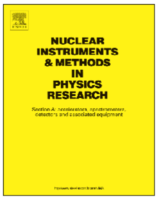
Nuclear Instruments and Methods in Physics Research A 778 (2015) 40–60

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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



Focal-plane detector system for the KATRIN experiment

J.F. Amsbaugh[a], J. Barrett[b], A. Beglarian[c], T. Bergmann[c], H. Bichsel[a], L.I. Bodine[a], J. Bonn[d,1], N.M. Boyd[a], T.H. Burritt[a], Z. Chaoui[e], S. Chilingaryan[c], T.J. Corona[f,g], P.J. Doe[a], J.A. Dunmore[a,2], S. Enomoto[a], J.A. Formaggio[b], F.M. Fränkle[f,g,3], D. Furse[b], H. Gemmeke[c], F. Glück[h,i], F. Harms[h], G.C. Harper[a], J. Hartmann[c], M.A. Howe[f,g], A. Kaboth[b], J. Kelsey[b], M. Knauer[j], A. Kopmann[c], M.L. Leber[a], E.L. Martin[a], K.J. Middleman[k], A.W. Myers[a,4], N.S. Oblath[b], D.S. Parno[a,*], D.A. Peterson[a], L. Petzold[c], D.G. Phillips II[f,g], P. Renschler[h], R.G.H. Robertson[a], J. Schwarz[h], M. Steidl[j], D. Tcherniakhovski[c], T. Thümmler[j], T.D. Van Wechel[a], B.A. VanDevender[a,4], S. Vöcking[l], B.L. Wall[a], K.L. Wierman[a,f,g], J.F. Wilkerson[f,g,m], S. Wüstling[c]

[a] *Center for Experimental Nuclear Physics and Astrophysics, Department of Physics, University of Washington, Seattle, WA 98195, USA*
[b] *Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[c] *Institute for Data Processing and Electronics, Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany*
[d] *Institute of Physics, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany*
[e] *Laboratory of Optoelectronics and Devices, University of Setif, UFA Setif, Setif 19000, Algeria*
[f] *Department of Physics, University of North Carolina, Chapel Hill, NC 27599, USA*
[g] *Triangle Universities Nuclear Laboratory, Durham, NC 27708, USA*
[h] *Institute for Experimental Nuclear Physics, Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany*
[i] *Wigner Research Center for Physics, P.O. Box 49, 1525 Budapest, Hungary*
[j] *Institute for Nuclear Physics, Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany*
[k] *ASTeC Vacuum Science Group, STFC Daresbury Laboratory, Warrington, Cheshire WA4 4AD, UK*
[l] *Institute of Nuclear Physics, Westfälische Wilhelms-Universität Münster, 48149 Münster, Germany*
[m] *Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*

ARTICLE INFO

Article history:
Received 9 April 2014
Received in revised form
19 December 2014
Accepted 20 December 2014
Available online 9 January 2015

Keywords:
Neutrino mass
Low-background counting
Si p-i-n diode
Vacuum
Data acquisition

ABSTRACT

The focal-plane detector system for the KArlsruhe TRItium Neutrino (KATRIN) experiment consists of a multi-pixel silicon p-i-n-diode array, custom readout electronics, two superconducting solenoid magnets, an ultra high-vacuum system, a high-vacuum system, calibration and monitoring devices, a scintillating veto, and a custom data-acquisition system. It is designed to detect the low-energy electrons selected by the KATRIN main spectrometer. We describe the system and summarize its performance after its final installation.

1. Introduction: The KATRIN Experiment

The discovery of neutrino flavor oscillation [1,2] showed that the neutrino flavor eigenstates ν_e, ν_μ, ν_τ are not states of fixed mass; instead, each is a coherent superposition of mass eigenstates ν_1, ν_2, ν_3. However, these and subsequent oscillation experiments are not sensitive to the absolute value of the neutrino mass, indicating only that at least two neutrinos have mass, and at least one of them has a mass ≥ 48 meV [3]. Neutrino mass is considered to provide unique early insight into electroweak physics beyond the standard model, and plays a role in the evolution of large-scale structure in the universe. A laboratory determination of the mass scale would constrain cosmological models. Recently reported results from surveys of the cosmic microwave background, including the WMAP [4] and Planck missions [5], confirm that observational cosmology is indeed sensitive to the sum of the masses $\sum_j m_j$, but that the limit or value obtained depends

---

[*] Corresponding author.
E-mail address: dparno@uw.edu (D.S. Parno).
[1] Deceased.
[2] Present address: Department of Physics, University of Texas at El Paso, El Paso, TX, USA.
[3] Present address: Institute for Nuclear Physics, Karlsruhe Institute of Technology, Karlsruhe, Germany.
[4] Present address: Pacific Northwest National Lab, Richland, WA, USA.

http://dx.doi.org/10.1016/j.nima.2014.12.116
0168-9002/© 2015 Elsevier B.V. All rights reserved.

on the types of data and assumptions included in the analysis. With very conservative uncertainty estimates, one may obtain a limit of $\sum_j m_j \leq 1.3$ eV at the 95% confidence level [6].

The KArlsruhe TRItium Neutrino experiment [7], KATRIN, will make a model-independent measurement of the mass $m_{\overline{\nu}}$ of the electron antineutrino in the quasi-degenerate regime $(m_1 \approx m_2 \approx m_3)$. It continues a series of tritium-based experiments, including Mainz [8] and Troitsk [9,10], which established the present model-independent limit of $m_{\overline{\nu}} < 2$ eV [6].

Tritium beta decay, $^3\mathrm{H} \longrightarrow {}^3\mathrm{He}^+ + \mathrm{e}^- + \overline{\nu}_e$, has an endpoint energy of 18.6 keV and a half-life of 12.3 years. The shape of the electron energy spectrum near the endpoint is sensitive to the neutrino mass. The KATRIN experiment will use the Magnetic Adiabatic Collimation-Electrostatic (MAC-E) filter technique [11], in which multiple integrating measurements with varying thresholds are combined to map the spectral shape near the endpoint. KATRIN is currently under construction at the Karlsruhe Institute of Technology in Karlsruhe, Germany and is expected to achieve a sensitivity of 200 meV at the 90% confidence level.

Fig. 1 is a schematic of KATRIN's overall layout. A 10^{11}-Bq, windowless, gaseous tritium source provides beta electrons. An electron gun for calibration is located upstream in the rear section. Downstream of the source, an extensive transport section removes errant tritium molecules via differential and cryogenic pumping systems while guiding beta electrons adiabatically to the low-resolution pre-spectrometer [12]. The pre-spectrometer reduces the electron flux by seven orders of magnitude prior to entry into the main spectrometer, which further filters out lower-energy electrons with a designed energy resolution of 0.93 eV. Beta electrons that pass through these two MAC-E filters are magnetically guided to the focal-plane detector (FPD).

The focus of this paper is the FPD system, shown in Fig. 2. This system was constructed and commissioned at the University of Washington in Seattle, USA, prior to installation in Karlsruhe in summer 2011. In Section 2, we provide a detailed description of the elements of this system, including design constraints (Section 2.1) and upgrades undertaken in Karlsruhe. Section 3 presents detector performance results, primarily drawn from the commissioning of the system in Karlsruhe. In Section 4, we discuss the backgrounds and consider the way in which the FPD system affects the overall KATRIN measurement via its resolution and backgrounds.

2. Apparatus

In the KATRIN experiment, beta electrons produced near the endpoint energy of tritium decay will pass the energy threshold set by the main spectrometer and enter the FPD system (Fig. 2) at the spectrometer exit. This loosely collimated "beam" of beta electrons travels within a flux tube defined by the local magnetic field, which in the FPD system is provided by two warm-bore superconducting solenoids (Section 2.2). Beta electrons move through the bore of the high-field pinch magnet and past a gate valve that separates the main-spectrometer vacuum from the FPD-system vacuum system (Section 2.3), before entering the bore of the lower-field detector magnet and striking the multi-pixel silicon p-i-n-diode detector (Section 2.4). In this final stage of the electron trajectory, the flux tube is contained within a post-acceleration electrode that permits increasing the electron energy to a range with a more favorable background rate.

The first readout stage for detector signals consists of preamplifiers mounted directly onto feedthrough pins on the detector flange; preamplifier signals proceed along coaxial cables to the second stage, mounted outside the vacuum system (Section 2.5). A liquid-nitrogen thermosiphon (Section 2.6) cools the detector and preamplifiers through the post-acceleration electrode. A shield and a veto system (Section 2.7) line the bore of the detector magnet, reducing backgrounds in the detector. An electron source and a γ emitter (Section 2.8), located between the two magnets, serve as calibration sources.

FPD and veto data are recorded in a data-acquisition system with a graphical user interface (Section 2.9) while other hardware elements of the system are monitored and controlled via a separate slow-controls system (Section 2.10). The demands of the KATRIN experiment require an extensive data-management system, described in Section 2.11.

2.1. Design constraints

A number of strict requirements guided the FPD-system design. For example, the pinch magnet helps to complete KATRIN's primary MAC-E filter, and the quality of the FPD-system vacuum affects the performance of the main spectrometer. Here, we summarize the most important constraints on the system design, which fall into two categories: electromagnetic (Section 2.1.1) and vacuum (Section 2.1.2).

2.1.1. Electromagnetic constraints

The KATRIN spectrometers act as integrating high-pass filters. Superconducting magnets guide electrons adiabatically along magnetic

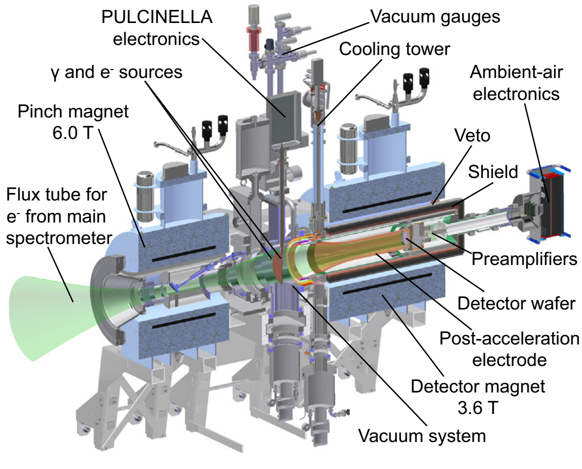


Fig. 2. The primary components of the FPD system. The main spectrometer is positioned at bottom left; the data acquisition system is located beyond the top right corner.

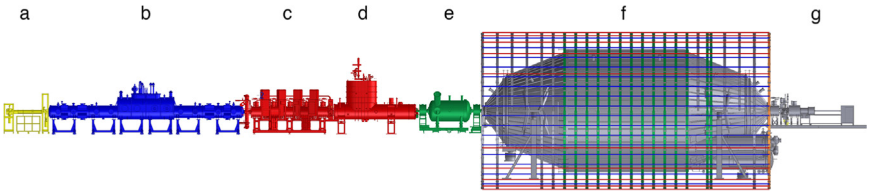


Fig. 1. Schematic overview of the 70-m KATRIN experimental beamline: (a) rear section, (b) tritium source, (c) differential-pumping section, (d) cryogenic-pumping section, (e) pre-spectrometer, (f) main spectrometer in air-coil framework, and (g) focal-plane detector system.