Molecular systems for tests of fundamental physics

Steven Hoekstra, RUG & Nikhef
Motivation: reach beyond the current limits of observation

The Ends of Evidence
Humans can probe the universe over a vast range of scales (white area), but many modern physics theories involve scales outside of this range (grey).

source: Quanta Magazine, 2015
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Humans can probe the universe over a vast range of scales (white area), but many modern physics theories involve scales outside of this range (grey).

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Molecules can be extremely sensitive quantum sensors for fundamental physics!
Molecules vs atoms
Extra complexity brings experimental challenges and new possibilities

Close-lying opposite parity levels: study parity violation (also chirality)

Heavy polar molecules: hugely enhanced electron-EDM sensitivity

Tunneling in molecular motion: extremely sensitive to value of constants
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Heavy polar molecules: hugely enhanced electron-EDM sensitivity

Tunneling in molecular motion: extremely sensitive to value of constants
The electron’s Electric Dipole Moment (eEDM) probing CP violation beyond the standard model

An EDM would arise along the same axis as the electron’s spin.

The charge cloud would be distorted, making one side slightly more negative than the other.

eEDM violates P, T and CP symmetry (provided CPT holds)

fig: Nature 553, 144 (2018)
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eEDM violates $P$, $T$ and CP symmetry (provided CPT holds)

*Standard model prediction*

$10^{-38}$

$10^{-36}$

$10^{-34}$

$10^{-32}$

$10^{-30}$

$10^{-28}$

$10^{-26}$

$10^{-24}$

$10^{-22}$

Excluded by experiments

Standard model extensions

Standard model prediction

*fig: Nature 553, 144 (2018)*
A history of measurements with steady progress
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1 order of magnitude / 8 years

last decade with molecules even steeper!
The electron’s electric dipole moment (eEDM) effectively a background-free method to probe new physics.
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\[ \frac{d_e}{e} \approx \kappa \left( \frac{\alpha_{\text{eff}}}{2\pi} \right)^n \left( \frac{m_e c^2}{\Lambda^2} \right) \sin(\phi_T) (hc) \]

The ThO result limits time-reversal-symmetry-violating new physics to energy scales above \( \Lambda \approx 30 \text{ TeV} \) or \( \Lambda \approx 3 \text{ TeV} \), for \( n=2 \) or \( 1 \), respectively.
How to measure a dipole moment?

However, electron also has magnetic dipole moment (and charge!)
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Solution: use electron embedded in a polar molecule!

Enhances E Shields B
Increasing the eEDM sensitivity

Effective electric field

Applied electric field (kV/cm)

$|P/E_{\text{eff}}|$ (GV/cm)
Increasing the eEDM sensitivity
Measure shift of molecular energy level that correlates with electric field direction reversal

statistical error: \[ \sigma_d = \frac{\hbar}{e} \frac{1}{2 |P| E_{\text{eff}} \tau \sqrt{\dot{N}T}} \]

Effective electric field

\begin{align*}
|P|E_{\text{eff}} \text{ (GV/cm)} & \quad 0 & 2 & 4 & 6 & 8 \\
0 & 10 & 20 & 30 & \quad \text{Applied electric field (kV/cm)}
\end{align*}
Increasing the eEDM sensitivity

Measure shift of molecular energy level that correlates with electric field direction reversal

Statistical error:

\[ \sigma_d = \frac{\hbar}{e} \frac{1}{2|P|E_{\text{eff}} \tau \sqrt{NT}} \]
Coherent interaction time

Key technique: Ramsey spin interferometer

- Laser pulse 1:
  Creates a quantum superposition, creating coherent excitation of all molecules
- Laser pulse 2:
  Measures state of the molecules through interference

- Resonance in molecules
- Time $T$

- Frequency set by external reference, tuned to molecular resonance

- Ramsey $\pi/2$ pulses
- Interference fringes
- Increasing $T$
Cold molecules offer longer coherent interaction times

fast beam

\[ \tau \sim 1-2 \text{ ms} \]
\[ L \sim 0.5 \text{ m} \]
\[ v \sim 250-500 \text{ m/s} \]
Cold molecules offer longer coherent interaction times.

**fast beam**
- $\tau \sim 1-2 \text{ ms}$
- $L \sim 0.5 \text{ m}$
- $v \sim 250-500 \text{ m/s}$

**slow beam**
- $\tau \sim 15 \text{ ms}$
- $L \sim 0.5 \text{ m}$
- $v \sim 30 \text{ m/s}$
Cold molecules offer longer coherent interaction times

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- **Slow beam**
  - $\tau \sim 15 \text{ ms}$
  - $L \sim 0.5 \text{ m}$
  - $v \sim 30 \text{ m/s}$

- **Fountain**
  - $\tau \sim 100 \text{ ms}$
  - $L \sim 0.5 \text{ m}$

- **Trap**
  - $\tau \sim 1\text{-}10 \text{ s}$
  - $L \sim 0.5 \text{ mm}$

Slow vertical beam

Molecules trapped in laser focus
Cold molecules offer longer coherent interaction times

**fast beam**
- $\tau \sim 1\text{-}2 \text{ ms}$
- $L \sim 0.5 \text{ m}$
- $v \sim 250\text{-}500 \text{ m/s}$

**slow beam**
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- $\tau \sim 100 \text{ ms}$
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**trap**
- $\tau \sim 1\text{-}10 \text{ s}$
- $L \sim 0.5 \text{ mm}$

Molecules trapped in laser focus

**Main challenge:**
how to maintain $N$ while increasing $t$

Strongly connected to choice of molecule!
Cold molecules offer longer coherent interaction times

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Strongly connected to choice of molecule!
eEDM experiments using molecules

ACME - beam of ThO molecules
John Doyle, David DeMille,
Gerald Gabrielse

Imperial College London - beam of
YbF molecules
Mike Tarbutt, Ben Sauer, Ed Hinds

JILA - trapped HfF+ ions
Eric Cornell, Jun Ye

Others are being set up:
Decelerated BaF beam experiment in Groningen,
The Netherlands (NL-eEDM)

Electric Dipole Measurements using Molecules within a Matrix

- York University
- Michigan State University
- University of Toronto
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NL-eEDM: A Nikhef research programme started in 2017…

…using slow BaF molecules and lasers!
Cold molecules offer longer coherent interaction times

Cold molecules offer longer coherent interaction times

Cold molecules offer longer coherent interaction times

Phase 1
- Molecular beam source
- Fast beam \( \tau = 1-2 \text{ ms} \)
- Decelerator

Phase 2
- Slow beam
- \( \tau = 10-30 \text{ ms} \)

Phase 3
- Fountain
- \( \tau \sim 1 \text{ s} \)
- Trap
- \( \tau = 1-10 \text{ s} \)

2017 to 2028 timeline

Institution logos:
- University of Groningen
- NIKHEF
- VU University Amsterdam
- UvA
- Dutch National Institute for (astro)Particle Physics

Faculty of Mathematics and Natural Sciences
Van Swinderen Institute for Particle Physics and Gravity
Interference data using fast molecular beam to demonstrate control over systematic effects

Create molecular beam → Quantum interference → Readout by fluorescence

Compare to theory that includes the full interaction of the molecule with light, electric and magnetic fields (optical Bloch equations)

Contains all relevant experimental parameters

Crucial for reduction of systematic effects

(A. Boeschoten et al, NL-eEDM collaboration, in prep.)
... and a corresponding increase in eEDM sensitivity!
The choice of molecule
Exciting developments - some examples

Molecules containing radioactive elements
Proposal:


Polyatomic molecules
Proposal:

Advanced cooling techniques
Direct laser cooling - now extending to heavier and more complex species

COLD MOLECULES

An optical tweezer array of ultracold molecules
Loïc Anderegg1,2, Lawrence W. Cheuk1,2, Yicheng Bao1,2, Sean Burchesky1,2, Wolfgang Ketterle2,3, Kang-Kuen Ni1,2,4, John M. Doyle1,2

 nature physics
PUBLISHED ONLINE: 28 AUGUST 2017 | DOI: 10.1038/NPHYS4241

Molecules cooled below the Doppler limit

Trapping of C2− in a digital ion trap
Alexander Hinterberger, Sebastian Gerber, Emanuel Oswald, Christian Zimmer, Julian Fesel and Michael Doser
CERN, European Laboratory for Particle Physics, 1211 Geneva, Switzerland
Journal of Physics B: Atomic, Molecular and Optical Physics, Volume 52, Number 22

Towards laser cooling of molecular anions - for antimatter physics
Advanced cooling techniques

Exciting developments - some examples

Deceleration and trapping of heavy diatomic molecules

Deceleration and Trapping of SrF Molecules


(LNL-eEDM Collaboration)
Quantum phase magnification

O. Hosten, R. Krishnakumar, N. J. Engelsen, M. A. Kasevich*

Quantum metrology exploits entangled states of particles to improve sensing precision beyond the limit achievable with uncorrelated particles. All previous methods required detection noise levels below this standard quantum limit to realize the benefits of the intrinsic sensitivity provided by these states. We experimentally demonstrate a widely applicable method for entanglement-enhanced measurements without low-noise detection. The method involves an intermediate quantum phase magnification step that eases implementation complexity. We used it to perform squeezed-state metrology 8 decibels below the standard quantum limit with a detection system that has a noise floor 10 decibels above the standard quantum limit.
NL-eEDM: Teamwork!

Scientific staff:
Anastasia Borschevsky
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