Improving Resolution for the KATRIN Detector Prototype

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Abstract

The initial KATRIN Detector prototype is a Hamamatsu S3204-09 window-less Si PIN photodiode. The KATRIN experiment is designed to analyze tritium beta decay and, from that analysis, measure the mass of the neutrino with an upper limit of 0.2 eV. To achieve this sensitivity the background must be extremely low and noise reduction is imperative. Determining the dead layer of the prototype detector surface and operating at sub-zero Celsius temperatures are critical aspects of such background lowering and noise-reduction.

1. Introduction

The Karlsruhe Tritium Neutrino Experiment (KATRIN) is a next generation tritium beta-decay neutrino experiment and will be an order of magnitude larger than previous neutrino mass experiments [1]. The primary goal is to obtain a direct measurement of the neutrino mass to a 0.2 eV/c^2 sensitivity [1].

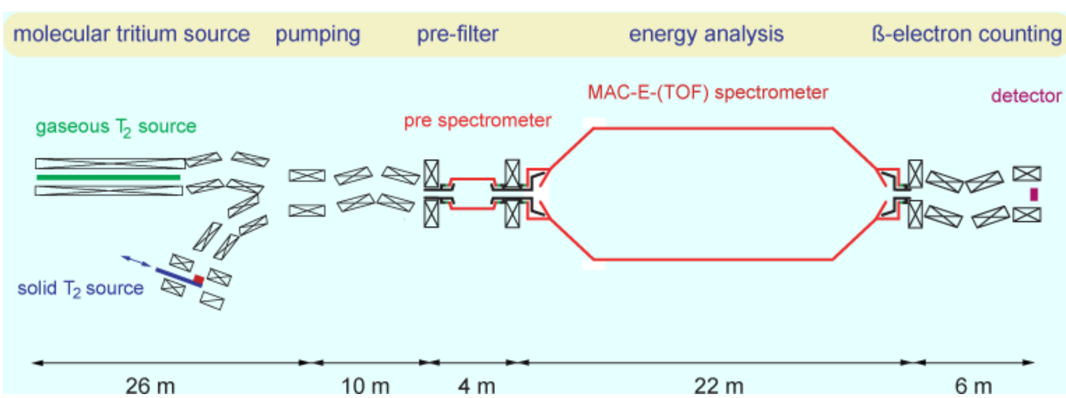

Figure 1 - KATRIN schematic [2]

The KATRIN apparatus is mainly comprised of a Windowless Gaseous Tritium Source (WGTS), a transport system where any remaining tritium is filtered out, a pre-spectrometer which filters out all but the highest energy electrons, a main spectrometer, and a detector used to count the emitted electrons [2].

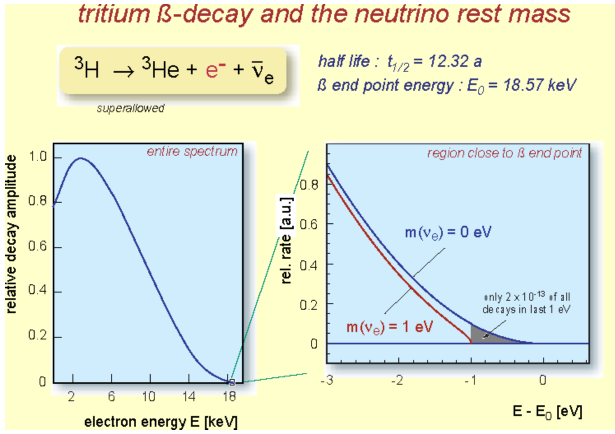

Figure 2 - Tritium Beta Decay [2]

KATRIN will be looking at the Fermi spectrum produced by the emitted beta particles. The theoretical spectrum, when the mass of the neutrino is assumed to be zero, will be contrasted with the experimental curve [2]. Only the highest energy beta particles will be considered though, because the critical part of the curve is its upper limit [2]. The deviation between the theoretical and experimental energy upper limit will ultimately result in a measurement of the neutrino mass.

2. The electron gun and silicon detector

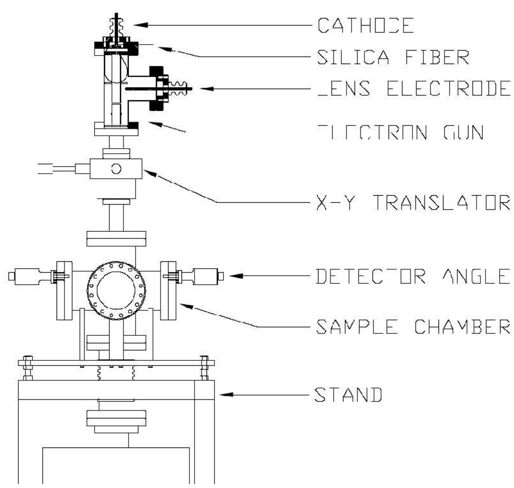

Figure 3 - Electron Gun and Vacuum System [3]

A monoenergetic electron gun was constructed at the University of Washington to simulate the beta-particles the final KATRIN detector will see [3]. There is UHV X-Y translator on the apparatus so that the gun can be positioned exactly to the center of the detector surface. Each sample chamber of apparatus is closed off with a 150 mm diameter stainless steel flange [3]. The flange used for the sample chamber holds the detector and a peltier cooling device in the vacuum system. Various other feedthroughs are also attached to the flange to allow temperature data to be recorded and to connect electronics. The pressure of the vacuum used is on the order of 10^{-17} Torr [3].

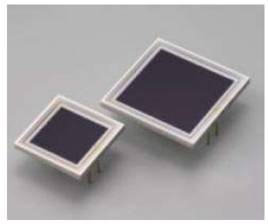

Figure 4 - Hamamatsu S3204-09 window-less Si PIN photodiodes [4]

The initial prototype for the KATRIN detector is a Hamamatsu S3204-09 window-less Si PIN photodiode, which has an active surface area of 18 cm x 18 cm [3]. The detector is mounted onto the flange by a ceramic platform that is can be rotated 360 degrees. This detector is the first prototype for the silicon pin diode that will be the final KATRIN detector. Plans for beginning testing on the final detector are schedule for the end of this year at the University of Washington.

3. Calculating the Dead Layer

The most significant source of error for the energy recorded by the detector is a dead layer located on the surface. A significant amount of energy is lost as the electrons pass through, so knowing the exact thickness of this layer is of critical importance so that necessary corrections can be made.

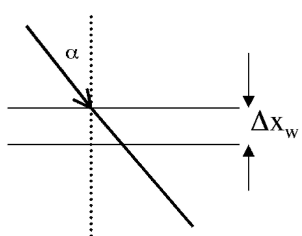

Figure 5 - Dead Layer and Angle of Incidence Relation

In order to measure the dead layer, the electron gun produced 25 keV electrons that were positioned to hit directly in the center of the detector surface area. The detector was then tilted between 30° and 60° from the normal at 5° intervals. The peak electron energy was measured at each angle using radioactive Ba^{133} and Am^{241} sources for energy calibration.

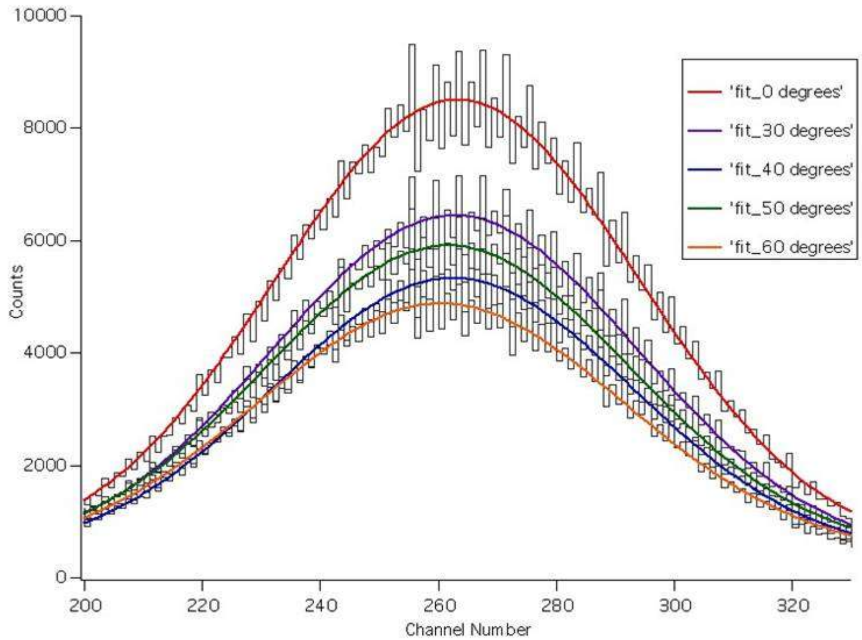

Figure 6 - Spectra Results after Tilting the Detector

The decrease in energy deposited in the detector when tilted is given by the formula:

$$\Delta E = dE/dx * \Delta x_w * (1/\cos\alpha - 1)$$

Where Δx_w is the dead layer thickness, α is the angle of incidence, and dE/dx is the energy loss per unit in the detector. For 25 keV electrons and silicon, the Bethe-Bloch formula gives a value of 2.108 keV/μm for dE/dx [5].

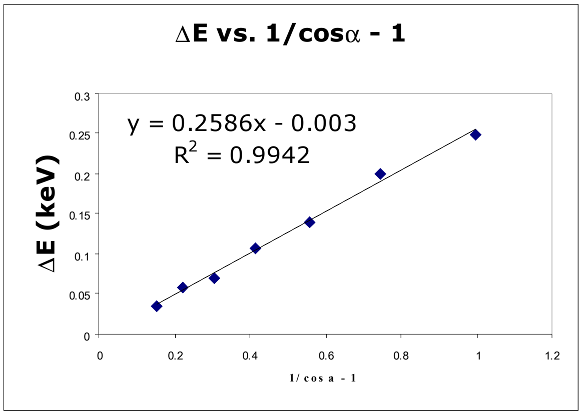

Figure 7 - Fitting the Tilting Data

The slope of the fit gives a dead layer thickness of 122 nm. This thickness, when assuming similar uncertainty, shows agreement with the measurement made the previous year of 107 +/- 10 nm [5].

4. Cooling Mechanisms

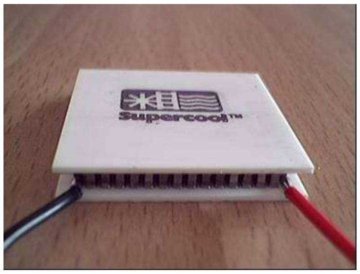

Figure 8 - Peltier Device [6]

The next step for improving the detector resolution was to reduce the amount of noise and make the peaks as clear as possible. The easier way to accomplish this was to bring the temperature of the detector down. A chiller using a 50-50 ethylene glycol and water mixture and a Peltier Device were used to accomplish this effect. A Peltier Device is a chip that creates a temperature differential between its two surfaces leaving one side "cold" and one side "hot" in comparison.

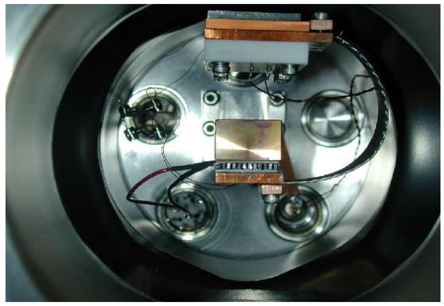

Figure 9 - Stainless Steel Flange and Experimental Set-up

The initial cooling design that was tested the previous year consisted of a peltier device soldered to a copper bar mounted on the main flange approximately an inch below the detector mounting. The copper was used as a heat sink for the hot side of the Peltier and the cold side of the Peltier was connected to the detector via insulated copper braid. This initial design was rather ill-conceived though, because the stainless steel flange acted like a heat sink which caused the copper bar to overheat, the low-temperature solder to melt, and one of the detector surfaces to be ruin. Additionally, it was discovered that the braid being used was not as thermally conductive as expected so new designs were drawn up.

For the next design phase, a method of removing the excess heat from the system was devised. Externally, the chiller was attached to the end of a copper rod so that the cooling fluid would circulate over the edge. The copper rod was then fed through the steel flange and thermally connected to the copper bar using a thin piece of copper metal. The cold side of the peltier was attached to the detector via another thin piece of copper metal and a small piece of copper foil for flexibility.

5. Conclusion

The largest source of error inherent in the photo-diode prototype was effectively resolved by making multiple measurements, over a time span of a year, of the surface dead layer. The second component to improving detector resolution, temperature-reduction, was less successful. The various design phases of the thermal-reduction project were plagued with mechanical failures and conductance problems. The flexible connector needed to transfer cold thermal energy to the detector casing is the largest contributor to the design failure. Ultimately, the copper foil employed, in various lengths, shapes, and folds, failed to conduct to a significant enough degree for a comparison to be made. The problem still remains to be resolved as the initial prototype cooling continues to be investigated before moving onto the more sophisticated technologies later this year.

References

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