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Progress Report on the Los Alamos Tritium Beta Decay Experiment

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ABSTRACT

Measurements near the endpoint of the tritium beta-decay spectrum using a gaseous molecular tritium source yield an essentially model-independent upper limit of 27 eV on the $\bar{\nu}_e$ mass at the 95% confidence level. Since demonstrating from this initial measurement the successful operation of a gaseous source based system, most of our effort has been concentrated towards the upgrade and optimization of the experimental apparatus. The emphasis of this work has been to eliminate or further reduce effects that generate systematic errors. Based on realistic projections from our initial measurement, an ultimate sensitivity to neutrino mass of 10 eV is expected.

1. Introduction

During 1986 an initial measurement using the Los Alamos gaseous molecular tritium source achieved a limit of 27 eV (95% CL) on the electron antineutrino mass[1]. A key reason for being able to set this essentially model independent limit was the employment of a gaseous molecular tritium source. The clear advantage of using such a source in tritium beta decay measurements is that the atomic final states populated during the decay of the tritium molecules (or atoms) are simple and well understood. A precise knowledge of any source's final state spectrum is prerequisite in determining an unambiguous and model independent value or limit on the neutrino mass. Additional advantages unique to a gaseous source are the elimination of backscattering and surface contamination that add uncertainties to solid source based measurements.

Although on physics grounds there are only advantages to using a gaseous source, it is technically complex to produce a source of sufficient intensity. Because of the complexities involved in building and operating a free gaseous source, our initial measurements were carried out with several simplified components in order to demonstrate the proof-of-principal operation of such a source. Having demonstrated the successful operation of the key elements of the measurement system and having successfully completed the acquisition and analysis of our initial data, we have now embarked on a program of upgrades and optimization of our experiment. We are also involved in ancillary measurements involving our $^{83}Kr^{m}$ calibration source to reduce the errors associated with its absolute decay energy as well as its line shape (atomic final states). Although most of the upgrades to be discussed were planned well before the initial data taking was started, there is no substitute for knowledge accrued during the operation of the actual system. Several additional improvements were implemented based on these experiences.

2. Experimental Apparatus

In order to better understand the upgrades and improvements that have been and are being implemented, the experimental apparatus that has been described in detail elsewhere[2] will be briefly described here. Molecular tritium enters a 3.7-m long, 3.8-cm inner diameter aluminum tube at the midpoint and is pumped away at the ends and recirculated. The source tube is located inside a superconducting solenoid so that betas from the decay of tritium spiral along the field lines without scattering from the tube walls. In the initial measurements the tube was held at approximately 160 K to increase the source strength and was uniformly biased to typically -8 kV. The equilibrium density of tritium in the source integrated along the axis during these measurements was 6.9×10^{15} tritium molecules/cm^2. At one end of the source, electrons are reflected by a magnetic pinch and at the other end are accelerated to ground potential. A hot filament located at the pinch emits thermal electrons that neutralize the space charge of positive ions trapped in the source. The betas are transported through a pumping restriction where the tritium is differentially pumped away. Then the betas are focused by nonadiabatic transport through a rapidly falling magnetic field to form an image on a 1-cm diameter collimator at the entrance to the spectrometer. The collimator defines an acceptance radius in the source tube such that decays originating more than 6.4 mm from the axis are not viewed by the spectrometer. A Si detector is located at a position where it intercepts a small fraction of the betas from decays in the source tube and serves to normalize the source strength. The spectrometer is a 5-m focal-length toroidal beta spectrometer similar in concept to the Tretyakov instrument[3], but with a number of modifications[2]. The earth's magnetic field is canceled to a level of <10 mG in the spectrometer volume by external coils. Betas from a 2.2-cm^2 area in the source tube are transmitted with about 1% net efficiency through the entrance collimator to a focal plane detector located at the focus of the spectrometer. The beta spectrum is scanned by changing the voltage applied to the source tube so that betas of constant energy are analyzed by the spectrometer. Accelerating the betas not only improves the emittance of the source, but also raises the energy of betas of interest well above backgrounds from decay of tritium elsewhere in the pumping restriction or spectrometer. The beta monitor (Si detector) is biased at the same voltage as the source tube.

In the initial measurement a position sensitive proportional counter 2 cm in diameter with a 2-mm-wide entrance slit was used. The energy resolution for 26-keV electrons was 20% and the position resolution 6 mm FWHM (position information was used to reject backgrounds outside the slit acceptance). The effective integral event rate in the last 100 eV was typically 0.12 counts/sec.

3. Hardware Upgrades and Improvements

The goal of our upgrade program is to ensure that the sensitivity of the experiment to neutrino mass will be 10 eV. We would like this limit to be determined primarily by the statistics and background and not by systematic uncertainties. For our initial result, the uncertainty due to statistics is four times larger than the systematic uncertainty. Given infinite statistics, systematic uncertainties would limit our present sensitivity to about 11 eV. As we will discuss, several of the dominant factors comprising this 11 eV systematic uncertainty have now been eliminated. Work is also underway on a new focal plane detector which should allow us to increase the count rate while reducing the background.

3.1 Source related improvements

In our initial measurements the superconducting solenoid enclosing the source was run in a uniform magnetic field configuration. However, in this configuration some of the electrons, 11.7(10)%, were trapped in the source by local field minima. These electrons could exit the source tube only by multiple scattering with the source gas. Although the percentage of electrons trapped in this field configuration could be calculated, the error in estimating this effect produced the major systematic uncertainty in our initial measurement. We have introduced a monotonic field gradient along the source, thus eliminating any trapping of betas in the source. This was possible because the superconducting solenoid magnet actually consists of 24 separate coils. A hexfet-technology based current-control system was constructed to achieve the gradient field.

Measurement of the instrumental resolution function with the $^{83}Kr^m$ calibration source[1,2] has verified that the electron trapping has been eliminated. Two other ancillary effects of utilizing a gradient field should be mentioned. The single scattering probability is reduced from about 6.5 to 5.0% since the betas have a shorter average path length as they spiral out of the source. The extraction efficiency of betas emerging from the source is reduced by ~25%.

Another area of the source that has been improved is the Kr recirculation system. In tritium measurements a Pd filter is used to allow only tritium gas to recirculate and thus eliminate the buildup of (and subsequent energy loss in) residual gases. However, the Pd filter only allows hydrogen isotopes to pass and thus could not be used during the Kr measurements. In our original Kr measurements the energy loss in the residual gas had to be calculated and accounted for in order to extract the proper instrumental resolution function. We have now installed a getter pump in the vacuum system which operates while krypton resolution measurements are underway. This getter pump will not pump noble gases such as Kr, but does eliminate the residual gas (N_2, O_2, as well as any tritium present). The use of this system has now eliminated energy-loss contributions in the observed resolution function.

The upgrade of the Si beta monitor detector system used for monitoring the total activity of the source is another source related improvement. Tritium buildup (during vacuum system shutdowns) on the original Si detector had reduced its effectiveness. A vacuum interlock and chamber for the Si detector has been added that allows the insertion of the Si detector into the main vacuum system only when needed during data taking. In addition, an improved Si detector was obtained and installed along with a 2-3 times lower noise fiber optic communication link. These improvements should reduce the error associated with pressure variation renormalization to a negligible value.

Finally, an unreliable and high maintenance freon chiller system used for cooling baffles on our mercury diffusion pumps was replaced with a simpler alcohol recirculation system. This system is very reliable and has substantially reduced unscheduled maintenance as well as eliminated occasional system shutdowns generated from failures of the freon based system.

3.2 Spectrometer improvements

In the quest to understand our spectrometer's acceptance and resolution better, detailed systematic measurements of the spectrometer resolution function were undertaken as a function of spectrometer acceptance and azimuthal angle. Several modifications and improvements were instituted based on these studies. For example, one disturbing aspect of our initial instrumental resolution function was the presence of a high-energy tail. The acceptance-angle based measurements revealed that this high-energy tail was produced by the magnetic field perturbations generated at the current-coils attachment points. Placing small baffles around these points completely eliminated the high-energy tail.

The azimuthal angle measurements indicated that the peak energy centroid was shifting as a function of angle, thus smearing out the spectrometer resolution function. It is thought that these shifts are a result of magnetic field non-uniformities, most probably caused by the presence of iron in the building. By dividing the spectrometer current loops into 12 individual segments, a linear least squares calculation could be performed to minimize the centroid shifts by adjusting the current in each of the 12 loops by the necessary amount. The system was then implemented simply by adding externally adjustable current shunts to the loops. The addition of this system helped optimize the spectrometer acceptance with no degradation of resolution. Finally, a careful realignment of the spectrometer was undertaken which resulted in an increased acceptance.

3.3 New Focal Plane Detector

The original position sensitive proportional counter focal plane detector was selected on the basis of simplicity, availability and cost.

Although limited in both energy and position resolution, this detector did have the virtue of simple interpretation in our initial data analysis. Work has now advanced on a 96-pad silicon microstrip focal plane detector system. The detector is an octagonal arrangement consisting of 8 wafers, as schematically shown in the figure 1. Each of the sapphire substrate carriers contains a 300-micron thick silicon microstrip wafer of 12 pads, .8 mm wide, covering an active area of 8 mm^2.

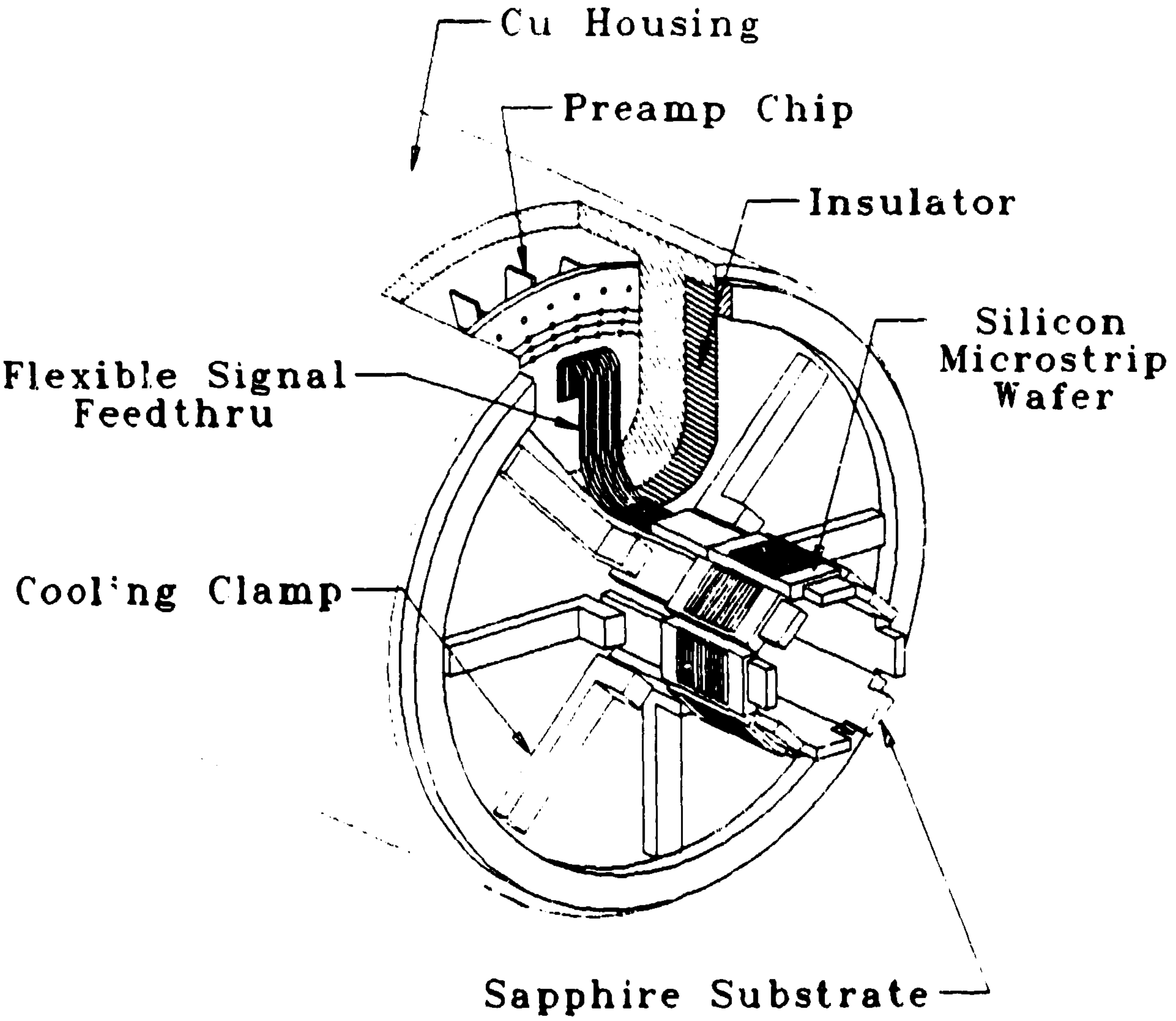

Fig. 1. Schematic representation of the microstrip focal plane detector. For clarity, the gas veto counter is not shown.

This detector, which has 7.5 times better effective position resolution than the proportional counter, should increase the count rate by a factor of four with improved energy resolution (10-15% FWHM at 20-25 keV). In our proportional counter, cosmic ray events constituted the major background because of the poor discrimination between betas and minimum ionizing radiation. However, the microstrip detector has improved rejection of background minimum ionizing radiation, which deposits much more energy than the betas of interest. As an additional precaution a gas proportional veto counter will be located in the center of the octagonal array to reject cosmic ray events.

The observed instrumental resolution will be improved by using the microstrip detector. The first reason is that with improved energy resolution and lower backgrounds it should be possible to run at lower incident electron energies of 22 keV instead of 26 keV. Since the width of the resolution function scales as the total energy of the particles being analyzed, one could gain ~13% from measuring at the lower energy. Another advantage of the new focal plane detector is that it has azimuthal angle resolution. As was earlier mentioned a shifting of the peak centroid as a function of angle was observed. The built in azimuthal resolution should allow for better corrections than the present method of using current compensation in the spectrometer coils. Finally, the improved position resolution (0.8 instead of 2.0 mm) will reduce that component of the total resolution function.

The detector related electronics starts with 32 Rel-Labs triple preamplifier chips located within a few centimeters of the wafers. The 96 signals are then brought out to a custom built amplifier and multiplexer box. There each pad has a biased shaping amplifier and an ECL logic generation circuit. The 12 analog signals associated with each wafer are multiplexed into a single channel and input into a commercial peak sensing ADC in CAMAC. All 8 wafers have analog multiplexer circuits and ADC channels. The ECL logic signals are input into a commercial CAMAC based 96-channel event register. Events of all possible multiplicities are registered and recorded in event mode by the PC computer based data acquisition system. Construction of the preamplifiers, the shaping amplifiers, the discrimination circuits, and the logic electronics has been completed.

A preliminary batch of 7 wafers has been fabricated at Lawrence Berkeley Laboratory. Although it was known that these preliminary wafers did not meet specifications, they were installed for debugging the electronics and computer data acquisition systems. These systems have now been successfully implemented and tested. Tests of energy resolution and number of live pads have been completed for the 7 wafers. The average number of live pads per wafer is 10 and the typical resolution is 3 keV at 60 keV. These results indicate that this preliminary microstrip detector is clearly superior to our original gas proportional counter which had a resolution of about 5 keV. The installation of this detector in the spectrometer has just commenced. The plan is to acquire both Kr and tritium data in order to develop data reduction and analysis techniques with the new detector system.

4. Optimized Data Acquisition Procedures

Having acquired our initial data it was possible to use the techniques expounded by Audi *et al.*[4] to determine the significance of each data point to the overall fit. By determining the relative importances and significances as a function of energy one can then optimize the time spent at each energy in order to maximize the sensitivity to fitted parameters. The result of implementing such a run scheme is that we can now achieve the same statistical accuracy on the neutrino mass in one fourth the time compared to our original method of spending equal time at each point.

5. Kr Calibration Source Measurements

A K-conversion electron line from gaseous $^{83}Kr^m$ is used for two separate purposes in our experiment; to calibrate the energy scale of the spectrometer and to determine the instrumental resolution function of the system. The energy of this electron line, 17835 eV, was previously known[5-7] to only 20 eV, corresponding to the uncertainty in energy, E_{32}, of the gamma transition at 32160(20) eV. We have recently completed new measurements, described in detail elsewhere[8], using a Si(Li) solid state detector that determine the energy of the E_{32} line to be 32147.6(24) eV. The Si(Li) detector was calibrated by using an ^{241}Am source which has lines at 26345.0(10) eV, at 59537.0 (10) eV, and a crossover transition line at 33192.0(14) eV[9-10]. The calibration was verified by measuring the energies of the $^{137}Ba^m$ X-ray doublet located at 32193.6(5) eV and 31817.1(5) eV[11]. The measurements of the $^{137}Ba^m$ doublet agreed to within 1.8 and 0.7 eV respectively, well within the experimental error bars. Based on the E_{32} line, the new work yields a K-shell conversion electron energy of 17820.4(25) eV which implies an endpoint energy for tritium decay of 18569.2(32) eV from the initial Los Alamos tritium beta-decay measurements.

A systematic check important to the determination of the tritium endpoint energy was also performed. The tritium endpoint energy determination is based on calibrations performed using the Kr source before and after a tritium measurement. However, during tritium measurements, there are about 5 x 10^7 decays/sec whereas for the Kr source measurements there are only 2 x 10^3 decays/sec. This calibration procedure is valid only if the space charge neutralization is equally complete for the two distinct measurements. An incomplete neutralization of the space charge during the much higher decay rate tritium measurement could introduce a systematic offset in the tritium endpoint energy. However, Kr resolution measurements performed with a mixture of the Kr and tritium gas, at identical pressures used during normal tritium measurements, revealed no shift in the Kr K-conversion line centroid energy.

After completing the hardware upgrades discussed in sections 3.1 and 3.2, high statistics studies of the instrumental resolution function were undertaken using the ^{83}Kr^m source. These measurements revealed a quite small (~10% total area) but long tail (~400 eV) on the low energy side of the resolution function. A continuum tail of this nature is not predicted from calculations, but was recently observed in a photoionization measurement of neon[12]. A tail of this magnitude, if attributed to the instrumental resolution and not the Kr source, can significantly influence the derived neutrino mass value. Measurements of the Kr line at several spectrometer energies indicate that the tail is associated with the atomic physics processes of the Kr source. Further confirmation of this was obtained by biasing the source tube to 19 keV and observing the resolution function from essentially moncenergetic thermal electrons emitted from the residual gas in the source. This resolution function had no low energy tail. However, it was realized that to eliminate possible systematic errors, an accurate determination of this tail could best be performed by making photoionization measurements on Kr using a synchrotron light source. Thus, a collaboration with scientists at the Stanford Synchrotron Radiation Laboratory (SSRL), LLNL, and the University of Oregon was formed and a proposal for such a measurement was submitted to the SSRL program advisory committee. The proposal was recently approved and run time to perform the experiment is expected during the summer of 1988.

6. Conclusions

With completion of the upgrades and measurements as discussed above, the major systematic uncertainty in the Los Alamos experiment should arise from the width of the total resolution function (spectrometer instrumental resolution function convoluted with the source energy loss distribution). Although our total resolution was modest ($\sigma^2 \sim 540$ eV^2 for the energy range of +50 to -150 eV) during our initial runs, we expect to improve it to better than 250 eV^2 in future runs. (We note here, that the variance is a somewhat more useful parameterization for skewed distributions than the FWHM parameterization, which is essentially meaningless.) It is important to realize that in our experiment the uncertainty in determining the total resolution function is less than in the experiments using solid sources. This is because the energy loss contribution to the total resolution function is substantially smaller with our gaseous source than with solid sources. In summary, the sensitivity limit from systematic effects in our experiment is expected to be at the level of a few eV.

The present schedule calls for acquiring high statistics tritium data with the upgraded system during the summer and fall of 1988. With these data and the completion of the Kr photoionization measurements a 10-eV neutrino mass should be revealed in a model independent manner.

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