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A MASSIVE NEUTRINO IN NUCLEAR BETA DECAY ?

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Abstract

We have continued our studies of the β-spectrum of ^{14}C using a germanium detector doped with ^{14}C. There is a feature in the β-spectrum 17 keV below the endpoint which could be explained by the hypothesis that there is a heavy neutrino emitted in the β-decay of ^{14}C with a mass of 17±1 keV and an emission probability of 1.26±0.25%. However, we also have performed a high statistics measurement of the inner bremsstrahlung spectrum of ^{55}Fe and find no indication of the emission of a 17-keV neutrino. We conclude that the origin of the "kink" that has been observed in some recent beta spectral measurements is not a neutrino.

BETA SPECTRUM OF ^{14}C

Over the past two and a half years, we have studied the beta spectrum of ^{14}C to search for evidence of heavy neutrino emission.[1,2] In this experiment, we have used a detector containing a 1.28-cm thick planar germanium crystal doped with ^{14}C.[3] The collection 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 anti-coincidence with the center region, we 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 experiment was conducted at Lawrence Berkeley Laboratory's Low Background Counting Facility. Signals from the center region and the guard ring portions of the ^{14}C crystal were processed through separate amplifiers. Data were acquired and recorded using a PC-based acquisition system. Three separate spectra were accumulated: (1) center region , (2) center region in anti-coincidence with the guard ring, and (3) guard ring. The guard ring veto signal used to generate spectrum (2) required that an event deposit more than 20 keV but less than 183 keV in the guard ring portion of the crystal. Data were collected in 4096 channels of 0.144 keV width. The ^{14}C crystal was counted for a total of 334 days. The background was measured by removing the ^{14}C crystal from the cryostat and replacing it with a similarly shaped ^{14}C-free planar guard-ring germanium crystal. 111 days of background data were accumulated with this crystal.

The experimental data were compared to the theoretically expected spectrum using a least-squares fitting procedure that we have described previously.[1,2] This analysis was performed on data in the energy range 100-160 keV. To illustrate the degree to which the calculated spectra agree with the data, we have divided the type (2) data by the results of the best fit obtained under the assumption of only massless neutrinos. This is illustrated in Fig. 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 is what is obtained by taking a spectrum containing a 1.3% admixture of a 17-keV neutrino (i.e., the best fit to the experimental data) and dividing it by the best fit obtained for $m_\nu = 0$. The difference in X^2 between these two

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curves is approximately 23 units, thus indicating that we have nearly a 5-σ effect.

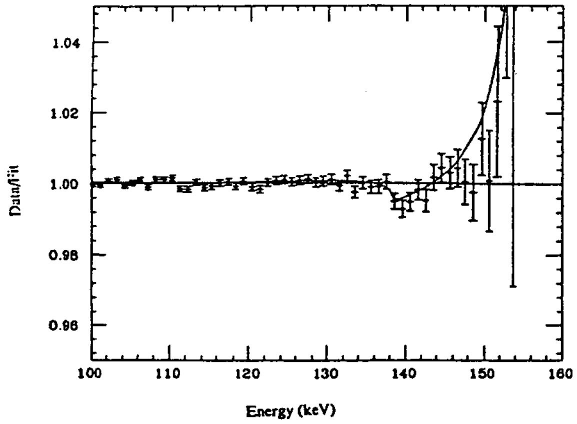

Fig. 1. The ratio of the ^{14}C data to a theoretical fit performed over the region 100-160 keV assuming $m_{\nu} = 0$. The horizontal line is the shape expected for zero-mass neutrinos. The curve illustrates the shape expected if a 17-keV neutrino were emitted in 1.3% of the ^{14}C beta decays.

In another type of analysis, we fit the region from 141 to 156 keV (i.e., the last 15 keV of the ^{14}C β spectrum). The results of this fit were extrapolated to lower energies and then divided into the experimental data. The results of this analysis are shown in Fig. 2. The horizontal line is the expectation for massless neutrinos. The curve, which shows the expectation for a 1.3% admixture of a 17-keV neutrino, agrees quite well with the data. It should be pointed out, however, that with this normalization, the error bars exaggerate the apparent significance of the result.

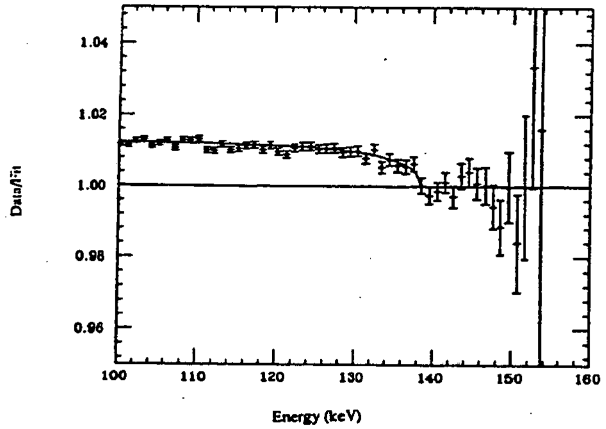

Fig. 2. The ratio of the ^{14}C data to the extrapolation of a theoretical fit performed over the region 141-156 keV assuming $m_{\nu} = 0$. The horizontal line is the shape expected for zero-mass neutrinos. The curve illustrates the shape expected if a 17-keV neutrino were emitted in 1.3% of the ^{14}C beta decays.

We have performed a number of tests to determine if some aspect of the detector response or the electronics could account for the "kink." Using external γ-ray sources, we searched for an anomaly 17 keV below the photopeak and found no such feature.[4] We did observe the Ge x-ray escape peak which occurs 10 keV below the photopeak. For a 166-keV γ ray, this peak is 0.1% as large as the photopeak and therefore cannot account for our result. We have also used a ramped pulse generator to test our ADC for non-linearities and found no evidence for a variation that could cause the effect observed in our data.

INNER BREMSSTRAHLUNG SPECTRUM OF ^{55}Fe

The electron-capture decay of ^{55}Fe is an allowed ground-state to ground-state transition with a Q_{EC} value of 231.7 keV and the probability of radiative electron capture, or inner bremsstrahlung (IB), is 3.25×10^{-5} (Ref. 5). In our search for small distortions in the spectrum of inner-bremsstrahlung, we used a source of ^{55}Fe purchased from New England Nuclear Co. Because γ-ray counting showed impurities of ^{60}Co, ^{54}Mn, ^{123}Te, ^{127}Te, and ^{59}Fe, we chemically purified the iron using ion-exchange techniques. The strength of the purified iron source was about 25 mCi. The ^{55}Fe source was placed inside a 1-mm thick plastic container and attached to the beryllium window of a 109-cm^3 HPGe detector. An additional absorber, made of copper and aluminum foils and placed between the source and the detector, reduced the intensity of Mn x-rays (from the EC decay of ^{55}Fe) in the spectrum.

As shown in Fig. 3, this entire assembly was then placed inside a NaI anti-coincidence shield consisting of a 30-cm by 30-cm annular detector and a 7.5-cm by 15-cm plug detector. These NaI detectors vetoed both Compton-scattered IB photons as well as external background radiation. The ^{55}Fe IB counting rate in the germanium detector was approximately 8000 s^{-1} Pileup-suppression was done using an Ortec 572 amplifier. Three types of data were recorded simultaneously on three separate ADC's: (1) Ge detector singles, (2) Ge detector singles with pileup rejection, and (3) Ge detector singles with pileup rejection and NaI detector veto. A total of approximately 145 days of ^{55}Fe data taking were recorded in 2-3 day intervals on a PC based acquisition system. The energy scale was internally calibrated using Pb x-rays and the γ rays from the ^{59}Fe impurity contained in the source, and subsequently it was verified with external calibration sources. Background and ^{59}Fe spectra were accumulated and stored between measurements of the ^{55}Fe source. After summing all the ^{55}Fe spectra and subtracting the ^{59}Fe and background contributions, we have approximately 1.1×10^7 counts per keV at an energy of 208 keV (i.e.the expected position of the "kink").

In all previous searches for heavy neutrino emission in beta or inner bremsstrahlung spectra (including our own ^{14}C experiment described above), in order to have the statistical sensitivity to see a 1% distortion, it was necessary to fit a fairly wide energy interval. In the present ^{55}Fe experiment, we have sufficiently high statistics that a true "local" analysis could be performed. It is well known that taking the second derivative of a spectrum can sometimes reveal small peaks that might otherwise be missed.[6] We have found that the second derivative technique is also a powerful way to reveal the distortion in a spectrum produced by the emission of a massive neutrino.

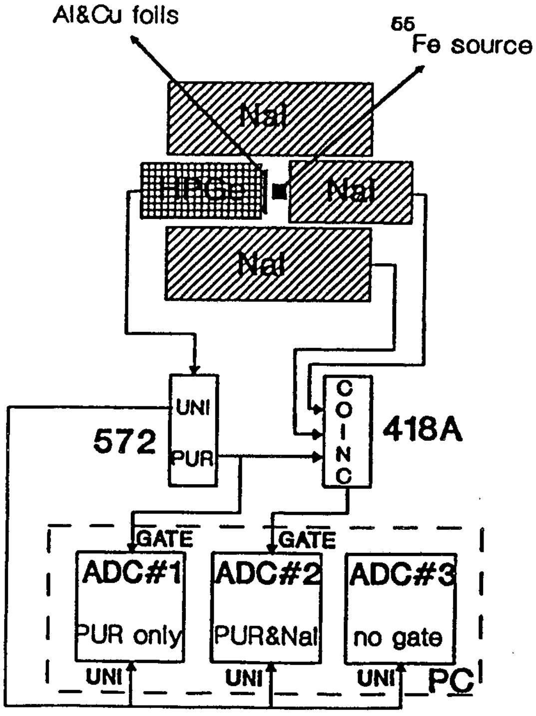

Fig.3. Schematic view of the system used in the ^{55}Fe IB experiment.

Fig. 4 illustrates the results of numerically taking the second derivative of ^{55}Fe IB spectra that contain 1.1×10^7 counts per keV at an energy of 208 keV. Fig.4(a) shows the second derivative of Monte Carlo data generated with a 1% admixture of a 17-keV neutrino. The feature observed around 208 keV is the signature of the 17-keV neutrino. Fig. 4(b) shows the results for Monte Carlo data generated with no heavy neutrino. As can be seen, for data of this type there is no structure near 208 keV. Parts (c) and (d) show the results of taking the second derivative of our type (3) experimental data. The winged-shape pattern around 192 keV seen in Fig. 4(c) is caused by an ^{59}Fe contaminant γ ray at this energy. A separate measurement done with a ^{59}Fe source allowed us to subtract this contaminant. The second derivative of the resulting spectrum is shown in Fig. 4(d). There is clearly no hint of a structure near 208 keV. Thus our ^{55}Fe experiment shows no evidence for the emission of a 17 keV neutrino.

In order to quantify the null result of our ^{55}Fe experiment, we have performed a fit to the region of the spectrum from 200-220 keV. Rather than calculating in detail the theoretically expected shape of the ^{55}Fe IB spectrum and then convoluting it with the detector response function, we have taken a much simpler approach. We make use of the fact that if the neutrino is massless, then an IB spectrum is a cubic function of the photon energy.[7] An admixture of a neutrino with mass, m_ν, and mixing angle, θ, modifies this shape in the follwing way.[8]

$$N_\gamma(E) = [a_0 + a_1E + a_2E^2 + a_3E^3] \times \left[1 + \tan^2\theta \left(1 - \frac{m_\nu^2}{(E_0-E)^2}\right)^{1/2}\right]. \quad (1)$$

In the fitting procedure, for each choice of m_ν and $\tan^2\theta$, a_0-a_3 were allowed to vary freely so as to minimze X^2. The results of this procedure for our type (3) data for $m_\nu = 0$ and for $m_\nu = 17$ keV, $\tan^2\theta = 0.007$ are shown in Fig. 5 (a) and (b), respectively. In part (a), the horizontal line is the expectation for massless neutrinos, and the X^2 for this fit is 157 for 149 degrees of freedom. In part (b) the horizontal line is the expectation for $m_\nu = 17$ keV, $\tan^2\theta = 0.007$, and the X^2 is 203 for 149 degrees of freedom. The results of the fits in which m_ν and $\tan^2\theta$ were varied are shown in Fig. 6. As can be clearly seen, our ^{55}Fe data excludes a 0.7% admixture of a 17-keV neutrino at about the 7σ level.

CONCLUSIONS

We have observed a distortion in the beta spectrum of ^{14}C that looks very much like that which would be produced if a neutrino with a mass of 17 keV were emitted in approximately 1% of all ^{14}C beta decays. However, our much higher statistics ^{55}Fe inner bremsstrahlung spectrum shows no evidence for the emission of a heavy neutrino. Recent magnetic spectrometer experiments on ^{35}S (Ref. 9) and ^{63}Ni (Ref. 10) and a ^{35}S search that used a solid-state silicon detector (Ref. 11) have also failed to see any evidence of heavy neutrino emission. We thus conclude that, whatever causes the "kink" in our ^{14}C spectrum, it is not a neutrino.

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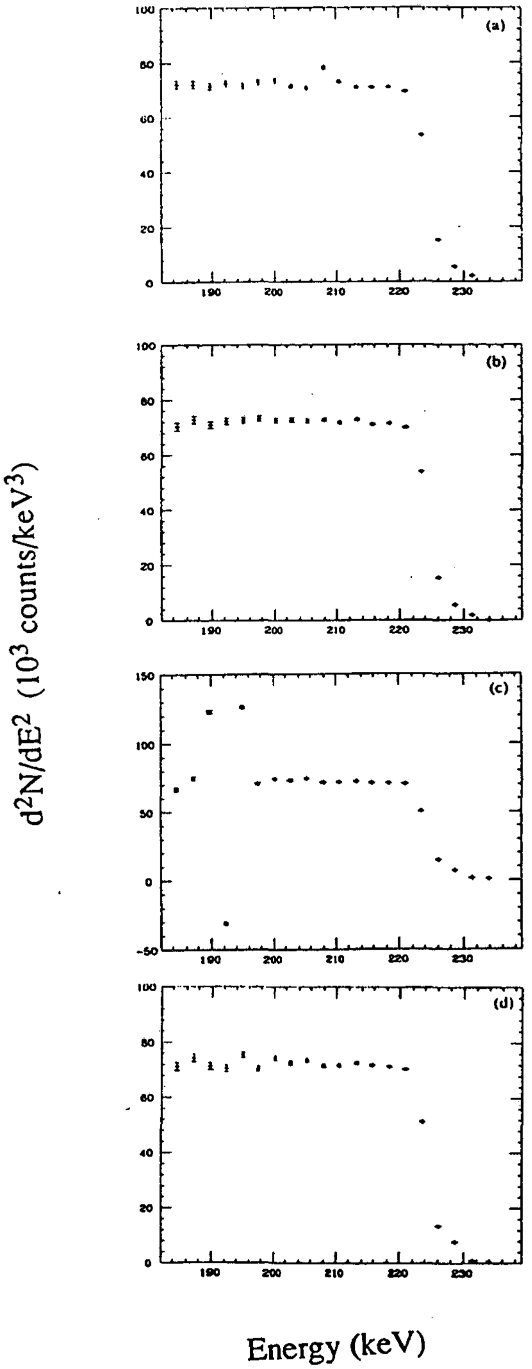

Fig. 4. The second derivative of inner bremsstrahlung spectra of ^{55}Fe. (a) Monte Carlo data generated with a 1% admixture of a 17-keV neutrino, (b) Monte Carlo data generated with $m_\nu = 0$, and (c) experimental data before subtracting ^{59}Fe contaminant, (d) experimental data after subtracting ^{59}Fe.

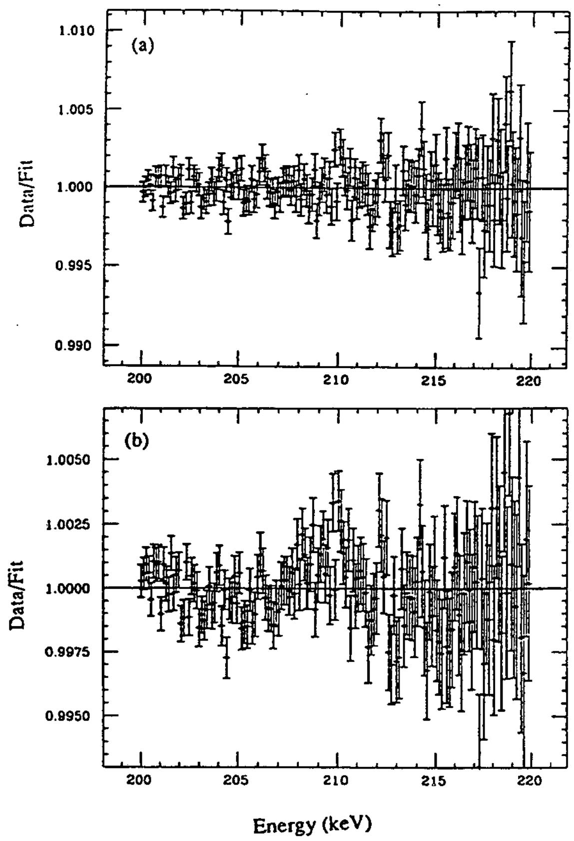

Fig. 5. Ratio of the type (3) ^{55}Fe data to fits using Eqn. 1. (a) Fit performed assuming $m_\nu = 0$. The horizontal line is the expectation for massless neutrinos. (b) Fit performed assuming $m_\nu = 17$ keV and $\tan^2\theta = 0.007$. The horizontal line is the expectation for $m_\nu = 17$ keV and $\tan^2\theta = 0.007$.

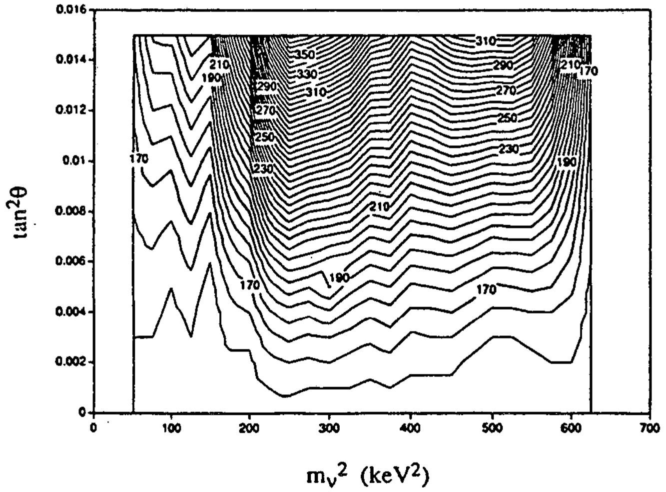

Fig. 6. Contours of X^2 as a function of m_ν and $\tan^2\theta$ for our type (3) ^{55}Fe data.

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