New physics with a positive or negative signal of $0\nu\beta\beta$

Johannes Bergström

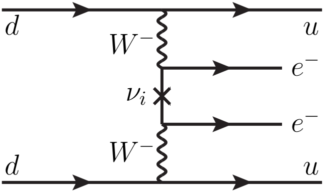
Department of Theoretical Physics, Royal Institute of Technology (KTH)

Talk at Europhysics Conference on High-Energy Physics 2011

Introduction

- ν-experiments imply that neutrinos are massive and lepton flavors mixed. Mixing angles and mass squared differences measured.
- Only upper bounds on the mass of the lightest neutrino, from beta decay experiments (kinematic) and cosmology (indirect).
- Neutrinos Dirac or Majorana particles. If Majorana, *neutrinoless double beta decay* can occur, $(A, Z) \rightarrow (A, Z + 2) + 2e^-$.
- Many near-future experiments related to neutrino masses and leptonic mixing ($0\nu\beta\beta$, β, cosmology, oscillation).

$0\nu\beta\beta$ through light neutrino exchange



- Decay rate:

$$\Gamma = G|\mathcal{M}^{0\nu}|^2|m_{ee}|^2$$

$G =$ known phase space factor

$|m_{ee}| = \left|m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\alpha} + m_3 s_{13}^2 e^{2i\beta}\right|$

$\mathcal{M}^{0\nu} =$ Nuclear matrix element (NME)

- Calculation of $\mathcal{M}^{0\nu}$ a notoriously difficult task $\Rightarrow$ underlying parameter inference uncertain.

Other mechanisms of $0\nu\beta\beta$

- Many extensions of the SM include breaking of lepton number and induce $0\nu\beta\beta$, and often also neutrino masses.
- New *heavy* physics describable using effective field theory (EFT) $\Rightarrow$ use EFT instead of treating specific high-energy models
  1: Alter the Lorentz and/or chirality structure of four-fermion vertex, keep the neutrino propagator. Studied extensively.
  2: Treat the whole interaction as point-like.

Other mechanisms of $0\nu\beta\beta$

- Many extensions of the SM include breaking of lepton number and induce $0\nu\beta\beta$, and often also neutrino masses.
- New *heavy* physics describable using effective field theory (EFT) $\Rightarrow$ use EFT instead of treating specific high-energy models
  1: Alter the Lorentz and/or chirality structure of four-fermion vertex, keep the neutrino propagator. Studied extensively.
  2: Treat the whole interaction as point-like.
- In case 2: General dimension-9 Lagrangian

$$\mathcal{L} = \frac{G_F^2}{2m_p}\left(\epsilon_1 JJj + \epsilon_2 J^{\mu\nu}J_{\mu\nu}j + \epsilon_3 J^{\mu}J_{\mu}j + \epsilon_4 J^{\mu}J_{\mu\nu}j^{\nu} + \epsilon_5 J^{\mu}Jj_{\mu}\right) + \text{h.c.},$$

where

$$J_{L,R} = \overline{u}\left(1 \mp \gamma_5\right)d, \quad J^{\mu}_{L,R} = \overline{u}\gamma^{\mu}\left(1 \mp \gamma_5\right)d, \quad j_{L,R} = \overline{e}\left(1 \mp \gamma_5\right)e^{c}, \text{ etc.}$$

$$\epsilon_i = \epsilon_i^{LRL}, \text{ etc.}$$

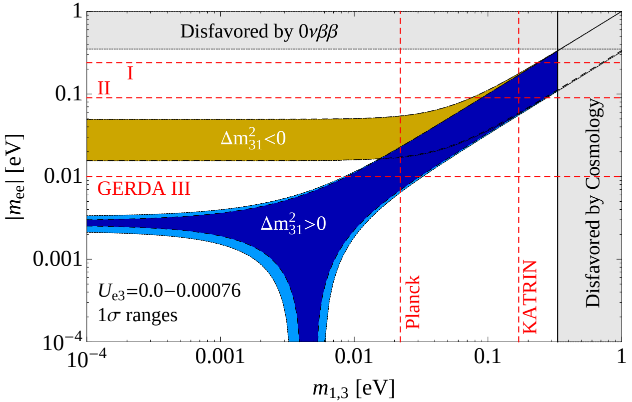
- Total decay rate including interferences with ν-exchange can be calculated.

Main question

- How does the combination of future results of experiments related to neutrino masses constrain new physics, parametrized by the effective couplings?
- The types of experiments one should consider are
  1. $0\nu\beta\beta$-experiments, sensitive to $|m_{ee}|$ and other new physics. GERDA as ex.
  2. β-decay experiments, sensitive to the effective kinematical mass m_β of ν_e. KATRIN as ex.
  3. Cosmological observations, sensitive to the effective sum of neutrino masses. Mainly Planck.

Current situation

- Effective mass $|m_{ee}|$ as a function of the smallest neutrino mass for normal (blue) and inverted (yellow) mass ordering.
- Regions disfavored by previous experimental results in gray.
- Sensitivities of considered experiments in red.



Analysis

- Define three benchmark scenarios A, B, and C.
- Only consider one ϵ-coefficient non-zero at a time.
- Use a χ^2-analysis to determine if the different measurements are consistent or not, taking into account the uncertainty in the NME.
- Interferences can only occur when the final state e^- have identical chiralities. Thus, only effective operators containing $j_R = \overline{e}\,(1+\gamma_5)\,e^c$ can interfere with the standard mechanism.

Scenario A

A: *Negative signal*, $T_{1/2}^{\text{bound}} = 2.8 \cdot 10^{27}$years (95 % C.L., 150 times H-M limit).

- No $0\nu\beta\beta$ can be established. Uncertain if neutrinos Dirac or Majorana. Upper bounds on new physics.
- $T_{1/2}^{\epsilon} > T_{1/2}^{\text{bound}}$ gives the upper bounds (using nominal NMEs) on the magnitudes of the coefficients of the effective operators as

	$\lvert\epsilon_1\rvert$	$\lvert\epsilon_2\rvert$	$\lvert\epsilon_3^{LLz,RRz}\rvert$	$\lvert\epsilon_3^{LRz,RLz}\rvert$	$\lvert\epsilon_4\rvert$	$\lvert\epsilon_5\rvert$
A	$1.6 \cdot 10^{-8}$	$9.5 \cdot 10^{-11}$	$1.2 \cdot 10^{-9}$	$7.3 \cdot 10^{-10}$	$7.9 \cdot 10^{-10}$	$7.1 \cdot 10^{-9}$

- As expected, an order of magnitude better that those based on the H-M limit.

Scenario B

B: *Consistent positive signal*

- Positive $0\nu\beta\beta$ rate consistent with positive signals from KATRIN and Planck. $0\nu\beta\beta$ could be attributed to the light ν-exchange.
- However, new physics could still contribute to $0\nu\beta\beta$, but only within the experimental error ($\simeq 23$ %).
- Choose lightest neutrino mass $m = 0.3$ eV, $T_{1/2}^{\text{obs}} = 5.0 \cdot 10^{25}$ years.
- Only few operators can interfere with ν-exchange $\Rightarrow$ neglect interferences.

	$\lvert\epsilon_1\rvert$	$\lvert\epsilon_2\rvert$	$\lvert\epsilon_3^{LLz,RRz}\rvert$	$\lvert\epsilon_3^{LRz,RLz}\rvert$	$\lvert\epsilon_4\rvert$	$\lvert\epsilon_5\rvert$
A	$1.6 \cdot 10^{-8}$	$9.5 \cdot 10^{-11}$	$1.2 \cdot 10^{-9}$	$7.3 \cdot 10^{-10}$	$7.9 \cdot 10^{-10}$	$7.1 \cdot 10^{-9}$
B	$5.8 \cdot 10^{-8}$	$3.5 \cdot 10^{-10}$	$4.5 \cdot 10^{-9}$	$2.7 \cdot 10^{-9}$	$2.9 \cdot 10^{-9}$	$2.6 \cdot 10^{-8}$

Scenario B

B: *Consistent positive signal*

- Positive $0\nu\beta\beta$ rate consistent with positive signals from KATRIN and Planck. $0\nu\beta\beta$ could be attributed to the light ν-exchange.
- However, new physics could still contribute to $0\nu\beta\beta$, but only within the experimental error ($\simeq 23$ %).
- Choose lightest neutrino mass $m = 0.3$ eV, $T_{1/2}^{\text{obs}} = 5.0 \cdot 10^{25}$ years.
- Only few operators can interfere with ν-exchange $\Rightarrow$ neglect interferences.

	$\lvert\epsilon_1\rvert$	$\lvert\epsilon_2\rvert$	$\lvert\epsilon_3^{LLz,RRz}\rvert$	$\lvert\epsilon_3^{LRz,RLz}\rvert$	$\lvert\epsilon_4\rvert$	$\lvert\epsilon_5\rvert$
A	$1.6 \cdot 10^{-8}$	$9.5 \cdot 10^{-11}$	$1.2 \cdot 10^{-9}$	$7.3 \cdot 10^{-10}$	$7.9 \cdot 10^{-10}$	$7.1 \cdot 10^{-9}$
B	$5.8 \cdot 10^{-8}$	$3.5 \cdot 10^{-10}$	$4.5 \cdot 10^{-9}$	$2.7 \cdot 10^{-9}$	$2.9 \cdot 10^{-9}$	$2.6 \cdot 10^{-8}$

- In those few cases where interferences occur, they are expected to dominate (unless the relative phase ϕ is very close to $\pi/2$).

	$\lvert\epsilon_1^{xyR} \cos\phi_1\rvert$	$\lvert\epsilon_2^{xyR} \cos\phi_2\rvert$	$\lvert\epsilon_3^{LLR,RRR} \cos\phi_3\rvert$	$\lvert\epsilon_3^{LRR,RLR} \cos\phi_3\rvert$
B (interf.)	$1.4 \cdot 10^{-8}$	$8.4 \cdot 10^{-11}$	$1.1 \cdot 10^{-9}$	$6.5 \cdot 10^{-10}$

Scenario C

C: *Inconsistent positive signal*

- A high rate of $0\nu\beta\beta$, inconsistent with negative signals in KATRIN and Planck, $T_{1/2}^{\rm obs} = 1.3 \cdot 10^{27}$ years
- ν-exchange can only contribute a small part of the $0\nu\beta\beta$ rate.
- The rest of the rate is the attributed to the new physics, giving non-zero estimates.

C	$\lvert\epsilon_1\rvert$	$\lvert\epsilon_2\rvert$	$\lvert\epsilon_3^{LLz,RRz}\rvert$	$\lvert\epsilon_3^{LRz,RLz}\rvert$	$\lvert\epsilon_4\rvert$	$\lvert\epsilon_5\rvert$
Estimate	$2.3 \cdot 10^{-8}$	$1.4 \cdot 10^{-10}$	$1.8 \cdot 10^{-9}$	$1.1 \cdot 10^{-9}$	$1.2 \cdot 10^{-9}$	$1.1 \cdot 10^{-8}$

Summary and conclusions

- Future bounds on the strength of different short-range contributions to $0\nu\beta\beta$ depend on the outcome of ongoing and planned experiments related to neutrino masses.
- For some scenarios, bounds on the coefficients ϵ_i of each effective operator can be determined.
- In some cases one can obtain non-zero estimates.
- More accurate calculations of NMEs will improve the robustness of the results.
- J. Bergström, A. Merle, and T. Ohlsson
Constraining new physics with a positive or negative signal of neutrino-less double beta decay
Journal of High Energy Physics **05**, 122 (2011), arXiv:1103.3015

Thanks for listening!

Questions?