Overview of and Future of BSM Calculations, $0\nu\beta\beta$, WIMPs

J. Engel

April 12, 2019

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Can β Decay Measurements Inform Other BSM Experiments?

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New Physics

Some Basic Questions

What underlies the Standard Model?

Why is the θ parameter in QCD so small?

Why is there more matter than antimatter in our universe?

Are neutrinos Majorana?

$\vdots$

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The observation (or continued non-observation) of electric dipole moments and $0\nu\beta\beta$ decay will help us address these questions.

Atomic EDMs yield some of the best experimental limits. Heavy diamagnetic atoms are particularly sensitive to new physics within the nucleus.

Many $\beta\beta$ decay candidates are also heavy.

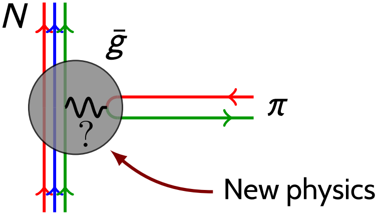
EDMs: How Atoms Can Get Them

EDMs require *CP* violation

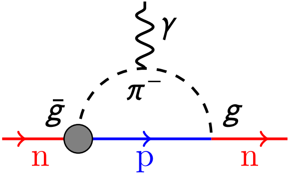
and

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)...

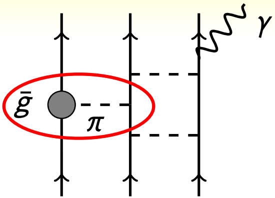


leading, e.g. to a neutron EDM...



EDMs: How Atoms Can Get Them (cont.)

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



Note: $\not{CP} = \not{T}$

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

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

EDMs: How Atoms Can Get Them (cont.)

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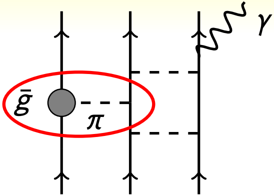

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Atoms gets an EDM from nuclei. But electronic shielding replaces nuclear dipole operator with "Schiff operator,"

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

making relevant nuclear quantity the Schiff moment:

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

EDMs: How Atoms Can Get Them (cont.)

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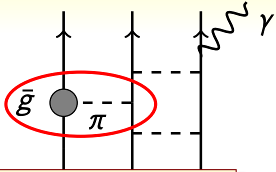

Note: $\not{CP} = \not{T}$

> 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.

nuclear dipole operator with "Schiff operator,"

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What to Compute

More precisely, because the $\bar{g}_i$ are so small,

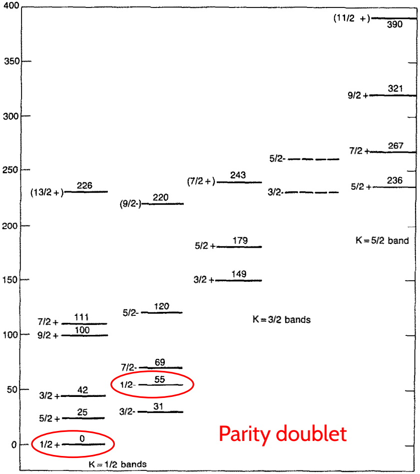
$$\langle S \rangle = \sum_i a_i \, g \, \bar{g}_i \,,$$

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

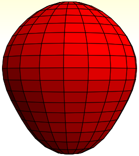
Most heavy nuclei must be treated in something like DFT for now, leading to uncertainty in the a_i that is large and difficult to estimate.

But other observables can help.

^{225}Ra: Octupole Physics

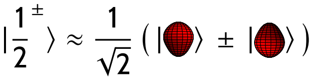


Unlike in other nuclei, these two states are the whole story.

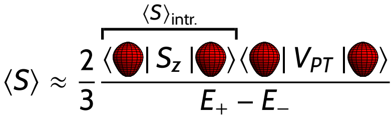


Deformed density

Two members of the parity doublet correspond to the same intrinsic mean-field state:



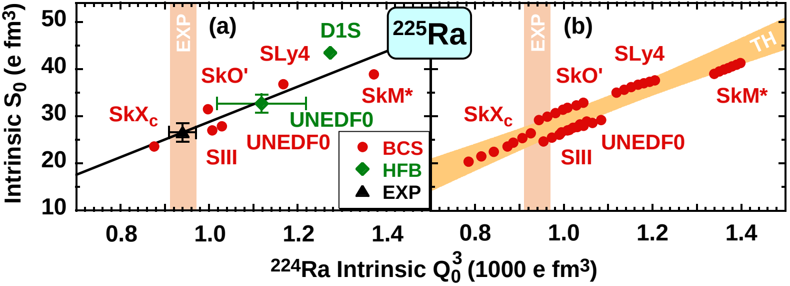
and, to good approximation,



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

Gaffney et al., 2013

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

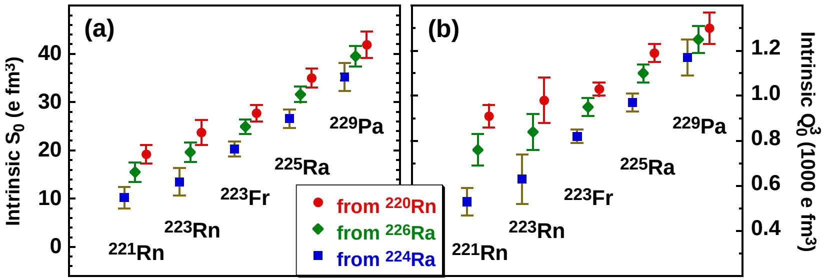


J. Dobaczewski, JE, M. Kortelainen, P. Becker

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

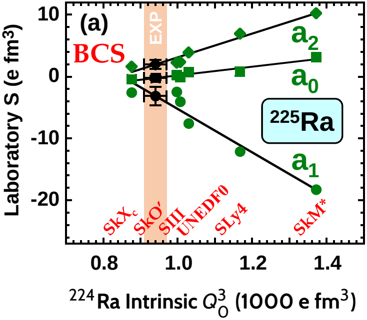
Will be determined at ANL.

Light Actinides More Generally



The error bars represent statistical uncertainty only, but systematic variation is not large.

Implications for Lab Schiff Moment



Looks good, but situation is more complicated when we include octupole moments in other nuclei. The resulting a_i for ^{225}Ra:

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

Range doesn't include systematic uncertainty.

Reducing Uncertainty of Lab Moments

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

Can β decay constrain its matrix element?

V_{PT} has same space-spin form as two-body axial-charge operator:

$$A^0_{2b} \propto \vec{\tau}_1 \times \vec{\tau}_2 \left(\vec{\sigma}_1 + \vec{\sigma}_2\right) \cdot \left(\vec{\nabla}_1 - \vec{\nabla}_2\right) \frac{e^{-m_\pi \left|\vec{r}_1 - \vec{r}_2\right|}}{m_\pi \left|\vec{r}_1 - \vec{r}_1\right|}$$

Because the one-body part,

$$A^0_{2b} \propto \frac{1}{M} \vec{\sigma} \cdot \vec{\nabla}$$

is suppressed by q/M, the pion-exchange contribution is significant.
Also, the effective one-body form of V_{PT}:

$$V^{\text{eff}}_{PT} \propto \vec{\sigma} \cdot \vec{\nabla} \rho$$

has a similar form.

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Can we measure

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

Because th

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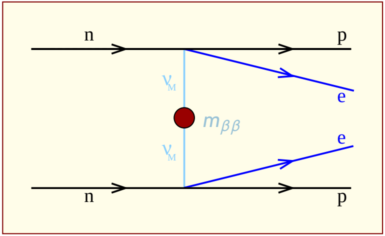
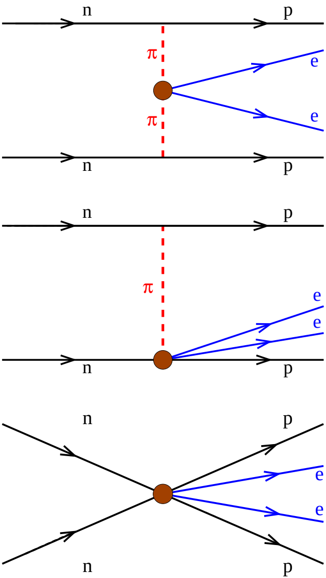
Review of $0\nu\beta\beta$ Decay

Standard operator



Other possibilities



Forbidden in Standard Model.

New physics inside blobs.

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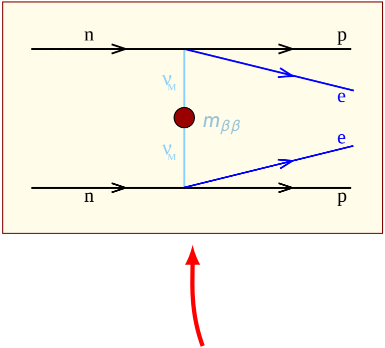
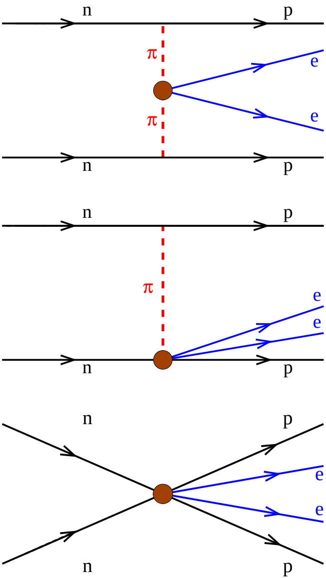


I'll focus on this one.

Forbidden in Standard Model.
New physics inside blobs.

Other possibilities



Nuclear Matrix Element (Simplified)

$$M^{0\nu} = g_A^2 \, M_{GT}^{0\nu} - g_V^2 \, M_F^{0\nu} + \ldots$$

Dominant piece

with

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

$$M_F^{0\nu} = \langle f | \, | \sum_{a,b} H_F(r_{ab}) \tau_a^+ \tau_b^+ \, | i \rangle$$

$$H_{GT}(r) \approx H_F(r) \approx \frac{R_{\text{nucl.}}}{r}$$

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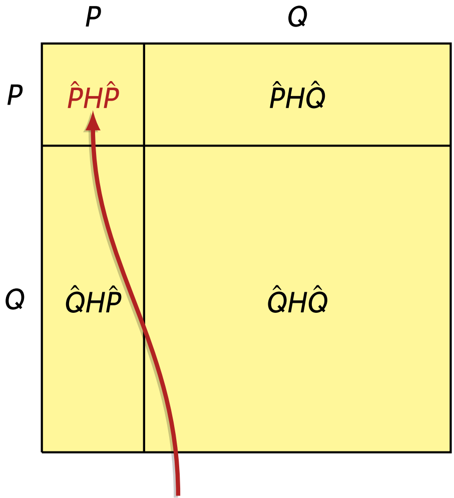
$$H_{GT}(r) \approx H_F(r) \approx \frac{R_{\text{nucl.}}}{r}$$

Also:

$$M_{2\nu} = g_A^2 \sum_m \frac{\langle f|\sum_a \vec{\sigma}_a \tau_a^+ \,|m\rangle \cdot \langle m|\sum_b \vec{\sigma}_b \tau_b^+ \,|i\rangle}{E_m - \frac{E_f + E_i}{2}}$$

Ab Initio Methods for (Fairly) Heavy Nuclei

Partition of Full Hilbert Space

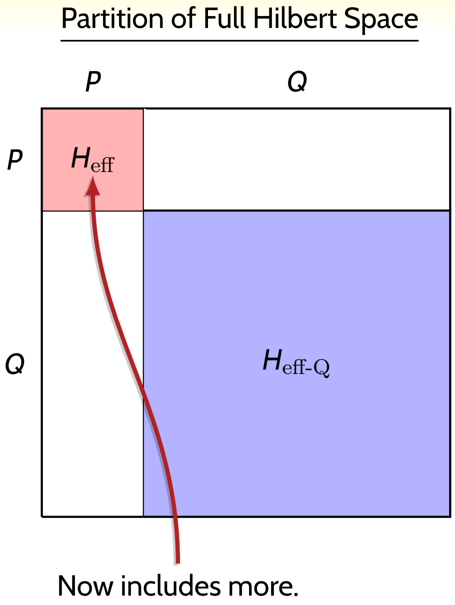


"Model" state or space

P = states we care about
Q = the rest

Task: Find unitary transformation to make H block-diagonal in P and Q, with H_{eff} in P reproducing most important eigenvalues.

Ab Initio Methods for (Fairly) Heavy Nuclei



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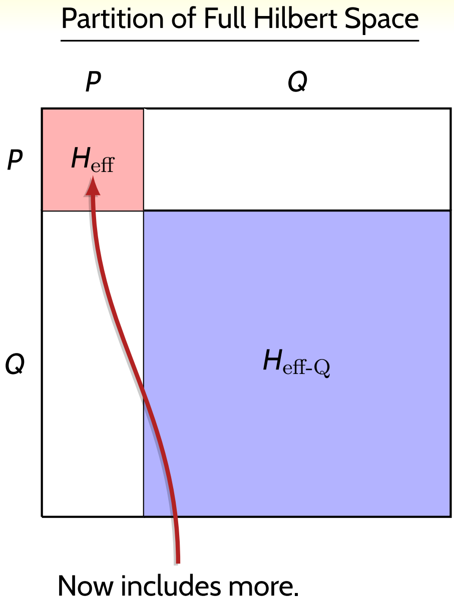

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For transition operator $\hat{M}$, must apply same transformation to get $\hat{M}_{\text{eff}}$.

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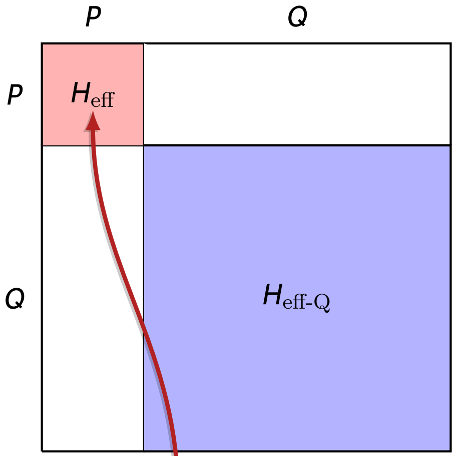

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For transition operator $\hat{M}$, must apply same transformation to get $\hat{M}_{\text{eff}}$.

As difficult as solving full problem. But N-body effective operators with $N > 2$ or 3 can be treated approximately.

Nov

Coupled Clusters

Wave function ansatz:

$$
\begin{aligned}
|\Psi\rangle &= e^{\hat{T}} \,|\text{Slater det.}\rangle \\
&= \exp\left(t^1_{ij} a^\dagger_i a_j + t^2_{ijkl} a^\dagger_i a^\dagger_j a_k a_l + \ldots\right) |\text{Slater det.}\rangle
\end{aligned}
$$

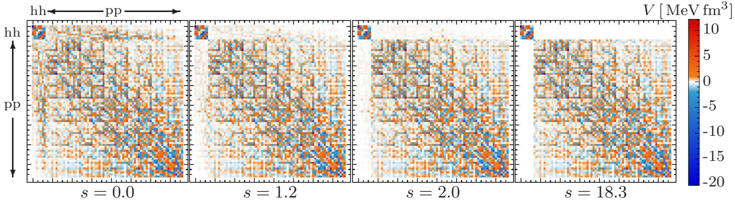
Then using a similarity transform:

$$
\hat{H} \longrightarrow e^{-\hat{T}} \hat{H} e^{\hat{T}} \,,
$$

means that you work with a Slater determinant rather than the fully correlated state when building excitations.

In-Medium Similarity Renormalization Group

Flow equation for effective Hamiltonian.
Gradually decouples shell-model space.



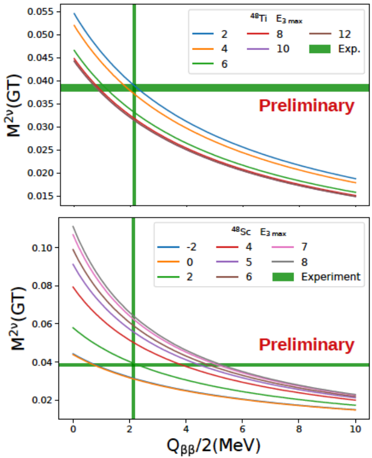
Hergert et al.

Trick is to keep all 1- and 2-body terms in *H* at each step after normal ordering (approximate treatment of 3-, 4- …terms).

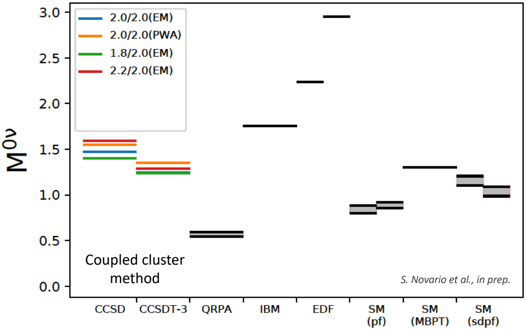
If model space contains just a single state, approach yields ground-state energy. If it is larger, result is effective interaction and operators.

$\beta\beta$ Decay in ^{48}Ca with Coupled Clusters

2ν



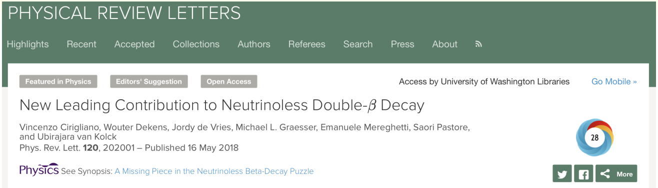
0ν



A little larger than shell-model result.

From G. Hagen

Small Fly in the Ointment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New Leading Contribution to Neutrinoless Double-β Decay

Vincenzo Cirigliano, Wouter Dekens, Jordy de Vries, Michael L. Graesser, Emanuele Mereghetti, Saori Pastore, and Ubirajara van Kolck

Phys. Rev. Lett. **120**, 202001 – Published 16 May 2018

Physics See Synopsis: A Missing Piece in the Neutrinoless Beta-Decay Puzzle

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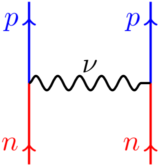
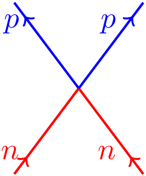
More

Usual light neutrino exchange:



must be supplemented, at same order in chiral EFT, by short-range operator (representing high-energy ν exchange):

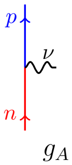


Coefficient of this term is unknown.

Two-Body Axial Current and Connection with β Decay

β Decay (simplified) with electron lines omitted

Leading order in χEFT:



Usual β-decay current.

Finite-momentum corrections at next order.

plus a contact

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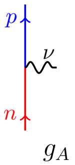

Usual β-decay current.

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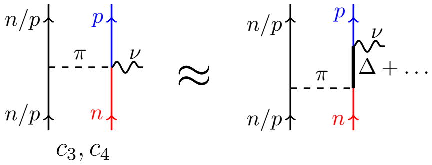
Higher order:



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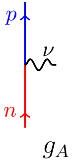
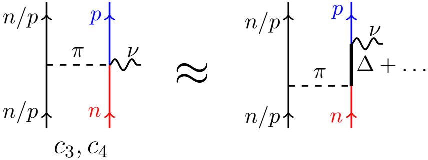


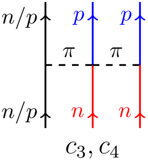
Usual β-decay current.

Finite-momentum corrections at next order.

Higher order:

Coefficients same as in three-body interaction:





plus a contact

Product of Currents

In first quantization, let

$$\sum_i \hat{O}_i^{1b} = \text{1-body operator in } J^+$$

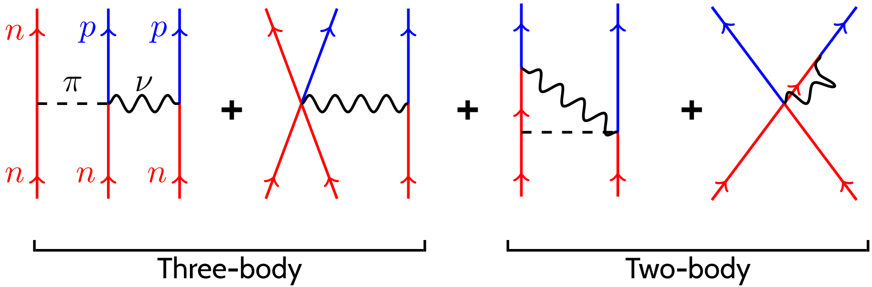
$$\sum_{ij} \hat{O}_{ij}^{2b} = \text{2-body operator in } J^+$$

$$J^+(\vec{q})J^+(-\vec{q}) = \sum_{ij} \hat{O}_i^{1b}\hat{O}_j^{1b} + \overbrace{\sum_{ijk}\left(\hat{O}_{ij}^{2b}\hat{O}_k^{1b} + \hat{O}_i^{1b}\hat{O}_{jk}^{2b}\right)}^{\text{3-body op.}} + \text{4-body}$$

$$+ \underbrace{\sum_{ij}\left(\hat{O}_{ij}^{2b}[\hat{O}_i^{1b} + \hat{O}_j^{1b}] + [\hat{O}_i^{1b} + \hat{O}_j^{1b}]\hat{O}_{ij}^{2b}\right)}_{\text{2-body op.}}$$

Inclusion of Two-Body Currents

Diagrams for these contributions:



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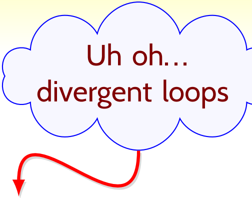

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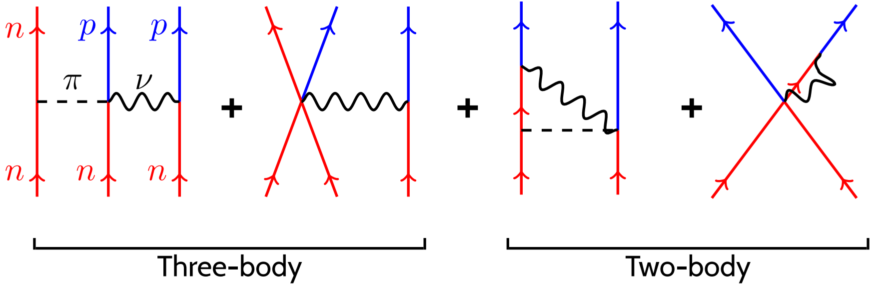
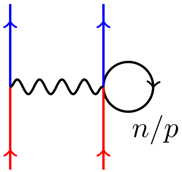


Prior Work on Effects in Heavy Systems

Javier, Doron, Achim: Symmetric Nuclear Matter

Normal ordered two-body current, to get effective one-body current. Corresponds to:



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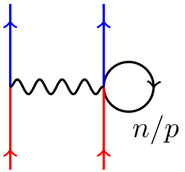


In nuclear matter:

$$g_A \longrightarrow g_A - g_A \frac{\rho}{F_\pi^2}\left[\frac{c_d}{g_A \Lambda} + \frac{2c_3}{3}\frac{q^2}{q^2 + 4m_\pi^2} + I(\rho, P)\left(\frac{2c_4 - 3_3}{3} + \frac{1}{6m}\right)\right]$$

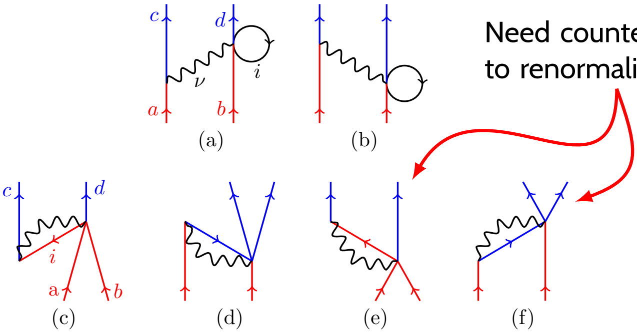
$I(\rho, P) \approx 2/3$ at nuclear density, with weak dependence on P.

$0\nu\beta\beta$ decay quenched by about 30%, somewhat less than $2\nu\beta\beta$ decay because of q dependence of effective g_A.

More Complete Nuclear Matter Calculation

With Simplest Operator: g_A at one-body vertex, c_D at two-body vertex

Goldstone (Time-Ordered) Diagrams



Need counter-term to renormalize these

$$\sum_{i<F} \langle F|\ p_d^\dagger \underbrace{n_i^\dagger n_a n_b \quad p_c^\dagger}\ n_i \quad |I\rangle$$

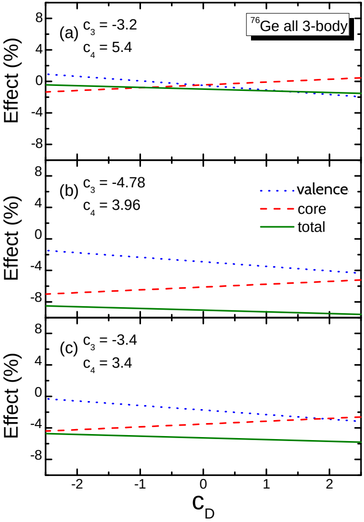
Three-body operators contribute (a) and (b) plus twice (c) and (d) ≈ 0.

$$(c) + (d) \approx -\frac{1}{2}\,[(a) + (b)]$$

$$(e) + (f) \approx (\Lambda/k_F - 1)\,[(a) + (b)]$$

^{76}Ge in Shell Model

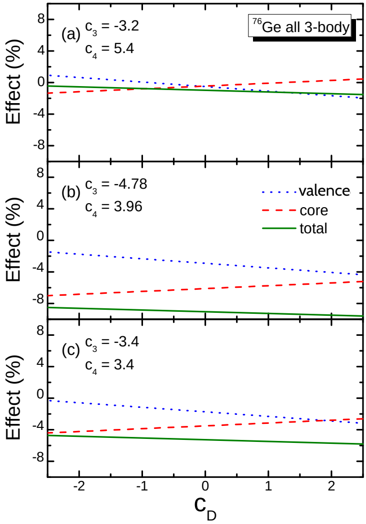
Three-body operators



Approximate ^{76}Ge wave function in *fp* shell, inert core underneath.

^{76}Ge in Shell Model

Three-body operators



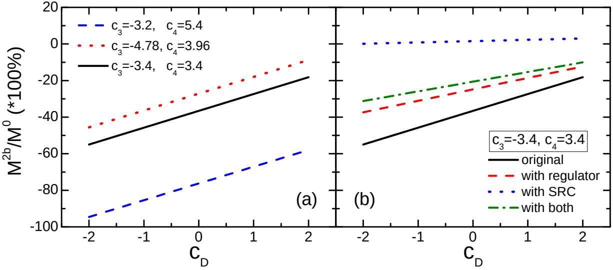
Approximate ^{76}Ge wave function in *fp* shell, inert core underneath.

Takeaway: Effects of three-body operators are small.

Two-Body Operators

With Nucleon Form Factors

Right side includes usual modifications.



Almost entire contribution from c_D and short-range parts of c_3, c_4.

Two-Body Operators

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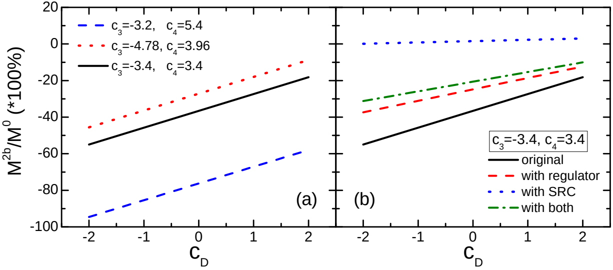

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Need counter term, just like in leading order. Help!

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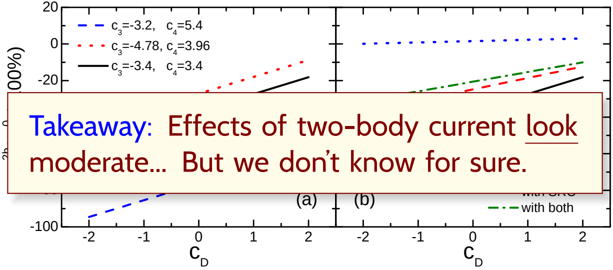

Takeaway: Effects of two-body current look moderate... But we don't know for sure.

Almost entire contribution from c_D and short-range parts of c_3, c_4.

Need counter term, just like in leading order. Help!

So, to Sum Up…

1. Schiff moments, for now, must be calculated in DFT, which makes drastic and uncontrolled approximations. Other observables can help constrain calculations.

   Can β-decay rates do that?

So, to Sum Up…

1. Schiff moments, for now, must be calculated in DFT, which makes drastic and uncontrolled approximations. Other observables can help constrain calculations.

   Can β-decay rates do that?

2. Application of chiral EFT to $0\nu\beta\beta$ decay implies short-range contribution to neutrino exchange with unknown coefficient. A similar issue hampers our ability to fully examine effects of the two-body current in $0\nu\beta\beta$ decay.

   The part for which we do know coefficients seems to quench very little, however.

Finally...

\begin{Acknowledgments}

Thanks!

\end{Acknowledgments}

\end{Talk}