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A Look at General Neutrino Interactions with KATRIN

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Neutrino physics harbours a number of unanswered questions, which can be addressed by searches for New Physics in precision experimental data. The theory of General Neutrino Interactions (GNI) offers for this purpose a model-independent approach for a broad search for New Physics. It is a generalisation of the already well-studied neutrino Non-Standard Interactions (NSI), taking into account all mathematically possible types of interactions. These novel interactions are embedded into higher dimensional Standard Model Effective Field Theory (SMEFT) operators, respecting Standard Model (SM) gauge symmetries. Experimentally, these can be investigated through a search for potential shape variations of the β-decay spectrum.

In this work we present the first proof-of-principle study searching for GNI at the Karlsruhe Tritium Neutrino (KATRIN) experiment. The main purpose of KATRIN is to measure the neutrino mass by precision spectroscopy of the tritium β-decay with target sensitivity of 0.2 eV. Recently, KATRIN has improved the upper bound on the effective electron-neutrino mass to 0.8 eV at 90 % confidence level [1]. This high-precision measurement enables to identify potential spectral modifications such as those caused by GNI by means of energy-dependent contributions to the event rate in KATRIN. The presented studies use simulated data reflecting the measurement conditions of the second KATRIN measurement campaign in 2019, using an energy window down to 40 eV below the end point of molecular tritium at 18.57 keV. Furthermore, the analysis framework is based on [4], taking into account the existence of a right-handed neutrino.

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1. The Theory of General Neutrino Interactions

The theory of General Neutrino Interactions (GNI) extends the theoretical framework of the well-studied neutrino Non-Standard Interactions (NSI). Here, not only additional vector, but also scalar, pseudoscalar, axial and tensor-like interactions between neutrinos and fermions are being considered. These novel interactions could contribute to the weak interaction as described by the charged-current Lagrangian [3]

$$\mathcal{L}_{\mathrm{GNI}}^{\mathrm{CC}} = -\frac{G_{\mathrm{F}} V_{\gamma\delta}}{\sqrt{2}} \sum_{j=1}^{10} \left(\overset{(\sim)}{\epsilon}_{j,\mathrm{ud}} \right)^{\alpha\beta\gamma\delta} \left(\bar{e}_\alpha O_j \nu_\beta \right) \left(\bar{u}_\gamma O'_j d_\delta \right) + h.c, \tag{1}$$

where the novel interactions $O^{(\prime)}$ connect the interacting particles. ϵ_j are the field strength tensors and therefore encode the strength of the novel interaction j in units of the SM Fermi interaction. Similarly, one can also write down the neutral-current Lagrangian for the GNI. To embed the low-energy GNI theory into a more fundamental theory, the GNI terms are matched to dimension 6 operators of the Effective Field Theory of the SM (SMEFT) with the possible extension by a right-handed neutrino (SMNEFT). This is based on the assumption, that the GNI arise from heavy New Physics above the weak scale. This allows New Physics to be explored in a comprehensive and model-independent way using precision measurements. Possible interaction channels for the search for GNI are Neutrino oscillation, Lepton Flavor Violating (LFV) processes in μ- and τ-decays, neutrino scattering such as CEνNS, π- and β-decay. Searches using different interaction channels are complementary since each is sensitive to a different combination of ϵ_j in the GNI Lagrangians [3, 4]. This work focuses on the search for GNI via the β-decay in KATRIN.

2. The KATRIN Experiment

The KATRIN experiment consists of a 70 m long beam line that employs a molecular tritium source along with a high-resolution electrostatic filter with magnetic adiabatic collimation filtering the tritium-decay electrons based on their energy [2]. With this setup the KATRIN collaboration aims at measuring the mass of the electron neutrino with a sensitivity of 0.2 eV at 90 % CL. Since a non-zero neutrino mass modifies the spectral shape close to the endpoint the analysis is based on a shape-only fit of the 40 eV energy interval below the tritium end point at 18.57 keV. Thanks to its high-precision measurement KATRIN has improved the upper bound on the effective electron-neutrino mass to 0.8 eV at 90 % CL [1].

3. Search for General Neutrino Interactions with KATRIN

Similar to the neutrino mass analysis also the GNI analysis is based on the search for characteristic spectral distortions. For the spectrum model used for direct kinematic measurements of the β-decay such as in KATRIN, these spectral distortions are described by an energy-dependent GNI term extending the total differential decay rate [4]

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} \propto \sum_{k=\beta,\mathrm{N}} \sqrt{(E_0 - E)^2 - m_k^2} \boxed{\xi_k \left[1 - b'_k \frac{m_k}{E_0 - E} \right]} \Theta(E_0 - m_k - E). \tag{2}$$

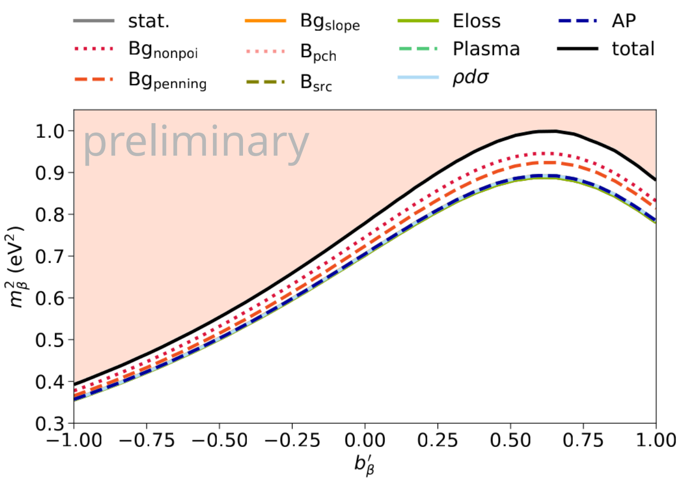

Figure 1: GNI sensitivity contour considering only a left-handed neutrino at 95 % CL, taking into account different systematic effects. The study was performed on simulated data of the KNM2 campaign.

The index β refers to the left-handed neutrino. When including a right-handed neutrino (N) the GNI term appears twice. Furthermore, the approximation $m_e \gg E$ is used. The dimensionless GNI coefficients ξ_k and b'_k are defined in terms of factors ϵ_j, U_{e4} and nuclear form factors g_V, g_S, g_T, and g_A. Setting $\xi_\mathrm{N} = b'_k = 0$ recovers the SM. For the sensitivity studies there are two scenarios to be considered: One with only a left-handed neutrino and one additionally including a right-handed neutrino. The studies for both cases have been performed on simulated data of the second KATRIN measurement campaign (KNM2). The sensitivity contour for only considering a left-handed neutrino is shown in figure 1. As expected from the neutrino mass analysis, large m_β^2 values are excluded and the ordering of the systematic effects agrees between the analyses. Despite the mild correlation found between the GNI parameter b'_β and the neutrino mass observable m_β^2 it is possible to probe more specific GNI scenarios, as listed at the end of this section. Since the sensitivity of the contour is dominated by statistics improvement is expected when extending the data set. For the case with a right-handed neutrino the sensitivity contours can be viewed in figure 2. The contour for $b'_\mathrm{N} = 0$ can be transformed into the parameter space of the light sterile neutrino analysis by using $\xi_\mathrm{N} = \tan^2\theta \cdot (g_\mathrm{A}^2 + 3g_\mathrm{V}^2)$. This was used for a cross-check between the two independent analyses, confirming the proper implementation of the GNI model and according behaviour of the systematic effects. The contours for all b'_N exclude large ξ_N. The difference in sensitivity stems from the b'_N term enhancing or diminishing the signal structure of the right-handed neutrino. Beyond that, one can probe more specific GNI scenarios by considering interactions individually. Here, the tensor-like interaction gives the strongest constraints at $\mathcal{O}(10^{-2})$. Constraints for similar parameters from other experiments as for example the LHC [6] and neutron decay [5] reach up to $\mathcal{O}(10^{-3})$. As for the previous GNI study, an improvement in sensitivity is expected when adding more data. Additionally, specific physics cases can be studied, such as a right-handed W-boson, different Leptoquark models, and a charged higgs by only looking at their specific ways of interaction.

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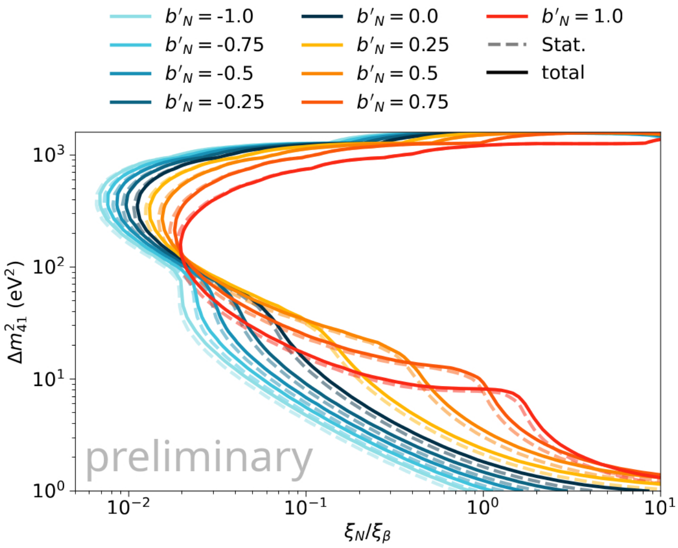

Figure 2: GNI sensitivity contour considering an additional right-handed neutrino at 95 % CL, taking into account systematic effects. The study was performed on simulated data of the KNM2 campaign.

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