中国科学技术大学
University of Science and Technology of China

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

Zheng-Tian Lu

University of Science and Technology of China (USTC)
Hefei National Laboratory

創寰宇學府
育天下英才
嚴濟慈題
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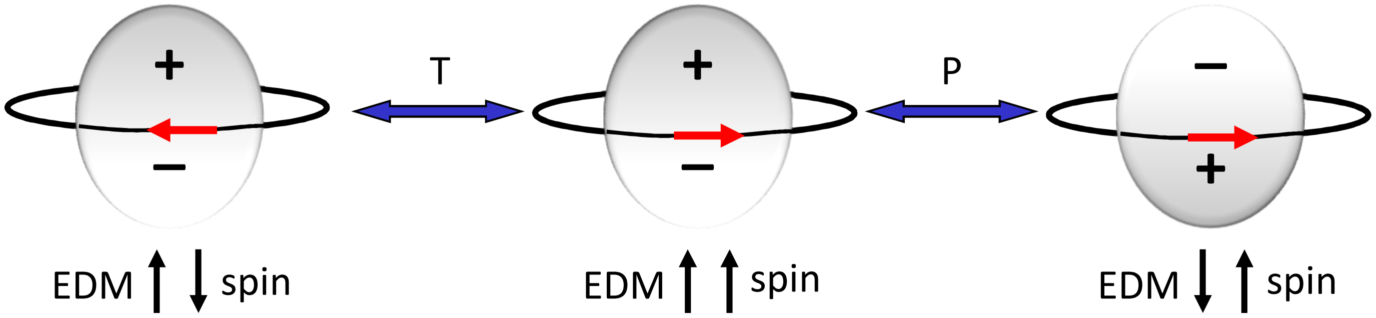
MITP workshop, Nov. 2024

Permanent EDM violates *P*-, *T*- symmetry

Induced EDM: $Energy = -\frac{1}{2}\alpha E^2$

Permanent EDM: $Energy = -d \cdot E$

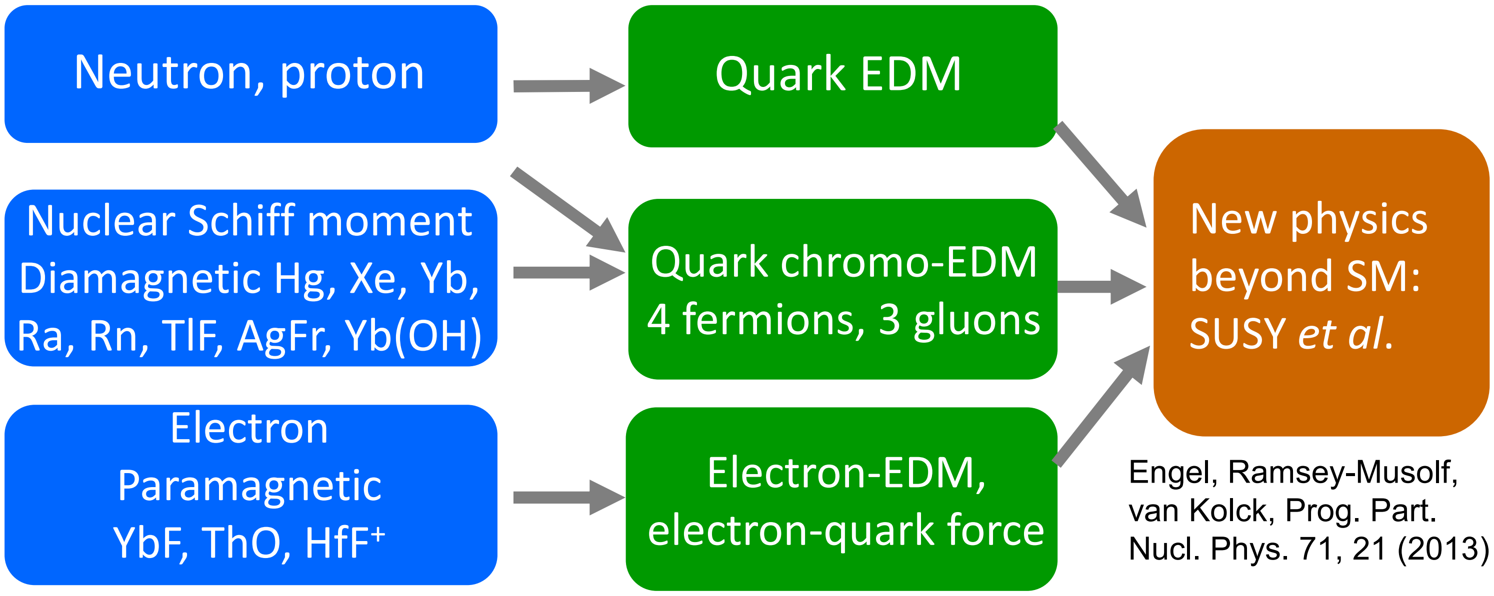


- CP problem in strong interaction: θ term

$$\mathcal{L}_{\mathrm{mass}} \to -m(\bar{\psi}_{\mathrm{L}}\psi_{\mathrm{R}} + \bar{\psi}_{\mathrm{R}}\psi_{\mathrm{L}}) + \frac{\theta g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

- SUSY: New elementary particles→ new $\cancel{CP}$ phase
- Origins of matter – antimatter asymmetry: New physical $\cancel{CP}$ mechanism

Searching for EDM in three different categories



PSI, US, Germany,
Japan, KAIST

Neutron, proton

Quark EDM

UWash, PTB,
Argonne, USTC,
CENTREX, UChicago

Nuclear Schiff moment
Diamagnetic Hg, Xe, Yb,
Ra, Rn, TlF, AgFr, Yb(OH)

Quark chromo-EDM
4 fermions, 3 gluons

ACME, JILA
Imperial college
ECNU

Electron
Paramagnetic
YbF, ThO, HfF^+

Electron-EDM,
electron-quark force

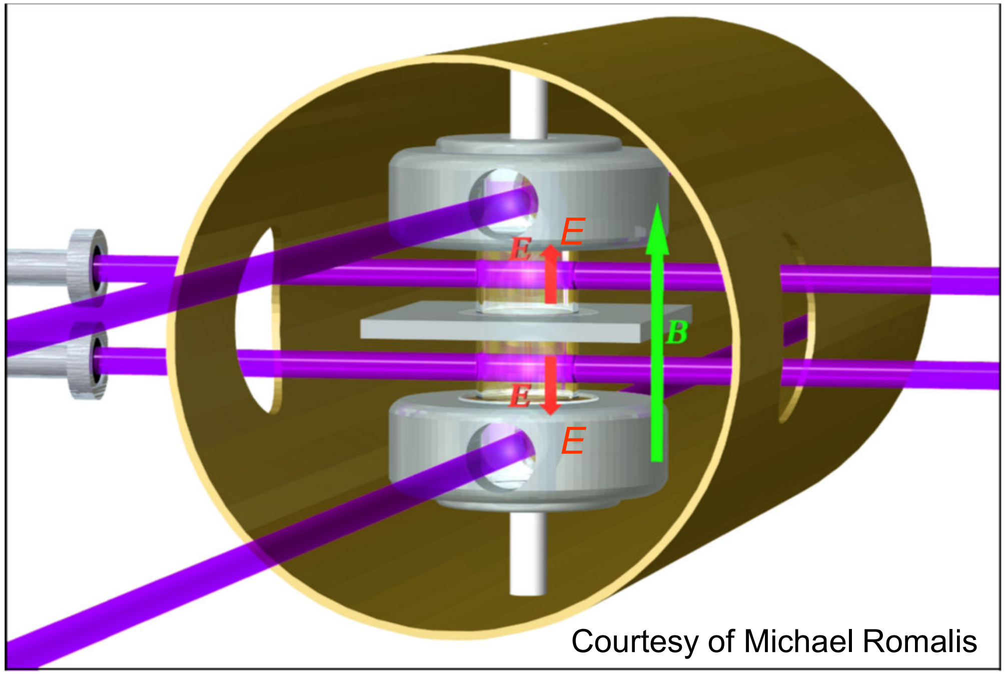
New physics
beyond SM:
SUSY *et al*.

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	4×10^{-30}	HfF^+ trap, ThO beam	10^{-35}
Neutron	2×10^{-26}	Neutrons – bottle	10^{-32}
^{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



Courtesy of Michael Romalis

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

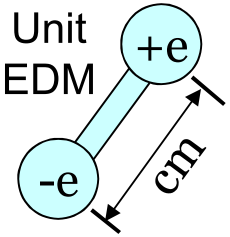
$$f_- = \frac{2\mu B - 2dE}{h} \approx 15\ \mathrm{Hz}$$

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

The best limit on atomic EDM

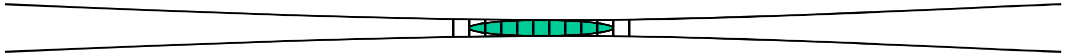
EDM (^{199}Hg) < 7 x 10^{-30} e-cm

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



Measure EDM in an Optical Dipole Trap (ODT)

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



Arthur Ashkin
2018 Nobel
Optical tweezer

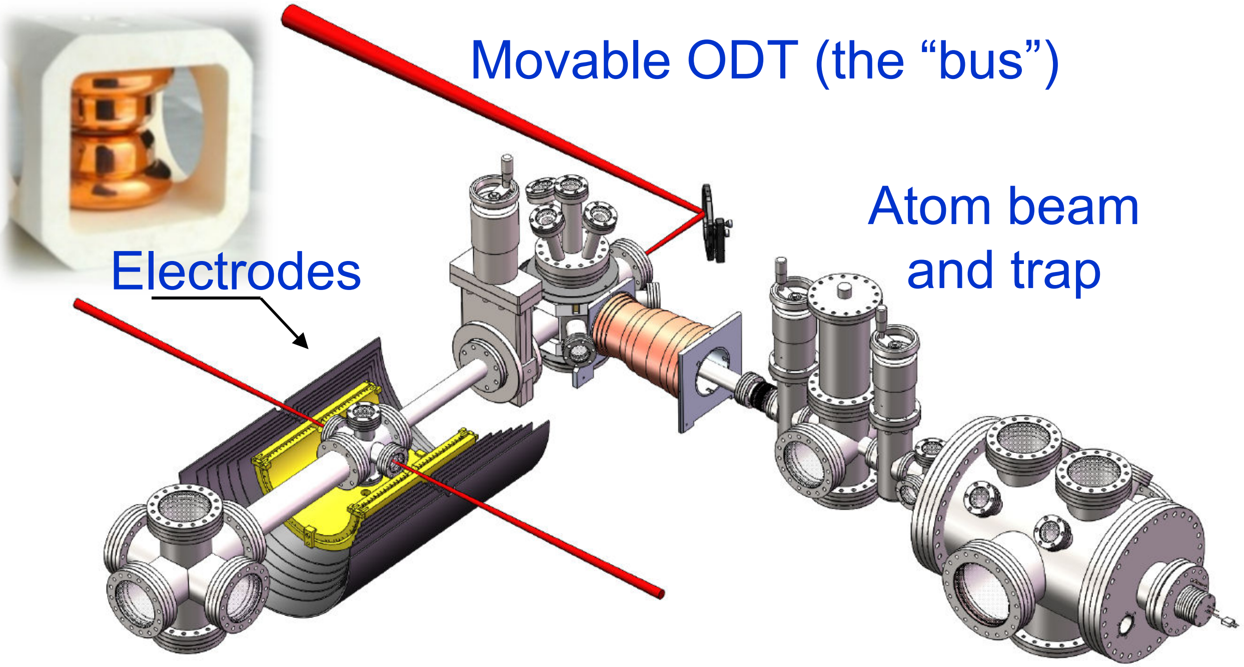
$$H = -\tilde{d}E = -\frac{1}{4}\alpha E_0^2$$

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

EDM in an optical dipole trap

- 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



Movable ODT (the “bus”)

Electrodes

Atom beam and trap

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

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

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

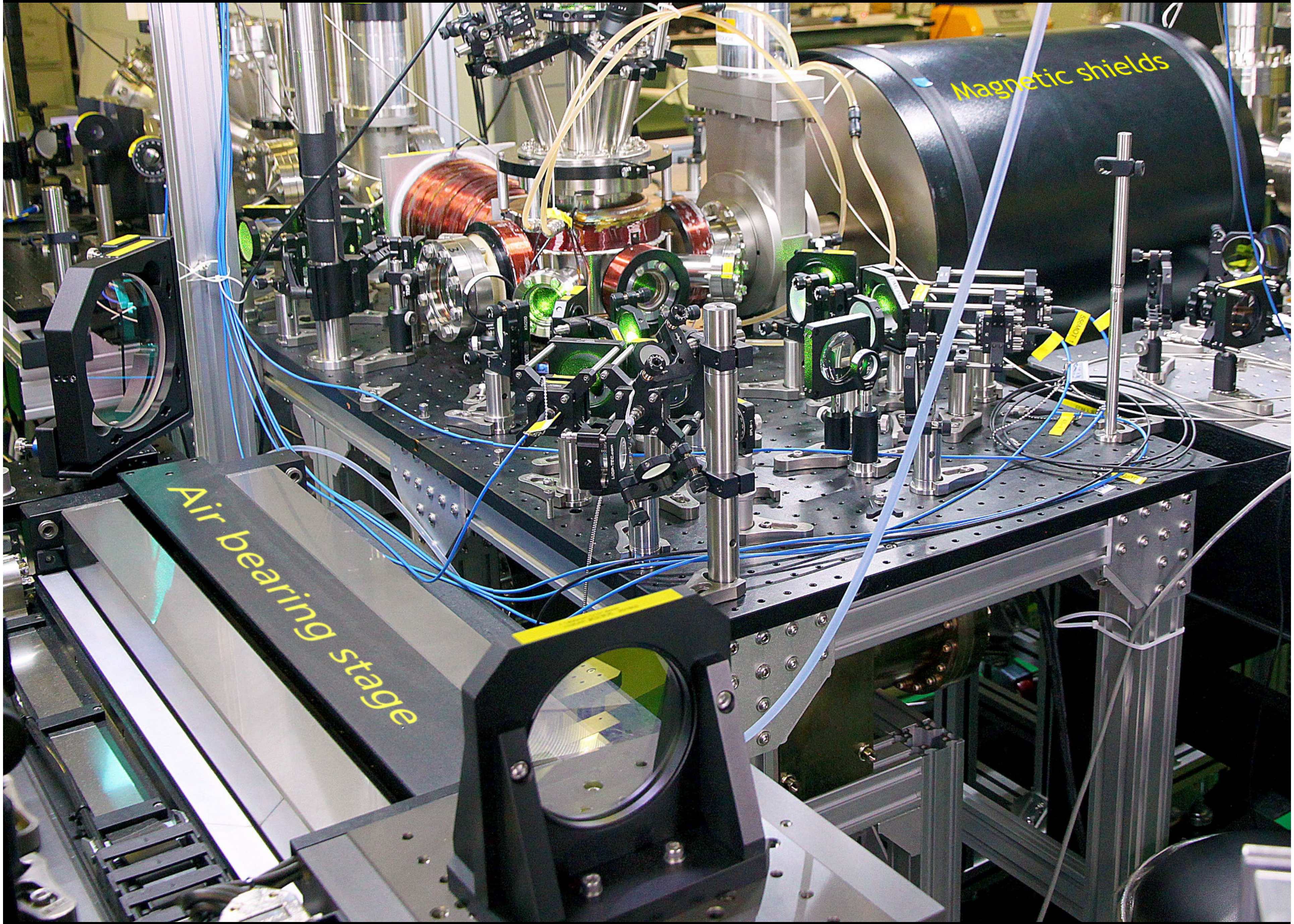
E: electric field

τ: precession time

N: atom number

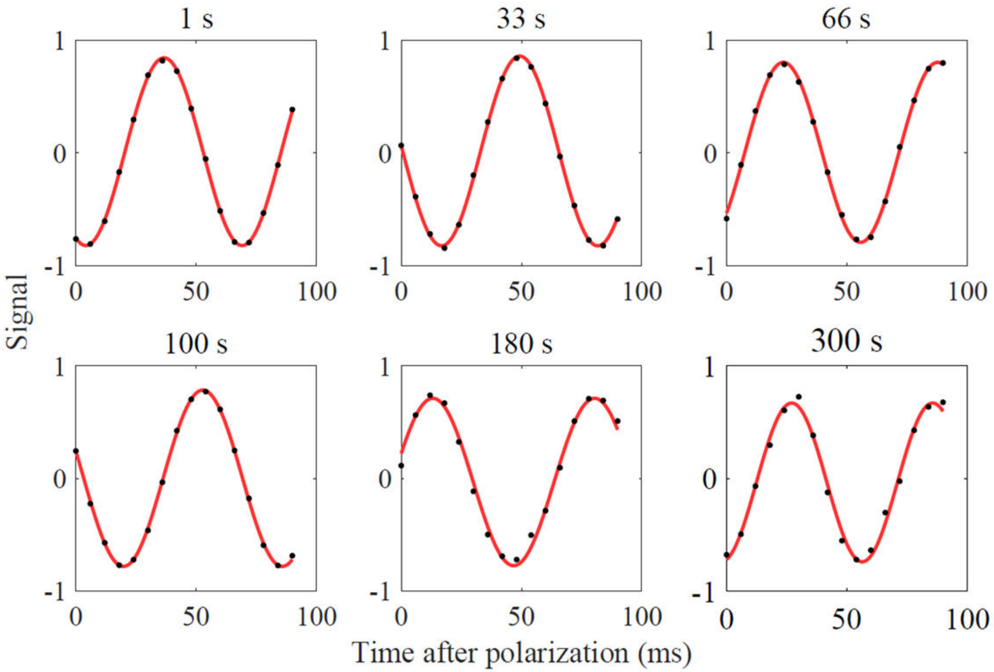
ε: spin – state detection efficiency

T : time of average


Magnetic shields
Air bearing stage

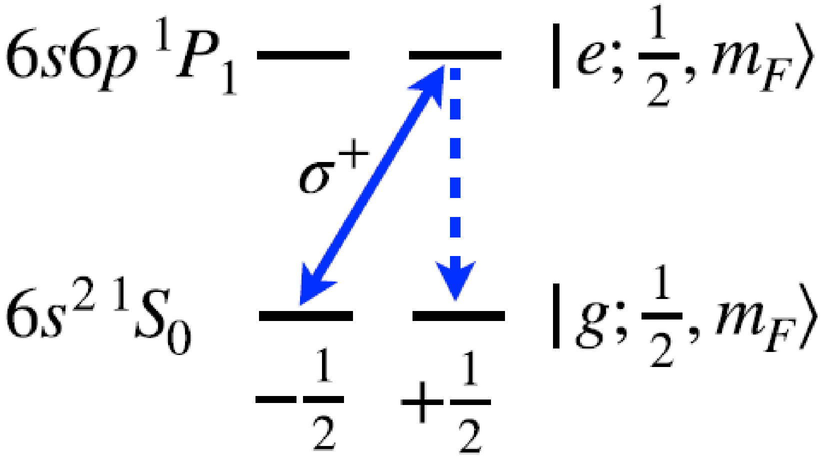
Long spin coherence time (T_2)

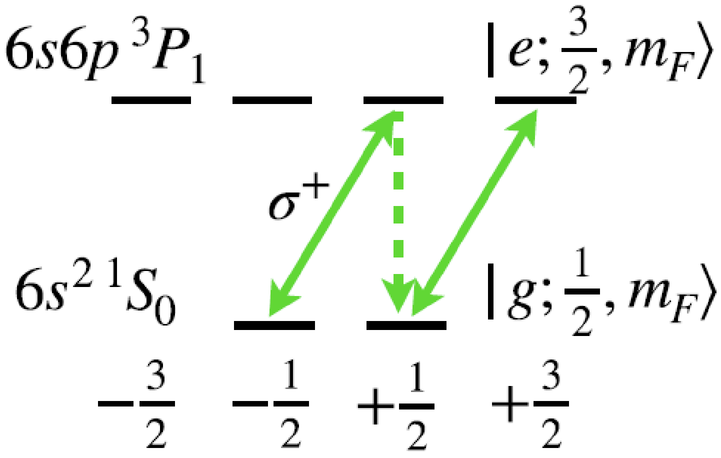
$$S_z = \frac{N_+ - N_-}{N_+ + N_-} = C\exp\left(-\frac{t}{T_2}\right)\cos(2\pi f t + \phi_0) + O$$



- 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)

Spin-state detection – conventional method





Bright state：
~ 3 photons
before state
“demolished”

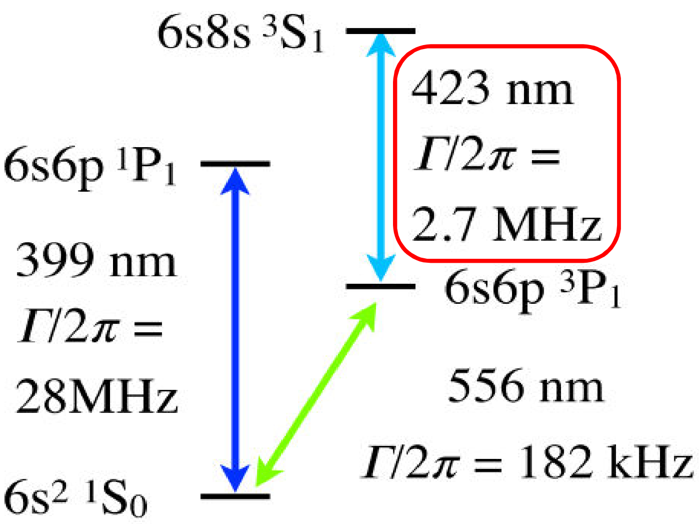
Dark state：
no photons,
state preserved

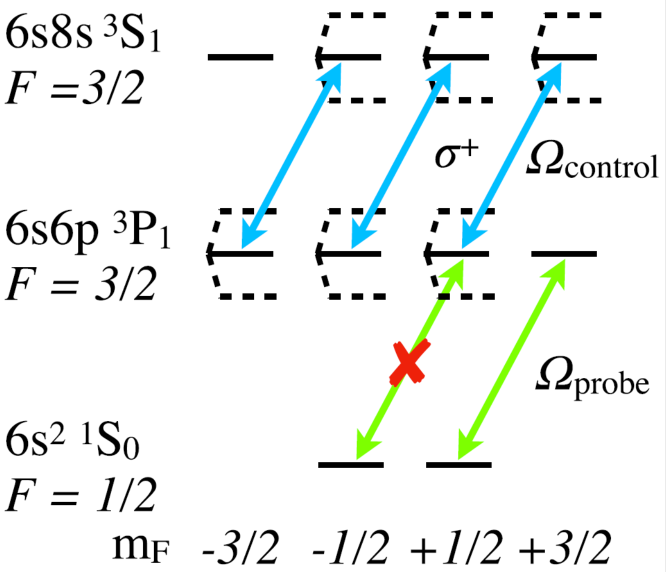
Bright state：
state
“demolished”

Brighter state:
cycling,
state preserved

Spin-state detection by a QND method

Y. Yang *et al.*, Phys Rev Applied 19, 054015 (2023)





- $\Omega_{control} \sim 2\pi \times 40MHz$
- $\Omega_{probe} \sim 2\pi \times 70kHz$
- 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,
state preserved

Spin-state detection by a QND method

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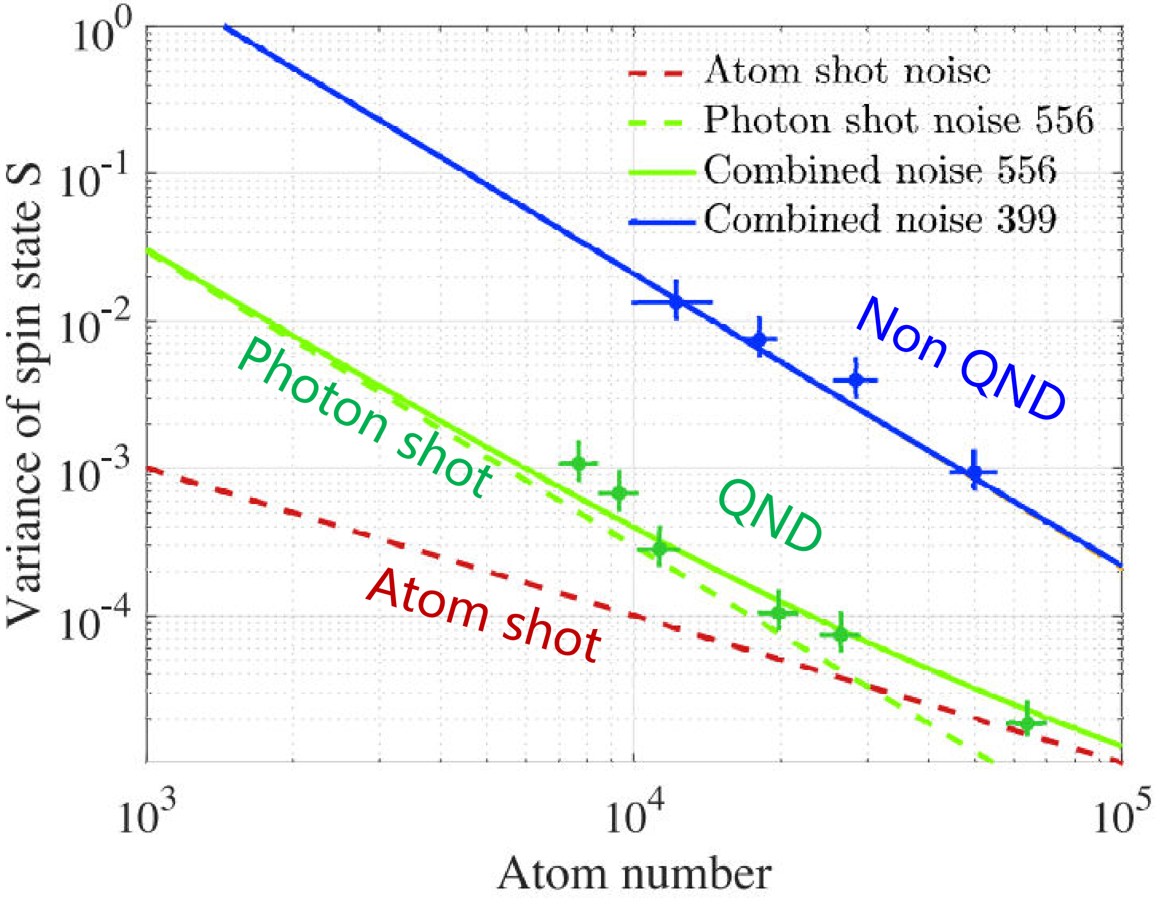


- Photons scattered non-QND: $\bar{n} \sim 2.5$ QND: $\bar{n} \sim 23$
- ~19 dB reduction of variance

Systematic errors

- effects correlated with E-field flipping

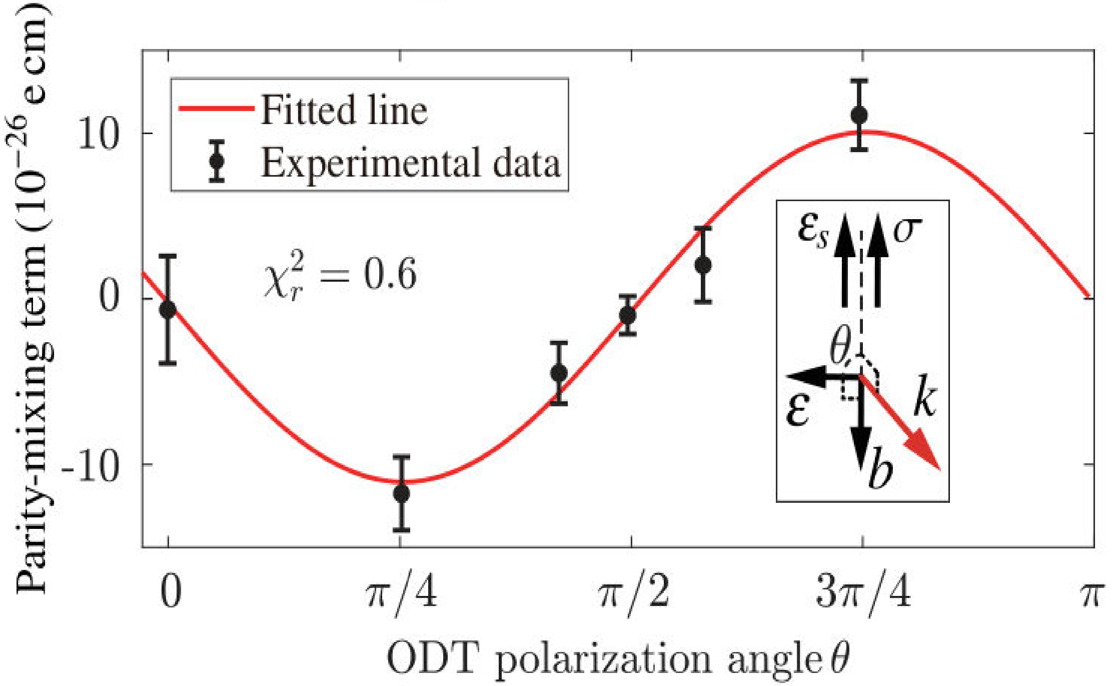
Source	Error
B-field correlations	2.5×10^{-28}
Parity mixing	2.6×10^{-28}
Leakage current	0.9×10^{-28}
ODT power effect	0.1×10^{-28}
E-squared effect	0.1×10^{-28}
Total	3.7×10^{-28}

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

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

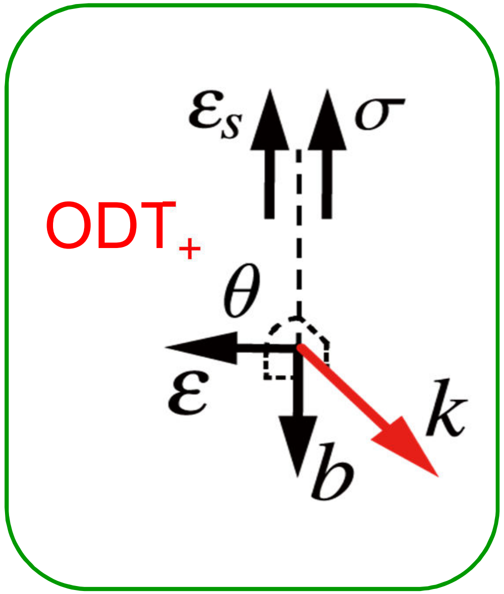
estimate : 2×10^{-25} $e\ cm$

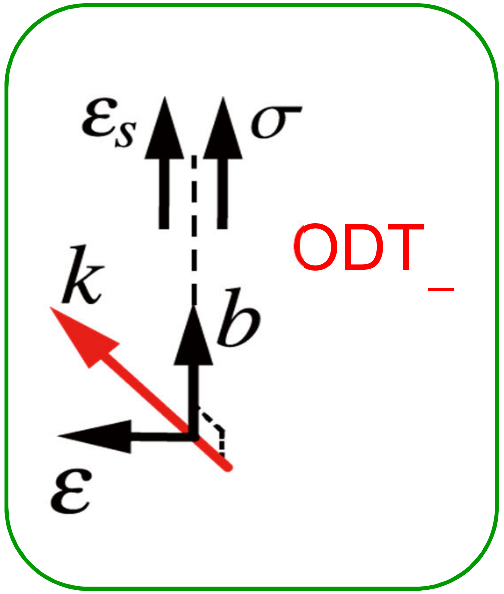
Calculation needed

Parity mixing

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

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





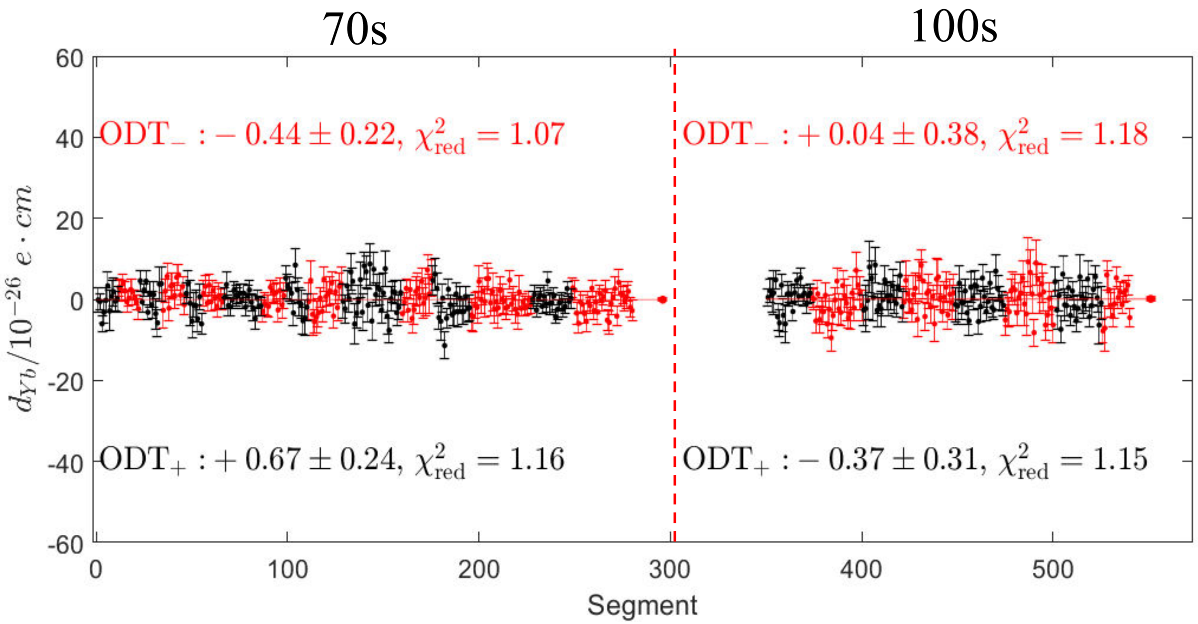
Control:

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

$(\theta_+ - \theta_-) = 0 \pm 3$ mrad

- Average between ODT+ and ODT−
- Residual parity mixing effect: 2.6×10^{-28} e cm
- Future: better k+ and k− balance in an optical cavity

^{171}Yb EDM measurement results



* Average ODT+ and ODT- to cancel parity-mixing systematic

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

E: $192\ kV/cm$

τ: $60 - 90\ s$

N: 8×104

ϵ_d: $\sim 50\%$

T : $840\ h$ (40 days)

$$\sigma^2_{\phi(\delta B)} \approx 3 \times \frac{1}{N_a\epsilon_d}$$

* B-field noise due to Seebeck effect

$$d(^{171}\mathrm{Yb}) = \left(0.3 \pm 1.4_{\mathrm{stat}} \pm 0.4_{\mathrm{syst}}\right) \times 10^{-27}\ \mathrm{e\ cm}$$

Upper limit (95%) : $|d(^{171}\mathrm{Yb})| < 2.8 \times 10^{-27}$ e cm

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

T.A. Zheng *et al.*, PRL **129**, 083001 (2022)

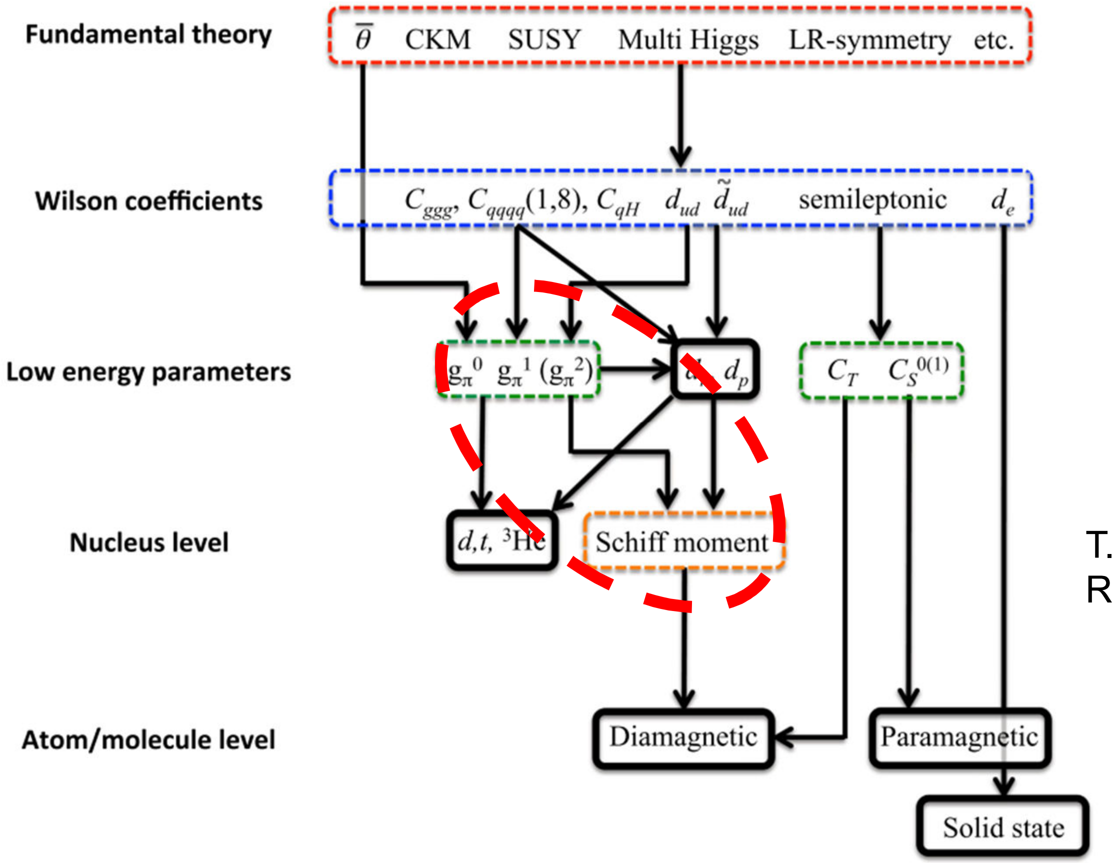
Upper limits on Schiff moments

Diamagnetic system	^{199}Hg	^{205}Tl^{19}F	^{129}Xe	^{171}Yb	^{225}Ra
EDM limit (10^{-27} e cm)	7.4×10^{-3} UWash16	6.5×10^{4} Yale91	1.4 PTB19	2.8 USTC23	1.4×10^{4} Argonne16
Schiff moment limit (10^{-10} e fm^3)	2.6×10^{-3}	1.5	5.2	1.6	1700
Schiff moment calc (10^{-8} e fm^3)	$-1.4\ \eta_{\mathrm{np}}$ Flambaum86	$1.2\ \eta_{\mathrm{pp}}$ $-\ 1.4\ \eta_{\mathrm{pn}}$ Flambaum86	$1.75\ \eta_{\mathrm{np}}$ Flambaum86	$-1.4\ \eta_{\mathrm{np}}$ Dzuba07	$300\ \eta_{\mathrm{n}},\ 1100\ \eta$ Flambaum03, Auerbach96

- First ^{171}Yb EDM result constrains BSM physics on the same order as ^{129}Xe, ^{225}Ra, ^{205}Tl^{19}F, all lagging behind ^{199}Hg.
- Global analysis needs different systems with complementary sensitivities to BSM parameters, rather than ^{199}Hg alone.

T. E. Chupp *et al.,* Rev. Mod. Phys. **91**, 015001 (2019)

Theories from CP violation to EDM



T. E. Chupp *et al.*,
RMP **91**, 015001 (2019)

Calculation of Schiff moments

- ^{199}Hg: J. H. de Jesus and J. Engel, PRC **72**, 045503 (2005)
- ^{225}Ra: J. Dobaczewski and J. Engel, PRL **94**, 232502 (2005)
- ^{171}Yb: nuclear calculation needed !

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

- 2024 setup: 300 kV/cm, copper
- Other works: 500 kV/cm, niobium - Ready *et al*. NIM A (2021)

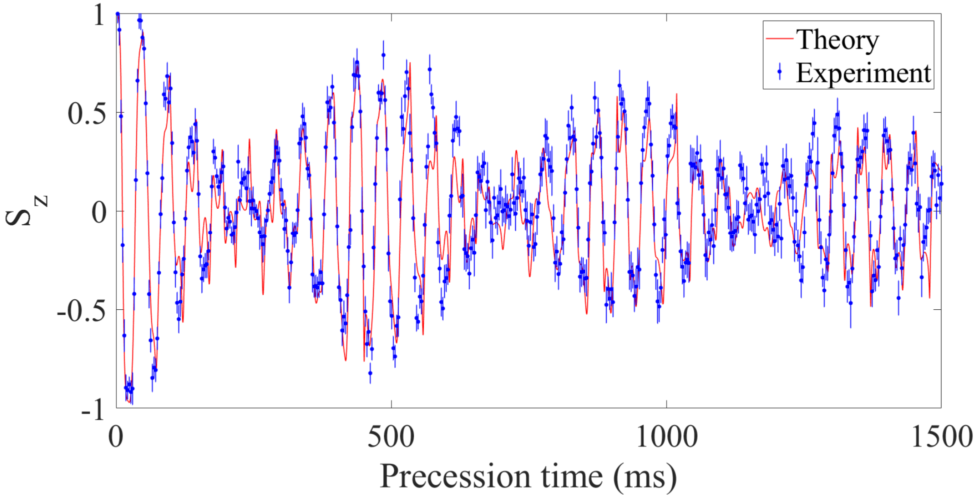
B-field

- 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)

^{173}Yb (I = 5/2) co-magnetometer

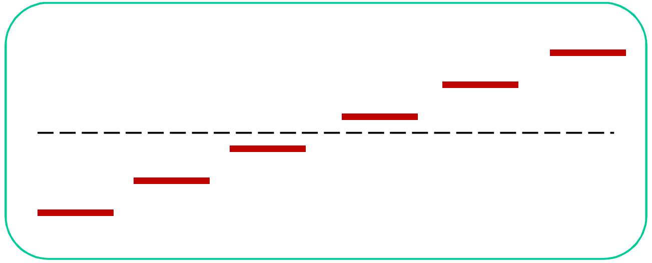
Prepare initial state: $|+5/2\rangle_x = \frac{1}{\sqrt{32}}\begin{pmatrix}1 & \sqrt{5} & \sqrt{10} & \sqrt{10} & \sqrt{5} & 1\end{pmatrix}$

Problem: decoherence due to spatially varying ODT light shift

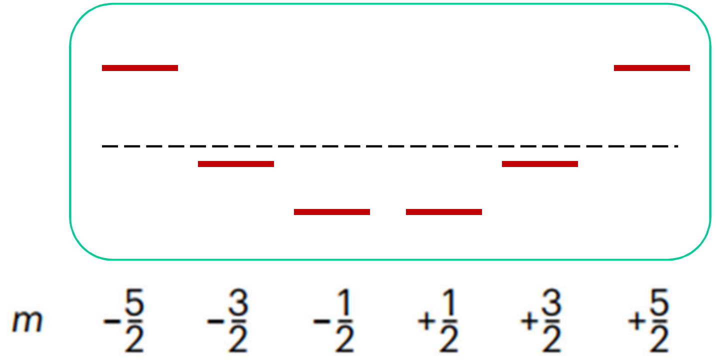


ODT tensor shift: $H_t = \Omega(\boldsymbol{r})F_z^2$

Zeeman shift F_z



Stark shift $(F_z)^2$



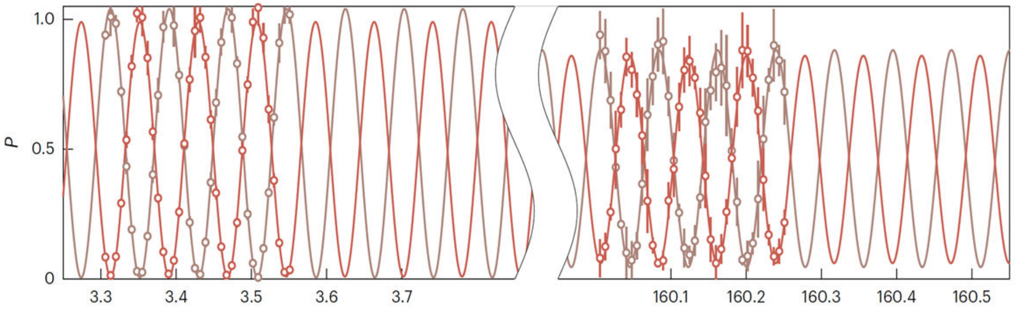
^{173}Yb (I = 5/2) co-magnetometer

$$|+5/2\rangle \xrightarrow{\pi/2} |\mathrm{Cat}\rangle = \frac{1}{\sqrt{2}}\left(\,|+5/2\rangle + |-5/2\rangle\,\right)$$

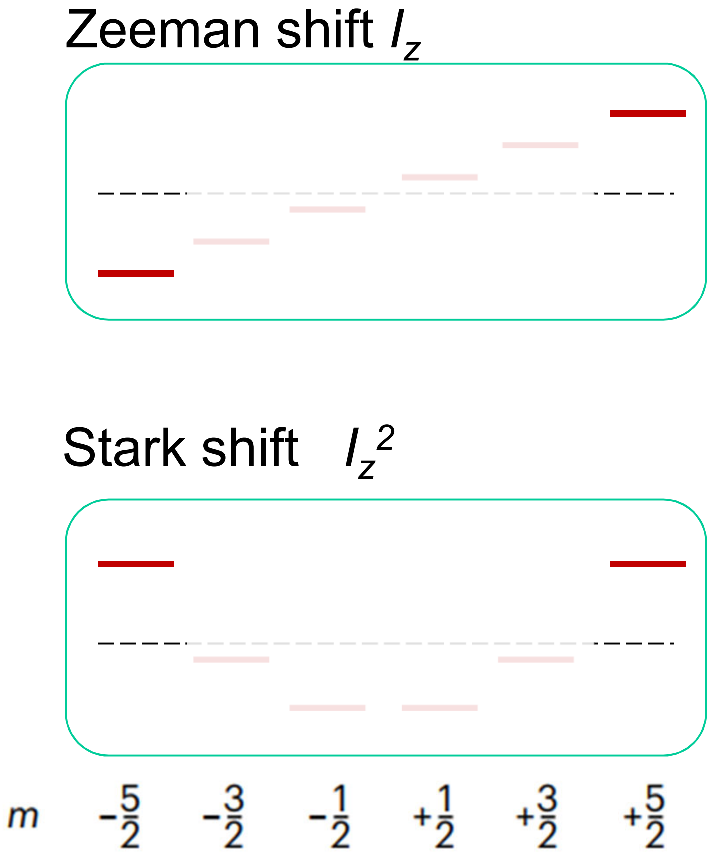
$High - spin\ {}^{\pi}/_{2}\ pulse$

$$H = \Omega(F_x - F_x^2)$$

$$t = \frac{\pi}{2\Omega} \qquad \Omega = 2\pi \cdot 0.5\ kHz$$



Coherence time ~ 1400 s



Y. Yang *et al.*, Nat. Photonics online (2024)

Outlook #2

^{171}Yb

2-electron system

Nuclear spin I = ½

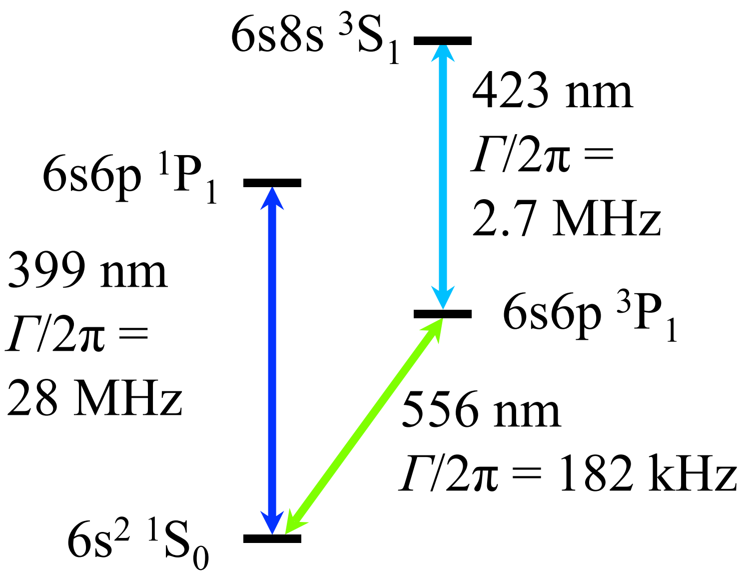
Stable and abundant

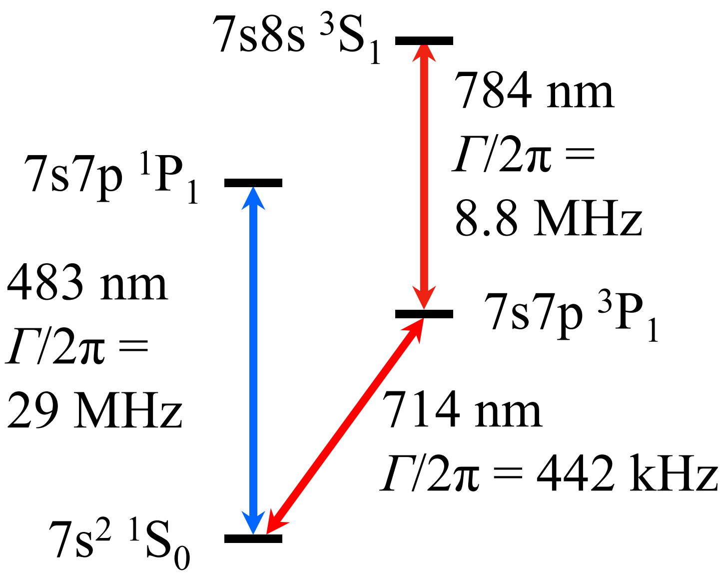
^{225}Ra:

Group II

Nuclear spin I = ½

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





^{171}Yb
E-28 e-cm

→

^{225}Ra
E-28 e-cm

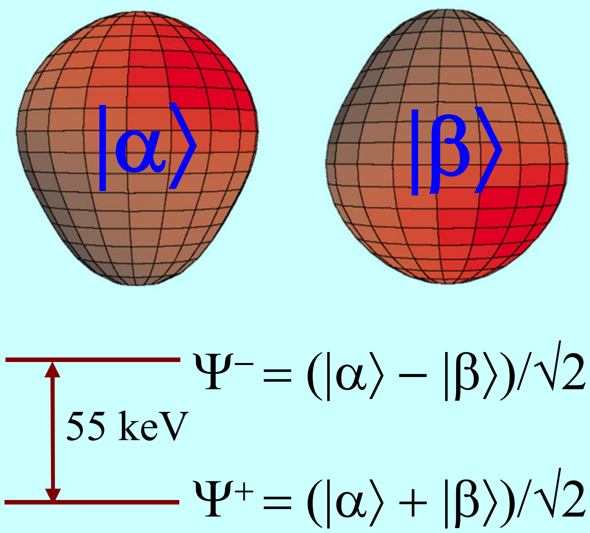
~

^{199}Hg
E-31 e-cm

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



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

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

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

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, PRC 91, 035502 (2015)

Collaboration and Support

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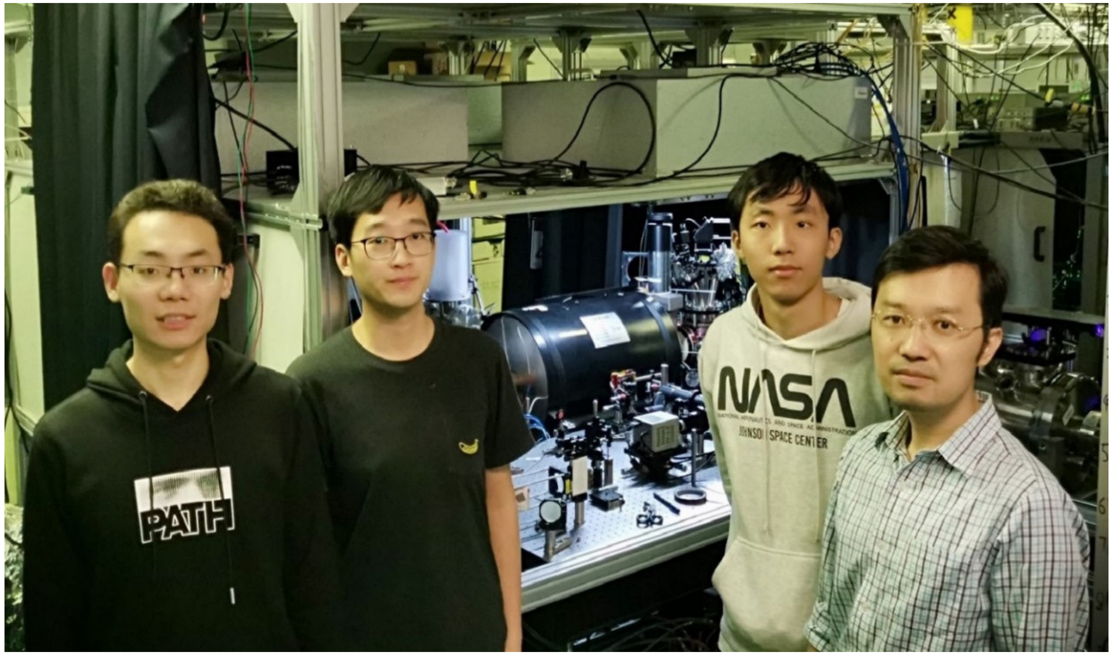

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