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TITLE: THE LOS ALAMOS FREE MOLECULAR AND ATOMIC TRITIUM BETA DECAY EXPERIMENT

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THE LOS ALAMOS FREE MOLECULAR AND ATOMIC TRITIUM BETA DECAY EXPERIMENT

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ABSTRACT

An initial measurement of the tritium beta decay spectrum spanning an energy range of 16.4 - 18.9 keV has been performed using a free molecular tritium gas source. With the data from this preliminary low statistics measurement (~72 hours of data), we are able to set an upper limit on the electron-antineutrino mass of 36 eV at the 95% confidence level. Measurements with a gaseous source eliminate many of the ambiguities arising from uncertainties associated with solid-source based measurements. The ultimate neutrino mass sensitivity of our system should be about 10 eV or less

1. Introduction

The existence of a non-zero electron-antineutrino mass as reported by Lubimov *et al.*[1] would have important consequences in our understanding of physics. A neutrino with mass could account for the dark matter observed in the universe. Many current theories in cosmology require non-baryonic dark matter. Also, in most realistic grand unified theories neutrino masses are quite natural. Thus, it is of critical importance to confirm or refute this result. Unfortunately, the selection of a tritiated complex amino acid, valine, as the measurement source has raised doubts about the current results. With the goal of making the most unambiguous measurement of tritium beta decay possible, a free molecular and atomic gaseous source and a high-resolution iron-free magnetic spectrometer have been constructed at Los Alamos. This system will be described along with the presentation of preliminary results from measurements of the beta spectrum of free gaseous molecular tritium.

2. Measurement Requirements

There are many important factors to consider in designing a tritium beta decay experiment that is capable of determining a neutrino mass of order 30 eV or less. The energy region of the beta decay spectrum which is sensitive to the neutrino mass is the region of about the same size as $m_\nu c^2$ directly below the endpoint energy. There are two consequences of this small region of sensitivity which impact any measurement. First, the count rate near the endpoint will be very small: for example, in the last 100 eV below the endpoint in tritium the decay branch is about 2×10^{-7} of the total decay. Thus, a source of reasonable strength and a measurement system that is efficient and has a good signal-to-background ratio is demanded. The second difficulty results from the small energy region of sensitivity to neutrino mass. Sensitivity to neutrino mass effects in the beta spectrum requires that the total system energy resolution should be comparable to $m_\nu c^2$. Note that the total system resolution is a convolution of the instrumental resolution and the source-related resolution functions. When comparing different experiments it is important to consider the total system resolution and not just the instrumental (spectrometer) resolution.

Thus, source strength, apparatus transmission, background, resolution, and systematic effects must be carefully considered in designing an experiment that is sensitive to neutrino mass. For the Los Alamos experiment we chose to build a Tretyakov type high-luminosity

magnetic spectrometer and to employ an intense gaseous tritium source. The next two sections will detail the reasons for selecting this arrangement and describe the experiment.

3. Properties of a Molecular or Atomic Gaseous Tritium Source

The principal reason for using a gaseous source of free atomic or molecular tritium is that it is the simplest possible system. This eliminates the numerous uncertainties and complications that arise in analyzing data obtained from a solid source. As we shall show, the price one pays for having the simplest data to interpret is that the experimental apparatus necessary to produce a gaseous source and measure the tritium beta spectrum is much more complicated than for a measurement based on a solid source.

There are several clear advantages to using a free gaseous source. First, the source resolution function is the narrowest possible. In a gaseous source the sole contribution to the source resolution function is the energy loss of electrons in the source. But, since a pure tritium source has the highest specific activity per unit mass of any source, then the source thickness and corresponding energy loss is the minimum possible. For all solid sources, except solid tritium, the energy loss per unit activity of tritium must be greater. Another advantage of a gaseous source is that the resolution function resulting from source energy losses can be carefully studied as a function of source thickness. This is because the source thickness is simply determined by the gas pressure in the source region and in our system it is trivial to adjust this pressure.

In addition to the energy-loss mechanism, solid sources have two additional processes which contribute to the source resolution function. One additional resolution smearing process is backscattering from the source backing substrate. The other effect is energy loss from contamination on the front surface of the source. There are ways to minimize the contribution from backscattering and contamination, but these effects are impossible to eliminate.

Another critical reason for choosing a gaseous source of pure tritium is that the so called "final state effects" are minimal and well understood. When a tritium atom decays to a $^3He^+$ ion there is a probability of populating any of the energetically allowed final atomic states of the daughter $^3He^+$ ion. In order to extract a neutrino mass from a tritium beta decay spectrum accurately it is necessary to know precisely

the branching ratios and energies for all possible final decay states and include this in the analysis. This is essential because the reported neutrino mass is of the same order as the binding energy of electrons in ^{3}He. Since the transition to each atomic state has a different endpoint, the shape of the total spectrum is complicated. Hence when experimental resolutions are folded in, the spectrum can resemble a decay with different branching ratios and a massive neutrino. The only cases for which the decay probabilities can be accurately determined are for atomic tritium ($T \rightarrow {}^3He^+$) and molecular tritium ($T_2 \rightarrow T^3He^+$).

For the simplest case, free atomic tritium decaying to a $^3He^+$ ion, the calculation of branching ratios and final states can be done to great accuracy[2] using the "sudden approximation" wherein the nuclear charge is assumed to change abruptly by one at the instant of β decay (Fig. 1). Recently, more difficult calculations of comparable accuracy to the atomic case have been performed[3,4] for molecular tritium (Fig. 2). In comparing the decay probabilities for the two cases it is obvious that in going from the atomic to the molecular case the branch to the ground state is reduced significantly and that the complexity of the decay scheme is increased. Obviously, the decay schemes from tritium in complex molecules or implanted into solid sources are even more complicated. Unfortunately, calculations of the final states for any systems other than atomic or molecular tritium are much less certain. The final states for many solid sources are for practical purposes impossible to calculate and require making some assumptions or approximations to simpler structures. For most experiments employing complicated molecular solid sources or sources of tritium implanted into solids, the uncertainty in knowledge of the final state effects is the dominant uncertainty in the measurements.

Using a gaseous source of tritium makes for a simple and clean interpretation of the beta decay spectrum, but does introduce certain difficulties into the actual measurement. Fortunately, these problems can all be solved by careful design of the experiment's apparatus. Obviously a gaseous source will be of low density and, thus, thin with low activity. But by building an extended source region with good extraction efficiency of the betas that decay in the region, one can overcome the low density problem. Another potential problem is that of source strength (pressure) fluctuations. It is impossible to have a constant source pressure, but by having a monitor system that measures the source activity at the same time as the beta spectrum measurement it is possible to know the source strength

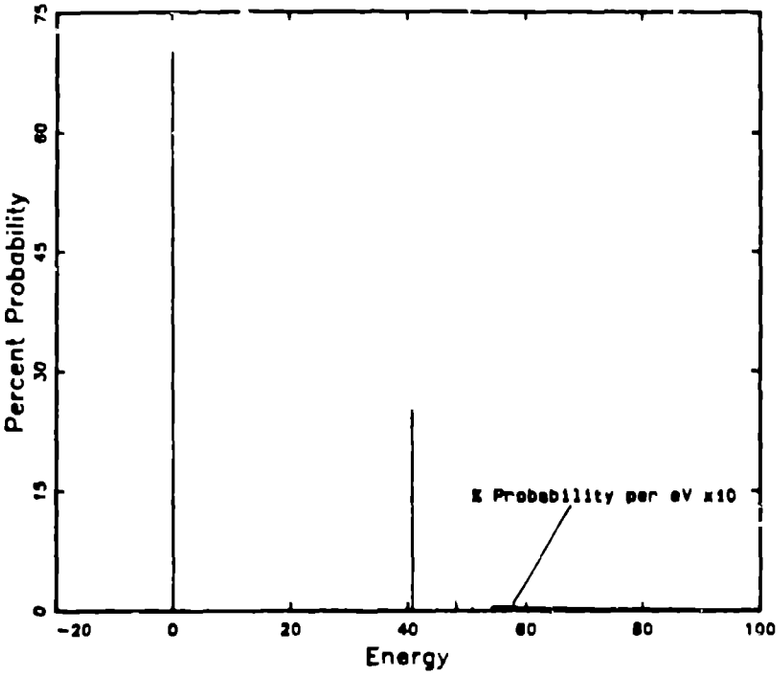

Fig. 1 Decay probabilities for $T \rightarrow {}^{3}He^{+}$ atomic final states versus energy of states. The continuum decay probabilities are multiplied x 10.

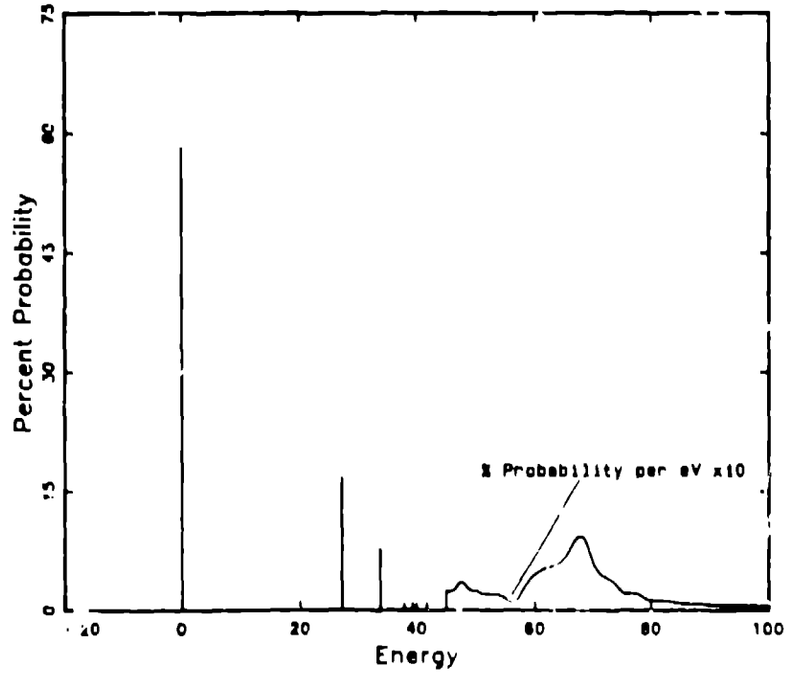

Fig. 2 Decay probabilities for $T_2 \rightarrow T^{3}He^{+}$ molecular final states versus energy of states. The continuum decay probabilities are multiplied x 10.

to great accuracy. One would also expect that contamination of the energy analyzing system would be extremely likely with a free gaseous source. However, as we will show in the next section, this problem is also solvable.

Finally, it is critical in any tritium experiment to be able to make an accurate determination of the total resolution function of the system. Obviously, the resolution of an extended gaseous source is not expected to be the same as for a solid source or an electron gun. There is, however, an ideal gaseous line source available. The short-lived (1.8 hours) ^{83m}Kr isomer, a daughter of 83-day ^{83}Rb isotope, has a narrow conversion line at 17.84 keV. The energy at which this line occurs is well matched with the energy region being measured in the tritium beta decay. Thus, it is possible to determine the instrumental resolution function by using this source and running under conditions essentially identical to those of the tritium source. It is also possible to determine energy loss in the source by mixing the Kr source (which has a negligible thickness) with either hydrogen or deuterium gas and observing the effect on the total resolution. Hence, the total resolution function for the entire measurement system can be experimentally verified.

4. Overview of the Los Alamos Experiment

A schematic view of the Los Alamos experiment is shown in Fig. 3. The apparatus can be divided for discussion purposes into three distinct sections: a source region, a pumping restriction and extraction section, and a toroidal magnetic spectrometer. The extended source is required to reach a sufficient source intensity. Placing this source in a strong axial magnetic field with a pinch at one end allows the extraction of most of the betas from the tritium decays into the extraction region. The pumping restriction and extraction region serves two purposes: to stop tritium molecules from reaching the spectrometer and to focus the betas emerging from the source region into the spectrometer. The toroidal spectrometer analyzes the momentum of the betas, allowing a precise measurement of the tritium energy spectrum near the endpoint.

a. Atomic and molecular source

The source decay region consists of a 3.86-m long 3.8-cm diameter highly polished aluminum tube which is pumped by Hg diffusion pumps located at each end. When running with atomic gas, molecular tritium at 300-mT pressure enters a Pyrex discharge tube where the molecules are dissociated

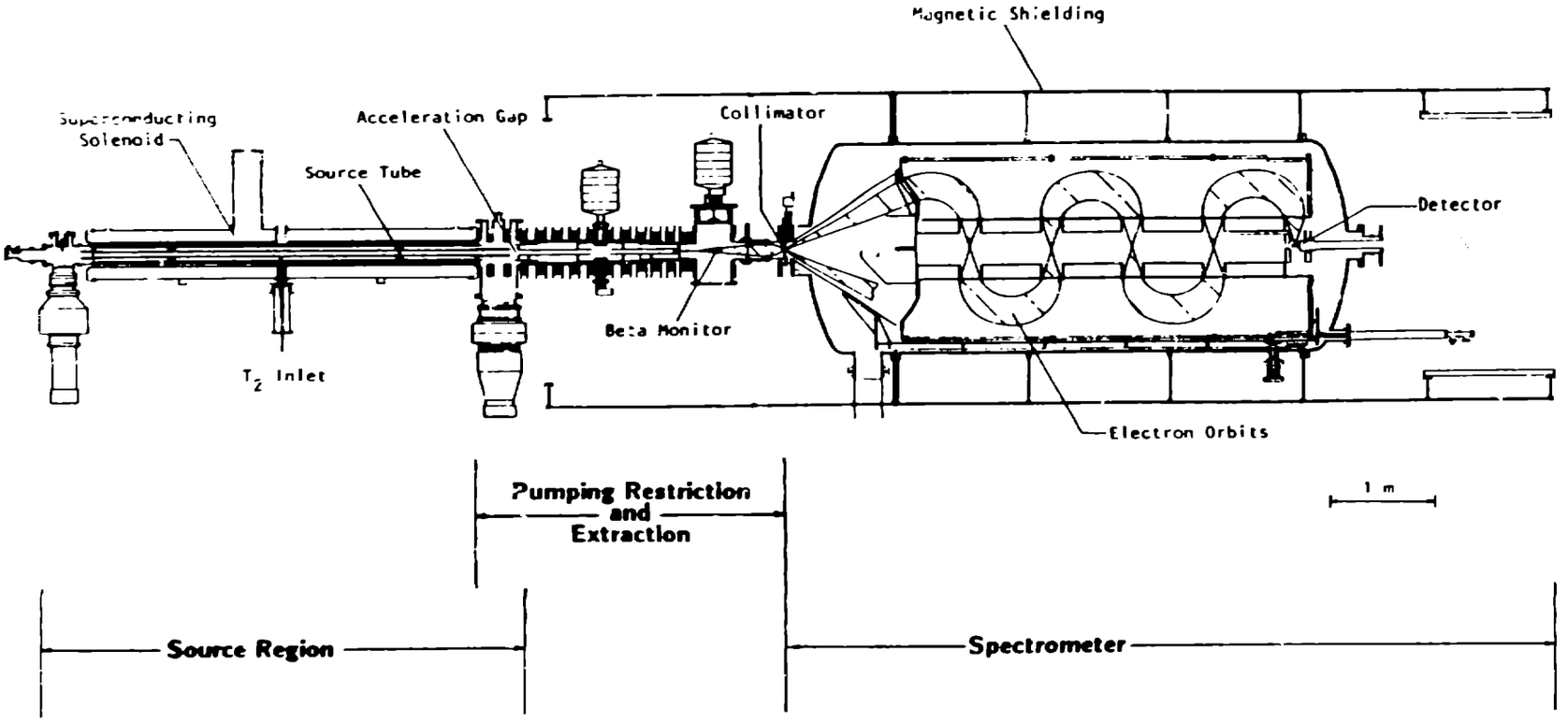

Fig. 3 Cross-sectional view of the Los Alamos gaseous tritium beta decay experiment.

in an RF discharge. The tritium atoms emerge through a small orifice into the source tube at the midpoint between the two pumps. The highly polished aluminum tube's surface has a thin layer of aluminum oxide which inhibits recombination. For hydrogen and deuterium, we have made measurements of recombination rates on aluminum at cyrogenic temperatures. Typically at 140K a hydrogen or deuterium atom can undergo 50,000 "bounces" before recombining. Tritium is not expected to behave very differently.

An equilibrium density of atomic T is built up as established by the influx and the conductance of the tube. The average atom bounces approximately 4,000 times on the walls before being pumped away, so recombination is small. The equivalent source thickness integrated along the axis is conservatively estimated to be 10^{15} - 10^{16} tritium atoms/cm^2 of 85-90% pure atomic tritium. The presence of a molecular component (10-15%) in the source gas is inevitable and not a serious problem if steps are taken to monitor and correct for it. The experimental molecular spectrum can be scaled and subtracted from the total atomic-plus-molecular spectrum to obtain a pure atomic spectrum. The molecular-to-atomic ratio must be known and will be measured by UV absorption spectroscopy. For measurements of the molecular tritium spectrum, the same system is used except that the RF dissociator is turned off. The source strength for molecular tritium can be 5 times higher than atomic, and is limited only by the energy loss in the source gas that can be tolerated.

The source region is in a solenoidal magnetic field of about 1.5 kG with a small axial gradient. The electrons are constrained to spiral about the field lines ($B\rho \leq 463$ Gauss-cm). At one end of the solenoid a pinch coil with a peak field of about 4 kG reflects most of the β's that start with a velocity component directed towards that end; as a result about 90% of the β's reach the weak field end of the solenoid. Sapphire standoffs allow the aluminum source tube to be thermally regulated to minimize recombination, but electrically isolated, so that the potential of the entire decay region can be varied up to 20 kV. (This bias is applied with a highly stable power supply and accurately measured with a voltage divider certified by two independent standards laboratories to be accurate to 2 V at 20 kV.) The biasing of the source tube allows the electrons emerging from the weak field end of the tube to be accelerated through a potential of typically 10 kV.

This acceleration is one of the critical features of the experiment. By biasing the source tube, the betas that decay in the source region are

accelerated when they emerge into the extraction region. This energy gain is never compensated by deceleration later in the apparatus. Hence, the betas decaying in the source region can be differentiated from background tritium decays that occur elsewhere in the system. The second advantage of acceleration is that the spatial component of phase space is reduced. Thus, not only is the background in the region of the shifted endpoint far lower than it would be at 18 keV, but the emittance of the beam is improved. The price paid is, of course, that higher resolving power is required in the spectrometer.

One final feature to note in the source region is the placement of a hot filament in the region of the magnetic pinch. A mechanism exists whereby the source potential might be altered by the space charge built up from positive ions remaining from decays in the source. These ions are effectively trapped by the magnetic field and the potentials at the ends. But thermal electrons emitted from the filament will neutralize these ions. The emission of electrons is self-regulating and depends on the space charge built up in the cell. This prevents the space charge from exceeding 1 V.

The acceleration of betas emerging from the weak field end of the source is accomplished at an acceleration gap located between the source tube and pumping restriction. Spectrum distortion can result from tritium decaying in the acceleration region. However, the fraction of detected decays occurring in the acceleration gap is less than 10^{-3} of the accepted decays from the source region.

Scanning the beta spectrum can be performed in several ways, but the preferred method is to vary the potential of the source tube while maintaining all magnetic fields fixed. While this causes a (smooth) energy-dependence of extraction efficiency, the advantage of presenting the extraction lens, spectrometer and focal plane detector with fixed-energy particles is considerable.

b. Pumping restriction and extraction region

The pumping restriction and extraction region is a differential pumping system that allows a windowless source while limiting tritium contamination of the spectrometer to 0.4 mCi/day. The accelerated beta particles from the source are focused to a collimator located at the object of the spectrometer. The collimator limits the acceptance of the spectrometer so that betas that emerge from or strike the source walls can

be rejected absolutely, independent of aberrations or imperfections in the electron-optical system. This is most important because a monolayer of adsorbed tritium would represent 3 orders of magnitude more activity than the gaseous source.

c. Spectrometer

Our spectrometer design was based on considerations of resolution, acceptance, background, and ease of injecting betas from a gaseous source. The resulting toroidal, iron-free, spectrometer (fig. 3) is similar to that of Tretyakov[5], but differs in a number of respects. First, electrons enter at an angle of $(24 \pm 5)^{o}$ to the axis because they are essentially injected from a beam instead of emerging from a solid source. Also, several significant improvements over the original Tretyakov design were incorporated in our spectrometer. By using curved non-linear conductors third-order aberrations that degrade the resolution were corrected for yielding a factor of 3 increase in solid angle and improved resolution. Another improvement is the use of thin copper strips (0.5 x 13 x 170 mm) to carry the current where electron orbits cross the axis. Use of these thin strips rather than thick water-cooled conductors allows approximately 75% of the electrons to be transmitted to the focal plane (compared to 4.5% in the original Tretyakov design). The spectrometer itself accepts 53% of the incoming cone of rays. Other transmission factors include detector efficiency (75%) and losses at the magnetic pinch (90% of 4π source is available). These factors lead to a calculated luminosity of 0.14 cm^2. The intrinsic resolution, $E/\Delta E$, of the spectrometer is at present about 1100.

To realize the full capabilities of the spectrometer it is necessary to reduce the influence of external magnetic fields, particularly the earth's field. The permissible transverse field is small, approximately 10^{-2} G, but rather large axial fields (0.1 G) can be tolerated. To achieve this level of magnetic shielding, an active shield comprised of two sine coils (conductors spaced around the vacuum vessel and driven in proportion to the sine of the angle from the transverse field direction) with fluxgate magnetometers to provide feedback to the coils is used. Detailed measurements of ambient and local variations of the magnetic field in the building where the spectrometer and source are situated, together with measurements of spectrometer resolution as a function of beta energy, indicate that this system provides the necessary transverse shielding.

The focal-line detector used in the spectrometer is a gas proportional counter with both position and energy sensitivity. In our present detector, 26 keV electrons are detected with an energy resolution of 20% and a position resolution of 4.0 mm. The efficiency (peak-to-total ratio) and the background count rate are 75% and 0.004 counts/sec, respectively.

Although the spectrometer does have a focal line length of a few resolution widths, it is essentially a point-by-point device. As mentioned earlier there will certainly be intensity fluctuations of the gaseous source. Thus, a satisfactory means of normalizing the intensity during each measurement point is required. This is accomplished by using a solid-state detector (Beta Monitor in Fig. 3) to detect a small fraction of betas which have been accelerated from the source before they are focused onto the spectrometer entrance collimator. As the spectrum is scanned by varying the source potential, it is necessary to float this solid-state detector at the same voltage as the tube to eliminate any variation of detector efficiency that might affect the normalization.

5. System Performance and Resolution Measurements

The entire system became fully operational and the first beta spectrum from a T_2 source was measured in June 1985. A variety of different tests and calibrations to study the electron-optical characteristics of the system has been performed to verify and accurately determine the system parameters. The initial transmission, resolution, and background performances of the system will be presented below. However, please note that in many cases these initial results are not the final values we expect to achieve.

a. Apparatus Transmission

From ray-tracing calculations we expect that about 25% of the effective source area can be extracted with very simple electron-optical design. Measurements with a solid ^{103}Ru source give a 25% focusing efficiency, in agreement with the calculations. However, measurements with the extended gaseous ^{83m}Kr source give a total extraction efficiency times spectrometer transmission a factor of three lower than calculated. This discrepancy is currently being studied.

At present, we vary the acceleration of the betas from the source to scan the beta spectrum, and leave the spectrometer at a fixed energy to accept 26 keV betas. The initial observed resolution width of the gaseous ^{83m}Kr isomer in the source was 65 eV FWHM (Fig. 5). Calculations were performed to deconvolute the intrinsic line width[6] of 2.26 eV and shake-up and shake-off effects[7,8,9] from the observed resolution. From our calculations we derive an instrumental resolution of 54 eV FWHM for the total system (Fig. 6). Note that care is needed to ensure that the linewidth, shake-up, and shake-off effects of the Kr source are known to sufficient accuracy. More detailed calculations and experimental studies using synchrotron light are also planned to verify these data.

The molecular tritium spectrum presented in this paper was taken with this 54 eV FWHM instrumental resolution. However, after these data were taken some modifications to the system were implemented and now an instrumental resolution of 37 eV FWHM has been achieved. While this is acceptable for initial data acquisition, we will continue to work to improve the resolution.

For the present molecular tritium data, the other component to the total system resolution, namely the energy loss of betas in the source, is negligible. The source thickness in these early measurements is extremely small, approximately 10^{-3} μg cm^{-2}. However in calculating the energy losses, the effective path length of the betas in the B-field must be taken into account since some electrons can travel up to 40 m in the source gas while spiraling around the field lines. Nevertheless, even for the electrons that travel farthest, the average energy loss is only about 0.5 eV. Fortunately, detailed measurements of inelastic cross sections for electrons on H_2 have been made, and even the small energy loss expected can be corrected. Actual resolution measurements using the Kr line source mixed with hydrogen or deuterium gas to achieve the source pressure used during tritium measurements are planned to verify the energy loss calculations.

c. Background

Background arises from several possible sources: cosmic rays, tritium, other radioactivity, and scattered electrons in the spectrometer. As has been described, rejection of tritium background is very high by virtue of the preacceleration and use of an energy-sensitive detector.

One of the advantages of Tretyakov's spectrometer design is its inherent suppression of scattering backgrounds. The spectrometer is in fact five spectrometers in tandem, and electrons with an energy a few

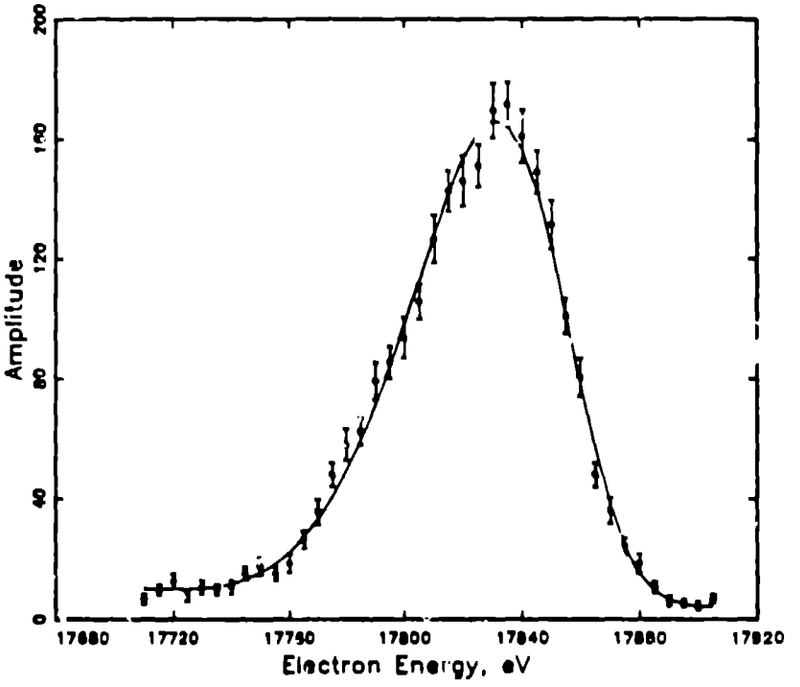

Fig. 5 ^{83m}Kr gaseous source 17.835 keV conversion line measured at a fixed spectrometer energy of 26 keV. The curved line is a calculation used to determine the instrumental resolution function.

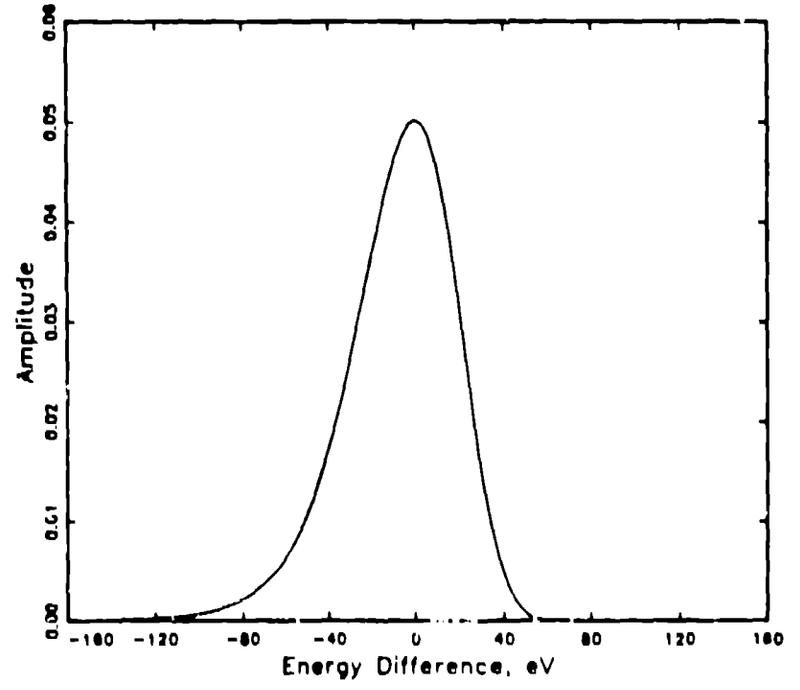

Fig. 6 The instrumental resolution function derived from the ^{83m}Kr gaseous source measurement shown in Fig. 5.

percent away from the focused energy are rejected at the first stage. The main scattering contribution thus comes from collisions with the inner conductors entailing very small energy losses and angular changes. This background scales with the signal and is estimated to be at the level of 10^{-3} or less. Experimental measurements of scattering made with the electron gun have confirmed that scattering is negligible.

Initially our chief background concern was that tritium contamination could eventually build up in the spectrometer and affect our background rate. However, after several months of running tritium, we have not observed any detectable change in the background. Thus, our built-in safeguards of the pumping restriction and a 50,000 ℓ/sec Ti sublimator pump located at the entrance to the spectrometer seem to be working very effectively.

The present background rate using a single-resistive-wire detector is 0.004 counts/sec. Tests indicate that the majority of this background is from cosmic ray muons. To reduce this component even further we are developing a multiwire detector to discriminate between through-going particles and stopping particles.

6. Molecular Tritium Data Acquisition and Analysis

A preliminary 3-day molecular tritium beta spectrum measurement was completed in January 1986. An energy range of 16.44 to 18.94 keV was covered in 10 eV steps. The energy region was scanned in a random fashion to eliminate time dependent systematic errors. To correct for the source strength the counts from the proportional counter were divided by the beta monitor counts. An additional correction for source strength fluctuations and an estimate of systematic errors in the normalized counts was obtained by repeatedly measuring a "calibration" energy point at 16.44 keV in between measurements of the "real" data points. (In other words after one or two measurements of data runs the 16.44 keV energy point would be remeasured.) The data points were measured for 600 secs while the calibration points were measured for 200 secs. The molecular source was run at reduced pressure because of a defect in one of the sapphire high-voltage standoffs. Nevertheless, in the last 100 eV of the spectrum we obtained a count rate of 0.15 sec^{-1}, which compares quite well with the rate obtained by Lubimov *et al.*, 0.04 sec^{-1}. The background count rate during the run was 0.004 sec^{-1}. The measured beta spectrum is shown in Fig. 7 along with a Kurie plot of the data. Note that the error bars include both the

statistical error and the systematic error based on all of the 16.44 keV calibration runs. The absolute energy calibration is based on the 17.835-keV Kr conversion line which is known to an accuracy of 20 eV [10].

These data were taken by keeping the magnetic fields and spectrometer field constant (to accept 26 keV betas), while the source potential was varied to scan the energy region. The advantage of this procedure is that the spectrometer acceptance, the detector background, and backscattering from the detector window are constant (for constant energy particles). Nevertheless, it is still possible for the efficiency of extraction to vary with the acceleration voltage. This is a smooth variation which is generally calculable But imperfections in the electron-optical system will almost certainly lead to small deviations from this ideal behavior, and an empirical correction similar to that used by Lubimov *et al.* and by Bergkvist[11] is required in fitting the data. However, the normalization of the count rate to the beta monitor, whose extraction efficiency tracks that of the spectrometer, cancels to first order the extraction efficiency variations and produces a very linear Kurie plot (Fig. 7). In fitting the data only a small quadratic correction term, less than 10^{-8} eV^{-2}, is necessary.

7. Data Analysis

The calculation of the predicted beta spectrum includes molecular final state calculations[3], Coulomb corrections, screening corrections, nuclear recoil effects[12], weak magnetism[12], and acceleration gap corrections (the last two corrections are negligible). The total system resolution function is then folded into the calculated data. A four-parameter fit using a non-linear least squares routine[13] is then performed for which the four parameters are, amplitude, endpoint energy, neutrino mass, and a extraction efficiency term.

The accuracy of the fitting code was checked by generating beta spectra including the same corrections listed above from a totally independent data-generation code. These two codes were developed by separate people totally independently to ensure a true check on the accuracy of the fitting code. Beta spectra using a variety of different parameters were calculated using the generation code. These data were then input into the fitting code and the resulting fit parameters were then compared to the original input parameters. Agreement was exceptional even for cases where very small neutrino masses (eV's) and poor resolution

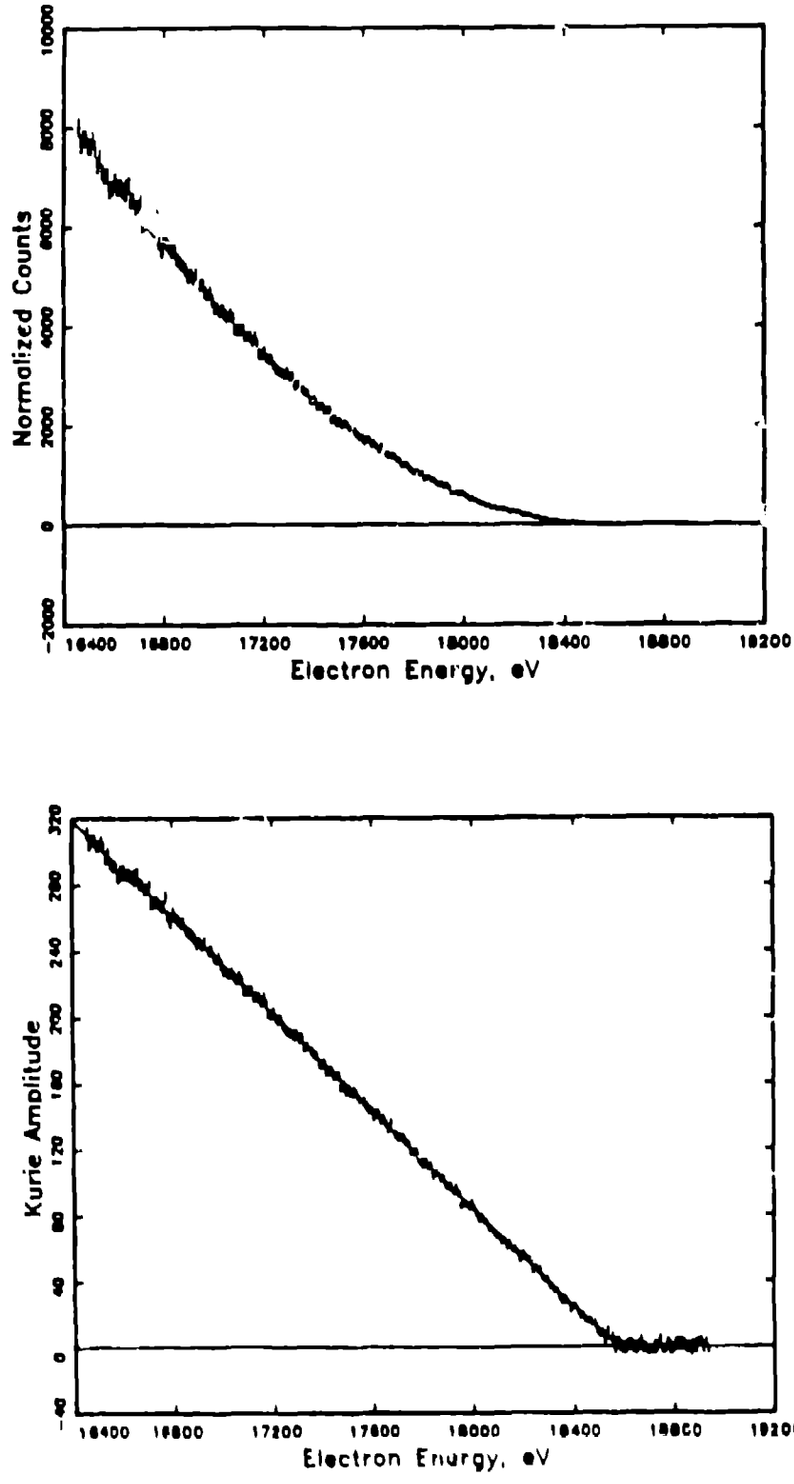

Fig. 7 The molecular tritium beta decay spectrum versus energy and Kurie plot for the same data. The line through the data in the Kurie plot is the calculated best fit for m_ν=0

functions (50-70 eV) were used. The results from this "blind" check of the fitting code give us a high level of confidence in our analysis procedure.

Another code was written to generate realistic Monte Carlo mock data. This allows us to investigate and determine the effects of various systematics and correlations between variables. It is essentially impossible to gauge these effects any other way. Crude analytical arguments and simplifications are not accurate because of the complicated correlations between parameters.

The molecular beta spectrum from our 3-day run was analyzed using the procedure outlined above. The resolution function used was the 54 eV FWHM total resolution function extracted from the Kr resolution function. A residual plot of the beta spectrum data versus the best fit is shown in Fig. 8. The residual for each data point is the difference between the measured value and calculated value divided by the point's error bar. The endpoint energy from this fit is 18.581 keV which yields an atomic mass difference for T-^{3}He of 18.597 ± 0.020 keV, where the uncertainty is dominated by the uncertainty in the ^{83m}Kr line energy.

From this short 3-day run we find that $m_\nu < 36$ eV at the 95% confidence level. The χ^2 best fit was for m_ν=0. The total χ^2 was 279 for 242 degrees of freedom. Figure 9 is a plot of χ^2 versus neutrino mass.

8. Conclusions

The preliminary 3 days of molecular tritium data we have presented here offers a hint of the eventual results possible using a free gaseous tritium source. With systematic errors at the few eV level and a spectrometer resolution in the 30 eV range (known to 1 eV accuracy), we will be statistics-limited down to a neutrino mass below 10 eV. With our expected event rate of 1 count/sec in the last 100 eV, and our demonstrated background level of 0.004 counts/sec, we should be able to set a limit on a neutrino mass of 10 eV (95% C.L.) using molecular tritium.

However, we are continuing work to improve the spectrometer resolution, increase the transmission and the source strength, and reduce backgrounds. The present limitations on these parameters have been largely identified and tractable solutions have been found. We plan to implement these improvements, perform systematic checks, and acquire sufficient statistics to set a limit of 10 eV or better with molecular tritium. Upon completion of running with molecular tritium, we will then bring the atomic tritium source into operation. Then systematic checks will be performed

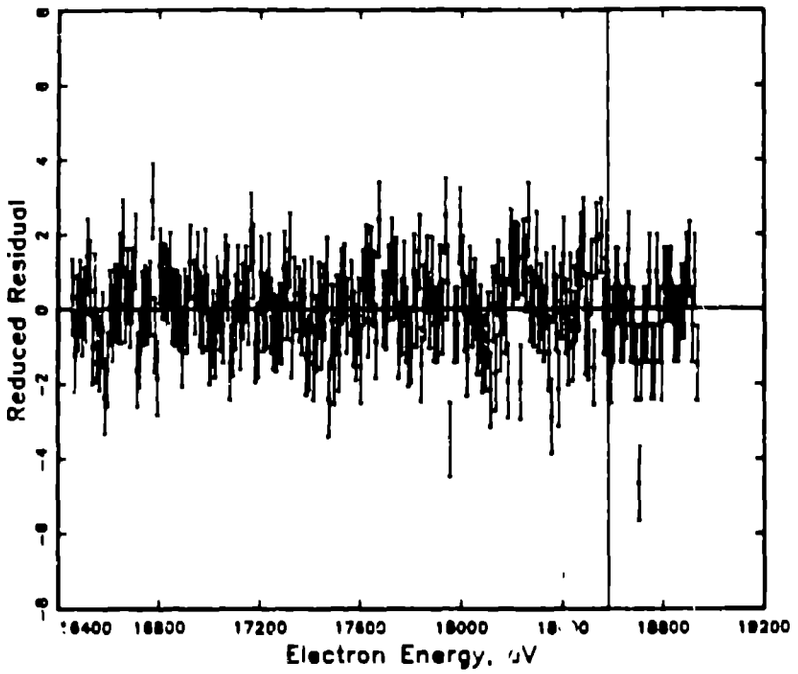

Fig. 8 A plot of reduced residuals calculated from the best fit to the molecular tritium data.

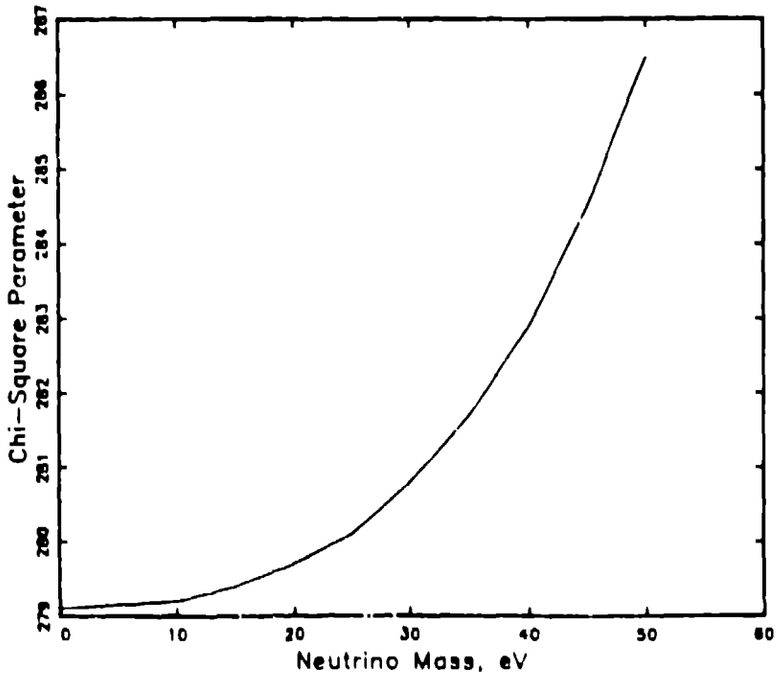

Fig. 9 χ^2 as a function of neutrino mass for the fit to the molecular tritium data.

and sufficient statistics accumulated to set a limit of 10 eV or better with atomic tritium.

Employing a gaseous source is admittedly experimentally complex, but we believe it is the approach that provides the most unambiguous information about a possible neutrino mass in the eV-range.

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