寻找原子的固有电偶极矩（EDM）

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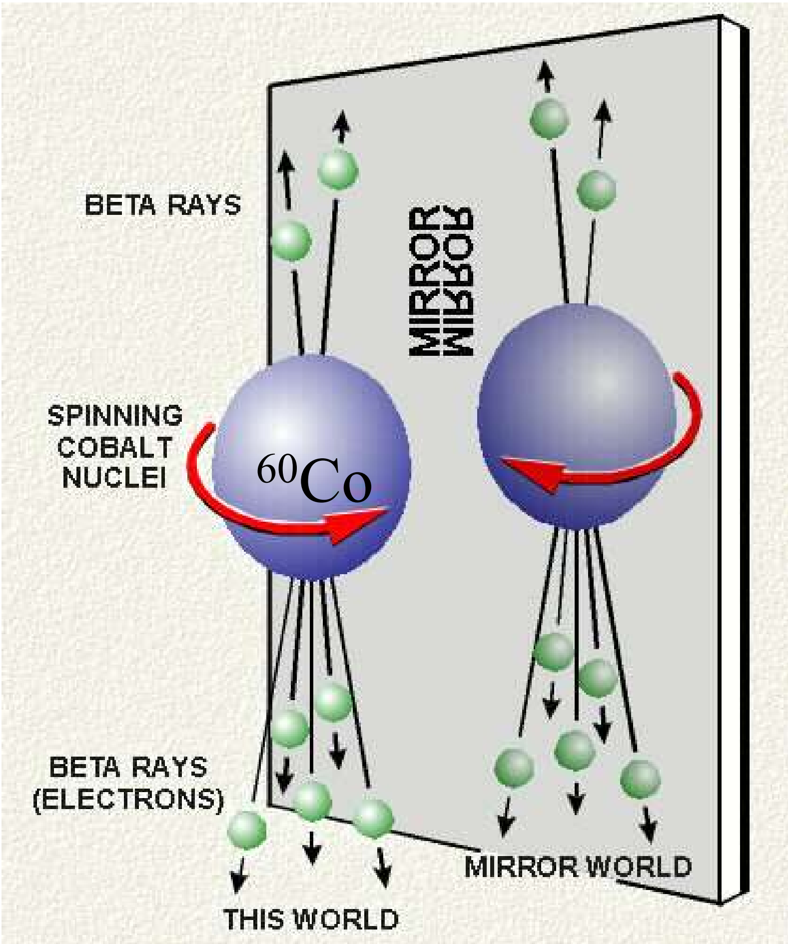
2021年 11月

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

离散基本对称性

宇称不守恒　　吴建雄等（1957）



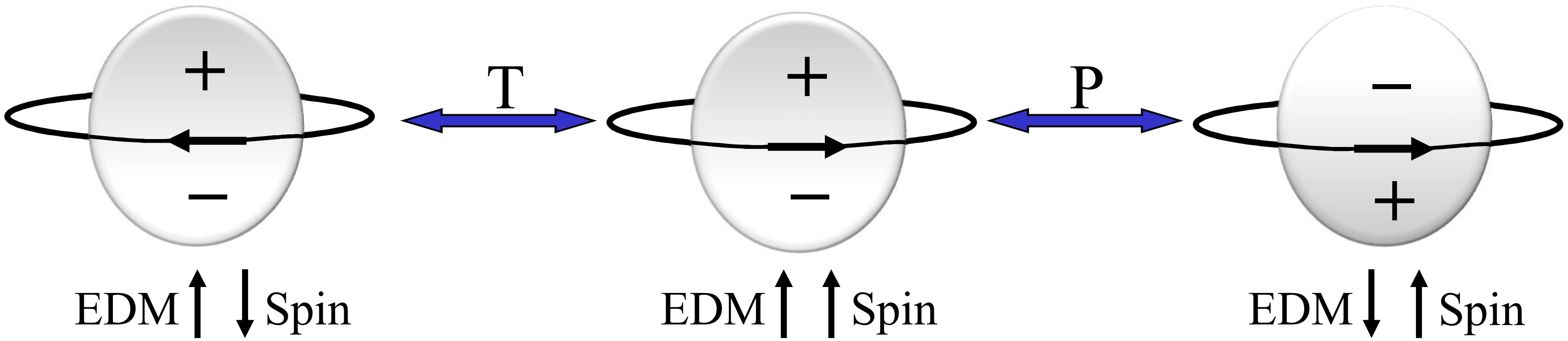
Pseudo-scalar $\vec{s} \cdot \vec{p}$

- ~~P~~ 宇称、空间反演
- ~~C~~ 电荷共轭
- ~~CP~~ 宇称-电荷共轭
- ~~T~~ 时间反演
- CPT 在遵守洛伦茨不变性的量子场论里是守恒的

Permanent EDM violates T or P

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

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



$\not{T} = \not{CP}$

$$H = \mu\, \vec{\sigma} \cdot \vec{B} + d\, \vec{\sigma} \cdot \vec{E}$$

T or P

$$H = \mu\, \vec{\sigma} \cdot \vec{B} - d\, \vec{\sigma} \cdot \vec{E}$$

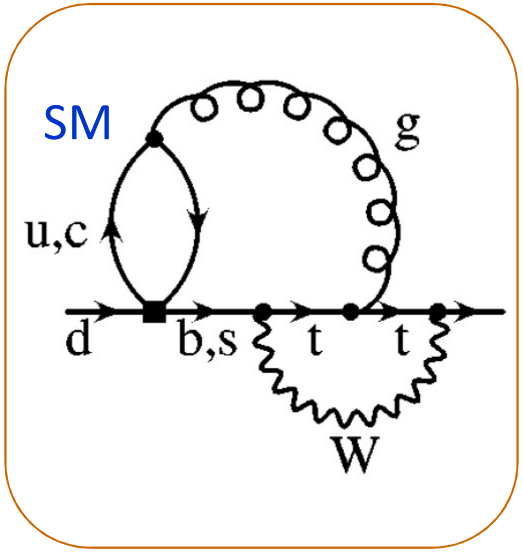
Probe for unknown ~~CP~~ mechanisms

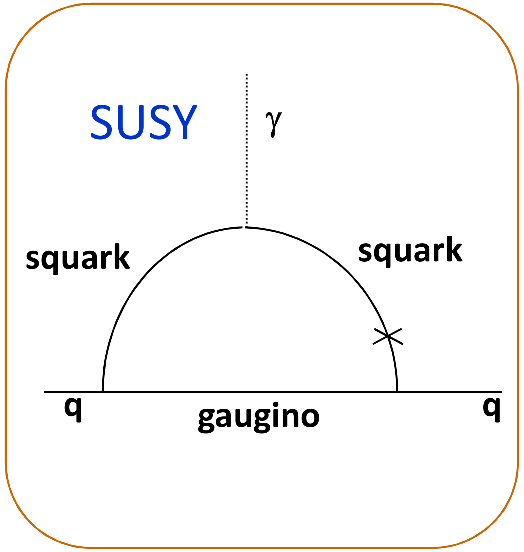
- Strong CP problem: the θ-term in QCD

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

- Supersymmetry: more particles → more ~~CP~~ phases

- Matter-antimatter asymmetry: requires additional ~~CP~~ mechanism(s)





New physics at
10 – 100 TeV

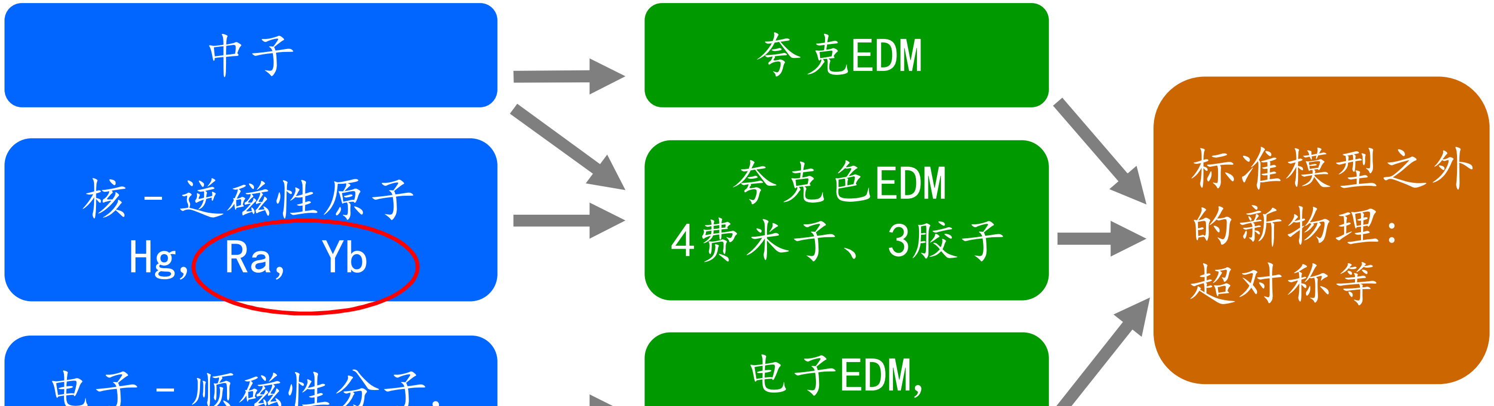
$$d_f \propto e \cdot \sin\phi_{CP} \cdot \frac{m_f}{\Lambda^2}$$

在三种不同系统中寻找 EDM

美、德、瑞士
日本-加拿大

华盛顿大学
阿贡-中科大

哈佛-耶鲁
伦敦帝国理工
美国国家标准局
华东师大



Engel et al., Prog. Part. Nucl. Phys. 71, 21 (2013)

系统	测量上限 (e-cm)	方法	标准模型预期值
电子	1.1 x 10^{-29}	原子束中的 ThO	10^{-38}
中子	1.6 x 10^{-26}	瓶中的超冷中子	10^{-31}
^{199}Hg	7 x 10^{-30}	玻璃管中的汞蒸汽	10^{-33}
^{171}Yb	未被测量	冷原子	10^{-33}
^{225}Ra	1.4 x 10^{-23}	冷原子	10^{-30}

EDM of the Neutron

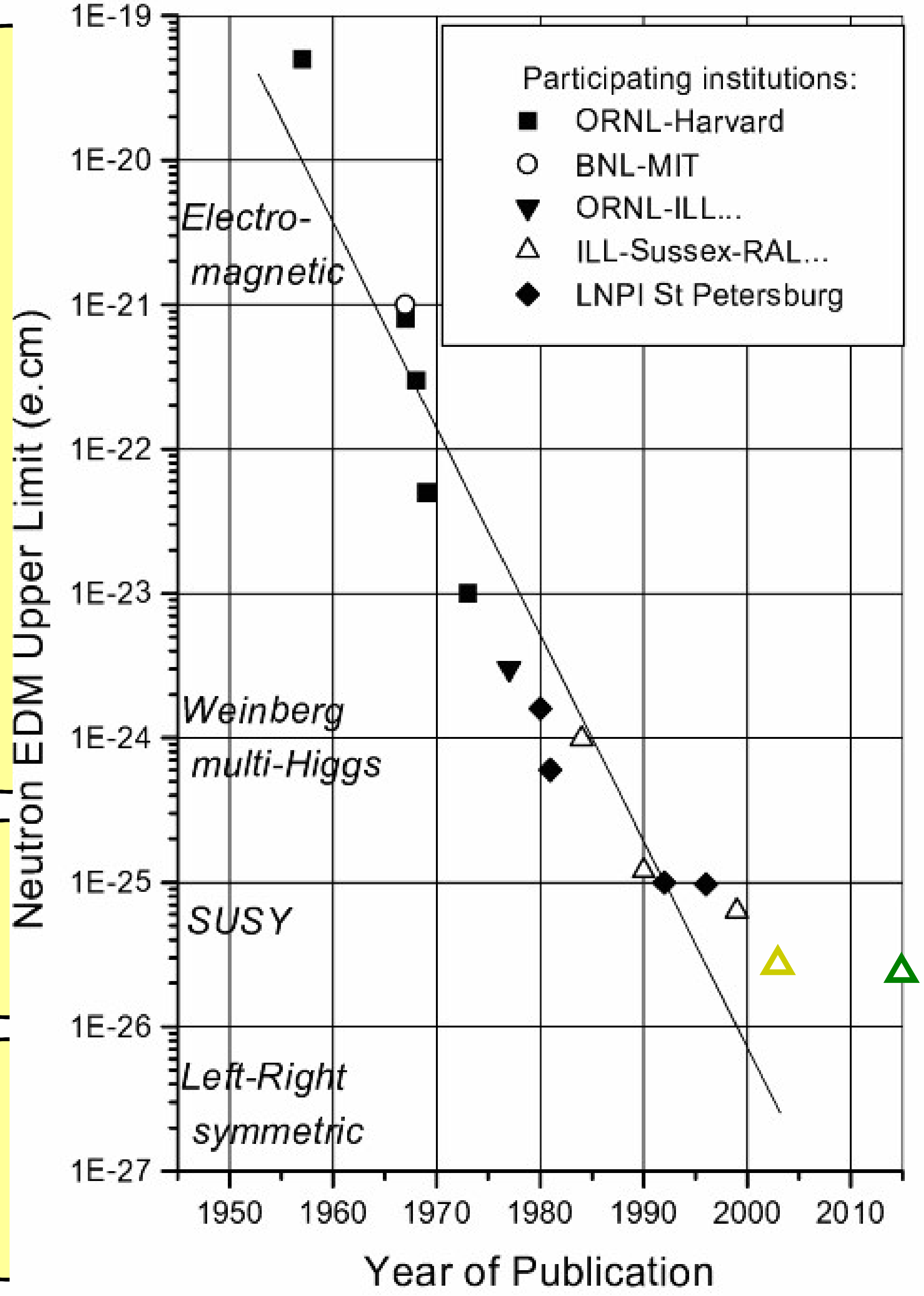
Beam

Limiting factor: $\delta \mathbf{B} \approx \mathbf{v} \times \mathbf{E} / c^2$

$$\omega = \mu \cdot B \pm d \cdot E$$

Ultra-cold neutron Storage

Cryo-storage



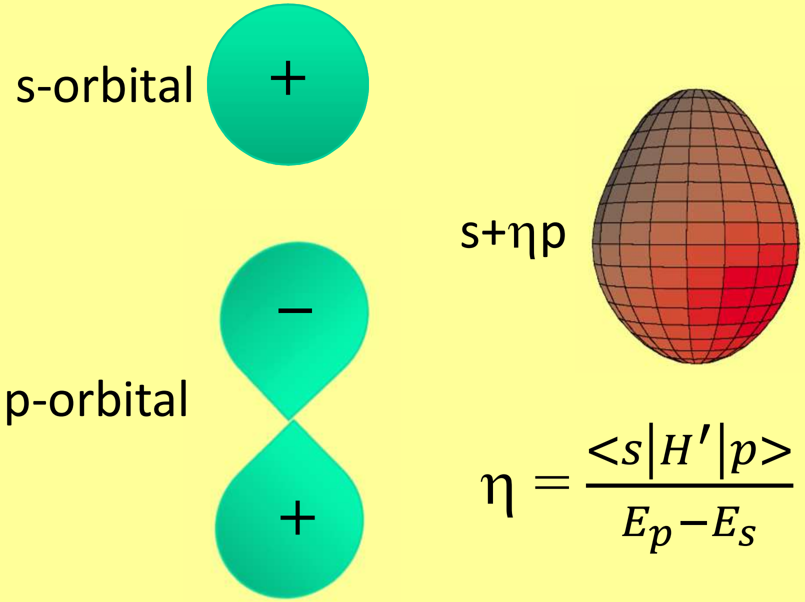
Probing eEDM in a neutral atom or molecule

$$H = -d_{atom} \cdot E_{ext} = -\langle d_e \cdot E_{int}\rangle \xrightarrow{define} -d_e \cdot E_{eff}$$

Problem: $\langle E_{int}\rangle = 0$ Insight: $\langle d_e \cdot E_{int}\rangle \neq d_e \cdot \langle E_{int}\rangle$

Enhancement factor! - P.G.H. Sandars, Phys. Lett. (1965)
Commins, Jackson, DeMille, Am. J. Phys. (2007)

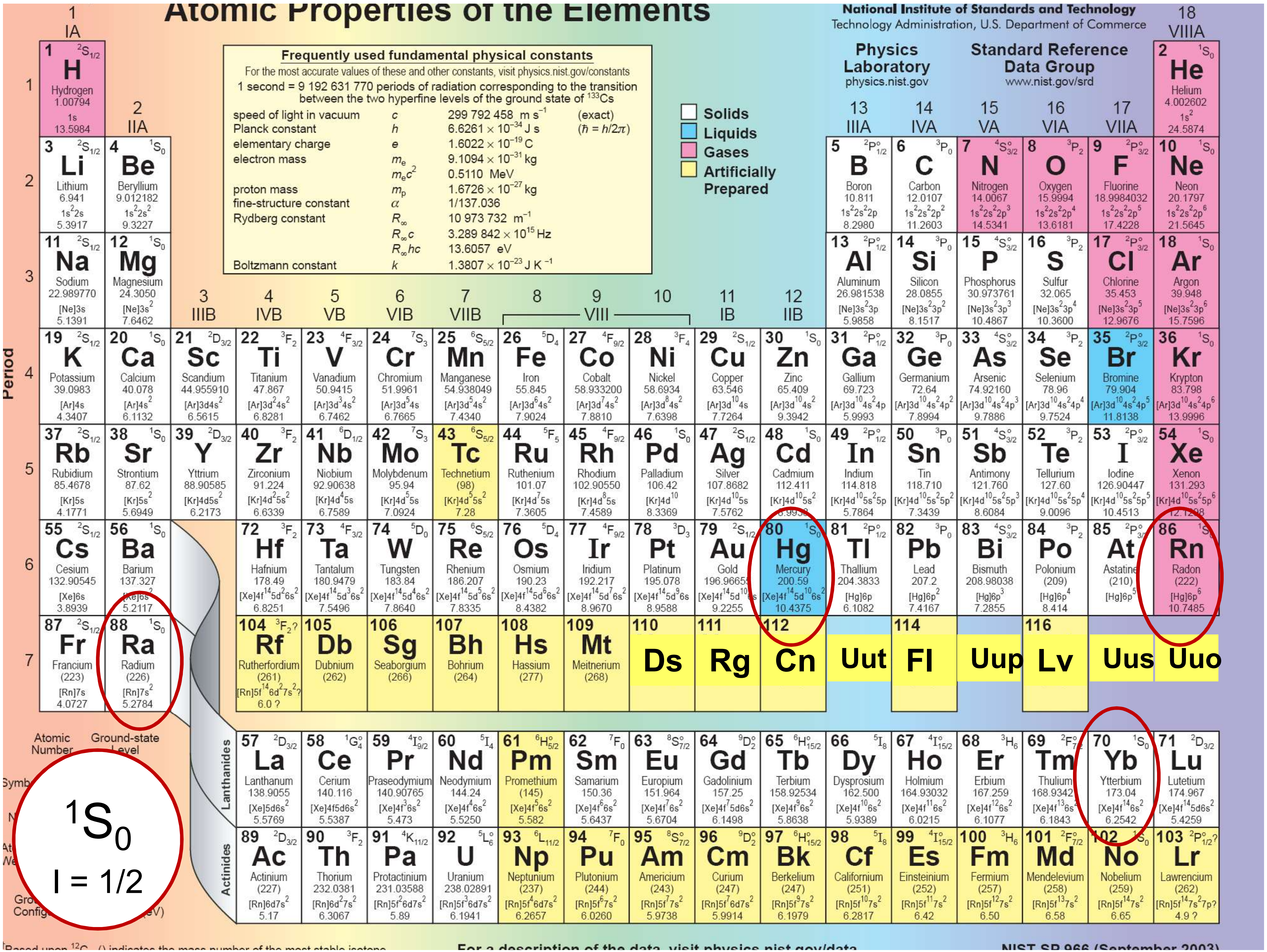
$$|E_{eff}| \quad Z^3 \alpha^2 (e/a_0^2) \cdot \mathcal{P} \sim \mathcal{P} \cdot 10^{11}\ \text{V/cm} \ @\ Z \sim 80$$



$$\eta = \frac{<s|H'|p>}{E_p - E_s}$$

	Tl atom	YbF	ThO
Mixing	s-p	Rotational levels	Ω-doublet
E_ext	100 kV/cm	20 kV/cm	10 V/cm
$\mathcal{P}$	10^{-3}	1	1
E_eff	70 MV/cm	18 GV/cm	80 GV/cm

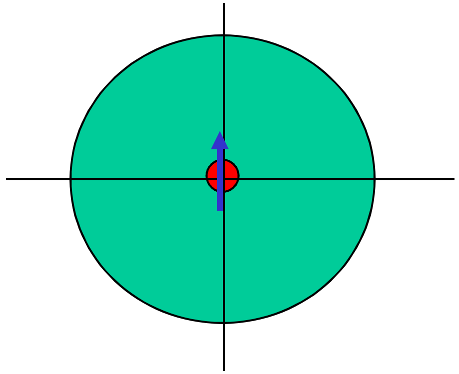
D. DeMille - Yale


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
1 H Hydrogen
2 He Helium
3 Li Lithium
4 Be Beryllium
5 B Boron
6 C Carbon
7 N Nitrogen
8 O Oxygen
9 F Fluorine
10 Ne Neon
11 Na Sodium
12 Mg Magnesium
13 Al Aluminum
14 Si Silicon
15 P Phosphorus
16 S Sulfur
17 Cl Chlorine
18 Ar Argon
19 K Potassium
20 Ca Calcium
21 Sc Scandium
22 Ti Titanium
23 V Vanadium
24 Cr Chromium
25 Mn Manganese
26 Fe Iron
27 Co Cobalt
28 Ni Nickel
29 Cu Copper
30 Zn Zinc
31 Ga Gallium
32 Ge Germanium
33 As Arsenic
34 Se Selenium
35 Br Bromine
36 Kr Krypton
37 Rb Rubidium
38 Sr Strontium
39 Y Yttrium
40 Zr Zirconium
41 Nb Niobium
42 Mo Molybdenum
43 Tc Technetium
44 Ru Ruthenium
45 Rh Rhodium
46 Pd Palladium
47 Ag Silver
48 Cd Cadmium
49 In Indium
50 Sn Tin
51 Sb Antimony
52 Te Tellurium
53 I Iodine
54 Xe Xenon
55 Cs Cesium
56 Ba Barium
72 Hf Hafnium
73 Ta Tantalum
74 W Tungsten
75 Re Rhenium
76 Os Osmium
77 Ir Iridium
78 Pt Platinum
79 Au Gold
80 Hg Mercury
81 Tl Thallium
82 Pb Lead
83 Bi Bismuth
84 Po Polonium
85 At Astatine
86 Rn Radon
87 Fr Francium
88 Ra Radium
104 Rf Rutherfordium
105 Db Dubnium
106 Sg Seaborgium
107 Bh Bohrium
108 Hs Hassium
109 Mt Meitnerium
110 Ds
111 Rg
112 Cn
Uut
114 Fl
Uup
116 Lv
Uus
Uuo
Lanthanides
57 La Lanthanum
58 Ce Cerium
59 Pr Praseodymium
60 Nd Neodymium
61 Pm Promethium
62 Sm Samarium
63 Eu Europium
64 Gd Gadolinium
65 Tb Terbium
66 Dy Dysprosium
67 Ho Holmium
68 Er Erbium
69 Tm Thulium
70 Yb Ytterbium
71 Lu Lutetium
Actinides
89 Ac Actinium
90 Th Thorium
91 Pa Protactinium
92 U Uranium
93 Np Neptunium
94 Pu Plutonium
95 Am Americium
96 Cm Curium
97 Bk Berkelium
98 Cf Californium
99 Es Einsteinium
100 Fm Fermium
101 Md Mendelevium
102 No Nobelium
103 Lr Lawrencium
Atomic Number
Ground-state Level
1S0
I = 1/2
For a description of the data, visit physics.nist.gov/data
NIST SP 966 (September 2003)

Measurability of Nuclear EDM

L.I. Schiff, Phys. Rev. 132, 2194 (1963)

Schiff shielding



$$d_{atom} = \tilde{d}_{atom} + d_{nucleus} = 0$$

However $d_{atom} = \tilde{d}_{atom} + d_{nucleus} \neq 0$

since nuclear charge distribution differs from EDM distribution.

$$d_{atom} \propto \boxed{d_{nucleus} \cdot \left(r_d^2 - r_c^2\right)} \cdot r_{atom}^{-1} \cdot r_c^{-1}$$

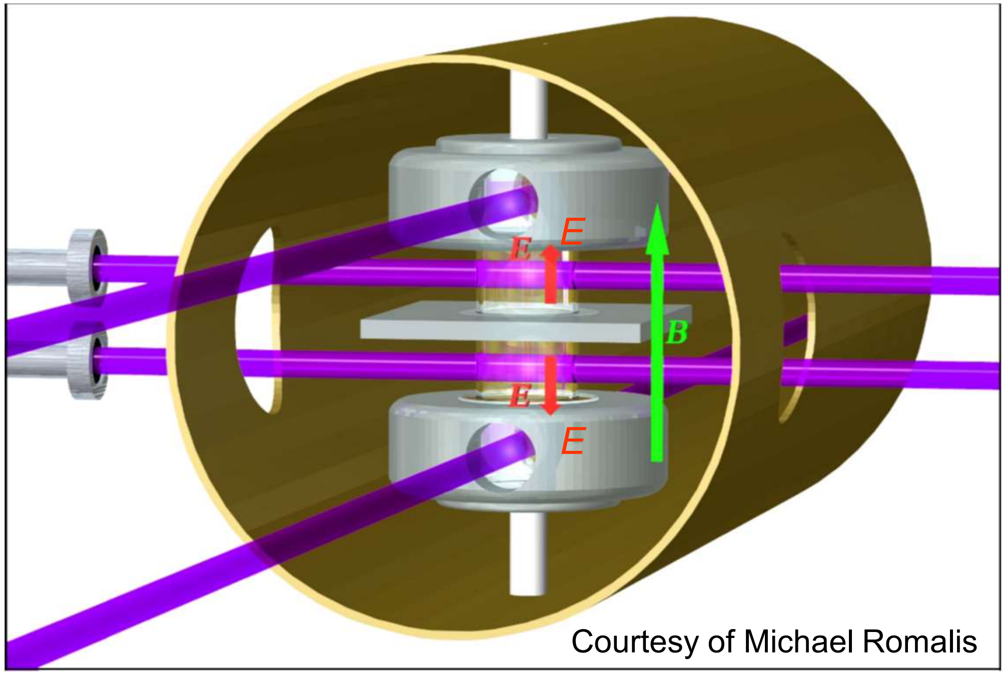
simplified ↗

Schiff moment —rigorous→

$$\vec{S} = \frac{\langle e r^2 \vec{r} \rangle}{10} - \frac{\langle r^2 \rangle \langle e \vec{r} \rangle}{6}$$

The Seattle EDM Measurement

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



Courtesy of Michael Romalis

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

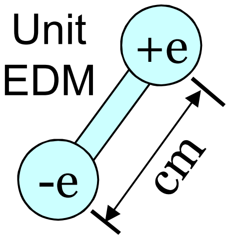
$$f_- = \frac{2\mu B - 2dE}{h} \approx 15\ \mathrm{Hz}$$

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

The best limit on atomic EDM

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

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

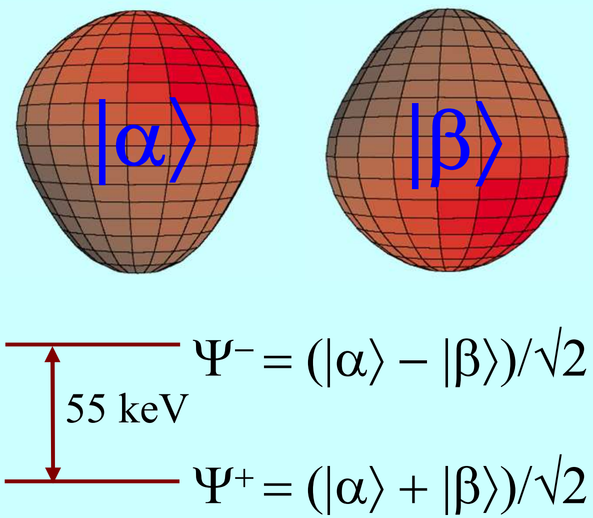


^{225}Ra的EDM：灵敏度高，计算可靠

^{225}Ra:
I = ½
$t_{1/2}$ = 15 d

- 能量接近，宇称相反的双能级系统 – Haxton & Henley, PRL (1983)
- 核八极变形导致较大的席夫极矩 – Auerbach, Flambaum *et al*. PRL (1996)
- 原子重，相对论效应高 (^{225}Ra / ^{199}Hg ~ 3) – Dzuba, Flambaum *et al*., PRA (2002)

宇称相反的双能级系统



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

放大倍数: EDM (^{225}Ra) / EDM (^{199}Hg)

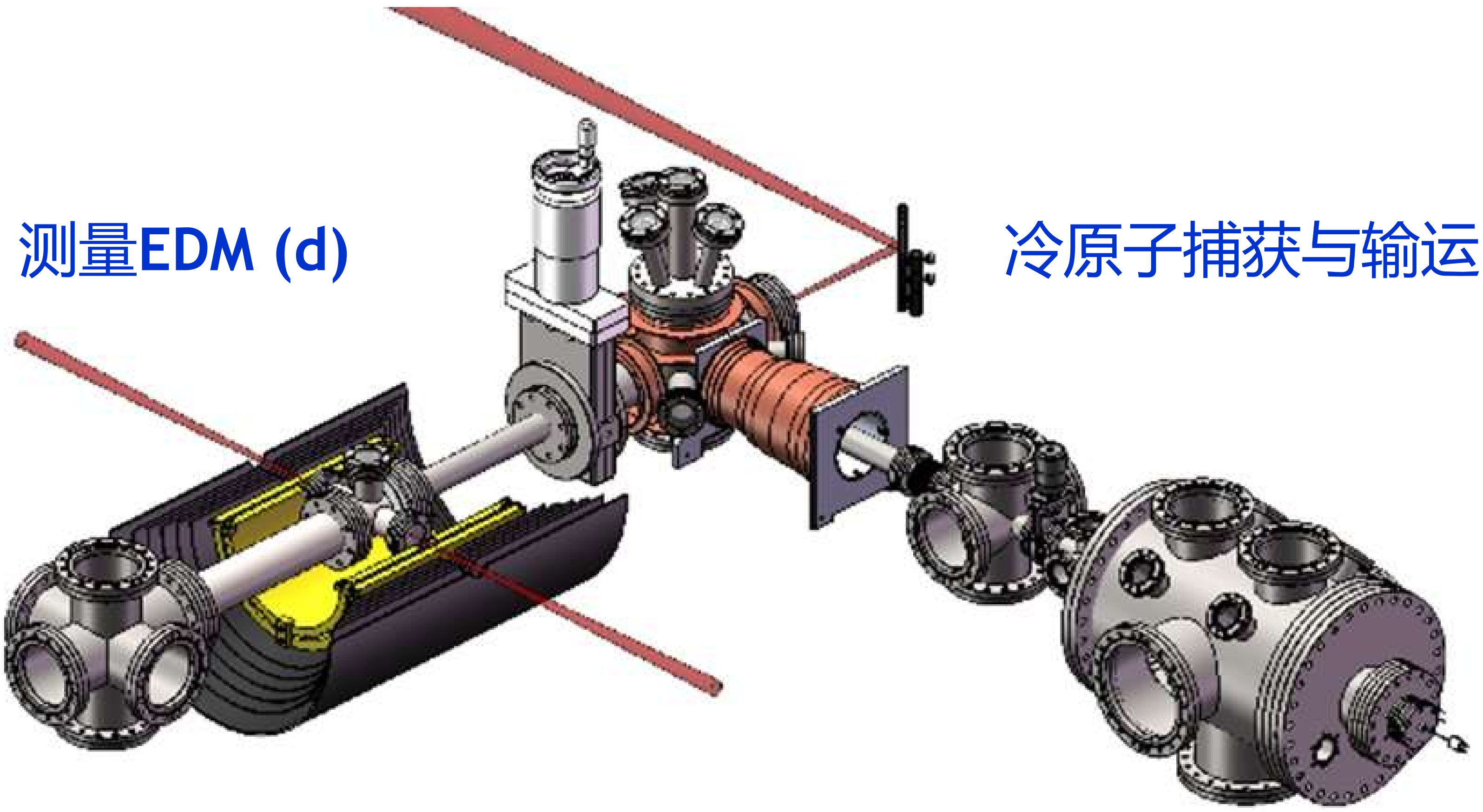
	Isoscalar	Isovector
Skyrme SIII	300	4000
Skyrme SkM*	300	2000
Skyrme SLy4	700	8000

Schiff moment of ^{225}Ra, Dobaczewski, Engel, PRL 94, 232502 (2005)
Schiff moment of ^{199}Hg, Ban *et al*., PRC 82 015501 (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, Phys. Rev. C 91, 035502 (2014)

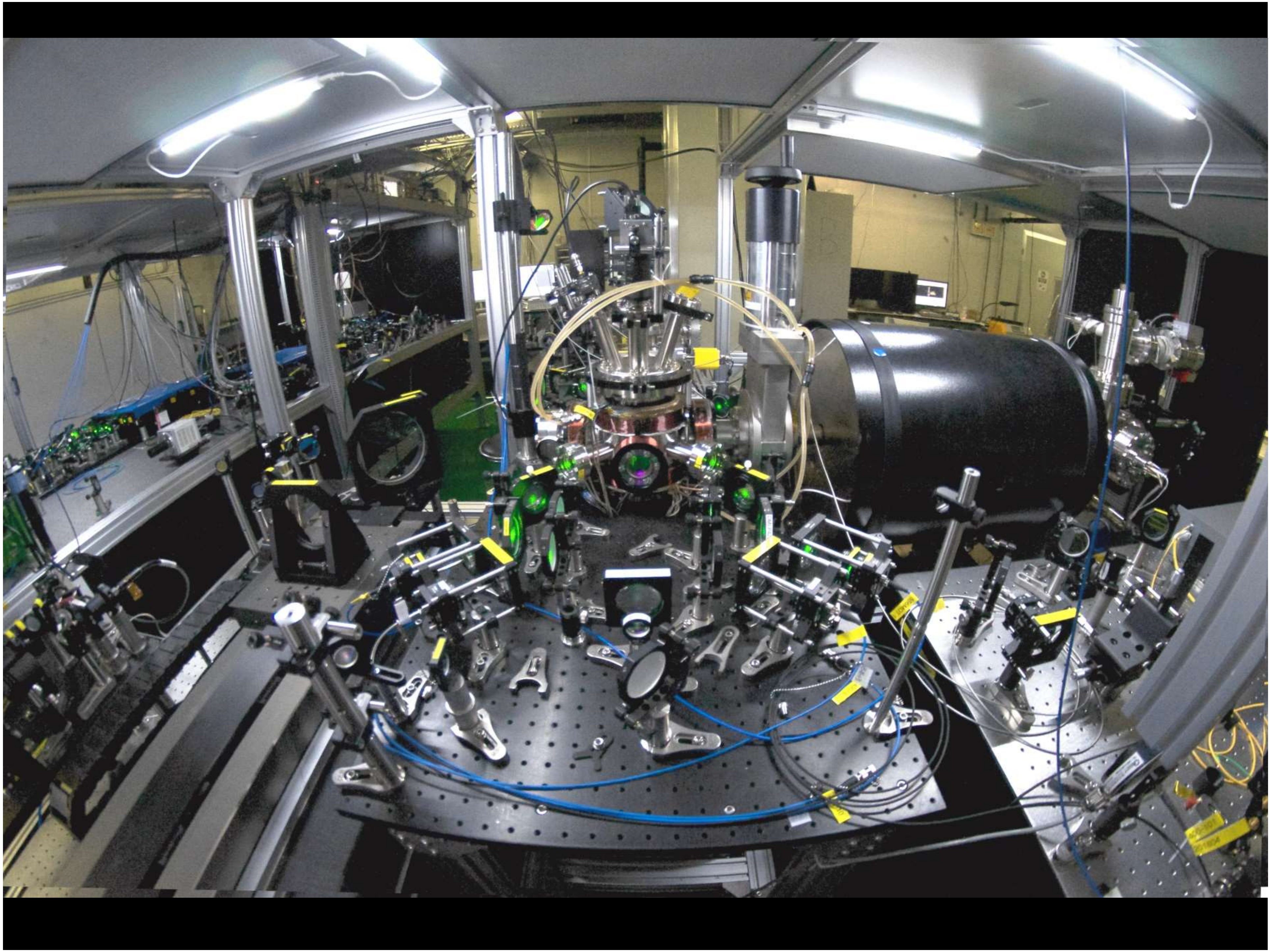
实验装置与方案



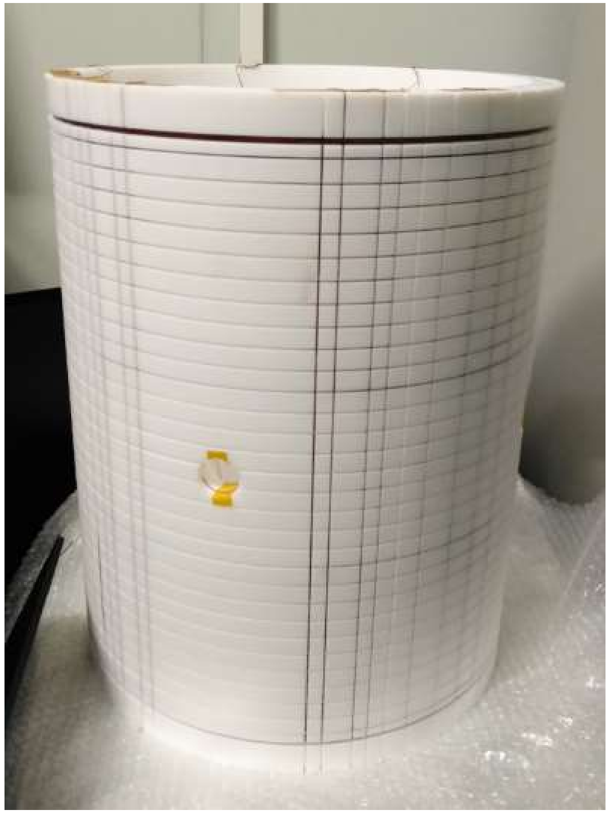
$$\varpi_{+} = 2\mu B + 2dE$$

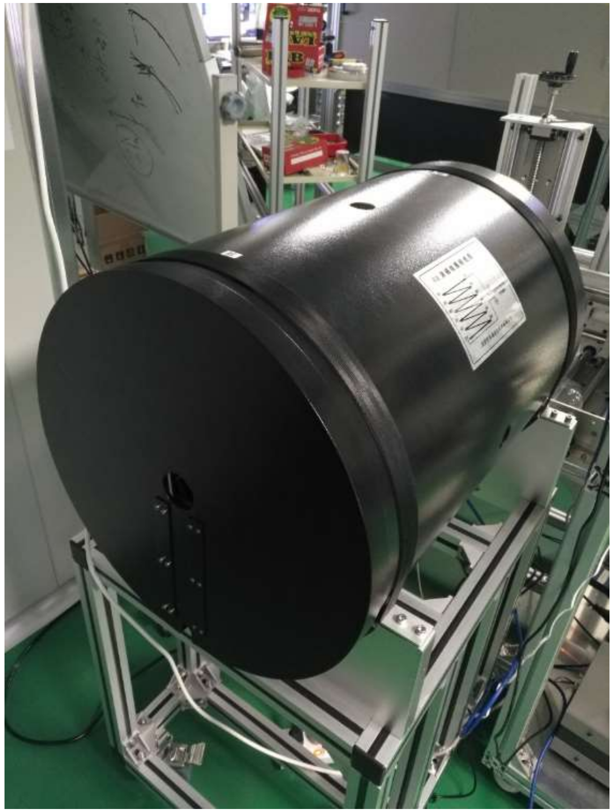
$$\varpi_{-} = 2\mu B - 2dE$$

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



均匀、稳定磁场B





Cos(θ) 线圈
B ~ 20 mGauss （= 2 μT）
dB/dy < 5E-4/cm
ΔB/B = 0.4 ppm (100 s)

μ-metal 磁屏蔽
屏蔽倍数: 50000

残余磁场 < 1 nT

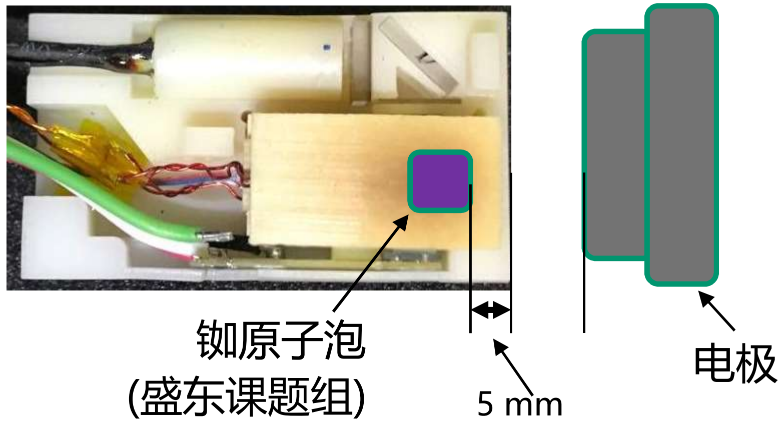
强电场

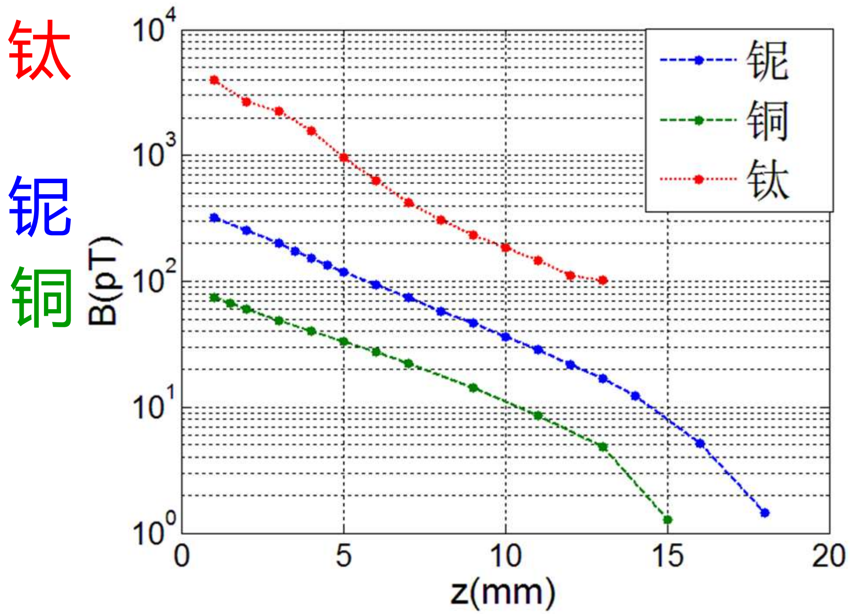
E=130 kV/cm

I_{avg}= 0.4 pA， I_{rms} = 58 pA

极性切换时间：2 s

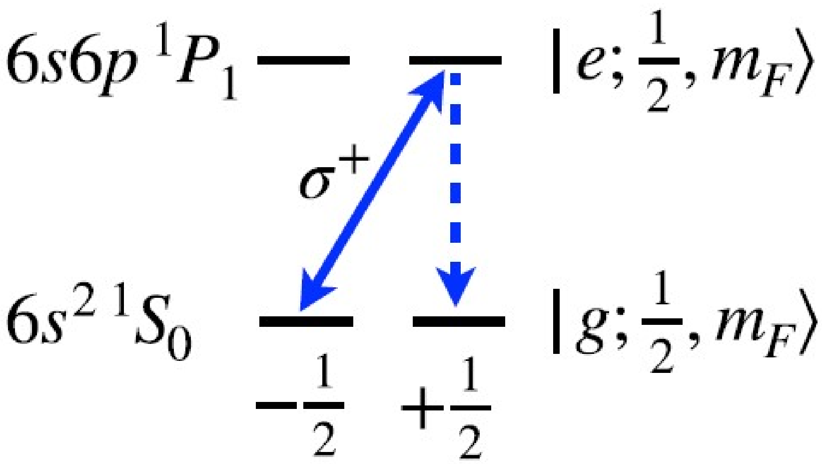
电极表面剩磁测量

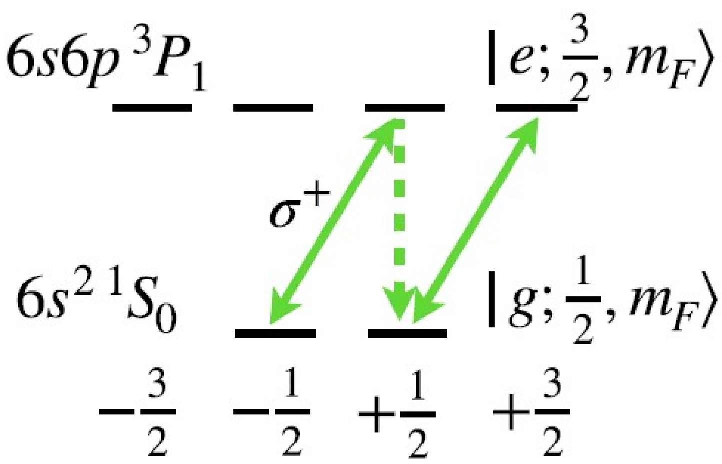




将钛换成铜后，T_2提高至与无电极时一致

自旋极化量子态探测 -- 传统方法



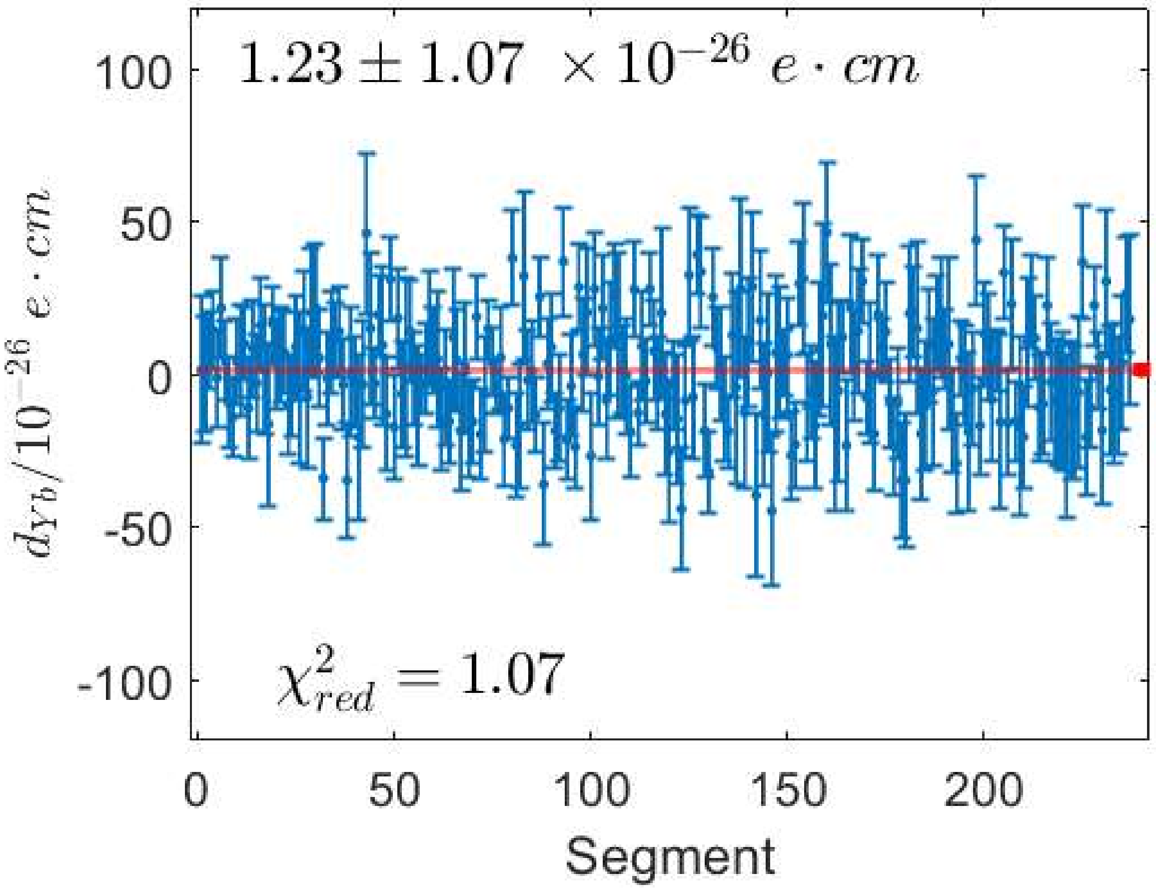


暗态：不吸收
亮态：吸收3个光子

无暗态
不能实现态选择测量

^{171}Yb原子EDM测量进度 1E-26

2021.03



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

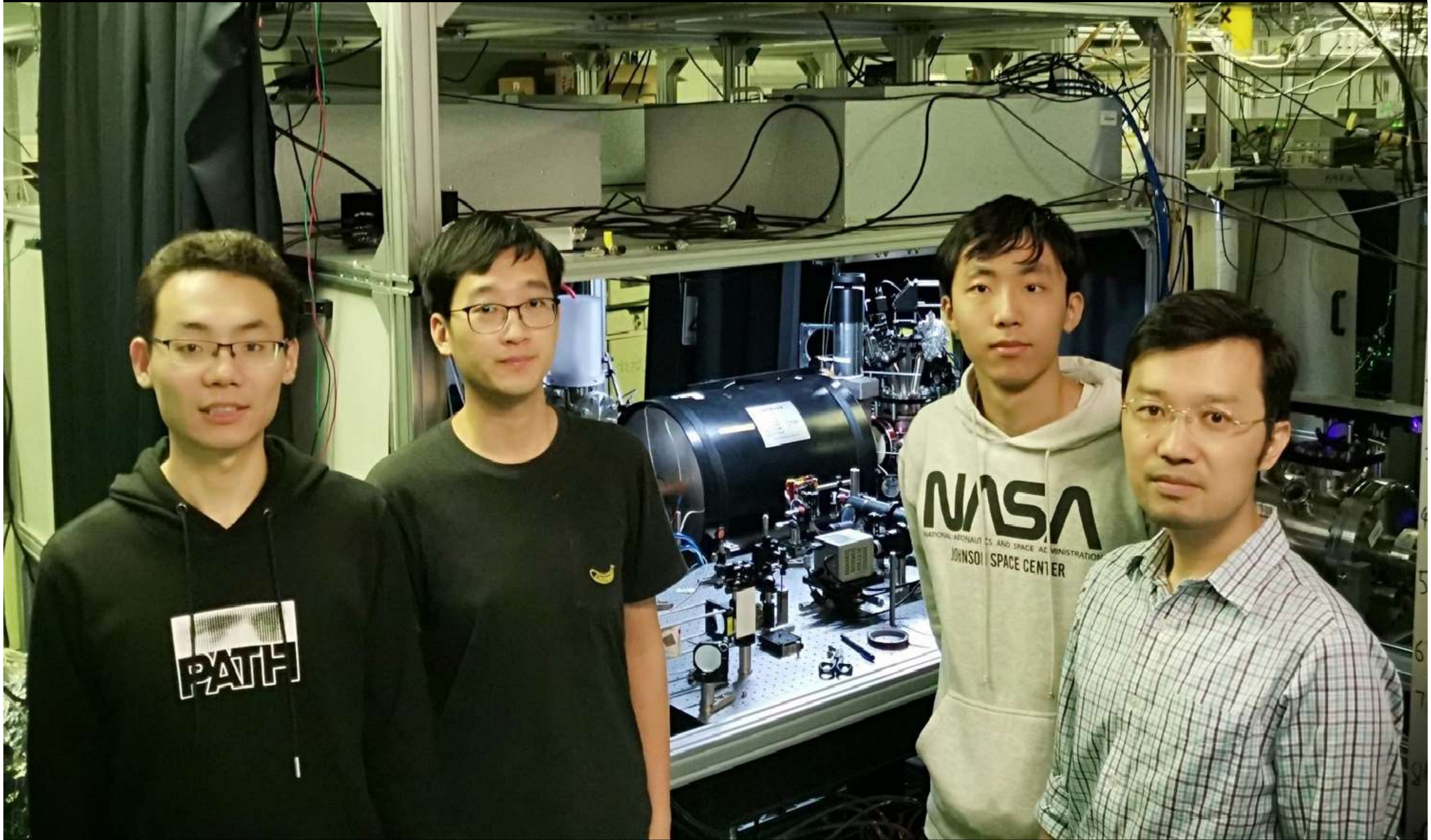
E： 71.8 kV/cm

τ： 96 s

N： 2×10^4

ε： ~30%

T : 260 h (13 d)



郑涛　　王绍政　　杨洋　　夏添