Novel Mechanisms for the Generation of EDMs in Paramagnetic Atoms and Molecules via Hadronic Sources of CP Violation

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Conventional Wisdom in the Classification of Atomic/Molecular EDM Experiments

Diamagnetic systems (contain *no* unpaired electrons) are mainly sensitive to **hadronic** sources of CP violation – e.g., **Hg**, **Xe**, **n**

Paramagnetic systems (contain *one or more* unpaired electrons) are mainly sensitive to **leptonic** sources of CP violation – e.g., **ThO**, **HfF^+**, **YbF**, **Tl, Cs**

For **semi-leptonic** sources of CP violation, the story is more complicated – the "classification" generally depends on whether the interactions involve mainly electron spin or nuclear spin

Leptonic CP Violation in Paramagnetic Molecules

Over the past decade, molecular experiments have improved the sensitivity to electron EDM d_e by more than 100-fold:

^{232}ThO bound: $|d_e| < 10^{-29}\ e\ \mathrm{cm}$

[Andreev *et al*. (ACME collaboration), *Nature* **562**, 355 (2018)]

Sensitivity boost comes from large *effective* electric field seen by unpaired electrons*: $E_{\mathrm{eff}} \sim 10 - 100\ \mathrm{GV/cm} \sim 10^5 E_{\mathrm{lab,max}}$

Small magnetic moment in $^3\Delta_1$ ThO state: $|\mu_{\mathrm{ThO}}(^3\Delta_1)| \sim 10^{-2}\mu_{\mathrm{B}}$

=> Less sensitive to (stray) magnetic fields

What about sensitivity of paramagnetic systems to hadronic CP violation?

* Molecules often have pairs of opposite-parity levels with *close* energies that can be *fully* mixed by modest applied electric fields, whereas atoms (usually) don't

Hadronic CP Violation in Diamagnetic Atoms

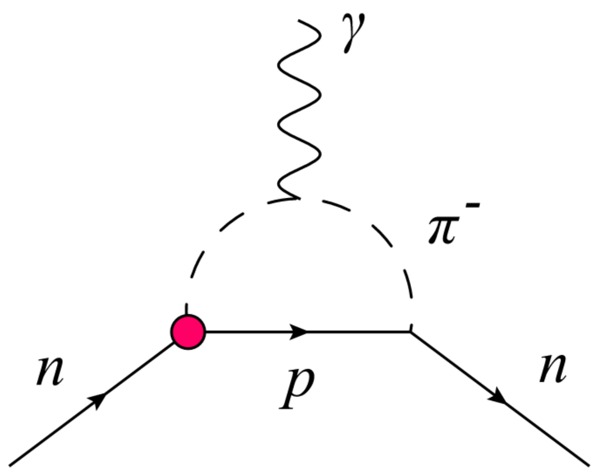
Nucleon EDMs: [Crewther, Di Vecchia, Veneziano, Witten, *PLB* **88**, 123 (1979)]

Intranuclear forces: [Haxton, Henley, *PRL* **51**, 1937 (1983)],

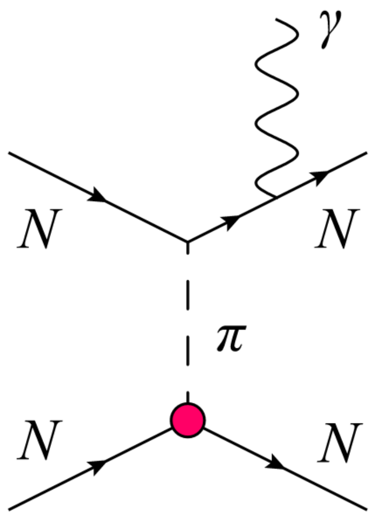
[O. Sushkov, Flambaum, Khriplovich, *JETP* **60**, 873 (1984)]

Illustrative example: $\mathcal{L} = \theta \frac{g_s^2}{32\pi^2} G\tilde{G}$

Nucleon EDMs



CP-violating intranuclear forces

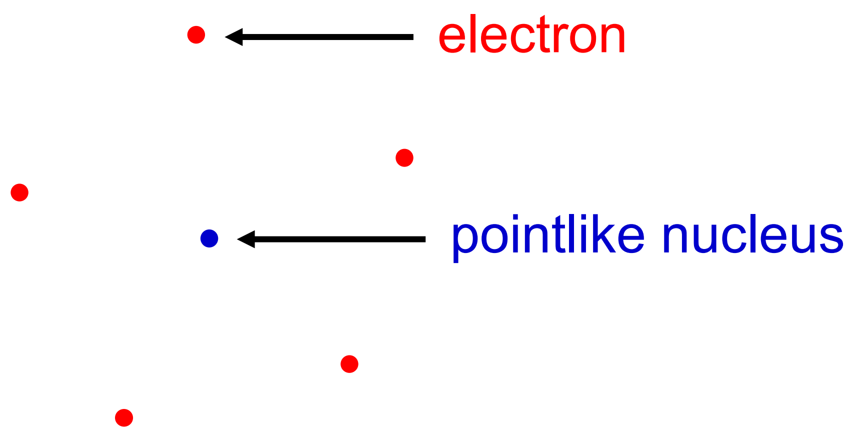


In nuclei, **tree-level** CP-violating intranuclear forces dominate over **loop-induced** nucleon EDMs [loop factor $= 1/(8\pi^2)$].

Schiff's Theorem

[Schiff, *Phys. Rev.* **132**, 2194 (1963)]

Schiff's Theorem: "In a neutral atom made up of point-like non-relativistic charged particles (interacting only electrostatically), the constituent EDMs are screened from an external electric field."



Classical explanation for nuclear EDM: A neutral atom does not accelerate in an external electric field!

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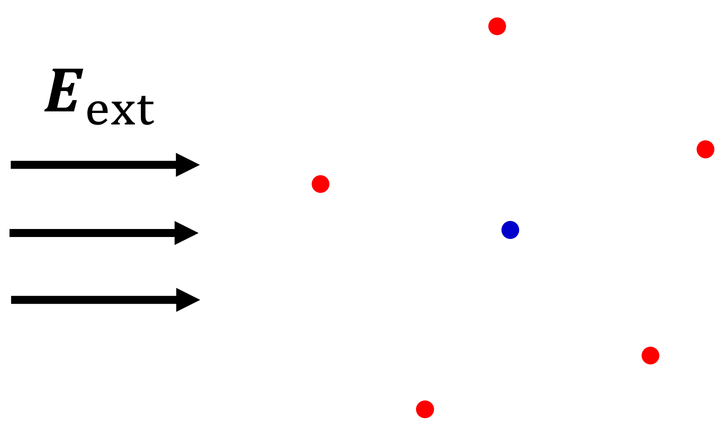

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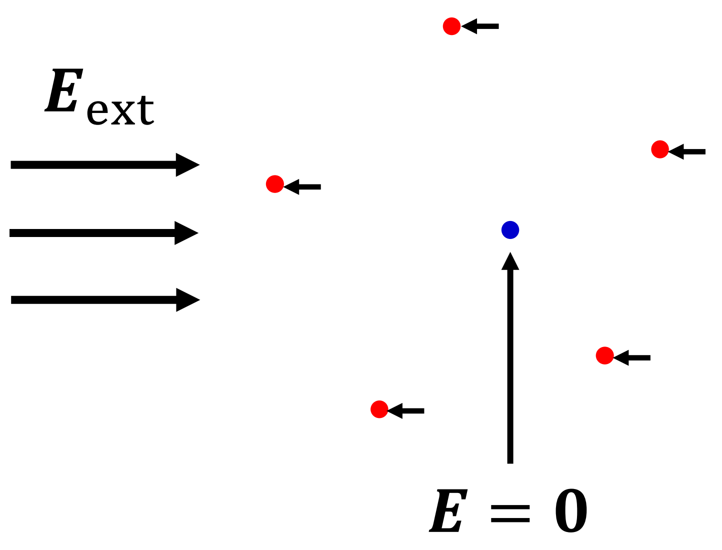

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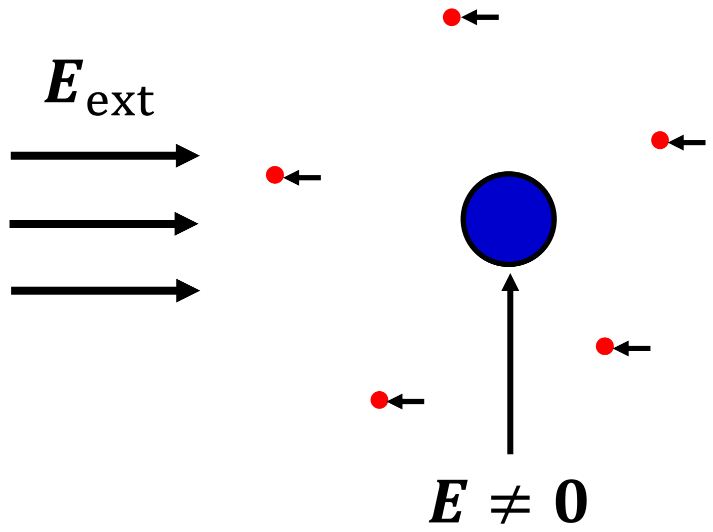
Lifting of Schiff's Theorem

[Sandars, *PRL* **19**, 1396 (1967)],
[O. Sushkov, Flambaum, Khriplovich, *JETP* **60**, 873 (1984)]

In real (heavy) atoms: Incomplete screening of external electric field due to finite nuclear size, parametrised by **nuclear Schiff moment**.

(= "screened nuclear EDM")

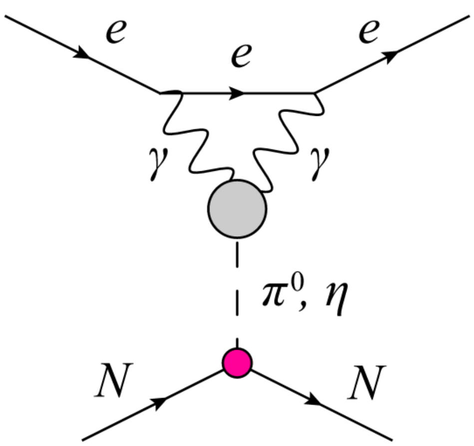


Hadronic CP Violation in Paramagnetic Molecules

[Flambaum, Pospelov, Ritz, Stadnik, *PRD* **102**, 035001 (2020)]

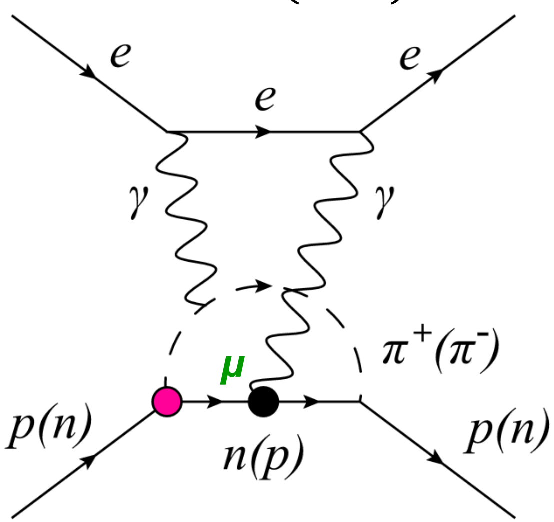
- Hadronic CP-violating effects arise via 2γ-exchange starting at **2-loop level**

LO: $\mathcal{O}\left(m_\pi^{-2}\right)$



CP-odd nucleon polarisabilities ($\propto \boldsymbol{E} \cdot \boldsymbol{B}$)

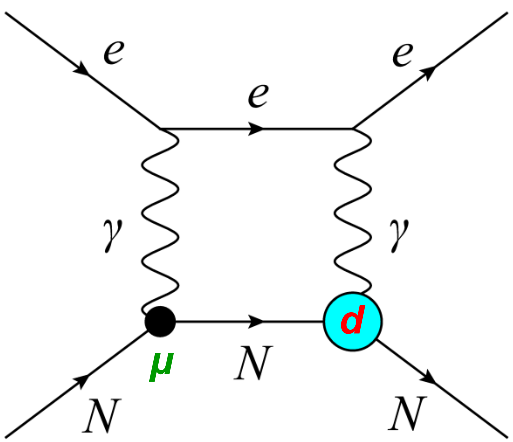
NLO: $\mathcal{O}\left(m_\pi^{-1}\right)$



CP-odd nucleon polarisabilities ($\propto \boldsymbol{E} \cdot \boldsymbol{B}$)

$(\boldsymbol{\mu} - \boldsymbol{d})$: $\mathcal{O}[\ln(A)/p_{\mathrm{F}}]$

[Fermi-gas model]



Internal nuclear excitations

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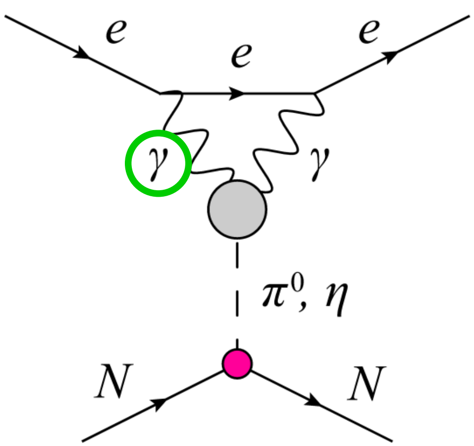

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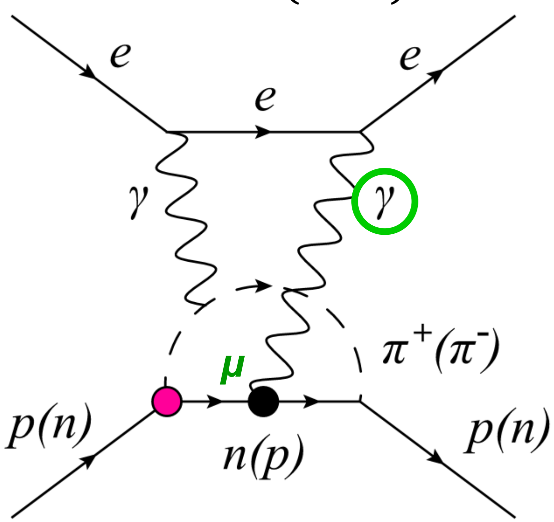

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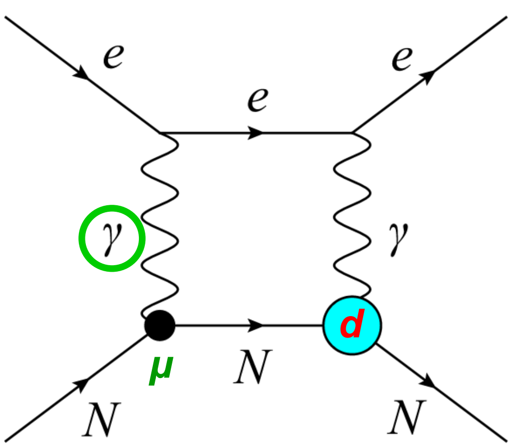

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  - **$\mathcal{O}(A)$-enhanced** CP-odd nuclear *scalar* polarisability

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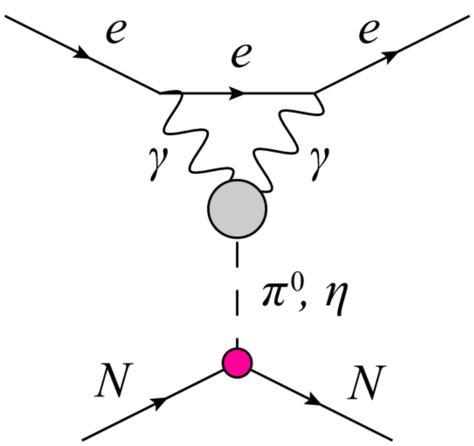

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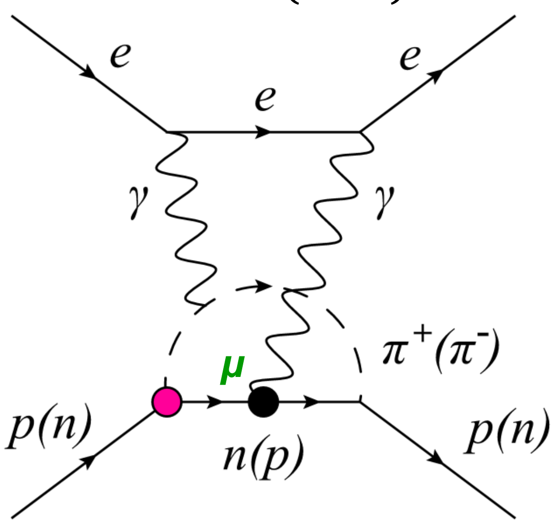

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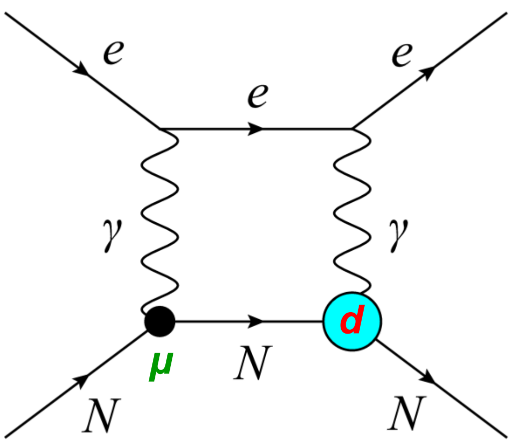

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- One of photons interacts *magnetically* with nucleus => **no Schiff screening**
  - $\boldsymbol{\mathcal{O}(A)}$**-enhanced** CP-odd nuclear *scalar* polarisability
  - Operative even in *spinless* nuclei (e.g., ^{232}ThO, $^{180}HfF^{+}$)

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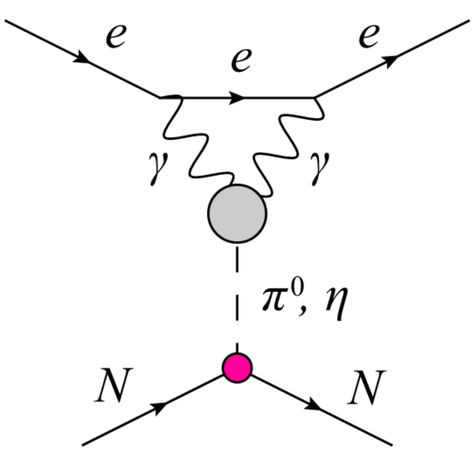

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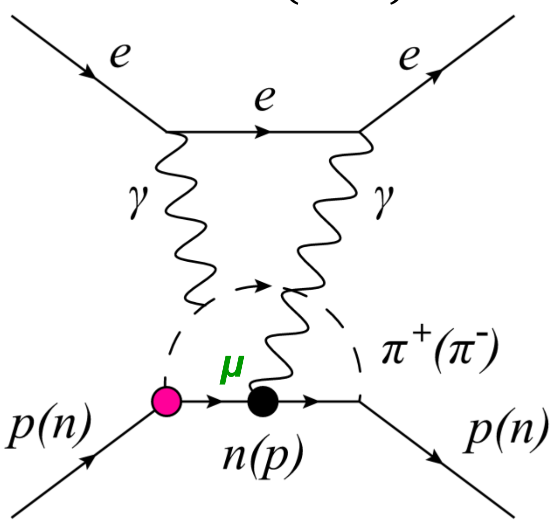

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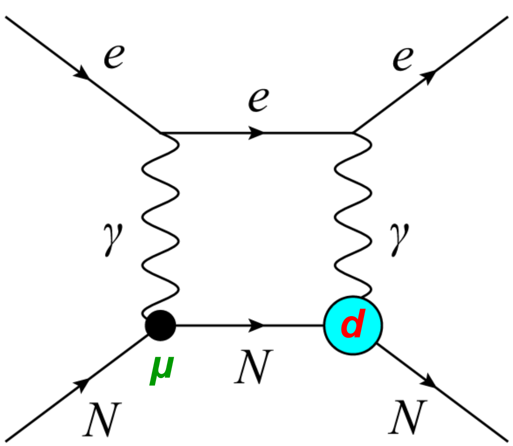

Internal nuclear excitations

Isoscalar CP-Odd π-N Coupling $\mathcal{L} = \bar{g}_{\pi NN}^{(1)} \pi^0 \bar{N} N$

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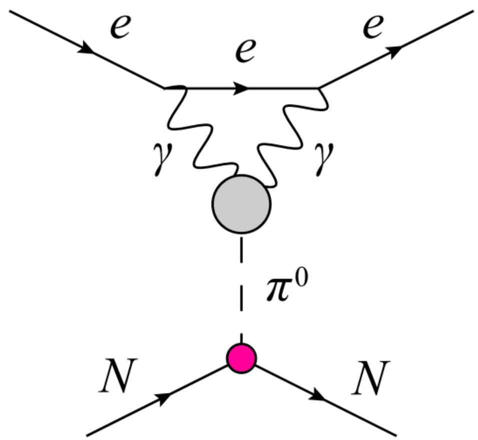

π^0 exchange

In molecules with *spinless* nuclei (e.g., ^{232}ThO, ^{180}HfF$^+$), effect dominated by a **"bulk"** property of the nucleus that grows with A in a regular manner, with *no contribution* from the nuclear Schiff moment mechanism (needs $I \neq 0$)

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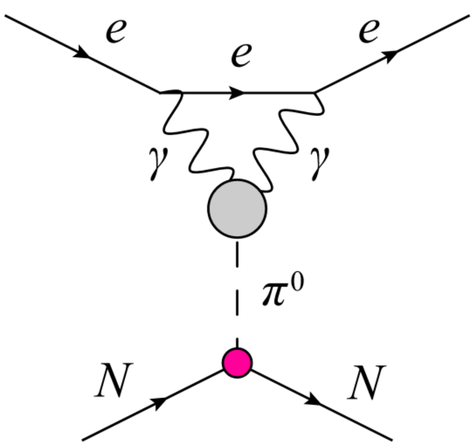

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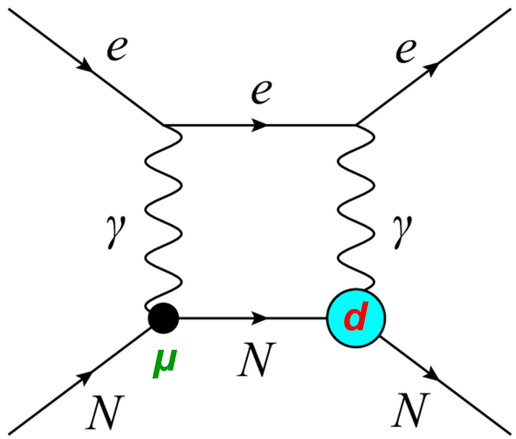
=> Clean bounds, since less sensitivity to details of nuclear structure

(cf. strong sensitivity of ^{199}Hg Schiff moment to assumptions about underlying nuclear structure – different models give different signs for sensitivity coefficient!)

Nucleon EDMs $\mathcal{L} = -\frac{i}{2} d_N \bar{N} F_{\mu\nu} \sigma^{\mu\nu} \gamma_5 N$

[Flambaum, Pospelov, Ritz, Stadnik, *PRD* **102**, 035001 (2020)]



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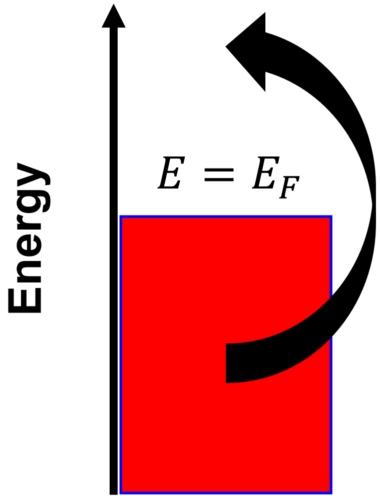

Continuum

Excitations to continuum above Fermi surface: $\sim \ln(A)/p_{\mathrm{F}}$ [Fermi-gas model]

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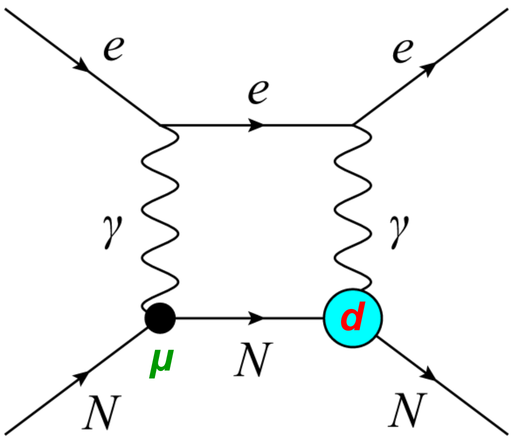

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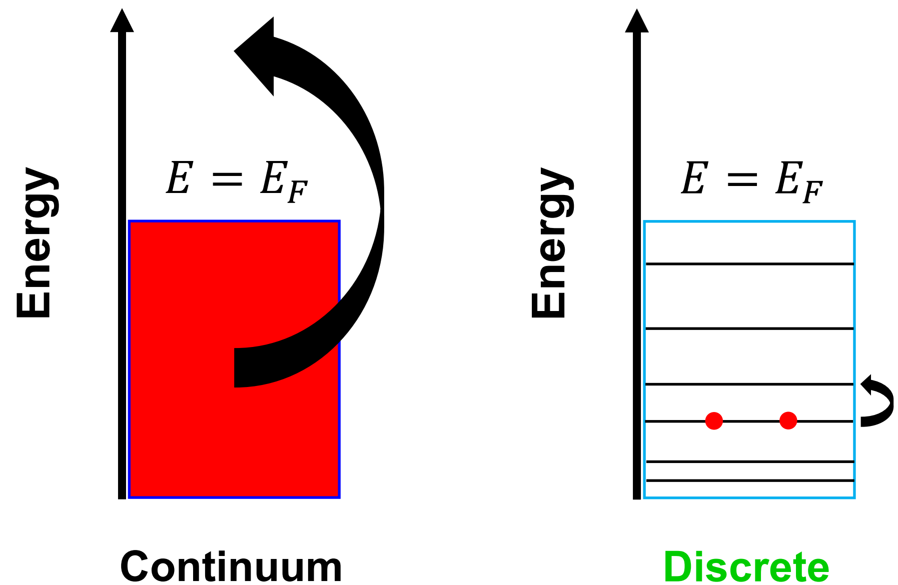

Excitations to continuum above Fermi surface: $\sim \ln(A)/p_{\mathrm{F}}$ [Fermi-gas model]

Discrete transitions between L-S doublets: $\sim[\mathcal{O}(10)/A] \times (1/\Delta E_{\mathrm{nucl}})$

[Giant resonance model – Flambaum, Samsonov, Tran Tan, *JHEP* **10** (2020) 077]

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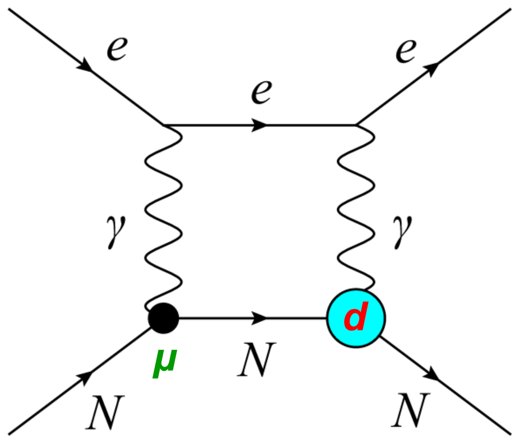

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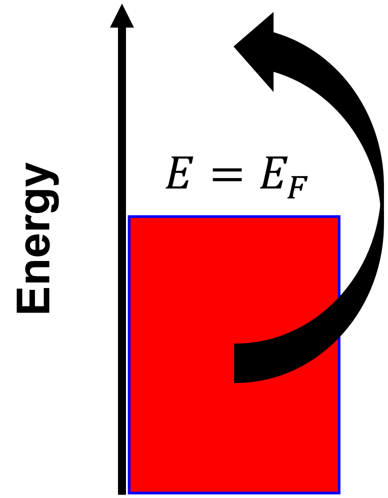

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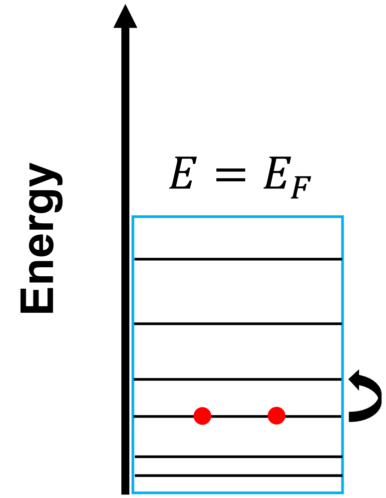

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For $A \sim 200$ and $\Delta E_{\mathrm{nucl}} \sim \mathrm{several\ MeV}$, the two contributions are comparable in size (and of the same sign)

QCD Vacuum Angle $\mathcal{L} = \theta \frac{g_s^2}{32\pi^2} G\tilde{G}$

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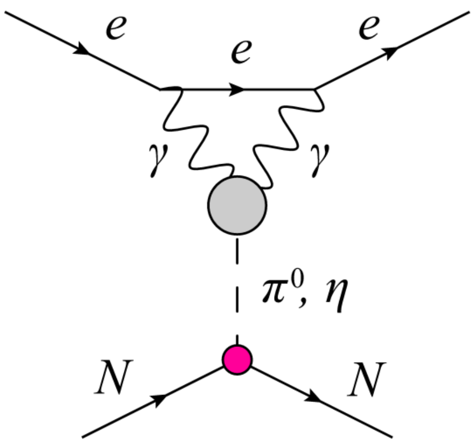
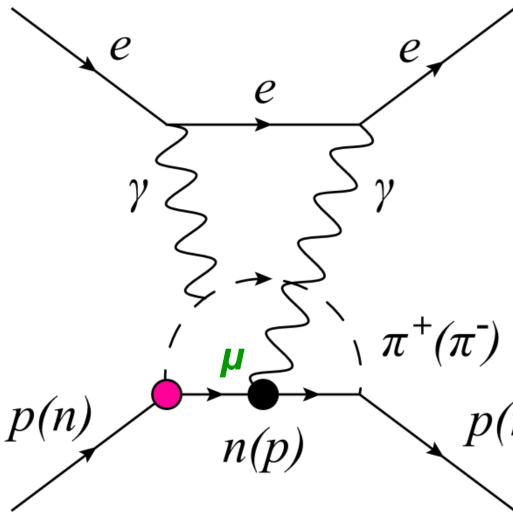


π^0, η contributions:
opposite sign
(near-cancellation
in heavy nuclei)

NLO: $\mathcal{O}(m_\pi^{-1})$



+

$(\boldsymbol{\mu} - \boldsymbol{d})$: $\mathcal{O}[\ln(A)/p_\mathrm{F}]$

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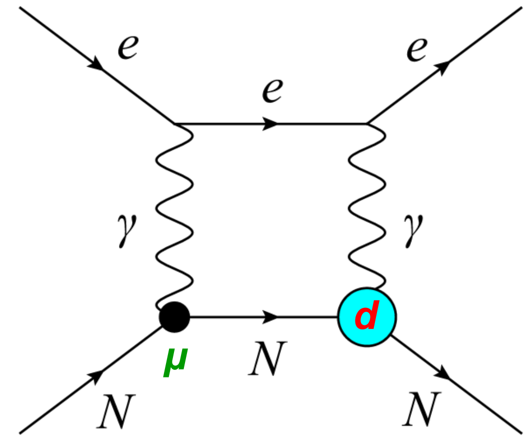

p, n contributions: ***same*** sign

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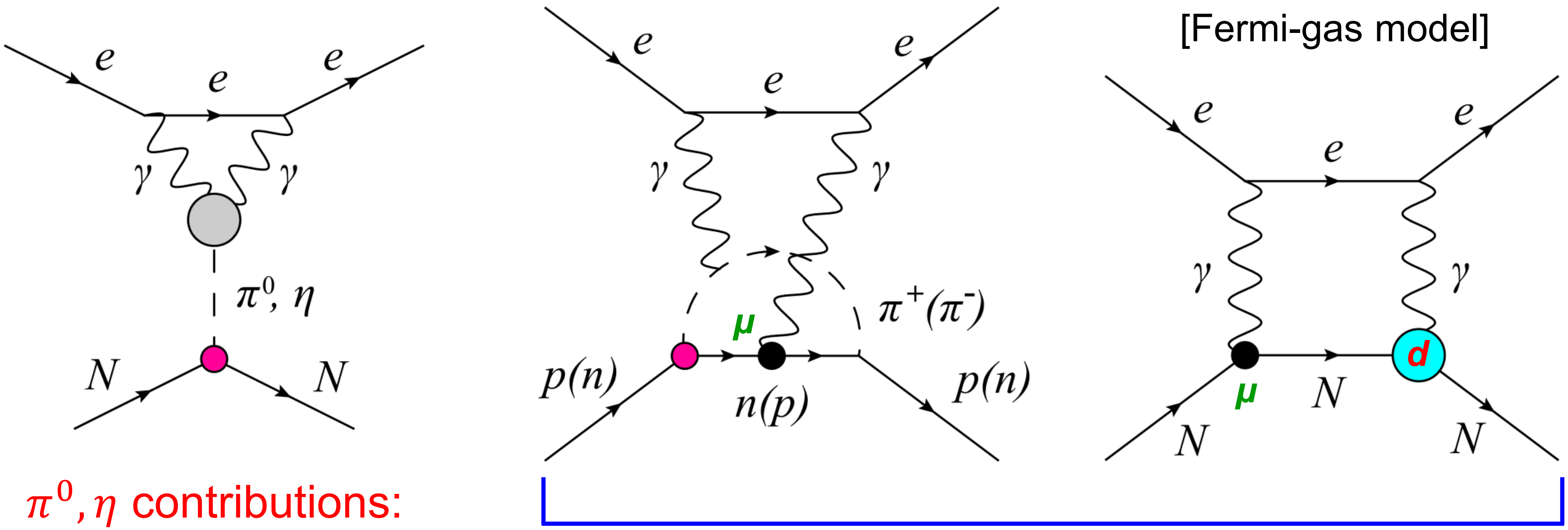

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p, n contributions: ***same*** sign

For $Z \sim 80$ & $A \sim 200$: $C_\mathrm{SP}(\theta) \approx \left[0.1_\mathrm{LO} + 1.0_\mathrm{NLO} + 1.7_{(\mu-d)}\right] \times 10^{-2}\theta \approx 0.03\theta$

$$\mathcal{L}_\mathrm{contact} = -\frac{G_F C_\mathrm{SP} \bar{N} N \bar{e} i\gamma_5 e}{\sqrt{2}}$$

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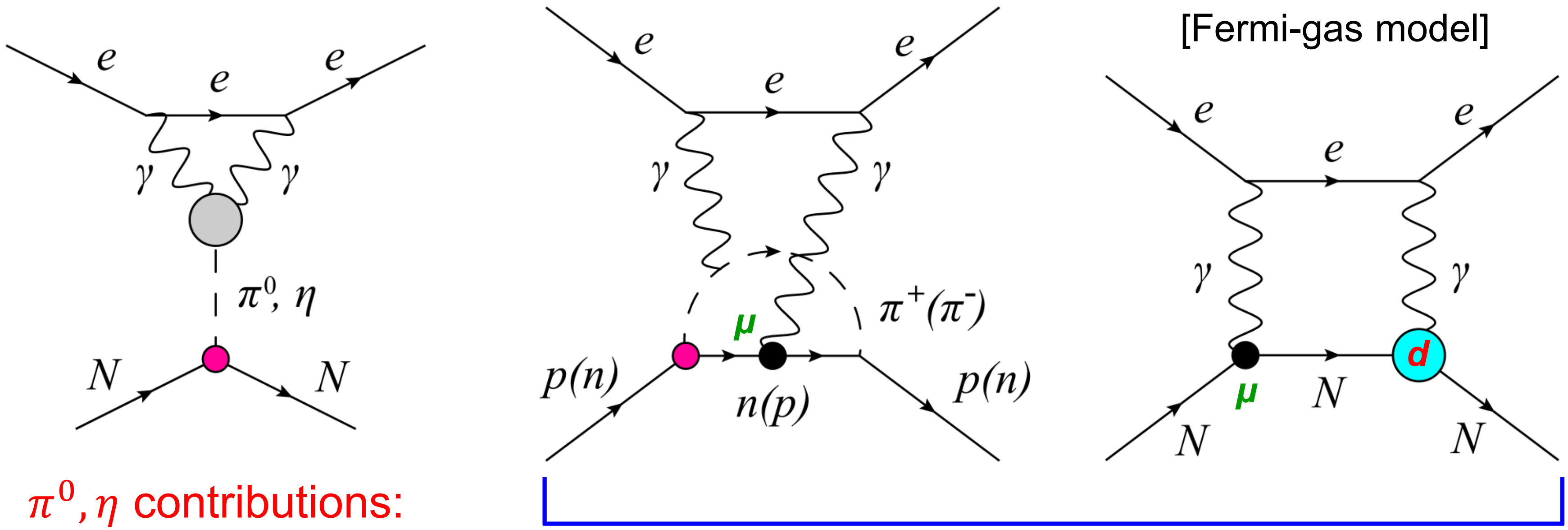

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Future work: η' contribution and other N²LO contributions, nuclear in-medium effects (NLO process), nuclear structure effects [$(\mu - d)$ process]

Bounds on Hadronic CP Violation Parameters

ThO bounds: [Flambaum, Pospelov, Ritz, Stadnik, *PRD* **102**, 035001 (2020)]

System	$\left\|\bar{g}_{\pi NN}^{(1)}\right\|$	$\left\|\tilde{d}_u - \tilde{d}_d\right\|$ (cm)	$\left\|d_p\right\|$ (e cm)	$\|\theta\|$
ThO	$\mathbf{4 \times 10^{-10}}$	$\mathbf{2 \times 10^{-24}}$	$\mathbf{2 \times 10^{-23}}$	$\mathbf{3 \times 10^{-8}}$
n	1.1×10^{-10}	5×10^{-25}	—	2.0×10^{-10}
Hg	1×10^{-12}	5×10^{-27}	2.0×10^{-25}	1.5×10^{-10}
Xe	6.7×10^{-8}	3×10^{-22}	3.2×10^{-22}	3.2×10^{-6}

* These limits can formally be null within nuclear uncertainties

Current bounds from molecules are $\sim 10 - 100$ times weaker than from Hg & n, but are $\sim 10 - 100$ times stronger than bounds from Xe

Summary

- Paramagnetic atoms and molecules are sensitive to hadronic sources of CP violation via two-photon-exchange processes
- We have placed novel and independent constraints on the hadronic CP-violation parameters $|\theta|$, $\left|d_p\right|$, $\left|\bar{g}_{\pi NN}^{(1)}\right|$ and $\left|\tilde{d}_u - \tilde{d}_d\right|$ using data from ThO EDM measurements (ACME experiment)
- Possible future work includes detailed study of nuclear structure effects, nuclear in-medium effects, η' and other N^2LO contributions