$0\nu\beta\beta$: Nuclear Physics and BSM measurements with $2\nu\beta\beta$

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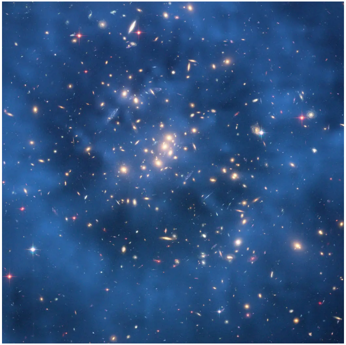
Neutrinos and the Standard Model

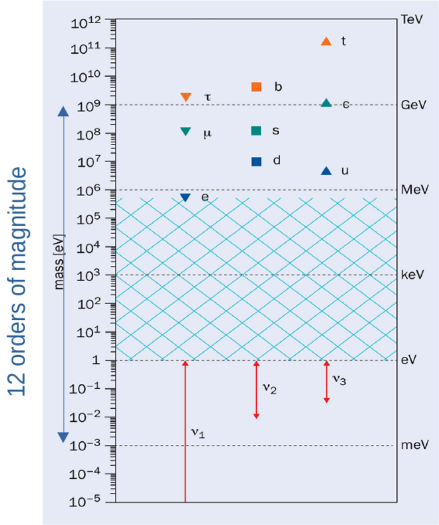
The Standard Model can not explain:

- What is **dark matter**?
- What is **dark energy**?
- Prevalence of **matter** over **antimatter**



- The original SM that we all learned in school predicts that neutrinos are strictly massless
- **We know that neutrinos have mass** from neutrino flavor oscillations

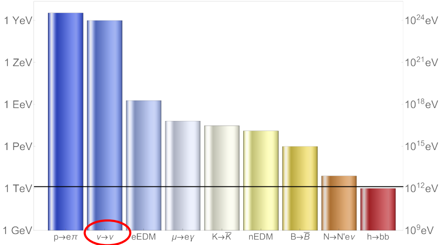
How are ν masses generated?



- Dirac neutrino masses: the neutrino mass is generated via the standard Higgs mechanism in the same way as leptons and quarks $\rightarrow$ ν's Yukawa couplings more than 6 orders of magnitude smaller.
- **Majorana mass term**

Neutrinos : Break on through to the other side

- **Effective Field Theory**: the Standard Model $\mathcal{L}_{\mathcal{SM}} = \mathcal{L}_{\mathrm{D}=4}$. The Lagrangian is expanded in powers of $1/\Lambda$.
- The first correction has a single dimension 5 operator, which gives rise to a Majorana mass term : $\mathcal{L} = -\frac{1}{2}\sum_i m_i \bar{\nu}_i \nu_i \propto \frac{1}{\Lambda}$
- New physics scale Λ explored by $0\nu\beta\beta$ searches with high sensitivity



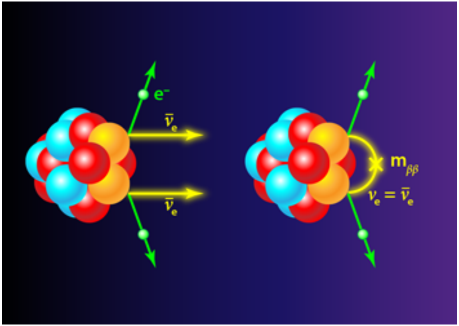
A. Falkowski lecture at CP2023 (https://indico.in2p3.fr/event/27893)

- The smallness of neutrino masses comes up naturally for Λ of the order of the GUT scale (see-saw model)
- Baryon-antibaryon asymmetry explained through leptogenesis

$2\nu\beta\beta$ and $0\nu\beta\beta$

$2\nu\beta\beta$
Lepton number is conserved

$0\nu\beta\beta$
Lepton number not conserved, creation of matter



Engels and Volker, Physics 11, 30, 2018

$0\nu\beta\beta$ decay half-life

Experimental observable: $0\nu\beta\beta$ decay rate : $\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1}$

$0\nu\beta\beta$ can happen by several mechanisms. Assuming the *light-neutrino exchange scenario*:

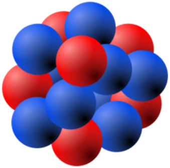
$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = g_A^4 \cdot \underbrace{G_{0\nu} \cdot |M_{0\nu}|^2}_{\text{nuclear}} \cdot \overbrace{\langle m_{\beta\beta}\rangle^2}^{\text{new physics}} / m_e^2$$

We measure $T_{1/2}^{0\nu\beta\beta}$ and interpret it in terms of $m_{\beta\beta}$ with inputs from theory:

- g_A is the coupling to the nucleon (axial vector coupling constant). For a bare nucleon $g_A \approx 1.27$.
- $G_{0\nu}$ is the Phase-space factor represents the kinematic of the decay. Depends on $Q_{\beta\beta}$, Z, electrons. Calculated with good accuracy.

Nuclear Matrix elements

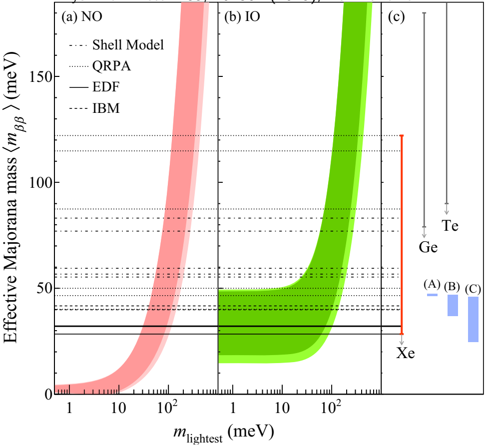
- $M_{0\nu}$, the nuclear matrix element, NME, relates to the nuclear structure of the initial and final state nuclei $\rightarrow$ we need to consider a many body problem $\rightarrow$ the hard part



- Difficult to calculate accurately. Differences $\sim$ factor 3 - 4 depending on the nuclear models

Effective Majorana mass

Phys. Rev. Lett. 135, 262501 (2025), KamLandZen



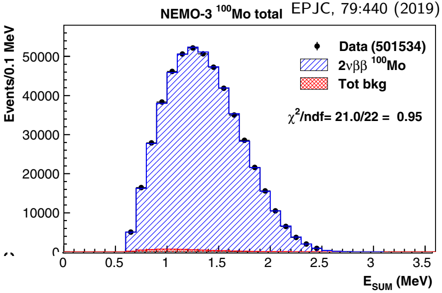
$$m_{\beta\beta} = \left| \sum_{i=1}^{3} \left| U_{ei}^2 \right| e^{i\phi_i} m_i \right|$$

- NME theoretical uncertainties introduce large uncertainties in the interpretation of $T_{1/2}^{0\nu}$ in terms of $m_{\beta\beta}$
- Prevent to determine accurately the expected sensitivities of future experiments

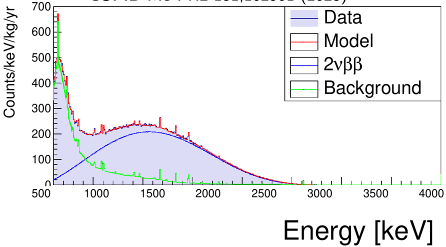
Experimental inputs to constrain nuclear models are critical to assess $m_{\beta\beta}$

$2\nu\beta\beta$ becomes the signal

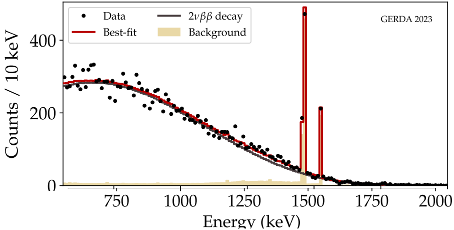
NEMO-3 ^{100}Mo total EPJC, 79:440 (2019)



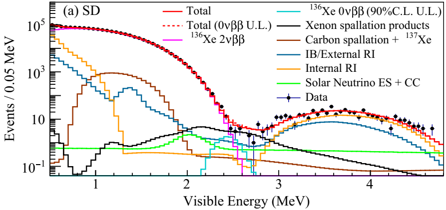
CUPID-Mo PRL 131,162501 (2023)



GERDA PRL 131, 142501 (2023)



KamLandZen PRL 135, 262501 (2025)



$2\nu\beta\beta$ rate and the quenching issue

$$\Gamma^{2\nu} = \frac{1}{T_{1/2}^{2\nu}} \simeq G_{2\nu} \cdot \underbrace{|\mathcal{M}_{2\nu}|^2}_{M_{2\nu} \cdot g_{2\nu}^2}$$

- Single β and $2\nu\beta\beta$ theoretical rates systematically overpredict experimental rates $\rightarrow \mathcal{M}_{2\nu}$ is overestimated
- Quenching of g_A ($g_{2\nu}$) ?
- The situation is more clear today:
- *Ab initio* or first principles nuclear structure methods, exploiting increasing computational performances, could describe β decay half-lives of light nuclei without any adjustments $\Rightarrow$
- There is a deficiency in the other many-body approaches due to approximations
- So far limited benchmarking with experimental data

$2\nu\beta\beta$ improved model

$$\Gamma^{2\nu} \simeq \; G_0 \cdot |M^{2\nu}_{GT}|^2 (g_A^{eff})^4$$

$2\nu\beta\beta$ improved model

$$\Gamma^{2\nu} \simeq \; G_0 \cdot |M_{GT}^{2\nu}|^2 (g_A^{eff})^4 + \xi_{31} G_2 \cdot |M_{GT}^{2\nu}|^2 (g_A^{eff})^4$$

- Taylor expansion in the lepton energies. [Phys. Rev. C 97, 034315 (2018)]
- $\xi_{31} = \frac{M_{GT-3}}{M_{GT}}$
- subleading $2\nu\beta\beta$ matrix elements

$2\nu\beta\beta$ improved model

$$\Gamma^{2\nu} \simeq G_0 \cdot |M^{2\nu}_{GT}|^2 (g_A^{eff})^4 + \xi_{31} G_2 \cdot |M^{2\nu}_{GT}|^2 (g_A^{eff})^4 + \frac{1}{3}\xi_{31}^2 G_{22} |M^{2\nu}_{GT}|^2 (g_A^{eff})^4$$

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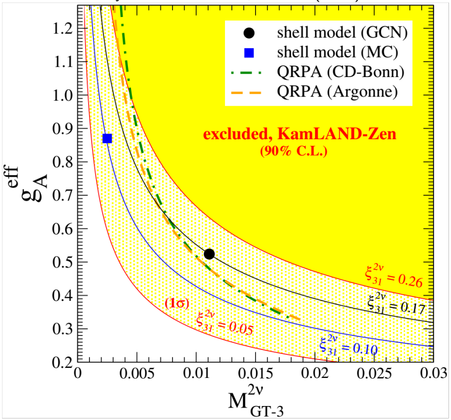
- Taylor expansion in the lepton energies. [Phys. Rev. C 97, 034315 (2018)]
- $\xi_{31} = \frac{M_{GT-3}}{M_{GT}}$
- $\xi_{51} = \frac{M_{GT-5}}{M_{GT}}$
- subleading $2\nu\beta\beta$ matrix elements

Experimental inputs to nuclear models : KamLand Zen

The shape of the $2\nu\beta\beta$ spectrum constrains $\xi_{31} = \frac{M_{GT-3}}{M_{GT}}$

Phys. Rev. Lett. 122, 192501 (2019)



$\xi_{31} < 0.26$ at 90 % C.L

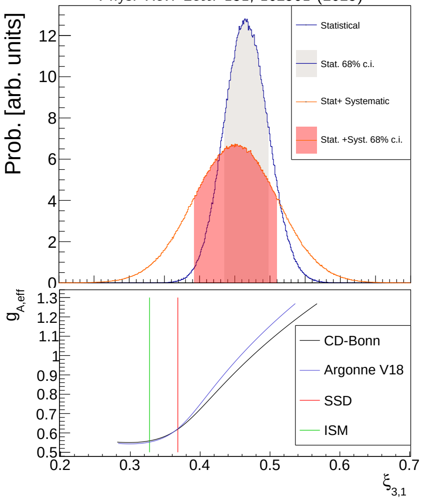
- Shell model predictions well consistent with 90% upper limit
- QRPA predictions consistent with upper limit, small region in g^{eff} is excluded

Experimental inputs to nuclear models : Cupid-Mo

$\xi_{3,1} = 0.45 \pm 0.03(\text{stat.}) \pm 0.05(\text{syst.})$

- Under HSD $\xi_{3,1} = 0$. Disfavoured by 8 σ
- Under SSD $\xi_{3,1} = 0.368$. Compatible at 1.4 σ
- Shell Model mildly incompatible ($\sim$ 2.1 σ)
- pn-QRPA compatible if the value of g_A^{eff} is moderately quenched (> 0.8) or unquenched.

Phys. Rev. Lett. 131, 162501 (2023)

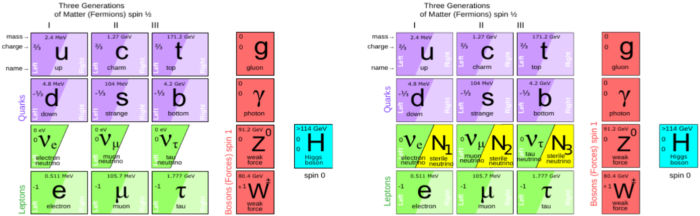


First **measurement** of $\xi_{3,1}$ and $g_{A,\text{eff}}$ based on $2\nu\beta\beta$ spectral shape study

Beyond Standard Model measurements with $2\nu\beta\beta$

Sterile neutrinos

- Neutrinos in the SM are massless **left-handed** fermions
- Simple extension of the SM: add spin 1/2 **right-handed** neutrinos, or sterile neutrinos, with mass M_{heavy}



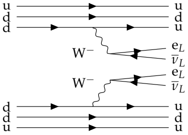
M. Shaposhnikov, J.Phys.Conf.Ser. 408 (2013) 012015

- Type-I seesaw mechanism can simultaneously explain
  - Smallness of the SM neutrino mass
  - baryogenesis via leptogenesis
  - dark matter if one RH neutrino has a mass in the keV range

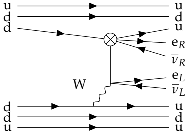
(for ex: Phys. Rev. D 100, 075029 (2019), Int. J. Mod. Phys. E 22, 1330019 (2013))

Sterile neutrinos and $2\nu\beta\beta$

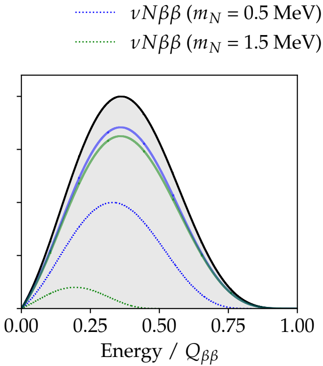
- Sterile neutrinos can be produced in any decay involving ν's
- Kinematically possible in $2\nu\beta\beta$ if sterile neutrino mass $M_N < Q_{\beta\beta}$
- It would distort the $2\nu\beta\beta$ shape



SM $2\nu\beta\beta$



with one sterile



dotted: pure $\nu N\beta\beta$decay, solid: $\sin^2\theta = 0.1$

$$\frac{d\Gamma^{tot}}{dE} = cos^4\theta \frac{d\Gamma_{2\nu,SM}}{dE} + 2cos^2\theta sin^2\theta \frac{d\Gamma_{\nu N}}{dE}$$

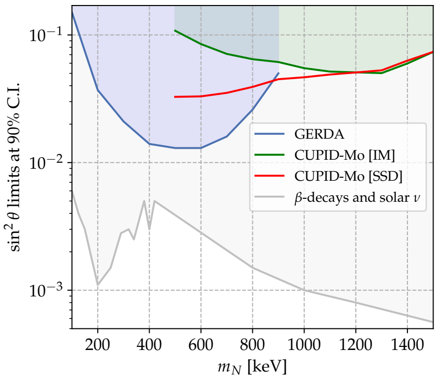
$\sin\theta \rightarrow$ active-sterile mixing

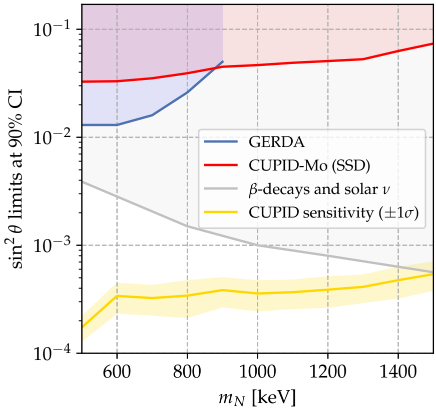
$$\sin\theta \simeq \frac{m_D}{M} \qquad \mathbf{M} = \begin{vmatrix} \frac{m_D^2}{M} & 0 \\ 0 & M \end{vmatrix}$$

$\frac{m_D^2}{M} = \mathrm{m}_{light}$, M= M_{heavy}

Sterile neutrinos limits from $2\nu\beta\beta$ in Cupid-Mo and GERDA

- $2\nu\beta\beta$ can explore the region in the sub-GeV range
- BSM results are affected by the standard $2\nu\beta\beta$ spectrum we use.





Summary

- The uncertainty in the nuclear matrix elements introduces large uncertainties in $T_{1/2}^{0\nu\beta\beta}$ interpretation in terms of $m_{\beta\beta}$.
- On the other hand, $\mathcal{M}_{2\nu}$ is overestimated ("quenching problem"). *Ab initio* methods provides proper answer, still:

→ Need for experimental inputs to constrain or tune nuclear models

- Thanks to large statistics of $2\nu\beta\beta$ collected by $0\nu\beta\beta$ experiments in the last 10 years, we can use $2\nu\beta\beta$ spectrum to give inputs to nuclear models.
- $2\nu\beta\beta$ spectral shape also can be used to put limits on beyond standard model processes, like sterile neutrinos.
  - Potential for competitive results from next generation $0\nu\beta\beta$ experiments


MEANWHILE in the SUBATOMIC WORLD...
I HAVE NO TRUE IDENTITY.... I SEEM TO OSCILLATE BETWEEN THREE PERSONALITIES!
Sigh... NEUTRINOS..

The see-saw mechanism

The See-Saw mechanism

After diagonalization: $$\mathbf{M}_{diag} = \begin{pmatrix} m_{light} & 0 \\ 0 & M_{heavy} \end{pmatrix}$$

Eigenvalues ("Physical" masses): $$\begin{cases} m_{light} \approx \dfrac{m_D^2}{M} \\ M_{heavy} \approx M \end{cases}$$

By plugging in a **top-quark-like** Dirac mass (**100 GeV**) and a GUT-scale (**10^{14} – 10^{16} GeV**) Majorana mass into the **seesaw formula**, we obtain light neutrinos in the **sub-eV range**, consistent with experimental data!

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Eigenvectors ("Physical" neutrino states):

Light → $\Psi_1 \approx \underbrace{(\nu_L + \nu_L^c)}_{Active} - \underbrace{\frac{m_D}{M}(\nu_R^c + \nu_R)}_{Sterile}$ — Familiar Standard Model light neutrinos

Heavy → $\Psi_2 \approx \underbrace{(\nu_R^c + \nu_R)}_{Sterile} + \underbrace{\frac{m_D}{M}(\nu_L + \nu_L^c)}_{Active}$ — Exotic never-observed very heavy neutrinos

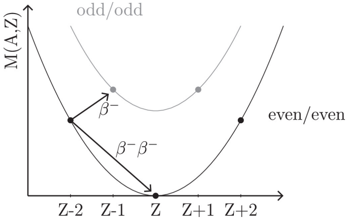
All physical neutrino states (light and heavy) are Majorana particles!

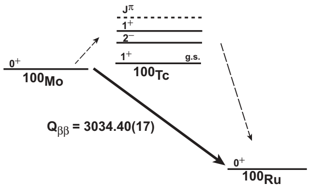
Neutrinos and antineutrinos are just different spin states of the same fundamental particle

$$(\nu_L + \nu_L^c)^c = \nu_L^c + \nu_L$$

$2\nu\beta\beta$ decay

- $(A,Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$
- $2\nu\beta\beta$ is observable in nuclei where single β decay is forbidden energetically due to nuclear pairing interaction





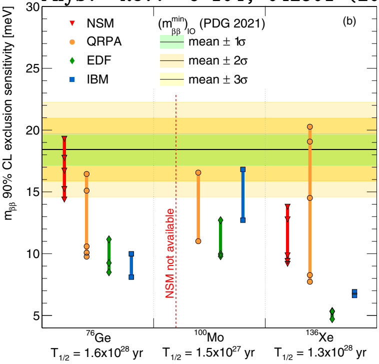
^{48}Ca	$\rightarrow$	^{48}Ti
^{76}Ge	$\rightarrow$	^{76}Se
^{82}Se	$\rightarrow$	^{82}Kr
^{96}Zr	$\rightarrow$	^{96}Mo
^{100}Mo	$\rightarrow$	^{100}Ru
^{116}Cd	$\rightarrow$	^{116}Sn
^{130}Te	$\rightarrow$	^{130}Xe
^{136}Xe	$\rightarrow$	^{136}Ba
^{150}Nd	$\rightarrow$	^{150}Sm

- Directly observed, with $T_{1/2}^{2\nu\beta\beta}$ between 10^{19} - 10^{21} years

Uncertainty in $0\nu\beta\beta$ sensitivity comes from NME's

- $M_{0\nu}$ relates to the nuclear structure of the initial and final state nuclei $\rightarrow$ we need to consider an N-body problem
- Difficult to calculate accurately. Differences $\sim$ factor 3 depending on the nuclear models

Phys. Rev. C 104, 042501 (2021)



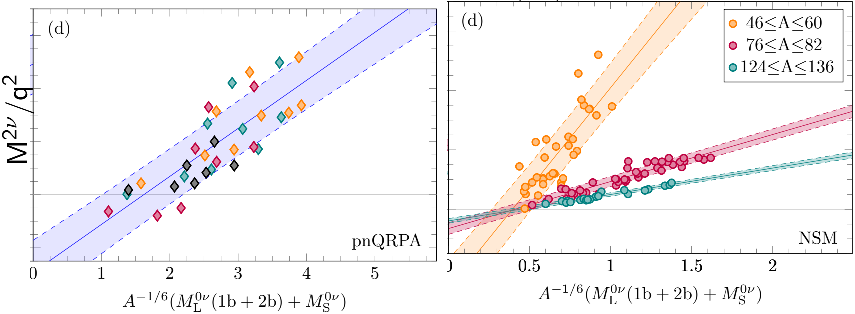
- NME theoretical uncertainties introduce large uncertainties in the interpretation of $T^{0\nu}_{1/2}$ in terms of $m_{\beta\beta}$
- Prevent to determine accurately the expected sensitivities of future experiments

Experimental inputs to constrain nuclear models are critical to

What can we learn from $2\nu\beta\beta$?

$0\nu\beta\beta$ and $2\nu\beta\beta$ involve same initial and final states, but permitted momentum transfers are larger in $0\nu\beta\beta$

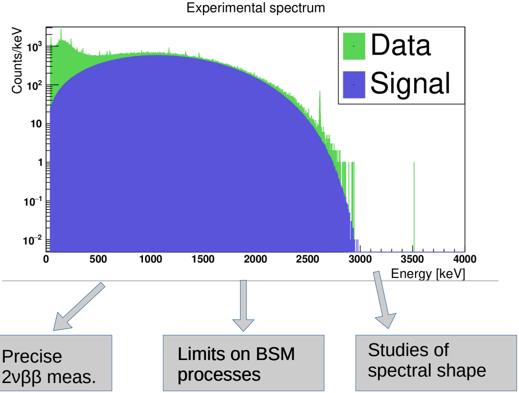
Phys. Rev. C 107, 4, 044305 (2023)



We can use $2\nu\beta\beta$ data to constraint $0\nu\beta\beta$ NME's!

$2\nu\beta\beta$ becomes the signal

- Starting in $\sim$2015 $0\nu\beta\beta$ experiments exploiting higher exposures, lower backgrounds and improvements in the measurement techniques start to measure $2\nu\beta\beta$ spectra with high precision.



Theoretical issues : g_A quenching?

$2\nu\beta\beta$ rate:

$$\left(T^{2\nu}_{1/2}\right)^{-1} = G_{2\nu} \cdot \underbrace{|M_{2\nu}|^2 \cdot g_{2\nu}^4}_{}$$

- Single β and $2\nu\beta\beta$ theoretical rates overpredict experimental rates $\rightarrow$ $|M_{2\nu}|^2 \cdot g_{2\nu}^4$ overestimated

What is the impact for $0\nu\beta\beta$ decay?

- Quenching of g_A w.r.t bare nucleon = 1.27? $g_{2\nu} \neq g_{0\nu}$
- Too large NME's?
- Both are related, we should consider g_A x NME

- Possible interpretation: quenching of g_A $g_{2\nu} \neq g_{0\nu}$
- **Generally speaking, uncertainties in nuclear models** introduce large uncertainties in $0\nu\beta\beta$ predictions

$2\nu\beta\beta$ spectrum is useful to extract observables to constrain nuclear models

$2\nu\beta\beta$ theoretical description

Here I would like to start with the general expression :

$$\frac{d\Gamma}{dE_1 dE_2} \propto F_0(Z, E_1) F_0(Z, E_2) p_1 p_2 \int_0^{E_i - E_f - E_1 - E_2} E_{\nu_1}^2 E_{\nu_2}^2 A^{2\nu} dE_{\nu_1}, \quad (1)$$

where $F_0(Z, E_1)$ is the Fermi function, E_1, E_2, p_1, p_2 are the two electron energies and momenta, E_{ν_2}, E_{ν_1} are the two neutrino energies and E_i, E_f the energies of the initial and final states. $A^{2\nu}$ involves matrix elements which depend on the lepton energies and on the sum over possible states of the intermediate nucleus:

$$A^{2\nu} = \frac{1}{4}|M_{GT}^K + M_{GT}^L|^2 + \frac{1}{12}|M_{GT}^K - M_{GT}^L|^2. \quad (2)$$

Here $M_{GT}^{K,L}$ are the Gamow Teller matrix elements given by:

$$M_{GT}^{K,L} = m_e \sum_n \left\langle 0_F^+ \right| |\tau_m^+ \vec{\sigma_m}| \left| 1_n^+ \right\rangle | \left\langle 1_n^+ \right| |\tau_m^+ \vec{\sigma_m}| \left| 0_I^+ \right\rangle \frac{C_n}{C_n^2 - \epsilon_{K,L}^2}, \quad (3)$$

where the sum goes over all possible states of the intermediate nucleus.

$2\nu\beta\beta$ theoretical description

In full generality,

$$\frac{d\Gamma^{2\nu}}{dE_1 dE_2} \propto \int_0^{E_i - E_f - E_1 - E_2} E^2_{\nu_1} E^2_{\nu_2} A^{2\nu} \, dE_{\nu_1}$$

$A^{2\nu}$ is a sum of the matrix elements, relating Final and Initial nuclear states and all possible states of the intermediate nucleus:

$$M^{K,L}_{GT} = m_e \sum_n \langle Final| \, |\tau^+_m \vec{\sigma_m}| \, |1^+_n\rangle \, | \, \langle 1^+_n| \, |\tau^+_m \vec{\sigma_m}| \, |Initial\rangle \, \frac{C_n}{C_n^2 - \epsilon^2_{K,L}} \quad (6)$$

And $C_n = E_n - (E_i + E_f)/2$.

This is a problem. A factorization is possible under some approximations:

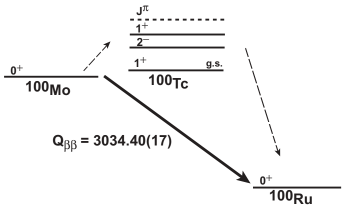
- SSD, Single State Dominance: decay goes through the lowest 1^+ state of the intermediate nucleus.
- HSD, High State Dominance: lepton energies are neglected w.r.t energies of intermediate states

$$\frac{d\Gamma}{dE_1 dE_2} \propto \overbrace{|M^{2\nu}_{GT}|^2}^{\text{matrix element}} \int_0^{E_i - E_f - E_1 - E_2} E^2_{\nu_1} E^2_{\nu_2} \, dE_{\nu_1} \, . \quad (7)$$

$2\nu\beta\beta$ theoretical description

$$\left(T_{1/2}^{2\nu}\right)^{-1} = G_{2\nu} \cdot |M_{2\nu}|^2 \cdot g_{2\nu}^4$$

- This factorization is possible only under some approximations:
  - SSD, Single State Dominance: decay goes through the lowest 1^+ state of ^{100}Tc
  - HSD, High State Dominance: lepton energies are neglected w.r.t energies of intermediate states of ^{100}Tc nucleus
  - The choice affects the theoretical spectral shapes



$2\nu\beta\beta$ improved model

- Improved model from Šimkovic *et al* (PRC97 (2018) 034515), Taylor expansion in the lepton energies of $2\nu\beta\beta$ decay rate:

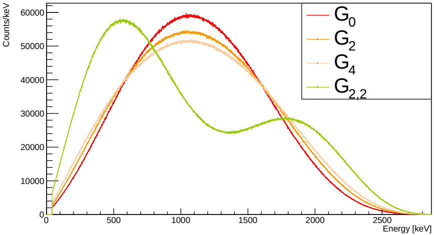
$$\frac{d\Gamma}{dE} = (g_A^{\text{eff}})^4 |M_{GT-1}|^2 \Big(\frac{dG_0}{dE} + \xi_{31} \frac{dG_2}{dE} + \frac{1}{3}\xi_{31}^2 \frac{dG_{22}}{dE} + \big(\frac{1}{3}\xi_{31}^2 + \xi_{51}\big) \frac{dG_4}{dE} \Big)$$

- g_A^{eff} effective axial vector coupling constant, tuned to reproduce experimental $T_{1/2}^{2\nu}$
- $\xi_{31} = \frac{M_{GT-3}}{M_{GT-1}}, \quad \xi_{51} = \frac{M_{GT-5}}{M_{GT-1}}$

Our motivation is to extract the values of novel observables to compare to theoretical predictions

$2\nu\beta\beta$ improved model fit with CUPID-Mo

Phys. Rev. Lett. 131, 162501 (2023)



dG_i/dE come from theory shape (produced by Jenni Kotila)

- We fit experimental data, with a Gaussian prior on ξ_{51}/ξ_{31}, that can be accurately calculated:
  - SSD: 0.367
  - pn-QRPA: 0.364 – 0.368
  - Shell: 0.349

CUPID-Mo $2\nu\beta\beta$ spectral shape results

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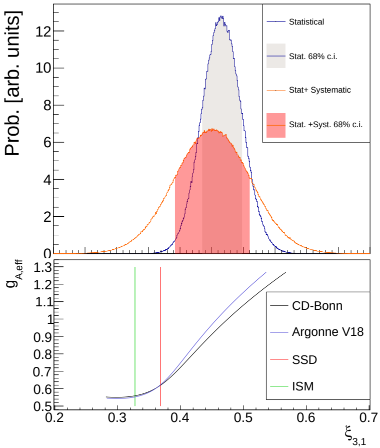
$\xi_{3,1} = 0.45 \pm 0.03(\text{stat.}) \pm 0.05(\text{syst.})$

- Under HSD $\xi_{3,1} = 0$. Disfavoured by 8 σ
- Under SSD $\xi_{3,1} = 0.368$. Compatible at 1.4 σ
- Shell Model mildly incompatible ($\sim$ 2.1 σ)
- Using $g_{A,\text{eff}}$ vs $\xi_{3,1}$ (from F. Šimkovic):

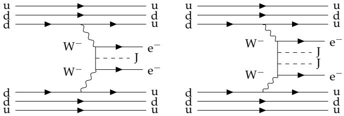


$g_{A,\text{eff}}(\text{pn-QRPA}) = 1.0 \pm 0.1\ (\text{stat.}) \pm 0.2(\text{syst}).$

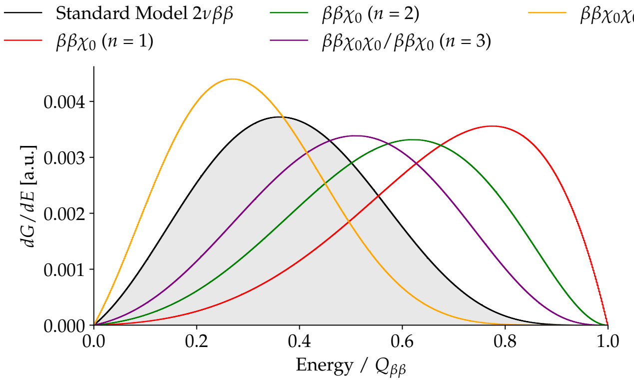
First measurement of $\xi_{3,1}$ and $g_{A,\text{eff}}$ based on $2\nu\beta\beta$ spectral shape study

Majorons

- $0\nu\beta\beta$ decay in the light neutrino exchange may occur with the emission of one or two Majorons (bosons).

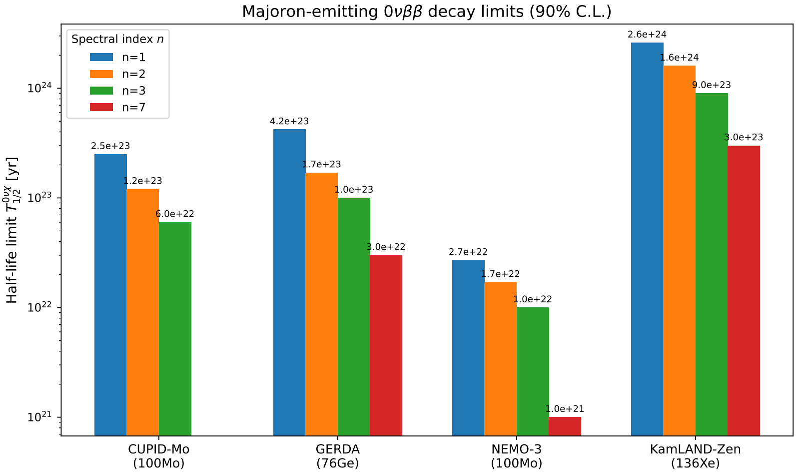


- This would distort the $2\nu\beta\beta$ spectrum.
- Different Majoron models predict different energy distributions



$$\frac{dG}{dE} \sim (Q_{\beta\beta} - E)^n$$

Limit to T1/2 of 0nbb with Majoron emission



- The BSM decay with Majorons is completely unrelated to the SM $2\nu\beta\beta$ $\rightarrow$ the lower the $2\nu\beta\beta$ decay rate, the higher the sensitivity (^{136}Xe)

Limits on sterile neutrinos mass and $2\nu\beta\beta$

- $2\nu\beta\beta$ can explore the region in the sub-GeV range
- below $\sim$ 100 keV $\rightarrow$ beta decays,
- above $\sim$ 100 MeV $\rightarrow$ High energy experiments, long baseline

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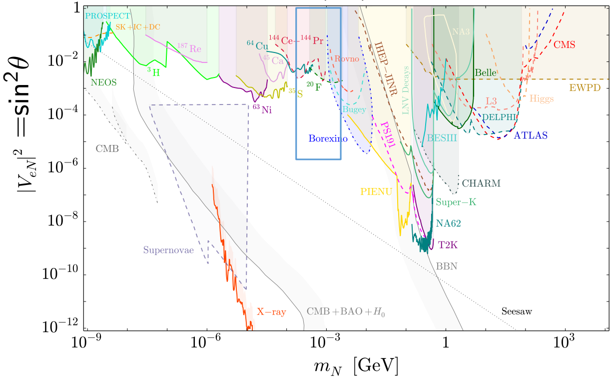

$0\nu\beta\beta$ in the presence of sterile neutrinos: limits

$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = g_A^4 \cdot G_{0\nu} \cdot |M_{0\nu}|^2 \cdot \left| \frac{m_{\nu_e}}{m_e^2} + \frac{\langle \boldsymbol{p}^2 \rangle}{m_e} \sum_{i=1}^{n_s} n \frac{V_{eN_i}^2 m_{N_i}}{\langle \boldsymbol{p}^2 \rangle + m_{N_i}^2} \right|^2$$

$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} < \text{experimental limits (assuming one sterile)} \rightarrow$$

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