Magneto-optical trapping and sub-Doppler cooling of molecules

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Laser cooling of atoms has revolutionised atomic physics

Bose-Einstein condensates
Clocks
Quantum gates
Quantum simulation
Measuring fundamental constants and forces

A new revolution is happening now with molecules

<table>
<thead>
<tr>
<th>Laser cooling</th>
<th>Magneto-optical trapping</th>
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<tbody>
<tr>
<td>SrF (Yale 2010)</td>
<td>SrF (Yale 2014)</td>
</tr>
<tr>
<td>YO (JILA 2013)</td>
<td>CaF (Imperial 2017)</td>
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<td>CaF (Imperial 2014)</td>
<td>CaF (Harvard 2017)</td>
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<td>SrOH (Harvard 2016)</td>
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</table>

Temperature ~ mK or just below

Sub-Doppler cooling (Imperial 2017)
Temperature ~ 50 μK
Temperature scale for molecular excitations

After D. S. Jin and J. Ye, Physics Today, 64, 27 (2011)
Some applications of cold/ultracold molecules

High-precision measurement: e.g. eEDM

My Lecture 3

Quantum Information: gates


Many-body physics: interactions


Cold/Ultracold Chemistry

Roati Lecture 2

D. S. Jin and J. Ye, Physics Today, 64, 27 (2011)
One way to make ultracold molecules: Stick ultracold atoms together

- Very successful, but these are all $^1\Sigma$ molecules with small dipole moments
- Direct laser cooling gives access to many more useful molecules – e.g. CaF, YbF
Basic idea of Doppler cooling

F_0 = \hbar k \times \text{scattering rate}

Red detuning

Doppler shift brings faster atoms closer to resonance

\therefore F = -F_0 - \alpha \nu

This cools

Base Temperature a few hundred \(\mu K\)
- after scattering \(\sim 10^5\) photons
Expt to slow and trap CaF

Source

a) Pulse emitted by source (2.5 cm from aperture)

- 280 µs

b) Velocity distribution

- 155 m/s
- 90 m/s
Cryogenic buffer gas source of CaF

Bulleid *et al.* PCCP (2013) DOI: 10.1039/c3cp51553b

Truppe *et al.* “A buffer gas beam source for short, intense and slow molecular pulses” ArXiv next month
Scheme for slowing CaF beam

10^4 photons will slow the beam enough

**Slowing Light**
- 120 mW → 531.0 nm
- 130 mW → 628.6 nm

Sidebands plug hyperfine leaks

Rotation

v = 0

X \text{^2\Sigma^+ (N=1)}

B \text{^2\Sigma^+ (N=0)}

A \text{^2\Pi_{1/2}} (J=1/2, \, p=+)}

531.0 nm

628.6 nm

v = 0

v = 1

v = 2

MHz
- 148 J=3/2, F=2
- 123 J=3/2, F=1
- 76 J=1/2, F=0
- 0 J=1/2, F=1

Photons will slow the beam enough

v = 0

rotational

v = 0

v = 1

v = 2
Slowing/cooling CaF beam with laser light

Zhelyazkova et al. PRA 89, 053416 (2014)
Truppe et al. NJP. 19 022001 (2017)
Biggest chirp gets molecules below 15 m/s

Below 15 m/s we measure

- $10^6$ per pulse in total
- $7 \times 10^5$ molecules per cm$^2$ per pulse
... now for the MOT

Standard ingredients of a MOT

- 6 red-detuned laser beams
- Magnetic quadrupole
  Provides a trapping force towards centre
- Circular polarisation opposite to B field
  and cools to low temperature
Molecules offer some new challenges...

- More ground states \((N=1)\) than excited \((N=0)\) (Type II) ➔ Dark ground states
- Excited state \(A^{2\Pi_{1/2}}\) has negligible g-factor ➔ No conventional MOT force

... identified and overcome in 3 beautiful papers:

  
Defines the problems & outlines solutions

Tarbutt & Steimle PRA 92, 053401 (2015)
  
Compares A-X and B-X MOT of CaF

Devlin & Tarbutt, New J. Phys. 18 123017 (2016)
  
Identifies and tames sub-Doppler forces in type II case

I will develop these points in lecture 5
Laser scheme for CaF A-X MOT

A $^2\Pi_{1/2}$
(J=1/2, p=+)

A-X MOT
- 606.3 nm
- 628.6 nm
- 628.1 nm
- 627.7 nm

$X ^2\Sigma^+ (N=1)$

Slowing
- 531.0 nm
- 628.6 nm

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<td>148</td>
<td>3/2</td>
<td>2</td>
</tr>
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<tr>
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<td>1/2</td>
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Application to CaF A-X MOT

\[ A^2 \Pi_{1/2} (J=1/2, F=0,1) \]

Predicted radial trap frequency: 110Hz
Predicted capture velocity: 14 m/s
A reminder of the experiment….

Slow the molecule, then load into MOT

130 cm
First, detect fluorescence in MOT region on a PMT

CCD image of CaF MOT

2 x 10^4 molecules
2 x 10^5 molecules/cm^3
radial frequency 100 Hz
capture velocity 11 m/s

dB/dz = 2.9 mT/cm
606 nm Intensity = 470 mW/cm^2
Detuning = -6 MHz (-0.75Γ')

MOTs often colder than Doppler because of polarisation gradients
(Nobel Prize - Chu/Phillips/Cohen-Tannoudji)

Polarisation gradient forces HEAT this type-II MOT.
(More on this in Lecture 5)

Devlin & Tarbutt, New J. Phys. 18, 123017 (2016)
Blue molasses cooling

For sub-Doppler cooling, switch to blue-detuned molasses:

- Load the MOT
- Ramp down the intensity to 1%
- Switch off the MOT coils
- Switch to 20 MHz blue detuning
- Turn the intensity back up again
- Hold
- Measure temperature
Cooling below the Doppler limit

Lowest possible T with Doppler cooling

First molecular laser cooling below Doppler limit

... and after fine tuning

Initial result ....
Sub-Doppler molasses cooling also for YbF

Probe laser → Camera

No cooling

Red molasses
molecules collect near ±1 m/s

Blue molasses
transverse $T \approx 50 \, \mu \text{K}$

Very strong sub-Doppler cooling

Transverse cooling

552 nm
568 nm
565 nm

YbF source
Transfer CaF to magnetic and microwave traps

Sympathetic cooling with ultracold atoms


Super-sensitive eEDM experiment on YbF

discarded helium beam

electric field plates

YbF in free-fall

ingredient beams

magnetic guide

buffer gas cell

cryocooler cold head

MOT coils


Single molecules in tweezer traps


Where now?