Theoretical issues in parity and time-reversal violation in atoms

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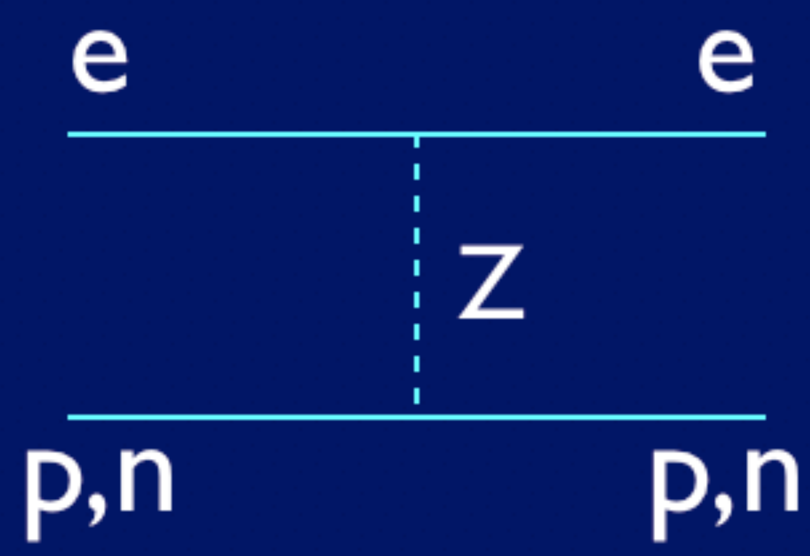
Atomic parity violation (APV)



- APV dominated by Z-boson exchange between electrons and nucleons

$$H = \frac{G}{\sqrt{2}}\left[C_{1p}\bar{e}\gamma_\mu\gamma_5 e\bar{p}\gamma^\mu p + C_{1n}\bar{e}\gamma_\mu\gamma_5 e\bar{n}\gamma^\mu n\right]$$

Standard model tree-level couplings: $C_{1p} = \frac{1}{2}\left(1 - 4\sin^2\theta_W\right)$; $C_{1n} = -\frac{1}{2}$

- In atom with Z protons and N neutrons obtain effective Hamiltonian parametrized by "nuclear weak charge" Q_W

$$h_{PV} = \frac{G}{2\sqrt{2}} Q_W \rho(r)\gamma_5$$

$$Q_W = 2(NC_{1n} + ZC_{1p}) \approx -N + Z(1 - 4\sin^2\theta_W) \approx -N$$

- APV amplitude $E_{PV} \propto Z^3$

[Bouchiat,Bouchiat]

Status

- Best measurement for cesium [Boulder '97]

$$-Im(E_{PV})/\beta = 1.5935(1 \pm 0.35\%)\,\mathrm{mV/cm}$$

- Atomic theory required for determination of E_{PV}:

$$E_{PV}(6S \to 7S) = \sum_n \left[\frac{\langle 7S|H_{PV}|nP\rangle\langle nP|D|6S\rangle}{E_{7S} - E_{nP}} + \frac{\langle 7S|D|nP\rangle\langle nP|H_{PV}|6S\rangle}{E_{6S} - E_{nP}} \right] = \xi Q_W$$

Atomic theory	$\delta E_{PV}/E_{PV}$	$Q_W - Q_W^{SM}$	Ref.
1% calculations		1.2 σ	Dzuba et al. '89; Blundell et al. '90
Reinterpretation 1%→0.4%		2.5 σ	Bennett & Wieman '99
Breit interaction	-0.6%		Derevianko '00
Vacuum polarization	+0.4%		Johnson et al. '01; Milstein & Sushkov '02
Neutron distribution	-0.2%		Derevianko '02
0.5% calculations		2.1 σ	Dzuba, Flambaum, Ginges '02
Self-energy and vertex radiative corrections	-0.7%		Kuchiev & Flambaum '02; Milstein et al. '02; Sapirstein et al. '03; Shabaev et al. '05; Flambaum & Ginges '05
Total		1.1 σ	

Method for atomic many-body calculations

[Dzuba, Flambaum, Sushkov]

- Starting point: relativistic Hartree-Fock, $(\boldsymbol{\alpha}\cdot\mathbf{p}+\beta m+V_{HF})\varphi=\epsilon\varphi$
- Include correlation corrections through "correlation potential",

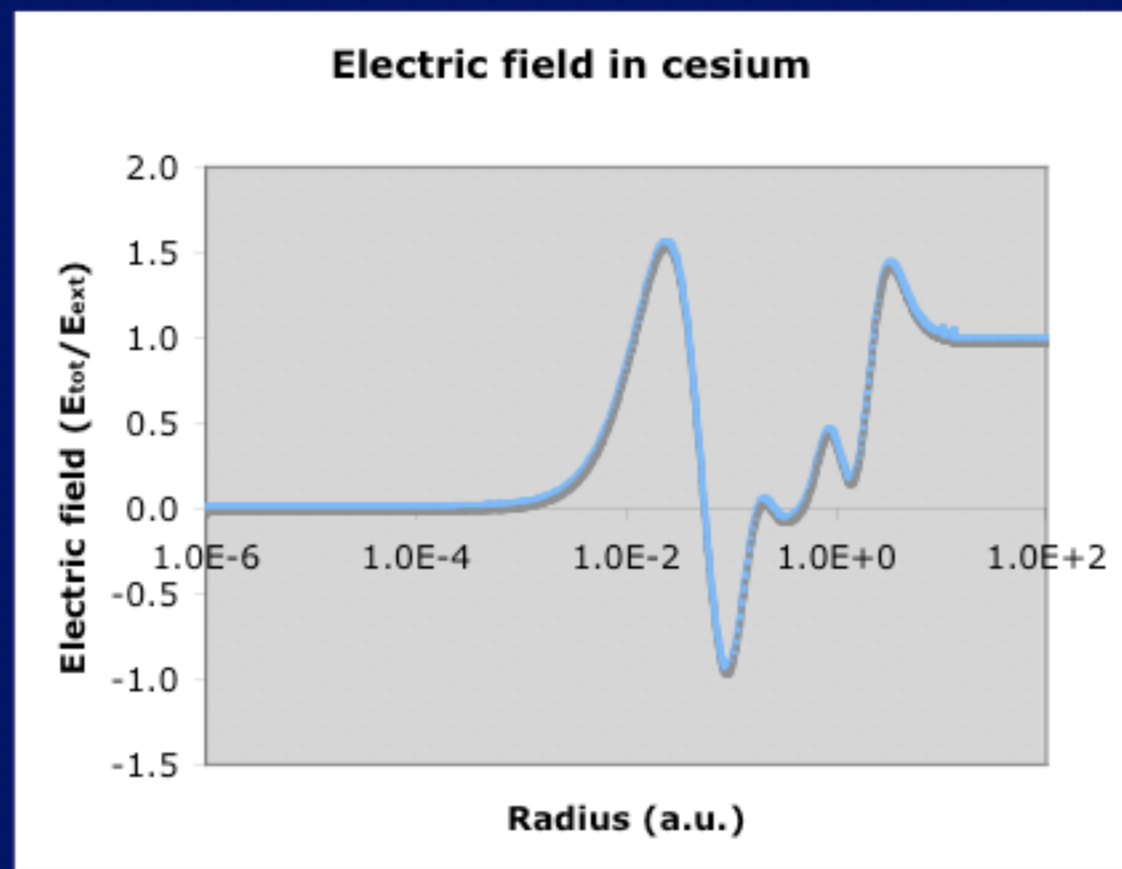
$V_{HF}\rightarrow V_{HF}+\Sigma$. In lowest order, Σ =

Three classes of diagrams included into Σ to all orders:

1. electron-electron screening

2. hole-particle interaction

3. nonlinear-in- Σ contributions

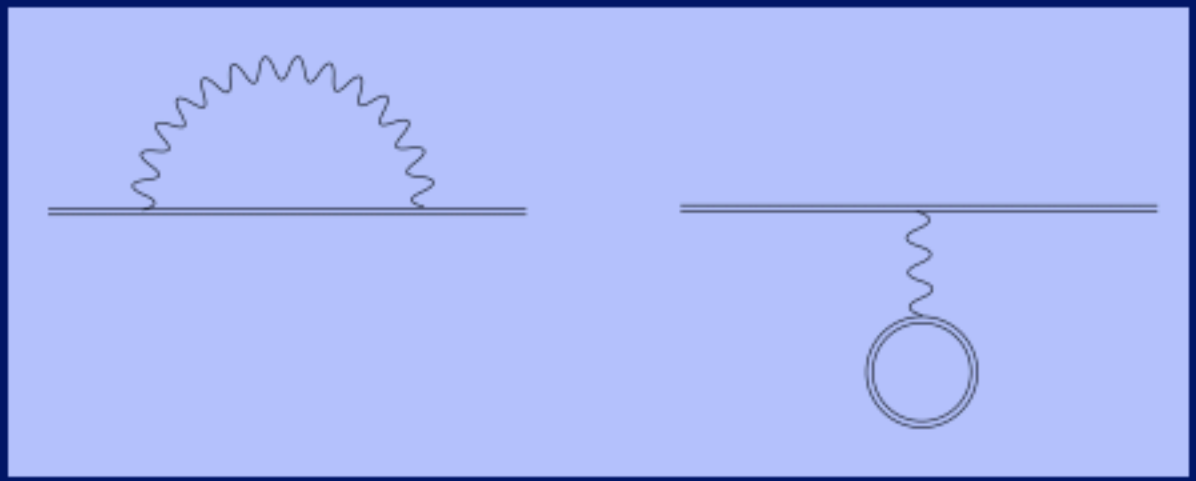


Inclusion of radiative corrections

[Flambaum, Ginges]

- Radiative potential *L* defined s.t.

$$\delta E_n = \langle n | L(r, r', E) | n \rangle$$



Shifts in neutral atoms:

- Lamb shift arises due to interactions at small distances where electrons are unscreened
- Energies of valence electrons in neutral atoms $E \sim 10^{-5} mc^2$

$\Rightarrow$ valence electron wave functions are proportional to Coulomb wave functions with high n:

$$\langle \psi | L | \psi \rangle_{\mathrm{neutral}} = \langle \psi | L | \psi \rangle_{\mathrm{H-like}} \frac{\rho(0)_{\mathrm{neutral}}}{\rho(0)_{\mathrm{H-like}}}$$

- Use approximate local potential V_{rad} fitted to Lamb shifts for high states of H-like ions Z

APV

Energies and E1 amplitudes for cesium

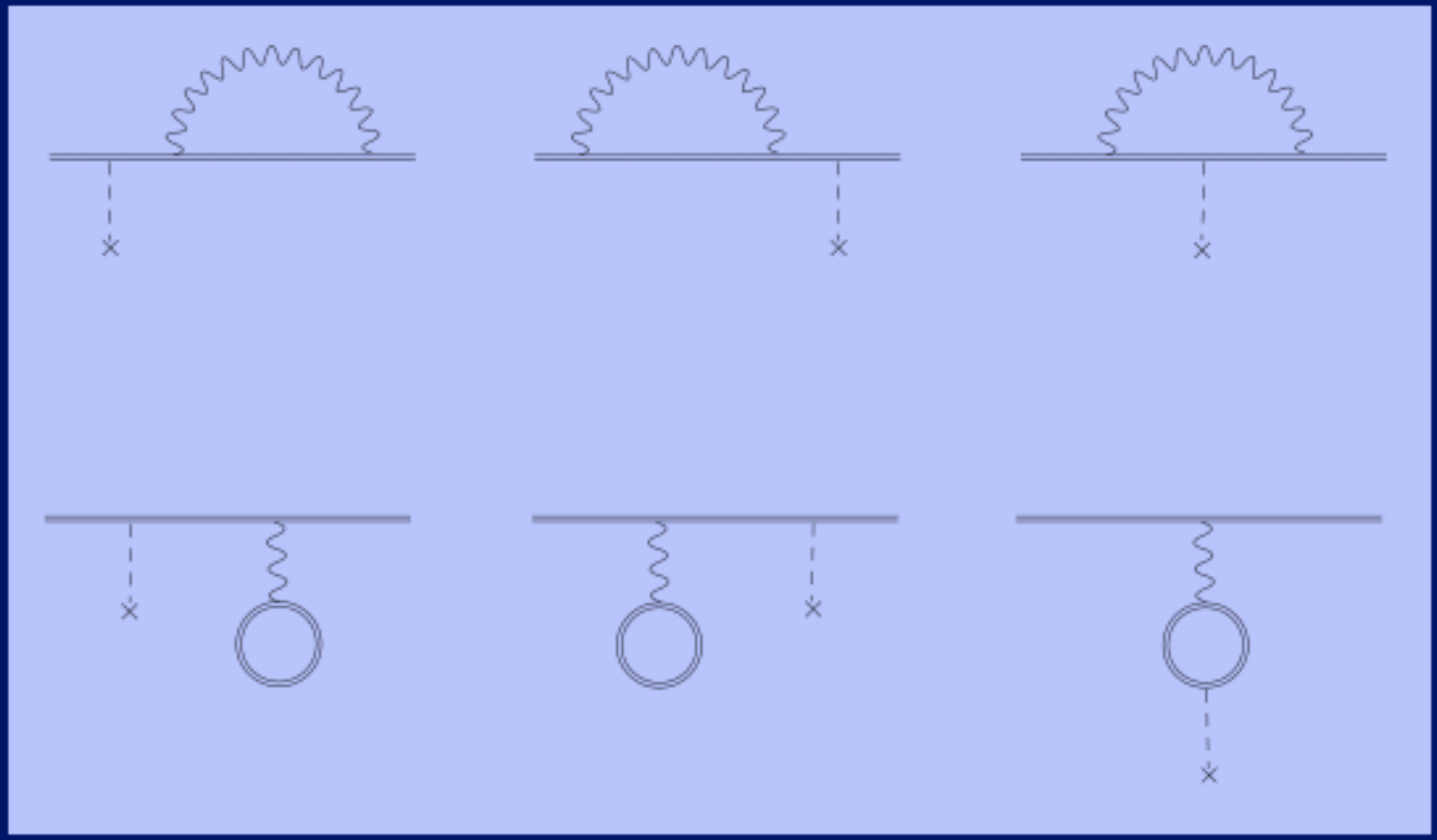
Add radiative potential to atomic procedures, $V_{HF} + V_{\rm rad}$

Result for Cs 6S Lamb shift $(\rm cm^{-1})$

Hartree-Fock	+core relaxation	+correlations	Labzowsky et al. '99	Sapirstein & Cheng
15.5	15.9	17.6	15-27	13-23

Correction to E_{PV}: -0.34%

Radiative potential gives largest contributions to E1 amplitude! Other (vertex, etc.) contributions are about Z^2 times smaller neutral atoms!

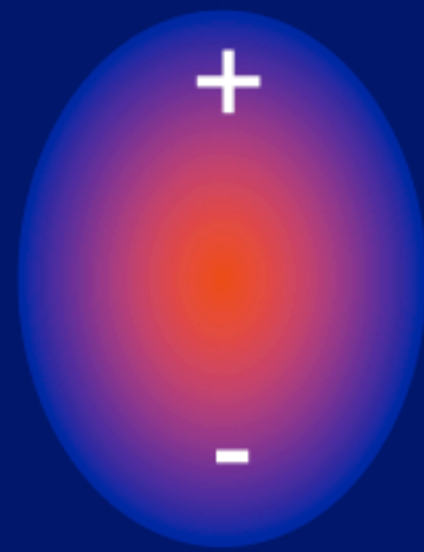


Result R for Cs 6S-6P, $\frac{E1}{E1_0} = 1 + \frac{\alpha}{\pi} R$

Hartree-Fock	+core polarization	+correlations	Sapirstein & Cheng
0.266	0.286	0.265	0.261

Correction to E_{PV}: +0.43%

Atomic electric dipole moments (EDMs)



- EDMs violate parity (P) and time-reversal (T)

$$\vec{d} \equiv \vec{r} \propto \vec{J}$$

- T-violation $\equiv$ CP-violation by CPT theorem
- Not enough standard model CP-violation to generate matter-antimatter asymmetry of universe!
- EDMs sensitive to new physics, SM EDMs suppressed

e.g., electron EDM

Best limit (90% c.l.) [Berkeley '02]

$|d_e| < 1.6 \times 10^{-27}\ e\,\mathrm{cm}$

[Commins]

Theory	$d_e \quad (e\,\mathrm{cm})$
Std. Mdl.	$< 10^{-38}$
SUSY	$10^{-28} - 10^{-25}$
Multi-Higgs	$10^{-28} - 10^{-26}$
Left-right	$10^{-28} - 10^{-26}$

- Atomic EDMs $d_{\mathrm{atom}} \propto Z^2, Z^3$ [Sandars]

Status

Best limits

$$|d(^{199}\mathrm{Hg})| < 2.1 \times 10^{-28} e\,\mathrm{cm}$$

(95% c.l., Seattle '01)

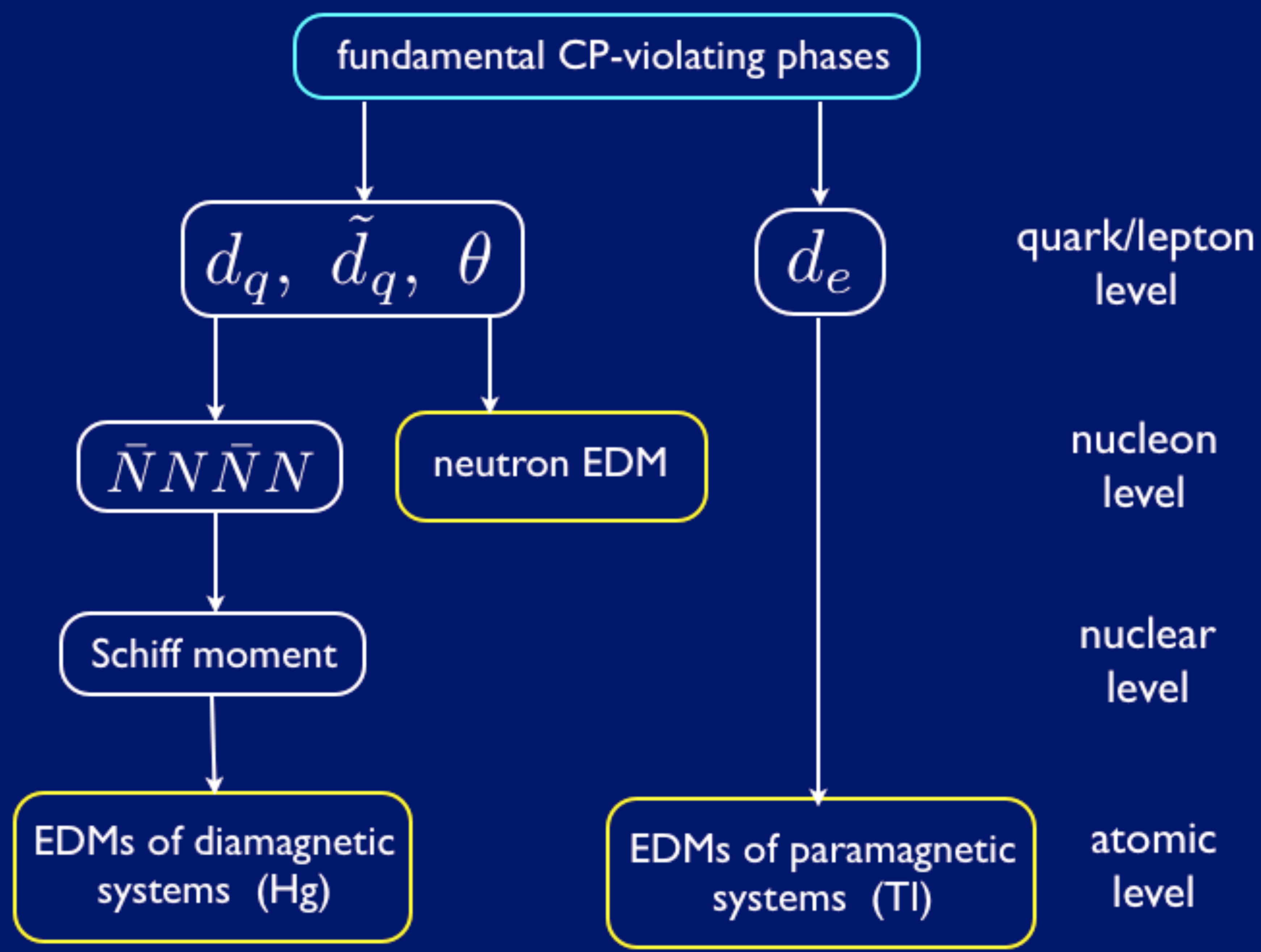
$$|d(^{205}\mathrm{Tl})| < 9.6 \times 10^{-25} e\,\mathrm{cm}$$

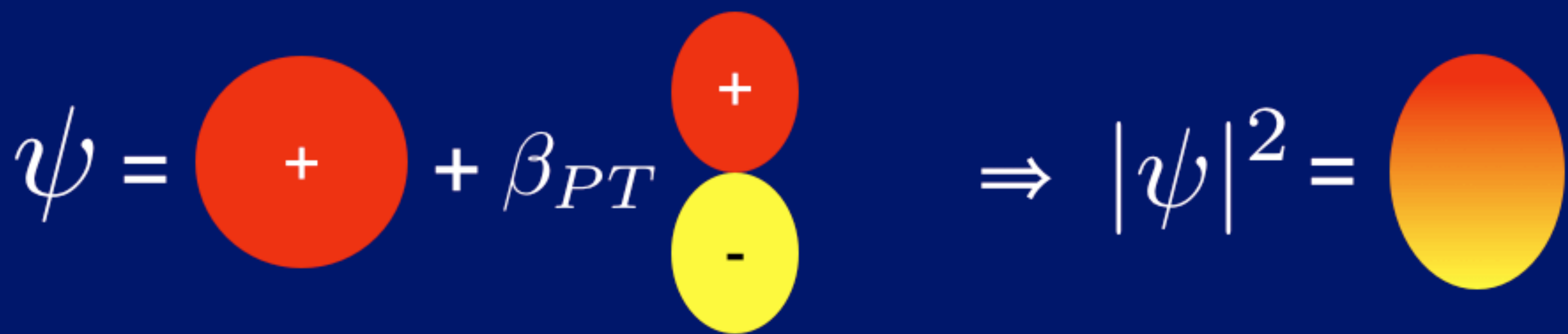
(90% c.l., Berkeley '02)

$$|d(n)| < 2.9 \times 10^{-26} e\,\mathrm{cm}$$

(90% c.l., Baker *et al.* '06)

Leading mechanisms for EDM generation





Atomic theory and application to radium

Need to calculate: $$d_{\rm atom} = 2\sum_N \frac{\langle 1|D|N\rangle\langle N|H_{PT}|1\rangle}{E_1 - E_N}$$

Configuration for Hg: [Xe]$4f^{14}5d^{10}6s^2$, Ra: [Rn]$7s^2$

Calculations for Hg and Ra $d_{\rm atom}(S)$ performed using two approaches
[Dzuba, Flambaum, Ginges, Kozlov '02]

(1) V^N approximation. TDHF
(2) V^{N-2} approximation. MBPT+CI+TDHF

} precision $\approx 20\%$

$$d(^{225}\mathrm{Ra})/d(^{199}\mathrm{Hg}) \sim \underbrace{3}_{\text{electronic enhancement}} \times \underbrace{10^2 - 10^3}_{\text{nuclear enhancement}}$$

[Dmitriev *et al.*; Dobaczewski & Engel; Flambaum & Zelevinsky]

Can also have huge electronic enhancement if measurements performed in metastable state 7s6d $^3D_2$, $d \sim 10^5\, d(\mathrm{Hg})$ [Flambaum; Flambaum, Dzuba, Ginges]

Semi-empirical fitting can be used to calculate radium spectra $\sim 0.1\%$ [Dzuba, Ginges '05]

Measurements underway at Argonne National Laboratory, USA, and Kernfysisch Versneller Instituut, Netherlands

Future directions

APV

- Full account of QED+MBPT
- Improvement in precision for correlation calculations. Derevianko aiming for 0.1% in Cs
- Paris group aiming for 0.1% Cs measurement, currently at 2.6%

EDMs

- Measurements underway in atoms, molecules, and solids
- Improvement in limit by 2-3 orders of magnitude will have huge impact on understanding of CP violation