Evidence for the Emission of a 17-keV Neutrino in the β Decay of ^{14}C

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We have studied the β spectrum of ^{14}C using a germanium detector containing a crystal with ^{14}C dissolved in it. We find a feature in the β spectrum 17 keV below the end point which can be explained by the hypothesis that there is a heavy neutrino emitted in the β decay of ^{14}C with a mass of 17 ± 2 keV and an emission probability of $(1.40 \pm 0.45 \pm 0.14)\%$.

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The observation of an anomaly or "kink" 17 keV below the end point in the β spectrum of ^3H was first reported by Simpson[1] and interpreted by him to correspond to the emission of a neutrino with a 3% admixture of a state of mass 17 keV. This report was criticized[2-5] on the grounds of both the experimental method and the data analysis. Moreover, it was quickly followed by a number of studies[6-13] which all claimed to rule out the hypothesis of 3% 17-keV neutrino admixture at various confidence levels. Finally, in 1989, there appeared new reports of β-spectrum anomalies in ^{35}S (Ref. 14) and ^3H (Ref. 15) corresponding to a $\sim 1\%$ admixture of a 17-keV neutrino.

If Simpson's results are correct, then this kink should be present in all β spectra. It is, therefore, important to test this claim for different nuclei. This prompted us to mount an experiment to look in detail at the β spectrum of ^{14}C. The β decay of ^{14}C is an allowed ground-state-to-ground-state transition with an end-point energy near 156 keV. Moreover, we were aware of a unique detector produced by Haller *et al.*[16] that was ideally suited for this experiment. The detector contains a germanium crystal grown from a melt of germanium which had ^{14}C-labeled carbon dissolved in it. This system functions as a windowless detector with a nearly ideal response function for the β particles emitted by the ^{14}C inside the crystal.

To produce such material, ^{14}C-labeled methane (enriched to 10% ^{14}C) was cracked into graphite on quartz crucibles. Germanium was then placed in these crucibles, melted, and pulled into single crystals. Autoradiographs of the crystal used in the present study (crystal No. 701 from Ref. 16) indicated that the ^{14}C is dispersed uniformly throughout the crystal. This detector has a ^{14}C concentration of 6×10^{11} cm^{-3} and a planar *p-i-n* diode structure with a thickness of 1.28 cm. The n^+ electrode is divided by a 1-mm-wide circular groove into a "center region," 3.2 cm in diameter, and an outer "guard ring." By operating the guard ring in an anticoincidence mode, one can reject events occurring near the boundary which are not fully contained within the center region. The ^{14}C β-decay counting rate from the center region of the crystal is 20 s^{-1}.

The present experiment was conducted at Lawrence Berkeley Laboratory's low background counting facility. A 1.3-cm-thick brass plate was placed on the front face of the detector which was then placed inside a graded shield made of Al, Cu, Cd, and Sn. 10–15 cm of low-activity lead surrounded the entire assembly. Signals from the center region and guard-ring portions of the ^{14}C crystal were separately processed through Tennelec model 243 amplifiers using 4-μs shaping times. Signals from a two-channel precision pulser were fed through the preamplifier at a rate of 5 Hz to monitor the gain and dc offset. Data were taken using an Ortec 916 PC-based acquisition system. Three separate spectra were accumulated using three separate analog-to-digital converters (ADC's): (1) center region, (2) center region in anticoincidence with guard ring, and (3) guard ring. The guard-ring veto signal used to generate spectrum (2) required that an event deposit between 20 and 183 keV in the guard-ring portion of the crystal. Data were collected in 4096 channels of 0.144 keV width and were recorded in 1-d time bins on the disk of an IBM PC/AT computer.

The ^{14}C crystal was counted for 122 d. After this period, the ^{14}C crystal was removed from the cryostat, and a similarly shaped planar guard-ring germanium crystal containing approximately the same amount of carbon, but no ^{14}C, was installed. The diameter of the center region of this crystal is 2.7 cm and the thickness is 1.42 cm. 52 d of background data were accumulated with this crystal. The centroids of the pulser peaks and those of the background γ-ray lines showed no significant variation (< 0.1 keV) over the course of these data-taking runs. Thus, all of the ^{14}C spectra were summed together without applying any gain shifts or offsets and are shown in Fig. 1(a). The result of summing all of the background spectra is shown in Fig. 1(b). The resulting background-subtracted ^{14}C β spectrum contains a total of 2.25×10^8 counts. There are $\sim 10^6$ counts in the last 17 keV of this spectrum, and there are $\sim 10^5$ counts/keV

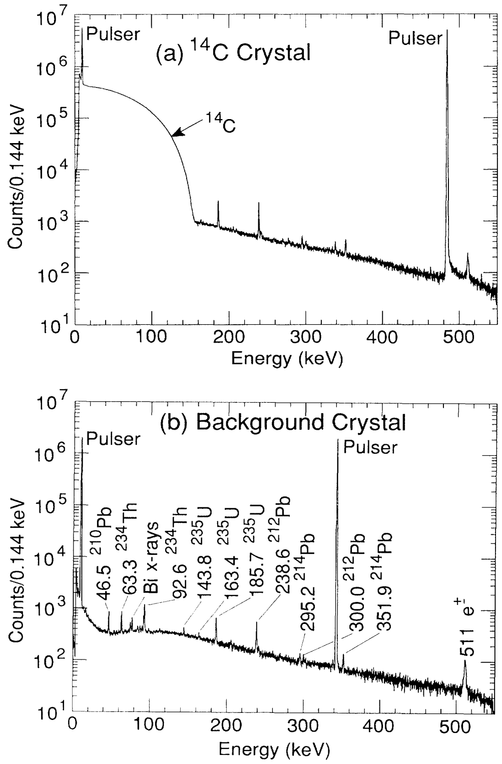

FIG. 1. (a) Type-(2) spectrum observed from 122 d of counting with the ^{14}C-doped germanium crystal. (b) Type-(2) spectrum observed from 52 d of counting with the background crystal. γ-ray energies are given in keV. Because of the different capacitances of the ^{14}C-doped crystal and the background crystal, it was not possible to place the upper pulser peak at the same position in the two spectra.

17 keV below the end point.

If in nuclear β decay there are actually two decay channels open, one associated with $m_\nu=0$ and one with $m_\nu\neq 0$, then the spectrum of β particles is given by the expression[17]

$$\frac{dN(E)}{dE}=(1-c)\frac{dN(E,m_\nu=0)}{dE}+c\frac{dN(E,m_\nu)}{dE}, \quad (1)$$

where

$$\frac{dN(E,m_\nu)}{dE}\propto AF(Z,E)pE(W-E)[(W-E)^2-m_\nu^2]^{1/2}. \quad (2)$$

In the case of ^{14}C, the coefficient c is very nearly equal to the probability of heavy-neutrino emission. A is the overall spectrum normalization factor, $F(Z,E)$ is the Fermi function for $Z=7$ with relativistic[18] and screening[19] corrections applied, E and p are the electron total energy and momentum, respectively, and W is the total decay energy. There have been discussions[20,21] as to possible deviations in the shape of the ^{14}C β spectrum from that expected for a pure allowed transition. To allow for smooth departures from an allowed shape, the above theoretical spectrum was multiplied by a "shape factor" of the form

$$1+\beta_1(W-E)+\beta_2(W-E)^2. \quad (3)$$

The resulting spectrum was then convoluted with the detector response function which we assume consists of a Gaussian-shaped peak and a flat tail extending down to zero kinetic energy. This tail is caused by β's and bremsstrahlung that escape from the surfaces of the crystal without being vetoed by the guard ring. The fraction of events in this tail is assumed to increase linearly with the β energy due to the increased range of the β's. Using external γ-ray sources and the background lines observed during the data taking, we determined that the FWHM of the Gaussian peak is 1.0 ± 0.1 keV over the energy range of interest. From the known ranges and bremsstrahlung energy losses of β's in germanium,[22] we estimate that this tail contains at most 1.5% of all 156-keV β^- events originating in the center region of the crystal. The response function of this detector for electrons originating within it was also calculated using the Monte Carlo code GEANT.[23] The results of these calculations indicate that this tail may actually contain only about 0.2% of all β-decay events. We performed analyses with the tail set equal to 0, 1.5%, and 4% and obtained similar results.

The experimental data were then compared to the theoretically expected spectrum using a least-squares-fitting procedure in which for given values of m_ν and c, the following five parameters were allowed to vary simultaneously: A, W, β_1, β_2, and the background normalization factor. This analysis was performed on the data in the energy range 100–160 keV both in 0.144-keV-wide energy bins (418 data points) and on a data set compressed to 1 keV per channel. The results of the analysis on the unbinned data are shown in Fig. 2(a). The minimum value of χ^2 obtained under the assumption of only massless neutrinos is 415. The absolute minimum value of χ^2 is 406 and is found for $m_\nu=17$ keV and $c=1.4\%$. Thus, there is a difference of 9 units of χ^2 between these two cases. This excludes the null hypothesis statistically (i.e., no heavy-neutrino emission) at the 99%-confidence level.[24]

To check on what sensitivity is expected from data of the quality we have obtained, we generated approximately fifty Monte Carlo data sets corresponding to the case of (i) $m_\nu=17$ keV, $c=(1.0\text{–}1.4)\%$, and five data sets for the case (ii) $m_\nu=0$. These data sets were then analyzed in the same manner as the experimental data. Typical results for case (i) are shown in Fig. 2(b). The minimum value of χ^2 obtained from this data set was 411 for $m_\nu=17.5$ keV, $c=1.2\%$. The value of χ^2 found for $m_\nu=0$ in this data set was 420. Figure 2(c) shows the results of the fitting procedure applied to an example of case (ii). The minimum value of $\chi^2=416$ occurs, as expected, for $m_\nu=0$, and the value obtained for $m_\nu=17$ keV, $c=1.4\%$ is 9 units larger. These results demon-

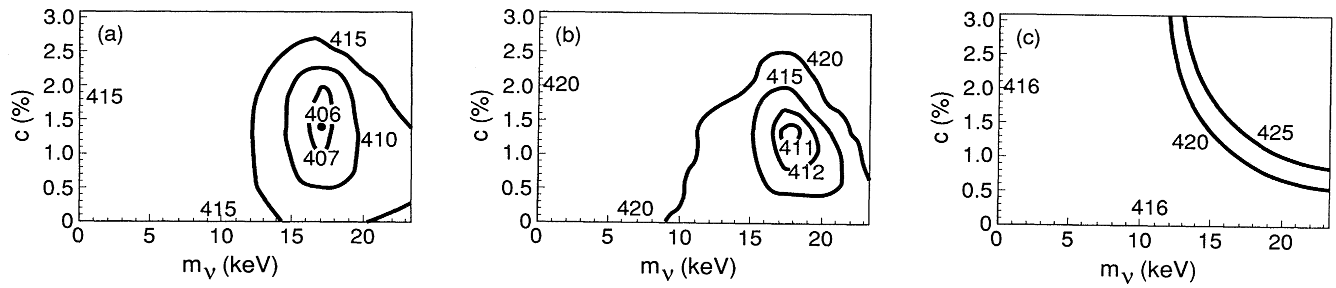

FIG. 2. Contour plots of χ^2 as a function of the neutrino mass m_ν and c. The curves are labeled by the values of χ^2. (a) Analysis of our type-(2) data; (b) analysis of Monte Carlo–generated data which contains a 1.4% fraction of a 17-keV neutrino; (c) analysis of Monte Carlo–generated data which contains only a zero-mass neutrino.

strate that our experiment has the statistical sensitivity to distinguish between these two cases at the level observed in our experimental data.

Various projections of these results can be made by fixing one parameter and allowing all others to vary in such a way as to minimize χ^2. Such a procedure allows for any possible correlations between the various parameters. The resulting χ^2 distributions turn out, as expected, to be nearly parabolic. From these parabolas, we obtain[24] $m_\nu = 17 \pm 2$ keV, $c = (1.40 \pm 0.45)\%$, $E_0 = W - m_e = 155.74 \pm 0.03$ keV, and the background normalization factor $= 3.39 \pm 0.04$ (1σ statistical uncertainties only). We find that there is a linear correlation between β_1 and the assumed fraction of events which are in the tail of the response function. β_1 changes from $(1.10 \pm 0.05) \times 10^{-3}$ keV^{-1} for a tail fraction of zero to $(0.76 \pm 0.05) \times 10^{-3}$ keV^{-1} for a tail fraction of 4%. The best-fit value obtained for β_2 is of order 10^{-8} keV^{-2}. However, we find that β_2 can be set equal to zero with no degradation in the quality of the fits. The range of possible β_1's we find agrees well with the value of 1.2×10^{-3} keV^{-1} obtained in a recent calculation of the ^{14}C shape factor.[25] The best-fit value of the background normalization factor agrees with those found by taking the ratios of the U and Th decay-chain γ-ray photopeak areas and the ratio of the continua observed just above the ^{14}C end point in the ^{14}C and background spectra.

We have performed a variety of tests to determine if some aspect of the detector response or data analysis could account for this kink. Using external γ-ray sources, we searched for an anomaly 17 keV below the photopeak and found no such feature at a level $\geq 10^{-3}$ of the photopeak. We did observe the Ge x-ray escape peak which occurs 10 keV below the photopeak. For a 122-keV γ ray, this peak is 0.1% as large as the photopeak and cannot account for our result. We used a ramped pulse generator to test the ADC used in collecting the type-(2) spectra for differential nonlinearities and found no evidence for variations $\geq 10^{-3}$ in 1–50-keV-wide intervals over the channel range used in our data analysis. We also looked for such effects by examining the linearity of our energy calibration and found similar results. From these tests we established that our systematic error in the determination of c is at most 10% and for E_0 is approximately 0.5 channel (0.07 keV). Thus, we report $c = (1.40 \pm 0.45 \pm 0.14)\%$ and $E_0 = 155.74 \pm 0.03 \pm 0.07$ keV. The present result for the end-point energy does not agree with the value of 156.476 ± 0.005 keV deduced from the mass spectrometry data of Smith and Wapstra,[26] but falls in the middle of the results of previous β end-point energy measurements.[26]

We performed a similar χ^2 analysis on the center-region singles spectrum, i.e., the type-(1) data. This spectrum also shows evidence of an anomaly 17 keV below the end point and yields $c = (0.75 \pm 0.40)\%$. Since these data were taken with a different ADC than that used to collect data of type (2), this test shows that the kink is not produced by a defect in one region of one particular ADC. It also demonstrates that the kink is not an artifact of the imperfect containment of energy in the center region of the detector. We have also found that the values obtained for m_ν, c, and E_0 are quite insensitive to the assumed value for the detector resolution.

To check that the kink is not an artifact of improper background subtraction, we tried another scheme for this subtraction. The continuous background above the ^{14}C end-point energy observed with the ^{14}C-doped detector was fitted using a fourth-order polynomial. Using the results of this fit, the background underneath the ^{14}C spectrum was computed and subtracted from the data. Analysis of this background-subtracted data (excluding a 4-keV-wide region centered on the 143.8-keV ^{235}U γ-ray line) again shows a kink 17 keV below the end point and yields $c = (1.2 \pm 0.5)\%$.

To illustrate the degree to which the calculated spectra agree with the data, we have divided the data by the results of the best fit obtained under the assumption of only massless neutrinos. This is illustrated in Fig. 3(a) for our type-(2) data, and in Fig. 3(b) for Monte Carlo data generated with $m_\nu = 17$ keV and $c = 1\%$. For display purposes, the data were compressed into 1-keV-wide bins. The horizontal line is the expectation for massless neutrinos. The curve shown in (a) is what one obtains

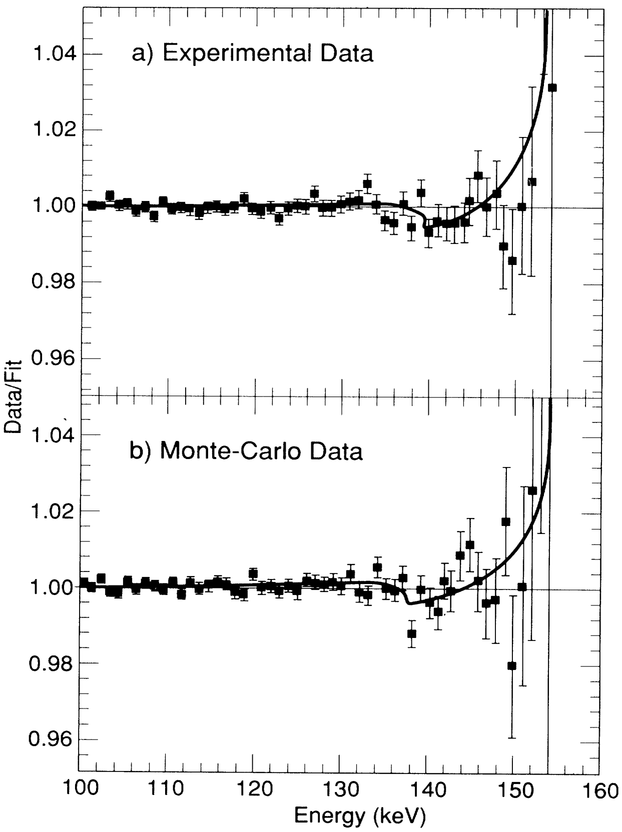

FIG. 3. The ratio of the data to a theoretical fit assuming the emission of only zero-mass neutrinos. The data were compressed to 1 keV/channel. The horizontal line is the shape expected for zero-mass neutrinos. The curves illustrate the shape expected from the best fits to the data. (a) Analysis of our type-(2) data; (b) analysis of Monte Carlo-generated data which contain a 1% fraction of a 17-keV neutrino.

by taking a spectrum containing a 1.4% admixture of 17-keV neutrinos (i.e., the best fit to the experimental data) and dividing it by the best fit obtained for $m_\nu=0$. The curve shown in (b) is obtained by taking a spectrum containing a 1.2% admixture of 17.5 keV (i.e., the best fit to the Monte Carlo data) and dividing it by the best fit obtained for $m_\nu=0$. While the difference in agreement between the data and the two fits is not striking to the eye, the statistical analysis indicates 9 units of χ^2 difference between the two curves, most of which is generated in the vicinity of the kink.

We have performed similar analyses on a smaller data set covering the energy range 125–160 keV using both the experimental and Monte Carlo-generated data. Using the values of β_1 and β_2 determined from the fits to the wider energy interval, the results of these analyses again show that a $\sim 1\%$ emission probability of a 17-keV neutrino gives a χ^2 value 9 units lower than that obtained assuming only massless neutrinos.

The results of the present study thus support the claim by Simpson that there is a 17-keV neutrino emitted with $\sim 1\%$ probability in nuclear β decay. Similar positive results have recently been obtained in studies of the inner bremsstrahlung spectrum of ^{71}Ge (Ref. 27) and the β^- decay of ^{35}S (Ref. 28). Zlimen *et al.*[27] find $m_\nu=17.2 \pm 1.3$ keV, $c=(1.6\pm0.5)\%$ and Hime and Jelley[28] find $m_\nu=17.2\pm0.5$ keV, $c=(0.85\pm0.06\pm0.05)\%$.

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