LA-UR -90-3465

CONF-9006276--2

LA-UR--90-3465

DE91 002319

TITLE LIMIT ON ELECTRON NEUTRINO MASS FROM OBSERVATION OF THE BETA DECAY OF MOLECULAR TRITIUM

AUTHOR(S) J. F. Wilkerson, T. J. Bowles, J. L. Friar, R.G.H. Robertson, G. J. Stephenson, Jr., and D. L. Wark, Physics Division

D. A. Knapp, Lawrence Livermore National Laboratory

SUBMITTED TO Proceedings of the 14th International Conference on Neutrino Physics and Astrophysics, CERN, Switzerland, 10-15 June 1990 (to be published in Nuclear Physics B, Proceedings Supplements Section)

LIMIT ON ν_e MASS FROM OBSERVATION OF THE BETA DECAY OF MOLECULAR TRITIUM

J. F. WILKERSON*†, T. J. BOWLES*, J. L. FRIAR‡, R. G. H. ROBERTSON*, G. J. STEPHENSON, JR.*, and D. L. WARK*§

Physics Division, Los Alamos National Laboratory, Los Alamos, NM 87545.

D. A. KNAPP

Physics Division, Lawrence Livermore National Laboratory, Livermore, CA 94550.

We report the most sensitive upper limit set on the mass of the electron antineutrino. The upper limit of 9.4 eV (95% confidence level) was obtained from a study of the shape of the beta decay spectrum of free molecular tritium. Achieving such a level of sensitivity required precise determinations of all processes that modify the shape of the observed spectrum. This result is in clear disagreement with a reported value for the mass of 26(5) eV.

1. INTRODUCTION

That the mass of the electron neutrino (or antineutrino; we make no distinction here) could be determined from the shape of beta spectra has been known since Fermi's formulation of the theory of beta decay. In 1981, a group at the Institute for Theoretical and Experimental Physics (ITEP) in Moscow reported[1] from their study of the tritium spectrum that ν_e had a mass of 35 eV, with revolutionary implications for particle physics and cosmology. More recent ITEP work[2] has reduced this value slightly to 26(5) eV, with a "model-independent" range of 17 to 40 eV. Fritschi et al.[3] found in a similar type of experiment at the University of Zürich an upper limit of 18 eV, and other measurements have neither confirmed nor contradicted these works.[4,5] Both the Zürich and ITEP experiments have very high statistical accuracy, and the difference between the two results must be a consequence of systematic effects.

The systematic effects which alter the observed shape of the beta spectrum arise from a variety of physical processes: decays to excited atomic states in the residual molecule, energy-losses in the source, instrumental resolution, and energy efficiency of the measurement system. Making an accurate determination of the ν_e mass requires not only acquiring sufficient statistics, but also that all these systematic processes be thoroughly understood and accounted for. For example, the disagreement between the Zürich and ITEP experiments most probably originates from insufficient knowledge about the systematic effects that arise from the multi-electron source materials used, for which molecular structure calculations are difficult to carry out to the necessary precision.

Unlike other experiments presently in operation, our experiment at the Los Alamos National Laboratory makes use of a gaseous source of T_2 to capitalize on the simplicity of the two-electron system. When tritium decays to ^{3}He, the orbital electrons are no longer in an eigenstate and distribute themselves over the set of

*Physics Division. †Speaker. ‡Theoretical Division. §Present address, Department of Physics, University of Oxford, Oxford United Kingdom, OX1 3NP.

eigenstates of the residual molecule. The resulting energy spread impressed on the outgoing beta must be very precisely calculated (at the 1% level) if serious errors in interpreting the data are to be avoided. Such calculations can be carried out with some confidence for atomic and molecular tritium, but with far less certainty for multi-electron solid sources. Use of a gaseous source also confers the advantages of minimal and well understood energy-loss corrections, and no backscatter corrections. Thus the gaseous source minimizes systematic uncertainties, but it is technically more difficult, and statistical accuracy can be hard to obtain. Finally, achieving a sensitivity to neutrino mass on the order of 10 eV has required us to perform a series of measurements to characterize the instrumental resolution function, the energy loss in the source, and the energy efficiency of the analyzing system.

2. BETA SPECTRUM MEASUREMENT METHOD

In an earlier paper[5] we described our apparatus briefly and reported the initial, essentially statistics limited result obtained with it: $\nu_e < 27$ eV at 95% confidence level (CL). Sensitivity to neutrino mass increases extremely slowly with data acquisition time, roughly as the fifth root so it was clear that significant improvement in the limit could only transpire through an increase in the data rates. To this end, we have made a number of improvements, the principal one being the replacement of the simple single-element proportional counter in the spectrometer with a 96-pad Si microstrip detector array. Additional details on these improvements can be found elsewhere.[6] The gross data rate is now 8 times higher than previously, and the signal-to-background about the same or better.

The beta spectrum is formed by setting the spectrometer to analyze a fixed momentum (equivalent to an energy of 23 keV) and scanning the accelerating voltage on the source. A typical data acquisition interval at a particular voltage is 35 seconds, at the end of which a 1024-channel spectrum from the Si energy-integrating source monitor detector and the contents of scalers used in dead-time correction are written to disk after the event-mode data. After every 5 data points, a calibration measurement at the voltage farthest from the endpoint (i.e. the highest voltage) is taken to monitor stability. Data voltages are repeated in random order with a frequency that weights the parts of the spectrum most significant in determining the neutrino mass. Data are recorded in sets of between 6800 - 13700 measurements. Before and after a tritium data set, the 17820-eV K-conversion line of $^{83}Kr^m$ is scanned and recorded two or three times to determine the instrumental resolution and spectrometer energy.

Analysis of the data begins with manual creation of a set of "windows" on the energy spectra from the individual pads. The windows include most of the counts from 23-keV electrons from the source, and exclude the bulk of the background counts from tritium in the spectrometer.

Each pad receives counts corresponding to a slightly different momentum, the total range being about 100 eV in energy from one end of the detector to the other. The data is thus organized by summing counts from corresponding pads on each wafer to form 12 spectra, each independently calibrated by a $^{83}Kr^m$ spectrum similarly formed. The "raw" tritium spectra can be compared to the theoretical spectrum modified by corrections for the final-state spectrum, instrumental resolution, energy loss, and apparatus efficiency. The neutrino mass and its variance are determined[5] from the shape of the Ξ^2 distributions generated from fits to the 12 spectra.

3. DETERMINATION OF SYSTEMATICS

3.1 Final state effects

The final-state spectrum (of the THe^+ ion) has the greatest influence on the observed tritium spectrum. Calculations from a number of independent groups have been reported for the decay of T_2 in the sudden approximation. The Martin-Cohen (MC) calculation[7] is truncated at 94 eV excitation, the Quantum Theory Project (QTP) calculation[8,9] is truncated at 164 eV and the Ågren-Carravetta calculation[10] at 90 eV. The last calculation has not yet been utilized in the analysis of our data. The MC and QTP calculations are in very good accord, the latter (the one we adopt) giving m_ν^2 8 eV^2 larger owing to its greater range. The MC calculation omits 1.3% of the strength, while the QTP one omits 0.5%, and the distribution of this strength is responsible for the difference between the variances, 545 eV^2 and 617 eV^2, respectively, and the sum-rule result of Kaplan and Smelov,[11] 1110 eV^2. Despite this large difference, the effect on neutrino mass is actually rather small, as we have found by simulating the missing 0.5 % of strength with discrete and continuous distributions that satisfy the sum rule. An upward correction to m_ν^2 of 20(10) eV^2 for the strength missing in the QTP calculation results.

The sudden approximation neglects the direct interaction between the outgoing beta and the orbital electrons. This "rescattering" contribution was first examined, for atomic T, by Williams and Koonin[12], who found changes less than 0.1% in the branching ratios. Certain corrections noted by Drukarev[13] and by Arafune[14] reduced those changes still further, but we observe that Williams and Koonin erroneously truncated their partial-wave expansion at $l = 0$ rather than $l = 37$, and they do not therefore rule out significant effects. Initial calculations for the atom by Friar[15] have now been followed by McCarthy[16] for the T_2 molecule. The calculations for the molecule were carried out in the limit of inelastic excitation of an orbital electron into the continuum with an energy large compared to its binding energy. Such a model is useful in this application because of the weighting of large inelasticities in the variance, and we find the T_2 rescattering contribution to be less than 2 eV^2.

Finally, we note the corrections we apply to the beta spectrum for final state effects from the two-electron THe^+ ion are the only major corrections that rely on calculations and not direct measurements.

3.2 Instrumental resolution function

Measurement of the instrumental resolution is accomplished by circulating $^{83}Kr^m$ (from the decay of ^{83}Rb) through the source and recording the nominally monoenergetic K-conversion line at 17820(3) eV. This single calibration is sufficient because, in our apparatus, the spectrometer is always set to analyze the same momentum, and spectra are obtained simply by scanning the acceleration voltage applied to the source. Conversion lines are accompanied by shakeup and shakeoff satellites, and, rather than rely on model dependent calculations for their positions and intensities, we have carried out a K-shell photoionization measurement on Kr at the Stanford Synchrotron Radiation Laboratory (SSRL).[17] Excellent agreement between the shapes of the spectra is obtained when the slightly better-resolution photoionization spectrum is convoluted with a Gaussian to match the internal-conversion data. Most important, a long tail (2×10^{-4} eV^{-1}) observed in the data but not predicted by theory is shown to be a part of the Kr spectrum (and not instrumental). A more detailed description of this work is given elsewhere.[17,18]

We have employed three independent fitting techniques to parameterize and determine the instrumental resolution function from the Kr conversion line measurement. The resulting distributions are shown in Figure 1. In one method we fit to the diagram line and first satellites of the Kr spectrum for which the

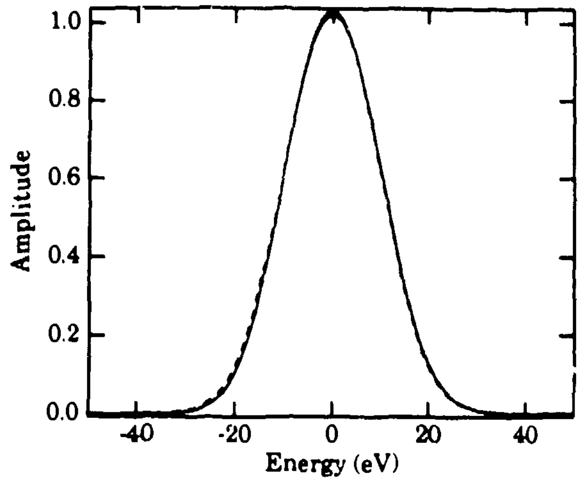

FIGURE 1.
Comparison of resolution functions for three independent fitting methods.

theoretical description appears to be good (solid line), in another we used a maximum entropy technique (dashed line), and in the final method we used information about the SSRL resolution function and measured photoionization spectrum to extract the instrumental resolution function (dotted line). For two of the methods, we found that a slightly skewed Gaussian with kurtosis described the instrumental resolution function well. The maximum entropy deconvolution requires no assumption about the functional form. The results from the three analysis techniques methods were in excellent agreement with the second moments of the distributions agreeing to better than 1%, which translates to changes of m_ν^2 when using the different distributions of less then 2 eV^2. Based on the the Gaussian variances between the 12 independent spectra obtained for each data set we estimated an uncertainty in the width and kurtosis of 12 eV^2 and an uncertainty of the skewness of 6 eV^2.

A measurement of the spectrum of thermal electrons from the source region accelerated to 19 keV showed evidence for a weak tail of 7×10^{-6} eV^{-1}, and the Kr data also shows evidence of marginal statistical significance for a residual tail at about this level. This residual tail being presumably of instrumental origin, we take the instrumental resolution to include an added flat tail of 7×10^{-6} eV^{-1} extending to 350 eV. The effect of the added tail on m_ν^2 is 15 eV^2, and we associate a 15 eV^2 uncertainty with it.

3.3 Energy loss in the source

Electrons lose energy by inelastic scattering as they spiral through the source gas. The cross section differential in energy has been constructed from various data, as described previously.[5] The total inelastic cross section is very tightly constrained by the Liu sum rule[19] to be $\sigma_0 = 3.474(11) \times 10^{-18}$ cm^2 at 18.5 keV.

The gas-density profile in the source is determined by kinetic theory from the measured throughput of gas scavenged by pumps into a calibrated volume, given the dimensions and temperature (130K) of the source tube. For each electron launched at coordinate z at an angle Θ, a mean superficial density $n(\Theta,z)$ can be computed by Monte Carlo methods. Plural interactions have a Poisson distribution related to the elementary mean densities and cross section. The energy-loss spectrum becomes

$$G(E) = \int_{z_1}^{z_2} \int_{C}^{C} \sum_{j} \frac{[n(\Theta,z)\sigma_0]^j \exp[-n(\Theta,z)\sigma_0]}{(1-C)\, j!} F^j(E)\, dz\, d(\cos\Theta) ,$$

where $F^j(E)$ is the j fold convolution of the unit normalized differential cross section (j=1,20). The angular integration includes only angles between 32 and 148 degrees, to comply with Monte Carlo calculations of the initial angle spectrum accepted by the spectrometer. The calculated probability of an electron interacting is 8.5 %, and the number of interactions per decay is 9.1 %, an indication of the generally small scattering probability and the very minor role played by plural interactions. Thus, the no-loss fraction, or number of electrons which exit the source without interacting is 91.5%. The stopping power computed with our differential cross section (which satisfies the Liu sum rule) is 0.44×10^{-16} eV-cm per atom, 18% below the Bethe stopping power.[20] This difference represents the major uncertainty in the calculated energy-loss estimates.

To verify and test these calculations, a simultaneous measurement of the tritium beta spectrum and the Kr conversion line spectrum was made. The source contained both molecular tritium gas, at its standard operating pressure, and Kr gas. The first step in the analysis procedure was to fit to the portion of the tritium spectrum that occurred at higher energies than the Kr conversion line. Using this fit, the tritium component was then removed from all of the data leaving only the Kr contribution, which had experienced energy loss in the tritium source. This remaining Kr spectrum was then compared with no-energy loss Kr data that was convolved with the calculated energy loss spectrum described earlier.

The initial comparison of these data sets indicated that calculated energy loss estimation was reasonable. However, a χ^2 search to determine the optimum measured energy loss revealed that the actual energy loss was slightly lower then expected. The no-loss fraction based on the direct T_2 + Kr measurement was found to be 93.5%, or 2% higher then the calculated value. One would perhaps consider this a negligible difference, but its effect on m_ν^2 is 25 eV^2.

3.4 Energy efficiency of the apparatus

The small variation of apparatus efficiency with acceleration voltage introduces a spectral distortion that can influence the neutrino mass derived. It is customary to parameterize this with empirically determined linear and quadratic correction terms α_1 and α_2 in the spectrum. In our apparatus both the spectrometric data and the monitor data are subject to efficiency corrections. The monitor efficiency function may easily be measured by plotting its rate, corrected for source pressure, against acceleration voltage, but there is no comparable method for the spectrometric data.

In both previous and present analyses of our tritium data we allow either α_1 or α_2 to be free fit parameters. (Our earlier opinion[5] that optimization of the transmission at the endpoint would produce only even order terms is incorrect because the optimization applies to total electron energy, not acceleration voltage.) Because of the limited energy range of the tritium data sets, 2650 eV or less, fits using either the linear or quadratic term are equally good and it is impossible to distinguish the between them using goodness of fit criteria. However, fitting both parameters simultaneously is not warranted because Ξ^2 per degree of freedom is worse.

In order to reduce the uncertainty resulting from our incomplete understanding of the system's energy efficiency a number of independent studies were carried out: Monte Carlo simulation of our transport system, measurements of the tritium spectrum over an extended energy region (9000-18000 eV), measurements of additional Kr conversion and Auger lines at 7403, 7624, 9035, 9110, 10800, and 12370 eV, and a systematic analysis of the sensitivity of m_ν^2 to the energy efficiency parameters.

The simulation studies proved to be rather input dependent with variations of over a factor of two for small changes in the input parameters. The wide scan tritium and additional Kr measurements were in good agreement with the α_1 or α_2 terms determined from best fits to the tritium data. However, since these measurements lacked the high statistics of the actual tritium data sets in the endpoint region,

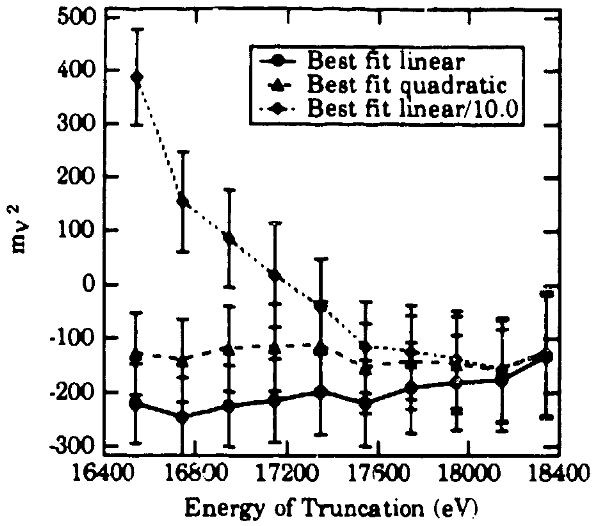

FIGURE 2.
Energy efficiency neutrino mass dependence truncation study.

they were not very sensitive tests of the energy efficiency in the region of interest.

The most effective means of determining the sensitivity of m_ν^2 to the energy efficiency parameters proved to be the systematic study of the actual tritium data sets. The basic algorithm was to determine the best linear (quadradic) fit for the entire data set. Then, this term was held constant, while a series of fits were made to increasingly truncated data sets. The results of these analyses are shown in Figure 2. From this analysis one concludes that the relative invariance of neutrino mass with truncated data sets indicates that the best-fit energy efficiency parameters are reasonable representations of the actual energy efficiency of the system (an example of a poor representation is also shown in the figure). Clearly, there is no statistical difference for m_ν^2 between the linear and quadratic fits, furthermore as one reduces the energy region fit the sensitivity of m_ν^2 to the energy efficiency is correspondingly reduced without sacrificing statistical sensitivity to m_ν^2. For this reason truncated data sets were used to determine the most reliable value for m_ν^2.

Because linear and quadratic corrections produce slightly different neutrino masses, we take the conservative viewpoint that we do not know which is the correct description of the curvature, and that the two choices are but a selection from a large variety of possible efficiency functions. Our best estimate of m_ν^2 is then the average of the α_1 and α_2 fits determined using all three data sets. The uncertainty associated with the efficiency correction is the difference between the α_1 and α_2 best fit m_ν^2 values, resulting in a 50 eV^2 systematic uncertainty.

3.5 Other possible systematics

There are contributions to the tritium linewidth not contained in the Kr calibration. The partition of recoil energy between internal and translational degrees of freedom of the THe^+ ion contributes[8] a variance of 9×10^{-2} eV^2. Zero-point vibrational motion in the T_2 molecule[21] and thermal motion create Doppler broadenings of variance 4×10^{-4} and 4×10^{-2} eV^2, respectively. These contributions are negligible.

Experimental tests of a number of possible sources of systematic error were conducted. Low-pressure T_2 gas in magnetic and electric fields suggests the production of T^+, T_2^+, and T_3^+ ions, and T^* and T_2^* metastables, in the source region. Positive ions are trapped in the source by the arrangement of fields and can escape only by migrating across field lines through scattering and charge exchange. Trapped ions were sought in two different experiments, one[22] in which $^{83}Kr^m$ and T_2 were introduced simultaneously into the source, and the second in which T_2 was introduced directly into the acceleration-gap region rather than the source midpoint. In neither case were trapped ions seen, and the second experiment sets a limit of 5×10^{-4} on the ratio of ions to neutrals, corresponding to an excess variance of order 0.2 eV^2. The cross sections for the production of metastables are lower than for ions, and their lifetimes in the source are shorter, owing to wall collisions.

Another test was to search for electrons scattered into the beam from the walls (which are highly contaminated with tritium). The apparatus was designed with a guard region between the wall and the part of the gas visible to the spectrometer equal to two or more electron radii, so that two consecutive scatters would be needed for an electron to enter the beam. Helium gas was introduced into the apparatus (hydrogen would have exchanged with the tritium) after tritium had been pumped away, and scattered electrons were sought in the spectrometer. As expected, none was seen, at a level of 10^{-4} of the source strength.

4. ANALYSIS OF DATA

Three separate data sets were acquired using the procedures described in section 2. Table 1 lists a summary of information about the three data sets. Note that the 8/88 and 8/89A data sets were acquired with as similar operating conditions as possible, while the 8/89B data set was intentionally taken at a different acceleration voltage as a check of possible systematic effects arising from the operating parameters. The maximum-likelihood procedure described earlier[5] was used to obtain values for m_ν^2, E_0, amplitude, background, and α_1 or α_2. These results, and their 1-σ statistical uncertainties, are also listed in the table.

In Table 2 we list the estimated uncertainties (1-σ) in m_ν^2 from all sources. We have not at this time considered all relevant contributions to the uncertainty in the endpoint energy, E_0. In principle, a useful test of the reliability of tritium beta decay experiments is the value obtained for the ^3H - ^3He mass difference. Our present endpoint energy is in good agreement with the one we obtained previously, and with some other experiments, but independent experimental information on the mass difference is not decisive yet.[22]

TABLE 1. Results from analysis of August, 1988 (8/88) and August 1989 data sets (8/89A and 8/89B); uncertainties are one standard deviation statistical.

	8/88		8/89A		8/89B		
	α_1	α_2	α_1	α_2	α_1	α_2	
E_{Spect}	23		23		24		eV
Resolution	85		94		106		eV^2
E_{min} - E_{max}	16545 - 19195		16540 - 19180		17540 - 19210		eV
m_ν^2	-198(87)	-90(84)	-79(172)	-36(175)	-170(71)	-157(67)	eV^2
E_0	18570.6(6)	18571.3(5)	18571.4(9)	18572.0(8)	18570.4(7)	18570.5(6)	eV
α_1	-2.3(2)	--------	-1.6(2)	--------	-1.0(7)	--------	x 10^{-5} eV^{-1}
α_2	--------	-7.8(6)	--------	-5.4(8)	--------	-6.2(43)	x 10^{-9} eV^{-2}
χ^2 (av.)	456	454	507	508	462	462	
D.O.F.	478		473		483		
Last 100 eV							
Counts	7859		4048		8230		
S/N	4.7		3.0		10.0		

TABLE 2. Contributions (eV^2) to the uncertainty in m_ν^2 at one standard deviation.

Analysis:	
Statistics	55
Beta monitor statistics, dead time	5
Energy Loss:	
18% in theoretical spectrum shape:	15
5% Uncertainty in source density	4
Resolution	
Width	12
Skewness	6
Tail	15
Final States	
Differences between theories	8
Region above truncation point	10
Rescattering	5
Apparatus Efficiency	
Linear vs Quadratic	50
Total	80

In Figure 3, we plot the residuals for the fit near the endpoint for $m_\nu = 0$ and 30 eV, from which it may be seen qualitatively that a 30-eV mass is rejected. That conclusion is borne out quantitatively when all uncertainty components are considered. The best-fit value of the neutrino mass squared is -147 +/- 55 +/- 58 eV^2. The three runs are distributed as expected for the 55-eV^2 statistical uncertainty, but the central value is about 1.8 standard deviations below zero when the statistical and systematic uncertainties are added in quadrature. The probability of such a result occurring by chance is 3.3%, rather low. When the true value of a parameter is known to be excluded from some region, classical statistics cannot be used for setting confidence limits on it, but a Bayesian approach is applicable.[23] One finds an upper limit of 9.4 eV on the neutrino

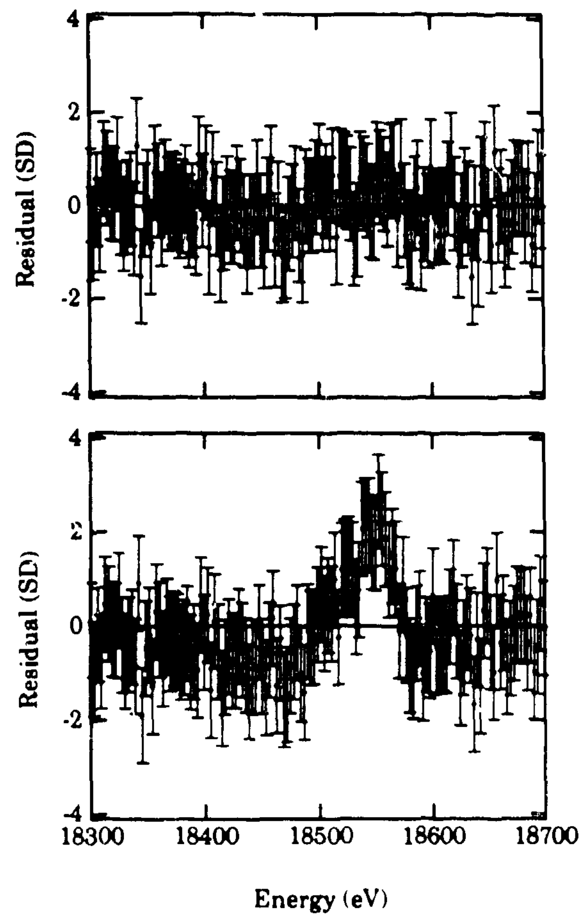

FIGURE 3.
Residuals in fits to neutrino masses of 0 (top) and 30 eV (bottom). All other parameters including α_1 have been allowed to vary.

mass at the 95% confidence level. If the measured value were to be shifted arbitrarily to 0 (leaving the variance unchanged) the corresponding upper limit would be 12.5 eV.

5. DISCUSSION OF RESULTS

A result lying 1.8 standard deviations into the non-physical region may be due to a) an improbable event, b) underestimate of a known systematic uncertainty, c) an unknown systematic effect, including physical effects not included in the atomic or weak-interaction models used to describe the data. Our post-facto tests of the major known ingredients of the analysis (instrumental resolution, energy loss, efficiency) have reassured us that the known systematic uncertainties have been appropriately estimated. However, our inability to calculate the energy efficiency of our apparatus accurately from first principles is not presently understood.

There are important theoretical inputs to the tritium beta decay analysis, not all of which can be thoroughly tested experimentally. The final-state spectrum (FSS) has a variance large compared to 147 eV^2, and must be very accurately calculated. That is the principal motivation for using T_2 as a source. Three different groups have calculated the FSS for T_2, and the agreement between them is at the level of 10 eV^2. However, while the calculations are quite different formally (especially in their treatment of the continuum), all make use of the Born-Oppenheimer approximation and the sudden approximation. Martin has estimated that inadequacies of the Born-Oppenheimer approximation are only at the level of 10^{-3} eV.[24] McCarthy's calculations[16] indicate that use of the sudden approximation entails errors of about 2 eV^2.

There is no known means of experimentally verifying the molecular FSS calculations in detail. Measurements of the branching ratio to the bound THe^+ ion and of the rovibrational infrared emission spectrum of THe^+ do not confirm the calculations, but experimental biases are probably responsible, as discussed by Comtet and Fournier[25]. The explicitly calculated variance of the FSS (C00 eV^2) falls far below the sum-rule value (1109 eV^2), but this is an expected consequence of missing strength (approximately 0.5%) at high excitation that, in simulations, has little effect (<10 eV^2) on the neutrino mass. There is excellent agreement (0.1%) between the energies of quasibound levels of HHe^+ determined by Schopman et al.[26] and the calculations of Kolos and Peek.[27] New experiments exploring the FSS would be very valuable.

The tritium beta spectra have been analyzed in the framework of conventional Fermi theory with a single, massive neutrino. Mixing with other massive or massless left-handed neutrinos does not lead to "wrong-sign" effects such as we see. Coupling of the electron with some amplitude to massive neutrinos through an interaction that violates parity less than maximally does require the addition to the theory of a "relativistic spinor" term.[28] This term influences the spectrum as another contribution to the resolution, and so would mimic a "wrong-sign" $m_\nu{}^2$, but we have not attempted to analyze our data in this context. Hughes and Stephenson[29] examined the possibility of tachyonic neutrinos, but concluded that associated production of tachyons and bradyons led to solutions of unbounded energy and were therefore unphysical. Another possibility is capture of relic neutrinos, which leads to emission of a monoenergetic electron of energy $E_0 + m_\nu c^2$. Our data can be fit as well by such a prescription as by the (ad hoc) negative $m_\nu{}^2$ used. The partial half-life of ^3H against such a putative decay branch is found to be 1.4(10) x 10^{10} years. Long though this is, it requires a neutrino density of order 10^{17} cm^{-3}, far above plausible estimates[30] in the galaxy (up to 10^8 cm^{-3}).

A 1.8-standard-deviation discrepancy is not large enough to warrant recourse to exotic solutions, and we find in our data no support for a neutrino mass larger than 10 eV. This limit is strongly in contradiction to the result of Lyubimov et al.[2] [26(5) eV, with a "model-independent" range of 17 to 40 eV]. While we cannot identify a specific reason for this disagreement, we have noted how sensitive the conclusions are to minute details of the final-state spectrum, energy loss, resolution, and other effects, and we venture that such effects may not be adequately known for complex solid material

For a value of the Hubble constant of 50 km/s/Mpc or greater, the sum of neutrino masses must be at least 22 eV in order to close the universe. Thus we conclude that the electron neutrino cannot close the universe by itself. We also remark that the time dispersion of neutrino events from the supernova SN1987a is not dominated by neutrino mass, but rather must reflect the actual cooling of the protoneutron star.

We gratefully acknowledge the help of J. M. Anaya, C. Doolen, and T. Stephenson in carrying out these experiments and D. Sivia for the maxiumum entropy calculation.

REFERENCES

1. V.A. Lubimov, E.G. Novikov, V.Z. Nozik, E.F. Tret'yakov, V.S. Kozik, Phys. Lett. 94B (1980) 266.
2. S. Boris et al., Phys. Rev. Lett. 58 (1987) 2019; S.D. Boris et al., Pis'ma Zh. Eksp. Teor. Fiz. 45 (1987) 267 [Sov. Phys. JETP Lett. 45 (1987) 333].
3. M. Fritschi, et al., Phys. Lett 173B (1986) 485.
4. H. Kawakami, et al., Phys. Lett. 187B (1987) 198.
5. J.F. Wilkerson, et al., Phys. Rev. Lett. 58 (1987) 2023.
6. T.B. Bowles, et al., in Yamada Conference XXIII, Nuclear Weak Process and Nuclear Structure, edited by M. Morita, E. Ejiri, H. Ohtsubo, and T. Sato (World Scientific, Singapore 1989), p. 209.
7. R.L. Martin and J S. Cohen, Phys. Lett. 110A (1985) 95.
8. W. Kolos, et al., Phys. Rev. A 31 (1985) 551.
9. O. Fackler, et al., Phys. Rev. Lett. 55 (1985) 1388.
10. H. Ågren and V. Carravetta, Phys. Rev. A38 (1988) 2707.
11. I.G. Kaplan and G.V. Smelov, in Proceedings of the International Symposium on Nuclear Beta Decays and Neutrino, edited by T.Kotani, H. Ejiri and E. Takasugi (World Scientific, Singapore 1986), p. 347.
12. R.D. Williams and S.E. Koonin, Phys. Rev. C27 (1983) 1815.
13. E.G. Drukarev and M.I. Strikman, Phys. Lett. B186 (1985) 1.
14. J. Arafune and T. Watanabe, Phys. Rev. C34 (1986) 336.
15. J.L. Friar, private communication.
16. I. McCarthy, private communication.
17. R.J. Bartlett, G.S. Brown, T.J. Bowles, B. Crasemann, J. Henderson, D.A. Knapp, R.G.H. Robertson, S. Schaphorst, S.L. Sorenson, W.J. Trela, D.L. Wark, and J.F. Wilkerson, (unpublished).
18. R.G.H. Robertson, et al., Proceedings of the VIIth Moriond Workshop, Les Arcs, France, January 1989 (to be published).
19. J.W. Liu, Phys. Rev. A7 (1973) 103.
20. M. Inokuti, Rev. Mod. Phys. 43 (1971) 297.
21. J.S. Cohen, private communication.
22. S.T. Staggs, et al., Phys. Rev. C 39 (1989) 1503.
23. Particle Data Group, Phys. Lett. 170B, 1 (1986).
24. R.G.H. Robertson and D.A. Knapp, Ann. Rev. Nucl. Part. Sci. 38 (1988) 185.
25. G. Comtet and P.G. Fournier, Phys. Rev. A39 (1989) 586.
26. J. Schopman, P.G. Fournier, and J. Los, Physica 63 (1973) 518.
27. W. Kolos and J. M. Peek, Chem. Phys. 12 (1976) 381.
28. J. J. Sakurai, Phys. Rev. Lett. 1 (1958) 40.
29. R.J. Hughes and G.J. Stephenson Jr., Phys. Lett. B244 (1990) 95.
30. J.M. Irvine and R.J. Humphreys, J. Phys. G9 (1983) 847.