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TITLE A LIMIT ON THE $\bar{\nu}_e$ MASS IN FREE MOLECULAR TRITIUM BETA DECAY

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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 final state effects in molecular tritium are accurately known and the data thus yield an essentially model independent upper limit of 29 eV on the $\bar{\nu}_e$ mass at the 95% confidence level.

The question of a nonzero neutrino mass has received considerable attention since the claims of Lyubimov et al (1) in 1980 were published which showed 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 considerable 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 one of the tritium atoms is comparable to the size of the neutrino mass observed. The effect of these final state effects is 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 carry out an experiment using free

molecular tritium as the source material. The final state effects have been accurately calculated for the tritium molecule (2-4) and the uncertainties in these calculations are at the level of approximately 1 eV. In addition, the energy loss in the source is small because the source consists of tritium only and there is no backscattering.

The system has been described in detail elsewhere (5) and will only be briefly described here. Molecular tritium is passed through a palladium leak and enters a 3.8-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 yields an integrated source intensity of 7.8×10^{15} tritium atoms/cm^2. At one end, the betas are reflected by a magnetic pinch and at the other end are accelerated to ground potential. Also located at this magnetic pinch is a hot filament that emits thermal electrons that neutralize the trapped positive atoms in the source. This keeps 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 projects an image down the center of the source tube so 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. 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 in diameter with a 2 mm wide entrance slit. The energy resolution for 26 keV betas is 20% and the position resolution is 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. By accelerating the betas by several keV, not only is the emittance of the source improved, but the betas of interest from the source are raised in energy 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.

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 (6) containing 5 mCi of ^{83}Rb, and produces a 17.835(20)-keV conversion line. The intrinsic width of the line is a 2.26-eV Lorentzian (7). The dominant shakeup satellite is located 25 eV below with an intensity of 8% of the main peak, as estimated by scaling the measurements of Spear et al. (8) according to the calculations of Carlson and Nestor (9). The same calculations were used to assign intensities to shakeoff satellites. The spectral distribution of shakeoff was taken to have the 2p Levinger form (10). The contribution from scattering of the conversion electrons from nitrogen molecules in the source gas (which builds up due to the recirculation of the krypton) has been calculated using existing experimental data (11-12)

and has been removed from the resolution function. These measurements yield a spectrometer resolution function which has a skewed Gaussian shape with a FWHM of 54 eV for the first data set and 38 eV for the last three data sets. 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 for the complete source and spectrometer consists of the skewed Gaussian optical resolution function as shown in Fig. 1 determined from the krypton measurements which is folded in with the energy loss spectrum of betas scattering from tritium molecules in the source. This energy loss spectrum was determined using the measured tritium density in the source tube together with Monte Carlo calculations of electron scattering on molecular tritium (13-14) including tracking betas along the magnetic field lines in the source region. Approximately 10% of the betas are trapped in local magnetic minima in the source region and must scatter several times to escape from the source region, while approximately 5% of the untrapped betas scatter before leaving the source region.

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 last run. The Kurie plot for the last run is shown in Fig. 2.

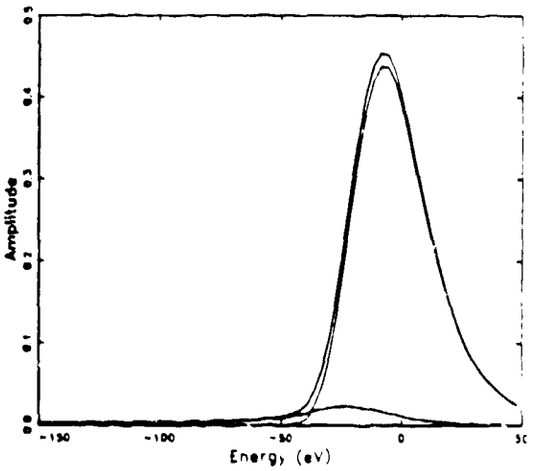

Fig. 1 Resolution function for Run 4-B showing optical resolution, energy loss component and sum of both.

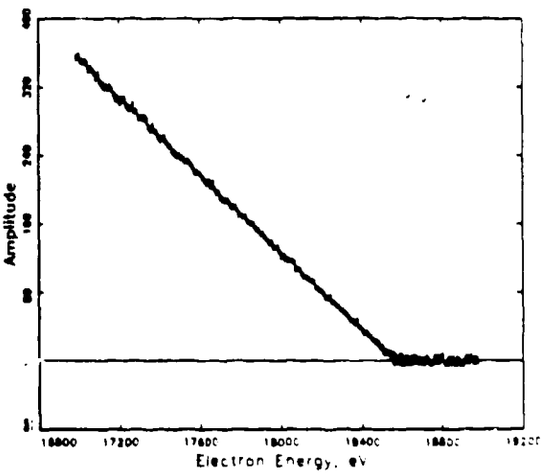

Fig. 2. Kurie Plot for Run 4-B.

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 system resolution and energy loss in the source are folded in with the calculated spectrum. A five-parameter fit (varying the amplitude (determined by 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 is characterized by a xi-squared parameter, which is analogous to the standard chi-squared parameter when using Gaussian statistics:

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

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 each point is

slightly renormalized for pressure variations in the source, this estimator was corrected by a factor y_i/σ_i^2, where σ_i^2 is the uncertainty in y_i. This factor is unity when the number of counts is small. The residuals plot (in which the best fit for $m_\nu = 0$ is subtracted from the data) for run 4-B is shown in Fig. 3. Extensive Monte Carlo calculations were carried out in order to study systematic effects and correlations between variables, and to verify the unbiased character of the fit estimator.

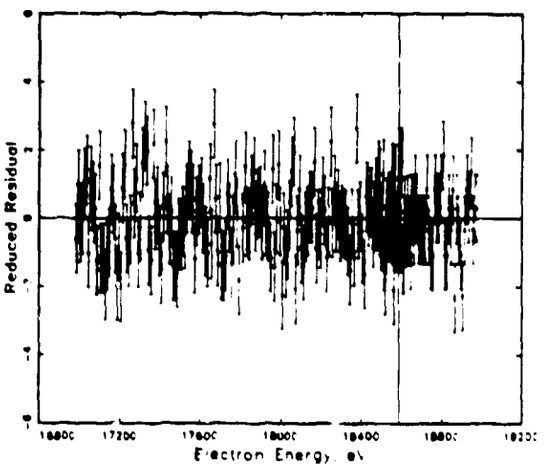

Fig. 3. Residual plot for Run 4-B with $m_\nu=0$.

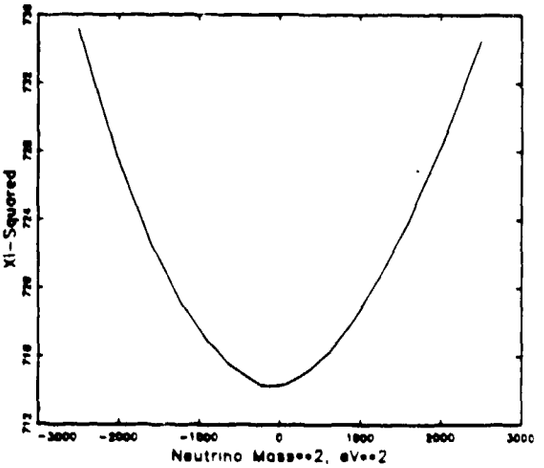

Fig. 4. Ξ^2 plot for all three runs.

In Table I we summarize run parameters and fit results for the three data sets. The spectrometer resolutions (ΔE) listed do not include the 21 eV wide focal plane slit contribution. 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 of the ^{83m}Kr calibration line, however. 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 was varied over the range 2500 to 300 eV. There was no statistical evidence that both linear and quadratic terms were required.

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

	RUN 3	RUN 4-A	RUN 4-B	COMBINED
E_{EFFECT} (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	724
Number of Data Points	254	250	220	
E_o(eV)	18584.8	18585.7	18584.4	18585.0
Δm_ν^2 (statistical)	1126	1720	688	
Δm_ν^2 (resolution)	70	364	52	638
Δm_ν^2 (energy loss)	50	28	25	
m_ν^2 (eV^2)	-1190	1880	-63	-186

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. An upper limit the mass of the electron antineutrino is 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 (15), 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. (16) and Iwahashi et al. (17). 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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