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

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ABSTRACT

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 endpoint 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±0.45%. This result is consistent with observations of similar anomalies in the β-decays of ^{3}H and ^{35}S. We also find the endpoint energy of the β-spectrum to be 155.74±0.03 keV, in disagreement with the most precise value reported in the literature.

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The existence of massive neutrinos would have profound implications for both particle physics and astrophysics. The observation of an anomaly or "kink", 17 keV below the endpoint in the β-spectrum of ^{3}H was first reported in 1985 by Simpson[1] and interpreted by him to correspond to the emission of an electron antineutrino with a 3% admixture of a state of mass = 17 keV. This report was criticized[2-5] on grounds of both experimental method and data analysis. Moreover, it was quickly followed by a number of studies of the β-spectra of ^{35}S (Refs. 6-10), ^{63}Ni (Ref. 11), and the internal bremsstrahlung spectra of ^{125}I (Ref. 12) and ^{55}Fe (Ref. 13), all of which claimed to rule out the 3%, 17-keV neutrino admixture hypothesis at various confidence levels. One of these data sets[7] was reanalyzed by Simpson[14] to show evidence for a 1-2% admixture of a 17-keV neutrino. Finally, in 1989, there appeared two reports of β-spectrum anomalies corresponding to a ~1% admixture of a 17-keV neutrino. Simpson and Hime[15] analyzed the β-spectrum of ^{35}S recorded with a cooled Si(Li) detector and an external source. Hime and Simpson[16] described an experiment done with ^{3}H implanted in an intrinsic germanium detector. In the first of these papers, the authors also carefully criticized most of the previous null result experiments.

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 nuclei with different Z and A. This would also provide a test of the possibility that the effects observed by Simpson were due to some atomic physics phenomena peculiar to his choice of sources. These questions 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 endpoint energy near 156 keV. Moreover, we were aware of a unique detector produced by Haller *et al.*[17] that was ideally suited for this experiment. The detector contains a germanium crystal grown from a melt of germanium which had ^{14}C-labelled carbon dissolved in it. This system thus 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-labelled methane was cracked into graphite on quartz crucibles. The ratio of ^{12}C to ^{14}C in the gas was 10.33. Germanium was then placed in these crucibles, melted, and pulled into single crystals. Autoradiographs performed on the crystal used in the present study (Crystal No. 701 from Ref. 17) 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 anti-coincidence 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. Further shielding was provided by 10-15 cm of low activity lead surrounding the entire assembly. The detector was operated at a reverse bias of 3000 V. Signals from the center region and the 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 this detector at a rate of 5 Hz to monitor the gain and DC offset of the electronics. Data were taken using an Ortec 916 PC-based acquisition system. Three separate spectra were accumulated: (1) center region , (2) center region in anti-coincidence with 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. All of the analyses described below were performed on spectra of type

(2). Data were collected in 4096 channels of 0.144 keV width and were recorded in 1-day time bins on the magnetic disc of an IBM PC/AT computer.

The ^{14}C crystal was counted for a total of 122 days. After this counting period, the ^{14}C crystal was removed from the cryostat, and a similarly shaped carbon-free planar guard-ring germanium crystal was installed. Fifty-two days of background data were accumulated with this crystal. The centroids of the pulser peaks and those of the background gamma-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 and are shown in Figure 1 (a). The result of summing all of the background spectra is shown in Figure 1(b). Using the ratios of the major U and Th decay-chain γ-ray lines observed in the two spectra one can appropriately scale the background spectrum. 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 at an energy of 139 keV (i.e., 17 keV below the endpoint).

If in nuclear beta 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:[18]

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

where

$$\frac{dN(E, m_\nu)}{dE} \propto A\,F(Z,E)\,p\,E\,(W-E)\,[(W-E)^2 - m_\nu^2]^{1/2}. \qquad (2)$$

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[19] and screening[20] corrections applied, E and p are the electron total energy and momentum, respectively, and W is the total decay energy. There have been discussions[21,22] as to possible deviations in the shape of

the ^{14}C beta spectrum from that expected for a pure allowed transition. To allow for possible smooth departures from an allowed shape, the above theoretical spectrum was multiplied by a "shape factor" of the form

$$\left(1 + \beta_1(W - E) + \beta_2(W - E)^2\right). \qquad (3)$$

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. The fraction of events in this tail is assumed to increase linearly with the β energy. 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 keV over the energy range of interest. From the known ranges and bremsstrahlung energy losses of β's in germanium,[23] 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.[24] The results of these calculations indicate that this tail may actually contain only about 0.2% of all β decay events. We therefore 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 in both 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 Figure 2(a). The minimum value of χ^2 obtained under the assumption of only massless neutrinos is 415. This corresponds to the value of χ^2 on both the horizontal (i.e. $m_\nu = 0$) and on the vertical axis (i.e. c = 0). 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 (i.e., no heavy neutrino emission) at the 99% confidence level.[25] The value obtained for β_1 is $\approx 1\times10^{-3}$ keV^{-1} and β_2 is essentially zero.

To check on what sensitivity is expected from data of the quality we have obtained, we generated approximately 50 Monte-Carlo data sets corresponding to the case of (i) $m_\nu = 17$ keV, c = (1.0 - 1.4)%, and 5 data sets for the case (ii) $m_\nu = 0$. These data sets were treated in exactly the same manner as the experimental data and were then analyzed using the least-squares method described above. 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 demonstrate 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 as way as to minimize χ^2. The results of this procedure for projections of m_ν, c, and the ^{14}C β-endpoint energy, $E_0 = (W-m_e)$, are shown in Figure 3. From these projections, we obtain $m_\nu = 17 \pm 2$ keV, c = 1.40 ± 0.45% and $E_0 = 155.74 \pm 0.03$ keV (all uncertainties are 1σ). The present result for the endpoint 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 beta endpoint energy measurements.[26]

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. 4 (a) for our experimental data, and in Fig. 4(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 part (a) is what one obtains 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 part (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 ~ 1% emission probability of a 17 keV neutrino gives a χ^2 value 9 units lower than that obtained assuming only massless neutrinos. We have also performed a variety of tests to determine if some aspect of the detector or electronics response 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. 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 therefore cannot account for our result. Finally, we 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.

The results of the present study of the β spectrum of ^{14}C thus support the claim by Simpson that there is a 17-keV neutrino emitted with ~1% probability in nuclear beta decay. Our analyses rule out the null hypothesis (i.e., no heavy neutrino emission) at the 99% confidence level. In addition, we have studied the inner bremsstrahlung spectrum of ^{55}Fe and also find indications of the emission of a 17-keV neutrino.[27] Recently we have learned of similar positive results obtained in a study of

the inner bremsstrahlung spectrum of ^{71}Ge (Ref. 28). We intend to continue our studies of ^{14}C with an improved detector that will contain a crystal with a much higher amount of ^{14}C. This will provide much greater sensitivity to the presence of massive neutrinos.

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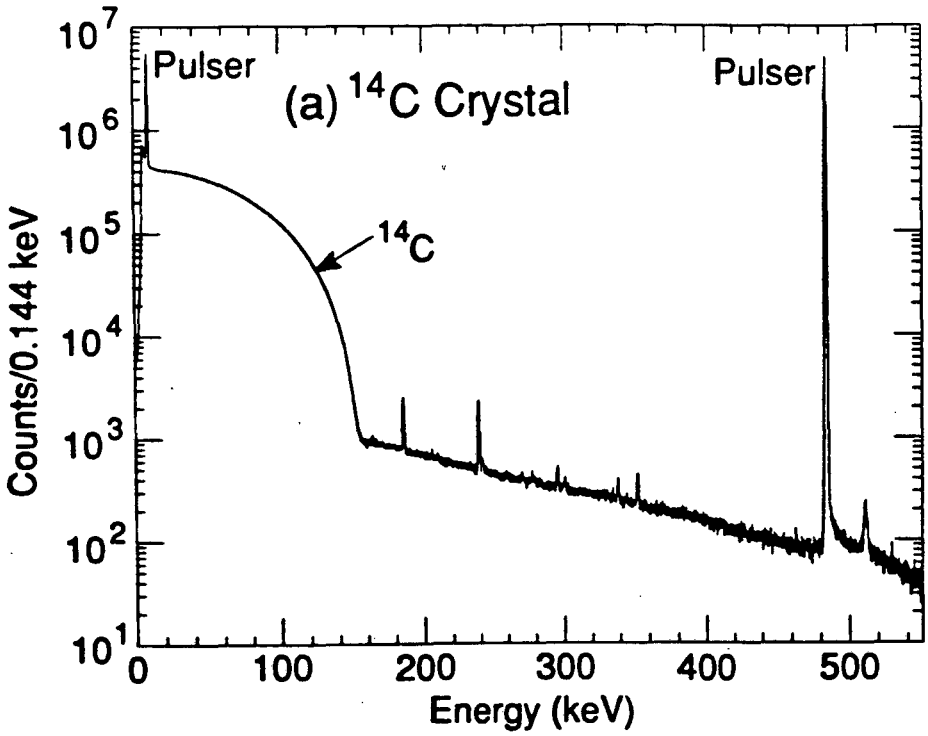
Figure Captions

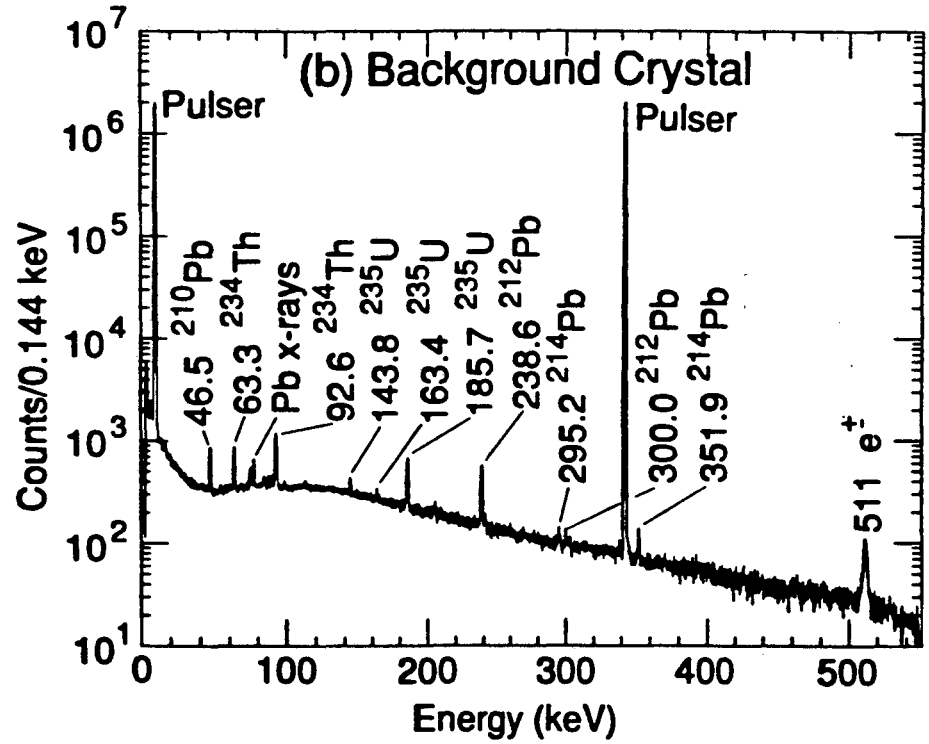
1. (a) Spectrum observed from 122 days of counting with the ^{14}C-doped germanium crystal . (b) Spectrum observed from 52 days of counting with the background crystal. Gamma-ray energies are given in keV. All of the gamma-ray lines seen in the background spectrum are also observed in the spectrum taken with the ^{14}C-doped crystal. Due to 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.

2. Contour plots of χ^2 as a function of the neutrino mass, m_ν, and c (where c is defined by Eqn. 1). The curves are labelled by the values of χ^2. (a) results from the analysis of our experimental data; (b) results from the analysis of Monte-Carlo generated data which contains a 1.4% fraction of a 17-keV neutrino; (c) results from the analysis of Monte-Carlo generated data which contains only a zero mass neutrino.

3. (a) χ^2 versus the neutrino mass, m_ν. (b) χ^2 versus c. (c) χ^2 versus the ^{14}C endpoint energy. Separate curves are shown for the cases of m_ν= 17 keV, and m_ν= 0.

4. 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 experimental data; (b) anaylsis of Monte-Carlo generated data which contain a 1% fraction of a 17-keV neutrino.





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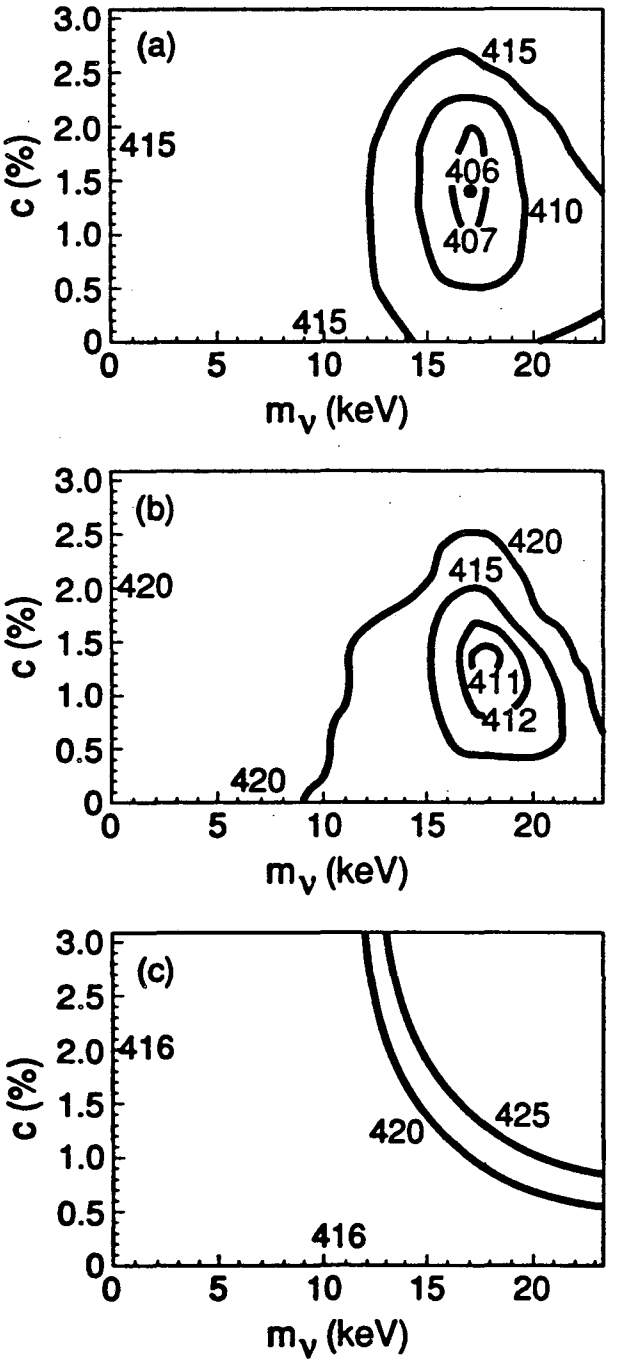
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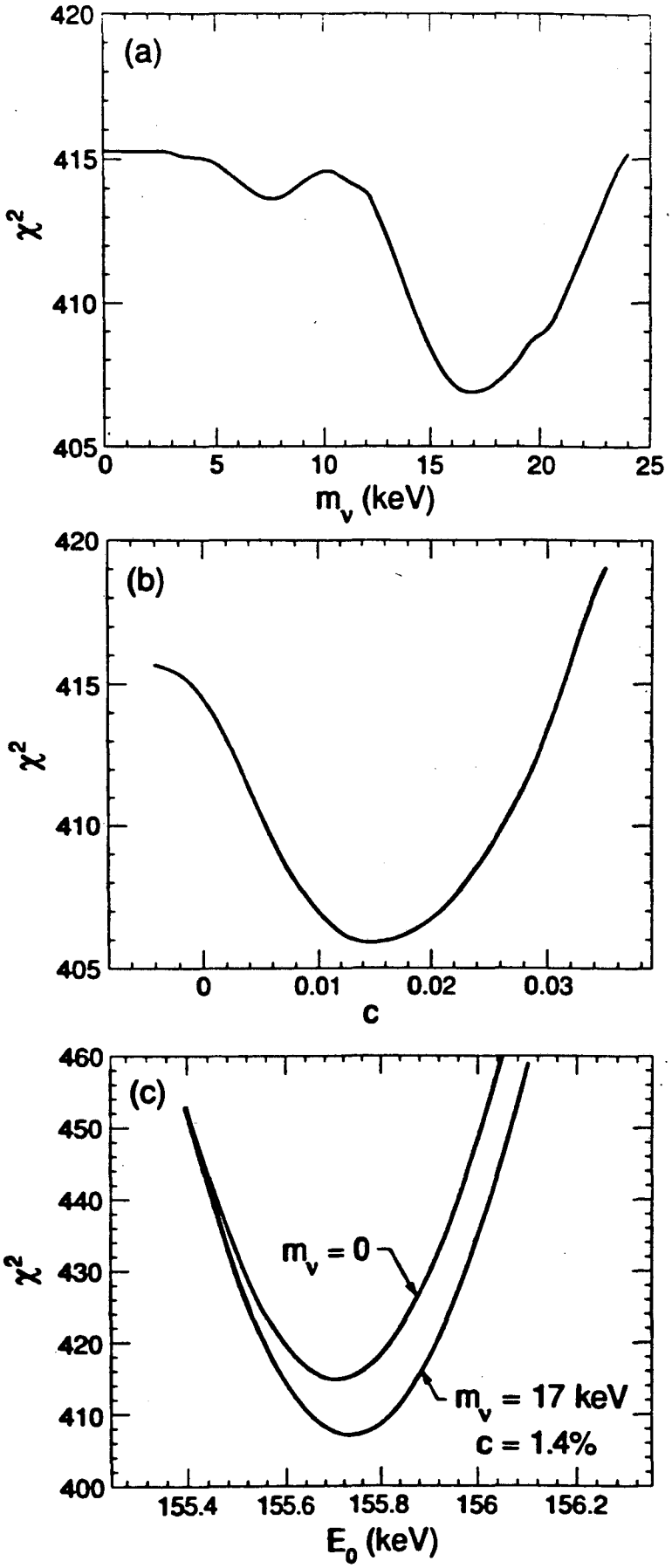
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0.02
0.03
c
(c)
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450
440
430
420
410
400
χ^2
$m_\nu = 0$
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c = 1.4%
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155.6
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156.2
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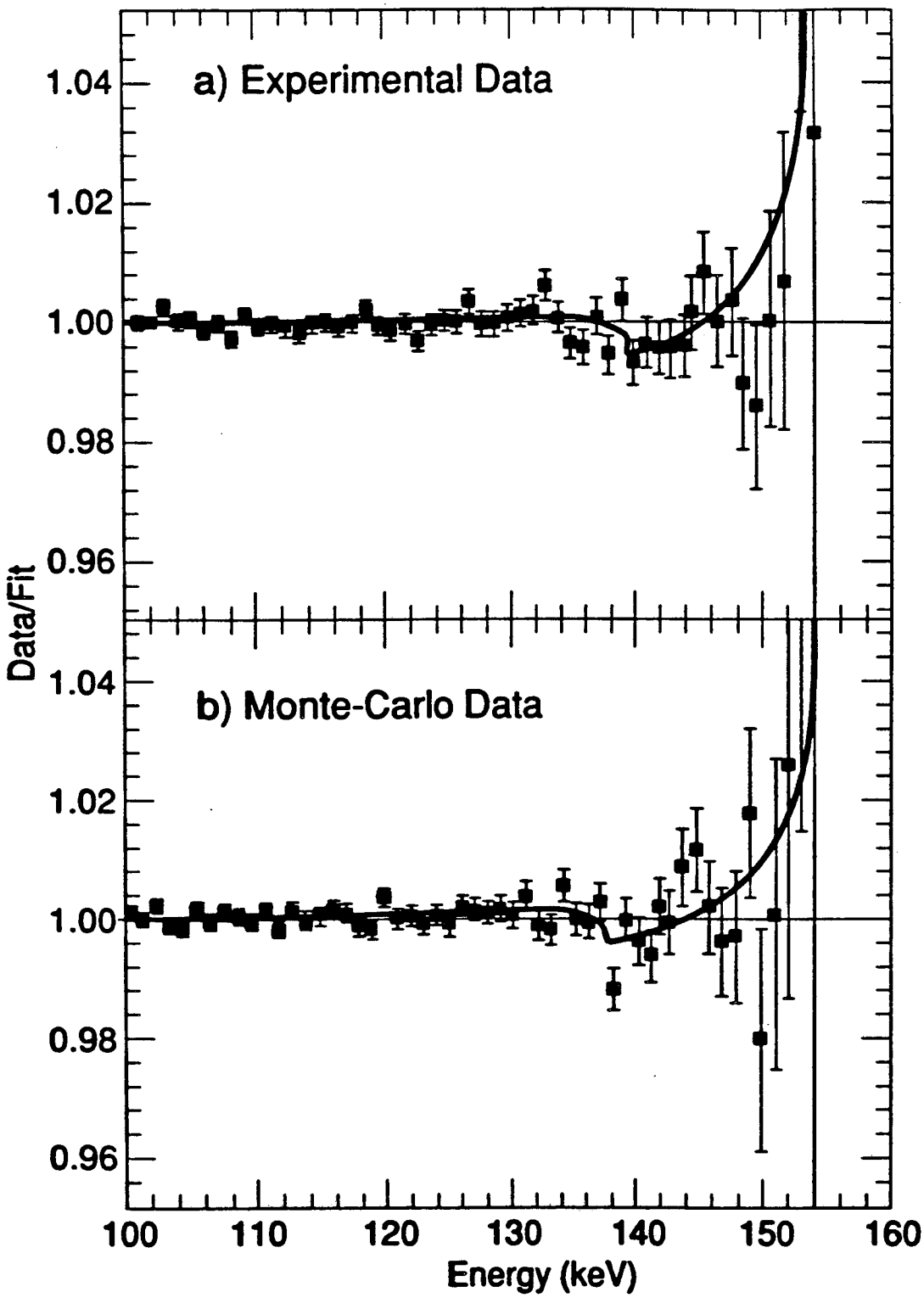

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