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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一九八八年五月

中国科学技术大学
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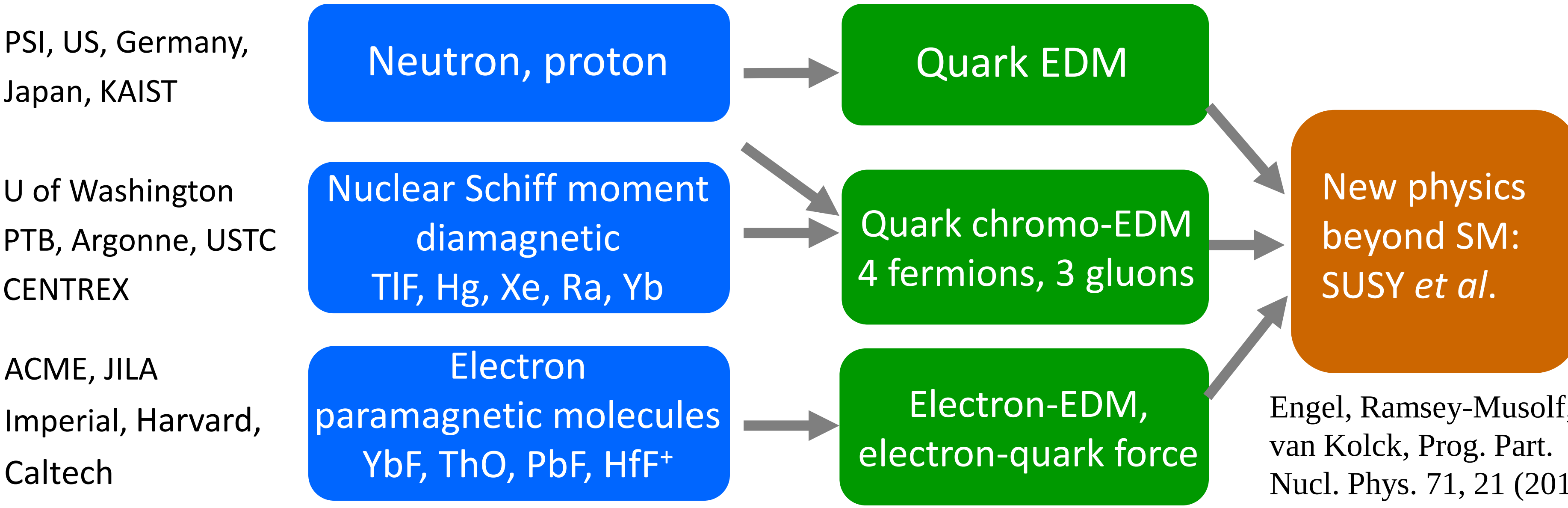
Searching for EDM in three different categories

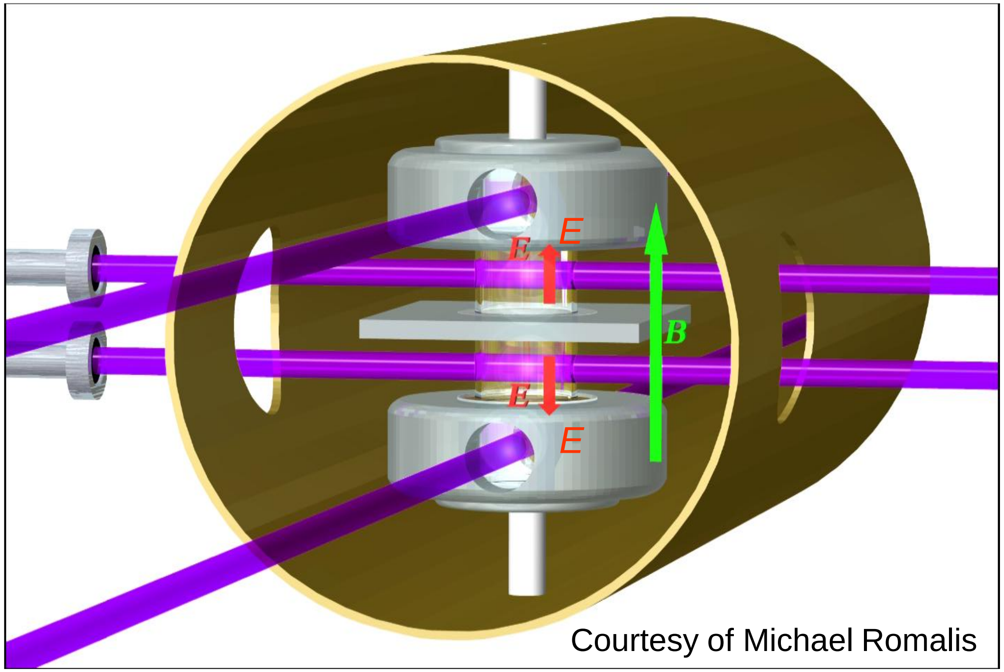


Engel, Ramsey-Musolf, van Kolck, Prog. Part. Nucl. Phys. 71, 21 (2013)

system	Upper limit (e-cm)	method	Value in Standard model (e-cm)
Electron	4×10^{-30}	Molecules – trap/beam	10^{-38}
Neutron	2×10^{-26}	Neutrons – bottle	10^{-31}
^{199}Hg	7×10^{-30}	Atoms – vapor cell	10^{-34}
^{171}Yb	??	Atoms – trap	10^{-34}

The Seattle EDM Measurement

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



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

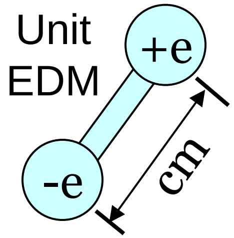
$$f_- = \frac{2\mu B - 2dE}{h} \approx 15 \text{ Hz}$$

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

The best limit on atomic EDM

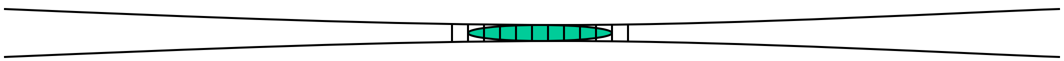
EDM (^{199}Hg) < 7 x 10^{-30} e-cm

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)



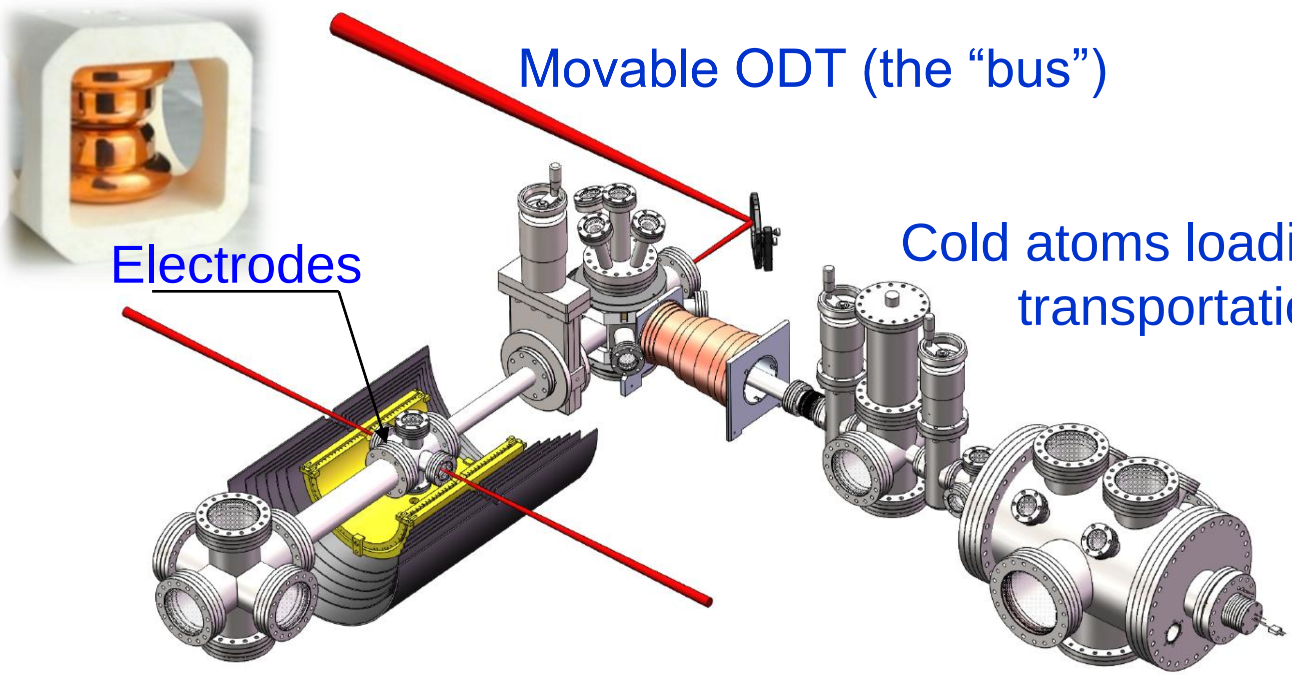
$$H = -\tilde{d}E = -\frac{1}{4}\alpha E_0^2$$

- 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
- E field is enhanced
- Cold scattering suppressed between cold Fermionic atoms
- Rayleigh scat. rate ~ 10^{-1} s^{-1} ; Raman scat. rate ~ 10^{-12} s^{-1}
- Parity mixing induced shift under control
- Conclusion: possible to reach 10^{-30} e cm for ^{199}Hg

^{171}Yb EDM Apparatus: Trapping + Science



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

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

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

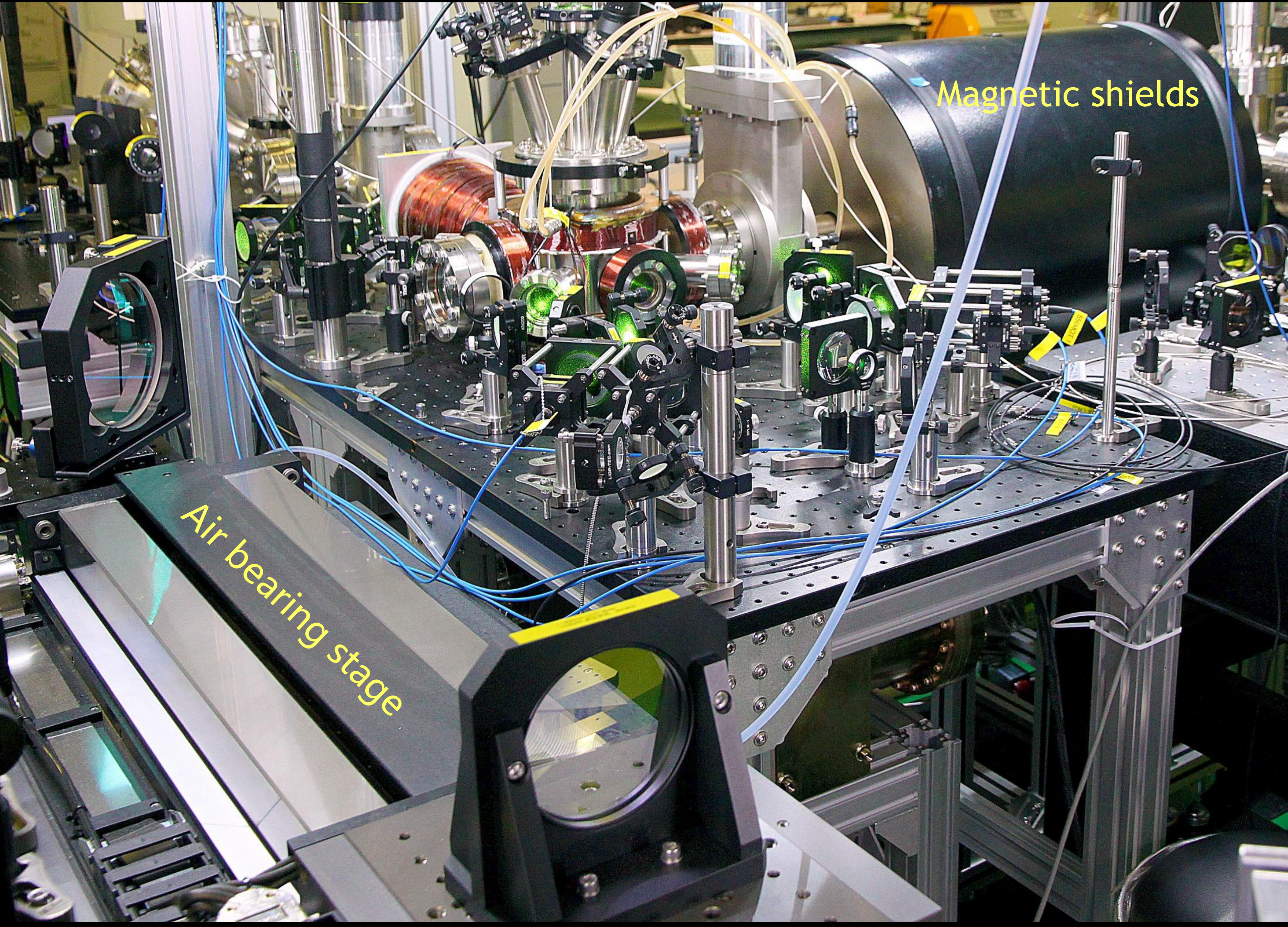
E: electric field

τ: precession time

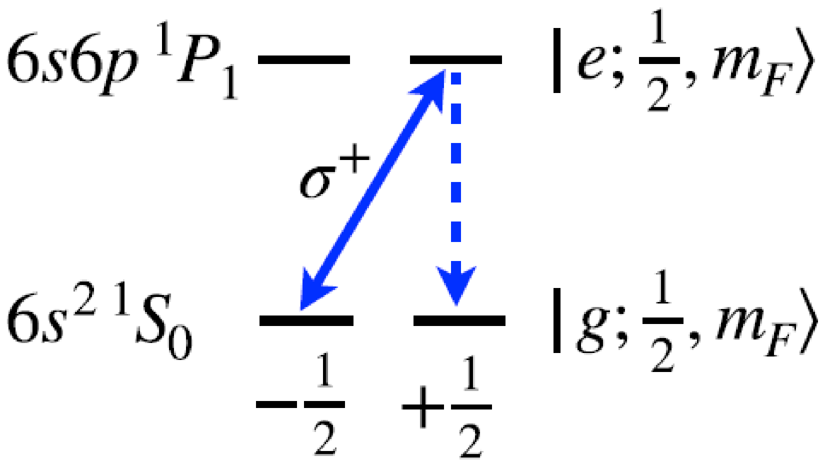
N: atom number

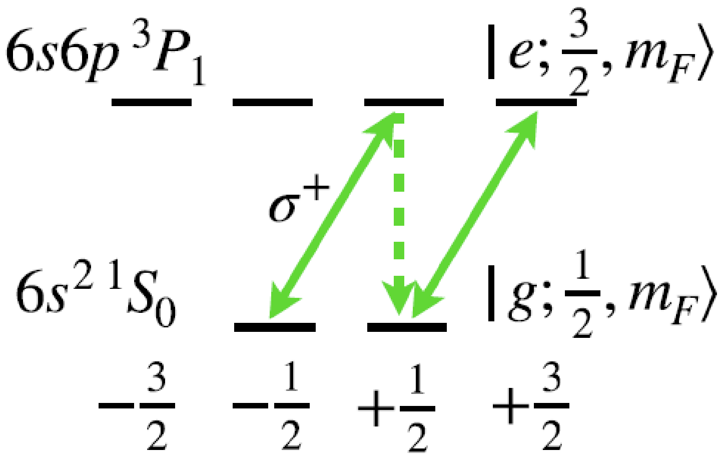
ε: spin – state detection efficiency

T: time of average


Magnetic shields
Air bearing stage

Spin-state detection – conventional method





Bright state:
~ 3 photons
before state
"demolished"

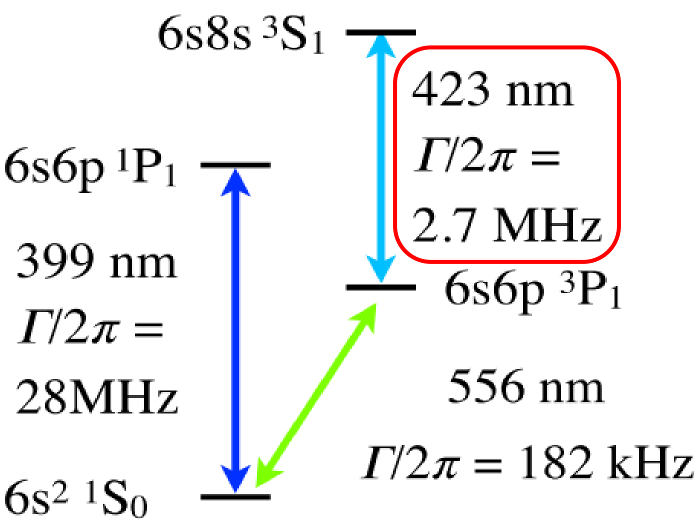
Dark state:
no photons,
state preserved

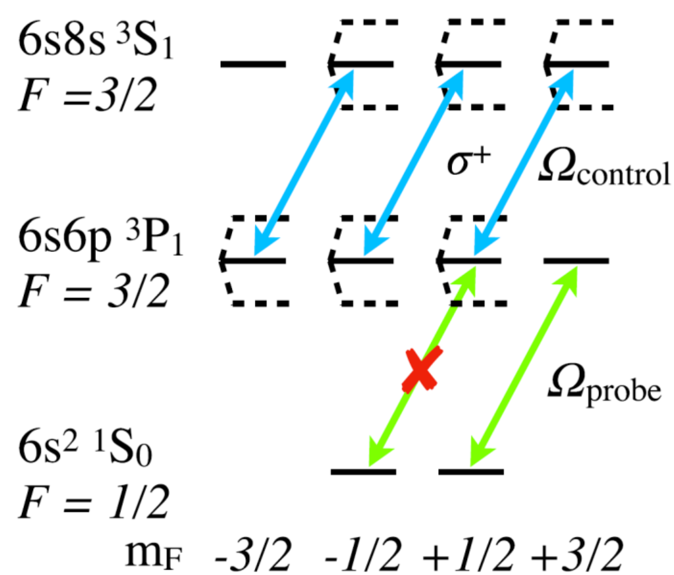
Bright state:
state
"demolished"

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

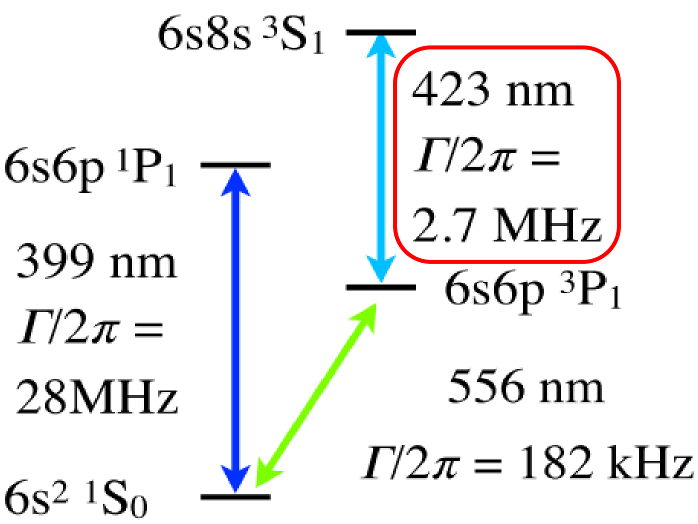
-- T. Zheng, M.S. Safronova *et al*., PRA 102, 062805 (2020)

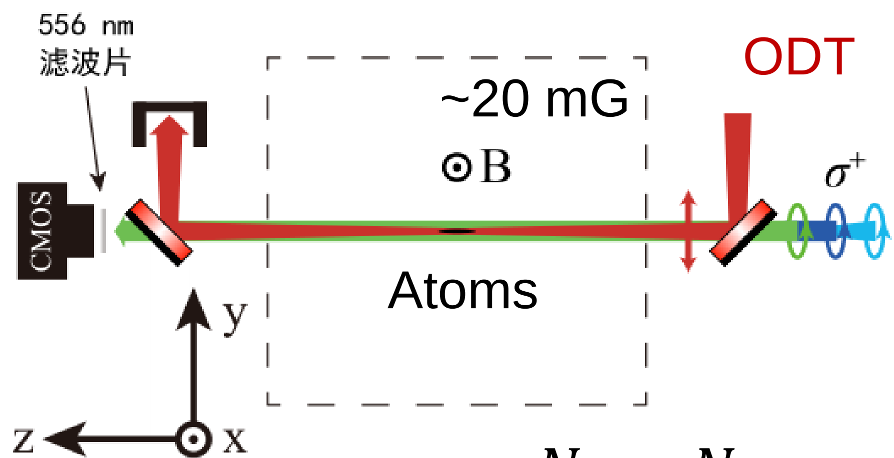
Dark state：
no photons,
state preserved

Bright state:
cycling,
state preserved

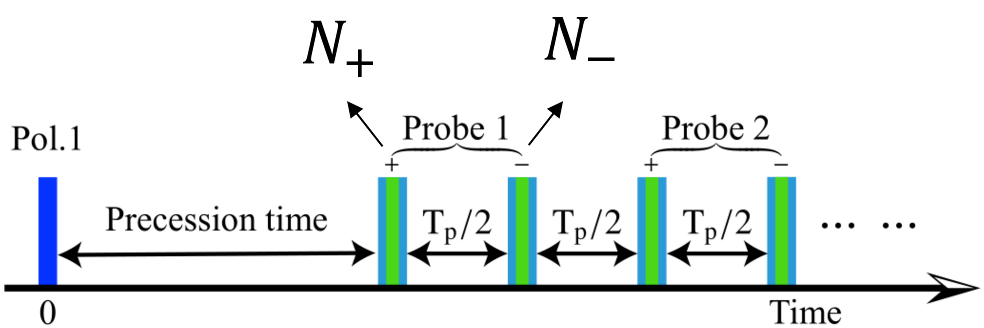
Larmor precession frequency measurement

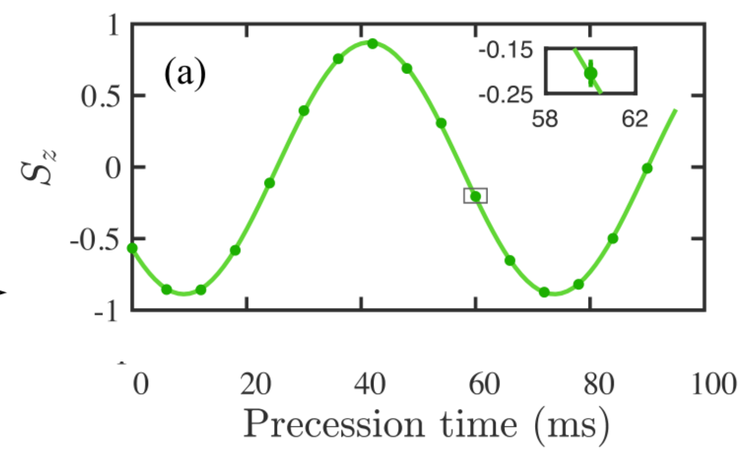
Quantum Non-Demolition



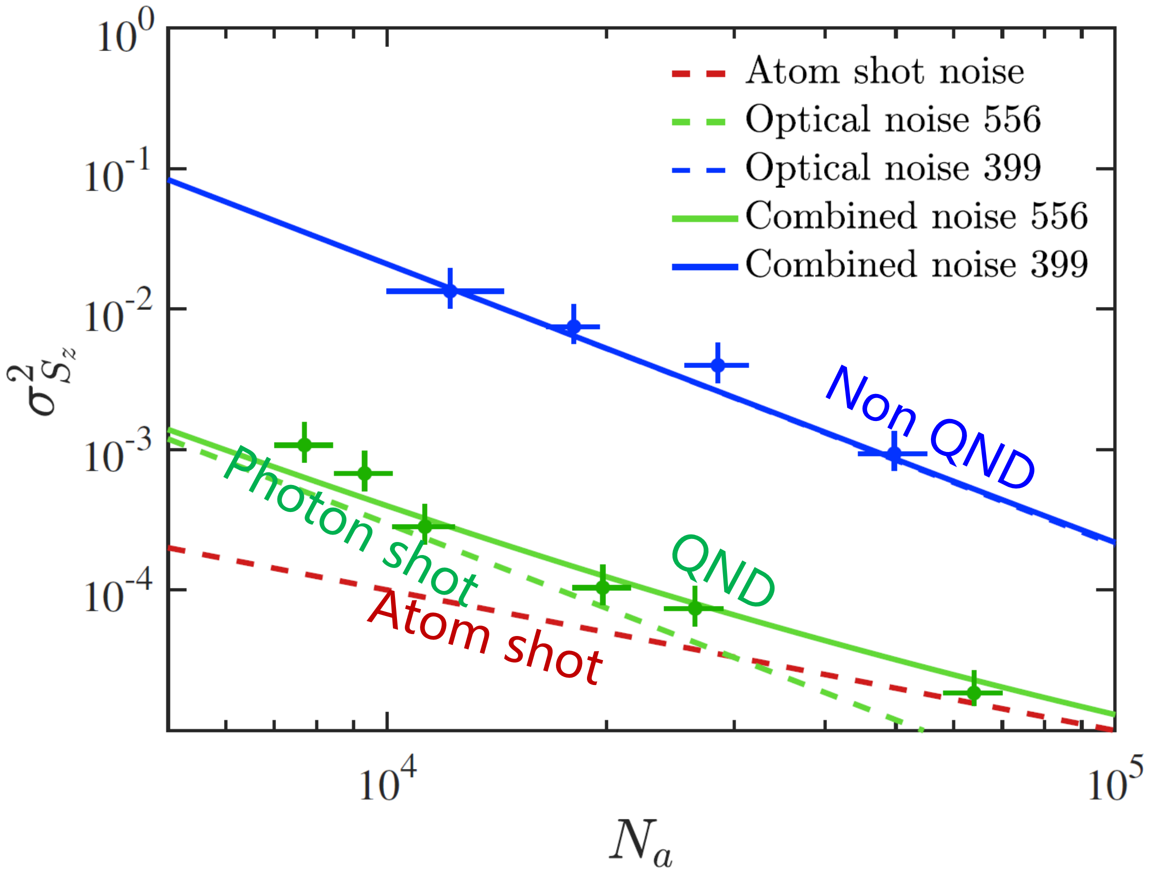


$$S_z = \frac{N_+ - N_-}{N_+ + N_-}$$





QND reduces measurement noise

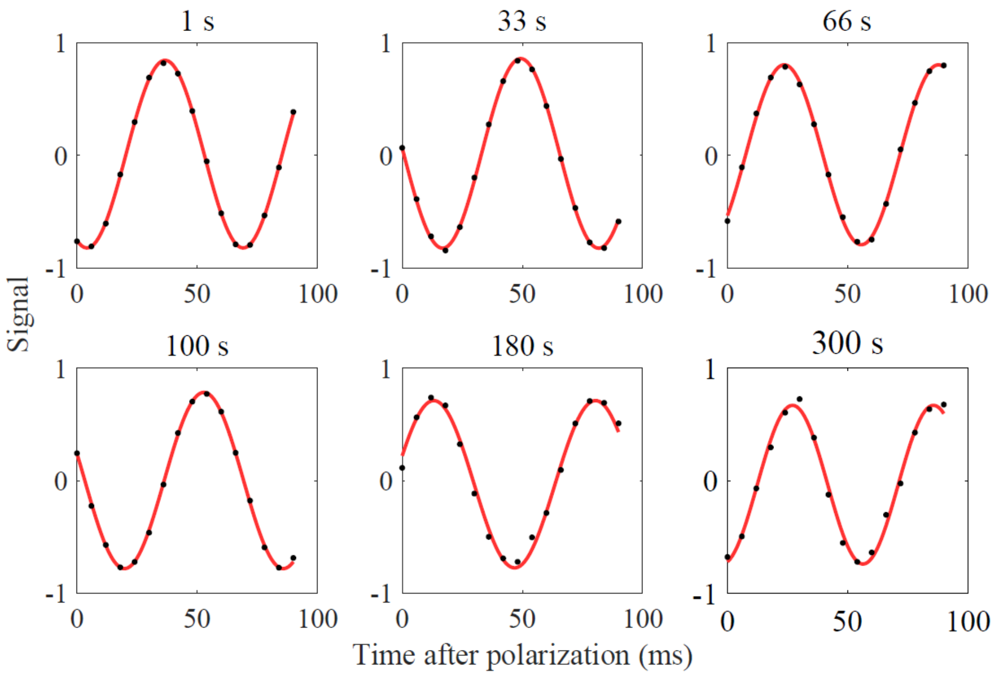


- Photons scattered non-QND: $\bar{n} \sim 2.5$ QND: $\bar{n} \sim 23$
- ~19 dB reduction of variance

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)

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



- Observed precession to: 300 s
- Vacuum-limited trap lifetime: 75 s
- EDM measurement precession time: 100 s
- T_2: $(9 \pm 4) \times 10^3$ s (2.5±1.1 hr)

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

Systematic errors

- effects correlated with E-field flipping

Source	Error (e-cm)
B-field correlations	$* \times 10^{-28}$
Parity mixing	$* \times 10^{-28}$
Leakage current	$* \times 10^{-28}$
ODT power effect	$* \times 10^{-28}$
E-squared effect	$* \times 10^{-28}$
Total	$* \times 10^{-28}$

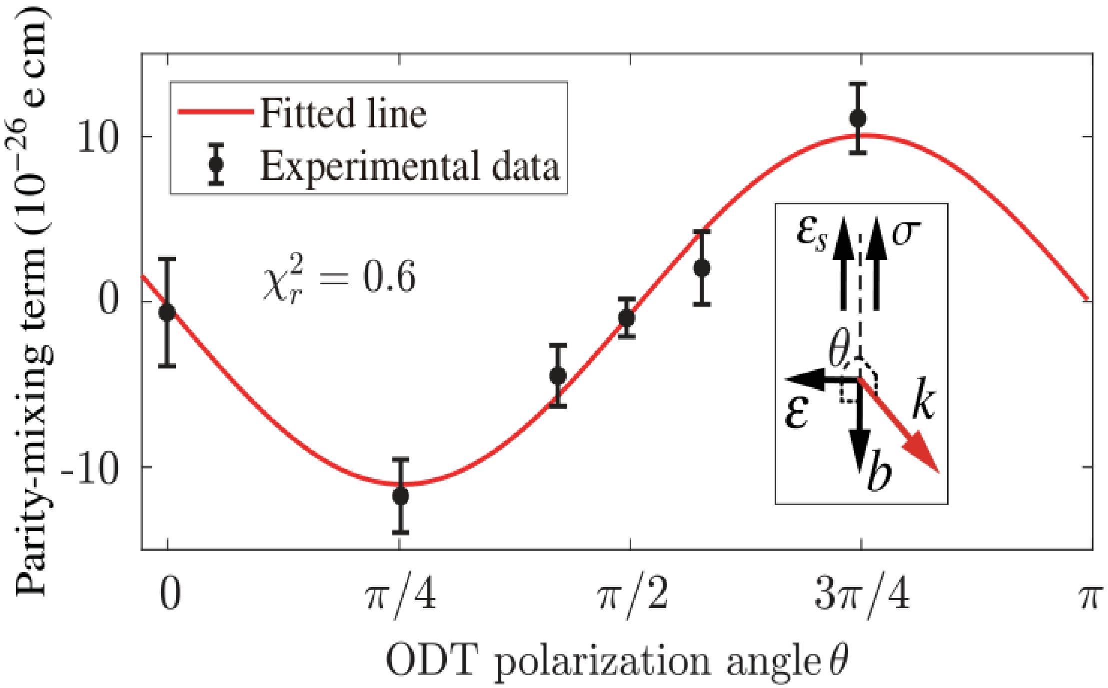
Parity mixing

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

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

$$\Delta\nu = -\frac{\nu^{(1)} + \nu^{(2)}}{2}\sin(2\theta)$$

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

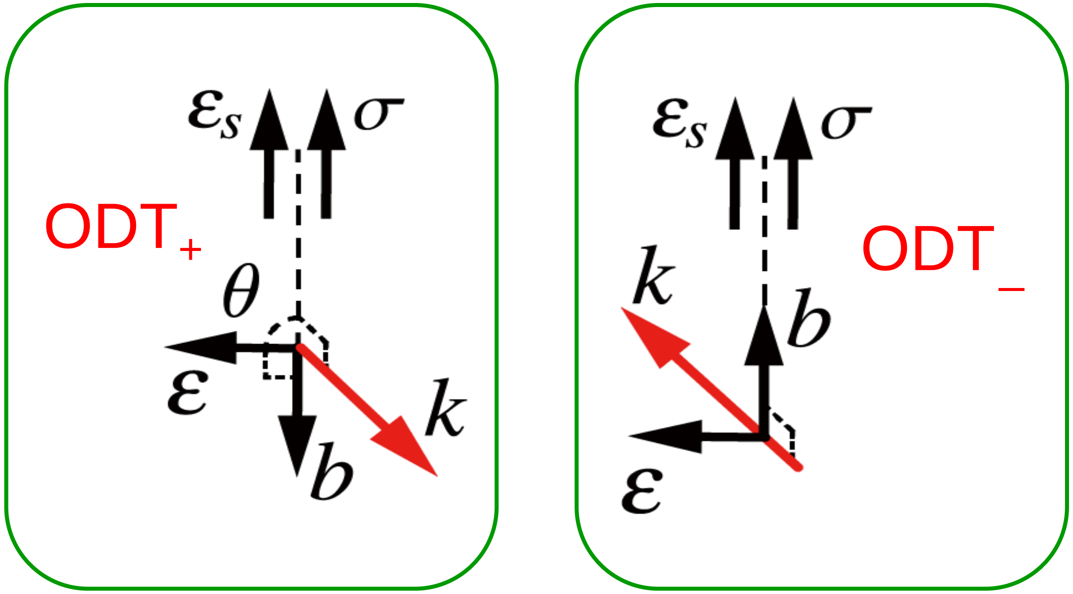
measurement : $1.2(2) \times 10^{-25}$ $e\ cm$ $(\varepsilon\cdot\varepsilon_s = \varepsilon\cdot\sigma = \sqrt{2}/2)$

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)



Control:

$\theta = \pi/2 \pm 50$ mrad

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

- Average between ODT+ and ODT−
- Residual parity mixing effect: 3×10^{-28} e cm

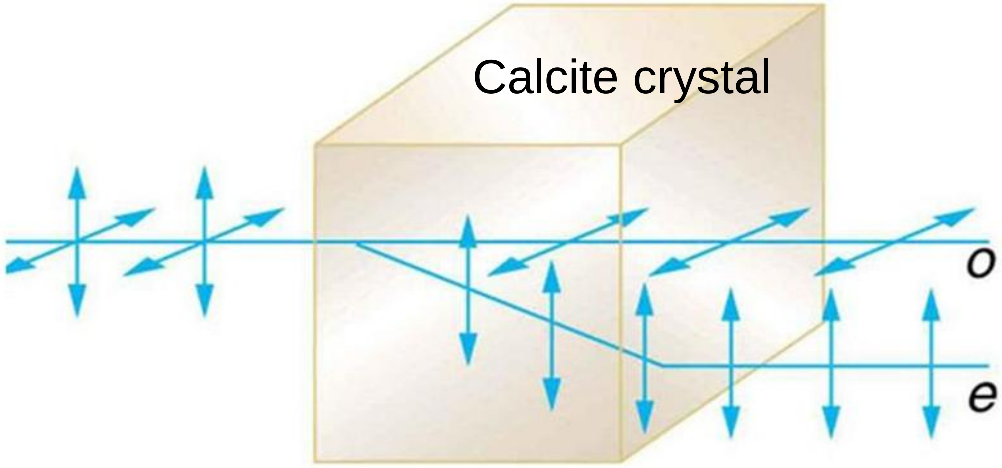
Measurement of the EDM of ^{171}Yb atoms in an ODT
T.A. Zheng *et al.*, PRL **129**, 083001 (2022)

Parity mixing

$$\Delta\nu = -\frac{\nu^{(1)} + \nu^{(2)}}{2}\sin(2\theta)$$

Parity mixing

$$\Delta\nu = -\frac{\nu^{(1)}+\nu^{(2)}}{2}\left[\sin(2\theta)+\sin\left(2(\theta+\frac{\pi}{2})\right)\right] = 0$$



- Average the two traps with perpendicular polarization
- Further average between $+k$ and $-k$
- Residual parity mixing effect : ** e cm
- Future: better $+k$ and $-k$ balance in an optical cavity

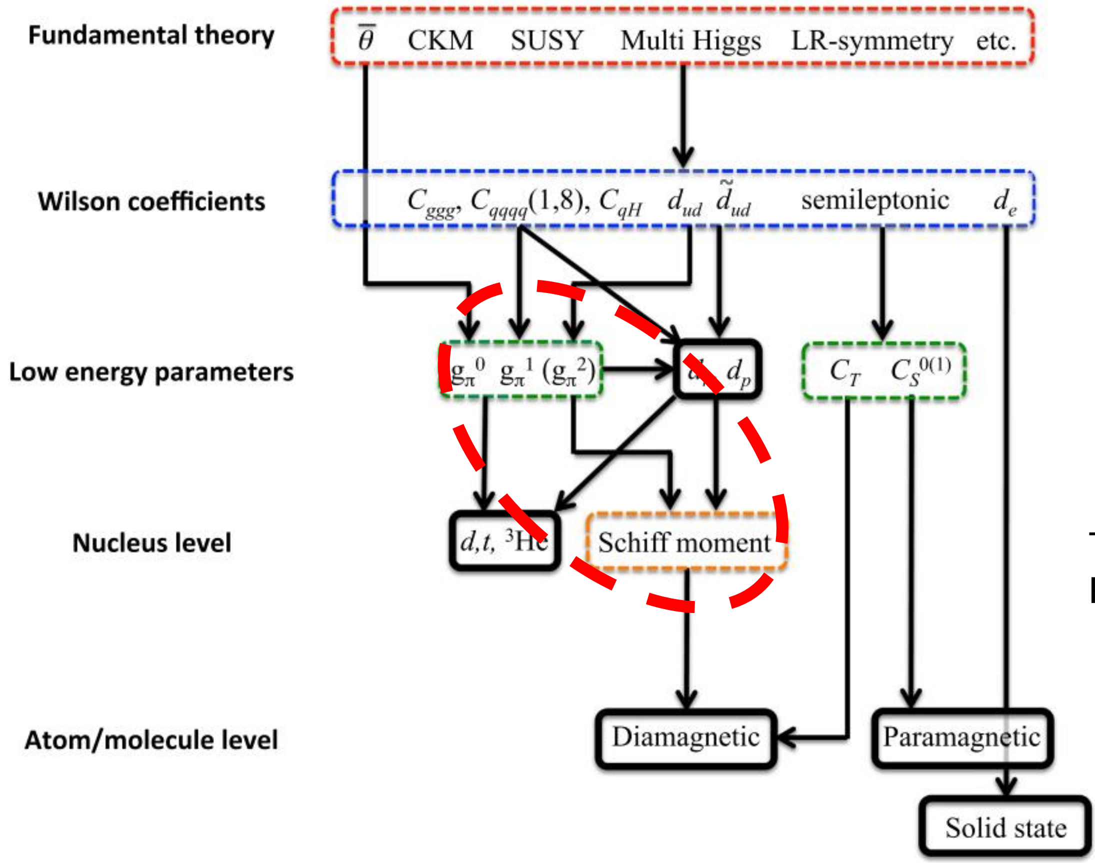
Upper limits on Schiff moments

Diamagnetic system	^{199}Hg	^{205}Tl^{19}F	^{129}Xe	^{171}Yb	^{225}Ra
EDM limit (10^{-26} e cm)	7.4×10^{-4} UWash16	6500 Yale91	0.14 PTB19	** USTC25	1400 Argonne16
Schiff moment limit (10^{-10} e fm^3)	2.6×10^{-3}	1.5	5.2	**	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

- The ^{171}Yb EDM result contributes to constraining BSM physics: better or worse than ^{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.

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 (^{171}Yb)

Upgrade: ^{171}Yb EDM precision improves into E-29 e-cm

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

E-field

- 2025 work: ** kV/cm, copper electrodes
- Other works: 500 kV/cm, niobium - Ready *et al*. NIM A (2021)

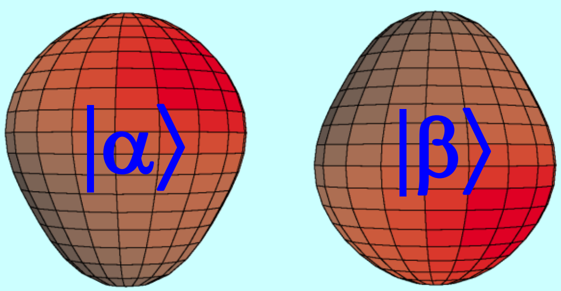
B-field

- Environmental noise: ~ 1 pT, use magnetometers
- Johnson noise, Seebeck effect: ~ 1 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, PRC 91, 035502 (2015)

Outlook (^{225}Ra)

^{171}Yb

2-electron system

Nuclear spin I = ½

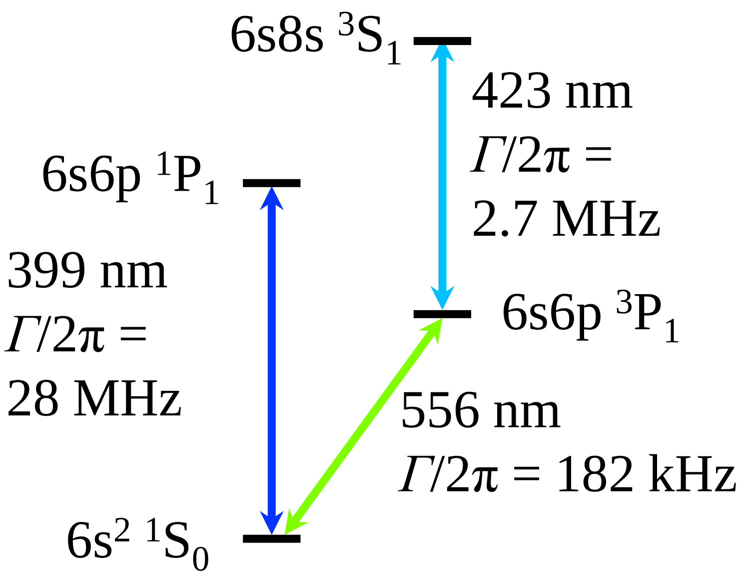
Stable and abundant

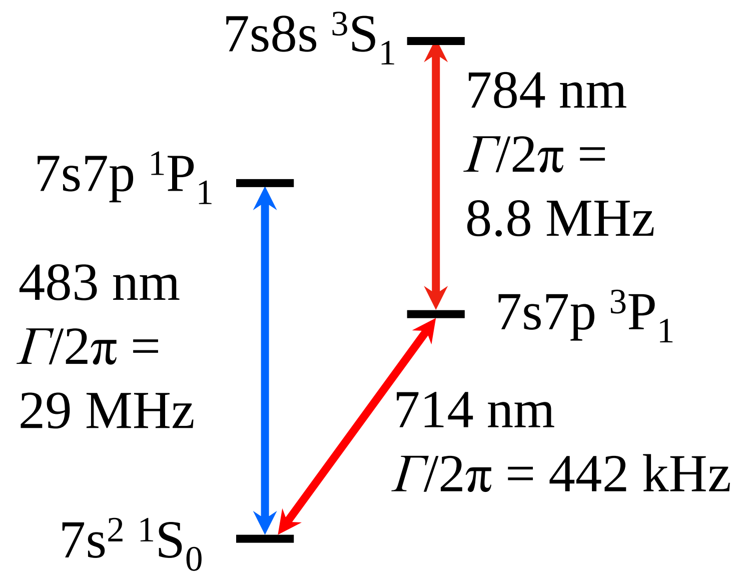
^{225}Ra:

Group II

Nuclear spin I = ½

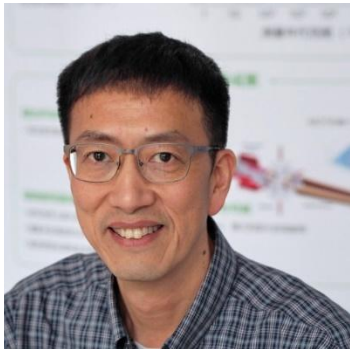
Radioactive $t_{1/2}$ = 15 d

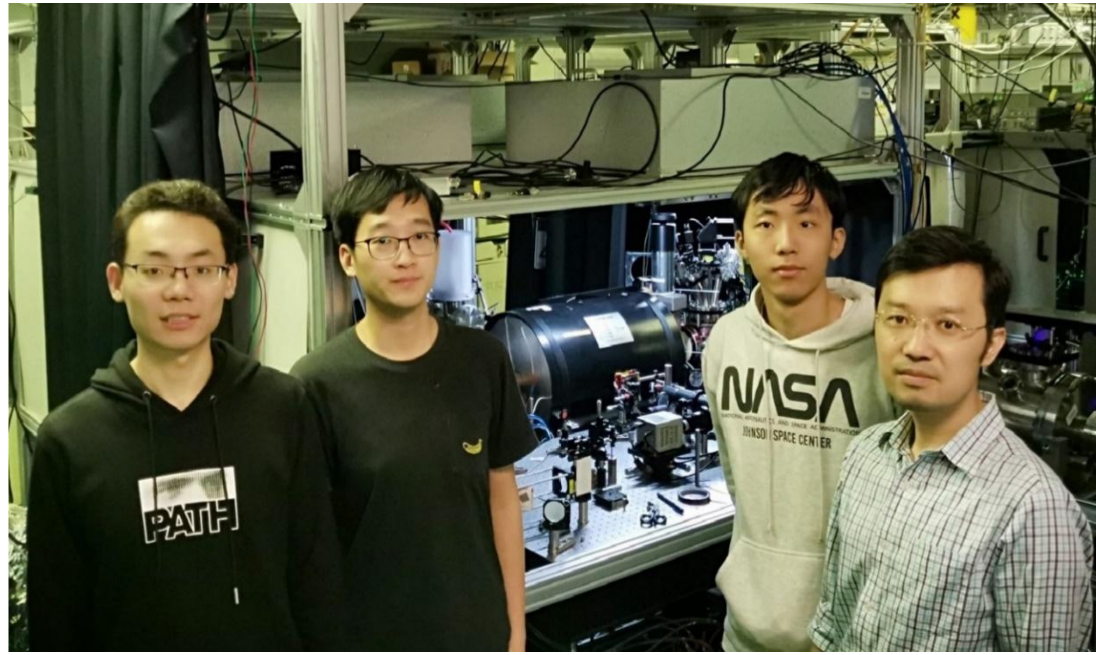




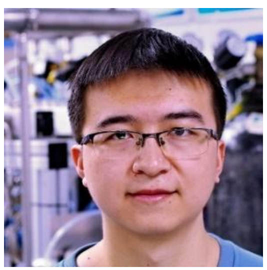
Collaboration and Support

USTC
HFNL





Z.-T. Lu, Tian Xia, Tao Zheng, Yang Yang,
S.-Z. Wang, S.-B. Wang, Z.-J. Tao



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