Sub-Doppler cooling of $^{40}$K in three-dimensional gray optical molasses

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Outline

- Experimental apparatus
- Motivation for sub-Doppler cooling
- Gray molasses in a nutshell
- Discussion of experimental results
- Final remarks
Experimental Apparatus

Typical flux for $^6\text{Li}$ and $^{40}\text{K}$: $\sim 10^9$ at/s
Best number of atoms achieved in MOT: $\sim 8 \times 10^9$ at for each species

Experimental Apparatus

Magnetic Transport of $^{40}$K

$T_0 = 300 \mu K$

$b' = 140 \text{ G} \cdot \text{cm}$

Heating $\sim 10/2 = 5\%$

<table>
<thead>
<tr>
<th></th>
<th>$\Delta t$ (s)</th>
<th>$\tau$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection</td>
<td>0.62</td>
<td>3</td>
</tr>
<tr>
<td>To Elbow</td>
<td>0.85</td>
<td>30</td>
</tr>
<tr>
<td>2\text{nd} arm</td>
<td>2.5</td>
<td>30</td>
</tr>
<tr>
<td>Total</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Efficiency $\geq 40\%$

Runaway evaporation not yet observed in the Science cell
Improving the initial conditions

Sub-Doppler cooling

\[ \text{MOT} \]

Narrow transition MOT

\[
\begin{array}{|c|c|c|}
\hline
\text{Isotope} & \lambda (\text{nm}) & T_D (\mu\text{K}) \\
\hline
\text{\textsuperscript{6}Li} & 323 & 18 \\
\text{\textsuperscript{40}K} & 405 & 24 \\
\hline
\end{array}
\]

\text{\textsuperscript{6}Li: Duarte, P. et al. PRA 84, 061406 (2011)}

\text{\textsuperscript{40}K: McKay, D. et al. PRA 84, 063420 (2011)}

Modugno, G. et al. PRA 60, R3373 (1999)
Cooling transition $F \rightarrow F' = F - 1$ involves 2 dark states

1. (Motional) coupling to the bright manifold in the “valley”
2. Loss of kinetic energy by climbing the potential hill
3. Optical pumping back to the dark manifold

Cohen-Tannoudji, C. - Collège de France
Numerical solving of the OBE

\[ I_{\text{cool}} = 20I_{\text{sat}} \]
\[ I_{\text{repump}} = I_{\text{cool}}/8 \]
\[ \delta = 3\Gamma \]
Experimental Sequence

MOT

\[ I_{\text{cool}} = 13 I_{\text{sat}} \]
\[ I_{\text{repump}} = I_{\text{cool}}/20 \]
\[ b' = 9 \text{ G} \cdot \text{cm}^{-1} \]
\[ N_0 = 5 - 7 \times 10^8 \]
\[ T \approx 200 \mu\text{K} \]
\[ I_{\text{sat}} = 1.75 \text{ mW/cm}^2 \]

C-MOT

\[ b' = 9 \stackrel{5\text{ms}}{\Rightarrow} 60 \text{ G} \cdot \text{cm}^{-1} \]
\[ T \sim 1-4 \text{ mK} \]
\[ \sigma_{\text{rms}} = 1.4 \text{ mm} \]

D\text{I\!I} Molasses

\[ I_{\text{cool}} = 14 I_{\text{sat}} \]
\[ I_{\text{repump}} = I_{\text{cool}}/8 \]
\[ \vec{B} = 0 \]

Fast cooling dynamics

Log scale!

Two dynamics

Fast cooling: 4mK to ~100μK in <1ms
Slow cooling: 100μK to 30uK in 6ms
Fast cooling dynamics

Two dynamics
- Fast cooling: 4mK to ~100μK in <1ms
- Slow cooling: 100uK to 30uK in 6ms

Capture efficiency in molasses = 100%

Plateau of low fluorescence ⇒ atoms trapped in dark states
Temperature determination

TOF = 3.5 ms

no molasses

$\tau_M = 1.5$ ms

TOF = 17 ms

$\tau_M = 6.0$ ms

$T \approx 3$ mK

$T \approx 1.20 \mu$K

$T \approx 36 \mu$K

$\approx 1.5$ cm

Time of flight (ms)

$\sigma_{\text{vert}}$ (mm)
Light intensity dependence

Varying light intensity

Two-step sequence

100% capture efficiency

\( D_1 \) cooling intensity \((l/l_{sat})\)

Temperature (\(\mu K\))

Atom number \((\times 10^8)\)

\(\tau_m\)

6 ms 2 ms

Final \( D_1 \) cooling intensity \((l/l_{sat})\)

Atom number \((\times 10^8)\)

Temperature (\(\mu K\))
**Optimal parameters**

Temperature limit of this scheme?

- ambient magnetic field bias compensated
- no atomic density dependence observed
- what is the limiting factor?
- role of the off-resonant excitation?

<table>
<thead>
<tr>
<th>duration (ms)</th>
<th>$I_{\text{cool}}/I_{\text{sat}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>capture phase</td>
<td>6</td>
</tr>
<tr>
<td>cooling phase</td>
<td>2</td>
</tr>
</tbody>
</table>

$\delta_{\text{cool}} = \delta_{\text{repump}} = +2.3\Gamma$

$I_{\text{repump}} = I_{\text{cool}}/8$

$T_{\text{final}} \approx 20\, \mu\text{K}$
Loading into a Quadrupole Trap

\[ b' = 76 \, \text{G} \cdot \text{cm}^{-1} \]
\[ N = 2.5 \times 10^8 \]
\[ T = 80 \, \mu\text{K} \]
\[ \text{PSD} \approx 2 \times 10^{-5} \]

<table>
<thead>
<tr>
<th>D\textsubscript{2} molasses [1]</th>
<th>Blue MOT [2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N )</td>
<td>~ \times 10^7</td>
</tr>
<tr>
<td>( T(\mu\text{K}) )</td>
<td>15</td>
</tr>
<tr>
<td>( n_0 (\text{cm}^{-3}) )</td>
<td>~ \times 10^{10}</td>
</tr>
<tr>
<td>PSD (\times 10^{-5})</td>
<td>0.4</td>
</tr>
</tbody>
</table>


DeMarco, B. et al. PRL 82, 4208 (1999)

Good starting point for evaporation

\[ \gamma_{\text{coll}} \approx 23 \, \text{s}^{-1} \]
Future Steps

- Test the improvement on transport efficiency to the science cell
- Evaporation in a hybrid trap
- Loading into a 1D optical lattice
- Study of a system with mixed dimensions

Lin, Y.-J. et al. PRA **79**, 063631 (2009)

Nishida, Y. PRA **82**, 011605(R) (2010)
**D_1 molasses for Lithium isotopes**
(preliminary results)

**6Li**

**7Li**

Vertical lin ⊥ lin 1D gray molasses

- no molasses
- with molasses

TOF = 2 ms

T_\text{vert} = 1 \text{ mK}

T_\text{vert} = 60 \text{ \mu K}

Thanks to Ulrich E. and Andrea B. for powerful laser source
Thanks for listening

arXiv:1210.1310 [cond-mat.quant-gas]