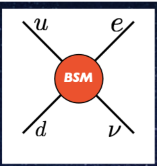
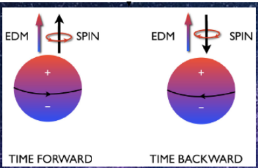
EDM-3: Schiff Moments

J. Engel

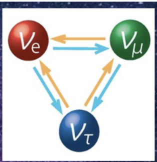
June 1, 2023



β decays and new particles



T & CP violation and the Origin of Matter

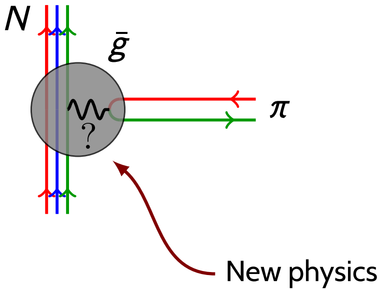


Neutrino properties & CP violation

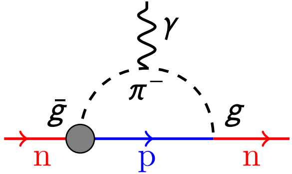
One Way Things get EDMs

We all believe that there is BSM CP violation.

It can work its way into hadrons and nuclei, e.g., through CP-violating πNN vertices …



leading, e.g. to a neutron EDM…

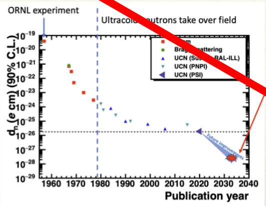


NTNP Slide from Kickoff Meeting

neutron EDM

Shindler:
Eur.Phys.J.A 57 (2021) 4, 128

Alcorcon et al.:
2022 Snowmass Summer Study

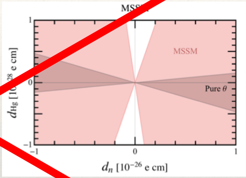


$$|d_n| < 1.8 \times 10^{-26}\ e\ \text{cm (90\% C.L.)}$$

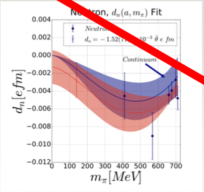
Abel et al.:
Phys.Rev.Lett. 124 (2020) 8, 081803

$$(d_n)_{SM} = (1-6)\times 10^{-32} e\ \ \text{cm}$$

$$\begin{aligned} d_n = & -(1.5\pm 0.7)\cdot 10^{-3}\bar{\theta} e\ \text{fm} \\ & -(0.2\pm 0.01)d_u + (0.78\pm 0.03)d_d + (0.0027\pm 0.016)d_s \\ & -(0.55\pm 0.28)e\tilde{d}_u - (1.1\pm 0.55)e\tilde{d}_d + (50\pm 40)\text{MeV}\, e\tilde{d}_G \end{aligned}$$



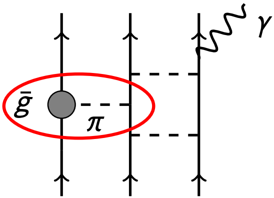
- 6 orders of magnitudes of background-free window for BSM discovery
- Lattice QCD provides the only theoretically robust way to determine hadronic matrix elements -> only way to interpret experimental results and disentangle all CP violating sources
- Need a portfolio of EDM experiments. Single EDM experiment not sufficient even if the LEC are correlated in a given model
- Use new method based on the GF to overcome the major hurdle (renormalization) that has prevented in the past any lattice EDM calculation -> first results on the θ term
- Goal —> Calculate all relevant contributions to the neutron EDM from the theta term and from BSM physics



Dragos, Luu, Shindler,
de Vries, Yousif:
Phys.Rev.C 103 (2021) 1

How Diamagnetic Atoms Get EDMs

The nucleus gets an EDM from the nucleon EDM and a *T*-violating *NN* interaction:



$$V_{PT} \propto \bar{g}g \times (\boldsymbol{\sigma}_1 \pm \boldsymbol{\sigma}_2) \cdot (\nabla_1 - \nabla_2) \frac{\exp\left(-m_\pi |\boldsymbol{r}_1 - \boldsymbol{r}_2|\right)}{m_\pi |\boldsymbol{r}_1 - \boldsymbol{r}_2|} + \text{contact terms/etc.}$$

Atoms get EDMs from nuclei. Electronic shielding replaces nuclear dipole operator with "Schiff operator,"

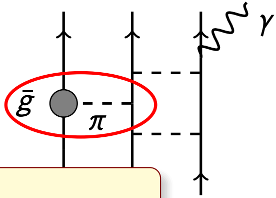
$$S \propto \sum_p \left(r_p^2 - \frac{5}{3} R_{\text{ch}}^2\right) z_p + \ldots ,$$

making relevant nuclear quantity the Schiff moment:

$$\langle S \rangle = \sum_m \frac{\langle 0 | S | m \rangle \langle m | V_{PT} | 0 \rangle}{E_0 - E_m} + c.c.$$

How Diamagnetic Atoms Get EDMs

The nucleus gets an EDM from the nucleon EDM and a *T*-violating *NN* interaction:



$V_{PT} \propto \bar{g}g$ … rms/etc.

Job of nuclear-structure theory: compute dependence of $\langle S \rangle$ on the three $\bar{g}$'s (and on the contact-term coefficients and nucleon EDM).

It's up to QCD/EFT to compute the dependence of the $\bar{g}$ vertices on fundamental sources of *CP* violation.

Atom… …clear dipole…

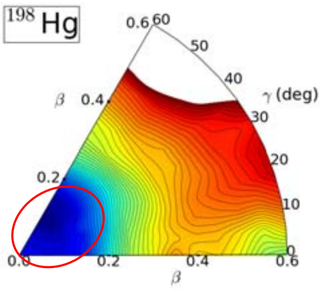
$$S \propto \sum_p \left(r_p \; - \; \frac{\;}{3} R_{\text{ch}} \right) z_p + \ldots ,$$

making relevant nuclear quantity the Schiff moment:

$$\langle S \rangle = \sum_m \frac{\langle 0 | S | m \rangle \langle m | V_{PT} | 0 \rangle}{E_0 - E_m} + c.c.$$

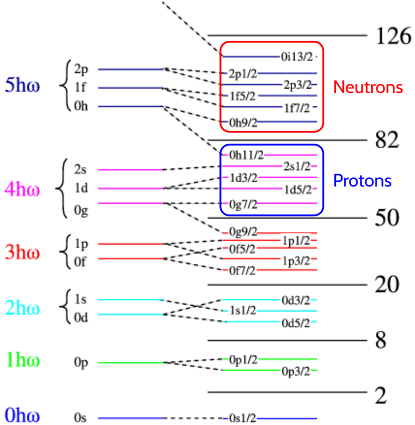
^{199}Hg and ^{129}Xe: Soft and Complicated

^{198}Hg has a very soft oblate minimum.



Prassa et al., EPJ Web Conf. **252** 02007 (2021).

Shell-Model Representation



Will construct an *ab initio* shell-model interaction that includes the CP-violating part.

More on Ab Initio Shell-Model Calculation

Valence-Space IMSRG: Include V_{PT} as part of the Hamiltonian, so that the flow generator η and the transformed Hamiltonian will have negative-parity parts η^- and H^- :

$$H(s) = H_+(s) + \lambda H_-(s) + \mathcal{O}(\lambda^2) \qquad \eta = \eta_+(s) + \lambda \eta_-(s)\,, \quad \lambda \ll 1$$

with

$$H_+(0) = T + V_\chi \qquad H_-(0) = V_{PT}\,, \quad \text{for some } \bar{g}$$

Grouping by powers of λ:

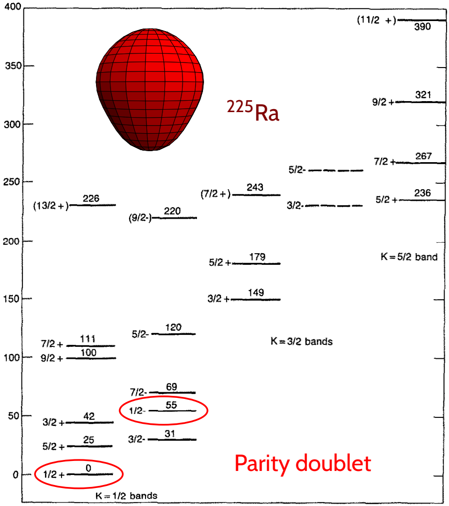
$$\frac{dH_+(s)}{ds} = [\eta_+(s), H_+(s)] + \mathcal{O}(\lambda^2)$$
$$\frac{d}{ds}H_-(s) = [\eta_+(s), H_-(s)] + [\eta_-(s), H_+(s)] + \mathcal{O}(\lambda^2)$$

η_+ and H_+ are what you get without V_{PT}.

You then evolve the Schiff operator, which develops a positive-parity part.

Ragnar, UNC postdoc David Kekejian, and I are working on this already.

A Little on Pear-Shaped Nuclei



Because V_{PT} is so weak:

$$\langle S \rangle = \sum_{i \neq 0} \frac{\langle 0|S|i\rangle \langle i|V_{PT}|0\rangle}{E_0 - E_i} + c.c.$$

$$\approx \frac{\langle 0|S|\bar{0}\rangle \langle \bar{0}|V_{PT}|0\rangle}{E_0 - E_{\bar{0}}} + c.c.$$

Mixing of the two states in the parity doublet by V_{PT} is the whole story here.

Schiff moments can be enhanced by two orders of magnitude or more.

IM-GCM for Schiff Moment of ^{225}Ra and Similar Nuclei

Required Improvements to Method

- More nucleons = larger spaces
  = more memory, processors
  = code refactorization for efficient supercomputer use
- Odd nuclei
- Tests of chiral interactions in really heavy nuclei.

Milestones/Synergy

MSU, ND, UNC work:

- Y1 Develop software and file formats to deploying EFT transition operators in *ab* initio calculations.
- Y1 Preliminary VS-IMSRG result for the Schiff moment of ^{199}Hg.
- Y2 Exploration of uncertainties in VS-IMSRG Schiff moments of ^{199}Hg and ^{129}Xe.
- **Y3 Results with uncertainties for Schiff moments of ^{199}Hg and ^{129}Xe.**
- Y4 Preliminary IM-GCM Schiff moment in ^{225}Ra.
- **Y5 Results with uncertainties for Schiff moments of ^{225}Ra.**

More Synergy?

- Coupled-cluster calculations?
- Comparison with QMC in light nuclei?
- EFT and QCD people: connecting V_{PT} with underlying models? Regulating counter terms? Higher order in chiral EFT?
- Your suggestion here ______________________