbar}{m} a^4$$
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The cooling efficiency $\gamma (\Delta \log p/\Delta \log N) = 5.6(3)\times10^{1}$ depends on the initial number of $^{133}$Cs.
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After loading the crossed dipole trap, $n_{\text{peak}}$ of $^{87}$Rb is $\sim 5 \times 10^{13}$ and $n_{\text{peak}}$ of $^{133}$Cs is $\sim 5 \times 10^{12}$. A strong interspecies inelastic losses are observed. The interspecies three-body loss rate coefficients of $\sim 10^{-25} - 10^{-26}$ are calculated by using the minority species lifetimes. $^{87}$Rb and $^{133}$Cs are transferred into $|1,+1>$ and $|3,+3>$ before the measurement.

- $\tau_{\text{Cs}} = 0.8(1) \text{ s}$, $\tau_{\text{Rb}} = 4(1) \& 70(10) \text{ s}$.
- $\tau_{\text{Rb}} = 0.9(2) \text{ s}$, $\tau_{\text{Cs}} = 2(1) \& 10(3) \text{ s}$.
$^{133}$Cs BEC in the cross-dipole trap

$\gamma = 2.5(2)$
$^{133}$Cs BEC in the cross-dipole trap

\[ \gamma = 5.6(3) \]

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To avoid the interspecies loss and optimise the transfer of $^{133}\text{Cs}$, RF frequency is reduced to remove all $^{87}\text{Rb}$. The resulting loading is highly efficient with $\sim 50\%$ of $^{133}\text{Cs}$ transferred into dipole trap. This is double the atoms number loaded compared to $^{87}\text{Rb}$ absence case.
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Vertical width of the $^{133}\text{Cs}$ condensate as a function of a magnetic field applied during a 50 ms time of flight expansion.

$$\mu = \frac{\hbar \omega_0}{2} \left( \frac{15 N a}{a_R \hbar 0} \right)^{2/5} = m \omega_0^2 R^2 / 2$$

(for a spherical trap)

Reviews of Modern Phys. 71, 463, 1999
\[ \Gamma_{El} = \langle n \rangle \sigma \langle v_R \rangle \propto \sigma = \frac{8\pi a^2}{1 + k^2 a^2}, \quad k = \frac{m \langle v_R \rangle}{\hbar} \]

\[ a(B) = \frac{\hbar}{\sqrt{\frac{m}{2\pi \sigma}}} \]

\[ a(B) \approx \frac{1}{1 + k^2 a^2} \]

\[ ^{87} \text{Rb} \ a \approx 100a_0 \]
Cs$_2$ Molecules

Graph showing scattering length vs. magnetic field with points at 19.8 G and 48 G highlighted.

Graph showing potential energy vs. magnetic field with atomic state, molecular bound state, and converted atoms to molecules highlighted.

Accepted by Eur. Phys. J. D, (2011)
Cs$_2$ Molecules

Cs$_2$ Molecules

- 4g(4) Feshbach resonance at 19.8 G (5mG wide), a cross rate of 47 G/s.
- Dissociate by 17 to 21 G in 130 µs.
- $N_{\text{Cs}_2} = 7 \times 10^3$
- Magnetic moment $\mu = 0.92(1) \mu_B$


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1) The calculated polarisabilities in atomic unit are \( \sim 572 \text{ a}_0^3 \) for \(^{133}\text{Cs}\) and \( \sim 425 \text{ a}_0^3 \) for \(^{87}\text{Rb}\) at 1550 nm. Phys. Rev. A, 73, 022505, 2006.

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lower 3 body loss by reduce the peak density
- change to a larger beam waist
- decompress trap

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\frac{\dot{N}}{N} = -L\langle n^2 \rangle, \quad L_3 = n_i C \frac{\hbar}{ma^4}
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Toward Dual BEC

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Lower 3 body loss by reduce the peak density
- change to a larger beam waist
- decompress trap

Immiscible quantum degenerate mixture:
the relative strength of the atomic interactions

$$\Delta = \frac{g_{\text{RbCs}}}{g_{\text{Rb}}g_{\text{Cs}}} > 1, g_{ij} = 2\pi \hbar^2 a_{ij} (\frac{m_i + m_j}{m_im_j})$$


In our case, $B = 22.4 \text{ G}$, $a_{\text{Rb}} = 100 \text{ a}_0$ and $a_{\text{Cs}} = 280 \text{ a}_0$, the observation of immiscibility require $a_{\text{RbCs}} > 165 \text{ a}_0$. 

arXiv:1102.1576
Toward Dual BEC

Innsbruck, H.C. Nagerl’s group:
BECs of $^{87}\text{Rb}$ and $^{133}\text{Cs}$ atoms in separate optical traps [arXiv:1101.1409]

<table>
<thead>
<tr>
<th>Beam</th>
<th>I,II</th>
<th>III</th>
<th>IVa</th>
<th>IVb</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>1070</td>
<td>1064.5</td>
<td>820</td>
<td>1064.5</td>
<td>1064.5</td>
</tr>
<tr>
<td>Waist radius (μm)</td>
<td>500</td>
<td>45</td>
<td>66</td>
<td>57</td>
<td>102</td>
</tr>
<tr>
<td>Rb depth / $k_B$ (μK)</td>
<td>13</td>
<td>8.5</td>
<td>24</td>
<td>10</td>
<td>6.0</td>
</tr>
<tr>
<td>Rb rad. freq. (Hz)</td>
<td>23</td>
<td>204</td>
<td>234</td>
<td>176</td>
<td>77</td>
</tr>
<tr>
<td>Cs depth / $k_B$ (μK)</td>
<td>24</td>
<td>15</td>
<td>-25</td>
<td>18</td>
<td>11</td>
</tr>
<tr>
<td>Cs rad. freq. (Hz)</td>
<td>25</td>
<td>220</td>
<td>192</td>
<td>189</td>
<td>83</td>
</tr>
</tbody>
</table>

Power of beam III (mW)
RbCs Feshbach Resonance

Phase Space Density

Trap tilt
Reduce beam intensities
Loading dipole trap
Rb cooling
Cs
RF evap. in magnetic trap

Atom Number
RbCs Feshbach Resonance

- Trap tilt
- Reduce beam intensities
- Cs
- Rb
- Loading dipole trap
- Rb cooling
- Cs
- RF evap. in magnetic trap

Phase Space Density vs. Atom Number

Accepted by Eur. Phys. J. D, (2011)
RbCs Feshbach Resonance

- Trap tilt
- Reduce beam intensities
- Loading dipole trap
- RF evap. in magnetic trap

Phase Space Density vs. Atom Number
Peak densities of $^{87}$Rb and $^{133}$Cs are $1.6(1) \times 10^{12}$ cm$^{-3}$ and $3.1(4) \times 10^{11}$ cm$^{-3}$.

The mixture contains $3.0(3) \times 10^{5}^{87}$Rb and $2.6(4) \times 10^{4}^{133}$Cs at 0.32(1) µK

- the temperature is well below the p-wave threshold ($k_B \times 56$ µK based upon $C_6$, Phys. Revs A 59, 390, 1999)
- The presented Feshbach spectrum near 180 G is measured by evolving the mixture at a specific homogeneous magnetic field for 5 sec and each data point corresponds to an average of 3-5 measurements.
Outline

• Bose-Einstein condensation of $^{87}\text{Rb}$ BEC
  - in a combined magnetic and optical trap
  - in a levitated crossed dipole trap

• Bose-Einstein condensation of $^{133}\text{Cs}$
  - a new method for the production of $^{133}\text{Cs}$ BEC
  - demonstrate the creation of Cs$_2$ molecules via magneto-association on the 4g(4)

• A quantum degenerate Bose Mixture of $^{87}\text{Rb}$ and $^{133}\text{Cs}$
  - observe a striking phase separation of the two species
  - observation of an interspecies Feshbach resonance at 181.7(5) G

• Stimulate Raman adiabatic passage (STIRAP)
  - a two-photon transition can used to transfer the Feshbach molecules into the rovibrational ground state or a more deeply bound state

• Conclusion
The adiabatic condition
\[ \sqrt{\Omega_p^2 + \Omega_s^2 \Delta \tau} >> 1 \]

\( \tau \), the overlap period of two pulses.
Rev. Mod. Phys 70, 1003, 1998
Pound-Drever Hall signal

Laser \rightarrow \text{Lock Box} \rightarrow \text{Oscillator Phase Shifter} \rightarrow \text{Cavity} \rightarrow \text{Mixer} \rightarrow \text{Low Pass Filter}

Black, Am. J. Phys. 69 (1) 79 (2001)
Pound-Drever Hall signal

Laser -> Lock Box -> Oscillator Phase Shifter -> Cavity

Mixer -> Low Pass Filter

Black, Am. J. Phys. 69 (1) 79 (2001)
STIRAP

Pound-Drever Hall signal

Laser

Lock Box

Oscillator

Phase Shifter

Cavity

Mixer

Low Pass Filter

High Finesse of 3000 → R ~99.91%

\( \nu_{\text{FSR}} = 750 \text{ MHz} \), cavity length= 20 cm

\( \delta \nu = 250 \text{ kHz} \)

(One planar mirror and one concave mirror \( r=50 \text{ cm} \))

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STIRAP

Pound-Drever Hall signal

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\(\delta v=250 \text{ kHz}

(One planar mirror and one concave mirror r=50 cm)
Conclusion

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  - in a combined magnetic and optical trap
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- A quantum degenerate Bose Mixture of $^{87}$Rb and $^{133}$Cs
  - observe a striking phase separation of the two species
  - observation of an interspecies Feshbach resonance at 181.7(5) G

- Stimulate Raman adiabatic passage (STIRAP)
  - a two-photon transition can used to transfer the Feshbach molecules into the rovibrational ground state or a more deeply bound state
  - two ECDLs (1569nm and 980nm) will be locked to a reference cavity which is stable by a reference ECDL (852nm).