



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

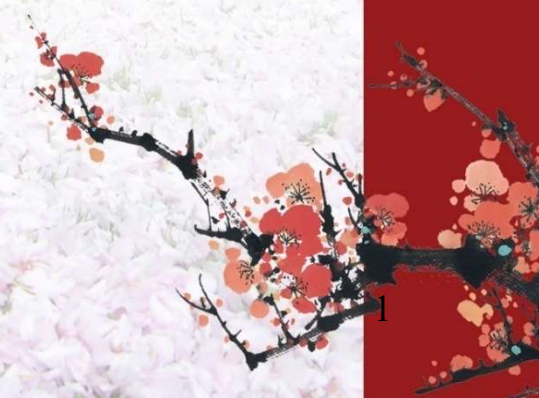
# 寻找原子的固有电偶极矩 (EDM)

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中国科学技术大学

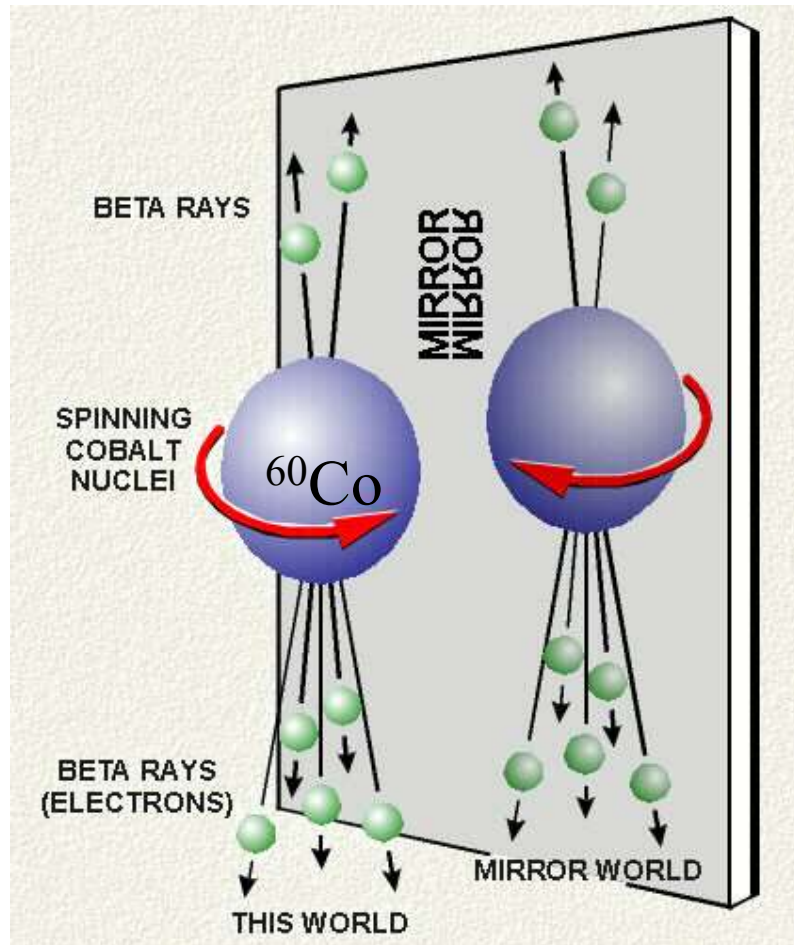
2021年 11月

創寰宇學府  
育天下英才  
嚴濟慈  
一九八八年五月



# 离散基本对称性

宇称不守恒 吴建雄等 (1957)



~~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

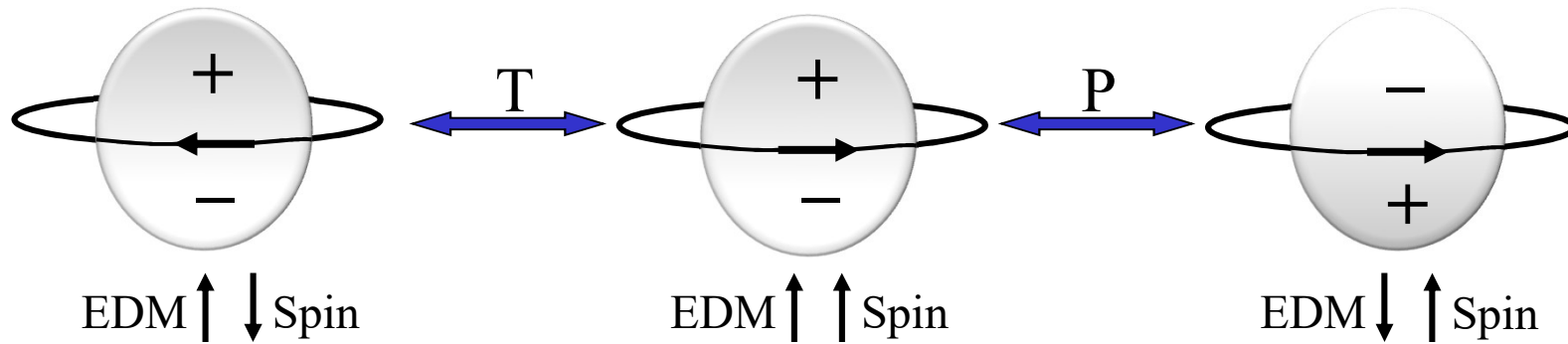
在遵守洛伦茨不变性的量子场论里是守恒的

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

## Permanent EDM violates T or P

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

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



~~T~~ = ~~CP~~

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

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

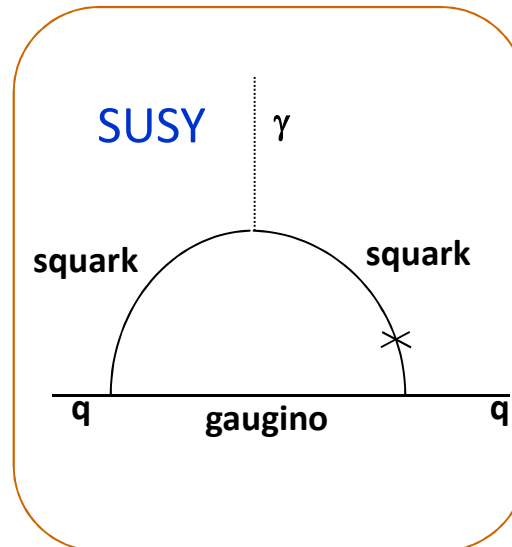
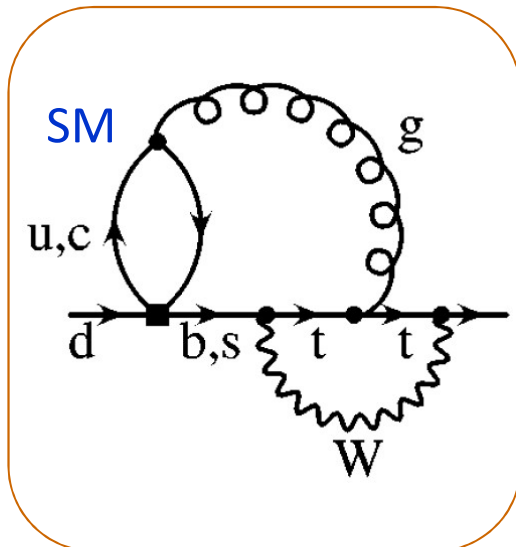
T or P

# Probe for unknown ~~CP~~ mechanisms

- Strong CP problem: the  $\theta$ -term in QCD

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

- Supersymmetry: more particles  $\rightarrow$  more ~~CP~~ phases
- Matter-antimatter asymmetry: requires additional ~~CP~~ mechanism(s)



New physics at  
10 – 100 TeV

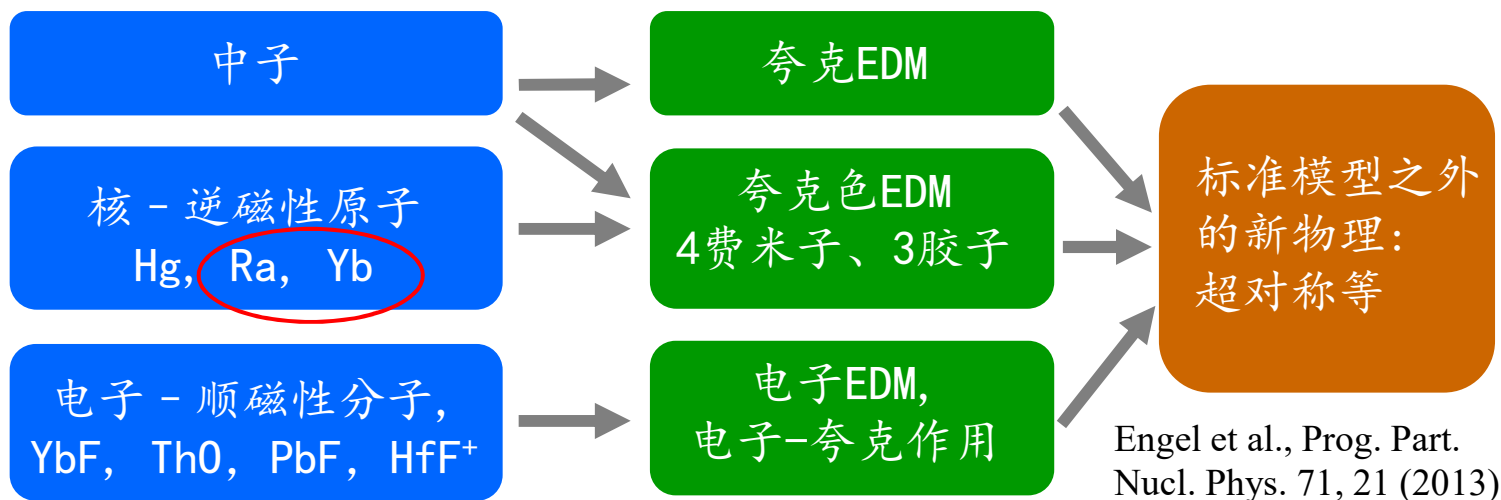
$$d_f \propto e \cdot \sin \phi_{CP} \cdot \frac{m_f}{\Lambda^2}$$

# 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	$1.1 \times 10^{-29}$	原子束中的 ThO	$10^{-38}$
中子	$1.6 \times 10^{-26}$	瓶中的超冷中子	$10^{-31}$
$^{199}\text{Hg}$	$7 \times 10^{-30}$	玻璃管中的汞蒸汽	$10^{-33}$
$^{171}\text{Yb}$	未被测量	冷原子	$10^{-33}$
$^{225}\text{Ra}$	$1.4 \times 10^{-23}$	冷原子	$10^{-30}$

# EDM of the Neutron

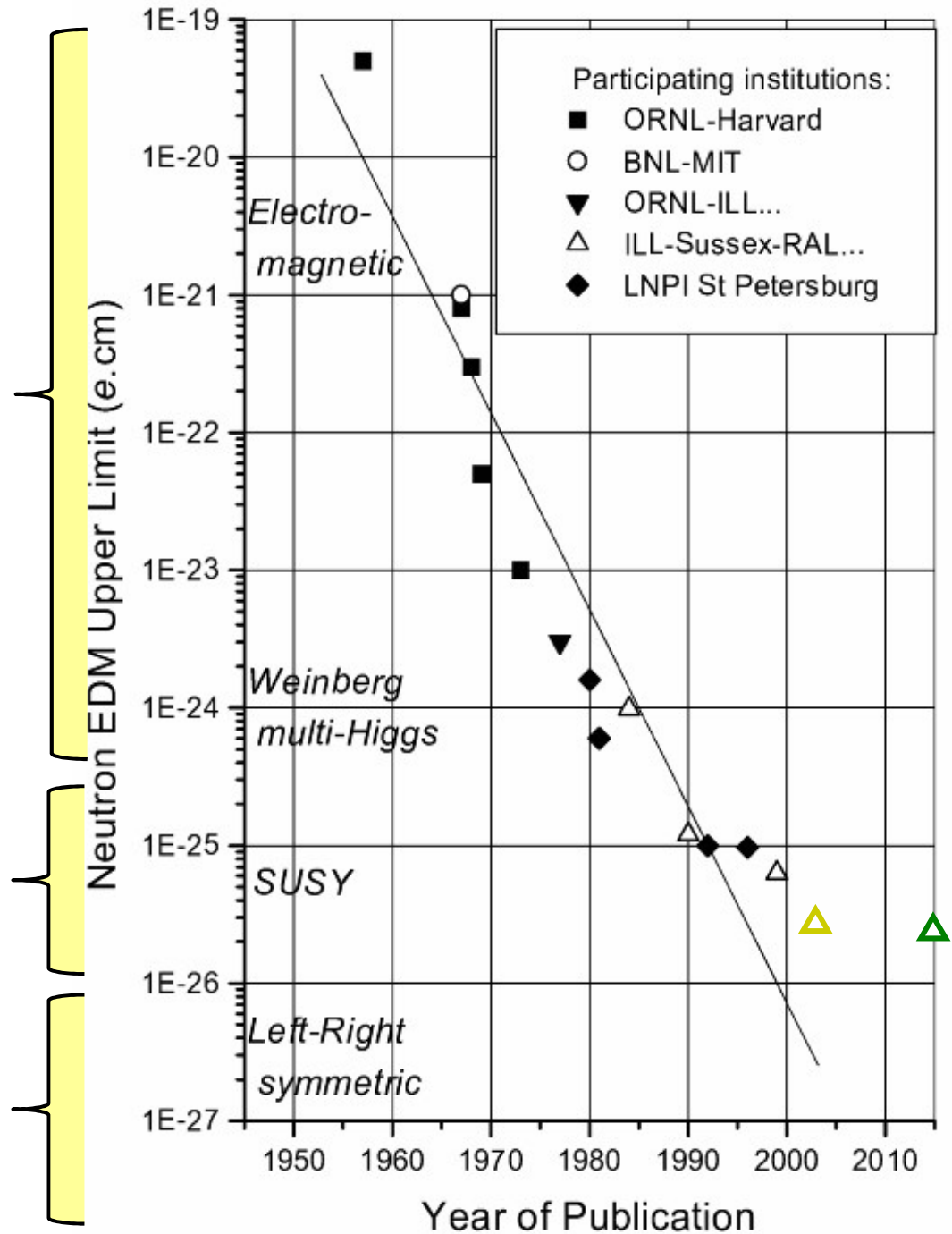
Beam

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



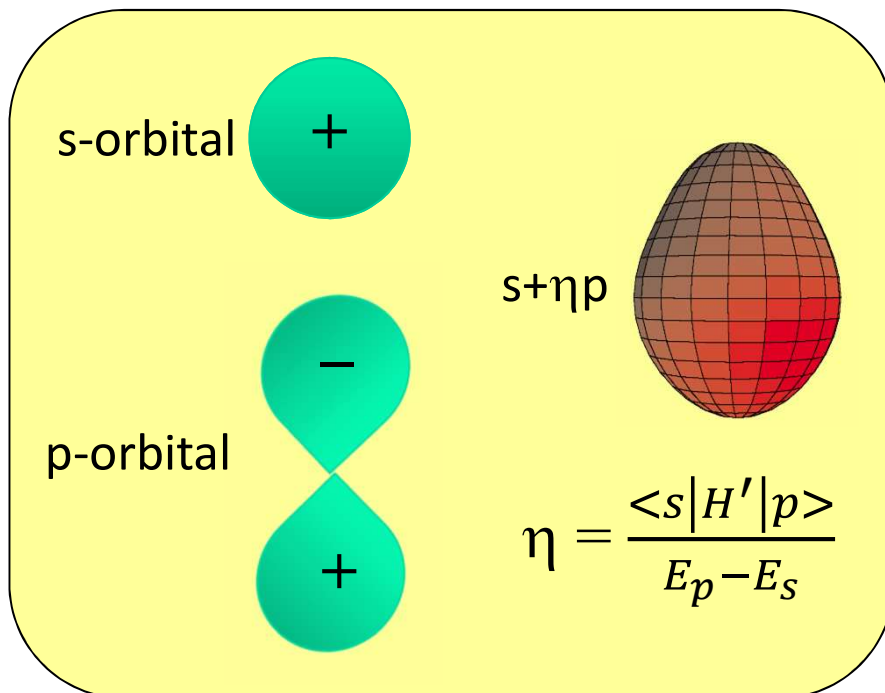
# Probing eEDM in a neutral atom or molecule

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

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)

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



	Tl atom	YbF	ThO
Mixing	s-p	Rotational levels	$\Omega$ -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

**Frequently used fundamental physical constants**  
For the most accurate values of these and other constants, visit [physics.nist.gov/constants](http://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 <sup>133</sup>Cs

speed of light in vacuum	<i>c</i>	299 792 458 m s <sup>-1</sup> (exact)
Planck constant	<i>h</i>	6.6261 × 10 <sup>-34</sup> J s ( <i>ħ</i> = <i>h</i> /2π)
elementary charge	<i>e</i>	1.6022 × 10 <sup>-19</sup> C
electron mass	<i>m<sub>e</sub></i>	9.1094 × 10 <sup>-31</sup> kg
	<i>m<sub>e</sub>c<sup>2</sup></i>	0.5110 MeV
proton mass	<i>m<sub>p</sub></i>	1.6726 × 10 <sup>-27</sup> kg
fine-structure constant	<i>α</i>	1/137.036
Rydberg constant	<i>R<sub>∞</sub></i>	10 973 732 m <sup>-1</sup>
	<i>R<sub>∞</sub>c</i>	3.289 842 × 10 <sup>15</sup> Hz
	<i>R<sub>∞</sub>hc</i>	13.6057 eV
Boltzmann constant	<i>k</i>	1.3807 × 10 <sup>-23</sup> J K <sup>-1</sup>

- Solids
- Liquids
- Gases
- Artificially Prepared

		Physics Laboratory physics.nist.gov				Standard Reference Data Group www.nist.gov/srd															
		13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA														
1	<sup>1</sup> S <sub>1/2</sub>	5 <b>B</b> Boron 10.811 1s <sup>2</sup> 2s <sup>2</sup> 2p 8.2980	6 <b>C</b> Carbon 12.0107 1s <sup>2</sup> 2s <sup>2</sup> 2p <sup>2</sup> 11.2603	7 <b>N</b> Nitrogen 14.0067 1s <sup>2</sup> 2s <sup>2</sup> 2p <sup>3</sup> 14.5341	8 <b>O</b> Oxygen 15.9994 1s <sup>2</sup> 2s <sup>2</sup> 2p <sup>4</sup> 13.6181	9 <b>F</b> Fluorine 18.9984032 1s <sup>2</sup> 2s <sup>2</sup> 2p <sup>5</sup> 17.4228	10 <b>Ne</b> Neon 20.1797 1s <sup>2</sup> 2s <sup>2</sup> 2p <sup>6</sup> 21.5645														
2	<sup>1</sup> S <sub>0</sub>	11 <b>Na</b> Sodium 22.989770 [Ne]3s 5.1391	12 <b>Mg</b> Magnesium 24.3050 [Ne]3s <sup>2</sup> 7.6462	13 <b>Al</b> Aluminum 26.981538 [Ne]3s <sup>2</sup> 3p 5.9858	14 <b>Si</b> Silicon 28.0855 [Ne]3s <sup>2</sup> 3p <sup>2</sup> 8.1517	15 <b>P</b> Phosphorus 30.973761 [Ne]3s <sup>2</sup> 3p <sup>3</sup> 10.4867	16 <b>S</b> Sulfur 32.065 [Ne]3s <sup>2</sup> 3p <sup>4</sup> 10.3600	17 <b>Cl</b> Chlorine 35.453 [Ne]3s <sup>2</sup> 3p <sup>5</sup> 12.9676	18 <b>Ar</b> Argon 39.948 [Ne]3s <sup>2</sup> 3p <sup>6</sup> 15.7596												
3	<sup>2</sup> S <sub>1/2</sub>	19 <b>K</b> Potassium 39.0983 [Ar]4s 4.3407	20 <b>Ca</b> Calcium 40.078 [Ar]4s <sup>2</sup> 6.1132	21 <b>Sc</b> Scandium 44.955910 [Ar]3d4s <sup>2</sup> 6.5615	22 <b>Ti</b> Titanium 47.867 [Ar]3d <sup>2</sup> 4s <sup>2</sup> 6.8281	23 <b>V</b> Vanadium 50.9415 [Ar]3d <sup>3</sup> 4s <sup>2</sup> 6.7462	24 <b>Cr</b> Chromium 51.9961 [Ar]3d <sup>5</sup> 4s 6.7665	25 <b>Mn</b> Manganese 54.938049 [Ar]3d <sup>5</sup> 4s <sup>2</sup> 7.4340	26 <b>Fe</b> Iron 55.845 [Ar]3d <sup>6</sup> 4s <sup>2</sup> 7.9024	27 <b>Co</b> Cobalt 58.933200 [Ar]3d <sup>7</sup> 4s <sup>2</sup> 7.8810	28 <b>Ni</b> Nickel 58.6934 [Ar]3d <sup>8</sup> 4s <sup>2</sup> 7.6398	29 <b>Cu</b> Copper 63.546 [Ar]3d <sup>10</sup> 4s 7.7264	30 <b>Zn</b> Zinc 65.409 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 9.3842	31 <b>Ga</b> Gallium 69.723 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p 5.9993	32 <b>Ge</b> Germanium 72.64 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>2</sup> 7.8984	33 <b>As</b> Arsenic 74.92160 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>3</sup> 9.7886	34 <b>Se</b> Selenium 78.96 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>4</sup> 9.7524	35 <b>Br</b> Bromine 79.904 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>5</sup> 11.8138	36 <b>Kr</b> Krypton 83.798 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>6</sup> 13.9996		
4	<sup>2</sup> S <sub>1/2</sub>	37 <b>Rb</b> Rubidium 85.4678 [Kr]5s 4.1771	38 <b>Sr</b> Strontium 87.62 [Kr]5s <sup>2</sup> 5.6949	39 <b>Y</b> Yttrium 88.90585 [Kr]4d5s <sup>2</sup> 6.2173	40 <b>Zr</b> Zirconium 91.224 [Kr]4d <sup>2</sup> 5s <sup>2</sup> 6.6339	41 <b>Nb</b> Niobium 92.90638 [Kr]4d <sup>4</sup> 5s 6.7589	42 <b>Mo</b> Molybdenum 95.94 [Kr]4d <sup>5</sup> 5s <sup>2</sup> 7.0924	43 <b>Tc</b> Technetium (98) [Kr]4d <sup>5</sup> 5s <sup>2</sup> 7.28	44 <b>Ru</b> Ruthenium 101.07 [Kr]4d <sup>8</sup> 5s 7.3605	45 <b>Rh</b> Rhodium 102.90550 [Kr]4d <sup>8</sup> 5s 7.4589	46 <b>Pd</b> Palladium 106.42 [Kr]4d <sup>10</sup> 8.3369	47 <b>Ag</b> Silver 107.8682 [Kr]4d <sup>10</sup> 5s 7.5762	48 <b>Cd</b> Cadmium 112.411 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 8.9935	49 <b>In</b> Indium 114.818 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p 5.7864	50 <b>Sn</b> Tin 118.710 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>2</sup> 7.3439	51 <b>Sb</b> Antimony 121.760 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>3</sup> 8.6084	52 <b>Te</b> Tellurium 127.60 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>4</sup> 9.0096	53 <b>I</b> Iodine 126.90447 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>5</sup> 10.4513	54 <b>Xe</b> Xenon 131.293 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>6</sup> 12.1298		
5	<sup>2</sup> S <sub>1/2</sub>	55 <b>Cs</b> Cesium 132.90545 [Xe]6s 3.8939	56 <b>Ba</b> Barium 137.327 [Xe]6s 5.2117	72 <b>Hf</b> Hafnium 178.49 [Xe]4f <sup>14</sup> 5d <sup>2</sup> 6s <sup>2</sup> 6.8251	73 <b>Ta</b> Tantalum 180.9479 [Xe]4f <sup>14</sup> 5d <sup>3</sup> 6s <sup>2</sup> 7.5496	74 <b>W</b> Tungsten 183.84 [Xe]4f <sup>14</sup> 5d <sup>4</sup> 6s <sup>2</sup> 7.8640	75 <b>Re</b> Rhenium 186.207 [Xe]4f <sup>14</sup> 5d <sup>5</sup> 6s <sup>2</sup> 7.8335	76 <b>Os</b> Osmium 190.23 [Xe]4f <sup>14</sup> 5d <sup>6</sup> 6s <sup>2</sup> 8.4382	77 <b>Ir</b> Iridium 192.217 [Xe]4f <sup>14</sup> 5d <sup>7</sup> 6s <sup>2</sup> 8.9670	78 <b>Pt</b> Platinum 195.078 [Xe]4f <sup>14</sup> 5d <sup>9</sup> 6s 8.9588	79 <b>Au</b> Gold 196.9665 [Xe]4f <sup>14</sup> 5d <sup>10</sup> 6s 9.2255	80 <b>Hg</b> Mercury 200.59 [Xe]4f <sup>14</sup> 5d <sup>10</sup> 6s 10.4375	81 <b>Tl</b> Thallium 204.3833 [Hg]6p 6.1082	82 <b>Pb</b> Lead 207.2 [Hg]6p <sup>2</sup> 7.4167	83 <b>Bi</b> Bismuth 208.98038 [Hg]6p <sup>3</sup> 7.2855	84 <b>Po</b> Polonium (209) [Hg]6p <sup>4</sup> 8.414	85 <b>At</b> Astatine (210) [Hg]6p <sup>5</sup>	86 <b>Rn</b> Radon (222) [Hg]6p <sup>6</sup> 10.7485			
6	<sup>2</sup> S <sub>1/2</sub>	87 <b>Fr</b> Francium (223) [Rn]7s 4.0727	88 <b>Ra</b> Radium (226) [Rn]7s <sup>2</sup> 5.2784	104 <b>Rf</b> Rutherfordium (261) [Rn]5f <sup>14</sup> 6d <sup>2</sup> 7s <sup>2</sup> 6.0 ?	105 <b>Db</b> Dubnium (262)	106 <b>Sg</b> Seaborgium (266)	107 <b>Bh</b> Bohrium (264)	108 <b>Hs</b> Hassium (277)	109 <b>Mt</b> Meitnerium (268)	110 <b>Ds</b>	111 <b>Rg</b>	112 <b>Cn</b>	114 <b>Uut</b>	116 <b>Uup</b>	118 <b>Uuq</b>	120 <b>Uuo</b>					
7	<sup>2</sup> S <sub>1/2</sub>			101 <b>La</b> Lanthanum 138.9055 [Xe]5d6s <sup>2</sup> 5.5769	102 <b>Ce</b> Cerium 140.116 [Xe]4f5d6s <sup>2</sup> 5.5387	103 <b>Pr</b> Praseodymium 140.90765 [Xe]4f <sup>3</sup> 6s <sup>2</sup> 5.473	104 <b>Nd</b> Neodymium 144.24 [Xe]4f <sup>4</sup> 6s <sup>2</sup> 5.5250	105 <b>Pm</b> Promethium (145) [Xe]4f <sup>5</sup> 6s <sup>2</sup> 5.582	106 <b>Sm</b> Samarium 150.36 [Xe]4f <sup>6</sup> 6s <sup>2</sup> 5.6437	107 <b>Eu</b> Europium 151.964 [Xe]4f <sup>7</sup> 6s <sup>2</sup> 5.6704	108 <b>Gd</b> Gadolinium 157.25 [Xe]4f <sup>7</sup> 6s <sup>2</sup> 6.1498	109 <b>Tb</b> Terbium 158.92534 [Xe]4f <sup>9</sup> 6s <sup>2</sup> 5.8638	110 <b>Dy</b> Dysprosium 162.500 [Xe]4f <sup>10</sup> 6s <sup>2</sup> 5.9389	111 <b>Ho</b> Holmium 164.93032 [Xe]4f <sup>11</sup> 6s <sup>2</sup> 6.0215	112 <b>Er</b> Erbium 167.259 [Xe]4f <sup>12</sup> 6s <sup>2</sup> 6.1077	113 <b>Tm</b> Thulium 168.9342 [Xe]4f <sup>13</sup> 6s <sup>2</sup> 6.1843	114 <b>Yb</b> Ytterbium 173.04 [Xe]4f <sup>14</sup> 6s <sup>2</sup> 6.2542	115 <b>Lu</b> Lutetium 174.967 [Xe]4f <sup>14</sup> 5d6s <sup>2</sup> 5.4259			
	<sup>2</sup> S <sub>1/2</sub>	89 <b>Ac</b> Actinium (227) [Rn]6d7s <sup>2</sup> 5.17	90 <b>Th</b> Thorium 232.0381 [Rn]6d <sup>2</sup> 7s <sup>2</sup> 6.3067	91 <b>Pa</b> Protactinium 231.03588 [Rn]5f <sup>2</sup> 6d7s <sup>2</sup> 5.89	92 <b>U</b> Uranium 238.02891 [Rn]5f <sup>3</sup> 6d7s <sup>2</sup> 6.1941	93 <b>Np</b> Neptunium (237) [Rn]5f <sup>4</sup> 6d7s <sup>2</sup> 6.2657	94 <b>Pu</b> Plutonium (244) [Rn]5f <sup>6</sup> 7s <sup>2</sup> 6.0260	95 <b>Am</b> Americium (243) [Rn]5f <sup>7</sup> 7s <sup>2</sup> 5.9738	96 <b>Cm</b> Curium (247) [Rn]5f <sup>8</sup> 7s <sup>2</sup> 5.9914	97 <b>Bk</b> Berkelium (247) [Rn]5f <sup>9</sup> 7s <sup>2</sup> 6.1979	98 <b>Cf</b> Californium (251) [Rn]5f <sup>10</sup> 7s <sup>2</sup> 6.2817	99 <b>Es</b> Einsteinium (252) [Rn]5f <sup>11</sup> 7s <sup>2</sup> 6.42	100 <b>Fm</b> Fermium (257) [Rn]5f <sup>12</sup> 7s <sup>2</sup> 6.50	101 <b>Md</b> Mendelevium (258) [Rn]5f <sup>13</sup> 7s <sup>2</sup> 6.58	102 <b>No</b> Nobelium (259) [Rn]5f <sup>14</sup> 7s <sup>2</sup> 6.65	103 <b>Lr</b> Lawrencium (260) [Rn]5f <sup>14</sup> 7s <sup>2</sup> 7p? 4.9 ?					

Period

Atomic Number

Ground-state Level

**1S<sub>0</sub>**  
**I = 1/2**

Lanthanides

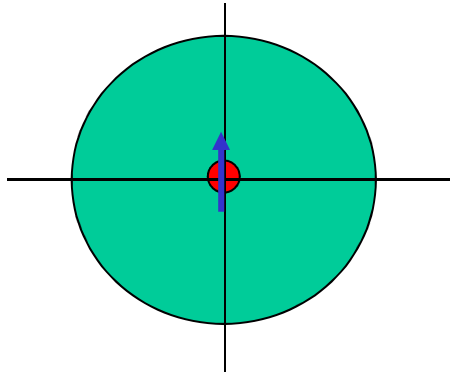
Actinides



# 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.

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

simplified

Schiff moment

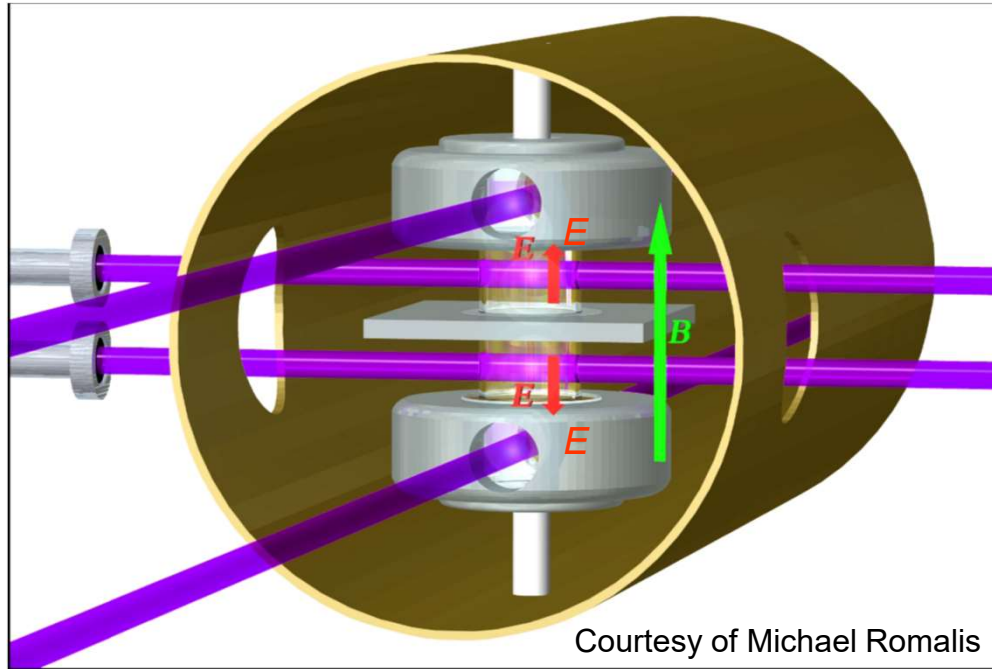
rigorous

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

# The Seattle EDM Measurement

**<sup>199</sup>Hg**

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



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

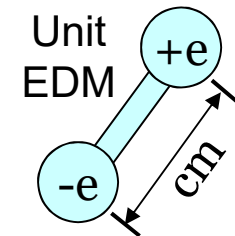
$$f_- = \frac{2\mu B - 2dE}{h} \approx 15 \text{ Hz}$$

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

**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)



## $^{225}\text{Ra}$ 的EDM: 灵敏度高, 计算可靠

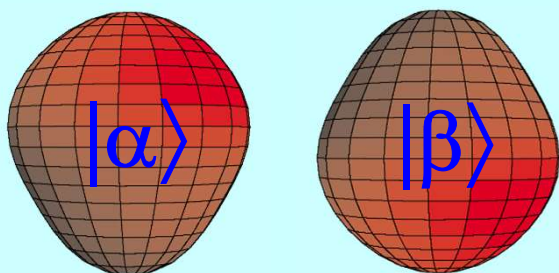
- 能量接近, 宇称相反的双能级系统 – Haxton & Henley, PRL (1983)
- 核八极变形导致较大的席夫极矩 – Auerbach, Flambaum *et al.* PRL (1996)
- 原子重, 相对论效应高 ( $^{225}\text{Ra} / ^{199}\text{Hg} \sim 3$ ) – Dzuba, Flambaum *et al.*, PRA (2002)

$^{225}\text{Ra}$ :

$$I = 1/2$$

$$t_{1/2} = 15 \text{ d}$$

宇称相反的双能级系统



$$\begin{array}{l} \text{---} \Psi^- = (|\alpha\rangle - |\beta\rangle)/\sqrt{2} \\ \uparrow \text{55 keV} \\ \text{---} \Psi^+ = (|\alpha\rangle + |\beta\rangle)/\sqrt{2} \end{array}$$

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

放大倍数: EDM ( $^{225}\text{Ra}$ ) / EDM ( $^{199}\text{Hg}$ )

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

*Schiff moment of  $^{225}\text{Ra}$ , Dobaczewski, Engel, PRL 94, 232502 (2005)*

*Schiff moment of  $^{199}\text{Hg}$ , Ban *et al.*, PRC 82 015501 (2010)*

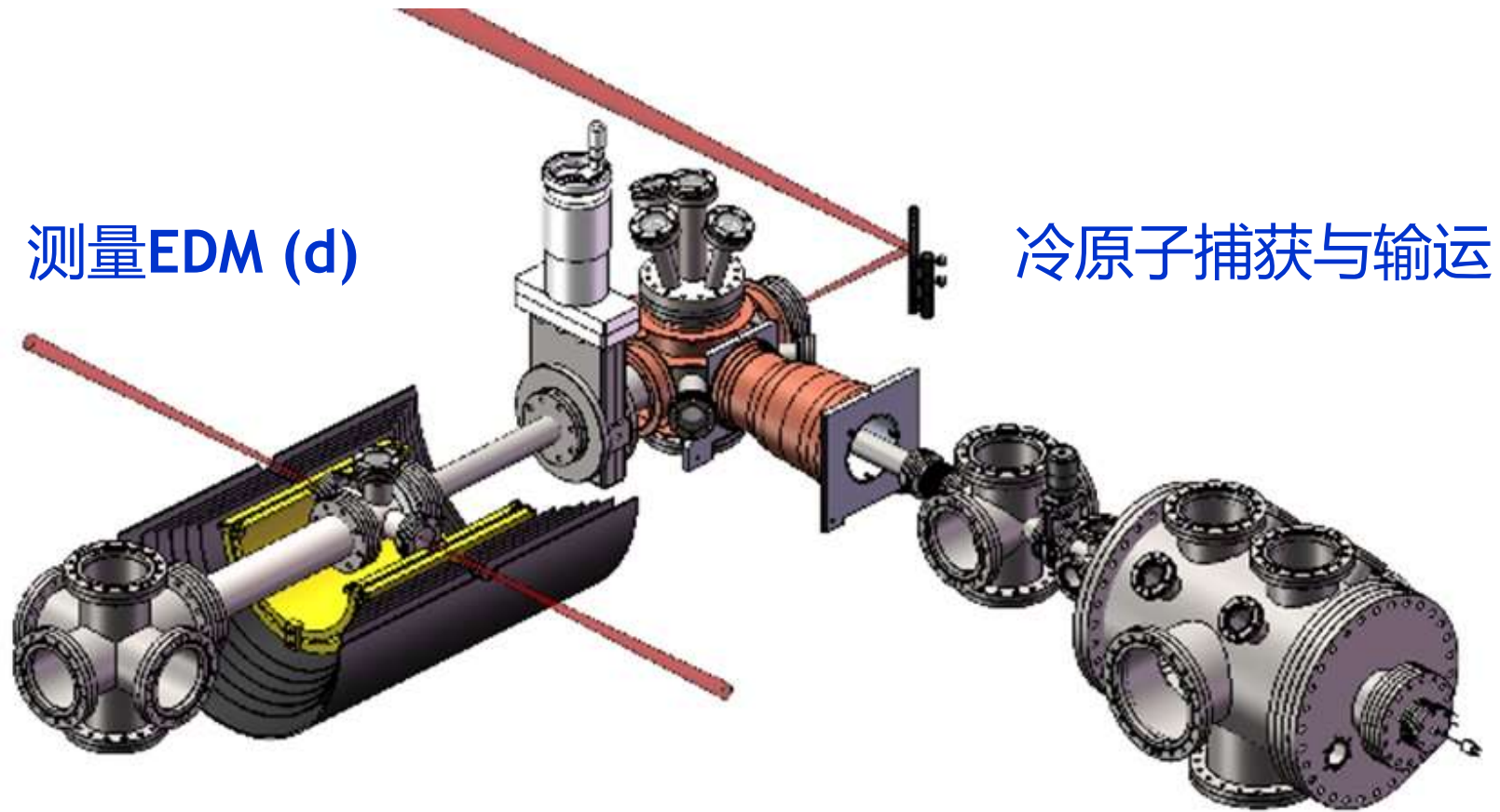
“[Nuclear structure] calculations in Ra are almost certainly more reliable than those in Hg.”

– 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

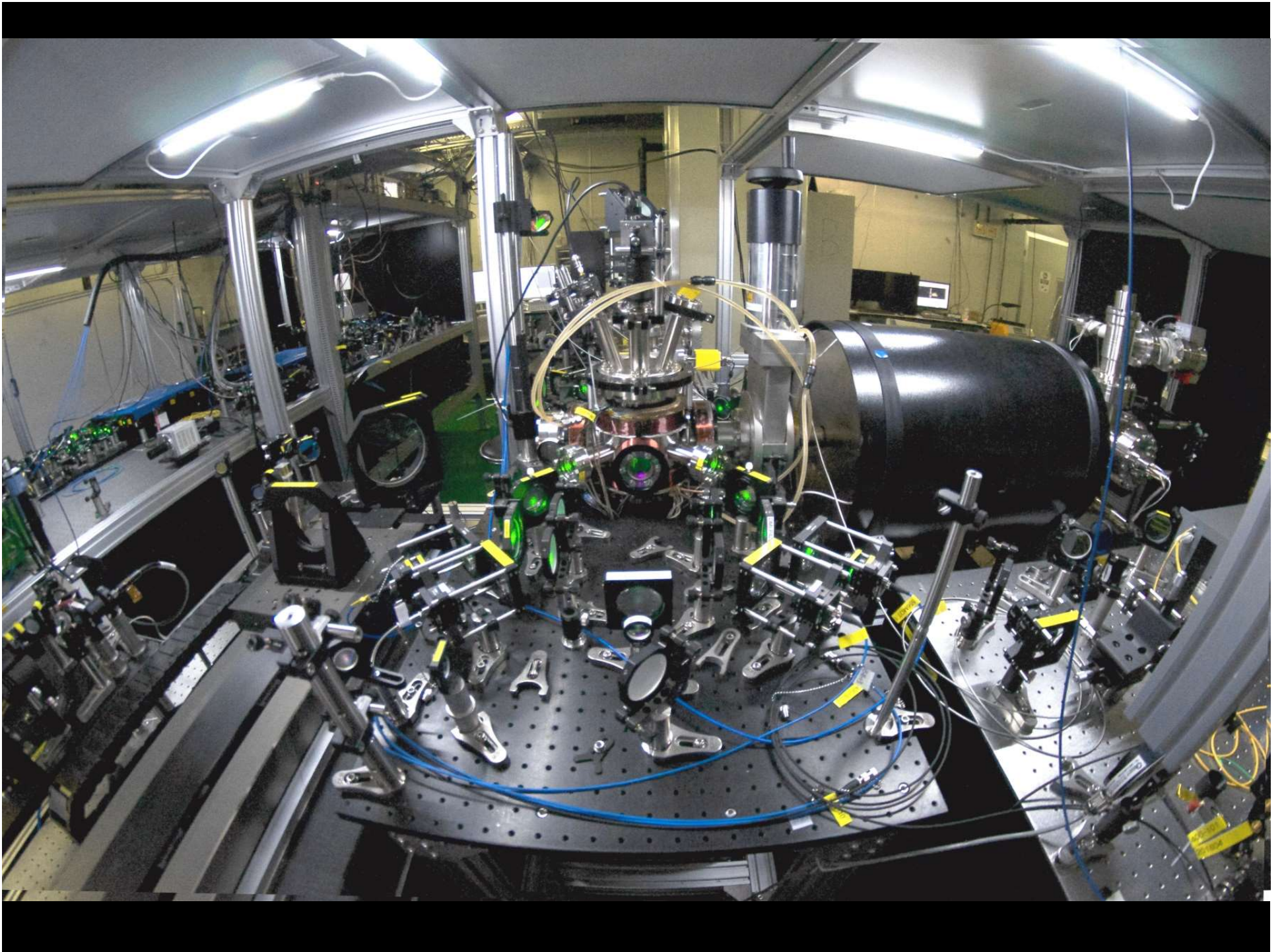


$$\omega_{+} = 2\mu B + 2dE$$

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

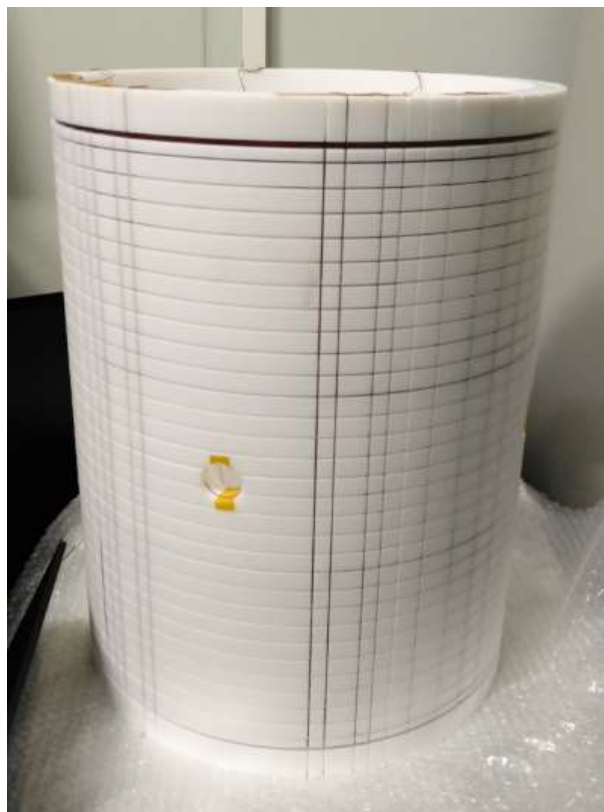
$$\delta d = \frac{\hbar}{2E\sqrt{\tau N \epsilon T}}$$







## 均匀、稳定磁场B



Cos( $\theta$ ) 线圈

$B \sim 20$  mGauss (=  $2 \mu\text{T}$ )

$\text{dB}/\text{dy} < 5\text{E-}4/\text{cm}$

$\Delta B/B = 0.4$  ppm (100 s)



$\mu$ -metal 磁屏蔽

屏蔽倍数: 50000



残余磁场  $< 1$  nT

## 强电场

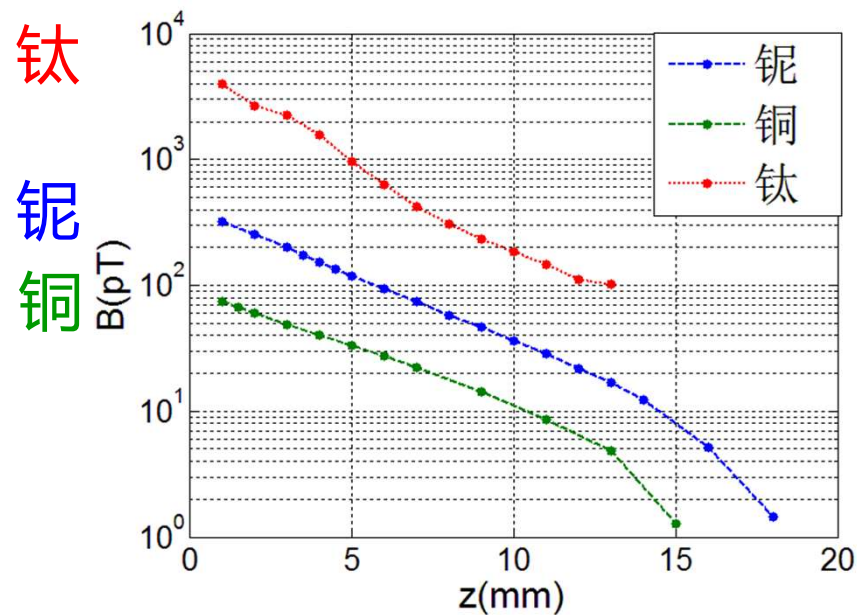
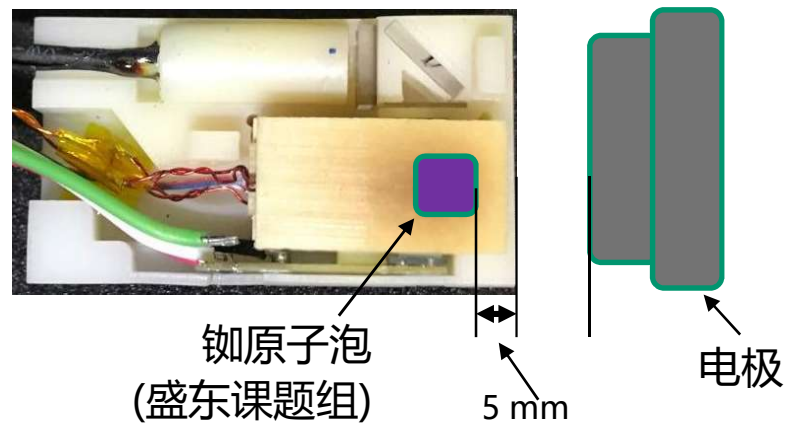


$$E = 130 \text{ kV/cm}$$

$$I_{\text{avg}} = 0.4 \text{ pA}, \quad I_{\text{rms}} = 58 \text{ pA}$$

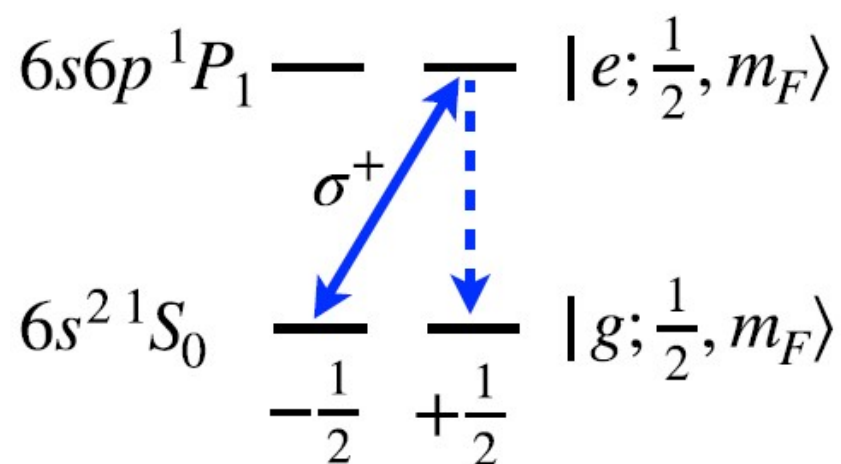
极性切换时间: 2 s

## 电极表面剩磁测量

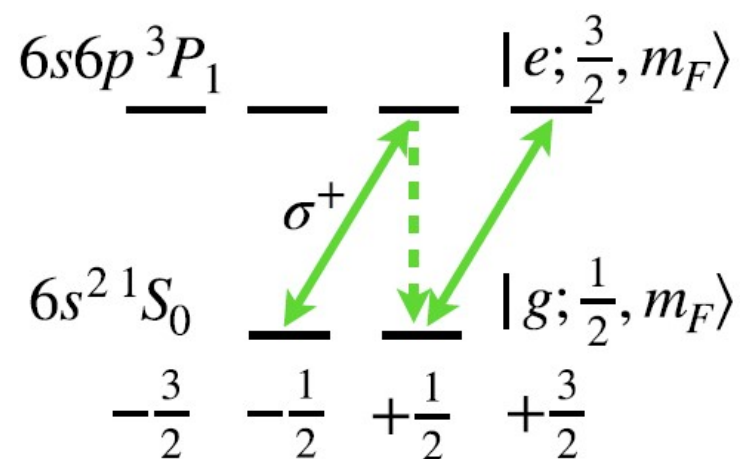


将钛换成铜后,  $T_2$ 提高至与无电极时一致

## 自旋极化量子态探测 -- 传统方法



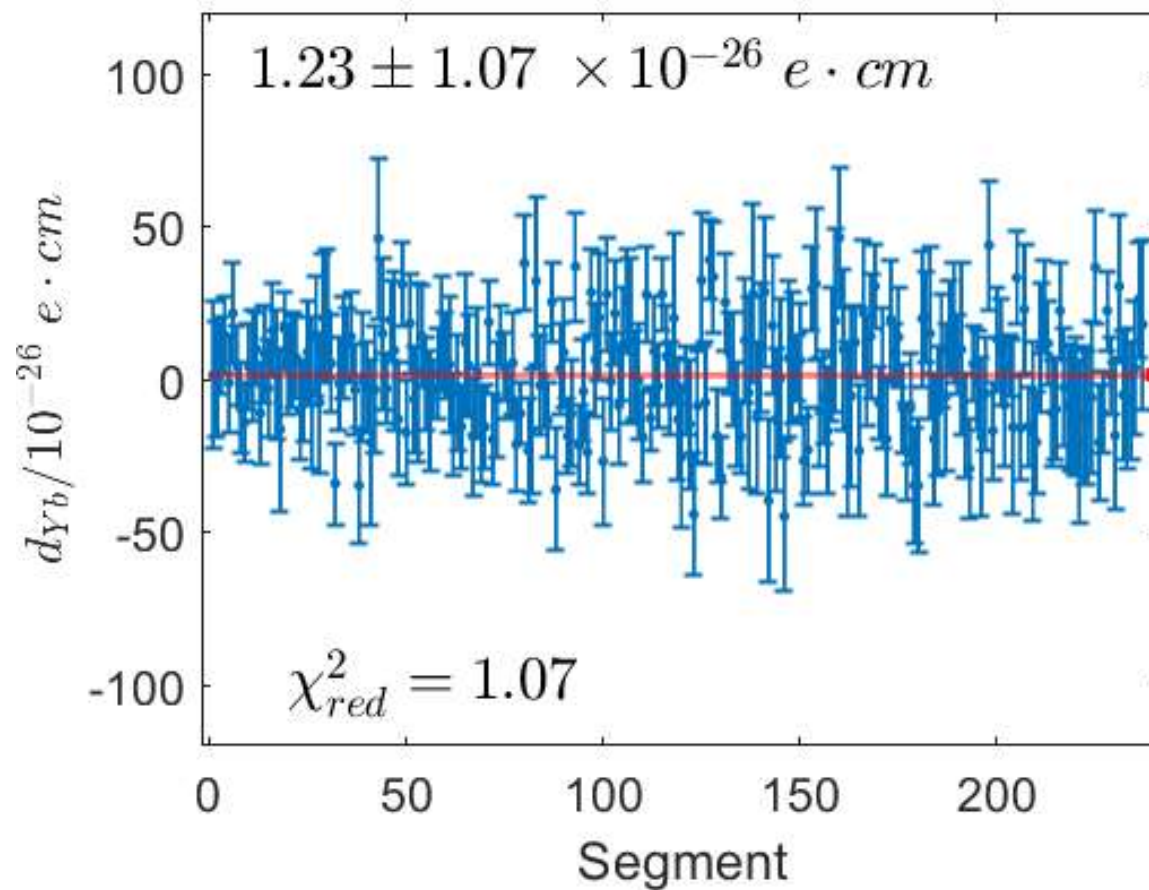
暗态：不吸收  
亮态：吸收3个光子



无暗态  
不能实现态选择测量

# $^{171}\text{Yb}$ 原子EDM测量进度 1E-26

2021.03



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

$E$ : 71.8 kV/cm

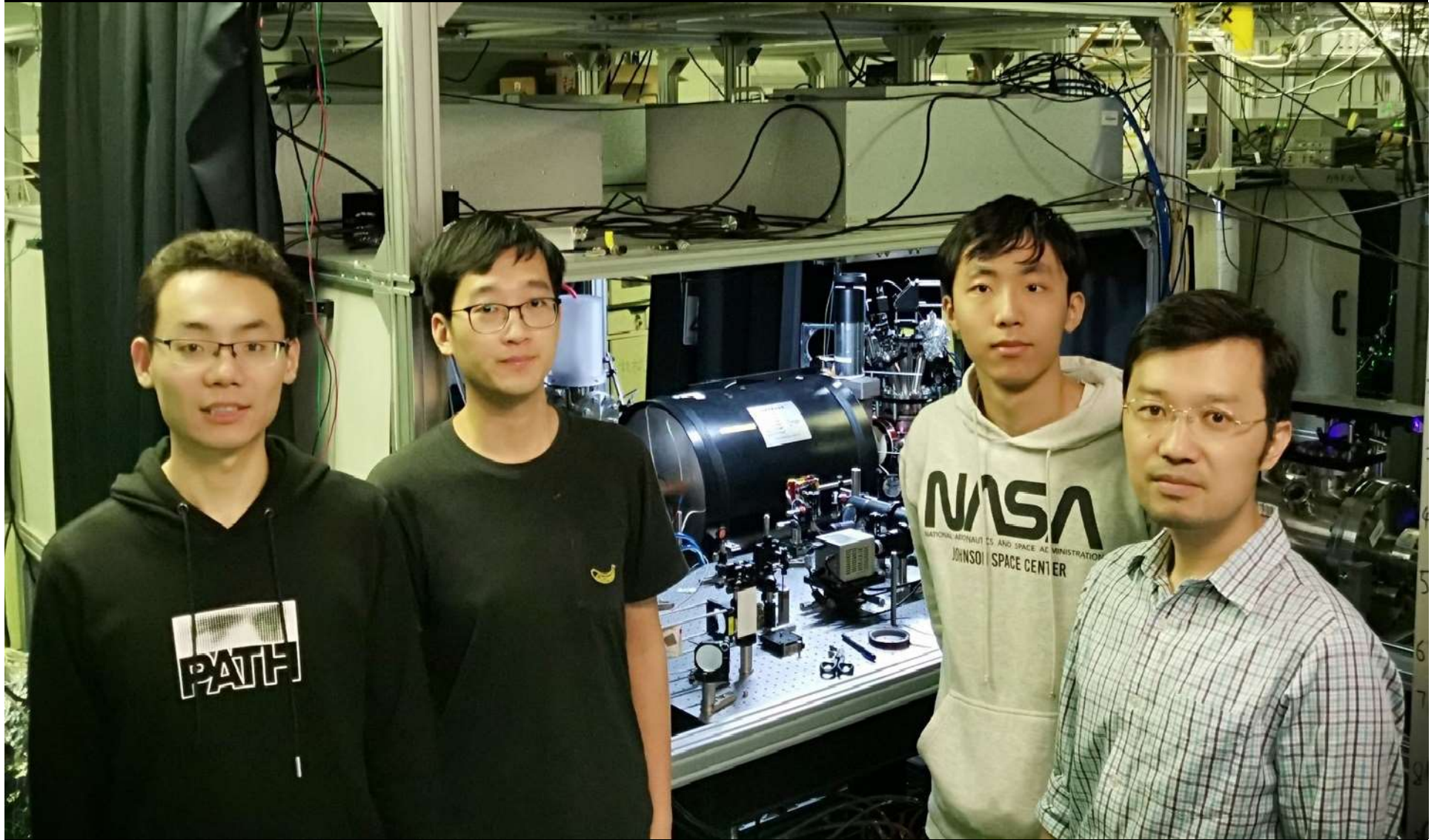
$\tau$ : 96 s

$N$ :  $2 \times 10^4$

$\epsilon$ : ~30%

$T$ : 260 h (13 d)





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