Progress and outlook in nuclear science on the search for new physics using EDMs

Roy J. Holt
Physics Division, Argonne National Laboratory
Outline

- Introduction
- The EDM experiments
  - leptonic
  - hadronic
- Summary
The big questions

- **Why do we exist?**
  - Why is there more matter than antimatter?
  - Only 1 part in $10^9$ of matter left from the big bang

- **Sakharov’s three conditions for a baryon asymmetry**
  - Baryon number violation
  - Microscopic C, CP (or T) violation
  - Thermal non-equilibrium

“The observation of a nonzero EDM in any of the above searches would constitute a major discovery with significant implications for the origin of matter and the nature of new forces in the early universe.”

*(NSAC Long Range Plan, 2015)*
Why EDMs?

- “... EDM searches shed light on one of the key questions for all of physics: why the present universe contains more visible matter than antimatter.” (*NSAC Long Range Plan, 2015*)

- “Improved sensitivities by a factor of 10–100 would imply reach on the scale of CPV interactions in the 10–50 TeV range, inaccessible at high-energy colliders today ...” (*NSAC Long Range Plan, 2015*)

- Impacts cosmology as well as high energy, nuclear, atomic and molecular physics

- No Standard Model background
**EDM Searches in Three Sectors**

- **Nucleons** (n, p)
- **Nuclei** (d, Hg, Xe, Ra, Rn)
- **Lepton** ($\mu^+$, YbF, ThO, HfF$^+$)

**Quark EDM**

**Quark Chromo-EDM**

**Lepton EDM**

**Physics beyond the Standard Model:** SUSY, etc.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Exp Limit (e-cm)</th>
<th>Method</th>
<th>Standard Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>$9 \times 10^{-29}$</td>
<td>ThO in a beam</td>
<td>$10^{-38}$</td>
</tr>
<tr>
<td>Neutron</td>
<td>$3 \times 10^{-26}$</td>
<td>UCN in a bottle</td>
<td>$10^{-31}$</td>
</tr>
<tr>
<td>$^{199}$Hg</td>
<td>$7.4 \times 10^{-30}$</td>
<td>Hg atoms in a cell</td>
<td>$10^{-33}$</td>
</tr>
</tbody>
</table>
Experiments worldwide

### Leptonic EDMs
- **YbF** (beam) - Imperial College
- **HfF⁺** (trapped) - JILA
- **ThO** (beam) - Harvard-Yale
- **²¹⁰Fr** (trapped) - CYRIC
- **²¹⁰Fr** (fountain) - TRIUMF
- **µ⁺** (ring) - FNAL
- **µ⁺** (ring) - J-PARC

### Hadronic EDMs
- **n** (vac) - ILL-PNPI
- **n** (beam,solid) - ILL
- **n** (vac) - PSI
- **n** (vac) - Munich-(ILL)
- **n** (⁴He) - RCNP-TRIUMF
- **n** (⁴He) - SNS nEDM
- **n** (vac) - J-PARC
- **n** (vac) - LANL
- **p** (ring) - (CERN)
- **d** (ring) - COSY
- **¹²⁹Xe** (cell) - Mainz/Juelich
- **¹²⁹Xe** (cell) - Tokyo Tech.
- **¹²⁹Xe** (cell) - Munich
- **¹⁹⁹Hg** (cell) - U. Washington
- **²²³Rn** (cell) - TRIUMF
- **²²⁵Ra** (trapped) - ANL (FRIB)
- **TlF** (beam) - Harvard-Yale
Precision in EDM measurements

\[ E = \hbar \omega = 2 \vec{d} \cdot \vec{E} \]

\[ \sigma_d = \frac{\Delta E}{2|\vec{E}|} \]

\[ \Delta E \Delta t \sim \hbar \]

\[ \nu = \frac{2 \vec{\mu} \cdot \vec{B} \pm 2 \vec{d} \cdot \vec{E}}{\hbar} \]

\[ \sigma_d = \frac{\hbar}{2|\vec{E}| \tau \sqrt{N}} \]

- E = electric field
- \( \nu \) = measured frequency
- \( \Delta E \Delta t \sim \hbar \)
- \( \sigma_d \) = precision
- \( \tau \) = coherence time
- \( N \) = number of counts

Ramsey separated oscillatory fields

1. "Spin up" neutron...
2. Apply 90° spin-flip pulse...
3. Free precession...
4. Second 90° spin-flip pulse...

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Systematics in EDM measurements

- Magnetic fields
  - shielding
- Field gradients
- (Co-)Magnetometry
- Correlations with E-field
- E x v effects
- Geometric phase effect
- ...

PSI n2EDM science chamber
Leptonic EDMs

Molecules: highly polarizable
10 V/cm -> $10^{10}$ V/cm effective electric field

$\mathcal{E}_{\text{eff}}$ - Effective Electric Field Inside the Molecule
$\mathbf{d}_e$ - Electric Dipole Moment of the Electron

$\mathcal{E}_{\text{lab}} \sim 100$ V/cm

$H^\prime_{de} = - \mathbf{d}_e \cdot \mathcal{E}_{\text{eff}}$

$\mathbf{d}_e$ interacts with $\mathcal{E}_{\text{eff}}$

$\mathcal{E}_{\text{eff}} \sim 10^{11}$ V/cm

Thanks to J. Doyle
Advanced Cold Molecule EDM

**Polar molecule:**
Large internal E-field (84 GV/cm) + Internal co-magnetometer to control systematics

Cryogenic molecular beam: large flux, good statistics

Thanks to D. DeMille

2nd generation upgrades now in place: >600x increase in count rate observed
Continuing search for new physics with ACME


Multi Higgs Left Right Symmetric

Lepton Flavor Changing

Split SUSY SO(10) GUT

Accidental Cancellations Approx. CP

Naïve SUSY Heavy sFermions

ACME Gen II (projected statistical)

ACME Ultimate (projected statistical)

ACME Gen II well underway! Results anticipated ~2017

Extended Technicolor

Alignment

Seesaw Neutrino Yukawa Couplings

Standard Model

Exact Universality

Multi Higgs

10^{-25} 10^{-26} 10^{-27} 10^{-28} 10^{-29} 10^{-30} 10^{-31} 10^{-32} 10^{-33} 10^{-34}

d_e (\text{e.cm})

\sim 10^{-40} 10^{-41}
YbF Electron EDM Measurement

Imperial College

Create YbF  Pump  Split  Evolve  Recombine  Probe

Increase number of molecules and detection efficiency

spin rotation angle $\propto d_e$

- Test EDM run to start late in 2016
- Expected sensitivity $2 \times 10^{-29}$ e-cm 90% CL
- Current limit $|d_e| < 9 \times 10^{-29}$ e-cm 90% CL
- Goal: intense slow beams $10^{-30}$ e-cm/day

$E = 10$ kV/cm  $\Rightarrow$  $|E_{int}| = 14.5$ GV/cm

Thanks to E Hinds
JILA eEDM Project
HfF\(^{+}): \ ^{3}\Delta_{1} \text{ in an ion trap}

- Effective E-field = 23.3 GV/cm
- Coherence time > 0.5 s
- Count rate = 5 /s

Data still blinded!
EDM = \( ? \pm 1.5\text{(stat)} \pm 0.025\text{(syst)} \times 10^{-28} \text{ e\cdot cm} \)
Expect x10 over next 2 years
Longer term: switch to ThF\(^{+}\)

Thanks to E. Cornell
Muon EDM

- Present limit: $|d_\mu| < 1.8 \times 10^{-19}$ e-cm CL=95%
- Induced motional E-field: $\vec{E}_m \propto \vec{\beta} \times \vec{B}$, $\gamma = 29.3 \Rightarrow E \sim 13$ GV/m
- Measure up and down slopes of muon decays: tracking detectors
- FNAL (2020) and J-PARC (2022): sensitivity $\sim O(10^{-21}$ e-cm)

$$\vec{\omega}_{\text{net}} = -\frac{q}{m} \left[ a_\mu \vec{B} - \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left( \frac{\vec{\beta} \times \vec{B}}{c} + \frac{\vec{E}}{c} \right) \right]$$

Thanks to D. Hertzog

Hadronic EDMs
# Neutron EDM searches

<table>
<thead>
<tr>
<th>Experiment</th>
<th>UCN source</th>
<th>cell</th>
<th>Measurement techniques</th>
<th>$\sigma_d$ Goal (10^{-20} e-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILL-PNPI</td>
<td>ILL turbine</td>
<td>Vac.</td>
<td>Ramsey technique for $\omega$, E=0 cell for magnetometer</td>
<td>Phase 1 $&lt; 100$</td>
</tr>
<tr>
<td></td>
<td>PNPI/Solid D$_2$</td>
<td></td>
<td></td>
<td>&lt; 10</td>
</tr>
<tr>
<td>ILL Crystal</td>
<td>Cold neutron Beam</td>
<td>solid</td>
<td>Crystal Diffraction, Non-Centrosymmetric crystal</td>
<td>&lt; 100</td>
</tr>
<tr>
<td>PSI EDM</td>
<td>Solid D$_2$</td>
<td>Vac.</td>
<td>Ramsey for $\omega$, external Cs &amp; Hg comag., Xe or Hg comagnetometer</td>
<td>Phase 1 $\sim 50$</td>
</tr>
<tr>
<td>Munich FRMII</td>
<td>ILL</td>
<td>Vac.</td>
<td>Room Temp., Hg Co-mag., also external 3He &amp; Cs mag.</td>
<td>Phase 2 $&lt; 5$</td>
</tr>
<tr>
<td></td>
<td>SUN</td>
<td></td>
<td></td>
<td>&lt; 5</td>
</tr>
<tr>
<td>RCNP/TRIUMF</td>
<td>Superfluid 4He</td>
<td>Vac.</td>
<td>Small vol., Xe co-mag. @ RCNP Then move to TRIUMF</td>
<td>&lt; 50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt; 5</td>
</tr>
<tr>
<td>SNS nEDM</td>
<td>Superfluid 4He</td>
<td>4He</td>
<td>Cryo-HV, 3He capture for $\omega$, 3He co-mag. with SQUIDS &amp; dressed spins, supercond.</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>JPARC</td>
<td>Solid D$_2$</td>
<td>Vac.</td>
<td>Under Development</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>JPARC</td>
<td>Solid D$_2$</td>
<td>Solid</td>
<td>Crystal Diffraction, Non-Centrosymmetric crystal</td>
<td>&lt; 10?</td>
</tr>
<tr>
<td>LANL</td>
<td>Solid D$_2$</td>
<td>Vac.</td>
<td>R &amp; D, Ramsey SOF, Hg co-mag.</td>
<td>$\sim 30$</td>
</tr>
</tbody>
</table>

Present neutron EDM limit $< 300$
The collaboration

- 13 Institutions
- 7 Countries
- 48 Members
- 10 PhD students
The PSI nEDM spectrometer

Four-layer Mu-metal shield
Vacuum chamber
Precession cell
Mercury lamp or UV laser
Mercury polarizing cell

High voltage lead
Cesium magnetometer
Electrode (HV)
Photomultiplier or photodiode
Electrode (ground)
Magnetic-field coils

Switch
Spin analyzers
Neutron detectors

5T SC-magnet

Thanks to K. Kirch, P. Schmidt-Wellenburg
nEDM@PSI statistical sensitivity

Daily sensitivity: \(< 1 \times 10^{-25} e \cdot cm\)

Accumulated sensitivity: \(< 1 \times 10^{-26} e \cdot cm\)

Thanks to K. Kirch, P. Schmidt-Wellenburg
Schedule of nEDM@PSI

- nEDM online sensitivity per day presently approaching $1 \times 10^{-25} \text{ ecm}$
- nEDM operation will come to an end in 2017
- n2EDM sensitivity will intrinsically be more than 5 times better than that of nEDM, plus additional gains from UCN source improvements
- n2EDM will be installed and commissioned in 2018/19
- n2EDM will start production data taking in 2020 and cut into the low $10^{-27} \text{ e-cm}$ region

Thanks to K. Kirch, P. Schmidt-Wellenburg
The TUM EDM experiment

- Contributions from Berkeley/Mainz, ILL, Jülich, LANL, Michigan, MSU, NCSU, PTB, RAL, TUM (FRM, Cluster), UIUC, Yale
- Ramsey experiment with UCN trapped at room temperature, ultimately cryogenic. Room temperature option already available.
- Double chamber with co-magnetometers as option (if needed)
- $^{199}$Hg, Cs, $^{129}$Xe, $^3$He, SQUID magnetometers with sufficient precision developed

The new flagship experiment at Super-SUN UCN source at ILL!

Projected sensitivity at ILL:
Super-SUN Stage I (2018) $\sigma = 2 \cdot 10^{-27}$ ecm
Super-SUN Stage II (2019) $\sigma = 4.2 \cdot 10^{-28}$ ecm (100 days)

Thanks to P. Fierlinger
Super-SUN superfluid helium source:
- Stage I: $4 \times 10^6$ UCN with Fomblin spectrum (2018)
- Stage II: $2 \times 10^7$ UCN with 230 neV polarized (2019)


Thanks to P. Fierlinger
nEDM Collaboration

R. Alarcon, A. Dipert
Arizona State University

G. Seidel
Brown University

D. Budker, B.K. Park
UC Berkeley

M. Blatnik, R. Carr, B. Filippone, C. Osthelder,
S. Slutsky, X. Sun, C. Swank
California Institute of Technology

M. Ahmed, M. Busch, P. –H. Chu, H. Gao
Duke University

I. Silvera
Harvard University

M. Karcz, C.-Y. Liu, J. Long, H.O. Meyer, M. Snow
Indiana University

Williamson, L. Yang
University of Illinois Urbana-Champaign

C. Crawford, T. Gorringe, W. Korsch,
E. Martin, N. Nouri, B. Plaster
University of Kentucky

S. Clayton, S. Currie, T. Ito, Y. Kim, M. Makela,
J. Ramsey, W. Wei, Z. Tang, W.Sondheim
Los Alamos National Lab

K. Dow, D. Hasell, E. Ihloff, J. Kelsey, J. Maxwell, R. Milner, R.
Redwine, E. Tsentalovich, C. Vidal
Massachusetts Institute of Technology

D. Dutta, E. Leggett
Mississippi State University

R. Golub, C. Gould, D. Haase, A. Hawari, P. Huffman,
E. Korobkina, K. Leung, A. Reid, A. Young
North Carolina State University

R. Allen, V. Cianciolo, Y. Efremenko, P. Mueller,
S. Penttila, W. Yao
Oak Ridge National Lab

M. Hayden
Simon Fraser University

G. Greene, N. Fomin
University of Tennessee

S. Stanislaus
Valparaiso University

S. Baeßler
University of Virginia

S. Lamoreaux
Yale University

Thanks to B. Filippone
Key Features of nEDM@SNS

• Sensitivity: $\sim 2 \times 10^{-28}$ e·cm, 100 times better than existing limit
• In-situ Production of UCN in superfluid helium (no UCN transport)
• Polarized $^3$He co-magnetometer
  – Also functions as neutron spin precession monitor via spin-dependent n-$^3$He capture cross section using wavelength-shifted scintillation light in the LHe
  – Ability to vary influence of external B-fields via “dressed spins”
    • Extra RF field allows synching of n & $^3$He relative precession frequency
• Superconducting Magnetic Shield
• Two cells with opposite E-field
• Control of central-volume temperature
  – Can vary $^3$He diffusion (mfp)- big change in geometric phase effect on $^3$He that allows minimization of this systematic effect

Thanks to B. Filippone
nEDM @ SNS

MAGNETIC SHIELD HOUSE

MEASUREMENT CELLS

MAGNET PACKAGE

POLARIZED 3He SOURCE

INJECTION MODULE

3He INTERCONNECT

NOTE: Neutron beam goes into page

Thanks to B. Filippone
Status of nEDM@SNS

- **2014-2017**: Critical Component Demonstration (CCD) phase is underway
  - Build working, full-scale, prototypes of technically-challenging subsystems (can use these in the full experiment)
  - 4yr National Science Foundation funds 5.5M$ for CCD
  - Department of Energy commitment of 1.8M$/yr for CCD

- **2018-2020**: Large Sale Integration (LSI) and Conventional Component Procurement (CCP)
  - LSI – Integrate Central Detector, Magnets and $^3$He systems
  - CCP – Includes Neutron Guide, Magnetic Shield, He Liquefier, etc

- **2021**: Begin Commissioning and Data-taking

Thanks to B. Filippone
Neutron EDM collaboration

• **KEK:** T. Adachi, S. Jeong, S. Kawasaki, Y. Watanabe
• **RCNP Osaka:** K. Hatanaka, I. Tanihata, R. Matsumiya, E. Pierre (also TRIUMF)
• **UBC:** E. Altiere, D. Jones, K. Madison, E. Miller, T. Momose, J. Weinands, T. Hayamizu
• **U Winnipeg:** C. Bidinosti, B. Jamieson, R. Mammei (also TRIUMF), J. Martin
• **U Manitoba:** T. Andalib, J. Birchall, M. Gericke, M. Lang, J. Mammei, S. Page, L. Rebenitsch, S. Hansen-Romu, S. Ahmed
• **TRIUMF:** C. Davis, B. Franke, K. Katsika, T. Kikawa, A. Konaka (also UVic and Osaka U.), F. Kuchler, L. Lee (also U. Manitoba), R. Picker (also SFU), W. Ramsay, W. van Oers (also U. Manitoba), T. Lindner (also UW)
• **UNBC:** E. Korkmaz
• **SFU:** J. Sonier

We are an open collaboration and are accepting new membership requests/

33 PhD members, 7 student members
Thanks to R. Picker

Phase 1 KEK apparatus
Phase 2 Double EDM cell
4-layer shield
Hg comag., dual Hg/Xe $O(10^{-27} \text{ e-cm})$
R&D Toward a new nEDM Experiment at LANL

Los Alamos National Laboratory
C.-Y. Liu, J. Long, W. Snow
Indiana University
A. Aleksandrova, J. Dadisman, B. Plaster
University of Kentucky
T. Chupp
University of Michigan
S. Lamoreaux
Yale University
E. Sharapov
Joint Institute of Nuclear Research

• Conventional room temperature Ramsey separated oscillatory field method
• Existing LANL SD$_2$ UCN source
• Sensitivity: $O(10^{-27}$ e-cm)
• Relatively fast implementation and low cost

Thanks to T. Ito
UCN density achievable with the previous source was already competitive with PSI.

The new UCN source is about to be commissioned.

If the expected performance (x 5-10) is achieved, it could provide a sensitivity of a few x $10^{-27}$ e–cm with existing technology.

Thanks to T. Ito
199Hg collaboration

The Team

Graduate Students
  Jennie Chen
  Brent Graner*

Scientific Glassblower
  Eric Lindahl

Faculty
  B. R. Heckel

Primary support from NSF
  * Supported by DOE Office of Nuclear Science

Past Contributors

E. N. Fortson (UW)
S. K. Lamoreaux (Yale)
M. V. Romalis (Princeton)
J. Jacobs (U. Montana)
B. Klipstein (JPL)
W. C. Griffith (U. Sussex)
M. D. Swallows (AOSense)
T. H. Loftus (AOSense)

Thanks to B. Heckel
Current EDM Experiment

\[ H = -(\mu \cdot \mathbf{B} + \mathbf{d} \cdot \mathbf{E}) \]

\[ \omega_c = \frac{\mu}{\hbar} \left( -\frac{8}{3} \frac{\partial^3 B}{\partial z^3} \Delta z^3 \right) + \frac{4dE}{\hbar} \]

Cancels up to 2\textsuperscript{nd} order gradient noise
Same EDM sensitivity as Middle Difference

\[ \omega_c = \Delta \omega_m - \frac{1}{3} \Delta \omega_o \]

T\textsubscript{2} Spin Relaxation: 300 - 600 sec

Thanks to B. Heckel
$^{199}\text{Hg EDM search}$

**Final EDM Data Set**

\[ d_{\text{Hg}} = (2.20 \pm 2.75_{\text{stat}} \pm 1.59_{\text{sys}}) \times 10^{-30} \text{e} \cdot \text{cm} \]

\[ |d_{\text{Hg}}| < 7.5 \times 10^{-30} \text{e} \cdot \text{cm} \]

at 95% C.L.


SM limit ~ 2045

Expect factor of 2-3 improvement with existing apparatus

Argonne National Laboratory

Thanks to B. Heckel
The HeXe experiment


- SEOP polarized $^3\text{He}$ and $^{129}\text{Xe}$ simultaneously placed in a cell
- Coherent precession of spins causes rotating magnetic dipole field
- Detection using SQUIDs
- fT noise vs. $\sim 10^4$ fT signal
- Cylindrical cells with Si electrodes
- projected EDM sensitivity: $-10^3 \text{ s } T^2$* while 5 kV applied to cell
- Investigation of systematics ongoing
- Goal with current setup: $< 10^{-29}$ ecm

Thanks to P. Fierlinger
Measurement and investigation of the Xenon-129 electric dipole moment
Progress

- measure with E field
- realistic expectation
  - $\delta \phi \approx 10 \mu$rad in a day
  - $\delta \nu \approx 18 \text{pHz in a day}$

$|d_{\text{Xe}}| < \frac{\pi \hbar}{2E (\gamma_{\text{He}}/\gamma_{\text{Xe}})} \delta \nu$

$1 \text{ Mar '16} \rightarrow < 1 \cdot 10^{-28} \text{ e cm in 4 hour}$

129Xe EDM planning

Axion search

129Xe EDM planning

Experimental setup

Commissioning setup

LIV experiment

EDM

Thanks to K. Jungmann
Progression of the Radium EDM Search

- 2006 – Atomic transitions identified and studied;
- 2007 – Magneto-optical trap (MOT) of radium realized;
- 2010 – Optical dipole trap (ODT) of radium realized;
- 2011 – Atoms transferred to the measurement trap;
- 2012 – Spin precession of Ra-225 in ODT observed;
- 2014 – First measurements of EDM of Ra-225;
- 2015 - Sensitivity improved by a factor of 36.

N.D. Scielzo et al., PRA Rapid 73, 010501 (2006)
J.R. Guest et al., PRL 98, 093001 (2007)
R.H. Parker et al., PRC 86, 065503 (2012)
R.H. Parker et al., PRL 114, 233002 (2015)
M. Bishof et al., PRC 94, 025501 (2016)
The Search for the Electric Dipole Moment of Radium-225

Radium Upper Limit (ANL 2016) \(1.4 \times 10^{-23}\) e-cm

Radium/Blue Slower (3 year) \(10^{-26}\) e-cm

New Radium Source (with FRIB) \(10^{-28}\) e-cm


Due to its nuclear octupole deformation, radium-225 is expected have an EDM of about 100 to 1000 times greater than that of other species.

<table>
<thead>
<tr>
<th>BSM parameter</th>
<th>(C_T)</th>
<th>(g_{\pi}^{(0)})</th>
<th>(g_{\pi}^{(1)})</th>
<th>(d_n) (e cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current limits (95% CL)</td>
<td>(2 \times 10^{-6})</td>
<td>(8 \times 10^{-9})</td>
<td>(1.2 \times 10^{-9})</td>
<td>(1.2 \times 10^{-22})</td>
</tr>
<tr>
<td>Improvement Factor (over current limit)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current + (^{225})Ra [10(^{-25}) e cm]</td>
<td>40</td>
<td>2</td>
<td>1.2</td>
<td>20</td>
</tr>
<tr>
<td>Current + (^{225})Ra [10(^{-26}) e cm]</td>
<td>200</td>
<td>8</td>
<td>4</td>
<td>60</td>
</tr>
</tbody>
</table>

CeNTREX: Cold molecule Nuclear Time-Reversal EXperiment
(D. DeMille [Yale], D. Kawall [UMass], S. Lamoreaux [Yale], T. Zelevinsky [Columbia])

New TlF molecule-based search for nuclear Schiff moment

complementary to $^{199}$Hg and n EDMs:

$^{205}$Tl primarily sensitive to proton EDM & $\theta$ QCD

Similar to $e$-EDM, enhanced by intra-molecular E-field

$\Rightarrow$ spin precession rate due to Schiff moment

$\sim 10^4 \times$ larger than in $^{199}$Hg atoms

for similar underlying physics contributions

+ internal co-magnetometer for systematics control

GOAL: use molecular “enhancement” + cycling detection & cooling to obtain improved sensitivity to hadronic CP-violating interactions

1\textsuperscript{st} generation target (est. ~2022): 30x improvement vs. $^{199}$Hg

Thanks to D. DeMille
- Sensitivity: ready for $10^{-29} \text{cm}$. Better than $10^{-30} \text{cm}$ with upgrade. Method/technique similar to muon $g-2$.
- Strong collaboration with major R&D activities in Korea and COSY/Germany. CERN is a candidate host lab.
- pEDM New-Physics reach: $10^3$-$10^4 \text{TeV}$. Needed as input to indicate New-Physics level before next large accelerator project. Decisive test of Baryogenesis.
- Great for students, post docs, faculty. Well rounded physics education, opportunities for major impact.
Deuteron EDM (JEDI Collaboration at COSY)

- Ions have the advantage of no Schiff shielding
- 2017: Use COSY ring as proof of principle and make initial measurement of d EDM
- $10^{-19}$-$10^{-20}$ e-cm
- 2019: Conceptual design for dedicated EDM ring at $10^{-29}$ e-cm
- For deuteron, both E and B fields required for “frozen spin” condition
- Align spin along direction of flight at magic momentum
- Search for time development of vertical polarization

Thanks to Frank Rathmann
EDM measurements for multiple systems are necessary

Global model independent analysis: 6 parameters

TVPV $\pi$-N interaction:

$$L_{\pi NN}^{TVPV} = \bar{N} \left[ \tilde{g}_\pi^{(0)} \cdot \pi + \tilde{g}_\pi^{(1)} \pi^0 + \tilde{g}_\pi^{(2)} (3 \tau_3 \pi^0 - \vec{\tau} \cdot \vec{\pi}) \right] N$$

TVPV $e$-$N$ interaction:

$$L_{eN}^{eff} = -\frac{G_F}{\sqrt{2}} \left\{ \bar{e} i \gamma_5 e \tilde{N} \left[ C_5^{(0)} + C_5^{(1)} \tau_3 \right] N - 8 \bar{e} \sigma_{\mu\nu} e v^\nu \tilde{N} \left[ C_T^{(0)} + C_T^{(1)} \tau_3 \right] S^\mu N \right\} + \cdots$$

<table>
<thead>
<tr>
<th>System</th>
<th>Current (e-cm)</th>
<th>Projected</th>
<th>$d_e$ (e-cm)</th>
<th>$C_S$</th>
<th>$C_T$</th>
<th>$\tilde{g}_\pi^{(0)}$</th>
<th>$\tilde{g}_\pi^{(1)}$</th>
<th>$\tilde{d}_n$ (e-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ThO</td>
<td>$5 \times 10^{-29}$</td>
<td>$5 \times 10^{-30}$</td>
<td>$4.0 \times 10^{-27}$</td>
<td>$3.2 \times 10^{-7}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fr</td>
<td>$d_e &lt; 10^{-28}$</td>
<td></td>
<td>$2.4 \times 10^{-27}$</td>
<td>$1.8 \times 10^{-7}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{129}$Xe</td>
<td>$3 \times 10^{-27}$</td>
<td>$3 \times 10^{-29}$</td>
<td></td>
<td></td>
<td>$3 \times 10^{-7}$</td>
<td>$3 \times 10^{-9}$</td>
<td>$1 \times 10^{-9}$</td>
<td>$5 \times 10^{-23}$</td>
</tr>
<tr>
<td>Neutron/Xe</td>
<td>$2 \times 10^{-28}$</td>
<td>$10^{-28}/3 \times 10^{-29}$</td>
<td></td>
<td></td>
<td>$1 \times 10^{-7}$</td>
<td>$1 \times 10^{-9}$</td>
<td>$4 \times 10^{-10}$</td>
<td>$2 \times 10^{-23}$</td>
</tr>
<tr>
<td>Ra</td>
<td>$10^{-25}$</td>
<td></td>
<td></td>
<td></td>
<td>$5 \times 10^{-8}$</td>
<td>$4 \times 10^{-9}$</td>
<td>$1 \times 10^{-9}$</td>
<td>$6 \times 10^{-23}$</td>
</tr>
<tr>
<td>”</td>
<td>$10^{-26}$</td>
<td></td>
<td></td>
<td></td>
<td>$1 \times 10^{-8}$</td>
<td>$1 \times 10^{-9}$</td>
<td>$3 \times 10^{-10}$</td>
<td>$2 \times 10^{-24}$</td>
</tr>
<tr>
<td>Neutron/Xe/Ra</td>
<td>$10^{-28}/3 \times 10^{-29}/10^{-27}$</td>
<td></td>
<td></td>
<td></td>
<td>$6 \times 10^{-9}$</td>
<td>$9 \times 10^{-10}$</td>
<td>$3 \times 10^{-10}$</td>
<td>$1 \times 10^{-24}$</td>
</tr>
</tbody>
</table>

T. Chupp and M. Ramsey-Musolf, PRC 91 (2015) 035502
Summary

- Many new technologies are being developed
- My expectation
  - New best sensitivities \((n, d, Ra, Xe, Hg, ThO, YbF, HfF^+)\) within 1-2 years
  - Factor of 5-10 improvement \((\mu, n, Ra, Xe, Rn, ThO, YbF, HfF^+/ThF^+)\) within 5 years
  - Factor of 50-100 improvement \((n, p, d, Ra, Rn, TlF, ThO, YbF, ThF^+)\) within 10 years
Extra slides
CENTREX 1st generation proposed schematic

Incorporates many methods from ACME & laser cooling experiments
(slow molecular beam, rotational cooling, cycling fluorescence for detection, etc.)

Design/construction phase
recently funded by Templeton Foundation & Heising-Simons Foundation

Future generations of CENTREX will also incorporate
--transverse laser cooling for increased flux
--laser slowing and/or trapping for increased interaction time

Thanks to D. DeMille
Faraday Rotation Detection

$^{199}\text{Hg}$

$6^1P_1$

$6^3P_2$

$6^3P_1$

$6^3P_0$

$189.4 \text{ nm}$

$253.7 \text{ nm}$

$6^1S_0$

$F = \frac{3}{2}, \frac{1}{2}$

$\mu = \frac{3}{2}, \frac{1}{2}$

22.15 GHz

Detection photodiodes

Glan-laser polarizer

Faraday-rotated light beam

1/2 waveplate

Hg vapor cell

Chopper wheel & 1/4-waveplate (pump phase)

Attenuator (probe phase)

Vertical-polarized 254 nm light

Thanks to B. Heckel
Increasing the number of molecules in the experiment

Put more molecules into the initial state

- Achieved x 9 population in initial state

Detect the molecules better at the final stage

- Achieved x 24 increase

Total signal increase (expected): 216

• Test EDM run to start late in 2016

• Expected sensitivity $2 \times 10^{-29}$ e-cm 90% CL

• Current limit $|d_e| < 9 \times 10^{-29}$ e-cm 90% CL

• Goal: intense slow beams $10^{-30}$ e-cm/day

Thanks to E Hinds
EDM: γff
CEDM: gff

Weinberg ggg:

Four fermion
• polarized $^3$He and $^{129}$Xe transported from Mainz by car

• $T_1 (^{129}$Xe) transport cell $\sim 7h$

Experiment

\[ \delta d = \frac{\hbar}{E P \epsilon \sqrt{\tau T N}} \]

- \( E \): 2kV/cm
- \( P \): 50%
- \( \epsilon \): 10^{-5}
- \( \tau \): several 10^4 s
- \( T \): \( \sim \) month
- \( N \): \( 10^{22} \)

- spin polarized \(^3\)He and \(^{129}\)Xe loaded in cell
- spin precession measured with SQUIDs
### Storage ring proton EDM experiment

**High precision, primarily electric storage ring**

- Crucial role of alignment, stability, field homogeneity, and shielding from perturbing magnetic fields.
- High beam intensity: \(N = 4 \times 10^{10}\) particles per fill.
- High polarization of stored polarized hadrons: \(P = 0.8\).
- Large electric fields: \(E = 10\) MV/m.
- Long spin coherence time: \(\tau_{SCT} = 1000\) s.
- Efficient polarimetry with
  - large analyzing power: \(A_y \simeq 0.6\),
  - and high efficiency detection \(f \simeq 0.005\).

- \(1 \times 10^{-29}\) e-cm achievable, statistically
“Magic” momentum

Spin precession frequency of particle relative to direction of flight:

\[
\tilde{\Omega} = \tilde{\Omega}_{\text{MDM}} - \tilde{\Omega}_{\text{cyc}}
= -\frac{q}{\gamma m} \left[ G\gamma \bar{B}_\perp + (1 + G)\bar{B}_\parallel - \left( G\gamma - \frac{\gamma}{\gamma^2 - 1} \right) \frac{\beta \times \vec{E}}{c} \right].
\]

\( \Rightarrow \tilde{\Omega} = 0 \) called frozen spin, because momentum and spin stay aligned.

- In the absence of magnetic fields \((B_\perp = \bar{B}_\parallel = 0)\),
  \[
  \tilde{\Omega} = 0, \text{ if } \left( G\gamma - \frac{\gamma}{\gamma^2 - 1} \right) = 0.
  \]

\[
G - \frac{1}{\gamma^2 - 1} = 0 \iff G = \frac{m^2}{p^2} \quad \Rightarrow \quad p = \frac{m}{\sqrt{G}} = 700.740 \text{ MeV} \ c^{-1}
\]
YbF Electron EDM

Signal:noise increases (√signal)

<table>
<thead>
<tr>
<th>Upgrade</th>
<th>Increase in signal:noise</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumping</td>
<td>2.2</td>
<td>Achieved</td>
</tr>
<tr>
<td>Optics</td>
<td>2</td>
<td>Achieved</td>
</tr>
<tr>
<td>Longer interaction time</td>
<td>1.5</td>
<td>Achieved</td>
</tr>
<tr>
<td>Shorter rf pulses</td>
<td>1.25</td>
<td>Achieved</td>
</tr>
<tr>
<td>Detection</td>
<td>3.5</td>
<td>In progress</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>28.9</strong></td>
<td></td>
</tr>
</tbody>
</table>

- Test EDM run to start late in 2016
- Expected $d_e$ sensitivity $2 \times 10^{-29}$ e.cm (90% conf.)
- Current limit $|d_e| < 9 \times 10^{-29}$ e.cm (90% conf.)
- Longer term: intense slow beams ~ $10^{-30}$ e-cm/day

Thanks to E Hinds
Expected achievable statistical sensitivity with the current LANL UCN source **without the upgrade**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$ (kV/cm)</td>
<td>12.0</td>
</tr>
<tr>
<td>$N$ (per cell)</td>
<td>14,700</td>
</tr>
<tr>
<td>$T_{\text{free}}$ (s)</td>
<td>180</td>
</tr>
<tr>
<td>$T_{\text{duty}}$ (s)</td>
<td>300</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.80</td>
</tr>
<tr>
<td>$\sigma$/day/cell ($10^{-26}$ e-cm)</td>
<td>9.3</td>
</tr>
<tr>
<td>$\sigma$/day ($10^{-26}$ e-cm) (for double cell)</td>
<td>6.5</td>
</tr>
<tr>
<td>$\sigma$/year* ($10^{-27}$ e-cm) (for double cell)</td>
<td>3.4</td>
</tr>
<tr>
<td>90% C.L./year* ($10^{-27}$ e-cm) (for double cell)</td>
<td>5.6</td>
</tr>
</tbody>
</table>

This estimate is based on the following:

- The estimate for $N$ is based on the results of the UCN storage test performed in January 2016 and **is not assuming the source upgrade**.

- The estimate for $E, T_{\text{free}}, T_{\text{duty}},$ and $\alpha$ is based on what has been achieved by other experiments.

**“year” = 365 live days. In practice it will take 3+ years to achieve this.**

Thanks to T. Ito
• Beamline and target commissioning fall 2016
• First UCN at TRIUMF summer 2017
• We will start with a prototype EDM apparatus from Japan (Phase 1), upgrade it as possible and develop techniques with it
• Source upgrades necessary for $10^{-27}$ ecm statistics shall come online 2019
• Our Phase 2 apparatus in 2020
  – Double EDM cell, room temperature, Ramsey technique
  – 4-layer magnetically shielded room
  – Self shielded $B_{0,1}$ coil
  – Start with $^{199}$Hg comag, then implement dual $^{199}$Hg/$^{129}$Xe comag to measure field and gradient simultaneously
“Phase 2” – to implement by 2020

R&D on Hg and Xe co-magnetometers is underway

- LD$_2$ moderator, to increase cold flux entering the superfluid
- New high-quality guides.
- World-competitive nEDM experiment apparatus

CFI Innovation Fund application in progress, in Canada. Scale $16M.

Slide thanks to J. Martin
Technical Challenges for nEDM@SNS

- 1200 L of superfluid Helium @ T = 0.5K
  - Must minimize heat sources
    - Eddy-current heating from AC B-fields → minimal conducting material
  - Large cooling plant required

- Highly sensitive to magnetic field variations and gradients
  - Significant magnetic shielding required
  - B-field uniformity of ppm/cm over measurement volume
  - Low-field operation: B = 3 μT

- High electric fields: E = 75 kV/cm
  - Producing and maintaining V > 600 kV in cryogenic environment

Thanks to B. Filippone
Summary
PSI UCN source

Protons

Spallation target $E_n \sim \text{MeV}$

D$_2$O moderator Neutrons thermalized to 25 meV

UCN convertor (solid D$_2$ @ 5K)

UCN storage volume

Neutron guide to experiments

Main shutter

Presently up to 30 UCN/cm$^3$ in experiments

Golub, R. & Pendlebury, J. M

PLA (1975) 133

Anghel, et. al

NIMA (2009) 272
n2EDM at PSI

- Two UCN precession chambers with opposite E fields
- Improved magnetometry
  - Hg – laser readout
  - Cs
  - $^3\text{He}$
# Neutron EDM with Super-SUN at ILL

<table>
<thead>
<tr>
<th></th>
<th>SuperSun stage I</th>
<th>SuperSun stage II</th>
</tr>
</thead>
<tbody>
<tr>
<td>UCN density</td>
<td>333 1/cm³</td>
<td>1670 1/cm³</td>
</tr>
<tr>
<td>Diluted density</td>
<td>80 1/cm³</td>
<td>400,8 1/cm³</td>
</tr>
<tr>
<td>Transfer loss factor</td>
<td>3</td>
<td>1,5</td>
</tr>
<tr>
<td>Source saturation loss factor</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Polarization loss factor</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Density in cells</td>
<td>6,7 1/cm³</td>
<td>133,6 1/cm³</td>
</tr>
<tr>
<td>2 EDM chamber volume</td>
<td>33,2 l</td>
<td>33,2 l</td>
</tr>
<tr>
<td>Neutrons per chamber</td>
<td>110556</td>
<td>2217760</td>
</tr>
<tr>
<td>EDM sensitivity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>2,00E+04 V/cm</td>
<td>2,00E+04 V/cm</td>
</tr>
<tr>
<td>alpha</td>
<td>0,85</td>
<td>0,85</td>
</tr>
<tr>
<td>T</td>
<td>250 s</td>
<td>250 s</td>
</tr>
<tr>
<td>N after time T (1/e)</td>
<td>398000</td>
<td>794000</td>
</tr>
<tr>
<td>Number of EDM cells</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Sensitivity (1 Sigma, 1 cell)</td>
<td>3,9E-25 ecm</td>
<td>8,7E-26 ecm</td>
</tr>
<tr>
<td>Sensitivity (1 Sigma, 2 cells)</td>
<td>2,7E-25 ecm</td>
<td>6,1E-26 ecm</td>
</tr>
<tr>
<td>Preparation time</td>
<td>150 s</td>
<td>150 s</td>
</tr>
<tr>
<td>Measurements per day</td>
<td>216</td>
<td>216</td>
</tr>
<tr>
<td>Sensitivity (1 Sigma, 2 cells) per day</td>
<td>1,9E-26 ecm</td>
<td>4,2E-27 ecm</td>
</tr>
<tr>
<td>Sensitivity 100 days</td>
<td>1,9E-27 ecm</td>
<td>4,2E-28 ecm</td>
</tr>
<tr>
<td>Limit 90% 100 days</td>
<td>3,00E-27 ecm</td>
<td>7,00E-28 ecm</td>
</tr>
</tbody>
</table>

Thanks to P. Fierlinger
Sensitivity and systematics

Super-SUN superfluid helium source:
- Stage I: $4 \times 10^6$ UCN with Fomblin spectrum (2018)
- Stage II: $2 \times 10^7$ UCN with 230 neV polarized (2019)

Control of systematics:
- $< 100$ pT/m B gradient over cell volume,
- $< 10$ fT/250 s drift: sufficient for $10^{-28}$ ecm level, even without comagnetometer

Potentially new class of systematics identified:
- Non-gaussian spin distributions in traps with gradients or E-fields
- Time-dependent shape of distributions

Thanks to P. Fierlinger
EDM search in HfF\(^+\) molecular ion

Optically deplete population out of one of the \(m_F\) levels

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

Molecules provide large effective electric fields

\[ E_{lab} = 10 \text{ V/cm} \]
\[ |E_{eff}| > 10^{10} \text{ V/cm} \]

1.5 x 10\(^{-28}\) e-cm

Expect x10 over next 2 years
Longer term: switch to ThF\(^+\)

Thanks to E. Cornell and J. Ye
Radium-224 exhibits properties of octupole deformation.

REX-ISOLDE (CERN)

Measured $B(E3, 0^+ \rightarrow 3^-)$ in $^{224}$Ra

**EDM of $^{225}$Ra enhanced**

- Closely spaced parity doublet – Haxton & Henley, PRL (1983)
- Large Schiff moment due to octupole deformation – Auerbach, Flambaum & Spevak, PRL (1996)
- Relativistic atomic structure ($^{225}$Ra / $^{199}$Hg ~ 3) – Dzuba, Flambaum, Ginges, Kozlov, PRA (2002)

Parity doublet

| $|\alpha\rangle$ | $|\beta\rangle$ |
|-------------------|-------------------|

$\Psi^- = (|\alpha\rangle - |\beta\rangle)/\sqrt{2}$  
$\Psi^+ = (|\alpha\rangle + |\beta\rangle)/\sqrt{2}$

55 keV

Schiff moment

$\text{Schiff\_moment} = \sum_{i \neq 0} \frac{\langle \psi_0 | \hat{S}_z | \psi_i \rangle \langle \psi_i | \hat{H}_{PT} | \psi_0 \rangle}{E_0 - E_i} + \text{c.c.}$

Enhancement Factor: EDM ($^{225}$Ra) / EDM ($^{199}$Hg)

<table>
<thead>
<tr>
<th></th>
<th>Isoscalar</th>
<th>Isovector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skyrme SIII</td>
<td>300</td>
<td>4000</td>
</tr>
<tr>
<td>Skyrme SkM*</td>
<td>300</td>
<td>2000</td>
</tr>
<tr>
<td>Skyrme SLy4</td>
<td>700</td>
<td>8000</td>
</tr>
</tbody>
</table>

Schiff moment of $^{225}$Ra, Dobaczewski, Engel, PRL (2005)
Schiff moment of $^{199}$Hg, Dobaczewski, Engel et al., PRC (2010)

“[Nuclear structure] calculations in Ra are almost certainly more reliable than those in Hg.”

**EDM measurement on $^{225}$Ra in a trap**

Collaboration of Argonne, Kentucky, Michigan State, Northwestern

- Efficient use of the rare $^{225}$Ra atoms
- High electric field (> 100 kV/cm)
- Long coherence time (~ 100 s)
- Negligible “v x E” systematic effect
- Octupole deformation enhancement

$^{225}$Ra:
- $I = \frac{1}{2}$
- $t_{1/2} = 15 \text{ d}$

Transverse cooling

**Oven:** $^{225}$Ra

**Zeeman Slower**

Statistical uncertainty

$$\delta d = \frac{\hbar}{2E\sqrt{\tau N\varepsilon T}}$$

- 100 kV/cm
- 100 s
- $10^6$
- 10%

Long-term goal: $\delta d = 3 \times 10^{-28} \text{ e cm}$

Magneto-optical Trap (MOT)

Optical dipole trap (ODT)

EDM measurement
Room for Improvement: more radium

**225Ra Yields**

- **225Ac**: 10 d
- **229Th**: 7.3 kyr
- **225Ra**: 15 d

Fr, Rn, ...
~4 hr

---

Presently available

- National Isotope Development Center, ORNL
  - Decay daughters of **229Th**
    - **225Ra**: $10^8$ /s

Projected

- FRIB (B. Sherrill, MSU)
  - Beam dump recovery with a **238U** beam
    - $6 \times 10^9$ /s
  - Dedicated running with a **232Th** beam
    - $5 \times 10^{10}$ /s

- ISOL@FRIB (I.C. Gomes and J. Nolen, Argonne)
  - Deuterons on thorium target, 1 mA x 400 MeV = 400 kW
    - $10^{13}$ /s

- MSU K1200 (R. Ronningen and J. Nolen, Argonne)
  - Deuterons on thorium target, 10 uA x 400 MeV = 4 kW
    - $10^{11}$ /s
The Radium Team

Argonne: Kevin Bailey, Michael Bishof, John Greene, Roy Holt, Nathan Lemke, Zheng-Tian Lu, Peter Mueller, Tom O’Connor, Richard Parker;

Kentucky: Mukut Kalita, Wolfgang Korsch;

Michigan State: Jaideep Singh;

Northwestern: Matt Dietrich.

Special Thanks To: Irshad Ahmad, Dave Potterveld
What does it take to measure the radium EDM?
Room for improvement: Blue Trap Upgrade

100x increase in N

Atom Velocity

Atom Flux

- 310 m/s
- 60 m/s
- 6d\textsuperscript{3}D\textsubscript{2}
- 430 \mu s
- 420 ns
- 7p\textsuperscript{3}P\textsubscript{1}
- 6d\textsuperscript{3}D\textsubscript{1}
- 6d\textsuperscript{3}D\textsubscript{2}
- 6 \text{ ns}
- 7p\textsuperscript{1}P\textsubscript{1}
- 7s\textsuperscript{2}1S\textsubscript{0}

Slow, 483 nm

Slow & Trap, 714 nm
**Jon Engel Calculations**

### Enhancement Factor: EDM (\(^{225}\text{Ra}\)) / EDM (\(^{199}\text{Hg}\))

<table>
<thead>
<tr>
<th>Skyrme Model</th>
<th>Isoscalar</th>
<th>Isovector</th>
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</thead>
<tbody>
<tr>
<td>SIII</td>
<td>300</td>
<td>4000</td>
<td>700</td>
</tr>
<tr>
<td>SkM(^*)</td>
<td>300</td>
<td>2000</td>
<td>500</td>
</tr>
<tr>
<td>SLy4</td>
<td>700</td>
<td>8000</td>
<td>1000</td>
</tr>
</tbody>
</table>

*Schiff moment of \(^{225}\text{Ra}, Dobaczewski, Engel (2005)*

*Schiff moment of \(^{199}\text{Hg}, Ban, Dobaczewski, Engel, Shukla (2010)*

### Enhancement Factor: EDM (\(^{225}\text{Ra}\)) / EDM (\(^{199}\text{Hg}\))

<table>
<thead>
<tr>
<th>Skyrme Model</th>
<th>Isoscalar</th>
<th>Isovector</th>
<th>Isotensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>SkM(^*)</td>
<td>1500</td>
<td>900</td>
<td>1500</td>
</tr>
<tr>
<td>SkO’</td>
<td>450</td>
<td>240</td>
<td>600</td>
</tr>
</tbody>
</table>

*Schiff moment of \(^{199}\text{Hg}, de Jesus & Engel, PRC72 (2005)*

*Schiff moment of \(^{225}\text{Ra}, Dobaczewski & Engel, PRL94 (2005)*
Outlook

- 2016-2017
  - Implement **STIRAP** – more efficient way to detect spin;
  - Longer trap lifetime;
- 2018-2020, **blue upgrade** – more efficient trap;
- Five-year goal (before FRIB): $10^{-26}$ e cm;
- 2021 and beyond (at FRIB): $3 \times 10^{-28}$ e cm;
- Far future: search for EDM in diatomic molecules
  - Effective E field is enhanced by a factor of $10^3$;
  - Reach the Standard Model value of $10^{-30}$ e cm.