New Limits on the 17 keV Neutrino

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We present results of new measurements of the β spectrum of ^{35}S, using the Caltech double-focusing, iron-free β spectrometer. Our data show no evidence for a heavy neutrino with a mass between 12 and 22 keV admixed to the usual light neutrino. In particular, we rule out, at the 6σ level, a 17 keV neutrino admixed at 0.85%, and give an upper limit (90% C.L.) of 0.2% for such a neutrino admixture. To demonstrate that our experiment is sensitive to spectral features such as those from heavy neutrinos we have induced an artificial kink by means of an absorber foil covering part of the source.

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In recent years, a number of studies using magnetic spectrometers have aimed at measuring, with high precision, the shapes of β spectra in the decays of ^{35}S [1-4] and ^{63}Ni [5-7]. These experiments were triggered in response to a paper by Simpson in 1985 [8] in which evidence is presented for a heavy neutrino with a mass of 17 keV. This claim has been reiterated in subsequent papers by Hime and Simpson [9], by Hime and Jelley [10], and by others [11-13]. While all reported evidence for a 17 keV neutrino is based on experiments with Si and Ge detectors (notwithstanding the negative results of Refs. [14,15]), no evidence for a heavy neutrino in the mass range of about 5-50 keV has been reported from magnetic spectrometer experiments [1-7]. The subject has been reviewed recently by Hime [16], Boehm and Vogel [17], and Morrison [18].

In an effort to shed light on the controversy over the existence of a 17 keV neutrino we have reexamined the ^{35}S β spectrum with the help of the Caltech double-focusing spectrometer. This spectrometer had been employed already in 1985 for a similar heavy neutrino search [2], albeit with a different detector (different backscatter corrections and, consequently, different shape factor). In our recent study we measure the magnetic field rather than the current and we pay careful attention to possible systematic effects. In addition, we demonstrate the sensitivity of our apparatus with the help of a simulated "kink" feature. A preliminary communication was presented in Ref. [4].

The 35-cm-radius, iron-free double-focusing $\sqrt{2}\pi$ magnetic spectrometer at Caltech (momentum resolution 0.27%) employed at its focus a silicon surface barrier detector cooled by Peltier elements to approximately 5 °C. Its energy spectrum is shown in Fig. 1 (top); the energy resolution between 120 and 160 keV is ≈ 4 keV FWHM. The detector has an active surface layer of 300 μm and an area of 4 mm × 25 mm. A pulser was used to monitor the stability of the electronics.

The spectrometer was calibrated using a 100-μCi ^{57}Co source vapor deposited onto a 0.9-μm-thick Mylar backing (gold coated). Two ^{35}S sources were prepared using a technique that is a combination of vapor deposition and aqueous deposition. A layer of barium was first deposited on the gold-coated Mylar through a mask in the shape of the desired source (2 mm × 20 mm). An aqueous solution of ammonium sulfate containing carrier-free ^{35}S was then brought into contact with the barium-coated region of the foil. After the solution had been in contact with the surface for about an hour, it was drawn off using a micropipette. This process, with a yield of about 40%, allowed us to make sources with strength (thickness) of 3 mCi (0.8 μg/cm^2) and 7 mCi (2.1 μg/cm^2). With this new technique for source preparation, the measured ^{35}S decay in the experiment was consistent with the tabulated [19] half-life of 87.4 d.

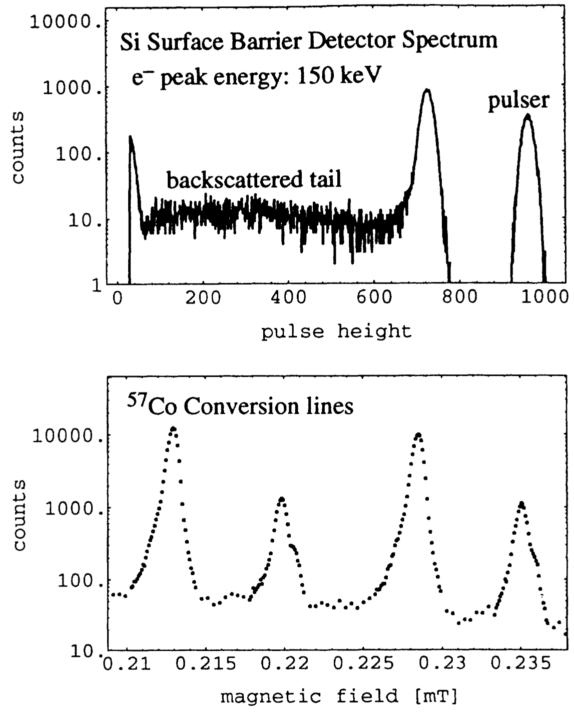

FIG. 1. Top panel: Si detector spectrum for electrons of 150 keV. Bottom panel: Internal conversion lines serving as response function from a spectrometer scan with a ^{57}Co source.

We directly monitored the magnetic field with two flux-gate magnetometers. A Bartington Instruments magnetometer and high field probe were used to measure the vertical component of the spectrometer field. A Walker Scientific magnetometer monitored the horizontal component of the ambient field, outside the spectrometer coils. The stability of the spectrometer field was better than 30 ppm over 15 min which, considering the steep slope of the spectrum near the end point, corresponds to a count-rate stability of better than 0.1%. We observed a secular variation in the ambient field consistent with typical fluctuations in the Earth's magnetic field. We also measured irregular but sizable ($\approx 1\%$ of the Earth's field) variations whose apparent origin is local to the building (see below). Field fluctuations were monitored throughout the experiment.

We used the ^{57}Co conversion lines to determine the spectrometer calibration and its response function (Gaussian). The conversion electron lines are shown in Fig. 1 (bottom).

Altogether, four data sets (runs A, B, C, and D) were acquired. Runs A and B were obtained with the 3-mCi source and runs C and D with the 7-mCi source. The spectra were measured in momentum steps of 0.5 keV/c (except run B where the step size was 0.2 keV/c) at 15 min per point, consistently sweeping from lower to higher energy. Each data point was corrected for source half-life and dead time. The background count rate in the detector, measured with the spectrometer set above the ^{35}S end point, was constant with momentum and amounted to 0.5% of the signal rate of 50 and 150 Hz at 150 keV for the two sources. It was subtracted from each data point.

The number of counts observed at each momentum setting was obtained by summing the counts in the detector spectrum, including those in the backscattered tail ($\approx 17\%$ of the spectrum), down to a fixed 20% of the peak energy (which amounts to 98% of the total spectrum intensity). Published parametrizations [20] of surface barrier detector response indicate that the fraction of counts excluded by this method has less than 0.3% energy dependence over the region of interest. The detector spectrum is shown in Fig. 1.

The corrected data were binned and fit with the allowed β spectrum for ^{35}S convoluted with the Gaussian response function determined from the ^{57}Co K-conversion lines. The spectral shape included Fermi function and radiative corrections [21]. A shape factor $f(p)$ given by $f(p)=1+k_1(p_0-p)+k_2(p_0-p)^2$ was introduced to account for a small smooth variation of the spectrometer acceptance with momentum. The quadratic shape factor k_2 was only needed for the wide scan A where it improved the χ^2 of the fit. It did not improve the fits of the narrow range run B, nor for runs C and D and was omitted for these runs. In all the fits the end point p_0, the normalization N, and shape factor k_1 (and k_2) were allowed to vary freely with the heavy neutrino mass M_ν set at fixed values. The admixture $|U|^2$ was set at fixed values or allowed to vary freely.

The data set A representing a 4-d run of the β spectrum between 131 and 164 keV yielded the following analysis. (See also illustrations in Fig. 2.) For zero admixture, the $\chi^2/N_{\rm DF}$ were 66/50, 51/49, and 37/48, re-

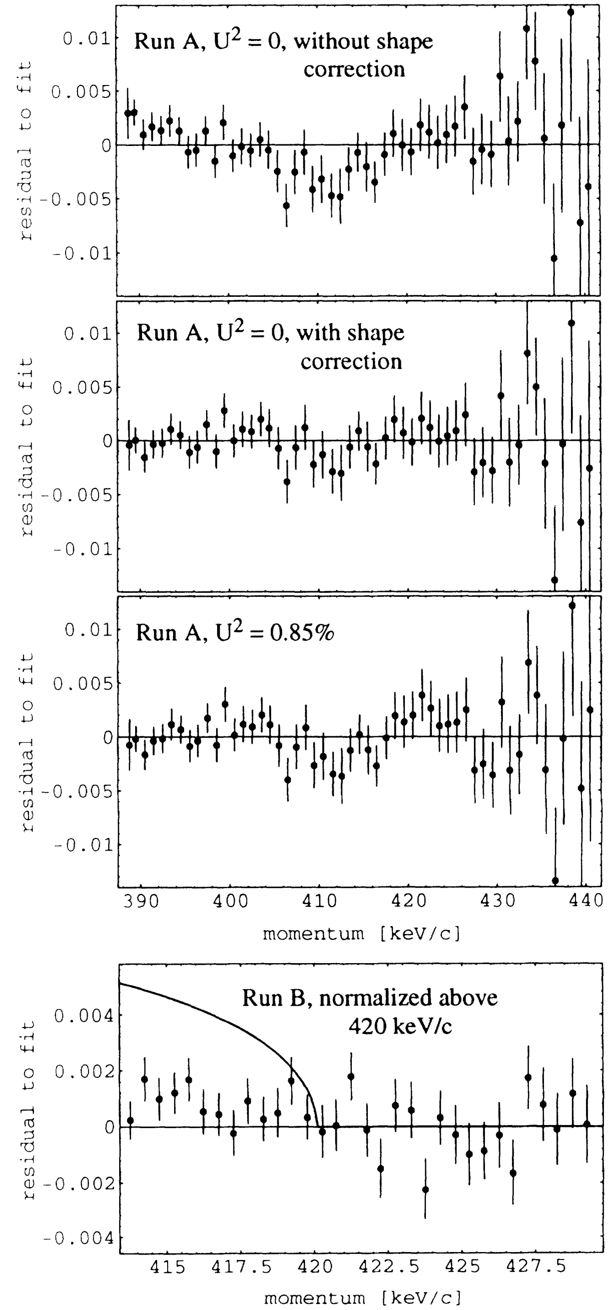

FIG. 2. Magnetic spectrometer data for selected fits for runs A and B. The momentum associated with a 17 keV "kink" is 420 keV/c. The solid curve in the bottom panel (run B) illustrates the expected behavior associated with a 17 keV neutrino. Here, the data points above 420 keV/c serve to normalize the data.

TABLE I. Results from four spectrometer experiments and combined limit for a 17 keV neutrino.

Run (range in keV)	Counts/(keV/c) at 420 keV/c	Shape parameters	$\chi^2/N_{\rm DF}$ $\lvert U\rvert^2=0.85\%$	$\chi^2/N_{\rm DF}$ $\lvert U\rvert^2=0$	$\lvert U_{eH}\rvert^2$ (%) best fit
A (131-164)	2.2×10^5	k_1,k_2	45.2/48	36.5/48	-0.58 ± 0.44
B (146-156)	2.8×10^6	k_1	36.4/29	25.7/29	-0.03 ± 0.27
C (122-163)	2.4×10^5	k_1	34.6/26	25.3/26	-0.04 ± 0.28
D (123-164)	2.6×10^5	k_1	42.5/37	28.4/37	0.06 ± 0.21
Average A-D					-0.05 ± 0.14
Limit (90% C.L.)					<0.20

spectively, correspond to the following shape parameters: $k_1=k_2=0$ (set), $k_1=(1.9\pm0.5)\times10^{-4}$ keV/c (fit) with $k_2=0$ (set), and $k_1=(1.2\pm0.3)\times10^{-3}$ keV/c with $k_2=(1.4\pm0.3)\times10^{-5}$ (keV/c)^2 (fit). For a 17 keV neutrino with $|U|^2=0.85\%$, the corresponding $\chi^2/N_{\rm DF}$ were 88/50, 87/49, and 45/48, respectively. Leaving $|U|^2$ free, we find the parameters displayed in Table I with $k_1=(-4.5\pm6.8)\times10^{-4}$ keV/c, $k_2=(8\pm6)\times10^{-6}$ (keV/c)^2. The end-point energy E_0 was 167.56 ± 0.03 keV with k_1 and k_2 fit.

In set B (146-156 keV) of 15-d duration, also shown in Fig. 2, a 10-keV region around the hypothetical kink for a 17 keV neutrino was scanned with high statistics. Fits for $|U|^2=0$ give $\chi^2/N_{\rm DF}=30/30$ and 26/29, respectively, with $k_1=0$ (set) and $k_1=(3.3\pm2.2)\times10^{-4}$ keV/c (fit). (Including k_2 gives $\chi^2/N_{\rm DF}=26/28$.) For $|U|^2=0.85\%$ we find $\chi^2/N_{\rm DF}=58/30$ and 36/29 with $k_1=0$ (set) and $k_1=(9.6\pm2.0)\times10^{-3}$ keV/c (fit). (Including k_2 gives $\chi^2/N_{\rm DF}=36/28$.) With $|U|^2$ free, we find the best-fit parameters given in Table I with $k_1=(3.8\pm4.8)\times10^{-4}$ keV/c. The end-point energy was 167.55 ± 0.04 keV. It should be noted that the magnitude of the shape factors over the energy range of interest is less than 1% as can be seen in the top display of Fig. 2.

The results of similar fits to the data of runs C and D are also displayed in Table I. For these runs we find $k_1\approx3\times10^{-4}$ keV/c, consistent with run B, with no improvement of χ^2 by the inclusion of k_2.

Considering the four runs to be independent data sets acquired under varying conditions (such as different sources), we now proceed to average the results of the fits from runs A, B, C, and D, neglecting possible correlated systematic errors. We find a mean value for the admixture to a 17 keV neutrino is $|U|^2=(-0.05\pm0.14)\%$, consistent with no mixing and we state a 90% C.L. upper limit for the admixture of a 17 keV neutrino of $|U|^2\leq0.20\%$. For all the quoted exclusions, the prescription of the Particle Data Group [22] for estimating parameters constrained to lie within a bounded physical region (positive $|U|^2$) was used.

The accuracy of the data presented here was ultimately limited by magnetic field disturbances local to the building. In particular, in runs C and D we observed such disturbances and identified their sources (powerful LIGO lasers), while none were seen in runs A and B. It was found that these external fields also influenced, to some degree, the shape factor.

A local field fluctuation can create a disturbance which is nonuniform across the path of the electrons in the spectrometer. If a probe samples the spectrometer field at only one point, such a nonuniform disturbance in the magnetic field can distort the count rate at that measured field setting. Therefore, for runs D and C the second probe was positioned at the diametrically opposite end of the spectrometer from the Bartington calibration probe. By measuring the field at two points which bracket the electron orbit, one can quantify the effects of external field gradients on the measured count rate. It was found that requiring agreement between the measured ratios of the two probes (for all field settings and all data points) to better than 1 part in 10^4 was sufficient to eliminate the count-rate shifts caused by observed, local, nonuniform field disturbance. The acceptance of data points required that they pass this field consistency cut. The two runs C and D with the 7-mCi source thus correspond to two different such ratios about which this field consistency cut was applied. It should be noted that the measured shape factors for runs B, C, and D are in good agreement.

In order to demonstrate that spectrometer experiments can detect a kink such as that produced by a hypothetical

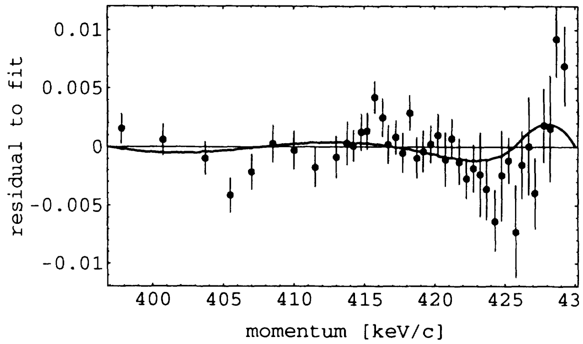

FIG. 3. Synthetic kink induced in the β spectrum with a 17-μm foil. The solid curve is the result of a computer simulation.

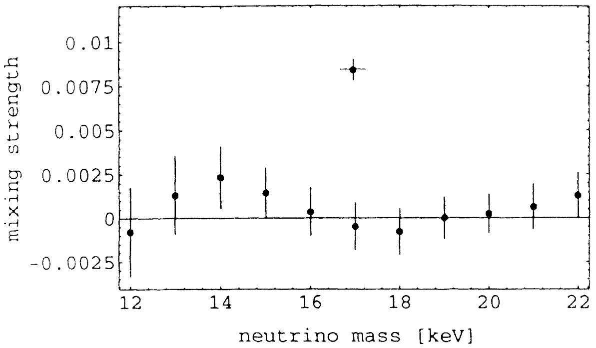

FIG. 4. Mixing strength vs mass of a heavy neutrino as obtained from our data. The data point at $|U|^2=0.85\%$ is taken from Ref. [10].

17 keV neutrino we have carried out the following auxiliary experiment. We have introduced a kink of known size and energy into the spectrum by masking off roughly 10% of the source with a 17-μm aluminum foil, which causes a minimum energy loss of 14 keV for 150-keV electrons passing through it. Taking the shape as estimated by an EGS4 calculation of electron transport through the foil, we predict an induced spectra distortion whose magnitude is equivalent to the distortion from a 1.5% admixture of a heavy neutrino, in a ±3-keV region around the distortion threshold. This is lower than the fraction of the source area covered because the spectral distortion created by energy loss is smoother than the kink expected for a heavy neutrino. In addition, some fraction of the electrons incident on the foil are scattered out of the transmission aperture of the spectrometer or backscattered towards the source, reducing the magnitude of the distortion. A spectrum was acquired over 48 h with the 7-mCi source and aluminum foil. The data in Fig. 3 show the residual to a β spectrum without heavy neutrino, ignorant of the foil distortion. Free linear and quadratic shape parameters were included. A kink is visible in the data and could not be removed by the inclusion of freely varying shape parameters ($\chi^2/N_{\mathrm{DF}}=61.9/37$), demonstrating the sensitivity of the spectrometer to a kink. The overlay solid curve shows the Monte Carlo simulated spectrum with energy loss.

In conclusion, from four independent data sets, we rule out, at the 6σ level, a 17 keV neutrino admixed with a strength of $|U|^2=0.85\%$ to the usual light neutrino contradicting the results of Simpson and others. At the 90% C.L. we rule out an admixture of $|U|^2\geq 0.20\%$ for a heavy neutrino in the mass range between 16 and 20 keV. For other masses, the $|U|^2$ values are shown in Fig. 4.

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