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On the 17-keV Neutrino

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"The pure and simple truth is rarely pure and never simple."
Oscar Wilde

Abstract

A brief review on the status of the 17-keV neutrino is presented. Several different experiments found spectral distortions which were consistently interpreted as evidence for a heavy neutrino admixture in β decay. Recent experiments, however, rule out the existence of a 17-keV neutrino as well as escaping criticisms of earlier null results. Moreover, the majority of positive results have been reinterpreted in terms of instrumental effects, despite the need for a different explanation in each case. Anomalies persist in the low energy region of the tritium spectrum which deserve further investigation.

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1 Introduction

The possible existence of a 17-keV neutrino has been a subject of debate for more than seven years. The intent of this paper is not to review in detail all experiments to date but to highlight those aspects of the debate which are most relevant to the present discussion. Concentration is on recent developments which finally point towards a resolution of "the 17-keV conundrum". Work during the past year has deepened our understanding of the difficulties in performing precision measurements of nuclear β decay spectra. In particular, the hazards associated with instrumental shape corrections are even more important than previously imagined. Indeed, seemingly innocuous effects make certain "null results" unreliable while others have the potential to masquerade as a "real" signal.

For this discussion it is sufficient to consider a two-state model of the electron neutrino:

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle,$$

where ν_1 and ν_2 are states of definite mass which couple to the weak interaction eigenstate ν_e. In this scheme, the β spectrum becomes an incoherent sum of two β spectra with different end-points. The Fermi-Kurie plot is defined in the conventional way, which is a linear function of the β energy in the case of a single-component, massless neutrino. With a heavy neutrino admixture the Kurie plot would exhibit two components shown schematically in Fig.1. The spectrum is said to exhibit a "kink" at the threshold energy, $Q - M_2$, and the size of this kink determines $\sin^2\theta$, the mixing probability for a heavy neutrino.

Searches for heavy neutrino admixtures in β decay spectra rely on a comparison between data and theory. It is customary to define a shape factor (Fig.2) which is simply the ratio of the experimental data to the theoretical spectrum in the absence of massive neutrinos. This comparison is made after folding instrumental corrections into the theoretical spectrum which generally lead to a departure from the ideal *Fermi* shape. It follows that sensitivity to the physical parameters of interest is dictated by one's ability to measure this shape accurately. While recognizing a threshold effect (in an otherwise featureless spectrum) is a function of energy resolution, the size of the distortion is governed by the magnitude of $\sin^2\theta$. Consequently, constraints on small values of the mixing probability are dictated by counting statistics and systematics causing energy dependent shape factors in the measured β spectrum.

The region over which the β spectrum is substantially nonlinear is not very wide in units of M_2. Specifically, with $M_2 = 17$ keV, 50% of the distortion occurs in the first 2.6 keV below the threshold. It is often difficult to obtain the statistical accuracy to observe a kink reliably, particularly when $\sin^2\theta$ is small. A significant part of the signal is contained, however, by noting a change in slope of the Kurie spectrum above and below the threshold. Hence, the signature for heavy neutrino emission exhibits two features – a local "kink" region where the spectrum is nonlinear, and a longer range effect associated with a global change in spectral shape. The latter part of the signal is most susceptible to systematic uncertainties associated with instrumental shape corrections.[1]

[1] Further details concerning the signature for heavy neutrino emission in β decay spectra and the effects of instrumental corrections can be found in refs [12,13]

2 History of the 17-keV Neutrino

2.1 A Tritium Experiment

The history of the 17-keV neutrino originates with Simpson who measured the β spectrum of tritium implanted into a silicon detector. The experiment is unique for its calorimetric design, providing a total absorption calorimeter that allowed a measurement of the tritium spectrum down to a low energy threshold of ~850 eV. Originally motivated as a means to study the tritium endpoint[1], the spectrum was later used to search for heavy neutrino admixtures in the range of 350 eV to 10 keV[2]. A subsequent analysis of the low energy region exposed an excess intensity below 1.6 keV, the result of which was interpreted as evidence for a 17-keV neutrino admixed at the 2-3% level[3]. The anomaly is the only departure observed in the tritium spectrum over the entire energy interval extending up to the endpoint of ~18.6 keV. Otherwise, the measurement is a beautiful reproduction of that predicted by Fermi theory.

The interpretation of heavy neutrino emission was scrutinized when it was pointed out[4] that an incorrect choice of the screening potential and exchange effects in atomic tritium could be the origin of the discrepancy. Simpson reanalysed his data[5] using what is generally agreed as the correct atomic physics for *free* tritium but found that the effect was not reduced by more than ~25%. This conclusion was verified by Weisnagel and Law[6] after performing a thorough analysis of Simpson's data including a self-consistent treatment of atomic screening corrections, exchange effects, as well as radiative corrections. The matter is further complicated since such experiments do not employ free tritium but rather tritium bound within a crystal lattice. In this case the uncertainties inherent in the atomic physics of bound tritium are more problematic[7]. Nonetheless, the ***sudden*** departure in the shape of the tritium spectrum is not easily described by conventional atomic physics. It seemed that the original tritium data still supported a 17-keV neutrino, albeit with a mixing probability of only ~1%.

2.2 Enter a Controversy

The 17-keV neutrino entered into oblivion after a flurry of experiments measuring the β decay of ^{35}S with an end-point energy of 167 keV. Measurements were performed with magnetic spectrometers[8] and with cooled silicon detectors[9]. Very low limits were claimed on the mixing probability for a 17-keV neutrino compared to the 2-3% suggested by Simpson. The 17 keV burial was nevertheless premature. All negative results were criticized[5], either for flaws in data analysis or for incomplete knowledge of systematic effects. It was even advocated[5,10] that two cases were consistent with the emission of a 17 keV neutrino. These conclusions were drawn after reconstructing spectra from the published shape factors and reanalysing the data over a narrow region around the threshold energy for a 17 keV neutrino. If there is any justification in such an analysis it derives from the potential risk of burying a heavy neutrino signal through seemingly innocuous assumptions in the data analysis. There is a fear, however, that this reanalysis over such a narrow region could mistake statistical fluctuations as a physical effect. Consequently, the claim of positive effects in these experiments is waning without a more rigorous treatment of the data.

A feature common to all magnetic spectrometer measurements is that, after known corrections are invoked to a data sample, one does not obtain a β spectrum shape in agreement with expectation. It is extremely difficult to *a priori* measure or calculate the energy-dependent efficiency of a magnetic spectrometer at the required level of accuracy. The problem is handled by applying a "shape correction factor" which normally takes the form of a polynomial in the β energy. The arguments applied assume that all systematic distortions are "smooth" and that such distortions cannot mask the signal for a heavy neutrino. In addition to the ^{35}S measurements, a detailed report described a search for a 17-keV neutrino in the ^{63}Ni spectrum at Chalk-River[11], perhaps the most impressive magnetic spectrometer measurement to date. Despite great attention to detail the measured shape deviates from the theory by $\sim$3.5% over the interval studied. While the Chalk-River data clearly rules out the 3% admixture originally claimed by Simpson, it remains questionable if the data retain sensitivity to heavy neutrino admixtures below the 1% level.

The potential to suppress one's sensitivity to a heavy neutrino signature through the use of *ad hoc* corections has been a catalyst for debate and a main ingredient for controversy concerning the 17-keV neutrino. The subtleties concerning the use of arbitrary shape corrections has not been fully appreciated until recently and this point will be discussed further below. Suffice it to say that the criticisms put forth do suggest that the bounds reported in these early experiments are overstated and that further experiments were required to resolve the matter.

2.3 Corroborative Evidence ?

An attempt to resolve the controversy was made in two new experiments carried out by Simpson and Hime at the University of Guelph. In the first place, the original Simpson experiment was repeated by implanting tritium into a hyperpure germanium detector[7], an experiment which circumvented many of the intrinsic uncertainties outstanding in the implanted silicon measurement[3]. There again, a sudden excess of counts was observed consistent with that first reported by Simpson. A second experiment used ^{35}S sources together with a silicon detector[12] where the higher energy electrons circumvent the difficulties associated with atomic physics in tritium decay. Such an experiment admits new difficulties, however, in that one is faced with the task of recording electron energy spectra from sources that are external to the detector. Nonetheless, a distortion appeared which could be described by the emission of a heavy neutrino and with parameters consistent with those extracted from the tritium experiments. It seemed more than a striking coincidence that two very different experiments should yield consistent results. The latter paper also quantified some of the criticisms applicable to the earlier negative experiments, with a concluding remark by Simpson that is well heeded.

> *"Contrary to intuition, a null result is not necessarily more reliable than a positive result"*.

The ^{35}S experiments at Guelph employed an uncollimated geometry which permits unnecessary energy losses when electrons penetrate the edges of the silicon detector. In addition, the lack of collimation allows stray electrons to scatter from material in the vacuum chamber which can enter the detector with less than their full energy. This motivated improved experiments, performed at Oxford University, which utilized a collimated geometry and thinner source substrates. Despite the change in geometry, ^{35}S measurements at Oxford[13,14] revealed a pronounced effect (Fig.3) representing an 8σ deviation from the shape expected for a massless neutrino spectrum. Once again, the distortion was well described by the emission of a 17-keV neutrino, consistent with reports on tritium and ^{35}S from the Guelph experiments. The ^{35}S measurement was complemented by a measurement of the ^{63}Ni spectrum[13,15], offering a systematic check owing to the different sources employed and the 100 keV shift in electron energy. The lower energy electrons in the case of ^{63}Ni decay lead to larger sytematic uncertainties[14,15]. Nonetheless, a distortion was observed which was also consistent with the emission of a 17-keV neutrino.

Meanwhile, a novel experiment employing a ^{14}C doped germanium detector was performed at Lawrence Berkeley Laboratory (LBL). Such an experiment reaps the benefits of both the tritium and ^{35}S experiments discussed here. On the one hand the bolometric style mimics the simplicity of the experiments employing implanted tritium. On the other hand, the endpoint energy of ^{14}C ($\sim$156 keV) yields electrons with energies comparable to that of ^{35}S decay such that atomic physics, problematic in the tritium case, are circumvented. The LBL group reported a distortion in their ^{14}C spectrum[16], also consistent with a $\sim 1\%$ admixture for a 17-keV neutrino.

Table 1: Positive Results

Experiment	Isotope	$(\sin^2\theta)\times 100$	M_2 (keV)	$Q - 17$ keV	ref.
Guelph	^3H in Si(Li)	1.10 ± 0.30	17.07 ± 0.09	1.6	[3,7]
	^3H in HPGe	1.11 ± 0.37	16.93 ± 0.07	1.6	[7]
	^{35}S	0.73 ± 0.11	16.9 ± 0.4	150	[12]
Oxford	^{35}S	0.78 ± 0.09	16.95 ± 0.35	150	[13,14,15]
	^{63}Ni	0.99 ± 0.22	16.75 ± 0.38	50	[14,15]
LBL	^{14}C in HPGe	1.26 ± 0.25	16.6 ± 0.6	139	[16]

The positive results summarized in table 1 derive from measurements using a variety of β emitters in different experimental environments, and spanning two orders of magnitude in the threshold energy for a 17 keV neutrino. Without resorting to a conspiracy the data seem to provide an overwhelming case for a 17 keV neutrino. While the reliability of the earlier null results remains questionable (see discussion below) more recent experiments (discussed in section 4) definitively rule out a 1% branch for a 17 keV neutrino. Herein lies "the 17 keV conundrum"!

3 Sensitivity and Shape Corrections

It has long been argued[5,12,13] that the null results asserted by the magnetic spectrometer experiments are largely overstated and that sensitivity to small admixtures of a heavy neutrino is limited by systematic uncertainties associated with instrumental shape corrections. The crux of the argument is that energy dependent shape corrections are not known *a priori* and the need for such corrections becomes apparent only after attempts at fitting data without such corrections. The problem is usually handled by applying smooth shape corrections in the form of a polynomial in the β energy. Both the form and order of such corrections is arbitrary, however, and the criteria for halting a given analysis is determined when a "good fit" is achieved - that is, when a flat shape factor is obtained.

Due to the nature of the signal, the addition of unknown degrees of freedom in a fitting routine creates additional correlations with the physical parameters of interest, consequently decreasing the overall sensitivity of a data sample. While it seems counter-intuitive that smooth corrections can mask a heavy neutrino signal one is reminded that a large part of the signal lies outside of the "kink" region. Moreover, the corrections invoked represent ~ 3 to 10% deviations from the *Fermi* shape, significant in comparison to a 1% admixture for a 17-keV neutrino. It remains a question of statistics whether or not the data retain sensitivity to a heavy neutrino signature when confined to a narrow energy interval.

The potential hazard in applying "arbitrary" shape corrections is quantified in the Monte Carlo studies by Bonvicini[17] who has clearly demonstrated the ability of a non-linear distortion to bury a heavy neutrino signal and still be "well-fitted" by smooth shape corrections. Hence, if instrumental shape corrections cannot be determined *independently* from the β decay measurement itself, systematic uncertainties can be estimated only by varying the type of shape correction applied and noting the correlation induced with the heavy neutrino mixing probability. As demonstrated in ref.[17], these correlations are potentially very strong and it is unlikely that the earlier "null experiments" are capable of ruling out a 17-keV neutrino admixed below the 1% level. The only way to overcome such correlations is to determine *a priori* any energy dependent instrumental effects in a given experiment. Otherwise, very large statistical samples of data are required in order that a "kink" be searched for *directly*.

4 Recent Null Results

The potential difficulty in applying arbitrary shape corrections has recently been circumvented in a magnetic spectrometer measurement of the ^{63}Ni spectrum at the Institute for Nuclear Studies (INS) in Tokyo[18]. Although unkown shape corrections are required in fitting the data, the very high statistics accumulated in the region of interest makes it extremely unlikely that a 17 keV neutrino has been overlooked in this experiment (Fig.4). Specifically, the $\sim 2.4 \times 10^9$ events accumulated between 39 and 60 keV allows one to search for a 17 keV "kink" directly. At the recent Moriond Workshop, Holzschuh[19] presented results from a ^{63}Ni measurement using the Zurich toroidal spectrometer where, again, a dedicated search in the "kink region" leaves little room for a 17 keV neutrino

Other magnetic spectrometer searches have continued over the past few years. Efforts at CalTech[20] have seen improvements in the performance and understanding of their spectrometer, and tests to demonstrate sensitivity to a 17-keV neutrino continue. The Princeton group have also continued their measurements of the ^{35}S spectrum[21], including a more rigorous treatment of systematic effects. In particular, it has been found that their need for a shape correction is greatly reduced when account is made for electrons which back-scatter from the source substrate. The back-scattering contribution has been studied in some detail and their limit on the mixing probability for a 17-keV neutrino appears quite stable against uncertainties in this correction. The accuracy of the Princeton measurement has further been demonstrated in that a good fit to the spectrum is achieved over a rather wide energy interval, without the need for further shape corrections.

Perhaps the most convincing evidence against the 17-keV neutrino follows from the ^{35}S measurement (Fig.5a) performed at Argonne National Laboratory[22]. A silicon detector was employed in the same vain as the Guelph and Oxford experiments, however, the use of a solenoidal magnetic field provides a natural form of collimation wherein electrons are focussed from the source into the detector with essentially 2π acceptance. Measurements of the electron response function included internal conversion electrons from ^{139}Ce, offering calibration lines bracketing the region of interest. In this way the response function could be interpolated over an energy interval relevant to the search for a 17-keV neutrino. The Argonne group have demonstrated the sensitivity of their experiment by performing an independent measurement with a small component of ^{14}C admixed into a ^{35}S source. A fit to the data reconstructs the spectrum beautifully (Fig.5b), a difficult if not impossible task without an accurate understanding of systematic uncertainties.

Table 2: Recent Null Results

Experiment	Isotope	$(\sin^2\theta)\times 100$	M_2 (keV)	ref.
INS Tokyo	^{63}Ni	$<$ 0.08 (95% CL)	10 - 25	[18]
Argonne	^{35}S	$<$ 0.25 (95% CL)	10 - 45	[22]
Princeton	^{35}S	$<$ 0.29 (95% CL)	17	[21]
Zurich	^{63}Ni	$<$ 0.11 (95% CL)	17	[19]

5 Electron Scattering Effects

The null results summarized in table 2 shine serious doubt on the existence of a 17 keV neutrino and one is forced to reexamine the possibility that instrumental artifacts are the origin of the anomalies observed in β decay spectra. This seems an ambitious task since one requires a different explanation for several different experiments. Electron scattering effects were considered by Piilonen and Abashian[23] who concluded that the distortions observed in the Oxford experiments could be due to an incomplete assessment of the electron response function. At question is the small amplitude for electrons which scatter intermediately from material between the source and detector. A first glance suggests that such a solution is untenable. Scattering effects are geometry dependent, and the change in geometry from the Guelph to Oxford apparatus was motivated as a systematic check against scattering effects. The null result from Argonne Laboratory strongly suggests, however, that scattering effects are the culprit in the Oxford and Guelph experiments since the focusing field in the Argonne geometry circumvents the need for material between the source and detector.

5.1 Experiments at Oxford

Experiments at Oxford[13-15] employed thin radiation sources in a cylindrical geometry with a cooled silicon detector. The aim was to provide a well defined geometry in which electrons are normally incident on silicon, an improvement on the scheme used at the University of Guelph[12] where no form of collimation was used. Chamfered apertures at the source and detector restricted electrons to be incident on the detector with angles less than 10 degrees. An aluminium baffle was placed between the source and detector to prevent interactions with the walls of the vacuum chamber. Apart from the intrinsic energy resolution of the detector one must accommodate the finite probability for ionization when electrons pass through the contact of the detector, as well as the fact that electrons can back-scatter from the silicon crystal. These effects create an instrumental energy dependence in the shape of the experimental spectrum, details of which are neccesary for an accurate comparison between data and theory[13].

Recently, this author studied the effects of scattering[24] described by Piilonen and Abashian[23]. Intermediate scattering effects (Fig.6a) represent second order corrections compared to those of energy loss and back-scattering effects (which were accounted for in the original analysis). Hence, it seems unlikely that such small effects could play a significant role, particularly when the results proved robust against uncertainties in the dominant components of the electron response function[13-15]. Nonetheless, the distribution of electrons scattered from the aluminum baffle is such that it effects primarily the last 20 keV of the ^{35}S spectrum. Indeed, a reanalysis of the Oxford ^{35}S and ^{63}Ni data produces an equally good fit to the data when the heavy neutrino hypothesis is simply replaced by that based on electron scattering effects[24].

The potential to suppress a heavy neutrino signal through an incorrect assessment of instrumental effects has been emphasized in this paper. One can only wonder if this reanalysis of the Oxford data has done nothing more than bury a "real" effect. In this vain a more rigorous analysis of calibration data (from internal conversion electron measurements performed in parallel with the Oxford β decay measuremets) was carried out. A small effect was unveiled which is in good agreement with the Monte Carlo simulations of intermediate scattering effects (Fig.6b). In addition, an independent study at Oxford has also demonstrated the importance of electron scattering effects. By performing a series of tests with variations on the source/detector geometry it is found that the Oxford experiment does not support the presence of a 17 keV neutrino[25].

5.2 Experiments at Guelph

The geometries employed in ^{35}S measurements at Guelph[12] are quite different than that at Oxford. Hence, it is non-intuitive, and seemingly contrived, that such similar effects appear in both experiments. Measurements at Guelph were made with ^{35}S sources in both "near" and "far" geometries without the use of baffles or apertures between the source and detector. A complete simulation of the Guelph geometry has proven an ambitious task since the absence of collimation at the source and detector allows many scattering sites. Furthermore, calibration data accumulated in the Guelph experiment are not rich enough to unfold all of the relevant components of the response function in this complicated geometry. The electron response function used in the Guelph analysis represents a first order approxomation to a more complicated description. For example, electrons can scatter from an effective aluminium baffle housing the detector in the Guelph "far" geometry. The resulting distribution takes a form very similar to that of electron scattering from the aluminium baffle in the Oxford geometry.

The Oxford data is clearly very sensitive to small, and presumably innocuous, departures from the "true" response function. Hence, it is feasible that the anomalies observed in the Guelph data are also susceptible to reinterpretation. Attempts at reanalysing the Guelph data have indicated the sensitivity to small variations on the electron response function. Without a more robust handle on the response function appropriate to the Guelph experiment the data cannot make a reliable case for the 17-keV neutrino admixed at the 1% level.

6 IBEC Measurements

Searches for a 17-keV neutrino using internal bremsstrahlung spectra have been made, although with less definite conclusions. A study of the ^{125}I spectrum[26] in 1986 lacks the statistics to rule out heavy neutrino admixtures below the 1% level. A positive result emerged from Zagreb[27] where Zlimen *et al.* employed ^{71}Ge. The statistically weak result is over-optimistic, however, even at the quoted 2σ level. While earlier studies of the ^{55}Fe spectrum[28] failed to find evidence for a 17-keV neutrino, a group at LBL reported an anomaly consistent with a 22-keV neutrino[29]. Furthermore, a measurement of the ^{71}Ge spectrum in Argentina[30] found, not a 17-keV neutrino, but an anaomaly prescribed by a 14-keV neutrino! While the discrepancy amongst the various IBEC experiments seriously calls into question their sensitivity, it is a clear indication that fortuitous results will arise when systematics are not completely understood. This point is further substantiated in the recent reanalysis of the ^{71}Ge spectrum at Argentina[31], where a more detailed analysis of instrumental response and uncertainties associated with p wave capture has lead to an upper limit of 0.5% on the mixing probability for a 17 keV neutrino.

A limiting feature of IBEC studies follows from the intrinsically low rates achievable. Consequently, large source volumes are required to obtain the desired activity with the result that the system exhibits a rather complicated response function for photons. Furthermore, the energy dependence in this response is difficult to determine at the required level of accuracy. A model of the response function must be invoked to account for un certainties due to energy dependent detector efficiency, photon self-absorption in a finite sized source, as well as Compton scattering and back-scattering effects. While the work at Argentina only marginally excludes a 17-keV neutrino, the recent work at LBL[32] using ^{55}Fe must be taken seriously. Despite a branching fraction of $\sim 3.3 \times 10^{-5}$, about 10^7 counts/keV have been acquired in the region of the expected kink. An analysis over a narrow region in the data is paramount to a *direct kink search* and excludes the presence of a 17-keV neutrino (admixed at the 0.8% level) at the 7σ level. An independent analysis using the second derivative of the spectrum (a procedure similar to that utilized by Simpson[2] in 1981), which shows a clear effect in a Monte Carlo simulation, is all but flat in the data. This "local" kink search circumvents the difficulties associated with long range, energy dependent effects which can otherwise limit one's sensitivity to a heavy neutrino signal. It thus seems that the IBEC measurements at LBL are also in serious conflict with the existence of a 17-keV neutrino.

7 Missing Links

7.1 Tritium Revisited

The experiment of Stoeffl *et al.*, using gaseous tritium in their large toroidal magnetic spectrometer, has unveiled interesting results in the low energy region of the tritium spectrum[33]. The superior energy resolution in the Livermore experiment allows an "end-to-end" measurement of the spectrum with a threshold of essentially zero energy. Surprisingly, a large excess of counts was discovered in the low energy region, amounting to ~30% of the total integrated spectrum. While much of the intensity is contained in the first 200 eV of the spectrum a long tail extends to higher energies. Interestingly enough, the deviation from the conventional shape occurs below ~1.6 keV, precisely where the deviation is observed in the tritium experiments at Guelph.

An explanation of the Livermore data, whether a molecular, atomic, or nuclear effect remains unkown. A possibility, suggested by Stoeffl, is that the excited final states of the HeT^+ molecule (also $\sim$ 30% of the tritium decay rate) autoionize. The low energy (shake-off) electrons that ensue would subsequently be collected in the spectrometer. Confidence in this interpretation relies on one accepting that essentially 100% of the excited final states proceed in this manner and a theoretical calculation would be useful in this regard.

How does the recent finding at Livermore relate to the anomalies observed in the tritium experiments of Simpson and Hime at Guelph? Two possibilities come to mind. One is that the rise below 1.6 keV was first seen by Simpson as an indication of a 17-keV neutrino but misinterpreted due to the higher threshold and poorer energy resolution. In this case the excess of counts must be due to interactions of the β electron and not from secondary electrons associated with atomic or molecular physics. On the other hand, the Guelph and Livermore observations may not be related. For example, if the excess observed at Livermore is associated with an atomic electron then the effect would not be observed in the Guelph experiments since it would accompany a β particle and the total energy of the two electrons would be summed in the detector.

7.2 LBL ^{14}C Measurements

While the results from the Livermore experiment are intriguing in their own right it is far from clear that they bare any resemblence to the original observation by Simpson. Equally baffling is the positive result obtained in the LBL ^{14}C experiment[16]. Indeed, an understanding of that spectrum requires yet another explanation, different than that for tritium or the experiments employing silicon detectors with external sources. A disadvantage in the ^{14}C experiment is that the response of the detector is not measured with monoenergetic electrons originating within the implanted detector, a problem shared with the experiments employing implanted tritium. Instead, only the intrinsic energy resolution is determined using external photon sources. Photons at the relevant energies interact predominantly via the photoelectric effect, ejecting photoelectrons that are indistinguishable from a β particle. Nonetheless, the sensitivity to small departures in the electron response function is clearly demonstrated in the reanalysis of the Oxford data. The latter result serves as a warning that the true response function might not be determined in the ^{14}C experiment.

The low rates ($\sim$25 Hz) in the ^{14}C experiment make background subtraction an important issue. The background is subtracted from a different detector (not containing ^{14}C) possibly leading to unkown discrepancies. Of greater concern is the need to veto degraded events that occur near the boundaries of the detector. The latter point seems relevant since an analysis of "unvetoed" *versus* "vetoed" data reduces the mixing probability for a 17-keV neutrino from 1.2% to 0.75%. This spread of 0.45% is too large to be the result solely of events occuring near the detector boundary. Studies have shown, however, that electronic cross-talk in the veto system can create anomalies in the spectrum. While further investigations are required to fully understand the problem, the LBL group have recently concluded that the latter effect is the likely culprit for the ^{14}C result[34].

Unlike the ^{3}H, ^{35}S, and ^{63}Ni spectra, ^{14}C exhibits a significant theoretical deviation from allowed β decay. This ***forbidden*** contribution to the shape of the ^{14}C spectrum is modelled by an additional parameter in the form of a linear shape factor. A measurement of the ^{14}C spectrum at Princeton finds both an endpoint energy and forbidden shape correction that are statistically different than the values deduced in the LBL experiment. Whether these discrepancies offer any insight into the LBL anomaly is not clear. Further insight may come from the ^{14}C experiment underway at Argonne National Laboratory. It will be interesting to see if the present generation of β decay measurements are sensitive to such phenomena as forbidden shape corrections.

8 Summary and Conclusions

The search for heavy neutrino admixtures in nuclear β decay spectra has proven a most ambitious task, and the difficulties inherent in such searches is clearly dominated by understanding systematic effects. Perhaps this observation is not uncommon to any search for physics beyond the standard model where we must probe nature beyond the 1% level. Studies over the past year have indicated that great care is required to understand energy dependent shape corrections. Indeed, seemingly innocuous assumptions can lead to both "negative" and "positive" claims for heavy neutrino emission when systematic effects are not properly taken into account.

Recent experiments definitively rule out the presence of a 17-keV neutrino and circumvent the criticisms applicable to earlier "null" results. It remains a remarkable coincidence that several different experiments found consistent evidence for a 17-keV neutrino, indicating a rather unique situation in the history of physics. On the one hand, experiments using external sources with silicon detectors have been reinterpreted in terms of electron scattering effects. It seems, despite the bizarre coincidence, that the ^{14}C anomaly is also the result of an instrumental artefact. It is perhaps ironic that the last remaining item awaiting to be resolved is the low energy excess in the tritium spectrum first seen by Simpson seven years ago. Whatever the reason, the anomaly is not the result of a 17-keV neutrino. What a pity!

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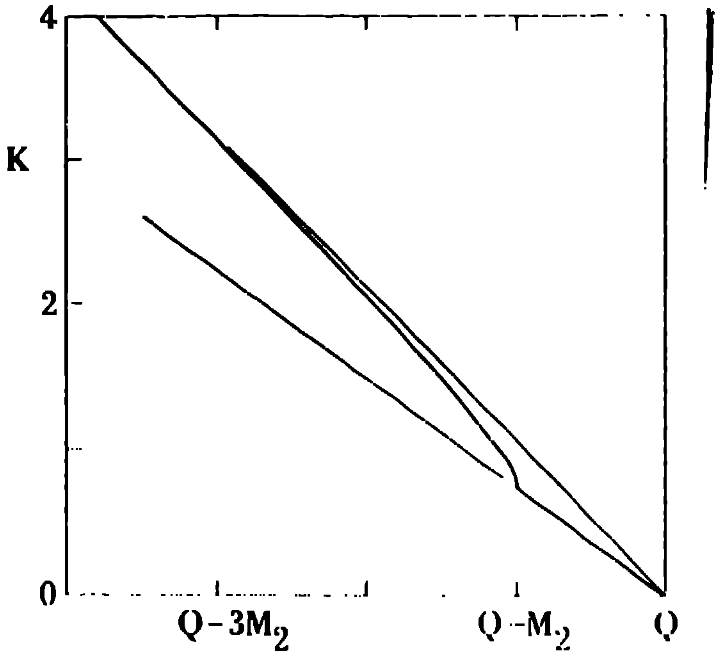
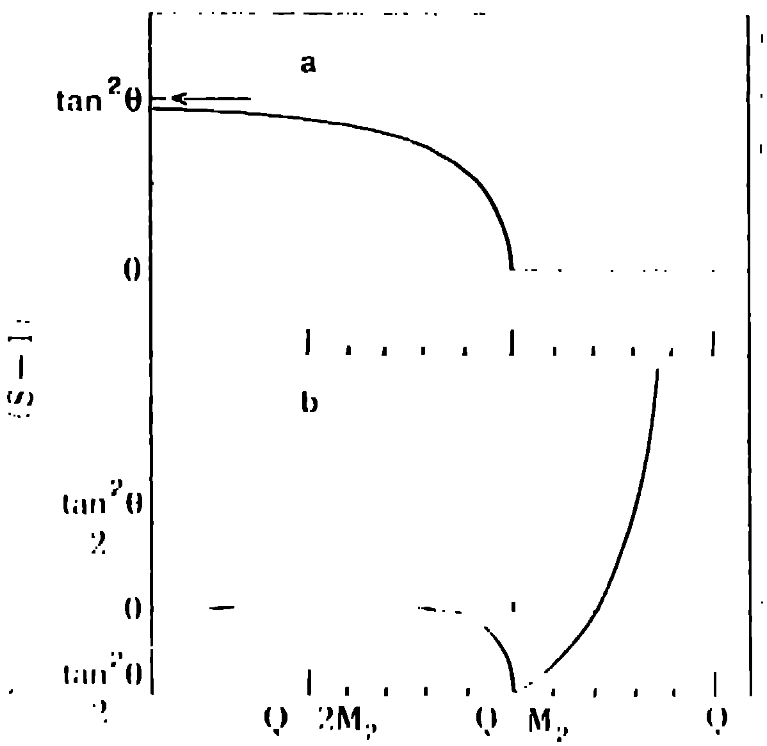
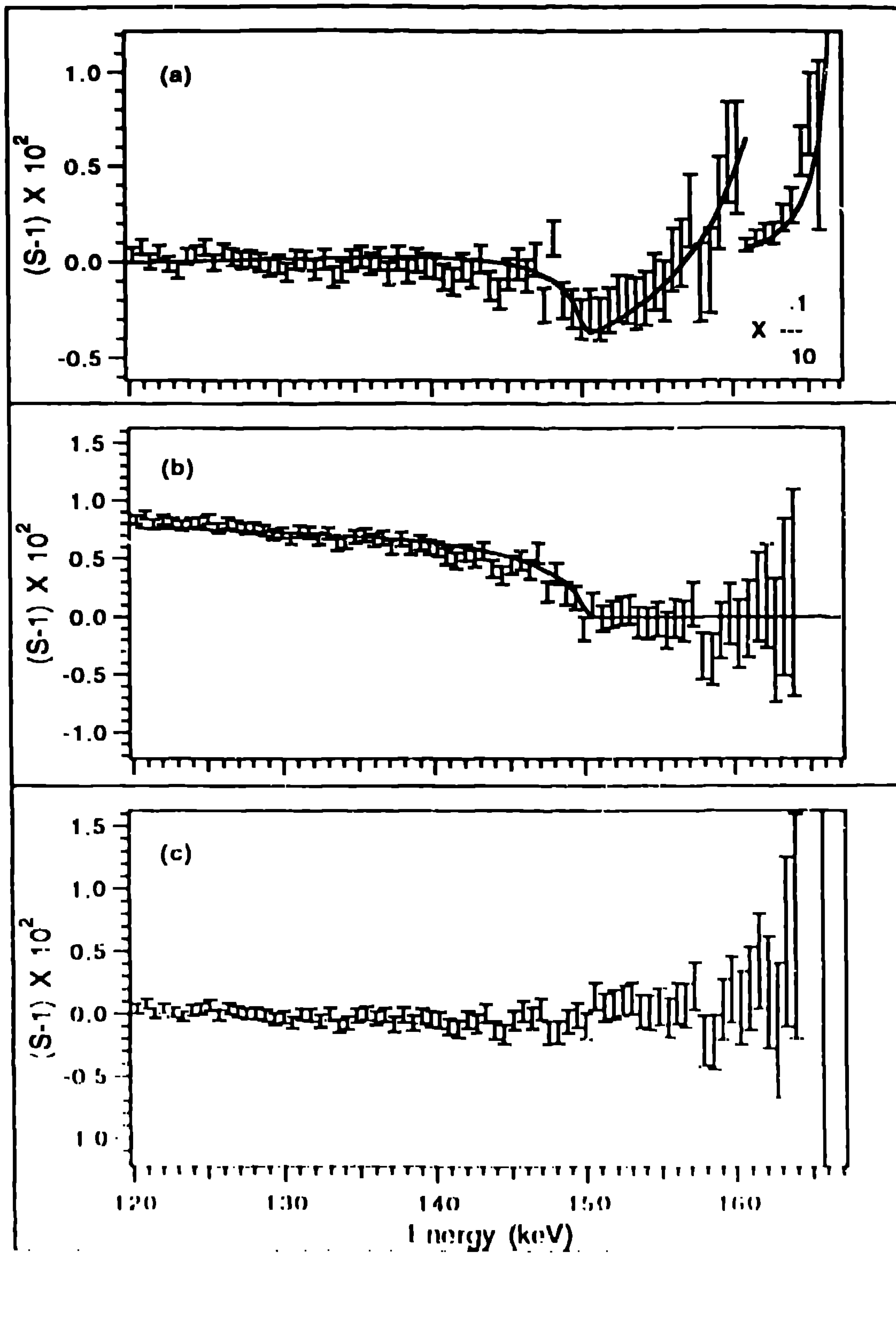


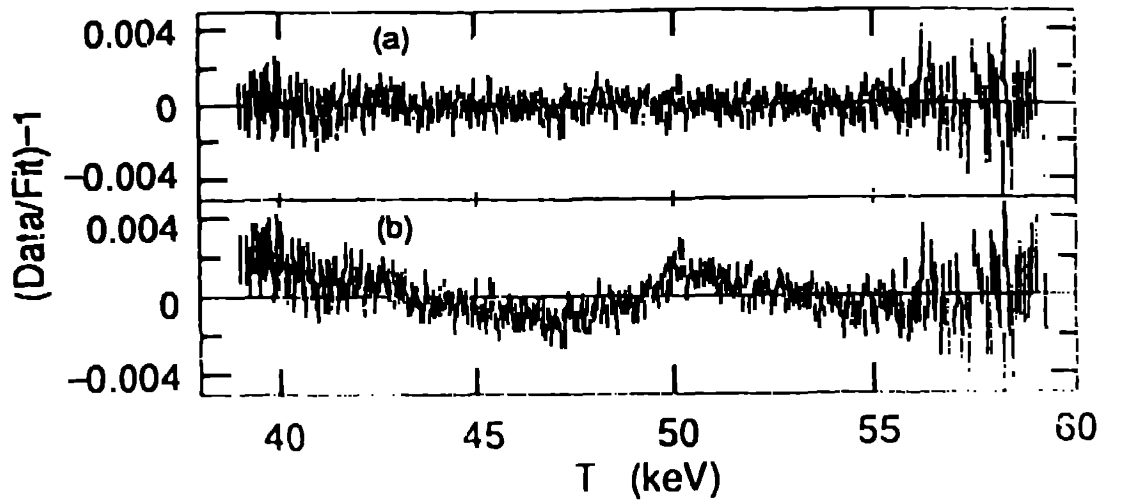
(Fig.1) Schematic diagram of a two component Kurie plot in the case for maximal mixing of the electron neutrino with one light ($M_1 \sim 0$) and one heavy (M_2) mass eigenstate.



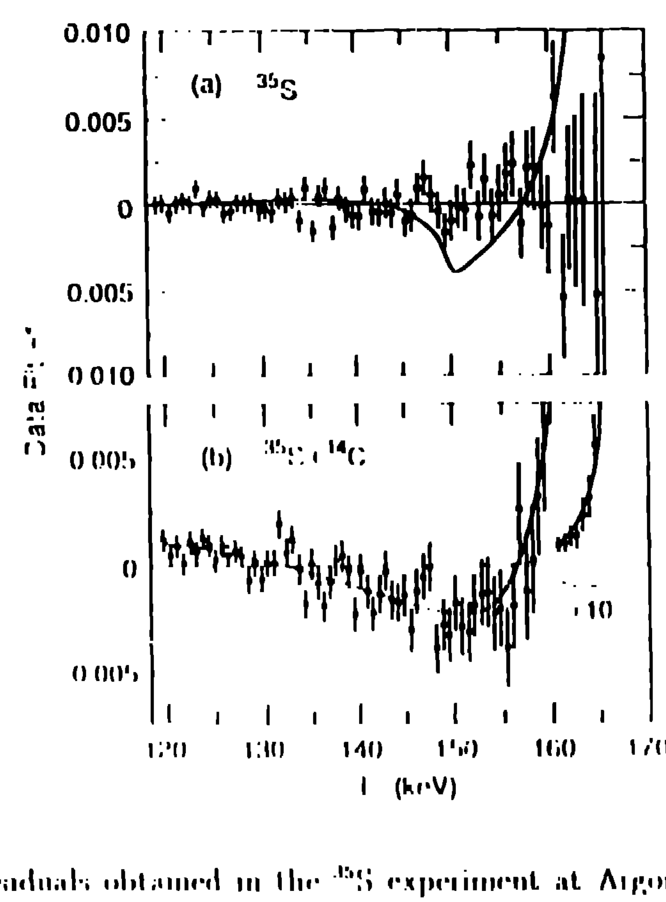
(Fig.2) Shape factor arising from a heavy neutrino with mass M_2 and mixing probability $\sin^2\theta$ when normalization is taken (a) above the threshold ($Q - M_2$) and (b) over the entire energy interval.



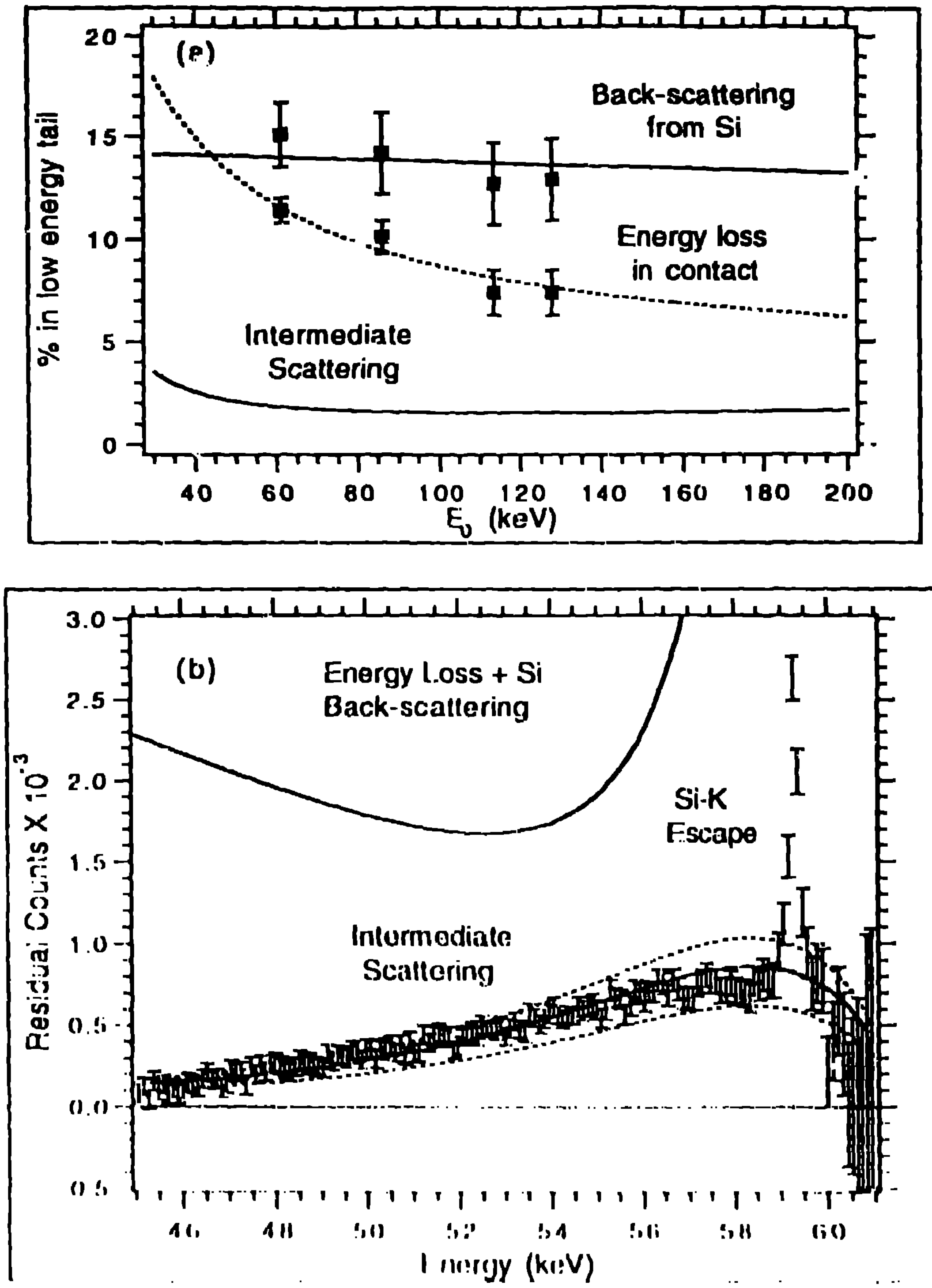
(Fig.3) Deviations in the ^{35}S spectrum observed at Oxford after normalizing data to a single component, massless neutrino spectrum (a) from 120 to 167 keV and (b) from 151 to 167 keV. (c) Residuals obtained for $M_2 = 17$ keV and $\sin^2\theta = 0.0085$



(Fig.4) Residuals obtained in the INS Tokyo ^{63}Ni experiment assuming (a) a massless neutrino spectrum and (b) a 1% admixture for a 17-keV neutrino.



(Fig.5) (a) Residuals obtained in the ^{35}S experiment at Argonne laboratory compared to that expected for a 0.85% admixture of a 17 keV neutrino (smooth curve). (b) Sensitivity test showing the deviation caused by a 1.4% admixture of ^{14}C.



(Fig.6) (a) Energy dependence of the various components of the electron response function in the Oxford geometry. The effects of intermediate scattering were uncovered in (b) a more detailed analysis of ^{109}Cd callibration data which lead to a reinterpretation of the ^{35}S and ^{63}Ni data taken at Oxford