PNRR MUR project PE0000023-NQSTI

Measuring the electric dipole moment of the electron using polar molecules in a parahydrogen matrix

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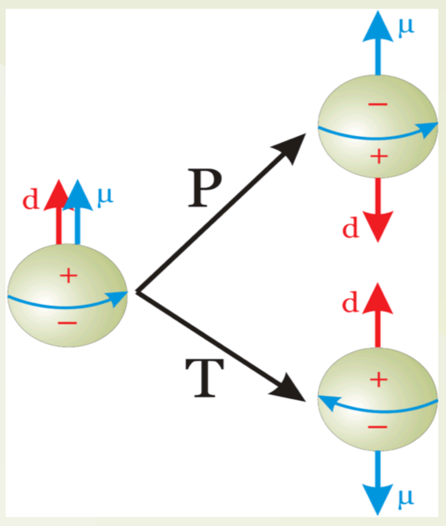
INTRODUCTION

The electric dipole moment of the electron (eEDM) is a possible source of CP violation.

A nonzero eEDM would imply an aspherical charge distribution along the electron's spin axis-> violation of T-symmetry and, through CPT conservation, of CP.



STANDARD MODEL PREDICTION

$$d_e^{SM} \leq 10^{-38} e\ cm$$

Several extensions of the Standard Model allow a much larger eEDM that is within reach of near-term experiments.

CURRENT EXPERIMENTAL LIMIT

$$d_e < 4.1\ \times 10^{-30} e\ cm$$

@ 90% confidence level

[T. S. Roussy *et al., Science* **381**,46-50 (2023)]

(obtained with trapped HfF+)

DETECTION STRATEGY

Measure electron spin precession in a magnetic field and detect any change in precession rate due to the presence of an electric field.

$$\phi = (g\,\mu_B \pm d_e E)\,t_p/\hbar$$

PRECESSION ANGLE

t_p = precession measurement time ≤ spin coherence time

- Use diatomic polar molecules (BaF, YbF, ThO) that have a single valance electron exposed to a huge effective molecular electric field (E_{eff} ~ 10 GV/cm)
- Perform the measurement for two opposite orientations of the electric field:

$$\delta d_e = \frac{\hbar}{2\,E_{eff}\sqrt{N}\,t_p}$$

SHOT NOISE LIMIT

Assuming:
N ≈ 10^{15} number of molecules (electrons) interrogated
t_p ≈ 0.1 s

$$\delta d_e = \sim 10^{-32} e\ cm$$

KEY INGREDIENTS:

- High number of molecules (challenging, BaF is very reactive!)
- long spin coherence time

MATRIX ISOLATION TECHNIQUE

Guest molecules are embedded within a matrix of pH_2 gas solidified at cryogenic temperature

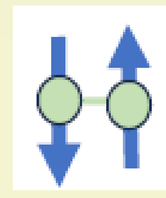
- Allows the confinement of many molecules within the measurement volume
- Minimal interactions between guest and host molecules -> long coherence time

(Rb atoms embedded in pH_2 ≈ hundreds of ms [J. Weinstein et al., PRL 125, 043601(2020)])

PHYDES EXPERIMENT:

Embed $^{138}Ba^{19}F$ molecules in a cryogenic parahydrogen crystal (n ≈ 10^{13} BaF molecules / cm^3) using the matrix isolation technique.

Parahydrogen (pH_2): anti-parallel nuclear spins, lower-energy state.



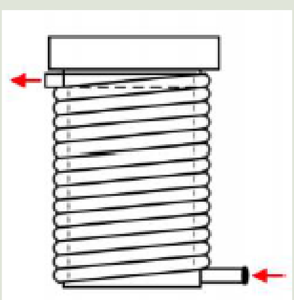
Stable hexagonal closed packed (hcp) structure. Lattice parameter ≈ 3.78 Å

Sub-systems:

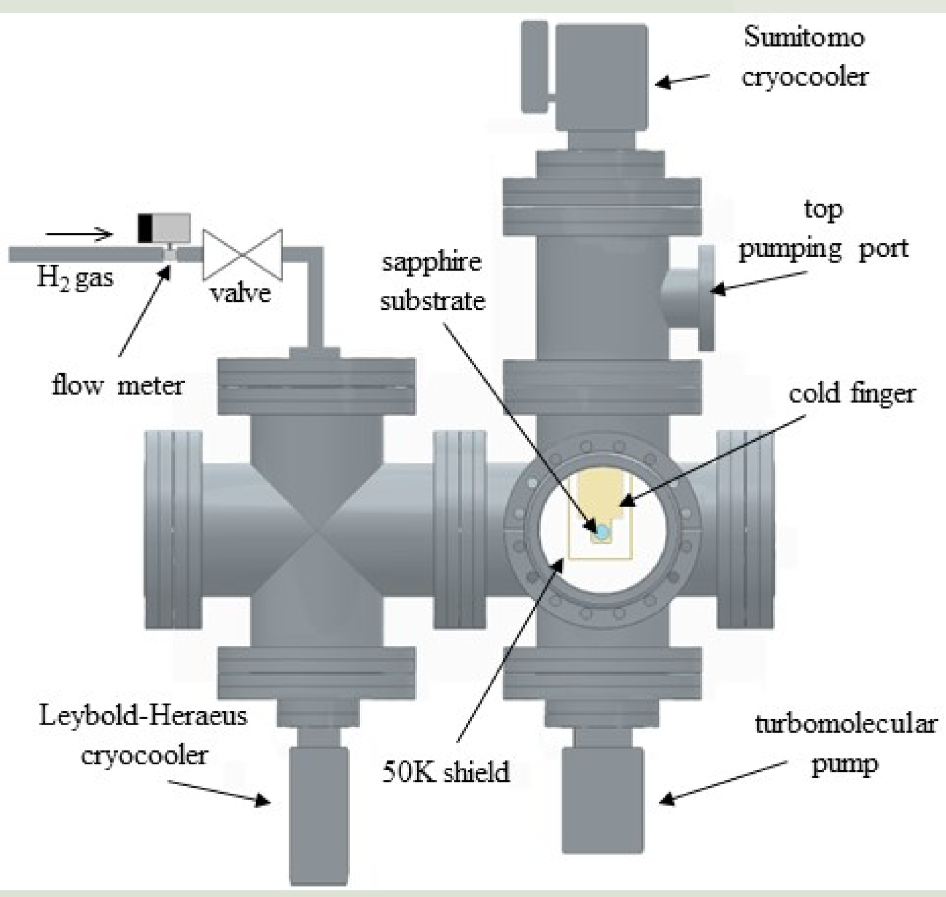
- Para-hydrogen production
- BaF production and isotopic selection

→ Condensation: growth of doped crystal

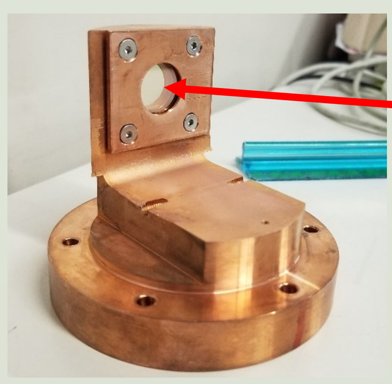
PARAHYDROGEN PRODUCTION



Hydrogen gas flows through a copper line filled with a hydrous ferric oxide catalyst that facilitates the conversion into the pH_2 state. The gas line is wound around the cold head of a cryocooler operating at 20 K.



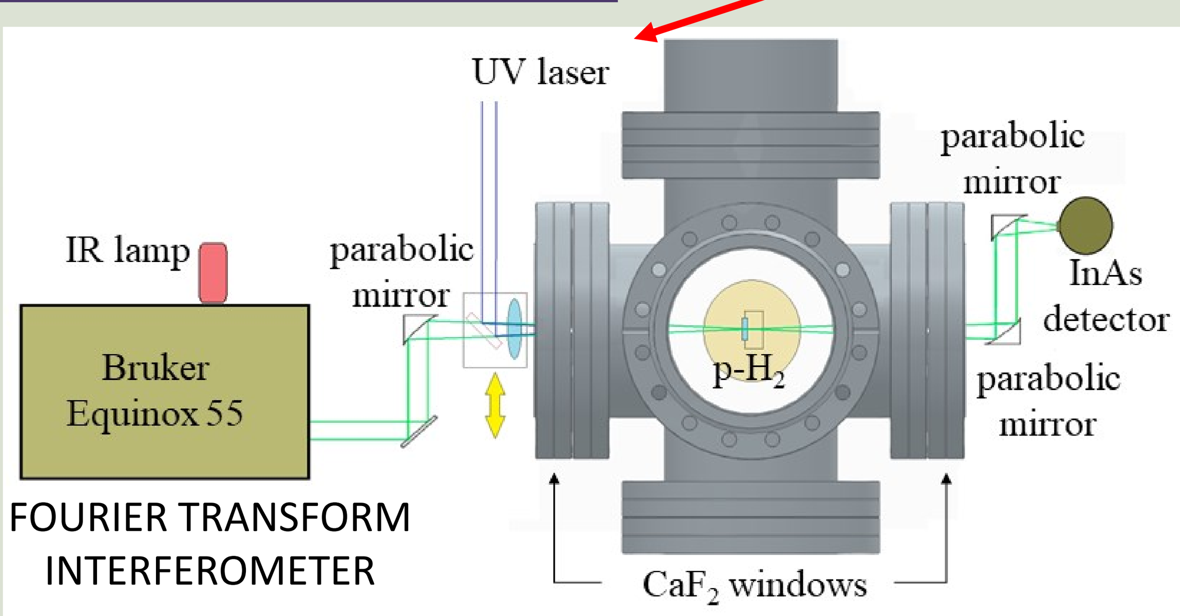
The pH_2 gas flow is directed through a 3 mm diameter nozzle positioned 30 mm from a 1" sapphire substrate.
pH_2 gas condenses on the sapphire substrate that is cooled to 2.9 K to form a solid crystal layer.



Substrate:
ϕ = 1''
$T_{sapphire}$ = 2.9 K

CHARACTERIZATION OF THE CRYOGENIC MATRIX

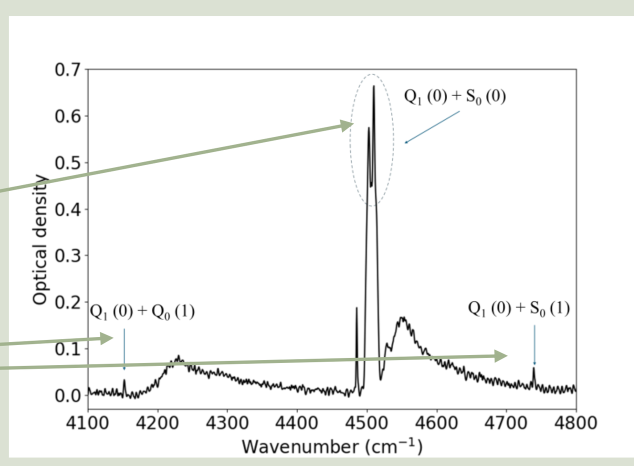
A Fourier transform interferometer with a near-infrared light source is used to measure the infrared absorption spectrum of the pH_2 matrix.

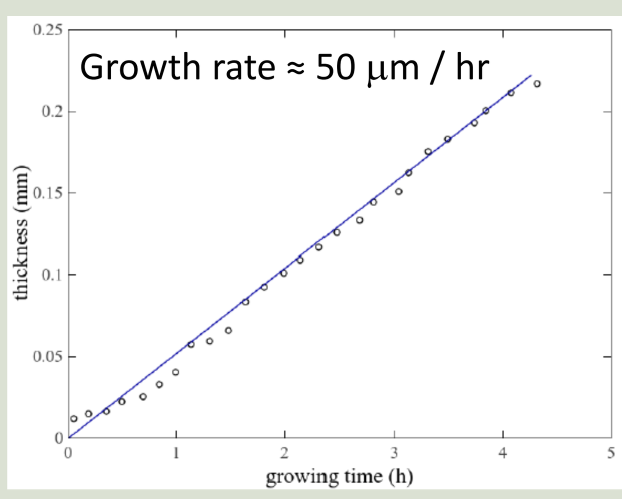


UV laser to neutralize BaF+ during crystal growth

Determine:

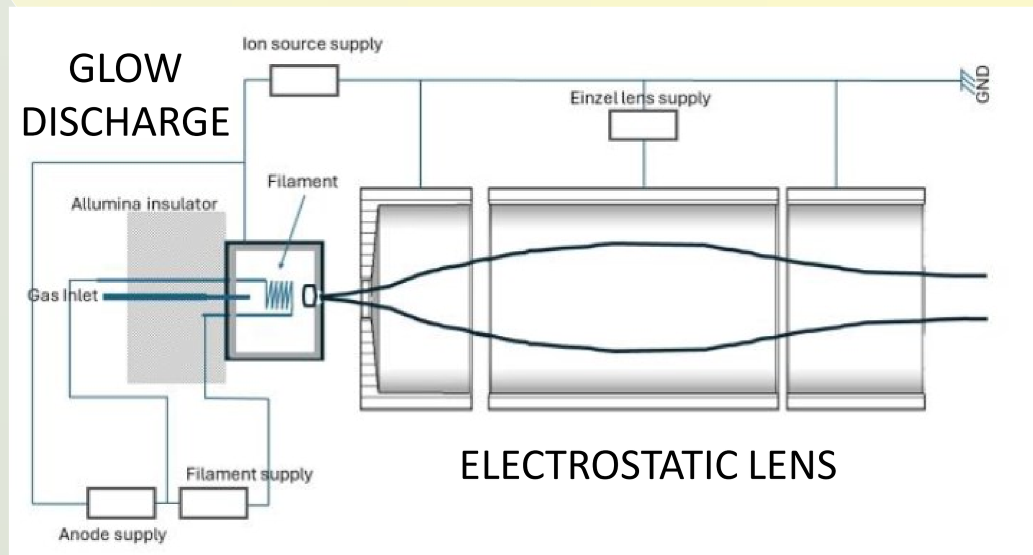
- Thickness of deposited layer
- Ortho/para concentration

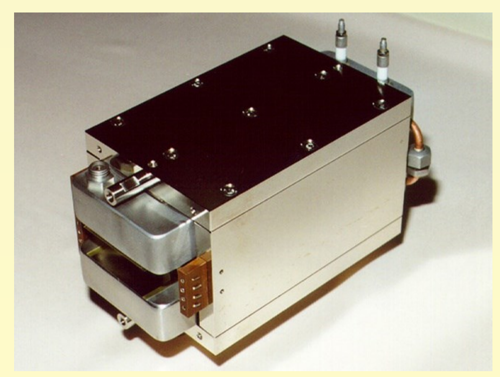




MOLECULAR SOURCE

- BaF produced in a glow discharge chamber from BaF_2 powder
- Molecules are accelerated to 1 keV
- Isotopic selection with a Wien velocity filter ($\vec{E} \times \vec{B}$)
- deceleration to ≈ 5 eV to merge with pH_2 gas flow on the growth substrate





WIEN FILTER

DECELERATOR

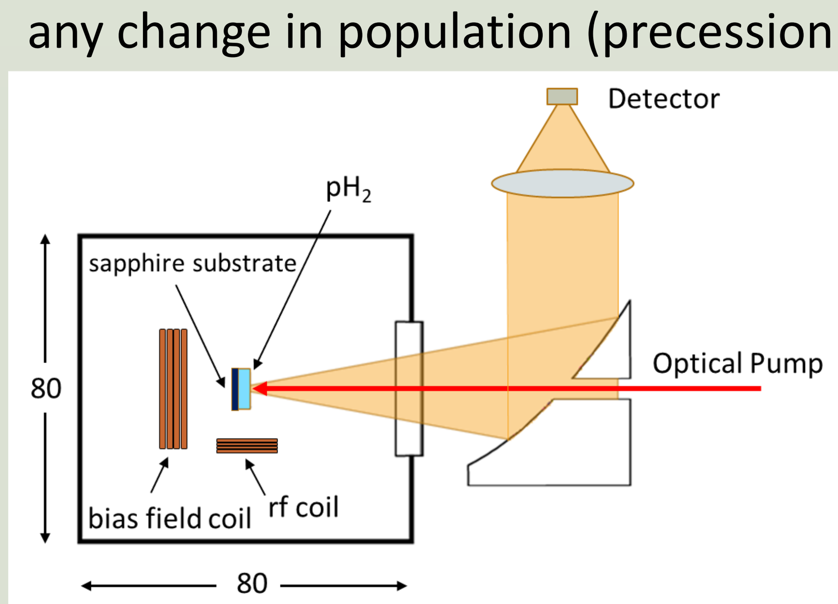
Current status:

- extracted a BaF+ beam @ 1 KeV with few μA
- after decelerator 20nA @ 5eV, 10 cm from output

Charge neutralization of BaF+ is done in pH2 → inject free electrons in the matrix
We developed a system to photo-extract electrons from a gold layer deposited on the growth substrate using UV laser pulses.

OPTICAL DETECTION WITH FLUORESCENCE SPECTROSCOPY

Measure the population of a prepared coherent superposition state and detect any change in population (precession angle) when E is reversed.



Laser induced fluorescence spectroscopy

- Optical Pump : Titanium Sapphire laser tuned to the transition $X^2\Sigma^+ \rightarrow A^2\Pi^{1/2}$ λ = 859.8 nm
- Observe fluorescence emission in wavelength interval 950-1100 nm

RF coils for state preparation and manipulation

OTHER DETECTION METHODS UNDER STUDY

- Magnetization: d_e and spin align with E field → net electronic spin polarization generates a bulk magnetization detectable with a SQUID
- EPR detection: measure precession frequency shift when E is applied

Ongoing R&D to evaluate sensitivity and pros/cons of the different detection schemes.

ACKNOWLEDGEMENTS

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