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Analysis strategies and treatment of systematic effects in the KATRIN experiment

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Abstract. The **Ka**rlsruhe **Tri**tium **N**eutrino (KATRIN) experiment aims to search for the effective electron antineutrino mass with a sensitivity of $0.2\,\mathrm{eV/c^2}$ (90 % C.L.) from the shape of the tritium β-decay electron energy spectrum. The first measurement campaign in KATRIN dedicated to the neutrino mass took place in spring 2019 with about 22 % of the nominal tritium activity. The goal of this pilot measurement was to reach a sensitivity competitive with past results while establishing a robust bias-free analysis and good initial understanding of systematic effects. Several different analysis techniques were developed independently and cross-checked on a set of fake Monte Carlo prior to real spectra. In this paper, I present an overview of the KATRIN analysis strategies and discuss their applications on the tritium spectra. The treatment of systematic effects is also discussed in detail. I conclude with a short outlook for the future neutrino mass measurement campaigns with KATRIN.

1. Introduction

The absolute mass scale of neutrinos, inaccessible in neutrino flavor oscillation experiments, is of principal importance in cosmology [1] and particle physics [2]. The KATRIN experiment [3, 4], situated in Karlsruhe, Germany, aims to address the absolute neutrino mass scale by a direct kinematic measurement of tritium β-decay. The signature of non-zero neutrino mass is a shape distortion of the continuous energy spectrum of β-electrons close to the kinematic endpoint. As the experimental resolution does not allow to distinguish different neutrino mass eigenvalues m_i, an effective electron antineutrino mass m_ν is observed as the incoherent sum

$$m_\nu^2 = \sum_i |U_{ei}|^2 \, m_i^2, \tag{1}$$

where U_{ei} are the relevant neutrino mixing matrix elements.

In tritium β-decay, only about 10^{-9} of all β-electrons have an energy close to the endpoint and are thus suitable for neutrino mass analysis. Therefore, KATRIN uses a high-luminosity windowless source of gaseous molecular tritium [5], which provides a gas column density of up to $5 \cdot 10^{17}$ molecules per cm^2 corresponding to a tritium activity of $10^{11}\,\mathrm{Bq}$. Besides, an electrostatic spectrometer of a MAC-E filter type [6, 7] is employed providing $\approx 0.37 \cdot 2\pi$ solid angle coverage. The existing laboratory limits suggest that the neutrino mass m_ν is smaller than about 2 eV [8, 9] (using $c = 1$). Thus, high energy resolution at the eV level is required and ensured by the MAC-E filter principle.

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1.1. First neutrino mass campaign

In the pilot neutrino mass measurement with the KATRIN apparatus, which took place in spring 2019, the hardware functionality of the entire beamline could be demonstrated for the first time with larger amounts of tritium. The experimental configuration in this "burn-in" phase were characterized by a lower gas density of about 22 % compared to the nominal value and an energy resolution of about 2.8 eV. In the four weeks dedicated to the measurement, about two million electrons in the neutrino mass sensitivity region of the β-spectrum were collected. Statistically, such an amount corresponds to only about five days of the nominal KATRIN measurement, yet it is rich enough to improve the existing laboratory limits on the neutrino mass. The recorded experimental information is thus an excellent dataset for development and applications of neutrino mass analysis methods.

2. Neutrino mass inference

2.1. KATRIN observable

The KATRIN experimental spectrum is given by two main ingredients. Firstly, Fermi theory describes the differential decay rate $R_\beta(E)$ of the molecular tritium as a function of electron energy E. Secondly, at a given retarding potential U the MAC-E filter principle yields the experimental response function $f_{\mathrm{calc}}(qU, E)$, where $q < 0$ is the electron's charge. Owing to the high-pass feature of the MAC-E filter, the differential rate is integrated over the response function to yield the observed integral spectrum rate $R_{\mathrm{calc}}(qU)$,

$$R_{\mathrm{calc}}(qU; \boldsymbol{\theta}) = A_{\mathrm{S}} \cdot N_{\mathrm{T}} \int_{qU}^{E_{0,\mathrm{eff}}} R_\beta(E;\, m_\nu^2, E_{0,\mathrm{eff}}) \cdot f_{\mathrm{calc}}(qU, E)\, \mathrm{d}E + R_{\mathrm{bg}}, \tag{2}$$

where N_{T} stands for pre-calculated expected total rate which depends on the amount of tritium, the accepted solid angle of the apparatus and detector efficiency. The symbol $\boldsymbol{\theta}$ denotes a list of free parameters that are inferred from the experimental spectrum: the neutrino mass squared m_ν^2, the effective endpoint $E_{0,\mathrm{eff}}$, the signal amplitude (normalization) A_{S}, and the constant background rate R_{bg}. Note that it is the square of the neutrino mass which is the observable in β-decay neutrino mass experiments. A typical spectrum fit obtained by maximum likelihood estimation is shown in Fig. 1a.

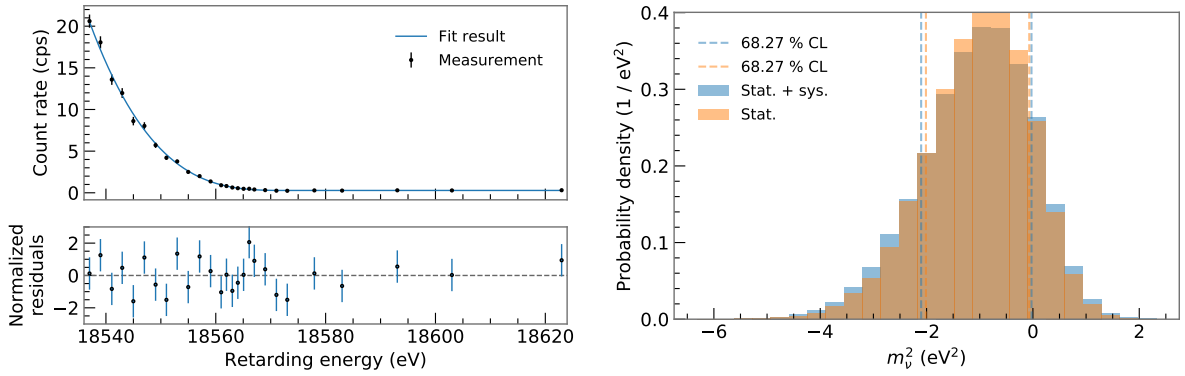
2.2. Analysis strategy

To ensure robust and bias-free result of the first KATRIN neutrino mass measurement, the analysis was approached from three perspectives.

Firstly, the inference procedures and treatment of systematic effects were frozen before applying them on real data. This was achieved by means of a set of artificial β-spectra that were computed using the KATRIN integral spectrum model initialized with the actual slow control readings of the apparatus. Thus, for each real scan a "twin" spectrum was obtained on which the inference could be tested.

Secondly, the real data was initially analysed using a "blinded" model of the β-spectrum with the intention of hiding the true inferred value of the neutrino mass. The blinding was achieved by using a modified distribution of tritium molecular final states that affects the shape of the differential spectrum. In such a way, only the neutrino mass was hidden while the other free parameters were not affected.

Lastly, two independent approaches to assess, include, and propagate systematic uncertainties were applied. This step ensured reproducibility of the final result among different analysis teams and provided an important cross-check. One approach is based on the method of covariance matrices, described in detail by L. Schlütter and T. Lasserre in a different paper in these proceedings. The other approach is based on Monte Carlo propagation of uncertainties, described in detail in the following.



(a) (b)

Figure 1: (a) Typical spectrum fit of an integral β-spectrum scan (stepping of the retarding energy qU) corresponding to about 2 h of measurement live time. The fit residuals are normalized to the statistical uncertainty. (b) Distributions of 50 000 samples of m_ν^2 from Monte Carlo propagation on real data, statistics only and statistics together with systematics. The vertical dashed lines denote the 1-σ confidence intervals.

3. Monte Carlo propagation of uncertainty

In principle, the input parameters $\boldsymbol{\eta}$, the uncertainties of which contribute to the systematic budget, could be treated as additional free parameters constrained by pull terms in the maximum likelihood estimation. However, having too many free parameters does not seem technically feasible. Furthermore, varying $\boldsymbol{\eta}$ leads to expensive re-computing of the entire response function in each step of the numerical optimization. Instead, we adopt propagation of systematic uncertainty by minimizing the negative log-likelihood function many times with randomized but fixed values of the input parameters $\boldsymbol{\eta}$ [10, 11, 12, 13].

In the first step, we keep $\boldsymbol{\eta}$ fixed at the values $\hat{\boldsymbol{\eta}}_{\text{in}}$ that are best to our knowledge but sample the statistical uncertainty. Monte Carlo (MC) integral spectra are generated assuming a Poisson distribution of the spectrum counts and the best-fit parameter values $\hat{\boldsymbol{\theta}}_{\text{data}}$ that were obtained by fitting the original data. A fit of each such MC spectrum in turn yields the estimates $\hat{\boldsymbol{\theta}}_{\text{sample}}$. Distribution of the set of all estimates $\{\hat{\boldsymbol{\theta}}_{\text{sample}}\}$ then provides the statistical uncertainty of $\boldsymbol{\theta}$.

In the second step, we allow the input parameters $\boldsymbol{\eta}$ to vary within their respective uncertainties, i.e. the model itself is randomized by initializing it with randomized values $\boldsymbol{\eta}_{\text{sample}}$. The same original spectrum is fitted in each trial, i.e. no statistical randomization is performed, yielding $\hat{\boldsymbol{\theta}}_{\text{sample}}$. We could proceed as above and use the distribution of $\{\hat{\boldsymbol{\theta}}_{\text{sample}}\}$ to obtain the systematic uncertainty. In such a way, we would only take into account the external information on the input parameters $\boldsymbol{\eta}$ that we have put in. However, the original data itself contains some information on $\boldsymbol{\eta}$, although often the external information constrains the parameters $\boldsymbol{\eta}$ much more strongly than the data. We thus modify the distribution of $\{\hat{\boldsymbol{\theta}}_{\text{sample}}\}$ by weighting each sample $\hat{\boldsymbol{\theta}}_{\text{sample}}$ with the corresponding likelihood value $\mathcal{L}(\hat{\boldsymbol{\theta}}_{\text{sample}})$.

In the last step, the statistics-only and systematics-only steps described above are combined. The model randomized with $\boldsymbol{\eta}_{\text{sample}}$, as in the second step, is used to fit MC spectra that are themselves statistically randomized, as in the first step. The fit yields $\hat{\boldsymbol{\theta}}_{\text{sample}}$ and we utilize the likelihood values $\mathcal{L}(\hat{\boldsymbol{\theta}}_{\text{sample}})$, that come from the fit of the original data in addition to the fit of the MC data, to obtain the sample distribution. This distribution then provides the combined statistical and systematic uncertainty.

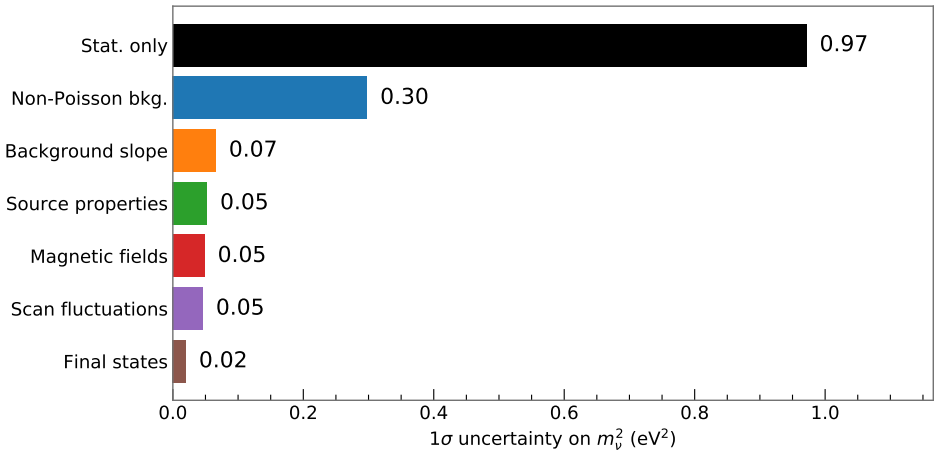


Figure 2: Uncertainty budget of the first neutrino mass campaign at the KATRIN experiment obtained with the method of Monte Carlo propagation of uncertainty.

4. Uncertainty budget

We present here the application of the Monte Carlo propagation method on the data obtained in the first KATRIN neutrino mass measurement [14]. The histogram of neutrino mass squared values obtained for statistics only and statistics combined with systematics is shown in Fig. 1b. Furthermore, the breakdown of the total uncertainty into the individual contributions is shown in Fig. 2. The total uncertainty budget is dominated by the statistical uncertainty of $0.97\,\mathrm{eV}^2$ as compared to the systematic uncertainty of $0.32\,\mathrm{eV}^2$.

5. Conclusion

A successful first physics measurement of the effective electron antineutrino mass was carried out at the KATRIN experiment. The campaign showed preparation of the apparatus for high-resolution electron spectroscopy of tritium β-electrons and allowed for development of independent analysis methods ensuring robust and bias-free initial result. The Monte Carlo propagation of uncertainty, described in this contribution, proved to be a useful technique complementary to the method of covariance matrices. It is foreseen as a promising tool for future measurements with higher sensitivity to the neutrino mass.

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