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Search for new light bosons with the KATRIN experiment

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The Karlsruhe Tritium Neutrino (KATRIN) experiment is designed to measure the effective electron antineutrino mass with a sensitivity better than $m_\nu < 0.3\,\mathrm{eV}$ (90 % CL) using precision electron spectroscopy of tritium β-decay. This determination occurs in the spectral endpoint (E_0) region, up to some 10 eV below $E_0 \approx 18.6\,\mathrm{keV}$.

Light neutral pseudoscalars and vector bosons arise in many theories beyond the Standard Model (BSM). High-statistics β-spectroscopy with KATRIN is a complementary probe for these new physics theories regarding coupling strengths of bosons to neutrinos or electrons.

We consider different scenarios of the emission of additional bosons with characteristic signatures in the shape of the β-spectrum, described in JHEP 01 (2019) 206. We present the sensitivity estimates of the second measurement campaign (4×10^6 electrons in the analysis range of $[-40, +130]$ eV around E_0) to such light boson couplings.

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1. Emission of additional light bosons in tritium β-decay

New light pseudoscalar or vector bosons X are arising in many theories beyond the Standard Model (BSM) and can couple to electrons or neutrinos, e.g., through the interaction terms (ref. [1])

$$\mathrm{i}g_X\bar{\nu}_e\gamma^5\nu_e X,\ \mathrm{i}g_X\bar{e}\gamma^5 eX,\quad \text{or}\quad g_X\bar{\nu}_e\gamma^\mu P_\mathrm{L}\nu_e X_\mu,\ g_X\bar{e}\gamma^\mu eX_\mu,\ g_X j^\mu_{L_e}X_\mu, \tag{1}$$

where $j^\mu_{L_e} = \bar{\nu}_e\gamma^\mu P_\mathrm{L}\nu_e + \bar{e}\gamma^\mu e$ is the electronic lepton number current and g_X is the coupling constant. The energy of 18.6 keV released in tritium β-decay [2] enables emission of additional light particles. Using eq. (1), the electron energy spectrum is derived in [1], where it is parameterized as

$$\frac{\mathrm{d}\Gamma_X}{\mathrm{d}E} = g_X^2\,\mathcal{K}(m_X)\sqrt{\frac{E}{m_e}}\left(\frac{(E_0-(m_\nu+m_X))-E}{(E_0-(m_\nu+m_X))+m_e}\right)^{n(m_X)}\times F(Z+1,E). \tag{2}$$

Here, $E = E_e - m_e$ is the kinetic electron energy, m_ν (m_X) the neutrino (boson) mass, $E_0 \approx 18.6\,\mathrm{keV}$ is the usual kinematic endpoint of the decay ($m_\nu, m_X \to 0$), and $F(Z+1,E)$ the modified Fermi function, accounting for the Coulomb interaction between daughter nucleus and electron. Normalization $\mathcal{K}$ and spectral index n differ between the scenarios in eq. (1) and depend on the boson mass. The functions $\mathcal{K}(m_X)$ and $n(m_X)$ are computed in [1]. The full differential spectrum $\mathrm{d}\Gamma/\mathrm{d}E$ is modified by this additional decay channel. It becomes $\mathrm{d}\Gamma/\mathrm{d}E = \mathrm{d}\Gamma_\beta/\mathrm{d}E + \mathrm{d}\Gamma_X/\mathrm{d}E \geq \mathrm{d}\Gamma_\beta/\mathrm{d}E$, where $\mathrm{d}\Gamma_\beta$ is the well-known SM rate [2].

2. The KATRIN experiment

The Karlsruhe Tritium Neutrino (KATRIN) experiment is designed to measure the effective electron antineutrino mass m_ν using electron spectroscopy of tritium β-decay.
A relative spectroscopic precision on the level of 10^{-4} is achieved by magnetic adiabatic collimation in combination with an electrostatic (MAC-E) filter: β-electrons from the tritium source are adiabatically guided along the 70 m long setup onto the detector, while low-energy electrons are filtered out by varying the threshold of the MAC-E filter. The measurement is highly sensitive to spectral distortions in the endpoint region. KATRIN recently improved the upper limit on the neutrino mass to $m_\nu < 0.45\,\mathrm{eV}$ (90 % CL) [3]. The high-statistics and high-precision measurement of the spectrum allows to probe different scenarios of BSM bosons emission as described in sec. 1.

3. Analysis procedure and results

The analysis in this work is based on the dataset of the second measurement campaign of KATRIN [2], featuring 4×10^6 electrons in the analysis interval of $[-40,+130]$ eV around E_0. The light boson sensitivity is estimated using an unfluctuated (Asimov) copy of the data and comparing the SM case to an alternative hypothesis with admixture of a spectral branch with the boson emission in eq. (2). Systematic effects of the experimental setup are included as nuisance parameters in the likelihood estimation.
Figure 1 shows the resulting total sensitivity to the considered light BSM boson couplings g_X at 95 % CL over a mass range of $1\,\mathrm{meV} \leq m_X \leq 40\,\mathrm{eV}$. We find a loss of sensitivity towards large masses where no data points are present. The longitudinal component of the emitted vector for coupling to neutrino or electron gives rise to an m_X^{-2} divergence in the rate, which is mostly compensated for the coupling to j_{L_e}.
A breakdown of the individual systematic contributions to the overall sensitivity for four representative mass values m_X is achieved by variation of the corresponding nuisance parameters, while keeping the remaining systematics fixed. The 1σ (68.27 % CL) uncertainty due to the systematic effect i is estimated by $\sigma^2_{g_X,i} = \sigma^2_{g_X}(\text{stat.} + i) - \sigma^2_{g_X}(\text{stat.})$. In fig. 2, this breakdown is shown for the exclusive neutrino coupling scenarios in eq. (1). The remaining scenarios are not displayed, yet behaving similarly. The statistical uncertainty dominates over systematic effects. Source-related effects gain relevance for large masses $\mathcal{O}(10)$ eV, while they are in general leading over the background in fig. 2b. For details on the

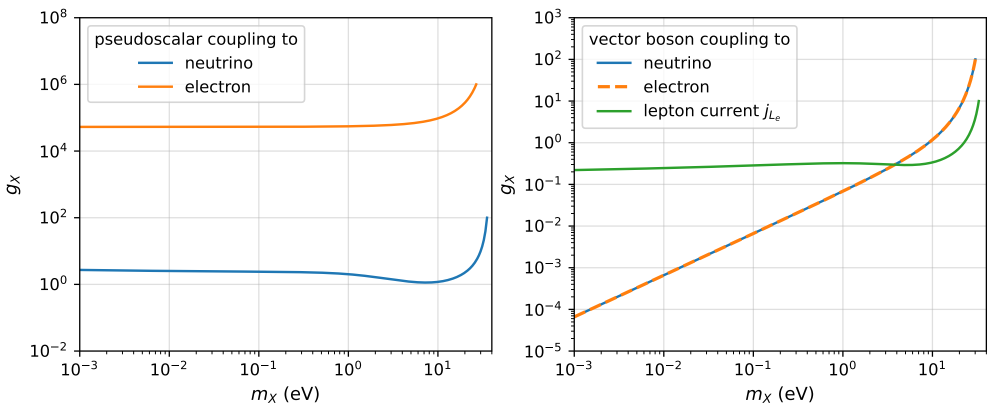
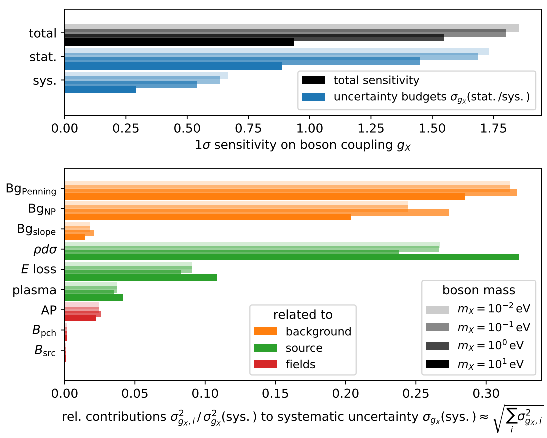
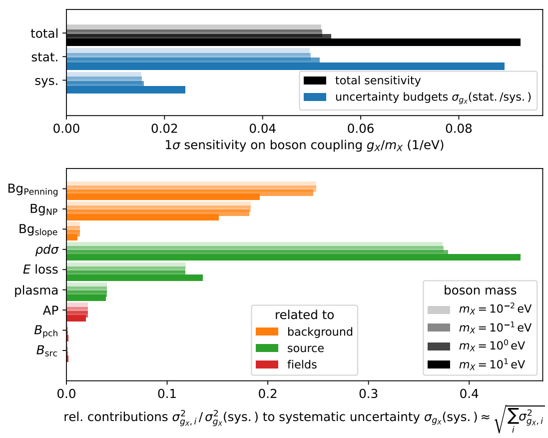


Figure 1: Sensitivity to light boson couplings g_X (95 % CL) in the scenarios from eq. (1).



(a) pseudoscalar - neutrino



(b) vector boson - neutrino

Figure 2: Breakdown of the individual 1σ contributions to the light boson coupling g_X sensitivities in fig. 1. Both scenarios with emission of a pseudoscalar (a) or vector (b) off the neutrino (ref. eq. (1)) are shown.

systematic effects, the reader should refer to [2, 3].

As the uncertainties are statistics-dominated, one expects a significant improvement of sensitivity to the new light bosons with more data taken by KATRIN. Such complementary laboratory probe provided by KATRIN offers a direct access to the BSM physics at the low energy scale as opposed to the other, high-energy range probes.

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