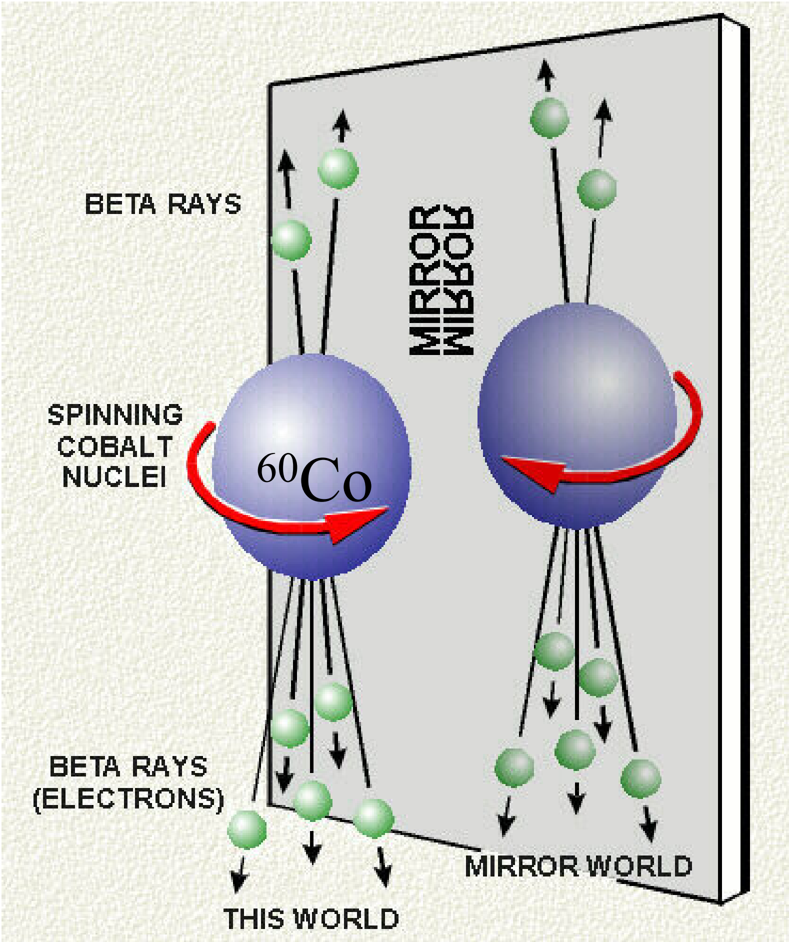
Parity violation – First observation

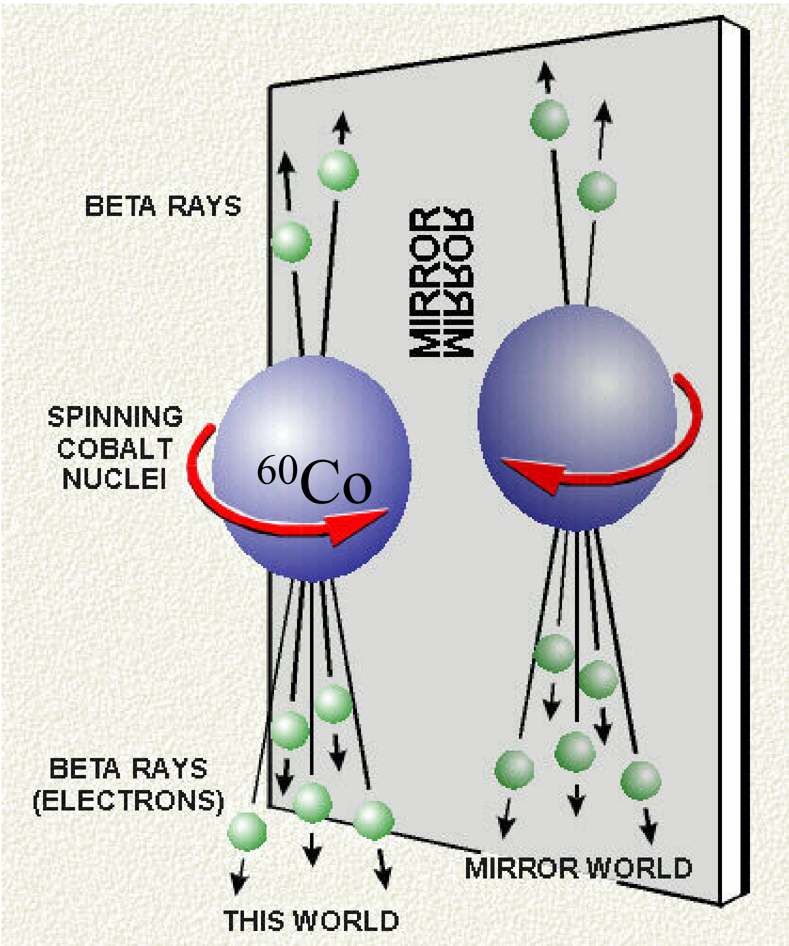


C. S. Wu *et al*. (1957)

吴健雄
1912 – 1997

Discrete Fundamental Symmetries

Parity violation – First observation



C. S. Wu *et al*. (1957)

- ~~P~~ Parity
- ~~C~~ Charge conjugation
- ~~CP~~ CP symmetry
- ~~T~~ Time reversal
- CPT CPT – Exact symmetry in quantum field theory with Lorentz invariance

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

Nov 20, 2025

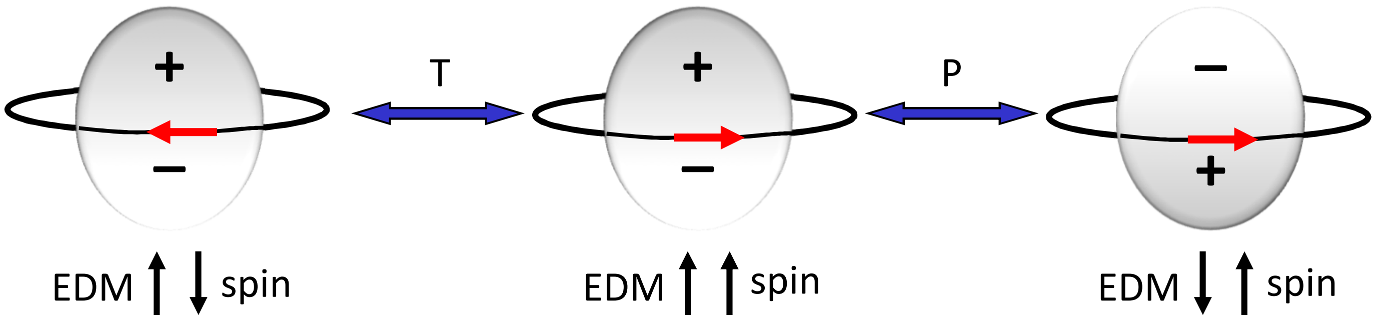
創寰宇學府
育天下英才
嚴濟慈題
一九八八年五月

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

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

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

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



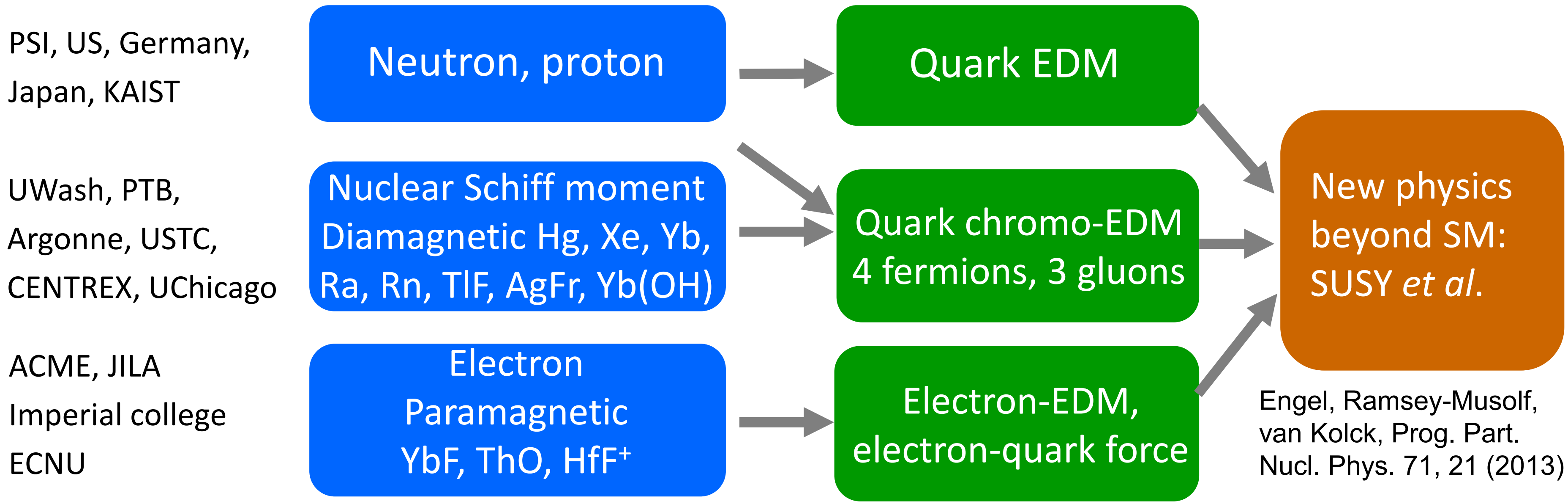
- CP problem in strong interaction: θ term

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

- SUSY: New elementary particles→ new ~~CP~~ phase

- Origins of matter – antimatter asymmetry: New physical ~~CP~~ mechanism

Searching for EDM in three different categories

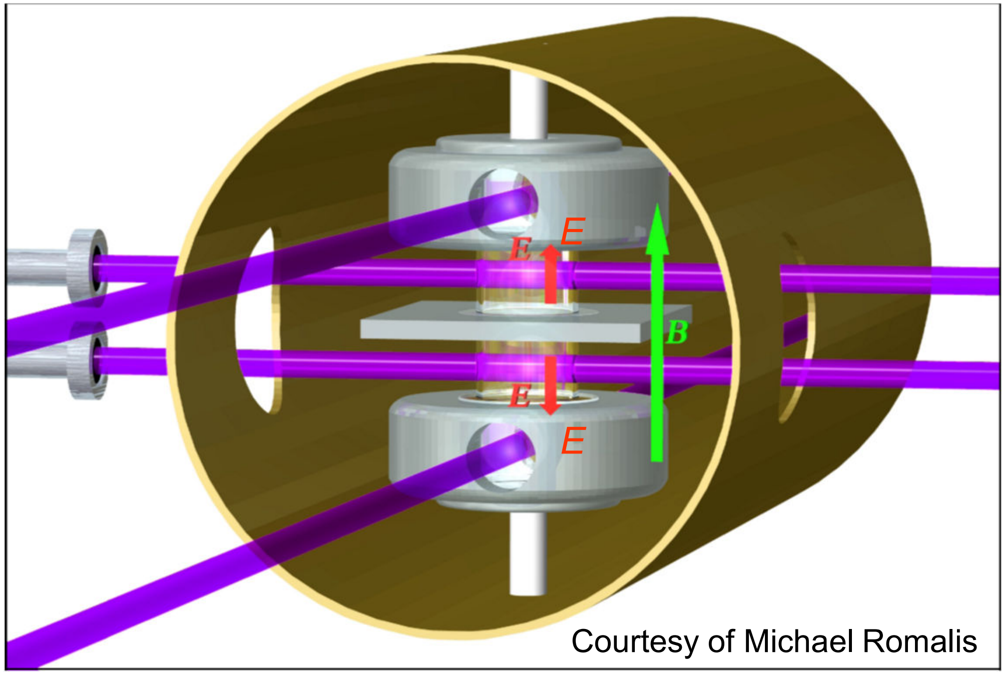


Engel, Ramsey-Musolf, van Kolck, Prog. Part. Nucl. Phys. 71, 21 (2013)

system	Upper limit (e-cm)	method	Value in Standard model (e-cm)
Electron	4×10^{-30}	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

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

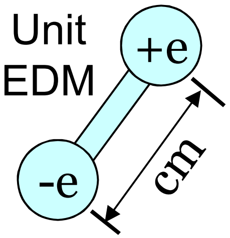
$$f_- = \frac{2\mu B - 2dE}{h} \approx 15\ \mathrm{Hz}$$

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

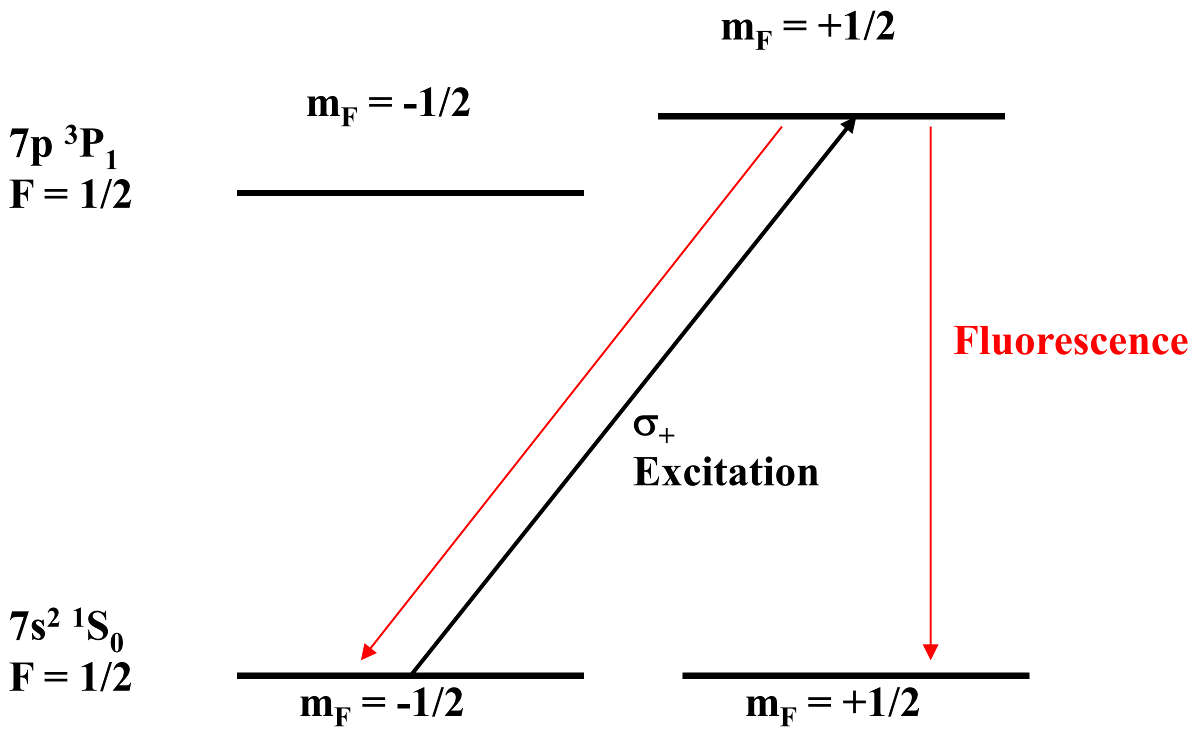
The best limit on atomic EDM

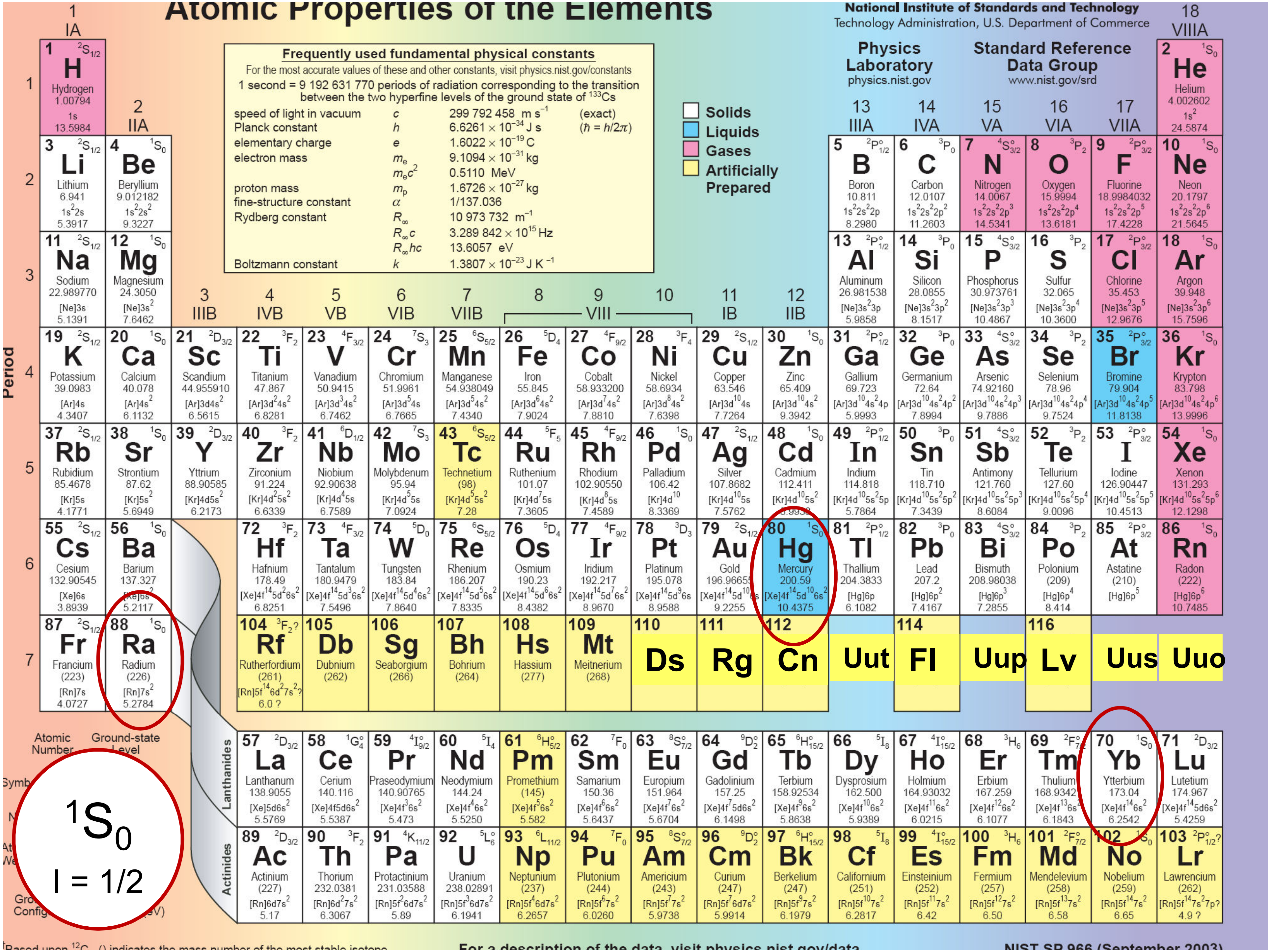
EDM (^{199}Hg) < 7 x 10^{-30} e-cm

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



Optical Pumping 光抽运



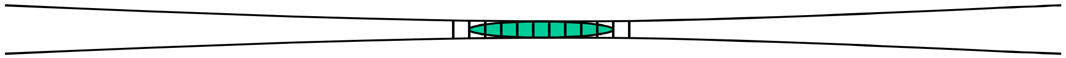

Atomic Properties of the Elements
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce
Physics Laboratory
physics.nist.gov
Standard Reference Data Group
www.nist.gov/srd
Frequently used fundamental physical constants
For the most accurate values of these and other constants, visit physics.nist.gov/constants
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of 133Cs
speed of light in vacuum c 299 792 458 m s−1 (exact)
Planck constant h 6.6261 × 10−34 J s (ħ = h/2π)
elementary charge e 1.6022 × 10−19 C
electron mass me 9.1094 × 10−31 kg
mec2 0.5110 MeV
proton mass mp 1.6726 × 10−27 kg
fine-structure constant α 1/137.036
Rydberg constant R∞ 10 973 732 m−1
R∞c 3.289 842 × 1015 Hz
R∞hc 13.6057 eV
Boltzmann constant k 1.3807 × 10−23 J K−1
Solids
Liquids
Gases
Artificially Prepared
Period
Lanthanides
Actinides
Atomic Number
Ground-state Level
For a description of the data, visit physics.nist.gov/data
NIST SP 966 (September 2003)

$^1S_0$

$I = 1/2$

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

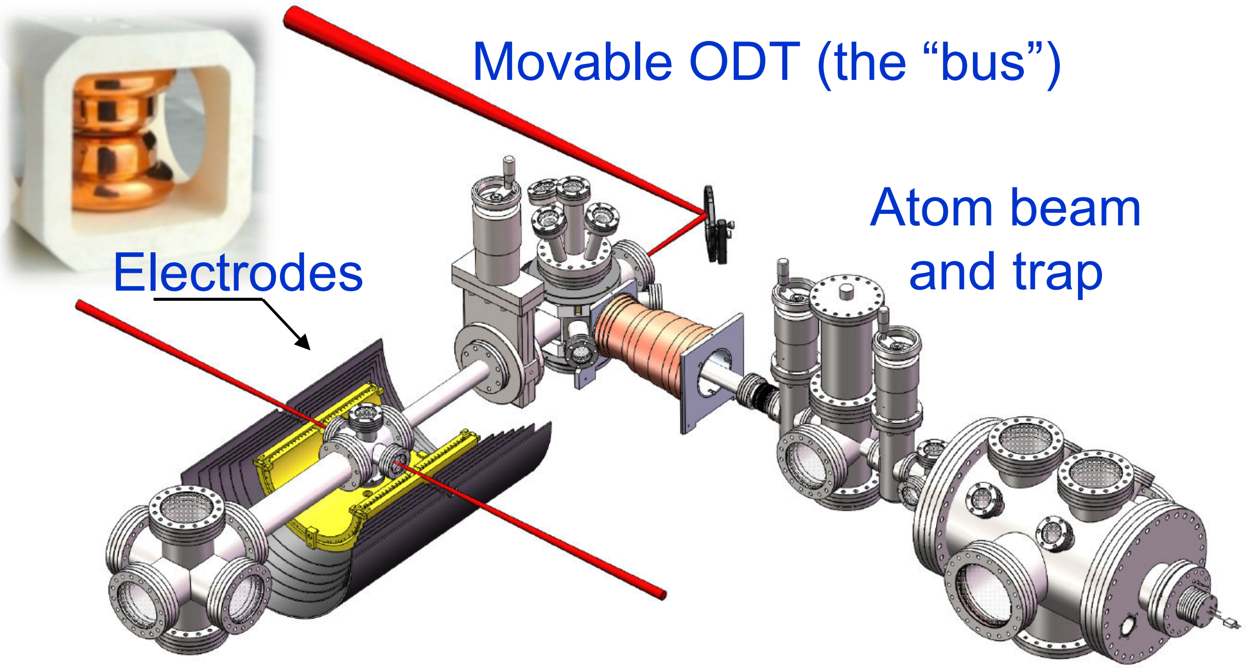
$$H = -\tilde{d}E = -\frac{1}{4}\alpha E_0^2$$

- 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



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

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

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

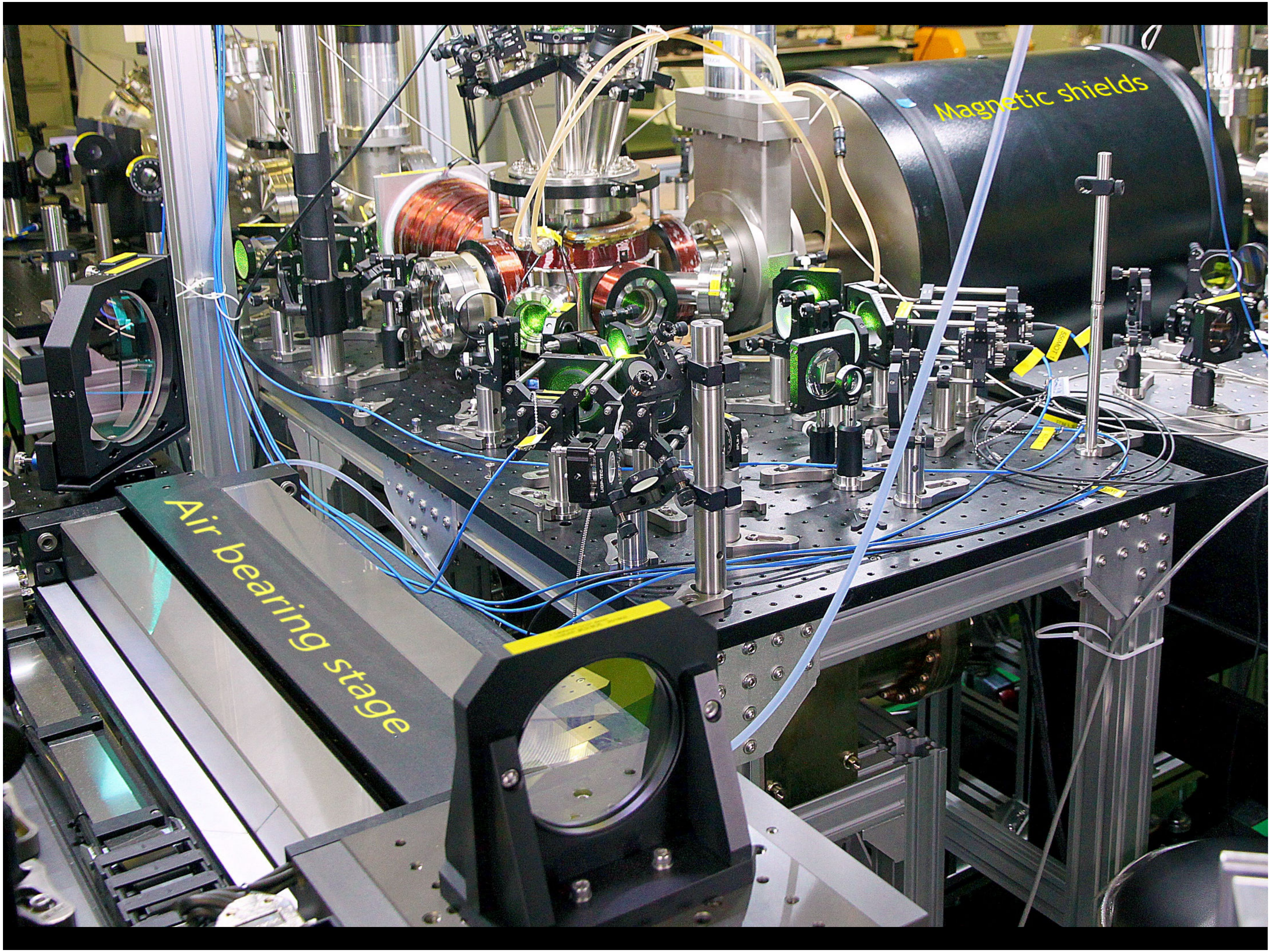
E: electric field

τ: precession time

N: atom number

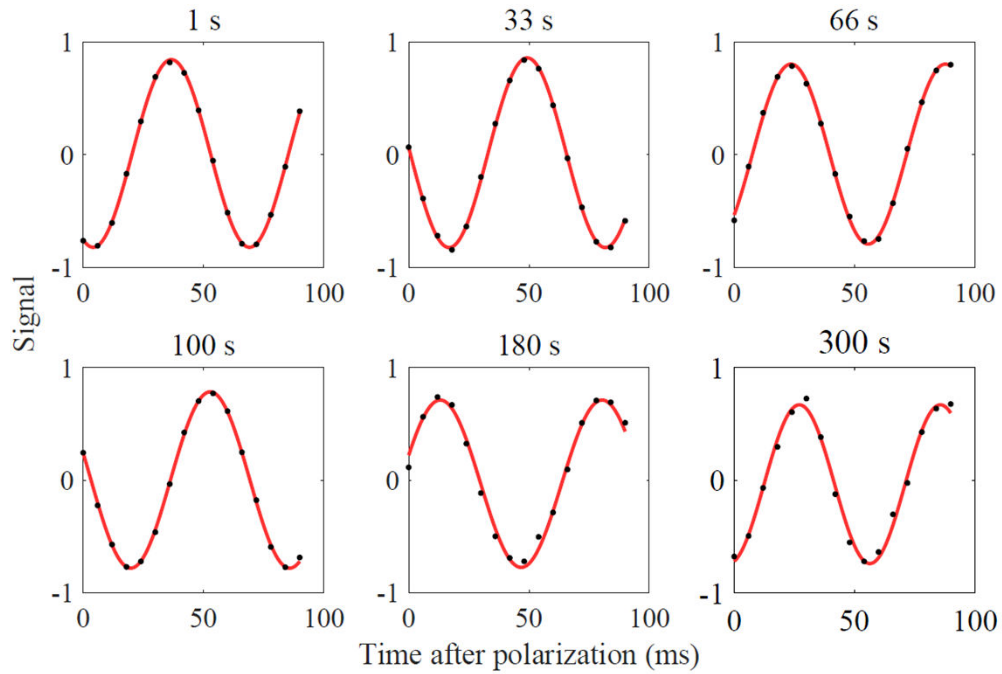
ε: spin – state detection efficiency

T : time of average


Magnetic shields
Air bearing stage

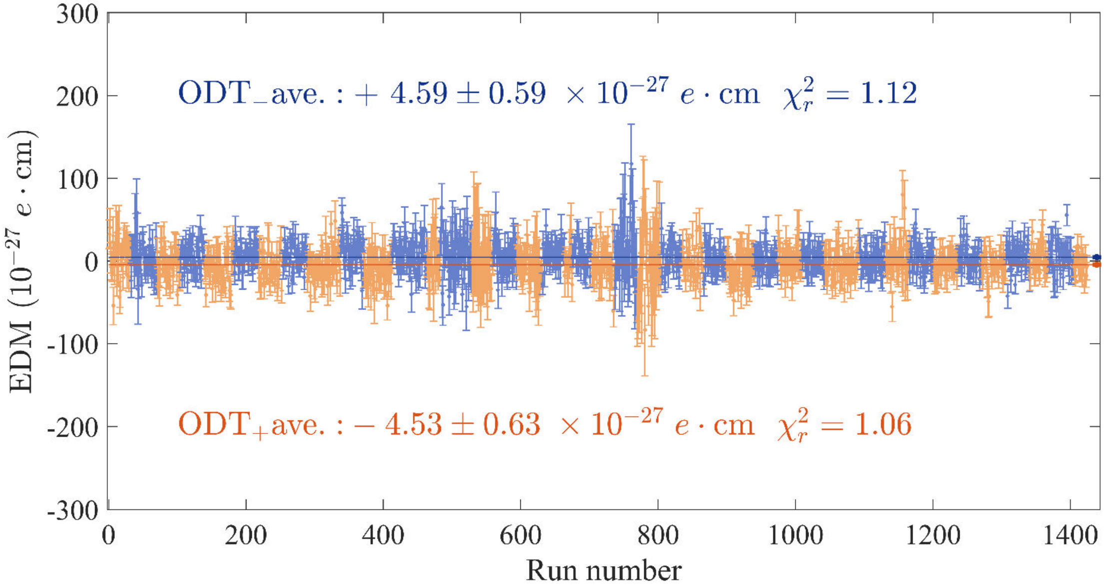
Long spin coherence time (T_2)

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



- 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)

^{171}Yb EDM measurement results



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

	ODT_+	ODT_-
E	236 kV/cm	
τ	75 s	
n	15554	15730
N_a	$\sim 1 \times 10^5$	
ϵ_d	0.5	
δB	~ 1 pT	

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

Preliminary result !!

$$d(^{171}\mathrm{Yb}) = \left(0.3 \pm 3.7_{\mathrm{stat}} \pm 1.2_{\mathrm{syst}}\right) \times 10^{-28}\ \mathrm{e\ cm}$$

$$\text{Upper limit (95\%)} \ : \ |d(^{171}\mathrm{Yb})| < 8 \times 10^{-28}\ \mathrm{e\ cm}$$

* 19× improved over 2022 result

Measurement of the EDM of ^{171}Yb atoms in an ODT, T.A. Zheng *et al.*, PRL **129**, 083001 (2022)
*****New limit on ^{171}Yb EDM, S.-Z. Wang *et al.*, in preparation*****

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)

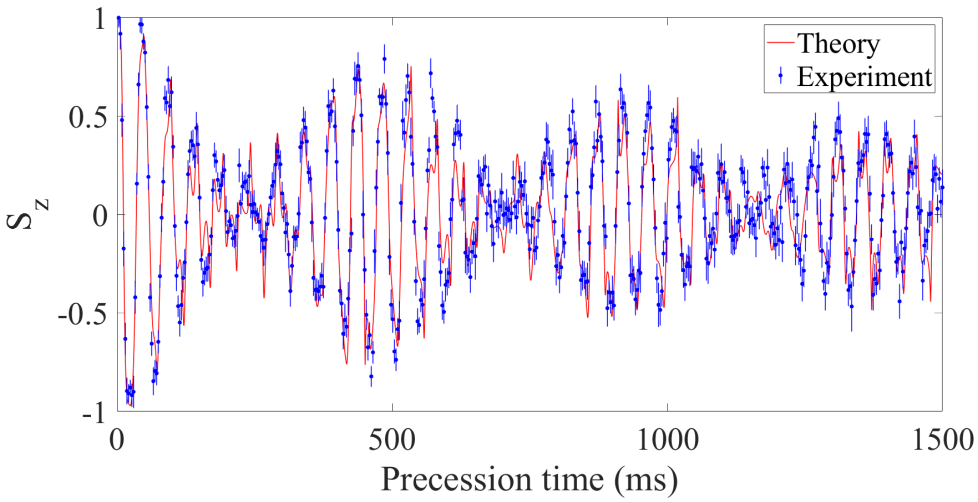
B-field

- 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

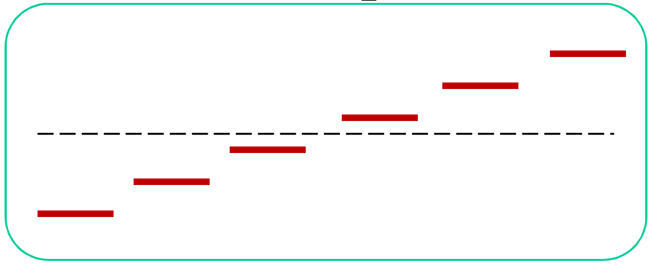
Prepare initial state: $|+5/2\rangle_x = \frac{1}{\sqrt{32}}\left(1\ \sqrt{5}\ \sqrt{10}\ \sqrt{10}\ \sqrt{5}\ 1\right)$

Problem: decoherence due to spatially varying ODT light shift

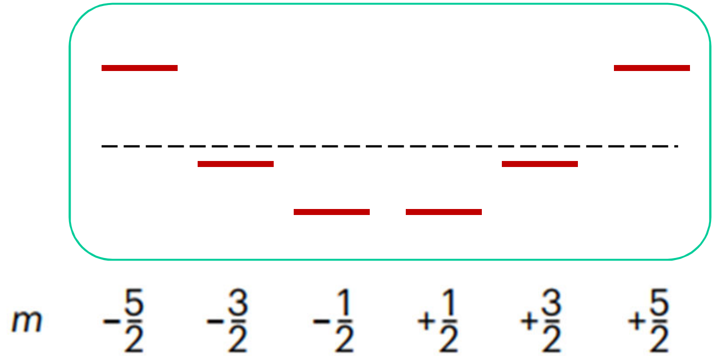


ODT tensor shift: $H_t = \Omega(\boldsymbol{r})F_z^2$

Zeeman shift F_z



Stark shift $(F_z)^2$



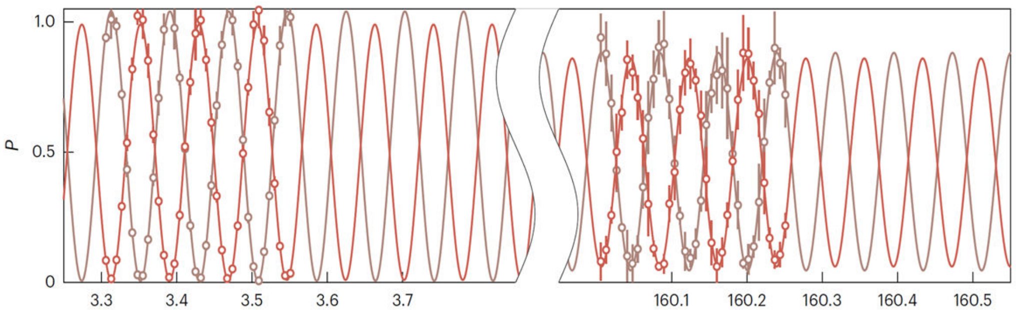
^{173}Yb (I = 5/2) co-magnetometer

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

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

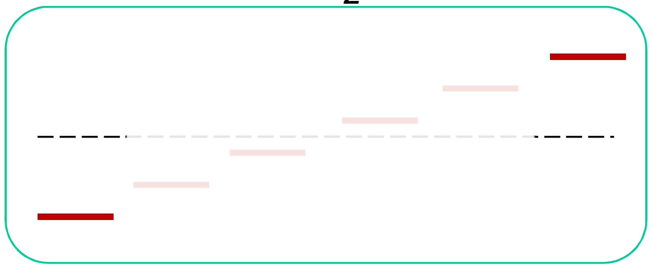
$$H = \Omega(F_x - F_x^2)$$

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

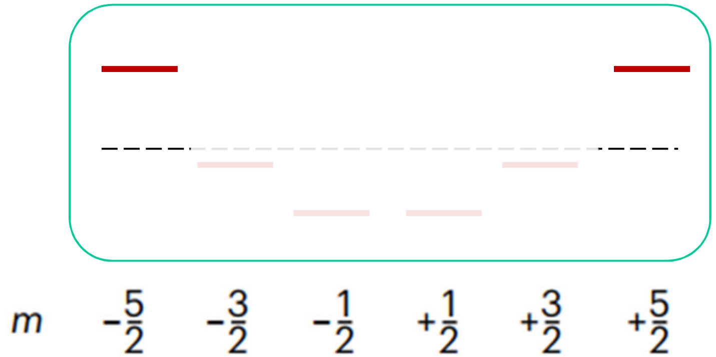


Coherence time ~ 1400 s

Zeeman shift I_z



Stark shift I_z^2



Y. Yang *et al.*, Minute-scale Schroedinger–cat state of spin-5/2 atoms
Nat. Photonics 19, 89 (2025)

Collaboration and Support

USTC

Xin-Peng Lin
Z.-T. Lu
Wei-Tao Luo
Zhi-Jin Tao
Shou-Bo Wang
Shao-Zhen Wang
Tian Xia
Yang Yang
Jie-Ling Zhang
Tao Zheng
Chang-Ling Zou

We acknowledge support by:

- Ministry of Science and Technology
- National Natural Science Foundation
- Chinese Academy of Sciences

林鑫鹏、王守博、王绍政
陶知进
夏添