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AUTHOR(S): Robert Graham Hamish Robertson

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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DIRECT MEASUREMENTS OF NEUTRINO MASS -- A STATUS REPORT

R. G. H. Robertson
Physics Division, Los Alamos National Laboratory,
Los Alamos, NM 87545, U. S. A.

ABSTRACT

Some recent developments in the experimental search for neutrino mass are discussed. New data from Los Alamos on the electron neutrino mass as measured in tritium beta decay give an upper limit of 9.3 eV at the 95% confidence level. This result is not consistent with the long-standing ITEP result of 26(5) eV within a "model-independent" range of 17 to 40 eV. It now appears that the electron neutrino is not sufficiently massive to close the universe by itself. Hime and Jelley report finding new evidence for a 17-keV neutrino in the β decay of ^{35}S and ^{63}Ni. Many other experiments are being reported and the situation is still unresolved.

1. Introduction

The continuing intensive experimental search for neutrino mass is motivated by the profound implications for cosmology and for particle physics. As is well known, the universe would be gravitationally closed by a neutrino having a mass of a few tens of eV, and the 1980 report[1] by the group at the Institute for Theoretical and Experimental Physics (ITEP) in Moscow of a 35 eV electron neutrino mass therefore aroused great interest. In the intervening 11 years, the ITEP group have improved their apparatus, taken more data, refined their analysis, and still find qualitatively the same result. New experiments at the Los Alamos National Laboratory on the beta decay of free molecular tritium[2] now give an upper limit of 9.3 eV, in disagreement with the ITEP result. Experiments at the Institute for Nuclear Studies in Tokyo[3] and at the University of Zürich[4] also give no support to the ITEP claim.

While there has been no recent work on the mass of the μ neutrino, a vigorous program of research on the τ continues. The Argus collaboration at DESY has observed[5] several examples of the decay of the τ to 5 charged pions, and can set an upper limit of 35 MeV on the mass of ν_τ. This represents a substantial advance over the previous limit (also Argus[6]) of 70 MeV. At present one can see no direct laboratory technique that would probe μ and τ masses to the levels allowed by cosmology for stable neutrinos, although there is the distinct possibility that the masses of these neutrinos might be observed through oscillations.

The new work of Simpson and Hime[7,8] and Hime and Jelley[9,10] appears to show evidence for a small admixture of a 17-keV neutrino in the electron neutrino, in contradiction with a number of other experiments.

2. Tritium Beta Decay Experiments

2.1 Method

It has been known for more than 50 years that the energy spectrum of electrons emitted in beta decay yields information about the mass of the electron neutrino. Tritium is especially suitable for this work in view of its large matrix element, low energy release, simple atomic structure and convenient half-life. The beta spectrum may be written:

$$N(E) = C\, F(Z_f,R,E)\, p_e\, E\, \Sigma_i w_i(E_0-E_i-E)[(E_0-E_i-E)^2-m_\nu^2c^4]^{1/2}$$

$$\times [1 + \alpha_1(E_0-E) + \alpha_2(E_0-E)^2]\ ;\ \ E \le E_0-E_i-m_\nu c^2$$

where $F(Z_f,R,E)$, a smoothly varying function of energy, is the Fermi function that corrects for Coulomb distortion of the outgoing wave. The total energy is E_0. Small theoretical and experimental corrections are absorbed in the polynomial with coefficients α_1 and α_2. Weak magnetism and nuclear recoil give[11] α_1 a value of 2.312×10^{-9} eV^{-1}. The summation is over all final states of the daughter system. Each final state has a different energy, and calculating the energies E_i and branching ratios w_i to the final states is a matter of fundamental importance in all tritium experiments. Equally important, but more amenable to experimental checks, are energy loss as the electron traverses the source material, instrumental resolution, and backscattering.

In 1980, 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[12] has reduced this value slightly to 26(5) eV, with a "model-independent" range of 17 to 40 eV. Fritschi et al.[13] found in a similar type of experiment at the University of Zürich an upper limit of 18 eV. Both the Zürich and ITEP experiments had 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.

2.2 The Los Alamos Experiment

Unlike other experiments presently in operation, the experiment[2,14] 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. The final-state 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. Thus the gaseous source minimizes systematic uncertainties, but it is technically more difficult, and statistical accuracy can be hard to obtain.

The Los Alamos group reported[14] in 1987 an initial result, $m_\nu < 27$ eV at 95% confidence level (CL), which showed that it was possible to perform experiments with gaseous sources at a useful level of sensitivity. The precision of the result was limited almost entirely by statistical accuracy, systematic effects being very much smaller. 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, a number of improvements were made, the principal one being the replacement of the simple single-element proportional counter in the spectrometer with a 96-pad Si microstrip detector array.

The new detector is an octagonal array of 300-μm thick planar passivated Si wafers (n-type) each with a sensitive area of 7 x 10 mm^2. The sensitive area is subdivided into 12 strips on 0.83-mm centers by readout pads. There are thus 96 microstrips tiling the surface of a 2-cm diameter cylinder. For 23-keV electrons, resolutions of 2.5 to 4.0 keV FWHM are observed.

Numerous other improvements were made. An axial gradient was superimposed on the magnetic field of the source to eliminate the trapping of electrons, which previously necessitated a large and complex correction. Baffles were installed in the spectrometer, and the acceptance reduced by half, to improve the lineshape. A getter pump was added to remove atmospheric gases that caused extra energy loss when Kr was being recirculated. The stability and background of the Si detector that monitors the source strength was improved, and the source density was stabilized with the addition of a servo regulator. Notwithstanding the loss in spectrometer acceptance, the gross data rate is 8 times higher than previously. Of the 96 channels, 9 are at present either non-functional or excessively noisy, and are not used.

The beta spectrum is formed by setting the spectrometer to analyze a fixed momentum (equivalent to an energy of 23 keV or 24 keV) and scanning the accelerating voltage on the source. 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.

Analysis of the data begins with manual creation of a set of 87 "windows" on the energy spectra from the individual pads. The windows include most of the counts from 23-keV or 24-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 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 are then estimated[14] from plots of the fit parameter Ξ^2 against m_ν^2. The square, not m_ν itself, is the appropriate variable because of the form in which it appears in the Fermi spectrum. Parabolic Ξ^2 plots are obtained, as required for a consistent treatment of uncertainties. The Fermi spectrum is not defined for negative m_ν^2, and it is necessary to devise a functional expression that continues the parabolic behavior of Ξ^2 into the non-physical regime. If m_ν^2 is actually zero, then, statistically, experiments will deliver negative values half the time. We adopt the following expression (similar to that given by Fritschi et al.[13]):

$$N_i(E) \sim \{(E_0 - E_i - E)^2 + k^2/2\}\, \Theta(E_0 - E_i - E),$$

where $k^2 = - m_\nu^2$, and Θ is the Heaviside function, and we have suppressed multiplicative factors.

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 gas-density profile in the source was 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. The cross section differential in energy has been constructed from various data[14] The stopping power computed with our differential cross section (which satisfies the Liu[15] sum rule, $\sigma_0 = 3.474(11) \times 10^{-18}$ cm^2 at 18.5 keV) is 0.44×10^{-16} eV-cm per atom, 18% below the Bethe stopping power.[16] 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 $m_\nu{}^2$ 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 $m_\nu{}^2$ larger than 0.2 eV^2.

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 the Los Alamos 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 calculations for their positions and intensities, a direct measurement of the equivalent Kr K-shell photoionization spectrum was made at the Stanford Synchrotron Radiation Laboratory.[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] A 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 included in the instrumental resolution a flat tail of 7×10^{-6} eV^{-1} extending to 350 eV, at which point its effect on m_v^2 maximizes. The effect of the added tail on m_v^2 is 15 eV^2, with a 15 eV^2 uncertainty. The shape of the instrumental line itself was taken to be a skewed Gaussian with kurtosis, the parameters for which were extracted by a) convolution of the theoretical spectrum, b) convolution of high-resolution photoionization data, and, c), maximum-entropy deconvolution of the theoretical spectrum (which method requires no assumption about the functional form). The three approaches agreed to better than 1%, representing an uncertainty in m_v^2 of less than 2 eV^2.

The small variation of apparatus efficiency with acceleration voltage introduces a spectral distortion that can influence the neutrino mass derived. It is customary to parametrize this with empirically determined linear and quadratic correction terms α_1 and α_2 in the spectrum. In the Los Alamos 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. Investigations of this effect included Monte Carlo simulation of the transport system, measurements of the tritium spectrum over an extended energy region (9 to 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_v^2 to empirical energy-efficiency parameters,[14] 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 freedom.) Then, with this term held constant, fits were made to increasingly truncated data sets. 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 a poor representation is also shown). To minimize sensitivity to α_1 and α_2, data sets truncated 825 eV below the endpoint were used to determine m_v^2. The best estimate of m_v^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.

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[19] 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 set 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.

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[20] 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.

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. The Martin-Cohen (MC) calculation[22] is truncated at 94 eV excitation, and the Quantum Theory Project (QTP) calculation[23] at 164 eV. The MC and QTP calculations are in very good accord, the latter (the one we adopt) giving an 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,[24] 1110 eV^2. Despite this apparently large discrepancy, the effect on neutrino mass is actually rather small, as was demonstrated 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 validity of the sudden approximation, on which all these calculations rest, has not seriously been questioned, largely because of the work of Williams and Koonin[25] (WK), who 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. WK, however, treated only s-wave final states, arguing that other partial waves would each contribute of order $(1/pa_0)^2 = (1/36)^2$, where p is the beta momentum, and a_0 the Bohr radius. They then invoked Intemann's argument[26] that the highest partial wave of interest would have an l of order pa_0, but erroneously found this quantity to be 1/36, whereas it is actually 36. A complete calculation appears to be very difficult, but Friar[11] has obtained a closed-form expression for the p-wave bound and continuum strengths. Friar showed that higher l contributions fall off very rapidly for bound states. McCarthy[27] carried out a calculation for the continuum in the limit that the energy of the ejected orbital electron is substantially larger than its binding energy (the interesting limit in this application) and showed that this interaction would cause shifts in the value of m_ν^2 of about 2 eV^2.

The results, and their 1-σ statistical uncertainties, are listed in Table I. In Table II are listed the estimated uncertainties (1-σ) in m_ν^2 from all sources.

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

Data Set	8-88		8-89A		8-89B		
Fit with	α_1	α_2	α_1	α_2	α_1	α_2	
Final Energy	23		23		24		keV
Resolution	85		95		106		eV^2
Data Range	16545 to 19195		16540 to 19180		17540 to 19210		eV
m_ν^2	-229(107)	-159(108)	19(190)	24(198)	-158(87)	-145(88)	eV^2
E_0-18568[a]	0.5(6)	1.3(5)	1.4(9)	2.1(8)	1.7(7)	1.9(6)	eV
$\alpha_1 x\ 10^5$	-2.3(2)	-----	-1.7(2)	-----	-1.1(7)	-----	eV^{-1}
$\alpha_2 x\ 10^9$	-----	-7.9(6)	-----	-5.4(8)	-----	-6.4(45)	eV^{-2}
Counts, S/N[b]	7859, 4.7		4048, 3.0		8230, 10.0		

[a]Mean E_0 = 18570.5(20) eV (see Ref. 19 for corrections and uncertainties).

[b]Total counts, signal-to-background in last 100 eV of beta spectrum.

In Figure 1 are plotted 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.Values of normalized Ξ^2 fell in the range 1.03 to 1.08, as expected for this Poissonian fit estimator with approximately 470 degrees of freedom. Figure 2 shows the residuals near the endpoint for m_ν fixed at 0 and 30 eV. The best-fit value of m_ν^2 is $-147 \pm 68 \pm 41$ eV^2. In order to set confidence limits on the true value of a quantity that is inherently non-negative, a Bayesian approach is needed.[28] 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 variance unchanged) the corresponding upper limit would be only 3.1 eV higher, an indication of the modest sensitivity of the Bayesian limit to negative fluctuations.

TABLE II. Contributions (eV^2) to the uncertainty in $m_\nu{}^2$ at one standard deviation.

Analysis (3 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

The three runs are distributed as expected for their statistical uncertainties, but the mean is nearly two 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 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 calculations[22,23,29] of the FSS for T_2 agree at the level of 10 eV^2. The universally applied Born-Oppenheimer[30] and sudden[27] approximations are estimated to entail errors less than 0.04 and about 2 eV^2, respectively. The partition of recoil energy between internal[31] 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[21] and thermal motion create Doppler broadenings of variance 0.0004 and 0.04 eV^2, respectively.

The beta 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.[32] Mixing with other massive or massless left-handed neutrinos does not lead to "wrong-sign" effects such as we see. Hughes and Stephenson[33] 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[34] that could mimic a negative $m_\nu{}^2$, 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 $E_{0i} + m_\nu c^2$. Our data can be fit well by such a prescription. The partial half-life of ^3H for such a putative decay branch is found to be 1.3 x $10^{10}/(1.0 \pm 0.5)$ years, with $m_\nu = 0$. Long though this is, it requires a neutrino density of order 10^{16} cm^{-3}, far above plausible estimates.[35]

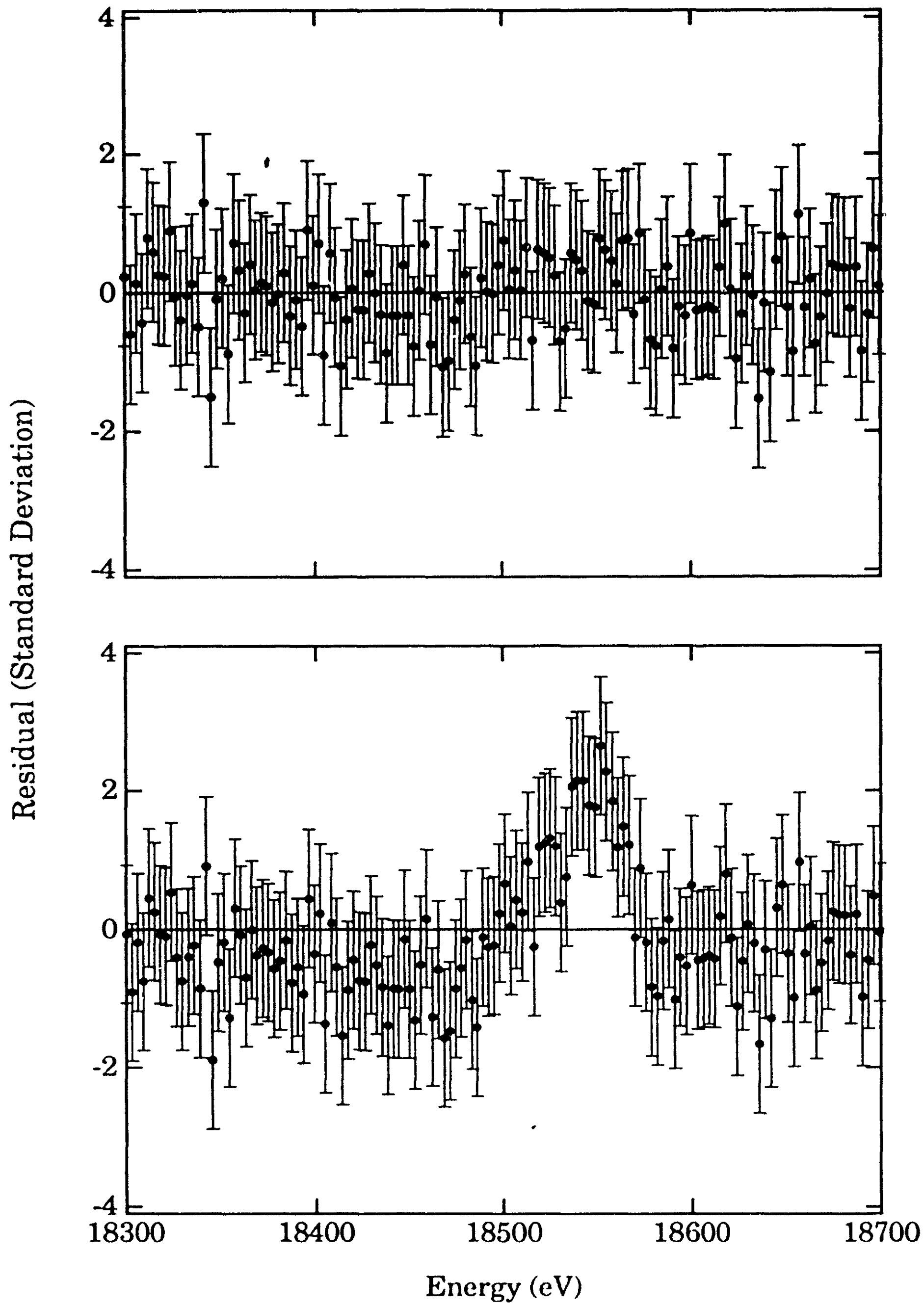

Fig.1. Residuals in fits to neutrino masses of 0 (top) and 30 eV (bottom). All other parameters including α_1 have been allowed to vary.

2.3 The INS (Tokyo) Experiment

A solid-source experiment in an iron-free $\pi\sqrt{2}$ spectrometer has been developed at the Institute for Nuclear Studies (INS) in Tokyo.[3] The INS group has modified their earlier experiment[36] by increasing the source size fivefold and the detector sixfold in area. The source is a thin Langmuir-Blodgett film of tritiated cadmium arachidate. The resolution in the most recently reported data is about 25 eV FWHM. For the data set acquired in the fall of 1988, 150,000 events were accumulated in the last 100 eV of the spectrum, including background. In the absence of theoretical calculations for the FSS of cadmium arachidate, the INS group has made use of the spectrum for valine calculated by Kaplan and collaborators.[24] Hence, as they point out, their result is model dependent, and it is difficult to assess what the size of the uncertainty added by this assumption might be. With that caveat, the result quoted for m_ν^2 is $-65\pm85\pm65$ eV^2, and the Bayesian upper limit on m_ν is given as 13 eV (95% CL).

2.4 The Zürich Experiment

The University of Zürich group has replaced the tritium-implanted carbon source[13] with a novel monomolecular film. As in the case of the INS experiment, a theoretical calculation of the final-state spectrum for this molecule ("OTS") has not been carried out, and the Kaplan-Smelov[24] calculation for CH_3T was used instead. The result quoted[4] for m_ν^2 is $-158\pm150\pm103$ eV^2, and the Bayesian upper limit on m_ν is given as 15.4 eV (95% CL). The group has also drawn attention to errors made in the original experiment[13] in which they reported an upper limit of 18 eV. Specifically, the energy resolution of the apparatus was underestimated, and the energy loss in long tails was underestimated (as we suggested earlier[36]). Fortunately, these errors largely cancelled each other.

2.5 The Electron Neutrino Mass

Although one cannot fail to be struck by the fact that all modern measurements of the tritium spectrum with the exception of ITEP are yielding slightly negative central values for m_ν^2, whether this is significant or not remains to be seen. A new experiment along the same general lines as the Los Alamos one is beginning operation at Lawrence Livermore National Laboratory,[37] and it will, like the Los Alamos one, be relatively free of the final-state uncertainty.

The modern data give no support for a non-zero neutrino mass. The 9.3-eV limit from the Los Alamos gaseous source experiment is strongly in contradiction with the ITEP result[1] [26(5) eV, with a "model-independent" range of 17 to 40 eV]. While we cannot identify a specific reason for this disagreement, the conclusions from tritium experiments are sensitive to minute details that, in our view, are not adequately known for complex solid source 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 SN1987a is not dominated by neutrino mass, but rather must reflect the actual cooling of the protoneutron star.

3. The 17-keV Neutrino?

3.1 Experimental Situation

In 1985 Simpson[38] reported that there was at the low-energy end of the tritium beta spectrum a distortion indicative of a 3% admixture of a 17.1-keV antineutrino with the dominant electron antineutrino. It was subsequently shown by Lindhard and Hansen[39] and by Eman and Tadic[40] that about 67% of the distortion could be explained by Simpson's use of an incorrect screening potential. A similar effect, exchange between the orbital electrons and the outgoing beta particle, was noted by Haxton[41] to be responsible for another 15% of the distortion. The remaining evidence for a 17-keV neutrino from beta decay of tritium in Si seemed too model-dependent to be conclusive.

The 18.6-keV Q-value for tritium beta decay makes tritium a poor candidate for revealing a 17-keV neutrino, and several groups took up the search in ^{35}S (Q = 167 keV) and ^{63}Ni (Q = 67 keV). In ^{35}S five groups claimed[42-46] to find no evidence for a 17-keV neutrino at levels below that found by Simpson. In every case, however, an error or omission was made that places the claim in doubt. The Princeton work of Altzitzoglu et al.[42] failed to allow the endpoint energy to vary when the data were fitted to a heavy neutrino admixture. In the experiment at INS, Tokyo, by Ohi et al.,[43] shape correction factors obtained for the assumption $m_\nu = 0$ were held fixed in subsequent fits searching for a non-zero mass. Indeed, as Simpson[47] has pointed out, their data in fact seems to show evidence for a 17-keV neutrino. Data from the ITEP experiment of Apalikov et al.[45] show an anomaly at 150 keV in both the narrow and wide-scan data, and the graphs illustrating the lack of fit to a 17-keV neutrino are transparently not fits, because the data points all lie on one side of the theoretical curve. Both linear and quadratic shape-correction terms were used, and the high precision (1 - 2 %) with which they were determined raises the question of whether further terms are needed. Datar et al.,[44] like Ohi et al.,[43] failed to allow all parameters to vary when searching for a massive neutrino admixture and Simpson[48] showed that, when this is corrected, their data give a best-fit value of 0.8% admixture of a 17-keV neutrino. Markey and Boehm[46] omitted shape-correction factors altogether without explanation, whereas subsequent experiments with the Caltech spectrometer have found a need for such terms (under somewhat different conditions). The most recent Caltech data[49] yield an upper limit of 0.6% at 90% CL. To the casual observer, those data appear to have an odd structure, and it would be of interest to see the variation in upper limit as a function of neutrino mass.

On the other hand, one very careful experiment exists that appears completely inconsistent with the hypothesis that a 17-keV neutrino is admixed with the electron neutrino. In the detailed study of ^{63}Ni carried out by Hetherington et al.[50] on the Chalk River $\pi\sqrt{2}$ spectrometer an upper limit of 0.3% (90% CL) was set on the heavy neutrino admixture. A linear shape correction was sufficient to describe the data, and higher-order terms had no statistical significance. The upper limit was obtained in a manner not in accord with the widely-accepted prescription of the Particle Data Group,[51] and would be even more restrictive had that been done. There is a very interesting feature that shows up in the plot of admixture limit versus neutrino mass (their Fig. 11). An anomaly corresponding to roughly a 0.5% admixture of an 8-keV neutrino appears with a significance greater than 2 standard deviations. We suggest that it is a result of K-shell shakeoff accompanying β decay, which produces a modification to the spectrum not very different from that of a massive neutrino. However, the integral probability for K-vacancy production is known to be at least an order of magnitude smaller[52]. Both Simpson[48] and Hime[53] have criticized this work on the grounds that the shape correction factor masks much of the effect of an admixed heavy neutrino, but in a correct analysis this effect (a correlation coefficient) is properly accounted for in the uncertainties.

Hime and Simpson[8] then reported not only that the beta spectrum of tritium implanted in Ge shows the effect of a heavy neutrino admixture, but also that there is strong evidence in ^{35}S for the same admixture.[7] From the tritium-in-germanium data, Hime and Simpson conclude that there is a 1.1(5)% admixture of a 16.9(1)-keV neutrino, in good agreement with the revised values from the earlier experiment[38] on tritium implanted in Si. The ^{35}S result is lower, but still consistent, at 0.73(9,6)% admixture of a 16.9(4)-keV neutrino. (The uncertainties in parentheses are statistical and systematic, respectively.) In Table III we summarize the relevant measurements, to the best of our knowledge.

Hime and Jelley[9] at Oxford carried out a new Si detector experiment on ^{35}S in which some concerns about the Guelph work (backing thickness, collimation, response function) were addressed. The results were in agreement with the 17-keV neutrino hypothesis. ^{63}Ni was then examined[10] with the same conclusions, although in this case, as Hime and Jelley point out, the corrections are delicate and about the same size as the effect. Somewhat unexpectedly, an experiment [54] on ^{14}C grown in a Ge detector at Lawrence Berkeley Laboratory also yielded positive evidence for a 17-keV neutrino, although the statistics are not as high, and the use of a different detector for background subtraction can be criticized. Zlimen et al.[55] claim evidence for a 17-keV neutrino from experiments on the internal bremsstrahlung spectrum of ^{71}Ge. The data are of marginal statistical significance as presented, and, unfortunately, the analysis is incorrect owing to neglect of correlation terms introduced by extrapolation.

Table III. Measurements and calculations relating to the 17-keV neutrino proposed by Simpson.

		Spectrometer[a]	m_ν(keV)	$\sin^2\theta$	
Simpson	T in Si	X	17.1(2)	0.03	
Haxton		Exchange Corrections			
Lindhard & Hansen		Screening Corrections			
Simpson (revised)			17.1(2)	0.011(3)	
Altzitzoglu et al.	^{35}S	M		<0.004	99% CL
Ohi et al.	^{35}S	X		<0.0015	90% CL
Apalikov et al.	^{35}S	M		<0.0017	90% CL
Datar et al.	^{35}S	X		<0.006	90% CL
Markey & Boehm	^{35}S	M		<0.003	90% CL
Hetherington et al.	^{63}Ni	M		<0.003	90% CL
Hime & Simpson	T in Ge	X	16.9(1)	0.011(5)	
Simpson & Hime	^{35}S	X	16.9(4)	0.0073(9,6)	
Hime & Jelley	^{35}S	X	17.2(5)	0.0085(6,5)	
Sur et al.	^{14}C	X	17(1)	0.013(3)	
Becker et al.	^{35}S	M		<0.006	90% CL
Zlimen et al.	^{71}Ge (IB)	X	17.2(12)	0.016(7)	
Hime and Jelley	^{63}Ni	X	16.75(35,15)	0.0099(12,18)	
Simpson	^{45}Ca	X	(in progress)		
Stoeffl	T_2 gas	M	(in progress)		

[a] X = Crystal Spectrometer, M = Magnetic Spectrometer

3.2 Conclusions on the 17 keV Neutrino

In a matter as fundamental as this, it would be unwise to jump to conclusions. The Si detector data are of high statistical significance, carefully analyzed, and appear to show strong evidence for a 17-keV neutrino admixing at about the 0.9% level with the electron neutrino. At the same time, no magnetic spectrometer experiment has yet shown any evidence for it, although most experiments that have claimed to rule it out do not stand up to close scrutiny. By using a higher Q-value β-emitter to calibrate the spectrometer efficiency *vs.* energy,[56] a major point of contention could be eliminated. New, carefully executed experiments of every type are needed.

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10 / 29 / 91