

# Lawrence Berkeley National Laboratory

## LBL Publications

### Title

Evidence for the Emission of a 17-keV Neutrino in the  $\beta$  Decay of  $^{14}\text{C}$

### Permalink

<https://escholarship.org/uc/item/9tr5v2h8>

### Journal

Physical review letters, 66(19)

### Authors

Sur, B.  
Norman, E.B.  
Lesko, K.T.  
[et al.](#)

### Publication Date

1990-12-01



# Lawrence Berkeley Laboratory

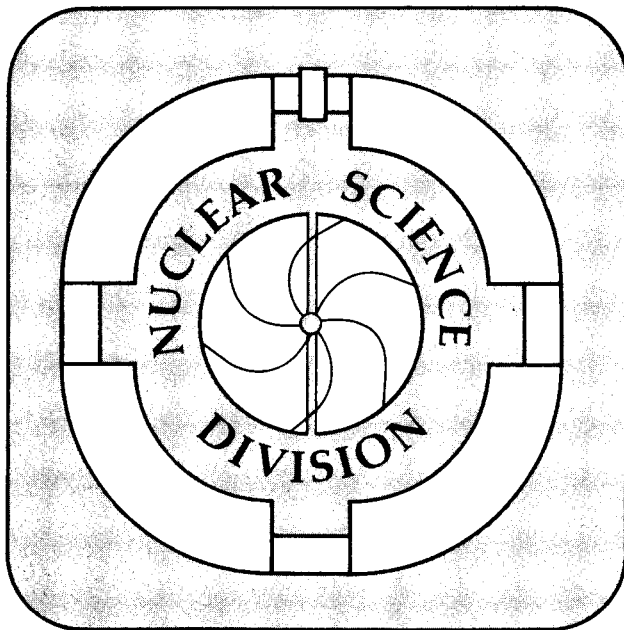
UNIVERSITY OF CALIFORNIA

Submitted to Physical Review Letters

## Evidence for the Emission of a 17-keV Neutrino in the $\beta$ Decay of $^{14}\text{C}$

B. Sur, E.B. Norman, K.T. Lesko, M.M. Hindi, R.-M. Larimer,  
P.N. Luke, and E.E. Haller

December 1990



1 LOAN COPY 1  
1 Circulates 1  
1 for 2 weeks 1  
Bldg. 50 Library.  
COPY 2

LBL-30109

## **DISCLAIMER**

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

**Evidence for the Emission of a 17-keV Neutrino  
in the  $\beta$  Decay of  $^{14}\text{C}$**

B. Sur, E.B. Norman, K.T. Lesko, M.M. Hindi, R.-M. Larimer, P.N. Luke  
and E.E. Haller

Nuclear Science Division  
Lawrence Berkeley Laboratory  
University of California  
Berkeley, Ca 94720, USA

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098

# Evidence for the Emission of a 17-keV Neutrino in the $\beta$ Decay of $^{14}\text{C}$

Bhaskar Sur,<sup>(1)\*</sup> Eric B. Norman,<sup>(1)</sup> K. T. Lesko,<sup>(1)</sup> M. M. Hindi,<sup>(1),(2)</sup> Ruth-Mary Larimer,<sup>(1)</sup> Paul N. Luke,<sup>(3)</sup> William L. Hansen,<sup>(3)</sup> and Eugene E. Haller<sup>(3),(4)</sup>

<sup>(1)</sup>Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, CA 94720

<sup>(2)</sup> Physics Department, Tennessee Technological University, Cookeville, TN 38505

<sup>(3)</sup>Engineering Division, Lawrence Berkeley Laboratory, Berkeley, CA 94720

<sup>(4)</sup> Dept. of Materials Science and Mineral Engineering, Univ. of California, Berkeley, CA 94720

## ABSTRACT

We have studied the  $\beta$ -spectrum of  $^{14}\text{C}$  using a germanium detector containing a crystal with  $^{14}\text{C}$  dissolved in it. We find a feature in the  $\beta$ -spectrum 17 keV below the endpoint which can be explained by the hypothesis that there is a heavy neutrino emitted in the  $\beta$ -decay of  $^{14}\text{C}$  with a mass of  $17\pm 2$  keV and an emission probability of  $1.40\pm 0.45\%$ . This result is consistent with observations of similar anomalies in the  $\beta$ -decays of  $^3\text{H}$  and  $^{35}\text{S}$ . We also find the endpoint energy of the  $\beta$ -spectrum to be  $155.74\pm 0.03$  keV, in disagreement with the most precise value reported in the literature.

PACS No. 23.40.Bw, 14.60.Gh, 27.20.+n

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  $\beta$ -spectrum of  $^3\text{H}$  was first reported in 1985 by Simpson<sup>1</sup> 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<sup>2-5</sup> on grounds of both experimental method and data analysis. Moreover, it was quickly followed by a number of studies of the  $\beta$ -spectra of  $^{35}\text{S}$  (Refs. 6-10),  $^{63}\text{Ni}$  (Ref. 11), and the internal bremsstrahlung spectra of  $^{125}\text{I}$  (Ref. 12) and  $^{55}\text{Fe}$  (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<sup>7</sup> was reanalyzed by Simpson<sup>14</sup> to show evidence for a 1-2% admixture of a 17-keV neutrino. Finally, in 1989, there appeared two reports of  $\beta$ -spectrum anomalies corresponding to a ~1% admixture of a 17-keV neutrino. Simpson and Hime<sup>15</sup> analyzed the  $\beta$ -spectrum of  $^{35}\text{S}$  recorded with a cooled Si(Li) detector and an external source. Hime and Simpson<sup>16</sup> described an experiment done with  $^3\text{H}$  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  $\beta$  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  $\beta$ -spectrum of  $^{14}\text{C}$ . The  $\beta$  decay of  $^{14}\text{C}$  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.*<sup>17</sup> that was ideally suited for this experiment. The detector contains a germanium crystal grown from a melt of germanium which had  $^{14}\text{C}$ -labelled carbon dissolved in it. This system thus functions as a windowless detector

with a nearly ideal response function for the  $\beta$  particles emitted by the  $^{14}\text{C}$  inside the crystal.

To produce such material,  $^{14}\text{C}$ -labelled methane was cracked into graphite on quartz crucibles. The ratio of  $^{12}\text{C}$  to  $^{14}\text{C}$  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  $^{14}\text{C}$  is dispersed uniformly throughout the crystal. This detector has a  $^{14}\text{C}$  concentration of  $6 \times 10^{11} \text{ cm}^{-3}$  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  $^{14}\text{C}$   $\beta$  decay counting rate from the center region of the crystal is  $20 \text{ s}^{-1}$ .

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  $^{14}\text{C}$  crystal were separately processed through Tennelec Model 243 amplifiers using 4- $\mu\text{s}$  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  $^{14}\text{C}$  crystal was counted for a total of 122 days. After this counting period, the  $^{14}\text{C}$  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  $^{14}\text{C}$  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  $\gamma$ -ray lines observed in the two spectra one can appropriately scale the background spectrum. The resulting background-subtracted  $^{14}\text{C}$   $\beta$  spectrum contains a total of  $2.25 \times 10^8$  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  $\beta$  particles is given by the expression:<sup>18</sup>

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

where

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

In the case of  $^{14}\text{C}$ , 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<sup>19</sup> and screening<sup>20</sup> corrections applied,  $E$  and  $p$  are the electron total energy and momentum, respectively, and  $W$  is the total decay energy. There have been discussions<sup>21,22</sup> as to possible deviations in the shape of



the  $^{14}\text{C}$  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

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

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. The fraction of events in this tail is assumed to increase linearly with the  $\beta$  energy. Using external  $\gamma$ -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  $\beta$ 's in germanium,<sup>23</sup> we estimate that this tail contains at most 1.5% of all 156-keV  $\beta^-$  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.<sup>24</sup> The results of these calculations indicate that this tail may actually contain only about 0.2% of all  $\beta$  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  $m_\nu$  and  $c$ , the following five parameters were allowed to vary simultaneously:  $A, W, \beta_1, \beta_2$ , 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  $\chi^2$  obtained under the assumption of only massless neutrinos is 415. This corresponds to the value of  $\chi^2$  on both the horizontal (i.e.  $m_\nu = 0$ ) and on the vertical axis (i.e.  $c = 0$ ). The absolute minimum value of  $\chi^2$  is 406 and is found for  $m_\nu = 17$  keV and  $c = 1.4\%$ . Thus, there is a difference of 9 units of  $\chi^2$  between these two cases. This excludes the null

hypothesis (i.e., no heavy neutrino emission) at the 99% confidence level.<sup>25</sup> The value obtained for  $\beta_1$  is  $= 1 \times 10^{-3} \text{ keV}^{-1}$  and  $\beta_2$  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)  $m_\nu = 17 \text{ keV}$ ,  $c = (1.0 - 1.4)\%$ , 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  $\chi^2$  obtained from this data set was 411 for  $m_\nu = 17.5 \text{ keV}$ ,  $c = 1.2\%$ . The value of  $\chi^2$  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  $m_\nu = 17 \text{ keV}$ ,  $c = 1.4\%$  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 a way as to minimize  $\chi^2$ . The results of this procedure for projections of  $m_\nu$ ,  $c$ , and the  $^{14}\text{C}$   $\beta$ -endpoint energy,  $E_0 = (W - m_e)$ , are shown in Figure 3. From these projections, we obtain  $m_\nu = 17 \pm 2 \text{ keV}$ ,  $c = 1.40 \pm 0.45\%$  and  $E_0 = 155.74 \pm 0.03 \text{ keV}$  (all uncertainties are  $1\sigma$ ). The present result for the endpoint energy does not agree with the value of  $156.476 \pm 0.005 \text{ keV}$  deduced from the mass spectrometry data of Smith and Wapstra,<sup>26</sup> but falls in the middle of the results of previous beta endpoint energy measurements.<sup>26</sup>

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  $m_\nu = 17 \text{ keV}$  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  $\chi^2$  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  $\beta_1$  and  $\beta_2$  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  $\chi^2$  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  $\gamma$ -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  $\gamma$  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  $\beta$  spectrum of  $^{14}\text{C}$  thus support the claim by Simpson that there is a 17-keV neutrino emitted with  $\sim 1\%$  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  $^{55}\text{Fe}$  and also find indications of the emission of a 17-keV neutrino.<sup>27</sup> Recently we have learned of similar positive results obtained in a study of

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

We wish to thank C. P. Cork, F. S. Goulding, D. A. Landis, A. R. Smith, T. R. Ho and J. T. Witort, and K. L. Wedding for their assistance in various aspects of this work. We also wish to thank E. D. Commins and L. A. Khalfin for their comments and suggestions regarding this manuscript. This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Nuclear Physics Division, of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098. M. M. Hindi is also supported in part by the U. S. Department of Energy under Contract No. DE-FG05-87ER40314.

## References

\* Present address: Physics Department, Queen's University, Kingston, ON, K7L 9N6,  
Canada

1. J. J. Simpson, Phys. Rev. Lett. 54, 1891 (1985).
2. B. Eman and D. Tadic, Phys. Rev. C 33, 2128 (1986).
3. J. Lindhard and P. G. Hansen, Phys. Rev. Lett. 57, 965 (1986).
4. W. C. Haxton, Phys. Rev. Lett. 55, 807 (1985).
5. G. R. Kalbfleisch and K. A. Milton, Phys. Rev. Lett. 55, 2225 (1985).
6. T. Altzitzoglou *et al.*, Phys. Rev. Lett. 55, 799 (1985).
7. T. Ohi *et al.*, Phys. Lett. 160B, 322 (1985).
8. V. M. Datar *et al.*, Nature (London) 318, 547 (1985).
9. A. Apalikov *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. 42, 233 (1985) [JETP Lett. 42, 289 (1985)].
10. J. Markey and F. Boehm, Phys. Rev. C 32, 2215 (1985).
11. D. W. Hetherington *et al.*, Phys. Rev. C 36, 1504 (1987).

12. M. J. G. Borge *et al.*, *Physica Scripta* 34, 591 (1986).
13. I. Zlimen, S. Kaucic, A. Ljubicic, and B. A. Logan, *Physica Scripta* 38, 539 (1988).
14. J. J. Simpson, *Phys. Lett.* 174B, 113 (1986).
15. J. J. Simpson and A. Hime, *Phys. Rev. D* 39, 1825 (1989).
16. A. Hime and J. J. Simpson, *Phys. Rev. D* 39, 1837 (1989).
17. E. E. Haller, W. L. Hansen, P. Luke, R. McMurray, and B. Jarrett, *IEEE Trans. Nucl. Sci.* Vol. NS-29, No. 1, 745 (1982).
18. F. Boehm and P. Vogel, *Physics of Massive Neutrinos*, (Cambridge Univ. Press, Cambridge, 1987) p. 68.
19. H. Behrens and J. Janecke, *Landolt-Bornstein. New Series* (Springer, Berlin, 1969), Group I, Vol. 4.
20. M. E. Rose, *Phys. Rev.* 49, 727 (1936).
21. A. V. Pohm, R. C. Waddell, J. P. Powers, and E. N. Jensen, *Phys. Rev.* 97, 432 (1955).
22. Ch. Sonntag *et al.*, *Lett. Nuovo Cim.* IV, 717 (1970).

23. L. Pages, E. Bertel, H. Joffre, and L. Sklavenitis, *Atomic Data* **4**, 1 (1972).
24. R. Brun, F. Bruyant, M. Maire, A. C. McPherson, and P. Zancarini, GEANT3, CERN, DD/EE/84-1 (1987).
25. W. H. Press, B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling, Numerical Recipes (Cambridge Univ. Press, Cambridge, 1986) p. 536.
26. L. G. Smith and A. H. Wapstra, *Phys. Rev. C* **11**, 1392 (1975).
27. E. B. Norman *et al.*, Proc. 14th Europhys. Conf. on Nucl. Phys., Bratislava, Czechoslovakia, Oct. 1990, to be published.
28. I. Zliven, A. Ljubicic, S. Kaucic, and B. A. Logan, Proc. 14th Europhys. Conf. on Nucl. Phys., Bratislava, Czechoslovakia, Oct. 1990, to be published.

## Figure Captions

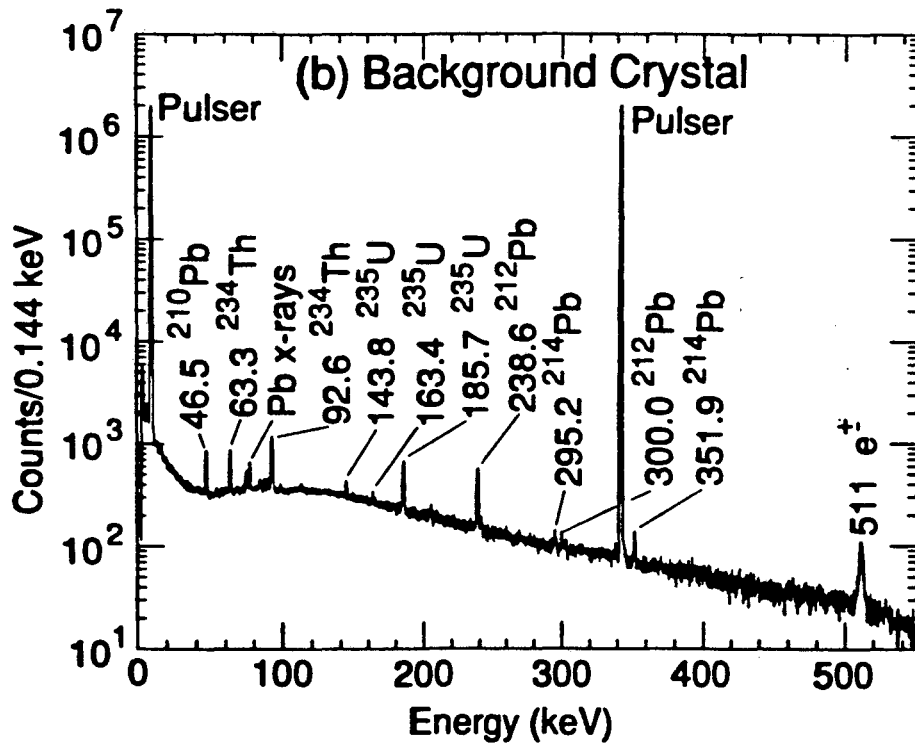
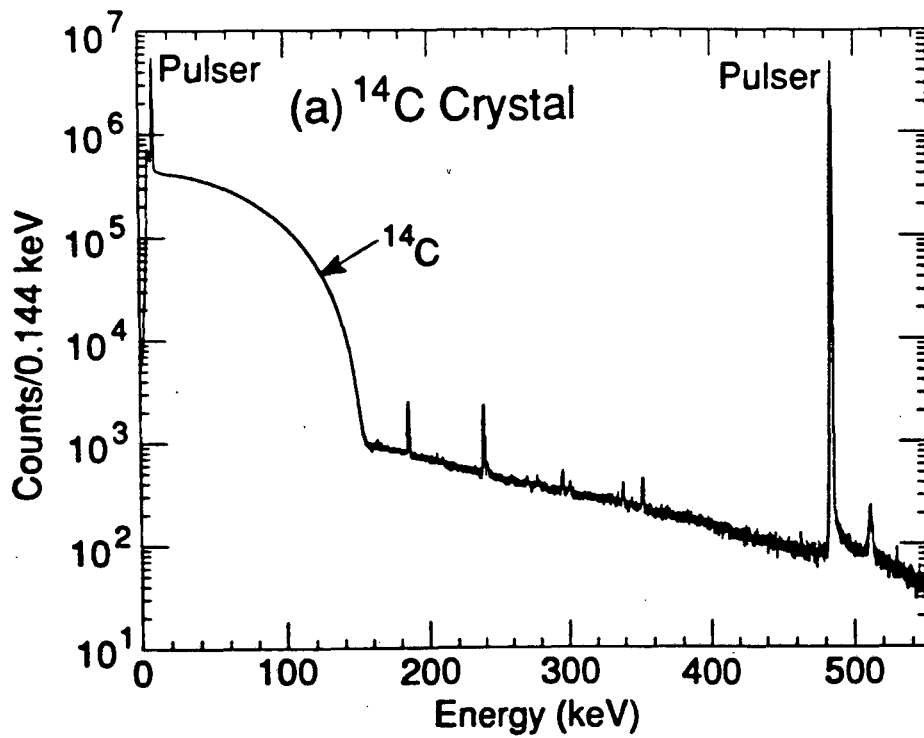
1. (a) Spectrum observed from 122 days of counting with the  $^{14}\text{C}$ -doped germanium crystal . (b) Spectrum observed from 52 days of counting with the background crystal. Gamma-ray energies are given in keV. All of the gamma-ray lines seen in the background spectrum are also observed in the spectrum taken with the  $^{14}\text{C}$ -doped crystal. Due to the different capacitances of the  $^{14}\text{C}$ -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  $\chi^2$  as a function of the neutrino mass,  $m_\nu$ , and  $c$  (where  $c$  is defined by Eqn. 1). The curves are labelled by the values of  $\chi^2$ . (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.

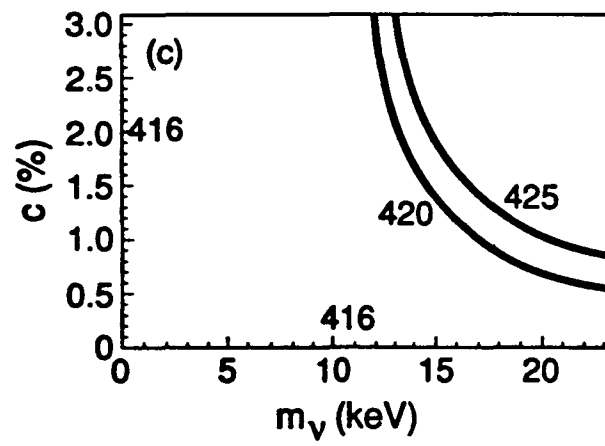
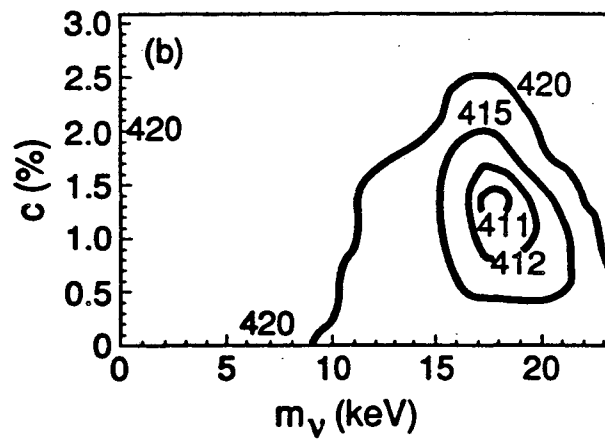
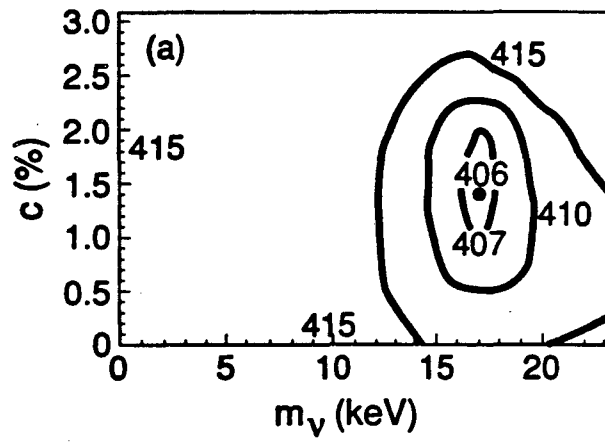
3. (a)  $\chi^2$  versus the neutrino mass,  $m_\nu$ . (b)  $\chi^2$  versus  $c$ . (c)  $\chi^2$  versus the  $^{14}\text{C}$  endpoint energy. Separate curves are shown for the cases of  $m_\nu = 17$  keV, and  $m_\nu = 0$ .

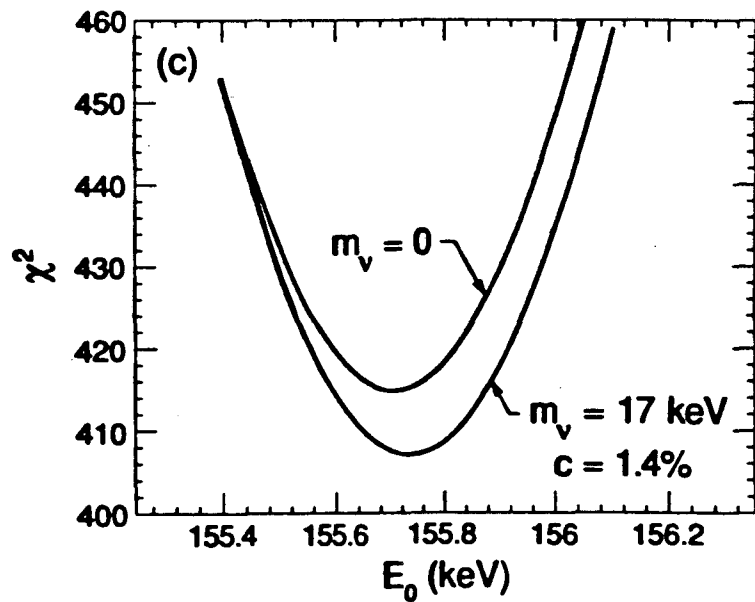
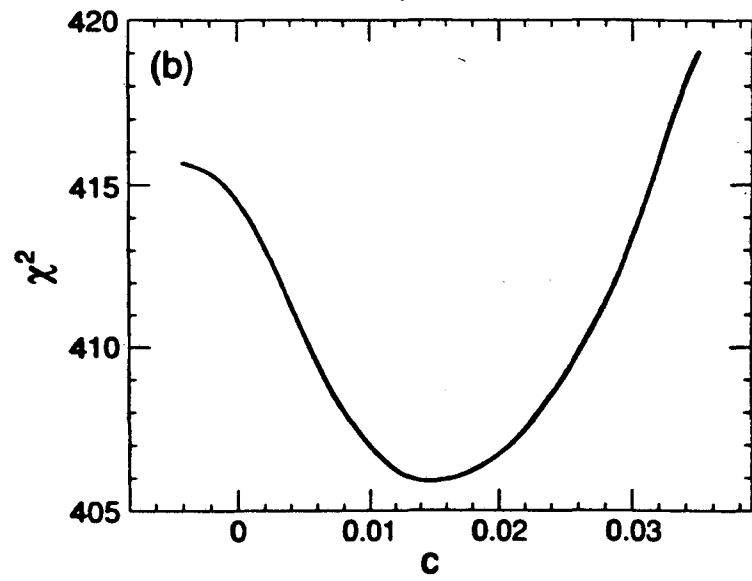
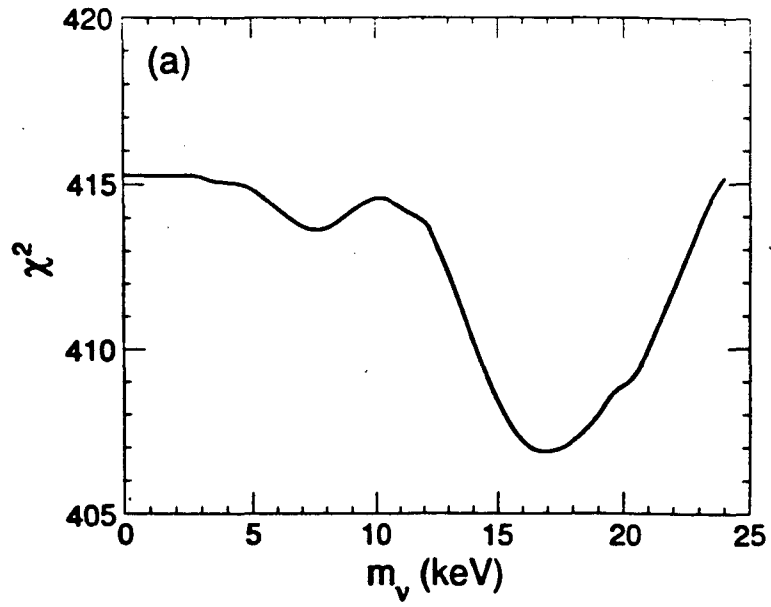
4. The ratio of the data to a theoretical fit assuming the emission of only zero-mass neutrinos. The data were compressed to 1 keV/channel. The horizontal line is the shape expected for zero-mass neutrinos. The curves illustrate the shape expected from the best fits to the data. (a) analysis of our experimental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



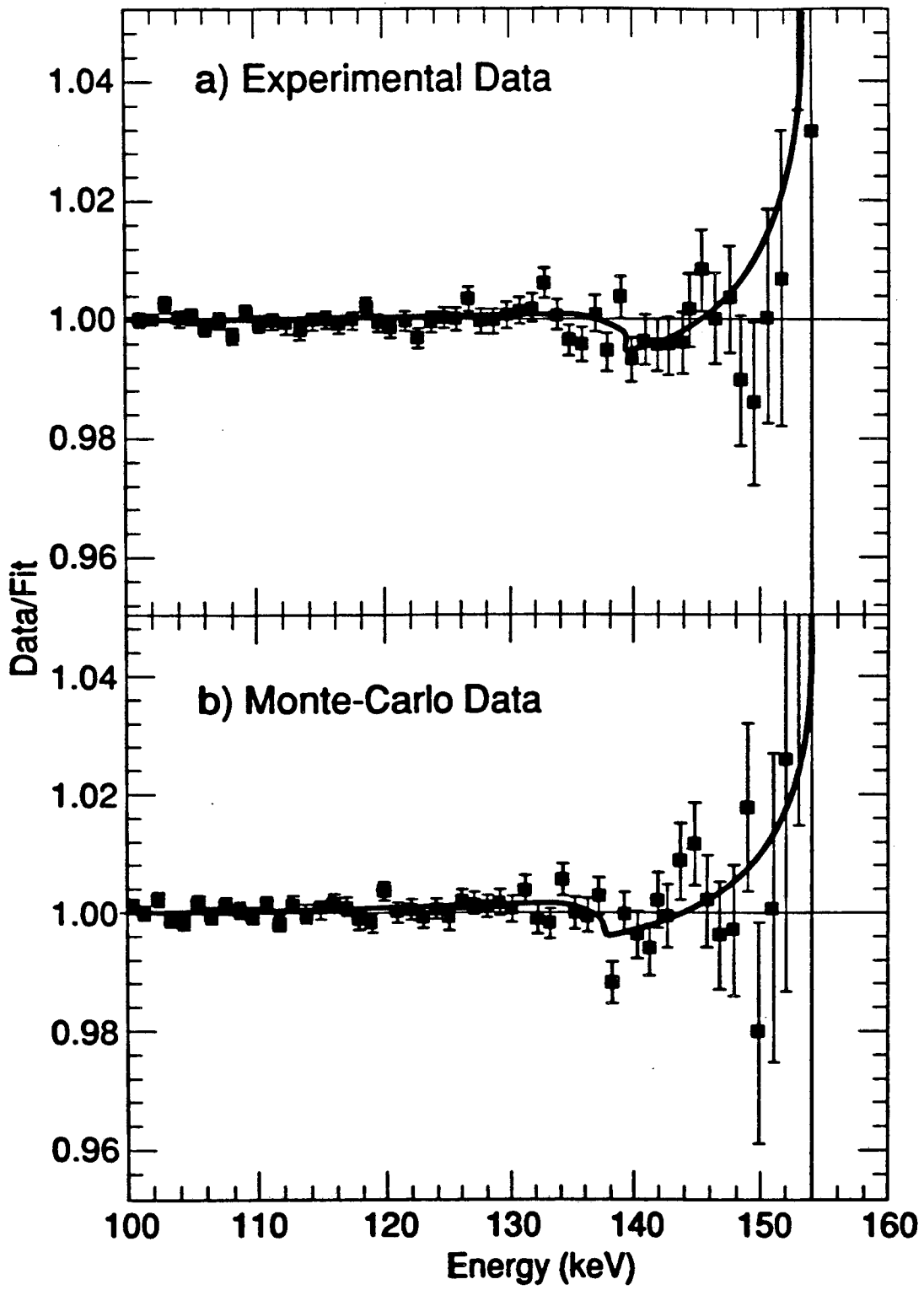


XBL 9010-4730





XBL 9011-5309



XBL 9010-4728

LAWRENCE BERKELEY LABORATORY  
UNIVERSITY OF CALIFORNIA  
INFORMATION RESOURCES DEPARTMENT  
BERKELEY, CALIFORNIA 94720