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Deconvolution of the energy loss function of the KATRIN experiment

V. Hannen[a,*], I. Heese[a], C. Weinheimer[a], A. Sejersen Riis[b], K. Valerius[c]

[a] Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Wilhelm-Klemm-Str. 9, 48149 Münster, Germany
[b] Department of Physics and Astronomy, University of Aarhus, Ny Munkegade, DK-8000 Aarhus C, Denmark
[c] Institut für Kernphysik, Karlsruher Institut für Technologie, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

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ABSTRACT

The KATRIN experiment aims at a direct and model independent determination of the neutrino mass with 0.2 eV/c^2 sensitivity (at 90% C.L.) via a measurement of the endpoint region of the tritium beta-decay spectrum. The main components of the experiment are a windowless gaseous tritium source (WGTS), differential and cryogenic pumping sections and a tandem of a pre- and a main-spectrometer, applying the concept of magnetic adiabatic collimation with an electrostatic retardation potential to analyze the energy of beta decay electrons and to guide electrons passing the filter onto a segmented silicon PIN detector.

One of the important systematic uncertainties of such an experiment are due to energy losses of β-decay electrons by elastic and inelastic scattering off tritium molecules within the source volume which alter the shape of the measured spectrum. To correct for these effects an independent measurement of the corresponding energy loss function is required. In this work we describe a deconvolution method to extract the energy loss function from measurements of the response function of the experiment at different column densities of the WGTS using a monoenergetic electron source.

1. Introduction

The KArlsruhe TRItium Neutrino (KATRIN) experiment aims at determining the neutrino mass in a model independent way from the kinematics of tritium β-decay. The observable in this case is an "average electron anti-neutrino mass" given by the incoherent sum of neutrino mass eigenstates weighted by the squared elements of the mixing matrix. The experiment combines a Windowless Gaseous Tritium Source (WGTS) and a high resolution electrostatic retarding spectrometer (MAC-E filter) to measure the spectral shape of β-decay electrons close to the endpoint energy at 18.6 keV with an unprecedented precision. KATRIN's sensitivity to the neutrino mass will be 0.2 eV/c^2 (at 90% C.L.) after 3 years worth of data taking [1]. An observed mass signal of 0.35 eV/c^2 will have a 5σ significance at the expected level of statistic and systematic uncertainties. In order to reach the desired sensitivity, all systematic effects of the measurement must be well under control with the major systematic uncertainties being allowed to contribute no more than $\Delta m^2 = 0.0075$ eV^2/c^4 to the systematic error budget.

An overview of the KATRIN experiment is shown in Fig. 1. The experiment starts with the WGTS where molecular T_2 gas is injected at the center of the source and removed at both ends by turbo-molecular pumps. The T_2 gas is kept at a constant temperature of 30 K within the source that is operated at a column density of $5 \cdot 10^{17}$cm^{-2}. The operational parameters of the source cryostat are monitored by a complex sensor network and a dedicated calibration and monitoring section at the rear of the source system [2]. About 10^{10} β-decay electrons are emitted per second into the accepted forward solid angle with pitch angles less than $\theta_{max} = 51^\circ$ and are guided magnetically through the transport section to the spectrometer tandem consisting of pre- and main-spectrometers. The task of the transport section made up of a differential pumping section and a cryo-pumping section is to suppress the flow of T_2molecules into the direction of the spectrometers by at least a factor of 10^{14} in order to reduce experimental background from tritium decays within the spectrometers. A first energy discrimination is performed by the pre-spectrometer which rejects the low energy part of the β spectrum (up to 300 eV below the endpoint) and thereby reduces the rate of electrons going into the main spectrometer to approximately 10^3 s^{-1}. Like the pre-spectrometer the main spectrometer operates as a so-called MAC-E filter [3] and has the task to perform a precise energy analysis of the decay electrons.

In a MAC-E filter electrons are guided magnetically against an electrostatic retardation potential that can only be surpassed by electrons with sufficiently high longitudinal energy with respect to the electric field. Here the longitudinal energy is given

* Corresponding author.
E-mail address: hannen@uni-muenster.de (V. Hannen).

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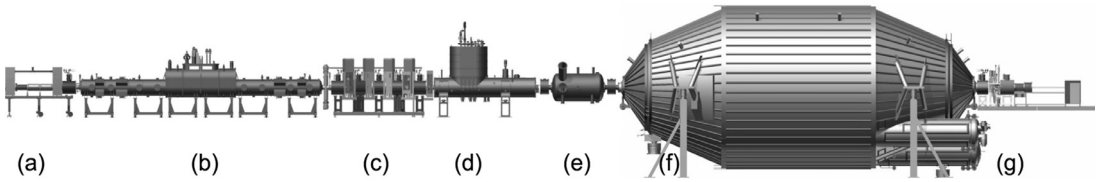

Fig. 1. Overview of the KATRIN experiment. The main components are: (a) calibration and monitoring system, (b) windowless gaseous tritium source, (c) differential and (d) cryogenic pumping sections, (e) pre-spectrometer, (f) main spectrometer, (g) detector system. Overall length ca. 70 m.

by $E_{\parallel} = E_{\text{kin}} \cdot \cos^2\theta$ with E_{kin} being the kinetic energy of the electron and θ being the angle between electron momentum and magnetic field direction. The transverse energy is accordingly given by $E_{\perp} = E_{\text{kin}} \cdot \sin^2\theta$. The spectrometer acts as a high pass filter with a transmission function describing the observed electron rate as a function of the electron surplus energy (see Section 3.1). To reduce the amount of transversal energy of the electrons that is not analyzed by the spectrometer, the technique of magnetic adiabatic collimation is used. The idea is that the magnetic guiding field drops by several orders of magnitude from the entrance of the spectrometer to the analyzing plane, where the electric potential reaches its maximum. If the gradient of the magnetic field is small enough, such that the field is approximately constant along one cyclotron loop of the electron movement, the magnetic moment of the cyclotron motion $\mu = E_{\perp}/B$ (non-relativistic) is constant, and as B drops the transversal energy of the electrons is converted into longitudinal energy $E_{\parallel}$ that can be analyzed by the spectrometer. By varying the electric potential of the spectrometer it is then possible to scan the relevant region around the endpoint energy of tritium β-decay and accumulate a spectrum. Electrons with sufficient energy to pass the spectrometer are finally detected by a 148 pixel silicon PIN detector [4] at the end of the setup.

Among the main systematical uncertainties of the experiment are energy losses from inelastic scattering of electrons in the source, fluctuations of the source density, fluctuations of the spectrometer analyzing potential, uncertainties in the transmission function and uncertainties in the final state distribution of the daughter molecules left after the decay reaction. A sophisticated calibration and monitoring system is being set up to keep the aforementioned systematic effects under control. While there is some information on the energy loss of 18.6 keV electrons in gaseous tritium or quench condensed deuterium from the former neutrino mass experiments in Troitsk and Mainz [5], precise experimental information on energy losses of electrons with energies near the endpoint of the tritium β spectrum are only available for molecular hydrogen as target gas [6,7].

A measurement of the energy differential scattering cross section of 18.6 keV electrons off molecular tritium is therefore highly desirable. Such a measurement can be performed using a monoenergetic source of electrons mounted upstream of the WGTS to determine the response function of the overall experiment at different column densities of the source. A deconvolution method suitable to extract the energy loss function from the data will be presented in the following sections.

Once the energy loss function for tritium is known with sufficient accuracy, the same measurement setup can be used for an independent check of the column density of the WGTS during intervals between the regular measurement cycles of the KATRIN experiment [1].

2. Energy loss function

The processes contributing to the energy loss of electrons traversing the molecular tritium gas within the WGTS are excitation of rotational and vibrational states of the T_2 molecules, excitation of electronic molecular states, dissociation and ionization of the molecules.

Aseev et al. [5] report on measurements of energy losses of electrons in gaseous tritium and in quench condensed deuterium films. Because of the limited energy resolution of a few eV the shape of the energy loss spectrum was not directly extracted from the data in their analysis, but approximated by a Gaussian representing electronic excitations and dissociation and a one-sided Lorentzian curve representing the continuum caused by ionization of the molecules. The parameters of the two functions were then adapted to fit the observed integral energy spectra obtained with an 18.6 keV mono-energetic electron source for gaseous tritium or from 17.8 keV mono-energetic conversion electrons from a ^{83m}Kr film covered by various thicknesses of D_2 absorbers. In both cases, energy losses caused by rotational and vibrational excitations of the molecules without electronic excitation could not be resolved and were neglected.

More detailed information is available for the scattering of 25 keV electrons from molecular hydrogen gas [6,7] where direct measurements of the energy loss function with resolutions down to 40 meV have been performed (see Fig. 2). This information about the scattering of electrons from molecular hydrogen has been implemented into a computer code by Glück [8] that can be used in simulations to generate energy losses ΔE and scattering angles $\Delta\varphi$ in individual scattering events. The spectral shape produced with this routine is shown in Fig. 3. It is used in a toy Monte Carlo simulation of the WGTS to evaluate the deconvolution methods described in the following sections.

The probability for an electron of kinetic energy E to lose a specific amount of energy ΔE in a single scattering event is described by the differential energy loss function $\frac{\mathrm{d}\sigma}{\mathrm{d}\Delta\mathrm{E}}$. For our purpose, we normalize the function by the total inelastic scattering cross section σ_{tot}, obtaining[1]

$$f(\Delta E) = \frac{1}{\sigma_{\text{tot}}} \cdot \frac{\mathrm{d}\sigma}{\mathrm{d}\Delta\mathrm{E}} \qquad \text{with} \qquad \int_0^{E/2} f(\Delta E)\,\mathrm{d}\Delta\mathrm{E} = 1\,. \tag{1}$$

The total inelastic scattering cross section for 18.6 keV electrons off gaseous tritium is given by $\sigma_{\text{tot}}(T_2) = (3.40 \pm 0.07) \cdot 10^{-18}$ cm^2 [5]. The above mentioned code by Glück [8] for scattering of 18.6 keV electrons off hydrogen gives a total inelastic cross section of $\sigma_{\text{tot}}(H_2) = 3.7 \cdot 10^{-18}$ cm^2.

3. Deconvolution method

In the following sections we describe suitable mathematical methods to extract the energy loss function of 18.6 keV electrons in gaseous tritium from a series of measurements of the overall response function of the experiment at different column densities of the WGTS.

[1] The integral over the energy losses runs up to $E/2$ since the incoming electron and the secondary electron in an ionisation process (assuming E is larger than twice the ionisation energy) are identical quantum particles.