



Electric Dipole moment Measurements using Molecules in a Matrix (EDM³)

Eric Hessels

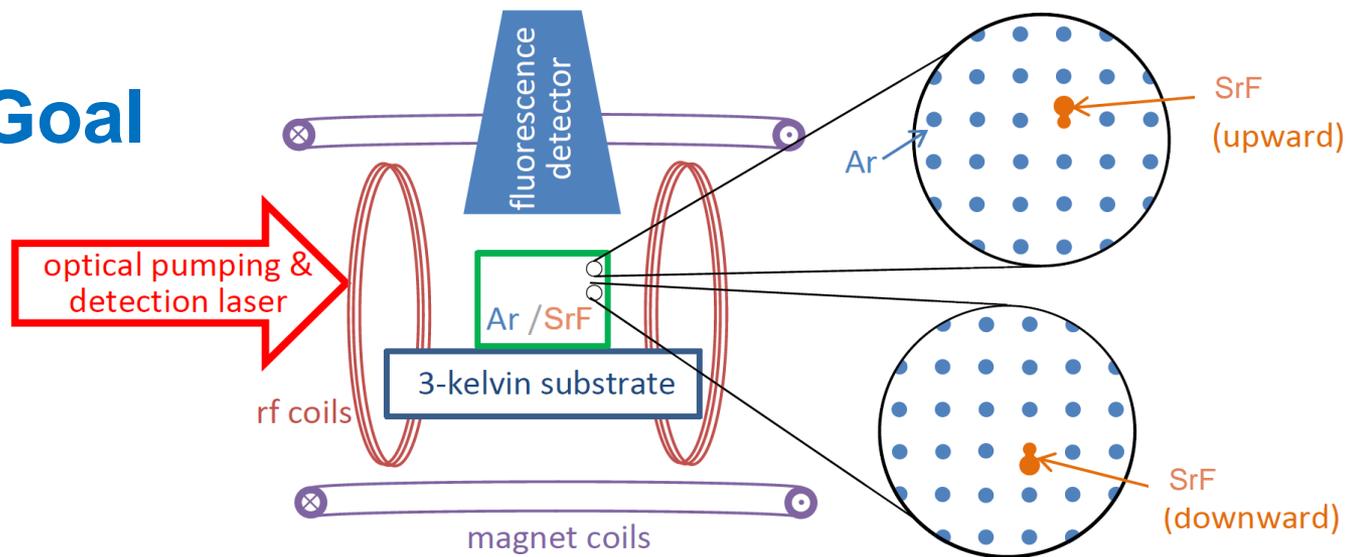


York University
Toronto Canada

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Ontario Research Fund
NSERC Subatomic Project Grants
York University



Our Goal



EDM³ aims to make electron electric dipole moment (d_e) measurements using SrF molecules embedded in cryogenic solid argon

Use a large number of (~ 1 ppb SrF:Ar, $\sim 1\text{mm}^3$, $\sim 10^{11}$ SrF)

Molecular orientation fixed by matrix – no need for external E field

Systematic effects for d_e measurement are expected to be favorable:
small volume, cold, stationary, simultaneous measurements on interspersed molecules of opposite orientation – acts as excellent co-magnetometer

Has the potential to improve d_e measurements by orders of magnitude



Some Numbers – *potential* precision

The statistically accuracy of d_e is limited to: $\delta d_e = \frac{\hbar}{2 E_{\text{eff}} \sqrt{N} T}$

A total (integrated) N electrons that precess for a time T

E_{eff} is the effective field in the polar molecule, $< \sim 100 \text{ GV/cm}$ for polar molecules of interest -- need large N and T

Current limit: JILA (HfF^+): $|d_e| < 4.1 \times 10^{-30} \text{ e cm}$ $N \sim 10^8$; $T \sim 1 \text{ s}$

ACME (ThO): $|d_e| < 11 \times 10^{-30} \text{ e cm}$ $N \sim 10^{12}$; $T \sim 1 \text{ ms}$

We are using SrF: $E_{\text{eff}} = 2.16 \text{ GV/cm}$

10^{11} SrF used 10^8 times (every 30 ms for 1 month): N of up to 10^{19}

Precession time of $T = 10 \text{ ms}$, could lead to $\delta d_e < 10^{-32} \text{ e cm}$

Potential for a very precise measurement

Even higher precision imaginable for larger numbers of molecules, a molecule with higher E_{eff} and more months of data collection

Can dream of limits as low as 10^{-35} e cm (SM prediction)



Motivation (why measure an electron EDM?)

Test physics beyond the Standard Model

Most extension to the SM predict a $d_e \gg 10^{-35}$ ecm (due to CP violation needed to explain matter/antimatter asymmetry)

More precise measurement of d_e would guide SM extensions

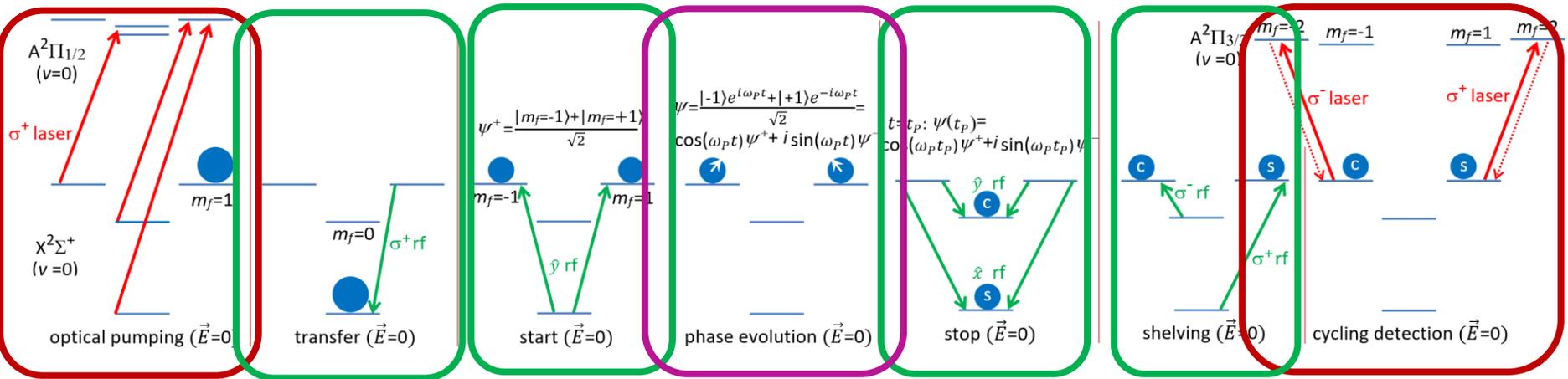
Current limit on d_e already tests physics at >10 -TeV level

A 10^3 improvement would test physics at 30 times higher energies – approaching PeV energies



Measurement Scheme

Similar to other d_e measurements – except with molecules frozen into an argon solid



Use lasers to optically pump molecules into one hyperfine state and to detect with laser-induced fluorescence

Use rf to transfer populations between hyperfine states

Allows for measurement of precession from electric and magnetic dipole moments. Interspersed molecules of opposite orientation and field reversal separate electric and magnetic effects



What Has Been Accomplished to Date?

Assembled a team



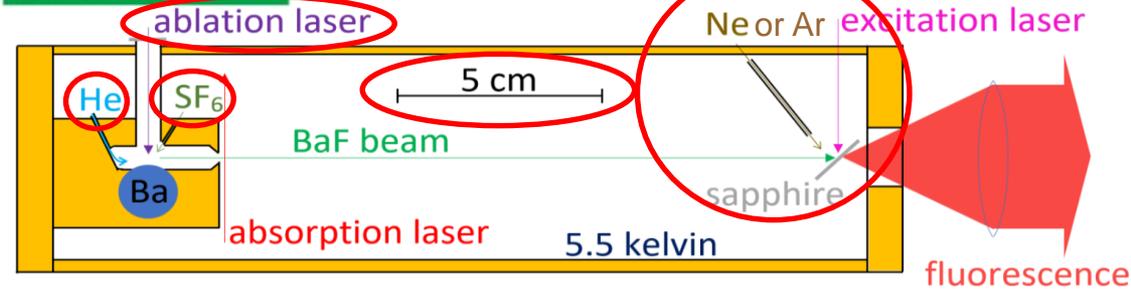
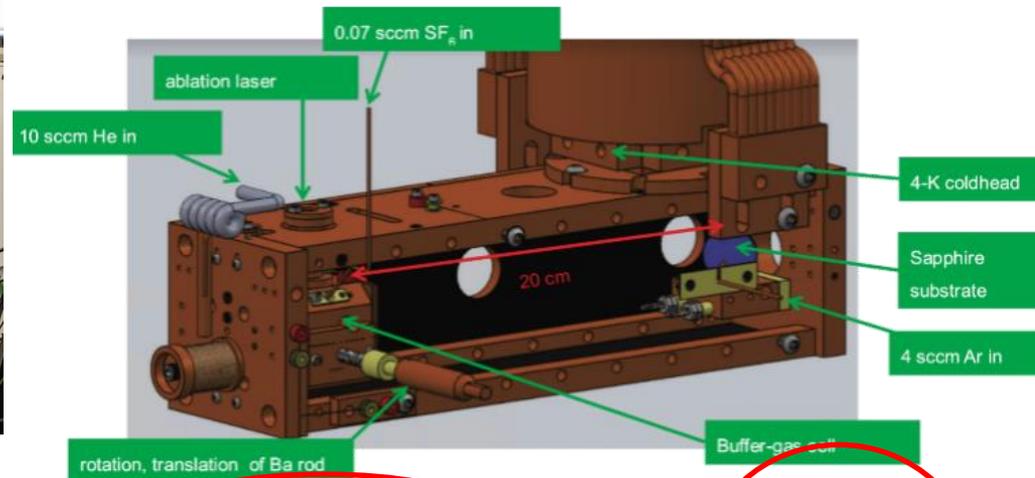
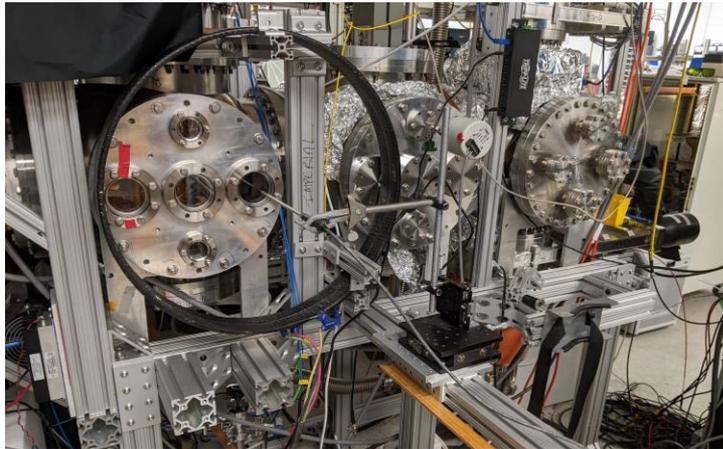
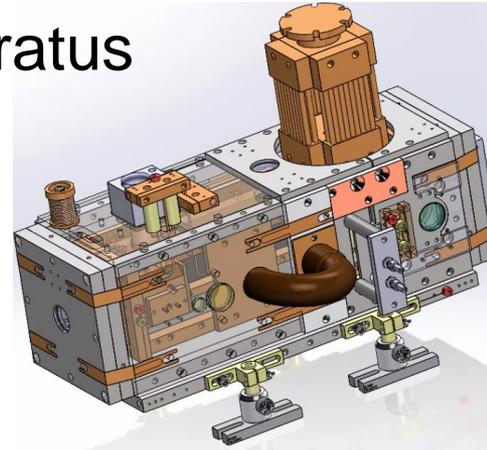
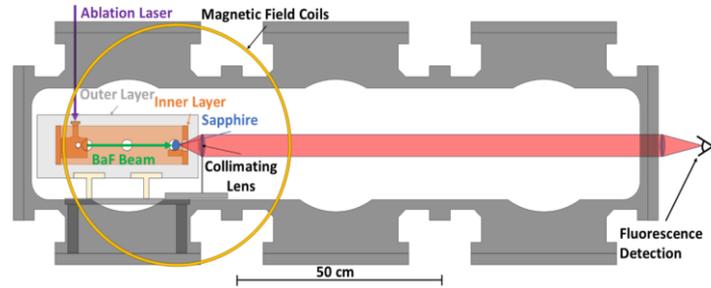
Physics/Chemistry
Experiment and Theory

Extensive sharing of ideas/designs with groups of
Jaideep Singh (FRIB)
Amar Vutha (University of Toronto)
Michael Tarbutt (Imperial College)
Jonathan Weinstein (University of Nevada, Reno)
and others



What Has Been Accomplished to Date?

Assembled 1st generation apparatus

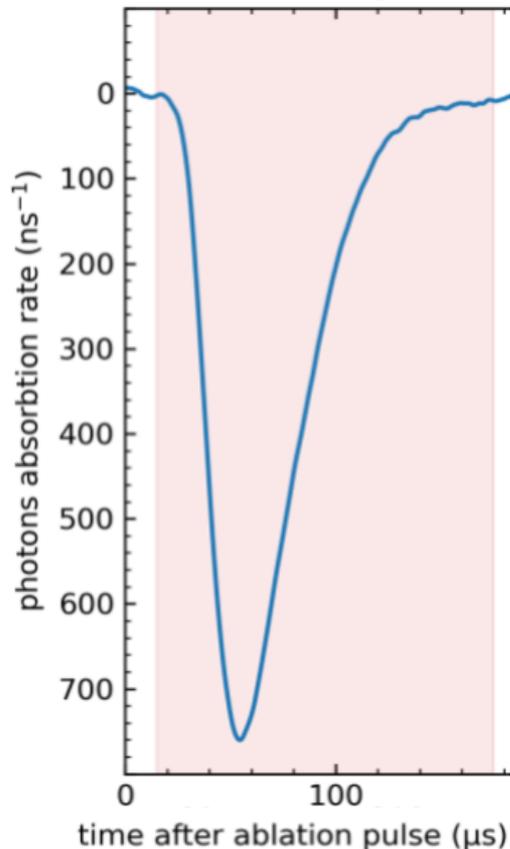


What Has Been Accomplished to Date?

Assembled cryogenic solids with 1ppb BaF (and now SrF)

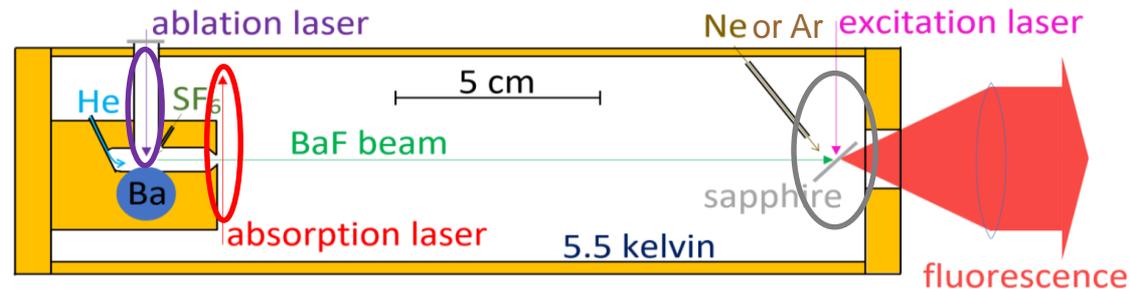
Matrix isolated barium monofluoride: Assembling a sample of BaF molecules for a measurement of the electron electric dipole moment

Z. Corriveau, R.L. Lambo, D. Heinrich, J. Perez Garcia, N.T. McCall, H.-M. Yau, T. Chauhan, G.K. Koyanagi, A. Marsman, M.C. George, C.H. Storry, M. Horbatsch, and E.A. Hessels*
Department of Physics and Astronomy, York University, Toronto, Ontario M3J 1P3, Canada
(Dated: October 8, 2024)



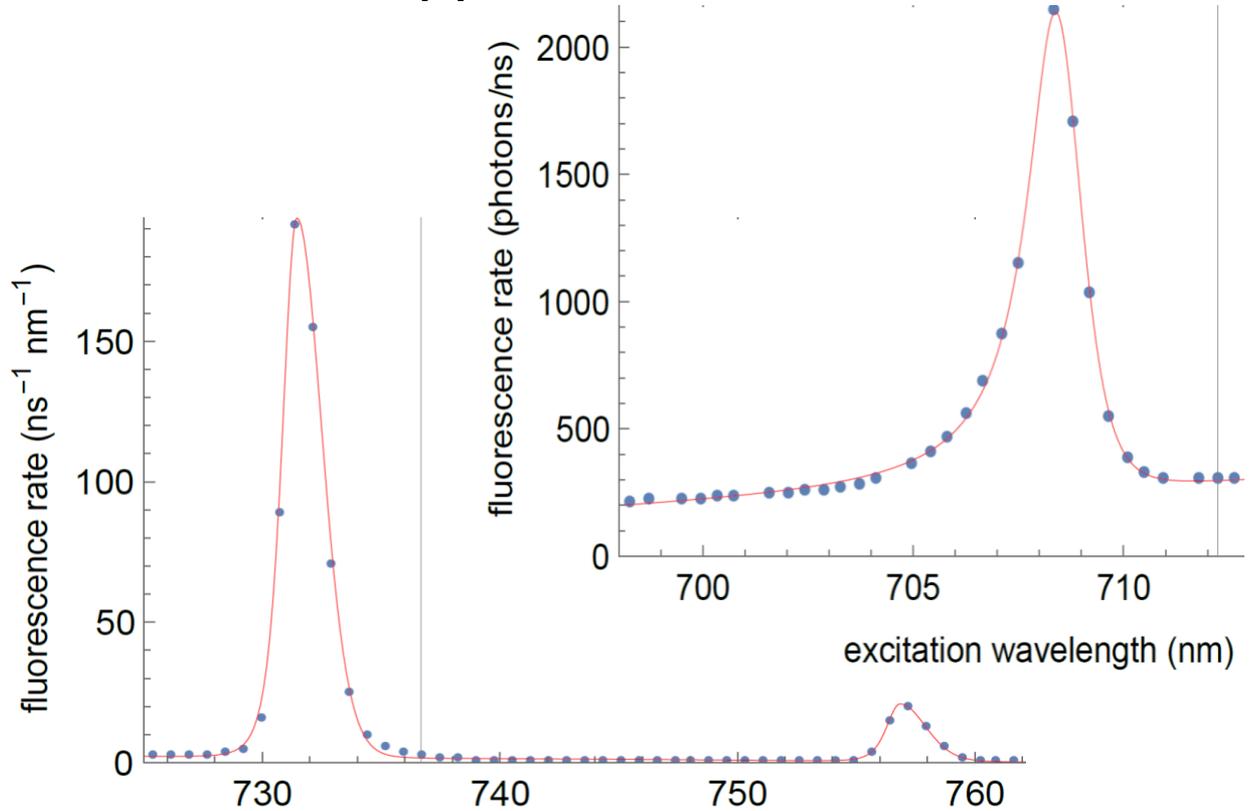
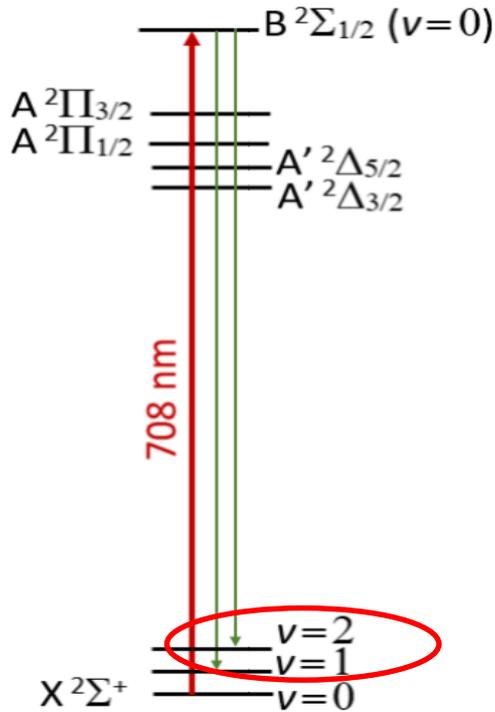
Intense beam of BaF molecules

$5 \times 10^{10}/\text{mm}^3$ at the substrate 20 cm downstream from 20 000 ablation pulses (1 hour)

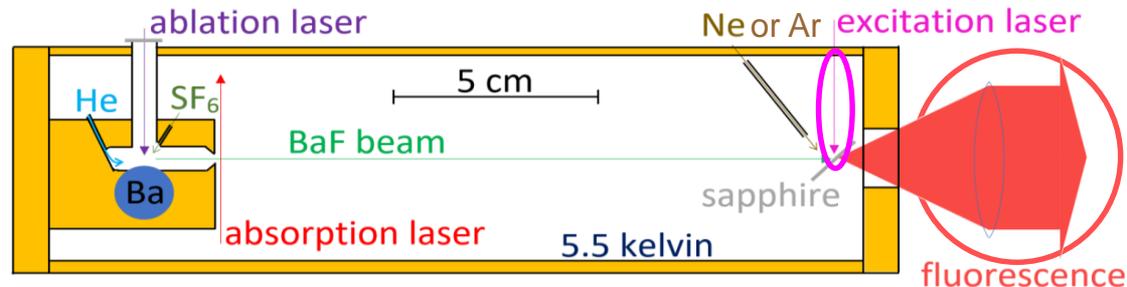


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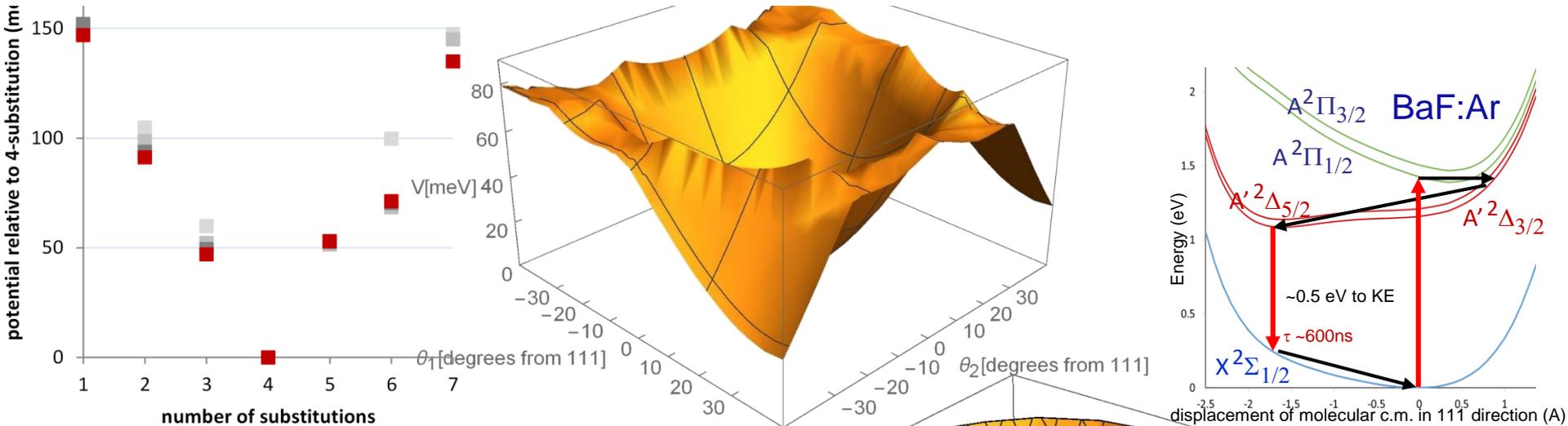


$>10^{10}$ BaF embedded/ mm^3
 large fraction of beam
 frozen into inert-gas solid

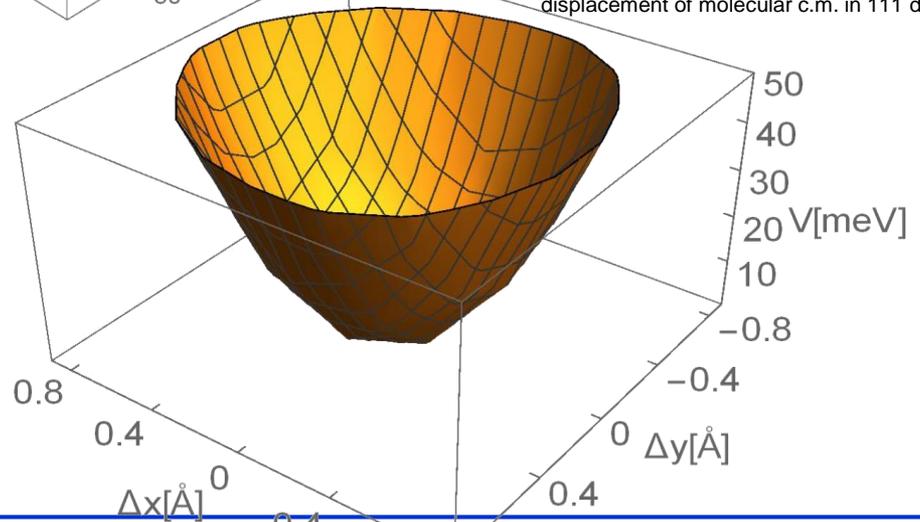
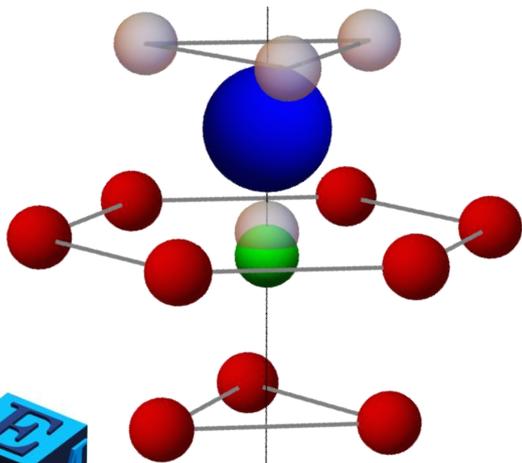


What Has Been Accomplished to Date?

Large theoretical efforts: BaF (and SrF) substitutes for 4 Ar atoms, is oriented along the Ar crystal's 111 axis, is strongly restrained from rotating or migrating, and fluoresces further into the infrared

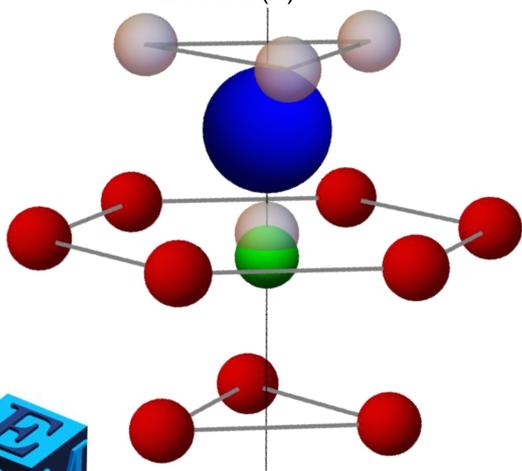
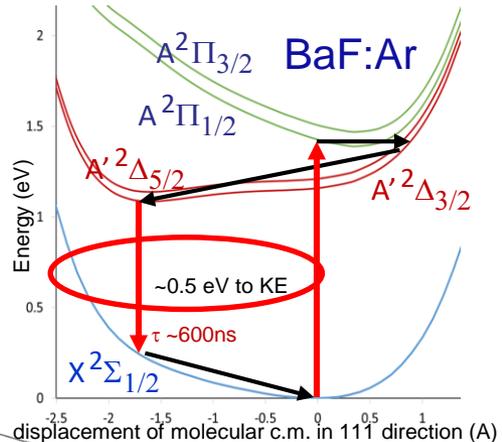
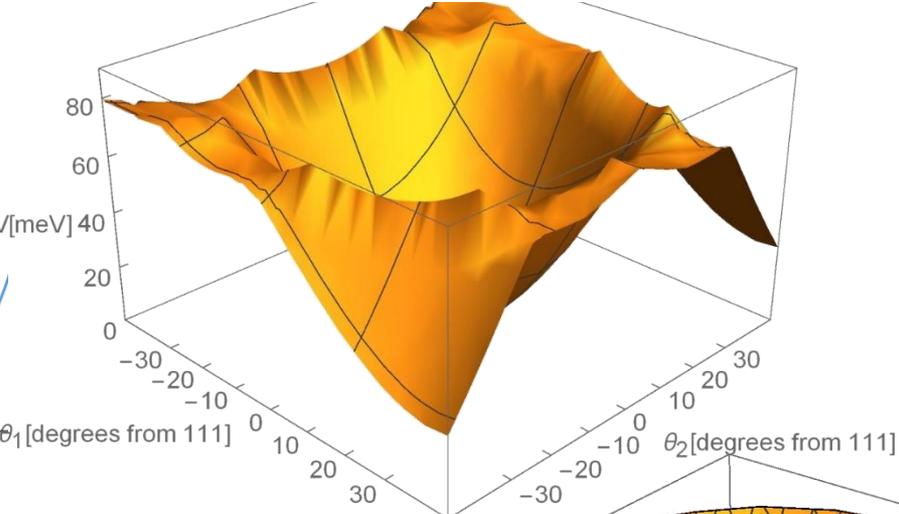
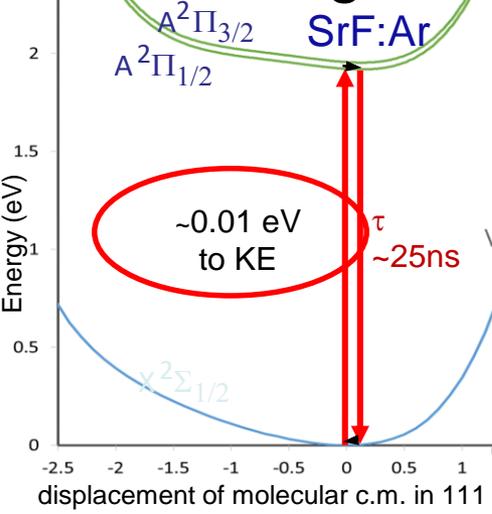


1000x
thermal
energy
at 1K

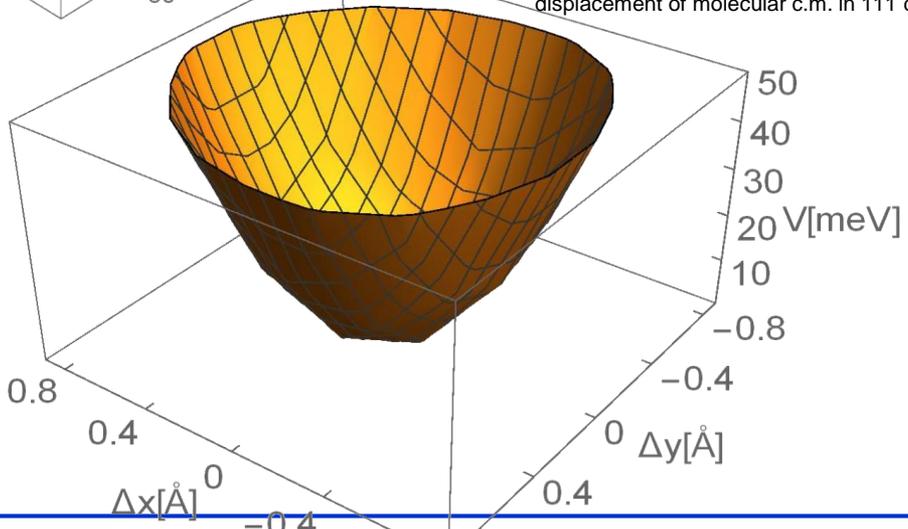


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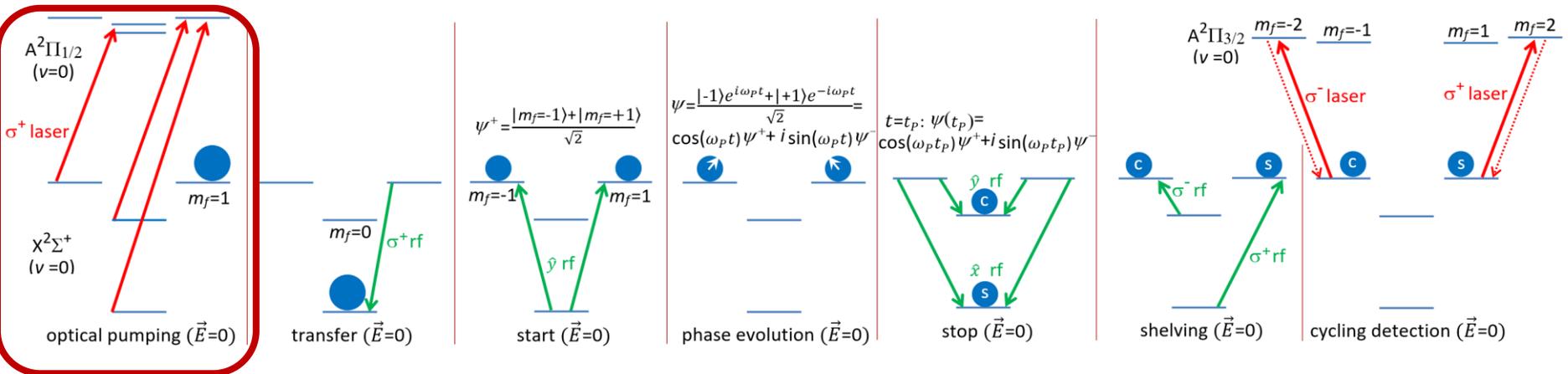
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1000x thermal energy at 1K



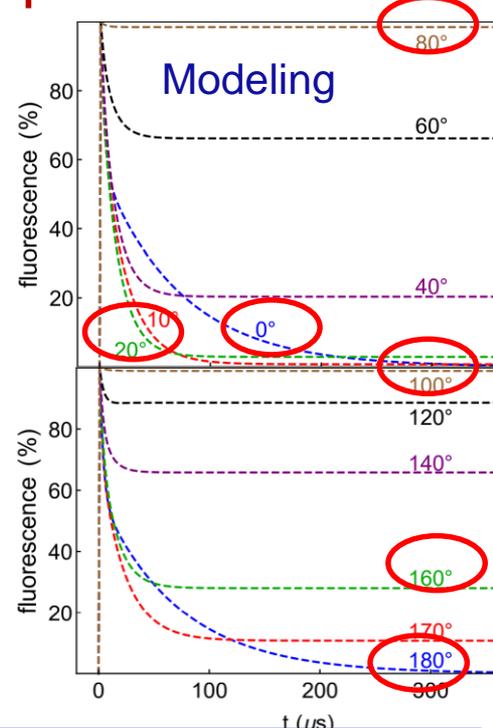
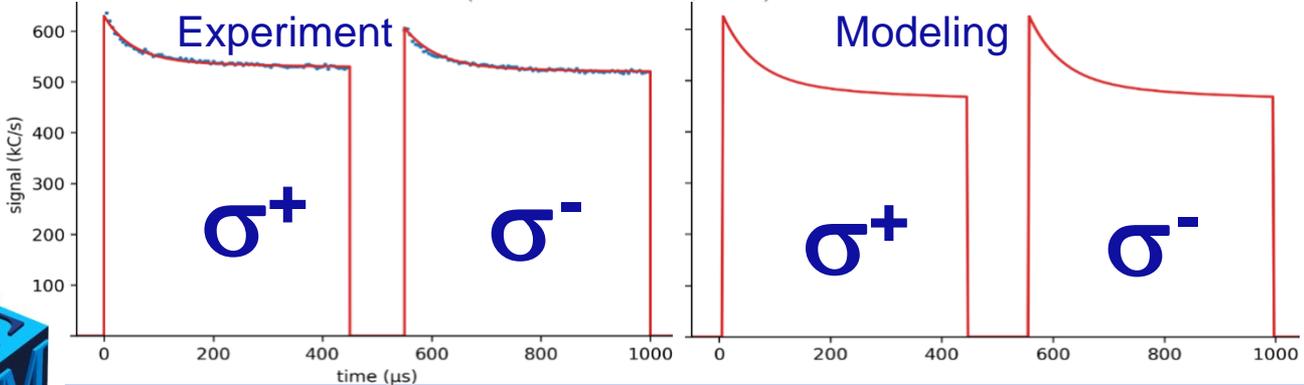
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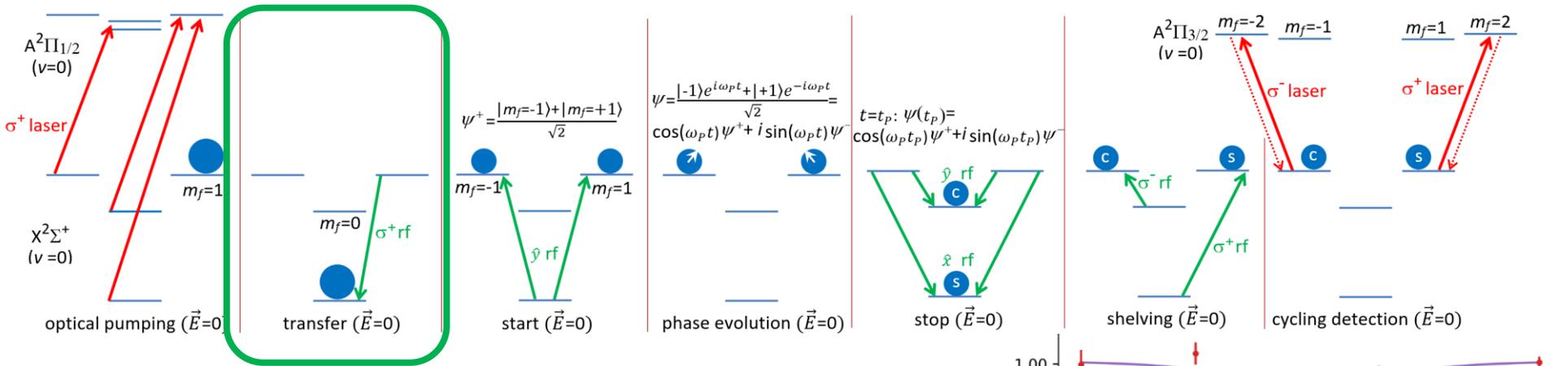
Efficient optical pumping demonstrated; Bonus: depends on BaF orientation – useful for eEDM measurement

Optical pumping of matrix-isolated barium monofluoride: dependence on the orientation of the BaF molecular axis

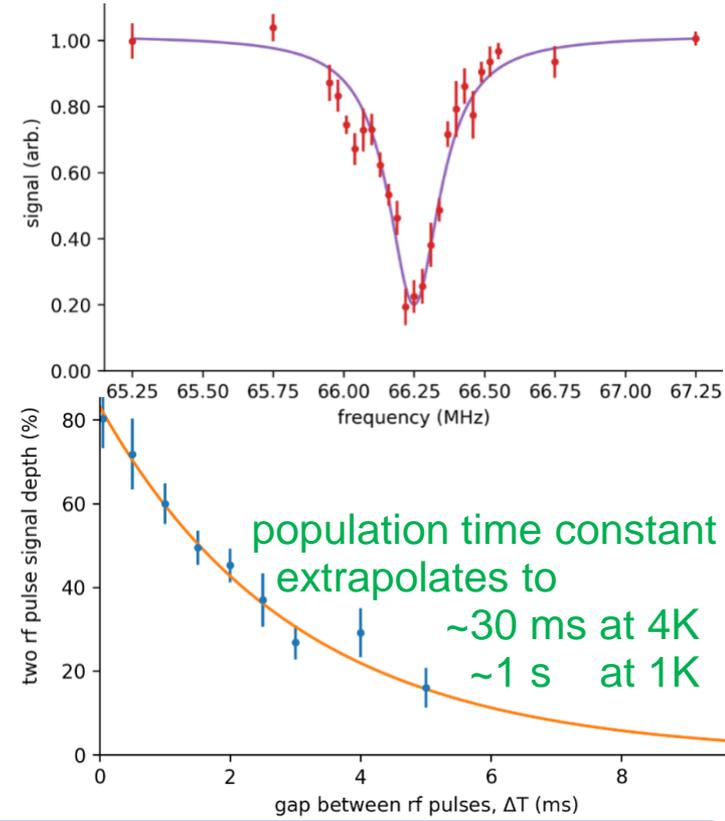
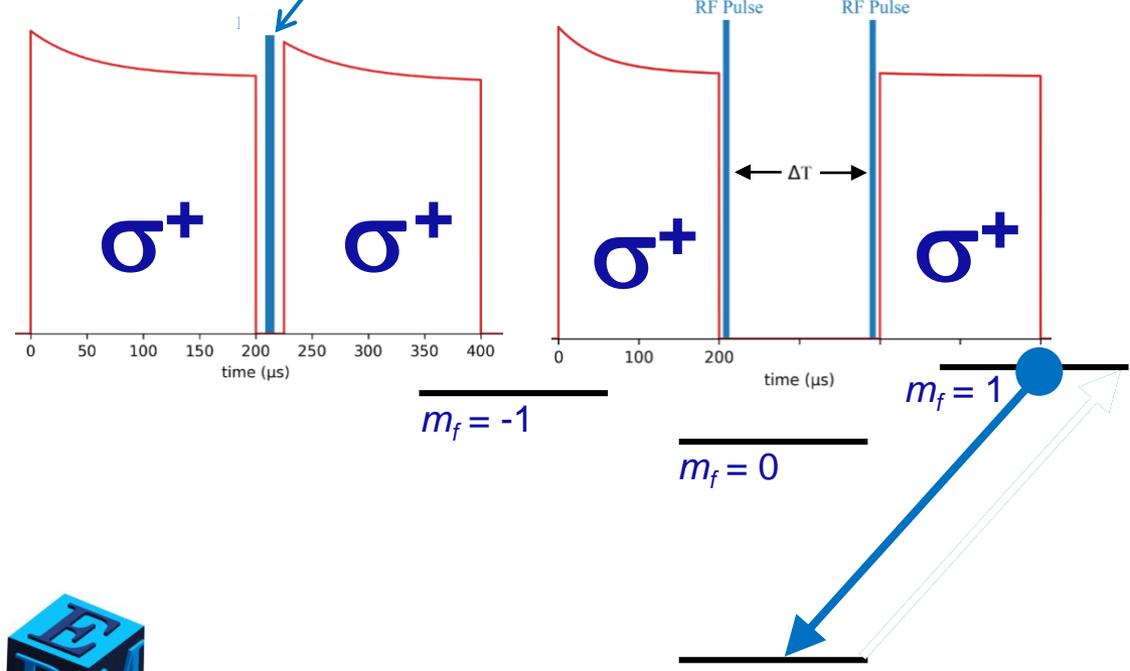
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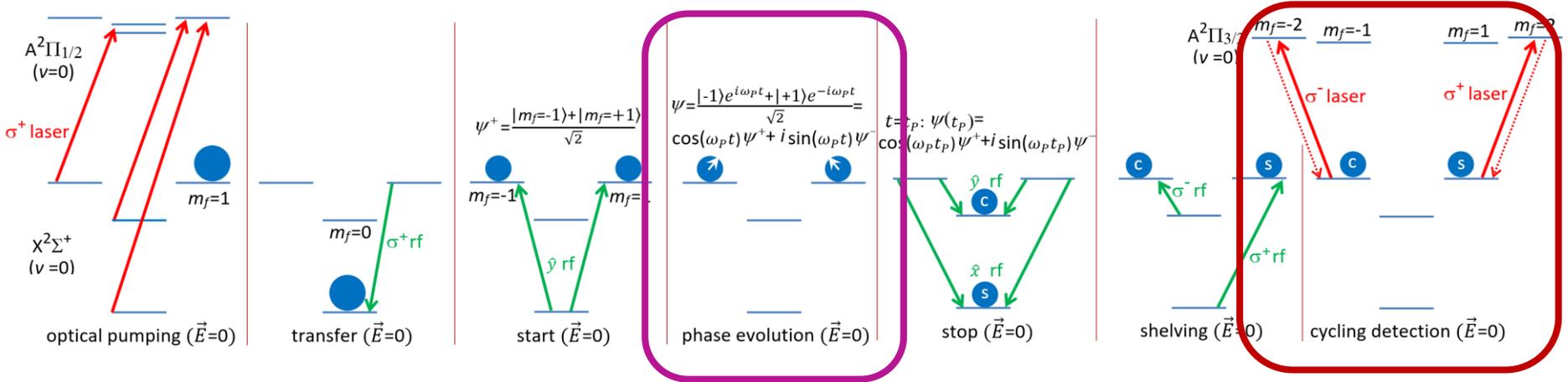
What Has Been Accomplished to Date?



8- μ s RF pulse
rf transitions demonstrated



What Has Been Accomplished to Date?



Efficient detection using laser-induced fluorescence demonstrated

For the precession (phase evolution) step, the environment of the molecules has to be exquisitely controlled: colder, fewer impurities in solid and magnetic-field temporal and spatial uniformity controlled at the nGauss level



What we are working on now

Temperature:

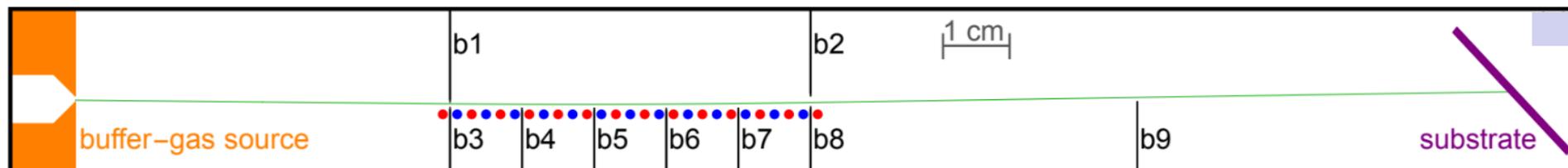
Recently reduced temperature to 3K

Designed and soon will receive system that will get to 1K

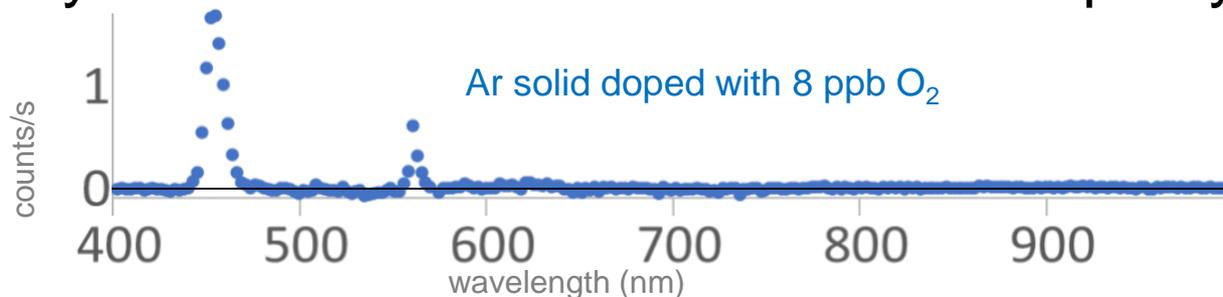
Purity:

We have a getter system for purifying our Ar

We have designed an electrostatic deflector to remove impurities from our molecular beam



We are using x-ray-induced fluorescence to measure purity



What we are working on now

Magnetic field:

New Al/Ti/Cu ultrahigh vacuum apparatus

Actively cancelling lab B field down to 10's of μGauss in a 300 cm^3 volume (up to 1 kHz – 60/120 Hz, subway, etc.)

Designed and built Pb superconducting magnetic shield

Acts of a “Meisner shield” to expel field lines

- hard since field lines get pinned to imperfections
- only works for sub-mGauss fields with very high purity Pb

Active system plus Pb shield will reduce spatial and temporal variations of fields to the nGauss level

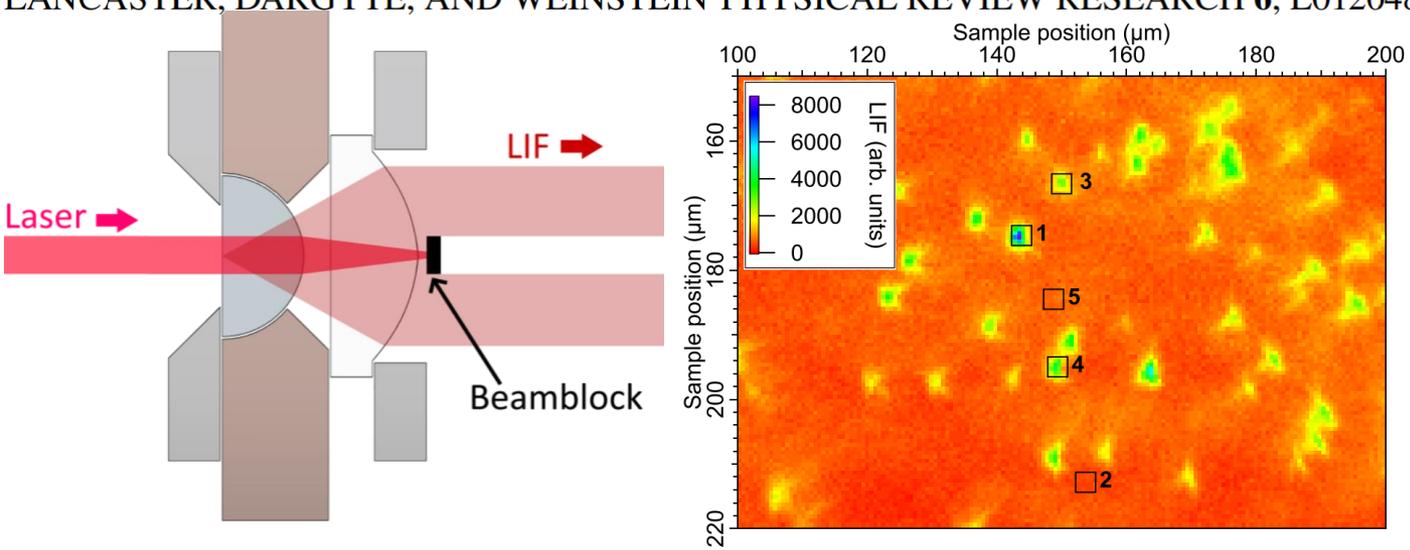
Magnet coils inside of shield to apply reversible B field



Next Step

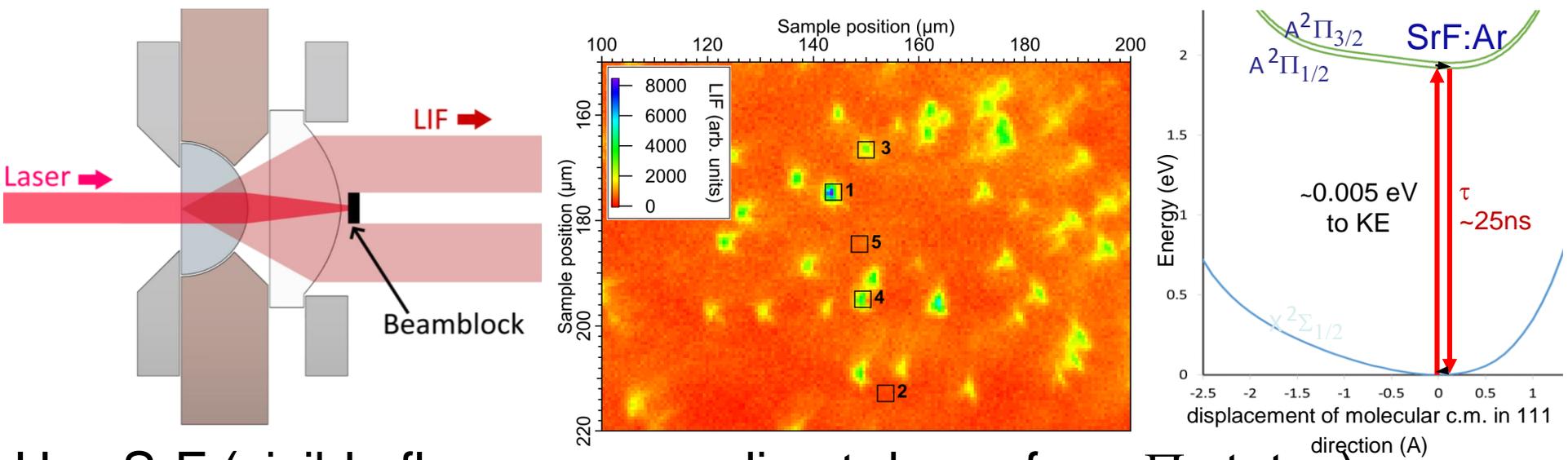
Perform full experiment on individually imaged molecules
(following the scheme used by Weinstein and others)

LANCASTER, DARGYTE, AND WEINSTEIN PHYSICAL REVIEW RESEARCH 6, L012048 (2024)



Next Step

Perform full experiment on individually imaged molecules (following the scheme used recently by Weinstein, et al)



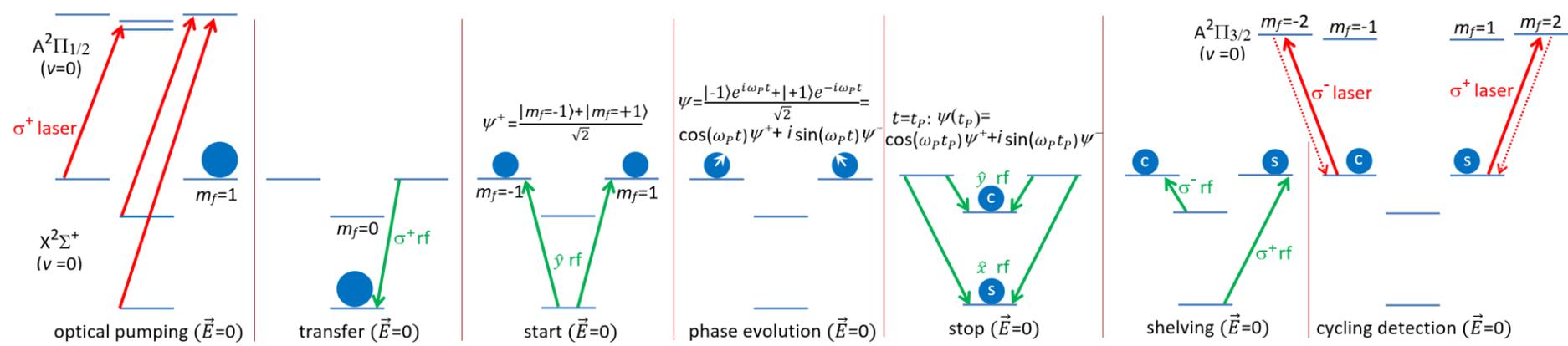
Use SrF (visible fluorescence, direct decay from Π states)

Allows for study of orientation and environment of each molecule

2-micron resolution, 2 mm² field of view in our design

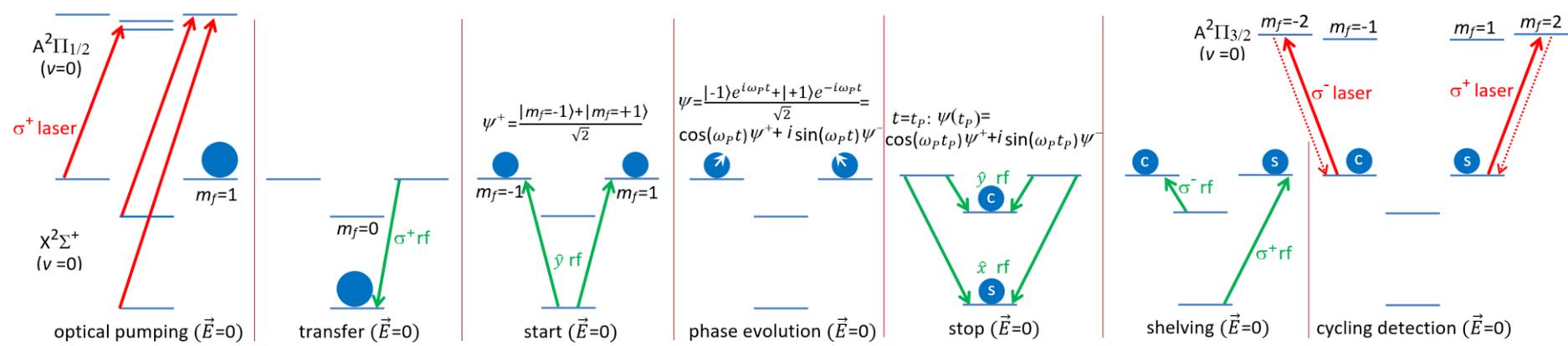
Allows for 20 000 individual molecules to be viewed simultaneously





Do separately recorded eEDM measurements on each of the 20000 SrF molecules

- Use SrF (visible fluorescence, direct decay from Π states)
- Allows for study of orientation and environment of each molecule
- 2-micron resolution, 2 mm² field of view in our design
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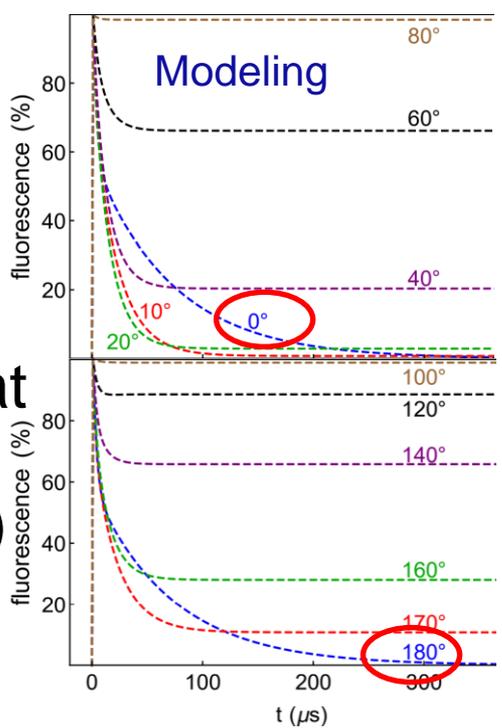


Do separately recorded eEDM measurements on each of the 20000 SrF molecules

Use only molecules at 0 or 180 degrees (25% of molecules)

Allows for d_e measurement with molecules that do not have exactly identical environments (slightly different precession rates) (T_2 , not T_2^*)

Imaged molecules could allow for an ultraprecise d_e measurement



$$\delta d_e = 7 \times 10^{-31} e \text{ cm} \sqrt{\frac{20\,000}{N_{\text{mol}}}} \sqrt{\frac{1 \text{ s}}{T_{\text{prec}}}} \sqrt{\frac{1 \text{ month}}{T_{\text{tot}}}} \left(\frac{2.16 \text{ GV/cm}}{E_{\text{eff}}} \right)$$



Timeline

2 years: individual molecule imaging studies

5 years: full implementation of technique and d_e measurement

continuing: measurements of increasing precision – the first measurement will determine whether the next generation will continue to use individually-imaged molecules

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Summary

Goal: measure CP violation responsible for matter/antimatter asymmetry in the universe

Using molecules frozen in an inert-gas solid has the potential for a significant increase in precision for an eEDM measurement

Many of the steps needed for an eEDM measurement have been demonstrated

First measurement expected in five years

PRA 98 032513 (2018)

J Mol Spectr 391 111736 (2023)

Mol Phys 121 e2198044 (2023)

PRA 107 032811 (2023)

Mol Phys 121 e2232051 (2023)

PRA 108 012811 (2023)

arXiv:2410.04591

arXiv:2410.04598

arXiv:2410.04605

