Limit on $\bar{\nu}_e$ Mass from Free-Molecular-Tritium Beta Decay

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The beta spectrum of free molecular tritium has been measured in order to search for a finite electron-antineutrino mass. The final-state effects in molecular tritium are accurately known and the data thus yield an essentially model-independent upper limit of 27 eV on the ν_e mass at the 95% confidence level.

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The possibility that neutrino masses are nonzero has received considerable attention since Lyubimov *et al.*[1] in 1981 reported evidence for a finite electron-antineutrino mass, currently fixed[2] between 17 and 40 eV, with a best-fit value of 30 eV. On the other hand, Fritschi *et al.*,[3] also studying the beta decay of tritium, have reported an upper limit of 18 eV on the neutrino mass. If, as stated,[3] these results are in disagreement, the difference must be due to systematic problems, since the statistical evidence to support both claims is very strong. These problems likely originate in the use of complex source materials in which the energy given up in molecular excitations following the beta decay of a tritium atom is comparable to the size of the neutrino mass in question. These final-state effects are difficult to calculate for a molecule as complex as valine[1] or for tritium implanted in carbon.[3] In addition, energy loss and backscattering of the betas in traversing the solid source are appreciable and must be very accurately accounted for. These considerations have led us to develop an experiment using free molecular tritium as the source material. The final-state effects have been accurately calculated[4,5] for the tritium molecule, and the uncertainties[5] 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 experimental apparatus has been described in detail elsewhere.[6] Molecular tritium enters a 3.7-m-long, 3.8-cm-i.d. aluminum tube at the midpoint and is pumped away at the ends and recirculated. The tube is held at approximately 160 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 is 6.9×10^{15} tritium molecules/cm^2. Electrons (that are not trapped in local field minima) pass through an average thickness 2.7 times that value as they spiral through the source gas. At one end they 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 the space charge of positive ions trapped in the source. The betas are transported through a pumping restriction where the tritium is differentially pumped away and then they are focused by nonadiabatic transport through a rapidly falling magnetic field to form an image on a 1-cm-diam. collimator at the entrance to the spectrometer. The collimator defines an acceptance radius in the source tube such that decays originating more than 8.4 mm from the axis are not viewed by the spectrometer. A 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 and serves to normalize the source strength. The spectrometer is a 5-m focal-length toroidal beta spectrometer similar in concept to the Tretyakov instrument,[7] but with a number of modifications.[6] Betas from a 2.2-cm^2 area in the source tube are transmitted with about 1% net efficiency through the entrance collimator to a position-sensitive proportional counter at the focus of the spectrometer. The detector is 2 cm in diameter with a 2-mm-wide entrance slit. The energy resolution for 26-keV electrons is 20% and the position resolution 6 mm FWHM (position information is used to reject backgrounds outside the slit acceptance). The Earth's magnetic field is cancelled to a level of <10 mG in the spectrometer volume by external coils. The effective integral event rate in the last 100 eV was typically 0.12

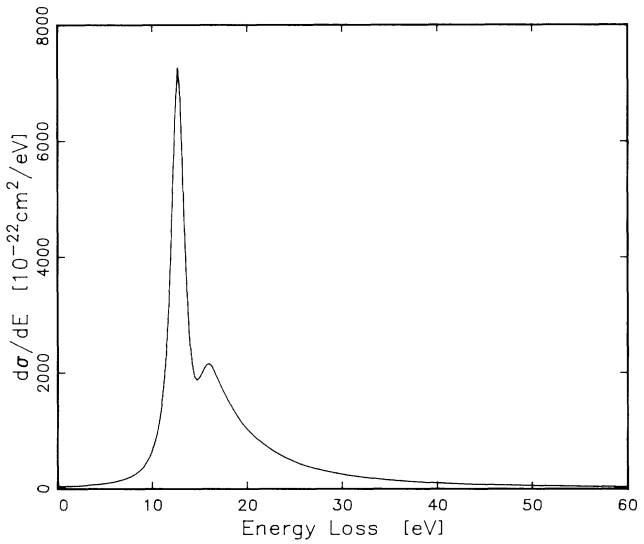

FIG. 1. Differential cross section for inelastic interactions of 18.5-keV electrons with H_2. The spectrum extends to 2 keV.

count/sec.

The beta spectrum is scanned by our changing the voltage applied to the source tube so that betas of constant energy are analyzed by the spectrometer. The acceleration of the betas not only improves the emittance of the source but also raises the energy of betas of interest well above backgrounds from decay of tritium elsewhere in the pumping restriction or spectrometer. The beta monitor is biased at the same voltage as the source tube.

To determine the instrumental resolution, $^{83}Kr^{m}$ is introduced into the source tube in the same manner as tritium. The krypton emanates from a mixed Na-Rb stearate[8] containing 5 mCi of ^{83}Rb, and produces a 17.835(20)-keV K-conversion line. The intrinsic line shape is a 2.26-eV-wide Lorentzian.[9] The dominant shakeup satellite is located 20 eV below with an intensity of 8.2% of the total, as estimated by the scaling of the measurements of Spears, Fischback, and Carlson[10] according to the calculations of Carlson and Nestor.[11] The same calculations were used to assign intensities to shakeoff satellites. The spectral distribution of shakeoff was taken to have the $2p$ Levinger form.[12] The spectral contribution from scattering of the conversion electrons by nitrogen molecules in the source gas (which accumulate during recirculation of the krypton) has been calculated from experimental data[13] and has been removed from the resolution function by the fitting of the amount of nitrogen. The fitted contributions, 10% to 15%, were proportional to measured source pressures. The spectrometer itself is well described by a skewed Gaussian convoluted with a rectangular slit-width contribution. The total resolution function is obtained by the convolution of the instrumental contribution with the energy-loss spectrum of scattering in the tritium gas, calculated by Monte Carlo methods from the known doubly differential cross sections[14] for electron scattering from H_2. Some of the electrons, 11.7(10)%, are trapped in the source by local field minima and must multiply scatter in order to escape, and 6.5(14)% of the untrapped electrons suffer a single interaction in the gas before being extracted (Fig. 1).

Measurements of backgrounds from the source and tritium contamination of the spectrometer reveal no backgrounds originating from the source walls or extraction region, nor any increase in spectrometer background after operation of the source and spectrometer with tritium for more than one month. The background rate has remained steady at approximately 1 count/200 sec and is primarily from cosmic rays.

Four data sets were taken, each of 3–4-d duration, with operating conditions given in Table I. In total, 3.8×10^6 events were recorded. All but the third run 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 sec each, followed by a 200-sec run at 16.44 keV in order to monitor time-dependent effects. 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 systematic effects in varying the extraction voltage (and therefore the extraction efficiency). Extra data points were taken

TABLE I. Summary of parameters and results from fitting procedure. Uncertainties are 1 standard deviation. In this paper, the uncertainty in the last digit is placed in parentheses; e.g., 18585.1(34) means 18585.1 ± 3.4.

Run	Ξ^2	Data points	E_0 (eV)	Resolution (FWHM) (eV)	Skewness	α_2 (10^{-8} eV^{-2})	Last 100 eV Counts	Last 100 eV Background	m_ν^2 (eV^2)[a]
3	273	254	18585.1(34)	55.6(12)	−0.123(14)	−1.32(19)	170	36	−805(926,85)
4A	209	250	18585.5(43)	36.0(13)	0.150(16)	−1.88(21)	93	28	2049(1795,156)
4B	230	220	18577.4(39)	36.2(15)	0.164(15)	−0.77(40)	273	53	−84(724,84)
4C	303	280	18582.9(29)	36.1(9)	0.150(16)	−0.23(15)	113	24	120(811,22)
All	1015	1004	18582.8(18)				649	141	−57(453,118)

[a]Uncertainties: (statistical, resolution).

in 5-eV steps near the end point in the third run. The fourth data set was recorded event by event, at randomly chosen energies for 55 sec, and at the 16.44-keV calibration energy for 110 sec every 10 min.

To analyze the data, a predicted beta spectrum was generated that includes the molecular final states,[4] screening corrections, nuclear-recoil effects, weak magnetism, and acceleration-gap effects (the last three are negligible). In the customary notation,

$$N(E)=CF(Z,R,E)p_eE\sum_i w_i(E_0-E_i-E)[(E_0-E_i-E)^2-m_\nu^2c^4]^{1/2}[1+\alpha_1(E_0-E)+\alpha_2(E_0-E)^2],$$

$$E\le E_0-E_i-m_\nu c^2.$$

Weak magnetism and nuclear recoil give[15] α_1 a value of 2.312×10^{-9} eV^{-1}. The total resolution, including energy loss in the source, was folded with the calculated spectrum. A five-parameter fit to the amplitude, end-point energy, neutrino mass, background level, and quadratic extraction-efficiency term[16] α_2 in a maximum-likelihood procedure with Poisson statistics was then performed. The resulting fit (Fig. 2) is characterized by a Ξ^2 parameter,[17] analogous to the usual χ^2 parameter,

$$\Xi^2=2\sum[s_i-y_i-y_i\ln(s_i/y_i)],$$

where s_i and y_i are the fit values and the measured value, respectively. (χ^2 minimization gives a biased estimate of areas, and results in an incorrectly fitted neutrino mass.) Because each point is 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 variance in y_i. This factor, unity when the number of counts is small, ranged from 0.2 to 0.8 at the low-energy end of the spectra. Dead-time corrections were necessary only in the beta-monitor data, as counting rates in the spectrometer did not exceed 30 sec^{-1}. Extensive Monte Carlo calculations were carried out to verify the unbiased character of the fit estimator.

In Table I we summarize run parameters and fit results. The indicated uncertainty in the end-point energy does not include the additonal 20-eV uncertainty in the energy[18] of the $^{83}Kr^m$ calibration line. The change in resolution between the data sets resulted mainly from improved cancellation of residual magnetic fields from the source magnets in the region of the spectrometer. The quadratic correction term varies from run to run because of both the changes in focus-coil setting and, in runs 4B and 4C, the 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 term, and gave similar results, but with slightly lower neutrino-mass limits. No nonstatistical variations were observed with either a (fixed) quadratic or a linear term when the fitting interval below the end point was varied over the range 2200 to 300 eV. Statistical tests showed that inclusion of both linear and quadratic terms was not warranted.

Statistical errors in m_ν^2 were extracted from the Ξ^2 plots [which were closely parabolic in positive m_ν^2 (Fig. 3)]. Resolution-function uncertainties in each run were then added in quadrature to the statistical error. To

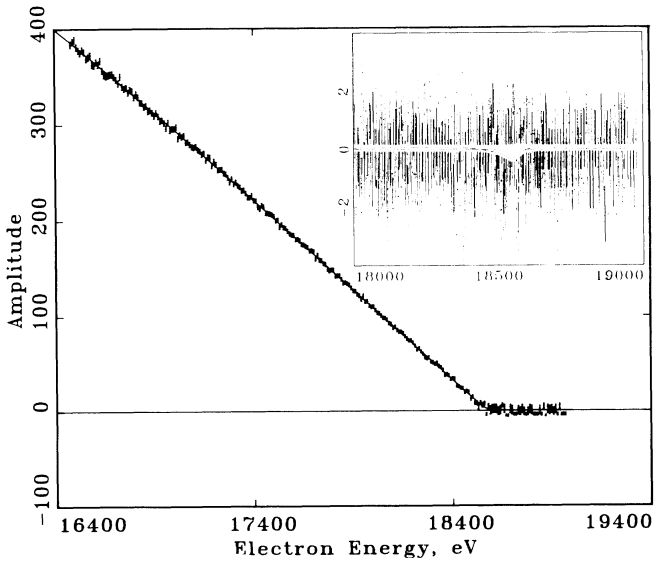

FIG. 2. Kurie plot for run 4A. Inset: Residuals (in standard deviations) for all data. The straight and curved lines are, respectively, the best fits for $m_\nu=0$ and 30 eV.

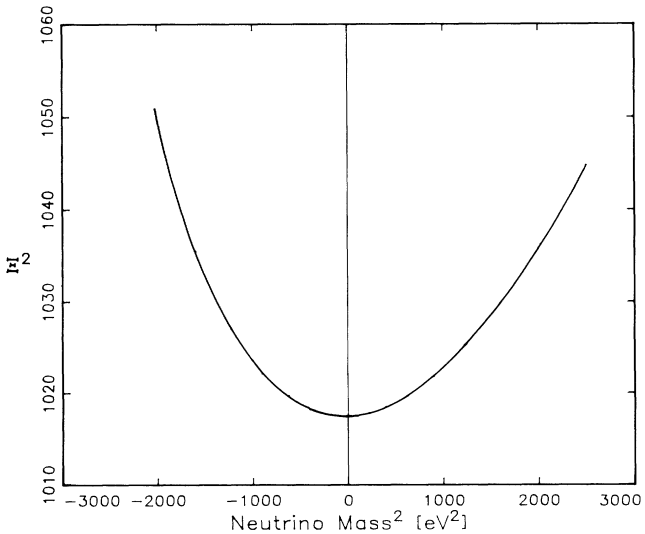

FIG. 3. Combined Ξ^2 plot for the data. At the minimum, Ξ^2 has the value 1015 for 984 degrees of freedom.

guard against the possibility of a correlated error, the average resolution error (87 eV^2) was also combined with the error in the final result, as were uncertainties from the measurement of the density of the source gas and the Monte Carlo simulation of multiple scattering (80 eV^2). Changes of 10% in the Kr shakeup and shakeoff intensities produced effects less than 1% of the final statistical error. These were the only uncertainties considered to be nonnegligible.

The uncertainty in the final result is predominantly statistical. An upper limit on the mass of the electron antineutrino is found to be 26.8 eV at the 95% confidence level (C.L.) or 23.3 eV at the 90% C.L. It does not support the central value reported by Boris *et al.*,[2] 30(2) eV, but neither does it exclude the lower part of the range 17 to 40 eV. It is compatible with the upper limits from solid-source experiments by Fritschi *et al.*[3] and Kawakami *et al.*[19] The present result is, for all practical purposes, model independent, and thus establishes the maximum mass the electron antineutrino can have. Improvements to the apparatus now in progress are expected to result in a sensitivity to neutrino mass in the vicinity of 10 eV.

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