Limit on $\bar{\nu}_e$ Mass from Observation of the β Decay of Molecular Tritium

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(Received 6 May 1991)

We report the most sensitive direct upper limit set on the mass m_ν of the electron antineutrino. Our measurements of the shape of the β decay spectrum of free molecular tritium yield, under the assumption of no new physics other than that of mass, a central value for m_ν^2 of $-147 \pm 68 \pm 41$ eV^2, which corresponds to an upper limit of 9.3 eV (95% confidence level) on m_ν. The result is in clear disagreement with a reported value of 26(5) eV.

That the mass of the electron neutrino (or antineutrino) could be determined from the shape of β spectra has been known since Fermi's formulation of the theory of β decay. A group at the Institute for Theoretical and Experimental Physics (ITEP) in Moscow have reported [1] from their studies of the tritium β spectrum that the $\bar{\nu}_e$ mass lies in the range 17–40 eV, with revolutionary implications for particle physics and cosmology. Not only are massive neutrinos incompatible with the otherwise successful minimal standard model of particle physics, a neutrino mass in that range would be sufficient both to close the Universe gravitationally and to account qualitatively for observational evidence for dark matter. Other experiments [2–4], however, do not support the ITEP claim.

When tritium decays to ^{3}He, the orbital electrons redistribute themselves over the set of eigenstates of the residual molecule. The resulting energy spread impressed on the outgoing β must be very precisely calculated 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, in contrast to the multielectron solid sources used heretofore [1–3]. Our experiment at the Los Alamos National Laboratory is the first to make use of a gaseous source of T$_2$ to capitalize on the simplicity of the two-electron system. The gaseous source also confers minimal, well understood energy-loss corrections, and freedom from backscatter; together with detailed measurements of the instrumental resolution function, energy-loss, energy efficiency, and other effects, it has made possible a reliable mass measurement at the 10-eV level.

In an earlier paper [4] we described our apparatus briefly and reported our initial result, $m_\nu < 27$ eV. The source is a tube fed at its midpoint with a steady flow of T$_2$ gas and placed on the axis of a solenoidal magnetic field whose strength decreases monotonically toward the extraction end. Electrons from β decay near the axis are guided to the object point of a toroidal-field magnetic spectrometer of 5-m focal length. The most significant of many improvements [5] made recently are the elimina-

tion of electron trapping in the source and replacement of the single-element proportional counter in the spectrometer by an octagonal array of Si microstrip detectors, each with twelve pads. Signals from pads at the same location along the dispersion axis are combined to form twelve simultaneously acquired spectra, each independently calibrated by a ^{83}Kr^m spectrum similarly formed.

Tritium data were acquired in 35-s runs at selected (negative) bias voltages applied to the source tube. The voltage settings were repeated in random order with the number of measurements at each voltage weighted by its sensitivity to neutrino mass. A Si detector monitored the source strength, as did periodic calibrations at the voltage at which the data rate was highest (the highest voltage).

The instrumental resolution was measured by circulating ^{83}Kr^m gas through the source and observing the nominally monoenergetic K-conversion line [6] at 17820.1(18) eV. A single calibration suffices because the spectrometer is set to a fixed energy (23 or 24 keV). The constancy of the resolution even with large changes in acceleration voltage was confirmed in studies of other ^{83}Kr^m lines.

Conversion lines have a natural width and are accompanied by shakeup and shakeoff satellites. The underlying instrumental resolution was extracted by (a) convolution of theoretical spectra, (b) convolution of high-resolution Kr K-shell photoionization data, and (c) maximum-entropy deconvolution of theoretical spectra. The maximum-entropy deconvolution requires no assumption about the functional form. A slightly skewed Gaussian with kurtosis described the instrumental resolution function well. The results from the three analysis methods were in excellent agreement, with the second moments of the distributions agreeing to better than 1%, corresponding to m_ν^2 variations of less than 2 eV^2. A more detailed description of this work is given elsewhere [7,8]. A comparable contribution to resolution-function uncertainty stems from fluctuations in resolution parameters between the twelve spectra.

Both the Kr data and a spectrum of thermal electrons from the source region accelerated to 19 keV marginal

evidence for a residual tail of 7×10^{-6} eV^{-1} near the peak. This being presumably of instrumental origin, we include in the instrumental resolution a tail of that magnitude extending 350 eV below the peak. At that point, its effect on m_ν^2 maximizes at 15 eV^2, and we associate a 15-eV^2 uncertainty with it.

Electrons lose energy by inelastic scattering as they spiral through the source gas. Monte Carlo simulations yield a no-loss fraction, the number of electrons that exit the source without interacting, of 91.5%. The stopping power computed with our differential cross section [4] [which satisfies the Liu [9] sum rule, $\sigma_0 = 3.474(11) \times 10^{-18}$ cm^2 at 18.5 keV] is 0.44×10^{-16} eV cm/atom, 18% below the Bethe stopping power [10]. To test these calculations, measurements of the ^{83}Kr^m spectrum in the presence and absence of tritium gas at the usual operating pressure were made. The no-loss Kr data were convolved with the calculated energy-loss spectrum for a range of source densities. A χ^2 search gave an excellent fit, with a no-loss fraction slightly higher than expected, 93.5%, the effect of which on m_ν^2 is -25 eV^2. Experimental searches for trapped ions in the source and for electrons scattered into the beam from the source walls (which are highly contaminated with tritium) proved negative, and exclude contributions to m_ν^2 larger than 0.2 eV^2.

The small variation of apparatus efficiency with acceleration voltage introduces a spectral distortion that can influence the neutrino mass derived. Investigations of this effect included Monte Carlo simulation of the transport system, measurements of the tritium spectrum over an extended energy region (9–18 keV), and measurements of additional ^{83}Kr^m conversion and Auger lines at 7403, 7624, 9035, 9110, 10800, and 12370 eV. But the most effective approach proved to be a systematic analysis of the sensitivity of m_ν^2 to empirical energy-efficiency parameters [4], α_1 (linear) and α_2 (quadratic), determined from the tritium spectra themselves. First, the best value of α_1 or α_2 for an entire data set was determined. (To fit both at once is not warranted because the goodness-of-fit estimator [4] Ξ^2 is larger per degree of
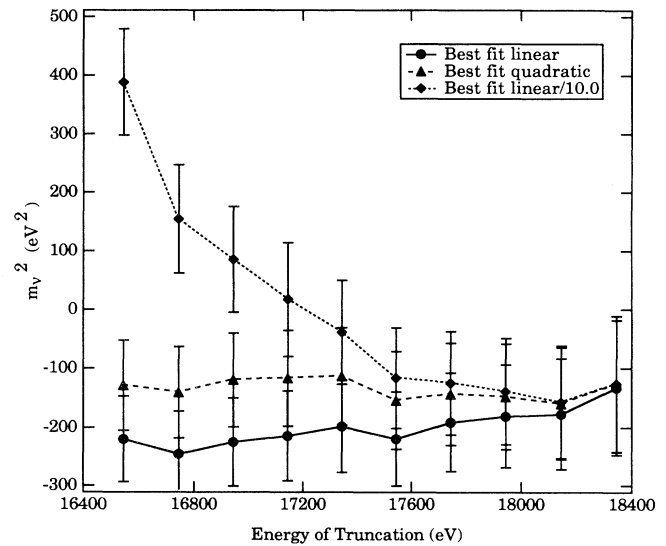

FIG. 1. Dependence of m_ν^2 on truncation energy for three different choices of efficiency parametrization.

freedom.) Then, with this term held constant, fits were made to increasingly truncated data sets. Typical results are shown in Fig. 1. The relative invariance of neutrino mass with truncation of the data sets indicates that the parameters are reasonable representations of the actual energy efficiency of the system (an example of poor representation is also shown). To minimize sensitivity to α_1 and α_2, data sets truncated 825 eV below the end point were used to determine m_ν^2. Our best estimate of m_ν^2 is taken to be the average of the α_1 and α_2 fits for all three data sets. The systematic uncertainty associated with the efficiency correction is estimated as the difference between the average m_ν^2 values for linear and quadratic fits, 32 eV^2.

Table I summarizes the three data sets acquired, and in Table II we list the estimated uncertainties in m_ν^2 from all sources. Values of normalized Ξ^2 fell in the range 1.03–1.08, as expected for this Poissonian-fit estimator

TABLE I. Results from three data sets; uncertainties are 1 standard deviation statistical.

Data set fit with	8-88		8-89A		8-89B	
	α_1	α_2	α_1	α_2	α_1	α_2
Final energy (keV)	23		23		24	
Resolution (eV^2)	85		95		106	
Data range (eV)	16545–19195		16540–19180		17540–19210	
m_ν^2 (eV^2)	$-229(107)$	$-159(108)$	19(190)	24(198)	$-158(87)$	$-145(88)$
$E_0 - 18568$ (eV)[a]	0.5(6)	1.3(5)	1.4(9)	2.1(8)	1.7(7)	1.9(6)
α_1 (10^{-5} eV^{-1})	$-2.3(2)$	$\cdots$	$-1.7(2)$	$\cdots$	$-1.1(7)$	$\cdots$
α_2 (10^{-9} eV^{-2})	$\cdots$	$-7.9(6)$	$\cdots$	$-5.4(8)$	$\cdots$	$-6.4(45)$
Counts, S/N[b]	7859, 4.7		4048, 3.0		8230, 10.0	

[a]Mean $E_0 = 18570.5(20)$ eV (see Ref. [6] for corrections and uncertainties).
[b]Total counts, signal-to-background ratio in last 100 eV of β spectrum.

TABLE II. Contributions (eV^2) to the uncertainty in m_v^2 at 1 standard deviation.

Analysis (three runs):	
Statistics	67
Beta monitor statistics, dead time	5
Energy loss:	
18% in theoretical spectrum shape	15
5% uncertainty in source density	4
Resolution:	
Variance of response function	5
Tail	15
Final States:	
Differences between theories	8
Limited configuration space	10
Sudden approximation	2
Apparatus efficiency:	
Linear vs quadratic	32
Total	79

FIG. 2. Residuals in fits to neutrino masses of 0 (top) and 30 eV (bottom). All other parameters including a_1 have been allowed to vary.

with approximately 470 degrees of freedom. Figure 2 shows the residuals near the end point for m_v fixed at 0 and 30 eV. The best-fit value of m_v^2 is $-147 \pm 68 \pm 41$ eV^2. The functional form of the spectrum used in the negative-m_v^2 regime is that given by Fritschi et al. [2], truncated at $E = E_{0i}$. This form gives parabolic Ξ^2 distributions, as required for a consistent treatment of uncertainties. In order to set confidence limits on the true value of a quantity that is inherently non-negative, a Bayesian approach is needed [11]. Adding the uncertainties in quadrature, one finds an upper limit of 9.3 eV on the neutrino mass at the 95% confidence level. If the measured value were to be shifted arbitrarily to 0 (leaving the variances unchanged), the corresponding upper limit would be only 3.1 eV higher, an indication of the modest sensitivity of Bayesian limits to negative fluctuations.

The three runs are distributed as expected for their statistical uncertainties, but the mean is nearly 2 standard deviations below zero. That may reflect an improbable (3%) occurrence or an unknown systematic effect, including physics outside the atomic or weak-interaction models used. Our post facto tests of major ingredients of the analysis (instrumental resolution, energy loss, efficiency) have reassured us that the known systematic uncertainties have been appropriately estimated.

There are theoretical inputs to the 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 calculations [12–14] of the FSS for T_2 agree at the level of 10 eV^2. The universally applied Born-Oppenheimer [11] and sudden [15] approximations are estimated to entail errors less than 0.04 and about 2 eV^2, respectively. The partition of recoil energy between
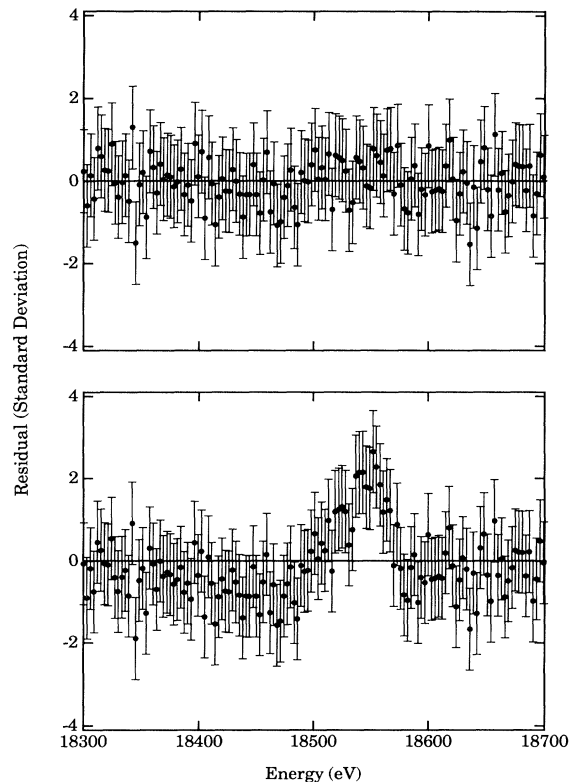
internal [16] and translational degrees of freedom of the THe$^+$ ion contributes a variance of 0.09 eV^2. Zero-point vibration in the T_2 molecule [17] and thermal motion create Doppler broadenings of variance 0.0004 and 0.04 eV^2, respectively.

The β spectra have been analyzed in the framework of conventional Fermi theory with a single, massive neutrino. Recoil-order corrections, screening, and radiative corrections are all negligible [18]. Mixing with other massive or massless left-handed neutrinos does not lead to "wrong-sign" effects such as we see. Hughes and Stephenson [19] examined and rejected the possibility of tachyonic neutrinos. Coupling of the electron to massive neutrinos through an interaction that violates parity less than maximally does introduce a "relativistic spinor" term [20] that could mimic a negative m_v^2, as could (unexpected) final-state interactions of massive neutrinos. Another possibility is capture of relic neutrinos, which leads to emission of monoenergetic electrons of energy $E_{0i} + m_v c^2$. Our data can be fitted well by such a prescription. The partial half-life of ^3H for such a putative decay branch is found to be $1.3 \times 10^{10}/(1.0 \pm 0.5)$ yr, with $m_v = 0$. Long though this is, it requires a neutrino density of order 10^{16} cm^{-3}, far above plausible estimates [21].

A 2-standard-deviation effect is not sufficiently large to demand recourse to exotic solutions, and we find in our data no support for a nonzero neutrino mass. Our 9.3-eV limit is strongly in contradiction with the ITEP result [1] [26(5) eV, with a "model-independent" range of 17–40 eV]. While we cannot identify a specific reason for this disagreement, the conclusions are sensitive to minute details that, in our view, are not adequately known for complex solid materials.

If the Hubble constant is 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, by itself, close the Universe. We also remark that our data show that the time dispersion of neutrino events from the supernova 1987A is not dominated by neutrino mass, but rather must reflect the actual cooling of the protoneutron star.

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[1] V. A. Lubimov et al., Phys. Lett. 94B, 266 (1980); S. Boris et al., Phys. Rev. Lett. 58, 2019 (1987); S. D. Boris et al., Pis'ma Zh. Eksp. Teor. Fiz. 45, 267 (1987) [JETP Lett. 45, 333 (1987)].

[2] M. Fritschi et al., Phys. Lett. B 173, 485 (1986).

[3] H. Kawakami et al., Phys. Lett. B 187, 198 (1987); H. Kawakami et al., Phys. Lett. B 256, 105 (1991).

[4] J. F. Wilkerson et al., Phys. Rev. Lett. 58, 2023 (1987).

[5] T. J. 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.

[6] S. T. Staggs et al., Phys. Rev. C 39, 1503 (1989).

[7] D. L. Wark et al., Los Alamos National Laboratory Report No. LA-UR-91-10 (unpublished).

[8] R. G. H. Robertson et al., in Tests of Fundamental Laws in Physics, Proceedings of the Twenty-Fourth Rencontre de Moriond, edited by O. Fackler and J. Tran Thanh Vanh (Editions Frontiéres, Gif-sur-Yvette, France, 1989), p. 255.

[9] J. W. Liu, Phys. Rev. A 7, 103 (1973).

[10] M. Inokuti, Rev. Mod. Phys. 43, 297 (1971).

[11] See, R. G. H. Robertson and D. A. Knapp, Annu. Rev. Nucl. Part. Sci. 38, 185 (1988).

[12] R. L. Martin and J. S. Cohen, Phys. Lett. A 110, 95 (1985).

[13] O. Fackler et al., Phys. Rev. Lett. 55, 1388 (1985).

[14] H. Ågren and V. Carravetta, Phys. Rev. A 38, 2707 (1988).

[15] I. E. McCarthy (private communication).

[16] W. Kolos et al., Phys. Rev. A 31, 551 (1985).

[17] J. S. Cohen (private communication).

[18] D. H. Wilkinson (private communication).

[19] R. J. Hughes and G. J. Stephenson, Jr., Phys. Lett. B 244, 95 (1990).

[20] J. J. Sakurai, Phys. Rev. Lett. 1, 40 (1958); K.-E. Bergkvist, Nucl. Phys. B39, 317 (1972).

[21] J. M. Irvine and R. J. Humphreys, J. Phys. G 9, 847 (1983).