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Status of the KATRIN Experiment and prospects to search for keV-mass sterile neutrinos in tritium β-decay

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Abstract

In this contribution the current status and future perspectives of the Karlsruhe Tritium Neutrino (KATRIN) Experiment are presented. The prime goal of this single β-decay experiment is to probe the absolute neutrino mass scale with a sensitivity of 200 meV (90% CL). We discuss first results of the recent main spectrometer commissioning measurements, successfully verifying the spectrometer's basic vacuum, transmission and background properties. We also discuss the prospects of making use of the KATRIN tritium source, to search for sterile neutrinos in the multi-keV mass range constituting a classical candidate for Warm Dark Matter. Due to the very high source luminosity, a statistical sensitivity down to active-sterile mixing angles of $\sin^2\theta < 1 \cdot 10^{-7}$ (90% CL) could be reached.

Keywords: Neutrino mass, Sterile Neutrinos, Warm Dark Matter, Low Energy Physics, Low Background, Tritium beta decay, MAC-E Filter

1. Introduction

The knowledge of the absolute neutrino mass scale is an extremely important input parameter both for cosmological models and for the fundamental understanding of the nature of particle masses. A measurement of the absolute mass scale would distinguish between the so-called hierarchical mass scenario, corresponding to a very light neutrino mass scale, where the neutrino mass eigenstates are well separated, and the degenerate regime, corresponding to a heavier mass scale, where their mass differences can be neglected. This information would shed light on the neutrino mass generation mechanism. If the degenerate regime is realized in nature, neutrinos would have a large impact on the structure formation of the early universe. The neutrino mass would then be an important input parameter for cosmological simulations. So far, only a lower limit of 0.05 eV [1, 2, 3], provided by neutrino oscillation experiments, and an upper bound of 2 eV [4, 5] from direct neutrino mass experiments is limiting the parameter range.

Three fundamental techniques are currently explored to probe the neutrino mass: cosmological studies of the formation and evolution of large-scale structures (LSS), the search for neutrinoless double β-decay ($0\nu\beta\beta$), and the investigation of single β-decay. The advantage of the latter is that it is solely based on the well understood kinematics of the decay, making it basically model independent. Its challenge is its scalability in order to reach to mass sensitivities in the meV range. KATRIN is perusing a spectrometer-based technique to measure the endpoint region of the tritium β-decay spectrum and is thereby pushing the current technological limits.

In section 2 the basic working principle of KATRIN will be explained and the main components will be introduced. Section 3 focuses on the recent main spectrometer commissioning measurements, investigating its vacuum, transmission and background properties. Finally, in section 4 an investigation on the sensitivity of a future KATRIN-like experiment in the search for sterile neutrinos in the keV mass range will be presented.

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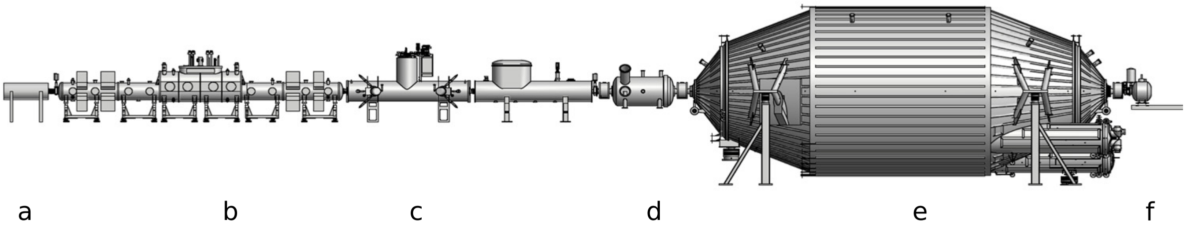

Figure 1. Main components of the KATRIN experimental setup. a: rear section, b: windowless gaseous tritium source, c: differential and cryogenic pumping section, d: prespectrometer, e: main spectrometer, f: focal plane detector.

2. The KATRIN Experiment

The KATRIN experiment is a next generation, large-scale, tritium β-decay experiment currently under construction at the Karlsruhe Institute of Technology (KIT); it will prospectively start taking data in 2016. KATRIN is designed to measure the effective electron anti-neutrino mass $m_{\overline{\nu}_e}$, defined as

$$m_{\overline{\nu}_e} = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}, \tag{1}$$

where U_{ei} denote the Pontecorvo-Maki-Nakagawa-Sakata leptonic mixing matrix elements and m_i are the neutrino mass eigenstates. The design sensitivity of KATRIN is 200 meV at 90% confidence level [6, 7] for 3 full beam years of measurement time.

The experiment will use a model-independent technique based on the kinematics of tritium β-decay. It will analyze the shape of the electron energy spectrum in a narrow region close to the tritium decay endpoint at $E_0 = 18.6$ keV. A non-zero neutrino mass reduces the maximum energy of the electron and changes the shape of the tritium β-spectrum in the immediate vicinity of the endpoint. To reach the neutrino mass sensitivity, several criteria including high energy resolution, high signal count rates and low background must be fulfilled.

The 70 m long KATRIN setup (see figure 1) combines a windowless gaseous tritium source (WGTS) of high stability and luminosity with a large electrostatic retarding spectrometer with an energy resolution of < 1 eV [6, 7, 8]. A magnetic guidance system adiabatically transports the electrons created in the molecular tritium source towards the spectrometer where the energy analysis takes place. The spectrometer, working as an electrostatic filter, transmits only those electrons which have sufficient energy to overcome the retarding potential. The transmitted electrons are then counted at a focal plane detector [9]. By measuring the count rate for different filter voltages, the shape of the integrated energy spectrum can be determined.

Since the spectrometer section must be essentially tritium-free to limit the background to a low level, the tritium flow is reduced by 14 orders of magnitude from the WGTS to the spectrometer section. This large suppression factor will be achieved by a combination of a system of differential pumping and cryo traps [10, 11].

From the electron creation in the WGTS until the energy analysis in the central analyzing plane of the main spectrometer, the magnetic field drops by four orders of magnitude, in order to parallelize the electron momenta via the magnetic gradient force. This combination of Magnetic Adiabatic Collimation with Electrostatic filter, called the MAC-E filter principle, allows for large solid angle acceptance, combined with high energy resolution [12, 13].

3. Main spectrometer commissioning measurements

In 2013 the first main spectrometer commissioning measurements took place. The major goal of these measurements was to to investigate the properties of the main spectrometer with respect to vacuum, transmission of electrons, and background.

In this section the major components of the main spectrometer, designed to achieve these goals will be presented. Secondly, initial results of transmission measurements and background investigations will be presented.

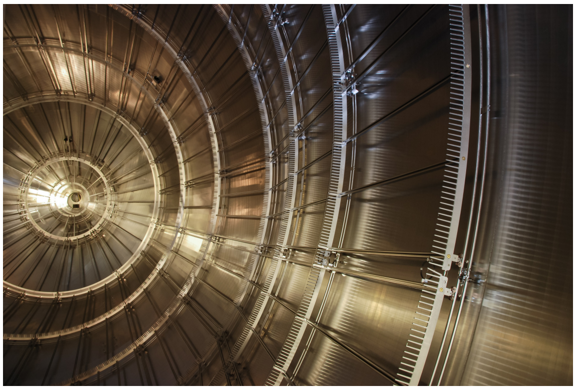

Figure 2. Left: The Air coil system consists of 3 sets of current loops distributed over a cylidrical surface around the main spectrometer. The 2 sets of axial loops compensate the 2 components of the earth magnetic field which are orthogonal to the spectrometer axis. The set of axial loops provide an axisymmtric correction field, which allows for precise adjusting of the magnetic field gradients and provides a magnetic field that prevents background electrons from penetrating the sensitive volume of the spectrometer. Right: The inner electrode system consists of more than 24 000 wires of a diameter of 300 μm (outer layer) and 200 μm (inner layer) at a distance of 15 cm (outer layer) and 22 cm (inner layer) to the surface of the main spectrometer tank. It serves as additional electric shielding against background electrons emitted from the tank wall as well as electric potential defining element.

Important main spectrometer components

To achieve a pressure in the UHV regime of 10^{-11} mbar the main spectrometer is equipped with six cascaded Turbo Molecular Pumps (TMPs) connected to the main spectrometer vessel in parallel, and three large getter pumps (NEG) with an overall pumping speed of 10^6 l/s for H_2 [14]. The entire spectrometer was slowly (1°/h) heated first to 200 C° to evaporate and remove water from the large spectrometer surface of 690 m^2, then the temperature was further increased to 300 C° to activate the getter material. After a 600 h long baking cycle a pressure of $p < 10^{-10}$ mbar could be reached [15].

To achieve the desired transmission and background properties, the main spectrometer is equipped with two important electromagnetic design components: A large air coil system [16] and a two layer inner wire electrode [17], see figure 2. The combination of these components provides the fine tuning of the magnetic and electric fields inside the spectrometer for adiabatic transport of the β-electrons and allows for magnetic and electric shielding against background due to electrons emitted from the inner surface of the spectrometer vessel. As KATRIN is not an underground experiment this background is mainly induced by cosmic muons hitting the large surface of the main spectrometer.

Transmission properties

The transmission properties were tested by using an angular selective electron gun (e-gun) installed at the entrance of the main spectrometer [18]. The e-gun electron rate was measured while successively lowering the retarding potential until full transmission of the electron beam. Figure 3 shows a very smooth and narrow transmission function, limited at present by the e-gun characteristics. The very good agreement between simulation and data proofs that the main spectrometer transmits electrons as expected. A detailed discussion of these measurements will be published in [15].

Background performance

The initial background rate, without any optimization, was measured to be ∼1 cps. This low rate is due to the careful electromagnetic design of all components, preventing the formation of even tiny penning traps, which can lead to background rates of up to 10^5 cps [19]. Furthermore, this result demonstrates the functionality of the magnetic shielding of cosmic muon induced background. Without electromagnetic shielding, an electron rate of ∼ 10^5 electrons per second is expected from the inner surface of the main spectrometer. However, the background suppression still needs to be improved in order to achieve the design value of 10^{-2} cps.

Detailed background analyses have revealed two major background sources contributing equally: muon-induced secondary electrons from the vessel walls, and radon decays inside the spectrometer volume. The latter has been

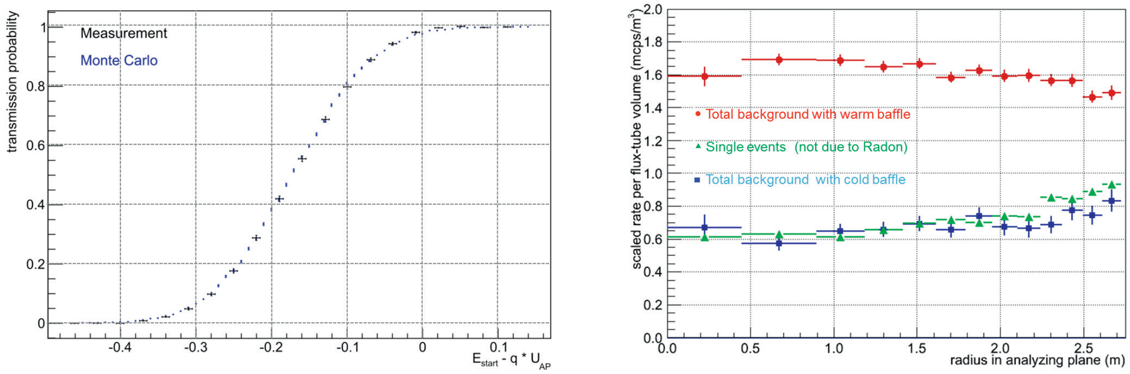

Figure 3. Left: Transmission probability of electrons from an e-gun as a function of the difference of starting energy and retarding potential (black crosses). This transmission function was measured at the center of the main spectrometer, and the e-gun was set to emit electrons with zero angle relative to the spectrometer axis. In this setting, the width of the function is dominated by the energy distribution of the e-gun. The Monte Carlo simulation (blue dots), where electron created with a Gaussian energy distribution are fully tracked through the spectrometer, is in very good agreement with the measurement. Right: Radial distribution of the total background rate (red circles). An off-line analysis of a dedicated measurement at high pressure, allowed to identify radon induced background and to eliminate it from the total background rate (green triangles). A measurement with a cooled baffle system results in a background level equivalent to the one without radon induced events (blue squares).

studied already in great detail in [20, 21, 22, 23]. With test experiments at the prespectrometer it was shown that a single radon decay in the sensitive volume of the spectrometer can lead to very high background rates. High-energy electrons, accompanying radon α-decays are magnetically stored in the spectrometer for time periods of up to hours. While cooling down by ionizing residual gas molecules, they may produce up to hundreds of secondary electrons. These low-energy secondary electrons eventually leave the spectrometer and give rise to large background rates.

To mitigate this background a number of different reduction techniques have been developed and successfully tested [24, 25, 26]. A very efficient passive reduction technique is based on liquid nitrogen cooled baffle system that traps radon atoms emanating from the getter pumps and the vessel surface outside of the active flux tube. A first measurement with a cooled baffle system shows the high efficiency of this technique: The background due to radon decays is reduced to an almost negligible level, see figure 3.

The remaining background is expected to be reduced to the desired level when making full use of the electric shielding with the wire electrode. In this initial commissioning phase, for technical reasons, only identical shielding potentials could be applied to both wire layers. Initial measurements with different shielding potentials point to a further background reduction by about two orders of magnitude, which would allow to reach the design goal in the next measurement phase. A detailed discussion on the background performance will be published in [15].

4. Sterile neutrino search in tritium β-decay

One way to generate neutrino masses is to add right-handed neutrinos to the Standard Model (SM), the so-called sterile neutrinos. This new species would not feel any of the SM interactions but it could mix with the active neutrinos. Relic sterile neutrinos in the keV range are ideal candidates for the so-called Warm Dark Matter. They are in agreement with cosmological observations on large scales, while at the same time they can explain mass distributions in the sub-galactic scale and thereby resolve the tensions in purely cold dark matter scenarios [27, 28, 29].

Although the KATRIN experiment is focused to measure the effective electron neutrino mass in a narrow region close to the endpoint, the unique properties of its gaseous tritium source would allow a high-sensitivity search for keV-mass sterile neutrinos. In the following we discuss first investigations of the physics potential of such a search.

Signature of a sterile neutrino in the tritium β-decay spectrum

In the super-allowed β-decay of tritium an electron (anti-)neutrino eigenstate is created, which is a superposition of different mass eigenstates. Consequently, the tritium spectrum is a superposition of spectra each corresponding to a single mass eigenstate. However, since the mass splittings between the three light mass eigenstates are so small, no current direct neutrino mass experiment can resolve it. Instead an "effective electron neutrino" mass, as defined in equation 1, is measured.

In case of a small admixture of a keV neutrino mass eigenstate to the electron neutrino flavor state, the four different mass eigenstates will no longer form one effective neutrino mass term. Instead, due to the large mass splitting, the spectrum $\frac{d\Gamma}{dE}$ will be a superposition of two spectra of very different shape: the β-decay spectrum corresponding to the light effective mass term $m_{\bar{\nu}_e}$ and the spectrum corresponding to the heavy mass eigenstate m_{heavy}. This can be expressed as

$$\frac{d\Gamma}{dE} = \cos^2(\theta)\frac{d\Gamma}{dE}(m_{\bar{\nu}_e}) \cdot \Theta(E_0 - E - m_{\bar{\nu}_e}) + \sin^2(\theta)\frac{d\Gamma}{dE}(m_{\text{heavy}}) \cdot \Theta(E_0 - E - m_{\text{heavy}}), \tag{2}$$

where E is the kinetic energy of the electron, $\sin^2(\theta)$ denotes the mixing of the heavy mass state to the electron neutrino flavor state and $E_0 = 18.6$ keV is the endpoint energy. Thus, a heavy sterile neutrino would manifest itself as a tiny kink away from the β-decay endpoint in the tritium spectrum, see figure 4.

Considering the fact that only 10^{-13} of all β-electrons are created with an energy in the last eV of the tritium spectrum, the KATRIN tritium source has been designed to provide a very high signal count rate to reach the desired light neutrino mass sensitivity. The source is implemented as a gaseous molecular tritium source of of high luminosity (10^{11} decays per second) and stability. Especially, these source properties are of prime importance when looking for sterile neutrinos in the eV [30, 31, 32] to multi-keV range. In the latter case, a shape measurement extending over the entire β-decay spectrum, would require extensive modifications of the present KATRIN set-up. In particular, it would entail the implementation of a very large detector array that would allow a differential energy measurement even for the high source luminosity of KATRIN.

Expected sensitivity

Figure 4 shows that from a purely statistical point of view a 3 years measurement with the KATRIN source strength can reach a sensitivity of a mixing angle down to $\sin^2\theta \sim 10^{-8}$, probing the cosmologically favored parameter space. In this investigation, both an integral and a differential mode are considered. The integral mode would make use of the main spectrometer to measure the integral flux of beta-particles passing the filter potential, whereas in the differential mode an energy-resolving detector system is assumed. To mitigate the requirements on the detector system with respect to high rates, and at the same time to reduce systematic effects due scattering of β-electrons in the tritium source, the source luminosity can be reduced, which of course lowers the sensitivity, correspondingly, see figure 4.

To asses the final sensitivity theoretical and experimental uncertainties need to be taken into account. In [33] the effect of theoretical uncertainties on the tritium spectrum was investigated with a spectral fit approach. Hereby, we implement the state-of-the-art description of the tritium spectrum, allowing for an uncertainty in the parameters describing the corrections to the tritium spectrum. These investigations show that smooth shape corrections do not mimic a kink with $\sin^2(\theta) > 10^{-7}$. However, a good parametrization of all corrections to the β-spectrum is necessary to perform a spectral fit.

An alternate approach, studied in [34], makes use of wavelet transformation in order to search for the local kink signature of a sterile neutrino in the keV mass range. It is demonstrated that the wavelet approach is largely insensitive to the exact shape of the tritium spectrum. Consequently, an exact knowledge of the spectral shape would not be required and spectral shape uncertainties would not reduce the sensitivity. To make full use of this powerful analysis technique, however, a high energy resolution (FWHM < 500 eV) is necessary in order not to wash out the local kink signature.

5. Conclusion

KATRIN is designed to directly measure the neutrino mass with a sensitivity of 200 meV (90%CL) after 3 full beam years of measurement time. With the first commissioning measurements of the main spectrometer an essential mile stone towards this goal has been achieved. A very good vacuum in the UHV regime could be reached, a smooth transmission of electrons through the spectrometer could be demonstrated and the expected transmission characteristic

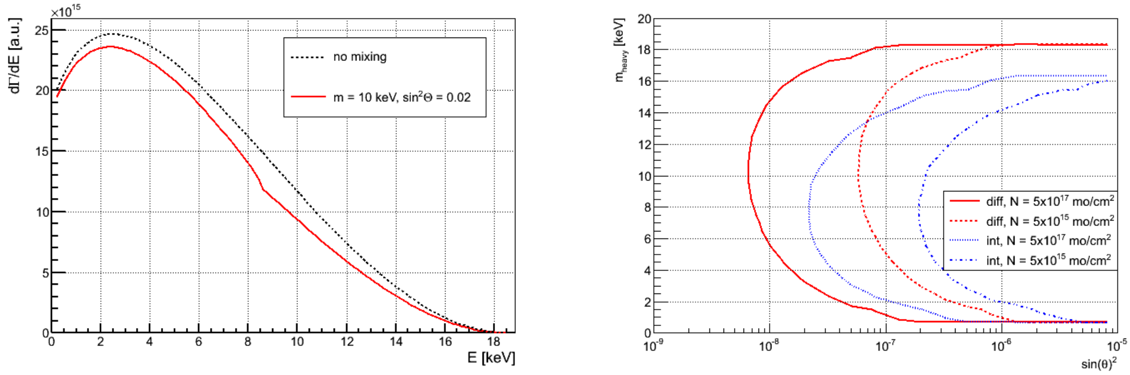

Figure 4. Left: This figure compares the spectrum with no mixing (dashed black line) to a spectrum with an admixture of a sterile neutrino of a mass of 10 keV and a mixing angle of $\sin^2\theta = 0.2$ (solid red line). One can clearly see a kink-like signature of the sterile neutrino at its mass below the endpoint and its influence on the spectral shape below the kink energy. Right: 90% statistical exclusion limit of a differential measurement of 3 years with the expected KATRIN source strength of $9.4 \cdot 10^{10}$ electrons per second (red solid line), a reduced column density (red dashed line) and an integral measurement with the full source strength (blue dotted line) and reduced source strength (blue dotted dashed line).

could be verified. Most importantly, a low initial background rate of 1 cps was observed, rewarding the careful electromagnetic design of the spectrometer. The main background components have been identified to be due to electrons from the inner surface of the spectrometer and radon decay inside the sensitive volume. A further reduction to reach the design goal of 10^{-2} cps is expected when running with a cooled baffle system and the full operation of the two layer inner wire electrode system.

The unique properties of the KATRIN tritium source with regard to luminosity and stability allow not only a high-sensitivity measurement of the effective electron neutrino mass but also offer great potential for a high-sensitivity search for sterile neutrinos in the keV-mass regime, given the feasibility to modify the present experimental set-up at a later stage to cover the entire tritium β-decay spectrum. After 3 years of measurement time the sensitivity to active-sterile neutrino mixing could be extended into a region of interest for cosmology. Detailed investigations of analysis techniques and careful study of systematic effects associated with such a measurement are ongoing.

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References

[1] Y. Fukuda *et al.* (Super-Kamiokande Collaboration), *Evidence for Oscillation of Atmospheric Neutrinos*, Phys. Rev. Lett. **81**, 1562–1567 (1998)

[2] Q. R. Ahmad *et al.* (SNO Collaboration), *Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory*, Phys. Rev. Lett. **89**, 011301 (2002)

[3] K. Eguchi *et al.* (KamLAND Collaboration), *First Results from KamLAND: Evidence for Reactor Anti-Neutrino Disappearance*, Phys. Rev. Lett. **90**, 021802 (2003)

[4] V. M. Lobashev *et al.*, *Direct search for neutrino mass and anomaly in the tritium beta-spectrum: Status of Troitsk neutrino mass experiment*, Nucl. Phys. B 91, 1-3, 280–286 (2001).

[5] Ch. Kraus *et al.*, *Final results from phase II of the Mainz neutrino mass search in tritium*, The Europ. Phys. Jour. C 40, 4, 447–468", (2005).

[6] J. Angrik *et al.*, (KATRIN Collaboration), *KATRIN Design Report 2004*, Wissenschaftliche Berichte, FZ Karlsruhe 7090, (2004).

[7] G. Drexlin V. Hannen, S. Mertens, and C. Weinheimer, *Current Direct Neutrino Mass Experiments*, Adv. High Energy Physics, (2013).

[8] M. Babutzka *et al.*, *Monitoring of the properties of the KATRIN Windowless Gaseous Tritium Source*, New J. Phys. **14** (2012) 103046.

[9] J. A. Dunmore *et al.*, *KATRIN focal plane detector*, J. of Phys., Conference Series **136**, 042056 (2008).

[10] S. Lukic *et al.*, *Measurement of the gas-flow reduction factor of the KATRIN DPS2-F differential pumping section*, Vacuum **86** (8) (2012) 1126–1133.

[11] W. Gil *et al.*, *The Cryogenic Pumping Section of the KATRIN Experiment*, Appl. Supercond., IEEE Trans. on Appl. supercod. **20** (3) (2010) 316–319.

[12] V. M. Lobashev and P. E. Spivak *A method for measuring the electron antineutrino rest mass*, Nucl. Instrum. Methods, 240, Issue 2, 305–310 (1985).

[13] A. Picard *et al. A solenoid retarding spectrometer with high resolution and transmission for keV electrons*, Nucl. Instrum. Methods 63, Issue 3, 345–358 (1992).

[14] J. Wolf *The Vacuum System of the KATRIN Neutrino Experiment*, Journal of the Vacuum Society of Japan Vol. 52, Number 5, (2009)

[15] KATRIN Collaboration, *First main spectrometer commissioning measurements*, to be published.

[16] F. Glueck *et al.*, *Electromagnetic design of the large-volume air coil system of the KATRIN experiment*, New J.Phys. **15** (2013) 083025.

[17] K. Valerius *et al. Electromagnetic design and inner electrode for the KATRIN main spectrometer*, Prog. Part. Nucl. Phys., 57, Issue 1, 58–60, (2006)

[18] K. Valerius *et al.*, *Prototype of an angular-selective photoelectron calibration source for the KATRIN experiment*, J. of Instr. **6** (2011).

[19] S. Mertens for the KATRIN Collaboration, *Electromagnetic design of the spectrometer section of the KATRIN experiment*, Prog. in Part. and Nucl. Phys. 64(2) (2010) 294–296.

[20] F. Fraenkle *et al. Radon induced background processes in the KATRIN pre-spectrometer*, Astropart. Phys. 35, Issue 3, 128–134, (2011).

[21] N. Wandkowsky *et al.*, *Modeling of electron emission processes accompanying radon-α-decays within electrostatic spectrometers*, New J. Phys. 15 (2013) 083040

[22] N. Wandkowsky *et al.*, *Validation of a model for radon-induced background processes in electrostatic spectrometers*, J. Phys. G 40 (2013) 8

[23] S. Mertens *et al.*, *Background due to stored electrons following nuclear decays in the KATRIN spectrometers and its impact on the neutrino mass sensitivity*, Astropart. Phys. 41 (2013) 52

[24] S. Goerhardt, PhD Thesis, KIT (2014).

[25] S. Mertens *et al.*, *Stochastic Heating by ECR as a Novel Means of Background Reduction in the KATRIN Spectrometers*, JINST 7 P08025

[26] N. Wandkowsky PhD Thesis, KIT (2013).

[27] A. Klypin, A.V. Kravtsov, O. Valenzuela, and F. Prada, *Where Are the Missing Galactic Satellites?*, Astrophys. J. **522**, 82 (1999).

[28] B. Moore *et al.*, *Dark matter substructure within galactic halos*, Astrophys. J. **524**, L19 (1999).

[29] J. Zavala *et al.*, *The velocity function in the local environment from LCDM and LWDM constrained simulations*, Astrophys. J. **700**, 1779 (2009).

[30] A. Sejersen-Riis and S. Hannestad, *Detecting sterile neutrinos with KATRIN like experiments*, JCAP (2011) 1475.

[31] J. A. Formaggio and J. Barrett, *Resolving the Reactor Neutrino Anomaly with the KATRIN Neutrino Experiment*, Phys. Lett. B 706 1 (2011) 68–71.

[32] A. Esmaili and Orlando L. G. Peres, *KATRIN Sensitivity to Sterile Neutrino Mass in the Shadow of Lightest Neutrino Mass*, Phys. Rev. D85 (2012) 117301.

[33] S. Mertens *et al. Direct Search of Warm Dark Matter keV Neutrinos In Next Generation Tritium Beta Decay Experiments*, to be published.

[34] S. Mertens *et al. A wavelet approach to search for sterile neutrinos in tritium β-decay spectra*, to be published.