Vacuum 158 (2018) 195–205

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum

Modelling of gas dynamical properties of the KATRIN tritium source and implications for the neutrino mass measurement

Laura Kuckert[a,*], Florian Heizmann[b,**], Guido Drexlin[b], Ferenc Glück[a], Markus Hötzel[b], Marco Kleesiek[b], Felix Sharipov[c], Kathrin Valerius[a]

[a] Institute for Nuclear Physics, Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
[b] Institute of Experimental Particle Physics, Karlsruhe Institute of Technology (KIT), Wolfgang-Gaede-Str. 1, 76131 Karlsruhe, Germany
[c] Departamento de Física, Universidade Federal do Paraná, Caixa Postal 19044, 81531-980, Curitiba, Brazil

ARTICLE INFO

Keywords:
Rarefied gas flow
Gas dynamics
Transitional flow
Viscous flow
Molecular flow
Vacuum
Hydrogen
Tritium
Simulation
Direct neutrino mass determination

ABSTRACT

The KATRIN experiment aims to measure the effective mass of the electron antineutrino from the analysis of electron spectra stemming from the β-decay of molecular tritium with a sensitivity of 200 meV/c^2. Therefore, a cumulative amount of about 40 g of gaseous tritium is circulated daily in a windowless source section. An accurate description of the gas flow through this section is of fundamental importance for the neutrino mass measurement as it significantly influences the generation and transport of β-decay electrons through the experimental setup. In this paper we present a comprehensive model consisting of calculations of rarefied gas flow through the different components of the source section ranging from viscous to free molecular flow. By connecting these simulations with a number of experimentally determined operational parameters the gas model can be refreshed regularly according to the measured operating conditions. In this work, measurement and modelling uncertainties are quantified with regard to their implications for the neutrino mass measurement. We find that the magnitude of systematic uncertainties related to the source model is represented by $|\Delta m_{\bar{\nu}}^2| = (3.06 \pm 0.24)\cdot 10^{-3}\mathrm{eV}^2/c^4$, and that the gas model is ready to be used in the analysis of upcoming KATRIN data.

1. Introduction

The determination of the absolute mass scale of neutrinos is one of the most fundamental open challenges in particle physics. A model-independent determination in a laboratory experiment can only be provided by experiments using the kinematics of β-decay like the KArlsruhe TRItium Neutrino (KATRIN) experiment which is currently in its commissioning phase.

KATRIN is designed to reach an unprecedented neutrino mass sensitivity of 200 meV (90% confidence level) by high-precision tritium β-decay spectroscopy combined with an ultra-luminous gaseous tritium source [1]. A schematic overview of the KATRIN experiment is shown in Fig. 1. The Windowless Gaseous Tritium Source (WGTS) [2–5] will provide a large β-decay rate of $10^{11}\ \mathrm{s}^{-1}$ by circulating a daily throughput of 40 g of tritium,[1] resulting in a column density in the WGTS beam tube of $\mathcal{N} = 5 \times 10^{21}\ \mathrm{m}^{-2}$ or 300 µg of tritium.

To prevent tritium from migrating into the spectrometers, the gas flow needs to be reduced by 14 orders of magnitude in adjacent pumping sections by kinetic (differential pumping section, DPS1/2) and cryogenic (cryogenic pumping section, CPS) pumping. The pre- and main spectrometer are of MAC-E filter type [6–9] and allow high-resolution energy analysis of the β-decay electrons by scanning the electrostatic spectrometer retarding potential.

The neutrino mass will be extracted by comparison of the experimentally measured electron spectrum to a theoretically modelled equivalent [10,11]. The modelling takes into account a variety of experimental effects, among which the electron-gas inelastic scattering processes inside the WGTS are of particular importance as they modify the electron energy. Understanding this effect requires precise knowledge of the column density $\mathcal{N}$, or the number density of gas molecules integrated along the beam tube axis, which is also an important input for plasma simulations.

In addition, the knowledge of the axial gas density distribution in the source section is necessary to correct for spatial inhomogeneities of

---

* Corresponding author.
** Corresponding author.
E-mail addresses: laura.neumann@ewetel.net (L. Kuckert), florian.heizmann@kit.edu (F. Heizmann).

[1] For this throughput, a tritium inventory of approximately 15 g is buffered in several vessels for KATRIN.

https://doi.org/10.1016/j.vacuum.2018.09.036
Received 29 June 2018; Received in revised form 9 September 2018; Accepted 17 September 2018

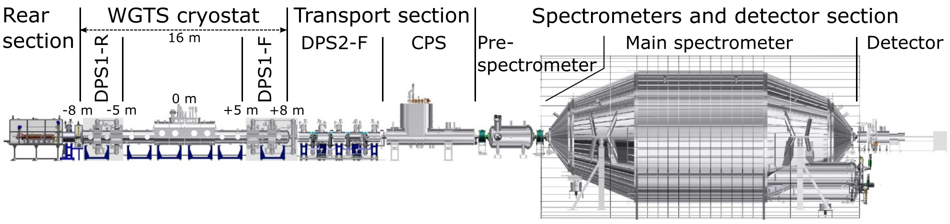

Fig. 1. Overview of the KATRIN experiment. Tritium gas is injected in the source (WGTS) and pumped out in adjacent pumping sections (DPS1/2, CPS). Electrons from β-decay are magnetically guided to the energy analysing spectrometer section and are counted at the detector.

parameters influencing the electron spectrum, such as magnetic field and temperature. The gas dynamics model used to determine this density distribution needs to cover a broad range of pressure regimes while providing a total uncertainty of 0.2% on the product of column density and scattering cross section, $\mathcal{N}\cdot\sigma$. At the same time, the gas dynamics model must be adjustable to account for varying operational parameters such as temperature and inlet pressure.

Malyshev et al. [12] described parts of such a highly accurate gas model focussing on the calculation of gas flow reduction factors. However, due to changes in the apparatus, these calculations need to be updated and refined. The goals of this work are to i) describe this refined gas model and ii) analyse its impact on the neutrino mass measurement considering experimentally determined parameters.

We start in section 2 with a description of the source and how its β-decay electron spectrum can be modelled before introducing the gas dynamics calculations of the particular components in section 3. Moreover, section 4 presents the determination of the column density by combining measurement and calculation. The corresponding uncertainties are analysed and their impact on the neutrino mass measurement is investigated. Finally, in section 5, we conclude this work with a summary of our findings.

2. Electrons from the KATRIN source section

The Windowless Gaseous Tritium Source (WGTS) provides β-decay electrons via a continuous tritium throughput of 1.8 mbar l s^{-1} (related to a temperature of 273.15 K). 99% of the decays happen in the central beam tube with a length L of 10 m and a diameter Ø of 90 mm to which differential pumping sections are attached at both the front and rear ends (DPS1-F and DPS1-R, see Fig. 1). Those 12 turbomolecular pumps[2] of type *Leybold TURBOVAC MAG W 2800* have a pumping speed of about 2000 l/s (H_2) each [13]. For tritium (T_2), the pumping speed can be approximated to 3000 l/s [14]. Including the conductance of the tube between pump port and pump leads to the same effective pumping speed of about 2000 l/s for H_2 and T_2.

The beam tube is surrounded by superconducting magnets that produce a homogeneous and stable magnetic field of 3.6 T, all housed within a complex large-scale cryostat infrastructure. The beam tube wall temperature is stabilised at 30 K to better than 0.1% using a two-phase neon cooling system [15] based on two coolant pipes bonded to the exterior wall of the tube. A proof of concept of the high stability cooling system was performed with a *Demonstrator* set-up [16] and has recently been successfully validated with the fully equipped cryostat system [17].

Tritium is injected at the midpoint of the beam tube with a pressure of 3.4×10^{-3} mbar through 415 small orifices (each 2 mm in diameter, see Fig. 3), resulting in an overall column density of tritium molecules $\mathcal{N}$ of $5 \times 10^{21}\,\mathrm{m}^{-2}$. A stable inlet pressure is provided using a temperature and pressure stabilised buffer vessel at the beginning of the tritium feed line (see Ref. [4] for details).

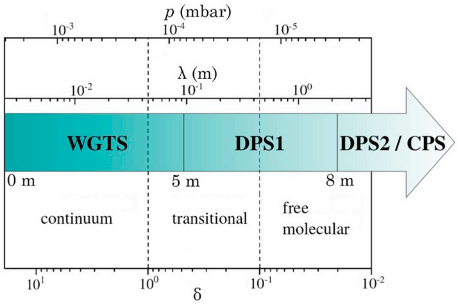

Fig. 2. Range of rarefaction parameter δ with associated rarefaction regimes, corresponding pressure p and equivalent free path λ, values for KATRIN measurement conditions. A constant tube radius of 45 mm in the source and transport section is assumed for illustration purposes.

To reach the required gas flow retention in the spectrometer direction, two further pumping sections are attached: the DPS2 [1,18] (differential pumping) and the CPS [19] (cryogenic pumping). The latter relies on cryosorption of tritium on a cold surface [20]. The β-decay electrons can pass the pumping sections as they are guided through magnetically. If they have enough energy to overcome the spectrometer retarding voltage they contribute to the measured spectrum. From this spectrum the neutrino mass will be extracted by fitting a model function with several free parameters, making an accurate modelling of the spectrum of β-decay electrons leaving the source and transport section indispensable.

Modelling of β-decay electron spectra. In the spectral modelling, all energy loss processes of β-decay electrons reaching the detector need to be considered. Together with the transmission characteristics of the spectrometer they can be accounted for using the concept of a response function $R(E, U, \theta, z)$ [10,11]. Thus, the signal rate $\dot{N}(U)$ for one of the 148 pixels of the detector at spectrometer retarding voltage U can be described as

$$\dot{N}(U) \propto \int_{-L/2}^{+L/2} n(z) \int_{qU}^{\infty} \frac{\mathrm{d}\Gamma}{\mathrm{d}E}\cdot R(E, U, z)\,\mathrm{d}E\,\mathrm{d}z \tag{1}$$

where $\frac{\mathrm{d}\Gamma}{\mathrm{d}E}$ denotes the differential rate of β-decay electrons at the time of decay and $n(z)$ the gas number density distribution along the longitudinal source beam tube symmetry axis z with origin $z = 0$ at the centre of the source.

One of the most important energy loss mechanisms to be included in the response function is inelastic scattering of electrons by gas molecules in the source. The probabilities $P_i(z, \theta)$ for an electron to scatter i-times depend on its pitch angle relative to the magnetic field at creation θ and can be computed using [21] as

$$P_i(z, \theta) = \frac{(\mathcal{N}_{\mathrm{eff}}(z, \theta)\cdot\sigma)^i}{i!} \mathrm{e}^{-\mathcal{N}_{\mathrm{eff}}(z, \theta)\cdot\sigma}, \tag{2}$$

with σ denoting the total inelastic scattering cross section and

$$\mathcal{N}_{\mathrm{eff}}(z, \theta) = \frac{1}{\cos\theta}\mathcal{N}(z) = \frac{1}{\cos\theta}\int_{z'=z}^{+L/2} n(z')\,\mathrm{d}z' \tag{3}$$

denoting the effective partial column density that accounts for increasing path lengths due to non-zero electron emission angle θ. Equations (2) and (3) assume that the angular distribution is not significantly affected by the small angular change due to scattering [11].

---

[2] Four at first pump port and two at second pump port, for front and rear side.