Electric dipole moment searches in atoms & molecules

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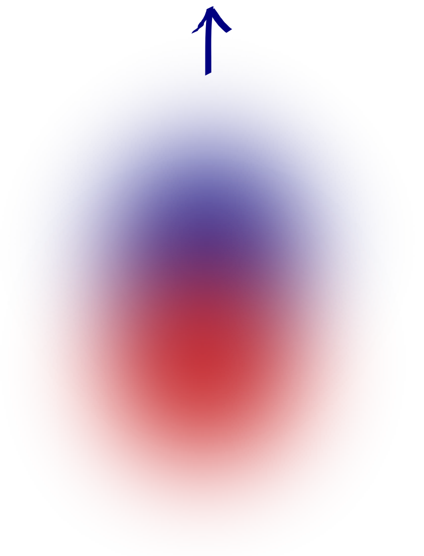
PSI 2022

Permanent electric dipole moment of a particle



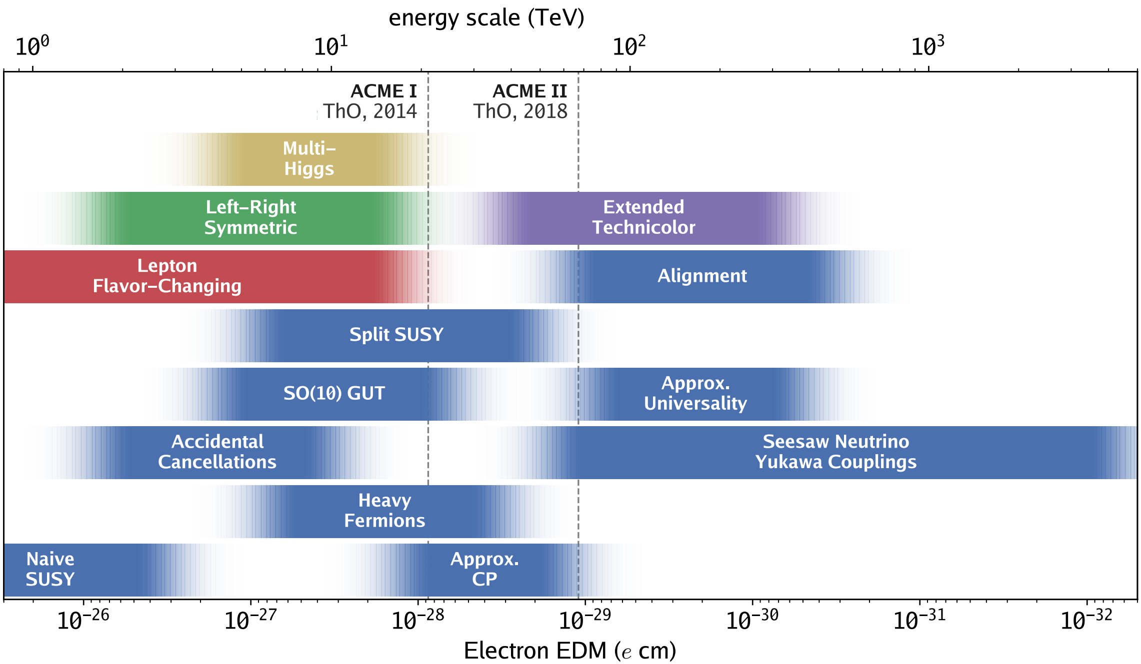
Asymmetry of charge distribution

Has to be oriented along spin vector

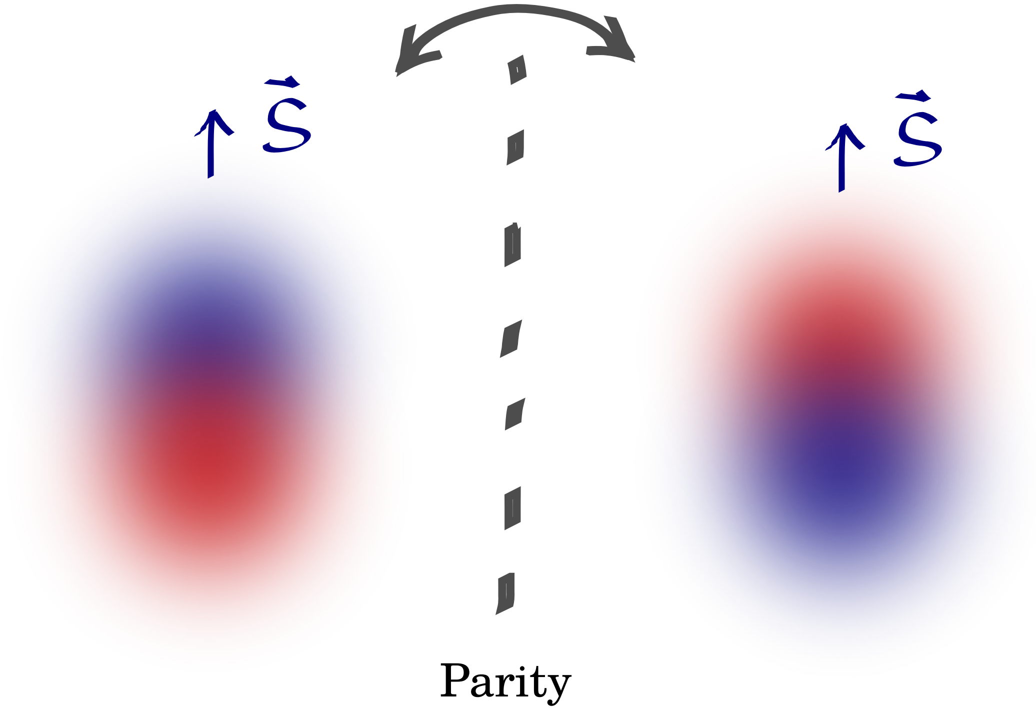
Wigner-Eckart theorem

Low-energy observable which
probes extremely high-energy physics

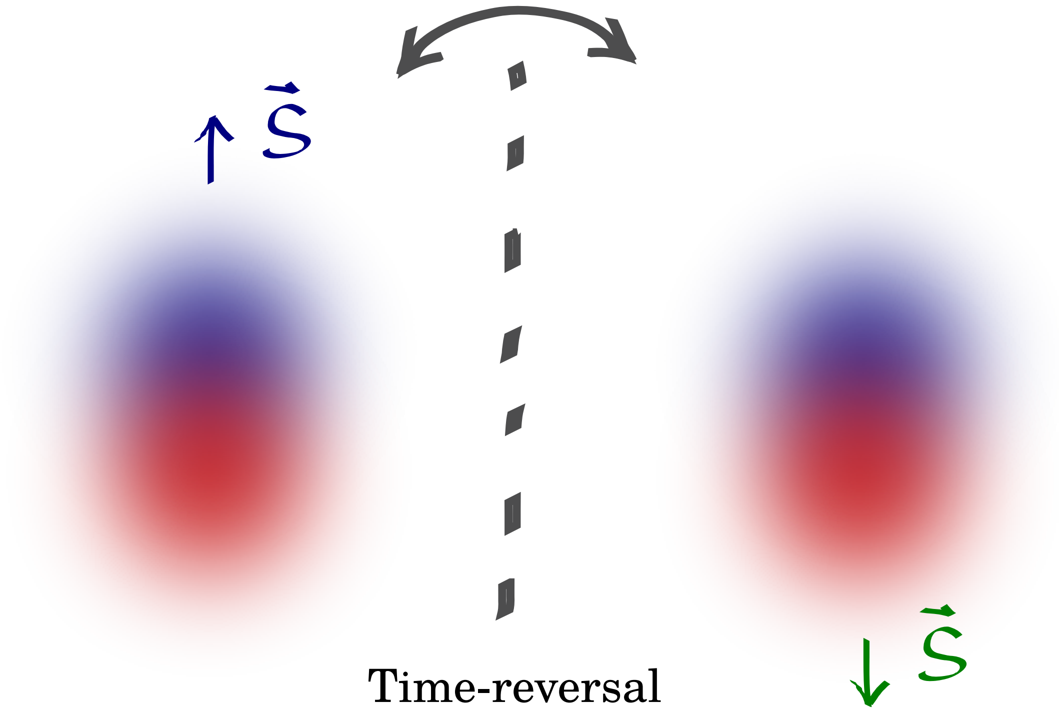
High energy reach



EDMs violate parity symmetry



EDMs violate time–reversal symmetry



Permanent electric dipole moment of a particle

Asymmetry of charge distribution

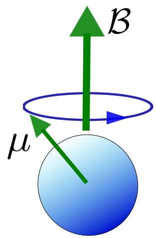
Has to be oriented along spin vector

Wigner-Eckart theorem

Low-energy observable which
probes extremely high-energy physics

model-independent signature
of some new P,T-violation

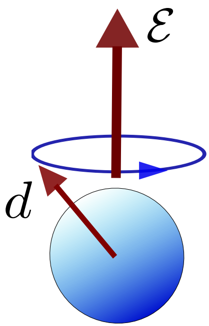
Measuring an electric dipole moment



[] B-field exerts torque on magnetic moment

[] Spin precession angle per unit time
is proportional to the magnetic moment

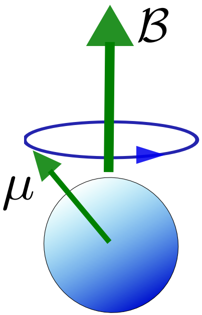
Similarly ....



[] E-field exerts torque on electric dipole moment

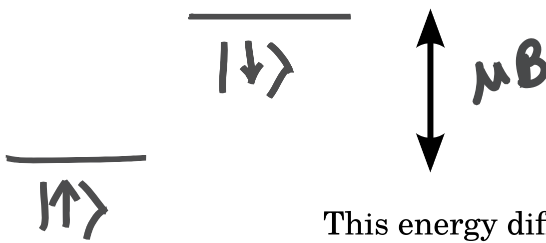
[] Spin precession angle per unit time
is proportional to the EDM

Quantum mechanical version



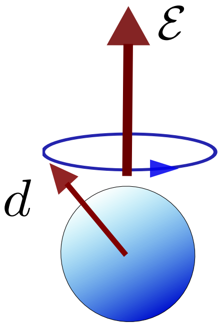
Zero magnetic field:

Non-zero magnetic field:



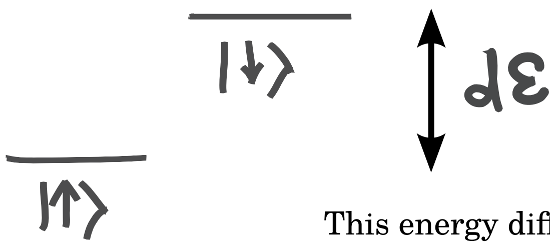
This energy difference gives the magnetic moment

Quantum mechanical version



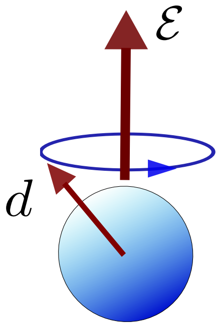
Zero electric field:

Non-zero electric field:



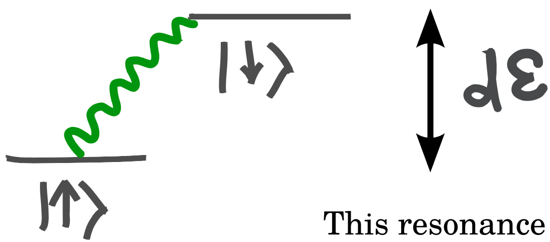
This energy difference gives the EDM

Quantum mechanical version



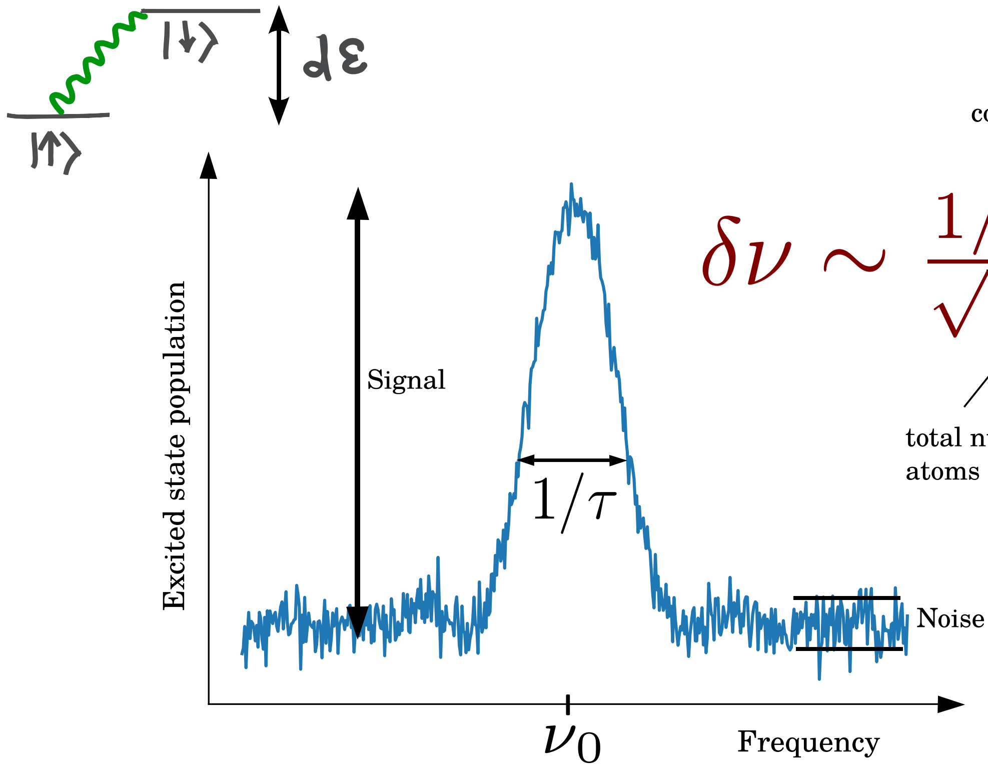
Zero electric field:

Non-zero electric field:



This resonance frequency gives the EDM

Electron spin resonance

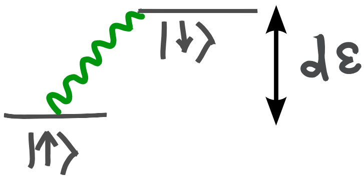


$$\delta\nu \sim \frac{1/\tau}{\sqrt{N}}$$

coherence time

total number of atoms measured

Precision of EDM experiments



$$\delta d = \frac{1}{\varepsilon \tau \sqrt{N}}$$

$$\delta \nu \sim \frac{1/\tau}{\sqrt{N}}$$

coherence time

total number of particles measured

So we always want:

... the largest electric field

... the longest coherence time

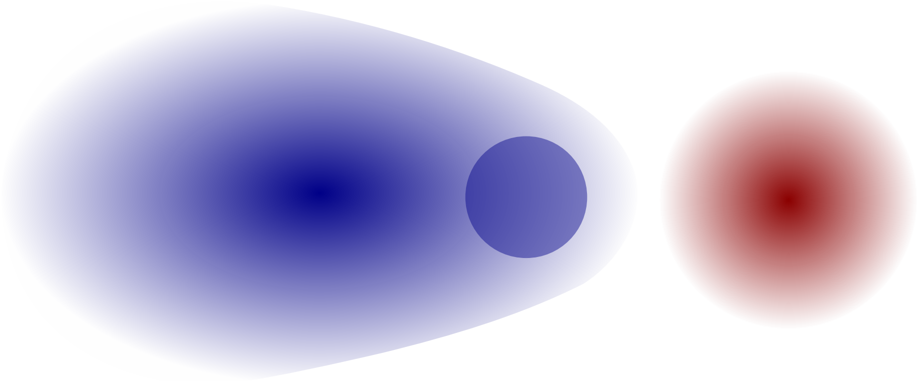
... lots and lots of particles

Ongoing EDM searches with atoms & molecules

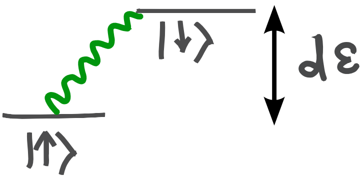
ThO	electron	(ACME) Chicago + Harvard + Northwestern)
HfF+, ThF+	electron	JILA
YbF	electron	Imperial College
YbOH	electron	(PolyEDM) CalTech + Harvard
BaF	electron	multiple groups
Hg	nuclear	Washington
Ra	nuclear	Argonne
Xe	nuclear	multiple groups
TlF	nuclear	(CENTREX) Chicago + Columbia + Yale

+ *more brewing ....*

A molecule is complicated



Precision of EDM experiments



$$\delta d = \frac{1}{\mathcal{E}\,\tau\sqrt{N}} \quad \longleftarrow \quad \delta\nu \sim \frac{1/\tau}{\sqrt{N}}$$

τ: coherence time

N: total number of particles measured

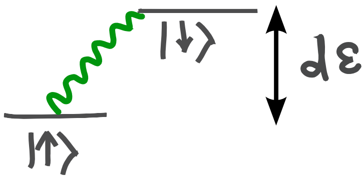
So we always want:

... the largest electric field $\longrightarrow$ *this is why we use atoms & molecules*

... the longest coherence time

... lots and lots of particles

Precision of EDM experiments



$$\delta d = \frac{1}{\varepsilon \tau \sqrt{N}}$$

$$\delta\nu \sim \frac{1/\tau}{\sqrt{N}}$$

coherence time (τ)

total number of particles measured (N)

So we always want:

... the largest electric field ⟶ *this is why we use atoms & molecules*

... the longest coherence time
... lots and lots of particles
] ⟶ *could also be improved using AMO techniques (cooling & trapping)*

Ongoing EDM searches with atoms & molecules

ThO	electron	(ACME) Chicago + Harvard + Northwestern)
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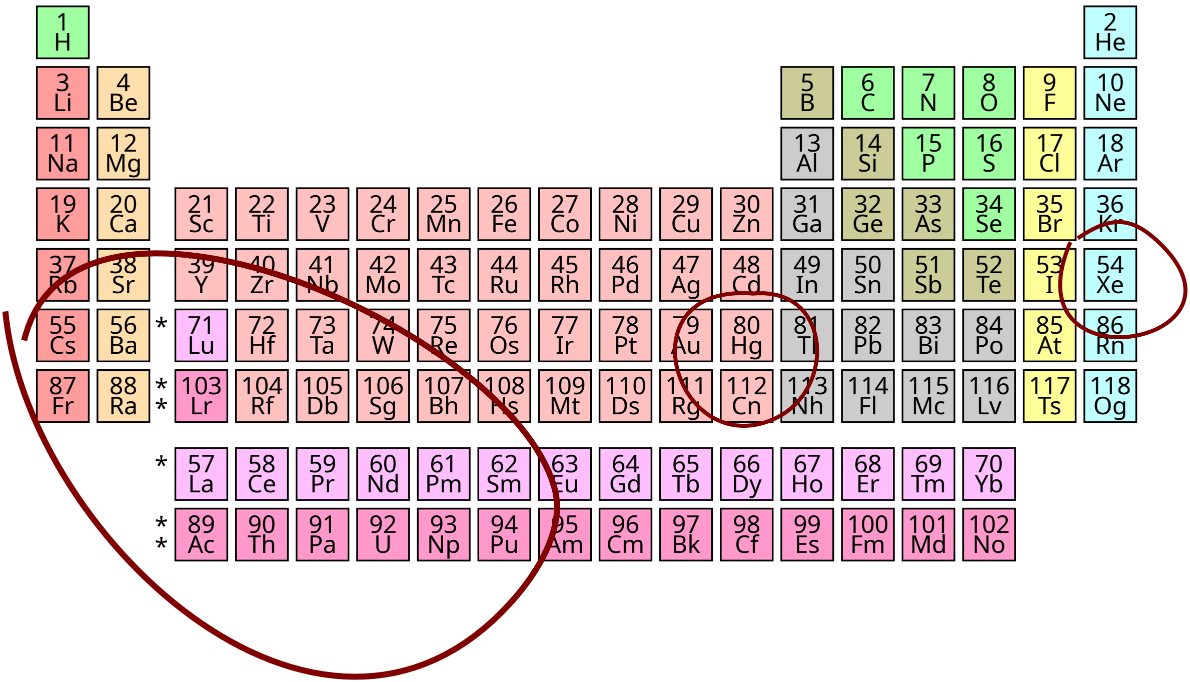

Why is the E–field so large in atoms & molecules ?

In fact, the field experienced by the EDMs of electrons or nuclei inside atoms & molecules is ZERO !

(non-relativistic point particles: Schiff's theorem)

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Electrons move ~relativistically inside heavy atoms (Salpeter, Sandars)

$\Rightarrow$ *electron EDM leads to P,T-violating energy shifts in atoms/molecules*

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(non-relativistic point particles: Schiff's theorem)

Electrons move ~relativistically inside heavy atoms (Salpeter, Sandars)

⇒ *electron EDM leads to P,T-violating energy shifts in atoms/molecules*

Nuclei are extended objects (Schiff)

⇒ *nuclear EDM leads to P,T-violating energy shifts in atoms/molecules*

P,T–violating energy shifts

So we never directly measure particle EDMs in atoms & molecules

What we measure are **P,T-violating energy level shifts** that depend on the *spin orientation* relative to *electrical polarization*

$$\Delta\nu = \Upsilon_{\rm PT}\,\vec{J}\cdot\hat{\mathcal{D}}$$

Electrons:

$$\Delta\nu = \Upsilon_{\rm PT}\,\vec{J}\cdot\hat{\mathcal{D}} \longrightarrow \vec{d}_{\rm atom}\cdot\vec{\mathcal{E}}_{\rm lab} \qquad \text{(atoms)}$$

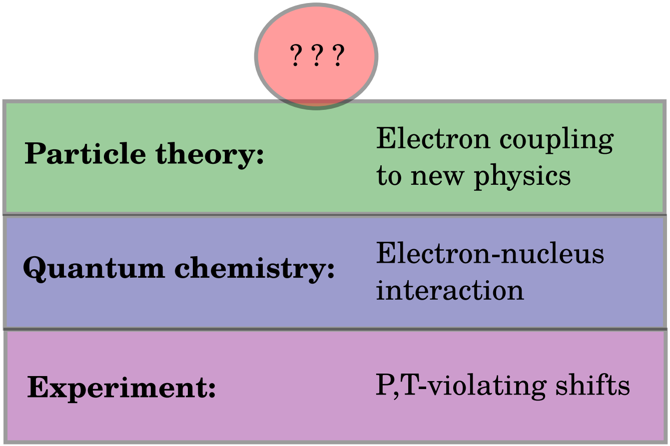
$$\Delta\nu = \Upsilon_{\rm PT}\,\vec{J}\cdot\hat{\mathcal{D}} \longrightarrow d_e\vec{\mathcal{E}}_{\rm eff}\;\vec{S}\cdot\hat{n} \qquad \text{(molecules)}$$

Nuclei:

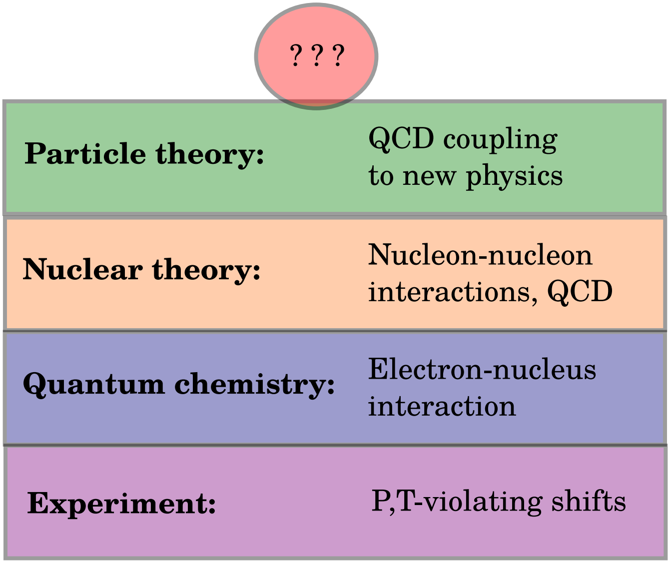
$$\Delta\nu = \Upsilon_{\rm PT}\,\vec{J}\cdot\hat{\mathcal{D}} \longrightarrow \vec{d}_{\rm atom}\cdot\vec{\mathcal{E}}_{\rm lab} \qquad \text{(atoms)}$$

$$\Delta\nu = \Upsilon_{\rm PT}\,\vec{J}\cdot\hat{\mathcal{D}} \longrightarrow (d_n R + 6\mathfrak{S})\,X\,\vec{I}\cdot\hat{n} \qquad \text{(molecules)}$$

Electron "EDM" experiments



Nuclear "EDM" experiments



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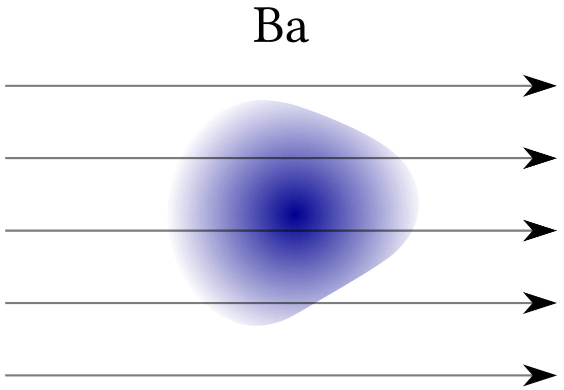
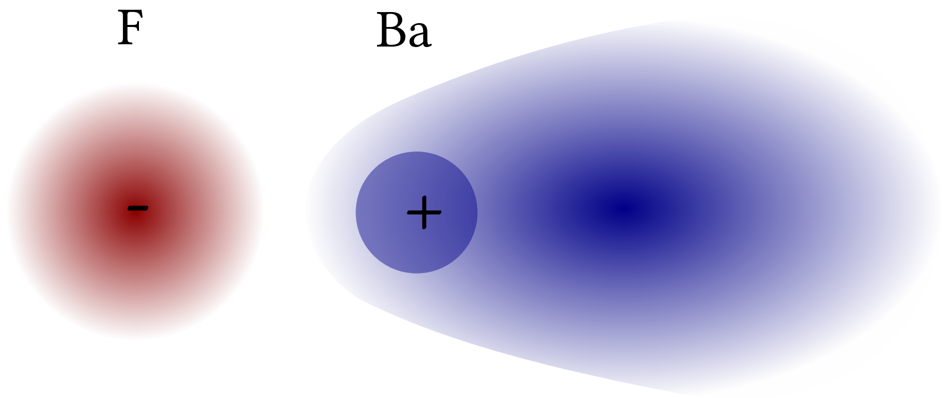
Why polar molecules?



Neutral atom in lab E-field

Why polar molecules?



Polar molecule = +ion subjected to large electric field from the -ion

Ongoing EDM searches with atoms & molecules

ThO	electron	molecular beam, laser spectroscopy
HfF+, ThF+	electron	ion trap, laser spectroscopy
YbF	electron	molecular beam, rf+laser spectroscopy
YbOH	electron	laser-cooled molecules
BaF	electron	molecular beam; matrix isolation
Hg	nuclear	vapour cell, rf spectroscopy
Ra	nuclear	optical trap
Xe	nuclear	cells, rf spectroscopy
TlF	nuclear	molecular beam, rf+laser spectroscopy

Recent results: electron EDM

Precision Measurement of the Electron's Electric Dipole Moment Using Trapped Molecular Ions

William B. Cairncross, Daniel N. Gresh, Matt Grau, Kevin C. Cossel, Tanya S. Roussy, Yiqi Ni, Yan Zhou, Jun Ye, and Eric A. Cornell

Phys. Rev. Lett. **119**, 153001 – Published 9 October 2017

Improved limit on the electric dipole moment of the electron

ACME Collaboration

Nature **562**, 355–360 (2018) | Cite this article

$$|d_e| \lesssim 10^{-29}\ e\ \mathrm{cm}$$

Recent results: nuclear EDMs

Reduced Limit on the Permanent Electric Dipole Moment of $^{199}\mathrm{Hg}$

B. Graner, Y. Chen ((陳宜)), E. G. Lindahl, and B. R. Heckel
Phys. Rev. Lett. **116**, 161601 – Published 18 April 2016; Erratum Phys. Rev. Lett. **119**, 119901 (2017)

New Limit on the Permanent Electric Dipole Moment of $^{129}\mathrm{Xe}$ Using $^{3}\mathrm{He}$ Comagnetometry and SQUID Detection

N. Sachdeva, I. Fan, E. Babcock, M. Burghoff, T. E. Chupp, S. Degenkolb, P. Fierlinger, S. Haude, E. Kraegeloh, W. Kilian, S. Knappe-Grüneberg, F. Kuchler, T. Liu, M. Marino, J. Meinel, K. Rolfs, Z. Salhi, A. Schnabel, J. T. Singh, S. Stuiber, W. A. Terrano, L. Trahms, and J. Voigt
Phys. Rev. Lett. **123**, 143003 – Published 4 October 2019

Measurement of the permanent electric dipole moment of the $^{129}\mathrm{Xe}$ atom

F. Allmendinger, I. Engin, W. Heil, S. Karpuk, H.-J. Krause, B. Niederländer, A. Offenhäusser, M. Repetto, U. Schmidt, and S. Zimmer
Phys. Rev. A **100**, 022505 – Published 7 August 2019

Improved limit on the $^{225}\mathrm{Ra}$ electric dipole moment

Michael Bishof, Richard H. Parker, Kevin G. Bailey, John P. Greene, Roy J. Holt, Mukut R. Kalita, Wolfgang Korsch, Nathan D. Lemke, Zheng-Tian Lu, Peter Mueller, Thomas P. O'Connor, Jaideep T. Singh, and Matthew R. Dietrich
Phys. Rev. C **94**, 025501 – Published 3 August 2016

Where next?

Techniques will continue to improve (larger coherence times, more atoms)

Creative choices of experimental systems to maximize amplification of P,T-violation (e.g., radioactive molecules @ TRIUMF, FrAg @ Chicago)

Nuclear theory improvements to better connect experimental measurements with new physics parameters

Work in my group

Developing new techniques for electron EDM measurements

… *trapping large quantities of molecules in neon ice crystals*
eg, arXiv: 2207.07279

Exploring new experimental systems

… *octupole-deformed nuclei doped in non-centrosymmetric crystals*

Please talk to me if you are interested.

We have openings for students & postdocs!

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