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New evidence against 17-keV neutrino emission in the β decay momentum spectrum of ^{35}S

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We have measured the electron β decay spectrum of ^{35}S with an iron-free magnetic spectrometer. In particular, we have searched for the 17-keV neutrino claimed by various authors to exist at the 0.8–1.1 % level. We have successfully fit our data over a large portion of the spectrum (40–166 keV) and find no evidence for the 17-keV neutrino. The branch is determined to be $(0.01 \pm 0.15)\%$, which is in serious disagreement (5σ) with the $(0.84 \pm 0.06)\%$ branch claimed by Hime and Jelley.

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In 1985, Simpson published measurements of the β decay spectrum of tritium in which he claimed evidence for a 17-keV electron antineutrino with a mixing fraction of 3% [1]. Shortly thereafter, several groups [2–6] published data inconsistent with this claim, including our group at Princeton which measured the β decay spectrum of ^{35}S with a magnetic spectrometer and determined the 17-keV branch to be $(-0.29 \pm 0.21)\%$ [7]. Following these data, Hime and Simpson, Simpson and Hime, and Hime and Jelley [8–10] published new data on ^{3}H decay and measurements of ^{35}S with evidence of a 17-keV branch at a lower limit of 0.8–1.1 %. A recent experiment at LBL also claims evidence of a 1.4% 17-keV branch in the β decay spectrum of ^{14}C within a germanium detector [11].

Though the Princeton 1985 experiment rules out branches above 0.4% at the 99% confidence level, and a reanalysis of these data by methods employed in the present work [12] confirms the exclusion of a smaller branch at 0.8%, the importance of these new claims were motivation for a second measurement. For this work, we have remeasured the β decay spectrum of ^{35}S,

$$^{35}\mathrm{S} \to {}^{35}\mathrm{Cl} + e^- + \bar{\nu}_e \quad (t_{1/2} = 87\ \mathrm{d},\ T_0 = 167\ \mathrm{keV}),$$

using the same spectrometer but employ new technologies, better detectors, improved data analysis, and a much larger data set (fits down to 40 keV) to help reduce and understand any instrumental distortions that may influence our ability to find the 17-keV neutrino.

We measure the momentum spectrum of ^{35}S using the iron-free intermediate-image magnetic spectrometer illustrated in Fig. 1 [13]. Electrons emanating from a source placed at the center of the first set of coils are focused at the midplane of the spectrometer and then again at the center of the second set of coils. An annular slit placed at the midplane selects a particular momentum bite of electrons to be transmitted depending on the

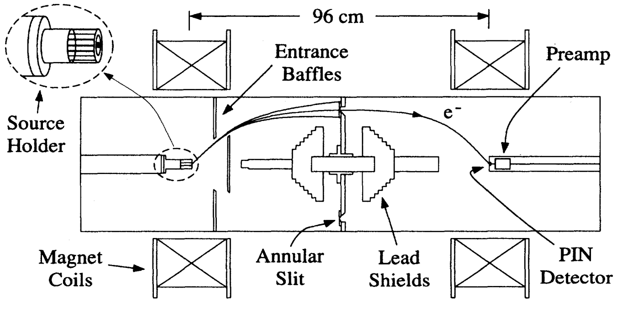

FIG. 1. A cross section through the center of the spectrometer shows the radial projections of three different electron trajectories. At a given main coil current, only electrons leaving the source within a small (1%) specific momentum range will be able to traverse the annular slit and reach the detector.

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main coil current. Entrance baffles further define the momentum resolution of the spectrometer by restricting electron take-off angles to 47° ± 5°. A detector placed at the center of the second set of coils counts all particles transmitted at each coil current selected. As evidenced by the absence of a significant low energy tail (see below), scattering from the entrance baffles and annular slit is negligible for our geometry since small detector size, large source-detector separation, and tightly bunched electron orbits make it very difficult for scattered electrons to find their way into the detector.

For this experiment we chose an annular slit width of 2 mm and a ^{35}S spot size of 3 mm, yielding a momentum resolution, $\Delta p/p$, of 1.16% [full width at half maximum (FWHM)] and an overall acceptance of 2.4% of 4π. The spectrometer is calibrated by K-conversion electrons with kinetic energies of 144.58(3) and 218.64(4) keV resulting from the 2.8-d decay of ^{111}In to ^{111}Cd [14]. Sources of ^{111}In were prepared identically to the ^{35}S source (see below).

The spectrometer resolution function, $\mathcal{R}$, can be found by scanning the main coil current, I, through the region of the 144-keV ^{111}In line (Fig. 2). Ideally this resolution function depends upon only the ratio I/p, and is thus scalable to all energies. However, the actual spectrometer response at other energies may deviate from this ideal resolution function for the following reasons. First, backscattering of electrons to lower energies by the source substrate and source holder creates a small low energy tail (10^{-4} of peak rate) extending towards zero current in the resolution function. We fit for this effect in our final analysis below. Second, background magnetic fields which do not scale with the main coil current (i.e., the Earth's field) can cause energy-dependent steering of the emitted electrons. This effect is minimized by reducing transverse background fields around the spectrometer using two sets of perpendicular "cancellation" coils set in a near-Helmholtz geometry. Background axial fields are canceled by an offset in the main coil current. Values for these nulling currents are determined by demanding that the response functions for the 144- and 218-keV ^{111}In lines scale proportionally with their momentum. A three-axis fluxgate magnetometer continuously monitors background fields at the 100-μG level enabling us to adjust the cancellation coil currents on-line.

The single ^{35}S source and various ^{111}In sources used were made by ion implantation at 55 keV into 40-μg/cm^2 carbon foils floated on 1.0-μm Mylar substrates (138 μg/cm^2). The Mylar substrate is thicker than the Formvar substrate used in the previous 1985 work, but is needed for structural support during ion implantation and is our primary source of unwanted backscattering. A total of 15 μCi of ^{35}S were accumulated for our source.

The source holders were designed to minimize scattering. Each consists of a 125-μm Al source ring (1.9 cm I.D., 3.2 cm O.D.) supported by 250-μm Al legs, 3.8 cm long, mounted to an Al base (see Fig. 1, inset). The carbon foils are floated on top of the Mylar substrate which is stretched and glued to the source ring. After implantation, the sources are introduced into the spectrometer by mounting the holder on the end of a brass tube which slides through a vacuum seal into the main chamber. Repeatability of source positioning within the spectrometer is very important for proper energy calibration. Custom slides and fixtures allow us to accurately reproduce the source position each time to better than 75 μm which corresponds to an uncertainty in energy calibration, and thus the fitted ^{35}S end point, of 60 eV. However, our major systematic error in calibration comes from instabilities during the implantation process which yields slightly different activity distributions for each source. In order to quantify this error, two separate ^{111}In calibration sources were produced and resolution functions derived from each of these sources are used to fit the ^{35}S data.

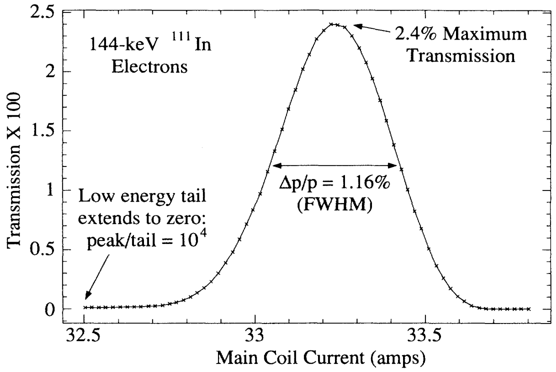

FIG. 2. The spectrometer resolution function is obtained by scanning the main coil current over the 144-keV ^{111}In electron-conversion line from one of two calibration sources. Dividing the x axis by the momentum of a 144-keV electron yields the scalable function $\mathcal{R}(I/p)$ since orbits in the spectrometer are solely determined by the ratio of electron momentum to magnetic field. The low energy tail shown is due to electron backscattering in the source (see text).

Transmitted electrons are counted by a Hamamatsu 500-μm 9x9 mm^2 PIN-diode detector operating at room temperature. This detector draws less than 25 nA at its normal bias of 90 V and has a resolution of 3.9 keV (FHWM) for the full-absorption peak of 144-keV ^{111}In electrons. Detector spectra are acquired by an Ortec 2001 preamp, a Canberra 2022 amplifier, a Lecroy 3512 analog-to-digital converter (ADC) set to 8-bit gain, and a Lecroy 3588 16K histogramming memory capable of storing 64 256-channel spectra at once. In Fig. 3 we present a detector spectrum for ^{35}S electrons at 150 keV (solid line). Since the main field of the spectrometer selects the momentum observed, a detailed energy-dependent model of the detector spectrum is not needed—our analysis requires only the total of all counts observed in the detector. Counts can be summed directly down to the electronics noise threshold at 13 keV, but counts "lost" below the noise must be estimated.

We have employed the general purpose "electron-gamma shower" Monte Carlo computer code (EGS4) [15] to simulate detector spectra and predict the number of counts lost below the noise. A modified version of the code, provided by Piilonen [16], was used to properly simulate the low energy region of the backscattered tail. The predicted spectrum which best fits our 150-keV data has been overlaid in Fig. 3 (dotted line). The agreement

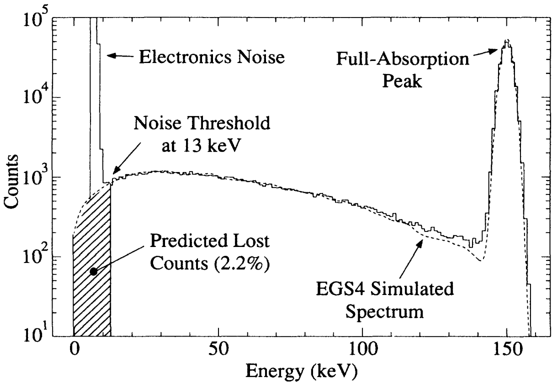

FIG. 3. The PIN-diode detector spectrum for ^{35}S electrons at 150 keV is shown with the solid line above. Our analysis requires the sum total of all counts in the spectrum, but electronics noise below 13 keV prevents us from summing counts in that region. EGS4 Monte Carlo simulations of the spectrum (dotted line) are used to predict the number of counts lost below the noise (see text).

between the computed and experimental spectra, normalized only to total counts, is excellent. For example, the fraction of counts in the experimental spectrum between 13 and 50 keV is 11.9% of the total, to be compared with 12.0% predicted by the Monte Carlo simulation. By simulating detector spectra at various electron kinetic energies, T, we calculate a lost-counts correction fraction $L_F(T)$, which has values of 14.0, 3.6, 2.2, and 1.7% at 40, 110, 150, and 170 keV, respectively. The conclusions of this paper remain unchanged if simulated spectra from the unmodified version of EGS4 are instead used to predict $L_F(T)$. It should be noted that for the original 1985 experiment, lost counts were estimated by simple linear extrapolation. Recently, the data have been reanalyzed using the better lost-counts predictions of EGS4. This procedure has all but eliminated the smooth distortion previously seen in the shape factor for the 1985 data—the spectrum is now flat to better than 0.2% across the fitted region 110–170 keV [12].

The ^{35}S and ^{111}In momentum scans were generated by accumulating 120-sec detector spectra over scanning regions containing 64 discrete settings of the main coil current (up to 43 A). The ^{35}S data were accumulated for two months over three regions: 74 scans from 14–183 keV, 156 scans from 105–176 keV, and 110 scans from 143–183 keV. Multiple scans within a given region are added together by summing their corresponding detector spectra, but individual spectra are rejected if a background field fluctuation above 5 mG or a main coil current fluctuation above 14.5 mA is recorded during acquisition. The peak detector count rate for ^{35}S was 150 Hz at 70 keV. A dead time of 0.2–0.4% was measured using a 142-Hz pulser and a detector background rate of 0.03–0.04 Hz was determined by acquiring spectra for each region at energies well beyond the ^{35}S end point and also at zero field. In addition to these corrections, each scan was normalized to a common date using an 87.4-d half-life [14] which corresponds to a 0.1% relative decay across each scanning region. Finally, the spectra were summed above noise threshold and converted into an absolute observed count rate, R_{obs}, as a function of main coil current, I.

Calculations have shown the theoretical β decay spectrum of ^{35}S has an allowed shape to within 0.02% [17]. If we assume the usual zero-mass electron neutrino state has a small fractional admixture, X, of a massive-neutrino component, $m_\nu = 17$ keV, the momentum decay spectrum becomes

$$d\lambda = (G^2/4\pi)\,(E_0 - E)^2\, p^2\, dp\, F_0 L_0 R_c(E) \times \left\{ 1 - X \left(1 - \sqrt{1 - m_\nu^2/(E_0 - E)^2} \right) \right\},$$

where G is the weak-interaction coupling constant, $F_0 L_0$ is the Fermi function [18], R_c is a radiative correction factor [18], E and p are electron total energy and momentum, and E_0 is the total end-point energy.

We fit our ^{35}S data by convolving this allowed spectrum shape with the spectrometer's resolution function, $\mathcal{R}(I/p)$, and the detector's lost-counts correction, $[1 - L_F(T)]$. Source backscattering discussed above has been modeled using EGS4 and is found to have $1/T^2$ energy scaling similar to screened Mott scattering. We account for this effect by introducing a factor of $(1 + \alpha/T^2)$ into our analysis, where α is a constant fit by the data. A factor of $(1 + AT)$, A fit by the data, is also included to absorb any residual corrections not specifically identified.

The data set is fit over the range 40–166 keV using resolution functions derived from each of the two ^{111}In calibration sources (numbered 1 and 2). In Table I we present the results of such fits for varying conditions of X, the 17-keV neutrino mixing fraction. In lines 1 and 2, the mixing fraction was set to zero (i.e., no 17-keV neutrino). For both fits we achieve reasonable values of χ^2. Comparing the two sets of parameters reveals the effects of differing resolution functions. As anticipated, the fitted end-point energy is significantly shifted ($\approx$160 eV). However, the linear and backscattering parameters, A and α, are statistically identical and therefore *not* sensitive to details of the spectrometer resolution function.

In lines 3 and 4 we fit the data again but now allow the 17-keV mixing fraction to vary. For both fits, allowance of a 17-keV neutrino does not significantly reduce χ^2—the resulting fitted values of the mixing fraction show no evidence of a 17-keV neutrino. Noteworthy is the fact that, as before, all fitted parameters except the end point are statistically unchanged by the differing resolution functions. This demonstrates that our ability to

TABLE I. Summary of fitted parameters using resolution functions from each ^{111}In calibration source.

Fit[a]	End point $E_0 - m_e$ (keV)	Linear AT (%/MeV)	Backscat. α/T^2 (keV^2)	Branch X (%)	DOF[b]	χ^2
1	167.149(6)	-6.6(1.4)	175(3)	0.00	122	137.3
2	167.305(6)	-7.4(1.4)	175(3)	0.00	122	135.3
1	167.147(9)	-6.7(1.4)	175(3)	-0.04(15)	121	137.2
2	167.308(9)	-7.3(1.4)	175(3)	0.05(15)	121	135.2
1	167.186(6)	-4.8(1.4)	179(3)	0.84	122	170.0
2	167.343(6)	-5.6(1.4)	179(3)	0.84	122	161.9

[a] Fits 1 and 2 correspond to calibration sources 1 and 2.
[b] Degrees of freedom.

fit for a 17-keV neutrino branch is unhindered by small uncertainty in the resolution function even though this creates a noticeable systematic shift in the fitted ^{35}S end point.

By averaging values from the two fits that included a 17-keV neutrino branch we achieve the following final results: The ^{35}S β decay end point is $167.228 \pm 0.009 \pm 0.100$ keV, where the 100-eV systematic error is due to resolution function uncertainty. No evidence is seen for a 17-keV neutrino branch—the mixing fraction is determined to be $(0.01 \pm 0.15)\%$.

In lines 5 and 6 of Table I we force the 17-keV mixing fraction to be 0.84% and refit the data. For both fits χ^2 increases by over 25 units indicating that a 0.84% 17-keV neutrino branch is indeed inconsistent with our data set at the 5σ level. In Fig. 4 we present the overall shape factor $S(E)$, defined as data/fit, for parameters from line 1 of Table I which have the 17-keV neutrino branch fixed at zero. If our equations admitting only the zero-mass neutrino are correct, this shape factor should be flat. At our level of statistics this appears to be true. On the same graph we have also shown the fit from line 5 of Table I, which assumed a 17-keV neutrino branch of 0.84%.

Our analysis has successfully fit the data at energies as low as 40 keV giving us confidence in our fitted parameters. Except for the fitted values of E_0, our parameters are fairly insensitive to the systematic uncertainty of the spectrometer resolution function. We therefore conclude there is no statistical evidence for a 17-keV electron neutrino branch in the β decay spectrum of ^{35}S. A branch of $(-0.13 \pm 0.15)\%$, determined by the reanalysis of the 1985 data [12], also supports this finding. These results are in serious disagreement (5σ) with the $(0.84 \pm 0.06)\%$ branch claimed by Hime and Jelley [10] and other previous results [8,9,11]. Recent measurements of the momentum spectrum of ^{35}S at Caltech [19] (using a $\pi\sqrt{2}$ spectrometer) and at Argonne [20] (using a solid-state detector and magnetic reflector) both reach this same conclusion. A reanalysis of the Hime and Jelley data by Piilonen and Abashian [16], and by Hime [21], have both shown that the evidence for a 17-keV branch in the data may be due to scattering effects not accounted for in the original analysis.

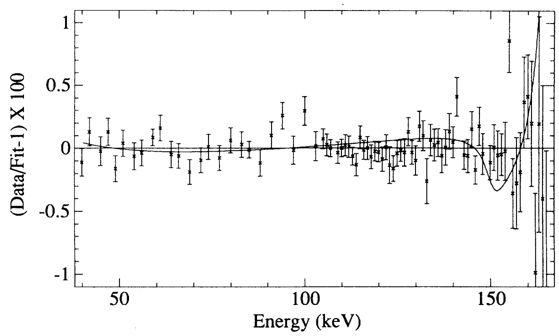

FIG. 4. The shape factor, defined as data/fit, has been plotted assuming no 17-keV neutrino branch. If this assumption is correct, the data should be flat. Overlayed is a curved line representing the best fit to the data assuming a 17-keV neutrino branch of 0.84%.

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