Source Calibration for Project 8

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Measurement of the final state electron energy in tritium beta decay provides a model independent probe of the neutrino mass. However, reaching sufficient electron energy resolution may be be beyond the realm of current methods. Project 8 is a new experiment employing a novel, high-resolution non-destructive technique to measure the energy of single electrons via detection of the cyclotron radiation signal emitted by the electron in a magnetic field. The tritium endpoint energy of 18.6 keV in a 1T field corresponds to 26 GHz RF signal, and to test the sensitivity of this method, Project 8 will first attempt to demonstrate RF sensitivity to the 17.8 keV monoenergetic electrons as ^{83m}Kr decays to the stable ^{83}Kr. This project will explore the behavior of the krypton gas around liquid nitrogen temperatures to characterize the formation of a krypton monolayer on the surface of the vacuum chamber. The study hopes to find the optimal conditions to ensure minimal noise due to the electron-krypton scattering while still having enough concentration to produce a detectable signal.

I. INTRODUCTION

The Standard Model assumes that neutrinos aremassless particles, but experiments such as the observation of neutrino oscillations provides evidences for massive neutrinos. The precise measurement of the neutrino mass has implications not only for particle physics but for precision cosmology.

Direct measurement of the neutrino mass rely on detecting the electron energy spectrum in decays that involve a neutrino. This spectrum, especially its endpoint, is sensitive to the neutrino mass, and the beta decay spectrum ($n \rightarrow p + e^- + \bar{\nu}_e$) has been historically used. Due to its relatively low endpoint energy of 18.6 kev, tritium is favored as the source for beta decays. The Karlsruhe Tritium Neutrino Experiment (KATRIN) will have one of the most sensitive spectrometers which could detect the neutrino up to 0.2 eV [1]. However, any future experiment that employs the same techniques as KATRIN will require an even larger spectrometer to increase its sensitivity.

Project 8 [2] is a new experiment that hopes to push the sensitivity of neutrino mass measurements without the inherent scaling problems present in classical spectrometers. It will measure the energy of single electrons via detection of the cyclotron radiation signal emitted by the electron in the magnetic field. The circular motion of the electron will have a cyclotron frequency of

$$\omega = \frac{qB}{m_e + E}, \tag{1}$$

a quantity dependent on the electron kinetic energy, thus providing a nondestructive technique for spectroscopy. For a reference design of 1T, the maximum electron energy in the tritium beta decay corresponds to a 27 GHz RF signal.

A prototype for this experimental concept is currently being constructed at the University of Washington. Although data from a tritium source is not expected to come anytime soon, the group intends to demonstrate RF sensitivity in the region of interest by detecting the 17.8 keV monoenergetic electrons from the decay of ^{83m}Kr to the stable ^{83}Kr. The ^{83m}Kr gas will be accumulated from a cell of ^{83}Rb and introduced to the experimental volume which Project 8 will cool to temperatures near or below liquid nitrogen to minimize noise.

There is some concern about the behavior of the krypton gas at such temperatures. The vapor pressure of a gas is the pressure at which it is at thermal equilibrium with its condensed phases, and pressures above this vapor pressure will cause the gas to condense. Condensation is normally not a problem. In fact, it is the idea behind cyropumping in which the chamber is cooled to force the condensation of gas molecules thus further lowering the pressure of the system. In the case of the krypton source, it would be important to know whether the krypton will form a monolayer on the surface of vacuum chamber to avoid pumping out all of the krypton molecules. Reference guides such as those provided by the America Vacuum Society [3] indicate that the vapor pressure of krypton at 77 K lies between 1 and 10 Torr which is orders of magnitude higher than the expected operating pressure of the ex-

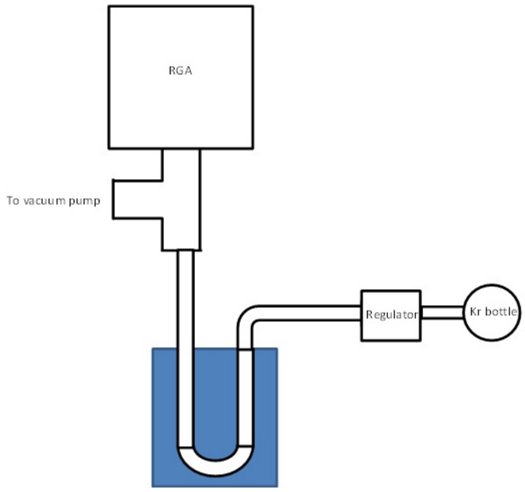

FIG. 1: Experimental setup

periment. Therefore, there is no immediate concern over the condensation of all the krypton molecules, but there remains some uncertainty over the behavior of the gas at the operating pressure below 1 μTorr.

The goal of this project was to observe the behavior of the krypton gas at 77 K to ensure that there is no significant condensation occurring that could hinder the detection of the signal from the electrons.

II. EXPERIMENTAL SETUP

The experimental setup (Figure 1) is fairly simple consisting of a stainless steel tube connecting a residual gas analyzer (RGA) and a bottle of krypton gas. The RGA detects the partial pressures of the component gases and serves as a monitor for changes in the pressure of the krypton gas. A roughing pump and small turbomolecular pump maintain the vacuum in the system by pumping from a tee between the RGA and the stainless steel tubing, and a regulator controls the flow of the krypton gas from the bottle to the tube and RGA. Part of the tube is immersed in liquid nitrogen to lower the gas temperature.

A. Temperature Standoff

A sufficient enough temperature standoff must be created to protect the vacuum integrity because the connection between the tee and the stainless steel tubing is sealed by an elastomer O-ring. Cooling the O-ring below its normal temperature range could compromise its ability to seal. A fluorocarbon (Viton) O-ring has a minimum temperature range of -25°C or 248.15K, so the tube from the point it touches the liquid nitrogen bath to the O-ring must be long enough to raise the temperature to this level.

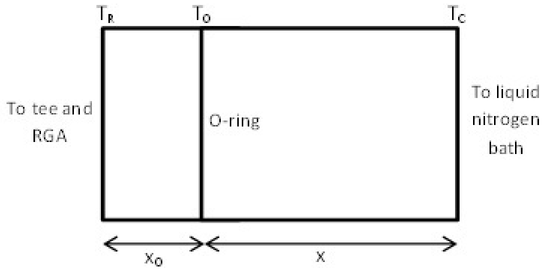

FIG. 2: Temperature standoff

Since the calculation for the design of the tube does not need to be too exact, it is simplified by assuming that the heat flows in only one-dimension along the length of the tube. This considers the conduction of heat while ignoring the contribution from radiative heat loss, so a more detailed calculation would lower the length requirement for the temperature standoff. The problem can be seen as composite plane walls as shown in Figure 2. Room temperature is denoted by T_R, O-ring temperature by T_O, and liquid nitrogen by T_C. The heat transfer [4] is summarized by the following system of equations

$$T_R - T_O = \dot{Q}\frac{x_0}{kA} \tag{2}$$

$$T_O - T_C = \dot{Q}\frac{x}{kA}, \tag{3}$$

where the $\dot{Q}$ is the rate of heat transfer, k is the thermal conductivity, A is the cross-sectional area, and x_0 is the distance of the O-ring from the end of the tube. Combining equations (2) and (3), and solving for x, an equation for the length of the tube is derived as

$$x = \frac{T_O - T_C}{T_R - T_O}x_0. \tag{4}$$

For a Viton O-ring placed 0.50in from the end of the stainless steel tubing, a length of at least 1.72in is required for the temperature standoff.

B. Residual Gas Analyzer

The experiment relies on a residual gas analyzer to monitor the partial pressure of the krypton gas as it is introduced into the system and cooled. An RGA is a small mass spectrometer that ionizes some of the gas in vacuum system, separates each ion by mass, and then stores the ion current at each mass. A Model RGA100 by Stanford Research Systems [5] was used. It can scan masses from 1 to 100 amu, and has two detectors: a Faraday cup (FC) and a continuous dynode electron multiplier (CDEM). The RGA then converts the ion currents to partial pressures. The operating ranges and the minimum detectable partial pressure (MDPP) for the two detectors are summarized in the table below.

Detector	Operating Range	MDPP
FC	10^{-4} Torr to UHV	5×10^{-11} Torr
CDEM	10^{-6} Torr to UHV	5×10^{-14} Tor

TABLE I: Summary of RGA detectors

Although there is some overlap in the operating ranges of the two detectors, the FC is more routinely used for pressures above 10^{-9} Torr.

III. DATA ANALYSIS

A. Background

Before data was taken, the system was pumped out and baked overnight achieving pressures in the order of 10^{-7} Torr. The pressure was too high for the CDEM, so the data was gathered using the FC. A background scan overnight is shown in Figure 3 where the blue line corresponds to the 83 amu. The valve on the krypton bottle remained closed and the regulator valve was set so the pressure in the tube is minimized. Since no krypton was introduced to the system yet, this signal comes from noise in the FC detector with some contributions from residual hydrocarbons. It is normally distributed with a mean of 2.93×10^{-10} Torr and a standard deviation of 1.02×10^{-10} Torr.

B. Krypton Abundances

A typical scan from the histogram mode of the RGA is plotted in Figure 4. The krypton signal is evident in the peaks around 82, 83, 84, and 86 amu. To check that the RGA is recording the correct partial pressures, the percent abundance for each krypton isotope was calculated and compared with values in the literature which are included in Table II along with the respective percent error. The percent error for the more abundant isotopes falls within 10.0% of the accepted values. However, the error for the isotopes ^{80}Kr and ^{78}Kr appears too large because a closer look at the data reveals that their average partial pressures fall within bounds of the background signal. The rest of the isotopes have signals large enough to be differentiated from the background, and the RGA is detecting reasonable partial pressures.

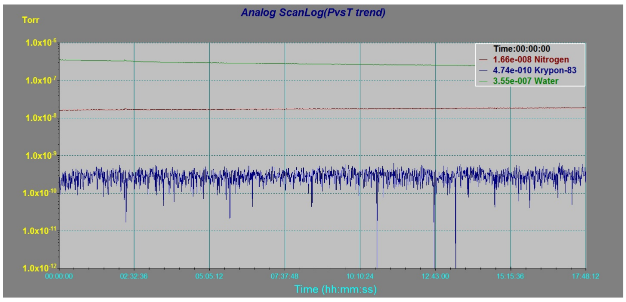

FIG. 3: Background Scan

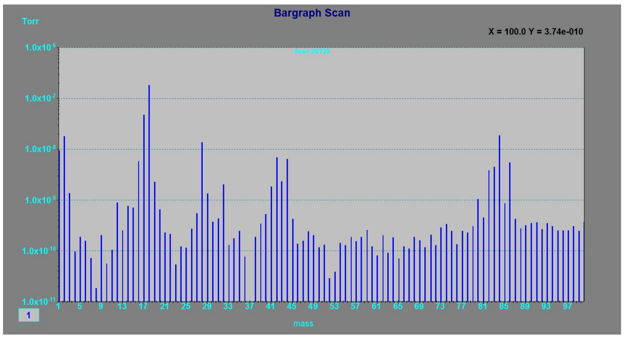

FIG. 4: Histogram Mode

amu	Literature (%)	Measured (%)	% error
84	56.9	55.2	2.9
86	17.4	15.9	8.8
83	11.6	12.8	10.0
82	11.5	12.1	4.8
80	2.3	2.9	27.0
78	0.3	0.1	294.7

TABLE II: Percent Abundance of Krypton

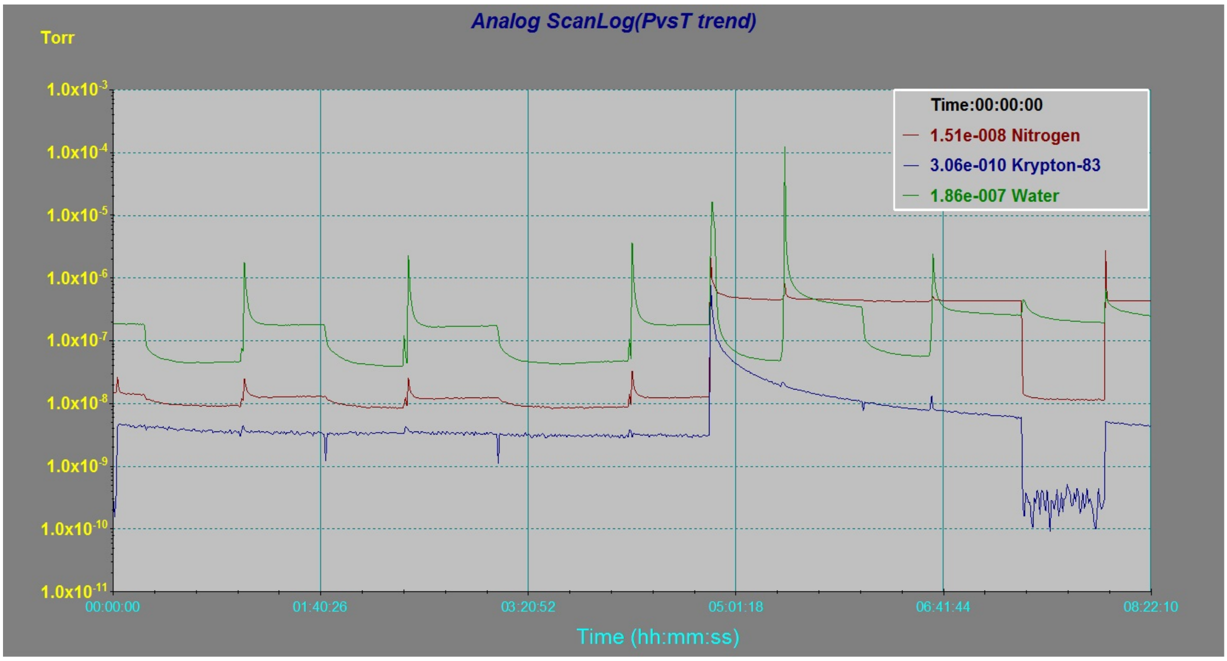

FIG. 5: Pressure vs Time

C. Results

Figure 5 plots the partial pressure over time for nitrogen, water, and ^{83}Kr and continues from the background scan (Figure 3). The pressure for the nitrogen and water are included to serve as reference points for abrupt changes in the system. This is most salient for water which freezes at such pressure ranges and when cooled to 77K. This is most evident at around times like 00:15:00, 01:42:00, and 03:05:00 when the stainless steel tube is immersed in a dewar filled with liquid nitrogen. Nitrogen behaves similarly though at a less pronounced rate. Notice also the small peaks for water and nitrogen near 01:00:00, 02:20:00, and 04:10:00 immediately followed by a much larger spike in the pressure. The small initial increase in the pressures comes from the removal of the liquid nitrogen dewar, and the abrupt increase only happens onces the ice formed on the outer surface of the tubing has melted.

The regulator valve remained closed during all that time to keep the tube at the lowest possible pressure when the valve to the krypton bottle was quickly opened then closed again. Krypton gas accumulated between the regulator and the bottle while letting a small amount of gas through to the stainless tube. This resulted in the order of magnitude increase in the average partial pressure from the background of 2.93×10^{-10} Torr to 3.31×10^{-9} Torr. Excluding the small bumps whenever the tube is cooled to 77K and warmed to room temperature, the overall slight decreasing trend in the krypton partial pressure between 00:02:00 to 04:46:00 is comparable to its behavior when the system is left alone with the vacuum pumps and no cooling.

One would expect the krypton partial pressure to exhibit a similar decline and saturation that the water and nitrogen do if a considerable amount of the krypton gas condenses on the surface of the stainless steel tube. Instead, the krypton pressures makes only makes a small and brief dip to about 1.1×10^{-9} Torr before going back up to the average levels. A possible explanation could be the regulator letting more krypton into the tube to compensate for a pressure drop due to the cooling. It was impossible to quantify this since the total pressures were too low with both the inlet and outlet gauges of the regulator reading 0 bar no matter how the valve is adjusted.

Between 04:48:00 and 07:18:00, the regulator valve was opened to flush the system with the accumulated gases between the bottle and the regulator. This was done to check if the similar behavior occurs when the gas can flow more freely across the regulator. All the gas pressures rose by about two orders of magnitude followed by a quick decline. The same bumps and dips in the krypton pressure is present when the tube is either cooled or warmed. The krypton pressure was allowed to decrease to the same level before the regulator valve was opened, at which point

(07:20:00) the valve was closed tight. Here, the krypton pressure returned to background levels before the introduction of krypton. The pressure differential was insufficient to sustain the previous levels. This implies that the regulator plays a huge role in the pressure levels that the RGA detects.

D. Other tests

The electron multiplier was turned on briefly to verify that the observed behavior was not solely from the Faraday cup. It recorded the same background levels pointing to hydrocarbon contamination. It also found the same minor jumps from the abrupt temperature changes.

At this point, the regulator was replaced by a needle valve. The system again required baking and pumping for a couple of nights before data was taken. Unfortunately, the valve leaked whenever it was not tightly closed or fully opened. So the system was pumped with the valve closed, and once the background was taken, the krypton bottle was opened. The valve, however, stopped any krypton from entering the tube, so no pressure changes were observed. Loosening the valve slightly caused a leak that overwhelmed the RGA's ability to accurately record partial pressures. When krypton was introduced while the valve was fully opened, the krypton partial pressure shot up and quickly disappeared to the background levels. This did not allow for enough time to cool the tubing. Closing the valve to the pump could solve this problem, but the overall vacuum quickly degraded.

E. Estimates for Radioactive Source

The experiment described above was done using a bottle of non-radioactive krypton. The significantly larger volume of the available gas simplified the RGA detection of krypton. However, Project 8 needs the ^{83m}Kr from the decay of ^{83}Rb. Assuming that the gas mixture of ^{83m}Kr and ^{83}Kr from the radioactive ^{83}Rb source behaves as an ideal gas, one could estimate its pressure. The ^{83}Rb source at the University of Washington has an activity of approximately 0.15mCi or 5.5 $\times 10^{6}$ decays/second. Letting the gas accumulate for 3 hours, there should be at most 6.0 $\times 10^{10}$ krypton molecules. Then for an experimental volume of 10L cooled at 77K, the pressure from the ideal gas law is 5 $\times 10^{-11}$ Torr. This is just at the minimum detectable partial pressure of the Faraday cup, so the electron multiplier would be needed to detect such a small signal. Even then, the signal from the hydrocarbons resulting in pressures above 10^{-10} Torr for masses above 50 amu would just as easily hide the krypton pressure. The RGA needs to be much cleaner to detect the radioactive krypton.

IV. CONCLUSION

Both detectors of the RGA showed similar background noise for masses above 50 amu, possibly due to hydrocarbons in the RGA. They were also able to the detect the krypton gas from the bottle. The pressure of the krypton remains fairly constant when the tube is cooled to 77K leading one to conclude that there possibly is no formation of krypton condensation on the surface of the stainless steel tube. If that were the case then as long as one operated at pressures below the vapor pressure at a given temperature, then the krypton gas would not be trapped on the surface. However, the presence of the pressure dips right after cooling and its disappearance implies that it is possible that there is some surface condensation and deposition, but its effects are hidden by a slow influx of gas through the regulator. Further tests is required to demonstrate if this is the case.

Using the radioactive source presents its own problems because the krypton gas it emits will be at pressures lower than those studied here. The pressure is at the level of the Faraday cup's minimum detectable pressure while it will be hidden from the hydrocarbon peaks in the electron multiplier.

[1] J. Angrik et al., Report No. FZKA-7090, Forschungszentrum Karlsruh, 2005, http://bibliothek.fzk.de/zb/abstracts/7090.htm.

[2] B. Monreal and J.A. Formaggio, *Relativistic cyclotron radiation detection of tritium decay electrons as a new technique for measuring the neutrino mass*, Phys. Rev. D 80 (2009) 051301 (R).

[3] AVS Reference Guide: Vapor Pressure Data,

http://www.aip.org/avsguide/refguide/vapor.html.

[4] S. Kakac and Y. Yener, *Heat Conduction* 2nd ed. Hemisphere Publishing, New York, 1985.

[5] Operating Manual and Programming Reference for the Stanford Research System Model RGA100.