Towards ACME III: Optical Cycling Tests in Beam Box II
Towards ACME III

Main uncertainty equation:

\[ \delta d_e = \frac{\hbar}{2C\tau\mathcal{E}_{\text{eff}}\sqrt{\dot{n}T}} \]  \hspace{1cm} (1)

- Maxed out contrast $C$: $\sim 0.95$
- Maxed out precession time $\tau$: $\sim 1\,\text{ms}$ while $H$-state lifetime is $1.3\,\text{ms}$
- Maxed out $E_{\text{eff}}$: fully polarized at applied $\mathcal{E} \approx 10\,\text{V/cm}$
- Two major ways left to improve ACME:
  - Reduce sources of systematic error
  - Average more (increase $T$)
  - Increase molecule flux $\dot{n}$
Main uncertainty equation:

\[
\delta d_e = \frac{\dot{n}}{2C \tau \mathcal{E}_{\text{eff}} \sqrt{\dot{n} T}}
\]  

(1)

- Two ways to improve \( N \):
  - Increase initial molecular flux (improve beam source production of useful molecules in \( X \))
  - **Increase efficiency in using molecules produced by beam source**
Ablation beam source:
- $\sim 10^{11}$ molecules per pulse, 90% in $|X, J = 0, 1, 2, 3\rangle$
- $\sim 0.1\%$ reach detection region 1.1 m away (due to beam divergence)

Rotational cooling ($X \rightarrow C$): $\sim 50\%$ of initial molecules in $X$ ultimately end up in $J = 0$

STIRAP transfers $\sim 75\%$ of $|X, J = 0\rangle$ to $H$

Spin precession occurs in interaction region

$H$-state molecules excited to $I$ by 703 nm and $\sim 90\%$ decay to $X$

**Only 5% of photons emitted by molecules are detected**!

Final figure: $\sim 10^6$ photons per pulse (actual: $\sim 300,000$)
Current measurement scheme: detect 512 nm photons emitted by spin-precessed molecules decaying from $I \rightarrow X$

ACME II detection inefficiencies:
- Geometric collection efficiency: $\sim 20\%$
- Quantum efficiency of PDs: $\sim 25\%$
- Total: $\sim 5\%$ of decaying molecules detected

Goal: become molecule shot noise limited by detecting one photon per molecule in experimental state
How to Maximize Detection Efficiency

Three elements to improve:

- Improve solid angle of collection optics - detection outside of interaction region with optimized reflector
- Improve quantum efficiency of detectors - upgrading to cooled SiPMs (≈ 50% QE at 512 nm)
- **Increase number of photons per molecule - optical cycling**
How to Maximize Detection Efficiency

Three elements to improve:

- Improve solid angle of collection optics - detection outside of interaction region with optimized reflector
- Improve quantum efficiency of detectors - upgrading to cooled SiPMs ($\approx 50\%$ QE at 512 nm)
- **Increase number of photons per molecule - optical cycling**
  - At end of precession, project molecules into orthogonal long-lived states (**shelving**)
  - Outside of interaction region, stimulate with light tuned to transition with **high branching ratio**
  - Switch rapidly in cycling between two orthogonal states (parity-selective switching)
Questions to answer:

1. **What is the branching ratio of the transition?** ($X \rightarrow I$, $X \rightarrow C$, other?)
2. **How many lasers will we need?** (Repumps?)
3. Will we have enough laser power? (Transition dipole moment)
4. How will the angular distributions of the decay affect the gain? (Will be limited by worst-detected decay.)
Optical Cycling Schemes

Assuming no repumps. Scheme 1:

Needs one 703 nm, three 512 nm lasers for basic cycling.
Optical Cycling Schemes

Assuming no repumps. Scheme 2:

Needs two 703 nm, two 512 nm lasers for basic cycling.
Determining Branching Ratio

- Branching ratio of $X - C$: $\sim 75\%$.
- Branching ratio of $X - I$: measured (roughly) by Steimle (2014) to be $\sim 91\%$

Note: assumes no branches $I \rightarrow A \ ^3\Pi_{0^+} \ (1119 \ \text{nm})$, $I \rightarrow ^3\Pi_{0^-} \ (\text{unseen state})$, $I \rightarrow B ^3\Pi_1 \ (1163 \ \text{nm})$.

<table>
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<tr>
<th>Band</th>
<th>Assignment</th>
<th>Trans.</th>
<th>Energy</th>
<th>Diff.</th>
<th>$%$</th>
<th>Td</th>
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<td>A</td>
<td>$I(\Omega = 1)(v = 0) \rightarrow X ^1\Sigma^+(v = 0)$</td>
<td>19538</td>
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<td>B</td>
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<td>C</td>
<td>$E(\Omega = 0^+)(v = 0) \rightarrow X ^1\Sigma^+(v = 0)$</td>
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<td>0</td>
<td>0</td>
<td>&lt;1</td>
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<td>D</td>
<td>$I(\Omega = 1)(v = 0) \rightarrow H ^3\Delta_1(v = 0)$</td>
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<td>E</td>
<td>$I(\Omega = 1)(v = 0) \rightarrow Q ^3\Delta_2(v = 0)$</td>
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<td>3</td>
<td>0.59</td>
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</table>
Considerations for choosing right transition:

- $X - I$ (512 nm) has 2x transition dipole moment cf. $X - C$ (690 nm)
- TAs, DL Pro available for 690 nm (power up to hundreds of mW)
- No TAs for 512 nm - DL Pro HP available up to $\sim$ 20 mW, need to double above that
- If we need 1-2 repumps anyway, then $X - C$ might be easier
- Depending on divergence of beam, might need more 1-2x more power. **Need to consider possible magnetic lens to compress beam.**
Rotational cooling in ACME II with $X - I$ (May 2017):

- Normal gain using $X - C$: $\sim 1.8$ at 16 mW
- Expect $X - I$ saturation at 5-10 mW, but windows have only 60% transmission at 512 nm
Rotational cooling in ACME II with $X - I$ (May 2017):

**Conclusion:** $X - I$ branching ratio at least equal to $X - C$, but need more specialized measurement.
Question 1: Planned Tests in Beam Box II

Test 1: Pump-probe measurement of branching ratio

Three configurations for probe laser absorption (690 nm):

1. $R(0)$ without pump
2. $R(0)$ with pump
3. $Q(2)$ without pump
Question 1: Planned Tests in Beam Box II

\[ \frac{\sigma_{pump}}{\sigma_{R(0)}} = \frac{P_0^0 + \frac{3}{5} \frac{(2/3)A}{1-(1/3)A} P_2^0}{P_0^0} = 1 + \frac{3}{5} \frac{(2/3)A}{1-(1/3)A} \frac{P_2^0}{P_0^0} \]  \hspace{1cm} (2)

Taken from rotational cooling write-ups (Zack, Brendon).
\[ A = \text{branching ratio}. \]

\[ \frac{P_2^0}{P_0^0} = \frac{1}{6} \frac{A_{Q(2)}}{A_{R(0)}} \]  \hspace{1cm} (3)

\[ \Rightarrow A = 3 - \frac{3A_{Q(2)}^0}{A_{Q(2)}^0 - 5A_{R(0)}^0 + 5A_{pump}^R}, \]  \hspace{1cm} (4)
Question 1: Planned Tests in Beam Box II

Test 2: Simple cycling

Address orthogonal magnetic sublevels by switching between three configurations: 1) x-polarized, 2) z-polarized, 3) rapidly switching both

Compare gain in signal 3) compared to sum 1) + 2)

E. Kirilov found a gain of $\sim 2$ with $X - C$

Auxiliary question: can we rotationally cool outside of the cell?
Question 2: Do we need repumps?

- Current detection efficiency of 5% - maximum gain of 20.
- However, from Zack’s paper on cycling phase noise:
  - Overall noise comes from combination of phase projection, photon cycling noise, detection noise
  - Results in gain of \(20/F\), defined by
    \[
    F = 2 + \frac{q}{p} - 2q
    \]  
    (5)
    where \(1/q \propto \#\) of photons cycled, \(p =\) detection probability.
    \(F \to 2\) as \(q \to 0\) \(\implies\) max gain of \(\sim 10\).
  - **Caveat**: photons also emitted by Poisson process (if not in a dark state!)
  - With more photons cycled, can still increase gain to \(\sim 15\) at \(\sim 100\) photons cycled.
  - Conclusion for now: might need anywhere from 10-100 photons, better detection (larger \(p\)) helps
Question 2: Repumping options

$X - I$ as main transition:

$I (J=1) \rightarrow X (v=1), ~1\% (536 \text{ nm})$

$512 \text{ nm} (~91\%)$

$Q (J=2), 745 \text{ nm} (~3\%)$

$J = 2, +$

$H (J=1), 703 \text{ nm} (~5\%)$

$J = 1, -$

$X J = 0, +$

$J = 2, +$
Question 2: Repumping options

Number of lasers needed for each repump transition (assuming scheme 1):

- Main (\( \sim 91\% = 11 \) photons): \( 3 \times 512 \) nm
- \(+ \ H - I \ (\sim 96\% = 25 \) photons\): add \( 2 \times 703 \) nm (total: 5 lasers)
- \(+ \ H - Q \ (\sim 99\% = 100 \) photons\): add \( 2 \times 745 \) nm (total: 7 lasers)

Note: small uncertainties can have drastic effect on # of photons!
Also possible is repumping through \( C \)-state (1090 nm, 1196 nm):

- More accessible wavelengths (TAs available)
- Less effective: \(+ H - C \) gives \( \sim 94\%\), \(+ Q - C \) gives \( \sim 96\%\)
Measure $X - I$ branching ratio using pump-probe absorption/fluorescence measurement

Perform simple cycling in BB II using current beam line

Construct test collection optics setup:
- Optimize collection efficiency
- Reduce potential scatter
- Integrate with SiPM (?)

Experiment with repumps: $H - C$ (1090 nm), $Q - C$ (1196 nm) to decide on final cycling scheme

Note usefulness of Q-C laser - both for cycling and magnetic lens STIRAP!