# Zeeman-Sisyphus deceleration of CaF molecules

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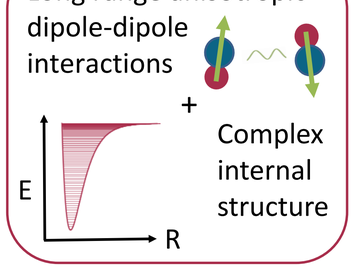
## Motivation

**Molecular properties** + **Ultracold temperatures** → **Potential applications**

Long range anisotropic dipole-dipole interactions + Complex internal structure




Extend observation times +

Greater control of quantum state

Platform for quantum simulation of many body Hamiltonians [1]

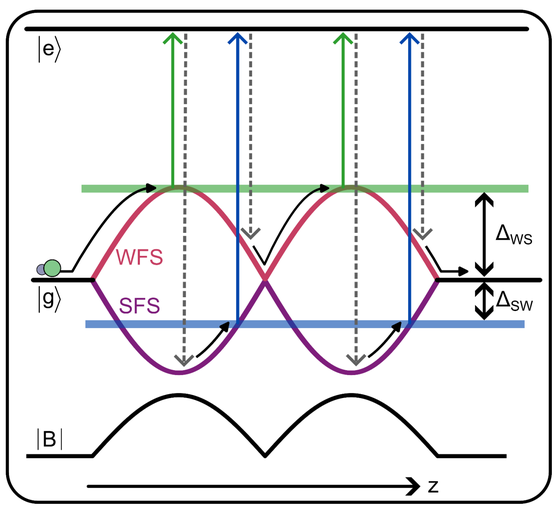
Precise tests of fundamental physics [2]

Examine role of quantum effects in chemical reactions [3]

**Direct laser cooling** is proving to be a successful technique for producing cold molecules

## Theory

Molecules pass through a spatially varying magnetic field. They are optically pumped into a **weak field seeking (WFS) state** in a **region of high B field** and a **strong field seeking (SFS) state** in a region of low B field → Molecules continually climb up the potential hill.




**Requirements:**

- A ground state split into wfs and sfs manifold.
- Excited state with negligible Zeeman splitting.

Energy lost per stage: $\Delta E_{\text{stage}} \sim 2\mu_B B_{\max}$

Average deceleration force: $F = \frac{h(\Delta_{ws}-\Delta_{sw})}{L}$

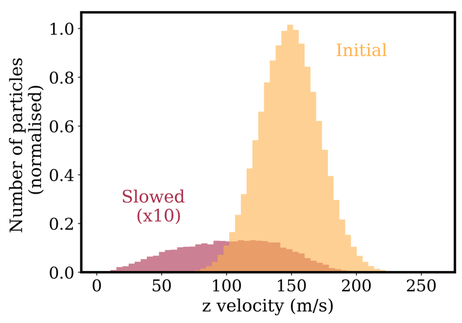
For maximum deceleration, $\Delta_{sw} = 0$. However, this would prevent optical pumping. $\Delta_{sw} \neq 0$ also increases the transverse acceptance of the decelerator.

The ZS decelerator was first proposed in [5] and the concept has been subsequently demonstrated using superconducting magnetic coils [6,7]

## Simulation results

Simulations done by Bethan Humphreys based on code by James Crilly, supervised by Dr David Carty and Dr Hannah Williams

Simulated using a million molecules into decelerator, $\Delta_{sw}$ = -2.5 GHz, $\Delta_{ws}$= 17 GHz




Reduction in mean forward velocity to **102 m/s**

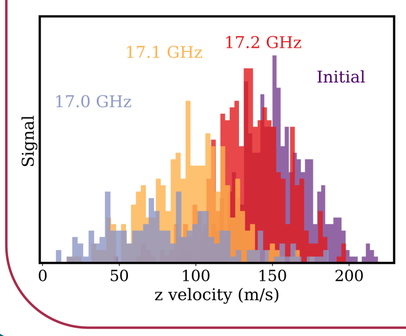
**0.28%** of the million molecules entering the decelerator are decelerated **below 50 m/s**

**For a pulse of $10^{11}$ molecules from the source, expect ~ $10^6$ out from the decelerator below 50m/s**

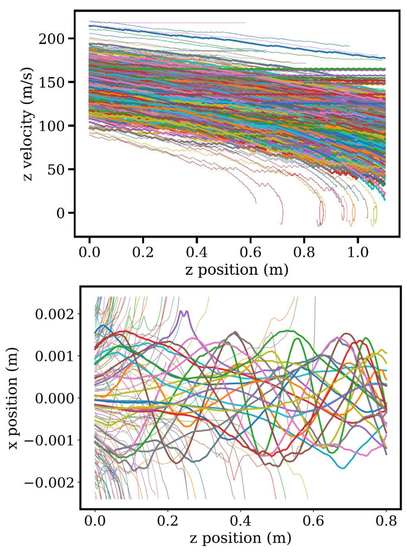
**Impact of $\Delta_{ws}$**

17 GHz chosen to maximise output at the slow tail

Detune above this: slower molecules never come into resonance and are not decelerated



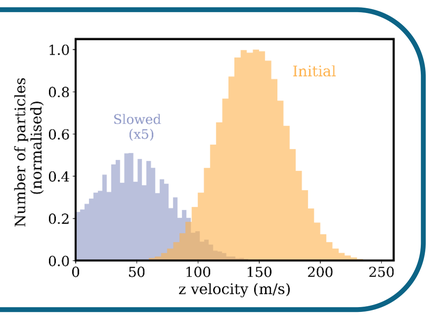

Below this: now on resonance with slower molecules, which come to rest before exiting




## Zeeman-Sisyphus deceleration for CaH

This simulation used a 1.8m long decelerator, with $B_{\max}$ = 1 T, molecular constants from [10, 11]

- Reduction in mean forward velocity from **145** to **51 m/s**
- **6%** of the million molecules slowed **below 50 m/s**
- Reduction in mean forward velocity from **145** to **51 m/s**




## References

[1] Blackmore J.A., et al. *Quant. Sci. And Tech.* **4** 1 (2018)
[2] DeMille D., et al. *Science* **357** 990 (2017)
[3] Krems R.V. *Phys. Chem. Chem. Phys.* **10** (2008)
[4] Xu S., et al. *New J. Phys.* **23** 063062 (2021)
[5] Fitch N.J. et al. *ChemPhysChem* **17** 22 (2016)
[6] Augenbraun B.L. et al. *Phys. Rev. Lett.* **127** 263002 (2021)
[7] Sawaoka H. et al. *Phys. Rev. A* **107** 022810 (2023)
[8] Truppe S. et. al. New J. Phys. **19** 022001 (2017)
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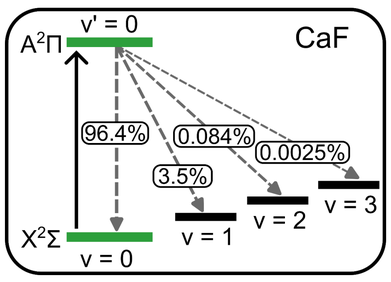
[11] Frum C.I. et al. *Astrophys. J.* **408** (1993)

## Why Zeeman-Sisyphus?

For closed rotational transitions, diatomic molecules require a type II MOT ($N \geq N'$) → **weaker trapping forces** and **lower MOT capture velocities,** ~24 m/s for CaF [4].

CaF are made in a cryogenic buffer gas source. Molecules exit the source at ~150 m/s, so must be slowed. Molecules can be slowed using chirped laser slowing [8].

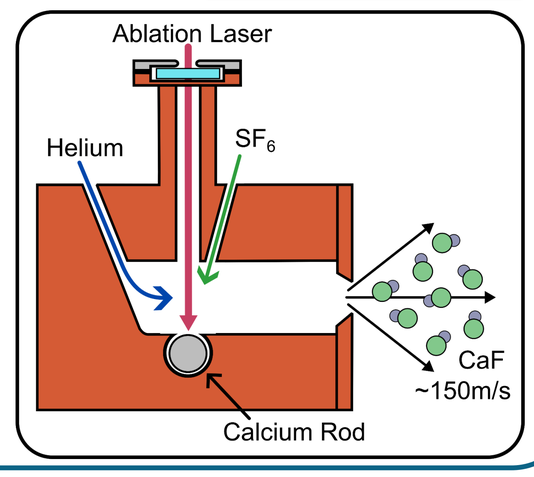



### Challenges

- Laser slowing requires ~$10^4$ photon scatters → decay out of cooling cycle
- Range of transverse velocities from source → loss from pluming
- Time dependent methods → only address portions of pulses

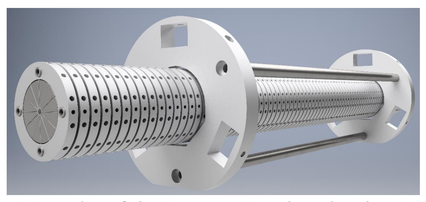
### Zeeman-Sisyphus

- Requires fewer photons
- Incorporates transverse guiding
- Time independent




## Decelerator Design for CaF

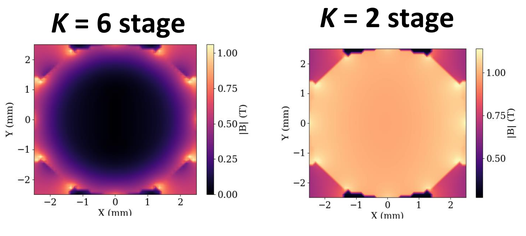
To generate the spatially varying magnetic field, we use **80 permanent magnet stages.**

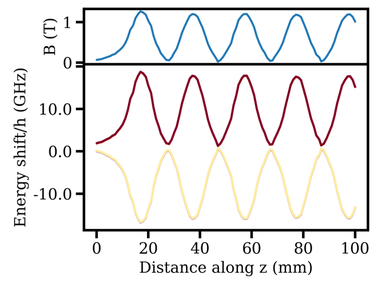


3D render of the Zeeman-Sisyphus decelerator

The magnetic field landscape is created using approximate Halbach cylinders made up of N52 NdFeB wedge magnets with residual magnetisation 1.44T

***K* = 2 stages** generate a transversely uniform high magnetic field regions.
***K* = 6 stages** are interleaved with ***K* = 2** stages to create zero field regions and provide transverse guiding.




Measured B field in decelerator and calculated splitting of $X^2\Sigma^+$state

Electronic ground state, $X^2\Sigma^+$ ($v = 0, N = 1$), has ~28 GHz/T splitting between SFS and WFS.
First electronic excited state, $A^2\Pi_{1/2}$ ($v = 0, J = 1/2$), has ~0.6 GHz/T splitting.

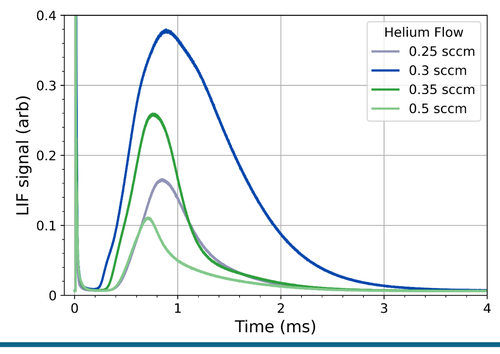
For CaF, with $B_{\max} \sim 1\ T$, $\Delta E_{\text{stage}} \sim h \times 28\ GHz$

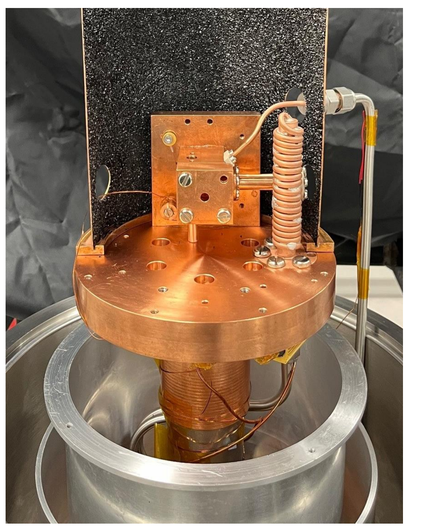
Requires at least **60 deceleration stages** to bring molecules down from 150 m/s to $v_{\text{capture}} \sim 24$ m/s.

Only scatters ~ $10^2$ **photons** in this process, much fewer than the $10^4$ required for traditional laser slowing → promising for molecules with poor branching ratios

## Experimental Progress

We have built a buffer gas source for CaF and have seen our first molecular signal.
Currently characterising and improving the source, then will assemble the decelerator.



## Frequency control

Need two frequencies for the optical pumping 19.5GHz apart at 606.1nm, each with ~250mW power, without any intermediate frequencies

Achievable with a 9.5GHz electro-optical modulator (Qubig).

However, the EOM's frequency can only be adjusted ±50MHz.
Add in AOM(s) operating at 250MHz and/or 110MHz to give finer frequency control.