Towards a measurement of the electron's electric dipole moment with trapped YbF molecules

Stefan Popa[1], Andrew D. White[1], Jorge Mellado−Muñoz[2], **Guanchen Peng**[1], Simeng Li[1],

Horacio Septien−Gonzalez[1], Michail Athanasakis−Kaklamanakis[1], Jongseok Lim[1], Ben E. Sauer[1] and Michael R. Tarbutt[1]

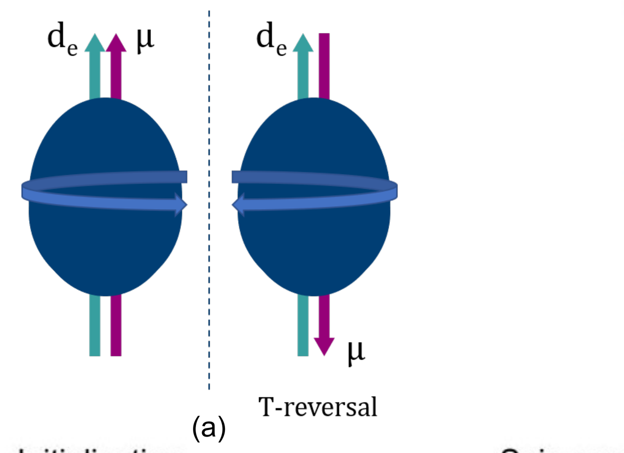
[1]Imperial College London, London, United Kingdom. [2]Istituto Nazionale di Ottica, Firenze FI, Italy

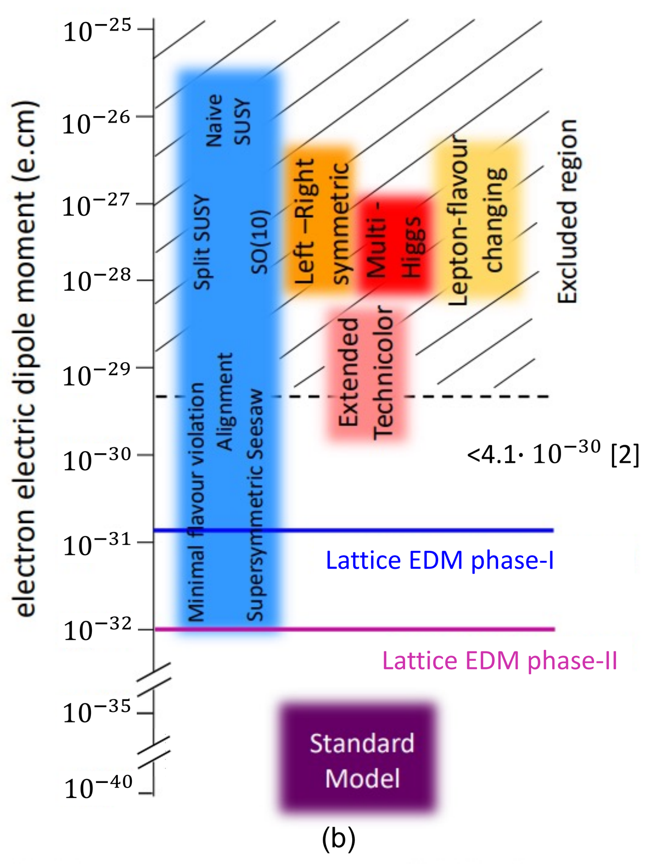
Imperial College London

Introduction

The Standard Model is unable to account for the observed asymmetry of anti-matter to matter.

An **electron** having an **electric dipole moment** (eEDM) violates the time-reversal symmetry can probe predictions from theories beyond the Standard Model [1].





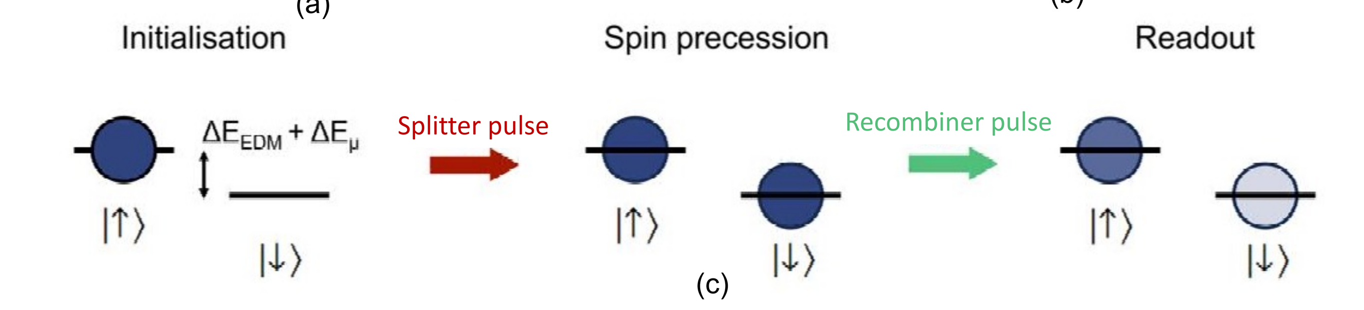
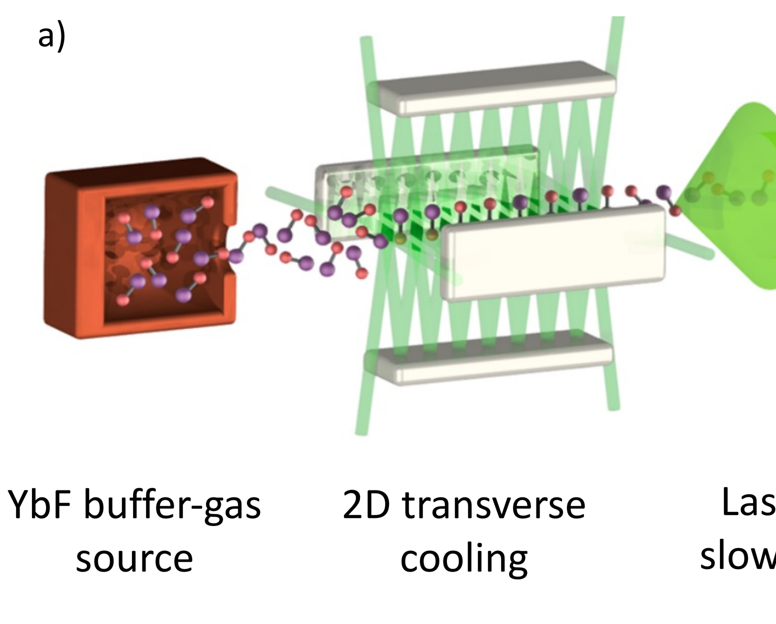


Figure 1: The electron's electric dipole moment. (a) The violation of the T-reversal symmetry for an electron that has an electric dipole moment (eEDM). (b) Current experiment constrains on eEDM, and its predictions from various models. (c) A Ramsey interferometer to measure the eEDM.

Method

YbF molecules are produced, laser cooled, then **slowed** before being captured in a **magneto-optical trap** (MOT). The molecules can then be transferred to an **optical lattice** for an **eEDM measurement** [3].



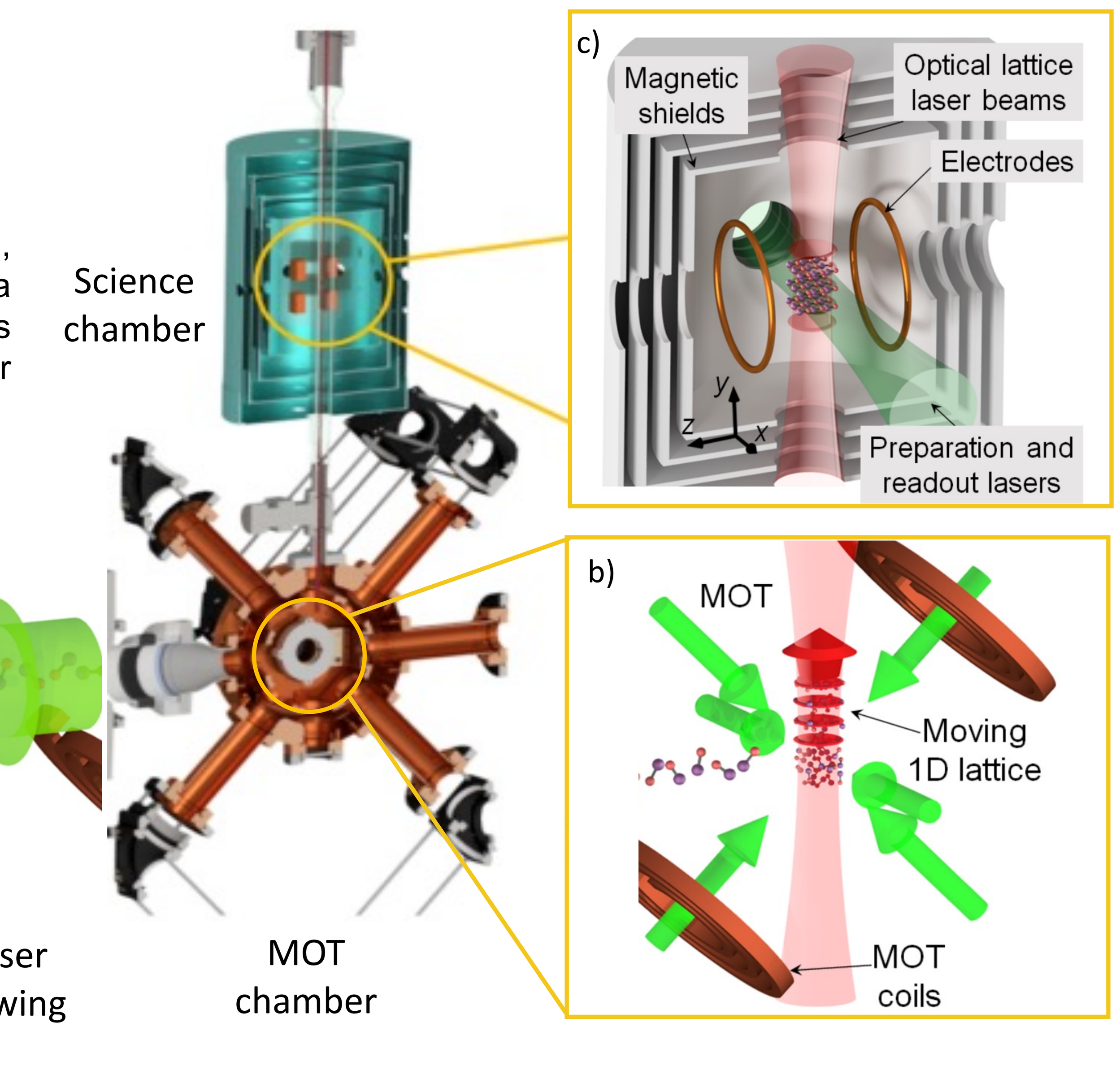
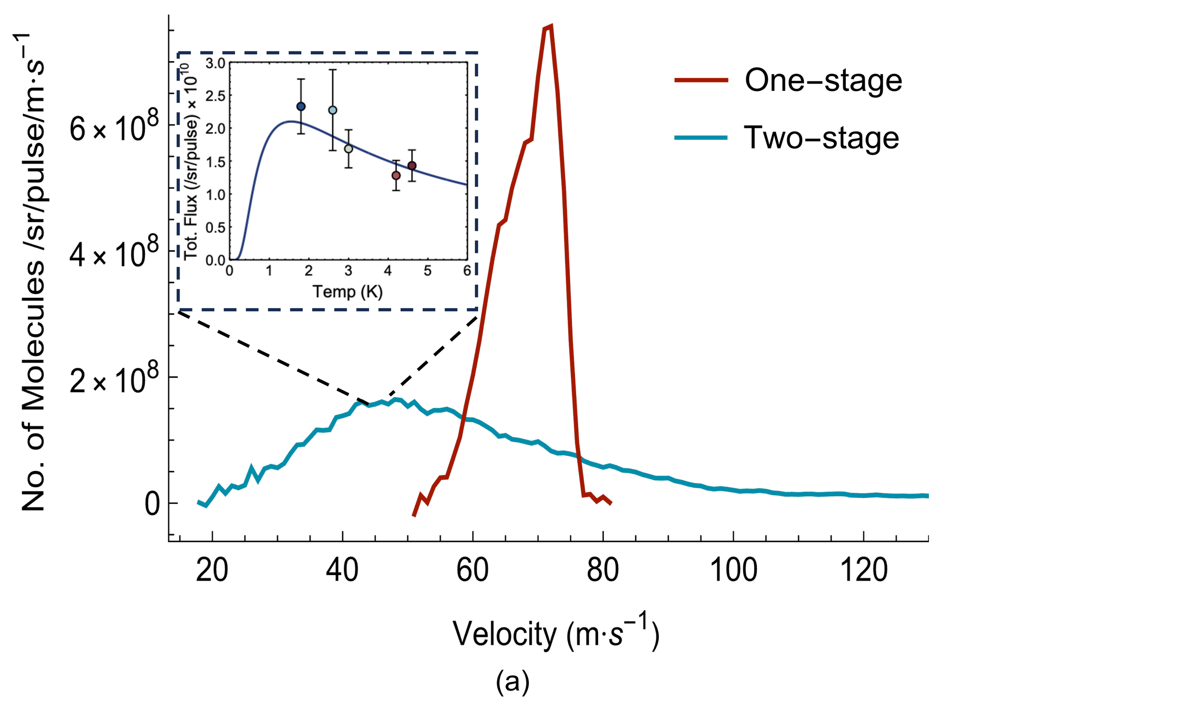


Figure 2: A schematic of the proposed experiment. (a) YbF molecules are produced, laser cooled, then **slowed** before being captured in a **magneto-optical trap** (MOT). (b) Loading molecules from a MOT to an optical lattice. (c) The design of the science chamber for the eEDM measurement.

Result: A source of slower molecules

YbF is made by laser ablation of ytterbium (Yb) in the presence of sulphur hexafluoride (SF_6) inside a **two-stage** cell based on the design in [4]. Compared to a **4 K** cooled cell producing molecular beams with a forward velocity of **~150m/s**, our cell [5] cooled to **1.8 K** produces

- One-stage produces **4 · 10¹⁰** molecules per pulse per steradian at a peak velocity of **72 m·s⁻¹**.
- Two-stages produces **1.5 · 10¹⁰** molecules per pulse per steradian at a peak velocity of **49 m·s⁻¹**.



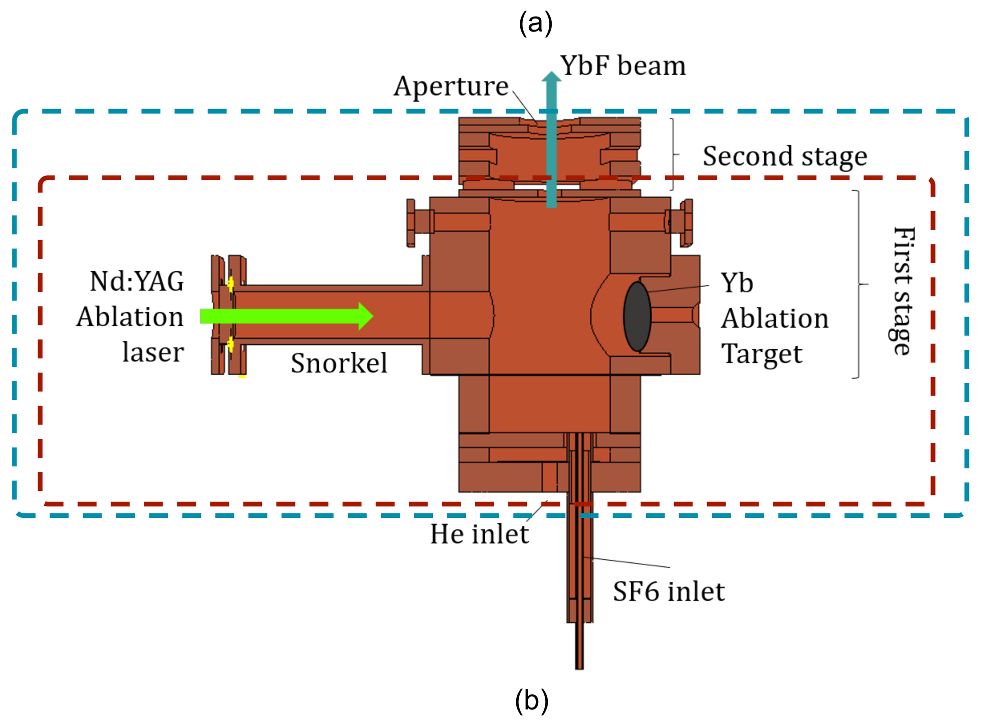


Figure 3: The cryogenic buffer gas cell and its charaterisation. (a) The velocity distribution of our molecular beam. (b) A schematics of the design we use to produce our slow molecular beam.

Result: Radiation pressure slowing – preliminary and limitation

The main slowing laser (552 nm) plus two vibrational repumps (568 nm & 565 nm) was used to slow the molecular beam. We observed **56% loss of molecule** after slowing the forward velocity by ≈**5 m/s** after scattering ≈ 10^3 photons.

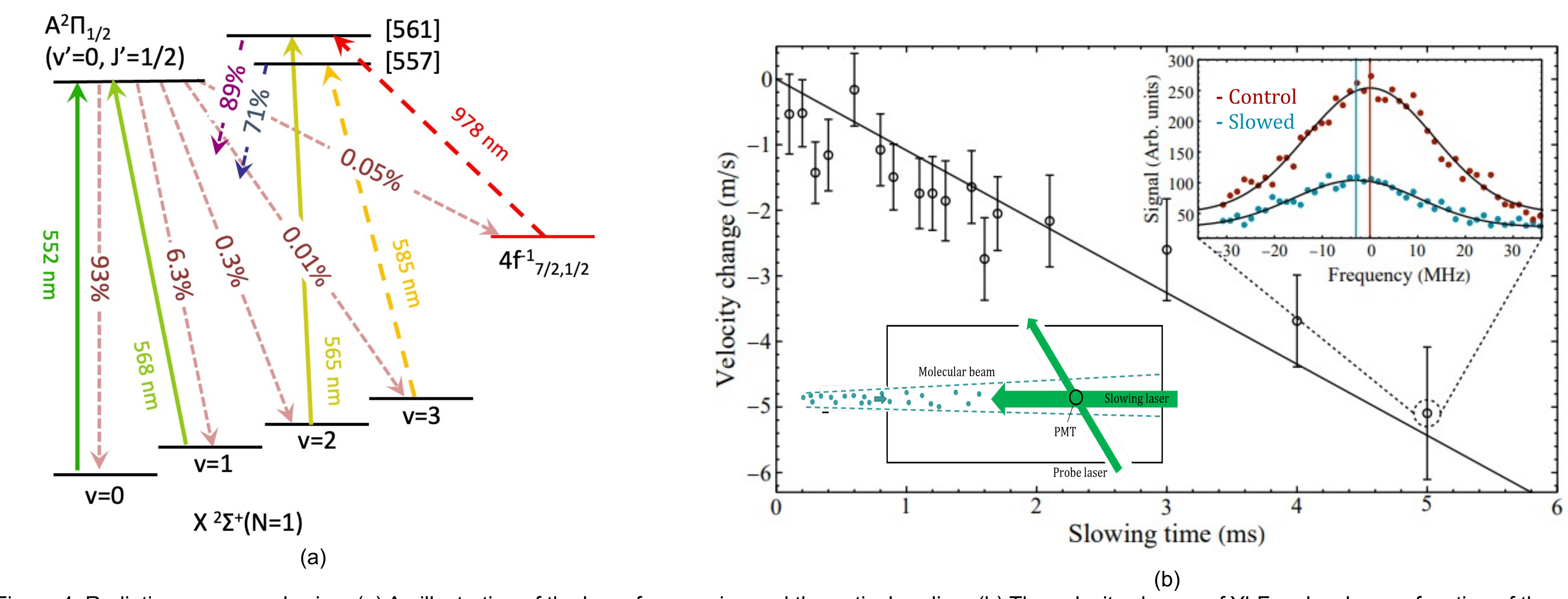
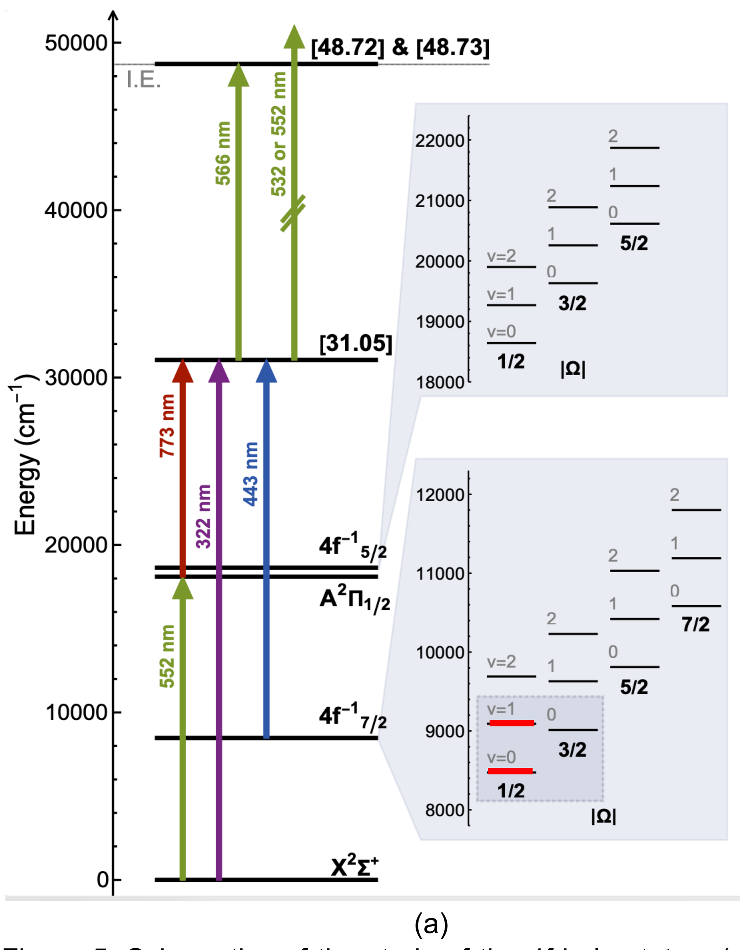


Figure 4: Radiation pressure slowing. (a) An illustration of the laser frequencies and the optical cycling. (b) The velocity change of YbF molecule as a function of the slowing time.

Leaking to 4f states can explain our observation of **the loss of molecule** after scattering ~10^4 photons. Thus, we used a two-photon resonantly enhanced ionisation to study the 4f hole states [6].



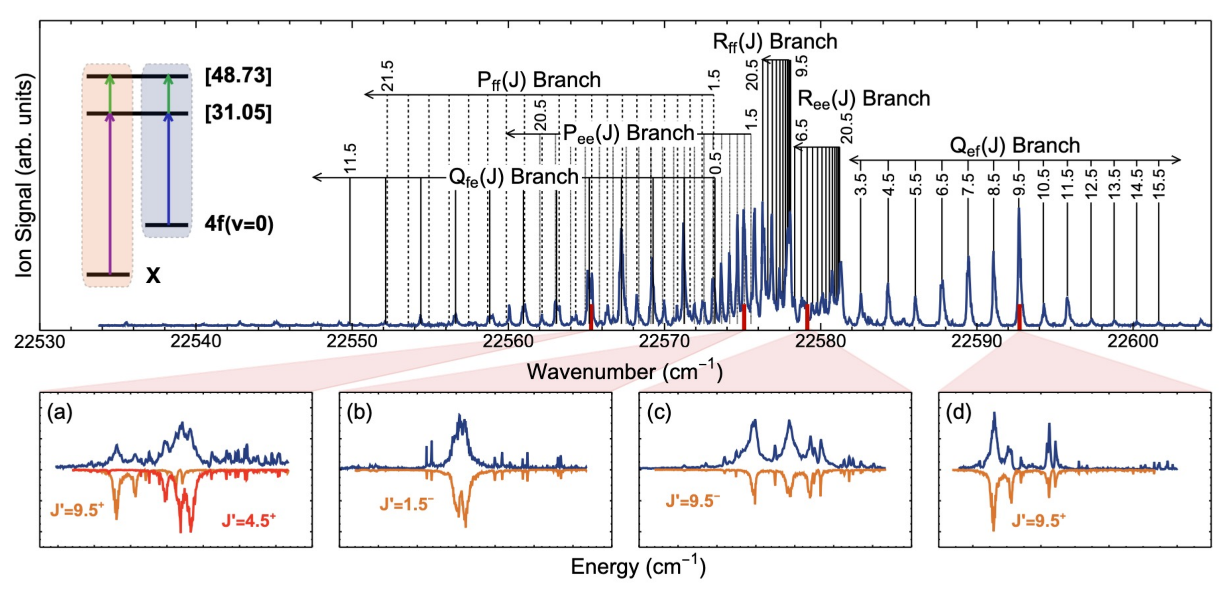


Figure 5: Schematics of the study of the 4f-hole states. (a) Various lasers and energy levels used to characterize the 4f-hole states. (b) The spectroscopic study of the states of v=0 of the 4f-hole states.

*This spectroscopy was performed at the Fritz Haber Institute in collaboration with the group of Gerard Meijer.

Result: simulation of a Magneto-optical trap

Once laser slowing is achieved, we need to capture the molecules in **a magneto-optical trap** (MOT). To avoid Zeeman dark state, transitions are addressed by two frequency components of opposite handedness and detuning to restore a confining force.

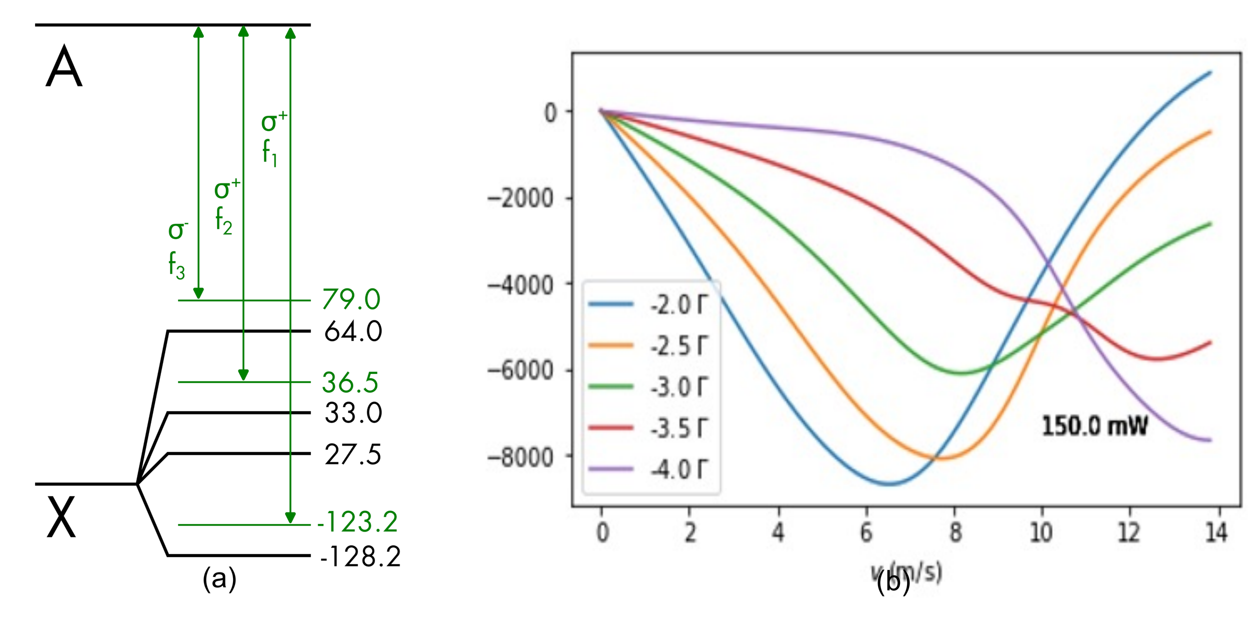


Figure 6: Simulation of a YbF MOT. (a) The cooling transitions and the laser frequencies used in the simulation. (b) The confining force as a function of the velocity of molecules for various laser detuning.

Summary and Outlook

We have

- developed a slow source of YbF to produce velocity distribution peaks at **49 m·s⁻¹**.
- studied 4f-holde states that can potentially be responsible for the loss of **56%** loss molecules after being slowed ≈**5 m/s** after scattering ≈ 10^3 photons.
- simulated a magneto-optical trap (MOT) of YbF molecules, which has a capture velocity of ≈ **10 m/s.**

We need to

- ☐ remain the most of the molecules in the cooling cycle by adding repump lasers for 4f state and v3.
- ☐ slow them further by implementing a frequency chirp to follow the changing Doppler shift as the molecules decelerate.
- ☐ make a MOT and load molecules into an optical lattice after cooling them to ~**10 μK** with a blue-detuned grey molasses.

Reference

[1] M. Pospelov and A. Ritz. CKM benchmarks for electron electric dipole moment experiments. *Phys. Rev. D*, 89:056006, 2014.

[2] Tanya S. Roussy et al. An improved bound on the electron's electric dipole moment. Science Vol. 381, No. 6653, 2023.

[3] N. J. Fitch, et al. Methods for measuring the electron's electric dipole moment using ultracold YbF molecules. *Quantum Sci. Technol.*, 6:014006, 2020.

[4] H.I.Lu et al. A cold and slow molecular beam. *Phys. Chem. Chem. Phys.*, 13, 18986-18990, 2011.

[5] A. D. White et al. In preparation.

[6] S. Popa et al. Understanding inner-shell excitations in molecules through spectroscopy of the 4f hole states of YbF. *PRX* 14, 021035, 2024

EPSRC · Science & Technology Facilities Council · Gordon and Betty Moore Foundation · Alfred P. Sloan Foundation