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Probing New Physics with Standard Double Beta Decay

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Introduction & Motivation

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- neutrinos – neutral, left-handed fermions, they mix → oscillate → have mass! → new physics needed to explain this
- Dirac or Majorana nature?
- Majorana masses ↔ LNV ↔ neutrinoless double beta ($0\nu\beta\beta$) decay
- searches for $0\nu\beta\beta$ decay → background: standard $2\nu\beta\beta$ decay data collected ~ 10^5 – 10^6 events
- New Physics in $2\nu\beta\beta$ decay? How would it look like?
- right-handed currents? → 2003.11836 (F. F. Deppisch, LG, F. Simkovic)
- neutrino self-interactions? → 2004.11919 (F. F. Deppisch, LG, W. Rodejohann, X. Xu)

Double Beta Decays

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- two-neutrino double beta decay

  $$(\mathrm{A},\ \mathrm{Z}) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$$

- neutrinoless double beta decay

  $$(A, Z) \rightarrow (A, Z+2) + 2e^-$$

  → lepton number violated

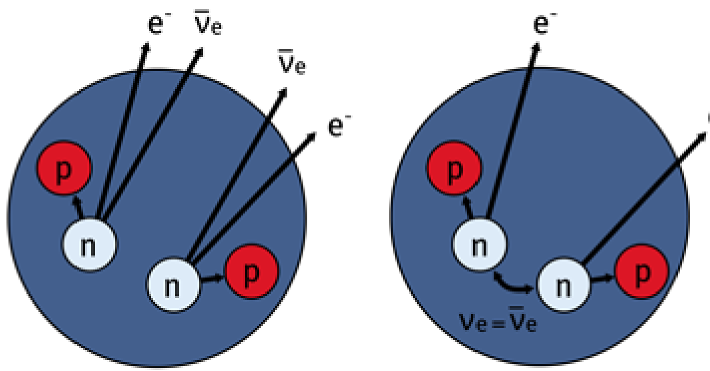
- experiments:

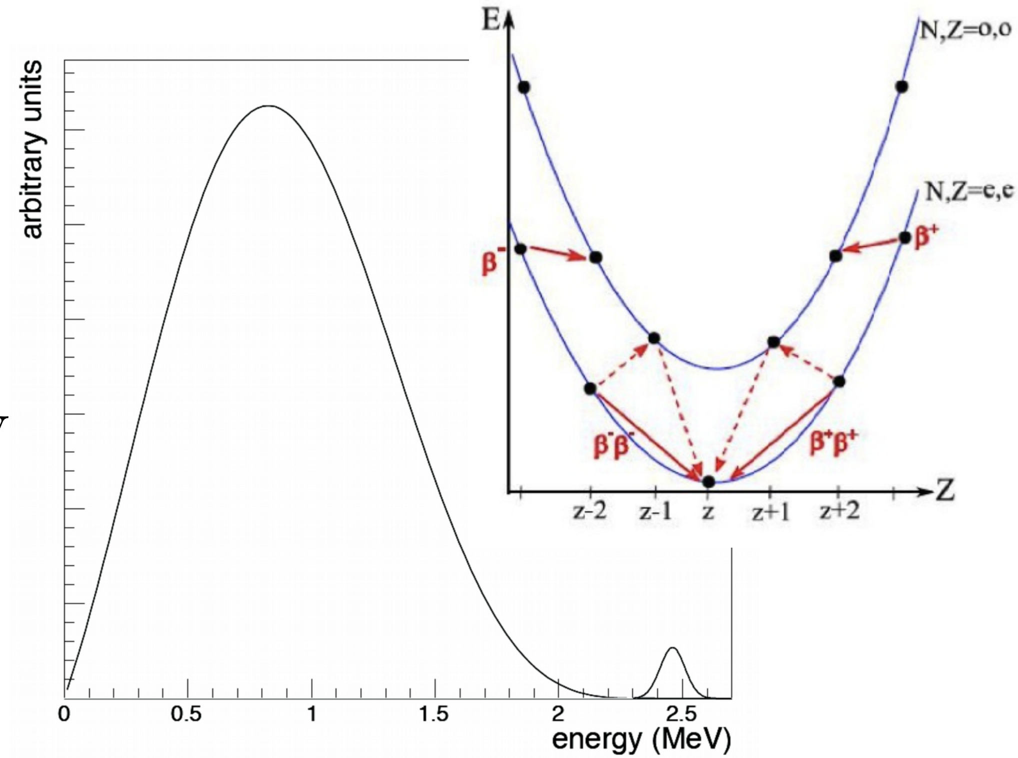
  $$\mathrm{T}_{1/2}^{2\nu\beta\beta} \sim 10^{18}\text{ - }10^{21}\ \mathrm{y}$$

  $$\mathrm{T}_{1/2}^{0\nu\beta\beta} \sim (0.1\ \mathrm{eV}/m_\nu)^2 \times 10^{26}\ \mathrm{y}$$

- a variety of isotopes:

  ^{76}Ge, ^{100}Mo, ^{130}Te, ^{136}Xe, ...





2νββ Decay

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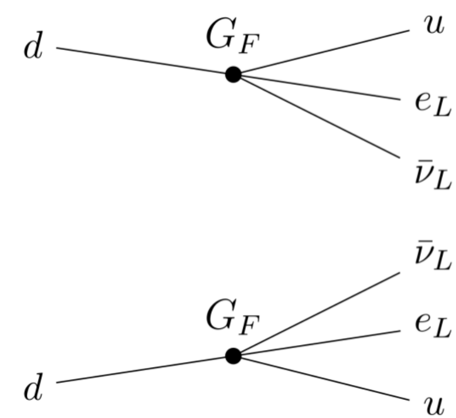
- half-life of 2νββ decay in the Standard Model:

$$[T_{1/2}^{2\nu\beta\beta}]^{-1} = G_{2\nu\beta\beta}|M_{2\nu\beta\beta}|^2$$

phase space factor (lepton part) — nuclear matrix element (nucleon part)



- full differential decay rate:

$$\frac{d\Gamma^{2\nu}}{dE_{e_1}\,dE_{e_2}\,d\cos\theta} = \frac{\Gamma^{2\nu}}{2}\boxed{\frac{d\Gamma^{2\nu}_{\mathrm{norm}}}{dE_{e_1}\,dE_{e_2}}}\left(1 + \boxed{\kappa^{2\nu}(E_{e_1}, E_{e_2})}\cos\theta\right)$$

- observables: electron energy distribution (single electron energy or total kinetic energy of the electrons) and angular correlation of the two emitted electrons (NEMO-3, SuperNEMO)

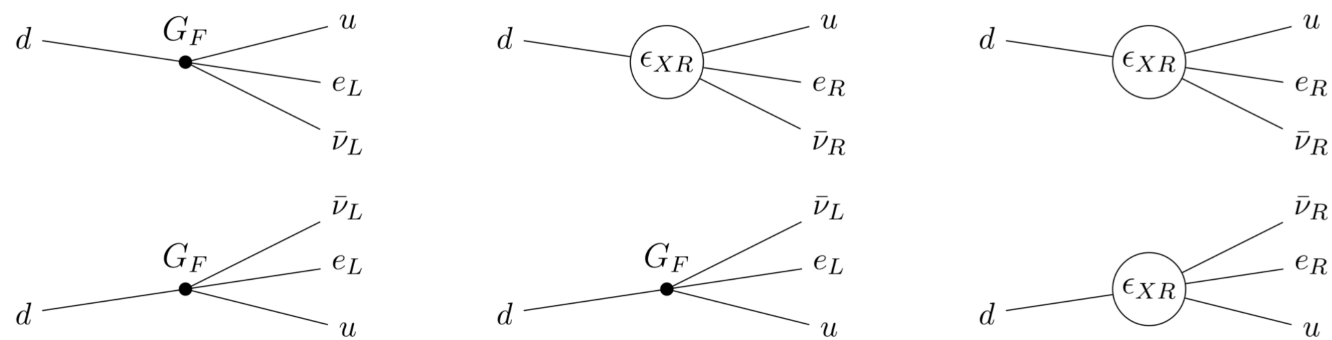
Exotic 2νββ Decay – RHCs

- 2νββ decay in presence of right-handed currents? → Lagrangian:

$$\mathcal{L} = \frac{G_F \cos\theta_C}{\sqrt{2}} \left((1 + \delta_{\rm SM} + \epsilon_{LL}) j_L^\mu J_{L\mu} + \epsilon_{RL} j_L^\mu J_{R\mu} + \epsilon_{LR} j_R^\mu J_{L\mu} + \epsilon_{RR} j_R^\mu J_{R\mu} \right) + \text{h.c.}$$

with $j^\mu_{L,R} = \bar{e}\gamma^\mu(1 \mp \gamma_5)\nu,\ J^\mu_{L,R} = \bar{u}\gamma^\mu(1 \mp \gamma_5)d$

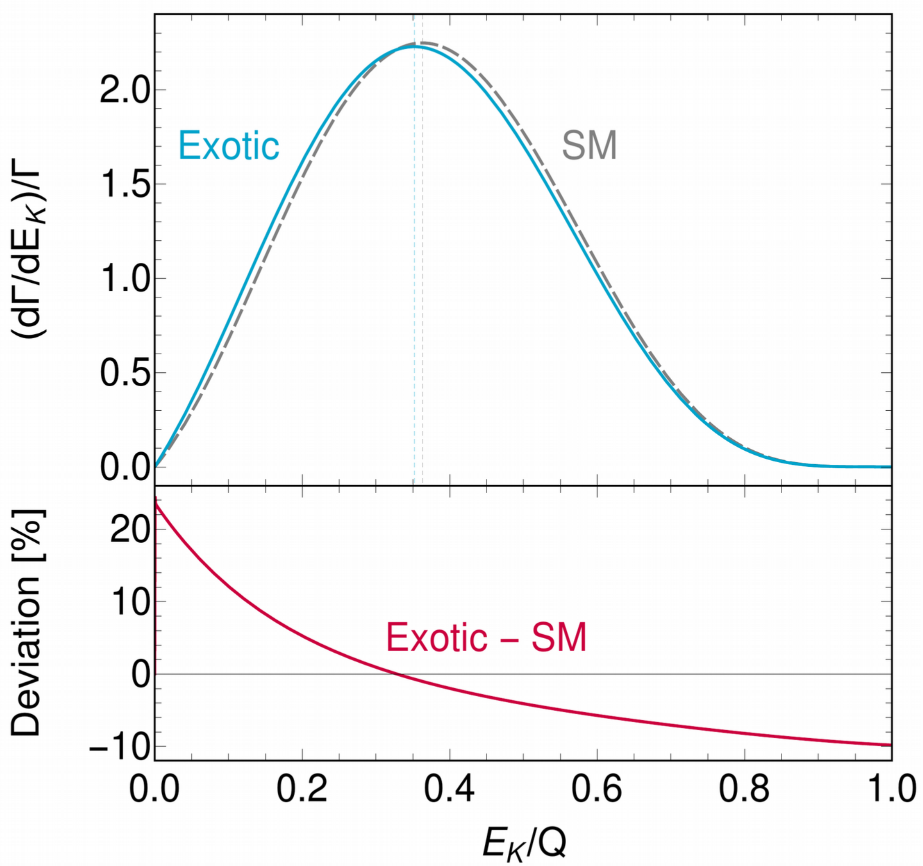
- contributions:

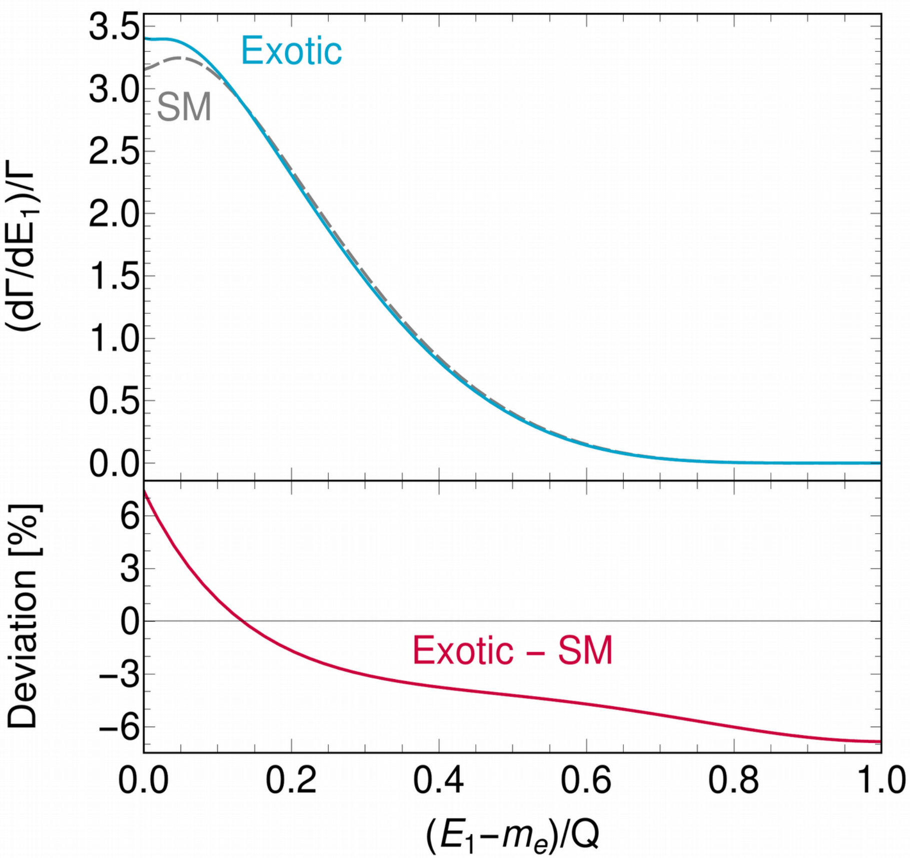


- take the one linear in exotic effective coupling ϵ_{XR}, calculate the observables and get the bound imposed by the experimental data
- rate: $[T_{1/2}^{2\nu\beta\beta}]^{-1} = \epsilon_{XR}^2 G_{2\nu\beta\beta} |M_{2\nu\beta\beta}|^2$
- here, everything for ^{100}Mo, other isotopes similar – see 2003.11836

Electron Energy Distribution

- 2νββ decay (both the SM and the exotic RHC-induced contributions) distribution in total kinetic (left) and single electron kinetic (right) energy





Electron Angular Correlation

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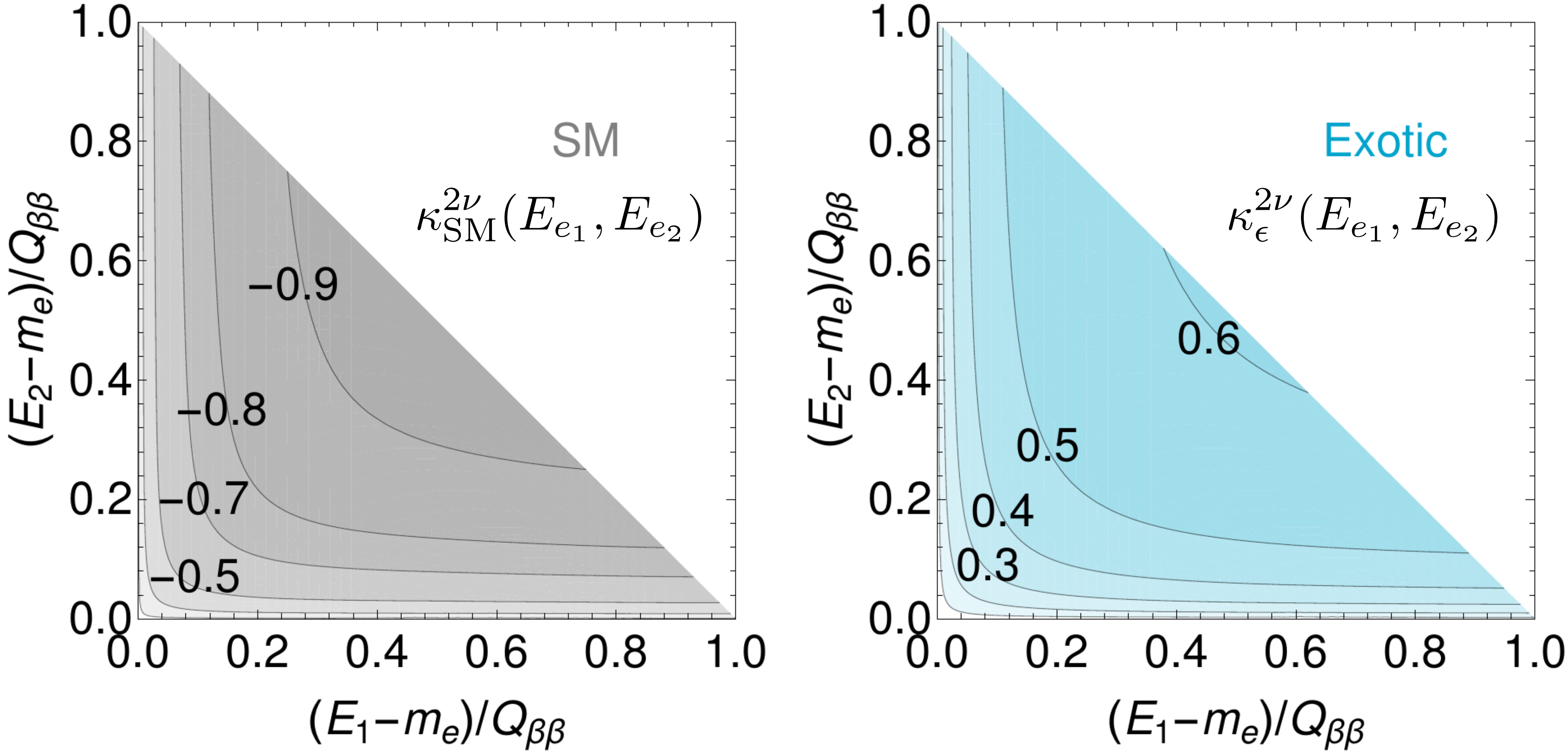
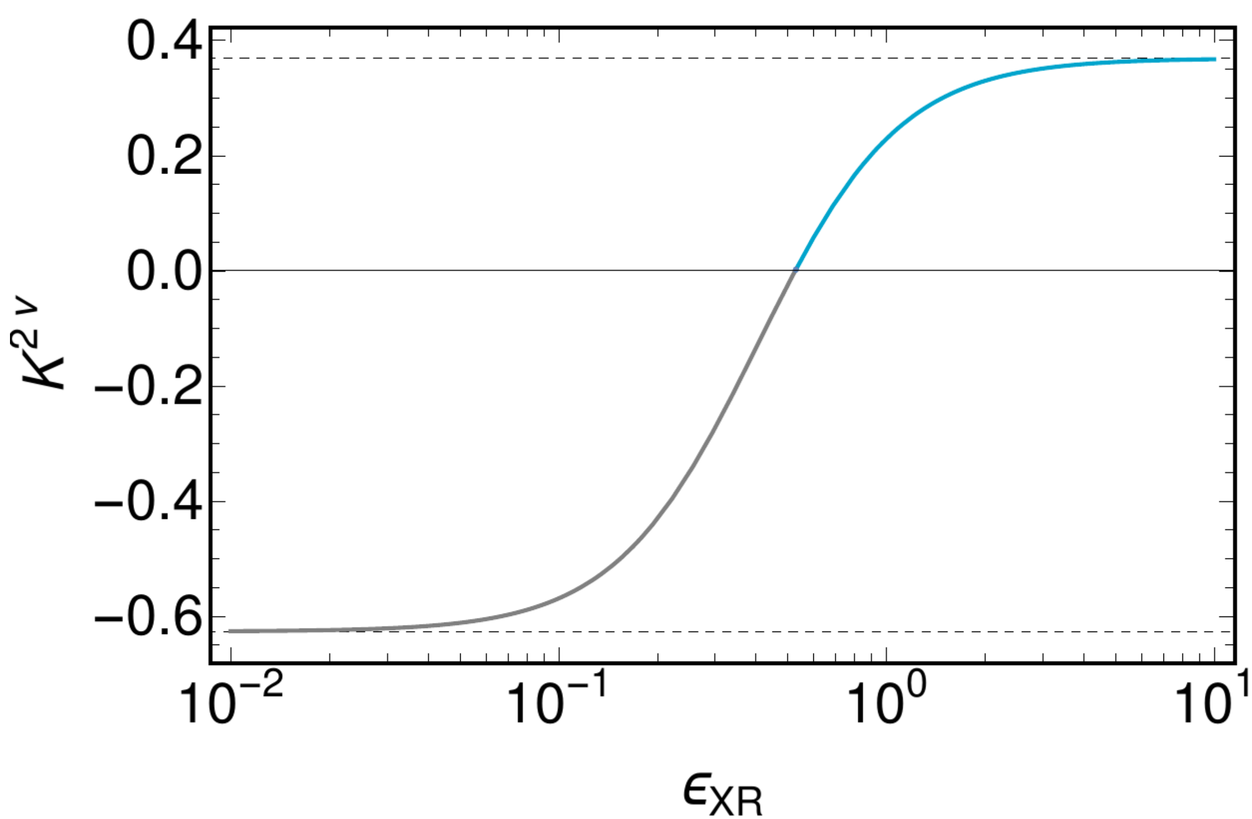
- angular correlation of the electrons in the SM 2νββ decay (left) and the exotic 2νββ decay induced by right-handed lepton currents (right)



Electron Angular Correlation

- observed angular correlation: mixture of the SM and exotic contributions – correlation factor $K^{2\nu}$ as a function of ϵ_{XR} interpolates between the SM ($\epsilon_{XR} = 0$, grey) and exotic ($\epsilon_{XR} >> 1$, blue) cases



Bound on ϵ_{XR} Coupling

- total rate – nuclear matrix elements not accurate enough
- electron energy distribution – small deviations, could be probed, but certain degeneracy given by nuclear structure effects
- best option: measure the angular correlation of the emitted electrons and look for the forward-backward asymmetry
- possible at NEMO-3 experiment using ^{100}Mo (or in future at SuperNEMO)
- insensitive of the overall rate
- largely insensitive to the nuclear part of the amplitude – QRPA used in our case, but very similar results expected to be obtained with other nuclear structure models

Bound on ϵ_{XR} Coupling

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- angular distribution: $\frac{\mathrm{d}\Gamma^{2\nu}}{\mathrm{d}\cos\theta} = \frac{\Gamma^{2\nu}}{2}\left(1 + K^{2\nu}\cos\theta\right)$

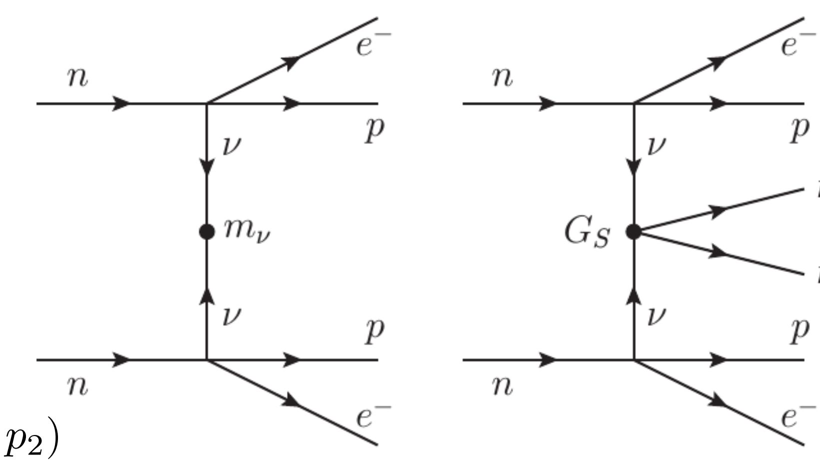
  with correlation factor: $K^{2\nu} \approx K^{2\nu}_{\mathrm{SM}} + \alpha\,\epsilon^2_{XR}$, for ^{100}Mo: $\alpha \approx 6.1$
- forward-backward asymmetry: $A^{2\nu}_{\theta} = \frac{N_{\theta>\pi/2} - N_{\theta<\pi/2}}{N_{\theta>\pi/2} + N_{\theta<\pi/2}} = \frac{1}{2}K^{2\nu}$
- estimated accuracy of NEMO-3: $K^{2\nu}_{\mathrm{SM}} = -0.63 \pm 0.0027$

  → bound on the effective coupling at 90% CL: $\boldsymbol{\epsilon_{XR} \lesssim 2.7 \times 10^{-2}}$
- more stringent limit than the one obtained from the standard beta decay measurements
- SuperNEMO would further improve this bound to: $\epsilon_{XR} \lesssim 4.8 \times 10^{-3}$
- estimates only, a dedicated experimental analysis necessary

ββ Decay Induced by νSI

- neutrino self-interaction – potential to resolve the 4σ Hubble tension
- effectively: $G_S\,(\nu\nu)\,(\nu\nu)$, where G_S should be much larger than G_F
- strong, but purely neutrino interaction → not easy to probe in a lab
- idea: νSI would induce a contribution to double beta decay
  - rate: $\Gamma_{\nu\mathrm{SI}} = \left|\frac{G_S m_e}{2R}\right|^2 \mathcal{G}_{\nu\mathrm{SI}} |\mathcal{M}_{0\nu}|^2$
  - nuclear matrix element approx. same as for 0νββ decay
  - phase space ~ 2νββ decay

$$\mathcal{G}_{\nu\mathrm{SI}} = \frac{2c_{\nu\mathrm{SI}}}{15}\int dp_1 dp_2 p_1^2 p_2^2 (Q - T_{12})^5 F^2(p_1, p_2)$$

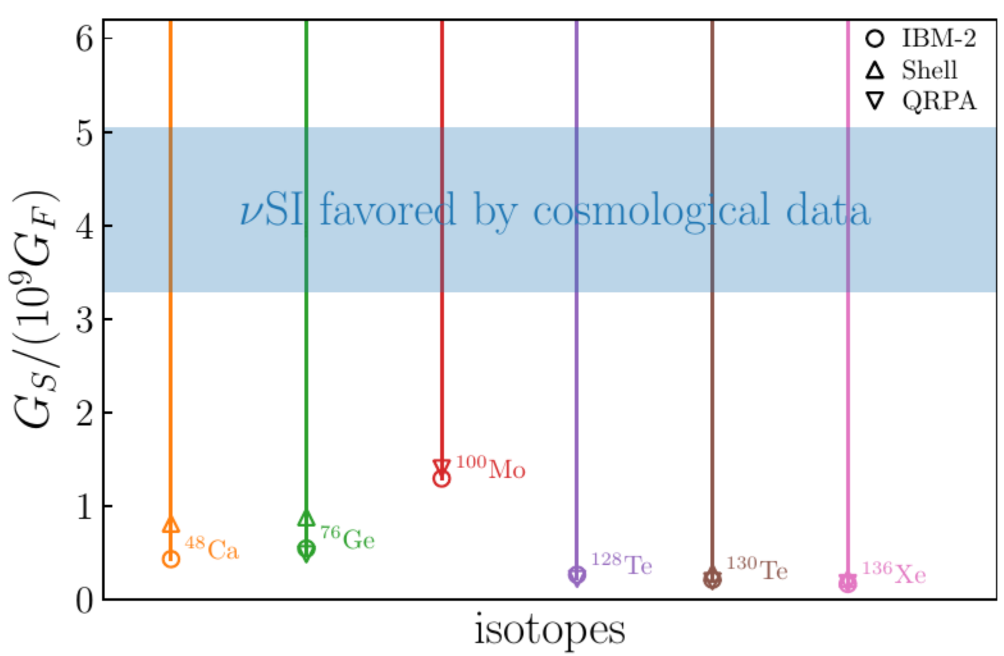


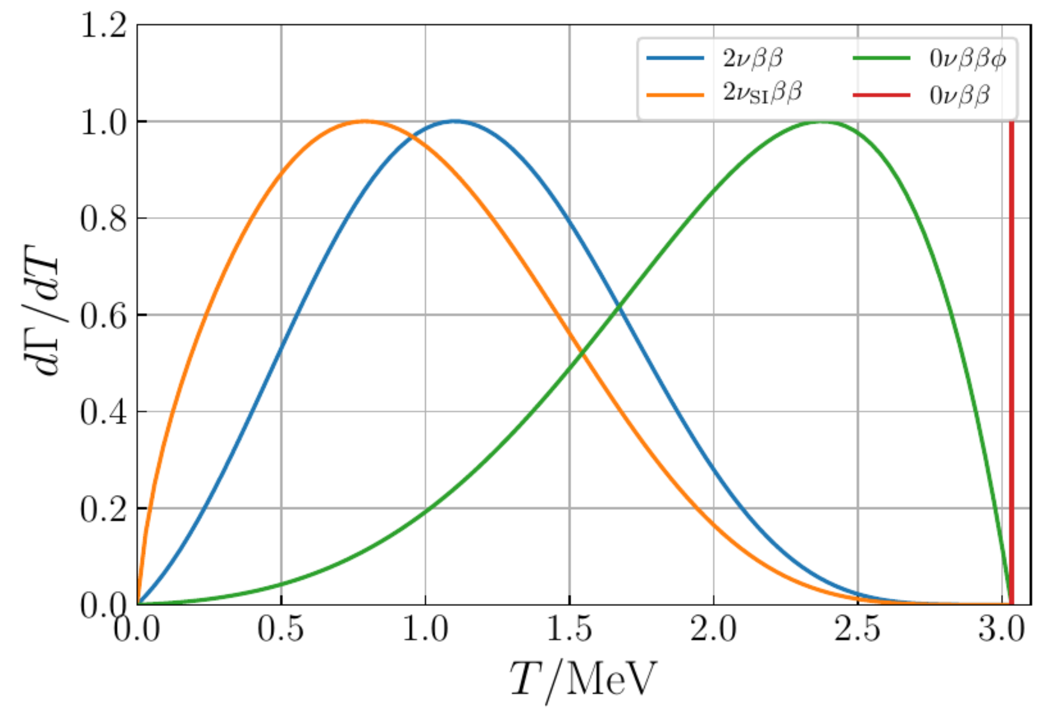
→ νSI could affect 2νββ decay – total rate, but also spectra

ββ Decay Induced by νSI

- now: using condition $\Gamma_{\nu\mathrm{SI}}/\Gamma_{2\nu}^{\mathrm{ex}} < 1$ self-interaction G_S can be constrained – from total rate (assuming G_S to be constant; left), or spectral shape (for energy dependent G_S; right)

$\rightarrow$ νSI preferred by cosmology is disfavoured by 2νββ decay





Conclusion

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- Although observation of $0\nu\beta\beta$ decay is the primary goal of double beta decay searches, its background process, $2\nu\beta\beta$ decay, can be also used as a probe of New Physics.
- Following a derivation of the contribution to $2\nu\beta\beta$ decay induced by general right-handed vector currents a stringent limit, competitive with other probes, on respective effective coupling has been obtained upon employing currently available data. → 2003.11836
- Study of the $\beta\beta$ decay contribution induced by neutrino self-interaction shows that the $2\nu\beta\beta$ decay observations disfavour the magnitudes of this new coupling preferred by cosmology. → 2004.11919

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Thank You for attention and stay safe!