A study of anisotropic inelastic collisions and slow/stopped light with nuclear spin

Mei-Ju Lu
2011Jun03
From the left:
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Outline

• Motivation

• Apparatus
  Buffer-gas cooling

• Measurements
  Collisional-induced relaxation
  Atom-light coherence
  Light storage and retrieval

• Conclusions
Collisions

• **Elastic collisions:**
  Colliding particles remain in the same internal energy states during the collisional events.

• **Inelastic collisions:**
  Colliding particles change their internal states, with their chemical constitutions remaining the same.

• **Chemical reaction:**
  Resulting products after collisions are different from the colliding particles.
Inelastic collisions

- Colliding particles change their internal states, with their chemical constitutions remaining the same.

Zeeman relaxation ($m$-changing)
Fine-structure changing collisions ($J$-changing)
Hyperfine-structure changing collisions ($F$-changing)

"Bad" collisions!~
Inelastic collisions cause a loss in the magnetic trap.
It is difficult to prepare atoms or molecules in a specific state.
Cryogenic system
Apparatus

Refrigerator

Vacuum Chamber

Cell

Target

Nd: YAG Laser

Diode laser

2nd optical table

1st optical table
Buffer-gas-cooled atoms

Cold cell with $^4\text{He}$
$T \sim 4 \text{ K}$

Laser ablation

He buffer-gas cooling via elastic collisions

cooling time: less than 0.5 ms

Observe atoms by absorption spectroscopy
Diffusion lifetimes

1. Optical Density (OD) = atomic density × absorption cross section × path length

2. Transmission = $e^{-\text{OD}}$; Transmission = 1 - Absorption

3. The lowest diffusion mode: $n(t) = n_0 \exp\left[-\frac{t}{\tau_D}\right]$
Cryogenically-cooled atomic vapor cell

Buffer-gas cooling is general to atoms or molecules (eg: We have observed Ti, Ga, In, Yb, Li, TiO & CaH at 5 K)

Note:
Not as cold as laser cooling ($\mu$K)
BGC is limited by helium vapor pressure (0.3K - 300K)
For our purpose, BGC is sufficient.

High optical density (eg: $^{173}$Yb, OD ~ 80)
Large atomic numbers (eg: $^{173}$Yb, $N \sim 10^{13}$ atoms)
Large atomic density (eg: $^{173}$Yb, $n \sim 10^{10}$ cm$^{-3}$)
In general:

<table>
<thead>
<tr>
<th></th>
<th>S-state atoms</th>
<th>Non-S-state atoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eg:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yb[^1S_0]</td>
<td></td>
<td>C[^3P_0]</td>
</tr>
<tr>
<td>Rb[^2S_{1/2}]</td>
<td></td>
<td>Si[^2P_0]</td>
</tr>
<tr>
<td>Cr[^7S_3]</td>
<td></td>
<td>O[^3P_2]</td>
</tr>
<tr>
<td>Orbital angular momentum</td>
<td>Zero</td>
<td>Non-zero</td>
</tr>
<tr>
<td>Electronic shell structure</td>
<td>Spherical</td>
<td>Aspherical</td>
</tr>
<tr>
<td>Interaction potential</td>
<td>Isotropic</td>
<td>Anisotropic</td>
</tr>
</tbody>
</table>

The electronic interaction anisotropy usually causes large inelastic collisions.

Derevianko et al., PRL 90(6), 063002 (2003);
<table>
<thead>
<tr>
<th>Events</th>
<th>S-state atoms</th>
<th>Non-S-state atoms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yb(^{1S_0})-He Rb(^{2S_{1/2}})-He</td>
<td>C(^{3P_0})-He Si(^{2P_0})-He Al(^{2P_{1/2}})-Ar O(^{3P_2})-H C(^{3P_0})-H</td>
</tr>
<tr>
<td>Rate coefficient ([\text{cm}^3\text{s}^{-1}])</td>
<td>(&lt;10^{-17})</td>
<td>(&gt;10^{-12})</td>
</tr>
</tbody>
</table>


\[
k = \frac{1}{\tau n}
\]

\(k\) : rate coefficient  
\(1/\tau\) : inelastic collision rate  
\(n\) : density
Exceptions

- Measured Ti-He Zeeman relaxation rate coefficient: $k_m \sim 10^{-14}$ cm$^3$s$^{-1}$. 
  

- Submerged-shell structure: Titanium $[3d^2 \ 4s^2 \ ^3F_J]$, $^{48}$Ti (I=0) 
  a suppression of the anisotropic interaction potential

- Similar suppression for the fine-structure changing collisions?
- Fine-structure changing collisions is an important cooling mechanism in cold molecular clouds (~10 K).
Exceptions

- Measured Ti-He Zeeman relaxation rate coefficient: \( k_m \approx 10^{-14} \text{ cm}^3\text{s}^{-1} \).
  

- Submerged-shell structure: Titanium [\( 3d^2 4s^2 \, ^3F_j \)], \(^{48}\text{Ti} \) (I=0)
  
  a suppression of the anisotropic interaction potential

- Similar suppression for the fine-structure changing collisions?
  
- Fine-structure changing collisions is an important cooling mechanism in cold molecular clouds (\( \sim 10 \text{ K} \)).

\[
\begin{align*}
  C^+ (^2P_{3/2}) & \quad \text{~157\,\mu m}\quad C^+ (^2P_{1/2}) + H_2 & \rightarrow C^+ (^2P_{3/2}) + H_2 \\
  C^+ (^2P_{3/2}) & \rightarrow C^+ (^2P_{1/2}) + \text{photon}
\end{align*}
\]

Predicted rate coefficient \( k \sim 10^{-10} \text{ cm}^3\text{s}^{-1} \)

**48**Ti-He fine-structure changing collisions

**Optical pumping** to perturb J population

48Ti level structure

- 3d²4s⁴p \( ^3F \)
  - J=4: 25388.334 cm\(^{-1}\)
  - J=3: 25227.217 cm\(^{-1}\)
  - J=2: 25107.417 cm\(^{-1}\)

3d²4s² \( ^3F \)

- J=4: 386.874 cm\(^{-1}\)
- J=3: 170.132 cm\(^{-1}\)
- J=2: 0 cm\(^{-1}\)

NIST Atomic Spectra Database

\[ \text{48Ti} (a^3F_3) + \text{He} \rightarrow \text{Ti} (a^3F_2) + \text{He} \]

Optical density

Time after ablation [s]
48\text{Ti-He fine-structure changing collisions}

Monitoring the J population

Ti level structure

\[ 3d^24s^2 \ a^3F \rightarrow 3d^24s4p \ y^3F \]

J=4 \ 25388.334 \text{cm}^{-1}
J=3 \ 25227.217 \text{cm}^{-1}
J=2 \ 25107.417 \text{cm}^{-1}

\[ 3d^24s^2 \ a^3F \rightarrow 3d^24s4p \ y^3F \]

J=4 \ 386.874 \text{cm}^{-1}
J=3 \ 170.132 \text{cm}^{-1}
J=2 \ 0 \text{cm}^{-1}

NIST Atomic Spectra Database

\[
\text{Ti} (a^3F_3) + \text{He} \rightarrow \text{Ti} (a^3F_2) + \text{He}
\]

Time after ablation [sec]

Graph showing the population of J=2 and J=3 over time.
48Ti-He fine-structure changing collisions

\[ \frac{1}{\tau_{3\rightarrow2}} = n_{\text{He}} k_{3\rightarrow2} \]

- \( n_{\text{He}} \): Helium density
- \( k_{3\rightarrow2} \): Rate coefficient

Graph showing the relationship between inverse lifetime \( 1/\tau \) and helium density, with data points indicating initial decay and optical pumping.
48Ti-He fine-structure changing collisions

- **Submerged-shell structure**: Titanium [3d\(^2\) 4s\(^2\) 3F\(_J\)]

<table>
<thead>
<tr>
<th>48Ti-He</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>T [K]</td>
<td>k(_J) [cm(^3)s(^{-1})]</td>
</tr>
<tr>
<td>5.2</td>
<td>(4.4 ± 0.7) × 10(^{-15})</td>
</tr>
<tr>
<td>9.9</td>
<td>(5.3 ± 0.8) × 10(^{-15})</td>
</tr>
<tr>
<td>15.6</td>
<td>(7.7 ± 1.2) × 10(^{-15})</td>
</tr>
<tr>
<td>19.9</td>
<td>(9.8 ± 1.5) × 10(^{-15})</td>
</tr>
</tbody>
</table>

Lu et al, PRA 77, 060701(R) (2008)

1. A similar suppression in fine-structure changing collisions as that in Zeeman relaxation.

2. The result of Ti-He fine-structure measurements has been applied to a theoretical calculation.

Zygelman et al, PRA 78, 012795 (2008)
Open-shell atoms

- $^2P_{1/2}$-state atoms: Gallium [$4s^24p^2^2P_{1/2}$] and Indium [$5s^25p^2^2P_{1/2}$]

Probe ground state population

Optical pumping to perturb population

$^{69}\text{Ga} (I=3/2)$

$4s^25s^2^2S_{1/2}$

Pump (~mW)

Probe (~μW) 403nm

$^2P_3/2$

$^2P_1/2$

$4s^24p$

$^2P^o_3/2$

$^2P^o_1/2$

Optical density

Time after ablation [s]
Ga-He $F$-changing collisions

$^{69}$Ga ($I=3/2$)

$^2S_{1/2} \rightarrow F=2$

$^2P^o_{3/2} \rightarrow 3$

$^2P^o_{1/2} \rightarrow 2$

pump

probe

Normalized ratio

Time after ablation [s]

$|F=1>$ data

$|F=2>$ data
Ga-He $F$ and $J$-changing rates

\[
\frac{1}{\tau} = n_{\text{He}} k + \frac{1}{D n_{\text{He}}}
\]

$n_{\text{He}}$: Helium density
$k$: Rate coefficient
$D$: Diffusion coefficient
Ga-He Zeeman relaxation

\[ \sigma^+, \sigma^- \]

Probe (~μW)

\( B \)

coils (~ few G)

\( \lambda/4 \)

PBS

\( V, H \)

PD2

\[ |F' = 1\rangle \quad \begin{array}{ccc} -1 & 0 & +1 \end{array} \quad |m_{F'}\rangle \]

\[ |F = 2\rangle \quad \bullet \quad \bullet \quad \bullet \quad \bullet \quad \bullet \quad |m_F\rangle \]

\[ F_m \]

\[ F_m \]

\[ F_m \]

OD

0.1

Time after ablation [s]
Ga-He Zeeman relaxation

\[ B \]

\[ \sigma^+, \sigma^- \]

Probe (\(\sim \mu W\))

Pump (\(\sim mW\))

\[ \lambda/4 \]

PBS

\[ V, H \]

\[ V \]

\[ \sigma^+, \sigma^- \]

coils (\(\sim \) few G)

\[ |F' = 1\rangle \]

\[ |F = 2\rangle \]

\[ |m_F\rangle \]

\[ |m_F'\rangle \]

OD

Time after ablation [s]
Ga-He Zeeman relaxation

$\sigma^+, \sigma^-$

Probe ($\sim \mu W$)

$|F' = 1\rangle = \frac{-1}{\sqrt{2}} |0\rangle + \frac{1}{\sqrt{2}} |1\rangle$

$|F = 2\rangle = \frac{-2}{\sqrt{5}} |0\rangle + \frac{1}{\sqrt{5}} |1\rangle + \frac{1}{\sqrt{5}} |2\rangle$

 coils ($\sim$ few G)

$B$

$\lambda/4$

PBS

$V, H$

$H \rightarrow$ PD2

$V \rightarrow$ PD1

$\text{OD}$

Time after ablation [s]
<table>
<thead>
<tr>
<th>Events</th>
<th>$^{69}$Ga$[^2P_{1/2}]$-He</th>
<th>$^{115}$In$[^2P_{1/2}]$-He</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate coefficient</td>
<td>Experiment</td>
<td>Theory</td>
</tr>
<tr>
<td>$k_J$</td>
<td>(1.0+-0.3)</td>
<td>1.3</td>
</tr>
<tr>
<td>$k_F$</td>
<td>(5.3+-1.3)</td>
<td>6.6</td>
</tr>
<tr>
<td>$k_m$</td>
<td>&lt; 300</td>
<td>2.3</td>
</tr>
</tbody>
</table>

(in the unit of $10^{-17}$ cm$^3$s$^{-1}$)

Tscherbul et al., PRA 80, 040701(R) (2009)

- Prior work:
  a. C$[^3P_0]$, Si$[^2P_0]$-He; Al$[^2P_{1/2}]$-Ar; O$[^3P_2]$, C$[^3P_0]$-H: $k > 10^{-12}$ cm$^3$s$^{-1}$
  b. Ti$[^3F_2]$-He: $k_J \sim 10^{-15}$ cm$^3$s$^{-1}$

- The electron-density distribution of atoms in $^2P_{1/2}$ electronic states is spherically symmetric and that of $^2P_{3/2}$ atoms is not.

- Ground-state fine-structure splitting
  Ga: 826 cm$^{-1}$
  In: 2213 cm$^{-1}$
Summary

• The combined technique of laser ablation, buffer-gas cooling and optical pumping is applicable to measure inelastic collisions.

• We have measured a suppression in Ti-He fine-structure changing collisions due to titanium's submerged shell structure.

• The measured inelastic collisions rates of Ga-He and In-He are about five orders smaller than other open-shelled atoms and about one order smaller than Ti-He.

• $^2\text{P}_{1/2}$-state atoms may be good for evaporative cooling in a magnetic trap.
Light storage and retrieval

- Quantum communication:
  Carrier: photons (fastest, polarization)
  Storage: atoms (spin states, long coherence time)

- A direct transmission of quantum states for a long distance is impossible!
  In an optical fiber: Transmission = $10^{-0.2L/10}$
  \( L=5 \text{ km}, T=0.8; \ L=100 \text{ km}, T=10^{-2}; \ L=500 \text{ km}, T=10^{-10} \)

- Quantum repeater
  Successful operations are probabilistic.
  Need quantum memory

- Classical light storage and retrieval
  Slow/stopped light

Briegel et al., PRL 81(26), 5932 (1998); DLCZ Nature 414, 413 (2001)
Slow light

For a light pulse traveling in a dispersive medium:

\[ v_{\text{phase}} = \frac{c}{n}; \quad v_{\text{group}} = \frac{c}{n(\omega) + \omega \frac{dn(\omega)}{d\omega}} \]

i) \( \frac{dn(\omega)}{d\omega} \) → large, \( v_{\text{group}} \) → slow

ii) no absorption of the light pulse
Slow light

For a light pulse traveling in a dispersive medium:

\[ v_{\text{phase}} = \frac{c}{n}; \quad v_{\text{group}} = \frac{c}{n(\omega) + \omega \frac{dn(\omega)}{d\omega}} \]

i) \( \frac{dn(\omega)}{d\omega} \rightarrow \text{large}, \quad v_{\text{group}} \rightarrow \text{slow} \)

ii) no absorption of the light pulse

- For a linear absorptive medium, the derivative is small.
- Light pulse can be slow down by using electromagnetically-induced transparency (EIT).

Harris et al., PRA 46(1), R29 (1992)
Absorption $\Delta_p$, detuning

$|1\rangle$  $|2\rangle$  $|3\rangle$
Absorption

Absorption

\( \Delta_p \), detuning

\( \omega_p \)

\( \omega_c \)
Absorption

\[ \Delta_p, \text{detuning} \]

Absorption

\[ \Delta_p, \text{detuning} \]

EIT
Electromagnetically-induced transparency (EIT)

Controlled with \( \Delta_p \) and probe state |3⟩, |2⟩, |1⟩ transitions are shown.

\[
(n-1) \quad \Delta_p, \text{detuning}
\]

\[
\text{absorption} \quad \Delta_p, \text{detuning}
\]
Electromagnetically-induced transparency (EIT)

The nonlinear effect depends on the control beam power.
Electromagnetically-induced transparency (EIT)

Get the condition to Slow Light!~
**Dark state** \[ |a^0\rangle = \cos \theta |1\rangle - \sin \theta |2\rangle \]

**Bright state**
\[ |a^+\rangle = \sin \theta \sin \phi |1\rangle + \cos \theta \sin \phi |2\rangle + \cos \phi |3\rangle \]

\[ |a^-\rangle = \sin \theta \cos \phi |1\rangle + \cos \theta \cos \phi |2\rangle - \sin \phi |3\rangle \]

- Angles are associated to the intensities of both fields
- **No excited state population: no absorption**
Two-photon resonance: \((\delta=\Delta_p-\Delta_c=0)\) \(\hbar(\omega_p-\omega_c) = E_2 - E_1\)

EIT happens as long as the frequency difference between two optical fields matches with the energy difference of two lower energy levels.
EIT-based atomic ensemble

1. **Strong atom-photon coupling**
   Need: **large atomic density**

2. **Good isolation from environment**
   Need: **long coherence times**

   often disturbed by
   inelastic collisions, stray magnetic field, and thermal diffusion/atomic motion

Other system: electronic spin of alkali gas or solids
UNR: use pure **nuclear spin system** to accomplish those needs
**Atom choices**

- **Ground state** $^1S_0$ atoms ($J=0$, $L=0$ and $S=0$)
  no coupling between electronic and nuclear spins.
  nuclear spin has much better collisional behaviors than electronic spin.

- **Isotopes with nuclear spin** ($I \neq 0$)
  less effects from stray magnetic fields.

- **Atomic Ytterbium** (optical transition $\sim 400$ nm)
  $^{168}\text{Yb}$, $^{170}\text{Yb}$, $^{172}\text{Yb}$, $^{174}\text{Yb}$, $^{176}\text{Yb}$
  $^{171}\text{Yb}$ ($I=1/2$), and $^{173}\text{Yb}$ ($I=5/2$)
  structure for EIT
  good natural abundance

\[ \frac{\mu_N}{\mu_e} \sim \frac{1}{1837} \]
**Setup**

- **AOM**: acousto-optic modulator, controlling beam power
- **EOM**: electro-optic modulator, rotating beam polarization
- **W4**: quarter-wave plate, turning linear-pol. to circular-pol.
- **L**: lens combination, expanding the beam

Detection device =W4+ Wollaston Prism + PD1 and PD2
Yb EIT

\[ 6s6p \, {}^1P_1 \, F' = 5/2 \quad m_F = -5/2, -3/2, -1/2, +1/2, +3/2, +5/2 \]

\[ 6s^2 \, {}^1S_0 \, F = 5/2 \quad m_F = -5/2, -3/2, -1/2, +1/2, +3/2, +5/2 \]
Appling a magnetic field to induce two-photon detuning $\delta$

$6s6p \ ^1P_1 \ F' = 5/2$

$6s^2 \ ^1S_0 \ F = 5/2$
probe
Two-photon resonance ($\delta=0$)

EIT
For a Doppler-broaden thermal gas,

\[ \Gamma_{\text{EIT}} = 2\gamma_g + \frac{\Omega_c^2}{W_D + \gamma} \]

Rabi frequency
\[ \Omega_c \propto \sqrt{I_c} \]

\[ (\Delta=0) \]

\[ \Gamma_{\text{EIT}} = 10 \text{ Hz} \]
\[ \Gamma_{\text{EIT}} = 200 \text{ Hz} \]
Why isn't the transparency better?

- Off-resonance absorption of light by the other isotopes

Solution: switching to an isotopically-enriched $^{173}\text{Yb}$ target
Slow light

\[ \tau_{\text{delay}} = \frac{L}{V_g} - \frac{L}{c}; \]

\( \tau_{\text{pulse}} = 60 \ \mu s \)

\( \tau_{\text{delay}} = 12 \ \mu s \)
Slow light

\[
\tau_{\text{delay}} = \frac{L}{v_g} - \frac{L}{c};
\]

\[
\tau_{\text{pulse}} = 60 \text{ \mu s}
\]

\[
\tau_{\text{delay}} = 12 \text{ \mu s}
\]

\[
v_g \sim 100 \text{ m/s}
\]

\[
v_g \sim 3 \times 10^{-7} c
\]
Delay-bandwidth product (DBW)

\[ \tau_{\text{delay}} = \text{OD}_0 \frac{(W_D + \gamma)\Omega_c^2}{(2\gamma g (W_D + \gamma) + \Omega_c^2)^2}; \quad \Gamma_{\text{EIT}} = 2\gamma g + \frac{\Omega_c^2}{W_D + \gamma} \]

Goldfarb et. al. *EPL* **82** 54002 (2008)

i) For long \( \tau_{\text{delay}} \), need large \( \text{OD}_0 \); small \( \Omega_c, \gamma g \)

(want \( v_g \to 0, \Omega_c \to 0 \))

ii) For no absorption, require \( \frac{1}{\tau_{\text{pulse}}} < \Gamma_{\text{EIT}} \), \( \therefore \) large \( \Omega_c \)
Delay-bandwidth product (DBW)

\[ \tau_{\text{delay}} = OD_0 \frac{(W_D + \gamma)\Omega_c^2}{(2\gamma_g(W_D + \gamma) + \Omega_c^2)^2} ; \quad \Gamma_{\text{EIT}} = 2\gamma_g + \frac{\Omega_c^2}{W_D + \gamma} \]

Goldfarb et. al. *EPL* **82** 54002 (2008)

i) For long \( \tau_{\text{delay}} \), need large \( OD_0 \); small \( \Omega_c, \gamma_g \)

\( \text{(want } v_g \rightarrow 0, \Omega_c \rightarrow 0) \)

ii) For no absorption, require \( \frac{1}{\tau_{\text{pulse}}} < \Gamma_{\text{EIT}} \), \( \therefore \) large \( \Omega_c \)

\[ 1 \ll \text{DBW} = \tau_{\text{delay}} \cdot \frac{1}{\tau_{\text{pulse}}} < OD_0 \]
• Radiation trapping
Re-emitted photons w/ random polarization mess up atom-light coherence.
Stopped light

Need FWHM

$\tau < 10 \text{ ms}$

$\tau = \text{storage}$

Stopped light

leak

Int. [normalized]

0.5

0.4

0.3

0.2

0.1

0.0

-100

0

100

Time [\text{\mu s}]
Stopped light

\[ \tau_{\text{storage}} = 10 \text{ ms} \]

Diagram shows a sequence of devices labeled AOM, EOM, W4, L, PBS, and PD2. A graph illustrates intensity over time, with a peak labeled as 'leak' and another labeled as 'retrieval.'
Stopped light

Efficiency = \frac{\text{the energy of the retrieved pulse}}{\text{the energy of the input pulse}}

Decoherence due to diffusion:
an exponential fit gives a storage lifetime of 0.11s.
Stopped light

A storage lifetime is up to 0.3 s.
Quantum communication

It takes about 17 ms for a light pulse to travel across the north America.

~ 5000 km
Yb data v.s. state of the art

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Methodology</th>
<th>Paper Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2009 Hau Na BEC</td>
<td>PRL 103 233602</td>
</tr>
<tr>
<td>B</td>
<td>2007 Walsworth Warm Rb vapor</td>
<td>PRL 98 243602</td>
</tr>
<tr>
<td>C</td>
<td>2009 Kuzmich Rb 1D lattice</td>
<td>Nat. Phys. 5 100</td>
</tr>
<tr>
<td>D</td>
<td>2010 Kuzmich Rb &quot;magic&quot; lattice</td>
<td>PRA 81, 041805(R)</td>
</tr>
<tr>
<td>E</td>
<td>2009 Bloch Rb Mott Insulator</td>
<td>PRL 103 033003</td>
</tr>
</tbody>
</table>

![Graph](image)

- **Yb data v.s. state of the art**
- **Efficiency** vs. **Storage time [s]**
- UNR; nHe ~ 1.5e17 cm\(^{-3}\), bias field
Conclusions

• We use cryogenically-cooled $^1S_0$ atomic ensembles to have high optical densities and long spin coherence times.

• By applying EIT techniques in a nuclear spin system, we have observed an atom-light coherence time better than 100 ms.

• We have a storage lifetime up to hundreds of milliseconds and show a competitive performance than other system.
\[ 2P_{1/2} : s = 1/2, l = 1, j = 1/2 \]

\[ |j = 1/2, m_j = 1/2\rangle = \sqrt{\frac{2}{3}} Y^1_1 |\frac{1}{2}, -\frac{1}{2}\rangle - \sqrt{\frac{1}{3}} Y^0_1 |\frac{1}{2}, -\frac{1}{2}\rangle \]

\[ |\psi|^2 \propto \frac{2}{3} |Y^1_1|^2 + \frac{1}{3} |Y^0_1|^2 = 1 \]

\[ 2P_{3/2} : s = 1/2, l = 1, j = 3/2 \]

\[ |j = 3/2, m_j = 3/2\rangle = Y^1_1 |\frac{1}{2}, \frac{1}{2}\rangle \]

\[ |j = 3/2, m_j = 1/2\rangle = \sqrt{\frac{1}{3}} Y^1_1 |\frac{1}{2}, -\frac{1}{2}\rangle + \sqrt{\frac{2}{3}} Y^0_1 |\frac{1}{2}, \frac{1}{2}\rangle \]

\[ |\psi_{3/2,3/2}|^2 \propto |Y^1_1|^2 = \frac{3}{8\pi} \sin^2 \theta \]

\[ |\psi_{3/2,1/2}|^2 \propto \frac{1}{3} |Y^1_1|^2 + \frac{2}{3} |Y^0_1|^2 = \frac{1}{8\pi} (1 + \cos^2 \theta) \]
Kramers-Kronig Relation

Classical Electrodynamics (1998)
J. D. Jackson

\( \chi \) : susceptibility
\( \text{Im}[\chi] \) : absorption
\( 1 + \frac{1}{2} \text{Re}[\chi] \) : index of refraction
Citations to Previously Published Work

• Fine-structure changing collisions in atomic titanium
  Mei-Ju Lu, Kyle S. Hardman, Jonathan D. Weinstein, and Bernard Zygelman

• Inelastic titanium-titanium collisions
  Mei-Ju Lu, Vijay Singh, and Jonathan D. Weinstein

• Cold TiO-He collisions
  Mei-Ju Lu and Jonathan D. Weinstein
  *New Journal of Physics* 11, 055015 (2009)

• Suppression of Zeeman relaxation in cold collisions of $^2\text{P}_{1/2}$ atoms
  T. V. Tscherbul, A. A. Buchachenko, A. Dalgarno, M.-J. Lu, and J. D. Weinstein
  *Physical Review A* 80, 040701(R) (2009)

• Electromagnetically induced transparency with nuclear spin
  Mei-Ju Lu and Jonathan D. Weinstein

• Stopped light with a cryogenic ensemble of $^{173}\text{Yb}$ atoms
  Mei-Ju Lu, Franklin Jose, and Jonathan D. Weinstein
  *Physical Review A* 82, 061802(R) (2010)
Diffusion lifetimes

i) At low $n_{\text{He}}$, $\tau_D$ is linearly increasing with $n_{\text{He}}$.

ii) At high $n_{\text{He}}$, diffusion is not the only atom loss mechanism.
Spatial compression: $c / v_g$

For a 60 $\mu$s long pulse (18000 m long in space),

if $\tau_{\text{delay}} = 12 \mu$s, $v_g = \frac{10 \text{ cm}}{12 \mu\text{s}} = 8.3 \times 10^5 \text{ cm/s}$.

Spatial compression $= \frac{c}{v_g} = 3.6 \times 10^4 = \frac{18000 \text{ m}}{0.5 \text{ m}}$

The length of the atomic cloud is 10 cm
Decoherence

- **Inelastic collisions**
  coated cell, buffer gas, $J = 0$ atoms, Mott insulator

- **Inhomogeneous magnetic fields**
  magnetic shielding,
  nuclear spins,
  using magnetically insensitive states (clock transitions)

- **Thermal diffusion/ atomic motion**
  Cryogenic He buffer gas, optical lattice/ Mott insulator,
  Bose-Einstein Condensation,
  solids/crystal
Yb spectrum

Transmission = $e^{-OD}$

Optical Density (OD) = atom density × absorption cross section × path length

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Nuclear Spin</th>
<th>Abundance</th>
<th>Gyromagnetic ratio $\gamma$ [Hz / Gauss]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{173}\text{Yb}$</td>
<td>5/2</td>
<td>16.12%</td>
<td>- 206.5</td>
</tr>
</tbody>
</table>

$398.8 \text{ nm}$

$25068 \text{ cm}^{-1}$

$A = 1.92 \times 10^8 \text{ s}^{-1}$

$\Gamma_{\text{natural}} = 30 \text{ MHz}$

$6s^2 \ ^1S_0$

$6s6p \ ^1P_1$

$84 \text{ MHz}$

$737 \text{ MHz}$

T ~ 5K

Blue diode laser
Yb Pressure broadening

![Graph showing the relationship between FWHM and Helium density. The graph includes data points for GauFWHM and LorFWHM, and a fitted line with equation \( y = a + b \times x \). The parameters for the fit are \( a = 0.03 \) and \( b = 1.77 \times 10^{-19} \).]
Prior Work

\[ \frac{1}{\tau} = k \cdot n \]

\[ k = \sigma \cdot \bar{v}_r \]

<table>
<thead>
<tr>
<th>Events</th>
<th>Rate coefficient [cm³s⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>\textsuperscript{173}Yb\left[\textsuperscript{1}S\textsubscript{0}\right]-He</td>
<td>$&lt; 9 \times 10^{-18}$</td>
</tr>
<tr>
<td>Rb\left[\textsuperscript{2}S\textsubscript{1/2}\right]-He</td>
<td>$\sim 10^{-19}$</td>
</tr>
<tr>
<td>Al\left[\textsuperscript{2}P\textsubscript{1/2}\right]-Ar</td>
<td>$10^{-12} \sim 10^{-10}$</td>
</tr>
<tr>
<td>C\left[\textsuperscript{3}P\textsubscript{0}\right], Si\left[\textsuperscript{2}P\textsubscript{0}\right]-He</td>
<td></td>
</tr>
<tr>
<td>O\left[\textsuperscript{3}P\textsubscript{2}\right], C\left[\textsuperscript{3}P\textsubscript{0}\right]-H</td>
<td></td>
</tr>
<tr>
<td>Ca*-Ca* [4s4p \textsuperscript{3}P\textsubscript{2}]</td>
<td>$3 \times 10^{-10}$</td>
</tr>
<tr>
<td>Yb*-Yb* [6s6p \textsuperscript{3}P\textsubscript{2}]</td>
<td>$1.0(3) \times 10^{-11}$</td>
</tr>
<tr>
<td>Sr*-Sr* [5s5p \textsuperscript{3}P\textsubscript{0}]</td>
<td>$(5 \pm 3) \times 10^{-12}$</td>
</tr>
</tbody>
</table>

\( \frac{1}{\tau} \): rate  
\( k \): rate coefficient  
\( n \): atomic density  
\( \sigma \): cross-section  
\( \bar{v}_r \): relative velocity  

Walker et al, PRA 56, 2090 (1997)  
Hemmerich et al, PRL 96, 073003 (2006)  
Yamaguchi et al, PRL 101, 233002 (2008)  
Traverso et al, PRA 79, 060702 (2009)