Search for electric dipole moment of the electron with laser-cooled radioactive atoms

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Collaborators


CYRIC; Univ. of Tokyo; TMU; TAT; RCNP; JAEA; Kyoto Univ.; IITR; Tohoku Univ.; Kyusyu Univ.;
Symmetry and its violation

• Parity (spatial inversion symmetry) is violated.
  – 1956 T.D.Lee and C.N.Yang
  – 1957 C.S.Wu

• How about the time reversal symmetry?

$^{60}\text{Co} \rightarrow ^{60}\text{Ni} + e^- + \nu$
Search for the violation of time reversal symmetry

- Nonzero EDM $d$ will violate the time reversal symmetry as well as the parity.

Permanent electric dipole moment (EDM) $d$

- Require extremely-high experimental precisions!

→ Laser cooling and trapping techniques
Journey of electron-EDM search

An electron EDM can induce a net atomic EDM. → The net EDM of a heavy atom can be many times larger than the electron EDM.


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No experimental result of EDM search for cooled/trapped radioactive atoms
EDM measurement

\[
\begin{align*}
B \neq 0 & \quad E = 0 & & \text{Cs EDM CELL experiment} \\
E = 0 & \quad B \neq 0 & & \text{Tl EDM BEAM experiment}
\end{align*}
\]

\[
\begin{align*}
B = 0 & \quad E = 0 & & m = +1/2 \\
E \parallel B & \quad B \neq 0 & & 2\mu_B \\
E \parallel -B & \quad B \neq 0 & & 2\mu_B + 2dE \\
B \neq 0 & \quad E = 0 & & 2\mu_B - 2dE \\
E = 0 & \quad B \neq 0 & & m = -1/2
\end{align*}
\]

Magnetic dipole moment \( \mu \)
Electric dipole moment \( d \)
Limitations of cell and collinear beam experiment

Systematic errors in EDM experiments

- Motional magnetic fields, \( B_m = \frac{v \times E}{c^2} \)
- Misalignment of static magnetic field \( B_0 \) with static electric field \( E \); cause a component of \( B_m \) to lie along \( B_0 \)
- Magnetic field \( B_E \), generated by leakage and/or changing currents, inaccuracy of high voltage electric field reversals, correlated with \( E \)
- Geometric phase shifts generated by complicated field gradients
- Magnetic Johnson noise generated by traditionally used metals in Electric field plates, vacuum chamber, magnetic shield etc

These effects limit the precision of e-EDM measurement...

Some of effects originate from the motion of the particles.
To overcome these systematic errors, laser cooling and trapping is employed for measuring the e-EDM.
Laser cooling and trapping

Absorption and emission → Change momentum

Absorption = one-sided
Emission = isotropic

→ Cool down

1-dimensional cooling
(e.g. deceleration of atomic beam)

ω_l + kv = ω_a Doppler shift

... Zeeman shift

3-dimensional cooling
(e.g. trap of atom)

MOT: magneto-optical trap

Atom cloud

Anti-Helmholtz coil

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Francium

- Heaviest alkali metal = Francium:
  - simple electronic structure and large nucleus
  - Enhancement of EDM: Z=87 → K~10^3

Enhancement factor:

\[ K \sim \frac{d_{\text{atom}}}{d_e} \sim Z^3 \alpha^2 \]

- Laser cooling and trapping techniques: localize atoms
  → Reduce systematic errors

- No stable isotopes: radioactive atom
  - Several isotopes with long half-life
    - $^{210}\text{Fr} = 3.2$ min, $^{211}\text{Fr} = 3.1$ min, $^{212}\text{Fr} = 20.$ min.
Overview of Fr EDM experiment

**Francium:** heaviest alkali element
Advantage to EDM experiment

Production using cyclotron

Rubidium: one of alkali elements
Useful for pilot experiments

Ionization

Stable isotopes

Ion beam transport

Neutralization

Laser cooling & trapping

EDM measurement

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Mini Laser-Cooled Rubidium Factory

Rb-ion source (Ionization)

Ion-beam focus lens & diagnosis (Ion beam transport)

Beam converter (Neutralization)

MOT (Laser cooling & trap)

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Rubidium-Ion Source

Saha-Langmuir equation

\[
\frac{n^+}{n^0} = \frac{1}{2} \exp\left(\frac{E_{WF} - E_{IP}}{kT}\right)
\]

Thermal ionization \( \leftrightarrow E_{IP}(\text{Fr}) < E_{WF}(\text{Mo}) \)

\( E_{IP} \) (Ionization potential): Fr 4.1 eV

\( E_{WF} \) (work function): Mo 4.6 eV

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Ion beam focus lens (electrostatic quadrupole triplet)

Ion trajectory simulation by TOSCA (finite-element technique)

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Beam converter

Saha-Langmuir equation

\[ \frac{n^+}{n^0} = \frac{1}{2} \exp \left( \frac{E_{WF} - E_{IP}}{kT} \right) \]

for ionizer

Thermal ionization \( \Leftarrow \) \( E_{IP} < E_{WF}(Mo) \)

\( E_{IP} \) (Ionization potential): Fr 4.1 eV

\( E_{WF} \) (work function): Mo 4.6 eV

for neutralizer

Thermal neutralization \( \Leftarrow \) \( E_{IP} > E_{WF}(Y) \)

\( E_{WF} \) (work function): Y 3.1 eV

Atom:
- Ion potential
- Neutral atom

Target:
- Work function
- HIGH \( \rightarrow \) Ionization
- LOW \( \rightarrow \) Neutralization

Positive ion

Hot metal
Magneto-optical trap (MOT)

Neutralized Rb

Trap!

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Mini Laser-Cooled Rubidium Factory

Rb-ion source (Ionization)

Ion-beam focus lens & diagnosis (Ion beam transport)

Beam converter (Neutralization)

MOT (Laser cooling & trap)

Rb Trap!

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This guy is the trapped Rb!

dia. ~ 2 mm

The maximum $10^6$ atoms in trap

More trapped atoms are required!!
Laser-cooled francium factory @ CYRIC

Cyclotron and Radioisotope Center (CYRIC), Tohoku University

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Laser room

Optical fiber

Ext. room

Cyclotron

Target room

EDM meas. area (Ext. room)

Wall

Beam swinger

$^{185}_{18}O^{5+}$ (100MeV)

$^{197}_{97}Au + ^{18}_{8}O \rightarrow Fr + xn$

Fr$^+$ (5 keV)

10 meter

neutralize

Fr atom

trap

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**Fr⁺-ion source ~ Thermal ionizer**

**Fusion reaction:** \(^{18}\text{O} + ^{197}\text{Au} \rightarrow ^{210}\text{Fr} + 5\text{n}\)

**Saha-Langmuir equation**

\[
\frac{n^+}{n^0} = \frac{1}{2} \exp \left( \frac{E_{WF} - E_{IP}}{kT} \right)
\]

Thermal ionization \(\leftarrow E_{IP}(\text{Fr}) < E_{WF}(\text{Au})\)

**\(E_{IP}\) (Ionization potential):** Fr 4.1 eV

**\(E_{WF}\) (work function):** Au 5.1 eV

Ions can be extracted by electric fields.

**Desorption from high-temperature liquid target**

- **Faster diffusion**
- **Convection flow**
- **Clear surface**

\(\Rightarrow\) Efficient Ion Production

**Available for molten gold.**

**Rb beam test w/o cyclotron.**

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Beam swinger

\[ ^{197}\text{Au} + ^{18}\text{O} \rightarrow ^{197}\text{Fr} + \text{xn} \]

Fr atom

neutralize

trap

10 meter

1st beam diagnosis system

4th beam diagnosis system

Target room

EDM meas. area (Ext. room)

Laser-cooled francium factory @ CYRIC

Cyclotron and Radioisotope Center (CYRIC), Tohoku University

東北大学サイクロトロン・ラジオアイソトープセンター

AVF Cyclotron

2012 November

Beam swinger

\[ ^{18}\text{O}^{5+} (100\text{MeV}) \]

Fr\(^{+}\) (5 keV)
Francium is identified using SSD in Diagnosis system.

**Solid State Detector:**
detect alpha particles from unstable nuclei.

Checking source $^{241}\text{Am}$ placed near SSD for energy calibration.

Alpha-decay spectrum was obtained at a diagnosis system

Blue: originating from $^{241}\text{Am}$

Green: originating from $^{208-212}\text{Fr}$ and also daughter nuclei
Experimental results (2012.Nov.)

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- **Gold target (room temperature)**

- **Molten gold (~1000 °C)**

Achieved $^{210}\text{Fr}^+$ yield: $\sim 10^6$ ion/sec
Laser-cooled francium factory @ CYRIC

Cyclotron and Radioisotope Center (CYRIC), Tohoku University

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Beam swinger

$^{180}_{\text{O}}^{5+} [\text{100 MeV}]$

Fr\(^+\) (5 keV)

$^{197}_{\text{Au}} + ^{180}_{\text{O}} \rightarrow \text{Fr} + \text{xn}$

10 meter

1st beam diagnosis system

4th beam diagnosis system

Target room

EDM meas. area (Ext. room)

neutralize

Fr atom

trap

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Laser-cooled francium factory @ CYRIC

Cyclotron and Radioisotope Center (CYRIC), Tohoku University

**Beam converter**

AVF Cyclotron

2013 February

1\textsuperscript{st} beam diagnosis system

10 meter

197\textsuperscript{Au} + 18\textsuperscript{O} \rightarrow Fr + xn

Fr\textsuperscript{+} (5 keV)

180\textsuperscript{O}\textsuperscript{5+} (100MeV)

Beam swinger

197\textsuperscript{Au} + 18\textsuperscript{O} \rightarrow Fr + xn

Target room

Wall

EDM meas. area (Ext. room)

Fr atom

neutralize

trap

Beam diagnosis system

2012 November 1\textsuperscript{st} beam diagnosis system

2013 February

Beam converter

Beam swinger

AVF Cyclotron

197\textsuperscript{Au} + 18\textsuperscript{O} \rightarrow Fr + xn

Fr\textsuperscript{+} (5 keV)

180\textsuperscript{O}\textsuperscript{5+} (100MeV)

Beam swinger

197\textsuperscript{Au} + 18\textsuperscript{O} \rightarrow Fr + xn

Target room

Wall

EDM meas. area (Ext. room)

Fr atom

neutralize

trap

Beam diagnosis system

2012 November 1\textsuperscript{st} beam diagnosis system

2013 February
Fr neutralization (2013.Mar.)

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- $^{241}\text{Am} (5.49 \text{ MeV})$
- $^{211}\text{Fr} (6.53 \text{ MeV})$
- $^{210}\text{Fr} (6.54 \text{ MeV})$
- $^{208}\text{Fr} (6.64 \text{ MeV})$
- $^{209}\text{Fr} (6.65 \text{ MeV})$

Preliminary
Orthotropic type beam converter

Neutralizer target: Y
($T_{\text{melt}}=1526^\circ\text{C, } E_{WF}=3.1\text{eV}$)

Ionizer oven: Pt
($T_{\text{melt}}=3825^\circ\text{C, } E_{WF}=5.6\text{eV}$)

Electric field simulation by OPERA-3d/TOSCA

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Towards the highly efficient trap and EDM measurement...

Beam converter  Transverse cooling  Zeeman slower  

$1^{st}$ MOT (diagnosis)  

$2^{nd}$ MOT (reservoir)  

EDM measurement chamber  

Optical trap  

Optical tweezer  

Magnetic shield  

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Summary and Outlook

**GOAL**
Fr-EDM experiment

**SETUP**

- Mini laser-cooled Rb factory

  - Rb ionization
  - Ion transport
  - Neutralization
  - Trap

  - Laser-cooled Fr factory at Cyclotron & Radioisotope Center

  - Fr ion production
  - Ion transport
  - Neutralization
  - Trap

- Upgrade of each device
- Francium trapping
- Development of EDM measurement system

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