Searching for New Physics with Neutrinoless Double-Beta Decay

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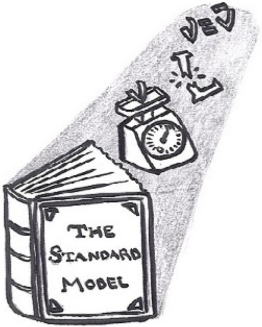
UNIVERSITAT DE BARCELONA

Outline

Motivation

- Current knowledge on particles and interactions between them is based on the Standard Model (SM) of particle physics



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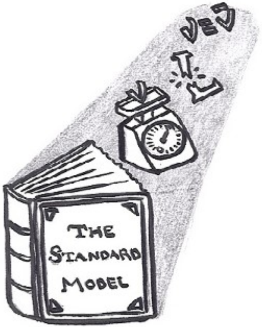
- According to the SM, neutrinos are extremely weakly interacting, massless fermions



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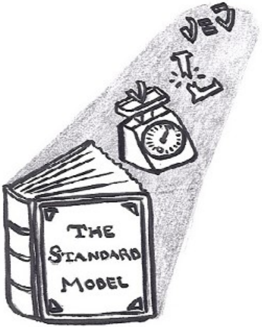
- Yet we know from solar neutrino experiments that neutrinos must have a non-zero mass



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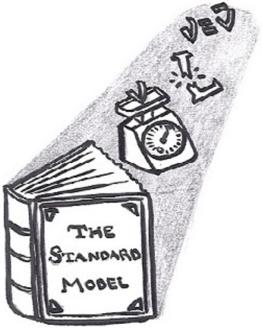

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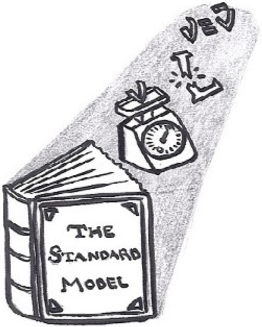
  - What else is there beyond the SM?



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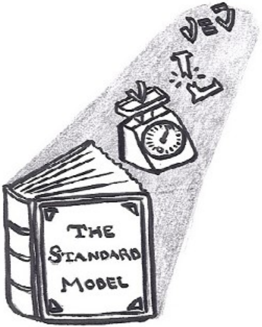
- *What could we learn from double-beta decay of nuclei?*



Early History of Double-Beta Decay

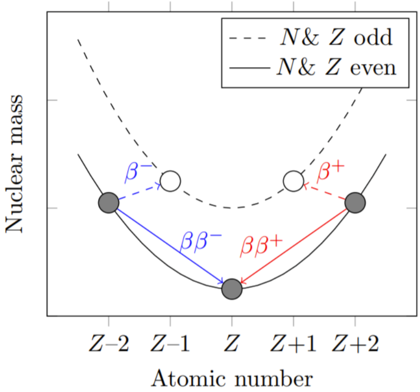
Maria Goeppert-Mayer	*Ettore Majorana*	*Wendel H. Furry*
		
Idea of double-beta decay	Idea of Majorana particles	Idea of neutrinoless double-beta decay
1935	1937	1939

→ 1935 → 1937 → 1939 → ...

Double-Beta Decay

$$\beta^- : \ \mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$$
$$\beta^+ : \ p \rightarrow n + e^+ + \nu_e$$

- May happen, when β-decay is not energetically allowed



Double-Beta Decay

$$\begin{array}{|l|} \hline \beta^- : \; \mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^- + \bar{\nu}_\mathrm{e} \\ \beta^+ : \; p \rightarrow n + e^+ + \nu_e \\ \hline \end{array}$$

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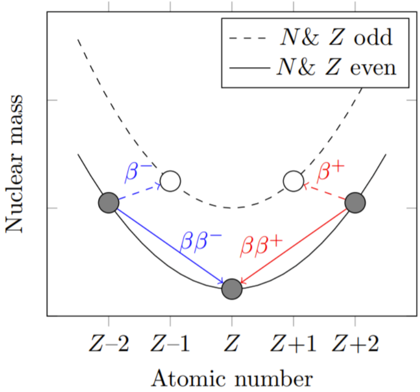
- Two modes:



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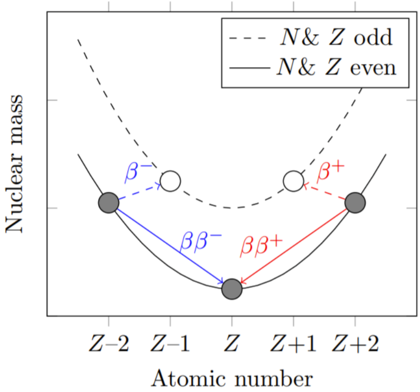
  - Standard two-neutrino $\beta\beta$ decay ($2\nu\beta\beta$)



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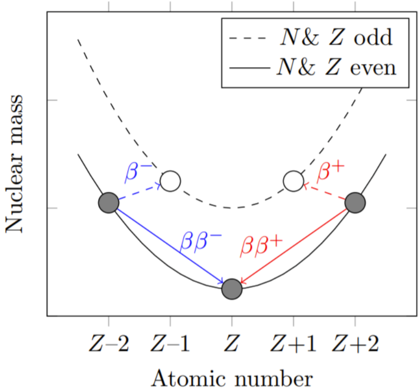
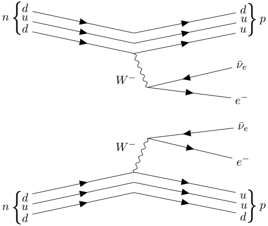
- May happen, when β-decay is not energetically allowed
- Two modes:
  - Standard two-neutrino $\beta\beta$ decay ($2\nu\beta\beta$)
  - Hypothetical neutrinoless $\beta\beta$ ($0\nu\beta\beta$) decay



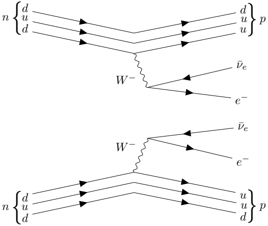
Two-Neutrino Double-Beta ($2\nu\beta\beta$) Decay



$$ {}^A_Z\mathrm{X}_N \rightarrow {}^{A}_{Z+2}\mathrm{Y}_{N-2} + 2e^- + 2\bar{\nu}_e $$

- Allowed by the Standard Model

Two-Neutrino Double-Beta ($2\nu\beta\beta$) Decay



$$^{A}_{Z}\mathrm{X}_N \rightarrow {}^{A}_{Z+2}\,\mathrm{Y}_{N-2} + 2e^- + 2\bar{\nu}_e$$

- Allowed by the Standard Model
- Observed in 11 nuclei (out of the $\sim$ 5000 known nuclei)

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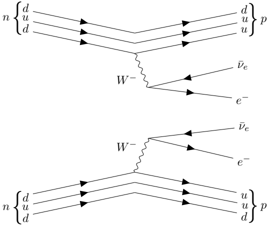

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- Observed in 11 nuclei (out of the ~ 5000 known nuclei)
    - $t_{1/2}^{2\nu} \gtrsim 10^{20}$ years (age of the Universe: $\sim 10^{10}$ years)

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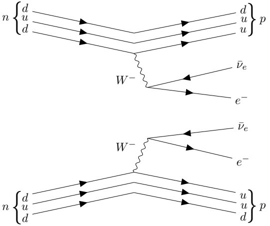
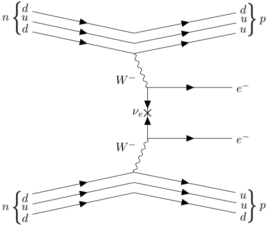


$$^{A}_{Z}\mathrm{X}_{N} \rightarrow {}^{A}_{Z+2}\,\mathrm{Y}_{N-2} + 2e^{-} + 2\bar{\nu}_{e}$$

- Allowed by the Standard Model
- Observed in 11 nuclei (out of the $\sim$ 5000 known nuclei)
  - $t_{1/2}^{2\nu} \gtrsim 10^{20}$ years (age of the Universe: $\sim 10^{10}$ years)
  - Rarest measured nuclear process!

Neutrinoless Double-Beta ($0\nu\beta\beta$) Decay



$$^A_Z\mathrm{X}_N \rightarrow {}^A_{Z+2}\mathrm{Y}_{N-2} + 2e^-$$

- Requires that the neutrino is its own antiparticle

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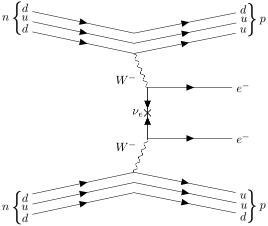

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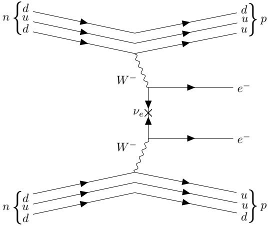

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- Requires that the neutrino is its own antiparticle
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- $\frac{1}{t^{0\nu}_{1/2}} \propto |\frac{m_{\beta\beta}}{m_e}|^2, \quad m_{\beta\beta} = \sum_i^{\text{light}} U_{ei}^2 m_i \;\rightarrow$ Neutrino masses!

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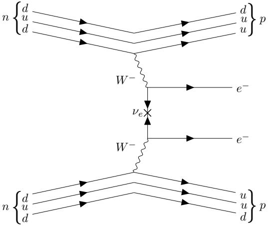

$$^{A}_{Z}\mathrm{X}_N \rightarrow ^{A}_{Z+2}\mathrm{Y}_{N-2} + 2e^-$$

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- $\frac{1}{t_{1/2}^{0\nu}} \propto |\frac{m_{\beta\beta}}{m_e}|^2, \quad m_{\beta\beta} = \sum_i^{\mathrm{light}} U_{ei}^2 m_i \rightarrow$ Neutrino masses!
- Has not (yet) been measured!

Half-life of $0\nu\beta\beta$ Decay

$$\boxed{\frac{1}{t_{1/2}^{0\nu}} = g_{\rm A}^4 G_{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2}$$

[1] J. Engel and J. Menéndez, *Rep. Prog. Phys.* **80**, 046301 (2017), updated.

Half-life of $0\nu\beta\beta$ Decay

What would be measured

$$\frac{1}{t_{1/2}^{0\nu}} = g_{\mathrm{A}}^4 G_{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

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- Axial-vector coupling ($g_A^{\text{free}} \approx 1.27$)

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- Axial-vector coupling ($g_A^{\rm free} \approx 1.27$)
  - Quenched or not?

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- Axial-vector coupling ($g_{\rm A}^{\rm free} \approx 1.27$)
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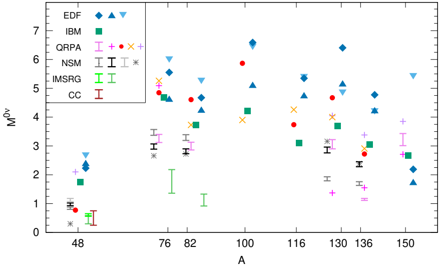
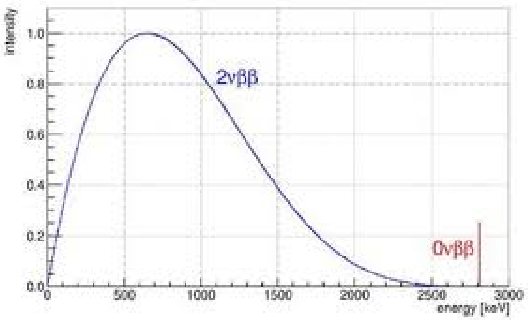


Matrix elements of $0\nu\beta\beta$ decays [1]

[1] J. Engel and J. Menéndez, *Rep. Prog. Phys.* **80**, 046301 (2017), updated.

Difficulty of $0\nu\beta\beta$-Decay Experiments

This is what they want to measure...



Sketchy energy spectrum of the emitted electrons in $\beta\beta$ decays [2]

$$t^{2\nu}_{1/2} \approx 10^{20} \text{ y}, \qquad \mathrm{t}^{0\nu}_{1/2} \geq 10^{25} \text{ y}$$

[2] cobra-experiment.com

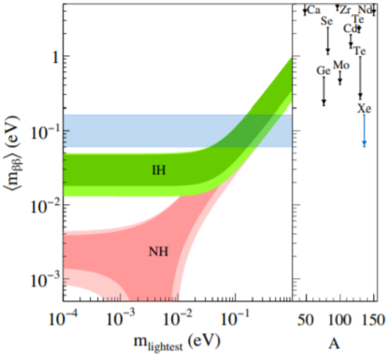
Current Status of $0\nu\beta\beta$-Decay Experiments

$$\frac{1}{t_{1/2}^{0\nu}} = g_{\mathrm{A}}^4 G_{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

- Large-scale experiments: CUORE(Italy), GERDA(Italy), CUPID(Italy), MAJORANA(US), EXO-200(US), KamLAND-Zen(Japan), NEXT(Spain), ...

NH: $m_1 < m_2 < m_3$

IH: $m_3 < m_1 < m_2$



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[J. Engel and J. Menéndez, Rep. Prog. Phys. **80**,*046301 (2017)]*

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- Currently, most stringent half-life limit $t_{1/2}^{0\nu}(^{76}\mathrm{Ge}) \geq 1.8 \times 10^{26}$ y

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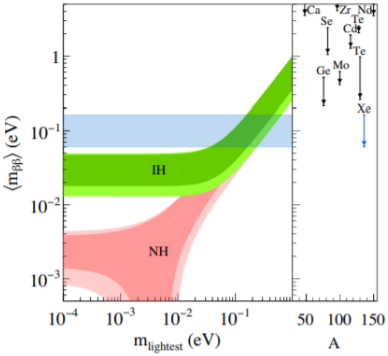

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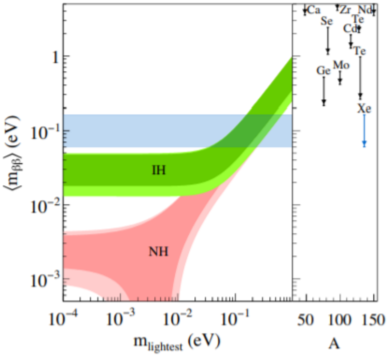

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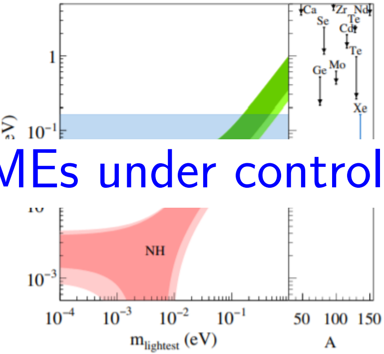

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[J. Engel and J. Menéndez, Rep. Prog. Phys. **80***,046301 (2017)]*

We need to get the NMEs under control!

Outline

$0\nu\beta\beta$-Decay Nuclear Matrix Elements

- Assuming the standard mechanism

$$[t_{1/2}^{0\nu}]^{-1} = g_{\mathrm{A}}^4 G_{0\nu} |M_{\mathrm{L}}^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

$0\nu\beta\beta$-Decay Nuclear Matrix Elements

- Assuming the standard mechanism

$$[t_{1/2}^{0\nu}]^{-1} = g_{\rm A}^4 G_{0\nu} |M_{\rm L}^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

- The matrix element can be written as

$$M_{\rm L}^{0\nu} = M_{\rm GT}^{0\nu} - \left(\frac{g_{\rm V}}{g_{\rm A}}\right)^2 M_{\rm F}^{0\nu} - M_{\rm T}^{0\nu}$$

$0\nu\beta\beta$-Decay Nuclear Matrix Elements

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- However, there seems to be something missing...

The Contact Term

PHYSICAL REVIEW LETTERS **120,** 202001 (2018)

Editors' Suggestion   Featured in Physics

New Leading Contribution to Neutrinoless Double-β Decay

Vincenzo Cirigliano,[1] Wouter Dekens,[1] Jordy de Vries,[2] Michael L. Graesser,[1] Emanuele Mereghetti,[1] Saori Pastore,[1] and Ubirajara van Kolck[3,4]

[1]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[2]*Nikhef, Theory Group, Science Park 105, 1098 XG Amsterdam, The Netherlands*
[3]*Institut de Physique Nucléaire, CNRS/IN2P3, Université Paris-Sud, Université Paris-Saclay, 91406 Orsay, France*
[4]*Department of Physics, University of Arizona, Tucson, Arizona 85721, USA*

(Received 1 March 2018; revised manuscript received 28 March 2018; published 16 May 2018)

Within the framework of chiral effective field theory, we discuss the leading contributions to the neutrinoless double-beta decay transition operator induced by light Majorana neutrinos. Based on renormalization arguments in both dimensional regularization with minimal subtraction and a coordinate-space cutoff scheme, we show the need to introduce a leading-order short-range operator, missing in all current calculations. We discuss strategies to determine the finite part of the short-range coupling by matching to lattice QCD or by relating it via chiral symmetry to isospin-breaking observables in the two-nucleon sector. Finally, we speculate on the impact of this new contribution on nuclear matrix elements of relevance to experiment.

The Contact Term

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New Leading Contribution to Neutrinoless Double-β Decay

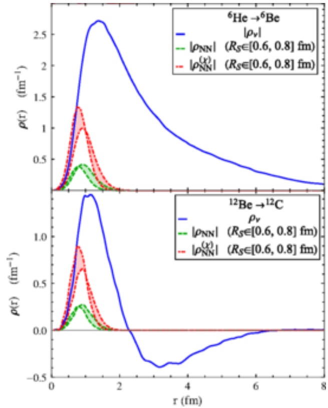
$$[t_{1/2}^{0\nu}]^{-1} = g_{\mathrm{A}}^4 G_{0\nu} |M_{\mathrm{L}}^{0\nu} + M_{\mathrm{S}}^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

neutrinoless double-beta decay transition operator induced by light Majorana neutrinos. Based on renormalization arguments in both dimensional regularization with minimal subtraction and a coordinate-space cutoff scheme, we show the need to introduce a leading-order short-range operator, missing in all current calculations. We discuss strategies to determine the finite part of the short-range coupling by matching to lattice QCD or by relating it via chiral symmetry to isospin-breaking observables in the two-nucleon sector. Finally, we speculate on the impact of this new contribution on nuclear matrix elements of relevance to experiment.

The Contact Term - First ab initio Results

- Contact term enhances the NMEs by [3]

$$\begin{cases} 5 \sim 15\% \text{ for } {}^{6}\mathrm{He} \\ 20 \sim 80\% \text{ for } {}^{12}\mathrm{Be} \end{cases}$$



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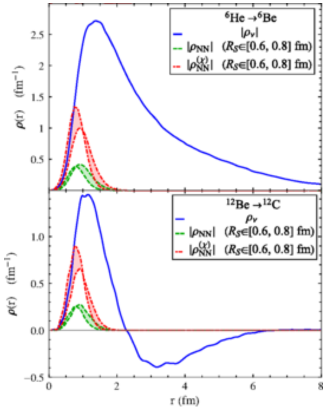

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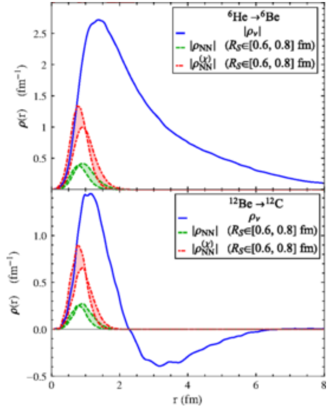

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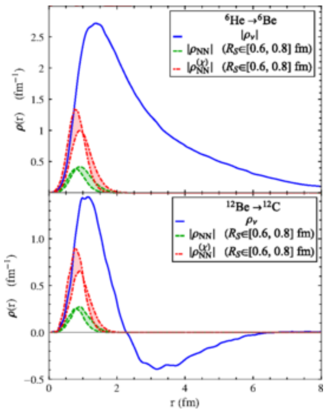
  - Good news for the experiments!
- How about the heavier candidates?



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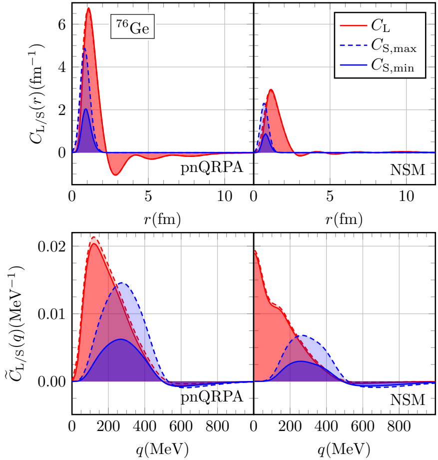
Contact Term in pnQRPA and NSM

Candidates: $^{76}\mathrm{Ge} \cdots {}^{136}\mathrm{Xe}$



In pnQRPA:

$M_{\mathrm{S}}/M_{\mathrm{L}} \approx 30 - 80\%$

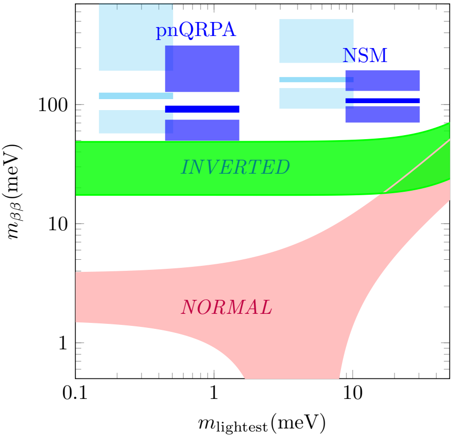
In NSM:

$M_{\mathrm{S}}/M_{\mathrm{L}} \approx 15 - 50\%$

[LJ, P. Soriano and J. Menéndez, Phys. Lett. B **823**, *136720 (2021)]*

Effective Neutrino Masses

- Effective neutrino masses combining our NMEs with experimental data [5]



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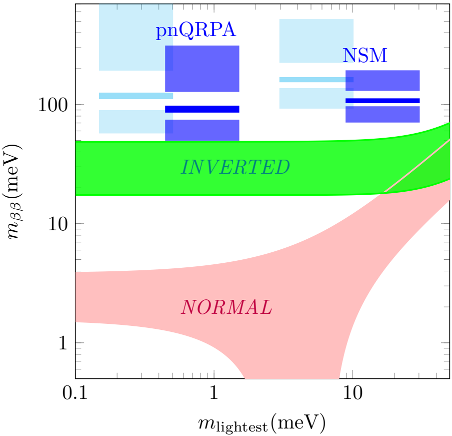
Effective Neutrino Masses

- Effective neutrino masses combining our NMEs with experimental data [5]
- Middle bands: $M_{\mathrm{L}}^{(0\nu)}$
  Lower bands: $M_{\mathrm{L}}^{(0\nu)} + M_{\mathrm{S}}^{(0\nu)}$
  Upper bands: $M_{\mathrm{L}}^{(0\nu)} - M_{\mathrm{S}}^{(0\nu)}$



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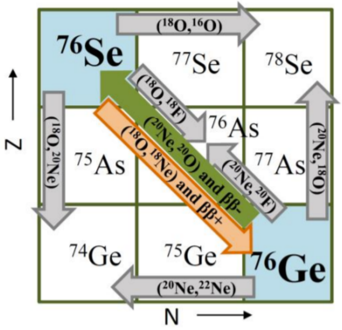
Outline

Probing $0\nu\beta\beta$-Decay by Charge-Exchange Reactions

- Double charge-exchange reaction (strong interaction) can be related to $0\nu\beta\beta$ decay (weak interaction)



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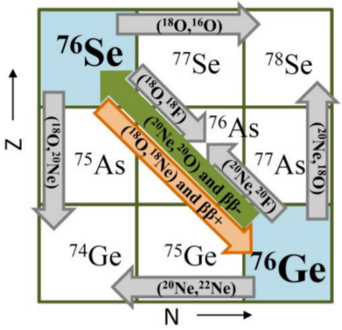

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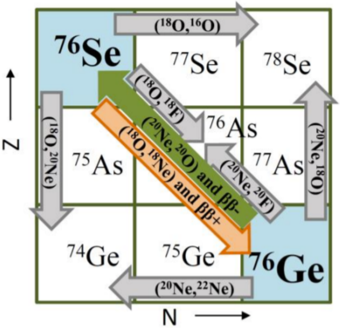
  - Difficult, but possible!



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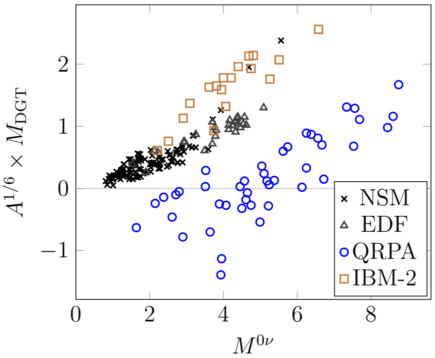
$M^{0\nu}$ vs. M_{DGT}

- Linear correlations between double Gamow-Teller (DGT) and $0\nu\beta\beta$ in all the studied models [6,7]



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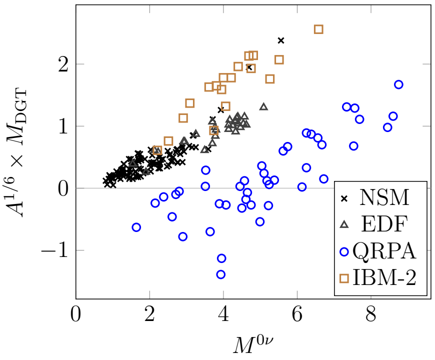
  - Measuring DGT reaction could help constrain $M^{0\nu}$!



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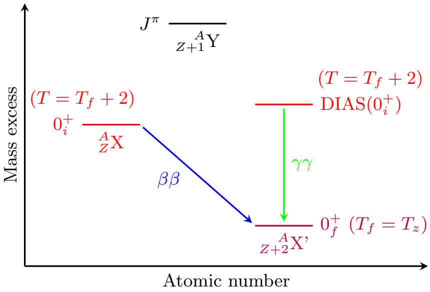

Isospin z-projection:

$$T_z = (N - Z)/2$$

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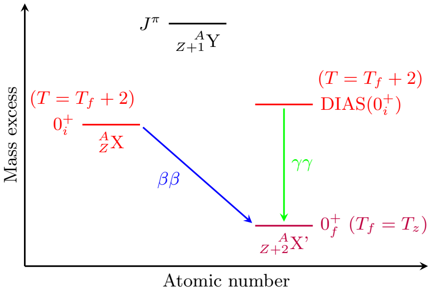

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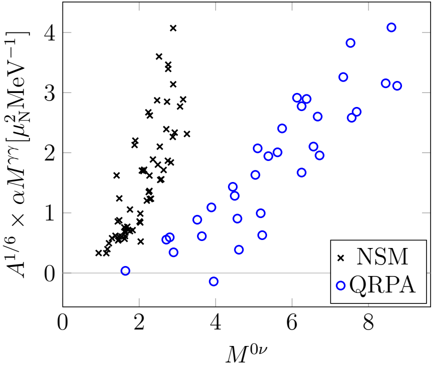

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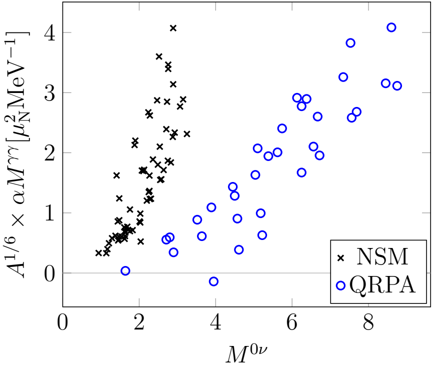

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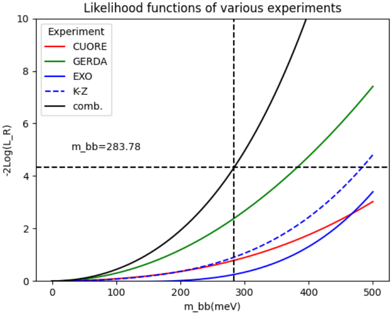
Outline

Summary

- Observing $0\nu\beta\beta$ decay would shed light on neutrino properties and physics beyond the standard model
- Reliable nuclear matrix elements crucial for $0\nu\beta\beta$ studies
- Adding a new short-range term enhances the NMEs notably
- Related nuclear observables can help constrain the values of the $0\nu\beta\beta$-decay NMEs

Thank you!

Obtaining Majorana Bound from experiments



$$\Gamma^{0\nu} = \log(2) g_{\mathrm{A}}^4 G_{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2$$

- Input: log(likelihood) functions from experiments
- $\Gamma^{0\nu} \rightarrow m_{\beta\beta}$ with our NMEs
- 90% CI Bayesian bounds for $m_{\beta\beta}$ from 90% CI upper bounds on combined $\Gamma^{0\nu}$ [19]

[19] S. D. Biller, PRD **104**, 012002 (2021)

Operators of $0\nu\beta\beta$, DGT and M1M1 decays

- $0\nu\beta\beta$:

$$
\begin{aligned}
\mathcal{O}_{\mathrm{F}} &= h_{\mathrm{F}}(r, E_k)\tau^-\tau^- \\
\mathcal{O}_{\mathrm{GT}} &= h_{\mathrm{GT}}(r, E_k)\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2\tau^-\tau^- \\
\mathcal{O}_{\mathrm{T}} &= h_{\mathrm{T}}(r, E_k)S_{12}^{\mathrm{T}}\tau^-\tau^- \\
\mathcal{O}_{\mathrm{S}} &= 2g_\nu^{\mathrm{NN}}\tau^-\tau^-
\end{aligned}
$$

- DGT:

$$\mathcal{O} = [\boldsymbol{\sigma}_j\tau_j^- \times \boldsymbol{\sigma}_k\tau_k^-]^0$$

- M1M1:

$$\mathcal{O}^{\gamma\gamma} = \mathbf{M_1} \cdot \mathbf{M_1} \; ; \; \mathbf{M_1} = \mu_N\sqrt{\frac{3}{4\pi}}\sum_{i=1}^{A}(g_i^l\boldsymbol{\ell}_i + g_i^s\mathbf{s}_i)$$

NMEs of $0\nu\beta\beta$, DGT and M1M1 decays

- $0\nu\beta\beta$:

$$M_K^{0\nu} = \sum_{J^\pi,k_1,k_2,\mathcal{J}} \sum_{p,p',n,n'} (-1)^{j_n+j_{p'}+J+\mathcal{J}} \sqrt{2\mathcal{J}+1} \begin{Bmatrix} j_p & j_n & J \\ j_{n'} & j_{p'} & \mathcal{J} \end{Bmatrix} \times$$

$$\times (pp' : \mathcal{J}||\mathcal{O}_K||nn' : \mathcal{J})(0_f^+||[c_{p'}^\dagger \tilde{c}_{n'}]_J||J_{k_1}^\pi)\langle J_{k_1}^\pi|J_{k_2}^\pi\rangle(J_{k_2}^\pi||[c_p^\dagger \tilde{c}_n]_J||0_i^+) \,,$$

- DGT:

$$M_{\rm DGT} = \frac{1}{\sqrt{3}} \sum_{m,n} (0_{\rm gs,f}^+|| \sum_k t_k^- \boldsymbol{\sigma}_k ||1_m^+)\langle 1_m^+|1_n^+\rangle(1_n^+|| \sum_k t_k^- \boldsymbol{\sigma}_k ||0_{\rm gs,i}^+) \,,$$

- M1M1:

$$\alpha M^{\gamma\gamma}({\rm M1M1}) = \mu_{\rm N}^2 \frac{3}{4\pi} \sum_{m,n} \frac{\langle 1_m^+|1_n^+\rangle}{E_n - (E_i+E_f)/2}$$

$$\times (0_{\rm gs,f}^+|| \sum_k t_k^- (g_l^{T=1} \boldsymbol{\ell}_k + g_s^{T=1} \mathbf{s}_k)||1_m^+)$$

$$\times (1_n^+|| \sum_k t_k^- (g_l^{T=1} \boldsymbol{\ell}_k + g_s^{T=1} \mathbf{s}_k)||0_{\rm gs,i}^+) \,,$$