Cold molecules as a laboratory for particle physics

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Fundamental inversions

C  particle → antiparticle  \((Q \rightarrow -Q)\)

P  position → inverted  \((\vec{r} \rightarrow -\vec{r})\)

T  time → reversed  \((t \rightarrow -t)\)
Symmetries

Weak interactions are not symmetric under P or C

normal matter - n, μ, π - readily breaks C and P symmetry.

The combination CP is different

normal matter respects CP symmetry to a very high degree.

Time reversal T is equivalent to CP (CPT theorem)

normal matter respects T symmetry to a very high degree.
Electric dipole moment (EDM) breaks P and T symmetry

- Elementary particle
- Spin
- EDM

$P$ no big deal

$\mathcal{CP}$ big deal
Two motivations to measure EDMs

EDM violates T symmetries

Deeply connected to CP violation and the matter-antimatter asymmetry of the universe

EDM is effectively zero in standard model but big enough to measure in non-standard models

direct test of physics beyond the standard model
$CP$ from particles to atoms (main connections)

- **Field theory $CP$ model**
  - Higgs
  - SUSY Left/Right
- **Electron/quark level**
  - $d_e$
  - $d_q$
  - $d_{c_q}$
- **Nucleon level**
  - $d_n$
- **Nuclear level**
  - Schiff moment
- **Atom/molecule level**
  - $d_{para}$
  - $d_{dia}$
A bit of history

![Graph showing experimental limits on d (e.cm) from 1960 to 2000. The graph compares neutron and electron limits. The vertical axis represents the limit in e.cm, ranging from $10^{-38}$ to $10^{-20}$. The horizontal axis represents years from 1960 to 2000.](image)

- **Electromagnetic**
- **Multi Higgs**
- **SUSY $\phi \sim 1$**
- **Left-Right $\phi \sim \alpha/\pi$**

**Standard Model**
The Electron EDM
The basic idea of the method

$\eta d_e \sigma$

Interaction energy

$-d_e \eta \vec{E} \cdot \sigma$

odd under P and T

electric field

system containing electron
The most sensitive electron EDM expt.

At Berkeley using thallium atoms

final result

$d_e < 1.6 \times 10^{-27} \text{ e cm}$

B. C. Regan et al., (PRL Feb 2002)
Molecular electron EDM experiments
potentially very much more sensitive

The Sussex experiment uses ytterbium fluoride molecules
EAH, BE Sauer, J Hudson, M Tarbutt

Yale is preparing an experiment using lead oxide
D deMille et al.

Why use such complicated systems?.................
Because some heavy polar molecules have large $\eta E$

YbF is particularly good: $\eta \sim 10^6$

for Tl atoms $\eta$ is "only" $\sim -600$
Calculations of maximum $\eta$ in YbF

$\eta E$ (GV/cm)

F. A. Parpia

H. M. Quiney, H. Skaane, I. P. Grant

M. G. Kozlov

A. V. Titov, N. S. Mosyagin, V. F. Ezhov

M. G. Kozlov, V. F. Ezhov
Forming and probing a YbF beam

1500K heater

Mo crucible

Yb and AlF₃ mixture

YbF beam

PMT

mirror

probe laser
The A-X 0-0 band

bandhead at 552.1 nm
The lowest two levels of YbF in an electric field $E$

$X^2\Sigma^+ (N = 0, v = 0)$

Goal: to measure the splitting $2d_e \eta E$
Interferometer to measure $2d_e \eta E$

Phase difference = $2 \left( \mu_B B + d_e \eta E \right) T / \hbar$
The interferometer fringe

Phase difference = $2(\mu_B B + d_e \eta E) T / \hbar$
Calibrating the fringe

$\delta \phi = \frac{4\mu_B \delta B T}{\hbar}$

Detector count rate vs. Applied magnetic field
Measuring the edm

Detector count rate

$-4d_e \eta ET/h$

$\delta \phi = 4d_e \eta ET/h$

Applied magnetic field

$-B_0$

$B_0$
Typical edm data

~1 hour of data: 80 s per point
Summary of our edm data
(taken summer 2001)

edm ($10^{-26}$ e.cm)

1.1 \times 10^{10} counts (24 hours)
Histogram of measured $d_e/\sigma$

Mean value: $(-0.2 \pm 3.2) \times 10^{-26}$ e.cm

There is no sign of systematic errors

arXiv hep-ex0202014
Future $d_e$ prospects

**Trapped atoms** may work but ......
main problems: $B$ fields $\perp$ to $E$ (nG-pG)
$E \times v/c^2$
shifts due to trap light

**Cold molecules** are harder to produce but ......
A thousand times bigger edm effect

$-d_e \eta E \cdot \sigma$

$\sim 30$GV/cm

A million time less bothered by
stray or motional $B \perp$ (mG-$\mu$G)
1500K thermal source

174 Q(0)  172 P(8)

Laser offset frequency (MHz)

3×10^5 useful molecules per second

10K supersonic source

174 Q(0)  172 P(8)

Laser offset frequency (MHz)

3×10^7 useful molecules per second
Possible experiment with trapped molecules

- Supersonic source
- Decelerator
- Trap \( \tau \sim 1 \text{s} \)
- Pump
- Split
- Recombine
- Probe
- Interferometer
### Signal:noise figures

<table>
<thead>
<tr>
<th></th>
<th>this result</th>
<th>supersonic beam</th>
<th>cold cloud</th>
</tr>
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<tbody>
<tr>
<td>background</td>
<td>150kHz</td>
<td>640kHz</td>
<td>40kHz</td>
</tr>
<tr>
<td>fringe height</td>
<td>1.5 kHz</td>
<td><strong>160 kHz</strong></td>
<td>10 kHz</td>
</tr>
<tr>
<td>coherence time</td>
<td>1.5 ms</td>
<td>1 ms</td>
<td><strong>1 s</strong></td>
</tr>
<tr>
<td>$d_e$ in 1 day</td>
<td>$3 \times 10^{-26}$ e cm</td>
<td>$6 \times 10^{-28}$ e cm</td>
<td>$3 \times 10^{-30}$ e cm</td>
</tr>
</tbody>
</table>

- Long time = narrow fringes
Current status of EDMs

- $d(\text{muon}) < 7 \times 10^{-19}$
- $d(\text{proton}) < 6 \times 10^{-23}$
- $d(\text{neutron}) < 6 \times 10^{-26}$
- $d(\text{electron}) < 1.6 \times 10^{-27}$

Cold molecules
Conclusion

Cold molecules have great potential to elucidate

- CP violation
- particle physics beyond the standard model
- matter/antimatter asymmetry of the universe

some of the most fundamental issues in physics