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SEARCHES FOR MASSIVE NEUTRINOS IN NUCLEAR BETA DECAY*

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ABSTRACT

The status of searches for massive neutrinos in nuclear beta decay is reviewed. The claim by an ITEP group that the electron antineutrino mass > 17 eV has been disputed by all the subsequent experiments. Current measurements of the tritium beta spectrum limit $m_{\bar{\nu}_e} < 10$ eV. The status of the 17 keV neutrino is reviewed. The strong null results from INS Tokyo and Argonne, and deficiencies in the experiments which reported positive effects, make it unreasonable to ascribe the spectral distortions seen by Simpson, Hime, and others to a 17 keV neutrino. Several new ideas on how to search for massive neutrinos in nuclear beta decay are discussed.

I. Introduction

The questions of whether neutrinos have mass, and whether the lepton families mix as do the quarks, are fundamental, with broad implications in particle physics and cosmology. Two very provocative experiments of the 1980's highlighted these questions. The first was a report from Lubimov's group at ITEP in Moscow in 1980 [1] that the electron antineutrino had a rest mass between 15 and 40 eV. The second was John Simpson's claim in 1985 [2] that a kink in the tritium beta spectrum was evidence that the electron antineutrino has a 17 keV component.

This paper reviews the recent experimental results on both these topics. Although the Lubimov result has been seriously questioned for some time, it is only within the past year that several of the experiments it provoked have reported their final results. These results provide the best direct limits on the electron antineutrino mass to date.

On the 17 keV neutrino front, this year has seen reanalysis of earlier results, thoughtful critiques of existing experiments, and decisive new results. I have chosen to include results that appeared after the time of the Trieste Workshop in this paper for the sake of completeness.

The organization of this paper is as follows. The first section reviews measurements of the tritium β spectrum near its endpoint, and the resulting mass limits on the electron antineutrino. The second section reviews experiments on 17 keV neutrinos, and focuses on new results and critical interpretations. This field of research has produced contradictory results and controversy; consequently it has stimulated new ideas on how to search for massive neutrinos in nuclear beta decay. These are briefly discussed in the third section of the paper.

II. Measurements of the Tritium Spectrum Near the Endpoint

A. *Signature of Massive ν_e*

The beta decay of tritium, $^3H \rightarrow {}^3He^+ e^- \bar{\nu}_e$, is distinguished by its very low Q value, 18.57 keV, which makes it maximally sensitive to the kinematic effects of finite neutrino mass. The transition is superallowed, a mix of Fermi and Gamow-Teller transitions. The electron energy spectrum, dN/dE, is determined by phase space and Coulomb corrections, with its normalization coming from the nuclear matrix element and the Fermi coupling strength

$$\frac{dN}{dE}\,(m_\nu, E_0^i) = K|M|^2\,F(E) \times pE(E_0^i - E)\left[(E_0^i - E)^2 - m_\nu^2\right]^{1/2}. \quad (1)$$

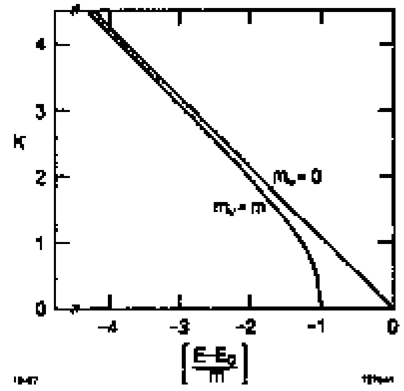

Figure 1. Kurie plot for nuclear beta decay. Finite neutrino mass lowers the endpoint and distorts the spectrum.

Here p and E are the electron momentum and total energy, E_0^i the endpoint energy corresponding to a particular final state i, and $F(E)$ the so-called Fermi function, which accounts for the Coulomb interaction between the electron and the Helium nucleus in the final state. Additional Coulomb corrections, which account for interactions with the atomic electrons, are inconsequential near the endpoint.

The spectral shape near the endpoint is sensitive to neutrino mass. This is shown on the Kurie plot of Fig. 1, where $K = \{dN/dE/(F(E)pE)\}^{1/2}$ is plotted against the electron energy. The endpoint shifts to $E_0 - m_\nu$, and the rate near the endpoint is depressed. The distortions will be washed out unless the energy resolution is comparable to m_ν. Only decays within about 3 m_ν of the endpoint are of use in searching for an effect, and these are a minute fraction of all decays, $\sim 10^{-10}\,(m_\nu/\mathrm{eV})^3$. Thus, beside good energy resolution, these experiments require great sensitivity and very low backgrounds.

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B. *Multiple Final States*

An additional effect complicates the electron spectrum near the endpoint. The atomic electrons which orbit the tritium nucleus are no longer in a unique eigenstate after the tritium decays. In monatomic tritium, atomic physics calculations [3] predict that about 70% of the decays result in a ground state helium ion. 25% in an excited state 40 eV higher in energy (*shake-up*), and the remainder in continuum, fully ionized states above 60 eV (*shake-off*). The pattern is more complicated in molecular tritium, although it is still thought to be reliably calculated. For tritiated. complex organic molecules, the calculations are less robust. In all these cases, the ion can be left in any one of several energy states; hence, a whole range of endpoint energies must be considered, and the spectrum becomes the weighted sum over the final states

$$\frac{dN}{dE_{ik}} = \sum_i w_i \frac{dN}{dE}\left(m_\nu, E_0^i\right) . \qquad (2)$$

Figure 2 shows the resulting Kurie plot.

C. *Fits to the Data*

It is common practice to account for small variations in detection efficiency with energy by multiplying the theoretical spectrum by a *shape factor*, e.g., $1 - \alpha(E - E_0)$. Detector resolution and energy loss effects are typically measured with internal conversion sources, and incorporated in a response function. This is convoluted with the shape-corrected spectrum to predict the measured spectrum. The parameters m_ν^2, E_0, α, and the normalization are adjusted to give a best-fit to the data.

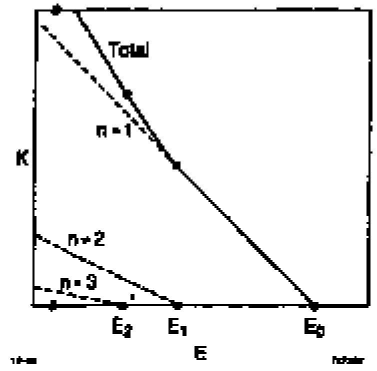

Figure 2. The spectrum of final states complicates the Kurie plot, giving rise to slope discontinuities.

D. *ITEP Results*

The ITEP group studied the endpoint of the tritium spectrum using a novel torroidal magnetic spectrometer with 45 eV FWHM resolution. The complex organic molecule valine ($C_5H_{11}NO_2$) was tritiated to serve as a source. Roughly 10^6 counts were accumulated in the last 100 eV of the spectrum. The group concluded [1] that the electron antineutrino mass was finite, $14 \leq m_\nu \leq 46$ eV (99% C.L.). This result was criticized because resolution effects and the complex final state effects were not correctly included. The final report from the group [4] addressed these criticisms with a refined apparatus, resolution function measurements, and detailed final state calculations. Their result, shown in Fig. 3, stills evidences finite neutrino mass. They conclude $m_\nu = 30.3^{+2}_{-8}$ eV. The vagueries of the atomic physics make it difficult to assign a systematic error. Instead the authors quote the range of m_ν for which their measured endpoint energy is consistent with the He–T mass difference. They find $17 < m_\nu < 40$ eV. This is the lone experiment reporting a finite electron antineutrino mass in the 20 eV range.

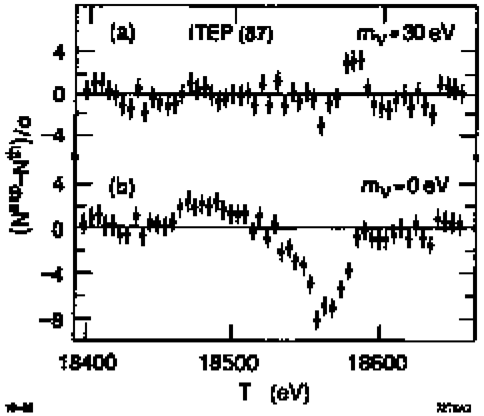

Figure 3. Tritium beta spectrum measured by the ITEP group[4] compared to fits with $m_\nu = 30$ eV and $m_\nu = 0$ eV. Finite neutrino mass was indicated.

E. *Recent Results*

The strong statistical, if questionable systematic, weight of the ITEP result stimulated several groups to repeat the experiment.

Groups at Zurich and Tokyo were the first to report results, and have continued to refine their work in the last year or so. Both have sources similar to the solid valine source of the Moscow experiment. Zurich uses T_2^+ ions embedded into a thin carbon layer (which they treat as CH_3T) evaporated onto an aluminum backing; Tokyo uses tritiated arachidic acid ($C_{20}H_{40}O_2$). Calculations of the spectrum of final states in these complex molecules have been made. Figure 4 demonstrates the sensitivity of the deduced neutrino mass to the assumed corrections. The Zurich group uses a magnetic spectrometer of the torroidal design used at ITEP; the Tokyo

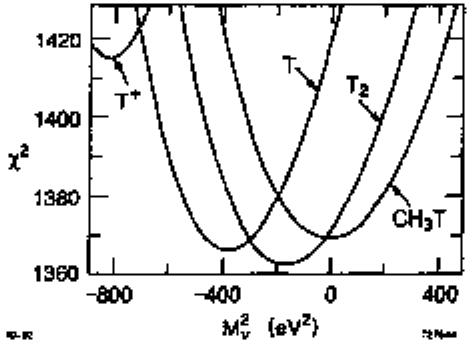

Figure 4. χ^2 versus m_ν^2 for fits to the tritium beta spectrum. with various assumptions about the spectrum of final states. The figure is from Ref. [5].

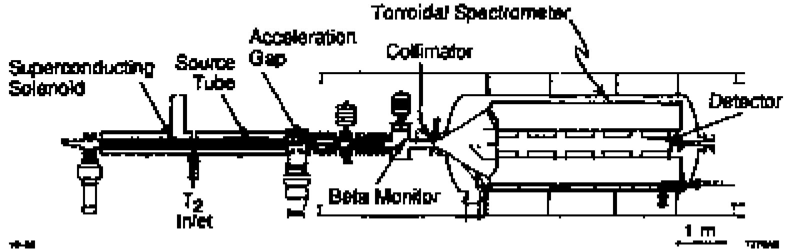

Figure 5. Apparatus used by the Los Alamos group for measurements of the tritium beta spectrum. incorporating a gaseous T_2 source. electron containment in a long solenoidal magnetic field. and an ITEP-style torroidal spectrometer.

group employs a $\pi\sqrt{2}$ Fe-free focusing spectrometer. Neither group sees evidence for finite neutrino mass. The Zurich group [5] finds $m_\nu^2 = -24 \pm 48 \pm 61$ eV²; and the Tokyo group [6] reports $m_\nu^2 = -65 \pm 85 \pm 65$ eV². Uncertainties in the spectrum of final states and in the resolution function contribute significantly to the systematic error.

In order to reduce the uncertainties associated with final state effects, a Los Alamos group undertook the development of a gaseous tritium source. Their apparatus, which incorporates an ITEP-style torroidal spectrometer is shown in Fig. 5. Two additional advantages accrue from this design: (1) good electron acceptance, provided by capturing and transporting decay electrons in a strong solenoidal field; and (2) a well-understood source where backscattering is essentially non-existent, and energy loss calculable and measurable. Handling gaseous tritium is tricky, requiring safety precautions, differential pumping, and very high vacuum in the spectrometer in order to avoid spurious volume and surface decays overwhelming the signal. A group at Livermore has constructed a similar device. and improved on the spectrometer's resolution. The Los Alamos group finds [7] $m_\nu^2 = -147 \pm 68 \pm 41$ eV² from a fit with roughly 10 k counts in the last 100 eV of the spectrum and 10 eV resolution. The Livermore group [8] has a preliminary result $m_\nu^2 = -72 \pm 41 \pm 30$ eV², and is continuing to improve their experiment. Their Kurie plot is shown in Fig. 6. Near the endpoint the data falls slightly above the fitted curve: the same is true of the Los Alamos data, and in fact is true of most of the current experiments. In consequence, the best fit value of m_ν^2 is slightly negative. which may indicate uncorrected systematics.

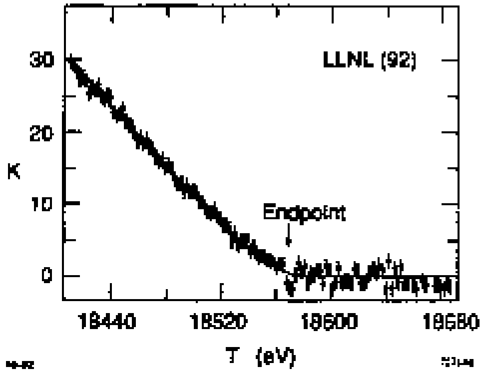

Figure 6. Kurie plot for T_2 decays near the endpoint. measured with the Livermore torroidal spectrometer [8].

Final state effects are also manageable in frozen tritium targets. which has prompted the work of a second Livermore group [9] and a group at Mainz [10]. The latter experiment has recently reported results. It utilizes a so-called solenoid-retarding spectrometer, which does integral measurements of the spectrum with 2π acceptance and 6 eV resolution. Their result is shown in Fig. 7. In contrast to other experiments, they fit only the last 137 eV of the spectrum. which minimizes their systematic error. Their target has roughly 20 monolayers of tritium on an aluminum backing; hence backscattering corrections must be carefully understood. and energy loss in the target corrected. They find $m_\nu^2 = -39 \pm 34 \pm 15$ eV².

F. Conclusions

Figure 8 summarizes the recent results. All of the experiments are in conflict with the ITEP claim that the electron antineutrino mass is > 17 eV. although

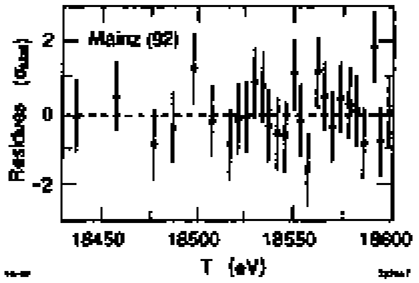

Figure 7. The endpoint region of the tritium spectrum, measured by the Mainz group [10].

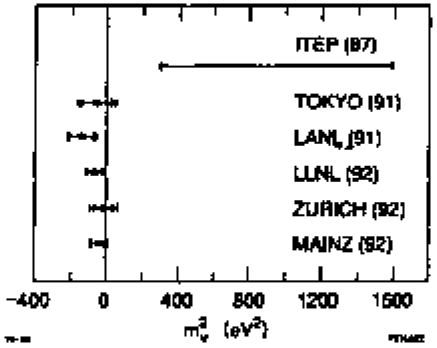

Figure 8. Summary of recent results on the electron antineutrino mass.

no decisive explanation has been offered for the Russian result. The best limit at present is from the Mainz group, $m_\nu < 7.2$ eV (95% C.L.). The recent experiments all find the endpoint energy near 18570 eV, in good agreement among themselves, and consistent with the measured mass difference of T and He^3 from cyclotron resonance measurements [11]. The Russian experiment reported an endpoint energy 18580.8 ± 4 eV. As noted above, all experiments find the best fit value of m_ν^2 to be slightly negative, though not significantly so. This coincidence has prompted some uneasiness, however, and begs further experimental refinement. The Mainz and Livermore experiments look capable of pushing the sensitivity to a few eV. Pushing the limits by another decade looks improbable with this technique, requiring a tenfold improvement in resolution and a thousandfold increase in source strength.

III. Status of Searches for the 17 keV Neutrino

A. *Kinks in Beta Spectra*

The possibility that the neutrino emitted in β decay might be the admixture of several mass eigenstates was explored in influential papers by Shrock and by McKellar [12] in 1980. For simplicity, imagine the electron antineutrino to be the superposition of two mass eigenstates,

$$|\bar{\nu}_e\rangle = \cos\theta\,|\bar{\nu}_1\rangle + \sin\theta\,|\bar{\nu}_2\rangle \ . \tag{3}$$

For suitable $m_{\nu 2}(Q > m_{\nu 2} > m_{\nu 1})$, and assuming the $\bar{\nu}_1$ is essentially massless, the resulting electron spectrum has two components,

$$\frac{dN}{dE} = \cos^2\theta\,\frac{dN}{dE}\,(m_\nu = 0) + \sin^2\theta\,\frac{dN}{dE}\,(m_\nu = m_{\nu 2}) \ . \tag{4}$$

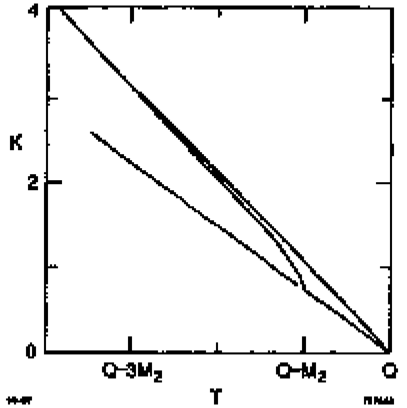

Figure 9. Distortion in the Kurie plot arising from the admixture of a massive neutrino in beta decay.

The Kurie plot is modified to that shown in Fig. 9. It develops a distinctive kink at the threshold for massive neutrino emission, $Q - m_{\nu 2}$. Shrock suggested, among other tests, to scan common beta spectra for such kinks. From the kink position and magnitude, the neutrino mass and mixing are derived.

The experimental signature depends on exactly how the data is fit. If one assumes a linear Kurie plot, and fits to the spectrum above the kink, i.e., to the region where the spectrum is genuinely one component, the data will show a departure from

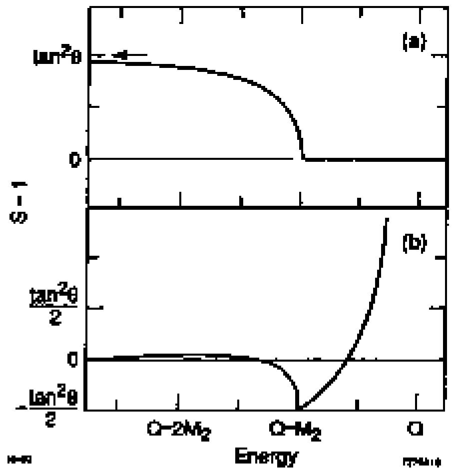

Figure 10. Shape factor signatures for massive admixed neutrinos depend on the fitting strategy: (a) shape factor when the data are fit above the heavy neutrino threshold; (b) shape factor when the data are fit throughout the kink region. The fit assumes a single massless neutrino in both cases.

the fit at $T = Q - m_{\nu 2}$. In terms of the shape factor, S, which is the ratio of the observed spectrum to the single-component expectation,

$$S = 1 + \tan^2\theta\left[1 - \frac{m_{\nu 2}^2}{(Q-T)^2}\right]^{1/2} \tag{5}$$

This is plotted in Fig. 10(a). In the case of the 17 keV searches described below, the spectral region beyond the kink may be poorly known. It is a region of low rate, potentially high background, and limited extent, making its extrapolation dubious. An alternative signature arises from a different fit strategy, in which the entire spectrum (kink and all) is fit to the one-component theory and deviations to this fit are sought. Fig. 10(b) shows how the threshold appears in such a fit. The exact shape is *experiment-dependent*, in that it depends on the extent of the region fit and the statistical weight of the points. But generally speaking, the kink in the spectrum extends over a few keV, and the maximum deviation is $\lesssim \tan^2\theta/2$. To see the effect of a 1% admixture of a 17 keV neutrino in a beta spectrum, it is required (1) that the resolution be good (FWHM $<$ 4 keV); (2) that there be sufficient statistics to see a .5% effect significantly ($N \sim 10^6$/keV); and (3) that instrumental effects not distort the spectrum at a level comparable to that of the effect. It is extremely difficult to measure a spectral shape to the 0.1% level required to see a 0.5% effect with certainty, as the confused history of this subject indirectly attests.

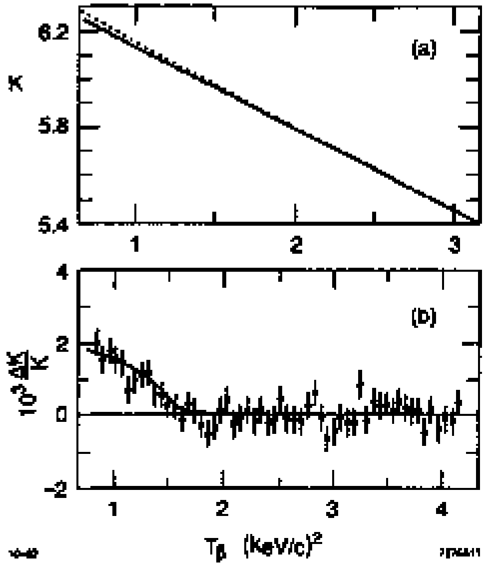

Figure 11. (a) Kurie plot for tritium as measured by Simpson [2]; (b) shape factor for T^+ implanted in Germanium, Simpson and Hime [15].

B. Simpson's Result in Tritium

Simpson [2] undertook precision measurements of the tritium beta spectrum using a novel technology. He implanted tritium ions in a silicon detector, which served as a total calorimeter for the emitted β's. The spectrum he obtained is shown in Fig. 11(a), and was well described by theoretical expectation above 1.5 keV without resorting to arbitrary shape factors. Simpson boldly interpreted the deviation in the spectrum at 1.5 keV as evidence for the emission of a 17.1 keV neutrino with mixing probability 3%. He subsequently revised this estimate to 1.1 ± 0.3% [13], after properly including screening and exchange corrections and the effects of the silicon environment.

C. Experiments Con and Pro

Simpson's original paper provoked a spate of experiments which sought, unsuccessfully, kinks in the spectra of ^{35}S and ^{63}Ni. Early results came from magnetic spectrometers [14] (Princeton, ITEP, Cal Tech, Chalk River), silicon beta calorimeters [15] (Bombay, Tokyo), and silicon photon calorimeters [16] (CERN, Zagreb), measuring the internal bremstrahlung spectrum associated with electron capture. (This spectrum also shows characteristic distortions, depending on neutrino mass and mixing). The results are summarized in Table I. Most of this work was not strong enough statistically or robust enough systematically to refute the revised claim for 1% (not 3%) mixing. The Chalk River data, however, strongly refuted even the revised claim. See Fig. 12.

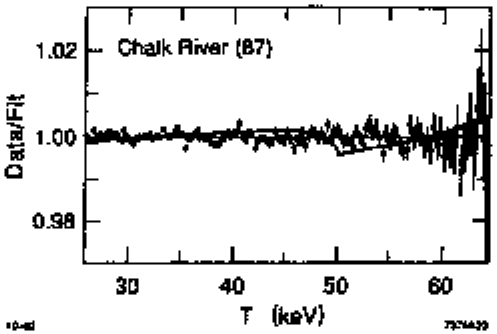

Figure 12. Shape factor in ^{63}Ni ($Q = 67$ keV) from the Chalk River experiment [16]. The fit includes a linear shape factor to correct for experimental distortions. The curve shows the shape expected for a 1% admixture of a 17 keV neutrino.

Simpson repeated the tritium measurements with Hime using a hyper-pure germanium detector, which was annealed after implantation to cure possible radiation damage. The crystal was calibrated *in situ* with photons, and the analysis incorporated the revisions mentioned above. The results of this work are shown in Fig. 11(b). There is a statistically significant spectral distortion near 1.5 keV. Simpson and Hime [13] interpreted this as evidence for a 16.9 ± 0.1 keV neutrino, admixed to the level of $\sin^2\theta = 1.1 \pm 0.14\%$.

Following their work in tritium, Hime and Simpson undertook an experiment in ^{35}S to confirm the effect. This experiment [17] used a silicon detector, but relied on an external source. Hime and Jelley [18] repeated the experiment at Oxford, and improved the definition of acceptance and the measurement of the electron response function. Both experiments saw statistically significant spectral distortions consistent with a 1% admixture of 17 keV neutrino. The Oxford results for ^{35}S are shown in Fig. 13. An LBL group [19] using a high purity germanium detector that had been doped with ^{14}C, claimed a similar result, finding $\sin^2\theta = 1.2 \pm 0.3\%$. An indication of 17 keV neutrinos was also reported by a Zagreb group [20] which quoted $\sin^2\theta = 1.6 \pm 0.8\%$. The coincidence of these results, made by several groups in studies of several nuclei, resurrected the possibility that a 17 keV neutrino did exist, mixed at the 1% level in nuclear beta decay.

Table I. Results of 17 keV Neutrino Experiments

Experiment	Isotope	$\sin^2\theta \times 100$	m_ν (keV)	Ref. No.
SOLID STATE β CALORIMETERS				
Guelph (85)	^{3}H	2–3	17.1	[2]
Reanalyzed		1.10 ± 0.30	17.1 ± 0.1	[13]
INS-Tokyo (85)	^{35}S	< 0.15 (90% C.L.)	17	[15]
Bombay (85)	^{35}S	< 0.60 (90% C.L.)	[17]	[15]
Guelph (89)	^{3}H	1.11 ± 0.14	16.9 ± 0.1	[13]
Guelph (89)	^{35}S	0.73 ± 0.14	16.9 ± 0.4	[17]
Oxford (91)	^{35}S	0.76 ± 0.09	17.0 ± 0.35	[18]
LBL (91)	^{14}C	−1.4 ± 0.45 ± 0.15	17 ± 2	[19]
Update		1.2 ± 0.3	1.71 ± 0.6	[19]
Argonne	^{35}S	−.04 ± .06 ± .08	17	[23]
SOLID STATE γ CALORIMETERS				
CERN (86)	^{125}I	< 2.0 (90% C.L.)	17	[16]
Zagreb (88)	^{55}Fe	< 1.6 (95% C.L.)	15-45	[16]
Zagreb (91)	^{71}Ge	1.6 ± 0.8	17.1 ± 1.3	[20]
GAS PROPORTIONAL CHAMBER CALORIMETER				
Oklahoma (92)	^{3}H	< 0.4 (99% C.L.)	17	[27]
MAGNETIC SPECTROMETERS				
Princeton (85)	^{35}S	< 0.40 (99% C.L.)	17	[14]
ITEP (85)	^{35}S	< 0.17 (90% C.L.)	17	[14]
Cal Tech (85)	^{35}S	< 0.25 (90% C.L.)	17	[14]
Chalk River (87)	^{63}Ni	< 0.28 (90% C.L.)	17	[14]
Cal Tech (92)	^{35}S	< 0.27 (90% C.L.)	17	[21]
INS–Tokyo (92)	^{63}Ni	< 0.10 (95% C.L.)	17	[22]

In response, several magnetic spectrometer groups returned to the problem. The Princeton and ITEP groups reanalyzed their earlier data, succeeded in reducing the magnitude of the shape corrections needed to describe the measured spectra, and left their original conclusions essentially unchanged. The Cal Tech group has repeated their original experiment several times, correcting field instabilities, achieving better control of systematics, and getting more probable fits as a result. From their studies of ^{35}S they conclude [21] that $\sin^2\theta < 0.27\%$ (90% C.L.). None of these experiments has seen any indication of a 17 keV neutrino.

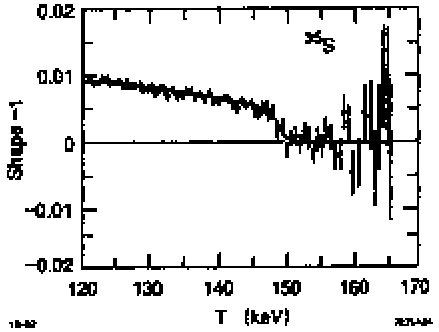

Figure 13. Shape factor for ^{35}S measured by Hime and Jelley[20].

D. *Two New Cons*

Two new, and very incisive experiments have recently reported null results in searching for the 17 keV neutrino. The first was a magnetic spectrometer experiment performed at the Institute for Nuclear Studies at the University of Tokyo [22], which studied ^{63}Ni decays with the $\pi\sqrt{2}$ iron-free spectrometer used in the tritium endpoint studies mentioned above. The principal modification to the apparatus was the addition of a 30-channel proportional wire chamber to the focal plane, which permitted a much larger statistic to be accumulated, roughly 2.4×10^9 counts in a relatively narrow 20 keV band around the expected threshold. Data was taken in a series of short runs in which the spectrometer setting was chosen randomly. The response function was measured using a ^{109}Cd source incorporated in a Nickel substrate to mimic energy loss and backscattering in the primary source. Each of the thirty channels is treated individually in the analysis, with a separate response function and individual shape factor. A global fit to the data is performed in which channel-to-channel normalization and shape are allowed to vary, but the mixing parameter is held common, as is the heavy neutrino mass. Their result is shown in Fig. 14(a). They find $\sin^2\theta = 0.00018 \pm 0.00033 \pm 0.00033$. The very high statistic, and the good resolution, make the experiment unique in that it is *kink-sensitive*. The data shown in Fig. 14(b), in which a 1% admixture of 17 keV neutrino has been assumed in the fit, mirror the expected signature, demonstrating the superb sensitivity of this experiment. No reasonable instrumental distortion could hide the sharp threshold expected. The probability of the first fit is good, indicating that channel-to-channel systematic differences are negligible to nearly the 10^{-4} level.

The second experiment [23] was performed at Argonne National Labs, and utilizes a small superconducting solenoid to capture a large fraction of the decays from a weak on-axis ^{35}S source and focus them on a silicon detector 40 cm distant.

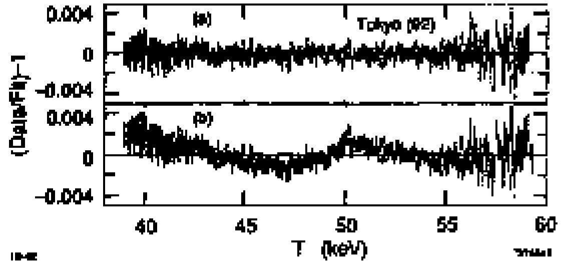

Figure 14. Shape factors for ^{63}Ni measured by the INS–Tokyo group assuming (a) no 17 keV neutrino, and (b) 1% mixture of 17 keV neutrino.

The electron energy is measured calorimetrically in the silicon. ^{139}Ce is used to calibrate the detector and measure the electron response function. The data are fit without an arbitrary shape correction and show no evidence of a kink: $\sin^2\theta = -0.0004 \pm 0.0008 \pm 0.0008$. See Fig. 15(a). Figure 15(b) demonstrates the sensitivity of the experiment to a small spectral distortion. The authors contaminated their ^{35}S source with roughly 1% of ^{14}C, which has $Q = 156$ keV, roughly 11 keV below that of ^{35}S. The nominal fit is a pure, one-component Fermi spectrum; the data follows instead the distorted shape expected when the admixture is taken into account. This demonstrates sensitivity to 1% effects.

E. *Assessment*

Have any experiments shown conclusively the presence or absence of a 17 keV neutrino?

Consider first the *shape-sensitive* experiments. With the exception of the INS Tokyo experiment, all the 17 keV experiments are sensitive to potential spectral distortions that might mimic or mask an effect. This is true because their statistical sensitivity derives from the detection of a change of slope in the Kurie plot in the vicinity of the 17 keV threshold, and not from detection of the *kink* itself. To prove that a shape distortion is not instrumental, it is necessary to measure the electron response function (shape and normalization) as a function of energy in an independent experiment. That is, one must measure the instrumental distortions. Strictly speaking, no experiment has done so (although the Argonne experiment has come close), so *all* experiments must address the possibility that shape factors are present in their spectra, perhaps *making*, perhaps eliminating a 17 keV neutrino. As Simpson [24] has argued, and Bonvicini [25] has demonstrated in a careful statistical analysis of these experiments, the presence of unknown shape factors reduces sensitivity to spectral anomalies and makes estimation of systematic errors questionable. Thus the

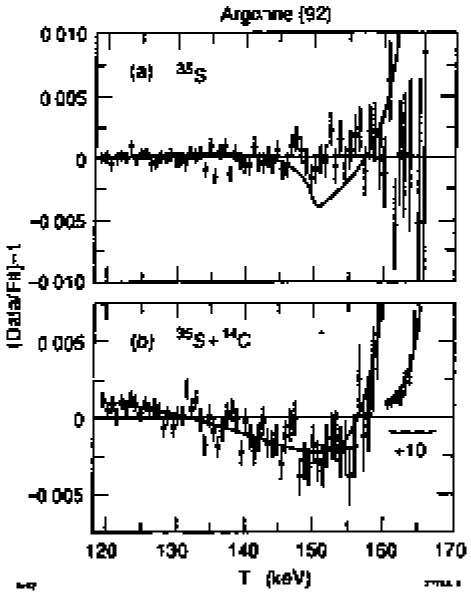

Figure 15 (a) Shape factor for ^{35}S measured by the Argonne experiment The curve shows the distortion expected from the 17 keV neutrino (b) Shape factor for a ^{35}S source with a small mixture of ^{14}C The data falls nicely on the curve, demonstrating sensitivity to small spectral distortions

Chalk River and Cal Tech results argue strongly against the existence of a 17 keV neutrino but do not convincingly exclude it On the other hand the conclusions of Hime and Jelley may be significantly changed if their experiment is reanalyzed with a (presumably) more accurate response function That is Piilonen and Abashian s claim [26] in their reanalysis in which they carefully Monte Carlo the Hime/Jelley experiment, accounting for energy loss scattering backscattering fluorescence etc They conclude a spectral distortion persists in the data but one that bears no resemblance to a massive neutrino threshold

The recent Argonne experiment is also shape sensitive but it has several advantages over the Hime/Jelley experiment in regard to its measurement of the electron response function First, it has very large acceptance for electrons and–thanks to magnetic confinement—no need for material apertures This permits the use of extremely thin sources, and great enough detector/source separation that the photon acceptance is negligibly small Thus it is unlikely that photo-induced processes will be misinterpreted as part of the electron spectrum and edge scattering

and energy loss in the source are non issues Second, it has profitably used a ^{139}Ce source to constrain its model of the electron response function the advantage being that several lines are used which bracket the kink region When this response function is convoluted with the Fermi spectrum, it accurately describes the data without recourse to arbitrary shape factors or massive neutrinos This strongly disagrees with earlier silicon calorimeter work It would be an airtight case if the normalization, as well as the shape of the electron response function, had been measured at several energies

The INS experiment, with its high statistics is very compelling It essentially is the addition of thirty independent experiments each with the statistical power of the *shape sensitive* experiments What is remarkable is that no subtle systematic distortion seems to be present at the 10^{-4} level so that the sum of all the spectra is distortion free, and the global fit to the no 17 keV hypothesis has a respectable goodness of fit A minor weakness is that there has been no demonstration that the experiment can see a small spectral distortion as was done in the Argonne and in the Cal Tech experiments It is a very strong result nevertheless

Given these two very strong null results, and appreciating that the experiments reporting positive effects have not demonstrated the absence of instrumental shape corrections, it is not reasonable to ascribe the spectral distortions seen by Simpson, Hime, and Jelley and others to a 17 keV neutrino These distortions are not yet explained, however In particular there has been little experimental study of the distortions seen in the tritium spectrum A recent study using a proportional chamber at Oklahoma [27] reports no effect but must contend with uncertain background subtractions Studies underway at Carleton [28] also using a proportional chamber calorimeter, and Livermore [29], using the beautiful toroidal spectrometer constructed for the endpoint measurements will address this issue and are eagerly awaited

The experiments which have ruled out the existence of 17 keV neutrinos have used their data to search for kinks across the beta spectrum and impose limits on the mixing strength of massive neutrinos as a function of neutrino mass These limits are summarized in Fig 16

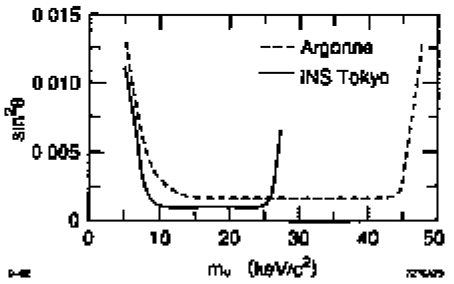

Figure 16 95% confidence limit on the mixing strength for heavy neutrinos in beta decay versus neutrino mass

IV. New Beta Decay Experiments

A. *Motivation*

The 17 keV neutrino controversy has sparked renewed interest in studies of nuclear beta decay, with several groups proposing new techniques. While the proximate motive for this work has disappeared, these advances in instrumentation promise to reduce instrumental distortions in spectral measurements. This could have significant impact in experiments which seek physical shape effects, like those expected in ^{14}C decay, and could allow more sensitive kink searches in future experiments. New techniques will also be used to study the tritium spectrum at low energies, where Simpson's anomalies have not been confirmed. Here we consider a few alternative technologies and a new approach to the problem.

B. *Gas Calorimeters*

The proportional chamber calorimeter at Carleton has already been mentioned. The device is a large, 10 atm. single-wire proportional counter using standard gases with a small admixture of tritium. High pressure and gold-coating on the chamber walls minimize backgrounds due to decays of adsorbed tritium. The resolution is relatively poor ($\Delta E/E = 15\%$), but adequate. The detector serves as a total absorption calorimeter, analogous to the implanted solid state detectors, but unlike these detectors, it can be calibrated throughout its volume, and can measure backgrounds with the tritium removed. Gain stability and uniformity and backgrounds are the major concerns.

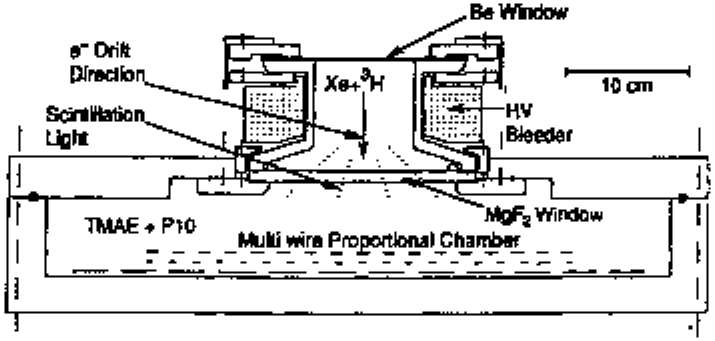

Figure 17. Gas scintillation proportional chamber for study of T_2 decays at Delft [32].

Gas scintillation proportional detectors are being developed by groups at Berkeley [30] and Delft [31]. The Delft detector is shown in Fig. 17. It consists of a decay region filled with tritiated xenon gas, in which a 5 kV/cm field is established. In this high field, ionization drifting toward the collection grid excites scintillations in the gas. The resulting photons pass through a MgF_2 window, and are detected in a proportional chamber filled with TMAE and P10. The time development, pulse-height, and position are recorded to measure the location and energy of the decay. The fact that many photons are released per primary electron gives the device good energy resolution. The Berkeley device measures ^{14}C decays by mixing radioactive CO_2 with xenon, operates at high pressures, and uses waveshifter fibers for readout. Both are total absorption calorimeters with *implanted* sources. The technologies will take time to mature, but are promising.

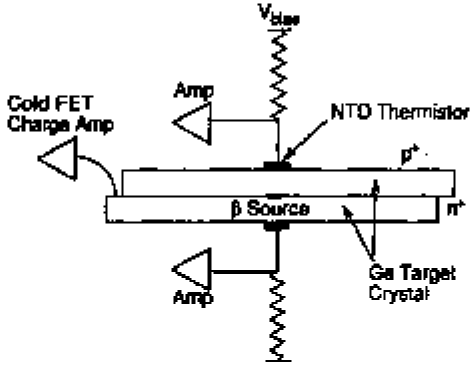

Figure 18. Proposed Cryogenic solid state detector for simultaneous phonon and ionization measurements from Ref. 32.

C. *Cryogenic Detectors*

Cryogenic solid-state detectors can measure energy lost into ionization and phonons simultaneously. At 20° mK, very low fields can fully deplete the detectors, allowing charge collection without the generation of much thermal noise. Since the detector's heat capacity is proportional to the cube of the temperature, small (thermal) energy depositions lead to measurable temperature changes. A schematic detector is shown in Fig. 18. The temperature signal, which develops on a millisecond time scale, is detected by a thermister. A Berkeley group has achieved 1.8 keV resolution at 60 keV [32] in a test device. The ionization signal is also read out. As the diagram shows, a sandwich geometry is proposed that should completely contain the energy loss from the source. Unlike the ionization signal, the phonon signal should not suffer degradation due to detector dead layers. Background determination and calibration are straightforward in this detector, unlike implanted solid state detectors. An Oxford group [33] is also investigating the technique.

D Missing Mass Measurements

The approaches described above have a common strategy: measure the beta spectrum with very high precision in order to search for small anomalies. A different idea has been independently proposed by experimenters from SLAC [34], Stony Brook [35], and Texas [36]: reconstruct the mass missing in beta decay by measuring simultaneously the momenta of the decay electron and the recoiling nucleus. If the initial nucleus is nearly at rest, measurements of modest precision allow a reconstruction of neutrino mass with enough resolution to distinguish a 17 keV neutrino from one that is massless. Tritium is the preferred nucleus because its low Q value exaggerates the kinematic differences between massive and massless neutrinos.

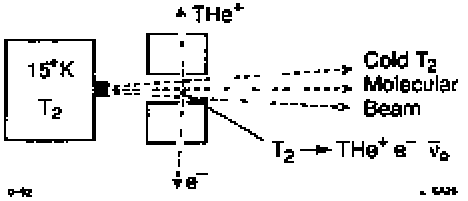

Figure 19 Schematic diagram of experiment to measure recoil mass in molecular tritium decay.

A schematic of the proposed SLAC experiment is shown in Fig. 19. An effusion beam is created from low pressure 15°K T_2 gas with a multichannel array. Skimming and aggressive differential pumping remove most of the unwanted gas. Decays are sampled from a small region, which is kept free of electric and magnetic fields. Collimators select back to back decays. The source is sufficiently tenuous that the chance of Van der Waals scattering on exiting is small. For electrons in the energy region of interest ($T < 1.5$ keV), the back to back topology accepts a large fraction of 17 keV decays and rejects most 0 mass decays. Figure 20 shows how clearly the electron and ion momenta are correlated with this back to back cut, and what a huge effect the presence of a 17 keV neutrino has on the kinematics. Unlike the spectral measurements, this experiment seeks to detect a gross effect.

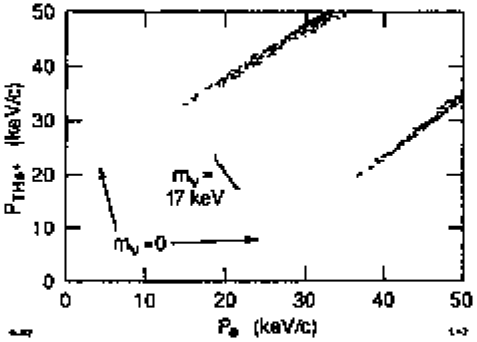

Figure 20 Correlations between ion and electron momenta for near back to back tritium decays ($\cos\theta < -.99$) for massless neutrinos (sharp bands, top and bottom) and 17 keV neutrinos (central band). Clean kinematic separation is possible.

Simulated results from this experiment are shown in Fig. 21. The Monte Carlo assumes an effective source of 10^{12} T_2 molecules, 30 msr acceptances in each spectrometer arm, and 2% momentum resolution. The electron energy is measured in a magnetic field, the ion velocity determined by time of flight. Roughly 10 decays/day appear in the 17 keV peak if 1% mixing obtains.

The experiment is not without technical challenges, most deriving from the difficulty in handling a radioactive gas and dealing with backgrounds originating from tritium adsorbed on vacuum vessel and detector surfaces. If spectral distortions persist in the low energy tritium β spectrum, this experiment could discriminate new particle production from subtle atomic effects, and it could search for massive neutrinos with good sensitivity.

V Conclusions

Precision measurements of the tritium beta spectrum near the endpoint have failed to confirm the claim by a Russian group that the electron antineutrino mass is ~ 20 eV. The best of these experiments presently limit the neutrino mass to be less than 7 eV, and could lower this bound to a few eV, nature willing.

The spectral distortion reported by Simpson, Hime, Jelley, and others as evidence for a 17 keV neutrino is not seen in a new round of experiments with improved sensitivity and improved systematics. Although the original effects are not yet explained, it is no longer reasonable to ascribe them to an exotic heavy neutrino

Experimental techniques are being developed which may bring new precision and sensitivity to β decay studies.

The study of nuclear beta decay, which is nearly 100 years old, still generates excitement and hot debate, and still addresses questions of fundamental importance to particle physics. These experiments have provided our best direct knowledge of the electron antineutrino mass, and have searched for neutrino mixing with great sensitivity.

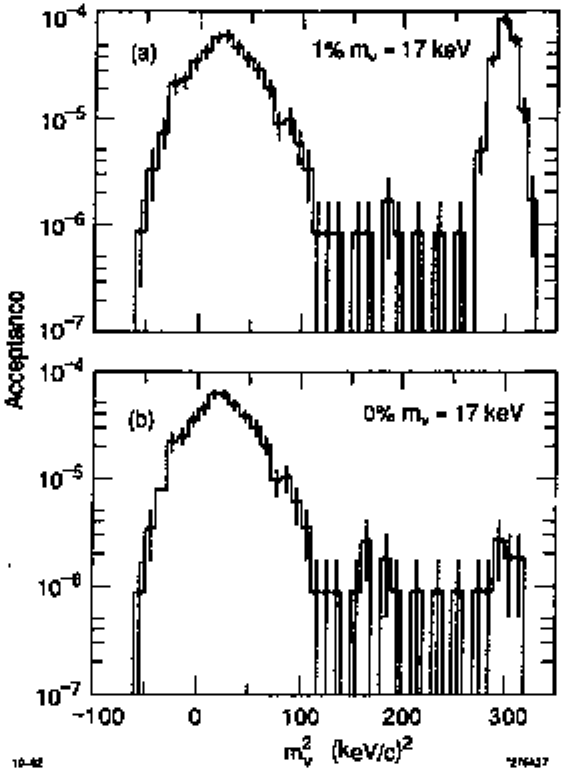

Figure 21. Simulated recoil mass spectra for tritium missing-mass experiment. The acceptance is plotted versus m_ν^2 for (a) 1% admixed 17 keV neutrino and (b) 0% 17 keV neutrino.

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