Measurement of the electric dipole moment (EDM) of ^{171}Yb atoms in an optical dipole trap (ODT)

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創寰宇學府
育天下英才
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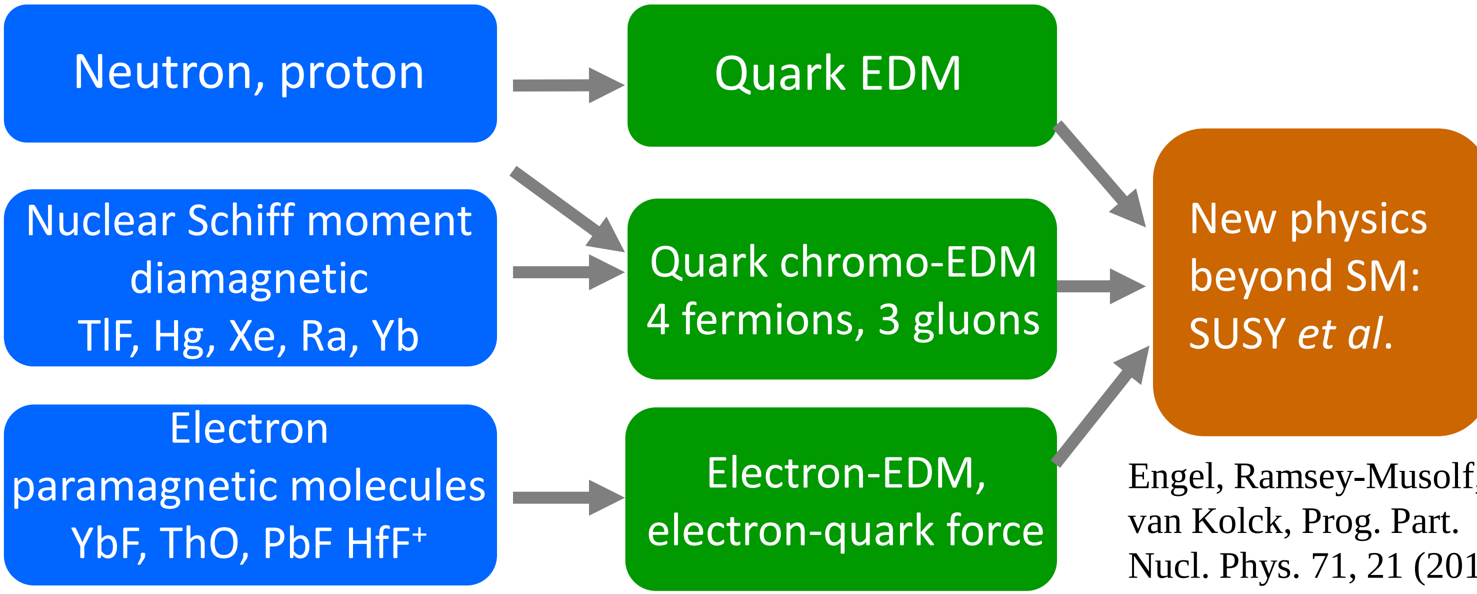
中国科学技术大学
University of Science and Technology of China

Searching for EDM in three different categories

PSI, US, Germany,
Japan, KAIST

U of Washington
PTB, Argonne, USTC
CENTREX

ACME, JILA
Imperial college
ECNU

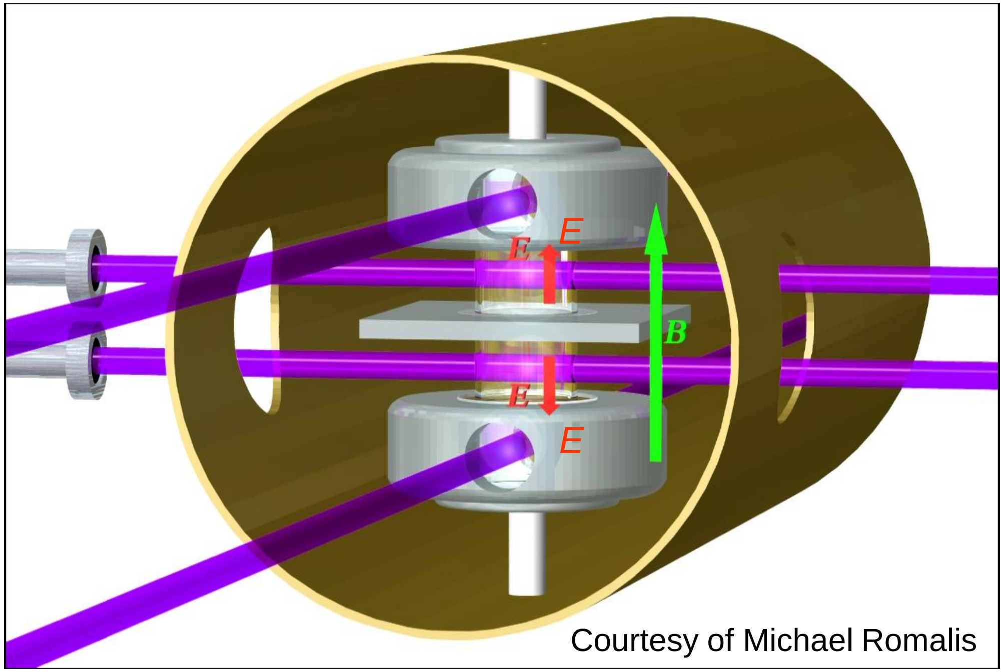


Engel, Ramsey-Musolf, van Kolck, Prog. Part. Nucl. Phys. 71, 21 (2013)

system	Upper limit (e-cm)	method	Value in Standard model (e-cm)
Electron	1×10^{-29}	Molecules – beam	10^{-38}
Neutron	2×10^{-26}	Neutrons – bottle	10^{-31}
^{199}Hg	7×10^{-30}	Atoms – vapor cell	10^{-34}
^{171}Yb	This work	Atoms – trap	10^{-34}

The Seattle EDM Measurement

^{199}Hg stable, high Z, groundstate $^1S_0$, I = ½, high vapor pressure



$$f_+ = \frac{2\mu B + 2dE}{h} \approx 15 \text{ Hz}$$

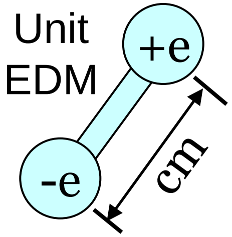
$$f_- = \frac{2\mu B - 2dE}{h} \approx 15 \text{ Hz}$$

$$|f_+ - f_-| < 25\, pHz$$

The best limit on atomic EDM

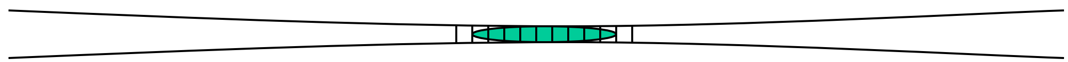
EDM (^{199}Hg) < 7 x 10^{-30} e-cm

Graner *et al*., Phys Rev Lett (2016)



Measure EDM in an Optical Dipole Trap

M.V. Romalis and E.N. Fortson, Phys. Rev. A 59, 4547 (1999)



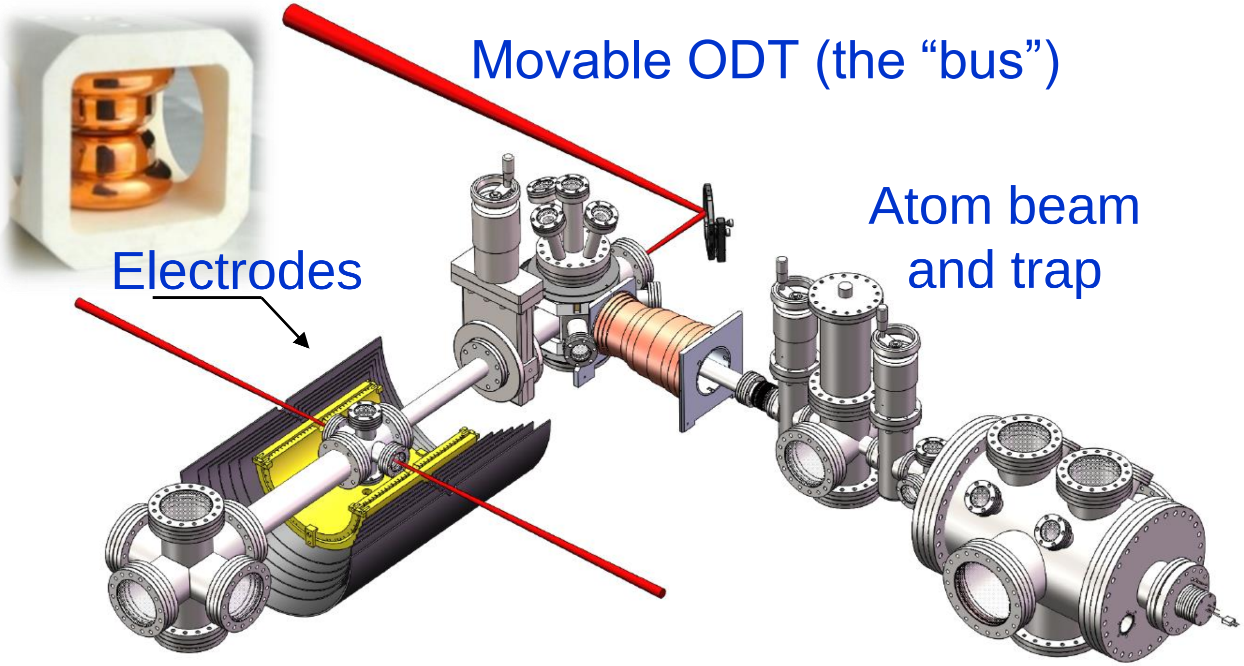
$$H = -\tilde{d}E = -\frac{1}{4}\alpha E_0^2$$

- Fiber laser: λ = 1036 nm, Power = 10 Watts
- Focused to 50 μm → trap depth 60 μK

EDM in an optical dipole trap (ODT)

- v x E , Berry's phase effects suppressed
- Cold scattering suppressed between cold Fermionic atoms
- Rayleigh scat. rate ~ 10^{-1} s^{-1} ; Raman scat. rate ~ 10^{-12} s^{-1}
- Vector light shift ~ μHz
- Parity mixing induced shift under control
- Conclusion: possible to reach 10^{-30} e cm for ^{199}Hg

^{171}Yb EDM Apparatus: Trapping + Science



$$\varpi_{+} = 2\mu B + 2dE$$

$$\varpi_{-} = 2\mu B - 2dE$$

$$\delta d = \frac{\hbar}{2E\sqrt{\tau N \varepsilon T}}$$

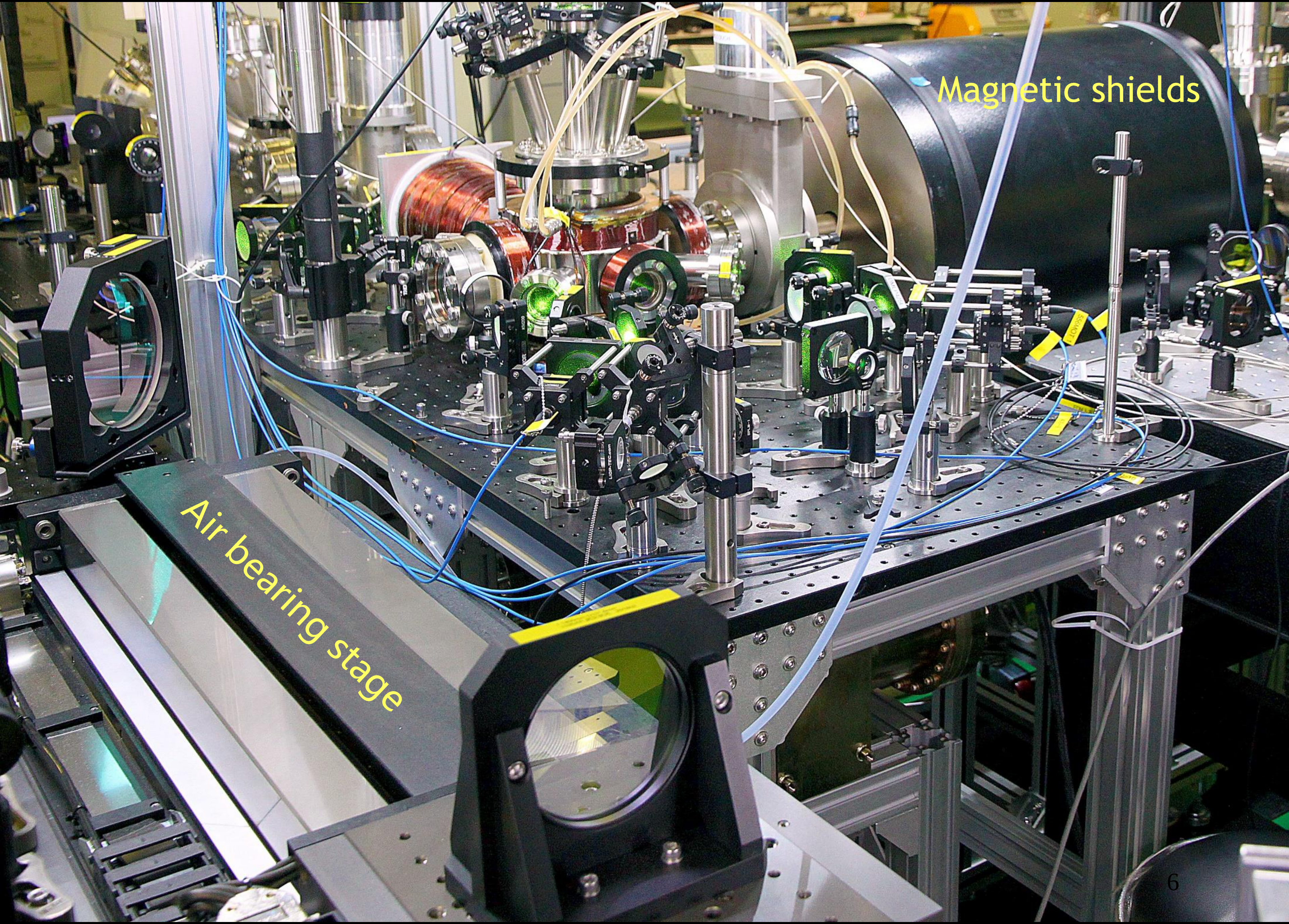
E: electric field

τ: precession time

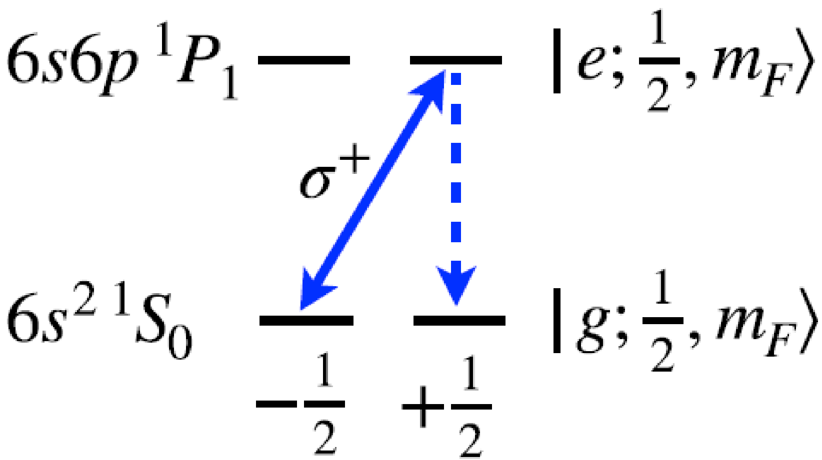
N: atom number

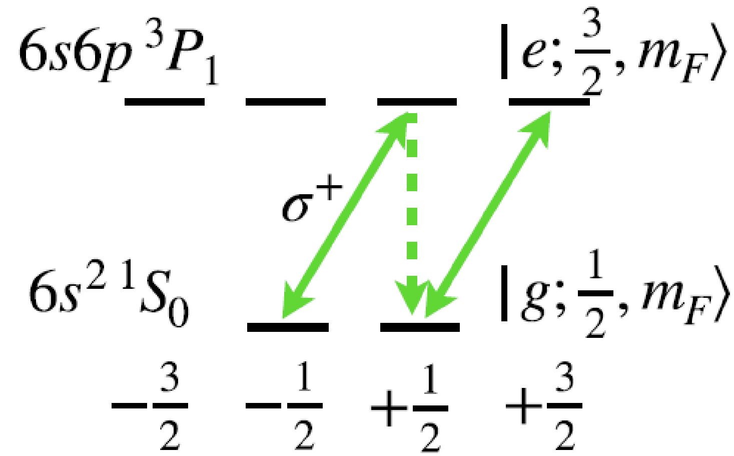
ε: spin – state detection efficiency

T: time of average


Magnetic shields
Air bearing stage

Spin-state detection – conventional method





Bright state:
~ 3 photons before state "demolished"

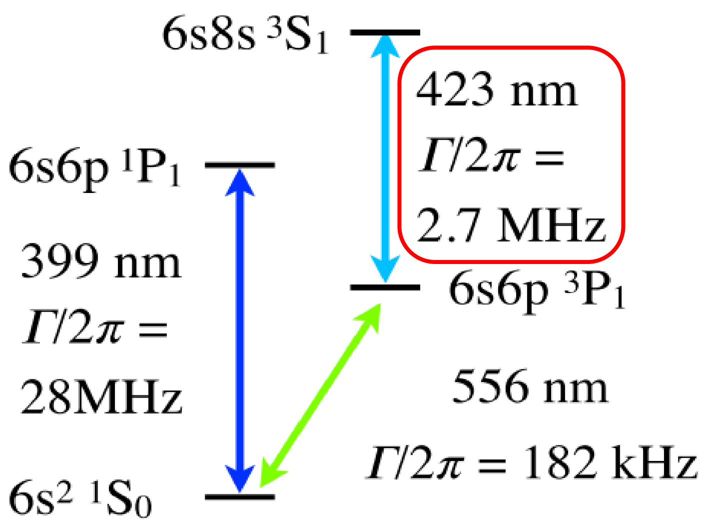
Dark state:
no photons, state preserved

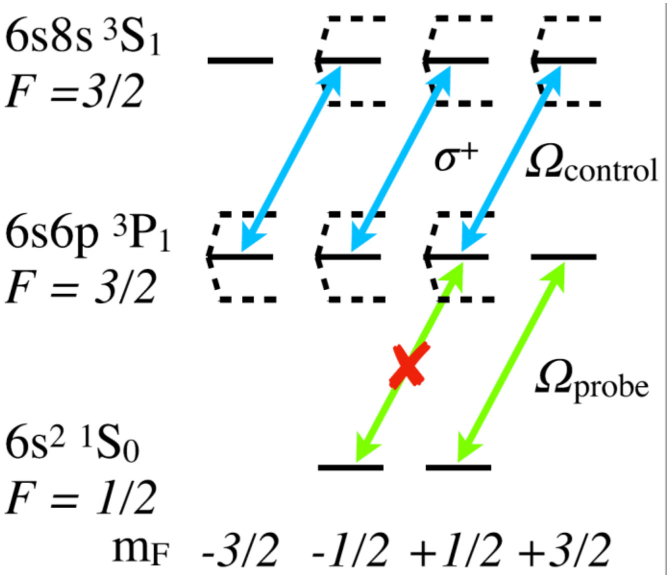
Bright state:
state "demolished"

Brighter state:
cycling, state preserved

Spin-state detection by a QND method

Quantum Non-Demolition





- $\Omega_{control} \sim 2\pi \times 40MHz$
- $\Omega_{probe} \sim 2\pi \times 70kHz$
- Spin flip suppressed by: $\Omega_c^2/(\Gamma_e \Gamma_c) \sim 10^3$
- Need ODT to be at magic wavelength
  -- T. Zheng, M.S. Safronova *et al.*, PRA (2020)

Dark state:
no photons,
state preserved

Bright state:
cycling,
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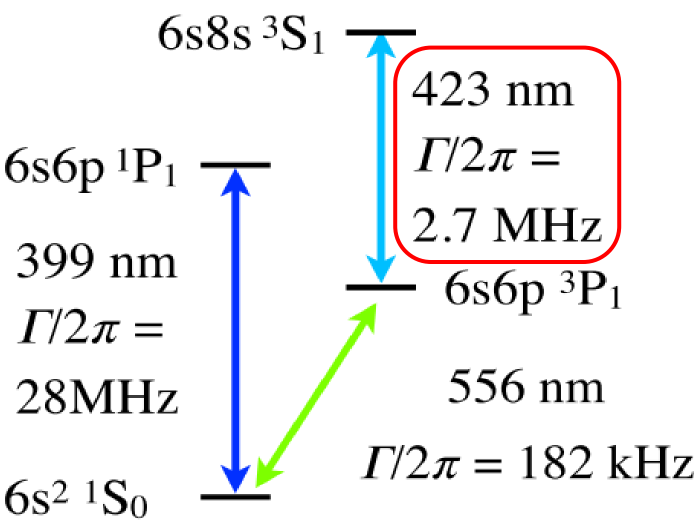
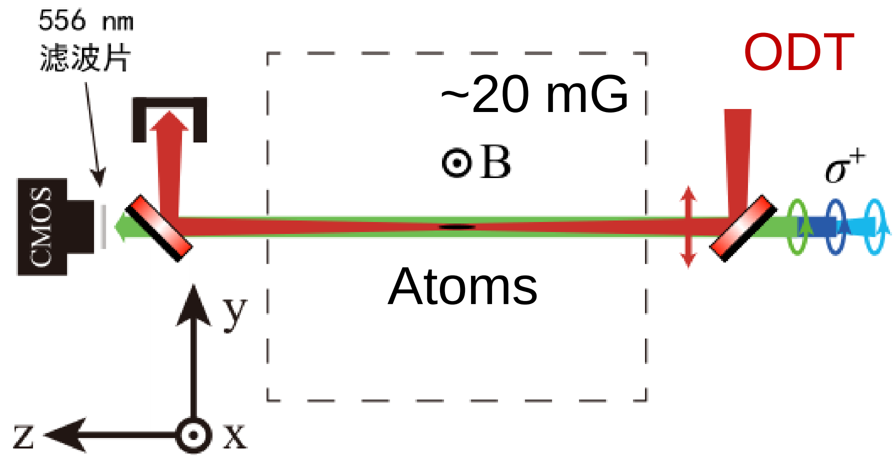
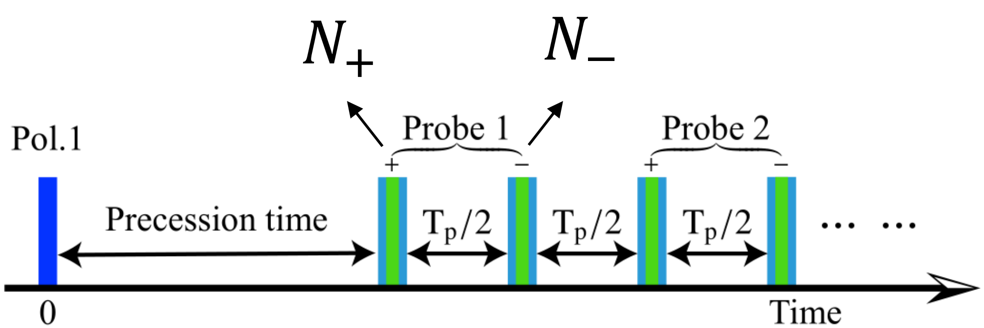
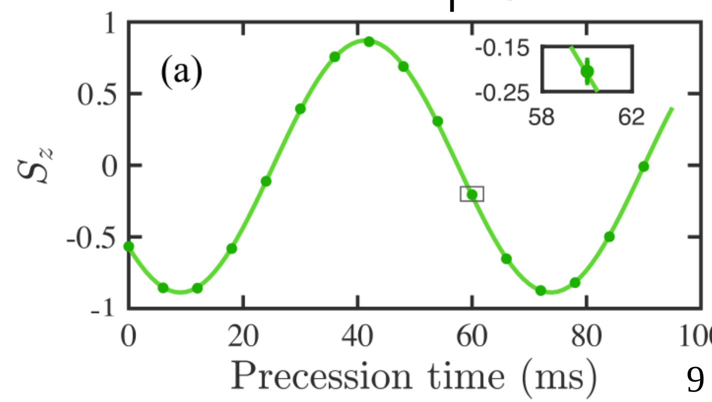


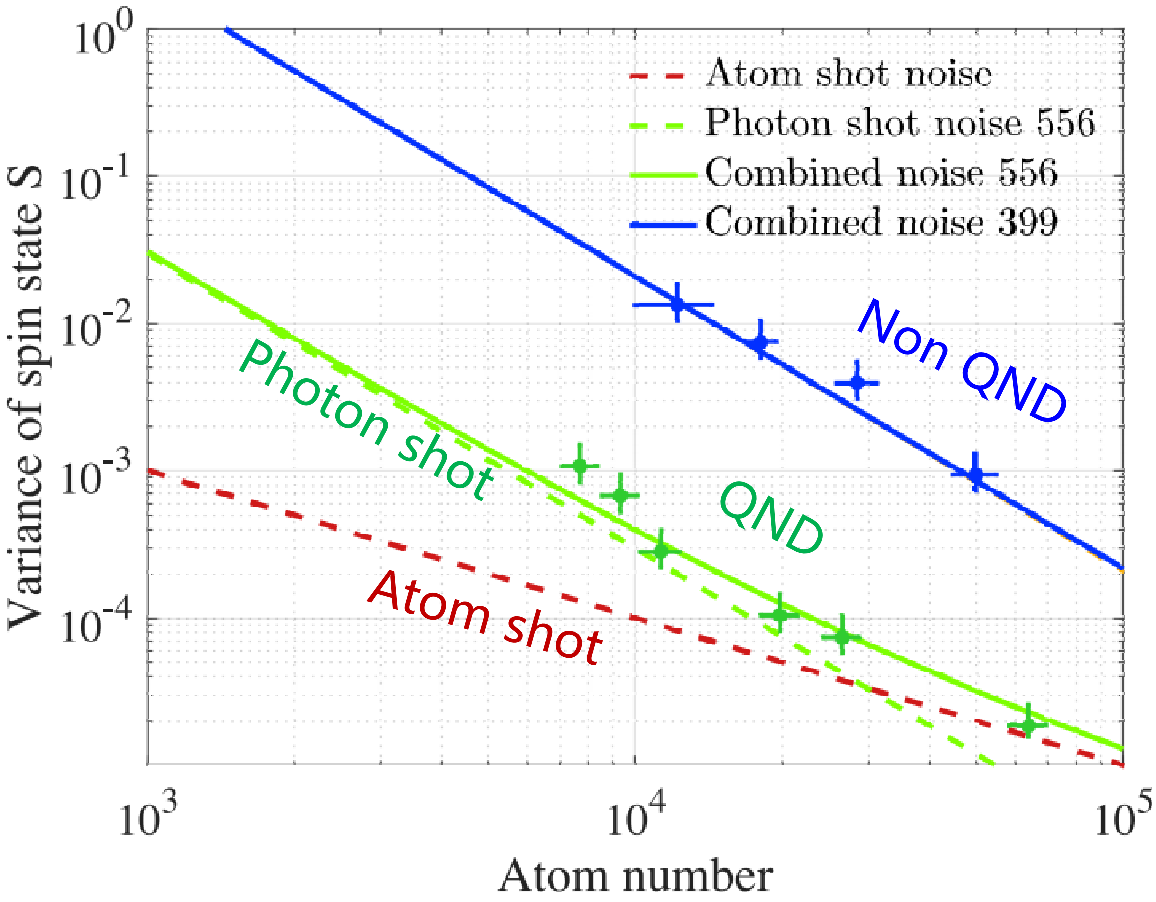


$$S_z = \frac{N_+ - N_-}{N_+ + N_-}$$





QND reduces measurement noise

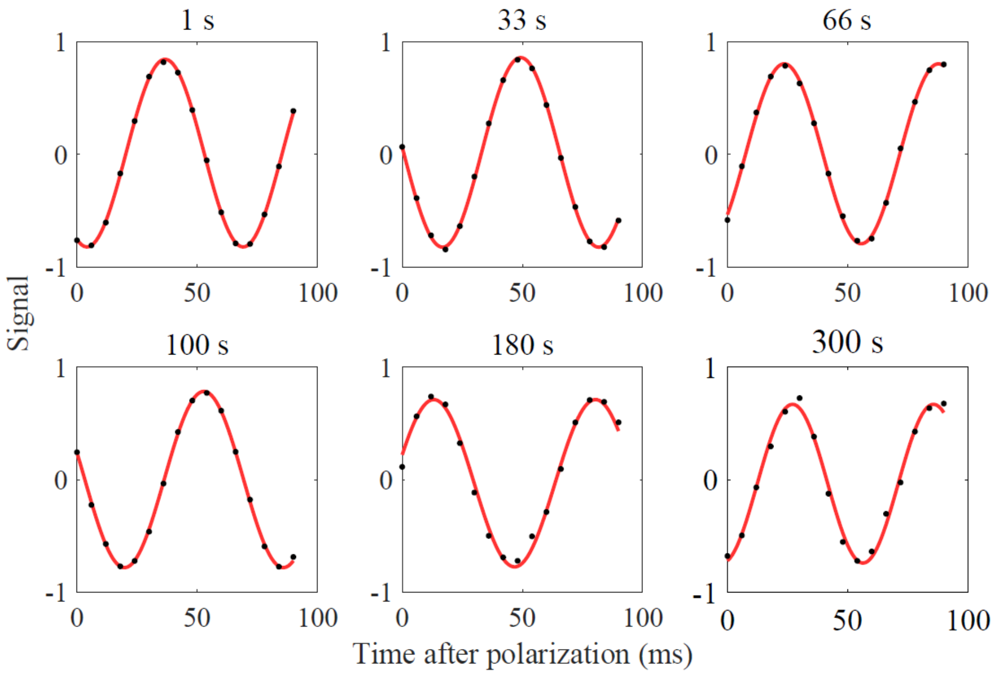


- Photons scattered non-QND: $\bar{n} \sim 2.5$ QND: $\bar{n} \sim 23$
- ~19 dB reduction of variance

QND measurement on the spin precession of laser-trapped ^{171}Yb atoms
Y.A. Yang *et al.*, Phys. Rev. Applied 19, 054015 (2023)

Long spin coherence time (T_2)

$$S_z = \frac{N_+ - N_-}{N_+ + N_-} = C \exp\left(-\frac{t}{T_2}\right) \cos(2\pi f t + \phi_0) + O$$



- Vacuum-limited trap lifetime: 75 s
- EDM measurement precession time: 96 s
- Observed precession to: 300 s
- T_2: (9 ± 4) x 10^3 s (2.5±1.1 hr)

Systematic errors

- effects correlated with E-field flipping

Source	Error
B-field correlations	1.00×10^{-27}
Parity mixing	0.59×10^{-27}
Leakage current	0.14×10^{-27}
ODT power effect	0.09×10^{-27}
E-squared effect	0.04×10^{-27}
Total	1.18×10^{-27}

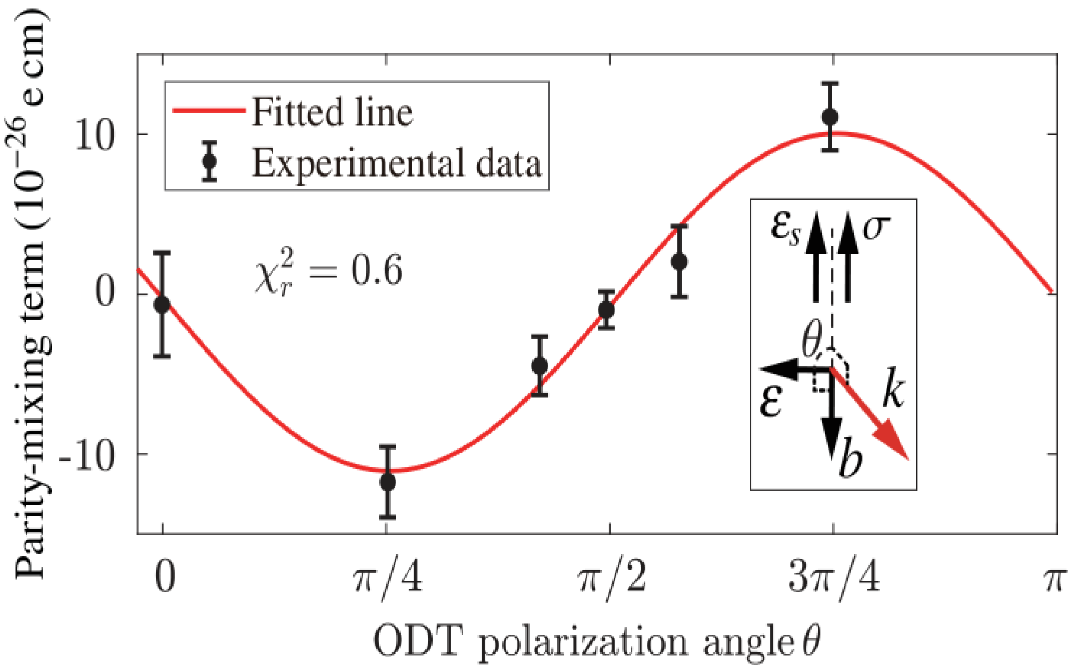
Parity mixing

$$\Delta E = \frac{e^2 \mu_B E_0^2 E_S}{4\hbar^2} \sum_{J',J'',m',m''} \left[\frac{\langle J',m'|\boldsymbol{\varepsilon}\cdot\boldsymbol{r}|J,m\rangle\langle J'',m''|\boldsymbol{b}^*\cdot(\boldsymbol{L}+2\boldsymbol{S})|J',m'\rangle\langle J,m|\boldsymbol{\varepsilon}_s\cdot\boldsymbol{r}|J'',m''\rangle}{(\omega_{J'}-\omega)(\omega_{J''}-\omega)} \right.$$

$$\left. + \frac{\langle J,m'|\boldsymbol{b}\cdot(\boldsymbol{L}+2\boldsymbol{S})|J,m\rangle\langle J',m'|\boldsymbol{\varepsilon}^*\cdot\boldsymbol{r}|J,m'\rangle\langle J,m|\boldsymbol{\varepsilon}_s\cdot\boldsymbol{r}|J',m'\rangle}{\omega_{J'}(\omega_{J'}-\omega)} + \text{perm.} + \text{c.r.} \right]$$

M.V. Romalis and E.N. Fortson, Phys. Rev. A 59, 4547 (1999)

T-even, P-even
yet EDM-like



$\boldsymbol{\varepsilon}$: ac E-field of ODT

$\boldsymbol{b}$: ac B-field of ODT

$\boldsymbol{\varepsilon_s}$: Static E-field

$\boldsymbol{\sigma}$: Quantization axis

Static B-field

measurement : $1.2(2) \times 10^{-25}$ $e\ cm$ $(\varepsilon \cdot \varepsilon_s = \varepsilon \cdot \sigma = \sqrt{2}/2)$

calculation : 2×10^{-25} $e\ cm$ $(\varepsilon \cdot \varepsilon_s = \varepsilon \cdot \sigma = \sqrt{2}/2)$

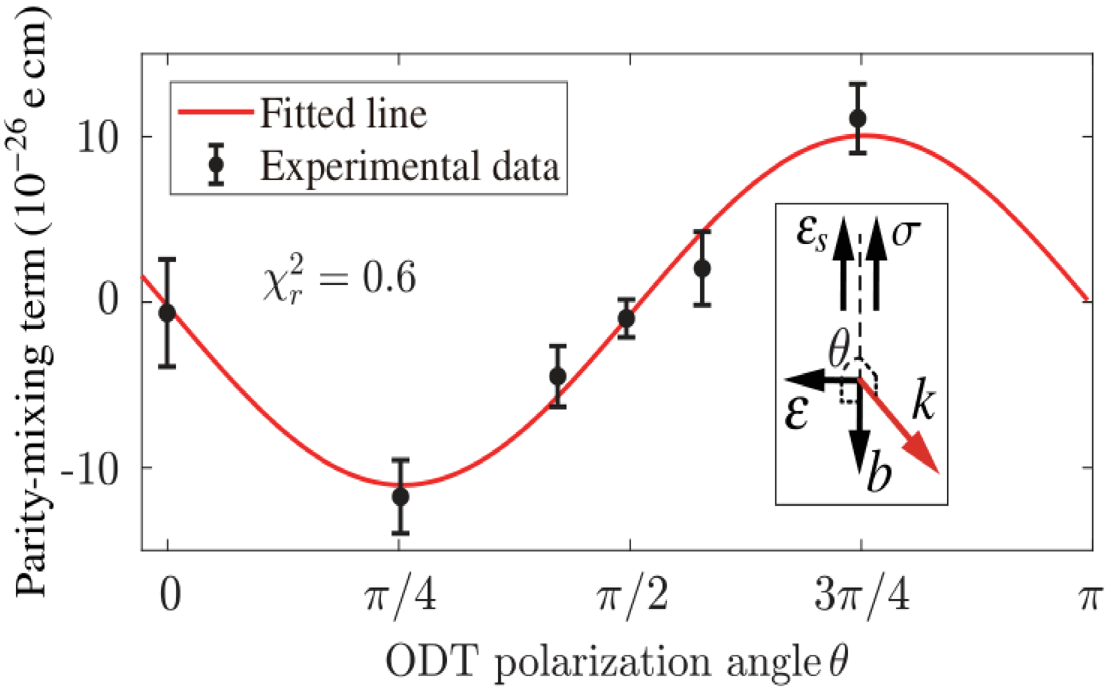
Parity mixing

$$\Delta\nu_{F=I\pm 1/2} = \mp[\nu^1_{MD}(\hat{\boldsymbol{b}}\cdot\hat{\boldsymbol{\sigma}})(\hat{\boldsymbol{\varepsilon}}\cdot\hat{\boldsymbol{\varepsilon}}_s) + \nu^2_{MD}(\hat{\boldsymbol{b}}\cdot\hat{\boldsymbol{\varepsilon}}_s)(\hat{\boldsymbol{\varepsilon}}\cdot\hat{\boldsymbol{\sigma}})]m$$

M.V. Romalis and E.N. Fortson, Phys. Rev. A 59, 4547 (1999)

$$\Delta\nu \approx -\frac{\nu_1+\nu_2}{2}\sin(2\theta),\ (0 \le \theta < \pi)$$

T-even, P-even
yet EDM-like



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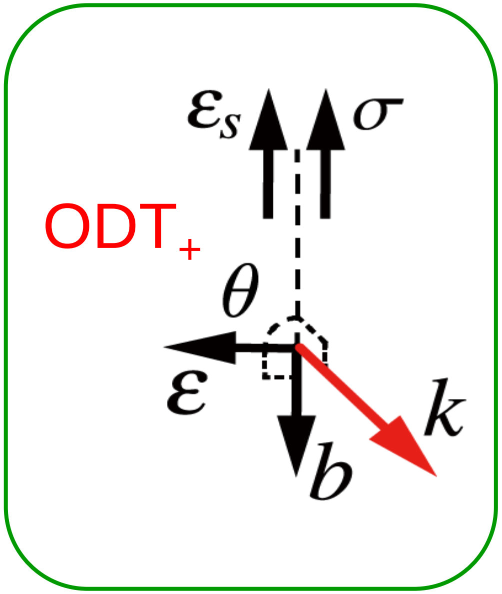
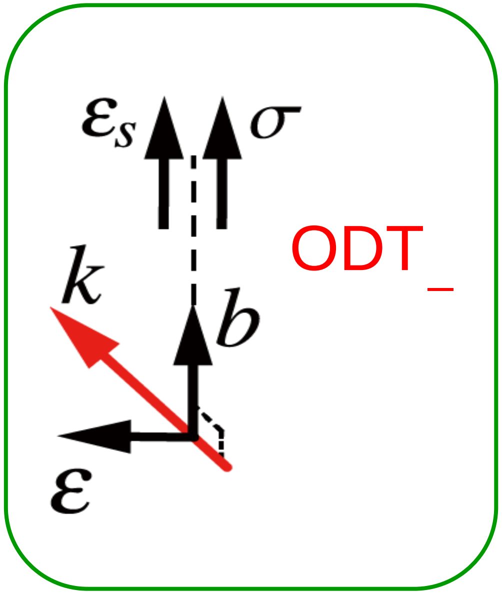




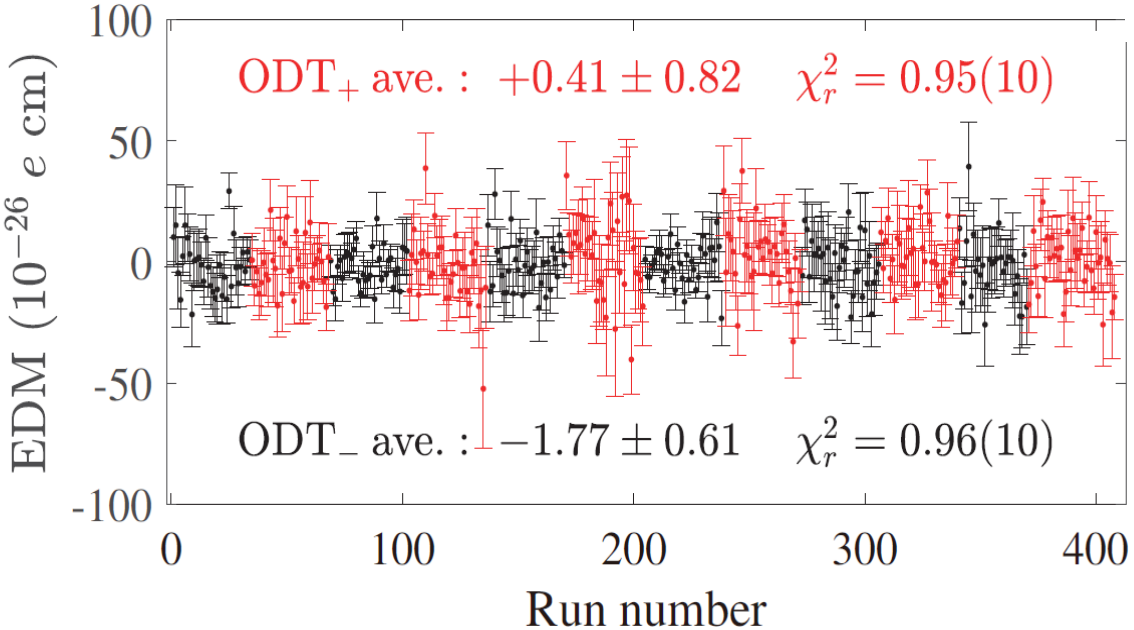
Control:

$\theta = \pi/2 \pm 80$ mrad

$(\theta_+ - \theta_-) = 0 \pm 7$ mrad

- Average between ODT+ and ODT−
- Residual parity mixing effect: 6×10^{-28} e cm
- Future: better k+ and k− balance in an optical cavity

^{171}Yb EDM measurement results



$$\delta d = \frac{\hbar}{2E\tau\sqrt{n}}\sqrt{\frac{1}{N_a\epsilon_d} + \sigma^2_{\phi(\delta B)}}$$

E: 73 kV/cm

τ: 96 s

N: 6×10^4

ϵ_d: ~50%

T : 510 h (22 d)

$$\sigma^2_{\phi(\delta B)} \approx 4 \times \frac{1}{N_a\epsilon_d}$$

$$d(^{171}\text{Yb}) = \left(-6.8 \pm 5.1_{\text{stat}} \pm 1.2_{\text{syst}}\right) \times 10^{-27} \text{ e cm}$$

Upper limit (95%) : $|d(^{171}\text{Yb})| < 1.5 \times 10^{-26}$ e cm

Measurement of the EDM of ^{171}Yb atoms in an ODT
T.A. Zheng *et al.*, Phys. Rev. Lett. 129, 083001 (2022)

Upper limits on Schiff moments

Diamagnetic system	$^{205}Tl^{19}F$	^{199}Hg	^{129}Xe	^{225}Ra	^{171}Yb
Upper limit of EDM (E-26 e cm)	6500 [Yale-1991]	7.4×10^{-4} [U of Washington-2016]	0.14 [PTB-2019]	1400 [Argonne-2016]	1.5 [USTC-2022]
Upper limit of Schiff moment (e fm^3)* 10^{10}	8.8	2.6×10^{-3}	5.2	1700	7.9
Calculation of Schiff moment (e fm^3)* 10^8	$1.2\,\eta_{pp} - 1.4\,\eta_{pn}$ [Flambaum-86]	$-1.4\,\eta_{np}$ [Flambaum-86]	$1.75\,\eta_{np}$ [Flambaum-86]	$300\,\eta_n$, $1100\,\eta$ [Flambaum-03, Auerbach-96]	$\sim -1.4\,\eta_{np}$ [Dzuba-07]

- The first ^{171}Yb EDM result contributes to constraining BSM physics: on the same order of as ^{129}Xe, ^{225}Ra, ^{205}Tl^{19}F, although lagging ^{199}Hg.
- The global analysis of EDM results requires different systems with complementary sensitivities to BSM parameters, rather than ^{199}Hg alone.

Outlook #1

Upgrade: ^{171}Yb EDM precision improves into E-28 e-cm

- ❖ Larger E-field
- ❖ Longer trap lifetime
- ❖ Less B-field noise
- ❖ Optical cavity

E-field

- This work: 73 kV/cm, copper electrodes
- Test setup: 200 kV/cm, copper
- Other works: 500 kV/cm, niobium - Ready, et al. NIM A (2021)

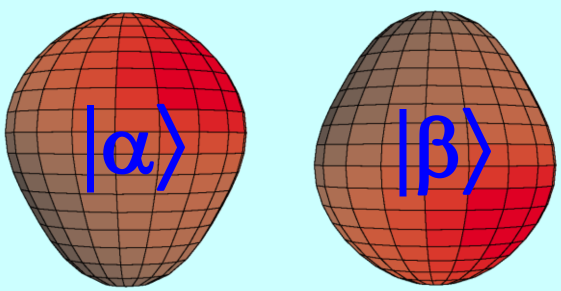
B-field

- This work: ~ 3 pT over 100 s, Seebeck effect due to ODT heating
- Environmental noise: ~ 1 pT, use magnetometers
- Johnson noise: ~ 0.6 pT, use co-magnetometer (^{173}Yb)

EDM of ^{225}Ra enhanced and more reliably calculated

- Closely spaced parity doublet – Haxton & Henley, PRL (1983)
- Large Schiff moment due to octupole deformation – Auerbach, Flambaum & Spevak, PRL (1996)
- Relativistic atomic structure (^{225}Ra / ^{199}Hg ~ 3) – Dzuba, Flambaum, Ginges, Kozlov, PRA (2002)

Parity doublet



$$\Psi^{-} = (|\alpha\rangle - |\beta\rangle)/\sqrt{2}$$

55 keV

$$\Psi^{+} = (|\alpha\rangle + |\beta\rangle)/\sqrt{2}$$

$$Schiff\_moment = \sum_{i \neq 0} \frac{\langle \psi_0 | \hat{S}_z | \psi_i \rangle \langle \psi_i | \hat{H}_{PT} | \psi_0 \rangle}{E_0 - E_i} + c.c.$$

Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

	Isoscalar	Isovector
Skyrme SIII	300	4000
Skyrme SkM*	300	2000
Skyrme SLy4	700	8000

Schiff moment of ^{225}Ra, Dobaczewski, Engel, PRL (2005)
Schiff moment of ^{199}Hg, Dobaczewski, Engel *et al*., PRC (2010)

"[Nuclear structure] calculations in Ra are almost certainly more reliable than those in Hg."

– Engel, Ramsey-Musolf, van Kolck, Prog. Part. Nucl. Phys. (2013)

Constraining parameters in a global EDM analysis.

– Chupp, Ramsey-Musolf, arXiv1407.1064 (2014)

Outlook #2

^{171}Yb

2-electron system

Nuclear spin I = ½

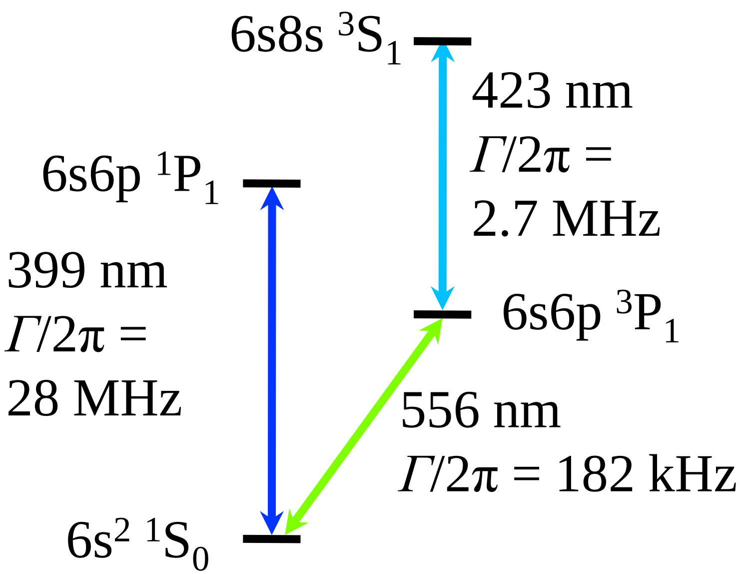
Stable and abundant

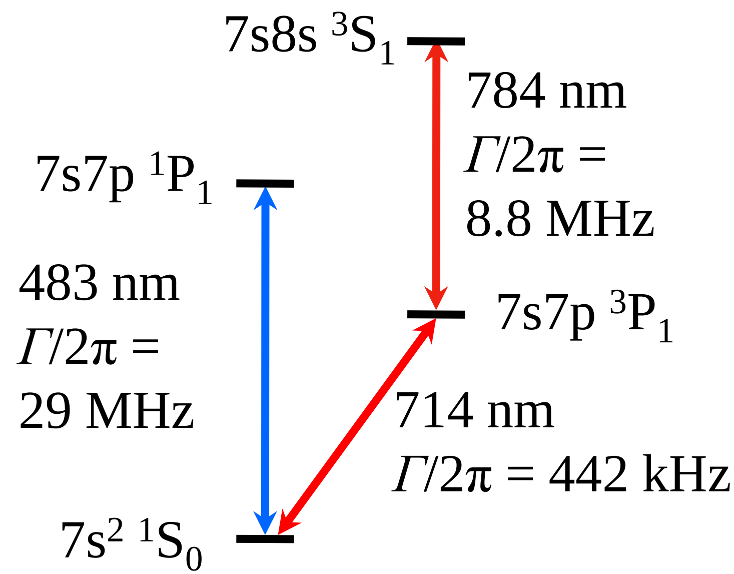
^{225}Ra:

Group II

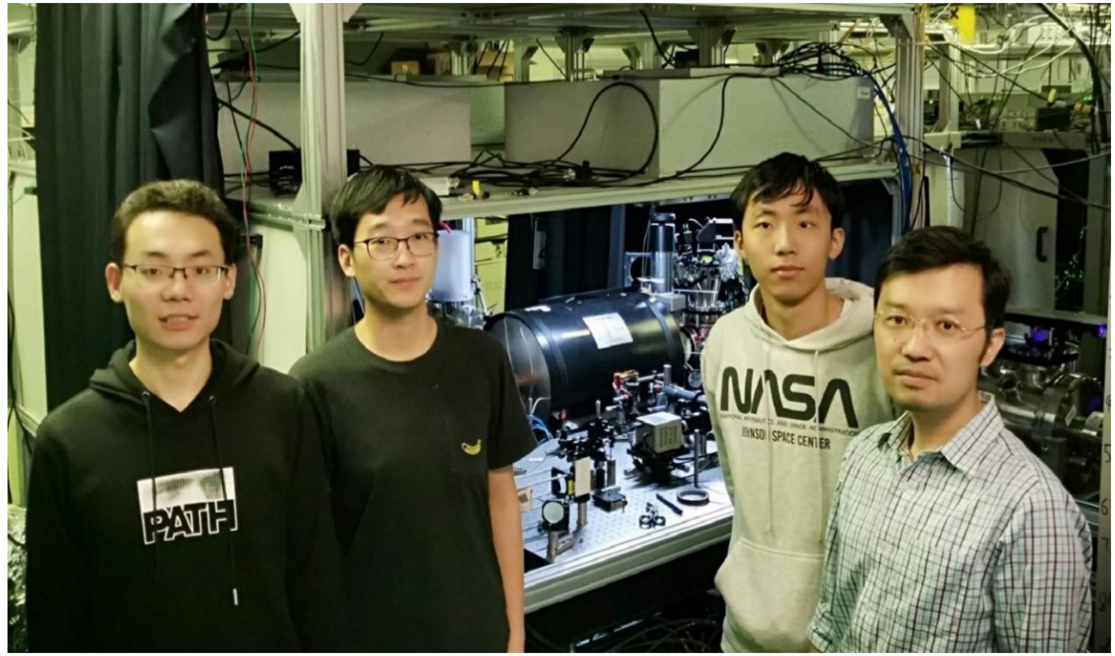
Nuclear spin I = ½

Radioactive $t_{1/2}$ = 15 d





Collaboration and Support



USTC

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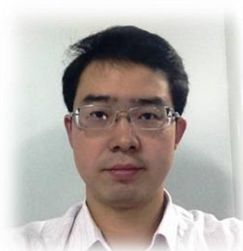

Michigan State University

Jaideep Singh

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