Making cold sodium molecules

Photoassociation of sodium in a Bose-Einstein condensate

Production of molecules in a MOT and spectroscopy of the lowest triplet state of \( \text{Na}_2 \)

$\text{ONR, NASA}$
Production of Na$_2$ molecules in a MOT and spectroscopy of the lowest triplet state of Na$_2$

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**EXPERIMENTAL OVERVIEW**

magneto-optical trap ("MOT")
\[ n \sim 10^{10} \text{ cm}^{-3} \]

"dark spot" MOT*
\[ n \sim 10^{11} \text{ cm}^{-3} \]
\[ T \sim 500 \mu \text{K} \]

◊ **Alternate trap and probe lasers at \( \sim 10 \mu \text{s intervals} \)**

Multi-color spectroscopy of the (triplet) ground state of Na$_2$

ionization vs. trap loss
similar work in Li, K, Rb, Cs
Autler-Townes splitting of lines

Ion signal (arb. units)

Frequency of laser L1 (GHz)

|e1> and |g> dressed by L2

L2 present, L1 scanned

L2 blocked, L1 scanned

|e1> and |g>

L1

|e1>

L3

|g>

L3

L2

|g>
bound-state resonances

photoassociation resonances

\[ 0^+ (S + P_{1/2}) \]

\[ e_1 \]

\[ |e_1> \]

bound-state resonances

photoassociation resonances

\[ 0^+ (S + P_{1/2}) \]

\[ a \bar{3}Σ_u^+ \]

Energy (GHz)

incoming flux

\[ f_1 + f_2 \]

\[ v = 15 \]

\[ 4s \]

\[ 1s/3s \]

\[ 2s \]
theory: E. Tiesinga
Lineshapes vs. power

\(|e_1>: 16945.94; \ 0_g, J=0 (v = 119)\\
|e_2>: 16936.44; \ 0_g, J=0 (v = 114)\)
Lineshape issues:

one color

Two color

lineshape formula:
J. Bohn and P. Julienne,
PRA 54, 4637 (1996);
60, 414 (1999)
triplet potential(s) $\sim 160 \text{ cm}^{-1}$ deep

strongly mixed with singlet potentials near dissociation ($v = 14, 15$)

vibrational, rotational, hyperfine and spin-dipole - spin-dipole structure
Fixed Total Energy

Doubly-excited ionizing states mapped out

Intermediate states - experiment and theory

$0_g^-$ near dissociation

$^3\Sigma_g^+ 500 \text{ cm}^{-1}$ deep in well

accurate theoretical description gives us quantum numbers on intermediate lines
Binding Energy (GHz)

(uncalibrated)
Rough plot of $(E - E_v)$ for all lines

- $l = 0$
- $l = 1$
- $l = 2$
- $l = 3$
- $v = 6$
- $v = 14$

Legend:
- + theory
- □ calibrated data
- ○ rough data
spin-spin dipole/
second order spin-orbit
on top of hyperfine interactions
Spin-spin dipole effect: "relativistic effect"
-electron spin-dipole/electron spin-dipole interaction; $R^{-3}$ behavior
-second order spin-orbit interaction has terms of same form but they are small in $\text{Na}_2$

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$E_v$ deviations from present best potential

$\text{Na}_2 a^3\Sigma_u^+$ potential from E. Tiemann, Hannover
transitions to $0_g^{-} (S+P_{1/2})$ and "a" states

- For $v=88$ (-164.685 cm$^{-1}$)
  - Ionizer tuning: 17067.62 cm$^{-1}$
  - 586 nm
  - Energy is -0.2 cm$^{-1}$ from that found from Eite's table (16791.52 cm$^{-1}$)

- For $v=14$ (-3389 cm$^{-1}$)
  - Ionizer tuning: 16793.42 cm$^{-1}$
  - 595.5 nm
  - Energy is -0.2 cm$^{-1}$ from that found from Eite's table (16791.52 cm$^{-1}$)

- For $v=13$ (-1.126 cm$^{-1}$)
  - Ionizer tuning: 16791.32 cm$^{-1}$
  - 586 nm
  - Energy is -0.2 cm$^{-1}$ from that found from Eite's table (16791.52 cm$^{-1}$)

- For $v=5$ (-64.19 cm$^{-1}$)
  - Ionizer tuning: 13631 cm$^{-1}$
  - 733.6 nm
  - Energy is -0.2 cm$^{-1}$ from that found from Eite's table (16791.52 cm$^{-1}$)

- For $v=0$ (-161.48 cm$^{-1}$)
  - Ionizer tuning: 13568 cm$^{-1}$
  - 737.0 nm
  - Energy is -0.2 cm$^{-1}$ from that found from Eite's table (16791.52 cm$^{-1}$)

- The "7-laser experiment"
Summary

• Measured photoassociation rates in a BEC
  We can convert a BEC to molecules in a few microseconds!

• Results agree with photoassociation theory
  Simple classical depletion arguments fail. Nothing is fundamentally special about photoassociation in a BEC

• The transition is not yet saturated
  We are not at the unitarity limit.

• We have observed a number of bound states of the lowest triplet potential of Na$_2$, comprising vibrational, rotational, hyperfine and spin-spin dipole structure.

• We can accurately determine the quantum numbers of these states

• We should achieve 10 - 30 MHz precision.
Photoassociation of sodium in a Bose-Einstein condensate

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Motivation, questions and ideas

- Is photoassociation in a BEC special?
  
  Or just a colder and more dense sample…

  (with lineshapes, widths, lightshifts adjusted accordingly...?)

- How fast can you convert an atomic BEC into molecules? What timescales are there?

- Can we saturate the molecular transition?
How fast can you make molecules in a BEC?

- Excitation removes pairs of atoms

Do you have to wait for new atoms to move to fill in the "holes" and create new pairs?

\[ v \sim \frac{\hbar}{mR_{TF}} \sim 0.5 \text{ mm/s} \]

Characteristic time: \[ \tau \sim n^{-1/3}/v \sim 250 \mu s \]
Photoassociate all pairs of atoms at $R_c$

for Thomas-Fermi distribution

and $R_c = 2 \text{ nm}, \quad \tau \sim 10 \mu\text{s}$
The sodium Bose condensate

Laser cool

Magnetically trap, Evaporatively cool

....BEC

Density

macroscopic wave function

every 30 seconds
4 x 10^6 atoms
Thomas-Fermi diameter: 21 x 30 x 42 μm
Trap frequency 272, 192, 136 Hz
Density ~5x 10^{14} cm^{-3}
Phase Contrast Imaging

Photoassociation leads to trap loss

Measure remaining number of atoms

Use phase contrast imaging to determine initial number of atoms in condensate

Reduce noise due to shot-to-shot fluctuations in the initial number

Phase plate is a 2 pixel liquid crystal retarder

\[ \phi = 25 \text{ mm} \]

\[ \phi = 500 \mu\text{m} \]

5 \mu m lead

50 msec between images; limited by camera readout time
Level scheme

\[ F = 1, \ m_F = -1 \]

\[ 16913.4 \text{ cm}^{-1} \]

\( (40 \text{ cm}^{-1} \text{ red from } 3S + 3P_{1/2}) \)

\( \sim 8 \text{ ns lifetime} \)
The experimental set up

-1200 GHz

-15 MHz

Focused to 100 µm

phase contrast & absorption imaging

BEC

MOT

Dye laser 0.5W
Large light shift!

due to d-wave shape resonance
the light shift

\[ \Delta E = \int dE' \frac{\Omega(E')}{E - E'} \]

Weighted density (\( \Omega \)) of red states is much greater than weighted density of blue states

\( \Rightarrow \) Light shift is negative
Line Shape

\[ \nu = 16953 \text{ cm}^{-1} \]
\[ \tau = 100 \mu\text{s} \]
\[ I = 140 \text{ W/cm}^2 \]

Predicted FWHM = 19 MHz
Loss vs. Pulse Length

\[ \frac{dn(\vec{r}, t)}{dt} = -K n^2(\vec{r}, t), \quad N(t) = \int n(\vec{r}, t)d^3r \]

\[ \frac{N(\tau)}{N(0)} = \frac{15}{2} \tau^{-5/2} \left[ \tau^{1/2} + \frac{1}{3} \tau^{3/2} - (1 + \tau)^{1/2} \tanh^{-1} \left( \sqrt{\frac{\tau}{1 + \tau}} \right) \right] \]

\[ \tau = Kn_0 t \]

\[ K = 5.3 \times 10^{-11} \text{ cm}^3\text{s}^{-1} @ 150 \text{ W/cm}^2 \]
Loss vs. Pulse Energy

No signs of saturation
Why so fast?

Quantum mechanics

\[ n^{-1/3} \sim 3000 \ a_0 \]

Our result: \[ \sigma \sim (18000 \ a_0)^2 \]

Unitarity Limit \[ \sigma \sim (900000 \ a_0)^2 \]

- even though \( R_c = 40 \ a_0 \)
Semi-classical 2-body theory:

\[ \text{flux} = 4\pi R_c^2 v \]

\[ R \sim R_C \]

\[ K_{\text{max}} = \sigma_{\text{max}} \bar{v} = \pi R_c^2 \bar{v} \]

\[ \bar{v} \sim \frac{h}{mR_{\text{Thomas-Fermi}}} \sim 0.5 \text{ mm/s} \]

For \( A^1\Sigma_u^+, v=135 \) \( E_b \sim 40 \text{ cm}^{-1} \)
\( R_C \sim 2 \text{ nm} \)

\[ K_{\text{max}} = 6.3 \times 10^{-16} \text{ cm}^3/\text{s} \text{ independent of intensity} \]

\[ K_{\text{measured}} = 5 \times 10^{-11} \text{ cm}^3/\text{s} \text{ at 150 W/cm}^2 \]
Should this bother us?

"$K_{\text{max}}$" classical $= 6 \times 10^{-16}$ cm$^3$/s

$K_{\text{measured}} = 5 \times 10^{-11}$ cm$^3$/s at 150 W/cm$^2$

$K_{\text{unitarity}} = \frac{\hbar \lambda}{2m} = 8 \times 10^{-8}$ cm$^3$/s

$K_{\text{scattering theory}} = \frac{4\hbar}{mk} |T|^2 \approx \frac{4\hbar}{mk} \frac{\Gamma}{\gamma_0}$

$= 6 \times 10^{-11}$ cm$^3$/s at 150 W/cm$^2$
$K_{J-M} = \frac{hn^{-1/3}}{m} = 3.4 \times 10^{-8} \text{ cm}^3/\text{s} \quad \text{at peak } n$

$= 3.7 \times 10^{-8} \text{ cm}^3/\text{s} \quad \text{averaged over Thomas-Fermi distribution}$

-problems predicting correct limits at low $n$