Experimental Search for a Heavy Neutrino in the Beta Spectrum of ^{35}S

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We present results of an experimental study of the shape of the energy spectrum for the decay $^{35}S \to {}^{35}Cl + e^- + \nu_e$. The measurements were performed to search for evidence of a beta-decay branch with a heavy neutrino. No evidence for heavy neutrinos is observed. In particular, our limit for the branch to a 17-keV neutrino is 0.4%, in serious disagreement with the 3% branch claimed by Simpson.

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In a recent measurement of the beta-energy spectrum for tritium decay, Simpson[1] has claimed that a kink observed near 1.6 keV might be due to a weak branch with a neutrino having a mass of 17 keV. If the kink is indeed due to a heavy-neutrino decay branch, there should be a similar kink at 17 keV below the end point in other beta-decay spectra. We have made a search for such a kink in the momentum spectrum of the ^{35}S beta decay

$$^{35}S \to {}^{35}Cl + e^- + \nu_e \quad (t_{1/2} = 87 \text{ d}, \ E_0 = 167 \text{ keV}).$$

(E_0 is the kinetic energy.) Our motivation for choosing this decay is that the relatively low end-point energy puts the suggested kink at a convenient kinetic energy of 150 keV. In addition, ^{35}S has a simple allowed spectrum shape which is only very slightly affected by higher-order matrix elements.[2] Finally, the ^{35}S and ^3H decays both involve electron antineutrinos.

To specify the momentum spectrum with heavy neutrinos we note first that the weak-interaction states of the known neutrinos ν_e, ν_μ, and ν_τ are related to the mass eigenstates ν_1, ν_2, and ν_3 by the unitary transformation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}.$$

The momentum spectrum for electron decay is then given by

$$d\lambda = (G^2/4\pi) p^2 (E_0 - E)^2 dp \, F_0 L_0 R(E) S(E) \{ U_{e1}^2 [1 - m_1^2/(E_0 - E)^2]^{1/2} + U_{e2}^2 [1 - m_2^2/(E_0 - E)^2]^{1/2} + U_{e3}^2 [1 - m_3^2/(E_0 - E)^2]^{1/2} \}.$$

Here G is the weak-interaction coupling constant, p and E are the electron momentum and energy, $F_0 L_0$ is the Fermi function,[3] R is a radiative correction factor,[3] S is the shape factor,[2] and m_i is the mass of neutrino ν_i. E_0 is the total energy available to the electron and neutrino. If the Simpson result is interpreted in terms of the mixing of just two neutrino mass states, ν_i and ν_j, the kink in the ^3H spectrum implies $U_{ei}^2 \approx 1$, $m_i \approx 0$, and $U_{ej}^2 = 0.03$, $m_j = 17$ keV. For simplicity we will also analyze the ^{35}S beta spectrum in terms of two-state mixing.

Measurements of the ^{35}S beta spectrum were made with the iron-free intermediate-image magnetic spectrometer[4] illustrated in Fig. 1. The source is positioned at the center of one coil and the detector is at the center of the other coil. Axial positioning of the source, which is critical for precise momentum–magnetic-field calibration, was achieved by use of a special fixture which reproduced the axial source position to ± 0.005 cm, corresponding to an uncertainty in the field-momentum calibration of 0.015%. The magnetic field profile produces an intermediate radial focus midway between the coils and a final focus at the center of the second coil, with a final magnification of approximately 1. Entrance baffles placed near the the source, which restrict the takeoff angle, are adjusted to produce a symmetric line shape for a monoenergetic electron line. For a given magnetic field and a point source, the radius and width of the annular slit determine the transmitted momentum p and the spread in momentum δp, respectively. The resolution $\delta p/p$ (FWHM) is 0.018 for the source size (5 mm diameter) and slit width (4.8 mm) used. At a kinetic energy of 150 keV, the position of the supposed kink onset, the energy resolution is 4.8 keV. This resolution is very suitable since the kink is such that it reaches 50% of its maximum as the energy drops by 2.6 keV below 150 keV.

The spectrometer was calibrated with the K-conversion-electron lines of ^{111}Cd that arise from the decay of ^{111}In(2.8 d). To minimize systematic errors in calibration, the ^{111}In was implanted in an identical source foil in the same way as the ^{35}S (see below). The two ^{111}In electron lines at 144.58(3) and

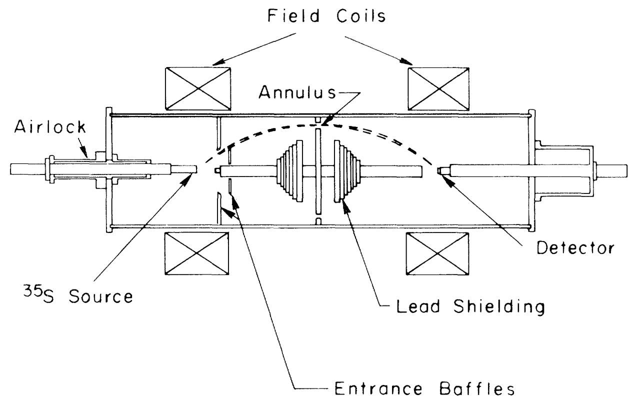

FIG. 1. Side view of the iron-free intermediate-image beta spectrometer. The two coils produce a magnetic field that is axially symmetric about the long axis of the spectrometer. The radial displacements of typical orbits are indicated by dashed lines.

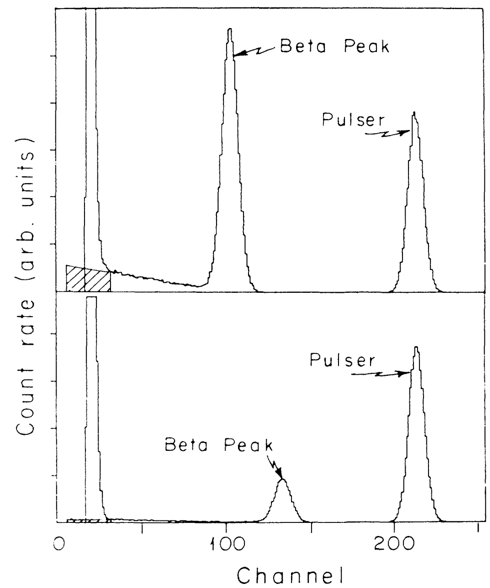

FIG. 2. The pulse-height spectra registered in the surface-barrier detector for electrons transmitted by the magnetic spectrometer. The tail below the full-energy beta peak is due to electrons that have scattered out of the detector before depositing all of their energy. The dashed line at the left is an estimate of the backscatter spectrum below the noise.

218.64(4) keV[5] bracket the end-point energy of ^{35}S. Calibration data were taken before, during, and after acquisition of the ^{35}S data. The uncertainty associated with fixing of the axial position of the sources is ± 50 eV (see above). The observed consistency of the three calibrations is such that beta energies calculated near the ^{35}S end-point energy agree within 1/5000 (± 30 eV), in reasonable agreement with the uncertainty due to axial positioning of the sources. Given the uncertainties in the energies of the calibration lines and the reproducibility of the calibrations, we believe that the energy is known to better than 100 eV near the end point.

The magnet was driven by a Spectromagnetics model 6003 current-regulated power supply under program control of a microcomputer.[6] A surface-barrier detector (450-mm^2 area, 1000 μm thick) was mounted at the focus of the spectrometer to record the transmitted intensity for each setting of the magnetic field. The detector noise was typically 13 keV. A smaller-area surface-barrier detector (100 mm^2) was also used for part of the data in an effort to obtain lower noise. The same computer controlled a CAMAC pulse-height-analysis system consisting of a LeCroy model 3512 analog-to-digital convertor and a model 3588 Histogramming Memory Module. This system was used to acquire the detector pulse-height spectrum for each of the 32 settings of the spectrometer.

Typical pulse-height spectra taken at kinetic energies of 110 and 150 keV are shown in Fig. 2. The peak at the right is that of an electronic pulser which is used to measure the system live time. The peak in the center is the full-energy peak due to focused electrons that deposit all their energy in the detector. The sharp increase in counts at low energies is due to electronic noise. Below the full-energy peak is a tail caused by electrons that deposit part of their energy before backscattering out of the detector. An estimate of the intensity of those events whose pulse heights are below the detector noise is made by our assuming a linear tail down to zero kinetic energy (see cross-hatched regions). The correction for counts below noise, as so specified, is found to be well described by a linear function of the focused beta energy varying from 16.5% at 110 keV to 11.2% at 165 keV. Because we do not know the actual shape of the low-energy tail below the noise, the true correction may have a different energy dependence. However, the systematic error in our procedure is likely neither to simulate a neutrino mass kink nor to cover up such a kink because the correction is a smooth function of the energy.

There is a 40-μg/cm^2 Au contact layer on the entrance side of the detector from which electrons can backscatter before they reach the sensitive region. Measurements of the transmission of electrons through an equivalent Au foil placed in front of the detector were made as a function of beta energy. The loss is about 2% at 100 keV and decreases by 1% from 110 to 167 keV. Again, we corrected the shape factor with a 1% linear variation to the slope, and any systematic error in this correction is unlikely to simulate or mask a neutrino mass effect.

A 15-μCi source of ^{35}S was prepared by isotope separation from a 25-mCi carrier-free sample purchased in the form of sulfuric acid from New England Nuclear, Inc. The mass-separated 60-keV $^{35}S^+$ ion beam from the Princeton Isotope Separator was implanted in a 5-mm-diam spot on a 40-μg/cm^2 carbon foil that was laid over four thin layers of Formvar (total backing thickness ≈ 20 μg/cm^2). Calculations of source scattering effects[6] indicate that the source backing is too thick for a study of the lower part of the spectrum, but above 100 keV the effects are not significant. The source foils were mounted on a thin aluminum ring (0.007-cm thick, 2-cm diameter, i.d., 3.2-cm diameter o.d.) attached by thin aluminum strips (7.5 cm long) to a positioning tube inserted into the spectrometer.

The main data set consists of several runs of 32 pulse-height spectra (256 channels each) taken approximately every 2 keV from about 100 keV to beyond the end-point energy. The data taken beyond the end point determine the background to be subtracted. In a typical run lasting 10 h, the field settings were scanned many times with a scan time of about 16 min. Since the scan time was very short compared to the half-life, the correction for radioactive decay is negligible.

The raw data were corrected for counts lost below the noise and for reflection off the Au layer. The ratio $y(E)$ is obtained by dividing the corrected intensities by the theoretical intensities at the same energies. The theoretical spectrum is calculated by convoluting the spectrometer-resolution function with the product of the phase-space factor (assuming a zero neutrino mass) $p^2(E_0-E)^2$, the Fermi function F_0L_0, and the radiative correction factor $R(E_0,E)$. Finally, the values of the ratios $y(E)$ were normalized by requiring that the average value be unity. The spectrometer-resolution function was determined from the empirical ^{111}In conversion-electron line shapes measured with sources implanted into the same spot size on carbon foils of the same thickness. The Fermi function was computed by methods[7] similar to those used for the tables of Behrens and Jaenecke[8] and included, in particular, the finite nuclear size and screening effects. Agreement between our calculations and the tabulated values of Behrens and Jaenecke is better than 0.01% for the few cases computed with screening given in their table.

In Fig. 3 we illustrate the spectrum ratio $y(E)_{\rm exp}$ obtained by the above procedure. An end-point energy E_0 of 166.80 ± 0.15 keV is in best agreement with our data. The uncertainty in the end-point energy is estimated from the sensitivity of the shape to small changes in the end-point energy and from the calibration uncertainty. This value is in excellent agreement with the value 166.84 ± 0.20 keV given in the recent tabulation of atomic masses by Wapstra and Audi.[9]

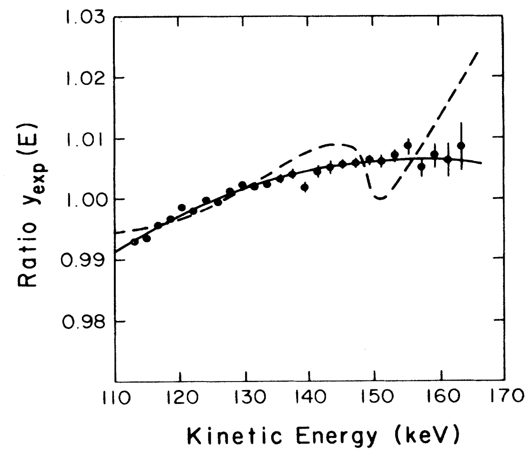

FIG. 3. The experimental ratio $y(E)_{\rm exp}$ of the measured intensity to the theoretical intensity assuming zero-mass neutrinos. The solid line through the points is the best fit with a linear plus quadratic function. The dashed line illustrates the best fit for a 17-keV neutrino with a branch intensity of $(U_{ej}/U_{ei})^2 = 0.03$.

If all corrections as described above are complete and if the neutrino masses are zero, the ratio $y(E)$ would then be the shape factor $S(E)$, which is constant in the allowed approximation. The energy dependence due to higher-order matrix elements is calculated to cause an increase in $S(E)$ of a negligible 0.013% over the entire spectrum.[2] The signature of a nonzero neutrino mass would be a kink in the ratio $y(E)$, described by the function

$$y(E)_{\rm exact} = 1 + d[1 - m_\nu^2/(E_0-E)^2]^{1/2},$$

where d is $(U_{ej}/U_{ei})^2$. Because the procedures we employ for correcting the raw counts are not exact, we expect that the experimental ratio $y(E)_{\rm exp}$ could have an additional smooth instrumental dependence on the kinetic energy E_K. Therefore, we assume the more general function

$$y(E)_{\rm exp} = a + bE_K + cE_K^2 + d[1 - m_\nu^2/(E_0-E)^2]^{1/2}.$$

For a given value of m_ν, we fit the data to obtain the best values for a, b, c, and d. A positive value for d signals a nonzero neutrino mass.

Our result for the ratio $y(E)_{\rm exp}$ exhibits no evidence for a kink of any significance. The slight slope and curvature to $y(E)_{\rm exp}$ are not unreasonable given that the corrections for instrumental distortions are approximate and of a comparable size. A four-parameter fit to the data assuming a neutrino mass of $m_\nu = 17$ keV yields a reduced χ^2 of 1.100 and the values $a = 0.803 \pm 0.003$, $b = (2.76 \pm 0.47) \times 10^{-3}$/keV, $c = -(9.3 \pm 1.9) \times 10^{-6}/(\text{keV})^2$, and $d = -(2.9 \pm 2.1) \times 10^{-3}$. The limit for d at the 99% confidence level is

$d \leqslant 4 \times 10^{-3}$, which is almost ten times smaller than Simpson's result. A three-parameter fit to this data (omitting the neutrino mass term) gives a very reasonable reduced χ^2 of 1.133 (with 24 degrees of freedom) and the values $a = 0.833 \pm 0.016$, $b = (2.2 \pm 0.2) \times 10^{-3}/\mathrm{keV}$, and $c = -(7.1 \pm 0.9) \times 10^{-6}/(\mathrm{keV})^2$. The curve for this fit is shown as the solid line in Fig. 3. Alternately, if we assume Simpson's value $d = 0.03$ and perform another three-parameter fit to a, b, and c, the reduced χ^2 increases to the unreasonable value of 11.4. The curve for this fit is illustrated as the dashed line in Fig. 3. Note that a, b, and c have changed drastically to try to compensate for the 3% kink.

In conclusion, our limit of 0.4% for the intensity of a 17-keV neutrino is in strong disagreement with the claim of Simpson for a 3% 17-keV-neutrino branch. Our data also set limits for the intensity of other masses that in general depend on the assumed mass but at the 99% confidence level rule out intensities greater than 0.75% for all masses between 5 and 50 keV.

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