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THE LOS ALAMOS EXPERIMENT ON THE BETA DECAY OF FREE MOLECULAR TRITIUM

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ABSTRACT

The beta spectrum of the decay of free molecular
tritium has been accurately measured in order to search
for a finite $\bar{\nu}_e$ mass. The betas orig'nating from the
decay of free tritium molecules in a differentially
pumped source region were momentum analyzed in a toroidal
beta spectrometer with 36-eV resolution. The final state
effects in molecular tritium are accurately known and the
data thus allow us to set an upper limit of 29.3 eV on
the $\bar{\nu}_e$ mass at the 95% confidence level.

Introduction

The question of a nonzero neutrino mass has received
considerable attention since Lyubimov et al.[1] in 1981 reported
evidence for an electron antineutrino mass between 14 and 46 eV, with
a best fit value of 35 eV. While the statistical evidence to support
such a claim is high, there are still concerns about possible
systematic problems in their experiment. Many of these concerns
revolve around the use of a very complex source material (tritiated
valine, an amino acid) in which the energy given up in final state
excitations of the molecule following the beta decay of a tritium
atom is comparable to the size of the neutrino mass observed. These

final state effects are difficult to calculate in a molecule as complex as valine. In addition, ionization energy loss and backscattering of the betas in traversing the solid source are appreciable and must be very accurately accounted for. These concerns have led us to develop an experiment using free molecular tritium as the source material. The final state effects have been accurately calculated[2,3] for the tritium molecule and the uncertainties in these calculations are at the level of approximately 1 eV^2. In addition, the energy loss in the source is small because the source consists of tritium only and there is no backscattering.

Method

The experimental apparatus has been described in detail elsewhere[4] and will only be briefly described here. Molecular tritium is passed through a palladium leak, enters a 3.7-m long, 3.8-cm inner diameter aluminum tube at the center, and is pumped away and recirculated at the ends. The tube is held at approximately 130 K to increase the source strength and is uniformly biased to typically -8 kV. The source tube is inside a superconducting solenoid so that betas from the decay of tritium spiral along the field lines without scattering from the tube walls. The equilibrium density of tritium in the source integrated along the axis was 7.8 x 10^{15} tritium atoms/cm^2. Electrons (that are not trapped in local field minima) pass through an average thickness 2.1 times this value as they spiral through the source gas. At one end, the betas 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 positive ions trapped in the source, keeping the change in source potential due to space charge buildup to less than a volt. The betas are guided through the pumping restriction where the tritium is differentially pumped away and then 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 on or close to the walls of the source tube are not viewed by the spectrometer. A small Si detector is located at a position in front of the collimator where it intercepts a small fraction of the betas from decays in the source tube. Its position is set so that it does not obstruct the view of the spectrometer and also does not see any betas originating

from decays of tritium on the source walls. This beta monitor serves
to normalize the source strength from point to point. The
spectrometer is a 5-m long, 2-m inner diameter, 72-coil toroidal beta
spectrometer similar in design to the Tretyakov instrument, but with
a number of improvements. The use of curved entrance and exit
conductors and thin (0.5 mm) conductors at the points where the betas
cross the coils results in greatly improved acceptance and
transmission. Betas from a 1.7-cm^2 area in the source tube are
transmitted with 25% efficiency through the spectrometer entrance
collimator and form a cone of 30° half angle into the spectrometer.
Betas between 19.5° and 29.5° are transmitted through the
spectrometer to a position sensitive gas proportional counter at the
focal plane of the spectrometer. The focal plane detector is 2 cm
diameter with a 2-mm-wide entrance slit. The energy resolution for
26 keV betas is 20% and the position resolution 4 mm FWHM (position
information is used to reject backgrounds outside of the slit
acceptance). The earth's magnetic field is cancelled to a level of
±10 mG in the spectrometer volume by a set of cosine coils wound
around the spectrometer, and the zero field setting is determined by
fluxgate magnetometers mounted in the spectrometer. The event rate
in the last 100 eV was typically 0.10 counts/sec.

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 by several keV not only
improves the emittance of the source but also raises the energy of
betas of interest from the source well above backgrounds from betas
originating from decay elsewhere in the pumping restriction or
spectrometer. The beta monitor is biased at the same voltage as the
source tube, which results in constant-energy betas being detected by
the beta monitor.

In order to determine the overall source and spectrometer
resolution, we introduce ^{83m}Kr into the source tube in the same
manner as tritium is injected. The krypton emanates from a mixed Na-
Rb stearate[5] containing 5 mCi of ^{83}Rb, and produces a 17.835(20)-keV
K-conversion line. The intrinsic width of the line is a 2.26-eV
Lorentzian[6]. The dominant shakeup satellite is located 20 eV below
with an intensity of 8% of the main peak, as estimated by scaling the
measurements of Spears et al.[7] according to the calculations of
Carlson and Nestor[8]. The same calculations were used to assign
intensities to shakeoff satellites. The spectral distribution of

shakeoff was taken to have the 2p Levinger form[9]. Figure 1 shows the shakeoff spectrum deduced. The spectral contribution from scattering
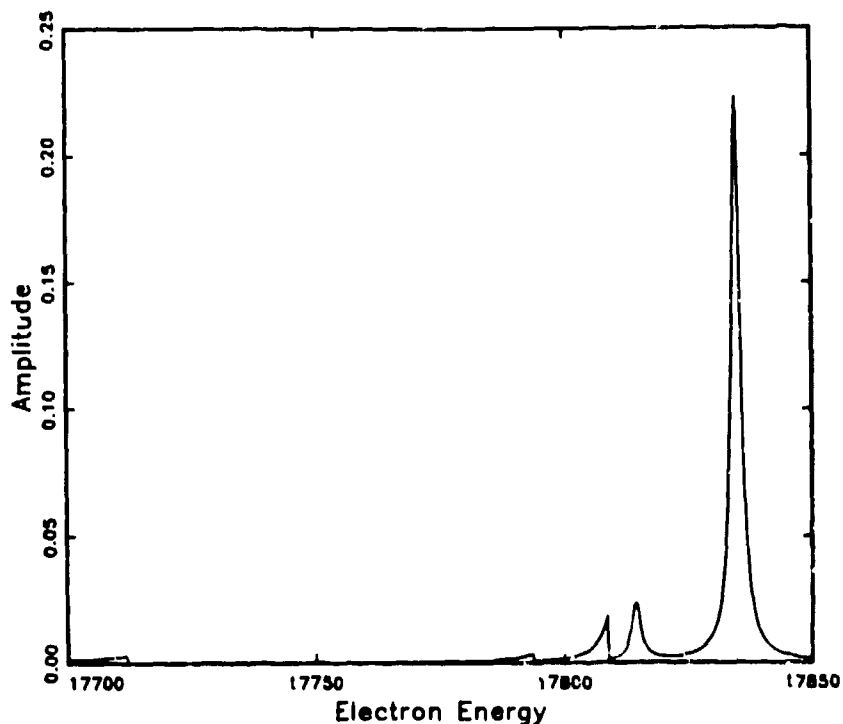

Fig. 1. Shakeup and shakeoff spectrum of Kr.

of the conversion electrons from nitrogen molecules in the source gas (which accumulate due to the recirculation of the krypton) has been calculated using existing experimental data[10] and has been removed from the resolution function by fitting the amount of nitrogen. The fitted contributions, 10 to 20%, were proportional to measured source pressures. These measurements yield a spectrometer resolution function which has a skewed Gaussian shape with a FWHM of 52 eV for the first data set and 32 eV for the last three data sets. (The contribution of the 21-eV exit slit is not included in these figures, but is taken into account in the analysis.) The change in resolution between the data sets was due mainly to improved cancellation of residual magnetic fields from the source magnets in the region of the spectrometer. The total resolution function is obtained by correcting this instrumental contribution for scattering in the tritium gas, which has two components, both calculated by Monte Carlo methods from the known doubly differential cross sections[11] for electron scattering from H_2. Some of the electrons, 11.8%, are trapped in the source by local field minima and must multiply scatter in order to escape, and 5.2% of the untrapped electrons suffer a
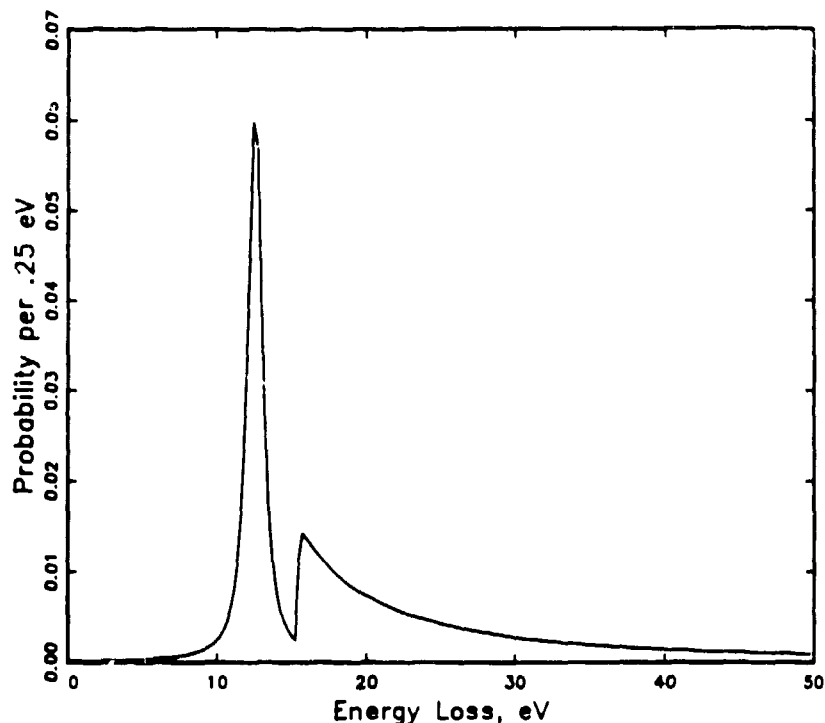
Fig. 2. Integral energy-loss spectrum for single interactions of 18.5-keV electrons with H_2.

single scatter in the gas before being extracted (Fig. 2).

Measurements of backgrounds from the source and tritium contamination of the spectrometer have been made and we do not observe any backgrounds originating from the source walls or extraction region. After operation of the source and spectrometer with tritium for more than one month, no increase in background from tritium contamination of the spectrometer has been observed. The background rate in the focal plane detector has remained constant at 1 count/270 sec and is primarily due to cosmic ray muons traversing the detector.

Three data sets were taken, each of 3-4 days duration, with operating conditions (given in Table I) varied somewhat between runs to check systematic effects. The first two runs were taken with the spectrometer set to analyze 26.0-keV betas. The beta spectrum was scanned from 16.44 to 18.94 keV in 10-eV steps. Two randomly selected data points were taken for 600 seconds each, followed by a 200-second data run at 16.44 keV in order to check for time dependent systematic errors. The third data set was taken in a similar manner, except that the spectrometer was set to analyze 26.5 keV betas in order to check for any systematic effects in varying the extraction voltage (and therefore the extraction efficiency). Extra data points were taken in 5-eV steps near the endpoint in the third run.

Other data sets taken were not used because resolution measurements were not available, or the runs were incomplete.

Analysis and Results

To analyze the data, a predicted beta spectrum is generated which includes the molecular final states, Coulomb corrections, screening corrections, nuclear recoil effects, weak magnetism, and acceleration gap effects (the last three are negligible). The total resolution, including energy loss in the source, is folded with the calculated spectrum. A five-parameter fit to the amplitude (determined by the total number of events), endpoint energy, neutrino mass, background level, and a quadratic extraction efficiency term in a maximum likelihood procedure with Poisson statistics is then performed. The resulting fit (Fig. 3) is characterized by a
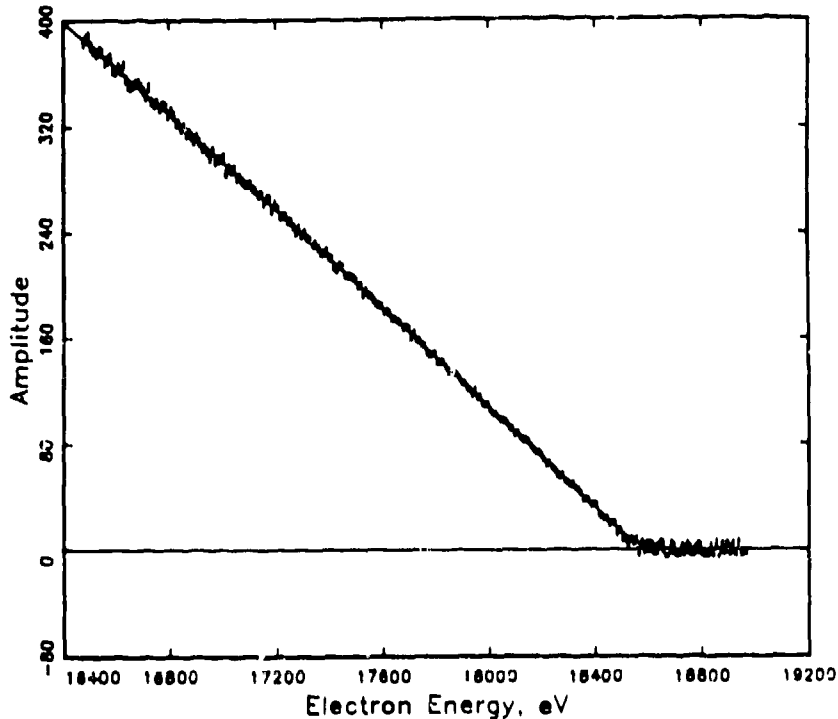

Fig. 3. Kurie plot for run 4A.

Xi-squared parameter, which is analogous to the standard chi-squared parameter:

$$\Xi^2 = 2\Sigma(s_i - y_i - y_i\ln(s_i/y_i)),$$

where s_i and y_i are the fit value and the measured value, respectively. (Chi-squared minimization gives a biased estimate of areas, and results in an incorrectly fitted neutrino mass.) Because

In Table I we summarize run parameters and fit results. The consistency between the measured endpoint energies is good, notwithstanding the large change in spectrometer resolution between runs 3 and 4A, and the change to 26.5 keV operation in run 4B. The overall uncertainty in the endpoint energy is dominated by the 20-eV uncertainty in the energy[12] of the ^{83m}Kr calibration line, however.

TABLE I. Summary of Parameters for each run and results from fitting procedure for each run. Uncertainties in Δm_ν^2 are 1σ.

	RUN 3	RUN 4-A	RUN 4-B	COMBINED
E_{spec} (keV)	26.0	26.0	26.5	
ΔE(FWHM,eV)	52.1 ± 1.7	32.0 ± 1.5	32.4 ± 1.3	
Skewness	.133	.153	.173	
Total Events	5,081,270	944,353	567,581	6,593,204
Counts in 100 eV	170	93	273	536
Background in 100 eV	36	28	53	117
Quadratic Term (10^{-8}/eV^2)	-1.28	-1.80	-0.64	
Number of Data Points	254	250	220	
E_0 (eV)	18584.8	18585.7	18584.4	18585.0
Δm_ν^2 (statistical, eV^2)	1126	1720	688	
Δm_ν^2 (resolution, eV^2)	70	364	52	638
Δm_ν^2 (e loss, eV^2)	50	28	25	
m_ν^2 (eV^2)	-1190	1880	-63	-186

The quadratic correction term varies from run to run owing both to changes in focus coil excitation and (in run 4B) to normalization of the source intensity by interpolation between calibration points rather than by the Si detector, which had become excessively contaminated. A linear term was tried in place of the quadratic one and gave similar results but with larger variations as the fitting interval was successively truncated. Such variations were within statistics with the (fixed) quadratic term when the fitting interval below the endpoint was varied over the range 2200 to 300 eV. There was no statistical evidence that both linear and quadratic terms were required.

interval was successively truncated. Such variations were within statistics with the (fixed) quadratic term when the fitting interval below the endpoint was varied over the range 2200 to 300 eV. There was no statistical evidence that both linear and quadratic terms were required.

Statistical errors in m_ν^2 were extracted from the Ξ^2 plots (which were closely parabolic in m_ν^2). A conservatively estimated systematic error arising from imperfect knowledge of the resolution function in each run was then added linearly to the statistical error. The resolution-function uncertainties have both systematic and statistical components, but are in any case believed to be largely uncorrelated from run to run. Finally, a systematic uncertainty from the measurement of the density of the source gas and the Monte Carlo simulation of multiple scattering was added linearly to the weighted average of all runs. These were the only systematic uncertainties considered to be non-negligible.

The uncertainty in the final result is predominantly statistical (Fig. 4). An upper limit on the mass of the electron antineutrino is
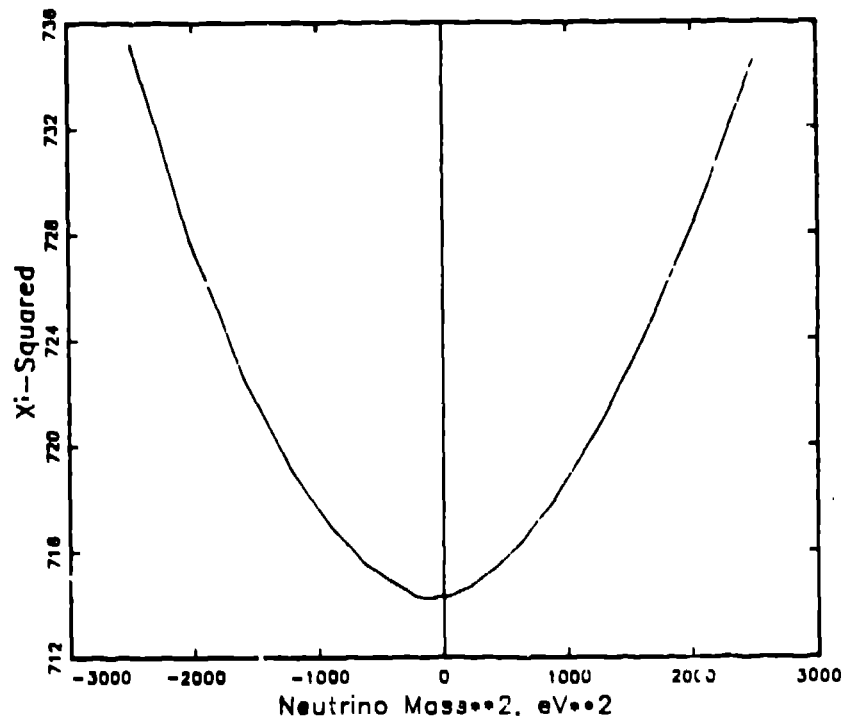

Fig. 4. Combined Xi-squared plot for the data. At the minimum, Xi-squared has the value 711 for 709 degrees of freedom.

found to be 29.3 eV at the 95% confidence level (C.L.) or 25.4 eV at the 90% C.L. It does not support the central value reported by

Lyubimov et al.[1], 30(2) eV, but neither does it exclude the lower part of the range 17 to 40 eV. It is also in agreement with the upper limits recently reported from solid-source experiments by Fritschi et al.[13] and Iwahashi et al.[14]. The present result is, for all practical purposes, model independent. Improvements to the apparatus transmission and resolution now in progress are expected to result in a sensitivity to neutrino mass in the vicinity of 10 eV.

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