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IMPROVED LIMIT ON THE MASS OF $\bar{\nu}_e$ FROM THE BETA DECAY OF MOLECULAR TRITIUM

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ABSTRACT

We report a new upper limit of 13.4 eV (95% confidence level) on the mass of the electron antineutrino from a study of the shape of the beta spectrum of free molecular tritium. This result appears to be inconsistent with a reported value for the mass of 26(5) eV. The electron neutrino is evidently not massive enough to close the universe by itself.

1. INTRODUCTION

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. A probable origin for such effects is the solid 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 a triton decays to ^3He, the daughter atom can be left in an excited final state. 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 less certainty for solid sources like those used by ITEP and Zürich. Use of a gaseous source also confers the advantages of minimal and well understood energy-loss corrections, and no backscatter corrections.

2. SYSTEM IMPROVEMENTS

In an earlier paper[5] we described our apparatus briefly and reported the initial result obtained with it: m_e < 27 eV at 95% confidence level (CL). Since this first result, we have made a number of improvements[21], the principal one being the replacement of the simple single-element proportional counter in the spectrometer with a 96-pad Si microstrip detector array.

3. DATA ACQUISITION, REDUCTION, AND ANALYSIS

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. Data voltages are repeated in random order with a frequency that reflects the parts of the spectrum most significant in determining the neutrino mass. Before and after a tritium data set, the 17820-eV K-conversion line of $^{83}Kr^m$ is recorded two or three times to determine the instrumental resolution and energy scale.

Each pad of the silicon microstrip detector 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 are thus organized by summing counts from the same pad numbers 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 energy loss, instrumental resolution, apparatus efficiency, and the final-state spectrum. The neutrino mass and its variance is then estimated[5] from a plot of the sum of χ^2 for all pads against m_ν^2.

Electrons lose energy by inelastic scattering as they spiral through the source gas. Monte Carlo calculations, together with the differential energy cross sections[5-7] and measurements of the source density determine the probability of an electron interacting to be 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.

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. Conversion lines are accompanied by shakeup and shakeoff satellites, and, rather than rely on calculations for their positions and intensities, we have carried out a K-shell photoionization measurement on Kr at the Stanford Synchrotron Radiation Laboratory.[8,9] 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. The Gaussian variances from these data for the 12 spectra from the silicon microstrip detector averaged about 120 eV^2. Other contributions to the tritium linewidth not contained in the Kr calibration, such as Doppler broadening and zero point motion and molecular vibrations of the T_2 molecule, are negligible.[11]

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 a_1 and a_2 in the spectrum. From Monte Carlo calculations, we find that the spectrometric efficiency is strictly linear, with $a_1 = -2.0(3) \times 10^{-5}$ eV^{-1}, in reasonable agreement with the value $-2.6(2) \times 10^{-5}$ derived by fitting the spectrum to a linear term only. Rather than rely on Monte Carlo calculations, and because linear and quadratic corrections produce different neutrino masses, we consider both linear and quadratic terms in the fit separately, adopt a mean value, and treat the total spread in neutrino mass squared (105 eV^2) as a systematic uncertainty.

Experimental tests of a number of possible sources of systematic error were conducted. In two different tests, trapped ions were searched for, and we set a limit of 5×10^{-4} on the ratio of ions or metastables to neutrals, corresponding to an excess variance of order 0.2 eV^2. Tests to search for electrons scattered into the beam from the walls (which are highly contaminated with tritium) indicated no contribution, with a limit set at a level of 10^{-4} of the source strength.

The final-state spectrum (of the THe^+ ion) has the most important influence on the tritium spectrum. Calculations have been reported for the decay of T_2 in the sudden approximation.[10,13-16] The uncertainty on neutrino mass of the different final state calculations is rather small.

The largest uncertainty due to final state effects is uncertainty about validity of the sudden approximation. Williams and Koonin[17] (WK) have claimed that the rescattering contributions (i.e., the interaction of the beta directly with orbital electrons) were less than 10^{-3} in the case of the atom. However, their treatment is limited and their argument that higher partial waves were unimportant was incorrect.[22] Calculations by Friar[18] indicate that m_ν^2 shifts upward by 3 eV^2, and we have doubled this contribution to make an estimate for the T_2 molecule. Friar also shows that higher ℓ contributions fall off very rapidly for bound states, and we find from a semiclassical model that this is true for the continuum as well. We estimate the total effect to be not more than about 3 times the p-wave, but the need for a complete continuum calculation for the T_2 molecule is manifest.

4. RESULTS

The tritium data set obtained (13400 measurements) spanned an interval of about 9 days and led to spectra totalling 8000 counts in the last 100 eV, of which 1400 were background. The spectra covered the range 16500-19200 eV. The maximum-likelihood procedure described earlier[5] was used to obtain values for m_ν^2, E_0, amplitude, background, a_1 and a_2. These results, and their 1-s statistical uncertainties, are listed in Table I.

Table I. Results from analysis of August, 1988 data; uncertainties are one standard deviation statistical.

	a_1 only	a_2 only	
m_ν^2	-250(90)	-145(90)	eV^2
E_0	18567.2	18569.2	eV
a_1	$-2.6(2) \times 10^{-5}$	--	eV^{-1}
a_2	--	$-8.8(5) \times 10^{-9}$	eV^{-2}
Ξ^2 (av.)	945.8	945.1	(892 D.O.F)

In Table II we list the estimated uncertainties (1-s) 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.

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

Analysis:	
Statistics	90
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	20
Apparatus Efficiency	
Linear vs Quadratic	105
Total	143

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 is then the average of the a_1 and a_2 fits, and the uncertainty associated with efficiency correction is the difference between them.

In Figure 1, 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.

As discussed elsewhere,[19] setting confidence levels on quantities physically forbidden from having negative values is a complex issue, especially when the measured value (through normal statistical fluctuations) falls in the non-physical regime. Our result (from the average of the fits with a_1 and a_2 separately) is $m_\nu^2 = -198(143)$ eV^2, which would have arisen in less than 8% of trials from a neutrino mass greater than 0 eV. To derive a confidence level on the mass is less straightforward. The Particle Data Group sets forth[20] a Bayesian prescription that is at least welldefined, if not rigorously justified. On that basis, we find a 95% confidence level upper limit on the neutrino mass of 13.4 eV.

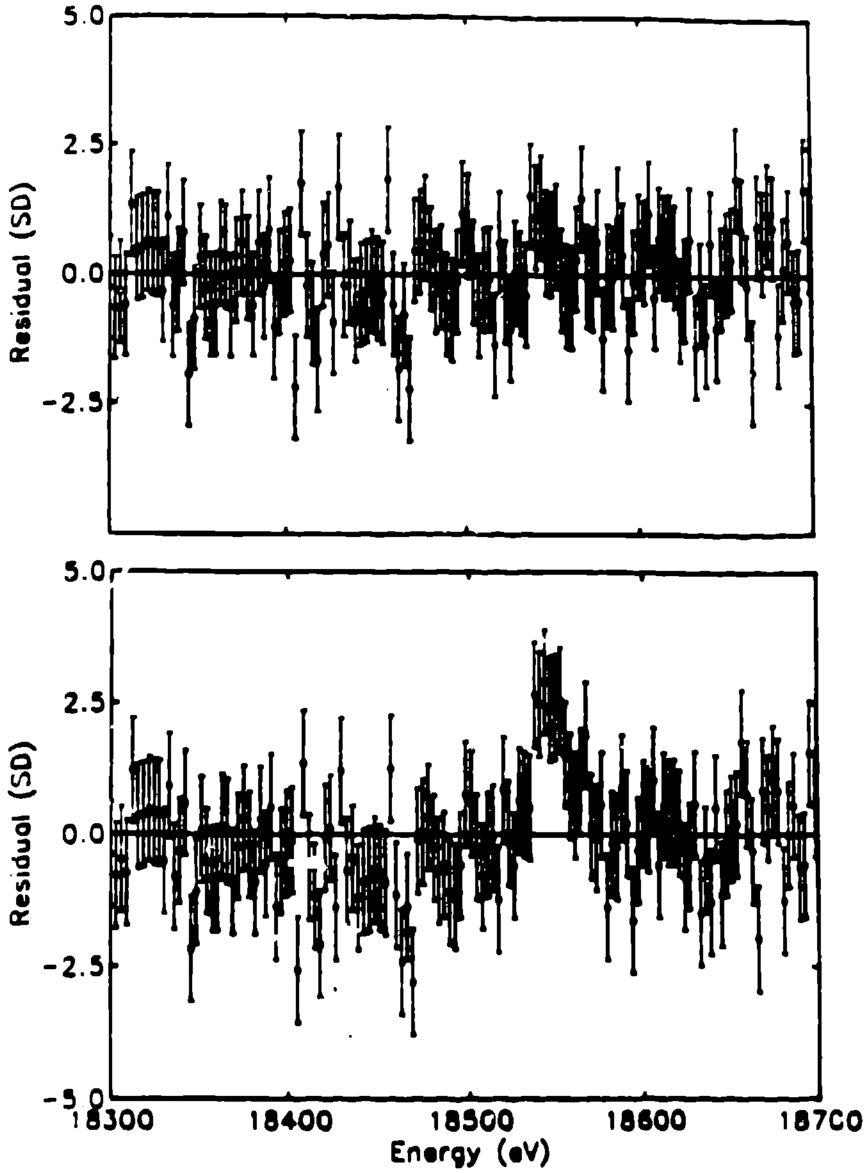

Fig.1. Residuals in fits to neutrino masses of 0 (top) and 30 eV (bottom). All other parameters including a_1 and a_2 have been allowed to vary.

5. CONCLUSIONS

The results of our experiment are entirely inconsistent with the ITEP result, 17 to 40 eV. We are not able to speculate usefully on the exact source of this disagreement, but we have noted how demanding this type of experiment is on the precision of all correction factors. Uncertainties in energy loss, backscattering, and final-state effects are presumably substantially larger for solid sources than for free molecular T_2. We note, finally, that this low limit on the mass of n_e should permit a new analysis of the neutrino data from the supernova SN1987a largely free of the time-dispersive effects introduced by neutrino mass, and that n_e is incapable of closing the universe by itself.

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