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The 17 keV Neutrino

F.E. Wietfeldt [(a)] and E.B. Norman [(b)]

[(a)] N.I.S.T.
Gaithersburg, MD 20899

and

[(b)] Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

April 1995

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The 17 keV Neutrino

F.E. Wietfeldt[(a)] and E.B. Norman

Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, California 94720

Abstract

A controversy over the possible existence of a 17 keV mass state coupled to the electron neutrino occurred during the period 1985–1994. A number of independent experiments found evidence for this state in nuclear decay spectra, while others did not. Ultimately a consensus that the 17 keV neutrino does not exist was reached. We review and evaluate the experiments that reported evidence for and against the 17 keV neutrino, and discuss the various issues of experimental systematics that contributed to the development and resolution of the controversy. We attempt to distill the lessons learned from this story and draw some general conclusions that are relevant to future research.

I. INTRODUCTION

In 1930 Pauli postulated the emission of a light neutral particle (later dubbed the neutrino by Fermi) in nuclear beta decay. The mass of the neutrino has been a fundamental question in physics ever since. In the Standard Model the three types of neutrino (ν_e, ν_μ, ν_τ) are treated as strictly massless; yet there is ample theoretical motivation for massive neutrinos. Neutrino mass would play a crucial role in cosmology, it could explain the observed solar neutrino deficit, and it may point the way to grand unified gauge groups.

Many experiments have searched for evidence of neutrino mass. Direct experiments have studied beta decay or electron capture and looked for small distortions that are indicative of emission of a massive neutrino. Indirect experiments have looked for evidence of neutrino oscillation and related phenomena. No experiment to date has found conclusive evidence for a neutrino mass inconsistent with zero. Tentative reports of neutrino masses have appeared in the literature, but all have been ultimately disproven.

We consider the recent case of the 17 keV neutrino. In 1985 John Simpson reported evidence for the emission of a 17 keV mass neutrino in a small fraction of tritium beta decays (Simpson, 1985). Initial efforts by other groups to confirm this report were negative. However a few years later several independent investigations found corroborating evidence for a 17 keV neutrino in different nuclear decay spectra, and an experimental controversy ensued. The evidence was hotly debated and new experiments were undertaken. These later results were unanimously negative and by 1993 a general conclusion was reached: there is no 17 keV neutrino. The positive reports were evidently wrong.

From the point of view of fundamental physics, the 17 keV neutrino is no longer interesting. The evidence against it is convincing. The general question of neutrino mass and mixing is still very important, but there is no further need to consider a small admixture of a 17 keV mass component in the electron neutrino. In a broader sense however the story of the 17 keV neutrino is still very relevant, and it should not be forgotten. It is a fascinating tale and an excellent case study of the scientific method; it teaches valuable lessons about

systematic effects in the use of precision spectroscopy to probe fundamental processes; and it raises a very interesting question: How did a number of different research groups, using different methods, all find evidence for something that doesn't exist?

In this paper we review and analyze the history of the 17 keV neutrino. In the first section we briefly discuss the theoretical basis of neutrino mass and mixing and how it is manifested in nuclear beta decay. We then divide the experiments into two groups: the first generation (1985–1991) where the positive and negative reports were roughly balanced and the controversy was at its height; and the second generation (1992–1994) where the experiments were generally more sensitive and the reports were overwhelmingly negative. For each group we review and compare the different experiments and discuss the major systematic issues involved. We then describe the recent work, by the original investigators and others, to explain the true origins of the 17 keV neutrino signals in the positive reports. Finally, we draw some broad conclusions and attempt to extract useful lessons from this story.

II. THEORETICAL BACKGROUND

A. Neutrino Mass and Mixing

In the Standard Model of electroweak interactions the fundamental fermions begin as massless particles. Chirality (handedness) is an exact symmetry, i.e. all fermions exist in strictly left- and right-handed versions. The left-handed fermions participate in the weak charged-current interaction (e.g. nuclear beta decay) while the right-handed fermions do not. This explains the maximal parity violation observed in weak interactions.

The charged fermions are known to have mass. Mass is added to the theory by introducing the Higgs field Φ, a complex scalar doublet field that couples to the fermions. Through the mechanism of spontaneous symmetry breaking, Φ obtains a non-zero vacuum expectation value which generates a mass term in the Lagrangian:

$$\mathcal{L}_{\text{mass}} = -\frac{v}{\sqrt{2}}\left(f_u \overline{u}_L u_R + f_d \overline{d}_L d_R + f_e \overline{e}_L e_R + f_{\nu_e} \overline{\nu_e}_L \nu_{eR} + \ldots\right) + \text{h.c.} \tag{1}$$

It contains in general a Dirac mass term for each of the six quarks (u, d, c, s, t, b) and six leptons $(e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau)$. The subscripts L and R correspond to the chirality of the fermion field operators. The mass term couples the left- and right-handed fields, breaking the chiral symmetry that is otherwise exact in the Lagrangian. The factor v is the vacuum expectation value of the Higgs field that generates the masses and the coefficients f are the coupling constants of the Higgs field to each fermion. The fundamental fermions are thus Dirac particles with masses given by:

$$m_l = \frac{v}{\sqrt{2}} f_l, \qquad (l = u, d, e, \nu_e, \ldots). \tag{2}$$

The coupling constants f_l, and hence the fermion masses, are not predicted by the theory and must be determined from experiment.

Present experimental evidence is consistent with all neutrino masses being equal to zero. The theory explains this by stipulating that the right-handed neutrino fields do not exist, so the neutrino terms in (1) vanish. This causes no trouble elsewhere in the Lagrangian;

neutrinos are neutral and do not couple to the electromagnetic interaction, and only the left-handed neutrino fields couple to the weak interaction. An equivalent viewpoint is to require $f_{\nu_e} = f_{\nu_\mu} = f_{\nu_\tau} = 0$. The right-handed neutrino fields then have no physical manifestation whatsoever. They do not appear at all in the Lagrangian, and so essentially do not exist. Neutrinos in the Standard Model are strictly massless.

It is possible that future experiments will show that neutrinos do in fact have mass. If so, massive neutrinos can be incorporated into an extension of the Standard Model without serious difficulty. The most straightforward way is to allow the ν_R fields to exist with $f_\nu \neq 0$ in (1). The neutrino becomes a massive Dirac particle, like the electron, with four distinct states: ν_L, ν_R, $\overline{\nu}_R$, and $\overline{\nu}_L$. The right-handed neutrino (and left-handed antineutrino) are sterile, i.e. they have no electroweak interaction. Yet the chiral states of a massive particle are not solutions of the Dirac equation, so a physical ν_R contains a small projection of the opposite chirality and hence may interact as a ν_L. Therefore all four states are physically observable.

Another possible scenario is to include a term of the following type in (1):

$$\mathcal{L}_{\nu\ \mathrm{mass}} = m_\nu \overline{\nu}_L^c \nu_L + \mathrm{h.c.} \tag{3}$$

called a Majorana term. The superscript c signifies charge conjugation. It couples the left-handed neutrino to the right-handed antineutrino, implying that they are opposite chiral states of the same particle. This is allowed only for a neutral particle, otherwise it would violate conservation of electric charge. There is no need for a sterile neutrino in this model; only two states exist. The Dirac or Majorana nature of the neutrino can in principle be determined experimentally; a Dirac neutrino respects total lepton number conservation while a Majorana neutrino necessarily violates it by ΔL=2. In addition, a Dirac neutrino is expected to possess a small magnetic moment, while a Majorana neutrino with a non-zero magnetic moment would violate CPT invariance. More complicated models using combinations of Dirac and/or Majorana masses have been proposed (see reviews by Bilenky and Petcov, 1987; Langacker, 1988).

The fermion mass eigenstates in $\mathcal{L}_{\text{mass}}$ are in general not the same as the states that couple to the weak interaction. Such a coincidence would imply an unexpected connection between the weak interaction and mass. In fact, we know from experiment that the quark weak states are related to the mass states by a unitary transformation, the Cabibbo-Kobayashi-Maskawa mixing matrix. A similar situation should occur in the lepton sector if neutrinos have mass. If the weak flavors ($l = e, \mu, \tau$) are defined in the basis of the charged lepton masses, then the neutrino weak states can be written

$$|\nu_l\rangle = \sum_i U_{li}|\nu_i\rangle \tag{4}$$

where ν_i are the mass states ($i = 1, 2, 3$). U is the leptonic mixing matrix.

Consider the simple case of two-component mixing. In addition to its dominant mass, ν_e would contain a small admixture of a different, possibly much larger mass (which would be dominant in ν_μ or ν_τ). The ν_e weak state would then be:

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle \tag{5}$$

where $\sin\theta$ and $\cos\theta$ are the elements of the leptonic mixing matrix and $|\nu_1\rangle$ and $|\nu_2\rangle$ are the mass eigenstates with masses m_1 and m_2. When a ν_e is created with a definite energy its two mass components will propagate with different wavelengths and interfere with each other coherently. It is straightforward to show that this causes an oscillation of lepton flavor (Pontecorvo, 1958; Bilenky and Pontecorvo, 1976; Kayser, 1981). Experimental searches for neutrino oscillations have yielded negative results, corresponding to upper limits on the parameter space of $m_2^2 - m_1^2$ and $\sin^2 2\theta$ (see Boehm and Vogel, 1992).

B. Kink Searches in Weak Decays

Neutrino oscillation is not the only observable consequence of neutrino mixing. If the electron neutrino is mixed as in (5) and m_2 is sufficiently large then any weak decay that includes ν_e in the final state will consist of a superposition of the spectra corresponding to m_1 and m_2:

$$\frac{dN(E)}{dE} = \cos^2\theta \frac{dN(E,m_1)}{dE} + \sin^2\theta \frac{dN(E,m_2)}{dE} \tag{6}$$

(Nakagawa, *et al.*, 1963; Schrock, 1980; McKellar, 1980; Kobzarev, *et al.*, 1980). This mixture is incoherent because for large m_2 ($m_2 - m_1$ greater than about 100 eV) the oscillation length is much smaller than any practical laboratory measurement distance. In a two-body decay (e.g. $\pi^- \to e\,\overline{\nu}_e$) this effect will cause a double peak in the electron energy spectrum. In a three body decay (e.g. nuclear beta decay) it will cause a characteristic kink in the continuous electron energy spectrum.

In nuclear beta decay the nucleus acquires one unit of charge (a neutron is converted into a proton) and an electron and electron-antineutrino are emitted. The shape of the differential beta energy spectrum is a result of the phase space of the emitted particles. Therefore it depends on the neutrino mass:

$$\frac{dN(E,m_\nu)}{dE} \propto F(Z,E)pE\,(Q-E)\left[(Q-E)^2 - m_\nu^2\right]^{\frac{1}{2}}. \tag{7}$$

E, p are the beta's energy and momentum, Q is the total decay energy, and the Fermi function $F(Z,E)$ accounts for final state coulomb effects. For $m_\nu = 0$ the maximum energy is $E = Q$ and the slope of the distribution approaches zero at that point. For $m_\nu \neq 0$ the maximum energy is $E = Q - m_\nu$ and the slope approaches infinity at the endpoint. If we take equation (6) with $m_1 \approx 0$ and $m_2 \gg m_1$ then we can write the observed beta spectrum as a product of the massless neutrino spectrum and a massive neutrino shape factor $S(E)$:

$$\frac{dN(E)}{dE} \propto \frac{dN(E,0)}{dE} S(E) \tag{8}$$

with

$$\begin{aligned} S(E) &= 1 + \tan^2\theta \left[1 - \frac{m_2^2}{(Q-E)^2}\right]^{\frac{1}{2}} && \text{for} \quad E \leq Q - m_2 \\ &= 1 && \text{for} \quad E > Q - m_2. \end{aligned} \tag{9}$$

For $E > Q - m_2$ the heavy neutrino is energetically forbidden and the spectrum is identical to the massless neutrino spectrum. There is a kink (slope discontinuity) at $E = Q - m_2$,

and below that point the relative amplitude rises to $1 + \tan^2\theta$. The values of m_2 and $\sin^2\theta$ will be the same in every beta spectrum having $Q > m_2$.

Figure 1(a) shows a plot of $S(E)$. The data points of an experimental spectrum containing a small massive neutrino component, divided by the best fit theoretical spectrum with no massive neutrino, will lie on this curve if the two spectra are normalized in the region $E > Q - m_2$. However in a typical experiment the normalization and Q are treated as free parameters and determined by a least-squares fit over a wide energy region; with each point weighted by its statistical uncertainty. In this case the data/fit points will lie on a distorted version of the same $S(E)$, shown in Figure 1(b). This curve diverges near the endpoint because Q will be underestimated if a massive neutrino admixture is present in the data but not included in the fit.

A Kurie plot is often used to analyze an experimental beta spectrum, especially to determine the endpoint energy. It is defined by:

$$K(E) = \left[\frac{\frac{dN(E)}{dE}\Big|_{\exp}}{pEF(E_e, Z)}\right]^{\frac{1}{2}} . \tag{10}$$

The Kurie plot of an allowed spectrum (with no massive neutrino) is a straight line. Figure 2 shows the effect of $S(E)$ on the Kurie plot of the spectrum. The asymptotic slope above the kink differs from the slope below the kink.

Electron capture by the nucleus is another decay process that can reveal information about neutrino mass. In the basic decay, an atomic electron is captured by the nucleus and a monoenergetic neutrino and x ray are emitted. There is an electromagnetic correction to this process in which the captured electron emits an internal bremsstrahlung (IB) photon (see Bambynek *et al.*, 1977). The neutrino and photon share the available decay energy, resulting in a continuous photon spectrum similar to a beta spectrum. For capture from the $1s$ shell:

$$\frac{dN(k, m_\nu)}{dk} \propto k\,(q_{1s} - k)\left[(q_{1s} - k)^2 - m_\nu^2\right]^{\frac{1}{2}} R_{1s}(k) \tag{11}$$

where k is the IB photon energy; q_{1s} is the decay Q-value minus the $1s$ electron binding

energy; and R_{1s} is a correction factor that accounts for the influence of the nuclear Coulomb field on the intermediate electron. It is clear by comparing (11) to (7) that the effect of neutrino mass on the shape of the spectrum is the same. One difference is that beta decay emits an antineutrino while a neutrino is emitted with electron capture. CPT invariance requires that a particle and its charge conjugate antiparticle have identical mass. However it has not been positively established that the particles we identify as neutrino and antineutrino are actually charge conjugate states; so it is possible that the masses are different. Nevertheless, in the absence of contrary evidence it is reasonable to assume that they are charge conjugates and have the same mass. A massive neutrino shape factor that is observed in beta decay should then also be exhibited in IBEC spectra:

$$\frac{dN(k)}{k} \propto \frac{dN(k,0)}{dk} S(k) \tag{12}$$

with

$$\begin{aligned} S(k) &= 1 + \tan^2\theta \left[1 - \frac{m_2^2}{(q_{1s}-k)^2}\right]^{\frac{1}{2}} \qquad && \text{for} \quad k \leq q_{1s} - m_2 \\ &= 1 && \text{for} \quad k > q_{1s} - m_2 \end{aligned} \tag{13}$$

III. THE FIRST GENERATION EXPERIMENTS

A. Simpson's Experiment

The saga of the 17 keV neutrino began in 1985 when John Simpson of the University of Guelph reported evidence of a low energy distortion in the tritium beta decay spectrum (Simpson, 1985 and 1981). The experiment consisted of a 200 mm^2 Si(Li) detector in which tritium ions had been implanted at energies from 10.5 to 15 MeV using a tandem Van de Graaff accelerator. The ions were implanted to a depth of 0.25 to 0.45 mm, sufficient to stop all of the tritium betas and bremsstrahlung photons. This approach should in principle provide an ideal gaussian response function for measuring the beta energy spectrum. The full energy is collected for each event with 100% efficiency over the entire range of the spectrum. The original motivation of the experiment was to study the spectral shape near the endpoint (18.6 keV). However, a divergence was observed at the other end of the spectrum, at an energy of 1.5 keV and below (Figure 3). Simpson found that the size and shape of this divergence could be adequately fit by including a massive neutrino component with $m_2 = 17.1 \pm 0.2$ keV and $\sin^2\theta = 0.03 \pm 0.01$ (see Equation 6).

This result drew considerable interest but was not widely accepted due to questions about systematic and theoretical uncertainties. The biggest issue concerned the low energy calibration. The energy scale of the detector was calibrated using flourescence x rays from Cu, Br, and Mo. These provided K x ray lines in the energy range 8–18 keV which were used for a high-energy calibration. A precision pulser was used to measure the linearity of the electronics over the entire energy range. This was then matched to the x-ray data to obtain the low-energy calibration. The linearity of the detector itself at low energy could not be measured. The shape and size of the observed 17 keV neutrino signal, obtained by fitting the tritium data in the region 0.7–3.2 keV, would certainly be affected (or perhaps even caused) by detector nonlinearity in that region. The problem was compounded by the possibility of Frenkel defects in the Si crystal caused by the tritium implantation. Such

defects can trap ionization charge for some events, shifting them to lower energies in the spectrum and creating a divergence akin to the observed effect. In fact, some degradation in the detector resolution was seen in the K x ray spectrum following the implantation. This was cured by a gentle annealing of the crystal. Unfortunately the effect of this annealing could not be monitored at low energy.

Shortly after Simpson announced his result, Haxton (1985) showed that conventional approximations used to treat exchange terms in beta decay and screening corrections to the Fermi function are not valid at energies below a few keV, where the wavelength of the beta becomes comparable to the atomic scale. He calculated the low energy exchange correction and found that it gave only a 0.1% enhancement at 1 keV compared to the conventional theory. However he argued that a proper treatment of screening correction could account for the low energy divergence in Simpson's tritium spectrum. Several theorists calculated the appropriate screening potential for free tritium (Eman and Tadić, 1986; Lindhard and Hansen, 1986; Drukarev and Strikman, 1986, 1987). When Simpson reanalyzed his data with this correction he found that the divergence was reduced by about 20%. Hime and Simpson (1989) later pointed out that the correct screening potential should be even smaller since the tritium is not free, but trapped inside a silicon lattice. They estimated this contribution and found that the best fit value of $\sin^2\theta$ in Simpson's data was further reduced to $1.1 \pm 0.3\%$.

B. Early Negative Results

1. Magnetic Spectrometers

Soon after Simpson's original tritium result was published, groups using magnetic spectrometers at Princeton, the Institute of Theoretical and Experimental Physics in Moscow, and at Caltech all reported negative results from searches for a 17-keV neutrino signal in the beta spectrum of ^{35}S. This isotope has an endpoint energy of 167 keV, putting the kink at 150 keV, much higher than the 1.5 keV position in tritium. This is an advantage because

atomic corrections which were relevant for tritium are negligible and experimental systematics are more easily understood at the higher energy. The disadvantage is that only 0.18% of beta events fall within 17 keV of the endpoint.

Altzitzoglou *et al.* (1985) at Princeton University used an iron-free intermediate-image magnetic spectrometer to study the beta spectrum of ^{35}S. A 15 μCi source of ^{35}S was prepared by using a mass separator to implant the activity into a backing of carbon plus formvar. The spectrometer was calibrated using a source of ^{111}In prepared in a similar manner. The ^{111}In source provided internal-conversion electron lines at 144.6 and 218.6 keV which covered the upper end of the region of interest in the ^{35}S spectrum. A 450-mm^2 by 1000-μm deep Si surface barrier detector was mounted at the spectrometer focus to detect the beta particles. In order to measure the entire ^{35}S beta energy spectrum, the magnetic spectrometer coils were swept through 32 different field settings using 16 minutes per scan. At each spectrometer setting the number of beta events was determined by integrating the spectrum observed in the silicon detector. This integration was complicated by electrons backscattering from the detector without depositing their full energy, producing a low energy tail in the detector response function which extended underneath and below the noise peak. Also, some electrons scattered off the gold layer on the front of the silicon detector. Both of these energy dependent effects were estimated and attempts were made to suitably correct the observed beta spectrum.

The data were fit to the theoretical spectrum after applying the various systematic corrections. A plot of the data divided by the best fit is shown in Figure 4. This ratio was not a horizontal line, but had a slope and curvature. Over the energy range that was analyzed (112-167 keV) the ratio of data/fit ranged from approximately 0.99 to 1.01. To accommodate this deviation a shape correction factor, containing terms linear and quadratic in energy, was introduced with coefficients left as free parameters in the fit. The authors argued that such a smooth correction would not hide the presence of a kink if it were present in the data. With this correction reasonably good fits were obtained to the data without a heavy neutrino. These fits got much worse when a 3% admixture of the 17-keV neutrino

was included. An upper limit of 0.4% (99% C.L.) was claimed for the admixture of a 17-keV neutrino.

A. M. Apalikov *et al.* (1985) studied the beta spectrum of ^{35}S using an iron-free toroidal magnetic spectrometer at the Institute of Theoretical and Experimental Physics in Moscow. The ^{35}S sources were prepared by the vacuum evaporation of the compound methionine, $C_5H_{11}NO_2{}^{35}S$, onto conducting glass substrates. The beta particles were detected with a six-channel proportional counter system filled with isobutane. In order to cover the region of the ^{35}S spectrum of interest, the spectrometer was scanned from 75-175 keV in 1-keV steps spending 100 seconds at each point. In addition, a narrow scan was done in 0.25-keV steps spending 200 seconds at each point from 145-170 keV.

The data were compared to the theoretically expected beta spectrum and deviations were observed which were attributed to instrumental effects such as electrons backscattering from the source substrate, the energy dependence of the detector efficiency, and electronic dead time. In order to accommodate these effects, a linear and quadratic shape correction factor was introduced in the same manner as in the Princeton experiment. Data from both the wide and narrow energy scans were analyzed with and without the presence of a heavy neutrino. The authors concluded that the upper limit on the possible admixture of a 17.1-keV neutrino was 0.17% (C.L.). Figure 5 illustrates the Kurie plots obtained from both the wide and narrow energy scans. It is interesting to note that there is a small distortion in the data near 150 keV—just the point where the 17-keV neutrino would produce a kink. This distortion was later pointed out by Simpson, who used it to reinterpret the data as supporting the presence of a 17 keV neutrino (Simpson, 1986a).

Another early result was that of Markey and Boehm (1985) who studied the ^{35}S beta spectrum using an iron-free double focussing magnetic spectrometer at Caltech. The 2 mCi source used in this experiment was prepared by depositing a solution containing $Na_2{}^{35}SO_4$ onto a thin mylar foil. The spectrometer was calibrated using a ^{139}Ce source that was prepared in the same manner as the ^{35}S source. This ^{139}Ce source provided internal conversion electron lines at 126.9 and 159.6 keV, which bracket the main region of interest in this search.

A 2-mm thick, liquid-nitrogen cooled Si(Li) detector, placed at the focus of the spectrometer, was used to count the number of beta particles transported at each spectrometer field setting. The detector response function measured with the ^{139}Ce source showed a low energy tail which extended below the detector noise peak. Thus the number of true beta events at each spectrometer setting had to be estimated by extrapolating this tail down to zero energy. The spectrometer was scanned in five runs from 110 to 166 keV using 2-keV-wide bins. When the data were analyzed, the ratio of data/theory was found to be consistent with unity in the energy range 110–166 keV. The authors point out that no shape correction was needed to obtain good fits to the data. Fits were made with and without a heavy neutrino admixture, and once again the best fit was obtained for the massless neutrino hypothesis. They reported a limit of $\sin^2\theta < 0.3\%$ (90% C.L.) for a 17 keV neutrino.

The final first generation magnetic spectrometer search for the 17 keV neutrino was that of Hetherington *et al.* (1987) who used the $\pi\sqrt{2}$ iron-free beta spectrometer at Chalk River Laboratories to study the beta spectrum of ^{63}Ni. The beta endpoint energy of ^{63}Ni is 67 keV, so it provides a much greater fraction of events within 17 keV of its endpoint than does ^{35}S. A multi-strip source with a total activity of approximately 2 mCi was prepared by evaporating the ^{63}Ni onto aluminum strips mounted on a thick Plexiglas backing. Appropriate DC bias voltages were applied to these strips to correct for their slightly different positions. A ^{169}Yb source prepared in the same manner was used to calibrate the system. This source provided internal conversion electrons at energies of 34, 50 and 71 keV.

An array of 22 proportional counters filled with isobutane was mounted at the spectrometer focus to count the beta particles at each field setting. The single entrance window, approximately 168 μg/cm^2 thick, was made of polypropylene coated with cellulose nitrate, chromium, and gold. The entrance slits of the three counters at each end of the array were covered with an aluminum plate. The data collected from these counters were used to correct for the background component which was observed to vary with time.

The spectrometer was scanned from 25 to 70 keV in 900 equal-momentum steps (approximately 60 eV at an electron energy of 50 keV), and an additional narrow-range scan was

made over the interval 46–54 keV. Detailed tests and calibrations were performed using the ^{169}Yb source and Monte Carlo simulations to determine the detectors' response functions, resolutions, and efficiencies; window transmission; and other systematic effects which could distort the ^{63}Ni beta spectrum. Data from both the wide range and narrow range scans were analyzed for the signature of a heavy neutrino. In both cases, corrections were needed for instrumental effects such as the variation in efficiency among the proportional counters, the loss of events below the lower-level discriminator thresholds, and the variation in the electron transmission through the detector window as a function of energy. In the energy interval 26–67 keV this window transmission varied in a non-linear manner by more than 10%, and in the narrow scan it varied by about 2%.

After all of these corrections were applied, it was found that a linear shape correction was needed to obtain satisfactory fits to the data from both the wide and narrow energy range scans. The zero neutrino mass hypothesis provided the best fits to the data in both cases. From the results from the wide scan, the authors concluded that the admixture of the 17-keV neutrino could be no more than 0.28% (90% C.L.), while from the narrow scan the upper limit was 0.44%. (90% C.L.). The data/fit from their analysis of the wide and narrow scan data are shown in Figure 6.

2. Solid-State Detectors

In 1985 two experiments were reported that used Si(Li) detectors to measure the beta spectrum of ^{35}S, and both found no evidence for Simpson's 17 keV neutrino. Datar *et al.* (1985) used a $Ba^{35}SO_4$ source deposited onto a thin aluminized polypropylene foil. The spectrum was collected with a 28-mm-diameter, 3-mm-thick windowless Si(Li) detector at a distance of 8 cm. Perspex collimators were employed to shield scattered electrons and bremsstrahlung photons from the detector. Conversion electron lines from ^{57}Co (115.0 and 129.4 keV) and ^{99m}Tc (119.4 keV) were used to measure the beta response function. The authors claimed an upper limit of $\sin^2\theta < 0.6\%$ (90% CL) for the mixing of a 17 keV

neutrino. The experimental data divided by the best fit are shown in Figure 7. There is some ambiguity in how the data were fit. The dashed curve indicating the expected shape factor for $\sin^2\theta$=0.03 is shown normalized above the kink position (150–166 keV), as in Figure 1(a). This is how the data would appear if $\sin^2\theta$ was varied in the fit while keeping all other parameters (*i.e.* the normalization and Q-value) fixed; and implies that they performed the analysis in that way. If so, they grossly overestimated the statistical sensitivity of their data to the effect. The normalization and Q-value should have been varied along with the mixing, causing the dashed curve to appear as in Figure 1(b). Also, the authors do not mention the goodness-of-fit, but judging from the deviations in Figure 7 it is quite poor. Therefore the claimed upper limit is dubious.

Ohi *et al.* (1985,1986) used a pair of 7-mm-thick Si(Li) detectors with a ^{35}S source sandwiched between (Figure 8). The source was deposited onto a 0.5 μm Mylar film and then covered by a similar film that was glued onto it. About 20% of the incident betas were observed to back-scatter out of the silicon detector, depositing less than full energy. This sandwich-detector design allowed back-scattered electrons to be vetoed, eliminating this problem for events above the veto threshold (5 keV). For events below this threshold the effect was worse compared to a single detector design because betas incident on the veto counter can back-scatter into the energy counter as well. The conversion electron line from the 570 keV transition in ^{207}Bi decay was used to measure the response function. This seems a poor choice since it is a single line far from the energy region of interest. The data/fit are shown in Figure 9(a). An upper limit of 0.15% (90% CL) for the admixture of a 17 keV neutrino was claimed. Again however, it is apparent from Figure 9(a) that while the experimental data were fit over the region 120–160 keV, the massive neutrino function $S(E)$ is shown normalized from ~150–160 keV (above the kink position), so the validity of this limit is questionable. In fact, in 1986 Simpson published a paper in which he pointed out this problem, and then reanalysed their data, claiming that a distortion at 150 keV was consistent with emission of a 1–2% 17 keV neutrino when the data were fit in the region above 150 keV (Simpson, 1986b). This is shown in Figure 9(b).

C. The 17-keV Neutrino Returns

By late 1988 a number of experiments using various isotopes and detectors had contradicted Simpson's result. None had confirmed it. The 17-keV neutrino seemed dead and soon to be forgotten. Then in 1989, in a dramatic turn of events, Simpson and his student Hime published a pair of papers describing two new results supporting the existence of the massive neutrino and soundly criticizing the negative experiments.

In the first experiment a cooled Si(Li) detector was used to collect the beta spectrum of an external source of ^{35}S (Simpson and Hime, 1989). Their apparatus is shown in Figure 10. A 200 mm^2 commercial Si(Li) detector was mounted onto a cold finger held at liquid nitrogen temperature. A copper cryopanel was installed inside the vacuum chamber to reduce the build-up of ice on the detector face. The detector's output signal was collected by a cold FET preamp installed directly behind it. The source was prepared by chemical adsorption of a $Ba^{35}SO_4$ solution onto a 10-μm Mylar foil, which was then attached to an acrylic ring mounted in front of the detector. No collimation was used between the source and detector. Calibration sources of ^{57}Co (conversion electron lines at 115 and 129 keV) were prepared in a similar way.

Two runs were made with different ^{35}S sources at different source-detector distances, a 0.5 μCi source was measured at 9 mm and a 5.0 μCi source was measured at 35 mm, such that in each run the counting rate was 2100 s^{-1}. Separate ^{57}Co calibration runs were also made at each distance. Each ^{35}S run contained 6.5×10^5 counts/keV at 150 keV (17 keV below the endpoint), about eight times the statistical sample of the similar experiment of Datar *et al.* (1985). Background and pulse pileup were calculated and fit to the ^{35}S data in the region above the endpoint, and then extrapolated down to the region fit. The full-energy peak of the detector response function was assumed to be gaussian. Its width was allowed to vary as a free parameter in the fits, giving σ=0.8 keV, which agreed with the ^{57}Co electron-line widths. The tail of the response, attributed to back-scattering from the detector and source backing, was assumed to be flat, and the tail fraction was varied as a

free parameter. The best fits gave a back-scatter fraction of about 30%, consistent with the observed tail fractions in the ^{57}Co lines and previous measurements of electron scattering from silicon using a diffuse source (Knop and Paul, 1965).

The data from each run were fit to the theoretical spectrum in the energy region 110–166 keV. The mass and mixing fraction of a second neutrino component were varied in the fits, and both data sets yielded a mass of 17 keV, although the admixtures disagreed slightly ($\sin^2\theta$=0.63 $\pm$ 0.13% for the weak source and 0.84 $\pm$ 0.13% for the strong source). The combined result was reported to be m_2=16.9 $\pm$ 0.4 keV with $\sin^2\theta$=0.73 $\pm$ 0.09(stat) $\pm$ 0.06(sys)%. The data/fit are seen in Figure 11. The estimated systematic error includes uncertainties in the width of the gaussian response, the background subtraction, and the effects of final-state shakeoff electrons in beta decay. No arbitrary shape corrections were needed to obtain good fits.

One can question the assumption of a flat tail in the detector response function that was used in fitting the data. The authors do cite several reports in the literature of an essentially flat tail due to incident electrons back-scattering from Si(Li) detectors. However the back-scatter fraction in this geometry was quite large (30%) and even a small energy-dependence in the shape could be important in this experiment (see the discussion in Section IV A). The ^{57}Co calibration spectrum is shown in Figure 12. The tails from the electron lines appear to be flat, but it is not convincing from this figure that a small departure from flatness did not produce a distortion in the beta spectrum at the level of 1%.

In the same paper, Simpson and Hime systematically discussed and criticized the negative ^{35}S and ^{63}Ni experiments. They compared the statistical sample in Datar *et al.* (1985) to that of their own ^{35}S experiment and argued that it was insufficient to rule out a 17 keV neutrino at the level of 1% (remember that Simpson's original paper claimed an admixture of 3%). They criticized the experiment of Ohi *et al.* (1985) for their double-Si(Li) detector design and for inconsistency in comparing their data to the 17-keV neutrino shape. They pointed out that the conversion electron spectrum shown in the paper of Markey and Boehm (1985) indicates a low-energy tail, caused by electrons backscattering from the de-

tector, containing about 60% of the total incident electrons, about a factor of four higher than the expected backscatter fraction. They argued that some important systematic effect was overlooked in that experiment. Finally, they criticized the magnetic spectrometer experiments of Altzitzoglou *et al.* (1985), Apalikov *et al.*(1985), and Hetherington *et al.* (1987) for using polynomial correction factors, with coefficients determined from the data, to correct for unknown systematic effects. They pointed out that this may tend to reduce an experiment's sensitivity to the distortion caused by a massive neutrino component (see the discussion in section IV A), so therefore these three experiments overstated their sensitivities. They ended the paper with the statement, "Contrary to one's intuition, a null result is not more reliable than a positive result."

The second paper (Hime and Simpson, 1989) reports an improvement on Simpson's original tritium experiment. Tritium ions were implanted into a 200-mm^2 $\times$ 7-mm-thick HPGe detector to a depth of 0.28–0.32 mm. The germanium detector used in this experiment had two significant advantages over the Si(Li) detector used previously. First, a germanium crystal can be heated to much higher temperatures than a Si(Li) without damaging the detector, so that radiation damage caused by the implantation could be effectively removed by annealing. Second, the K_α x ray in Ge is 9.9 keV compared to 2.3 keV for Si, therefore the energy calibration could be extended to low energies by measuring the x-ray escape peaks in germanium.

About 1.6×10^{11} tritons were deposited into the crystal (while installed in its cryostat) in a series of nine implantations. The face of the detector was then scanned using the 59-keV gamma-ray of ^{241}Am. This gamma-ray has an attenuation length of about 1 mm so it illuminated the entire range of implantation. A pulse-height defect of about 2% and a dead layer of about 0.6 mm were evident in the region of implantation. Annealing the detector at room temperature for 25 hours removed the pulse-height defect. Additional annealing cycles were performed up to 130°C (*in situ*) and 180°C (removed from the cryostat). The detector was then etched and reprocessed, and the dead layer seen by the 59 keV γ-ray scan was less than 1.4μm. The energy calibration was obtained by fluorescing samples of Se, Br,

Rb, Sr, Y, Zr, and Mo with 88-keV γ rays from a strong ^{109}Cd source. The resultant K x rays (11.2–17.2 keV) were collected in the ^{3}H-implanted detector. A photon in this energy range will interact in the Ge crystal primarily by producing a K-shell photoelectron and an associated Ge K_α x ray (9.9 keV). If the interaction occurs near the surface and this x ray escapes, the collected energy will be equal to the incident photon energy less 9.9 keV. By including these x-ray escape peaks, the energy calibration of the system was determined down to 1.3 keV.

Fractional deviations in the Kurie plots (ΔK/K) at low energy are shown in Figure 13 for two individual runs. The data in the lower plot were collected with improved resolution due to a change in the preamp and FET package. Both show a significant divergence below 2 keV, about 17 keV below the endpoint. The final combined result from fitting the data was m_2=16.9 $\pm$ 0.1 keV with $\sin^2\theta$=0.6–1.6%. The latter includes the effect of uncertainty in the screening potential for atomic tritium bound in a crystal lattice.

Up to this point all of the reports favoring the existence of a 17 keV neutrino were due to Simpson and Hime. The first truly independent positive result appeared in late 1990. A group at Lawrence Berkeley Laboratory (LBL) obtained a planar germanium crystal that was grown from a melt containing a small quantity of ^{14}C impurity. This crystal was produced in 1982 in order to study the solubility of carbon in germanium (Haller *et al.*, 1982). To make the crystals, a mixture of ^{14}C-methane (8.8%) and ^{12}C-methane was introduced into a silica reaction chamber which contained a silica crucible held at 1050°C. This temperature was high enough to pyrolyze the methane and coat all surfaces inside the chamber with free carbon. Two crucibles were coated in this way, and several germanium crystals were then grown in these crucibles. Some of the crystals were made into radiation detectors, and by integrating the resulting beta spectra, the total carbon concentrations were obtained, ranging from 1.0×10^{14} to 4.5×10^{15} cm^{-3}. Autoradiographs were taken by sandwiching thin slices of the crystals between sheets of x-ray film and allowing the film to be exposed to the ^{14}C beta activity for a period of three months. This revealed that much of the carbon was concentrated into clusters of varying size, although the absolute sizes and numbers of

clusters could not be quantitatively determined.

One of the crystals was melted and regrown in a bare crucible. An autoradiograph of this second-generation crystal showed no sign of clusters, and a radiation detector made from it measured a concentration of 6×10^{12} cm^{-3} total carbon (about 95% of the carbon was lost during the process). The physical dimensions of this detector are shown in Figure 14 (top). It is a 12.8-mm-thick planar crystal with a Boron-implanted p^+ contact and a Lithium-drifted n^+ contact. The n^+ contact is segmented into a 30-mm-diameter central region and an outer guard ring, separated by a 1-mm-wide circular groove. The purpose of the guard ring was to veto events that occur near the edge of the detector. Surface effects on the edge can cause the electric field lines to fringe outward and trap ionization charge at the surface, resulting in incomplete charge collection. In addition, betas from the ^{14}C close to the edge may escape without depositing their full energy. A small number of betas could still escape near the end contacts without generating a veto,resulting in a small tail in the detector's energy response.

The ^{14}C detector's counting rate was quite low (about 20 sec^{-1}) so environmental background was significant and had to be subtracted. To measure the background, a planar detector with a size and configuration similar to the ^{14}C detector was fabricated from a ^{14}C-free germanium crystal grown using an uncoated silica crucible. It had a thickness of 14.2 mm and a central region 26 mm in diameter. The dimensions of the background detector are shown in Figure 14 (bottom).

This experiment seemed an excellent way to search for the effect of a massive neutrino component. It was similar to Simpson's tritium experiment in that almost all events were fully contained within the active volume of the detector, so scattering and energy loss effects that complicate the response function were virtually eliminated. The endpoint energy of ^{14}C decay is 156 keV, so the kink from a 17 keV neutrino would appear at 139 keV, where atomic and environmental effects that were important in the case of tritium are negligible.

There was no practical way to measure the beta response function of the detector using an electron source. Instead it was assumed that the full-energy peak response for an inter-

nal beta is the same as for photoelectrons and Compton-scattered electrons. Therefore the energy calibration and peak shape were obtained using external gamma-ray sources. The low energy tail of the response function, due to betas that originate near the surface of the detector and escape without depositing their full energy, and without generating a veto signal, was estimated by Monte Carlo and found to be very small (about 0.2% for a 156 keV beta). The ^{14}C-doped crystal was counted in a low background environment. It was occasionally removed from the cryostat and switched with the background crystal, which was then counted in the same environment. The collected data were fit to the theoretical spectrum with the mass and mixing of a second neutrino component varied as free parameters. A preliminary result, based on 122 days of ^{14}C and 2 days of background data, found evidence for a massive neutrino with m_2=17 $\pm$ 2 keV and $\sin^2\theta$=1.40 $\pm$ 0.45 $\pm$ 0.14% (Sur *et al.*, 1991). The final data set, consisting of 392 days of ^{14}C (3×10^5 counts/keV at 139 keV) and 111 days of background, found m_2=16.6 $\pm$ 0.6 keV and $\sin^2\theta$=1.25 $\pm$ 0.25%, in excellent agreement with the results of Simpson and Hime. Figure 15 shows the data/fit.

Later in 1991, Hime, who had moved to Oxford, and Jelley reported new results from ^{35}S and ^{63}Ni (Hime and Jelley, 1991; Hime, 1991). The apparatus used was similar to the one at Guelph except that a set of aluminum and copper collimators were employed to restrict the detected betas to normal incidence (Figure 16). A weakness in the Guelph experiment was that the tail in the electron response function due to backscattering was quite large and not very well understood. It was assumed to be flat in the data analysis. The collimation in the Oxford design reduced the backscatter tail from 30% to about 12%. The shape of the response function including the tail was measured using K-shell internal conversion (IC) electron lines from ^{57}Co and ^{109}Cd (62.5, 115.0, and 129.4 keV) and extrapolated to the fit energy region (120–170 keV). The effects of back-scattering and energy loss in the thin gold detector window were studied using theoretical and Monte Carlo calculations and matched to the IC line data. Figure 17 shows the response function for the 129.4 keV IC line. This detailed response function was then used in fitting the experimental beta spectrum.

Two high-statistics runs with slightly different geometries were collected using the ^{35}S

source. Analyses of both runs showed strong evidence in favor of the 17 keV neutrino, and gave a best value of $\sin^2\theta = 0.0084 \pm 0.0006(\text{stat}) \pm 0.0005(\text{sys})$. The total data set contained 2×10^6 counts/keV at 150 keV. The data/fit plots are shown in Figure 18. The analysis was repeated using a 12% flat tail instead of the calculated shape, and similar values of the mass and mixing were obtained. The authors argued that this demonstrated the 17 keV neutrino signal was not sensitive to the detailed shape of the low energy tail. The ^{63}Ni data also supported the presence of a 17 keV neutrino, but the statistics were lower (6×10^5 counts/keV at 49 keV), and systematic uncertainties in the back-scatter tail were more problematic due to the lower endpoint ($E_{\text{kink}}/E_{\text{endpoint}}$ is lower compared to ^{35}S). A result of $\sin^2\theta = 0.0099 \pm 0.0012(\text{stat}) \pm 0.0018(\text{sys})$ was quoted. One item of possible concern was that the ^{35}S source was made from a precipitate of $BaSO_4$, while the ^{63}Ni and conversion line sources were made from hydroxides. If energy losses in these sources were significantly different, the detector response function used would have been incorrect. In fact, energy loss in the source was not included in the response function analysis at all. Hime argued that the sources were thin enough so that any possible difference would be insignificant (Hime, 1991).

D. IBEC Experiments

As discussed in section II, internal bremsstrahlung from electron capture (IBEC) photon spectra can be used to study the electron neutrino mass. This approach is complimentary to beta decay studies, which involve the electron antineutrino. The spectral effect is essentially the same although the experimental issues are quite different. A photon spectrum is most effectively measured using a large volume solid-state detector. Source scattering is not a serious problem, so large source volumes can be used as well. The main disadvantage is that photon scattering in the detector and surrounding materials is unavoidable and the scattered photon response function is quite complex. The IBEC theoretical shape is also more complicated than that of beta decay, due to capture from different electronic states.

The first 17 keV neutrino experiment to use the IBEC method was undertaken by a group at CERN (Borge *et al.*, 1986). They produced a source of ^{125}I (1s-capture endpoint of 146 keV) and counted it with a pair of planar Ge detectors. The statistical sample was rather small, but they were able to establish an upper limit of $\sin^2\theta < 0.02$ (98% CL) for a 17 keV mass neutrino component.

In 1987 an experiment in Zagreb measured the ^{55}Fe IBEC spectrum collected with a 56-cm^3 Ge(Li) detector (Žlimen *et al.*, 1987). The 1s-capture endpoint of this isotope is 225 keV. Because of the difficulty in determining the photon response function and efficiency over a wide range of energies, they restricted their analysis to the range 197.5–213.5 keV. The photopeak response shape was measured using external gamma ray line sources. They obtained the energy-dependent photopeak efficiency of the detector by fitting the experimental IBEC data above 213 keV to the theoretical spectrum and extrapolating this efficiency function down to the energy range of interest. The group claimed an upper limit of $\sin^2\theta < 0.007$ (3σ) for a neutrino in the mass range 16.4–17.4 keV. This limit was probably overstated because the uncertainty inherent in their method of treating the efficiency was not included, and also because the χ^2 minimum was taken at a negative (unphysical) value of $\sin^2\theta$.

The same group at Zagreb also studied the IBEC spectrum of ^{71}Ge and in 1991 reported the only positive evidence for a 17 keV neutrino in an IBEC measurement (Žlimen *et al.*, 1991). This isotope has a 1s-capture endpoint of 229 keV (measured by this experiment) and a half-life of 11.2 days. A 10 mCi source of ^{71}Ge was produced by the (n,γ) reaction and chemically separated to less than 0.1 ppm impurities. The final GeO_2 source was 3 mm thick and covered by a 0.6-mm-thick Plexiglas window. The source was counted using a 47-mm-diameter, 36.5-mm-thick commercial HPGe detector for a total of eight days. Great pains were taken to determine the detector response function and efficiency over a wide range of energies. Sources of ^{57}Co, ^{133}Ba, ^{137}Cs, ^{241}Am, ^{60}Co, and ^{152}Eu were counted in the same geometry and fit to a twelve-parameter response function. These parameters were then interpolated to obtain a continuous, energy-dependent photon response function.

The photopeak efficiency was fit to a three-parameter function. Furthermore, a quadratic polynomial was included to correct the shape of the experimental spectrum using the IBEC data above the 17 keV kink energy (202 keV). The complete data set had relatively low statistics (7×10^4 counts/keV at 202 keV). The best fit to the theory yielded m_2=17.2 $\pm$ 0.7 keV and $\sin^2\theta$=1.6 $\pm$ 0.5%. The data/theory (normalized above the kink position) is shown in Figure 19.

Later in 1991, two groups reported results from IBEC experiments that favored neutrino masses other than 17 keV. The LBL group studied the ^{55}Fe spectrum and found a preference for a 21 keV neutrino with a mixing of 0.85% in fits to the data (Norman *et al.*, 1991). However they pointed out that the kink position was strongly dependent on parameters used in their efficiency function, which was determined from test source data. A group in Buenos Aires found a best fit of 14 keV for a massive neutrino in the initial analysis of their ^{71}Ge spectrum (DiGregorio *et al.*, 1991). This result was later retracted.

E. Gas Detectors

Some attempts were made to search for the 17 keV neutrino signal using gas proportional detectors to collect beta decay spectra. The energy resolution of such a detector will be worse compared to a magnetic spectrometer or solid-state detector, but the systematic issues are different and so it is attractive as an independent approach. Baran and Kalbfleisch (1991, 1992, 1993) used a 0.13 m^3 cylindrical chamber with a single 50-μm-diameter Au-plated tungsten wire along its axis. The chamber was filled with P10 gas doped with tritium at 0.5 atm. The maximum range of a tritium beta in this environment is less than 2 cm, so the full energy was collected for most events. The measured energy resolution was 32% FWHM at 1.5 keV. Tritium absorbed on the chamber wall produced a large low-energy background (36% at 1 keV) that had to be subtracted, weakening the experiment's sensitivity to a low energy spectral distortion. The authors claimed an upper limit on the mixing of a 17 keV neutrino of $\sin^2\theta < 0.4\%$ (99% C.L.). Kuzminov and Osetrova (1991,1992) constructed a

1083 cm^3 multiwire proportional counter with an active guard ring to veto events on or near the wall. It was filled with a Xe-CO_2 mixture doped with ^{14}C and operated at a pressure of 5–10 atm. Unfortunately, the shape of the experimental beta spectrum near the endpoint was distorted by systematic effects and the authors were unable to establish a result regarding the 17 keV neutrino.

IV. AN EXPERIMENTAL CONTROVERSY

A. Summary of Experiments through 1991

By the end of 1991 the 17 keV neutrino had attracted a great deal of attention and the experimental controversy was at its height. A summary of the experiments is given in Table I. The numbers of positive and negative results were comparable; although the negative camp comprised ten different groups around the world, while Simpson and Hime accounted for most of the affirmative side. An important exception was the unexpected result in ^{14}C from LBL, which caused many skeptics to take the prospect of a 17 keV neutrino more seriously. A world average of the positive experiments, weighted by their reported uncertainties, gives m_2=16.95 keV and $\sin^2\theta$=0.93%. A fit of these points to the average yields a χ^2_ν of 0.17 for the mass and 1.48 for the mixing, remarkably good agreement considering the variety of techniques and isotopes used. This consistency was probably the strongest argument in support of the heavy neutrino. At the time it seemed unlikely that all of these experiments were wrong for completely different reasons.

Simpson, Hime, and other supporters argued quite effectively that several of the negative experiments were weakened by systematic problems (Princeton, ITEP, Caltech, and INS Tokyo) and some lacked the statistical sensitivity to rule out their result (Bombay, ISOLDE, and Zagreb ^{55}Fe). Simpson went so far as to reinterpret two of them as actually supporting the 17 keV neutrino (ITEP and INS Tokyo). Yet, many observers felt that so many groups failing to see the effect was sufficient cause for doubt. It was notable that the magnetic spectrometer experiments were unanimously negative, while the positive results were all obtained using silicon and germanium detectors. This suggested that some common solid-state effect may be mimicking a heavy neutrino signal; although it was difficult to conceive of a single phenomenon that could be responsible considering the different isotopes and techniques used.

One of the key issues at this stage was the use of arbitrary functions as shape corrections

to improve the quality of fits, required by all but one of the magnetic spectrometer experiments. At first some authors claimed that because a massive neutrino produces a kink in the spectrum, use of a smooth correction function in the analysis would not reduce their sensitivity to the effect. The presence or absence of a kink would still be apparent. Simpson and others later pointed out that this is not necessarily true. When a wide-range portion of a beta energy spectrum is fit to the theoretical spectrum, most of the statistical sensitivity to the massive neutrino shape factor S(E) comes from its overall shape rather than the local effect of the kink itself. This is best illustrated by considering the beta spectrum Kurie plot. Figure 20(a) shows the Kurie plot of a beta spectrum that contains a massive neutrino component (the shape has been greatly exaggerated for clarity). The slope above and below the kink are different. The best fit (minimum χ^2) Kurie plot without a massive neutrino is shown with no shape correction (dashed line), and a quadratic shape correction with coefficients determined from the fit (solid line). This shape correction accommodates much of the difference in slope, reducing sensitivity to the massive neutrino shape (Figure 20(b)). When a neutrino admixture of only 1% is considered, the difference is crucial.

Now, if the assummed form of the shape correction is actually the correct one, and its parameters are varied freely in the fit along with the neutrino mass and mixing (as was done in most of these experiments), then this loss of sensitivity will be manifested as a broadening of the χ^2 distribution and properly accounted for. However there is a systematic uncertainty in making that assumption. While a good fit may be obtained by using a low-order polynomial correction, deviation of the actual shape correction from this assummed form may correlate with the massive neutrino shape and further reduce the experiment's sensitivity. The only defense against this is to limit these shape corrections to be smaller than the 1% effect in question; or better yet not use them at all. Simpson and Hime (1989) and Hime (1991) discussed quantitative criteria for limiting the size of these shape corrections. This issue was later treated in detail by Bonvincini (1993), who also performed a series of Monte Carlo studies simulating several of the experiments. He showed that the presence of a distortion and the use of a polynomial correction function often caused the analysis to

miss the presence of a neutrino kink.

A related and even more important problem was that in those experiments where a shape correction was not needed to improve the fit (including the solid-state detector experiments), the presence of a smooth but unknown distortion in the data could correlate with the shape of S(E), and cause an apparent massive neutrino shape to be either created or hidden. This can also be seen in Figure 20. Suppose the experimental spectrum contains a distortion to begin with due to energy loss, scattering, detector inefficiency, or some other uncorrected systematic effect. When a massive neutrino component is allowed in the fit, and the χ^2 is minimized, the fit values of m_2 and $\sin^2\theta$ will deviate from the true values to best accommodate the distortion, yielding a statistically significant yet incorrect result. This concern put all of the above experiments into question, since they all used a wide range fit but none had convincingly demonstrated that system response and efficiencies were understood at the 1% level. A good way to address this issue would be to generate an experimental spectrum that deliberately contains a distortion similar to a 1% massive neutrino shape, and show that one's apparatus and analysis can find it. Some examples of this approach are discussed in Section V.

It was generally agreed that the controversy could be resolved only by more and improved experiments. New magnetic spectrometer experiments would have to assiduously identify and explore the systematic effects responsible for spectral distortions to obviate the need for arbitrary shape corrections. A major issue in all of the magnetic spectrometer experiments concerns how one determines the number of betas transmitted through the spectrometer at each field setting. In these experiments, the detector placed at the spectrometer focus is, in principle, simply meant to be a counter—recording with equal efficiency all betas that reach it. However the spectrum of events observed in the silicon detector or gas proportional counter used in these experiments inevitably contains a peak and a continuous tail extending down to zero energy. The peak corresponds to those events where the full energy of the beta (minus any loss in windows or other inactive material) is recorded. The tail results from backscattering of betas off the counter in which some but not all the energy is deposited.

The detector also has instrumental noise which effectively limits how low in energy one can actually look. Thus one is faced with the problem of how to integrate this spectrum in a consistent and energy-independent manner. In none of these experiments was the overall response function or efficiency of the apparatus over the range of energies fitted in their analysis actually measured. Various schemes, aided by the results of Monte Carlo calculations, were employed in analyzing the results of these early experiments. The fact that all but one of these experiments still required the use of arbitrary shape factors in order to get satisfactory fits to their data, may at least be partially due to the difficulty in integrating such spectra properly.

To a large extent this issue can be avoided by taking a very narrow energy scan, where systematic problems associated with energy variation would be expected to be small. However, one is then faced with the need for very high statistics in order to see a local distortion, i.e a neutrino kink. The Chalk River ^{63}Ni experiment did do this and in retrospect their analysis is convincing, but they lacked the statistical power to overcome concerns about systematic effects that were prevalent at the time of the first generation experiments.

For solid-state experiments employing external beta sources the dominant systematic problem is scattering. It causes a low-energy tail in the experimental response and will result in a spectral distortion if not properly measured and corrected for. Scattering in the source can be minimized by using the thinnest possible source and backing material. Besides the technical difficulty of preparing a uniform, thin source, this approach must be weighed against the need for a sufficiently strong sample to obtain adequate statistics. Backscattering of betas from solid-state detectors has been widely studied (see for example Planskoy, 1968; Tabata *et al.*, 1971; Damkjaer, 1982). The size and shape of this effect has a small but significant energy dependence. All of the relevant 17 keV neutrino experiments to this point in time had measured this backscatter tail using only one or two conversion electron line sources and assumed it was constant with energy. This was a potential source of distortion. In fact, Hykawy *et al.* (1993) showed, using Monte Carlo tests, that neglecting the energy dependence of backscattering can lead to a distortion that mimics a massive neutrino shape.

Use of collimators between source and detector simplify, but don't eliminate the need for, a thorough understanding of detector backscattering. Materials surrounding the source and detector are a third site for scattering which must be accounted for. Further experiments using external solid-state beta detectors would have to study the shape and energy-dependence of these effects using as many electron line sources as possible that bracket the energy range of interest.

Three of the experiments used beta sources internal to a solid-state detector. Ideally, the energy collection is complete for each decay and an unadulterated beta spectrum should result. However the response of a solid-state detector using internal electron line sources was never studied. This would be important to make experiments of this type more convincing.

B. Theoretical Consequences

The possible existence of a 17 keV mass neutrino was very difficult to reconcile with the Standard Model of particle physics, astrophysical theory and observation, and other experimental results. In the simplest picture, the 17 keV mass state is subdominant in ν_e and dominant in ν_μ or ν_τ:

$$|\nu_{17\,\mathrm{keV}}\rangle = \sin\theta|\nu_e\rangle + \cos\theta|\nu_{\mu(\tau)}\rangle \tag{14}$$

Experimental searches for $\nu_\mu \rightarrow \nu_e$ oscillations put a strict limit on mixing in the large Δm^2 regime: $\sin^2\theta < 3.4\times10^{-3}$ (Ahrens *et al.*, 1985), so the dominant flavor would have to be ν_τ. The best upper limit from an oscillation experiment sensitive to $\nu_e \rightarrow \nu_\tau$ gave $\sin^2\theta < 0.017$ (Erriquez *et al.*, 1981), tantalizingly close to Simpson's neutrino but unable to rule it out.

Limits on the Dirac/Majorana nature of a 17 keV neutrino were investigated. An astrophysical limit on the Dirac mass can be obtained based on the observed cooling rate of SN 1987A. Weak scattering inside the dense supernova would cause a significant fraction of trapped Dirac neutrinos to flip helicity into their "sterile" right-handed counterparts, which would then quickly escape, accelerating the cooling process. With conservative assumptions

the limit is $m_{\nu,\mathrm{Dirac}}$ <30 keV (Burrows *et al.*, 1992), so again the 17 keV neutrino was not quite excluded. Strict limits on a possible Majorana neutrino mass can be deduced from searches for neutrinoless double-beta decay ($\beta\beta_{0\nu}$), where the nucleus acquires two units of charge and emits two betas with no neutrinos in the final state. This process can occur only through a virtual Majorana neutrino (see Doi *et al.*, 1985 for a thorough review). Experimental searches for this process have led to an upper limit of order 1 eV for the Majorana mass, so the 17 keV neutrino could not be a simple Majorana neutrino. However this limit can be evaded by models that contain two Majorana neutrinos with degenerate mass, forming a so-called pseudo-Dirac neutrino. If they possess opposite CP eigenvalues their amplitudes for $\beta\beta_{0\nu}$ will cancel (Dugan *et al.*, 1985; Valle, 1985). This approach in turn causes trouble for those who wish to explain the apparent solar neutrino deficit by invoking MSW oscillation (Mikheyev and Smirnov, 1986; Wolfenstein, 1979), which requires a mass splitting of $\Delta m^2 \sim 10^{-5}$ eV^2 between ν_e and ν_μ or ν_τ. Measurements of the width of the Z resonance at LEP excluded a fourth light sequential neutrino. A tidy solution was suggested by Glashow (1991) who proposed a 6×6 neutrino mass matrix containing a rank two Majorana submatrix. The mass eigenvectors consist of two light Majorana neutrinos (ν_e and ν_μ) with a small mass splitting suitable for MSW oscillation, a much heavier, e.g. 17 keV, pseudo-Dirac neutrino (ν_τ), and two unobservable super-heavy neutrinos.

The greatest theoretical challenges to a 17 keV neutrino came from cosmology and astrophysics. Neutrinos are readily produced in nuclear processes and once made they have a tiny probability for interaction or annihilation. They were created in great quantity during the big bang, and many astronomical objects such as stars and supernovae are copious neutrino sources. This makes them the most abundant type of matter in the universe. Even with a tiny mass they could dominate the mass density of the universe. Big-bang relic 17 keV neutrinos would have collapsed the universe a long time ago, so they would have to be unstable with a lifetime $\tau < 10^{13}$ s, or rapidly annihilate each other in the early universe (Kolb and Turner, 1991). Radiative decay ($\nu_2 \rightarrow \nu_1\gamma$) was ruled out because it would produce effects in the present cosmic photon spectrum that are not observed. Pure neutrino

decay ($\nu_2 \rightarrow 3\nu$) of sufficient rate requires flavor-changing neutral currents that lead back to radiative decay of the heavy neutrino (Gronau and Yahalom, 1984). The most plausible scenarios had the 17 keV neutrino decay to a Goldstone boson, such as the Majoron that results from breaking lepton number conservation. These too were fraught with astrophysical constraints (Gelmini *et al.*, 1991). It was clear that if the 17 keV neutrino were real it would have bizarre properties and profound consequences for theoretical physics.

It is a tribute to theoretical ingenuity that in spite of all these troubles a number of viable, if somewhat contrived, models for the 17 keV neutrino were developed. See Hime *et al.* (1991), Gelmini *et al.* (1991), Smirnov and Valle (1992) and Nelson (1992) for interesting discussions of some of these models. Although the theoretical debate over the 17 keV neutrino was fascinating, the question of its existence remained an experimental issue. In the summary talk at the Workshop on the 17 keV Neutrino Question convened in Berkeley in December 1991, Bernard Sadoulet concluded, "The 17 keV neutrino may not exist, but it will not be because it cannot exist."

V. SECOND GENERATION EXPERIMENTS

In the summer of 1992 three new experiments were reported that each presented strong evidence against the 17 keV neutrino. A study of the ^{63}Ni beta spectrum using the iron-free $\pi\sqrt{2}$ magnetic spectrometer was conducted at INS Tokyo (Kawakami *et al.*, 1992; Oshima *et al.*, 1993). This effort was similar in design to the Chalk River ^{63}Ni experiment. The detector consisted of an array of 30 single-cell proportional counters mounted at the focal plane. The source (50 μg/cm^2 Ni), source backing (1300 μg/cm^2 Ni), and detector window (200 μg/cm^2 polyester) were quite thick, causing a large tail in the response function, which was determined using a single calibration line (K-conversion line from ^{109}Cd) measured in the same geometry. The ^{109}Cd activity was mixed together with stable nickel to produce a source of the same thickness and composition as the ^{63}Ni source.

The strength of this experiment came from its extremely high statistics: 1.1×10^8 counts/keV at the kink position (50 keV) were collected; about 50–100 times that of the first generation experiments. Typical counting rates during data acquisition were approximately 40 s^{-1} per cell near at 50 keV. With this statistical sample they were able to fit a narrow energy region (40–60 keV) and obtain sensitivity to the detailed shape of the kink. Variations in beta transmission through the counter window and in counting losses due to the discriminator threshold necessitated the use of a small linear shape correction factor in fitting the data. This factor produced a variation of $< 0.1\%$ over the energy scan. In addition to a traditional fit, they also performed a local search for a kink by comparing the relative normalizations determined from fits to their data above and below 50 keV. Neither analysis showed evidence for structures in the beta spectrum of ^{63}Ni. A 1% 17 keV neutrino was clearly absent in the data, as seen in Figure 21. The group quoted an upper limit of $\sin^2\theta < 0.073\%$ (95% CL) for a 17 keV neutrino.

An elegant experiment was performed at Argonne National Laboratory. Mortara *et al.* (1993) studied the beta spectrum of ^{35}S using a Si(Li) detector and an external source placed inside a superconducting solenoidal magnet. This was similar to the Hime and

Jelley experiment, however the magnetic field provided three significant improvements: the betas were focused onto the detector, increasing the acceptance and allowing the use of a weak, thin source; normal incidence was achieved without physical collimators, eliminating scattering problems; and betas backscattering out of the detector were reflected back in by the magnetic field, reducing the low energy tail in the response function. The last effect was achieved by shaping the axial field to form a magnetic mirror. The apparatus is shown in Figure 22.

The ^{35}S source ($10^{-4}\mu g/cm^2$), and source backing ($20\mu g/cm^2$) were very thin. Conversion electron lines from ^{139}Ce at 127, 160, and 165 keV were used to measure the detector response function. These energies bracket the region of interest unlike the ^{109}Cd and ^{57}Co lines used by Hime and Jelley. The backscatter fraction was determined to be less than 7%, and the shape of the backscatter tail was measured using the conversion lines and Monte Carlo simulation. The effect of energy loss in the detector dead layer was interpolated empirically from the conversion line data.

The data were fit to the theoretical shape in the energy region 120–170 keV and found to be consistent with no 17 keV neutrino. The data/fit are shown in Figure 23(a). The authors reported an upper limit on the mixing of $\sin^2\theta$ <0.19% (95% C.L.). In order to demonstrate sensitivity to the effect, a second ^{35}S source was made that was mixed with a small admixture of ^{14}C, which has an endpoint of 156 keV. The ^{14}C created a distortion in the spectrum with a size and shape similar to that of the 17 keV neutrino. When the data were analyzed the ^{14}C contamination was seen at the correct level (Figure 23(b)).

The Berkeley group that found the positive result in ^{14}C reported a new result from a high statistics study of the ^{55}Fe IBEC spectrum (Wietfeldt *et al.*, 1993). They used a Compton-suppressed HPGe detector to measure the IBEC photon spectrum from a chemically purified 25 mCi source over a period of six months. A total of 1.13×10^7 counts/keV at the expected kink position were collected. Background and impurity spectra were measured separately and subtracted. Instead of analyzing a large portion of the spectrum, which is susceptible to systematic distortions, they looked for the presence of a slope discontinuity near the

endpoint of the spectrum by taking its second numerical derivative. Figures 24(a,b) show the second derivatives of Monte Carlo spectra generated with and without a 1% 17 keV neutrino. The kink is seen as a peak at 208 keV. Figures 24(c,d) show the second derivatives of the experimental ^{55}Fe data before and after background subtraction. There is no sign of a massive neutrino kink.

In a separate analysis, narrow portions of the data were fit to an arbitrary third-order polynomial multiplied by the massive neutrino shape factor $S(E)$. In each fit the values of m_2 and $\sin^2\theta$ were fixed and the coefficients of the polynomial were varied freely to minimize χ^2. This test was sensitive to the presence of a slope discontinuity in the spectrum but relatively insensitive to smooth distortions caused by experimental systematics, which are easily accommodated by the polynomial. Figures 25(a,b) show the contours of minimum χ^2 for fits to Monte Carlo data with and without a 1% 17 keV neutrino, in the energy region 200–220 keV. Figure 25(c) shows a similar plot for fits to the actual ^{55}Fe data in the same region. An upper limit of 0.14% (95% C.L.) for a 17 keV neutrino was established (Wietfeldt, 1994).

Unlike all of the first generation efforts listed in Table I, these three experiments were able to convincingly demonstrate sensitivity to the small distortion caused by a 1% 17 keV neutrino, and its final demise seemed certain. In 1992–94 a number of additional experimental results were reported, all finding no evidence for the 17 keV neutrino. Some of these were improvements on previous experiments. Chen *et al* (1992) reported the results of a second ^{35}S experiment performed at Caltech using the same spectrometer employed by Markey and Boehm. They prepared 3 mCi (0.8 μg/cm^2) and 7 mCi (2.1 μg/cm^2) sources of ^{35}S by reacting ammonium sulfate with a barium substrate. Unlike the earlier Caltech experiment, the activities of these sources were observed to decay with a half-life consistent with the known value for ^{35}S. The spectrometer was calibrated using a 100 μCi ^{57}Co source deposited on a 0.9-μm-thick mylar backing. Beta particles transported by the spectrometer were detected using a 4-mm x 25-mm x 300-μm thick Si detector cooled to 5°C by a Peltier cooler.

In order to determine the number of betas transported at each field setting, the spectrum observed in the Si detector was integrated from the full-energy peak down to a point corresponding to 20% of the full energy. This included 98% of the total counts in the spectrum at each field setting. It was claimed that the fraction of events missed by this technique varied by less that 0.3% over the energy range of interest. Two sets of data were accumulated: a wide range scan from 131–164 keV, and a narrow scan from 146–156 keV. Analysis of the wide-scan data showed the need for both linear and quadratic shape factors, which is curious since an even wider region (110–166 keV) was fit in the original experiment (Markey and Boehm, 1985) and no such corrections were required. The narrow scan data required only a linear shape factor. Again, no evidence of heavy neutrino emission was observed, and an upper limit of 0.20% (90% C.L.) was established on the 17 keV neutrino admixture. Figure 26 shows the residuals from fits with and without a 0.85% 17 keV neutrino.

The authors attempted to demonstrate that this experiment was sensitive to small distortions in the beta spectrum by generating an artificial distortion in their ^{35}S spectrum. A 17-μm-thick aluminum foil was placed over approximately 10% of the source area. For 150-keV electrons, the minimum energy loss in such a foil is 14 keV. Through energy loss and scattering in this foil, a feature roughly similar to that caused by a 1% admixture of a heavy neutrino was produced. A plot of the residuals from the fit to this spectrum is shown in Figure 27.

Berman *et al.* (1993) reported the results of a second ^{35}S experiment performed at the Princeton University spectrometer. For this experiment, a 15-μCi source was prepared by implanting ^{35}S into a 138 μg/cm^2 mylar substrate. The spectrometer was calibrated using sources of ^{111}In implanted in similar mylar substrates. The beta particles were detected in a 500-μm-thick PIN diode at the focus that was operated at room temperature. Once again, in order to determine the number of beta particles transported at each spectrometer setting, the energy spectrum observed in the PIN diode was integrated from the full-energy peak down to zero energy. In this experiment the procedure was complicated by the fact that the noise peak of the PIN diode extended up to 13 keV. A Monte Carlo calculation was

performed to estimate the fraction of counts lost below the noise peak as a function of beta energy. A correction factor of the form $(1 + a/E^2)$, where E is the beta energy and a is a coefficient varied in the fits, was included to correct for backscattering in the source. An additional shape correction, linear in the beta energy, was included to accommodate a 0.8% systematic variation in the shape of the energy spectrum. Figure 28 shows the data/fit in the energy range 40–160 keV. The authors report that a 0.84% 17 keV neutrino was excluded at the 5σ level.

The group at Buenos Aires, who had earlier reported evidence for a 14 keV neutrino in the ^{71}Ge IBEC spectrum, reanalyzed the data from their experiment (DiGregorio *et al.*, 1993). This time they allowed the relative strength of p-wave to s-wave electron capture to vary as a free parameter in the fitting procedure. In the best fit this relative strength was changed by 4% of the theoretical prediction (Intemann, 1971), a discrepancy consistent with other experimental results (Bambynek *et al.*, 1977). The best fit value for a heavy neutrino mass was still about 14 keV, but its statistical significance was now much less. The chi-squared contours in the parameter space of neutrino mass and mixing are shown in Figure 29. The positive result of Žlimen *et al.* (1991) was excluded at a confidence level of 99%.

Holzschuh and Kündig (1993) of the Physik-Institut der Universität Zürich collected a high-statistics spectrum of the beta spectrum of ^{63}Ni using a magnetic spectrometer. With 3.8×10^7 counts per keV at 17 keV below the endpoint, they performed a narrow scan and were able to rule out a 1% 17 keV neutrino at the 15σ level. Abele *et al.* (1993) measured the ^{35}S beta spectrum using back-to-back Si surface barrier detectors inside a superconducting solenoid with a 7 Tesla magnetic field. Figure 30 depicts the apparatus, which was based on the design of the PERKEO neutron decay experiment (Bopp *et al.*, 1988), and was similar in philosophy to the Argonne ^{35}S experiment (Mortara *et al.*, 1993). The magnetic field provided an acceptance of 4π for betas emitted from a source in the center of the solenoid. Betas that backscattered from one detector were either reflected back into it or transported to the opposite detector by the magnetic field. The source and source

backing were extremely thin (5 μg/cm^2). Internal conversion lines from ^{139}Ce and ^{114m}In were used to measure the electron response function. Analysis of the collected spectra gave an upper limit of $\sin^2\theta < 0.19\%$ (90% C.L.). In addition, the authors found that if they neglected to suppress the betas backscattered from one of the detectors, a kink-like structure was produced in the opposite detector that could be well represented by a massive neutrino admixture, although the necessary neutrino mass was 33 keV. This is shown in Figure 31.

A study of the IBEC spectrum of ^{125}I was reported by a group at Tennessee Technological University (Hindi *et al.*, 1994). This experiment had a much larger statistical sample than the earlier work of Borge *et al.* (1986). A 2 cm^3 planar Ge detector was used to collect a total of 1.2×10^6 counts/keV at 17 keV below the $2p$ endpoint (128 keV). A search for the presence of a massive neutrino kink in the $2p$ and $3p$ spectra gave an upper limit of $\sin^2\theta < 0.4\%$ for a 17 keV neutrino.

A summary of the second generation 17 keV neutrino experiments (1992–1994) is presented in Table II. A world summary of all the results and limits on the mixing of a 17 keV neutrino is shown in Figure 32. The evidence against the existence of a 17 keV neutrino was convincing. The only task that remained was to understand the cause(s) for the positive results.

VI. EXPLAINING THE POSITIVE RESULTS

After a great deal of experimental effort the 17 keV neutrino was finally shown to be nonexistent. The fact remains however that seven different experiments, at four different institutions, using five different isotopes, found evidence for a 17 keV neutrino with a mixing of about 1%. The problem cannot be put to rest until we have some understanding of how this occurred. Fortunately the investigators responsible for positive results have since worked very hard to explain what happened. Initially there was hope that a common answer would be found, but eventually it became clear that each of these experiments would require a separate explanation.

Simpson has continued to examine the low energy spectral excess that he observed in the two implanted tritium experiments, but he has not found its cause. The original tritium-implanted Si(Li) experiment had problems with low-energy calibration and possible implantation defects and can perhaps be discounted. The later tritium-implanted Ge detector experiment overcame these problems and its result is still quite convincing. Unfortunately the detector has since sustained some damage which has hindered additional tests. It is interesting that Conway and Johnson (1959) saw a similar spectral excess in tritium using a proportional chamber, although they did not consider a massive neutrino hypothesis. The possibility remains that the effect in tritium is real, but is not caused by a 17 keV neutrino. Alternatively, it may be due to some environmental effect in silicon and germanium. Koonin has suggested a model for such an effect (1991), but this particular model is not supported by Simpson's tritium spectrum (Simpson, 1994). Recent experiments have studied the tritium beta spectrum at low energy using a gas proportional chamber (Baran and Kalbfleisch, 1992, 1993) and a magnetic spectrometer (Decman and Stoeffl, 1993). The former required a large background subtraction at low energy and the latter saw a huge low-energy divergence attributed to auto-ionization of the decay daughter, so unfortunately neither could convincingly exclude the 1% divergence observed by Simpson and Hime. We can hope that additional work will settle this matter for the case of tritium.

A lot of effort has been spent to explain the results of the Guelph and Oxford ^{35}S and ^{63}Ni experiments. Piilonen and Abashian (1992) conducted a Monte Carlo simulation of the Oxford apparatus that indicated a similarity between the 17 keV neutrino effect and the effect of betas scattering from the intermediate aluminum baffle into the detector (see Figure 16). This type of scattering had been neglected by Hime and Jelley in the analysis, since the baffle was quite thin (0.8 mm). Hime later performed his own Monte Carlo study and reproduced their result (Hime, 1993). Figure 33 shows the relative sizes and shapes, determined by Monte Carlo using a monoenergetic 100 keV electron source, of the low energy tail contributions caused by backscattering in the detector, energy loss in the detector dead layer, backscattering from the source substrate, penetration through the aluminum aperture in front of the detector, and scattering from the baffle. The sizes of the first and last of these were found to be independent of the initial energy, while that of the others varied with energy. The tail due to baffle scattering contains about 1.2% of the full-energy peak. It has a maximum at about 94% of the full energy, which is in the vicinity of the 17 keV neutrino kink at 90% of the endpoint energy. When the baffle scattering effect was included in a reanalysis of the Oxford ^{35}S data, the spectra could be fit using a single massless neutrino, and an upper limit of $\sin^2\theta < 0.35\%$ (90% C.L.) for a 17 keV neutrino was obtained. It certainly seems plausible that this effect could account for the 17 keV neutrino result in the Oxford ^{35}S experiment. It is difficult to believe however that this effect could have caused the same result in ^{63}Ni, where the 17 keV neutrino kink occurs at 75% of the endpoint energy. The ^{35}S experiment at Guelph had a much different geometry (Figure 10). In that case there was no intermediate baffle, so baffle scattering could hardly have been responsible for that result.

Meanwhile, Bowler and Jelley (1994,1995) have repeated the Oxford ^{35}S experiment using the original apparatus. In some of these runs a chamfered intermediate baffle was used in place of the original square-cut baffle. They found that scattering from this baffle was at most a minor contribution to the 17 keV neutrino effect. Instead they attribute the effect to energy losses in the chemically adsorbed $BaSO_4$ sources. When the effective source

thickness was allowed to vary in the fits the presence of a 17 keV neutrino was ruled out. This conclusion was supported by a proton microprobe study and a measurement of the Ba fluorescence x rays, which showed the sources to inhomogeneous and about 10^4 times thicker than originally believed. Hime had originally suggested and performed the x ray measurement although he concluded from it that the sources were much thinner (Hime, 1991). The sources used in the Guelph experiment were prepared in a similar way so it is possible, although it has not been demonstrated, that excessively thick sources could explain that result as well.

The group at Berkeley have continued tests of their ^{14}C-doped germanium detector. They found two significant features in its behavior that were not anticipated in the original analysis (Wietfeldt, 1994; Wietfeldt *et al.*, 1995). First, by scanning the detector with a highly collimated gamma ray source, they determined that ionization charge originating under the groove in the n^+ contact (see Figure 14) has a high probability for splitting between the center detector and guard ring. Second, by studying the two-dimensional energy spectrum of center-guard ring coincidences, they found that the carbon was not uniformly dissolved in the germanium crystal. Instead it is concentrated into clusters of about 10^{10} atoms, too small to be seen in the autoradiograph tests. In the original experiment the guard ring veto threshold was 20 keV, so for each ^{14}C decay under the groove where the guard ring collected less than 20 keV of equivalent charge, the portion of the charge collected in the center detector was inadvertently recorded as a good event. This represented an undesirable contamination in the spectrum. The shape of this "contamination" spectrum was affected by the spatial distribution of carbon clusters under the groove. It was measured and is shown in Figure 34(a). It resembles a beta spectrum with an endpoint energy of approximately 140 keV, about 17 keV below the ^{14}C endpoint. The ratio of the ^{14}C beta spectrum including this contamination to the spectrum with the contamination subtracted is shown in Figure 34(b). It is consistent with the size of the observed 17 keV neutrino effect. With this contamination removed, analysis of the ^{14}C beta spectrum no longer favored the presence of a 17 keV neutrino.

The single positive IBEC experiment from Zagreb has not yet been explained. It had relatively low statistics, and one can imagine that uncertainties in the complicated detector response function and the theoretical spectrum could have produced distortions that caused the fit to prefer a massive neutrino signal. The fact that other IBEC experiments saw evidence for 14 and 21 keV neutrinos gives support to this possibility.

VII. CONCLUSIONS

The 17 keV neutrino story represents a classic Hegelian dialectic. Simpson's initial report of the phenomenon in 1985 met with considerable skepticism (the thesis). After all, a 17 keV neutrino was completely unexpected, the experimental evidence favoring it was weak, and there seemed to be no theoretical basis for its existence. It was followed swiftly by negative experimental reports. A few years later, when new, more convincing positive results began to appear, it was generally realized that the initial reaction was premature. The field entered an antithetical period. The protagonists argued effectively that the early negative experiments were inconclusive. The theoretical community began to take it seriously and viable models for a 17 keV neutrino were discussed. Experimental reports on both sides were in direct conflict. Finally, the issues of experimental systematics and sensitivity were sorted out, and a new generation of experiments appeared that were able to conclusively rule out a 1% 17 keV neutrino. This was the synthesis. The 17 keV neutrino does not exist, but by studying the question of its existence we learned a lot about how to do these kinds of experiments correctly. In addition the entire subject of neutrino mass and mixing was stimulated, which led to a development of theoretical ideas that may be very useful in the future.

The 17 keV neutrino experiments taught how easily a systematic effect can masquerade as the signature for a new physical process. Obtaining a good χ^2 fit with the experimental spectral shape is not sufficient; a convincing experiment must independently demonstrate its sensitivity to the effect in question. Seemingly negligible influences on the spectrum must not be taken for granted. A fundamental problem in all of the positive experiments was a high sensitivity to the detailed shape of the energy response of the apparatus, and the failure to measure this response function in the energy region analyzed. In the Guelph and Oxford ^{35}S experiments the response was measured at low energies (63–129 keV) and extrapolated to the region of interest (120–170 keV). If higher energy electron lines had been used (e.g. ^{139}Ce, used by the Caltech and Argonne ^{35}S experiments) then anomalies in the response might have been noticed early in the experiment. The same point can be

made about the Oxford ^{63}Ni experiment, which used the single K-conversion line of ^{109}Cd at 61 keV to measure the response function for the energy region 30–62 keV. In Simpson's two tritium experiments and the LBL ^{14}C experiment, the beta response functions weren't measured at all, they were estimated using seemingly reasonable arguments. This was later shown to be woefully inadequate for the ^{14}C-doped detector. The lesson here is that an experimental response function should be measured at as many energies as possible, under the identical conditions as the beta spectrum, and bracket the energy range being fit. The more successful of the second generation experiments either measured the response function correctly (e.g. Argonne ^{35}S) or designed the experiment to be insensitive to the response function (e.g. INS ^{63}Ni and LBL ^{55}Fe). Future efforts that use precision spectroscopy to probe fundamental physics will benefit tremendously from this experience.

It seems an extraordinary coincidence that, within a span of six years, seven different experiments at four different institutions each saw evidence for a 1% 17 keV neutrino for different reasons. If one considers the entire parameter space for neutrino mass and mixing, such a coincidence is inconceivable. Due to practical limitations however, the whole parameter space was not available to these experiments. The positive experiments all used roughly similar methods and had similar levels of statistics, even though the isotopes and apparatus designs were different. One might estimate the relevant parameter space to be about $5 < m_2 < 25$ keV and $0.005 < \sin^2\theta < 0.03$. If an experiment of this type is going to mistake a systematic distortion for a massive neutrino admixture, the parameters should fall within these ranges. The experiment will not be sensitive to a very small mass or mixing, and it can distinguish a sufficiently large mass or mixing from a systematic effect. With this in mind, the likelihood of this coincidence is small but not prohibitive.

We must also consider that subtle psychological effects may have played a role in this story. Scientists are human, and despite their best intentions and almost instinctively skeptical nature, they can be unknowingly influenced by social or subconscious pressures. For example, there is probably a tendency to make an experimental result public more quickly if it corroborates a previously reported result. One is more hesitant to go public if the result is

something completely new, allowing more time to study the analysis and systematics. This may tend to bias a group of experiments toward agreement. Once Simpson announced that he had seen evidence of a 17-keV neutrino, a barrier of sorts was reduced. If one then went out and found a similar effect, it was easier to believe it was real and not the result of instrumental effects. As more positive results were reported, the this barrier became even smaller. As a result, some of these experiments may not have undergone the internal scrutiny they otherwise might have. This tendency is compounded by the fact that a positive result is inherently more exciting than a negative one, another possible source of subconcious bias.

In conclusion, we believe that active researchers can learn a great deal from the story of the 17 keV neutrino; and we predict it will be a conspicuous subject for both scientists and historians of science in the years to come. Previous reviews of the 17 keV neutrino can be found in Hime (1992,1993b). and Morrison (1993).

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[a]Present address: NIST, Gaithersburg, MD 20899.

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TABLES

TABLE I. 17 keV neutrino results as of December 1991 (see text for references).

Group	Method	Isotope	m_2(keV)[a]	$\sin^2\theta$(%)[a]
Positive:				
Guelph	Int. Si(Li)	^{3}H	17.1 ± 0.2	2–4[b]
	Ext. Si(Li)	^{35}S	16.9 ± 0.4	0.73 ± 0.11
	Int. Ge	^{3}H	16.9 ± 0.1	0.6–1.6
LBL	Int. Ge	^{14}C	17 ± 2	1.4 ± 0.5
Oxford	Ext. Si(Li)	^{35}S	17.0 ± 0.4	0.8 ± 0.08
	Ext. Si(Li)	^{63}Ni	16.8 ± 0.4	1.0 ± 0.2
Zagreb	IBEC	^{71}Ge	17.2 ± 0.7	1.6 ± 0.5
Negative:				
Princeton	Mag. Spec.	^{35}S	17	< 0.4 (99% CL)
ITEP	Mag. Spec.	^{35}S	17	< 0.17 (90% CL)
INS Tokyo	Ext. Si(Li)	^{35}S	17	< 0.15 (90% CL)
Bombay	Ext. Si(Li)	^{35}S	17	< 0.6 (90% CL)
Caltech	Mag. Spec.	^{35}S	17	< 0.3 (90% CL)
ISOLDE	IBEC	^{125}I	17	< 2 (98% CL)
Chalk River	Mag. Spec.	^{63}Ni	17	< 0.3 (90% CL)
Zagreb	IBEC	^{55}Fe	17	< 0.74 (99.7% CL)
ILL Grenoble[c]	Mag. Spec.	^{177}Lu	17	< 0.4 (68% CL)
U. Oklahoma	Int. gas	^{3}H	17	< 0.4 (99% CL)
Other:				
LBL	IBEC	^{55}Fe	21 ± 2	0.85 ± 0.45
Buenos Aires	IBEC	^{71}Ge	13.8 ± 1.8	0.8 ± 0.3

[a]Separately quoted errors have been added in quadrature.

[b]Later reduced to 1.1 ± 0.3

[c]S. Schönert, *et al.* (1991).

TABLE II. Second generation 17 keV neutrino experiments (see text for references).

Group	Method	Isotope	m_2(keV)	$\sin^2\theta$(%)
INS Tokyo	Mag. Spec.	^{63}Ni	17	< 0.073 (95% CL)
Caltech	Mag. Spec.	^{35}S	17	< 0.2 (90% CL)
Argonne	Ext. Si(Li)	^{35}S	17	< 0.2 (95% CL)
Buenos Aires	IBEC	^{71}Ge	17	< 0.5 (95% CL)
Berkeley	IBEC	^{55}Fe	17	< 0.2 (95% CL)
Princeton	Mag Spec.	^{35}S	17	< 0.3 (95% CL)[a]
U. Oklahoma	Int. gas	^{3}H	17	< 0.28 (99% CL)
Zürich	Mag. Spec.	^{63}Ni	17	< 0.15 (95% CL)[a]
ILL Grenoble	Ext. Si	^{35}S	17	< 0.18 (90% CL)
Tenn. Tech	IBEC	^{125}I	17	< 0.4 (90% CL)

[a]Estimated from the reference

FIGURES

FIG. 1. (a) The massive neutrino shape factor $S(E)$ for a beta decay spectrum normalized in the region $E > Q - m_2$. There is a kink (slope discontinuity) at $E = Q - m_2$ and a rising amplitude below that point. (b) The same $S(E)$ with the normalization and Q determined from a least squares fit over the entire energy region shown (the expected experimental shape factor).

FIG. 2. The effect of $S(E)$ on the Kurie plot of a beta spectrum (solid). The slope of each component is different (dashed).

FIG. 3. Data from Simpson (1985), showing the low energy portion of the measured tritium beta spectrum compared to the theoretical massless neutrino spectrum (solid line).

FIG. 4. The experimental ratio $y(E)_{\rm exp}$ of the measured intensity to the theoretical intensity assuming zero-mass neutrinos; from Altzitzoglou *et al* (1985). The solid line through the points is the best fit with a linear plus quadratic function. The dashed line illustrates the best fit for a 17-keV neutrino with $\sin^2\theta = 0.03$.

FIG. 5. Kurie plot of ^{35}S from Apalikov *et al.* (1985). The error bar is shown magnified by a factor of ten.

FIG. 6. Data/fit including a 17 keV neutrino with $\sin^2\theta = 0.03$ from the Chalk River ^{63}Ni experiment (Hetherington *et al.* (1987)). (a) Wide range scan. (b) Narrow range scan.

FIG. 7. Data/fit of ^{35}S from Datar *et al.* (1985). The dashed line indicates a 3% 17-keV neutrino.

FIG. 8. Side view of the source-detector configuration in Ohi *et al.* (1985).

FIG. 9. (a) Data/fit of ^{35}S from Ohi *et al.* (1985). (b) Simpson's reanalysis of the same data showing support for the 17 keV neutrino (normalization taken above 150 keV) (Simpson, 1986b).

FIG. 10. Schematic of the Guelph beta spectrometer (Simpson and Hime, 1989). (a) Acrylic source holder, (b) source, (c) source-holder mount, (d) source manipulator, (e,m,n,q,r) vacuum valves, (f) Si(Li) crystal, (g) cryopanel, (h,j) cold fingers, (i) preamplifier, (k,l) sorption pumps, (o,p) vacuum gauges.

FIG. 11. Combined data/fit from the Guelph ^{35}S experiment: (a) fit with a single massless neutrino ($\chi^2_\nu = 2.0$); (b) fit with a 0.75% 17 keV neutrino component ($\chi^2_\nu = 1.0$).

FIG. 12. ^{57}Co conversion electron spectrum measured with the Guelph beta spectrometer.

FIG. 13. Fractional deviations in the Kurie plot $\Delta K/K$ from the tritium-implanted germanium detector (Hime and Simpson, 1989). Both runs were taken post-annealing. Run C had improved resolution due to a preamp modification.

FIG. 14. Physical dimensions of the ^{14}C-doped germanium detector (top) and the non-radioactive background detector (bottom) (Haller *et al.*, 1982; Sur *et al.*, 1991).

FIG. 15. Data/fit of ^{14}C using a single massless neutrino component. The solid line shows the expectation for a 16.6 keV neutrino with $\sin^2\theta = 1.25\%$ (Wietfeldt *et al.*, 1994).

FIG. 16. The Oxford beta spectrometer (Hime and Jelley, 1991). (a) Si(Li) detector, (b) source substrate, (c) Al detector aperture, (d) Cu source aperture, (e) Al anti-scatter baffle, (f) linear motion feed-through, (g) liquid nitrogen cryo-panel, (h) teflon centering ring, (i) vacuum chamber.

FIG. 17. Measured and calculated response function for the 129.4 keV conversion electron line of ^{57}Co using the Oxford beta spectrometer.

FIG. 18. Oxford ^{35}S data/fit with a single massless neutrino component. In the upper plot the fit was taken over the energy range 120–167 keV. In the lower plot the fit was taken from 150–167 keV and extrapolated to lower energy. The solid line in each plot indicates the expected result for a 17 keV neutrino with $\sin^2\theta = 0.9\%$.

FIG. 19. Data/fit with a single massless neutrino component of the IBEC spectrum of ^{71}Ge. The data were fit above 202 keV and extrapolated to lower energy. The dashed line shows the expectation for a 17.2 keV neutrino with $\sin^2\theta = 1.6\%$ (Žlimen *et al.*, 1991).

FIG. 20. (a) The Kurie plot for a beta spectrum containing a massive neutrino admixture (exaggerated). Also shown are the best fit Kurie plots (no massive neutrino) with no shape correction (dashed), and a quadratic shape correction (solid). (b) The residual with no shape correction (dashed) and a quadratic shape correction (solid), revealing the loss in sensitivity when a smooth shape correction is used.

FIG. 21. Data/fit of ^{63}Ni including a 17 keV neutrino component with $\sin^2\theta$ equal to (a) 0.02% and (b) 1.0%, clearly ruling out the latter (Kawakami *et al.*, 1992).

FIG. 22. Schematic drawing of the Argonne beta spectrometer (Mortara *et al.*, 1993). The lower curve shows the axial magnetic field strength.

FIG. 23. Data from Mortara *et al.* (1993): (a) Data/fit for the ^{35}S data. The solid curve shows the expected result from a 17 keV neutrino with $\sin^2\theta$=0.85%. (b) Data/fit for the ^{35}S source containing 1.3% ^{14}C. The solid curve shows the expected result from this contamination.

FIG. 24. Second numerical derivatives of Monte Carlo ^{55}Fe data with (a) a 1% 17 keV neutrino and (b) no massive neutrino. The kink appears as a peak at 208 keV. Second derivatives of actual ^{55}Fe data taken (c) before background and impurity subtraction (revealing the ^{59}Fe impurity line at 192 keV) and (d) after background and impurity subtraction (Wietfeldt *et al.*, 1993).

FIG. 25. χ^2 contours for polynomial fits to Monte Carlo ^{55}Fe data with (a) a 1% 17 keV neutrino and (b) no massive neutrino. (c) A similar plot for the actual ^{55}Fe data. The region fit is 200–220 keV (154 points). Absolute minima are marked with an X (Wietfeldt *et al*, 1993).

FIG. 26. Residuals from fits to ^{35}S data including a linear and quadratic shape correction taken with the Caltech magnetic spectrometer (Chen *at al.*, 1992). Fits were made with a single massless neutrino component (top) and a 0.85% 17 keV neutrino (bottom).

FIG. 27. Synthetic distortion in the Caltech ^{35}S beta spectrum, produced using an aluminum degrader foil. The solid curve shows a computer simulation of the expected result.

FIG. 28. Data/fit of ^{35}S with a single massless neutrino component, from the Princeton magnetic spectrometer (Berman *et al.*, 1993). The solid line indicates the expectation with a 0.84% 17 keV neutrino.

FIG. 29. χ^2 contours of neutrino mass and mixing from the ^{71}Ge IBEC data of DiGregorio *et al.* (1993). The absolute minimum is plotted as a star. The data point shows the earlier result of Žlimen *et al.* (1991).

FIG. 30. Schematic diagram of the loss-free beta spectrometer at Grenoble (Abele *et al.*, 1993).

FIG. 31. Kink-like structure in the ^{35}S beta spectrum caused by electron backscattering (Abele *et al.*, 1993).

FIG. 32. World summary of the results and limits on the mixing of a 17 keV neutrino. Error bars are 1σ and upper limits are 95% CL, estimated from the references as necessary assuming gaussian-distributed errors.

FIG. 33. Monte Carlo calculations of the low-energy tail in the response function using the geometry of the Oxford beta spectrometer (Hime, 1993): (a) contributions due to backscattering from the silicon detector and energy loss in the detector contact; (b,c) components arising from baffle scattering, aperture penetration, and back-scattering from the source for two different geometrical configurations.

FIG. 34. (a) Contamination in the LBL ^{14}C spectrum caused by decays underneath the segmentation groove which were below the 20 keV veto threshold. (b) Ratio of contaminated and uncontaminated ^{14}C spectra collected at the same time (Wietfeldt *et al.*, 1995).

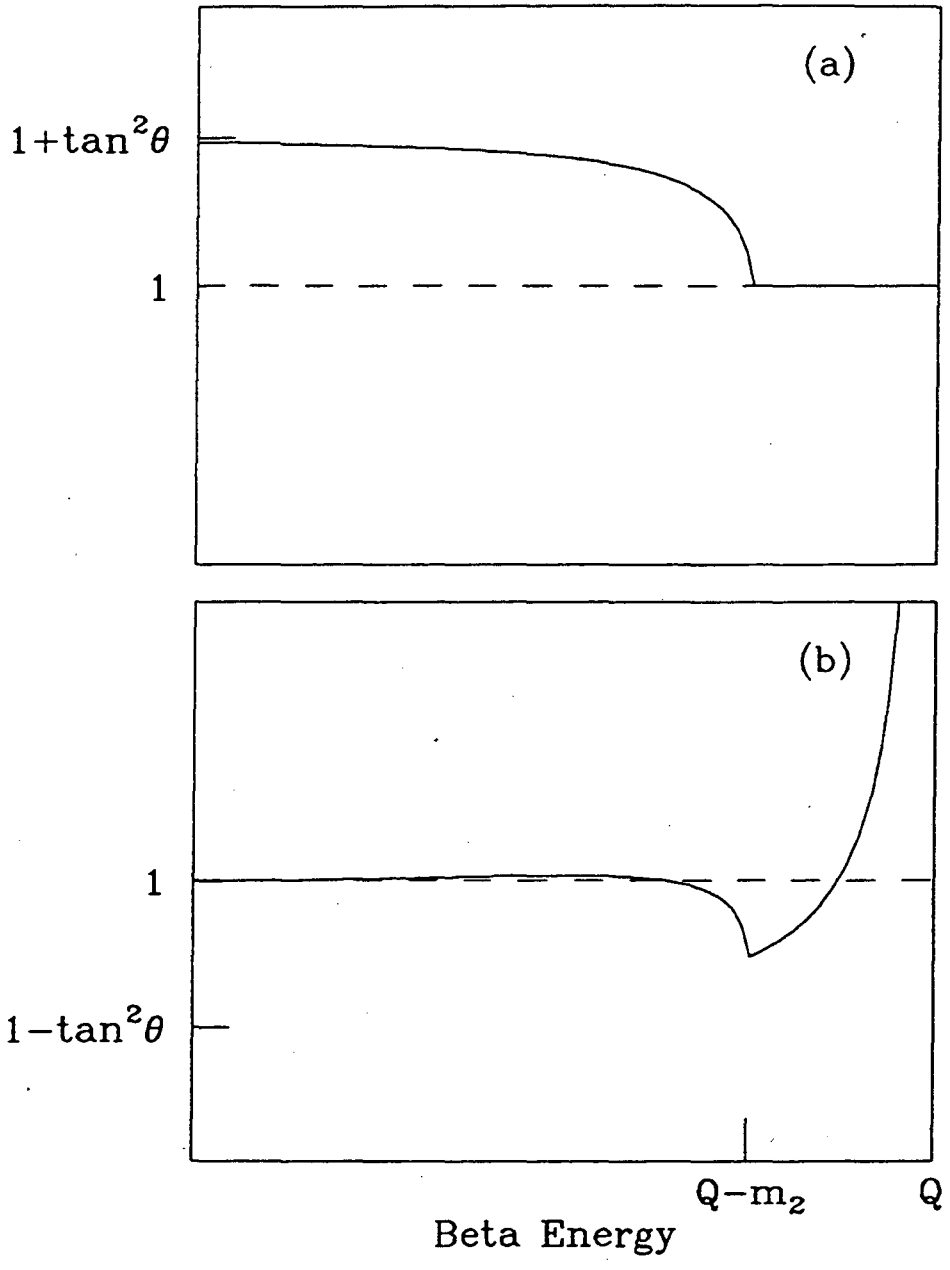


Figure 1

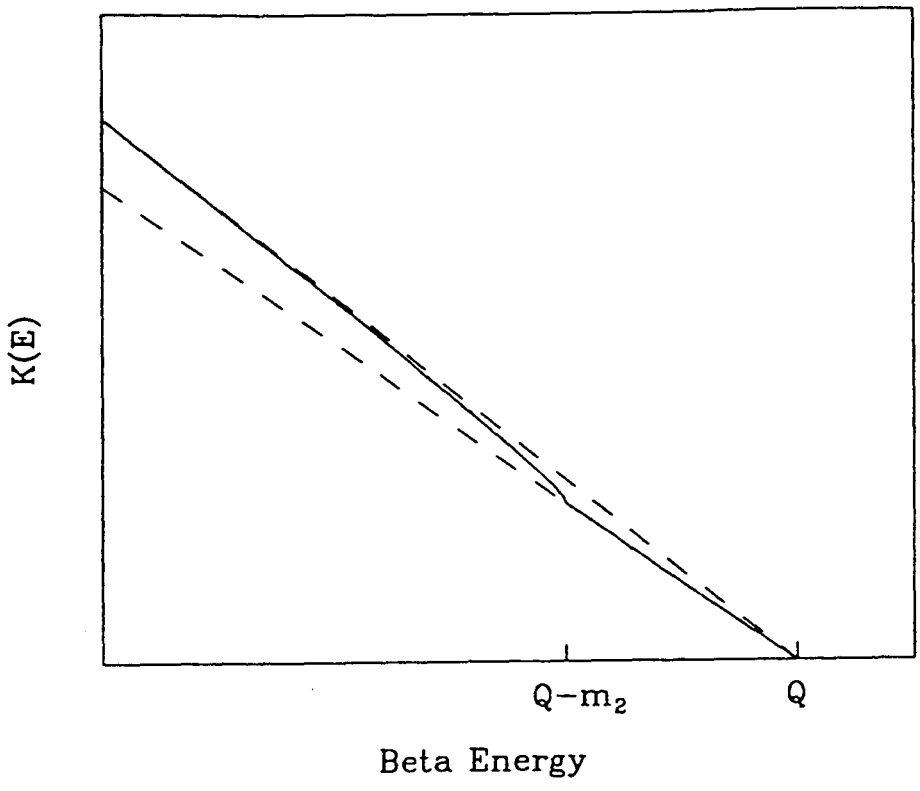


Figure 2

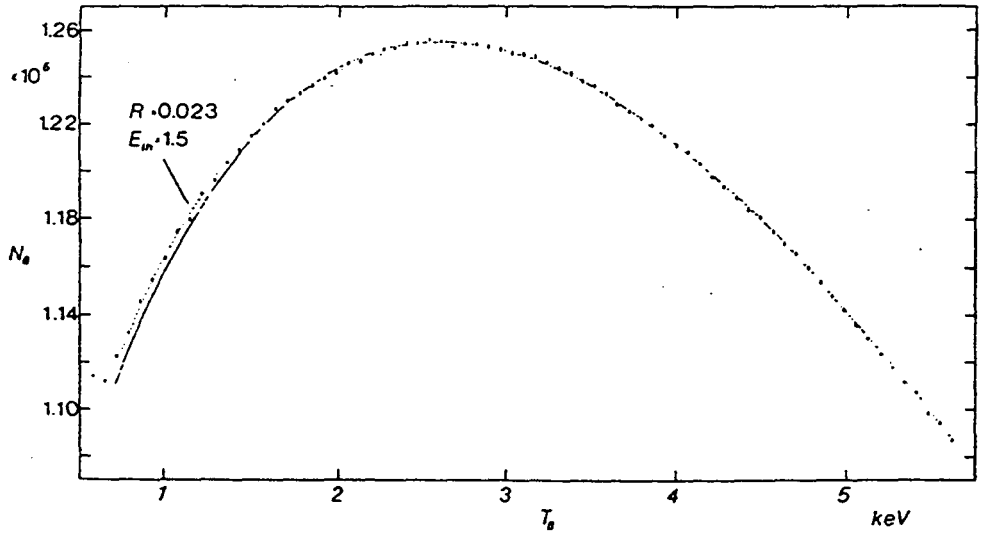


Figure 3

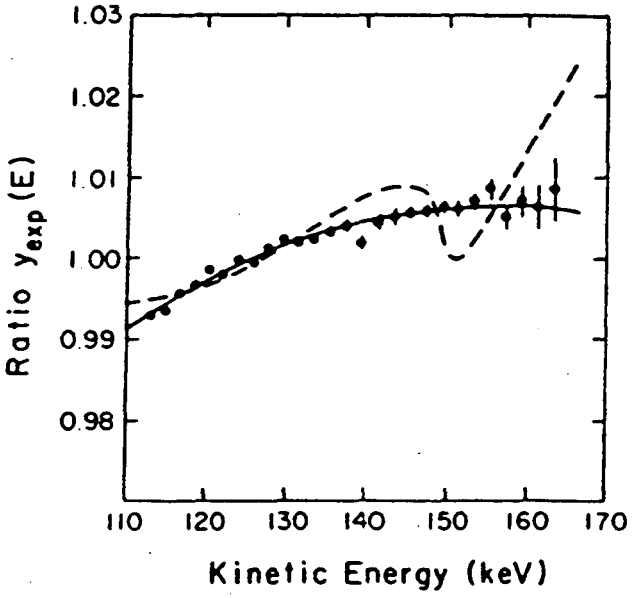


Figure 4

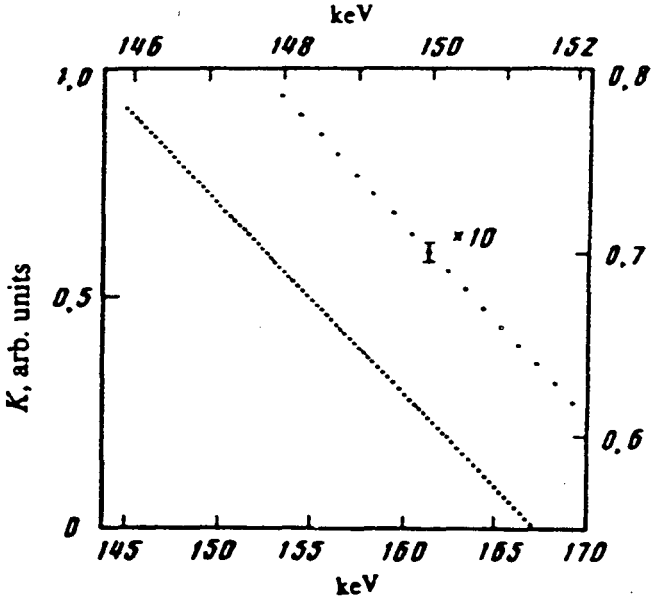


Figure 5

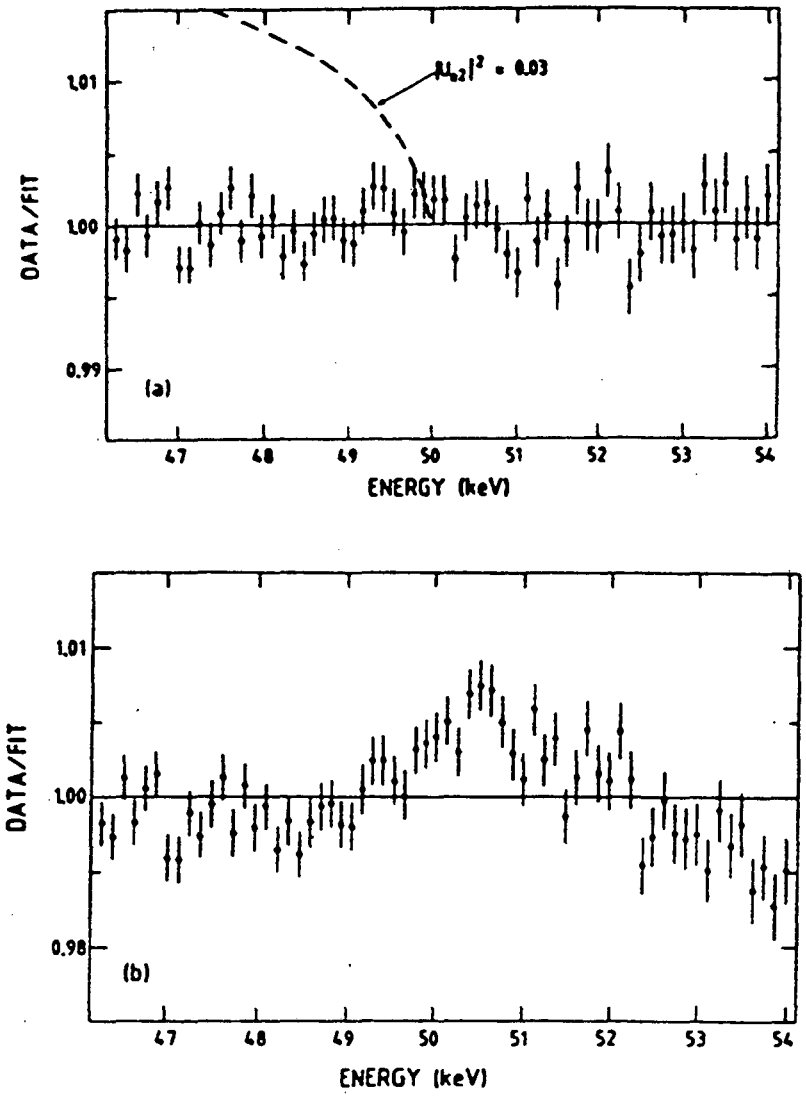
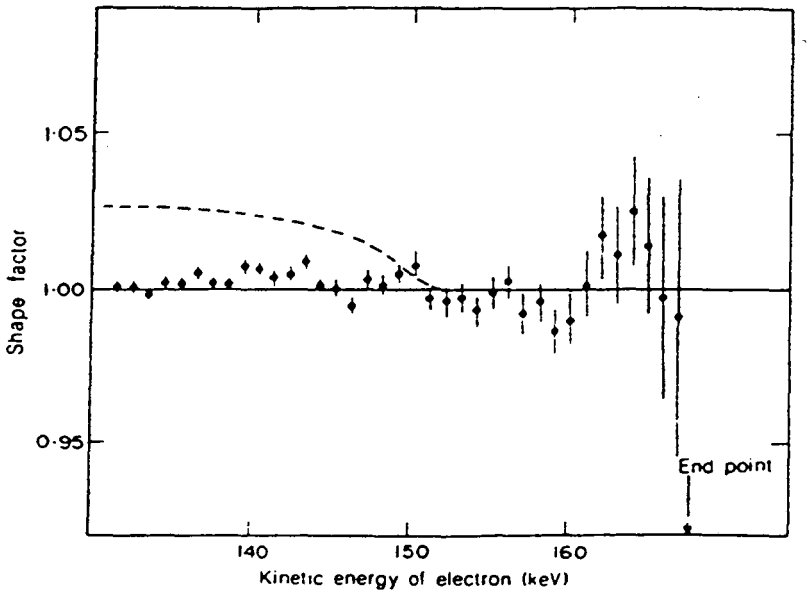

1.01
1.00
0.99
DATA/FIT
(a)
47
48
49
50
51
52
53
54
ENERGY (keV)
1.01
1.00
0.98
DATA/FIT
(b)
47
48
49
50
51
52
53
54
ENERGY (keV)

Figure 6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1·00
0·95
Shape factor
End point
140
150
160
Kinetic energy of electron (keV)

Figure 7

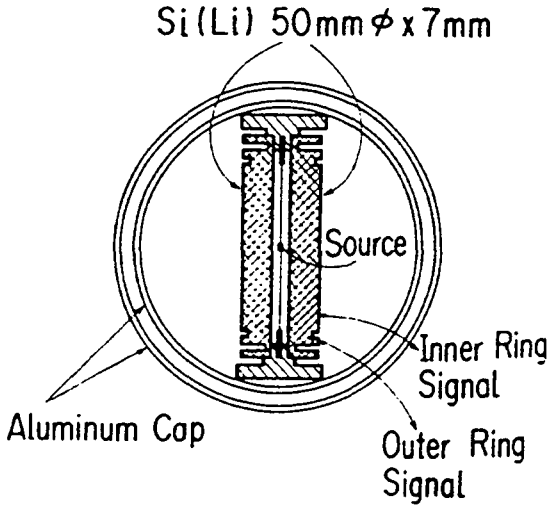
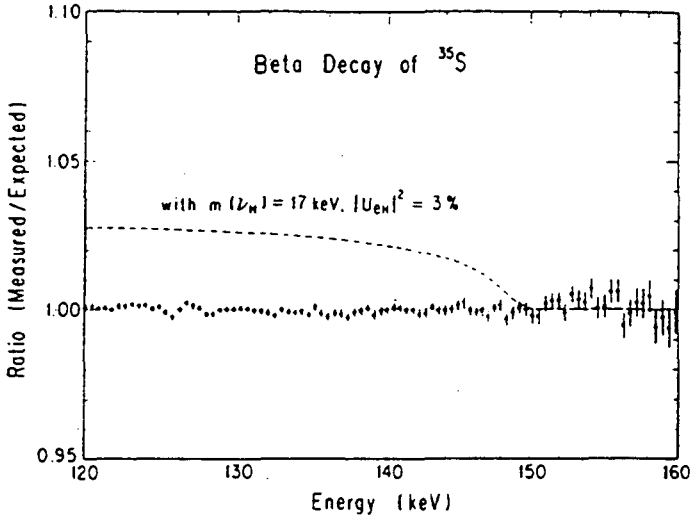
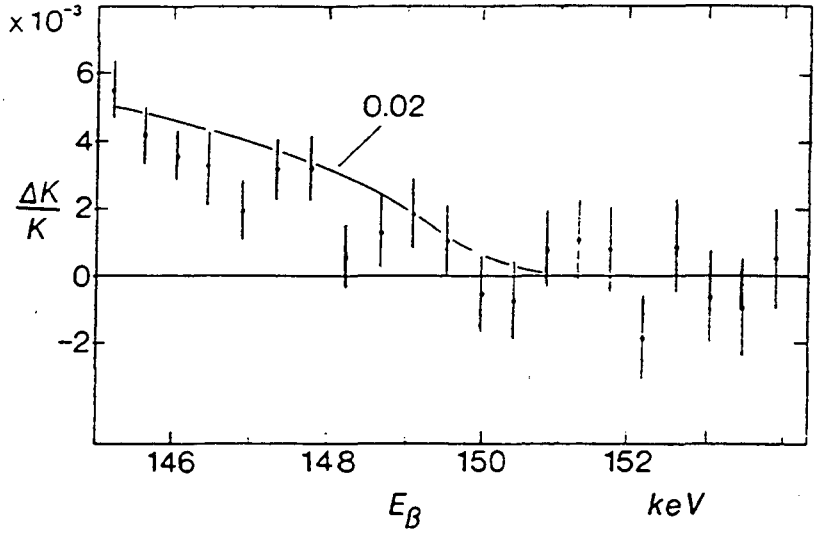


Figure 8



(a)



(b)

Figure 9

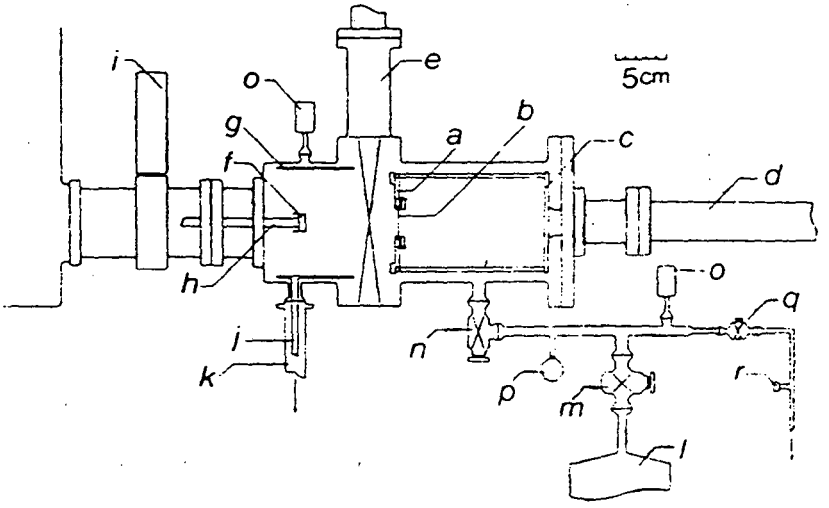


Figure 10

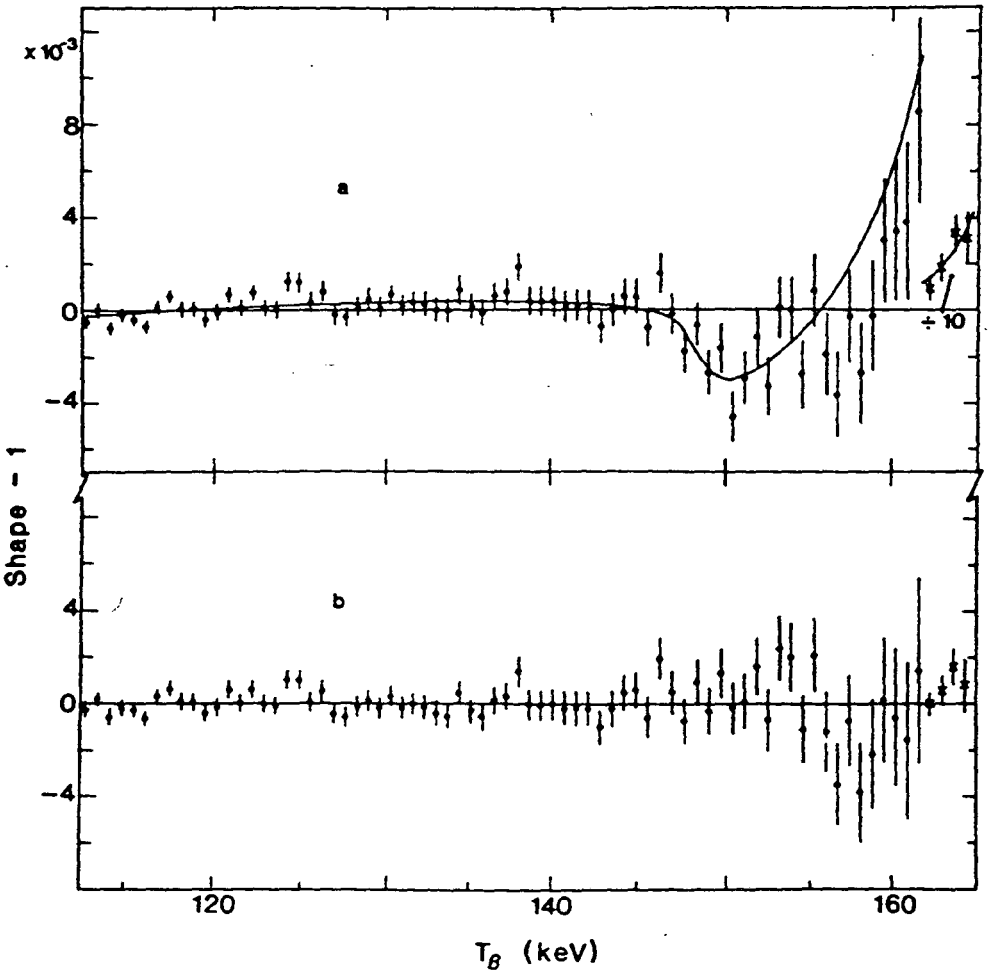


Figure 11

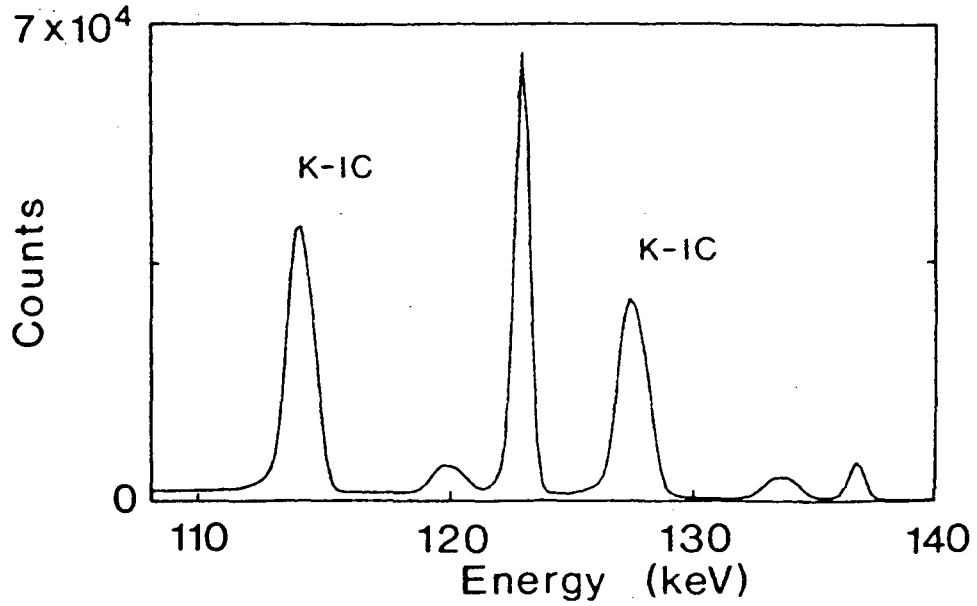


Figure 12

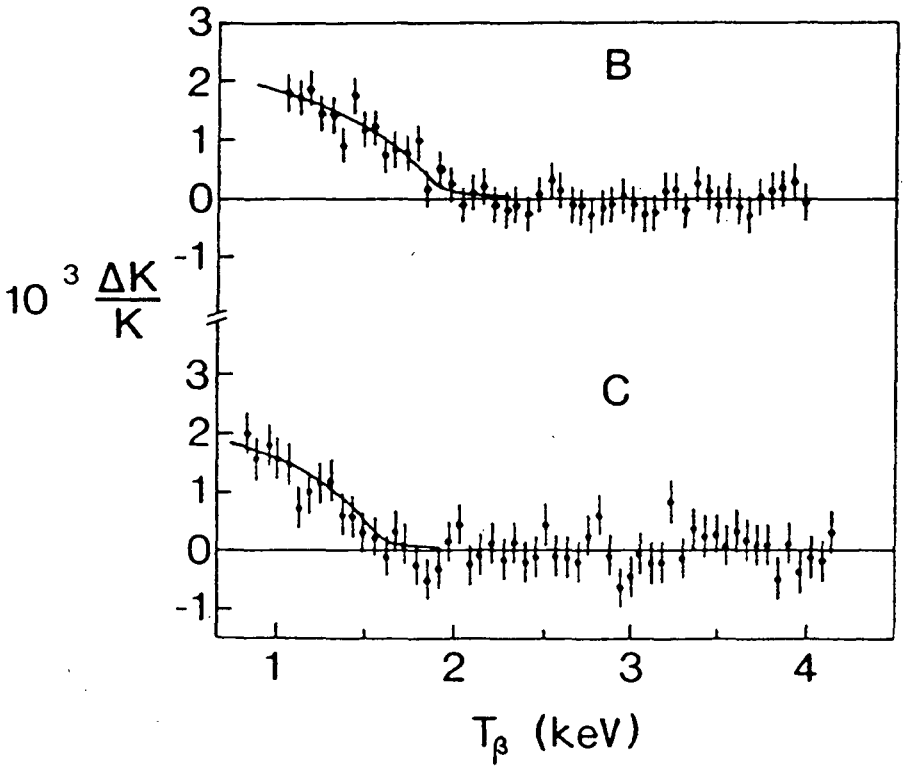


Figure 13

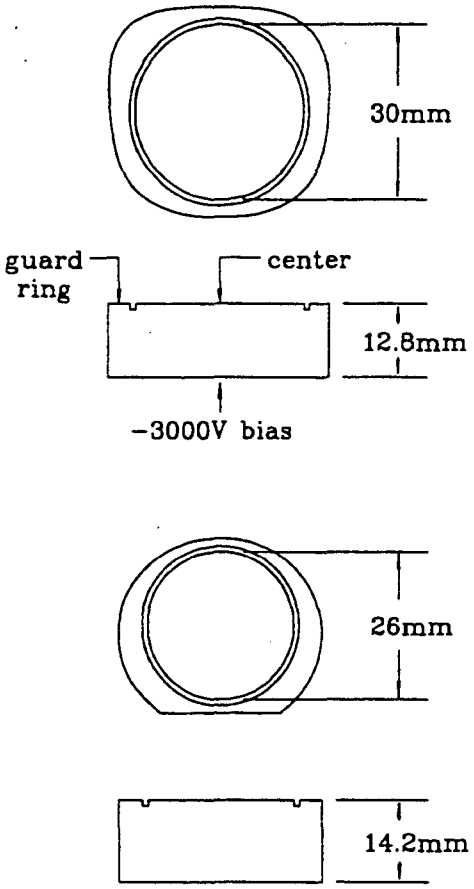


Figure 14

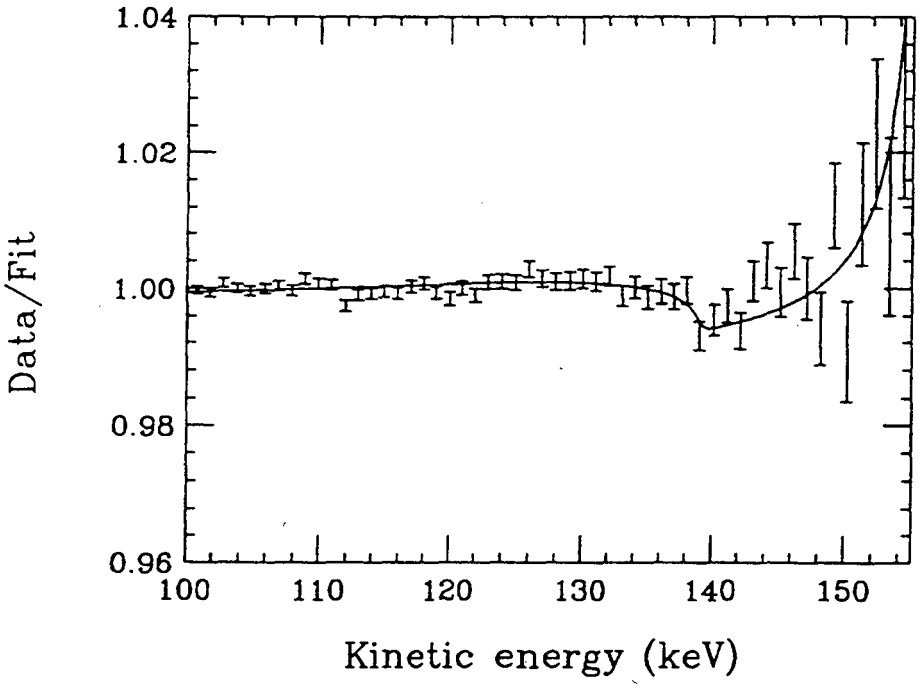


Figure 15

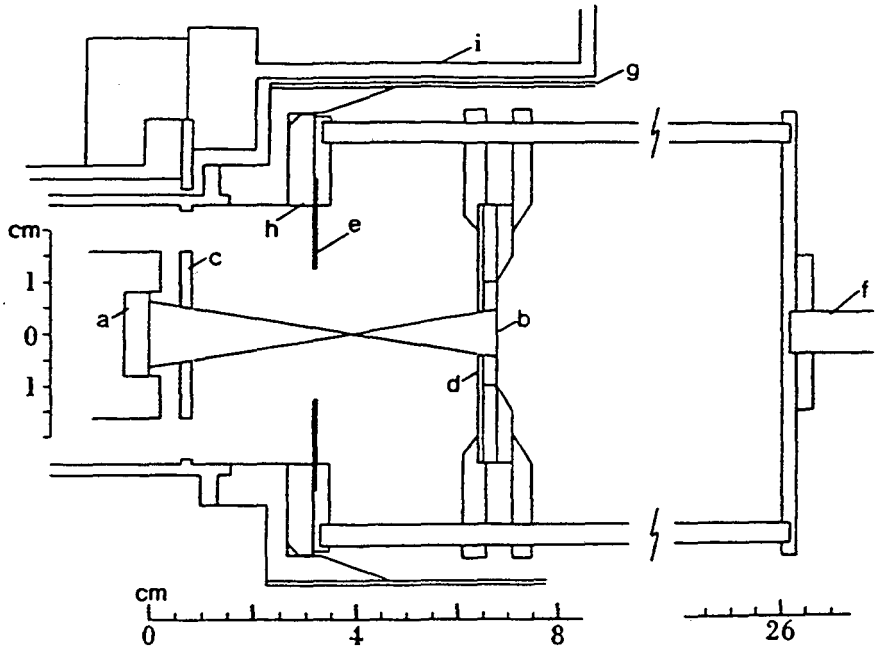


Figure 16

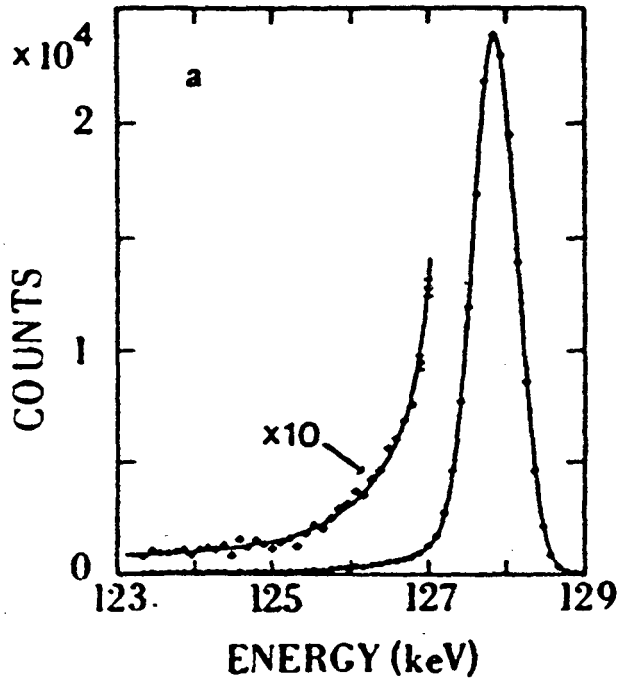


Figure 17

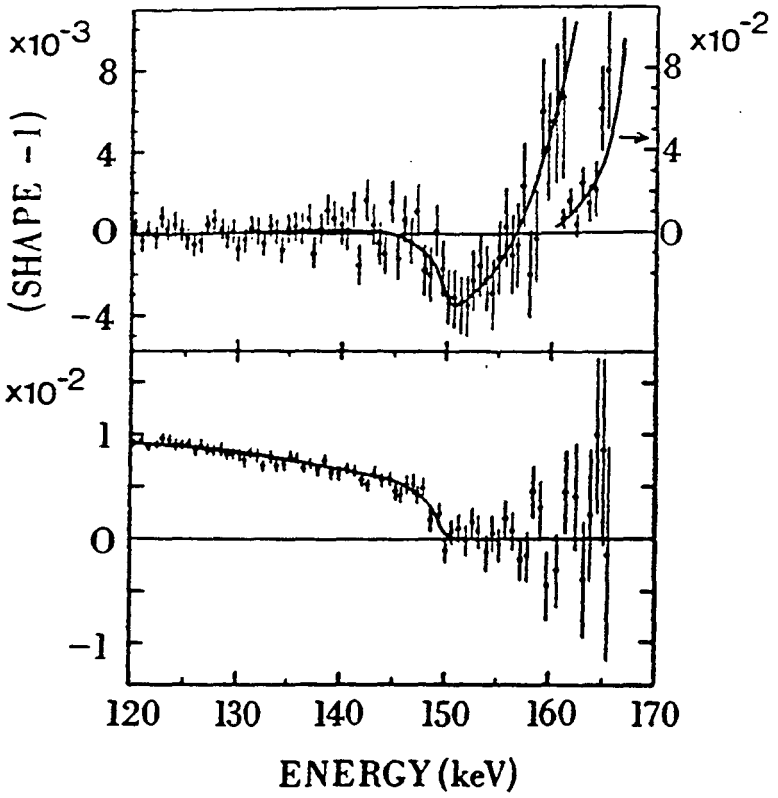


Figure 18

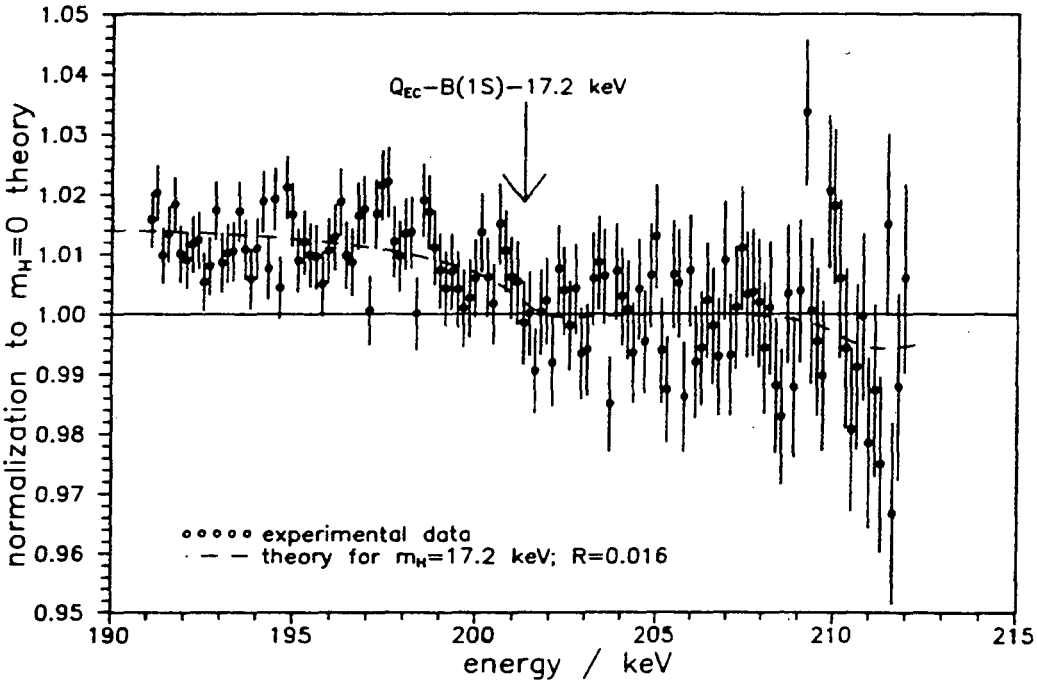

1.05
1.04
1.03
1.02
1.01
1.00
0.99
0.98
0.97
0.96
0.95
normalization to m_H=0 theory
Q_{EC}−B(1S)−17.2 keV
experimental data
theory for m_H=17.2 keV; R=0.016
190
195
200
205
210
215
energy / keV

Figure 19

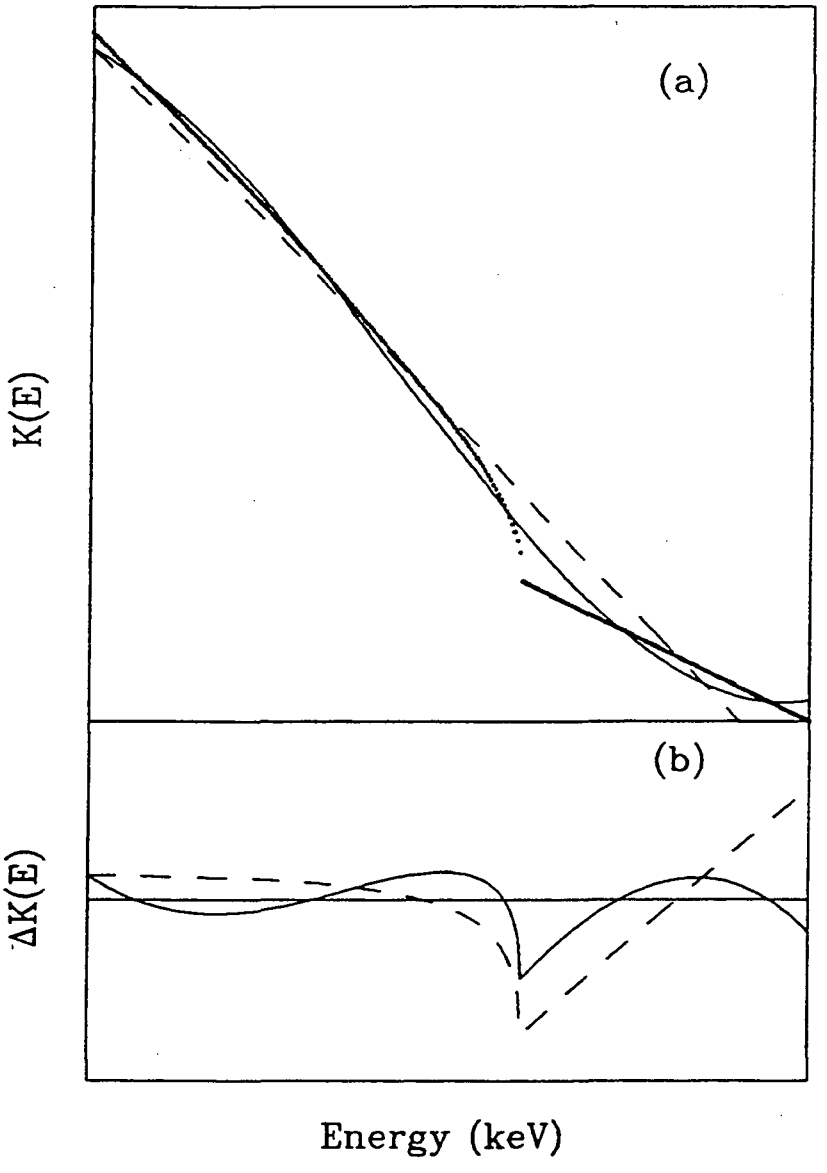


Figure 20

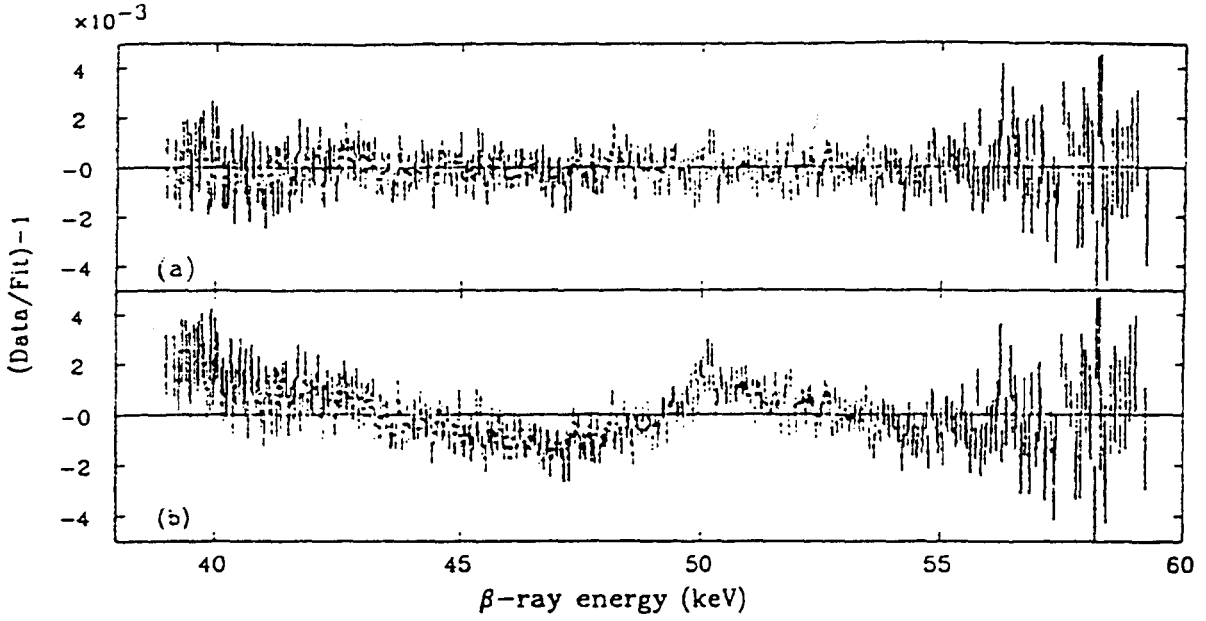


Figure 21

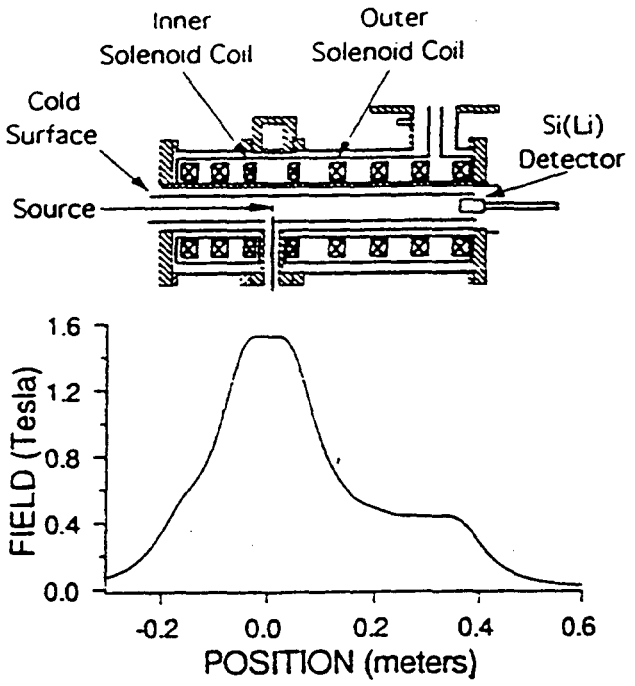
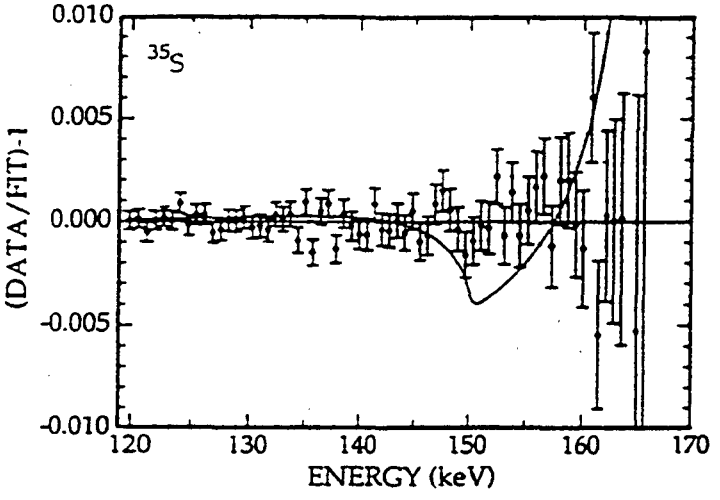
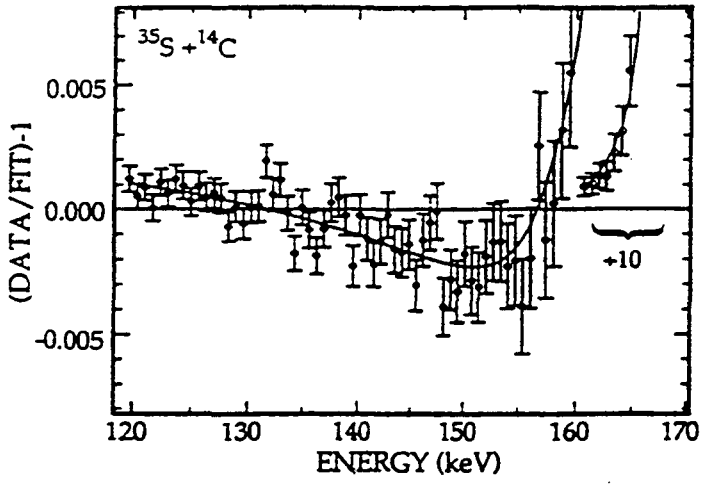


Figure 22


0.010
0.005
0.000
-0.005
-0.010
(DATA/FIT)-1
^{35}S
120
130
140
150
160
170
ENERGY (keV)

(a)


$^{35}S + ^{14}C$
0.005
0.000
-0.005
(DATA/FIT)-1
+10
120
130
140
150
160
170
ENERGY (keV)

(b)

Figure 23

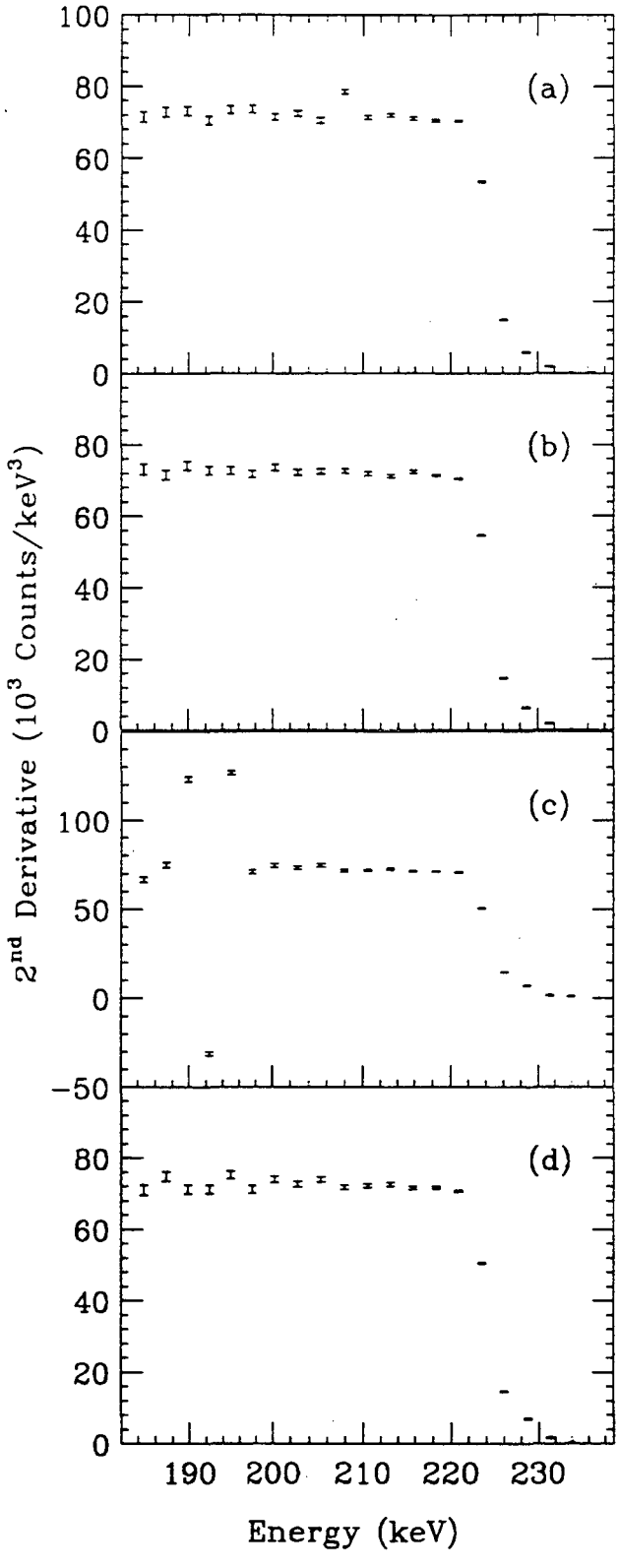

(a)
(b)
(c)
(d)
2nd Derivative (10^3 Counts/keV^3)
Energy (keV)
100
80
60
40
20
0
50
-50
190
200
210
220
230

Figure 24

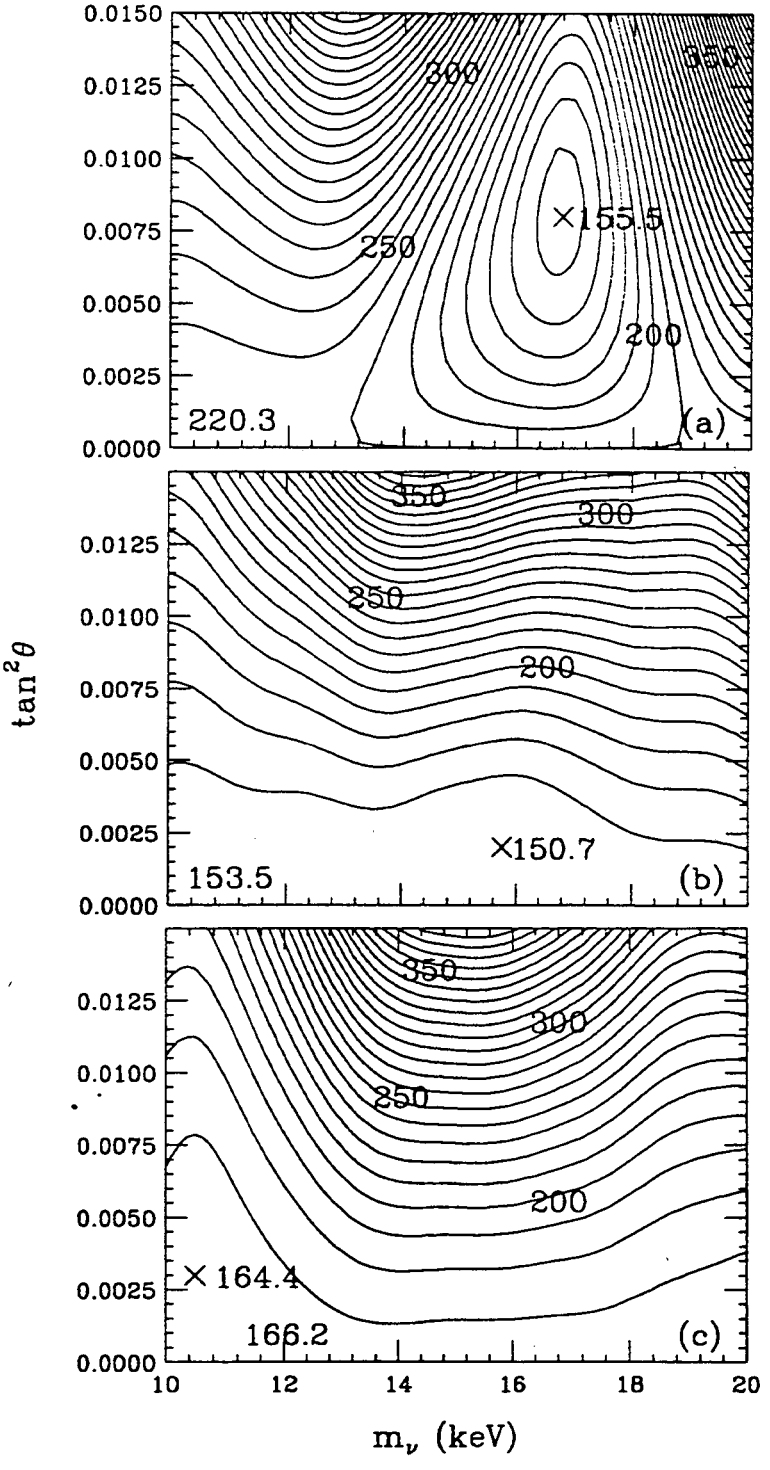

0.0150
0.0125
0.0100
0.0075
0.0050
0.0025
0.0000
300
350
250
×155.5
200
220.3
(a)
350
300
250
200
×150.7
153.5
(b)
350
300
250
200
× 164.4
166.2
(c)
10
12
14
16
18
20
$\tan^2\theta$
m_ν (keV)

Figure 25

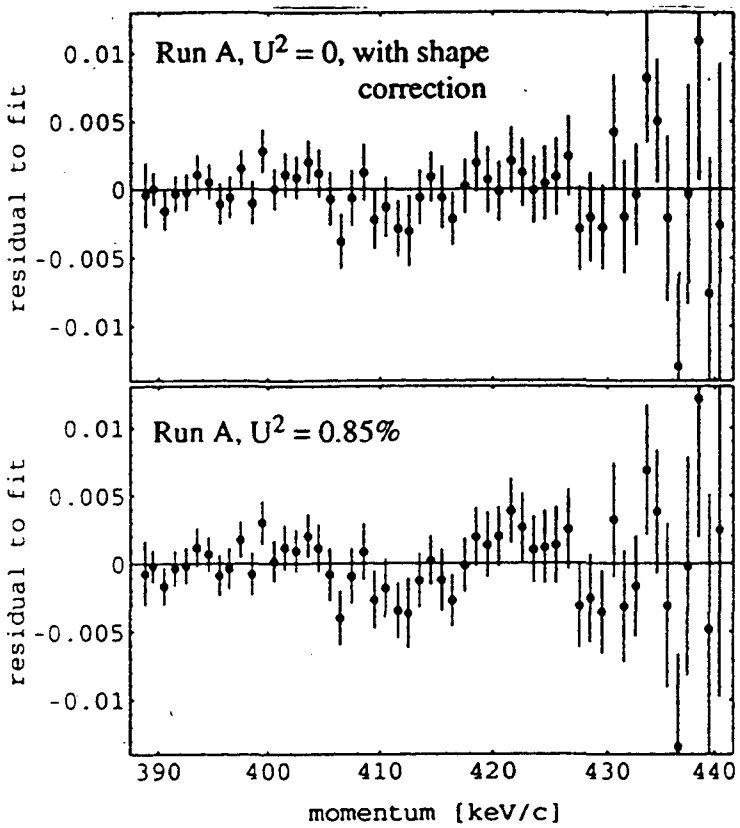


Figure 26

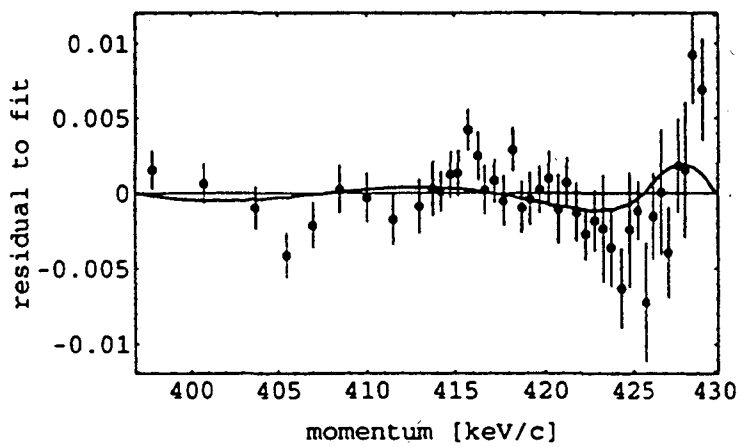


Figure 27

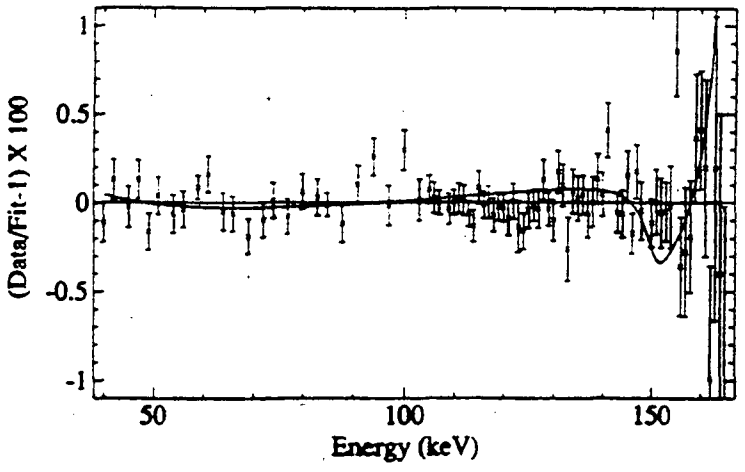


Figure 28

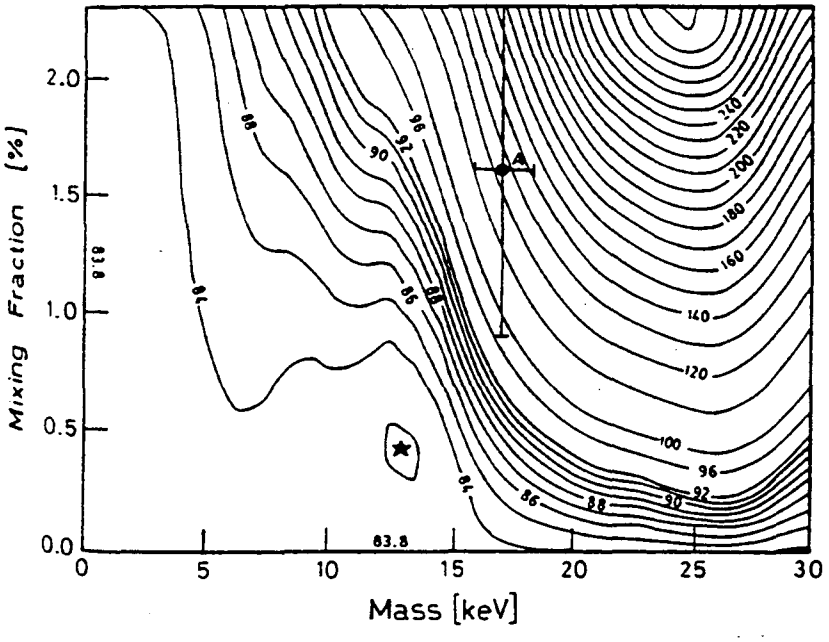


Figure 29

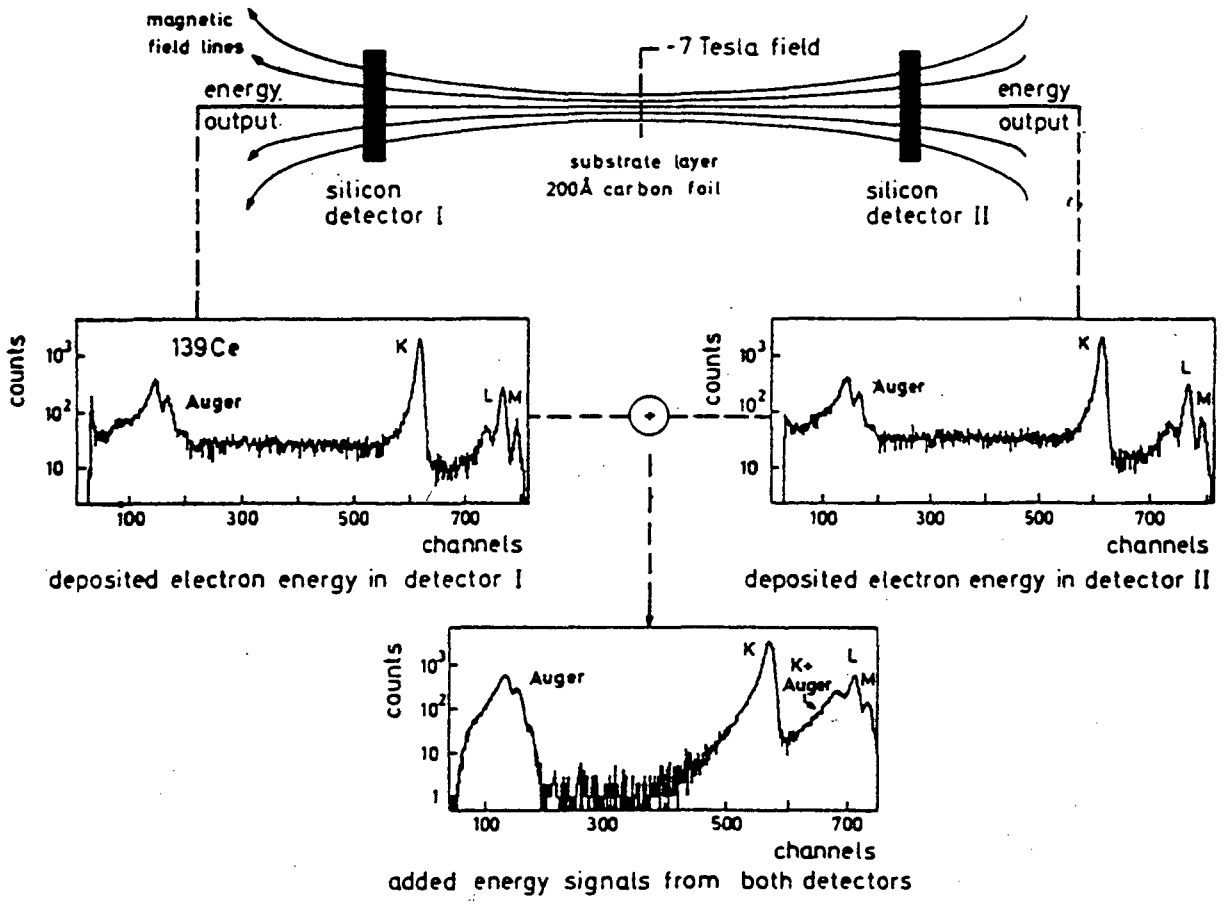


Figure 30

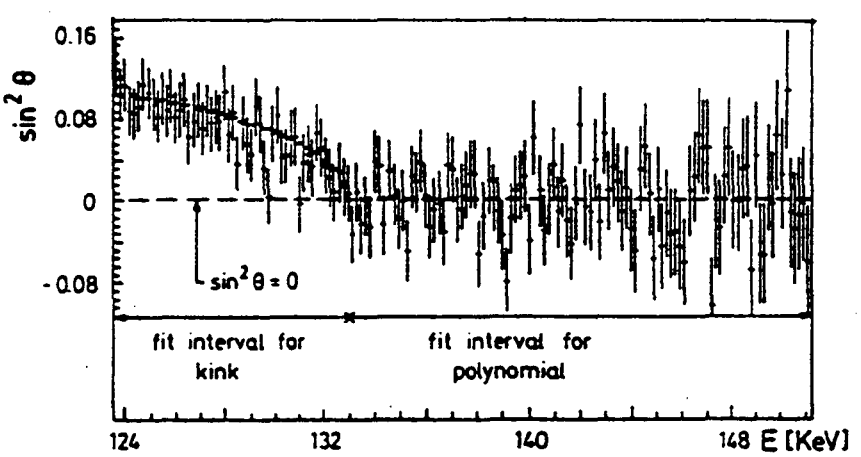


Figure 31

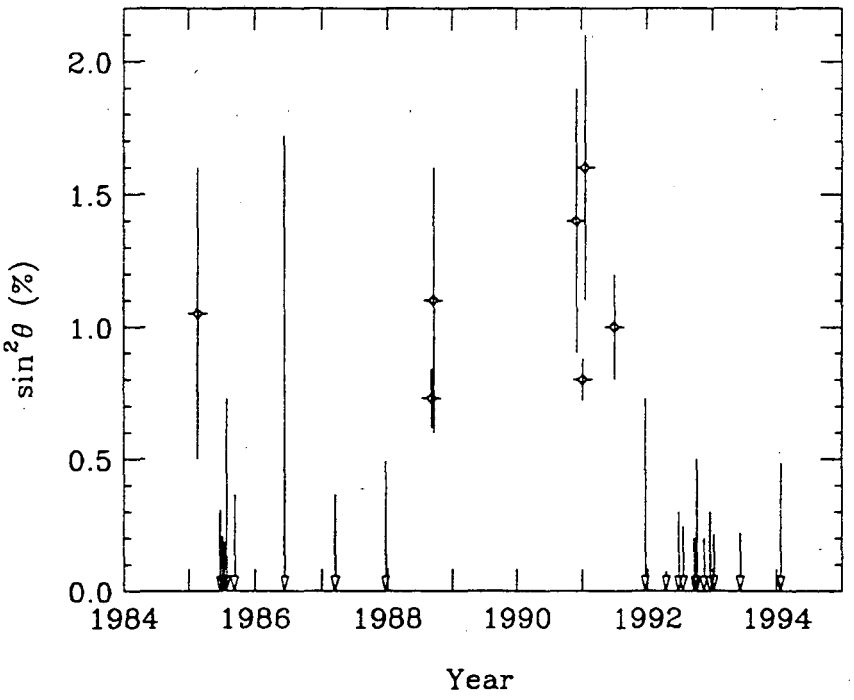


Figure 32

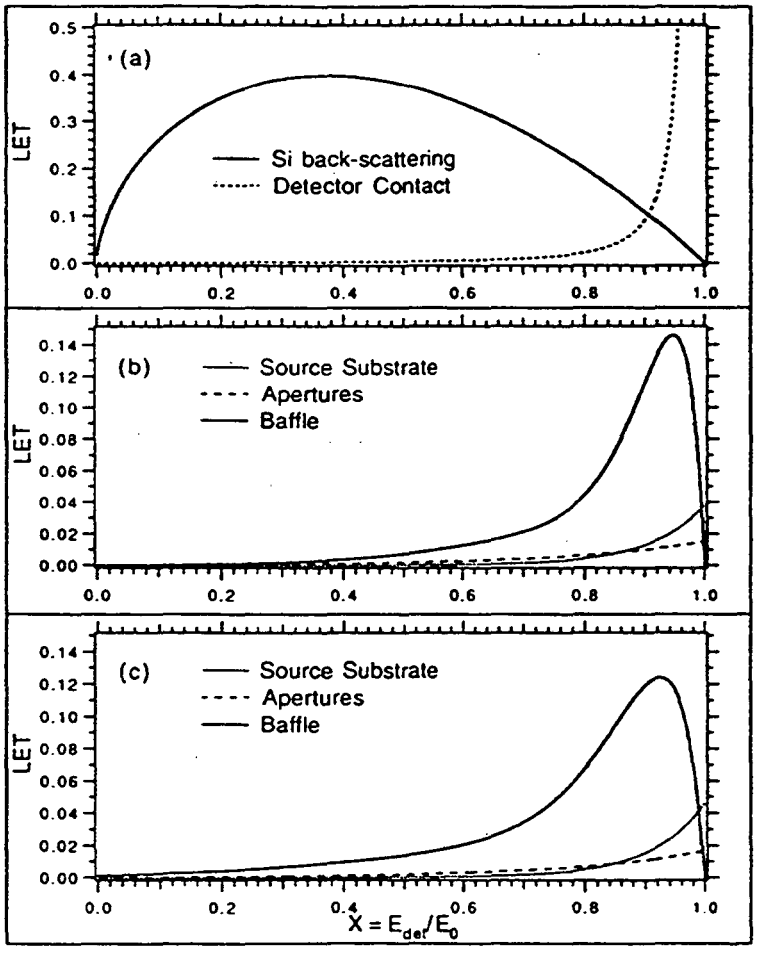


Figure 33

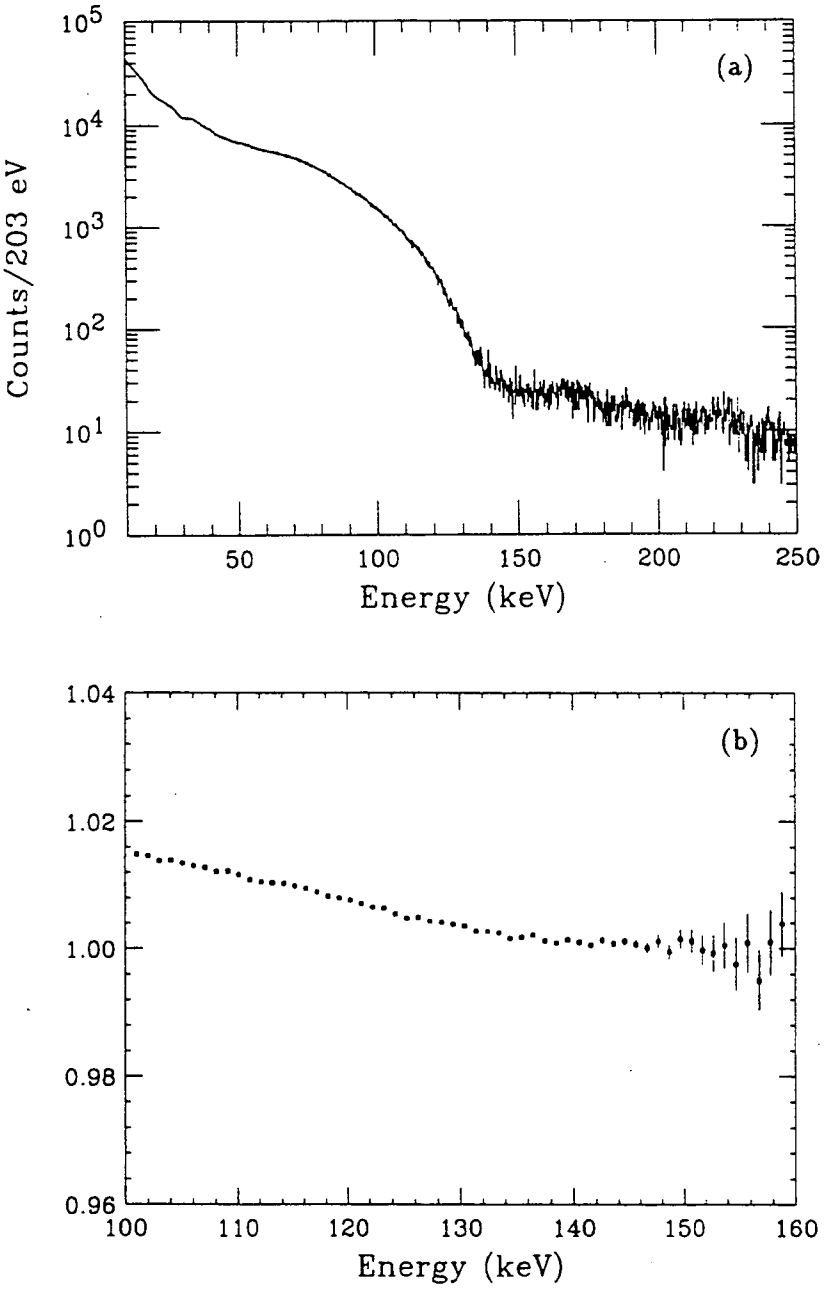

(a)
Counts/203 eV
10^5
10^4
10^3
10^2
10^1
10^0
50
100
150
200
250
Energy (keV)
(b)
1.04
1.02
1.00
0.98
0.96
100
110
120
130
140
150
160
Energy (keV)

Figure 34

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UNIVERSITY OF CALIFORNIA
TECHNICAL AND ELECTRONIC
INFORMATION DEPARTMENT
BERKELEY, CALIFORNIA 94720