Development of application system of electric field to laser cooled atoms toward search for EDM of electron using laser cooled Fr atoms

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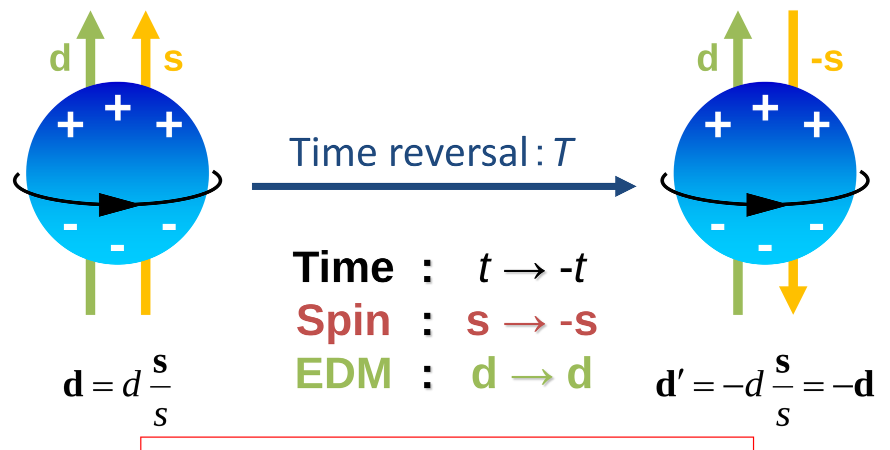
Abstract: An electron EDM search experiment using laser cooled francium atoms are planned at Cyclotron and Radioisotope Center, Tohoku University. In the EDM experiment, the application of the strong electric field are required. We are the electric field application system with transparent electrodes to realize the coexistence of three-dimensional laser cooling and electric field application.

Electric Dipole Moment (EDM)

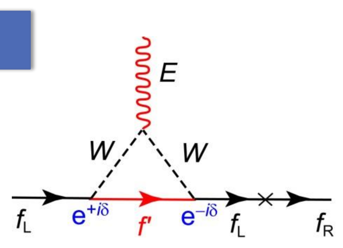


$d \neq 0$: *T*-violation ⇔ *CP*-violation

Standard Model (SM) — SM

predicts undetectably small EDM (10^{-5} times the present limits)

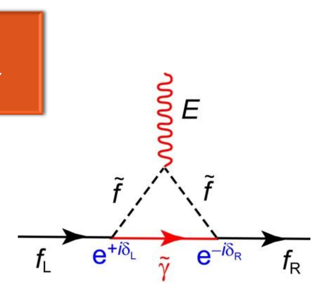
Cf. d_e ~ 10^{-37} *e*cm



Theories beyond the SM — (e.g.) SUSY

predict sizes of EDM to be reachable with current experiment conditions

Cf. d_e ~ 10^{-26} ~ 10^{-28} *e*cm



Search for EDM = Test of theories beyond the SM

e-EDM search with laser cooled Fr atom

EDM sensitivity (statistical limit)

$$\delta d_e = \hbar \frac{F}{R} \cdot \frac{1}{E} \cdot \frac{1}{\tau} \cdot \frac{1}{\sqrt{m}} \cdot \frac{1}{\sqrt{N}}$$

one measurement

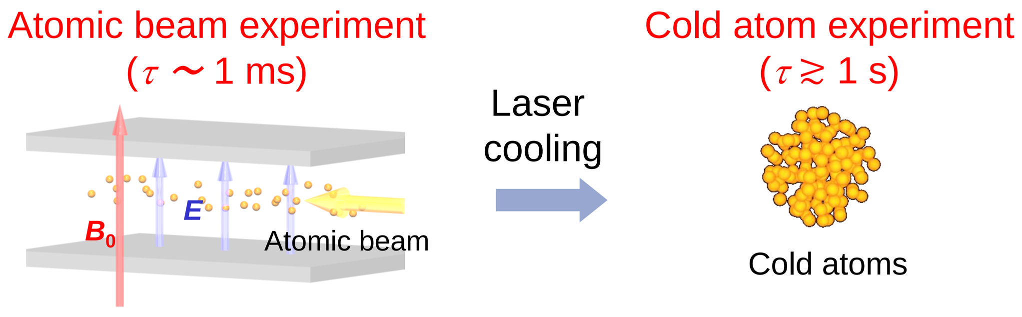
- F = 13/2: total angular momentum
- R = 895 : enhancement factor (Fr)
- E = 100 kV/cm : applied electric field
- τ = 10 s: interaction time
- m = 10^7: number of atoms
- N = 10^5 : number of measurements

$|d_e| < 10^{-29}$ *e*cm can be achieved.

Present limit: $|d_e| < 8.7 \times 10^{-29}$ *e*cm using ThO molecule

The ACME Collaboration *et al.*, Science **343**, 269 (2014).

The coherence time of longer than 1 s can be realized with laser cooled atoms, which is about 10^3 times longer than that of the atomic or molecular beam experiments.

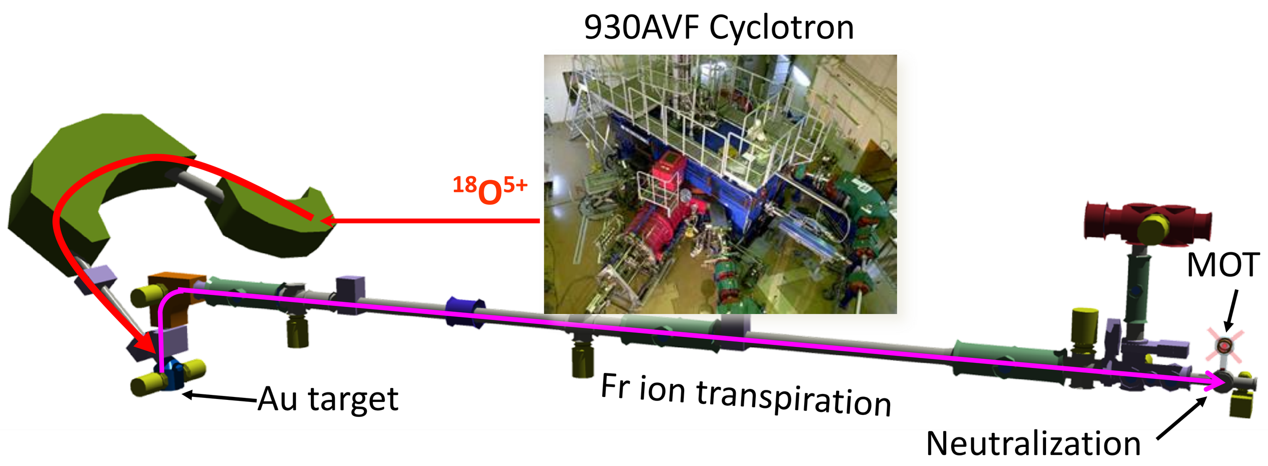


Systematic errors
- Motional magnetic fields
  $B_m \propto v \times E$
- Magnetic field inhomogeneity

- Suppression of the motion-induced magnetic filed
- Atomic ensembles in a small region

Precision measurement

Laser cooled Fr factory at CYRIC



Fr is produced through the nuclear fusion reaction with the $^{18}O^{5+}$ primary beam of 100 MeV accelerated by an AVF cyclotron and ^{197}Au target as ^{18}O + ^{197}Au -> $^{215-x}Fr$ + xn. The produce Fr is extracted as an ion and transported about 10 m away from the reaction point by using one electrostatic deflector, three electrostatic quadrupole triplets and three steerer electrodes to avoid damages from the radiations, such as neutrons and gamma rays, to the detectors and electrical devices. Then, the Fr ion is neutralized to apply the laser cooling technique; the magneto-optical Trap (MOT).

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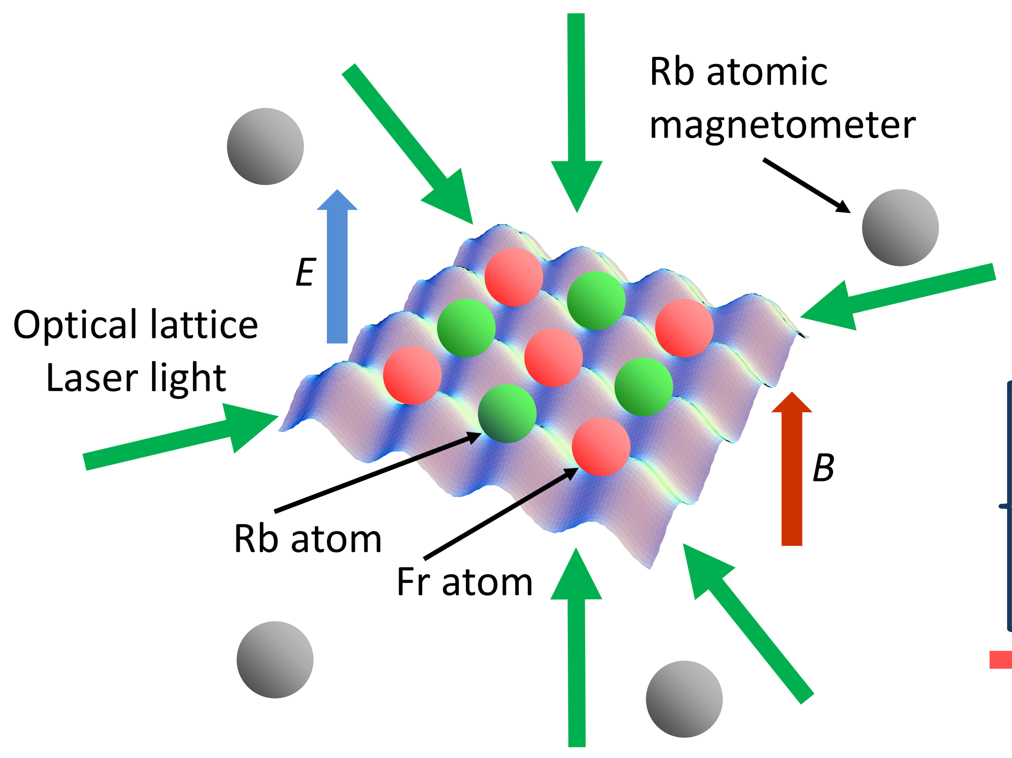
9. K. Harada, 11. A. Uchiyama,

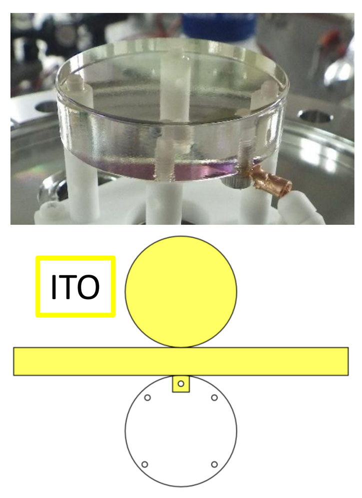
EDM measurement configuration



Planned EDM experiment:
Fr atoms trapped in optical lattice
- Trapped Rb atom: co-magnetometer
- Rb atomic magnetometer: field gradient
- Strong electric field application (E = 100 kV/cm) $\nu_{EDM} = -d \cdot E/h$
- three-dimensional laser light irradiation

Transparent electrode: glass plate coated by ITO (tin-doped indium oxide)

Electric field application system with ITO electrodes

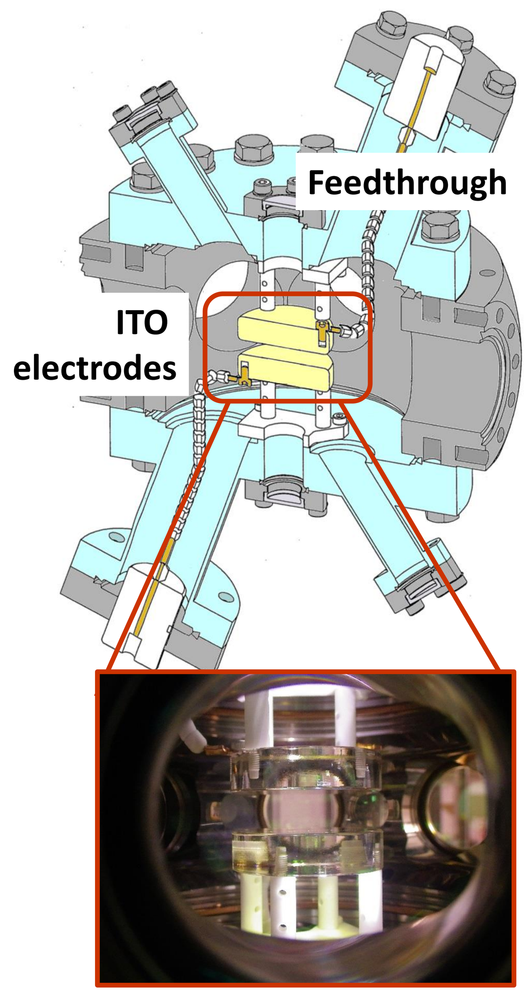


ITO feature
- Transparency: accessibility for laser light (transmission: ~ 84% @780 nm)
- Finite electrical resistance (~ 2 kΩ): suppression of magnetic Johnson noise

$$B_z = \mu_0 \sqrt{\frac{k_B T}{8\pi\rho} \frac{d}{z(z+d)}}\,\theta$$

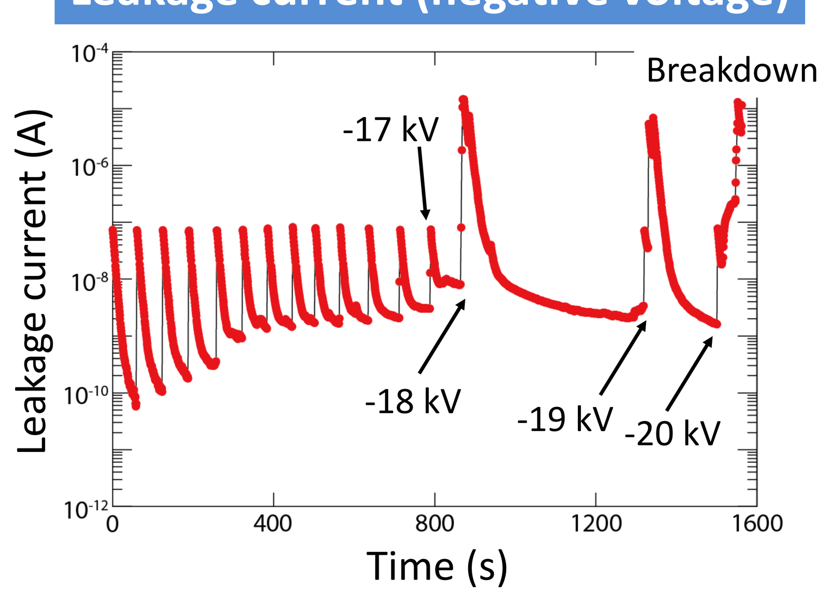
resistivity

C. T. Munger, Jr. PRA **72**, 012506 (2005).



- Glass thickness: 10 mm
- Glass diameter: ϕ40 mm
- Gap: ~ 1cm
- Vacuum Pressure: 10^{-8} Pa

Leakage current (negative voltage)



High voltage application

○**Positive: 50 kV application without breakdown** (sometime discharge)

○Negative: breakdown @ -20 kV
: Discharge occurs at an space except the gap between electrodes.
- Emission of electron from negative electrified place
- Nakedness of feedthrough connection area

Insulator cover of feedthrough

Spectroscopy of Rb atom applied electric field

Confirmation of the strength of the electric field applied to laser cooled atoms

Measurement of Stark shift of Rb atom (laser cooling :MOT)

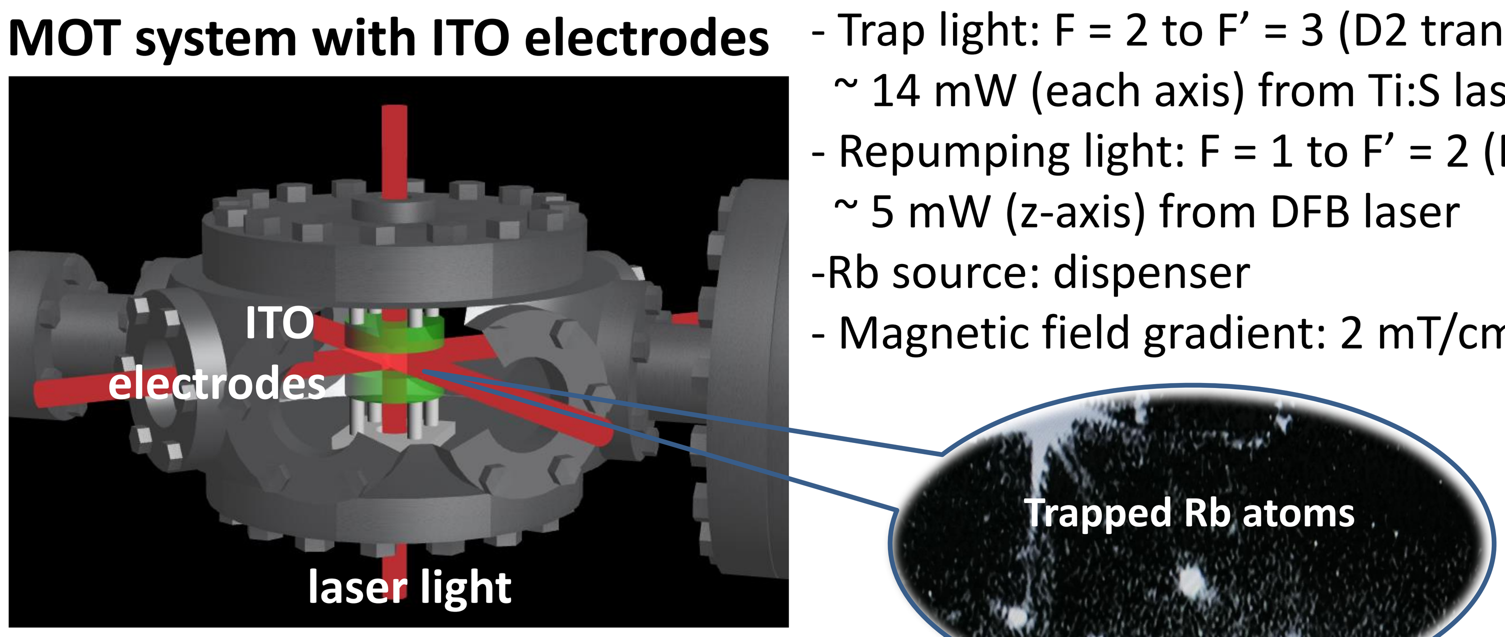
Stark shift

$$\mathcal{E} = -\frac{1}{2}\alpha_s E^2 - \frac{1}{2}\alpha_t E^2 \frac{[3m_F^2 - F(F+1)][3X(X+1) - 4F(F+1)J(J+1)]}{(2F+3)(2F+2)F(2F-1)J(2J-1)}$$

$$= -E^2 \left[\frac{1}{2}\alpha_s + \frac{2}{15}(m_F^2 - 4)\right]$$

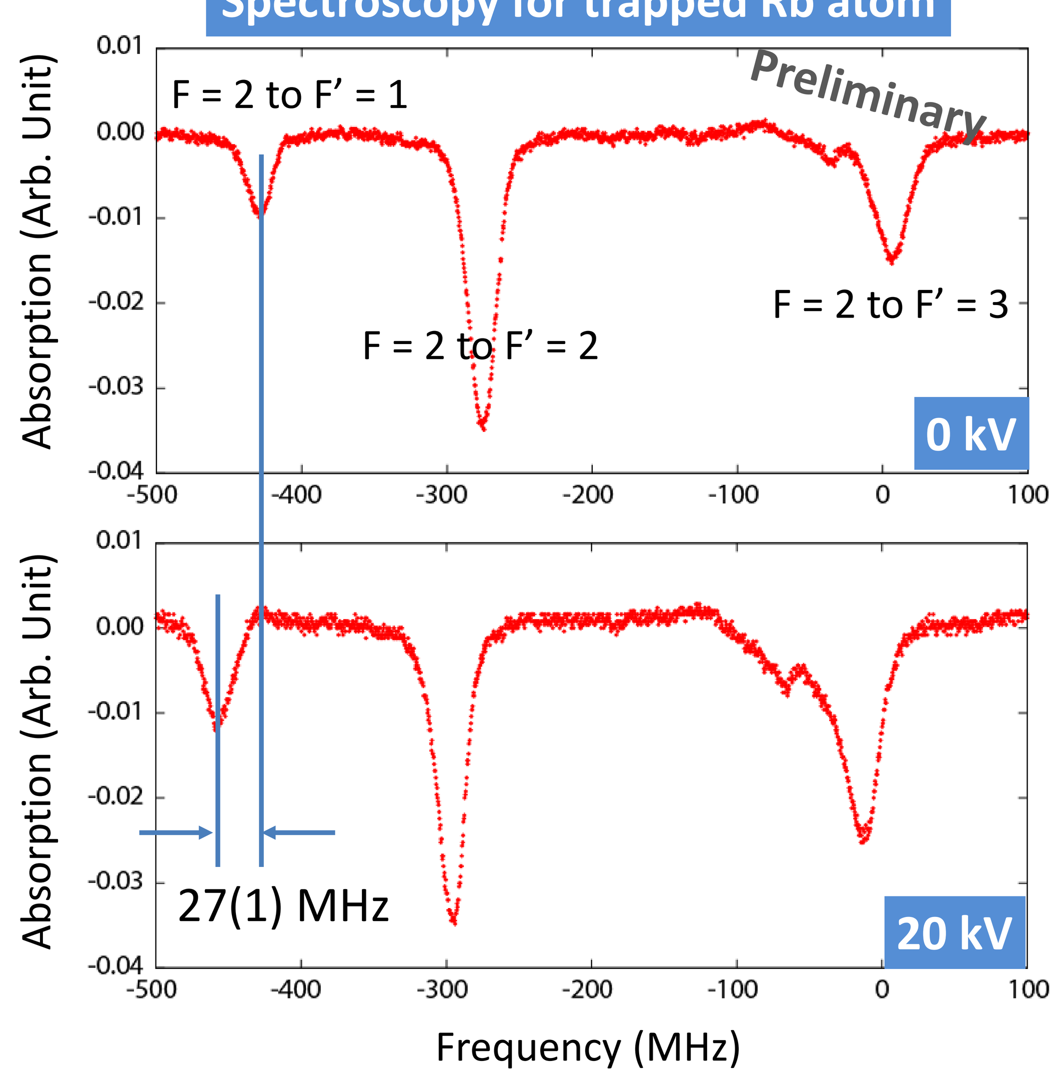
α_s = h·0.1340(8) Hz/(V/cm)^2, α_t = h·-0.0406(8) Hz/(V/cm)^2 — ^{87}Rb (D2 transition)

MOT system with ITO electrodes



- Trap light: F = 2 to F' = 3 (D2 transition)
  ~ 14 mW (each axis) from Ti:S laser
- Repumping light: F = 1 to F' = 2 (D2 transition)
  ~ 5 mW (z-axis) from DFB laser
- Rb source: dispenser
- Magnetic field gradient: 2 mT/cm

Spectroscopy for trapped Rb atom



- Probe light: F = 2 to F' (D2 transition)
  ~ 20 μW from DFB laser
- Repumping light : 10 kHz AM for lock-in detection

Measured shift 27(1) MHz of F = 2 to F' = 1 transition
→ E = 20.1(5) kV/cm^2
↔ assumed E = 20 kV/cm^2 (1 cm gap between electrodes)

More than 20 kV:
Difficulty for MOT due to the tensor Stark shift

Summary

We have been constructed the electric field application system utilizing the transparent ITO electrodes to apply the electric field to laser trapped atoms. Although the applicable negative voltage was limited to be -20 kV, the application of 50 kV positive voltage was realized without the breakdown. The field strength was evaluated by measuring the Stark shift of the Rb atom tapper by MOT.

8th International Workshop on "Fundamental Physics Using Atoms" (FPUA2015), 30 Nov - 1 Dec 2015, Wako, Japan