\(^{129}\text{Xe}\) EDM search experiment using active nuclear spin maser

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**EDM, the new physics indicator**

Electric dipole moment

\[ d = d \frac{s}{s} \]

T-violation

Discovery of the finite value of the EDM

→ Discovery of the new physics beyond the SM!!
The origin of atomic EDM

Schiff moment

\[ \hat{S}_{\text{ch}} = \frac{1}{10} \sum_{i=1}^{A} e_i \left( r_i^2 - \frac{5}{3} \langle r^2 \rangle_{\text{ch}} \right) r_i \]

- From a shell model point of view

\[
S(k) = \sum_{k=1}^{1} \frac{\left| \frac{1}{2_1} \right| \left| \text{ch}_{z} \right| \left| \frac{1}{2_2} \right|^* \left| \left| V_{\frac{1}{2}}^{PT} \left| \frac{1}{2_1} \right| \right|}{E_{1}^{(+)} - E_{k}^{(-)}} + \text{c. c.}
\]

The atomic EDM of the $^{129}$Xe

- EDM is generated through the Schiff moment (P,T-odd NN interaction, reflect nuclear structure)
- Stable nuclei, huge amount of atoms ($\sim 10^{23}$)


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Current status of the EDM searches

<table>
<thead>
<tr>
<th>Year of publication</th>
<th>Neutron</th>
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<tbody>
<tr>
<td>1950</td>
<td></td>
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<td>1960</td>
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<td>1970</td>
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<td>2000</td>
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<td>2010</td>
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**Our target**

\[ |d(^{129}\text{Xe})| = 10^{-28} \, \text{e} \cdot \text{cm} \]

\[ E = 10 \, \text{kV/cm} \]

**Prediction value of the EDM**

- \[ |d(^{199}\text{Hg})| < 3.1 \times 10^{-29} \, \text{ecm} \]
  Griffith et al., *PRL* 102 (2009) 101601

- \[ |d(^{129}\text{Xe})| < 4.1 \times 10^{-27} \, \text{ecm} \]
  Rosenberry and Chupp, *PRL* 86 (2001) 22

**Standard Model**

\[ (d_n = 10^{-(31-33)}) \]

[Pendlebury and Hinds, *NIM A* 440 (00) 471]
How to measure the EDM

- Energy splitting changes due to the EDM

\[ \begin{align*}
B = 0 & \quad E = 0 \\
B \neq 0 & \quad E = 0 \\
B = 0 & \quad E \neq 0 \\
B \neq 0 & \quad -E \neq 0
\end{align*} \]

\[ \begin{align*}
h\nu_0 & \quad h\nu_+ \\
h\nu_- & \quad h\nu_-
\end{align*} \]

\[ m = -1/2 \]

\[ m = +1/2 \]

\[ \nu_+ = \frac{2\mu B + 2dE}{h} \]

\[ \nu_- = \frac{2\mu B - 2dE}{h} \]

\[ d = \frac{h\Delta\nu}{4E} \]

\[ (\Delta\nu = \nu_+ - \nu_-) \]

- Consecutive measurement of spin precession (Maser)

\[ \delta\nu_{\text{final}} \propto \frac{\delta\phi}{T_m^{3/2}} = \left[ \text{Fourier width: } \frac{1}{T_m} \right] \times \frac{1}{[\text{data points: } T_m]^{1/2}} \]
Active nuclear spin maser

“Optically manipulated” spin maser with a feedback field generated by optical spin detection

$H = \alpha \mathbf{I} \cdot \mathbf{S}$

$= \frac{\alpha}{2}(I_+ S_- + I_- S_+) + \alpha I_z S_z$

Static magnetic field: $B_0 \sim \text{mG}$

Feedback system

Feedback circuit

Lock-in detection

Precession signal

Frequency precision of $^{129}$Xe maser

Frequency precision in one-shot measurement

$\Delta \nu \sim 10 \text{ nHz}$

Frequency stability between repeated measurements

$\Delta \nu \sim 1 \text{ mHz}$

Long term drifts of the external magnetic field
$^{3}$He co-magnetometry

- **$^{129}$Xe frequency:** $B_0 + \text{EDM}$
- **$^{3}$He frequency:** $B_0$

- *in situ* magnetometry
- Negligible EDM in $^{3}$He
- Correlation in phase: $\Phi_{Xe}(t) = \frac{\gamma_{Xe}}{\gamma_{He}} \Phi_{He}(t)$
Contact interaction with pol. Rb atoms

\[
\nu(^{129}\text{Xe}) = \frac{\gamma(^{129}\text{Xe})}{2\pi} \left\{ B_0 + \kappa_{\text{Rb-Xe}}[\text{Rb}]P_{\text{Rb}} \right\} \pm \frac{4d}{h}E \\
\nu(^{3}\text{He}) = \frac{\gamma(^{3}\text{He})}{2\pi} \left\{ B_0 + \kappa_{\text{Rb-He}}[\text{Rb}]P_{\text{Rb}} \right\}
\]

Static & Env. mag. field  Freq. shift due to pol. Rb

Frequency shift of \(^{129}\text{Xe}/^{3}\text{He} due to contact interaction with polarized Rb

\[\Delta \nu \propto \kappa \left[ \text{Rb} \right] P_{\text{Rb}}\]

<table>
<thead>
<tr>
<th>Rb number density</th>
<th>Rb Polarization</th>
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<tbody>
<tr>
<td>(\kappa_{0 \text{Xe-Rb}} = 493(31)) [1]</td>
<td>(\kappa_{0 \text{He-Rb}} = 4.52 + 0.00934T) [2]</td>
</tr>
</tbody>
</table>

Reduction of the pol. Rb atoms

Advantages

- Reduce $P_{Rb}$ at probe section
- Different temperature at pumping & probe sections

Difficulties

- Reduction of $P(^{129}Xe)$ as diffusion
- Reduction of maser signal due to reduced $P_{Rb}$

$\Delta v_{Xe/He}$ (Maser frequency shift) = $\propto \kappa_{Xe/He}$ (Coefficient) $\times [Rb] \times P_{Rb}$

- Double cell geometry
- Linearly polarized laser light
Experimental setup

Photo diode

3 layer magnetic shield

Static magnetic field coil

$B_0$

Photo Elastic Modulator

$\lambda/2$ plate

PBS

Pumping laser
- wave length: 794.76 nm (Rb D1 line)
- line width: $\sim 10$ MHz
- output: 1.8 W

Probe laser
- wave length: 794.76 nm (depend on measurement condition)
- line width: $\sim 10$ MHz
- output: 10 mW
Experimental setup

- Magnetic shield
- Env. field cancellation coil
- Lin. Pol. light
- Probe light
- Pumping light
First trial of $^{129}\text{Xe}/^{3}\text{He}$ dual spin maser with double cell geometry
129Xe/3He frequency analysis (1)

Maser frequencies (stable region, 100s averaged)
$^{129}\text{Xe}/^{3}\text{He}$ frequency analysis (2)

Verification is continued.
Towards measurement of Xe-EDM

Birth of the active feedback spin maser

Maser stability improvement
(B-field, temperature, gas pressure, etc...)

EDM measurement trial with spherical cell

$^3\text{He}/^{129}\text{Xe}$ maser (spherical cell)

Double cell geometry

$^3\text{He}/^{129}\text{Xe}$ maser (double cell)

Remaining (on going) steps
- Verification of $^3\text{He}$ co-magnetometry
- Development of EDM cell with transparent electrodes
Search for $^{129}$Xe EDM aiming at $10^{-28}$ $\text{ecm}$ region

Active nuclear spin maser
- Optical detection of spin + Artificial feedback

Development
- $^3$He co-magnetometry (reduce B-field fluctuation)
- Double-cell geometry (minimize interaction with pol. Rb)
- Dual spin masers of $^{129}$Xe/$^3$He using double cell

Future outlook
- Evaluation of systematic uncertainty
- EDM cell (with Electrode) development
- EDM measurement
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