Nuclear Structure and New Physics

J. Engel

University of North Carolina

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New Physics

Some Basic Questions

What underlies the Standard Model?

What are the consequences for neutrinos?

Why is the θ parameter in QCD so small?

Why is there more matter than antimatter in our universe?

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Low-energy experiments are an increasingly important part of the effort to address these questions.

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Examples: Searches for

Electric Dipole Moments (EDMs) and CP violation

β decay and breaking/extension of $SU(2)_L$

$0\nu\beta\beta$ decay and lepton-number violation

Dark Matter

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Nuclear structure, experiment and theory, has a lot to contribute.

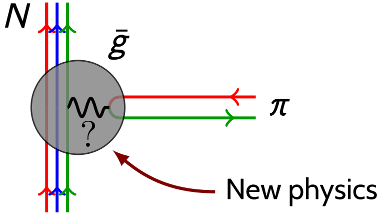
EDMs: How Atoms Can Get Them

EDMs require *CP* violation

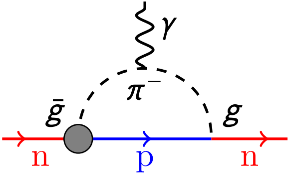
and

an undiscovered source of *CP* violation is required to explain why there is so much more matter than antimatter.

The source can work its way into nuclei through CP-violating πNN vertices (in chiral EFT)…

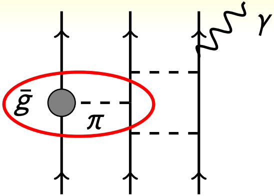


leading, e.g. to a neutron EDM…



EDMs: How Atoms Can Get Them (cont.)

…and to a nuclear EDM from the nucleon EDM or a *T*-violating *NN* interaction:



Note: $\cancel{CP} = \cancel{T}$

$$V_{PT} \propto \bar{g}\,(\boldsymbol{\sigma}_1 \pm \boldsymbol{\sigma}_2) \cdot (\boldsymbol{\nabla}_1 - \boldsymbol{\nabla}_2)\,\frac{\exp\left(-m_\pi|\boldsymbol{r}_1 - \boldsymbol{r}_2|\right)}{m_\pi|\boldsymbol{r}_1 - \boldsymbol{r}_2|} + \text{contact term}$$

The $\bar{g}$'s (isoscalar, isovector and isotensor) depend on source of CP violation.

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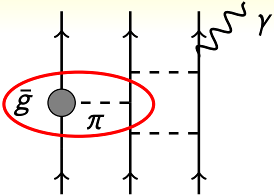

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Atom gets an EDM from nucleus. But electronic shielding replaces nuclear dipole operator with "Schiff operator,"

$$S \approx \sum_p r_p^2 z_p + \ldots\ ,$$

making relevant nuclear quantity the Schiff moment:

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

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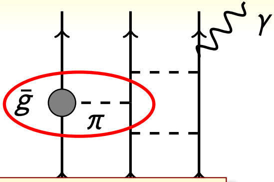

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Job of nuclear-structure theory: compute dependence of $\langle S \rangle$ on the $\bar{g}$'s (and on the contact term and nucleon EDM).

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

$$S \approx \sum_p r_p^2 z_p + \ldots ,$$

making relevant nuclear quantity the Schiff moment:

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

Uncertainties in Calculations

More precisely,

$$\langle S \rangle = \sum_i a_i \, g \, \bar{g}_i \,,$$

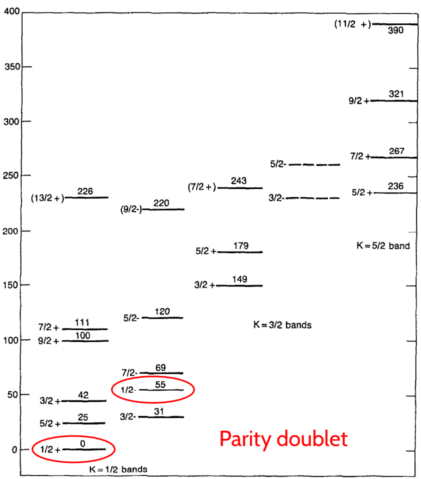
and we have to calculate the three a_i. These reflect action of both S and V_{PT}.

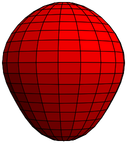
In the heavy and sometimes deformed nuclei used in atomic EDM experiments, only Skyrme DFT and more similar but more phenomenological models have been used.

The uncertainty in the a_i is large and difficult to estimate.

Nuclear-structure observables can help.

^{225}Ra: Octupole Physics





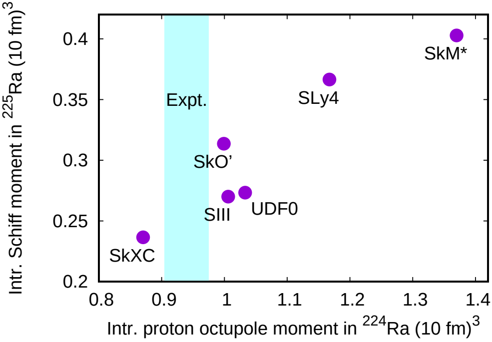
Deformed density

$|\tfrac{1}{2}^{\pm}\rangle = \frac{1}{\sqrt{2}}\Big(|$  $\rangle \pm |$  $\rangle \Big)$

$$\langle S \rangle \approx 2\frac{\langle \tfrac{1}{2}^{+} | S_z | \tfrac{1}{2}^{-} \rangle \langle \tfrac{1}{2}^{-} | V_{PT} | \tfrac{1}{2}^{+} \rangle}{E_+ - E_-}$$

Unlike in other nuclei, these two states are the whole story.

Correlation of $\langle S \rangle_{\text{intr.}}$ with Octupole Defm. in ^{224}Ra



J. Dobaczewski, JE, M. Kortelainen, P. Becker

Correlation with octupole moment of ^{225}Ra even better.

Will be determined at ANL.

Implications for Lab Schiff Moment

The resulting a_i:

	isoscalar	isovector	isotensor
Skyrme analysis	-0.4 – 0.8	-2 – -8	2 – 5

Range doesn't include systematiojc uncertainty.

The problem is that we don't have information about $\langle V_{PT} \rangle$.

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Can we find measurements that will constrain its matrix element?

- In one-body approximation $V_{PT} \approx \vec{\sigma} \cdot \vec{\nabla}\rho$. The closest simple one body operator is $\vec{\sigma} \cdot \vec{r}$.

  Can we measure $\langle 1/2^- | \vec{\sigma} \cdot \vec{r} \, | 1/2^+ \rangle$ or something like it?

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- What about charge-changing transition strength to isobar analog of $|1/2^-\rangle$ in ^{225}Fr? Axial-charge β decays in other nuclei?

  V_{PT} is similar to two-body current operator in axial-charge channel.

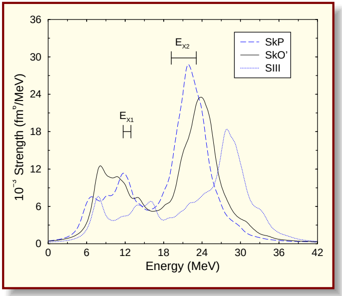
Reducing Uncertainty in $\langle S \rangle$ for ^{199}Hg

The Isotope with the Best Experimental EDM Limit

Here no single excited state dominates the sum.

Isoscalar dipole operator $\sum_{i=1}^{A} r_i^2 \vec{r}_i$ is isoscalar version of Schiff operator.

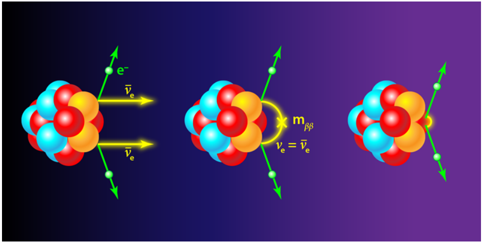
^{208}Pb



Can use measured strength distribution to constrain density functionals.

Can these mesaurements be done in Hg?

$\beta\beta$ Decay



Three mechanisms, the last two of which signal new physics.

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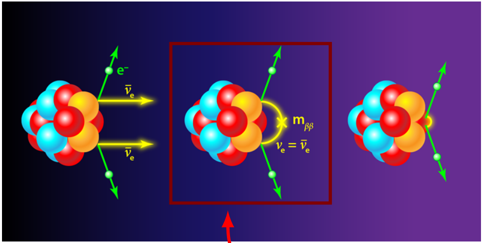

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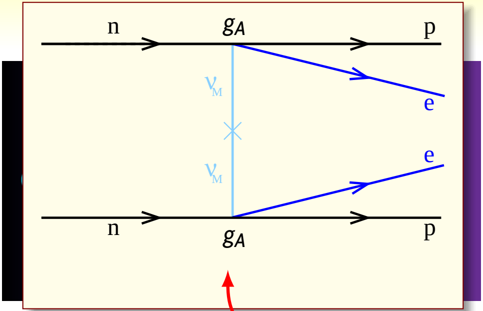

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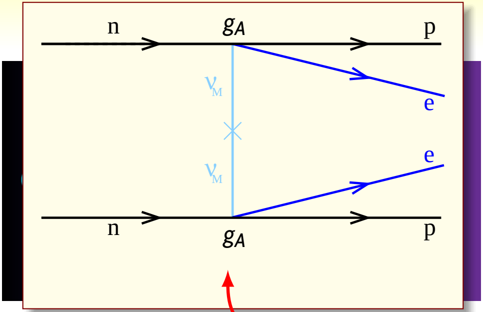

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Largest part of matrix element:

$$M_{GT}^{0\nu} = g_A^2 \langle f | \sum_{a,b} H(r_{ab}) \vec{\sigma}_a \cdot \vec{\sigma}_b \tau_a^+ \tau_b^+ | i \rangle$$

with

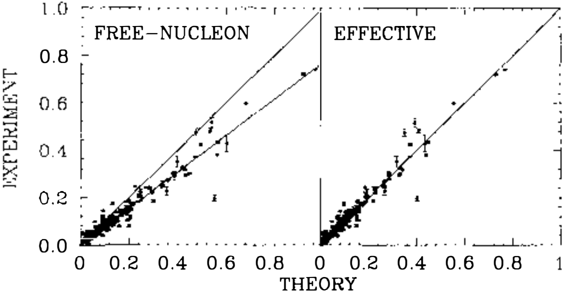
$$H(r) \approx \frac{R_{\text{nucl.}}}{r}$$

Quenching of g_A in β Decay

Leading order decay operator is $\vec{\sigma}\tau_+$.

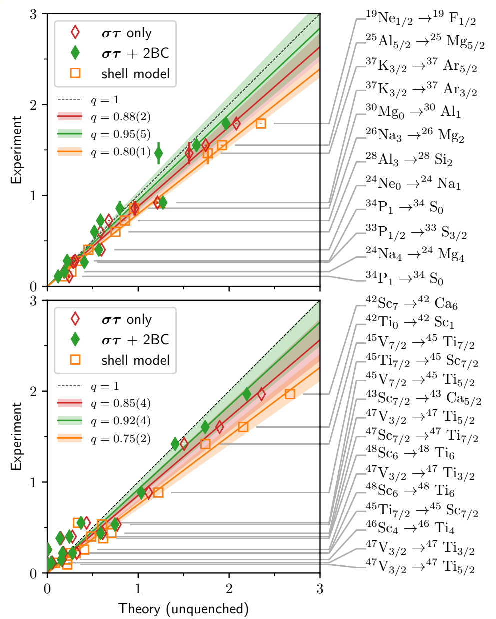
50-Year-Old Problem: Effective g_A needed in all calculations of shell-model (or related) type.

Brown & Wildenthal



Many suggestions about the cause but, until recently, no consensus.

Quenching in the *sd* and *pf* Shells



IMSRG calculation, preliminary

Figure from J.D. Holt

Quenching caused both by correlations from outside the model space and by the two-body current.

What about $0\nu\beta\beta$ Decay?

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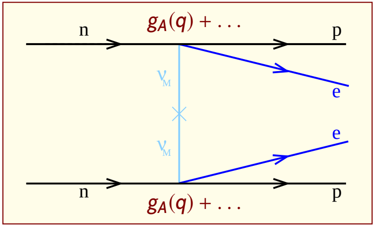


Here the current transfers momentum of 100 – 200 MeV (on average) to nucleons.

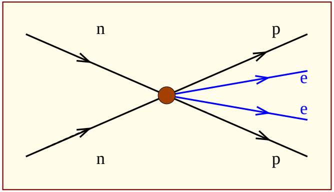
How much are such high-*q* transitions quenched? Can we look at:

- μ capture?
- ν scattering?

A Problem with Chiral Effective Theory of $\beta\beta$ Decay

Effects from beyond nucleon-pion degrees of freedom aggregated in "contact terms."

The $0\nu\beta\beta$ operator has one, corresponding to the exchange of a neutrino with really high momentum:



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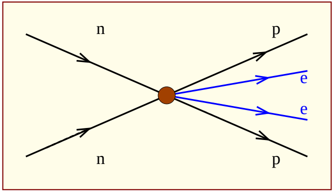

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Any alternatives?

What Can Theorists Contribute?

- Better $0\nu\beta\beta$ matrix elements

  Topical collaboration devoted to this and next item.

- Better calculations of Schiff moments

  Will require improved density functionals with well-determined statistical uncertainty.

- Ab initio calculations of interesting beta decay matrix elements, including recoil-order terms
- Improved calculations of radiative corrections in superallowed beta decay

  $W-\gamma$ box diagram particularly important.

- Linear response for understanding g_A quenching

  Both ab initio and density-functional methods important.

- $\vdots$

Finally…

\begin{Acknowledgments}

Thanks!

\end{Acknowledgments}

\end{Talk}