Fundamental Physics with Cold Radioactive Heavy Elements

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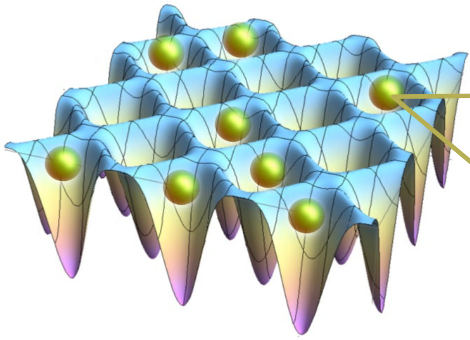
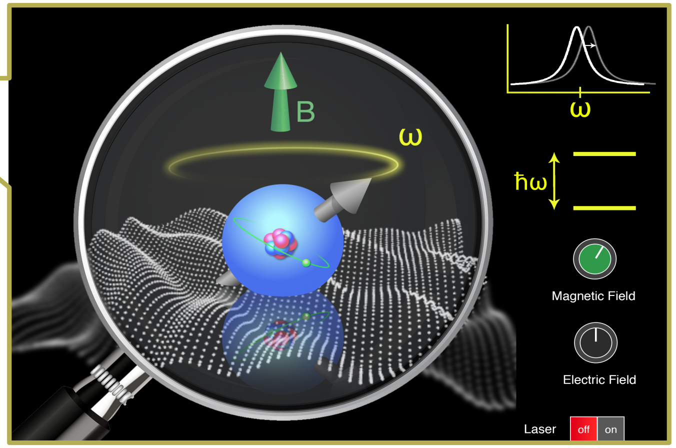
Quantum sensing with the crystal of the radioactive atoms

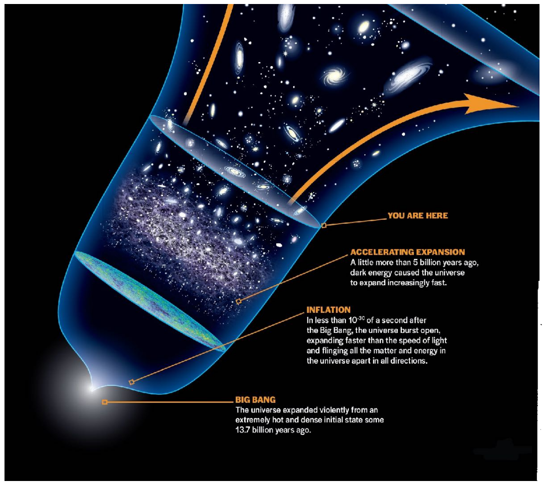
- Introduction
- Electric Dipole Moment（EDM）and Heavy Element
- Status of the experiment
- Co-magnetometer
- Future plan

Anti-matter disappearance mechanism in the universe

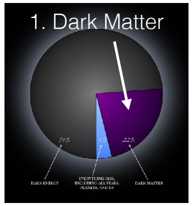




Quantum sensing with RI crystal of the cold atoms to search for the new particles



Two Mysteries



2. Matter-Antimatter Asymmetry

Sakharov's Conditions: Need CP-Violation

The Nobel Foundation

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of C asymmetry in the hot model of the expanding Universe (see [1]) by making use of effects of CP invariance violation (see [2]). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.

Matter dominated universe :

1. A baryon number violating interaction exists.

2. Departure from thermal equilibrium.

3. CP(Charge conjugation and Parity)-symmetry must be violated.

Standard Model CP-Violation : Not Enough

$$\eta = \frac{\text{(matter)} - \text{(antimatter)}}{\text{relic photons}} \propto \sin(\delta)$$

$$\eta_{\text{exp}} \approx 10^{-9}$$ PDG2022

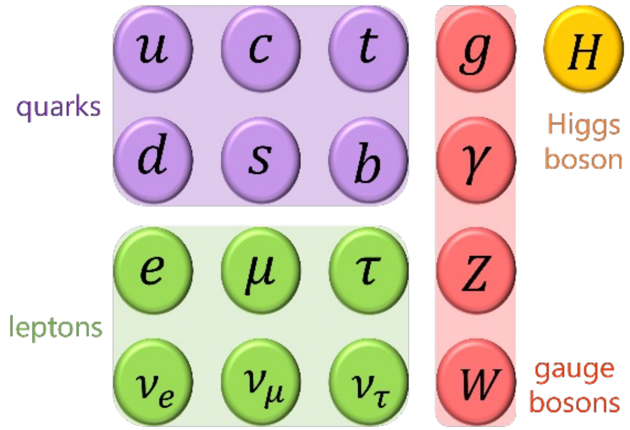
$$\eta_{\text{CKM}} \approx 10^{-26}$$ Huet & Sather PRD 51:379 (1995)

$$V = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\exp(-i\delta) \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}\exp(+i\delta) & +c_{12}c_{23} - s_{12}s_{23}s_{13}\exp(+i\delta) & s_{23}c_{13} \\ +s_{12}s_{23} - c_{12}c_{23}s_{13}\exp(+i\delta) & -c_{12}s_{23} - s_{12}c_{23}s_{13}\exp(+i\delta) & c_{23}c_{13} \end{bmatrix}$$

$$\delta = CP\text{-violating ``phase''}$$

Search for beyond-standard-model (BSM)

Big issues in particle physics now
- Is the discovered Higgs particle the SM one ?
- Where is BSM ?   TeV scale or higher energy scale ?



Remaining mysteries

- What is dark matter?
- How is neutrino mass generated?
- Why is the Higgs boson so light?
- Why do the proton and electron have same magnitude of charge?
- Why is antimatter so scarce in the Universe compared to matter?
- …

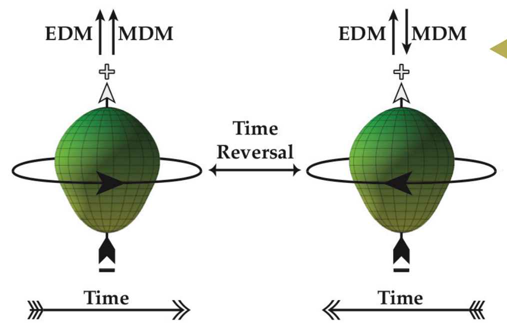
Where do we look for more CP violation ?

- Decays of B-mesons
- D-coefficient in nuclear beta-decay
- Double polarized neutron transmission
- Angular decay correlations of positronium
- Neutrino oscillations
- Neutrino less Double Beta Decay $0\nu\beta\beta$
- Nuclear magnetic quadrupole moments
- Electric Dipole Moment (EDM)
- …

Electric Dipole Moment：EDM

電気双極子能率：d
Electric Dipole Moment
EDM

Classical



$$\vec{d} = q\vec{r}$$

Time reversal violation

CPT invariance

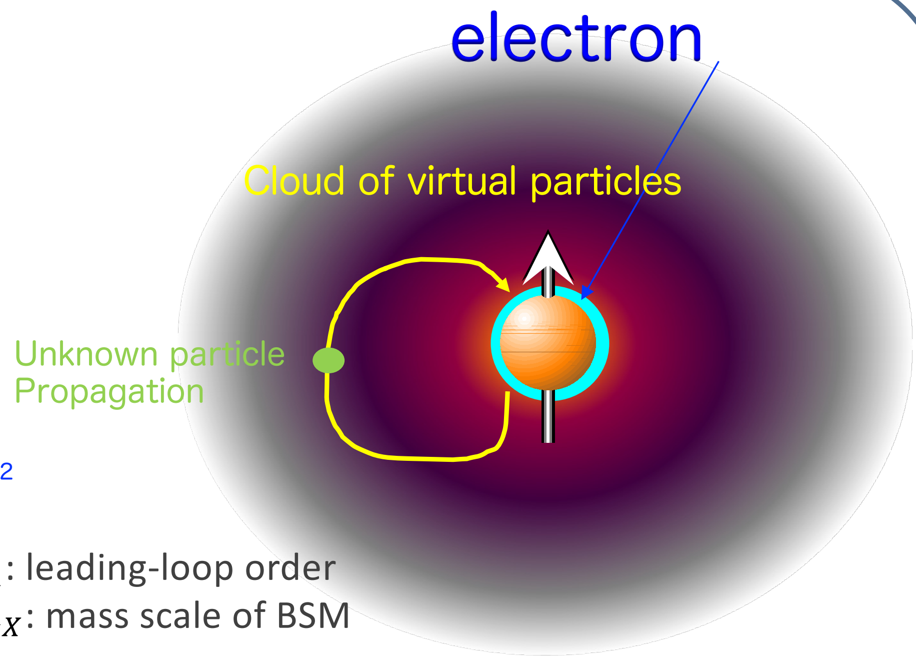
CP violation
(matter-antimatter asymmetry)

Microscopic

Quantum

Uncertainty principle
$\Delta E \times \Delta t \sim \hbar$

High energy physics：$E=mc^2$



$$d \propto \left(\frac{\alpha^2}{2\pi}\right)^{n_l} \left(\frac{m_e}{m_X}\right)^2$$

n_l: leading-loop order
m_X: mass scale of BSM

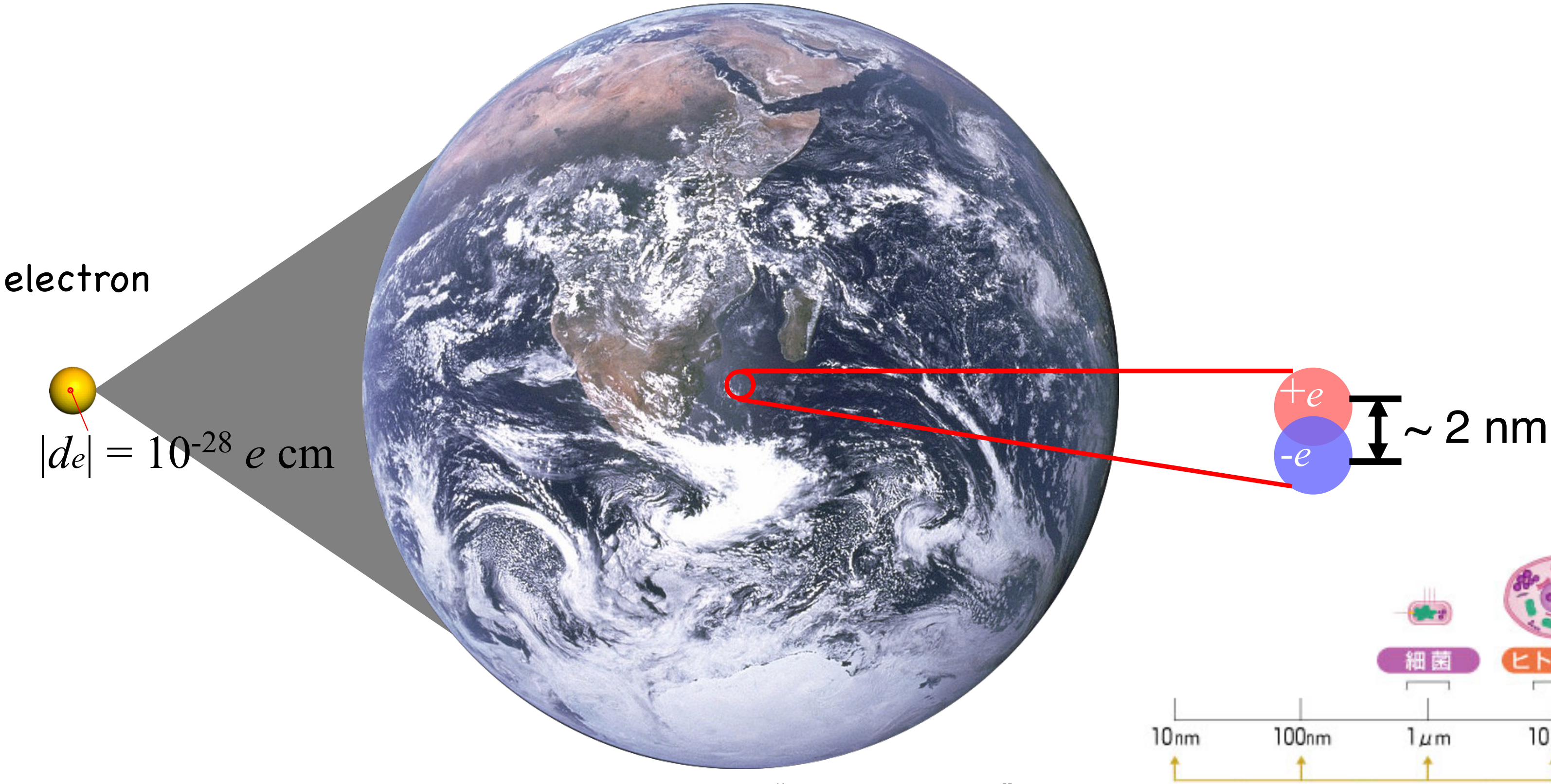
Mass of unknown particle：m_X

Particle Beyond Standard Model propagating
⇒　EDM appeared

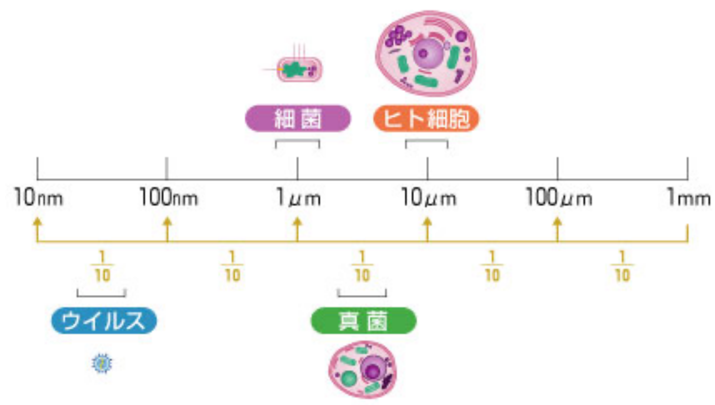
Vacuum polarization ~ quantum correction effect

Quite small size of EDM

Assuming EDM ~ 10^{-28} e・cm



“The Blue Marble”, NASA

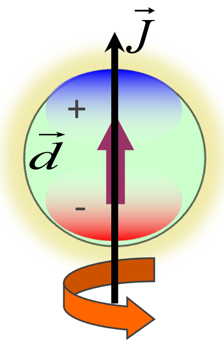


電子の古典半径 ~ 3 fm

地球の半径 ~ 6400 km

Permanent Electric Dipole Moment (EDM)

A probe for CP violation (T violation)



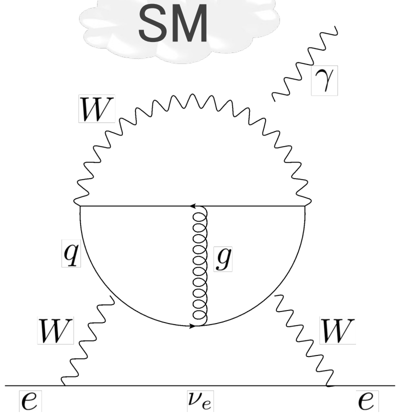
$\sim 10^{-39}\ e$ cm

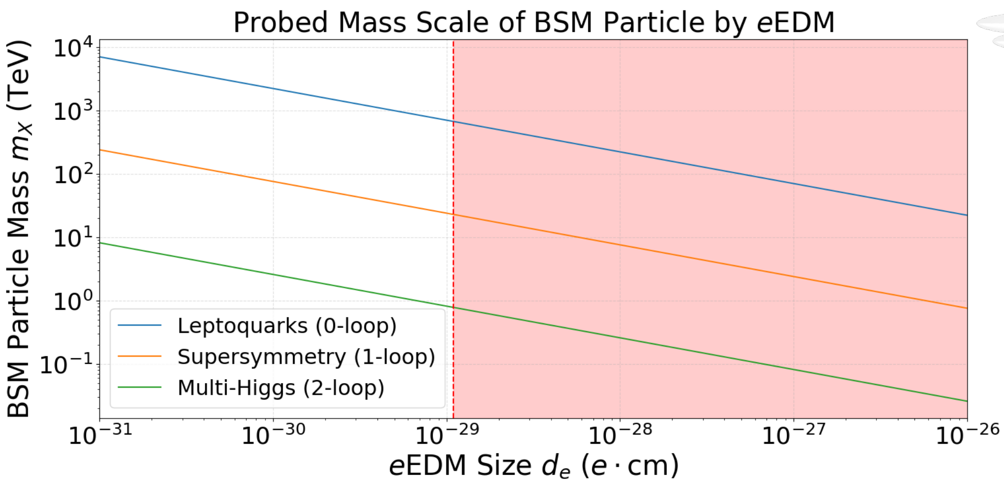
BSM?

$< 4.1{\times}10^{-30}\ e$ cm

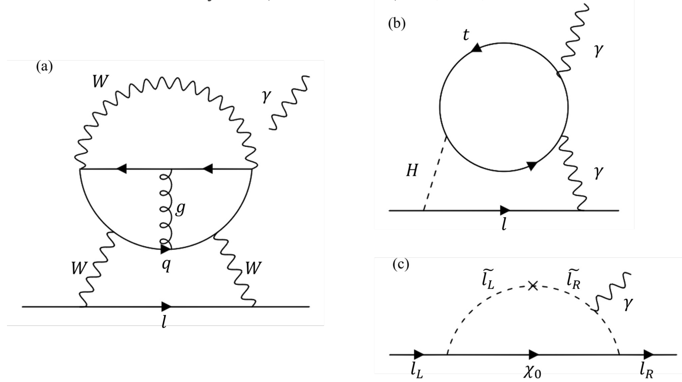
d_e

SM





Current upper limit
HfF+
T. S. Roussy et al., Science 381, 46 (2023).



$$d_e \propto \left(\frac{\alpha^2}{2\pi}\right)^{n_l} \left(\frac{m_e}{m_X}\right)^2$$

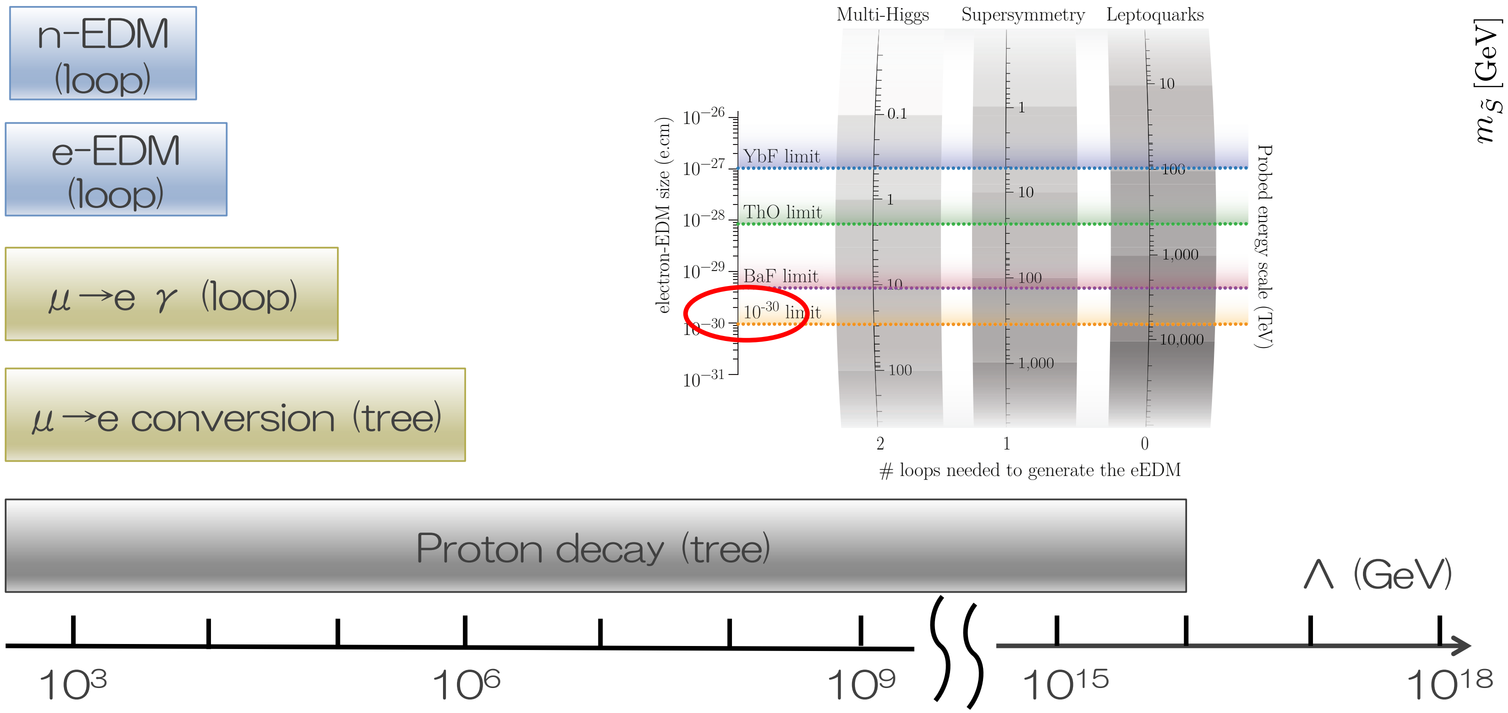
n_l: leading-loop order
m_X: mass scale of BSM

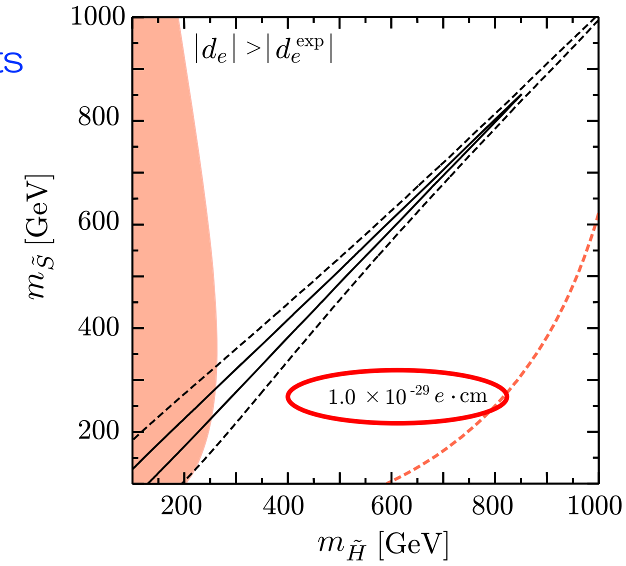
Search for symmetry breaking

Sensitivities of current experimental bounds on new physics scale (Λ).
Only one loop factors are included for the loop processes.
Small symmetry breaking parameters suppress the sensitivities.

EDMs and muon LFV are important to probe new physics at and beyond TeV scale

Possible verification of electroweak baryogenesis by electric dipole moments
EDM～10^{-30} ecm　:　one of the milestone





EDM in models extended by an extra Higgs doublet model

K.Fuyuto, J.Hisano, E.Senaha Phys. Lett. B755(2016)491

Heavy Elements (Radioisotope)

~ microscope to detect the CP violation~

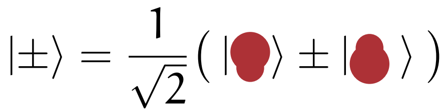
重元素～CP対称性の破れ（EDM）を拡大する顕微鏡

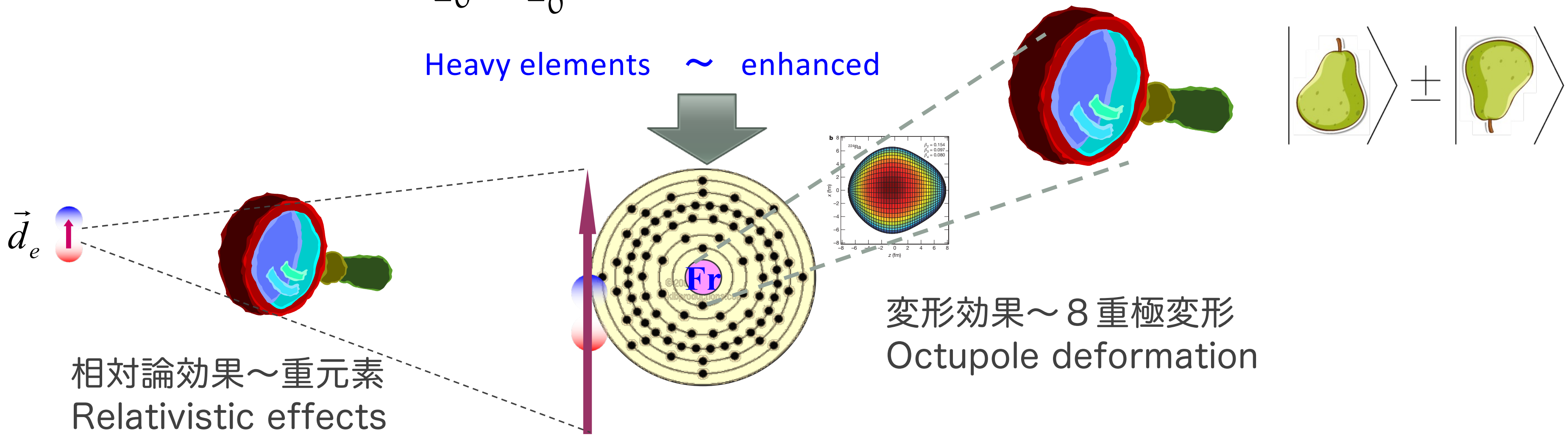
- 相対論効果 relativistic effects

$$K \sim \frac{d_{atom}}{d_e} \sim Z^3\alpha^2 \sim |\psi_s(0)|^2 VZ^5\alpha^2 \frac{e}{a_0^{\,2}}$$

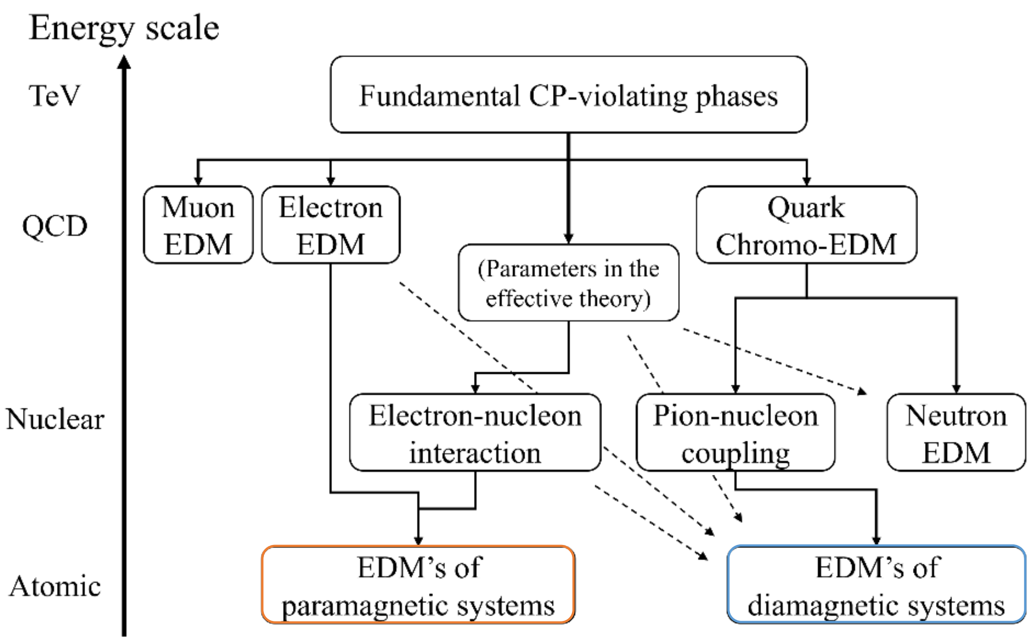
- 原子核変形効果 octupole deformation

$$\langle S \rangle \approx \frac{\langle 0|\, S_z\, |\bar{0}\rangle \langle \bar{0}|\, V_{PT}\, |0\rangle}{E_0 - E_{\bar{0}}} + \text{c.c.}$$



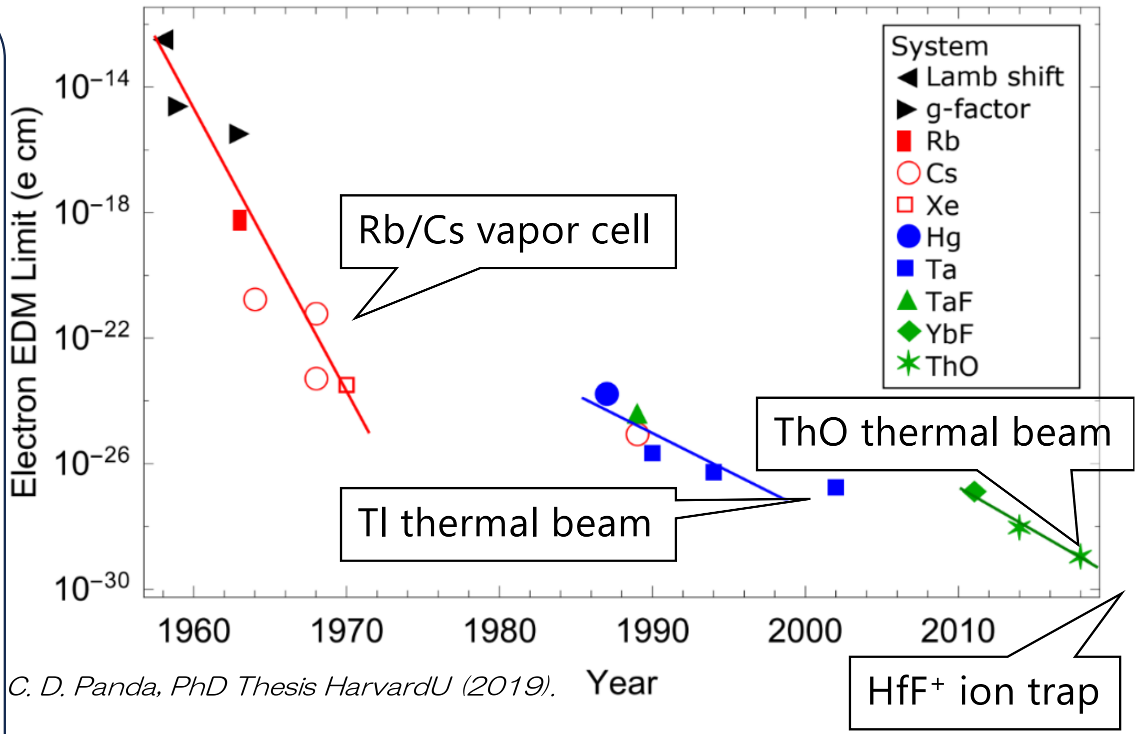


EDM of many-body system



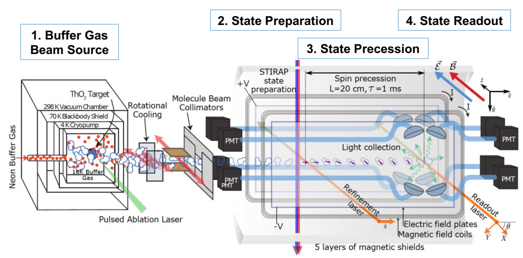
- Heavy atoms: Fr, Pa Ra, Rn
- Molecules: ThO, HfF+ RaF, FrAg

Sensitive to CP violating interactions

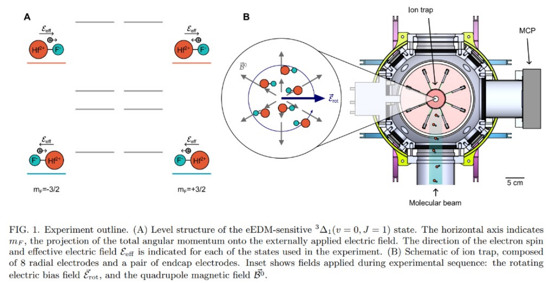


C. D. Panda, PhD Thesis HarvardU (2019).

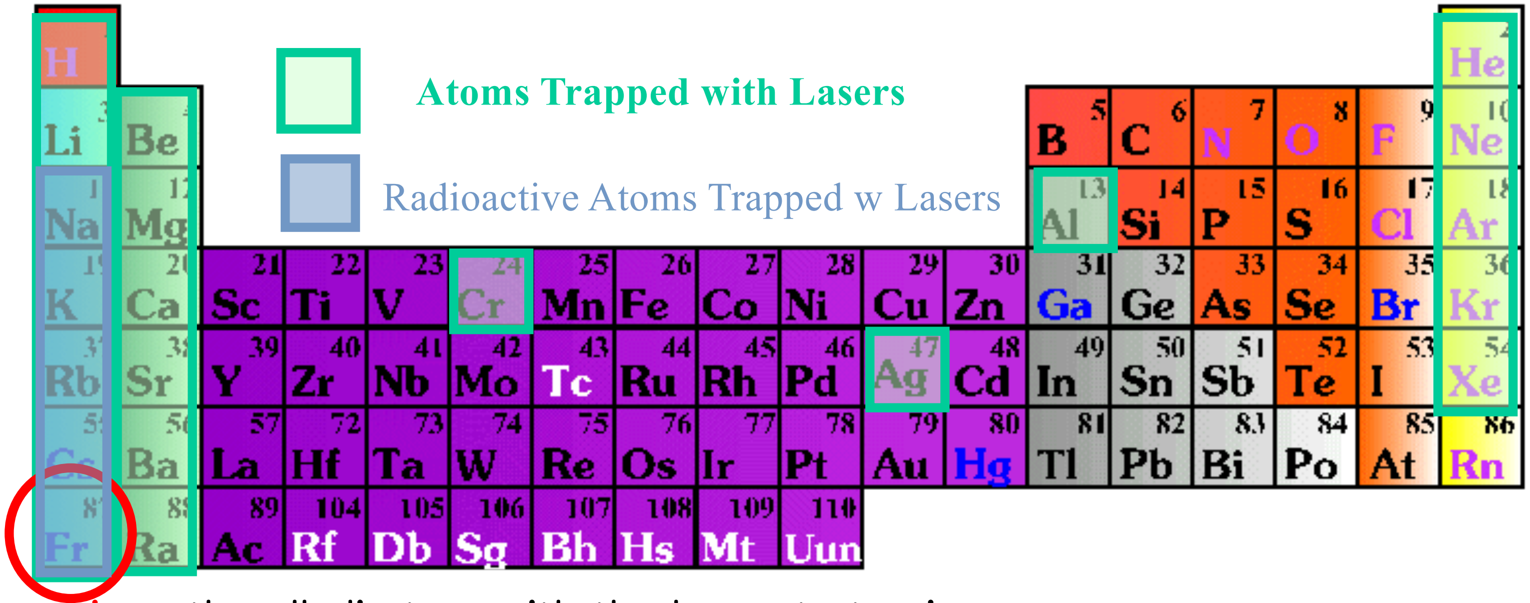
ACME II apparatus



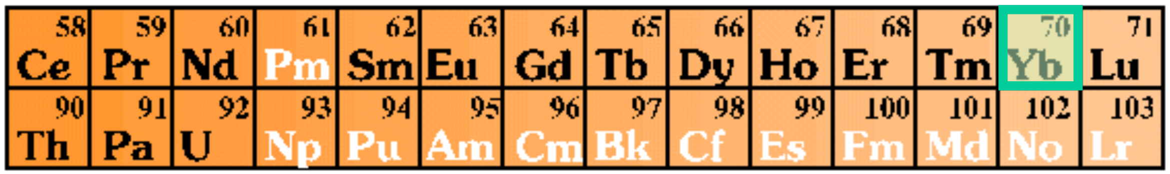
Science 381, 46 (2023), Tanya S. Roussy et al.



Candidate of the EDM search



Francium: the alkali atom with the largest atomic mass



- 7th period heavy elements
- Super Heavy Element

From ChemiCool.com

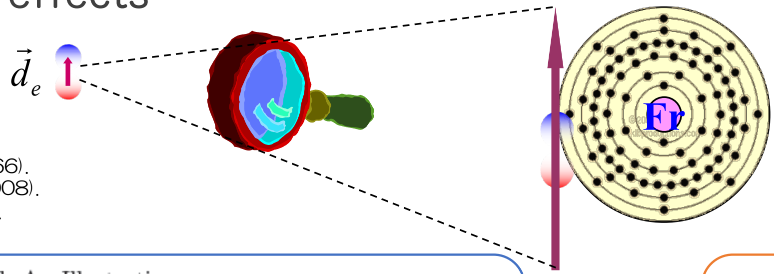
Marguerite Perey announcing the discovery of Francium 1939

Courtesy of the Curie Institute, Paris

e-EDM enhancement in atomic system
～Relativistic Coupled Cluster model ～

Heavy elements ～ EDM enhanced

Relativistic effects

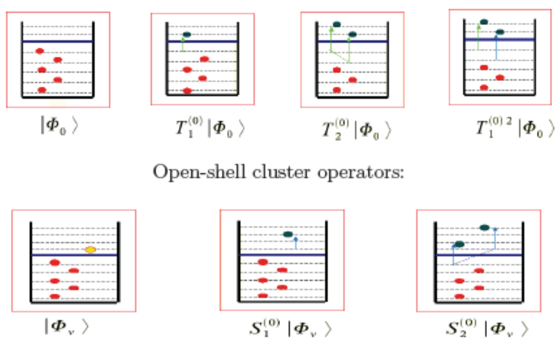


$$R \sim \frac{d_{atom}}{d_e} \sim Z^3\alpha^2 \sim |\psi_s(0)|^2 VZ^5\alpha^2 \frac{e}{a_0^{\ 2}}$$

Atom	$^{39}_{19}K$	$^{85}_{37}Rb$	$^{133}_{55}Cs$	$^{210}_{87}Fr$
R	2.42	27.5	114	799

P. G. H. Sandars, *Phys. Lett.* **22**, 290 (1966).
H. S. Nataraj *et al. PRL* **101**, 033002 (2008).
N. Shitara *et al. JHEP* **2021**, 124 (2021).

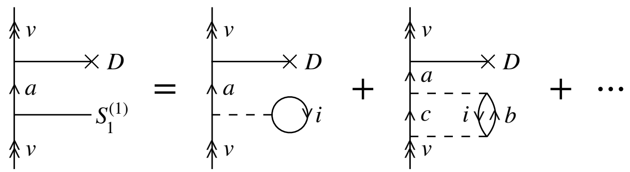
Coupled-cluster Method: An Illustration



Basis set		no. corr.ele./	eEDM EF		% corr.
Name	Details	no. virtuals	Dirac-Fock	CISD	
dyall.cv2z	27s 24p 15d 8f	19/83	784.34	893.44	12.21
		41/113		898.23	12.68
		59/201		900.50	12.90
dyall.cv3z	34s 30p 19d 12f 1g	19/179	789.43	897.19	12.01
dyall.cv4z	38s 35p 24d 19f 4g 1h	19/261	789.64	895.37	11.81

Calculation Accuracy Improved

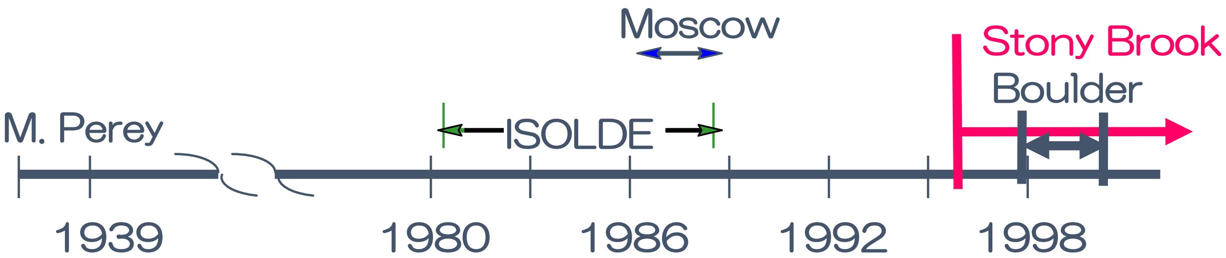
～ 10 years



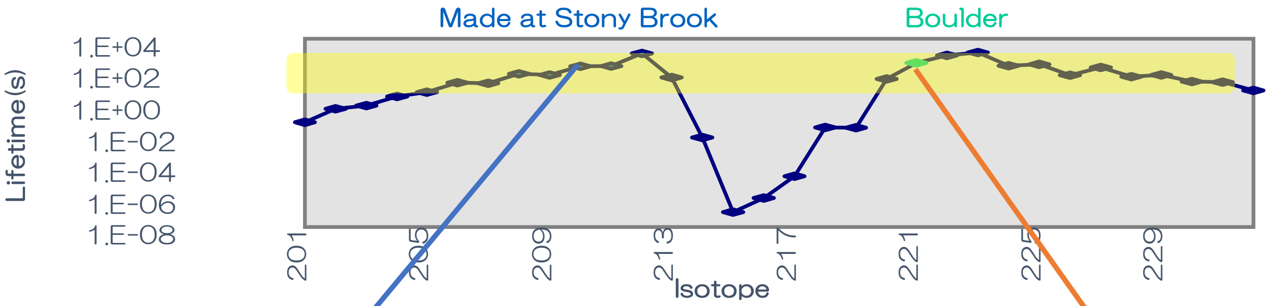
- Electron correlation：included
- Any configurations of electron excitations
- Including quantum effects (vacuum polarization
- Cs, Rb：ready
- Fr calculation ～ enhancement：799

Method	Correction	R
DF (DC)	-	727.24
RCCSD (DC)	0	812.19
RCCSD (DC+Breit)	-8.105	804.08
RCCSD (DC+QED)	-0.621	811.57
RCCSD (DC+pT)	-4.644	807.55
RCCSD (DC+Breit+QED+pT)	-13.369	798.82

Francium – MANY ISOTOPES :
New laboratory for fundamental physics



- LNL: PNC
- TRIUMF: PNC/anapole
- CNS/RIKEN: EDM



Laser cooling/trapping ~ possible

$$d_{\mathrm{atom}} = K d_e + R C_{S,P,T} + S$$

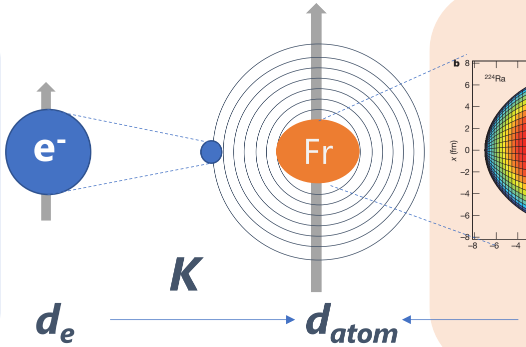
^{210}Fr

- Heaviest Alkali element
- eEDM enhancement

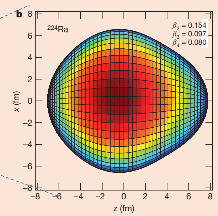
$T_{1/2} \sim 3$ min.

	Rb	Cs	Fr
K	27.5	114	799

Shitara, N., *et al.*, J. High Energ. Phys. **2021**(2021)124.



^{221}Fr



Octupole deformation

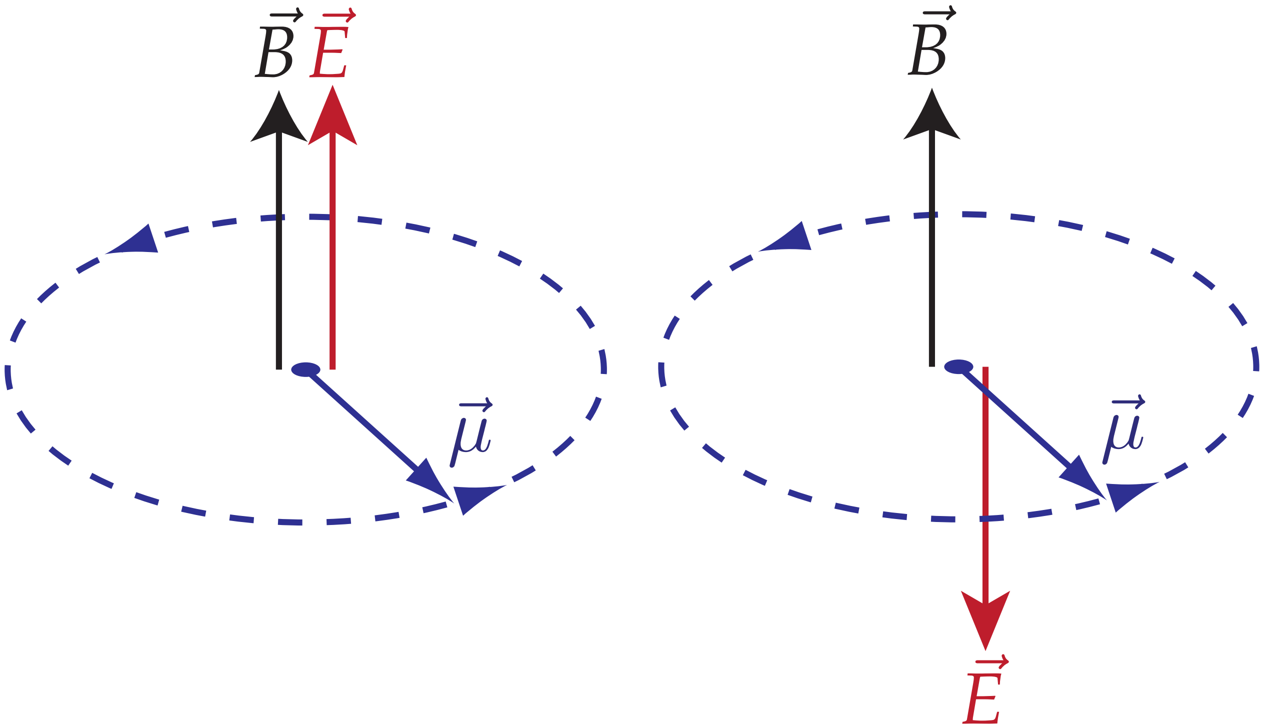
	^{223}Ra	^{225}Ra	^{223}Rn	^{221}Fr
β_2	0.125	0.143	0.129	0.106
β_3	0.100	0.099	0.081	0.100
β_4	0.076	0.082	0.078	0.069
β_5	0.042	0.035	0.024	0.045
β_6	0.018	0.016	0.023	0.020
E_c (keV)	212	221	213	305

$T_{1/2} \sim 5$ min.

$$\langle S \rangle \approx \frac{\langle 0 | S_z | \bar{0} \rangle \langle \bar{0} | V_{PT} | 0 \rangle}{E_0 - E_{\bar{0}}} + \mathrm{c.c.}$$

Measurement of the EDM

Always Measure Frequency
Example: Spin Precession of a Spin-1/2 Particle



$$h\nu_\uparrow = 2(\mu B_\uparrow + dE) \qquad h\nu_\downarrow = 2(\mu B_\downarrow - dE)$$

EDM sensitivity

Statistics & **Systematics**

$$\Delta\nu = \nu_{\uparrow} - \nu_{\downarrow} = \boxed{\frac{4dE}{h}} + \boxed{\frac{2\mu(B_{\uparrow} - B_{\downarrow})}{h}}$$

Quantum Projection Noise:

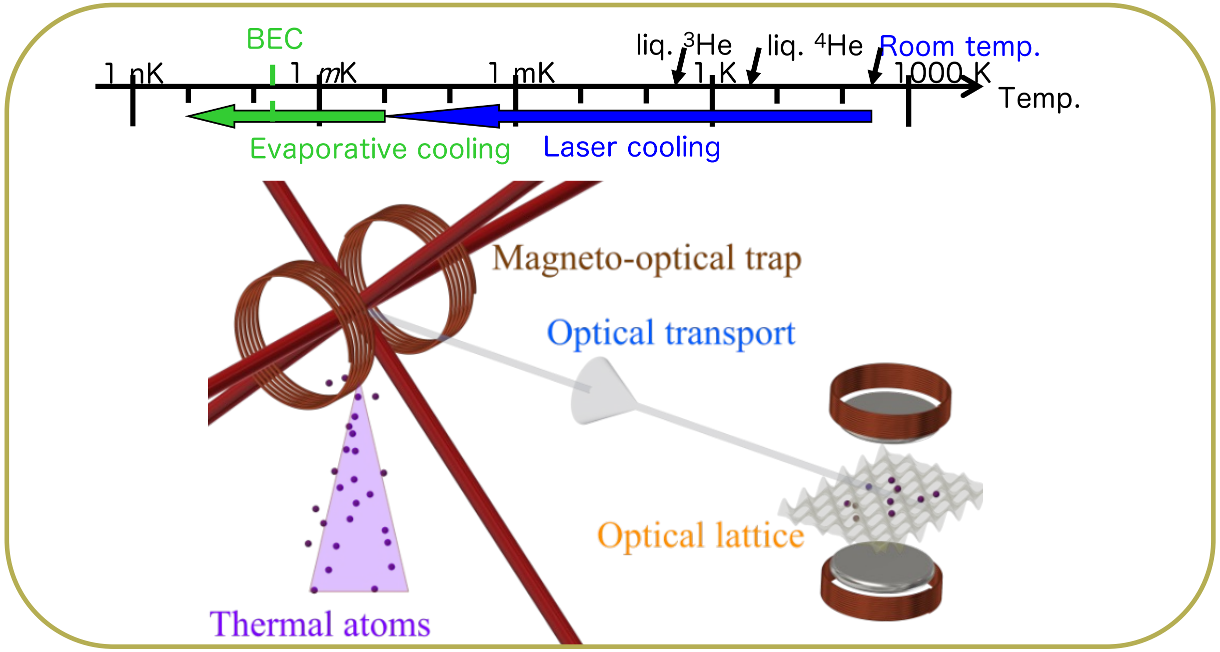
$$\delta d_e \sim \frac{h}{4\pi RET\sqrt{nN}}$$

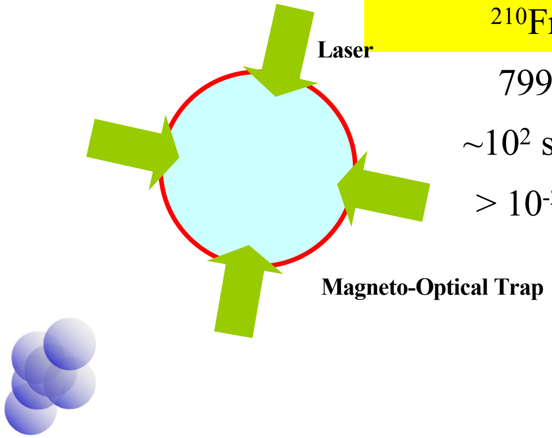
Electric field — Interaction time — Number of detected particles

Electron EDM search using laser-cooled Fr atoms

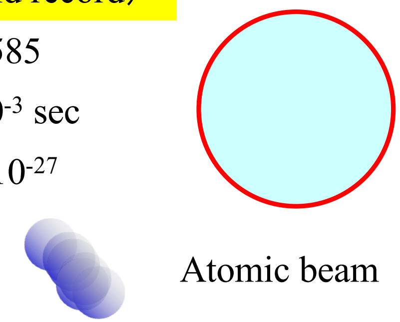
$$\delta d_e \sim \frac{h}{4\pi RET\sqrt{nN}}$$

- Large R (~799) ： for Fr
  - EDM enhancement factor
- Large nN (~10^7 Fr^+/s from fusion reaction)
- Long T (> 10 s) : interaction time
  - Collision-suppressed trapping by the optical lattice

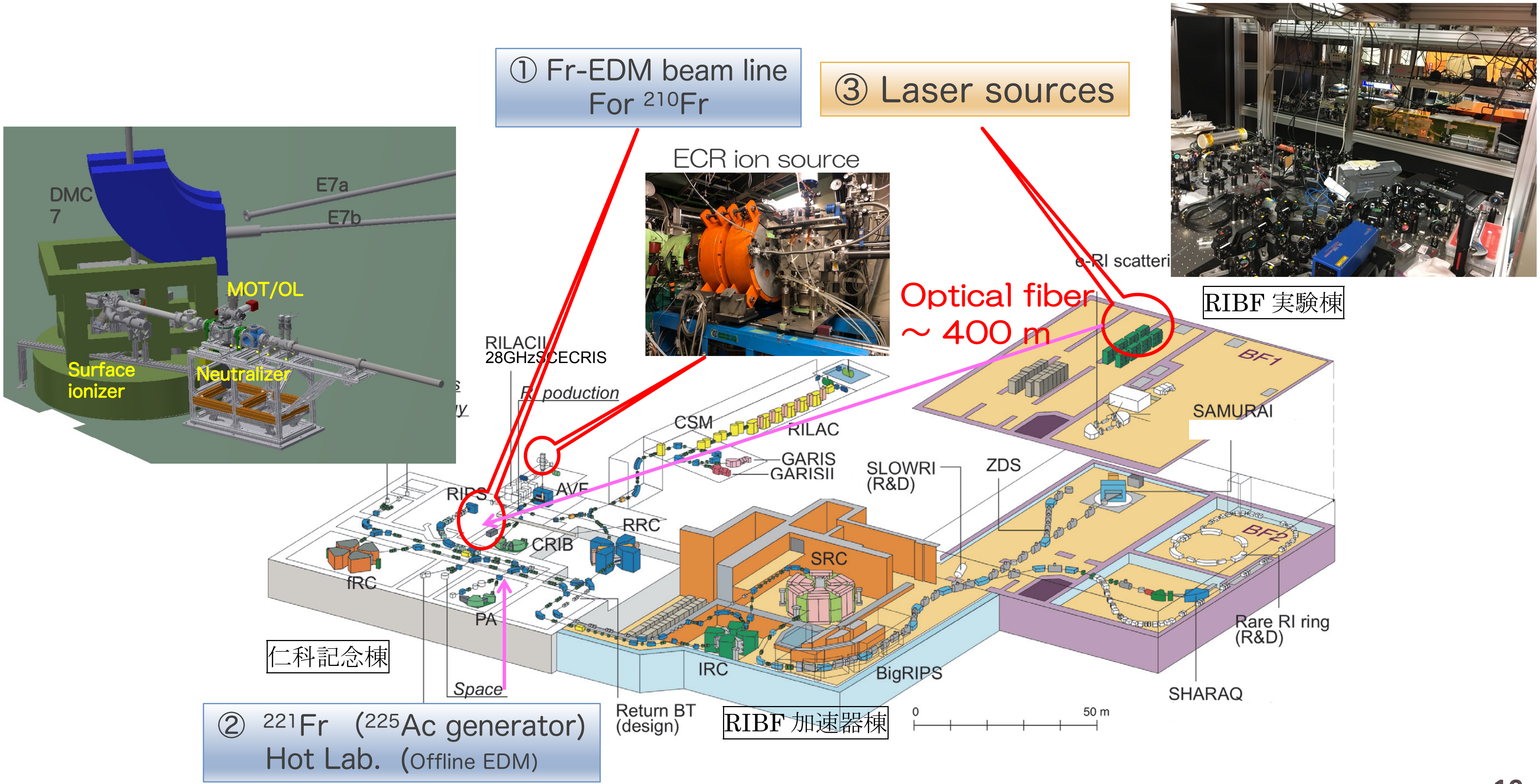




^{210}Fr		Tl (world record)
799	K: enhancement	585
~10^2 sec	τ: interaction time	~10^{-3} sec
> 10^{-29}	EDM (e・cm)	~10^{-27}



RIKEN RI BEAM FACTORY and EDM apparatus



^{210}Fr

Electron EDM enhancement

Calculated by the relativistic coupled-cluster theory to an accuracy of about 3%

	Rb	Cs	Fr
K	27.5	114	799

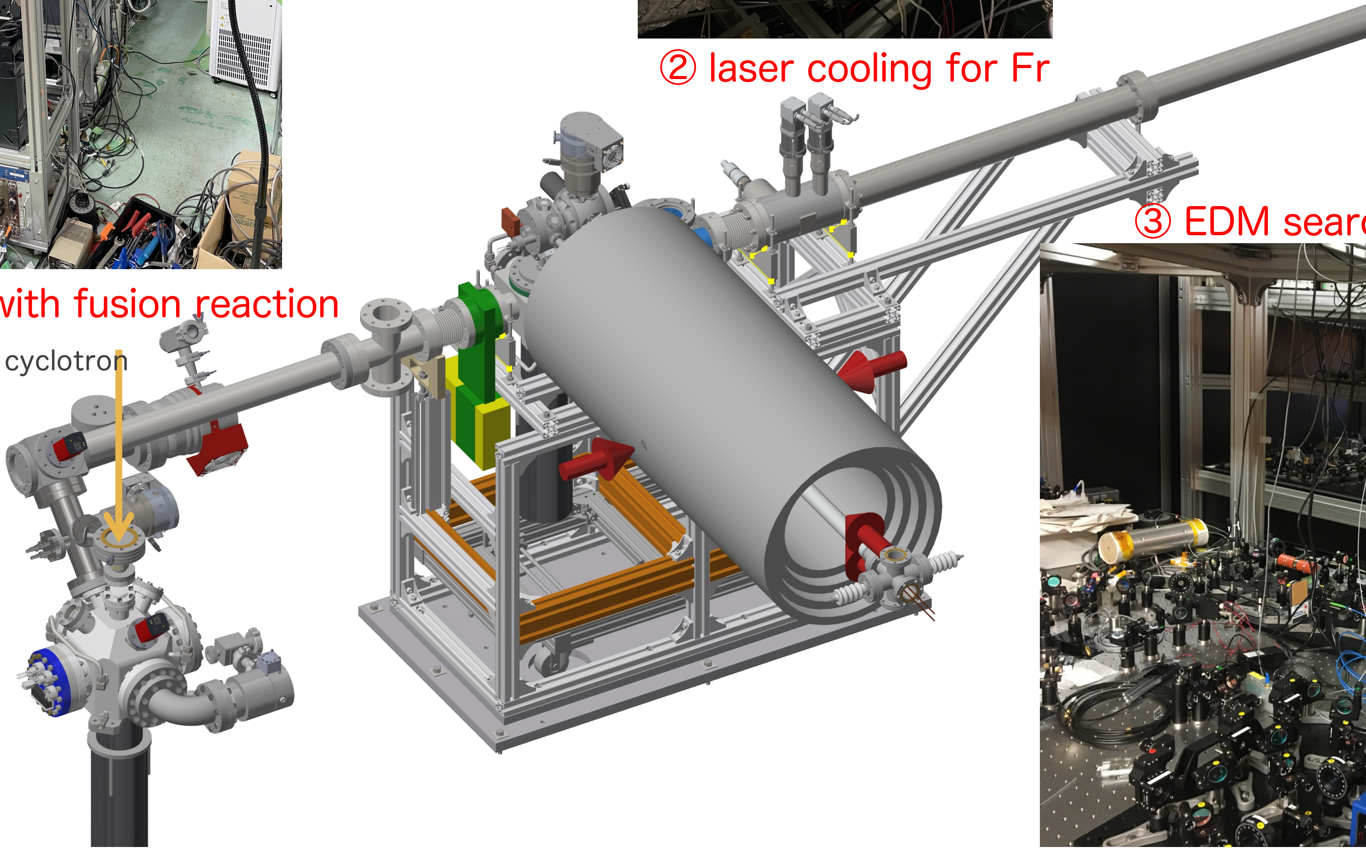
Shitara, N., *et al.*, J. High Energ. Phys. **2021**(2021)124.

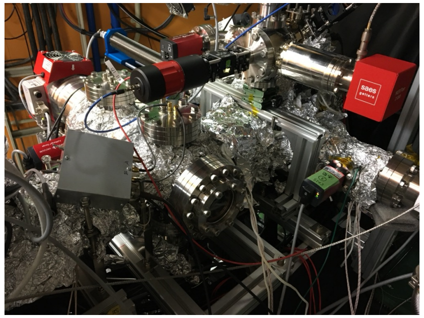
- Radioactive $T_{1/2}$~3min
- Make it by nuclear fusion reaction

Fr-EDM beam line

① Fr production with fusion reaction

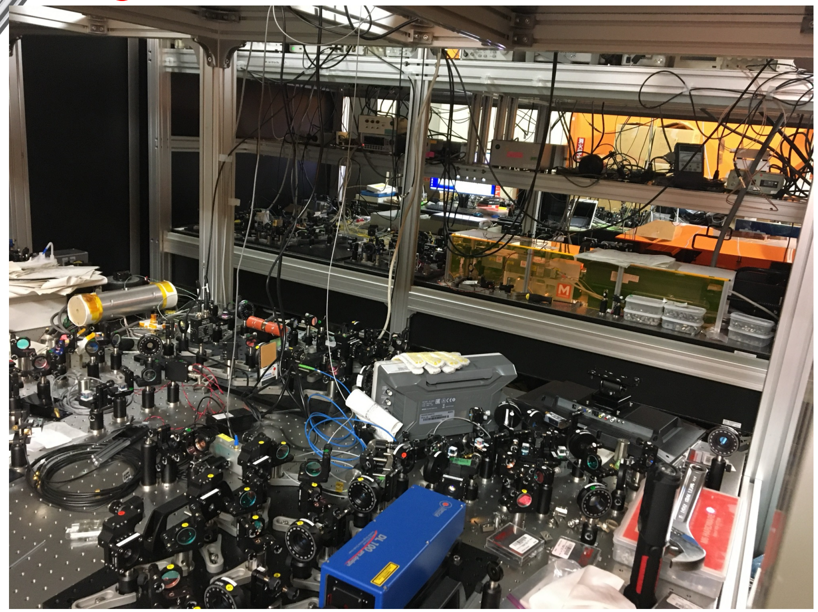
Primary beam from AVF cyclotron





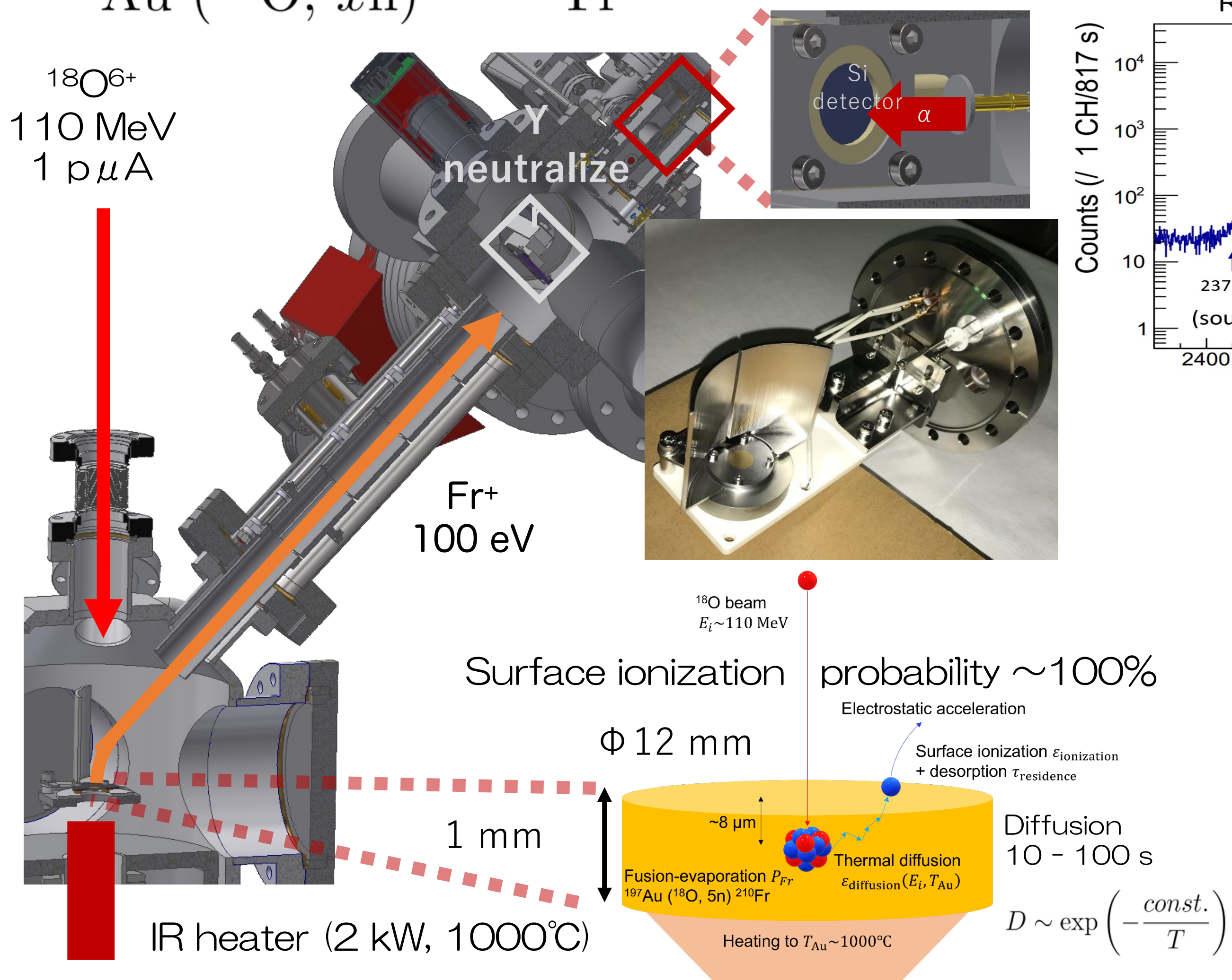
② laser cooling for Fr

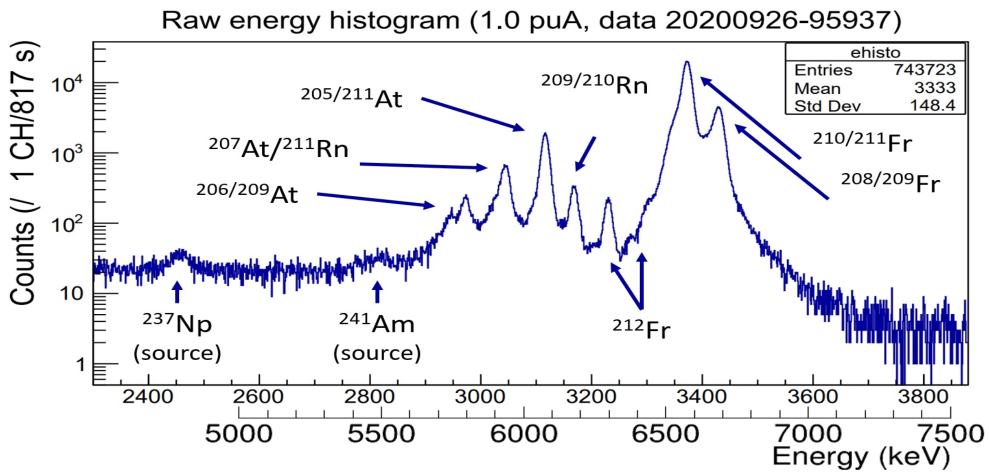
③ EDM search with the interferometer

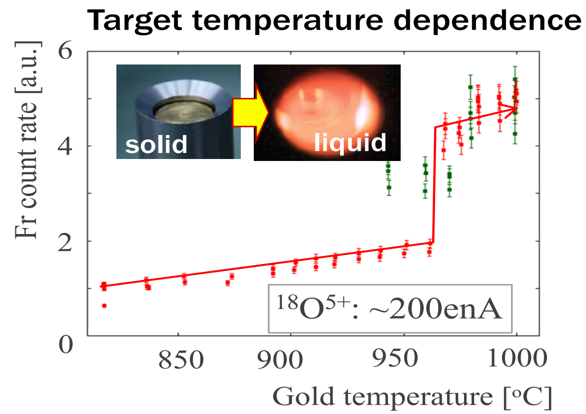


Fr ion production with nuclear fusion reaction

$^{197}\mathrm{Au}\ (^{18}\mathrm{O},\ xn)\ ^{215-x}\mathrm{Fr}$

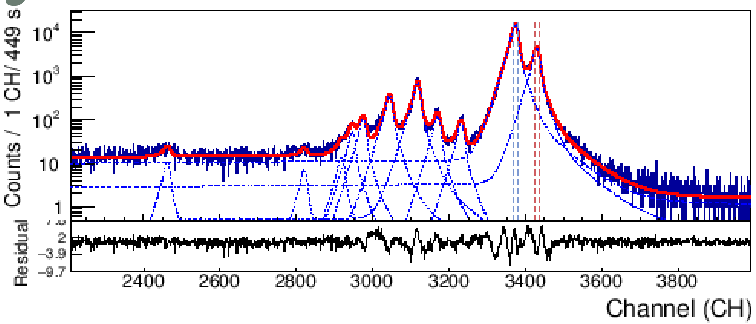


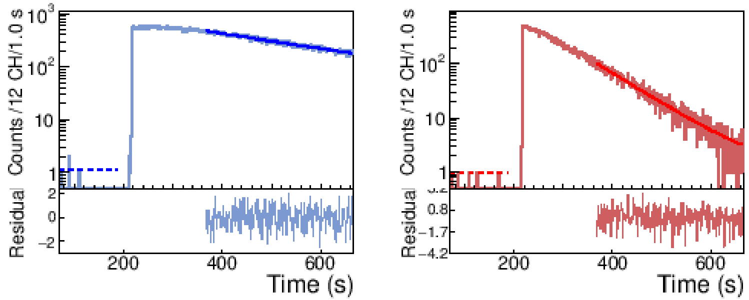




Fr production yield

- ^{210}Fr yield analysis
  1. Fit energy spectrum with multi-skewed Gaussian
     $$f(E) \ni \frac{1}{2\tau}\exp\left[\pm\frac{E-\mu}{\tau}+\frac{\sigma^2}{2\tau^2}\right]\mathrm{erfc}\left[\frac{1}{\sqrt{2}}\left(\pm\frac{E-\mu}{\sigma}+\frac{\sigma}{\tau}\right)\right]$$
  2. Fit decay curve at each peak
     $$S(t)=\tilde{S}_L e^{-\frac{t-t_1}{\tau_L}}$$
  3. Calculate ion beam flux
     $$f_{210}=\frac{P_{210}}{b_{210}P_{210}+b_{211}P_{211}}\frac{\tilde{S}_L}{\Omega_{\mathrm{SSD}}(e^{t_1/\tau_L}-e^{t_0/\tau_L})}=6.7^{+0.8}_{-0.6}\times 10^6\ \mathrm{s}^{-1}$$

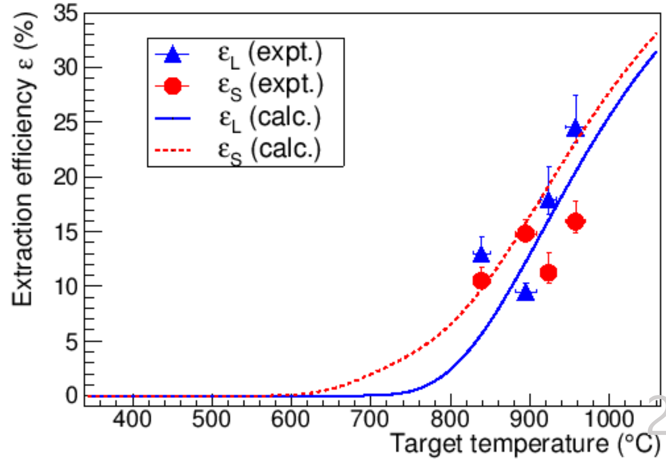




- Extraction efficiency: (Faraday cup) / (Target)

$$\varepsilon_L=\frac{1}{b_{210}P_{210}+b_{211}P_{211}}\frac{\tilde{S}_L}{\Omega_{\mathrm{SSD}}(e^{t_1/\tau_L}-e^{t_0/\tau_L})}=24.5^{+3.0}_{-1.4}\ \%$$

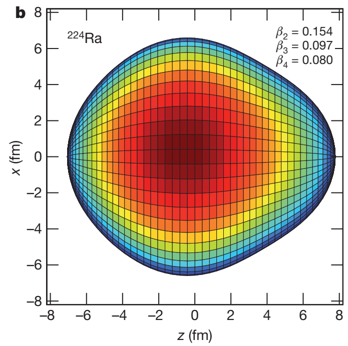
✓Efficient heating of the target
✓Efficient electrostatic transportation



N. Ozawa *et al.*, *RSI 94* (2023) 023306.

^{221}Fr

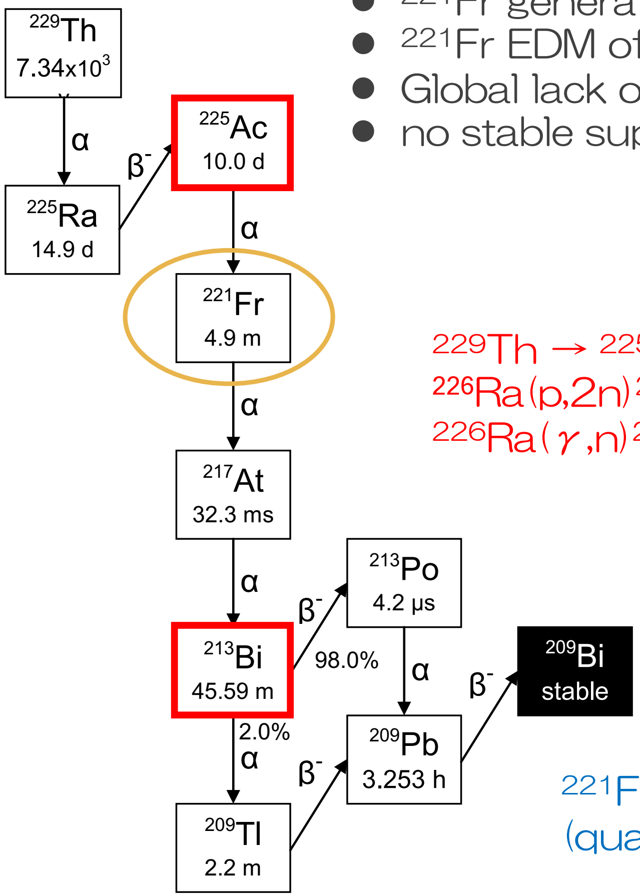
Searching for the nuclear EDM



Octupole deformation

- Radioactive $T_{1/2}$~5min
- Make it by generator ^{225}Ac
- Large Octupole deformation → Schiff moment nuclear EDM enhancement

^{225}Ac as the ^{221}Fr generator

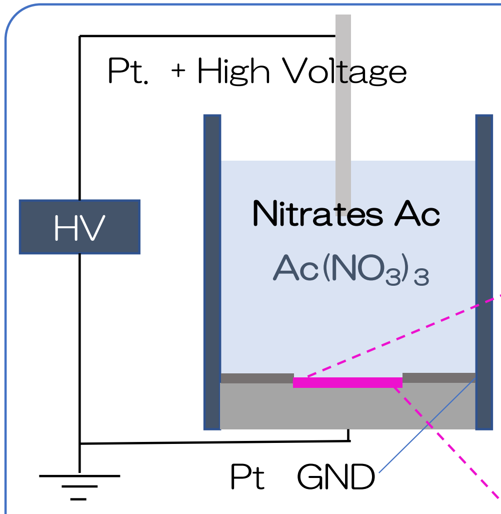


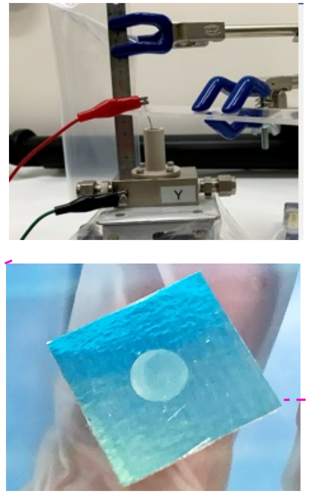
- ^{225}Ac：interest as the cancer treatment with alpha emitter
- ^{221}Fr generator （10days）
- ^{221}Fr EDM offline experiment
- Global lack of ^{225}Ac in recent years
- no stable supply in Japan even at a basic research scale (～100 MBq)

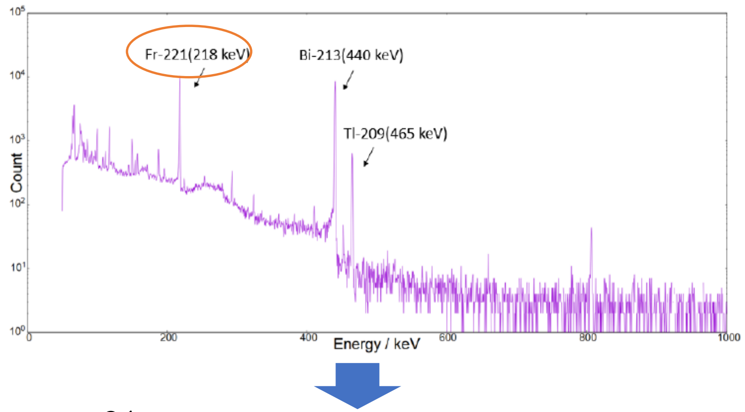
^{229}Th → ^{225}Ac：IMR, Tohoku univ.
^{226}Ra(p,2n)^{225}Ac： RIKEN
^{226}Ra(γ,n)^{225}Ra → ^{225}Ac：ELPH, Tohoku univ.

^{221}Fr EDM experiment to measure nuclear shiff moment
(quark EDM, CPV interaction …)

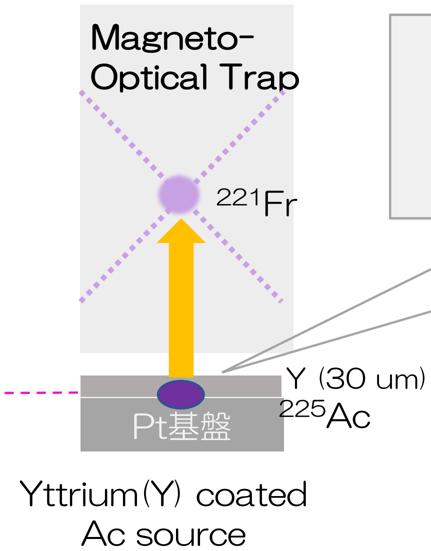
Ac source with molecular plating method

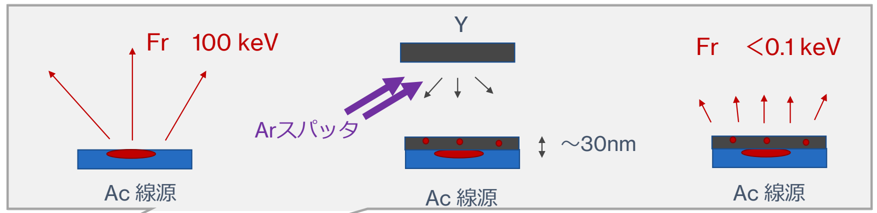


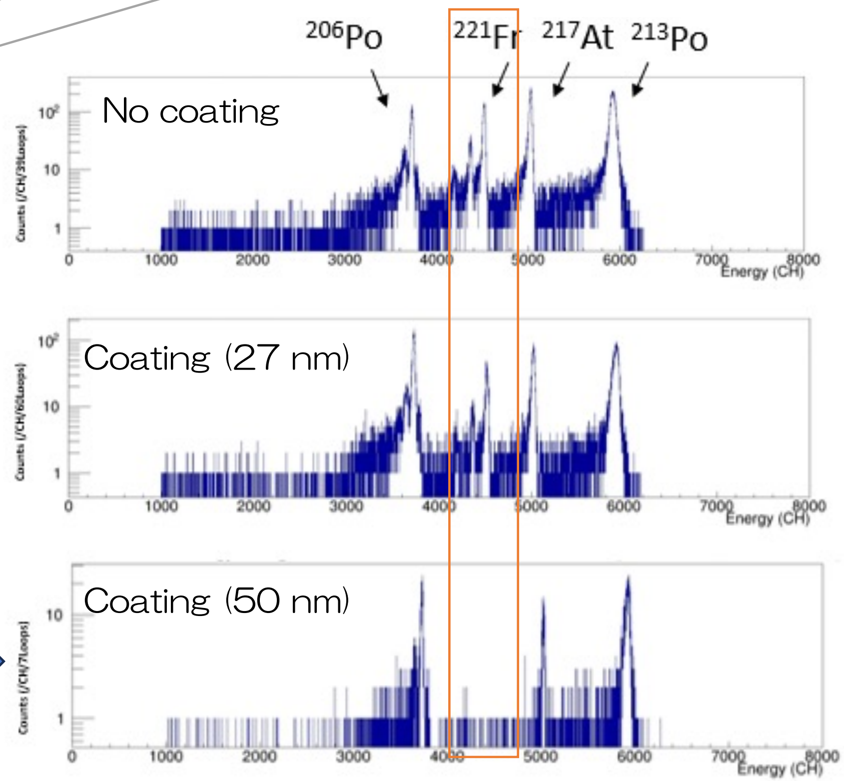




27 % electrodeposition efficiency
with 2.7 MBq Ac

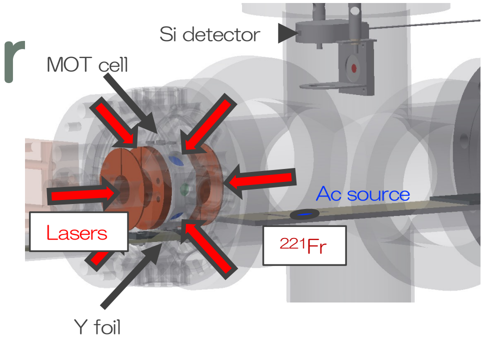




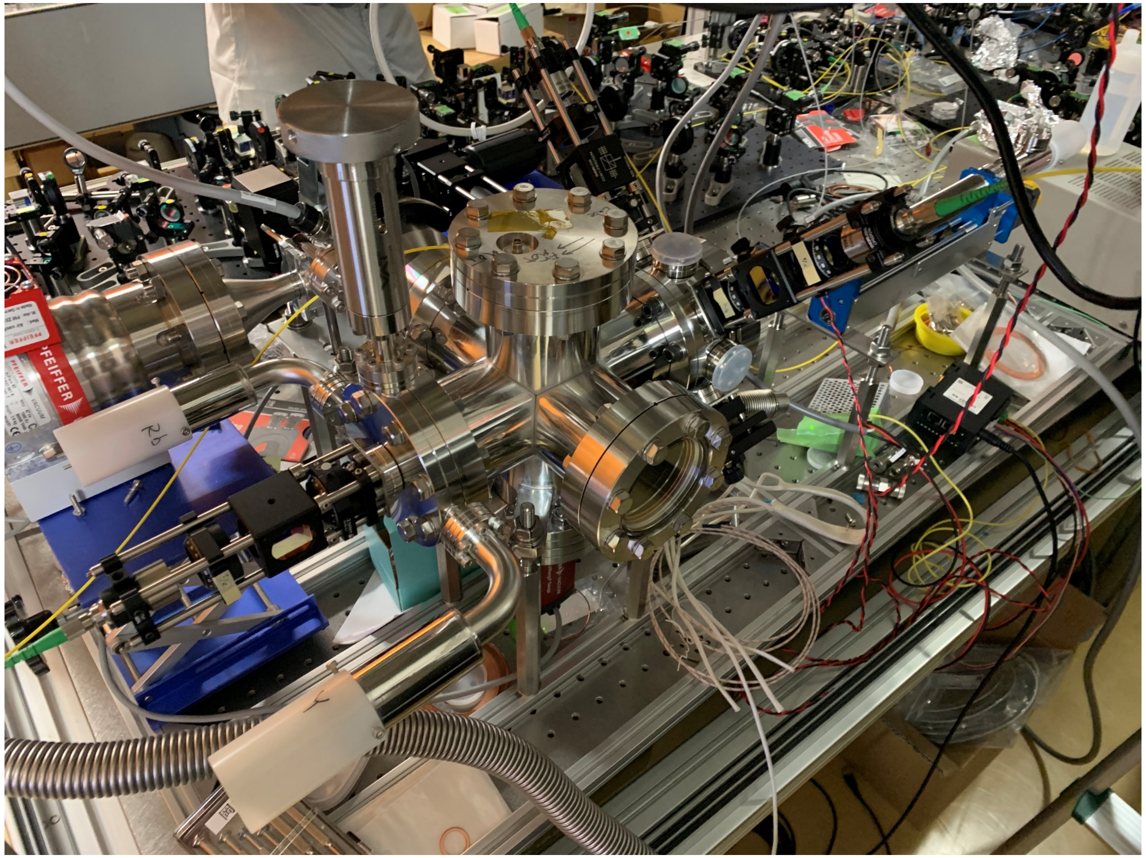


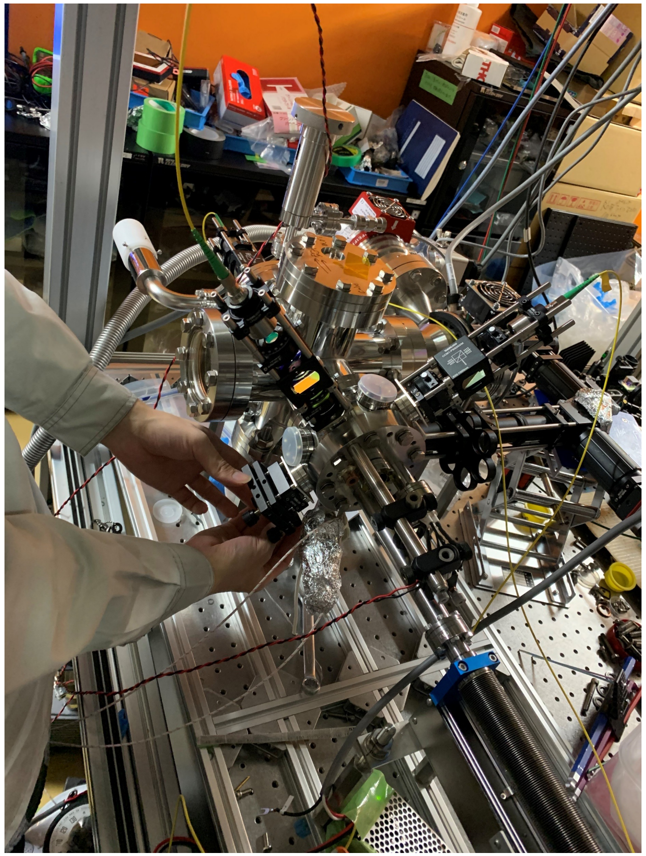
All Fr atoms
~ accumulated
inside the Y layer

Offline EDM with ^{221}Fr generator

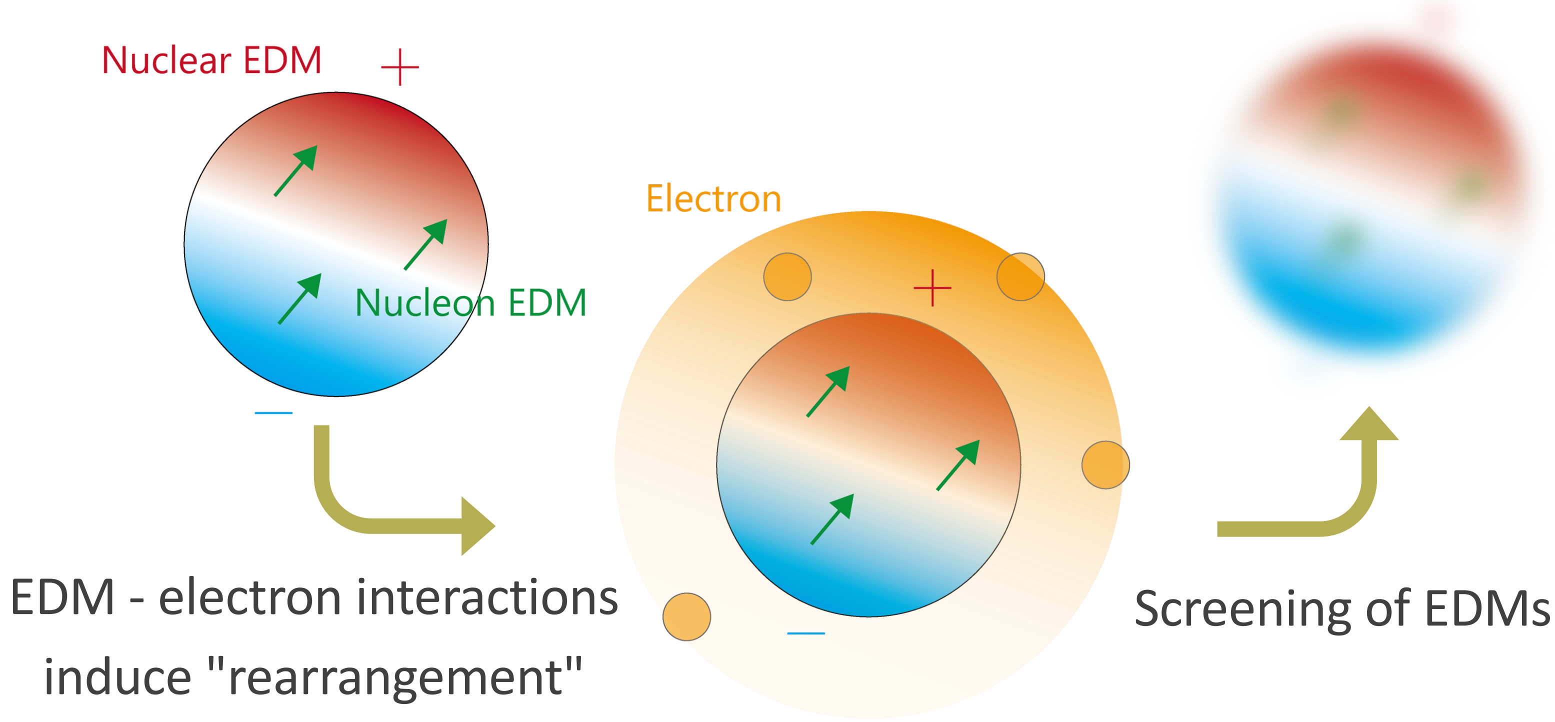


- 1st challenge of MOT with ^{225}Ac/^{221}Fr source ~ in progress
- All the apparatus ~ installed in the glove box at the hot lab. In RIKEN





Nuclear EDM ~ Shiff moment of ^{221}Fr



2nd & 3rd order nuclear Schiff moment (NSM) operators

$$S_{2,k} = \frac{1}{6}\sum_{a=1}^{A} d_{a,k}\left(r_a^2 - \langle r^2\rangle_{\mathrm{ch}}\right) + \frac{2}{15}\sum_{a=1}^{A} d_{a,j}\left(Q_{a,jk} - \langle Q_{jk}\rangle_{\mathrm{ch}}\right)$$

$$S_{3,k} = \frac{e}{10}\sum_{a=1}^{Z}\left[r_a^2 r_{a,k} - \frac{5}{3} r_{a,k}\langle r^2\rangle_{\mathrm{ch}} - \frac{4}{3} r_{a,j}\langle Q_{jk}\rangle_{\mathrm{ch}}\right]$$

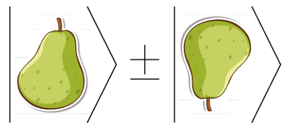
By Dr. K. Yanase

Enhancement of NSM due to octupole correlation

3rd order NSM contains the energy denominator

$$\langle \widetilde{\psi}^{(N)}_{\mathrm{g.s.}} | S_{3z} | \widetilde{\psi}^{(N)}_{\mathrm{g.s.}} \rangle = \sum_n \frac{\langle \psi^{(N)}_{\mathrm{g.s.}} | S_{3z} | \psi^{(N)}_n \rangle \langle \psi^{(N)}_n | \widetilde{V} | \psi^{(N)}_{\mathrm{g.s.}} \rangle}{E^{(N)}_{\mathrm{g.s.}} - E^{(N)}_n} + c.c.$$

Parity doublet caused by nuclear octupole correlations enhances the Schiff moment by orders of magnitude



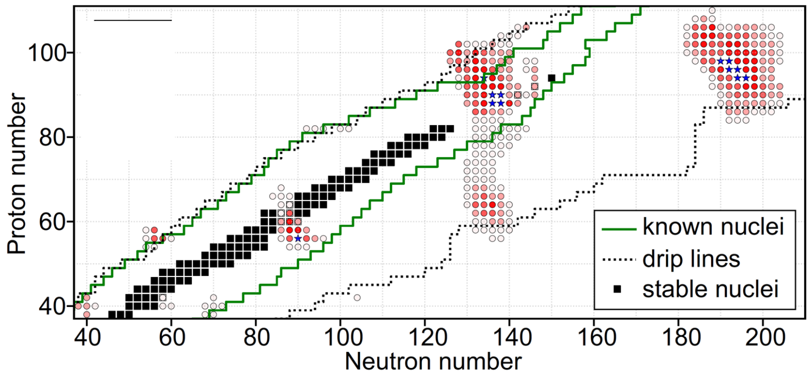
^{129}Xe, ^{199}Hg: $\Delta E_1 = 5\sim 10$ MeV

^{145}Ba: $\Delta E_1 = 0.32$ MeV

^{225}Ra: $\Delta E_1 = 0.06$ MeV

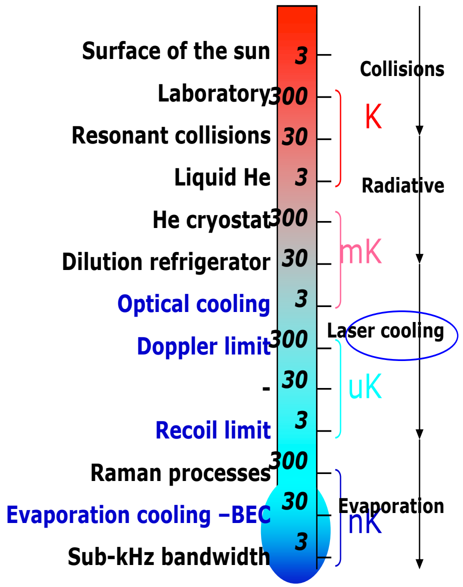
	^{223}Ra	^{225}Ra	^{223}Rn	^{221}Fr
β_2	0.125	0.143	0.129	0.106
β_3	0.100	0.099	0.081	0.100
β_4	0.076	0.082	0.078	0.069
β_5	0.042	0.035	0.024	0.045
β_6	0.018	0.016	0.023	0.020
E_c (keV)	212	221	213	305

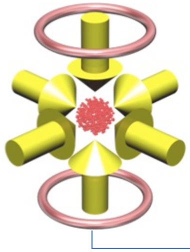
Spevak, V., N. Auerbach, and V. V. Flambaum.. *Physical Review C* 56.3 (1997): 1357.



^{221}Fr ～ good candidate of nuclear EDM (quark color charge EDM)

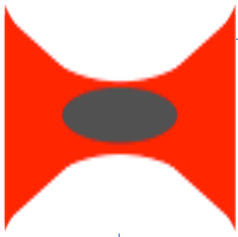
Cooling Procedure





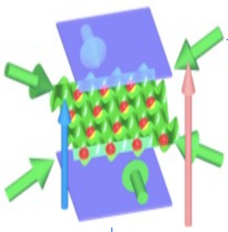
Magneto Optical Trap (MOT)

- Temperature : 65 uK ~ 210 uK
- Life time : a few 10 seconds
- Accumulate the Fr



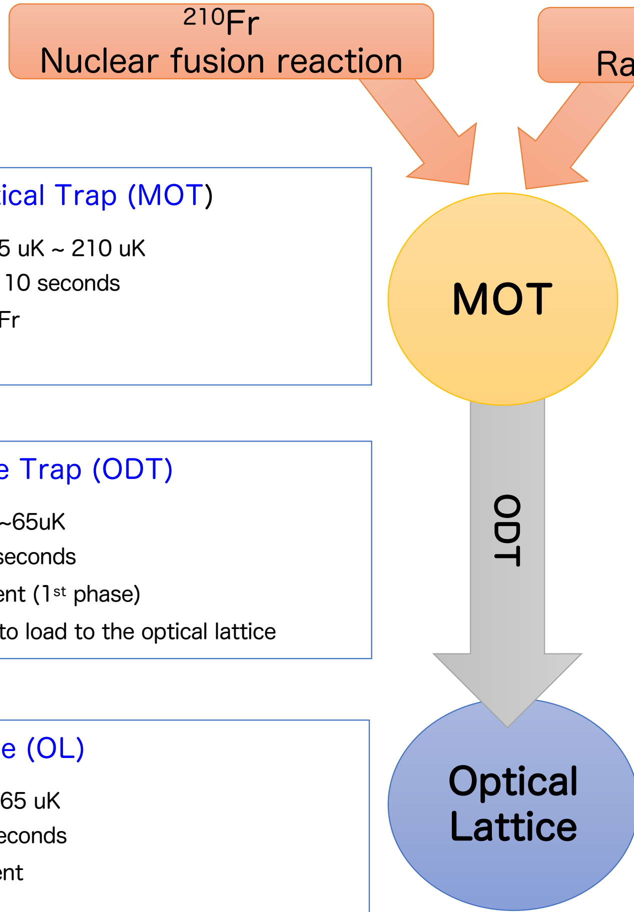
Optical Dipole Trap (ODT)

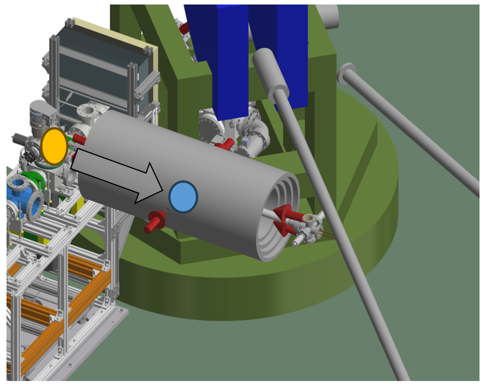
- Temperature : ~65uK
- Life time : > 10 seconds
- EDM measurement (1st phase)
- Optical tweezer to load to the optical lattice



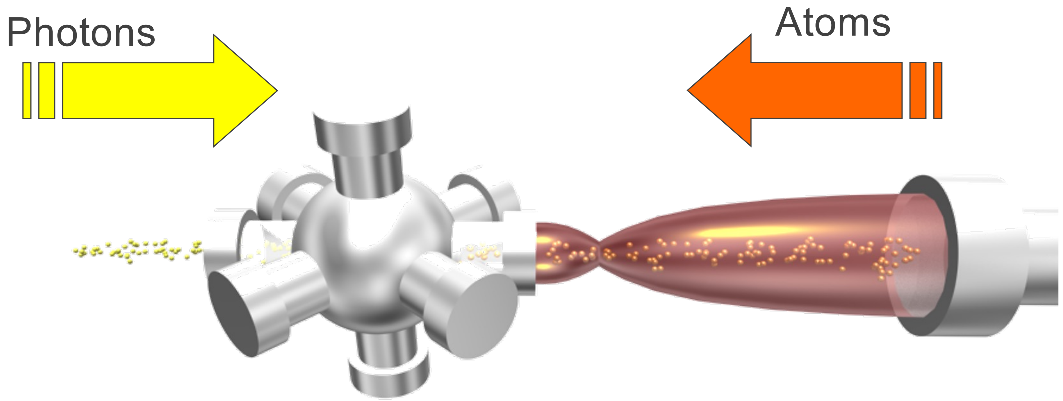
Optical Lattice (OL)

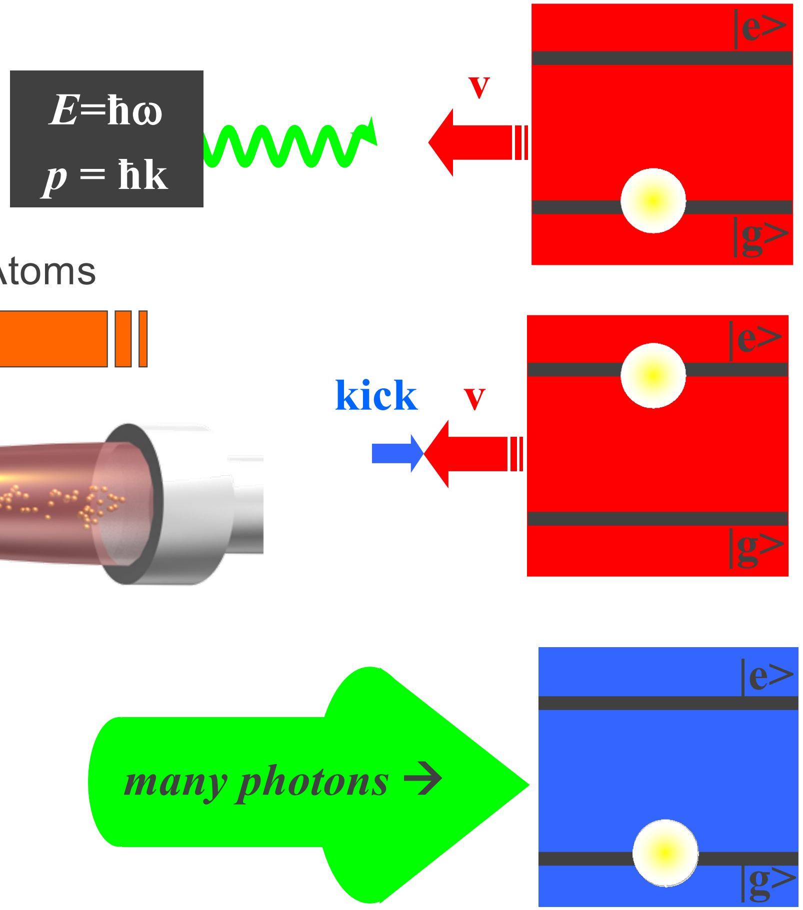
- Temperature : < 65 uK
- Life time: > 10 seconds
- EDM measurement
- Magnetometer





Neutral atom trap ~ Laser cooling

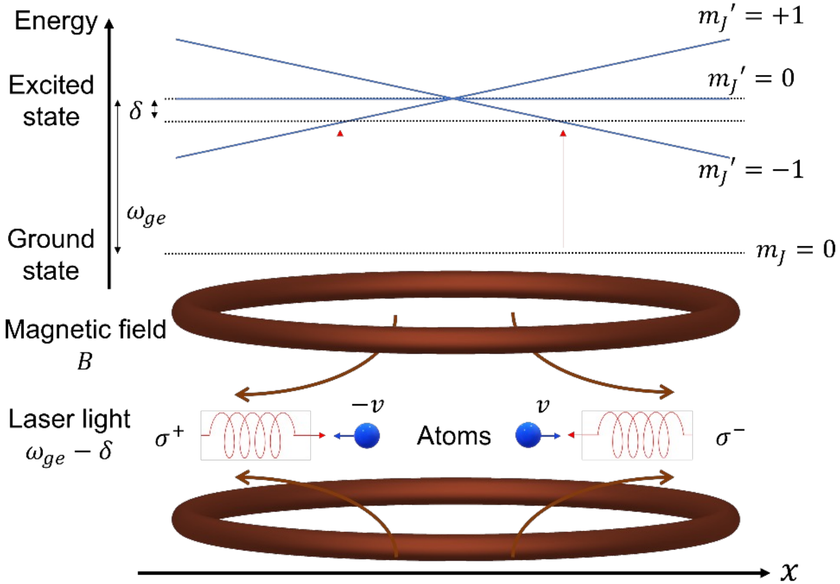




$$\text{Force} = \frac{dp}{dt} = \hbar k \times \gamma_P$$

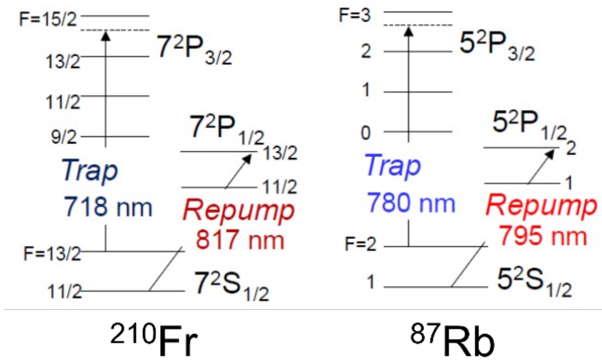
Typically an atom needs to scatter $\sim 10^5$ photons for slowing down

Laser cooling: MAGNETO-OPTICAL TRAP (MOT)

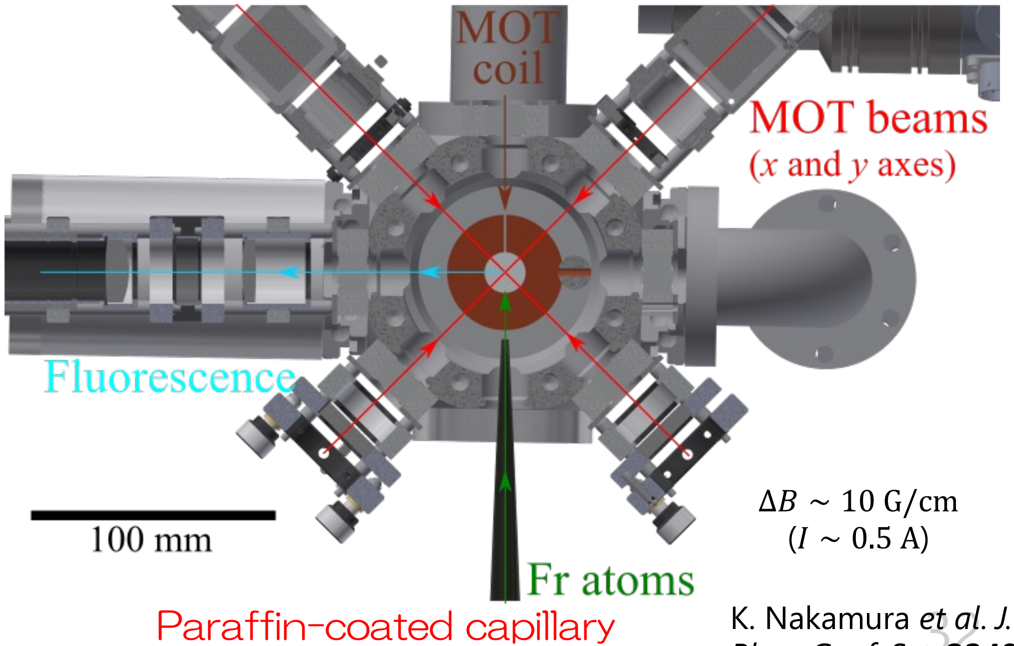


Effective restorative force exerted on atoms by repeated absorption/emission of photons

$\Gamma/2\pi = 7.6$ MHz



$\Gamma/2\pi = 7.6$ MHz

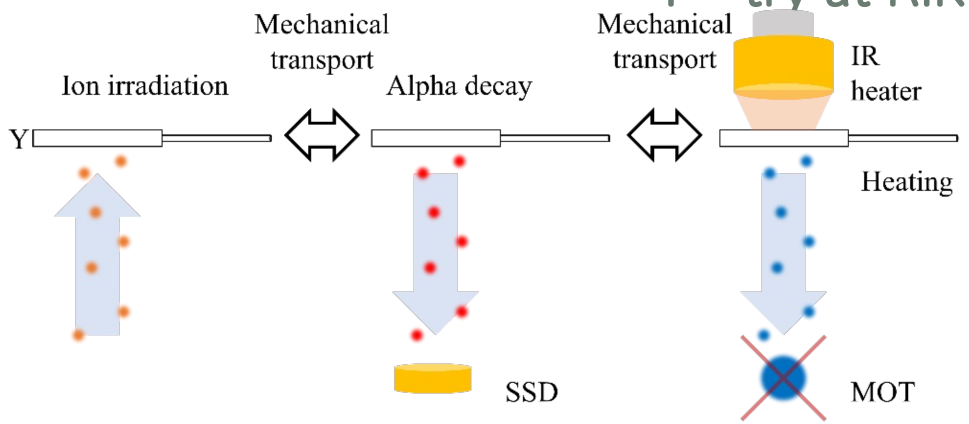


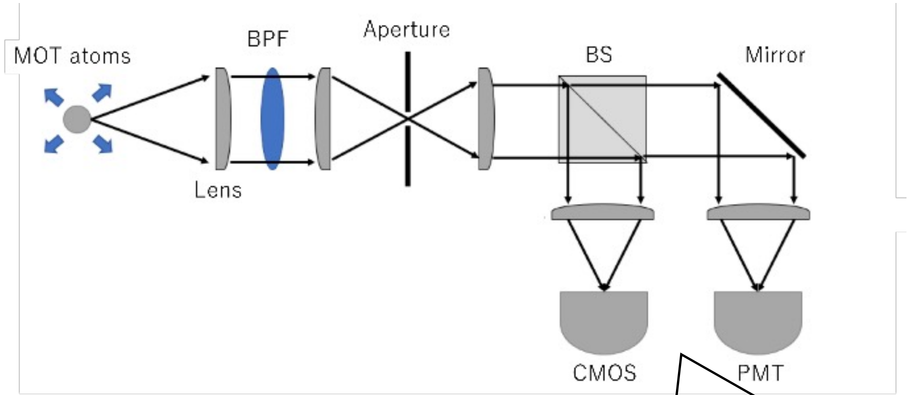
$\Delta B \sim 10$ G/cm
($I \sim 0.5$ A)

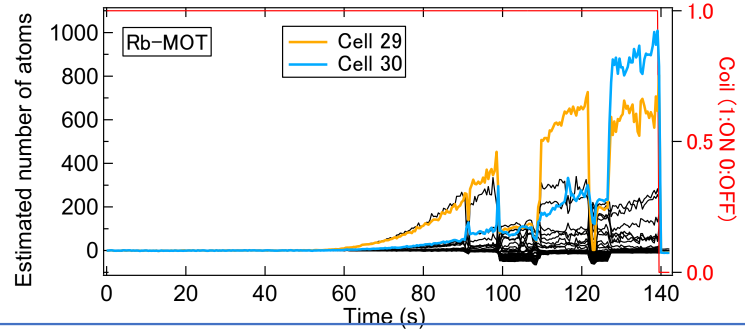
K. Nakamura *et al. J. Phys. Conf. Ser.* **2249**, (2022).

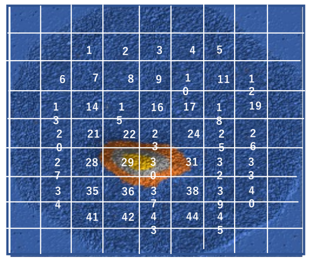
Neutralization and MOT

～1ST try at RIKEN in 2023～

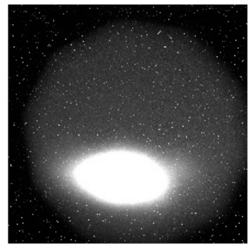




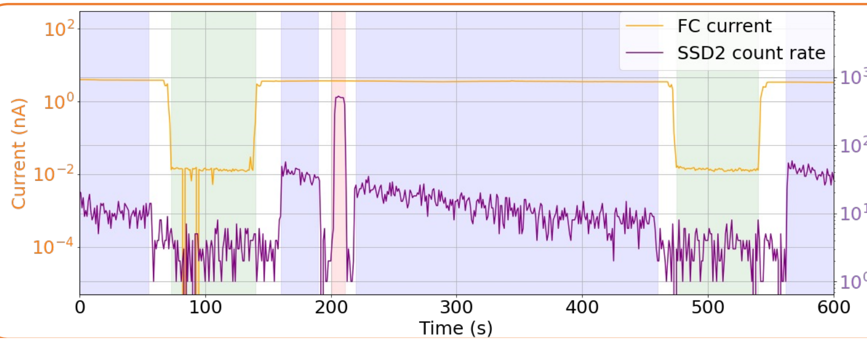


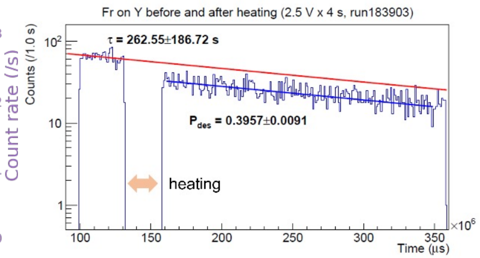


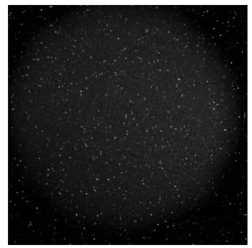
Exposure time: 100 ms



Calibration with ^{87}Rb





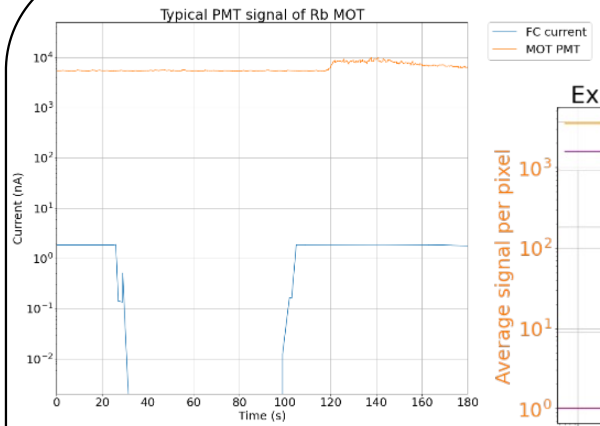


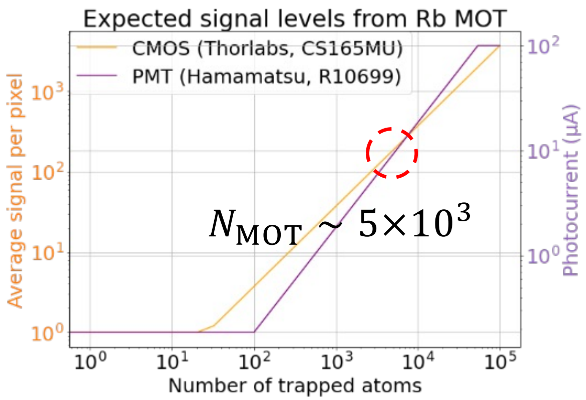
Attempt with ^{210}Fr

Trapping efficiency

$$P_{\text{des}}\varepsilon_{\text{MOT}} = \frac{N_{\text{MOT}}}{N_{\text{Y}}} = \frac{\text{Atoms trapped in MOT}}{\text{Ions accumulated on Y}}$$

^{87}Rb



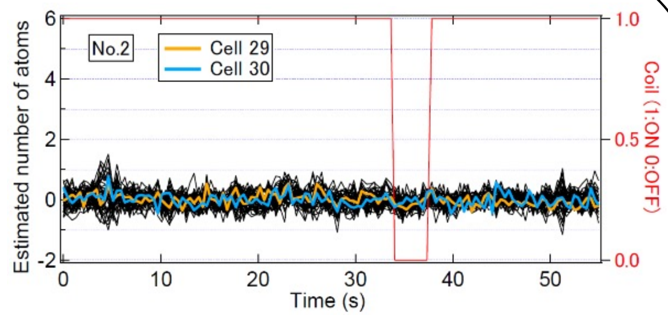


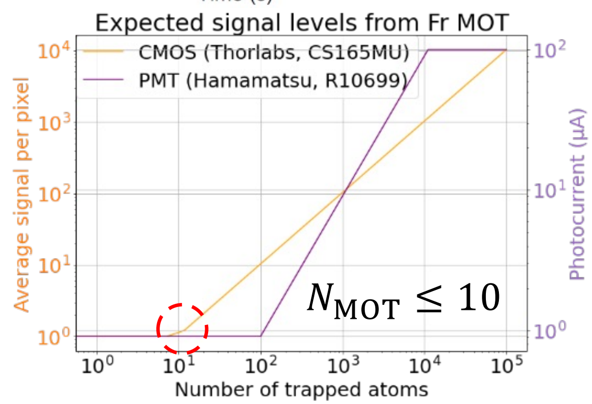
$N_{\text{MOT}} \sim 5\times10^{3}$

$N_{\text{Y}} \leq 0.278\times60\ \text{s}\times6\times10^{10}\ \text{s}^{-1} \sim 1\times10^{12}$

$\rightarrow P_{\text{des}}\varepsilon_{\text{MOT}} \geq 5\times10^{-9}$

^{210}Fr





$N_{\text{MOT}} \lesssim 10$

$N_{\text{Y}} \sim 275\ \text{s}\times10^{6}\ \text{s}^{-1}\times0.46 \sim 1\times10^{8}$

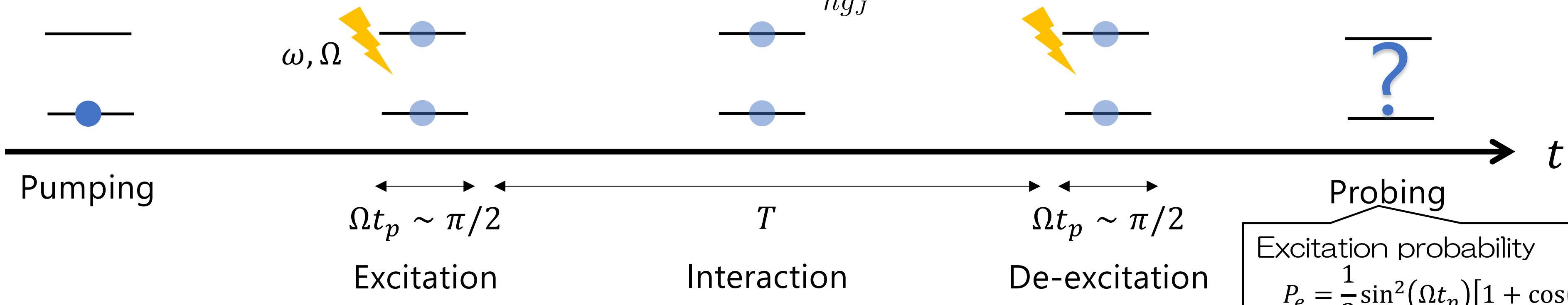
$\rightarrow P_{\text{des}}\varepsilon_{\text{MOT}} \lesssim 8\times10^{-8}$

✓Proof-of-principle for each component ~ Efficiency still low

Ramsey spectroscopy with stable atom Rb

- Sequence

$$\Delta\nu^{\mathrm{Fr}}_{d_e} = \frac{g'_F m'_F - g_F m_F}{h g_J} R d_e E$$

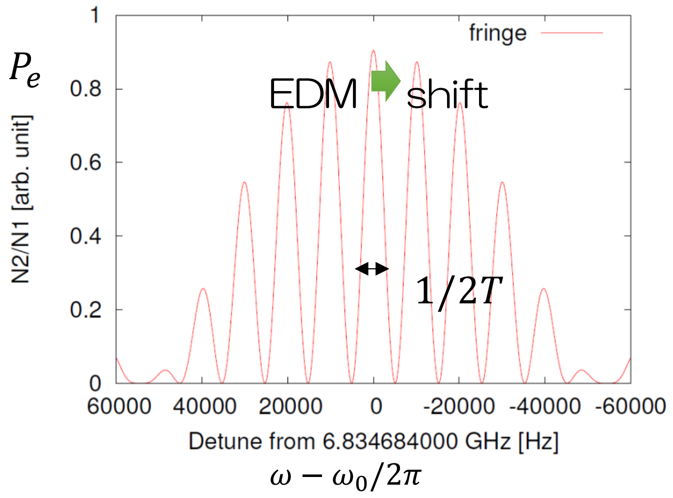


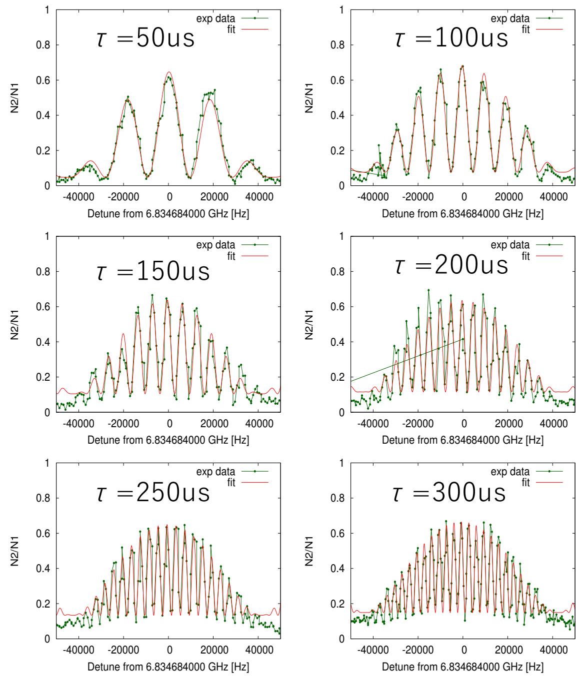
Excitation probability

$$P_e = \frac{1}{2}\sin^2(\Omega t_p)[1+\cos((\omega-\omega_0)T)]$$

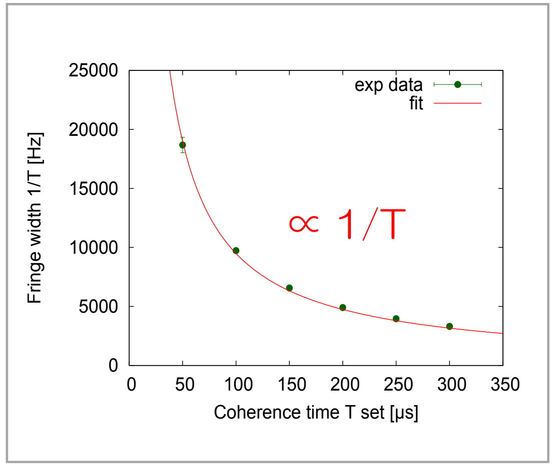
- Shot-noise limit

$$\Delta\nu \sim \frac{1}{2\pi T} \times \frac{1}{\sqrt{\text{Repetition}}}$$





Frequency resolution



10^{-25} ecm at 300 us

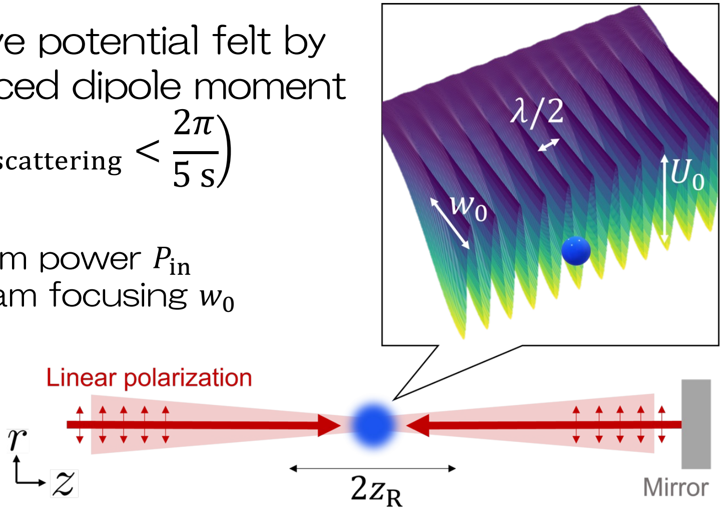
Need long interaction time ~ optical lattice

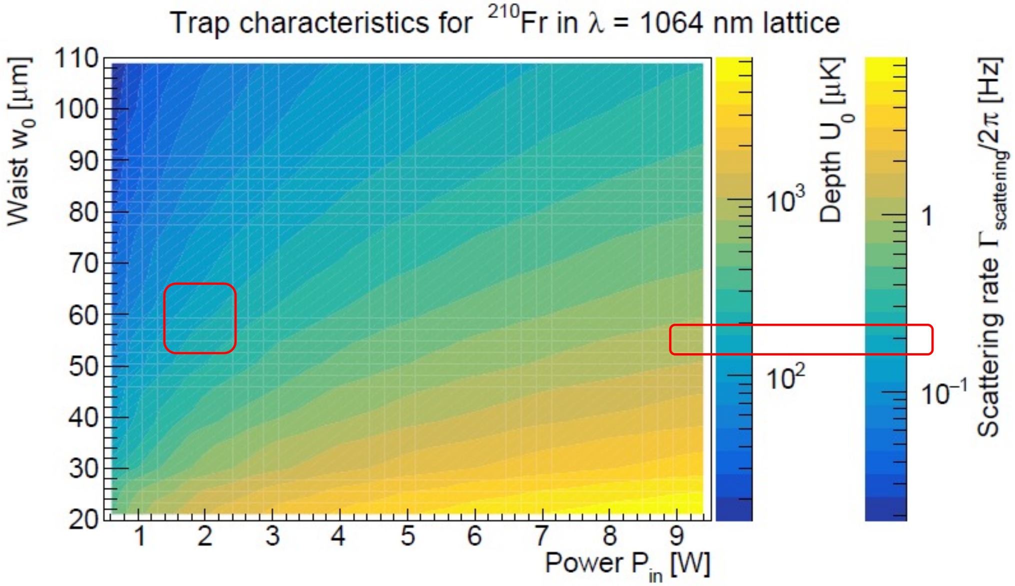
Laser trapping: Optical Lattice

Effective attractive potential felt by atoms due to induced dipole moment

$$U_0 \propto \frac{4P_{\mathrm{in}}}{w_0^2}\left(\propto \Gamma_{\mathrm{scattering}} < \frac{2\pi}{5\ \mathrm{s}}\right)$$

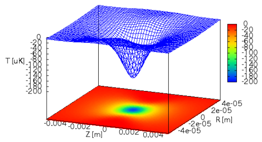
- ☐ High beam power P_{in}
- ☐ Tight beam focusing w_0



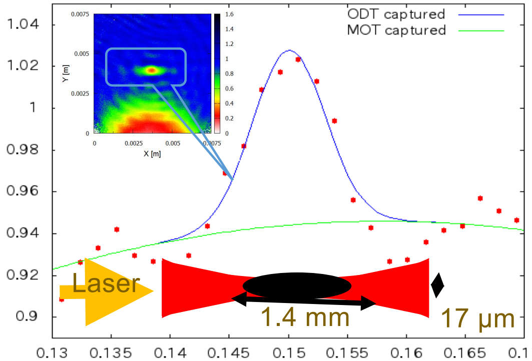


Optical Dipole Trap

- Same technique as optical lattice
- Extend to the optical lattice with the standing wave



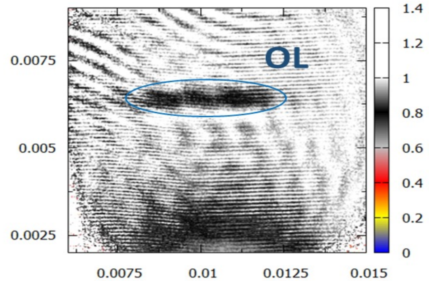
Trap potential ~11 mK

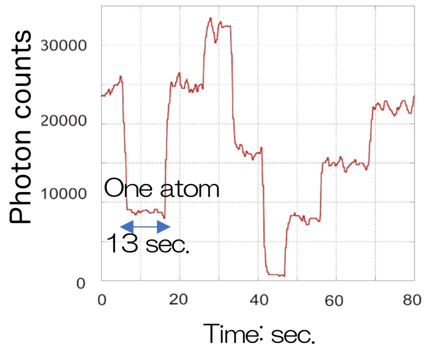


- ~20 uK
- ~10^6 atoms trapped

1 dim. Optical lattice

t = 35 ms





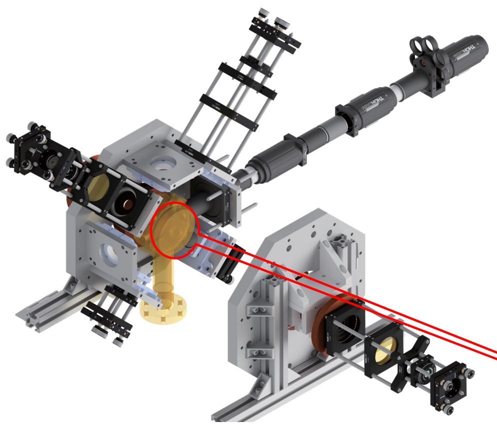
- Blue detuned optical lattice ~ photon scattering rate : 0.1/s
- Reduce the interaction between atoms
  ~ reduce the depolarization
- Long coherence time ~10 sec.
- 10^4 times interaction time ~ compared with 300 us
  → corresponding to d_e ~10^{-29} ecm

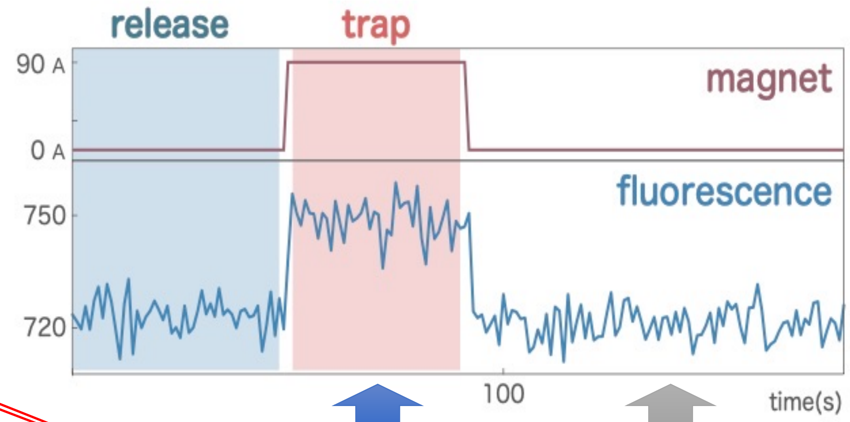
Cold Fr source

Laser cooled Fr apparatus ~ ready

- Laser cooling/trapping techniques for radioactive elements ~ established
- Optimization to increase the number of trapped atoms ~ in progress

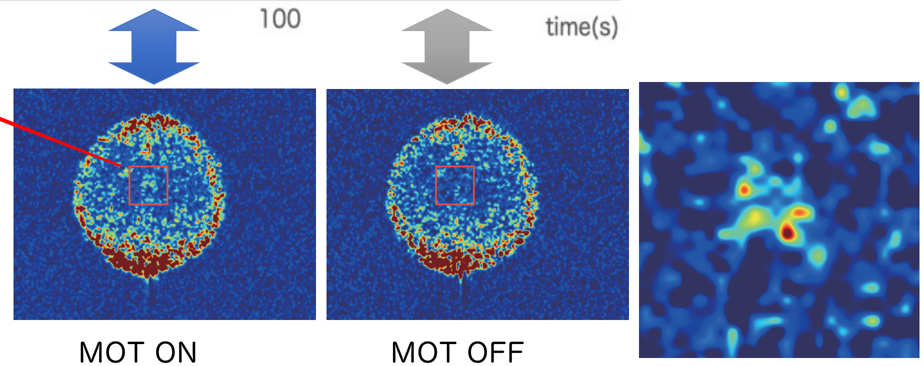
$$\Delta\nu = \nu_{\uparrow} - \nu_{\downarrow} = \boxed{\frac{4dE}{h}} + \frac{2\mu(B_{\uparrow} - B_{\downarrow})}{h}$$





< 10^3 Fr atoms at MOT

→ 10^6 atoms required for EDM
Neutralization efficiency
Other parameters ~ optimization



MOT ON   MOT OFF

Systematic error and Magnetometer

Magnetic Field Instabilities: Annoying

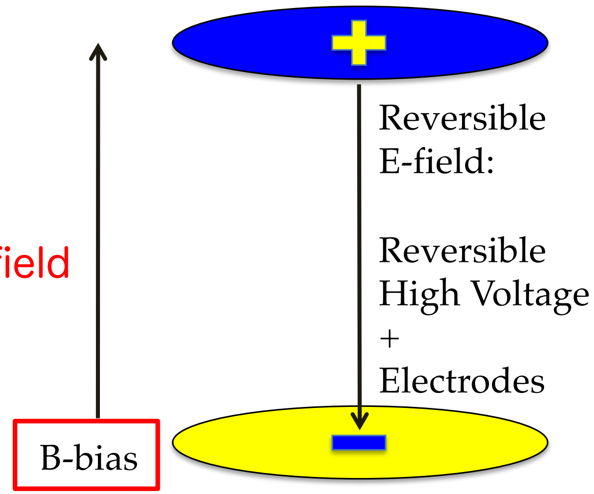
$$\Delta\nu = \nu_\uparrow - \nu_\downarrow = \frac{4dE}{h} + \boxed{\frac{2\mu(B_\uparrow - B_\downarrow)}{h}}$$

- Quite large contribution
- EDM false signal

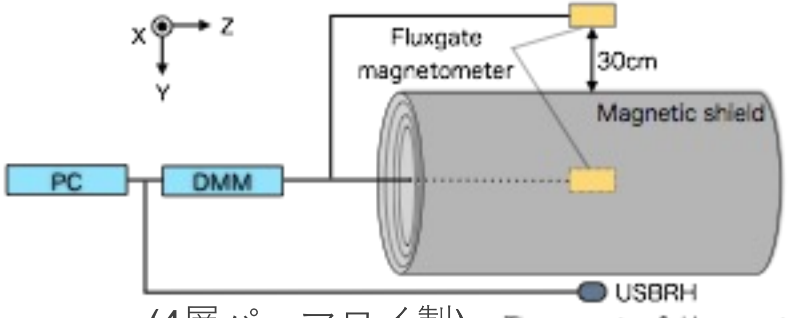
Instabilities adds noise &
limits the statistical precision.

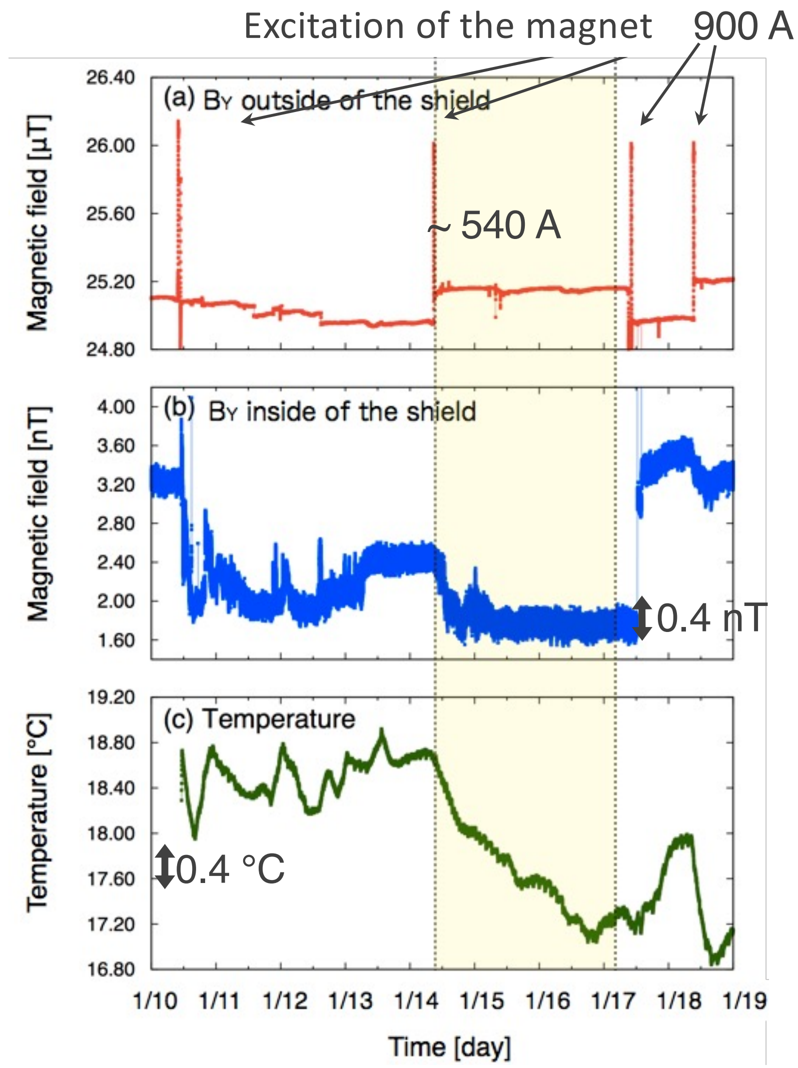
Many sources of the instabilities of the magnetic field

Ideal case: uniform and stable ~ difficult to realize



Environmental magnetic field measurement



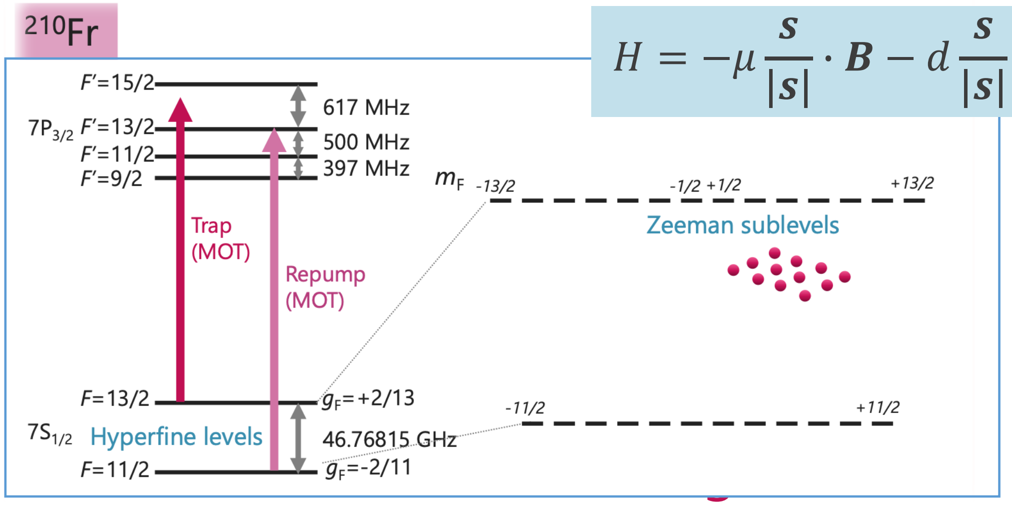


- Magnetic field shielding : 25 uT → 2nT
- Magnetic field change : clearly observed
  〜 magnet excitation, metro/car movement…
- Inside the shield : still change 〜0.4 nT

Energy shift in Optical Lattice

~ dominant component of systematic error ~

$$H = -\mu \frac{\boldsymbol{s}}{|\boldsymbol{s}|}\cdot \boldsymbol{B} - d\frac{\boldsymbol{s}}{|\boldsymbol{s}|}\cdot \boldsymbol{E}$$



Degeneracy is lifted:

- Magnetic field
- Electric field
- Laser applied to atoms

Many shifts

$\Delta\epsilon =$

$+m_F g_F \mu_B B$: Zeeman shift

$-\frac{1}{4}\alpha_S^{AC} E^2(\omega)$: AC scalar stark shift

$+\beta_V^{AC} m_F E^2(\omega)$: AC vector stark shift

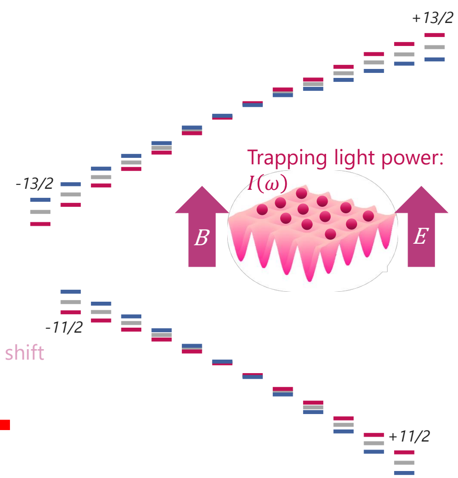
$-\frac{1}{4}\alpha_T^{AC} \frac{3m_F{}^2 - J(J+1)}{J(2J-1)} \frac{3|\varepsilon_z| - 1}{2} E^2(\omega)$

: AC tensor stark shift

$-\frac{1}{2}\alpha_S^{DC} E^2$: DC scalar stark shift

$-\frac{1}{2}\alpha_S^{DC}(F) \frac{3m_F{}^2 - F(F+1)}{F(2F-1)} E^2$: DC tensor stark shift

$+d_A m_F E$: EDM shift (DC vector stark shift)



Monitoring/measuring of the energy shift to extract the EDM

~ magnetometer

Dual atoms co-magnetometry ～ new idea

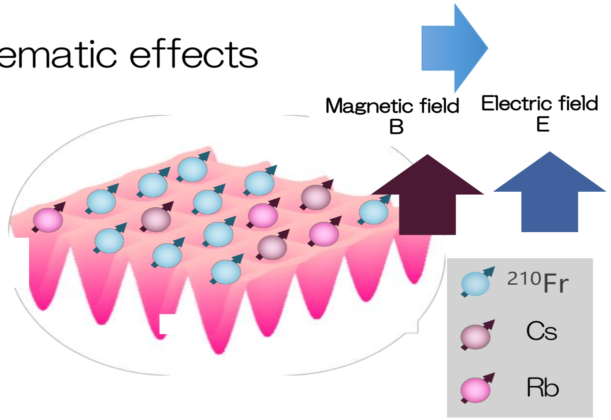
Monitor offset and long-time drift of systematic effects

$$h\nu = \Delta E_1(F, m_F) - \Delta E_2(F, -m_F)$$

$$= -2 m_F g_F \mu_B B$$: Zeeman shift ～magnetic field

$$-\alpha^{(1)}(F;\omega)\frac{m_F}{F}\frac{\theta I \sin\varphi}{\varepsilon_0 c}$$: Vector light shift

$$-2\frac{m_F}{F} d_{Fr} E$$: Shift from EDM

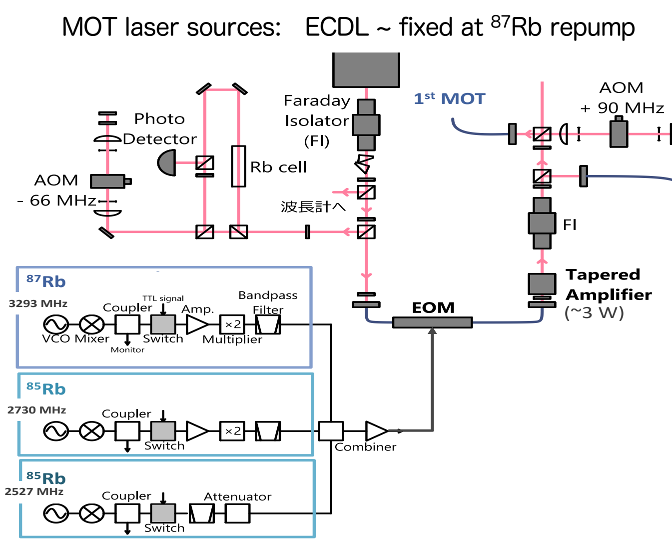


Measure 3 different atoms/isotopes

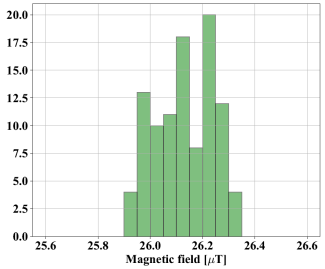
$$\Delta\nu_{\mathrm{meas}} = \Delta\nu_{\mathrm{EDM}} + \Delta\nu_{\mathrm{Zeeman}} + \Delta\nu_{\mathrm{AC}}$$

$$\begin{pmatrix} d_e \\ B \\ \mathcal{A}\cos\theta_k P_{\mathrm{in}} \end{pmatrix} = \begin{pmatrix} \chi^{(1)}_{\mathrm{EDM}} & \chi^{(1)}_{\mathrm{Zeeman}} & \chi^{(1)}_{\mathrm{AC}} \\ \chi^{(2)}_{\mathrm{EDM}} & \chi^{(2)}_{\mathrm{Zeeman}} & \chi^{(2)}_{\mathrm{AC}} \\ \chi^{(3)}_{\mathrm{EDM}} & \chi^{(3)}_{\mathrm{Zeeman}} & \chi^{(3)}_{\mathrm{AC}} \end{pmatrix}^{-1} \begin{pmatrix} \Delta\nu^{(1)}_{\mathrm{meas}} \\ \Delta\nu^{(2)}_{\mathrm{meas}} \\ \Delta\nu^{(3)}_{\mathrm{meas}} \end{pmatrix}$$

MOT laser sources: ECDL ~ fixed at ^{87}Rb repump



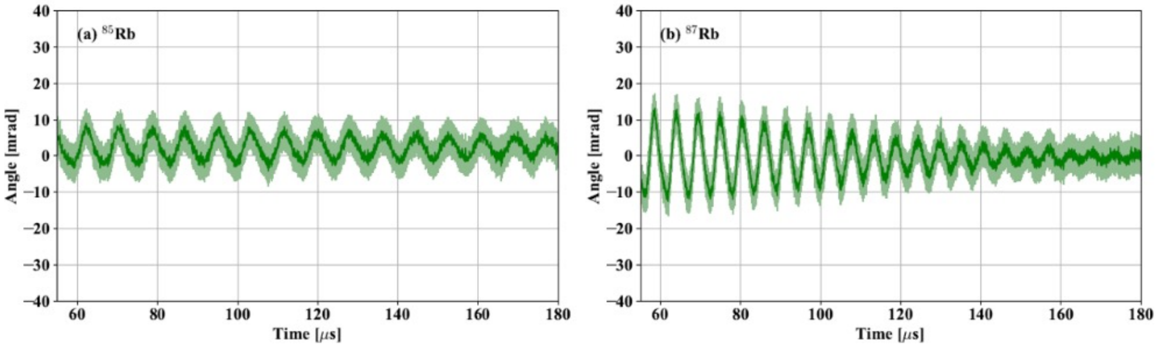
Magnetic filed measurement



Accuracy <0.1 μT

Dual atoms co-magnetometer
Prototype with ^{85}Rb-^{87}Rb ～ magnetic field < 0.1 uT
^{87}Rb (F=2) – ^{133}Cs (F=4) expected to yield

$$\Delta B = 2.2\ \mathrm{fT}, \Delta(\mathcal{A}\cos\theta_k P_{\mathrm{in}}) = 60\ \mu\mathrm{W}$$

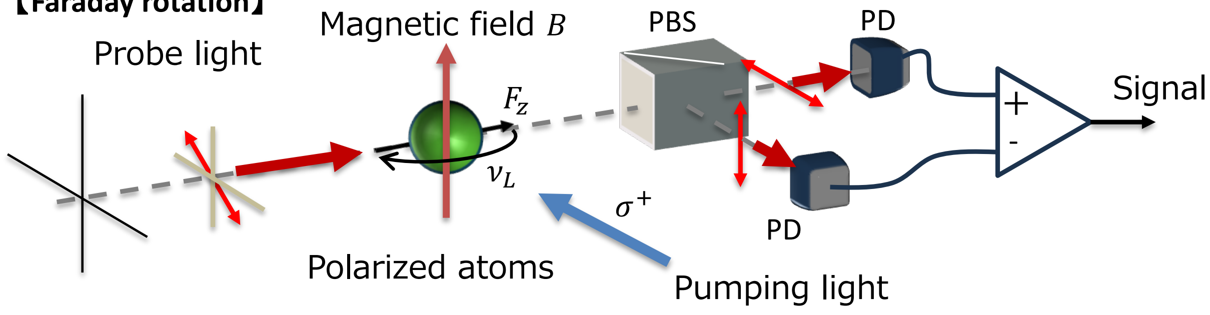


A. Uchiyama et al, RSI 89 (2018).

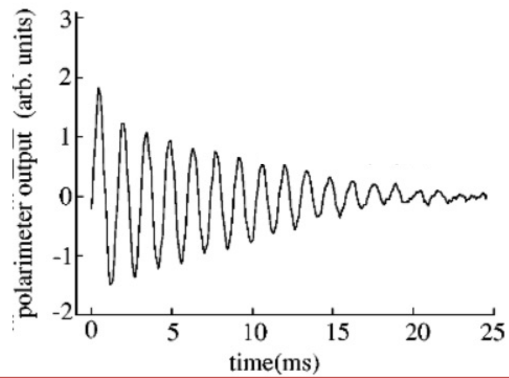
Co-magnetometer setup

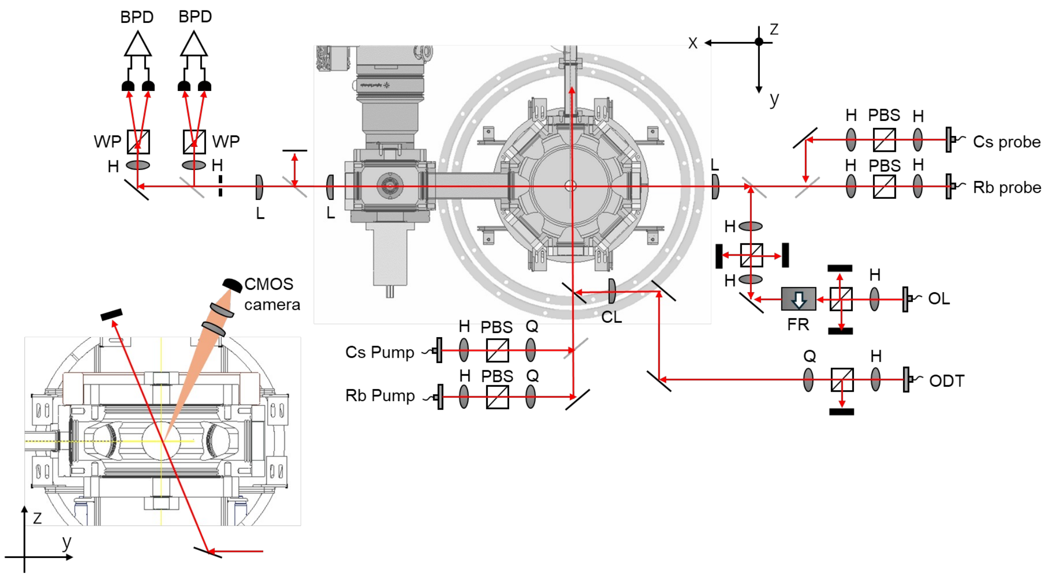
Rb/Cs

【Faraday rotation】



Spin precession frequency measured



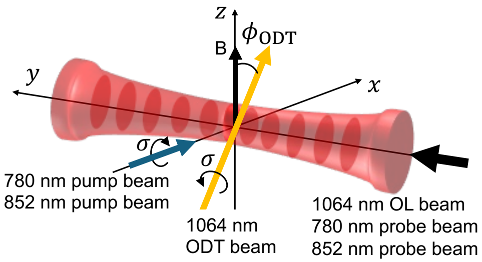


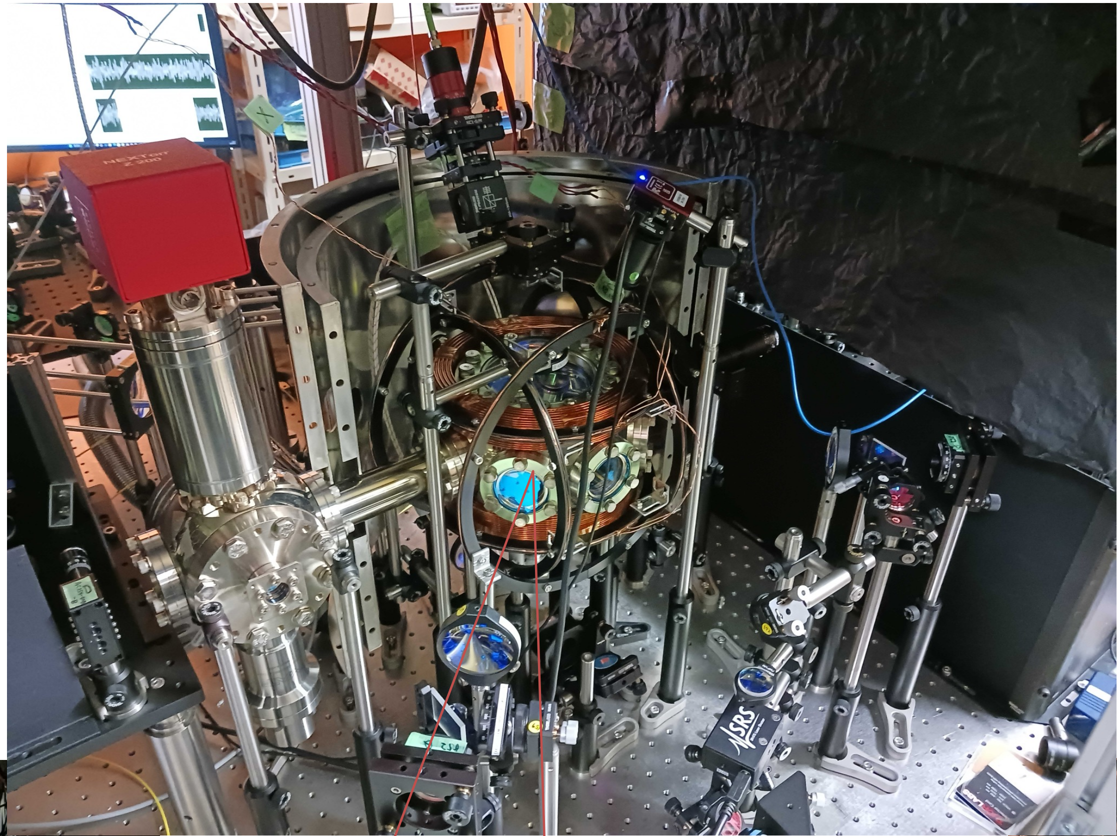
Refractive index for $\sigma^{\pm}$ circularly polarized probe light:

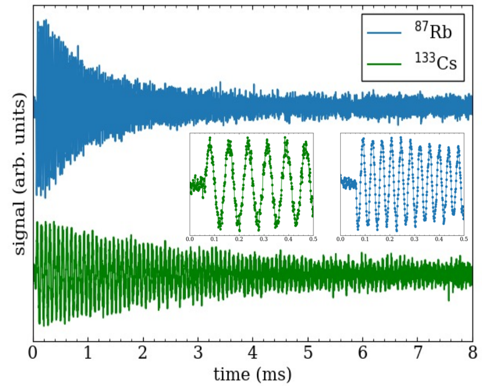
$$n_{\pm} = 1 + \frac{\rho \alpha^{(0)}(\Delta)}{2\varepsilon_0}\left(\frac{2}{3} \pm \frac{1}{3}\frac{\langle F_z \rangle}{F}\right)$$

Phase difference of $\sigma^{\pm}$ polarized probe light:

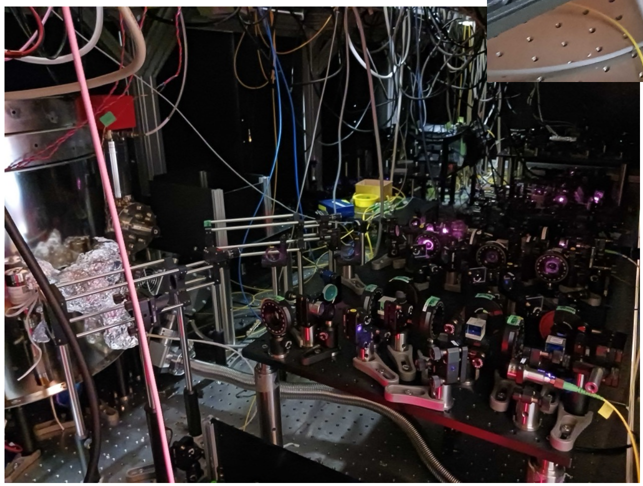
$$\phi = (n_+ - n_-)kl = -\frac{1}{6}\frac{\sigma \rho l}{\Delta/\Gamma}\frac{\langle F_z \rangle}{F}$$

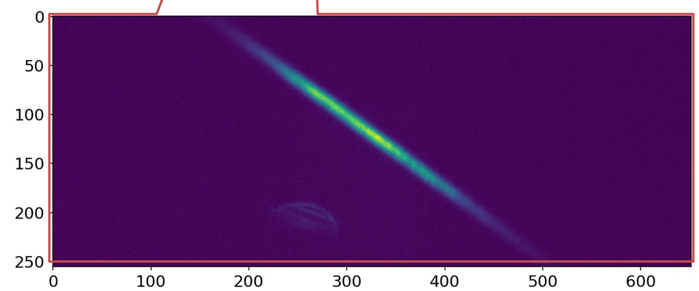




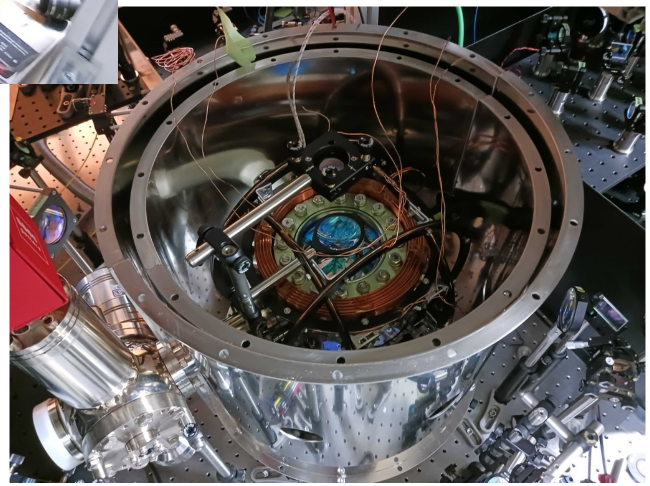


Developed by Dr. Nagase@UTokyo





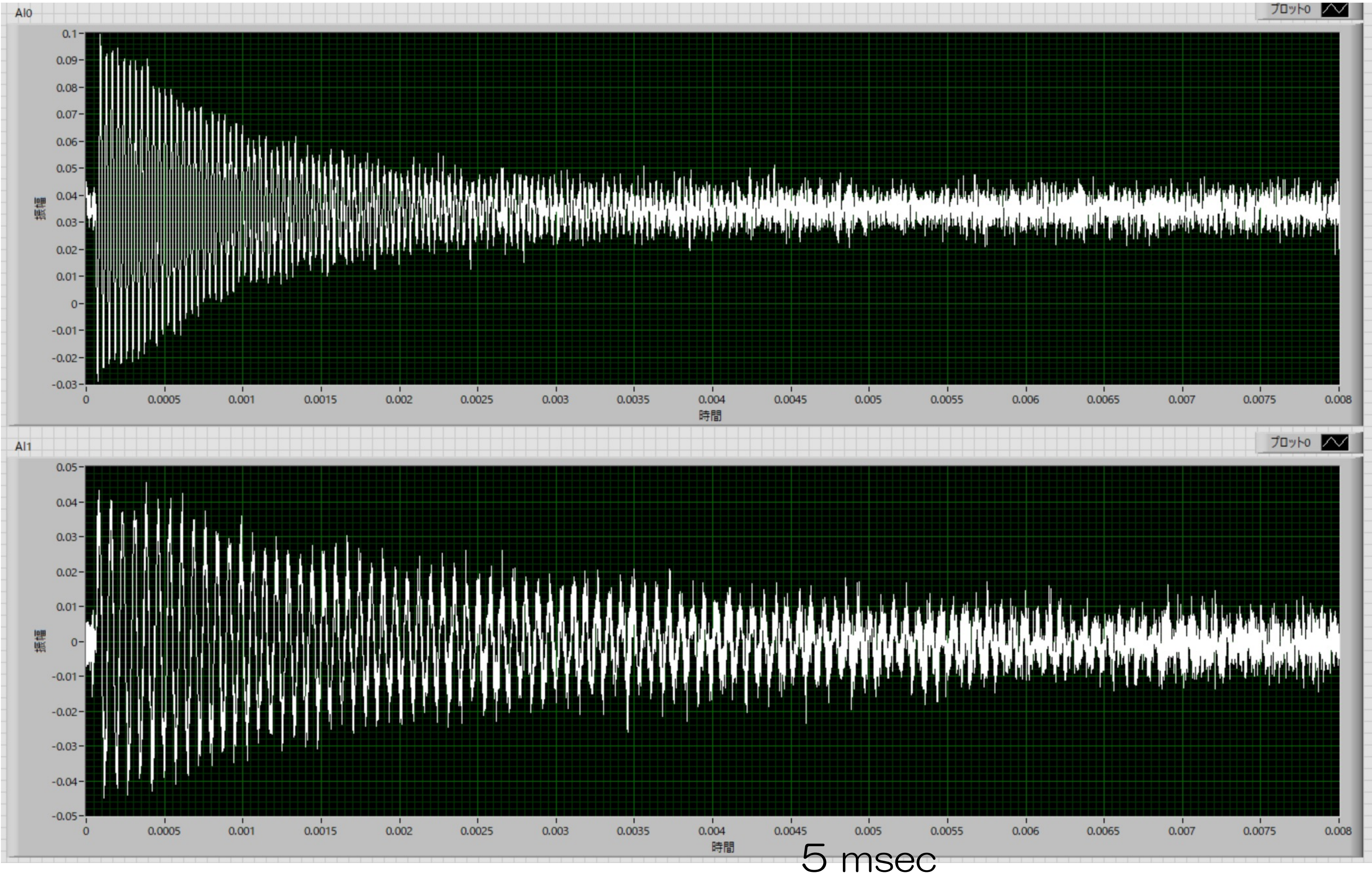
Cold Rb/Cs in the optical lattice



Signal of Faraday rotation

^{87}Rb

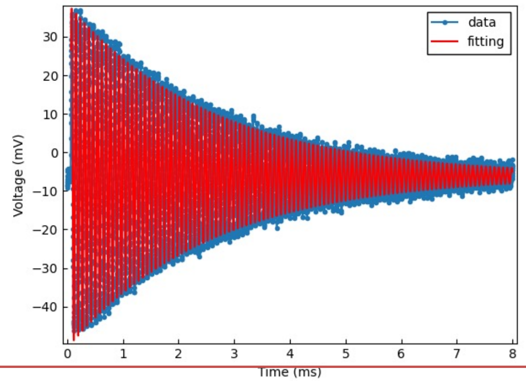
^{133}Cs



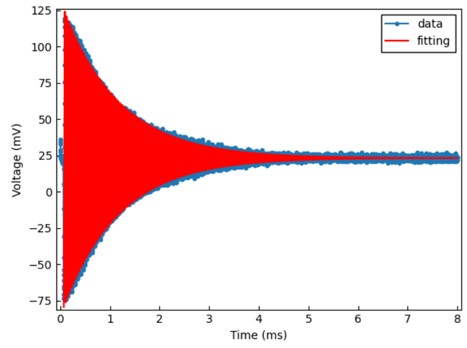
Spin precession ～　observed clearly

Spin precession frequencies for Rb/Cs

^{133}Cs



^{87}Rb



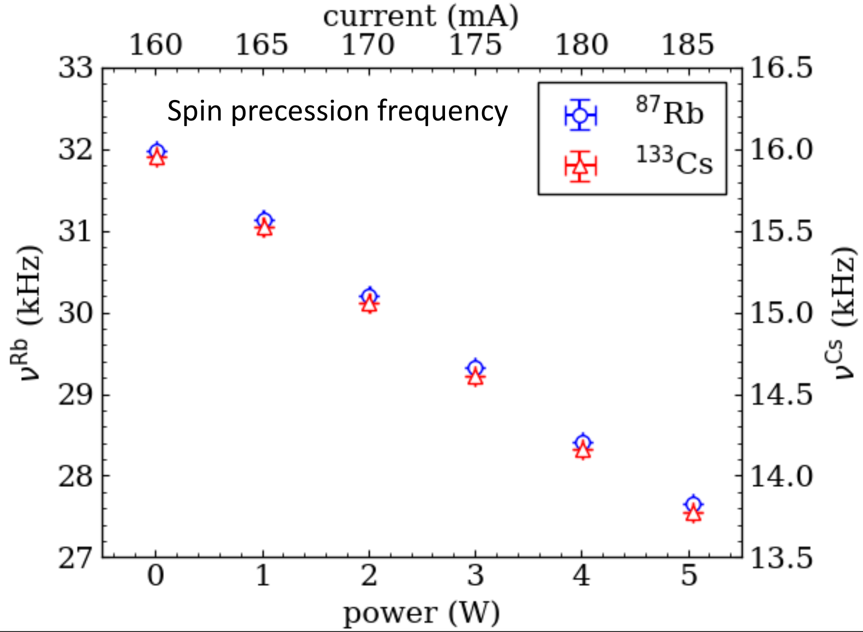
$$\nu^{\rm Rb} = g_F^{\rm Rb}\mu_B B/h + \alpha_{\rm Rb}^{(1)}(F=2;\Delta)\frac{1}{h\epsilon_0 c} I\varepsilon_{cp}\cos\phi$$

$$\nu^{\rm Cs} = g_F^{\rm Cs}\mu_B B/h + \alpha_{\rm Cs}^{(1)}(F=4;\Delta)\frac{1}{2h\epsilon_0 c} I\varepsilon_{cp}\cos\phi$$

$$B = \frac{\Gamma_{\rm Cs}\nu^{\rm Rb} - \Gamma_{\rm Rb}\nu^{\rm Cs}}{\gamma_{\rm Rb}\Gamma_{\rm Cs} - \gamma_{\rm Cs}\Gamma_{\rm Rb}}, \qquad \delta B = \frac{\sqrt{\Gamma_{\rm Cs}^2(\delta\nu^{\rm Rb})^2 + \Gamma_{\rm Rb}^2(\delta\nu^{\rm Cs})^2}}{|\gamma_{\rm Rb}\Gamma_{\rm Cs} - \gamma_{\rm Cs}\Gamma_{\rm Rb}|}$$

$$I\varepsilon_{\rm cp}\cos\phi = \frac{-\gamma_{\rm Cs}\nu^{\rm Rb} + \gamma_{\rm Rb}\nu^{\rm Cs}}{\gamma_{\rm Rb}\Gamma_{\rm Cs} - \gamma_{\rm Cs}\Gamma_{\rm Rb}}, \qquad \delta\left(I\varepsilon_{\rm cp}\cos\phi\right) = \frac{\sqrt{\gamma_{\rm Cs}^2(\delta\nu^{\rm Rb})^2 + \gamma_{\rm Rb}^2(\delta\nu^{\rm Cs})^2}}{|\gamma_{\rm Rb}\Gamma_{\rm Cs} - \gamma_{\rm Cs}\Gamma_{\rm Rb}|}$$

Experimental results



Status of the Fr-EDM

Predicted systematic errors

Energy shift	Shift item	Systematic error (10^{-29} ecm)	This project
Zeeman shift	magnetic field	1.34	dual species magnetometer
	applied current	1.34 x 10^{-5}	
	leakage current	0.04	
	Johnson noise	4.6 x 10^{-5}	
Vector light shift	polarization	0.46	dual species magnetometer
Atom collision shift	collision	0.14	optical lattice
	shift in OL	1.6 x 10^{-7}	
Geometrical phase		4.6 x 10^{-6}	cooling
Black body radiation		9.2 x 10^{-4}	cooling

- Cold Fr source in the optical lattice
- Dual atoms co-magnetometer

Dominant component ~ BBR
EDM accuracy 10^{-30} ecm ~ can be realized

Fr EDM ~ 10^{-30} ecm
- Long coherence time : 10 s
- Enhancement factor : 799 ~ largest in atoms

Dominant component of systematic errors :
- Zeeman shift
- Vector light shift
- Atom collision shift

are drastically reduced by dual atoms co-magnetometer and optical lattice.

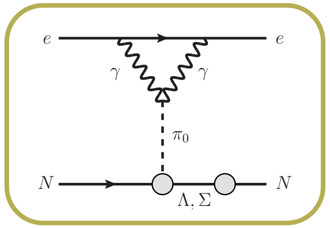
CP Violation effect in ^{210}Fr

$$D_a = 799\, d_e + 10.5 \times 10^{-18}\, C_N^{S-PS(0)}\, e\,\mathrm{cm}$$

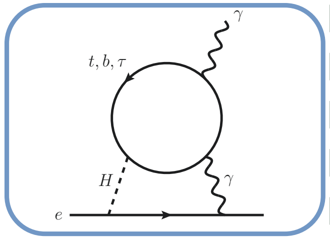
d_e | $C_{s\text{-}ps}$(CPV int.)

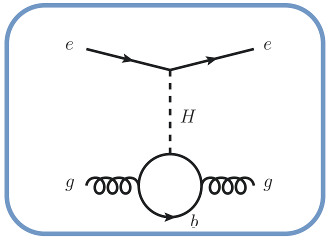
10^{-38} ecm

Standard model

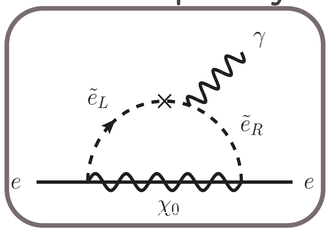


Double Higgs model

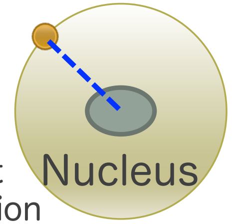




Super Symmetry model



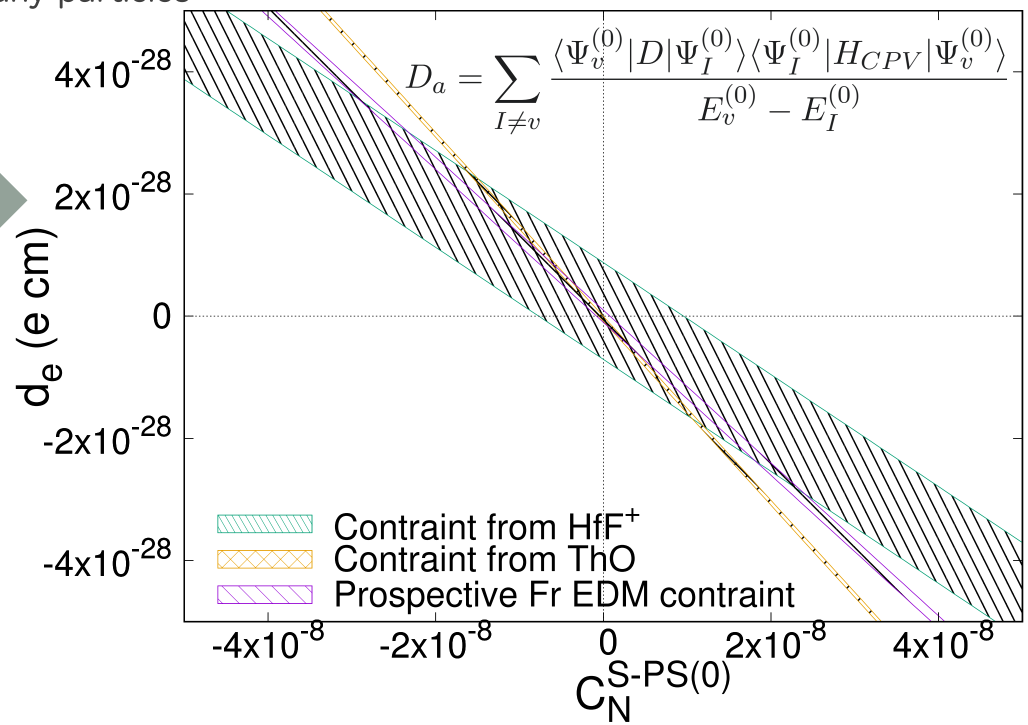
Extract each component from the different correlation pattern for many particles



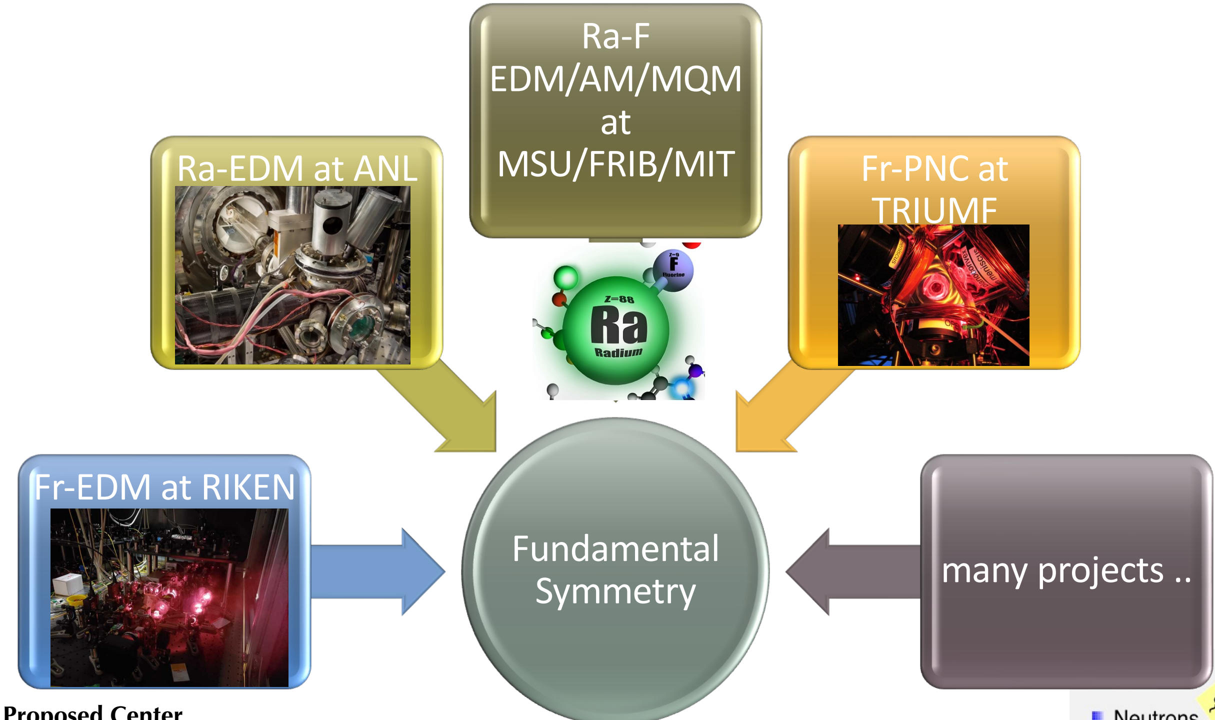
$d_A = R \cdot d_e + S \cdot C_{s\text{-}ps}$

$d_e + (S/R) \cdot C_{s\text{-}ps}$

Atomic/nuclear structure



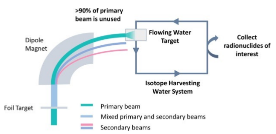
Fundamental physics with radioactive elements



FRIB **The Nuclear Pear Factory: A Proposed Center**

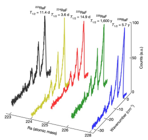
Nature 497:199 (2013)

A joint Experiment/Theory & AMO/Nuclear/Radiochemistry effort to calibrate the new physics sensitivity of pear-shaped nuclei and to carry out the requisite precursory work leading to ultrasensitive EDM searches.



NIMB 478 34 (2020)

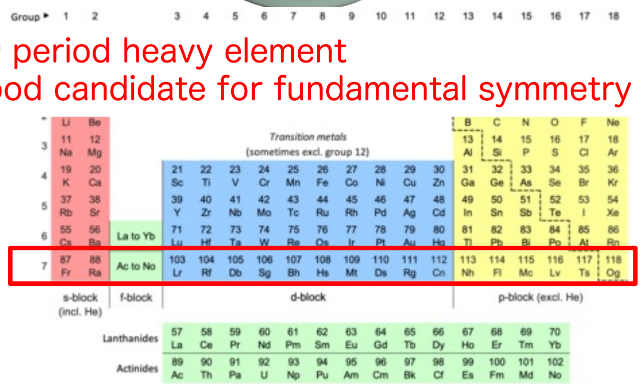
N P F

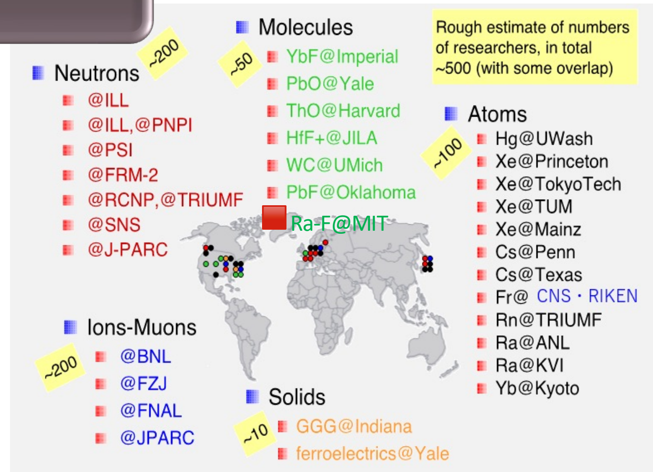


Nature 581:396 (2020)

https://physics.aps.org/articles/v14/103 & A.M. Jayich

7th period heavy element
Good candidate for fundamental symmetry study





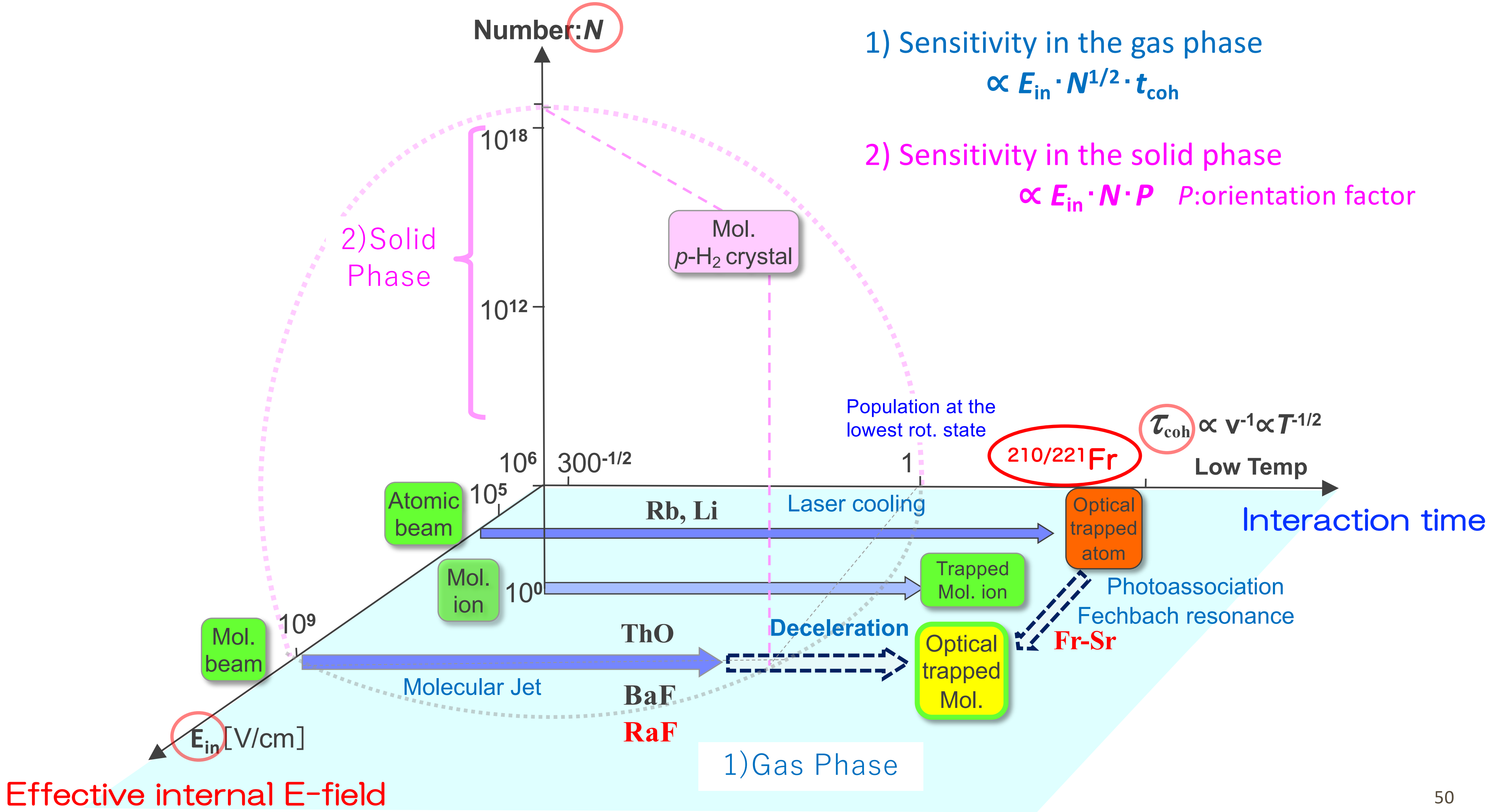
Toward to RI molecule

1) Sensitivity in the gas phase

$\propto E_{in} \cdot N^{1/2} \cdot t_{coh}$

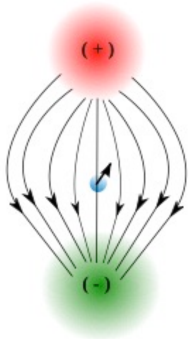
2) Sensitivity in the solid phase

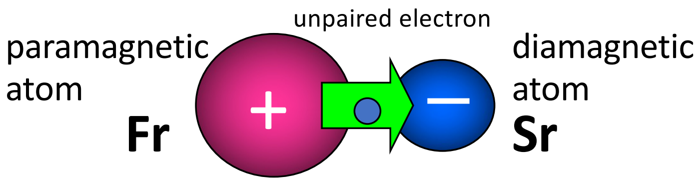
$\propto E_{in} \cdot N \cdot P$ P:orientation factor



Fr-Sr molecule

Ultracold trapped molecules associated by Feshbach resonance
from laser cooled Fr and Sr atoms.





effective field 2.7-4.2 GV/cm

$$\delta d_e = \frac{1}{|P|E_{eff}}\frac{\hbar}{\tau}\times\frac{1}{\sqrt{N}}\times\frac{1}{\sqrt{n}}$$

one measurement

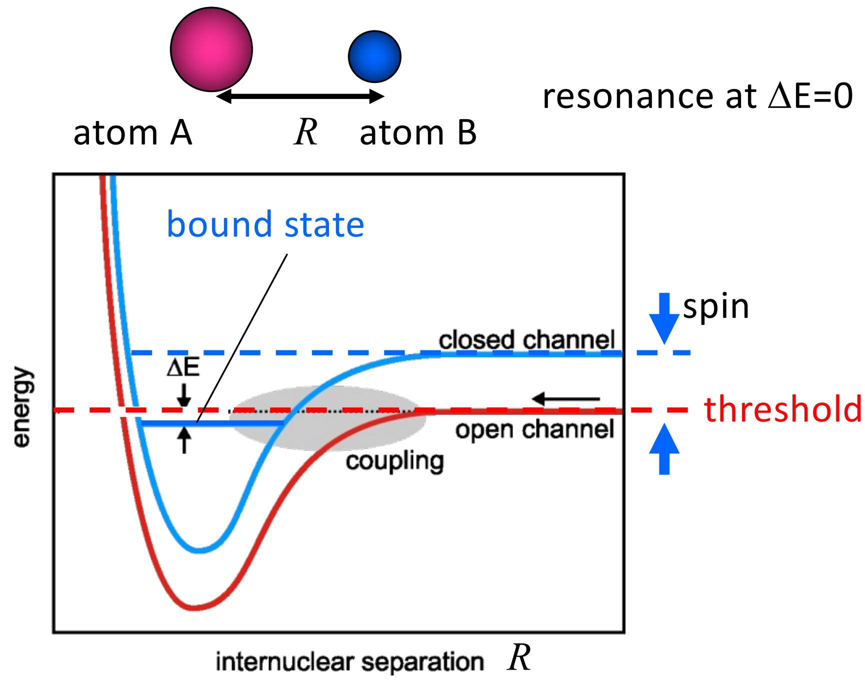
interaction time

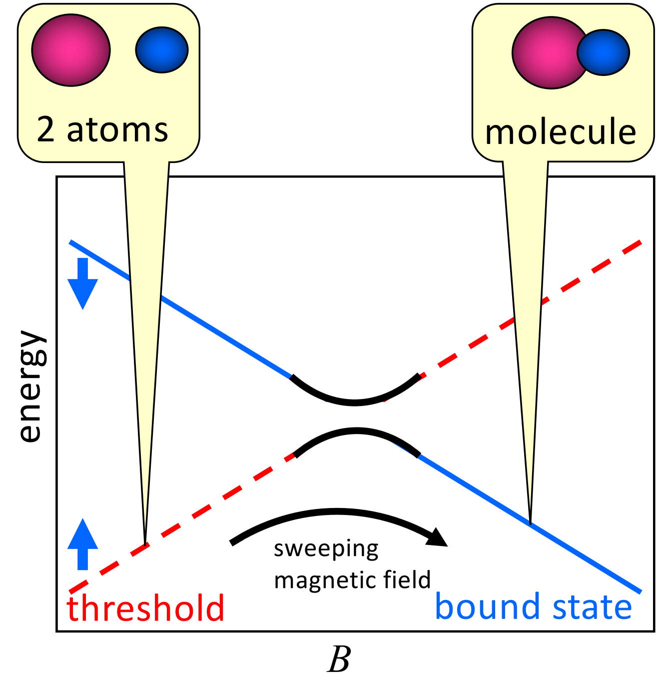
- molecular beam t ∼1 ms
- ultracold molecules t ∼ 1 s

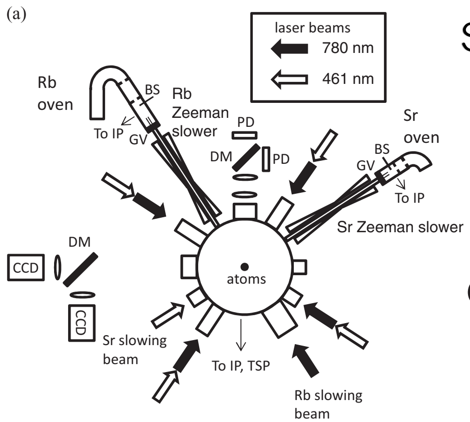
∼ 1 x 10^{-27} e cm @ 2.5 s
∼ 1 x 10^{-28} e cm @ 253 s
∼ 1 x 10^{-29} e cm @ 7 hours
∼ 5 x 10^{-30} e @ 1 day integration

if 4 GV/ cm, t = 1 s, N = 10^4

Association of molecules near Feshbach resonance

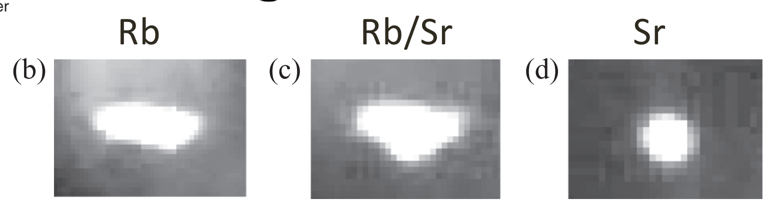






Simultaneous MOT of Rb and Sr ～ succeeded

- First step for Fr-Sr molecule production
- Basic technique to locate Fr and Rb to each cite of lattice
  ⇒ co-magnetometer



Possibility of superheavy molecules: LrX

PHYSICAL REVIEW A **104**, 062801 (2021)

Towards *CP*-violation studies on superheavy molecules: Theoretical and experimental perspectives

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Molecules containing superheavy atoms can be artificially created to serve as sensitive probes to study symmetry-violating phenomena. Here, we provide detailed theoretical studies of quantities relevant to the electron electric dipole moment (eEDM) and nucleus-electron scalar-pseudoscalar interactions in diatomic molecules containing superheavy lawrencium nuclei. The sensitivity to parity and time (or, equivalently, *CP*) reversal violating properties is studied for different neutral and ionic molecules. The effective electric fields in these systems are found to be about 3–4 times larger than other known molecules on which eEDM experiments are being performed. Similarly, these superheavy molecules exhibit an enhancement of more than 3 times for *CP*-violating scalar-pseudoscalar nucleus-electron interactions. Our preliminary analysis using the Woods-Saxon nuclear model also demonstrates that these results are sensitive to the diffuse surface interactions inside the Lr nucleus. We also briefly comment on some experimental aspects by discussing the production of these systems.

Molecule	$\mathcal{E}_{\rm eff}$ (GV/cm)
LrO	258.92
	250.21
	246.5
LrF^+	246.31
LrH^+	343.38
ThO	87
HgF	115.42
HfF^+	22.5
YbF	23.2

Large Effective Field

Lr molecules production yield

	Reaction	σ $_{prod}$ / nb	beam current	Transport +Mass sep. eff.	Beam intensity after Mass sep.(ion/min)
@JAEA	$^{249}Cf + ^{11}B$	122	200 pnA	~10 %	2
@RIKEN GARIS	$^{209}Bi + ^{48}Ca$	60	2000 pnA	~30%	30
@RIKEN ISOL*	$^{209}Bi + ^{48}Ca$	60	2000 pnA	~10%	10

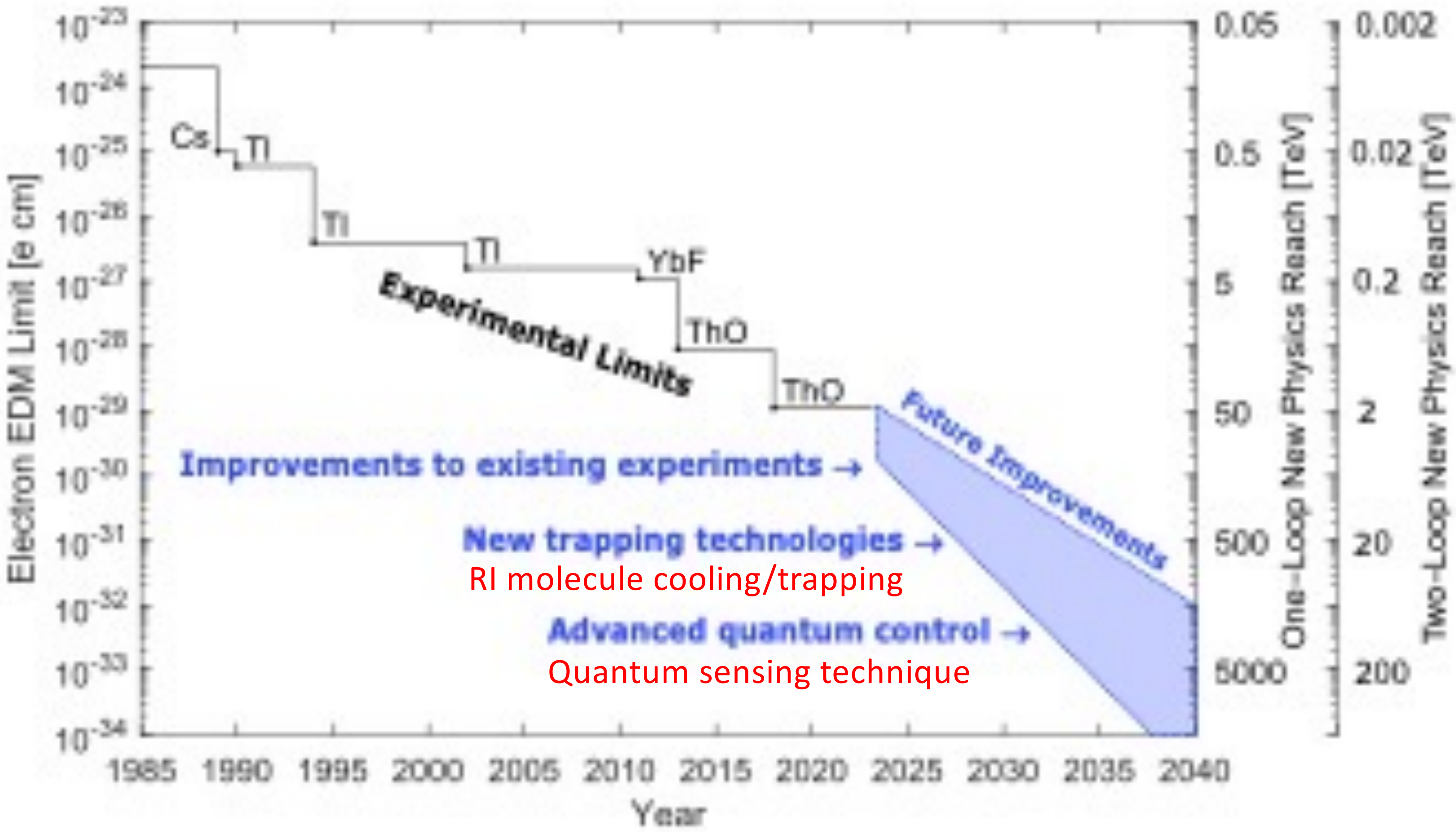
*** Assuming a gas-jet ISOL (similar to JAEA) is available at RIKEN RILAC**

Production of Lr molecules

LrO+ : Lr + trace amount O_2(contaminants in a carrier gas or additional O_2)
LrF+ : LnF_x ion beam has been produced @ CERN-ISOLDE in a molten metal target.
In the case of Lr, fluorination gas (ex. CF_4) needs to be introduced.

New idea of the quantum sensing is required for the limited number of the particles .

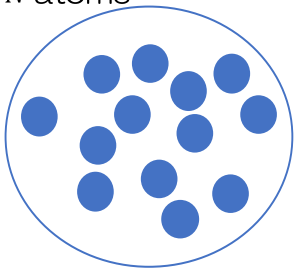
Future strategy



Quantum sensing of EDM with entangled Fr atoms

～ Uncertainty of the phase of Ramsey resonance with Squeezed Spin State ～

N atoms

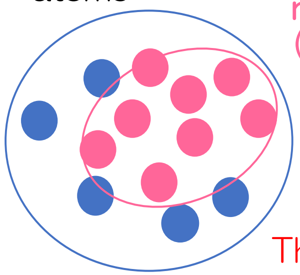


uncertainty

$$\delta\theta = \frac{1}{\sqrt{N}}$$

Standard Quantum Limit (SQL)

N atoms



k -particle negative correlation (the entangled quantum state)

$$\delta\theta = \frac{1}{\sqrt{kN}}$$

If $k = N$, $\delta\theta = \frac{1}{N}$

Heisenberg limit

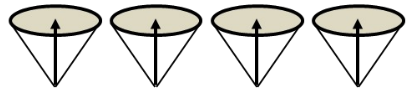
The uncertainty is below the SQL.

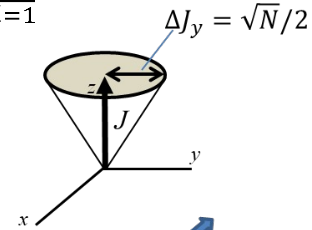
Spin Squeezed State（SSS）

M. Kitagawa, and M. Ueda, Phys. Rev. A **47**, 5138 (1993).

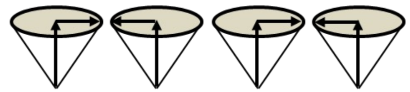
Collective spin $J = \sum_{i=1}^{N} j_i$

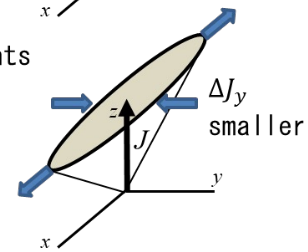
no correlation
(x, y components are random)



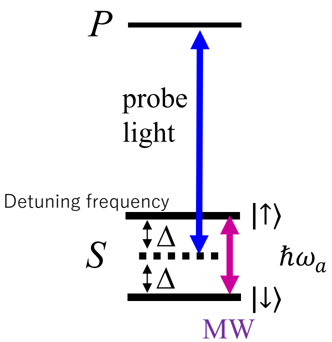


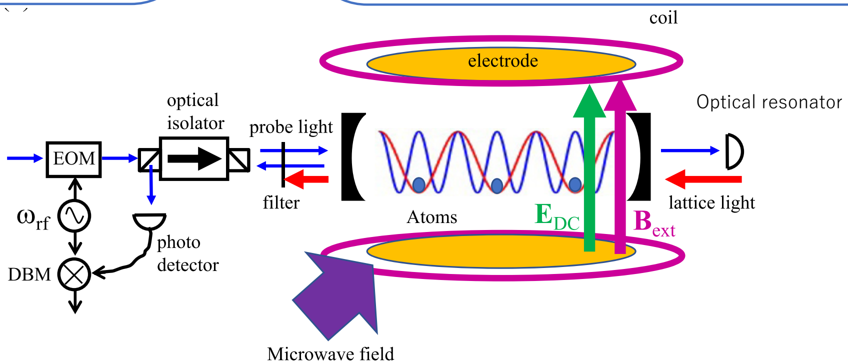
negative correlations of y components





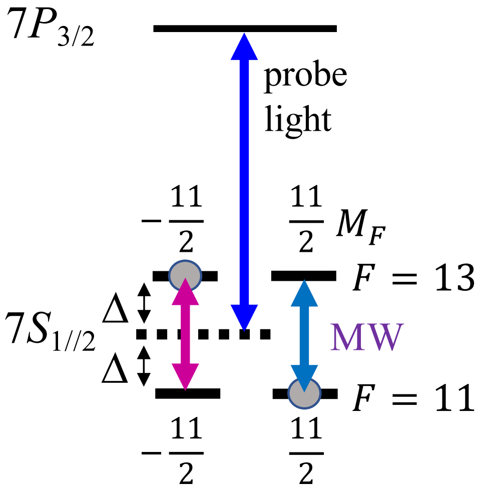
The SSS is the quantum entangled state with negative correlations between atoms

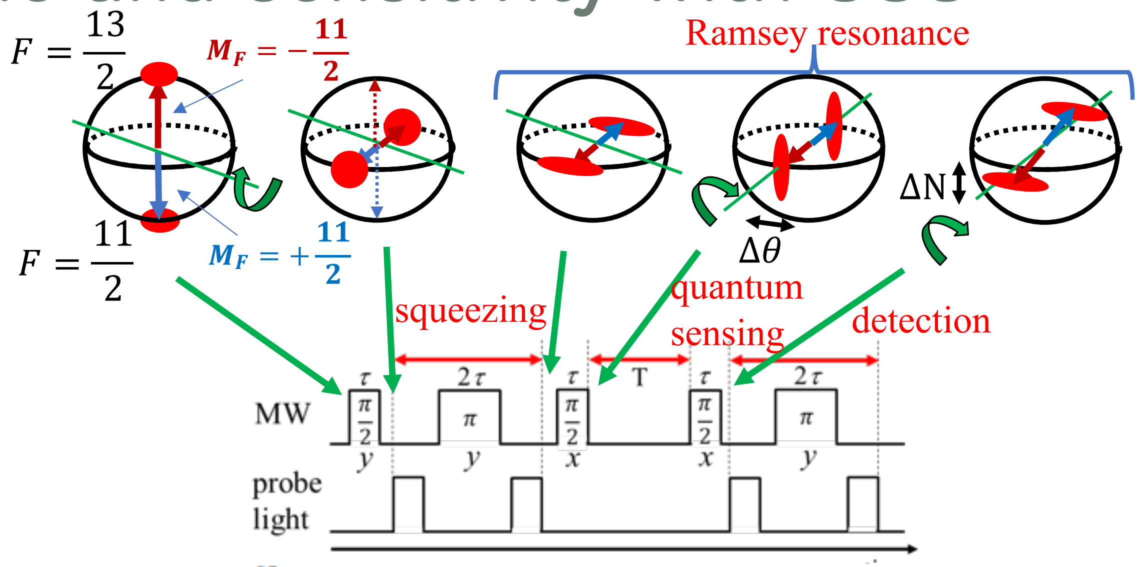




EDM detection scheme and sensitivity with SSS

Quantum sensing



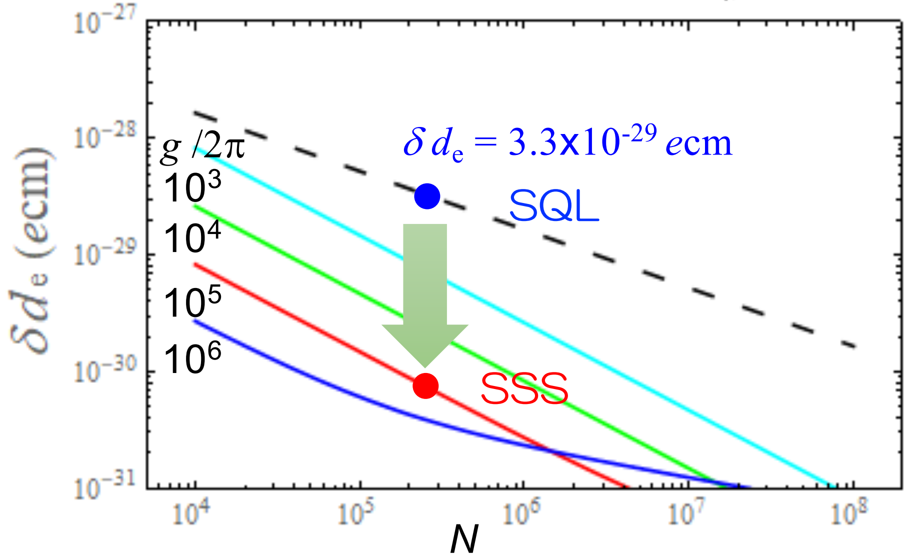


Quantum limit below SQL

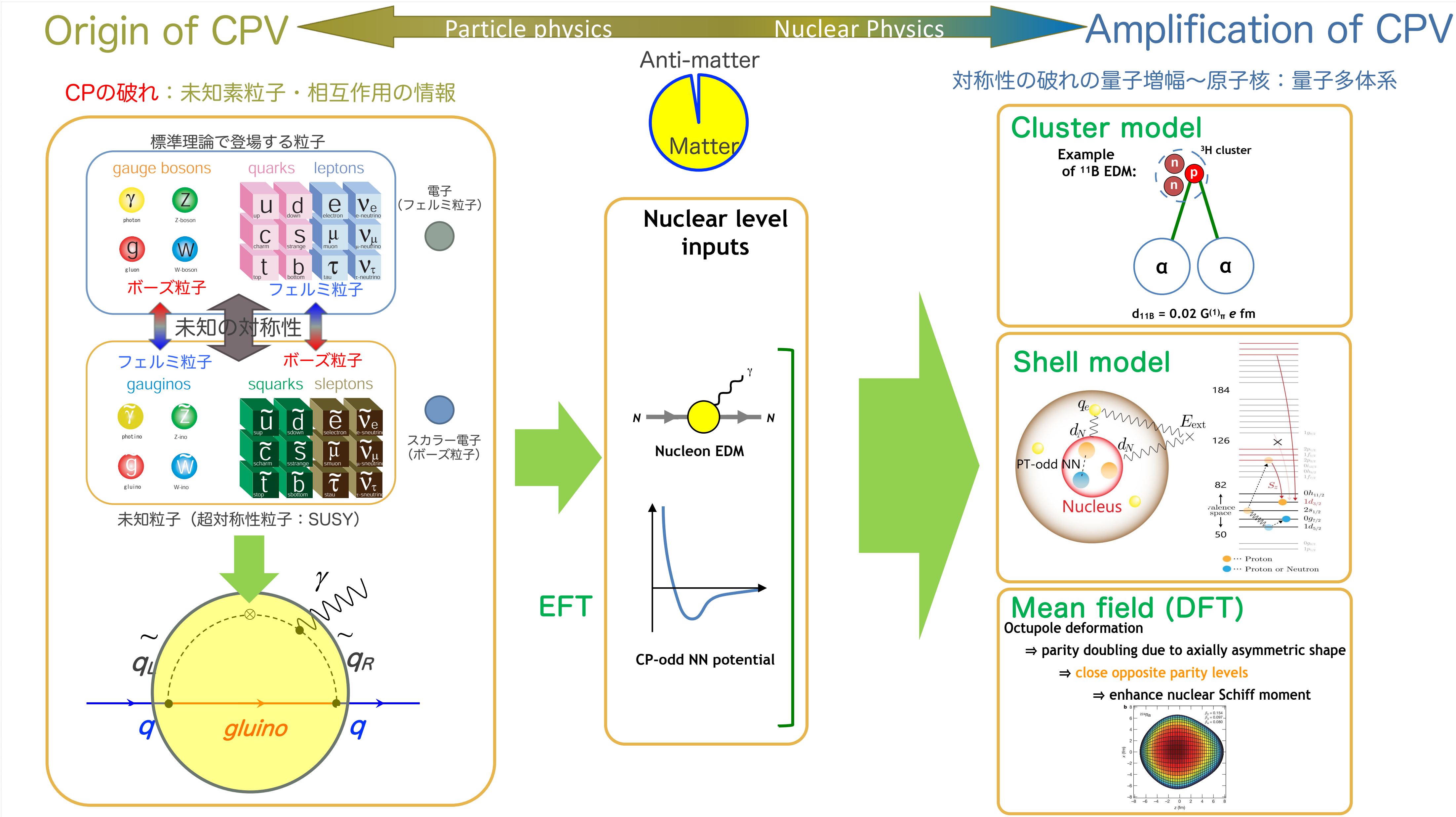
$$\delta d_e^{SSS} = \frac{13\hbar}{22RE_{DC}} \frac{\xi_R}{\sqrt{NTt_{total}}}$$

E = 100 kV cm^{-1} T = 1 s
t_{total} = 24h = 86400 s
N = 2.5x10^5
g /2p = 10^5 Hz
x_R = 1 / 44.2

$\delta d_e = 7.5\text{x}10^{-31}$ ecm

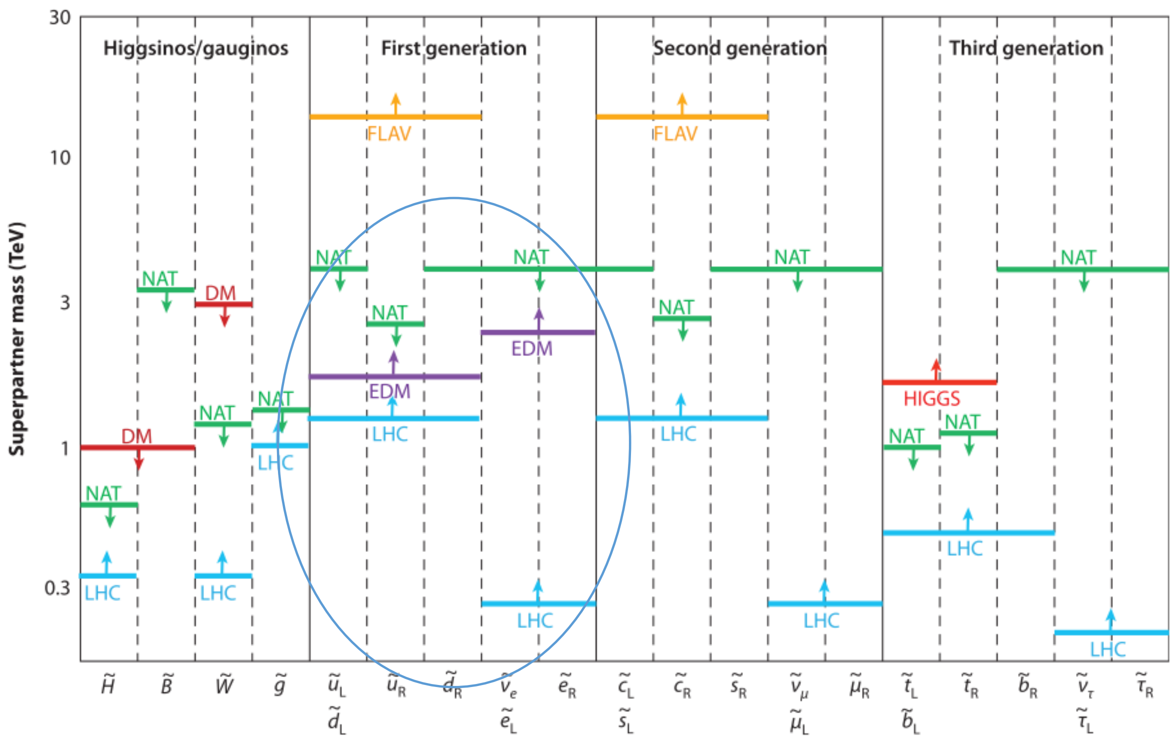


Quantum Sci. Technol. **6**, 044008 (2021).



Origin of CPV
Particle physics
Nuclear Physics
Amplification of CPV
Anti-matter
Matter
CPの破れ：未知素粒子・相互作用の情報
対称性の破れの量子増幅〜原子核：量子多体系
標準理論で登場する粒子
gauge bosons
quarks
leptons
photon
Z-boson
gluon
W-boson
up
down
electron
e-neutrino
charm
strange
muon
μ-neutrino
top
bottom
tau
τ-neutrino
ボーズ粒子
フェルミ粒子
電子（フェルミ粒子）
未知の対称性
フェルミ粒子
ボーズ粒子
gauginos
squarks
sleptons
photino
Z-ino
gluino
W-ino
sup
sdown
selectron
e-sneutrino
scharm
sstrange
smuon
stop
sbottom
stau
スカラー電子（ボーズ粒子）
未知粒子（超対称性粒子：SUSY）
γ
q̃L
q̃R
q
gluino
q
EFT
Nuclear level inputs
N
N
γ
Nucleon EDM
CP-odd NN potential
Cluster model
Example of ¹¹B EDM:
³H cluster
n
p
n
α
α
d₁₁B = 0.02 G⁽¹⁾π e fm
Shell model
qe
dN
dN
Eext
PT-odd NN
Nucleus
184
126
82
valence space
50
··· Proton
··· Proton or Neutron
Mean field (DFT)
Octupole deformation
⇒ parity doubling due to axially asymmetric shape
⇒ close opposite parity levels
⇒ enhance nuclear Schiff moment

Explored energy range

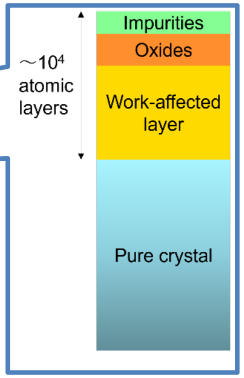


- e EDM with Fr atoms ∼ sensitive to the colorless SUSY particles
- LHC: hadron collider, and not so sensitive to colorless particles
- Fr EDM ∼ can explore the mass scale > TeV region : 10^{-30} ecm

Summary

Optical lattice（OL） atomic interferometer development ～ in progress to search for e-EDM
✓ Fr production ～ ready：extraction efficiency close to maximum
✓ OL and co-magnetometer：proof-of-principle with Rb/Cs atoms ～ ready

Improvement ～ in progress
- Increase Fr ion beam yield $f_{^{210}\mathrm{Fr}} \rightarrow 10\times{}^{30}/_{24.5}\times f_{^{210}\mathrm{Fr}}$ ～ ×10 intensification of primary beam
- Mass filter to reduce the BG
- Y surface purification ～ Baking + sputtering + annealing
- MOT cell installation $\varepsilon_{\mathrm{MOT}} \rightarrow 18\times\varepsilon_{\mathrm{MOT}}$ ～ Confine atoms within cell



Dual atoms co-magnetometer with optical lattice for Rb/Cs
➢ Successfully demonstrated the principle ～ for the first time
➢ At present, measurement accuracy ～ 100 pT achieved
➢ EDM sensitivity ～ 10^{-30} ecm ～ new physics energy scale > TeV can be explored

Thank you very much !

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