Radon-EDM Experiment

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TRIUMF E929
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E-929 Collaboration (Guelph, Michigan, SFU, TRIUMF)
TRIUMF
Canada's National Laboratory for Particle and Nuclear Physics

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Atomic Electric Dipole Moment
Separation of Charge along $\mathbf{J}$: $\langle d \rangle = g_d \langle J \rangle$

$\mathbf{d} = e \mathbf{r}$
$\langle \mathbf{d} \rangle = g_d \langle \mathbf{J} \rangle$
$\langle \mathbf{r} \rangle = \frac{g_d}{e} \langle \mathbf{J} \rangle$

if $T$ is a symmetry, $g_d = -g_d$

$\langle \mathbf{d} \rangle = e \langle \mathbf{r} \rangle = e \int \mathbf{r} \rho \ d^3r$

We measure $g_d \langle \mathbf{J} \cdot \mathbf{E} \rangle$

EDM Motivations
Undiscovered
Study CP violation: mass scale
Signal of NEW PHYSICS (beyond SM - CKM)
Cosmological Baryon Asymmetry
Octupole Deformation-Parity Doublets

(see Feynman vol 3.)

\[ |\psi_{\pm}\rangle = \frac{1}{\sqrt{2}} (|a\rangle \pm |b\rangle) \]

\[ S \sim \frac{< + | \eta r^3 \cos \theta | - >}{E_+ - E_-} \sim \frac{\eta \beta_2 \beta_3^2 Z A^{2/3} r_0^3}{E_+ - E_-} \]
Nuclei with Octupole Deformation/Vibration

(Haxton & Henley; Auerbach, Flambaum, Spevak; Engel et al., Hayes & Friar, etc.)

\[ S \sim \frac{<+|\eta r^3 \cos \theta|->}{E_+ - E_-} \sim \frac{\eta \beta_2 \beta_3 Z A^{2/3} r_0^3}{E_+ - E_-} \]

\[ \text{NOTES:}\]
Octupole Enhancements
Engel et al. agree with Flambaum et al.
Even octupole vibrations enhance \( S \) (Engel…, Flambaum& Zelevinsky)

Ref: Dzuba PRA66, 012111 (2002) - Uncertainties of 50%
*Based on Woods-Saxon Potential
† Nilsson Potential Prediction is 137 keV

\[ \begin{array}{cccccc}
\hline
\text{Isotopes} & 223\text{Rn} & 223\text{Ra} & 225\text{Ra} & 223\text{Fr} & 129\text{Xe} & 199\text{Hg} \\
\hline
\text{t}_{1/2} & 23.2 \text{ m} & 11.4 \text{ d} & 14.9 \text{ d} & 22 \text{ m} & & \\
\text{I} & 7/2 & 3/2 & 1/2 & 3/2 & 1/2 & 1/2 \\
\text{ΔE th (keV)} & 37^* & 170 & 47 & 75 & & \\
\text{ΔE exp (keV)} & - & 50.2 & 55.2 & 160.5 & & \\
10^{11}S \text{ (e-fm}^3) & 375 & 150 & 115 & 185 & 0.6 & -0.75 \\
10^{28}d_A \text{ (e-cm)} & 1250 & 1250 & 940 & 1050 & 0.3 & 2.1 \\
\hline
\end{array} \]
β-decay Studies of Rn Structure  
$8\pi @$ TRIUMF

- Very high-level density in the odd-A Rn isotopes within the β decay Q-value window
  - (e.g. ~ 3.2 MeV for $^{223}$At $\rightarrow ^{223}$Rn).

- Many/most of the transitions will be highly converted.

- Long chain of radioactive daughters requires flexible collect, count, move, cycles.

- In this environment a γ-ray or electron singles spectrum is of little use in establishing structure
  - (i.e. a decay scheme).

- High statistics β: γ-γ, γ-e, e-e are required (and then some painstaking spectroscopy).

- The $8\pi$ Spectrometer at ISAC is certainly the world’s best facility for such studies.

- Timeline Issues: At beams at ISAC – late 2008 or 2009(?) is probably the earliest
  - : Although the experiments themselves could be short (< 1 week),
  - expect at least a year of spectroscopic analysis before definitive structure results are obtained.
8-π detector array
Atomic Electric Dipole Moment

\[ P \text{ or } T + \_\_ \_ g_d > 0 \quad \text{gd} < 0 \]

Precision: \( (\sigma_d)^{-1} = 4E\Gamma^{-1} (S/N) \)

\[ S/N = \sqrt{\mathcal{A}^2 N_{Rn}} \]

Need high radon polarization and long relaxation.
Spin-Exchange Optical Pumping

- Optically pump the Rb with circularly polarized laser light.
- Spin-exchange collisions transfer the polarization to the radon nuclei.

Binary Collision: $\tau \sim 10^{-12}$ sec.

Buffer gas collisions

$5p_{1/2}$

$m_s = -1/2$

$m_s = +1/2$

van Der Waals Molecule:

$\tau$ is dependent on 3rd body ($N_2$) pressure.
8-Trigress detectors

Magnetic Shielding
(Active + Passive)
Gamma Ray Anisotropies

- Polarized nuclei emit gamma rays with calculable directional distributions.

\[ W(\theta) = \frac{1}{4\pi} \left\{ 1 + \frac{3}{2j_i(2j_i - 1)} \left[ \sum_{m_i} m_i^2 a_{m_i} - \frac{1}{3} j_i(j_i + 1) \right] P_2(\cos \theta) \right\} \]

\( j_f = j_i - 1 \) pure dipole transition

\( \delta = \frac{W(0^\circ)-W(90^\circ)}{W(0^\circ)+W(90^\circ)} \) for \( j_f = j_i + 1 \)
Gamma Anisotropy ($A=0.2 \pm 0.1$)

$T_2 = 30 \text{ s} \ E=5 \text{ kV/cm}$

Statistics Limited by HPGe Count Rate

<table>
<thead>
<tr>
<th></th>
<th>Gamma Anisotropy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Count Rate ($s^{-1}$)</td>
<td>$1.2 \times 10^5$</td>
</tr>
<tr>
<td>$A$</td>
<td>0.2</td>
</tr>
<tr>
<td>Background</td>
<td>0.01</td>
</tr>
<tr>
<td>Total N (100 Days)</td>
<td>$1 \times 10^{12}$</td>
</tr>
<tr>
<td>$\sigma_{dA}$ (e.cm)</td>
<td>$1 \times 10^{-26}$</td>
</tr>
</tbody>
</table>

$$W(\theta) = \frac{1}{4\pi} \left\{ 1 + \frac{3}{2j_i(2j_i-1)} \left[ \sum_{m_i} m_i^2 a_{m_i} - \frac{1}{3} j_i(j_i+1) \right] P_2(\cos \theta) \right\}$$

$\mathbf{j}_i = \mathbf{j}_i + 1$
Beta Asymmetry

\[ R = R_0 \left( 1 + \frac{p_e}{E_e} A_\beta \hat{J} \cdot \hat{r} \right) \]

\[ \xi A_\beta = \pm \kappa |g_A|^2 |<\sigma>|^2 - (g_V g_A^* + g_A g_V^*) <1><\sigma> \sqrt{\frac{J_i}{1 + J_1}}. \]

<table>
<thead>
<tr>
<th>( J_i^\pi )</th>
<th>( J_f^\pi )</th>
<th>( A_\beta )</th>
<th>note</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/2</td>
<td>9/2</td>
<td>+7/9</td>
<td>100% ( \beta^- ) decay; pure GT</td>
</tr>
<tr>
<td>7/2</td>
<td>-2/9</td>
<td></td>
<td>not pure GT</td>
</tr>
<tr>
<td>5/2</td>
<td>-1</td>
<td></td>
<td>pure GT</td>
</tr>
</tbody>
</table>

- No count rate limit (current detection mode)
- Discriminate species only by frequencies
- Scattered betas (lower effective A, Background)
We’ve started setting up at TIRUMF

ISAC I and ISAC II
Remote Tracking of Laboratory Fields:
(magnetometer at TRIUMF, Control in Michigan)
Tigress Detectors have arrived
Progress: High efficiency transfer of $^{120}$Xe at TRIUMF: from millstones to milestones

Maximum efficiency: $\varepsilon_{\text{max}} = 75\%$

1. Bombard foil
2. Heat foil: release to target chamber
3. Freeze to cold finger
4. PUSH to cell (buffer gas)

$^{120}$Cs (30 keV)

no radon at TRIUMF yet
Before Push

After Push
43% efficiency
Studies with $^{209}\text{Rn}$ @ Stony Brook

1. Make $^{209}\text{Fr}$ and implant in foil
2. $^{209}\text{Fr}$ (50s) $\rightarrow$ $^{209}\text{Rn}$ (28.5 m)
3. Heat foil: release to target chamber
4. Freeze to cell
5. Get about 500,000 $^{209}\text{Rn}$ in cell
Before transfer

After transfer

$^{209}$Rn (28.5 m)
EC, $e^+$

\begin{itemize}
  \item 408 keV
  \item 511 keV
  \item 337 keV
  \item 745 keV
  \item 689 keV
\end{itemize}

$\sim 500,000^{209}$Rn
The $^{209}$Rn Decay Scheme

\[ \delta^2 = \frac{a_1^2}{a_2^2} \]

$a_1 = 1 \Rightarrow$ pure dipole

$a_2 = 1 \Rightarrow$ pure quadrupole

require: \( a_1^2 + a_2^2 = 1 \)

<table>
<thead>
<tr>
<th>γ-ray Energy</th>
<th>Intensity</th>
<th>δ (Mixing Ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>337.45</td>
<td>14.5</td>
<td>$\infty$</td>
</tr>
<tr>
<td>408.32</td>
<td>50.3</td>
<td>0</td>
</tr>
<tr>
<td>689.26</td>
<td>9.7</td>
<td>&gt;3.57</td>
</tr>
<tr>
<td>745.78</td>
<td>22.8</td>
<td>&gt;2.86</td>
</tr>
</tbody>
</table>

from Table of Isotopes
Normalize 337 keV to 408 keV

T=130° C  Uncoated Pyrex

Laser off

Laser on

Alignment ≈ 20% of maximum (bootstrap)

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>Spin sequence</th>
<th>Anisotropy $R$</th>
<th>$R - 1$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>337</td>
<td>$\frac{1}{2}^-$ - $\frac{3}{2}^-$</td>
<td>0.903(14)</td>
<td>$-9.7 \pm 1.4$</td>
</tr>
<tr>
<td>408</td>
<td>$\frac{1}{2}^+$ - $\frac{3}{2}^-$</td>
<td>1.009(7)</td>
<td>$+0.9 \pm 0.7$</td>
</tr>
<tr>
<td>689</td>
<td>$\frac{1}{2}^-, \frac{3}{2}^-$</td>
<td>1.079(22)</td>
<td>$+7.9 \pm 2.2$</td>
</tr>
<tr>
<td>745</td>
<td>$\frac{1}{2}^-$ - $\frac{3}{2}^-$</td>
<td>1.129(14)</td>
<td>$+12.9 \pm 1.4$</td>
</tr>
</tbody>
</table>
Modeling Polarization

- Can calculate the expected angular distribution of gamma rays as a function of spin-exchange and relaxation rates.
- The spin-exchange rate $\gamma_{SE}$ depends on the Rb density, which depends on cell temperature.
- The dipole and quadrupole relaxation rates, $\Gamma_1$ and $\Gamma_2$, must be determined from data.

\[
\Gamma_2(T) = \Gamma_2^\infty e^{\Delta E / kT}
\]
Shows T2~4.5 h, dominated by Quadrupole Interactions ($\Gamma_2 >> \Gamma_1$)
Modeling Polarization

- Quadrupole relaxation should be the dominant mechanism.
- As a first approximation, set $\Gamma_1=0$, calculate $\gamma_{SE}$ for a given $T$, and calculate the expected anisotropies.
Fit for $\Gamma_2(T_a=300^{\circ}K)$

0.05 Hz for uncoated
0.03 Hz for coateds

Use $2.5 \times 10^{-21}$ cm$^2$

Improved by extensive measurements of $P_{Rb}$ under varying conditions
EDM Cell Development

We want a single cell @ 200C
Problems: leakage currents, materials
Silica (Fused Quartz) or Sapphire
IN PROGRESS (Celia Cunnigham)
Backgrounds

\[ \sigma_{\omega} = \frac{2}{T_2} \frac{1}{(S/N)} = \frac{2}{T_2} \frac{1}{\sqrt{A^2(1-B)^2N_\gamma}} \]

Build-up of decay products for \( \gamma \)-anistropy probe

Change cells (weekly?) - good for systematics

Scattered betas (beta asymmetry detection)
Systematics

Leakage currents -- must be minimized: **Multiple species**

Electric quadrupole moment (gradients/walls)

Change cells, cell shape/orientation: **Multiple species**

Electric field effects on shields, electronics, etc.

Check and measure with E=0

$E^2$ and $|E|$ effects (Stark shifts)

**Multiple Species**: J=1/2, 3/2, etc.

Motional effects $<v \times E>$ (negligible in gas cells)
Atomic Electric Dipole Moment Measurement Using Spin Exchange
Pumped Masers of $^{129}\text{Xe}$ and $^3\text{He}$

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University of Michigan, Ann Arbor, Michigan 48109
(Received 1 August 2000)

We have measured the $T$-odd permanent electric dipole moment of $^{129}\text{Xe}$ with spin exchange pumped masers and a $^3\text{He}$ comagnetometer. The comagnetometer provides a direct measure of several systematic effects that may limit electric dipole moment sensitivity, and we have directly measured the effects of changes in leakage current that result when the applied electric field is changed. Our result, $d(^{129}\text{Xe}) = 0.7 \pm 3.3\text{(stat)} \pm 0.1\text{(syst)} \times 10^{-27}\text{e cm}$, is a fourfold improvement in sensitivity.
What’s next?

Cell development: coatings/electrodes/temperatures

Laser Development

Cell characterization with natural xenon:
- 27% $^{129}$Xe (J=1/2); 21% $^{131}$Xe (J=3/2)

TRIUMF
set up (EDM) measurements with xenon isotopes

Measure Rn nuclear structure (8-π)

Build up to RADON EDM measurements (≈ 3 years)
Radon EDM Summary

$^{223}$Rn EDM projections

Gamma Anisotropy ($A=0.2 \pm 0.1$)

$T_2 = 30 \text{ s } E=5 \text{ kV/cm}$

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<th>Count Rate ($s^{-1}$)</th>
<th>Gamma Anisotropy</th>
<th>Beta asymmetry ISAC</th>
<th>ISAC $\times$ 20</th>
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<tbody>
<tr>
<td></td>
<td>$1.2 \times 10^5$</td>
<td>$5 \times 10^6$</td>
<td>$4 \times 10^7$</td>
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<td>$5 \times 10^{-28}$</td>
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Production rates: $1 \times 10^7$ (ISAC)