When Atomic Physicists *Escape:* Baryogenesis; Materials; Liquids

artist: Andy Singer
As of 2013, the electron electric dipole moment $\text{eEDM}$ was already known to be small $d_e < 10^{-27} \text{ e-cm} < 10^{-14} \text{ e r_{classical} (Berkeley, Imperial)}$

Why do better?
The situation, approximately 14 billion years before right now:

BANG
Then, shortly thereafter:
Then, the universe expanded and cooled:
Then, true love!
After the big bang cooled, most matter and antimatter annihilated, but tiny bit of matter left over, hooray! Why?
There is CP violation in known present-day particle physics but not enough. Where is it hiding?

As of 2013, the electron electric dipole moment $e$EDM was already known to be small
$d_e < 10^{-27} \text{ e-cm}$
$< 10^{-14} \text{ e r}_{\text{classical}}$ (Berkeley, Imperial)

Why do better?
Measuring electron EDM using molecular ions

JILA eEDM collaboration
Past Group Members

- **Laura Sinclair**
- Kang-Kuen Ni
- Kevin Cossel
- Russ Stutz
- Aaron Leanhardt
- Yiqi Ni
- Huanqian Loh
- Matt Grau

Local theory: John Bohn

Non local Theory: Bob Field

Still Less Local Theory

St. Petersburg quantum chemistry group

Thanks: NSF/PFC, NIST, and Marsico Foundation
How to measure eEDM? First, how do we measure eMDM?
How to measure $e$EDM?
Figure-of-merit:
What makes a good EDM experiment?

Combined Figure-of-merit:
\[ \text{eff} N = \frac{E}{E_1/\tau} \]
Figure-of-merit: What makes a good EDM experiment?

Big Electric Field!

$2d_eE$
Figure-of-merit: What makes a good EDM experiment?

- Big Electric Field!
- Long Coherence Time (narrow resonances)! 

Combined Figure-of-merit: \( \frac{\text{eff} N}{E_{\text{eff}} \tau} \)
Problem: Big E, long $\tau$. Electron accelerates quickly, and is gone????
Our approach. 1. Use molecule for big $E_{\text{eff}}$

(we follow Hinds and Demille in this)

\[ E_{\text{lab}} = 10 \text{ V/cm} \quad E_{\text{eff}} > 10^{10} \text{ V/cm} \]
Our approach. 2. Use trapped ion for long $\tau$

(atomic spectroscopy in ion traps sees many seconds)

We will work in an ion trap.
Secular trap motion at $\omega_{seco} \approx 2\pi(4 \text{ kHz})$

“RF” micromotion at $\omega_{rf} = 2\pi(50 \text{ kHz})$

Rotational micromotion at $\omega_{rot} = 2\pi(250 \text{ kHz})$

Rotating magnetic field: not sensitive to DC fields
Ramsey Fringe – Electron Spin Resonance

\[ \Delta E = 3g_u \mu_B B_r + 2d_e E_{\text{eff}} \]

\( \tau > 0.5 \text{ s} \)
2016.08.30 Matt Grau - Measuring the electron EDM with trapped molecular ions
<table>
<thead>
<tr>
<th>Frequency channel</th>
<th>All data</th>
<th>2017 only</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f^R$</td>
<td>2.6(9) mHz</td>
<td>3(1) mHz</td>
</tr>
<tr>
<td>$f^{DR}$</td>
<td>−0.6(8) mHz</td>
<td>−1(1) mHz</td>
</tr>
<tr>
<td>$f^{BD}$</td>
<td>34.5(8) mHz</td>
<td>34.4(1.0) mHz</td>
</tr>
<tr>
<td>$f^{BDR}$</td>
<td>0.4(9) mHz</td>
<td>−0.3(1.0) mHz</td>
</tr>
</tbody>
</table>
\[ f_{BD} = (0.10 \pm 0.87_{\text{stat}} \pm 0.20_{\text{syst}}) \text{ mHz} \]

\[ d_e = (0.09 \pm 0.77_{\text{stat}} \pm 0.18_{\text{syst}}) \times 10^{-28} \text{ e.cm} \]

\[ |d_e| < 1.4 \text{ mHz} \]

\[ |d_e| < 1.3 \times 10^{-28} \text{ e.cm} \]
Martin Jung, Preliminary

The graph shows the relationship between $C_s/10^7$ and $d_e/10^{-27}$ e-cm. The data is categorized by different materials:
- Green: ThO
- Blue: Ti
- Red: YbF
- Orange: HfF$^+$

The graph includes a legend indicating 'global w/o HfF$^+$' and 'global w/ HfF$^+$'.
Figure 9: EDM constraints on the stop parameter space in the MSSM, where stop loops with large $A$-term lift the Higgs mass to 125 GeV. The horizontal axis shows the common stop soft mass $m_{\text{stop}} = \tilde{m}_{Q_3} = \tilde{m}_{u_3}$. At left we fix $m_A = 400$ GeV and vary $\tan \beta$ on the vertical axis; at right we fix $\tan \beta = 10$ and vary $m_A$ on the vertical axis. In the brown/green shaded region, no choice of $A_t$ is sufficient to achieve the correct Higgs mass. In the rest of the parameter space, at each point we choose $A_t$ to achieve $m_h = 125$ GeV. Regions of parameter space to the left of the solid blue contours are excluded by measurements of ThO. Red solid and dashed contours denote the mercury EDM constraints for the cases (i) and (ii) discussed in Appendix C), respectively. The blue dashed and dot-dashed contours (“ACME II” and “ACME III”) are future projections. The dotted green lines display the tree-level Higgs fine tuning (26). We have fixed $|\mu| = 350$ GeV in these figures.
Figure 9: EDM constraints on the stop parameter space in the MSSM, where stop loops with large $A$-term lift the Higgs mass to 125 GeV. The horizontal axis shows the common stop soft mass $m_{stop} = \tilde{m}_{Q_3} = \tilde{m}_{u_3}$. At left we fix $m_A = 400$ GeV and vary $\tan \beta$ on the vertical axis; at right we fix $\tan \beta = 10$ and vary $m_A$ on the vertical axis. In the brown/green shaded region, no choice of $A_t$ is sufficient to achieve the correct Higgs mass. In the rest of the parameter space, at each point we choose $A_t$ to achieve $m_h = 125$ GeV. Regions of parameter space to the left of the solid blue contours are excluded by measurements of ThO. Red solid and dashed contours denote the mercury EDM constraints for the cases (i) and (ii) discussed in Appendix C), respectively. The blue dashed and dot-dashed contours (“ACME II” and “ACME III”) are future projections. The dotted green lines display the tree-level Higgs fine tuning (26). We have fixed $|\mu| = 350$ GeV in these figures.
Many other “AMO type” particle physics work. H. Muller

other electric dipole moment experiments in Harvard/Yale, Penn State

electric dipole moments of mercury atom, or radium atom, of neutron.

anomalies in magnetic moments

time-varying physical “constants”.

CPT violation? Gravity and antimatter? F. Sorrentino

search for axions

tests of gravitational theory. I Carusotto. G. Rosi. V. Fleurov

And let us recall the “O” in AMO. Optical detection of gravitational waves @ LIGO, VIRGO, maybe LISA? Optical gyrosopes. B Patricelli. D. Virgilio.
cold-atom capabilities:
  methods: lasers, evap cooling; individual atom detection
  confining potentials: magnetic, or optical. harmonic or square or lattice.
  bosons and fermions. tunable interactions. reduced dimensions.
  *many of these things changeable in real time,* 
  *dynamically*
  more recently, synthetic magnetic field.
Site-resolved imaging of single atoms on a 640-nm-period optical lattice, loaded with a high density Bose–Einstein condensate.

The Hubbard Model

Spin Correlation Function

Entropy Redistribution

Long-range Antiferromagnet

\[ (-1)^j C_d \]

\[ d \text{ (sites)} \]

Potential

\[ \Omega \]

Position
cold-atom capabilities:
methods: lasers, evaporative cooling.; individual atom detection
containers: magnetic, or optical. harmonic or square or lattice.

bosons and fermions. tunable interactions. reduced dimensions. many of these things changeable in real time, dynamically more recently, synthetic magnetic field. Few body, many body.

See talks from: M Koehl. G. Rossini. V. Fleurov
liquids:
Where most chemistry happens.
Where all life happens.
liquids:

Where most chemistry happens.

Where all life happens.

macroscopic definition:
has a free surface.
liquids:
Where most chemistry happens.
Where all life happens.

macroscopic definition: has a free surface.

but microscopically...
microscopically, a liquid is where one atom can move only if some other atoms get out of the way.
As physicists, we often like to approach a problem perturbatively. We start with...

A solid: lattice at T=0.
perturbatively add carriers, phonons, etc

A gas: noninteracting molecules with good \( k \).
perturbatively add rare k-changing collisions, mean field, etc
As physicists, we often like to approach a problem perturbatively. We start with...

A solid:
lattice at
T=0.
perturbatively add carriers, phonons, etc

A liquid:
??? Not T=0. No single-atom $k$
perturbatively add rare $k$-changing collisions, mean field, etc

A gas:
noninteracting molecules with good $k$.
Except, superfluid liquid! Liquid at $T=0$!

*Macroscopic* physics very exotic.
Except, superfluid liquid! Liquid at T=0! *Macroscopic* physics very exotic. *Microscopically* it’s actually easier to understand than a regular liquid.
Except, superfluid liquid! Liquid at T=0!  
*Macroscopic* physics very exotic.  
*Microscopically* it’s actually easier to understand than a regular liquid.

But comes only as liquid helium. 
Microscopic probes are difficult.
Microscopic probes in Liquid Helium are tricky.

\[ \text{LHe } T = 0.35 \text{ K} \]

\[ \text{LHe } T = 3.5 \text{ K} \]

FIG. 8. Observed scattering at \( T = 0.35 \text{ K} \). The dashed line is the GFMC prediction of Whitlock and Panoff broadened by the instrumental resolution function and by Silver's FSE broadening function.

FIG. 7. Observed scattering at \( T = 3.5 \text{ K} \). The dashed line is the PIMC prediction of Ceperley and Pollock broadened by the instrumental resolution function and by Silver's FSE broadening function.

Data from Sokol et al 1990.
Idea:
Ultracold atomic gases!
Many wonderful probes.
Tuneable interactions,
Tuneable dimensionality,
Lots more experimental tools than LHemium

Q: Can we make them liquid like, and in that way learn something about liquids?

A: Maybe.

Work in progress!
Strongly interacting degenerate bose fluid:
A few-body approach to a many-body challenge

Cathy Klauss, Xin Xie
Carlos Lopez-Abadia

Debbie Jin, E.C
Jose d’Incao
visiting scientist:  
Zoran Hadzibabic

former group members
Rob Wild, Phil Makotyn

Thanks:  NSF, NIST, NASA
This portion of the talk is dedicated to the memory of Deborah S. Jin (1968-2016).
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Work in progress!
Feshbach Resonance

\[ \delta B \]

\[ E_b \]

\[ B_{peak} = 155 \text{ G} \]
\[ \Delta = 10.7 \text{ G} \]

Strong, attractive interactions

Strong, repulsive interactions
Feshbach Resonance

\[ \alpha \]

Strong, repulsive interactions

Where we want to be

Strong, attractive interactions

\[ \delta B \]

\[ B_{\text{peak}} = 155 \text{ G} \]
\[ \Delta = 10.7 \text{ G} \]
Cold Bosons: The Regimes

Unitary Thermal Gas

Dilute hard-sphere, noncondensed gas

Degenerate Unitarity

LHY correction

Mean Field BEC

1/a
The 3-body recombination catastrophe.

Generic phase diagram
The 3-body recombination catastrophe.

Generic phase diagram
The 3-body recombination catastrophe.

Thermalization – two-body collisions
\[ \gamma \sim n a^2 \]

Decay – 3-body recombination
\[ \gamma \sim n^2 a^4 \]
Feshbach Resonance

\[ B_{peak} = 155 \text{ G} \]
\[ \Delta = 10.7 \text{ G} \]

Strong, repulsive interactions

Strong, attractive interactions

Where we want to be
Degenerate Unitarity

Two length scales

one length scale

DILUTE

DILUTE!

1/a

n^{-1/3}

n^{-1/3}

α

λ

Two length scales

not Dilute!
Degenerate Unitarity

\[ E_n \equiv \frac{\hbar^2 (6\pi^2 n)^{2/3}}{2m} \]

Two length scales

One length scale

\[ n^{-1/3} \]

\[ 1/a \]

Two length scales

\[ \lambda \]

\[ n^{-1/3} \]
Basic spherical BEC setup

\[ N_{BEC} = 6 \cdot 10^4 \]

\[ \omega = 2 \pi 10 \text{ Hz} \]

\[ \langle n \rangle = 5 \cdot 10^{12} \text{ cm}^{-3} \]

T < 10 nK
Feshbach Resonance

$B_{\text{peak}} = 155 \text{ G}$
$
\Delta = 10.7 \text{ G}$

$E$

5 $\mu$s

$B$

$\alpha$
Total atoms remaining v. time at unitarity
Total atoms remaining v. time at unitarity

Time constant \( \sim 6 t_n \)
(rate \( \sim (1/6) E_n \))
$\Gamma \sim n^{2/3}$
Loss Rate at Unitarity

\[ \Gamma \sim n^2 \]

\[ \Gamma \sim n^{2/3} \]
Cold Bosons: The Regimes

- Unitary Thermal Gas
- Dilute hard-sphere, noncondensed gas
- Degenerate Unitarity
- LHY correction
- Mean Field BEC

1/a
How can we learn more about this short-lived (but not infinitely short-lived) exotic, liquid-like *many-body* state?

First, let’s review underlying *few-body* physics.
Feshbach Resonance: evidence for existence of a two-body boundstate!
Three-body Efimov states

From Ferlaino and Grimm (Phys. Today, 2010)
Three-body Efimov states

From Ferlaino and Grimm (Phys. Today, 2010)
Feshbach Resonance: evidence for existence of a two-body boundstate!

Various ways to create a population in the molecule state.
Enhanced loss (changes in imaginary part of scattering length) identifies curve crossing in bound states.

Can we, instead, create a “population”? 

From Ferlaino and Grimm (Phys. Today, 2010)
Three-body Efimov states

From Ferlaino and Grimm (Phys. Today, 2010)
Lifetime at a $\to$ infinity is short but not infinitely short.

1. Jump on resonance
2. Let evolve
3. Ramp out to region of well-understood few-body phys.
4. Maybe, learn about physics that evolves at a $\to$ infinity
Jumping to Unitarity

\[ a = 100 \, a_0 \]

\[ \frac{1}{a} \]

Turn off interactions and allow the cloud to expand

\[ a = \pm \infty \]

hold time

image time
Dimer Dissociation

Energy (kHz)

B Field (Gauss)
Trimer Dissociation
molecule number

\[ N = A_1 e^{-t/t_1} + A_2 e^{-t/t_2} \]

\[
\begin{align*}
A_1 &= 950(120) \\
t_1 &= 125(36) \\
A_2 &= 4110(120) \\
t_2 &= 2170(130)
\end{align*}
\]

26 Sep 2016

- \( n: 0.208 \ (1.32) \ E12/cc \)
- \( \text{ramp: 10-760 (205) -10 \text{us / } 1.5 \text{tn}} \)
- \( \text{field: 159.2 / 698 \text{ a0}} \)
- \( \text{RF: \ c (10-30-10 \text{us)}} \)
  - 9dBm, 300 kHz, yes
- \( N: 82800 \ +/- \ 1800 \)
When Atomic Physicists Escape: Baryogenesis; Materials; Liquids
Three-body Efimov states

From Ferlaino and Grimm (Phys. Today, 2010)
$O_2$ (traditional two-atom molecule)

$^{85}\text{Rb}_3$ (Efimov molecule)
$^{85}\text{Rb}_3$ (Efimov molecule)
$^{85}\text{Rb}_3$ (Efimov molecule, generation 1)
$^{85}\text{Rb}_3$ (Efimov molecule, generation 1)

$^{85}\text{Rb}_3$ (Efimov molecule, generation 2)
From one “generation” to next,
linear size increases $\times 22.7$
binding energy decreases $\times 22.7^2 = 500$
volume increases $\times 22.7^3 = 12000$
$^{85}\text{Rb}_3$ (Efimov molecule, generation 2)
$^{85}\text{Rb}_3$ (Efimov molecule, generation 2)
From Ferlaino and Grimm (Phys. Today, 2010)
From one “generation” to next,
linear size increases \( x \ 22.7 \)
binding energy decreases \( x \ 22.7^2 = 500 \)
volume increases \( x \ 22.7^3 = 12000 \)
When Atomic Physicists Escape: Baryogenesis; Materials; Liquids
Ramsey Sequence

Transfer lasers prepare population in a single pair of Stark states
Ramsey Sequence

Optically deplete the population of one $m_F$ level using strobed circularly polarized light

Transfer
Ramsey Sequence

$\frac{\pi}{2}$ pulse puts system into the superposition

$$|m_F = -\frac{3}{2}\rangle + |m_F = +\frac{3}{2}\rangle$$

Transfer

\[\text{Hf} \quad \text{F} \quad +\]

\[\text{Hf} \quad \text{F} \quad +\]
Ramsey Sequence

Free evolution

\[ j''i \]
\[ J_xi \]
\[ J_yi \]
\[ J_\#i \]

Transfer

\[ \Delta E = 3g_u\mu_B B_r + 2d_e E_{eff} \]

\[ \Delta \phi = \frac{\Delta E}{\hbar} t \]
Ramsey Sequence

A second $\pi/2$ pulse projects the phase onto population

\[
\Delta P \propto \cos(\Delta \phi)
\]

Transfer

\[
\Delta E = 3g_u \mu_B B_r + 2d_e E_{eff}
\]
Ramsey Sequence

Optically deplete population out of one of the $m_F$ levels

$\Delta P \propto \cos(\Delta \phi)$

$\Delta E = 3g_u \mu_B B_r + 2d_e E_{eff}$
Ramsey Sequence

Dissociate all of the ions in the \( J = 1 \) level, and count Hf\(^+\) ions in the trap

\[
\Delta E = 3g_u \mu_B B_r + 2d_e E_{\text{eff}}
\]

Transfer
Ramsey Fringe

\[ \Delta E = 3g_u \mu_B B_r + 2d_e E_{eff} \]

\( \tau > 0.5 \text{ s} \)
Cold Bosons: The Regimes

Dilute hard-sphere, noncondensed gas
Cold Bosons: The Regimes

- Unitary Thermal Gas
- Dilute hard-sphere, noncondensed gas

- LHY correction
- Mean Field BEC
Degenerate Unitarity

Two length scales

Unitary Thermal Gas

Two length scales

Mean Field BEC
Degenerate Unitarity: Why is it interesting?

Two length scales

One length scale

Two length scales

$\lambda$

$n^{-1/3}$

$\alpha$

$\frac{1}{a}$
Three boson inelastic loss: The Regimes

confirmed by Paris group!

\[ \Gamma_3 \propto E_n \left( \frac{T_c}{T} \right)^2 \]

\[ a \rightarrow \lambda_{db} \sim T^{1/2} \]

\[ \Gamma_3 \propto E_n (na^3)^{4/3} \]

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Three boson inelastic loss: The Regimes

\[ \Gamma_3 \propto E_n \left( \frac{T_c}{T} \right)^2 \]

\[ \rightarrow T_{\text{depletion}} \sim T_c \]

\[ k_{\text{depletion}} \sim n^{1/3} \]

\[ \rightarrow \lambda_{db} \sim T^{1/2} \]

\[ a \rightarrow n^{-1/3} \sim T^{1/2} \]

\[ \Gamma_3 \propto E_n (na^3)^{4/3} \]

\[ \left( E_n \sim E_f \sim n^{2/3} \right) \]
Three boson inelastic loss: The Regimes

$\Gamma_3 \propto n^2 a^4$

$\Gamma_3 \propto n^{2/3} n^{4/3} a^4$

$\Gamma_3 \propto E_n (na^3)^{4/3}$