

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

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育天下英才
嚴濟慈
一九八八年五月

Stored Ions for Precision Measurements, Nov. 2023

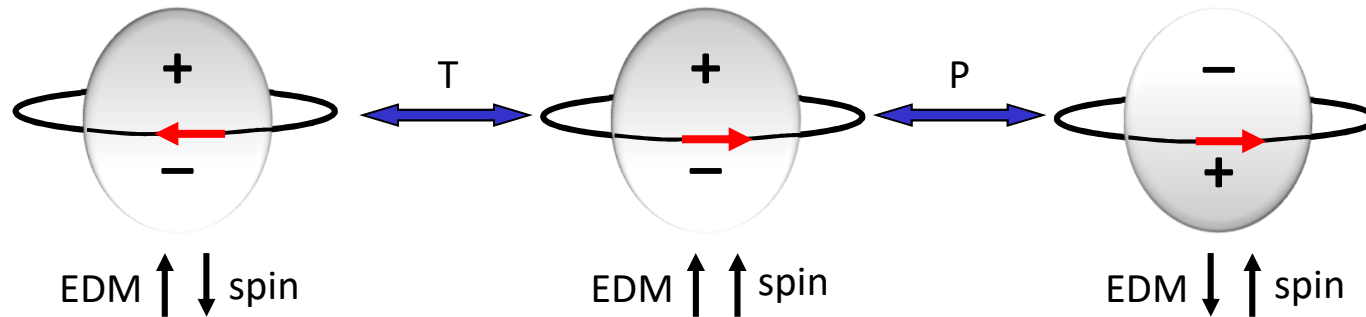


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University of Science and Technology of China

Permanent EDM violates P -, T - symmetry

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

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

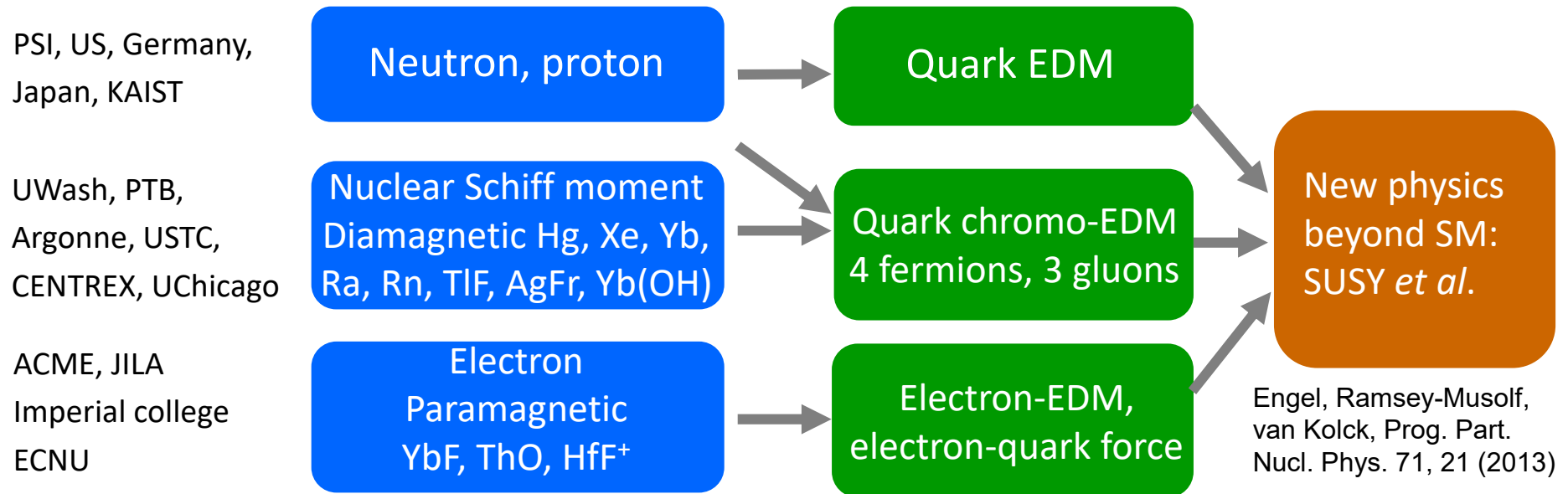


- CP problem in strong interaction: θ term

$$\mathcal{L}_{mass} \rightarrow -m(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L) + \frac{\theta g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

- SUSY: New elementary particles $\rightarrow$ new ~~CP~~ phase
- Origins of matter – antimatter asymmetry: New physical ~~CP~~ mechanism

Searching for EDM in three different categories



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}

Standard Model Prediction for Paramagnetic eEDM

Yohei Ema, Ting Gao, Maxim Pospelov, PRL **129**, 231801 (2022)

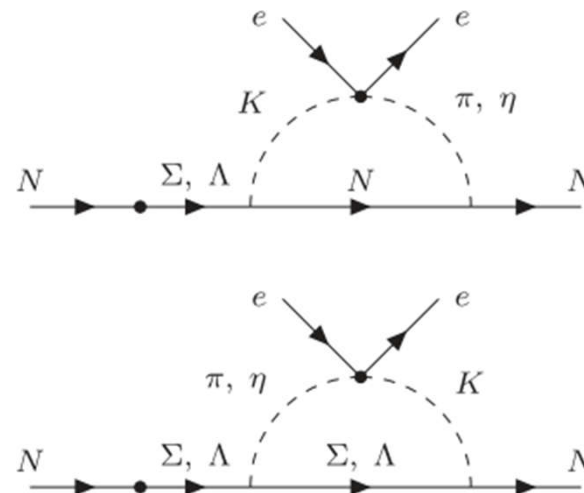
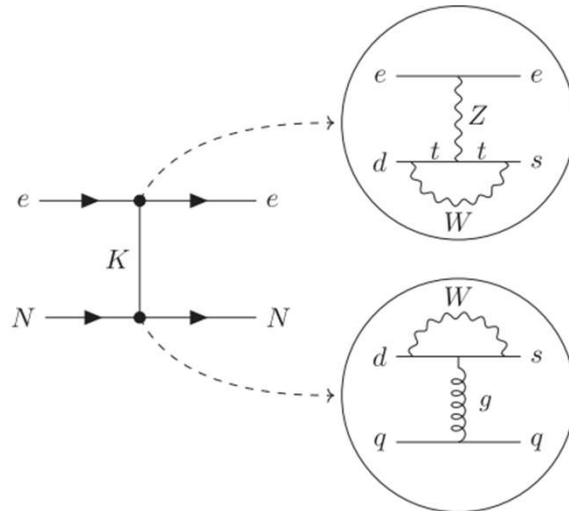
$$d_e^{\text{equiv}} = d_e + C_S \times 1.5 \times 10^{-20} \text{ e cm}$$

bare electron

10^{-38}

10^{-35}

Spin-dependent interaction
in heavy atoms and molecules

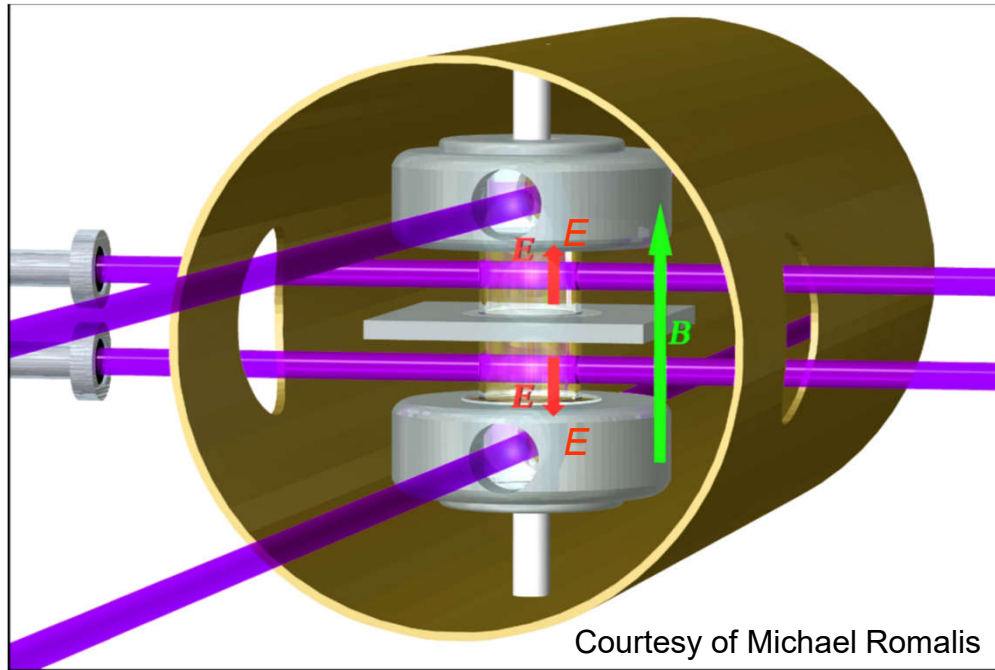


CP violation via CKM matrix mechanism

The Seattle EDM Measurement

¹⁹⁹Hg

stable, high Z, groundstate 1S_0 , $I = 1/2$, high vapor pressure



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

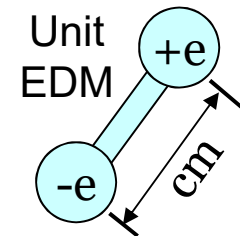
$$f_- = \frac{2\mu B - 2dE}{h} \approx 15 \text{ Hz}$$

$$|f_+ - f_-| < 25 \text{ pHz}$$

The best limit on atomic EDM

$$\text{EDM } (^{199}\text{Hg}) < 7 \times 10^{-30} \text{ e-cm}$$

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)



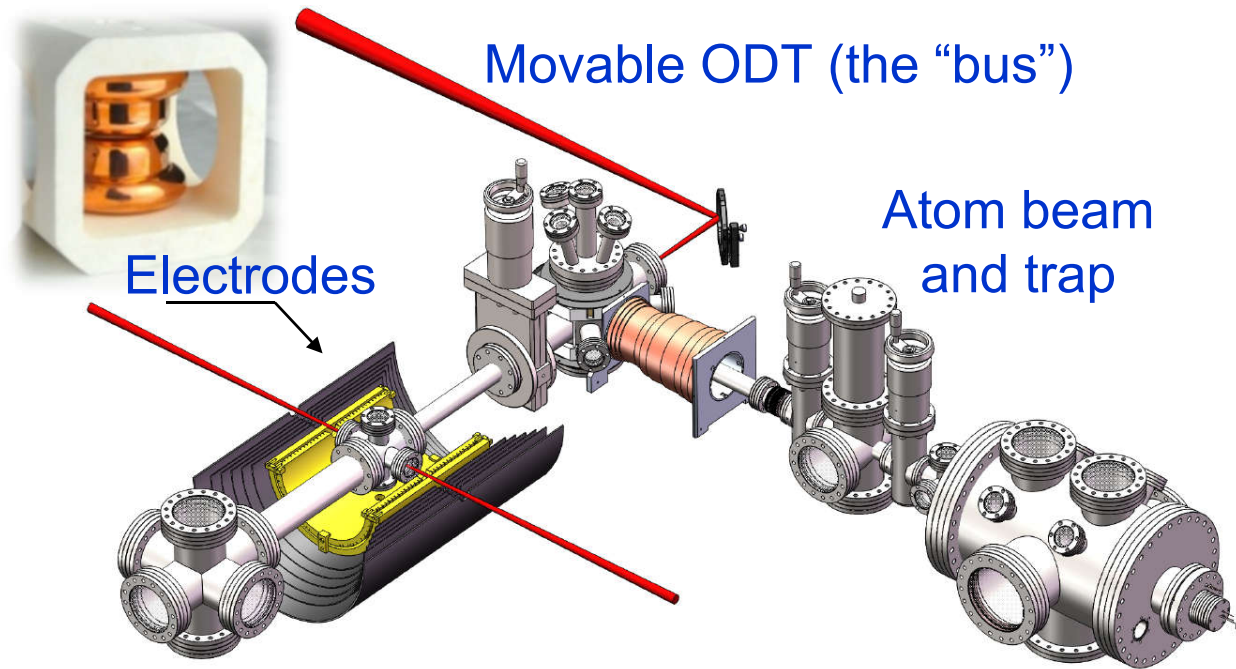
$$H = -\tilde{d}E = -\frac{1}{4}\alpha E_0^2$$

- Fiber laser: $\lambda = 1036 \text{ nm}$, Power = 10 Watts
- Focused to $50 \mu\text{m}$ $\rightarrow$ trap depth $60 \mu\text{K}$

EDM in an optical dipole trap (ODT)

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

^{171}Yb EDM Apparatus: Trapping + Science



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

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

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

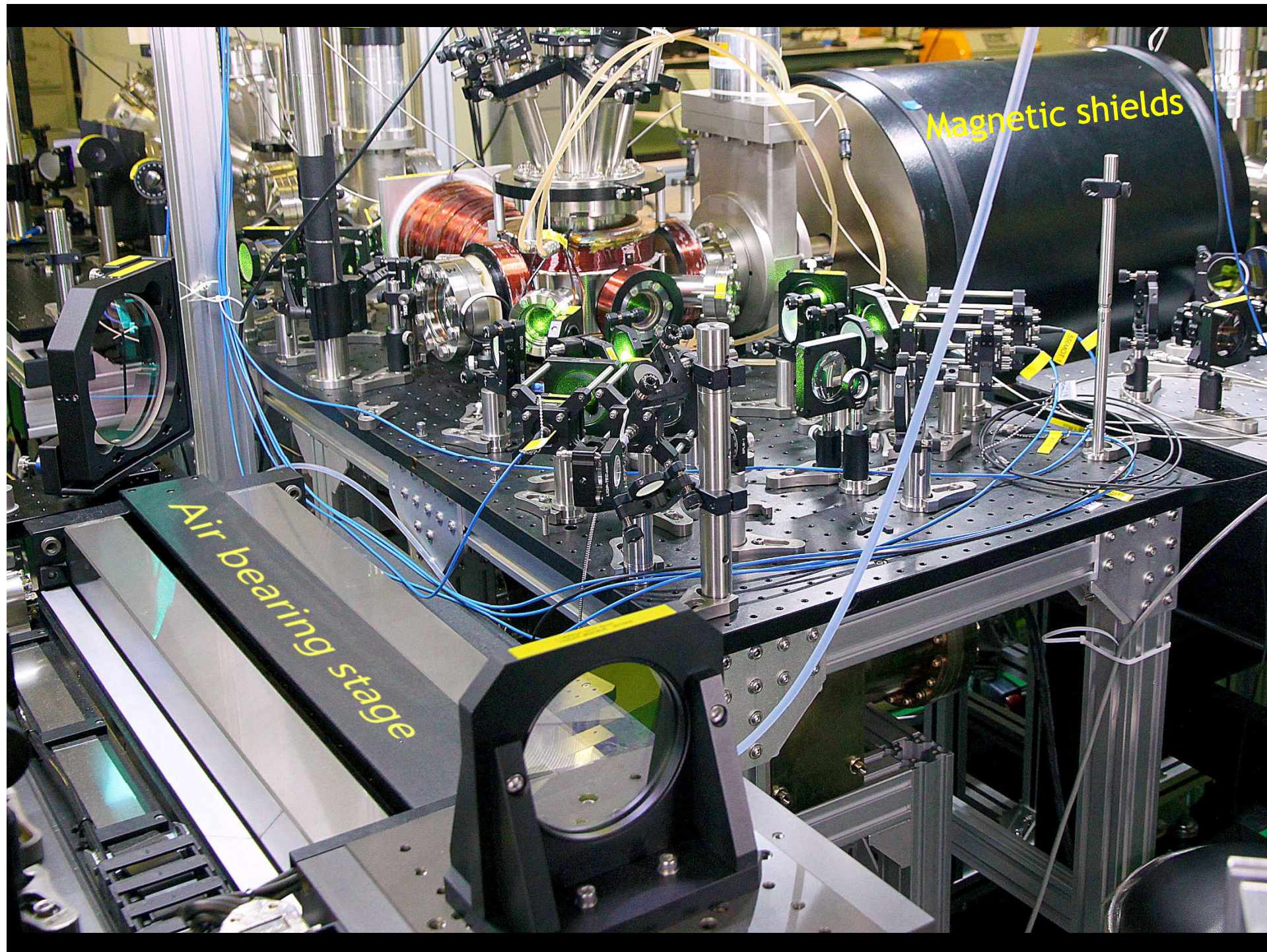
E : electric field

τ : precession time

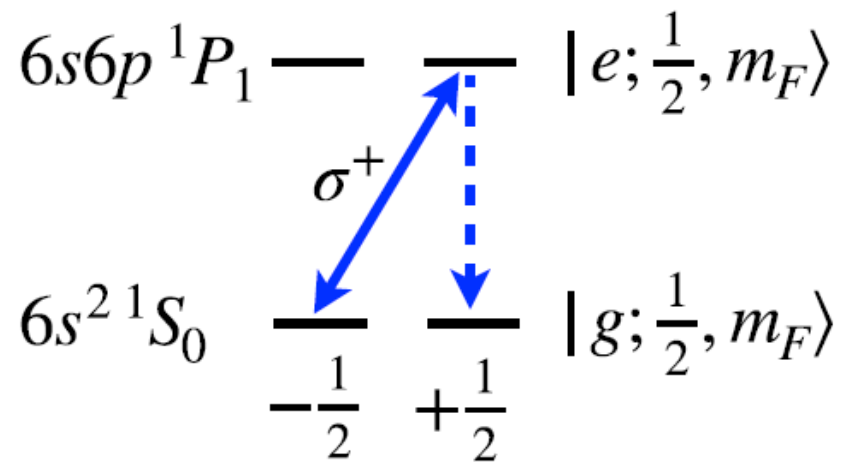
N : atom number

ε : spin – state detection efficiency

T : time of average

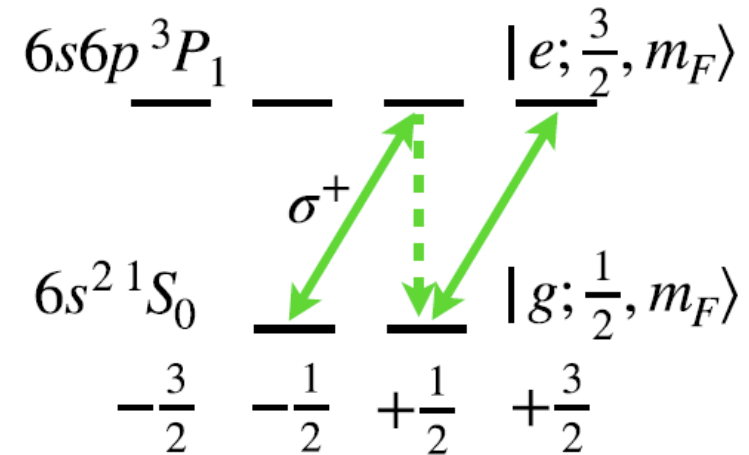


Spin-state detection – conventional method



Bright state:
~ 3 photons
before state
“demolished”

Dark state:
no photons,
state preserved

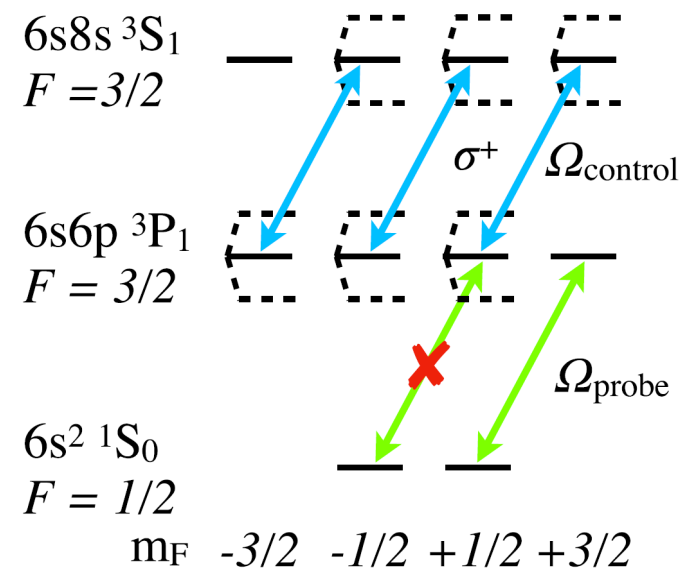
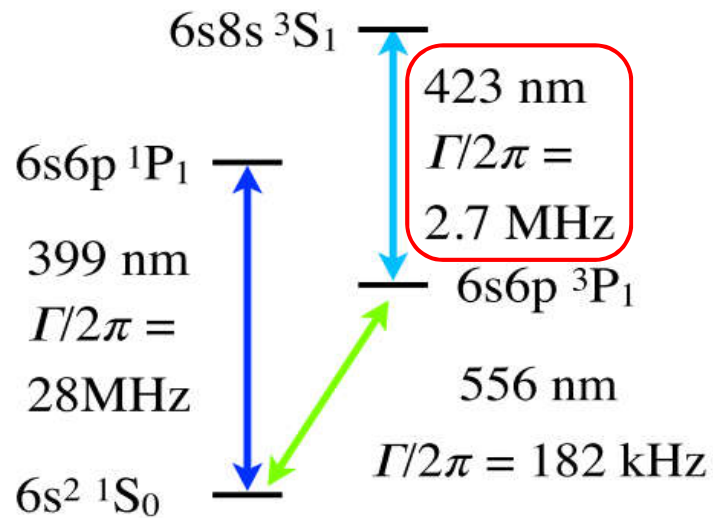


Bright state:
state
“demolished”

Brighter state:
cycling,
state preserved

Spin-state detection by a QND method

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



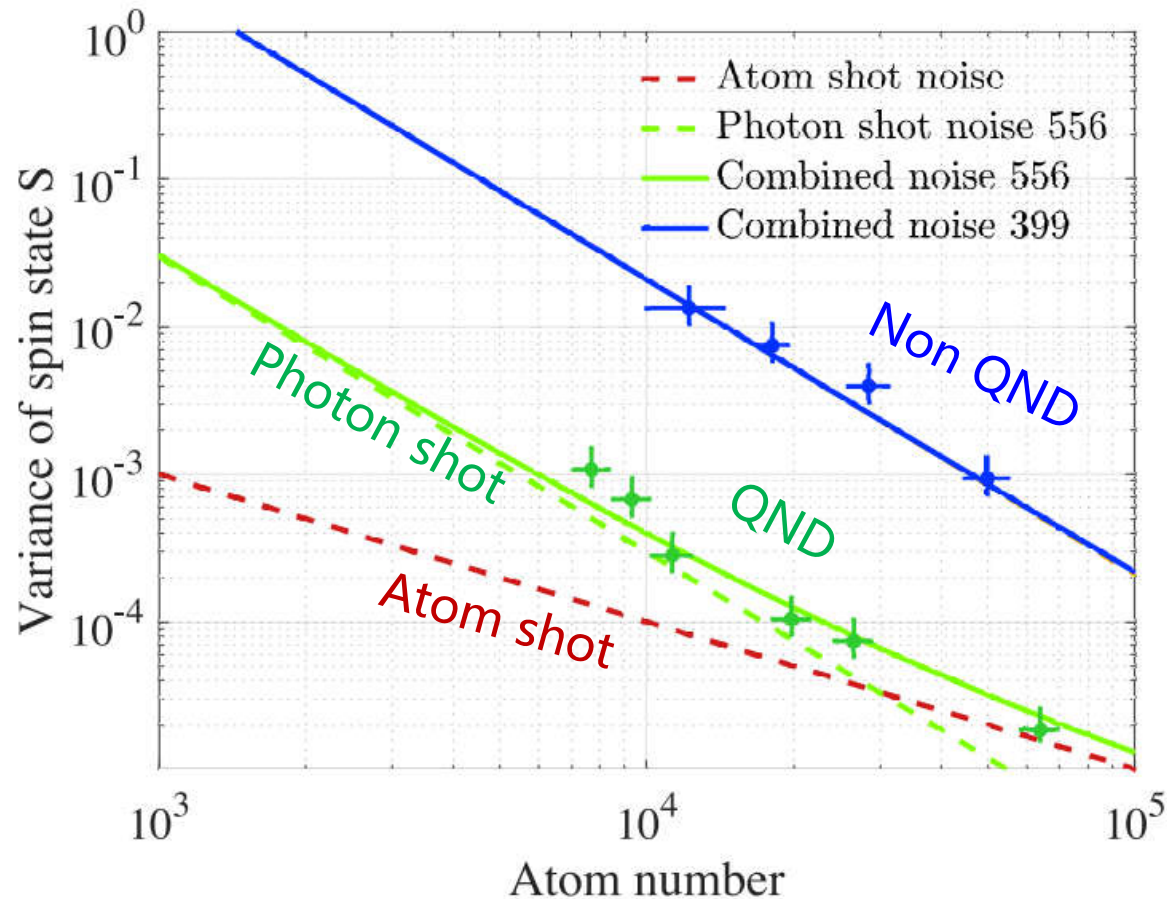
- $\Omega_{\text{control}} \sim 2\pi \times 40\text{ MHz}$
- $\Omega_{\text{probe}} \sim 2\pi \times 70\text{ kHz}$
- Spin flip suppressed by: $\Omega_c^2/(\Gamma_e \Gamma_c) \sim 10^3$
- Need ODT to be at magic wavelength
-- T. Zheng, M.S. Safronova *et al.*, PRA (2020)

Dark state:
no photons,
state preserved

Bright state:
cycling,
state preserved

Spin-state detection by a QND method

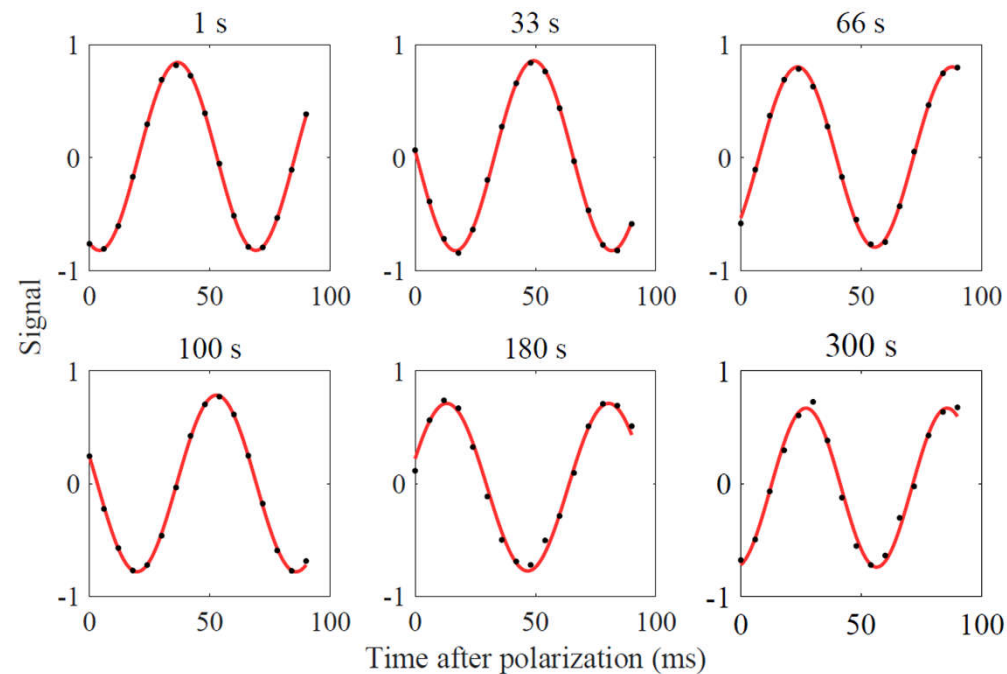
Yang *et al.*, Phys Rev Applied 19, 054015 (2023)



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

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 : $(9 \pm 4) \times 10^3$ s (2.5 ± 1.1 hr)

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}

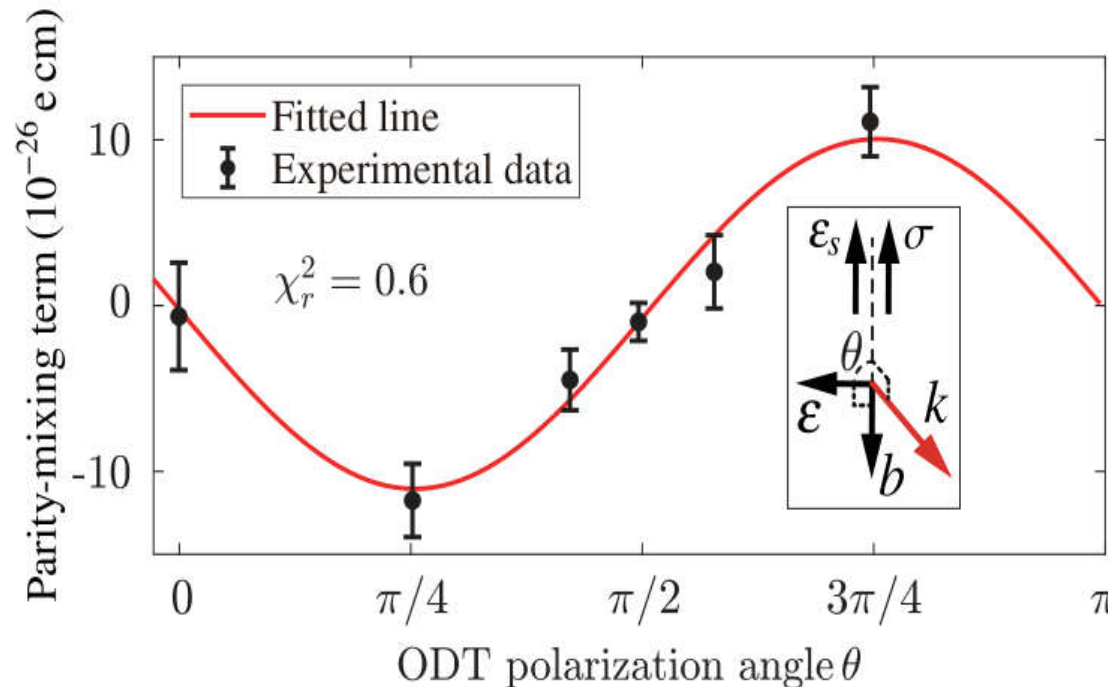
Parity mixing

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

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

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

T-even, P-even
yet EDM-like



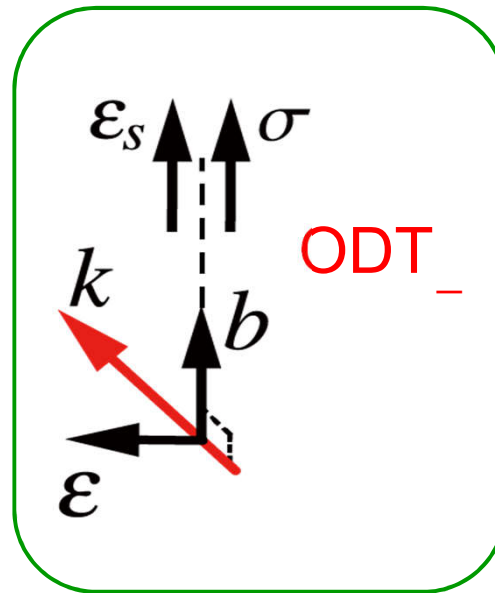
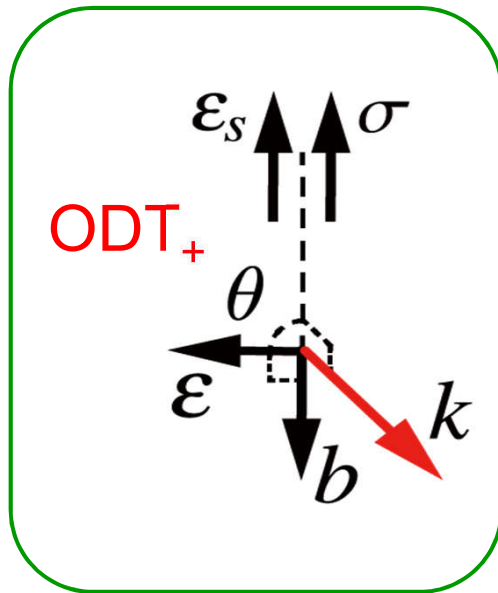
ϵ : ac E-field of ODT
 b : ac B-field of ODT
 ϵ_s : Static E-field
 σ : Quantization axis
 Static B-field

measurement : $1.2(2) \times 10^{-25} \text{ e cm}$ ($\epsilon \cdot \epsilon_s = \epsilon \cdot \sigma = \sqrt{2}/2$)
 calculation : $2 \times 10^{-25} \text{ e cm}$ ($\epsilon \cdot \epsilon_s = \epsilon \cdot \sigma = \sqrt{2}/2$)

Parity mixing

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

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



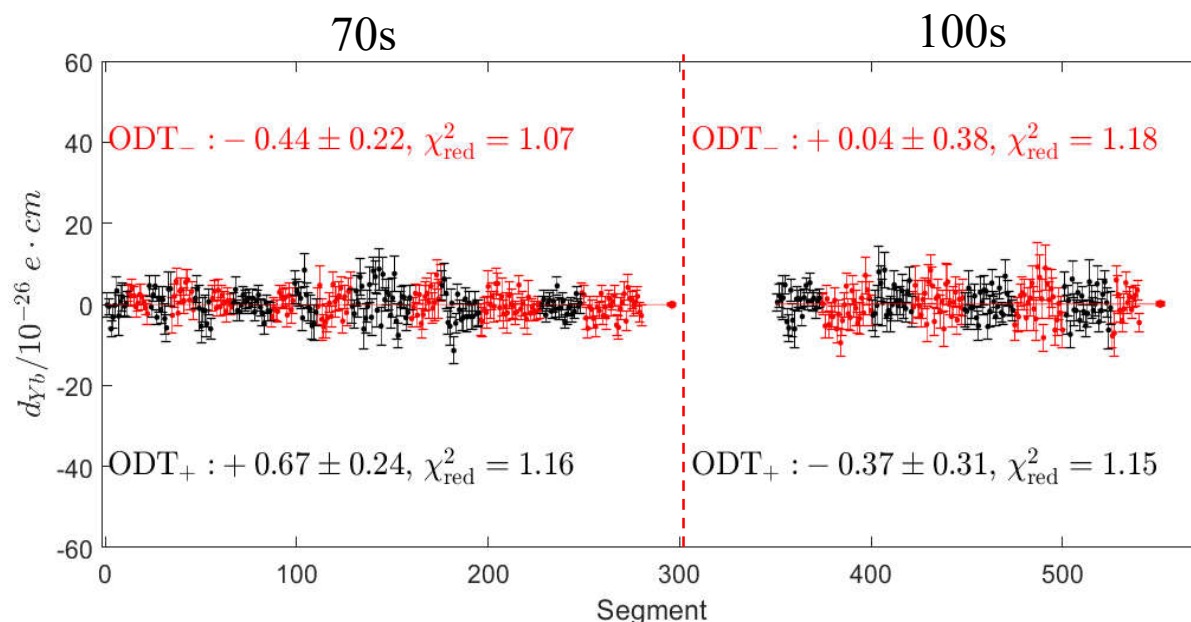
Control:

$$\theta = \pi/2 \pm 80 \text{ mrad}$$

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

- 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

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

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

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

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

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

$$E: 192 \text{ kV/cm}$$

$$\tau: 60 - 90 \text{ s}$$

$$N: 8 \times 10^4$$

$$\epsilon_d: \sim 50\%$$

$$T: 840 \text{ h (40 days)}$$

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

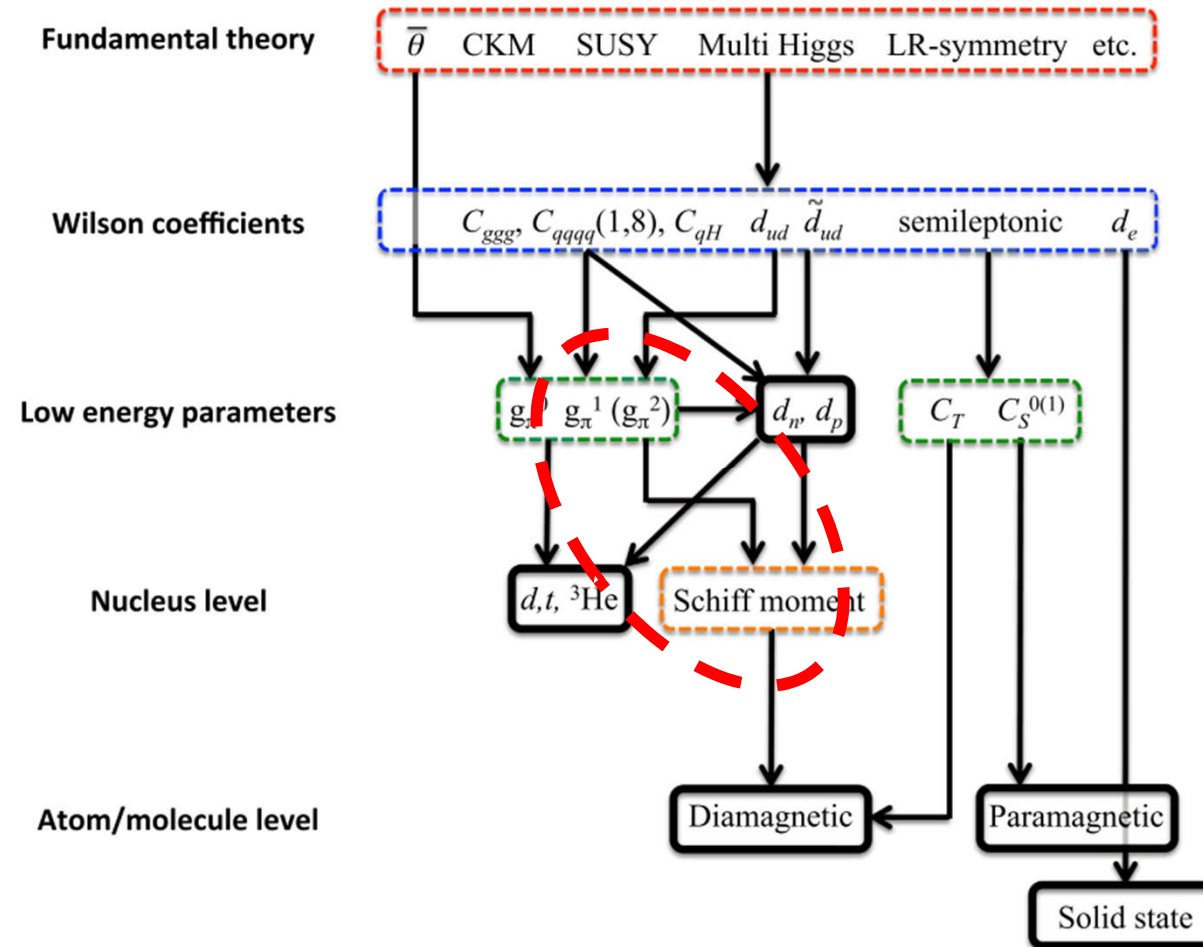
* B-field noise due to
Seebeck effect

Upper limits on Schiff moments

Diamagnetic system	^{199}Hg	$^{205}\text{Tl}^{19}\text{F}$	^{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)	$-1.4 \eta_{\text{np}}$ Flambaum86	$1.2 \eta_{\text{pp}}$ $-1.4 \eta_{\text{pn}}$ Flambaum86	$1.75 \eta_{\text{np}}$ Flambaum86	$-1.4 \eta_{\text{np}}$ Dzuba07	$300 \eta_{\text{n}}, 1100 \eta$ Flambaum03, Auerbach96

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

Need Theory on Schiff Moment of ^{171}Yb



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

Outlook #1

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

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

E-field

- 2023 setup: 200 kV/cm, copper
- Other works: 500 kV/cm, niobium - Ready *et al.* NIM A (2021)

B-field

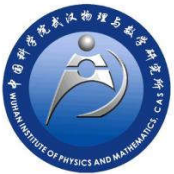
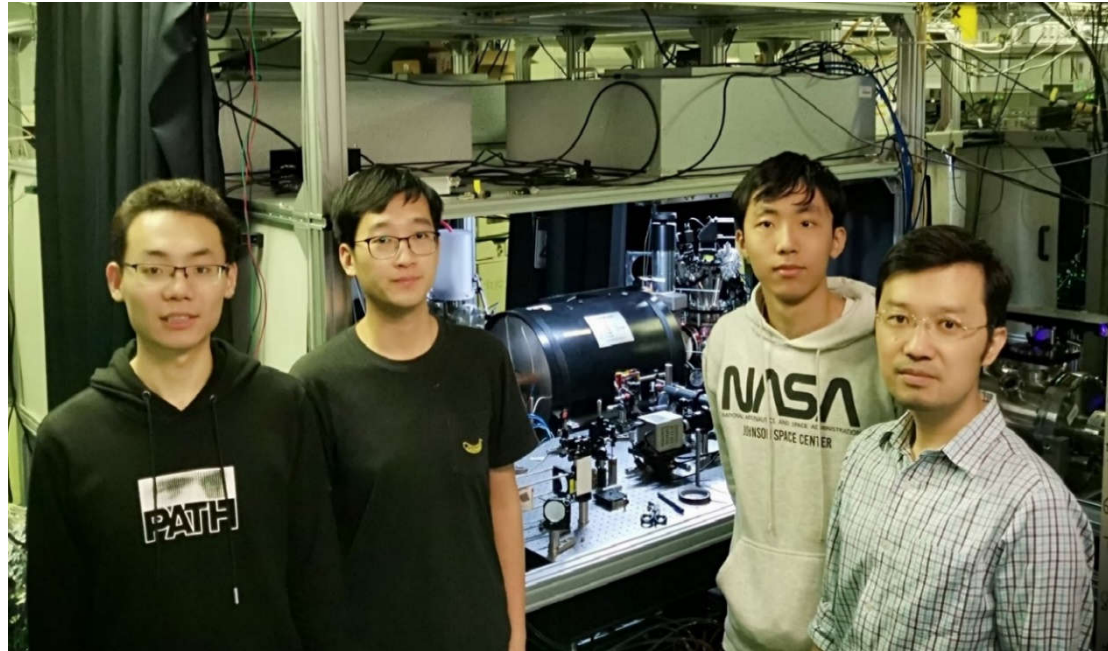
- This work: ~ 3 pT over 100 s, Seebeck effect due to ODT heating
- Environmental noise: ~ 1 pT, use magnetometers
- Johnson noise: ~ 0.6 pT, use co-magnetometer (^{173}Yb)

Collaboration and Support



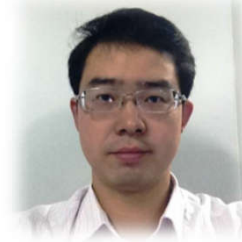
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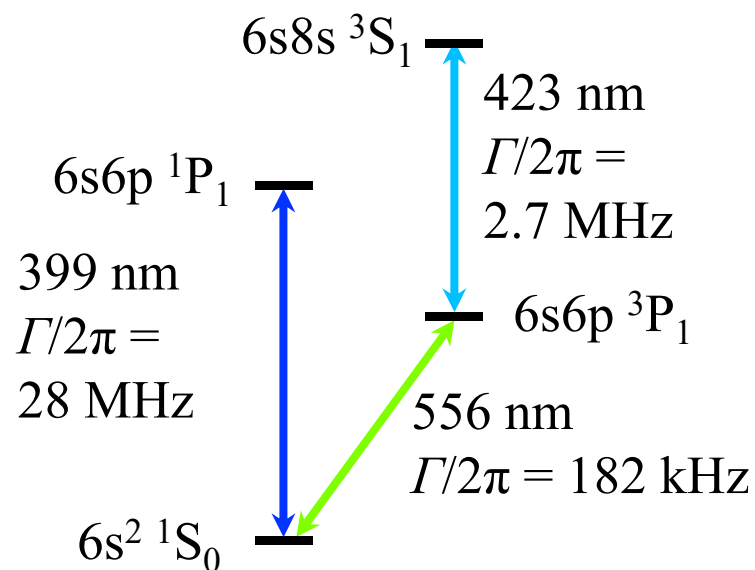
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Outlook #2

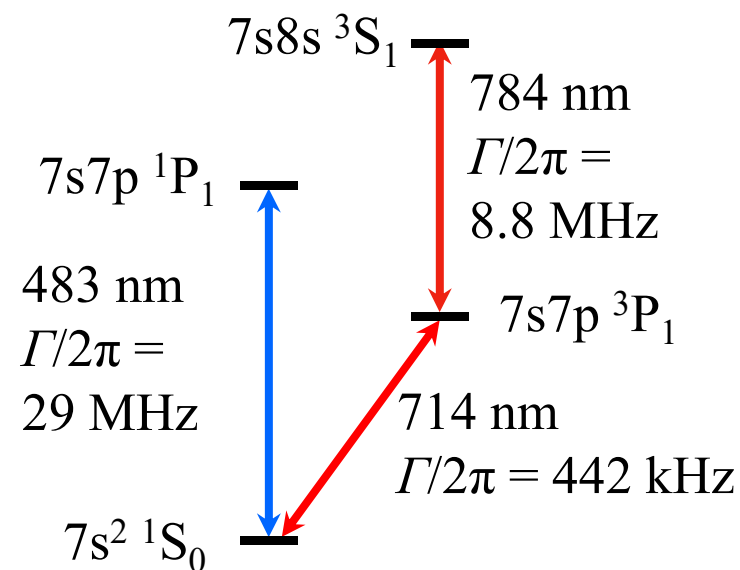
^{171}Yb

2-electron system
Nuclear spin $I = \frac{1}{2}$
Stable and abundant



^{225}Ra :

Group II
Nuclear spin $I = \frac{1}{2}$
Radioactive $t_{1/2} = 15\text{ d}$



^{171}Yb
E-28 e-cm



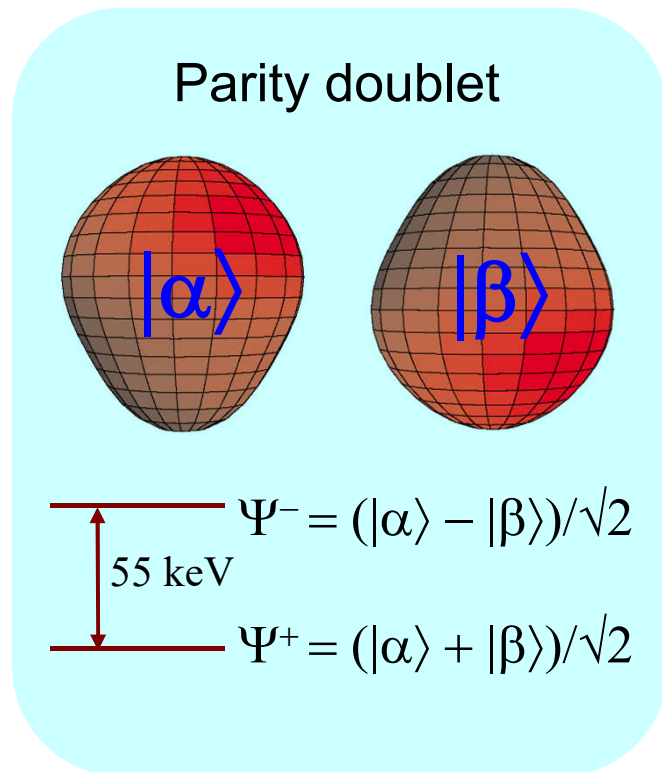
^{225}Ra
E-28 e-cm



^{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 ($^{225}\text{Ra} / ^{199}\text{Hg} \sim 3$) – Dzuba, Flambaum, Ginges, Kozlov, PRA (2002)



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

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.”

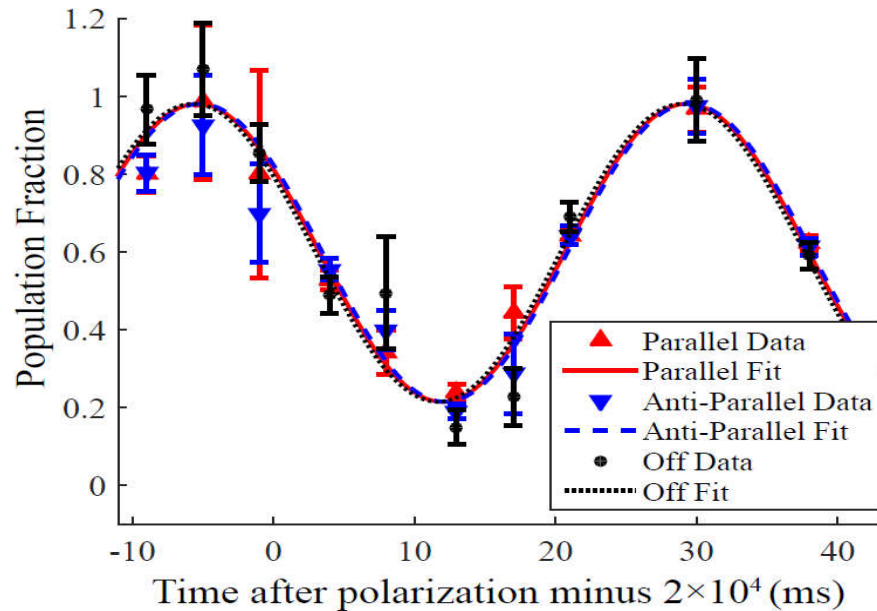
– Engel, Ramsey-Musolf, van Kolck, Prog. Part. Nucl. Phys. (2013)

Constraining parameters in a global EDM analysis.

– Chupp, Ramsey-Musolf, PRC 91, 035502 (2015)

Ra-EDM Results

Argonne National Laboratory



2007 – Laser trapping of ^{225}Ra

--- Guest *et al.*, PRL 98, 093001 (2007)

2014 – EDM $< 5.0 \times 10^{-22}$ e-cm (95%)

--- Parker *et al.*, PRL 114, 23302 (2015)

First EDM measurement on octupole deformed nucleus

2015 – EDM $< 1.4 \times 10^{-23}$ e-cm (95%)

--- Bishof *et al.*, PRC 94, 025501 (2016)

	E (kV/cm)	τ (s)	ε	N	T (hour)	EDM limit (e cm) 95% c.l.
Ra-225	70	20	0.2%	400	12	1.4E-23
Yb-171	192	96	50%	80,000	840	2.8E-27



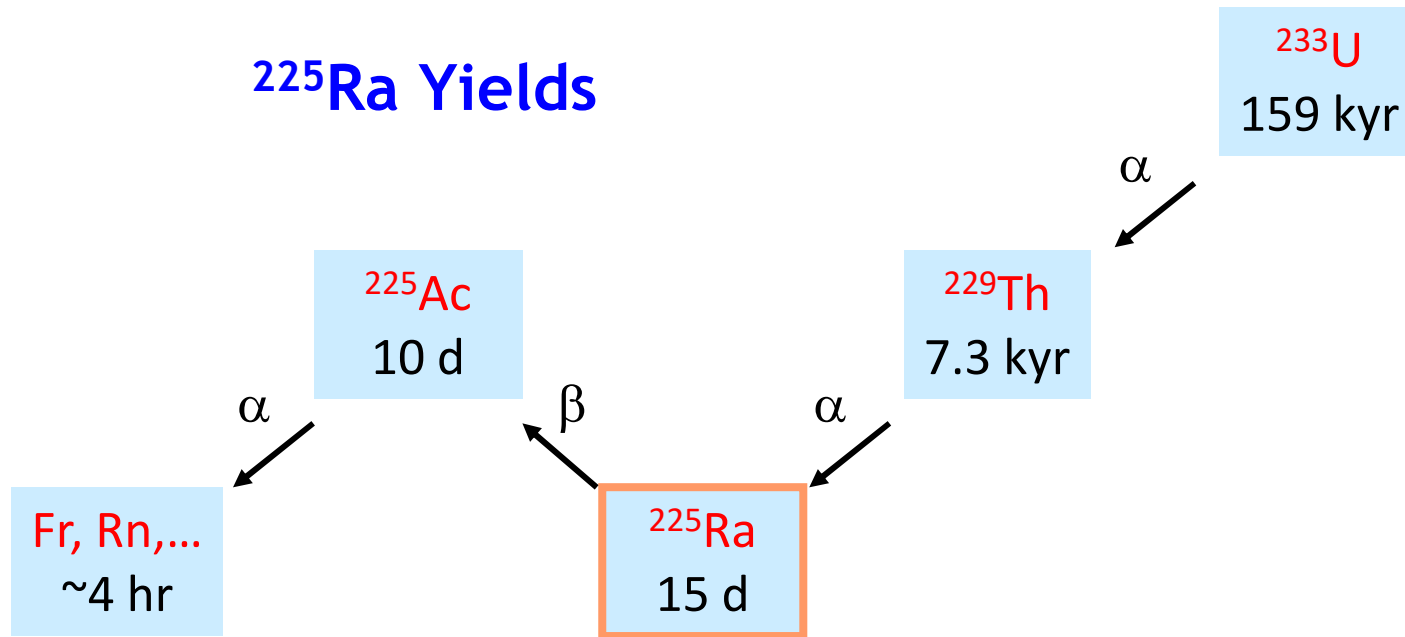
Argonne: Kevin Bailey, Michael Bischof, [John Greene](#), Roy Holt, [Nathan Lemke](#), Zheng-Tian Lu, Peter Mueller, Tom O'Connor, Richard Parker

Kentucky: Mukut Kalita, [Wolfgang Korsch](#)

Michigan State: [Jaideep Singh](#)

Northwestern: [Matt Dietrich](#)

^{225}Ra Yields



Presently available

- National Isotope Development Center, ORNL
 - Decay daughters of ^{229}Th ----- ^{225}Ra : 10^8 /s

Projected

- FRIB (B. Sherrill, MSU)
 - Beam dump recovery with a ^{238}U beam ----- 6×10^9 /s
 - Dedicated running with a ^{232}Th beam ----- 5×10^{10} /s
- MSU K1200 (R. Ronningen and J. Nolen, Argonne)
 - Deuterons on thorium target, 10 uA x 400 MeV = 4 kW ----- 10^{11} /s