Possible search for the electron EDM in an electrostatic storage ring

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Introduction

Overview

- Electric dipole moments violate P, T, and CP symmetries
- Current electron limit : $|d_e| \leq 1.0 \times 10^{-27}$ e·cm
- Physics beyond Standard Model can make EDMs non-zero
- Improving limits on EDMs ⇒ stricter limits on new physics

- Propose using WN$^+$ ions in storage ring to measure d_e
- Maybe factor 1000 improvement possible : $|d_e| \leq 10^{-30}$ e·cm
- Advantage from long coherence time of stored ions, $\tau \geq 0.1$ s

- Systematics appear under control at level of 10^{-31} e·cm

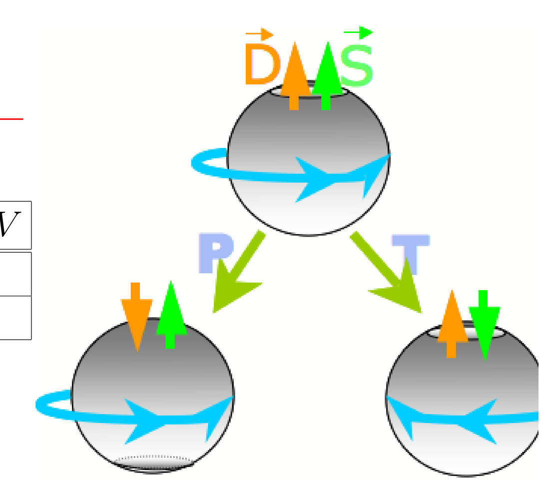
What is an Electric Dipole Moment (EDM) ?

$$H_{\text{Magnetic Dipole}} = -\vec{\mu}\cdot\vec{B} = -\mu\vec{\sigma}\cdot\vec{B}$$
$$H_{\text{Electric Dipole}} = -\vec{d}\cdot\vec{E} = -d\vec{\sigma}\cdot\vec{E}$$

Behavior under Parity and Time Reversal

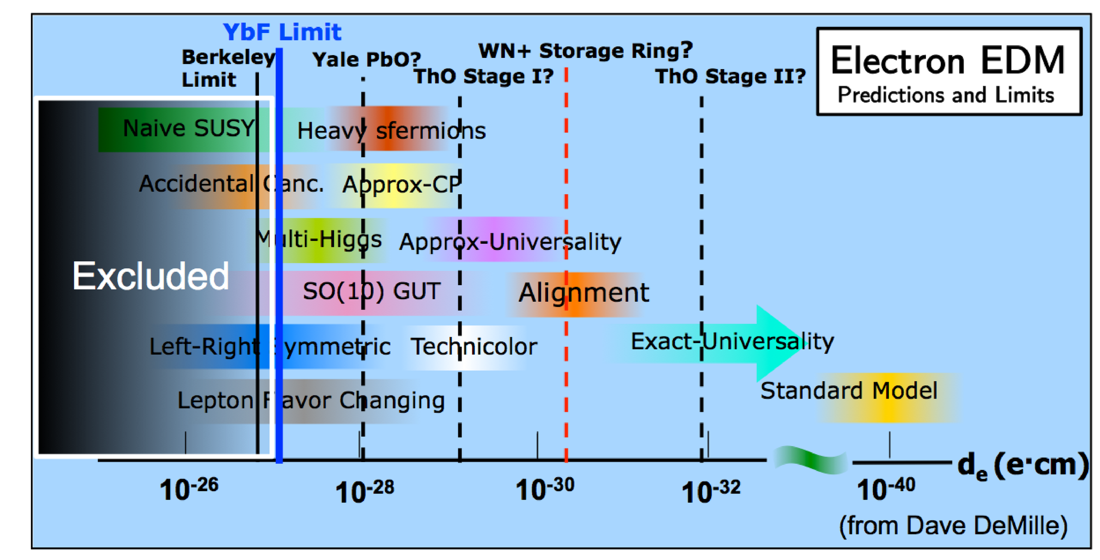
	$\vec{\sigma} \sim \vec{r}\times\vec{p}$	$\vec{B} \sim \vec{j}\times\vec{r}/\|\vec{r}\|^3$	$\vec{E} \sim -\vec{\nabla}V$
P	even	even	odd
T	odd	odd	even

- H_{Magnetic} is P-even, T-even
- H_{EDM} is P-odd, T-odd !!!



⇒ For particle to have an EDM, P and T must be violated
⇒ EDMs from new physics, with new sources of CP violation

What can we learn?



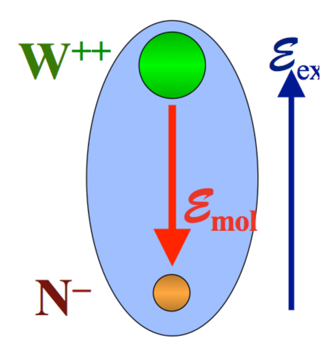
- Current limit $d_e \leq 1.0 \times 10^{-27}$ e·cm (YbF, Ed Hinds, 2011)
- d_e searches probe new physics, at scale of 10s of TeV
- Null results can exclude new physics beyond Standard Model

Proposed Experimental Technique

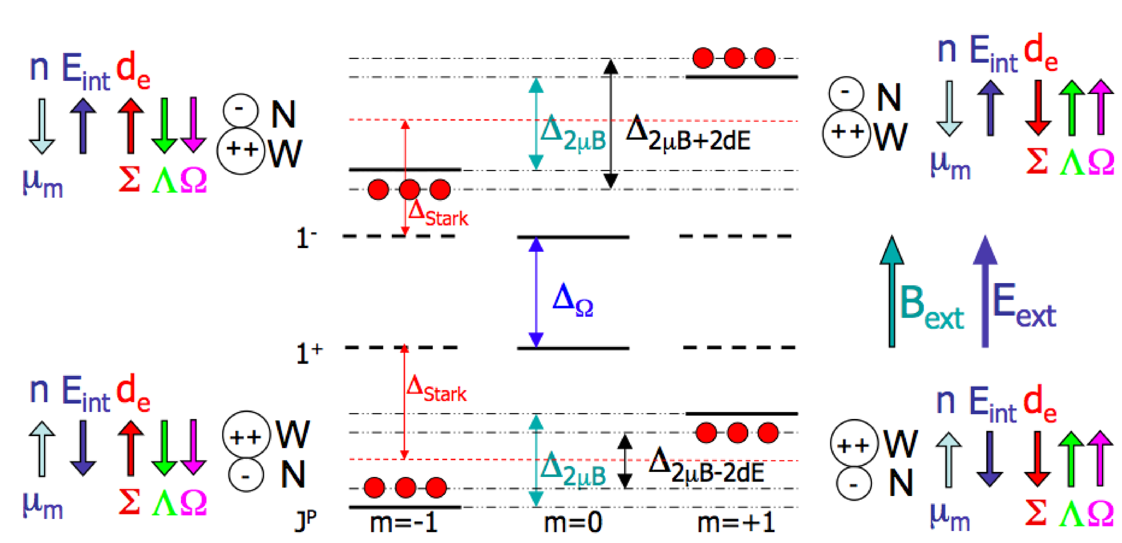
Paramagnetic polar molecules for eEDM searches

- Use heavy polar molecules with unpaired electron spin
- Can have large internal electric fields E_{mol}, easily polarized
- Bohn & Meyer : field of tungsten carbide WC $E_{\text{mol}} \approx 54$ GV/cm, E(WN$^+$) ≈ 45 GV/cm ≈ E(WC) since isoelectronic

⇒ Approach : polarize $\vec{E}_{\text{mol}}$ along $\vec{E}_{\text{ext}}$
- Polarize unpaired e^- parallel/anti-parallel to $\vec{E}_{\text{mol}}$
- Look for $\Delta E = d_e E_{\text{int}}$:
  $d_e = 1 \times 10^{-29}$ e·cm ⇔ 120 μHz
  $d_e = 1 \times 10^{-31}$ e·cm ⇔ 1.2 μHz
- Motivates searches in PbO, YbF, HfF$^+$, ThO, WC, and WN$^+$



Energy Levels and Measurement Scheme in WN$^+$



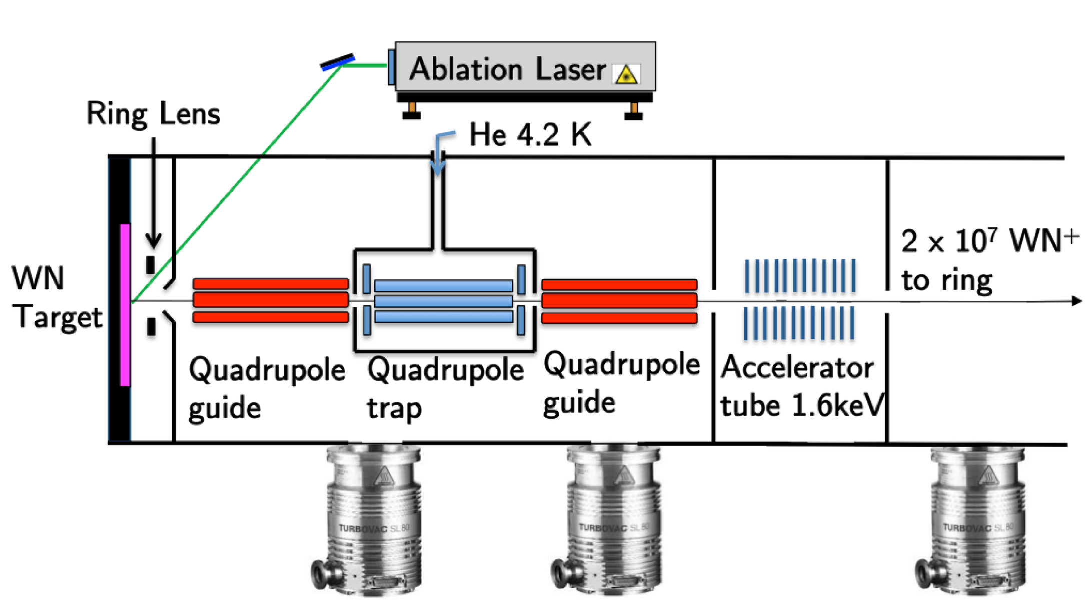
- Calculations suggest ground state of WN$^+$ is $^3\Delta_1$
- Observe EDM precession of M=±1 superposition state (●)
- Energy shifts by $4d_eE_{\text{mol}}$ between upper and lower Ω-doublets

Overview of experimental approach

- Ablate tungsten nitride (WN) target
- Trap few $\times 10^8$ WN$^+$ ions in linear quadrupole trap
- Cool with He buffer gas to 4.2 K
- Inject 2×10^7 ions from trap into electrostatic storage ring, accelerating by 1.6 keV to $v = 4 \times 10^4$ m/s
- Pump with $\hat{x}$-polarized laser, leaves dark state :
  $|\psi(0)>= \frac{1}{\sqrt{2}}[|J=1,M=-1,N\rangle > -|J=1,M=+1,N\rangle >]$
- After $\tau \approx 100$ ms, EDM-phase shift $\phi_{\text{EDM}} = d_eE_{\text{mol}}\tau/\hbar$:
  $|\psi(\tau)>= \frac{1}{\sqrt{2}}\left[e^{i\phi_{\text{EDM}}}|J=1,M=-1,N\rangle - e^{-i\phi_{\text{EDM}}}|J=1,M=+1,N\rangle\right]$
- Pump with $\hat{x}$ then $\hat{y}$ polarized light, detect fluorescence $F_{x,y}$, determines $\phi_{\text{EDM}} = (F_x - F_y)/(F_x + F_y)$
- Repeat with other doublet $N = \pm 1$ to reverse ϕ_{EDM}

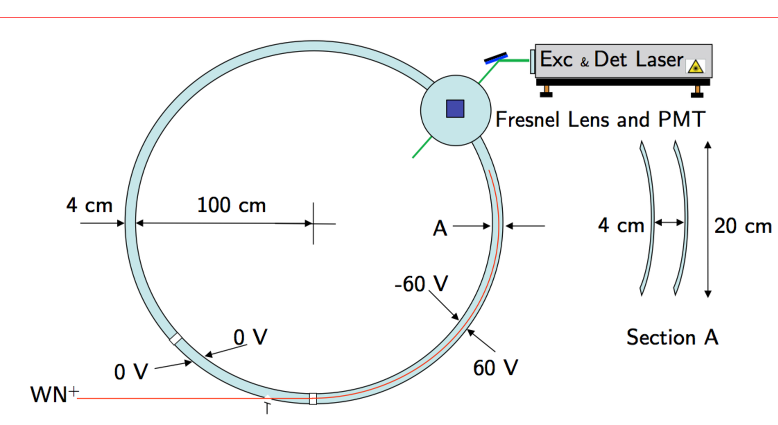
Experimental Technique and Coherence Time

Tungsten Nitride WN$^+$ Ion Source



- Roughly 15% of WN$^+$ ions in ground rotational state

How are the WN$^+$ ions stored?



- Ring of ITO-coated glass : conductive, transparent
- Radial E field ≈ -33 V/cm, curved for vertical focusing
- Turn off ≈ 1/8th of ring, inject ions along tangent, turn on
- Need $|\vec{E}_r|$ so Stark splitting larger than transverse Doppler width to resolve Ω−doublets

Coherence time and ion-ion interactions

- At 10^{-9} Torr in ring, mean free path ≈ 40 km, τ=1 s

$$\text{Vertical tune } Q_v = \sqrt{\frac{q}{m_{\text{ion}}}\frac{dE_y}{dy}\left(\frac{R}{v}\right)^2} = 0.87$$
$$\text{Laslett tune shift } \delta Q_v = -\frac{1}{2Q_v}\frac{R^2}{m_{\text{ion}}v^2}\frac{Nq^2}{2\pi\epsilon_0 2\pi R 2\sigma_v^2} \approx -0.0003$$

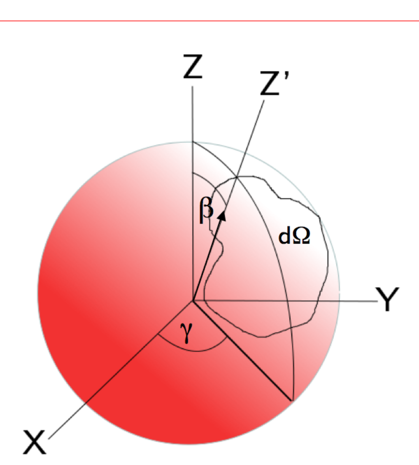
⇒ 2×10^7 ions/2000 cm^3, space-charge effects not significant

- What about ion-ion effects on coherence time?

$$\frac{1}{\tau} \approx n\sigma v_{\text{rel}},\ \sigma = \pi r^2, r \approx 10^{-6} \text{ cm so } |\vec{E}_{ion-ion}| \approx 0.5|\vec{E}_r|$$
$$\approx \frac{2\times 10^7 \text{ ions}}{2000 \text{ cm}^3} \times (3\times 10^{-8}\text{cm}^2) \times (2\times 10^4 \text{ cm/s})$$
$$\approx 6 \text{ s}^{-1} \Rightarrow \text{Coherence times of 150 ms achievable}$$

Systematics, Sensitivity Estimates, and Summary

Systematic Effects : Geometric Phases



- Betatron oscillations ⇒ $\vec{E}$ oscillates, rotating $\hat{H}$ ⇒ phase shifts
- Let $d\Omega$=solid angle enclosed by angular momentum vector
- Get phase shifts : $d\phi_{\text{geom}} \approx e^{iMd\Omega}$
- Opposite shift for $M = \pm 1$
  ⇒ looks like false EDM

- But : $d\phi_{\text{geom}}$ same for upper and lower Ω-doublets
  ⇒ phase shift cancels in comparison, eliminates false EDM
- Spin follows $\vec{E}$ field adiabatically : cyclotron freqency $\nu_{cyc} \approx$ 7 kHz $< \Delta_{\text{Stark}} \approx 40$ MHz; spins don't decohere

Statistical Sensitivity

- EDM-induced shift in energy : $h\Delta\nu_{\text{EDM}} \approx 2d_eE_{\text{mol}}$
- Uncertainty in frequency shift : $\delta(\Delta\nu_{\text{EDM}}) = 1/2\pi\tau\sqrt{N}$

$$\delta d_e \approx \frac{h}{4\pi E_{\text{mol}} \times \tau \times \sqrt{\text{Rep. Rate} \times N_{\text{stored ions}} \times f_{\text{excited}} \times f_{\text{detected}}}}$$
$$\approx \frac{6.626\times 10^{-34} J\cdot s}{4\pi \cdot 45\text{GV/cm} \cdot 1.6\cdot 10^{-19}\ J/eV \cdot 0.1\ s \cdot \sqrt{10\text{Hz}\cdot 3\times 10^6 \cdot 0.1 \cdot 0.01}}$$

$$\delta d_e \approx 4.2 \times 10^{-28}\ e\cdot\text{cm}/\sqrt{\text{Hz}}$$
$$\approx 2.0 \times 10^{-30}\ e\cdot\text{cm}/\sqrt{\text{day}}\ (50\%\ \text{efficiency})$$

- $f_{\text{detected}} = d\Omega \times$ Bandpass $\times$ QE $= 0.15 \times 0.33 \times 0.2 = 0.01$
- Systematics limit : few $\times 10^{-31}$ e·cm (under investigation).
- Improvements : select $J = 1$ with $\vec{E}$ gradient, increase τ, ...

Overcoming Systematic Effects and Summary

⇓ Experiment lacks an E field reversal with B field fixed
⇑ Does have B field reversal : reverses sign of EDM
⇑ Can switch to other Ω doublet to reverse EDM effect
⇑ Inject ions in opposite direction : geometric phase effects reverse sign, as do motional B field effects
⇓ Known problem : g-factors of Ω-doublets are slightly different, $\delta g < 10^{-4}$, looks like EDM shift
⇑ Can measure δg and $|\vec{B}|$ well enough for $\approx 10^{-31}$ e cm
⇑ WN$^+$ comes has 3 main isotopes : ^{182}WN (26%), ^{184}WN (31%), ^{186}WN (28%) : can make 3 simultaneous measurements with different signs of the EDM

⇒ Limit on $|d_e| \leq 10^{-30}$ e·cm seems possible