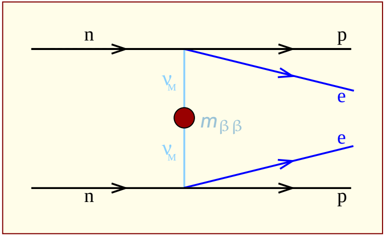
Quenching, Currents, EFT, and $\beta\beta$ Decay

J. Engel

June 20, 2018

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

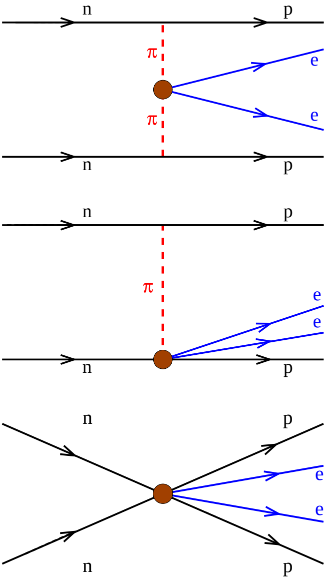
Standard operator



Forbidden in Standard Model.

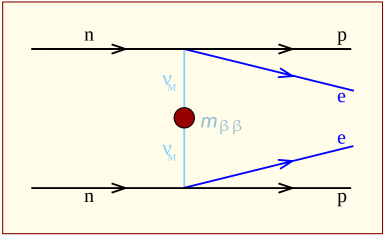
New physics inside blobs

Other possibilities



Review of 0νββ Decay

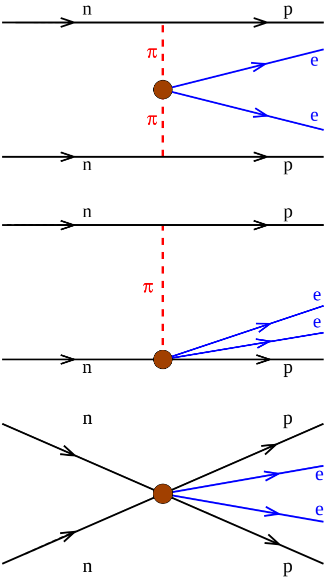
Standard operator



I'll focus on this one.

Forbidden in Standard Model.
New physics inside blobs

Other possibilities



Light-ν-Exchange Matrix Elements

Recent Values

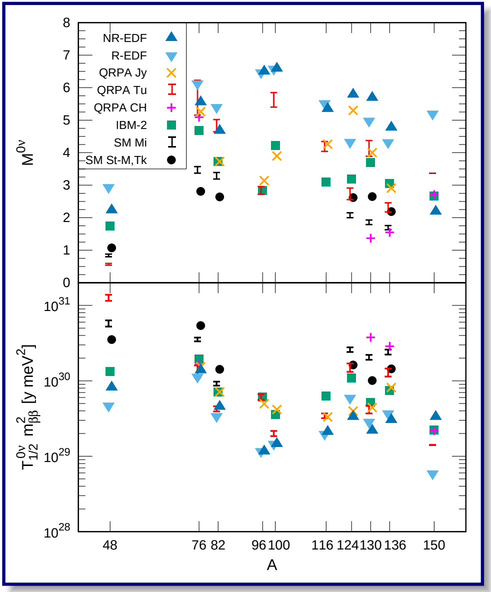
Rate $\propto |M^{0\nu}|^2 \, m_{\beta\beta}^2$

Significant spread. And all the models may miss important physics. And uncertainty hard to quantify

but

we’re making progress on *ab-initio* nuclear-structure calculations of these.

Basic ingredients, on the other hand…



Nuclear Matrix Element (Simplified)

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

Dominant piece

with

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

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

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

Nuclear Matrix Element (Simplified)

$$\boxed{M^{0\nu} = g_A^2\, M^{0\nu}_{GT} - g_V^2\, M^{0\nu}_{F} + \ldots}$$

Dominant piece

with

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

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

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

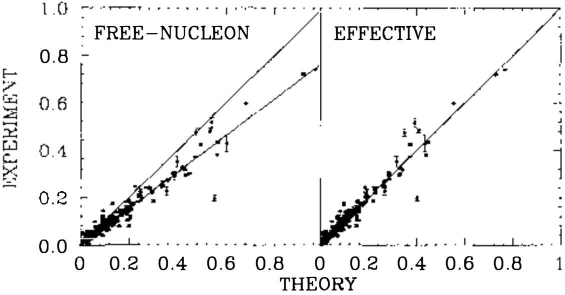
Also:

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

Gamow-Teller β Decay

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

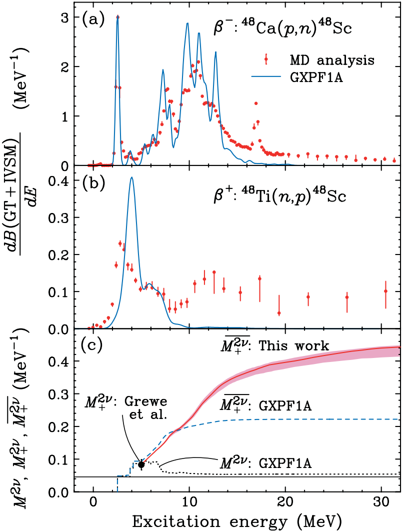
40-Year-Old Problem: Effective g_A needed in all calculations of shell-model type.



Lots of suggestion about the cause but no consensus.

Other Tests of $\vec{\sigma}\tau$ Strength Also Show Suppression

From Yako et al., PRL 103, 012503 (2009)

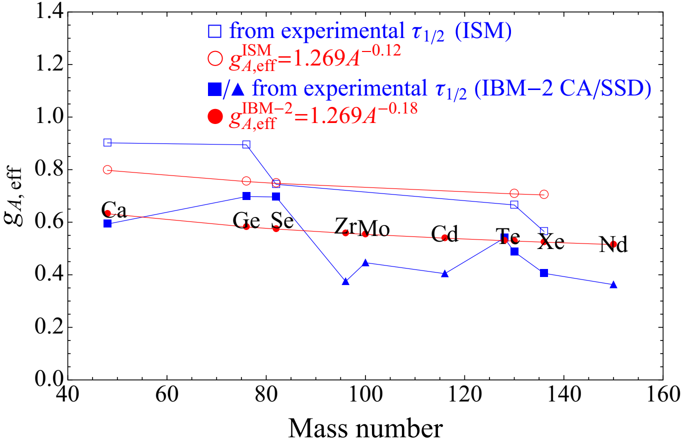


Only about 2/3 of theoretically expected strength observed.

And 2νββ Decay…

Anti-neutrinos come out instead of being exchanged

From F. Iachello



If quenching is this severe in 0ν decay, experimentalists will not be happy.

And 2νββ Decay…

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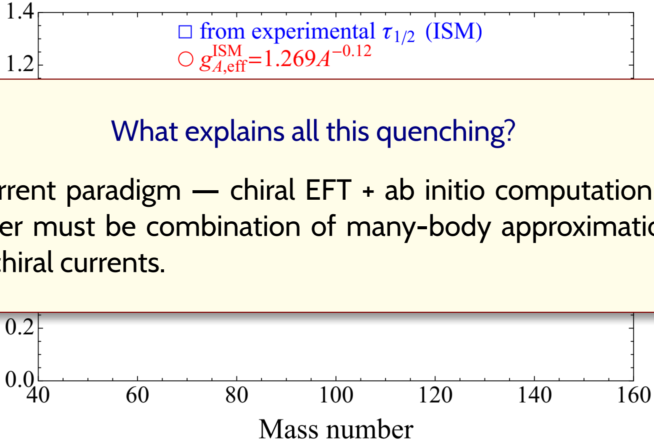


From F. Iachello

What explains all this quenching?

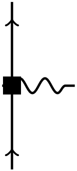
In current paradigm — chiral EFT + ab initio computation — answer must be combination of many-body approximations and chiral currents.

If quenching is this severe in 0ν decay, experimentalists will not be happy.

Axial Weak Current in Chiral EFT

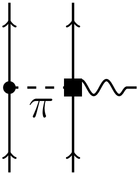
Simplified…

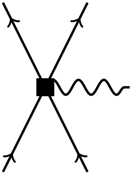
Leading order:



g_A, g_P

Three orders down:

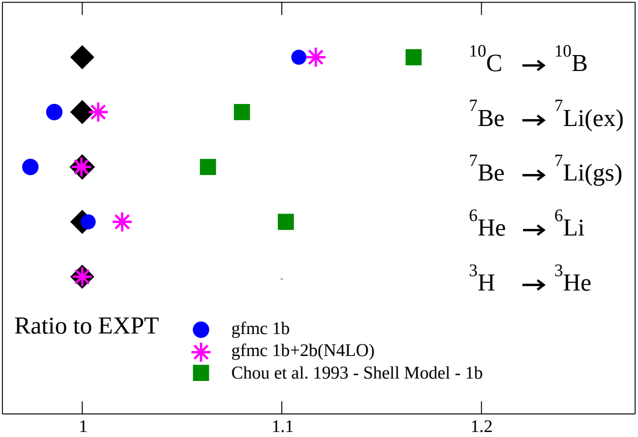




c_3, c_4 c_D

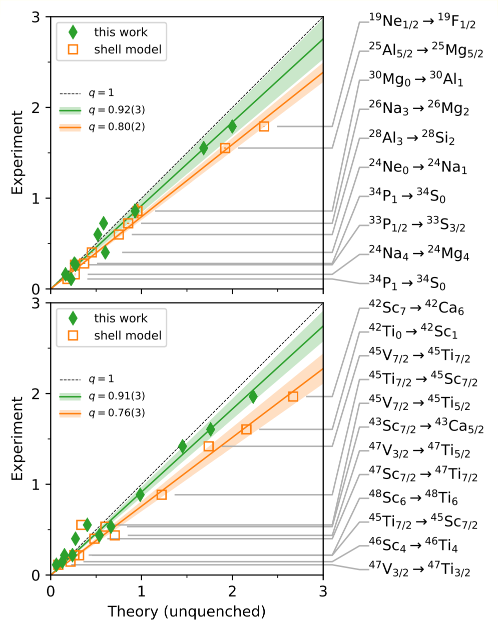
Two-Body Currents and Quenching in Light Nuclei

Pastore et al: β Decay with Quantum Monte Carlo



Most of the effects are from correlations outside the valence shell. Two-body currents don't do much.

…And in the *sd*-Shell



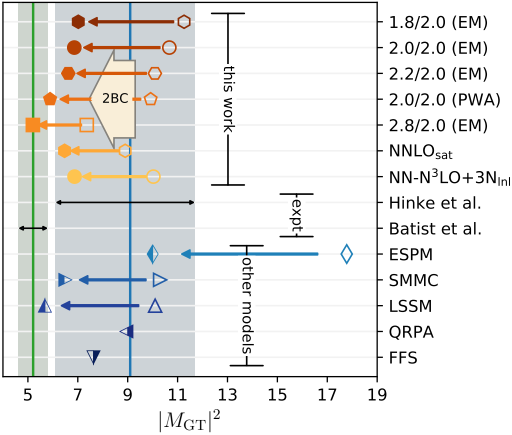
IMSRG calculation, Holt et al, preliminary

Shell model seems to include most correlations. Bulk of quenching comes from two-body current.

…And in ^{100}Sn

Coupled-Cluster Calculation of β Decay

Hagen et al, unpublished



Again, most of the quenching accounted for by two-body current.

And Quenching increases with mass.

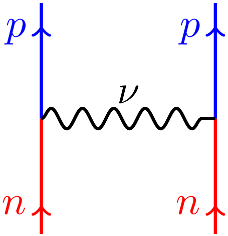
Spectator nucleons contribute coherently to two-body current.

Naive Inclusion in $0\nu\beta\beta$ Decay

Use closure approximation:

$$\hat{O} \propto \int \frac{J^{+}(\vec{q})J^{+}(-\vec{q})}{q(q+\bar{E})}\, d^3q$$

Leading diagram (electron lines omitted):



Product of Currents

In first quantization, let

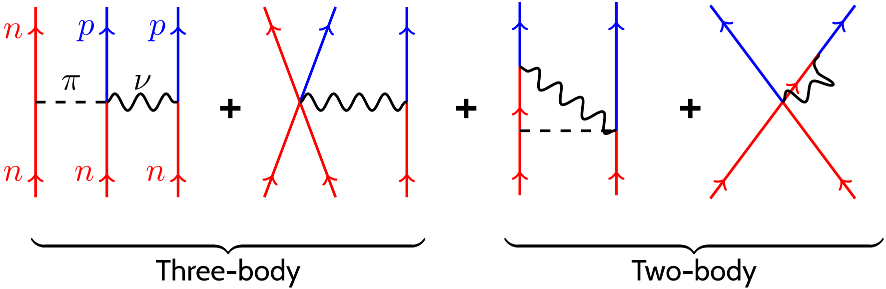
$$\sum_i \hat{O}_i^{1b} = \text{1-body operator in } J^+$$

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

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

Two-Body Currents in $0\nu\beta\beta$ Decay

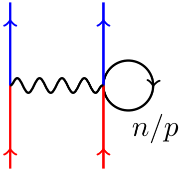
Diagrams for these contributions:



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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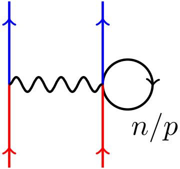


In nuclear matter:

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

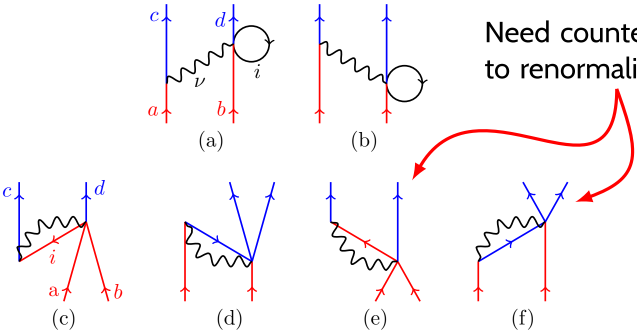
$I(\rho, P) \approx 2/3$ at nuclear density, with weak dependence on P.

$0\nu\beta\beta$ 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

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

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

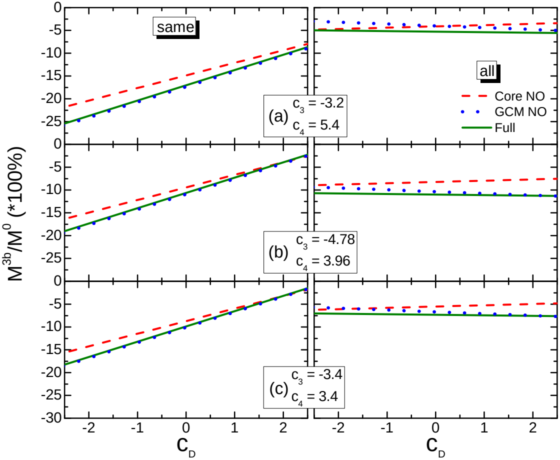
$$(c) + (d) \approx -\frac{1}{2}\left[(a) + (b)\right]$$

$$(e) + (f) \approx (\Lambda - k_F)\left[(a) + (b)\right]$$

^{76}Ge in Good Approximation to Shell Model

L.J. Wang has done calculation with approximate ^{76}Ge wave function in *fp* shell, inert core underneath.

Three-body operators

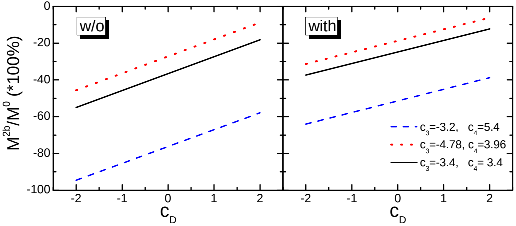


Left is contraction only within two-body current, right includes everything.

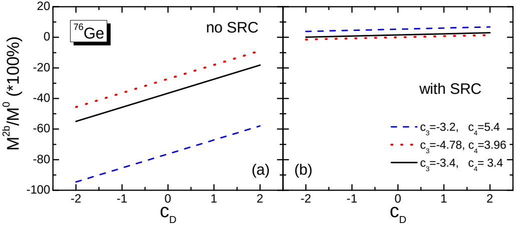
Two-Body Operators

With Nucleon Form Factors

Right side includes regulator.



Right side includes short-range correlations.

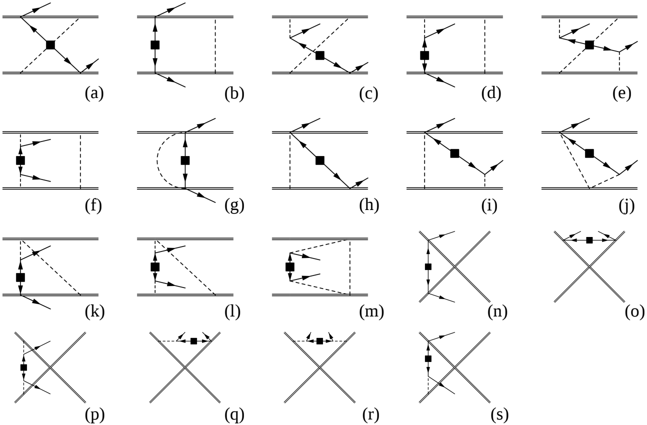


Almost entire contribution from c_D and short-range parts of c_3, c_4.

Meanwhile…

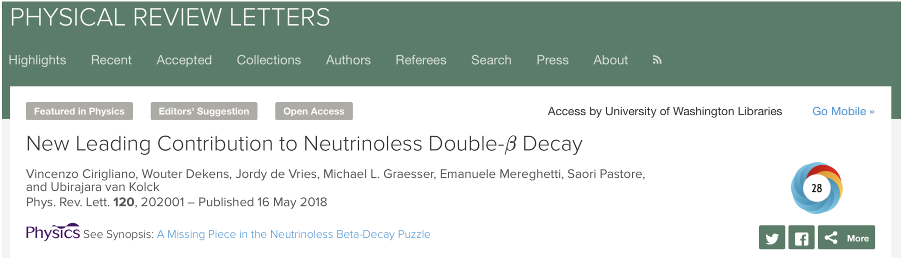
Vincenzo, Emanuele, Jordy, Bira, Saori, Wouter D., Michal G.: EFT for $\beta\beta$

At N^2LO:



Need contact to renormalize these; would also renormalize ours.

Furthermore…



PHYSICAL REVIEW LETTERS

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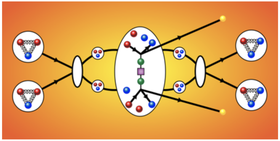
Synopsis: A Missing Piece in the Neutrinoless Beta-Decay Puzzle

May 16, 2018

The inclusion of short-range interactions in models of neutrinoless double-beta decay could impact the interpretation of experimental searches for the elusive decay.



J. de Vries/Nikhef; adapted by APS/Alan Stonebraker

So, to Sum Up…

1. Nice operators (three-body and long-range part of two-body in product of currents) quench $0\nu\beta\beta$ less than previously. c_D contributes very little.

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That's all; thanks.