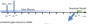
Probing Physics Beyond the Standard Model
with
the JILA electron's Electric Dipole Moment (eEDM) Experiment

Kia Boon Ng
Cornell/Ye JILA eEDM Collaboration
Developing New Directions, 5 November 2020

Where are we?


ACME, 2018
JILA, 2017
New Physics
Standard Model
10^{-28}
10^{-29}
10^{-38}
e cm

Experimental upper bound on eEDM

eEDM only appears in fourth loop

Cairncross, et al. *Physical review letters* 119.15 (2017): 153001.
Baron, et al. *Science* 343.6168 (2014): 269-272.
Baron, et al. *New Journal of Physics* 19.7 (2017): 073029.
ACME Collaboration, *Nature* volume 562, pages 355–360 (2018).

At JILA

```
|d_e| < 1.4 mHz

|d_e| < 1.3e-28 e.cm
```

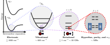
Dr. Will Cairncross
@ Harvard currently

- Molecular ions
  - Molecules: easily polarizable, etc.
  - Ions: trapped, for long coherence time
- Molecules of choice
  - HfF⁺: Generations I & II
  - ThF⁺: Generation III

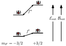
Me

Cairncross, et al. Physical review letters 119.15 (2017): 153001.

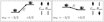
Molecules 101


$^3\Sigma^+$
$^3\Delta_1$
Energy
Internuclear separation
$^3\Delta_1$
$v = 0$
$J = 1$
Electronic
$\gtrsim 1000$ cm^{-1}
Vibrational
~ 600 cm^{-1}
Rotational
$\lesssim 1$ cm^{-1} ~ 30 GHz
Hyperfine, parity, and m_F
$\sim$ MHz

eEDM-sensitive state (science state)


f^u
f^l
$\mathcal{E}_{\text{ext}}$
$\mathcal{B}_{\text{ext}}$
$m_F = -3/2$
$+3/2$

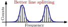
eEDM-sensitive state (science state)


$f^u_\uparrow$
$\mathcal{E}_{\rm rot}$
$\mathcal{B}_{\rm rot}$
$m_F = -3/2$
$+3/2$
$f^u_\downarrow$
$\mathcal{E}_{\rm rot}$
$\mathcal{B}_{\rm rot}$
$m_F = -3/2$
$+3/2$

$$f^u_{(\uparrow/\downarrow)} = |\pm 3 g \mu_B \mathcal{B}_{\rm rot} + 2 d_e \mathcal{E}_{\rm eff}|$$

$$d_e \mathcal{E}_{\rm eff} = \frac{1}{4}\left(f^u_\uparrow - f^u_\downarrow\right)$$

What we care about



$$\delta d_e \sim \frac{1}{\boxed{\mathcal{E}_{\text{eff}}}\boxed{\tau}\boxed{\sqrt{N}}}$$

Improvements

$\delta d_e \sim \frac{1}{E_{eff}\,\tau\,\sqrt{N}}$

Gen. III

	ThF⁺	HfF⁺
Effective *E*-field	35.2 *GV/cm*	23.4 *GV/cm*
Science state	0 cm⁻¹	977 cm⁻¹
Expected Coherence	~20 s	2 s

Gen. II

45° section view

[illegible]

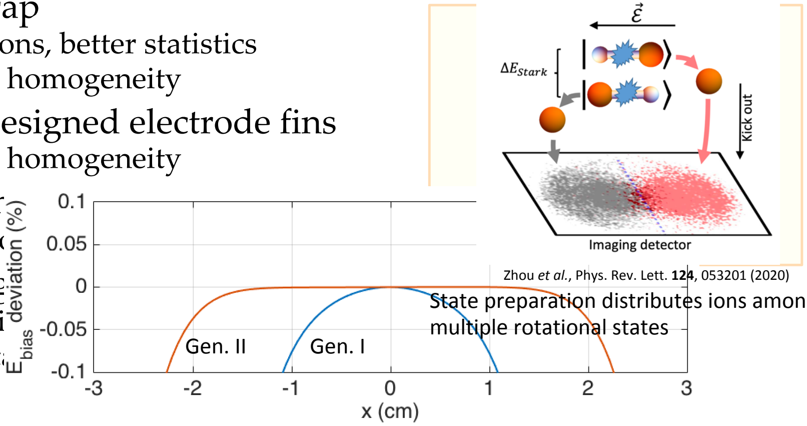
[illegible]

[illegible]

Generation II

* Co-developed with ThF$^+$ (Gen. III)

- Bigger trap
  - More ions, better statistics
  - *E*-field homogeneity
- Newly designed electrode fins
  - *E*-field homogeneity
- *Rotatio
  - More i
- *2D imag
  - Better i
  - Two-st



Zhou *et al.*, Phys. Rev. Lett. **124**, 053201 (2020)

State preparation distributes ions among multiple rotational states

Generation II

	Gen. I	Gen. II	Improvement on [illegible]	Notes
Ion number at side of fringe	5	150	5.5	Bigger trap More efficient state prep. New detection technique
Fringe contrast at late time	0.30	0.55	1.8	New detection technique
Ramsey interrogation time (s)	0.70	1.6	1.5	Bigger trap Better field homogeneity

x15 statistical sensitivity from Gen. I

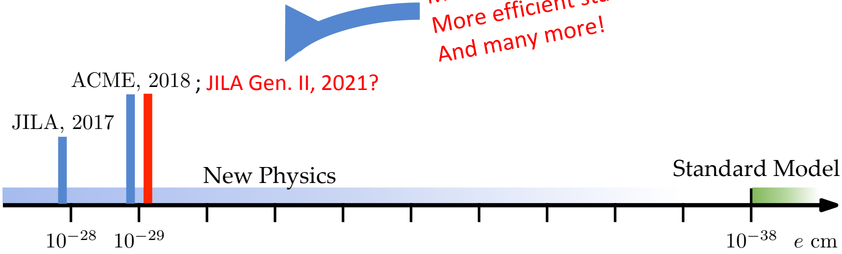
Generation II

- Optimized
  - State preparation
  - State detection

- Studying systematics of new trap

- Ready to go!

Where are we?



More ions!
More uniform E-fields!
More efficient state prep. & readout!
And many more!

Cairncross, et al. *Physical review letters* 119.15 (2017): 153001.
Baron, et al., *Science* 343.6168 (2014): 269-272.
Baron, et al., *New Journal of Physics* 19.7 (2017): 073029.
ACME Collaboration, *Nature* volume 562, pages355–360 (2018).

Improvements

$$\delta d_e \sim \frac{1}{E_{eff}\,\tau\,\sqrt{N}}$$

Gen. III

	ThF+	HfF+
Effective *E*-field	35.2 *GV/cm*	23.4 *GV/cm*
Science state	0 cm⁻¹	977 cm⁻¹
Expected Coherence	~20 s	2 s

Gen. II

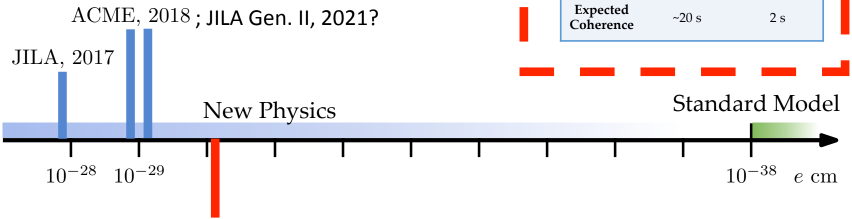
45° section view

[illegible], et al. New Journal of Physics [illegible]
[illegible], et al. Physical Review A [illegible]
[illegible], et al. Physical Review A [illegible]

Where can we be?

$$\delta d_e \sim \frac{1}{\mathcal{E}_{\text{eff}}\tau\sqrt{N}}$$

	ThF^+	HfF^+
Effective *E*-field	35.2 GV/cm	23.4 GV/cm
Science state	0 cm^{-1}	977 cm^{-1}
Expected Coherence	~20 s	2 s



JILA Gen. III @ 10^{-30} e·cm?

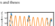
Cairncross, et al. *Physical review letters* 119.15 (2017): 153001.
Baron, et al., *Science* 343.6168 (2014): 269-272.
Baron, et al., *New Journal of Physics* 19.7 (2017): 073029.
ACME Collaboration, *Nature* volume 562, pages 355–360 (2018).

EXCEPT, no information of ThF^+ energy levels on NIST, Google, etc.

After a decade of spectroscopy

- Resulting in multiple papers and theses

- First Ramsey fringe!

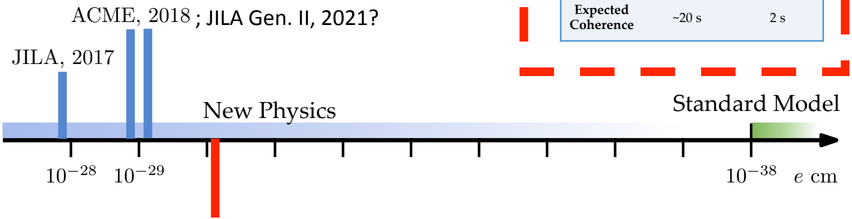


Zhou, et al., [illegible] (2019) 1-16
Gresh, et al., [illegible] (2016) 1-9
Barker, et al., [illegible] (2016) [illegible]
Ng, et al., in preparation

Where can we be?

$$\delta d_e \sim \frac{1}{\mathcal{E}_{\text{eff}}\tau\sqrt{N}}$$

	ThF$^+$	HfF$^+$
Effective E-field	35.2 GV/cm	23.4 GV/cm
Science state	0 cm^{-1}	977 cm^{-1}
Expected Coherence	~20 s	2 s



JILA Gen. III @ 10^{-30} e·cm?

ONLY?!

Cairncross, et al. *Physical review letters* 119.15 (2017): 153001.
Baron, et al., *Science* 343.6168 (2014): 269-272.
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$$\delta d_e \sim \frac{1}{\boxed{\mathcal{E}_{\mathrm{eff}}\tau}\boxed{\sqrt{N}}}$$

ThF$^+$:
- $\mathcal{E}_{\mathrm{eff}}$ is 1.5 times that of HfF$^+$
- τ is 10 times that of HfF$^+$

Run 100 experiments at once?

One experiment at a time

$$\delta d_e \sim \frac{1}{\mathcal{E}_{\text{eff}} \tau \sqrt{N}}$$

$$f_{\text{exp}} \approx 1/\tau$$

$$\boxed{\delta d_e \sim \frac{1}{\mathcal{E}_{\text{eff}} \sqrt{\tau} \sqrt{N_{\text{single}} \cdot T_{\text{tot}}}}}$$

100 experiments at a time

$$\delta d_e \sim \frac{1}{\mathcal{E}_{\rm eff}\tau\sqrt{N}} = \frac{1}{\mathcal{E}_{\rm eff}\tau\sqrt{N_{\rm single}\cdot f_{\rm rep}\cdot T_{\rm tot}}}$$

$f_{rep} = 5$ Hz
$\tau = 20$ s
$f_{rep}\,\tau = 100$

Paul trap 101

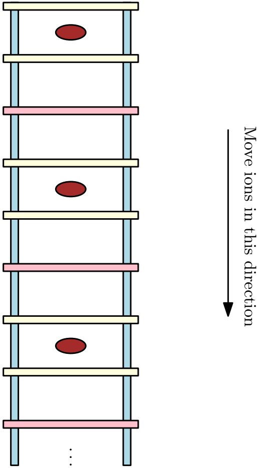
- Axial confinement
  - Potentials applied on end caps (red)
- Radial confinement
  - Time-varying potentials applied on radial electrodes (blue)

Side view

Paul trap 101 – *Bucket Brigade*

Side view
Bottom view

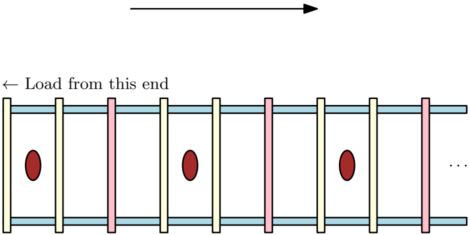
Paul trap 101 – *Bucket Brigade*


Move ions in this direction

Side view

Paul trap 101 – *Bucket Brigade*

Side view

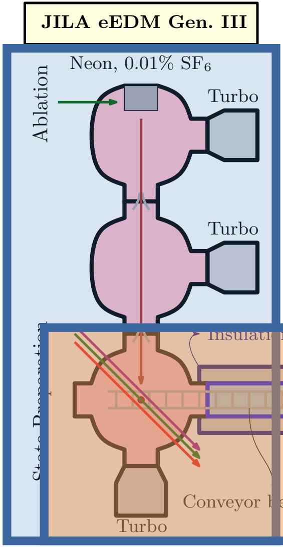


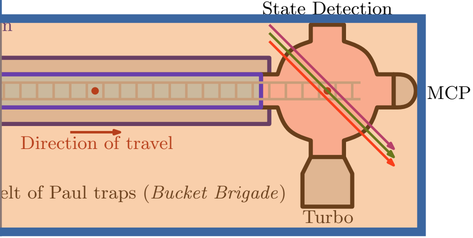
Move ions in this direction

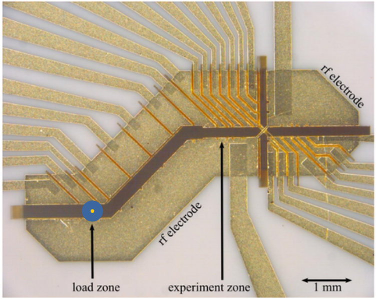
← Load from this end

. . .

Kick-out from that end →


JILA eEDM Gen. III
Neon, 0.01% SF_6
Ablation
Turbo
Turbo
State Preparation


State Detection
Insulation
MCP
Direction of travel
Conveyor belt of Paul traps (*Bucket Brigade*)
Turbo
Turbo

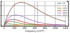

rf electrode
rf electrode
load zone
experiment zone
1 mm

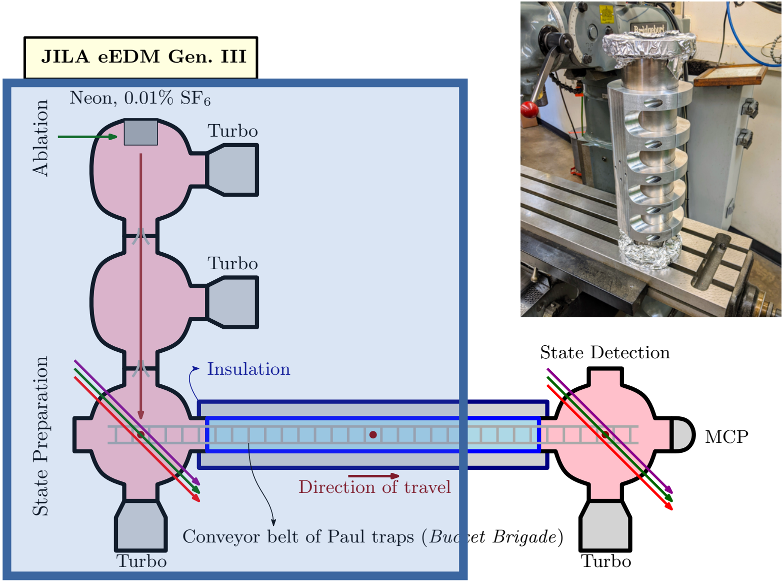
NIST, Ion Storage Group

JILA eEDM Gen. III

New in JILA eEDM Gen. III (*Bucket Brigade*)

Blackbody Radiation Excitation




JILA eEDM Gen. III
Neon, 0.01% SF_6
Ablation
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Turbo
Insulation
State Preparation
Direction of travel
Conveyor belt of Paul traps (*Bucket Brigade*)
Turbo
State Detection
MCP
Turbo

JILA eEDM Gen. III Prototype, 2021

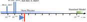
Generation III

	Gen. II	Gen. III	Improvement on $\delta d_e \times \sqrt{\text{hour}}$	Notes
Ion number at side of fringe	150	15	0.32	Smaller number of ions per bucket
Fringe contrast at late time	0.55	-	-	Students won’t graduate until they hit ≥0.55
Ramsey interrogation time (s)	1.6	20	13	Ground science state + cryogenics for BBR
Repetition rate (Hz)	0.63	5	2.8	Multiplexing
$\mathcal{E}_{\text{eff}}$ (GV/cm)	23	35	1.5	HfF^+ → ThF^+

x17 statistical sensitivity from Gen. II

Stay tuned!

$$\delta d_e \sim \frac{1}{\mathcal{E}_{\text{eff}}\tau\sqrt{N}}$$


ACME, 2018
JILA Gen. II, 2021?
JILA, 2017
New Physics
Standard Model
10^{-28}
10^{-29}
10^{-38}
e cm

JILA Gen. III @ 10^{-31} e-cm!

Cairncross, et al. *Physical review letters* 119.15 (2017): 153001.
Baron, et al. *Science* 343.6168 (2014): 269-272.
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Acknowledgement

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- Marsico Research Chair

JILA pfc

NIST

GORDON AND BETTY MOORE FOUNDATION

Alfred P. Sloan FOUNDATION

NSF

Current Members

PIs: Prof. Eric Cornell, Prof. Jun Ye
Gen II: Tanya Roussy, Trevor Wright, Dr. Luke Caldwell, Dr. Yuval Shagam
Gen III: Noah Schlossberger, Sun Yool Park, Anzhou Wang, Kia Boon Ng
Undergraduates: Antonio Vigil, Gus Santaella, Madeline Pettine