Lawrence Berkeley National Laboratory
LBL Publications

Title
Neutrinos

Permalink
https://escholarship.org/uc/item/3mj0q3gf

Author
Norman, E.B.

Publication Date
1991-10-01

eScholarship.org Powered by the California Digital Library
University of California

LBL-31335

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

To be published as a chapter in *McGraw-Hill Yearbook of Science and Technology*, 1993

Neutrinos

E.B. Norman

October 1991

U. C. Lawrence Berkeley Laboratory
Library, Berkeley

FOR REFERENCE

Not to be taken from this room

NUCLEAR SCIENCE DIVISION

LBL-31335
Copy 1
Bldg. 50 Library.

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. 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 liability or 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 and shall not be used for advertising or product endorsement purposes.

Lawrence Berkeley Laboratory is an equal opportunity employer.

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.

Neutrinos

Eric B. Norman
Nuclear Science Division
Lawrence Berkeley Laboratory
Berkeley, CA 94720

To be published in the 1993 McGraw-Hill Yearbook of Science and Technology

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.

Results of recent experiments suggest that the neutrino may be more than a thousand times more massive than previously believed. Studies performed at four different laboratories on the decays of five different isotopes indicate that a neutrino with a mass of 17 keV (17,000 electron volts) is emitted approximately 1% of the time in nuclear beta decay. Such a "heavy" neutrino would have profound implications in both particle physics and astrophysics.

Neutrino History. Early in this century, physicists discovered a type of radioactivity that is now known as beta decay. In this process, a neutron inside an atomic nucleus converts into a proton and an electron (beta particle). The proton remains bound inside the nucleus by the strong nuclear force, while the beta is ejected. The amount of energy available in such a decay, Q_β, is equal to the difference in rest-mass energy between the initial and final nuclear states. Up until this time, every process studied by physicists had obeyed the law of energy conservation - that is, the total energy of an isolated system does not change. Thus, it was expected all beta decays of a given isotope would produce electrons with a unique energy, Q_β. However, when the energy spectrum of the emitted electrons was first measured in the 1920's, a very surprising result was found. Instead of a single electron energy, what was observed was a continuous spectrum extending from zero energy up to the full decay energy, Q_β. At this point, physicists had two choices: either to give up their cherished belief in energy conservation or to hypothesize the existence of an additional unseen particle that is emitted in beta decay. This particle would share the available energy with the electron such that the sum of the two energies would equal Q_β. The particle that accompanies the electron emitted in nuclear beta decay is now known as the electron-type anti-neutrino. Related processes that have also been observed are (1) positron decay, in which a proton inside a nucleus converts into a neutron plus a positron plus an electron-type neutrino and (2) electron capture, in which a proton inside a nucleus captures a bound atomic electron and converts into a neutron plus an electron-type neutrino.

Neutrinos interact with matter only through the weak and gravitational forces. Thus, the direct detection of neutrinos is a formidable experimental challenge. It took nearly thirty years before the electron-type neutrino was detected in the laboratory. Since then, two additional types of neutrinos have been discovered: one associated with the muon, ν_μ, and one associated with the tau lepton, ν_τ. Today neutrino beams are routinely available at a number of accelerators around the world, and neutrino detectors are playing a major role in particle physics and astrophysics.

Massive Neutrinos? The fact that the spectrum of electrons emitted in nuclear beta decay appears to extend all the way up to the maximum energy allowed by energy conservation suggests that the neutrino is either massless or at least very low in mass. Studies of the high energy portion of the beta spectrum of tritium (^3H) have established that the mass of the electron-type antineutrino is less than 10 electron volts. It was suggested around 1980, however, that the object emitted in beta decay might not be a simple particle with a well defined mass. It might instead be a composite object made up of two particles with quite different masses. If one assumes that the major constituent is massless and that the other smaller component has a mass on the order of keV's, then beta decay spectra would be more complicated than previously thought. As illustrated in Fig. 1, each spectrum would actually consist of two components. The one associated with the emission of the massless neutrino would extend all the way up to Q_β, and the second weaker component associated with the emission of the massive neutrino would end at an energy of $Q_\beta - m_\nu c^2$, where m_ν is the mass of the heavy neutrino. In beta decay studies, one detects only the electron, not the neutrino. Thus one would observe the sum of these two spectra. At the energy where the spectrum associated with the emission of the heavy neutrino ends, there would be a change in the slope or a "kink" in the observed beta spectrum. This spectral feature is the signature of the emission of a heavy neutrino.

The first reported observation of such a "kink" came in 1985 when John Simpson from the University of Guelph in Canada claimed to see an excess number of events at low energy in the beta spectrum of tritium, which he interpreted as being due to the emission of a heavy neutrino. Most beta decay studies suffer from the problem of betas scattering within the radioactive source before reaching the detector and the problem of betas backscattering out of the detector. Both of these processes mimic the effect of the massive neutrino in that they result in an excess of low-energy events appearing in the beta energy spectrum. In order to be able to observe the tritium spectrum (Q_β = 18.6 keV) with a minimum of distortion, Simpson implanted the tritium into a silicon semiconductor detector. After the implantation, the beta particles from the tritium decays were detected via the ionization they produced in the silicon. A high voltage applied across the silicon crystal caused negatively-charged electrons to drift to one electrode while positively-charged ions drifted to the other electrode. The amount of ionization produced in such a device is proportional to the energy deposited by the beta particle. From a detailed study of the tritium beta spectral shape, Simpson inferred that a neutrino with a mass of 17 kev was occasionally emitted instead of the massless neutrino.

This unexpected result caused quite a stir in the physics community. Between 1985 and 1988, eight different groups at laboratories scattered around the world attempted to duplicate Simpson's results by studying the beta decays of several different isotopes using a variety of techniques. All of these subsequent experiments found no evidence of such a "kink" and each claimed to rule out the existence of a neutrino with a mass of 17 keV.

In 1989, however, Simpson presented results of two new experiments which again showed evidence for the emission of the heavy neutrino. The first experiment again involved tritium implanted in a semiconductor detector, but this time germanium was used instead of silicon. The point of this was to demonstrate that the "kink" was not an artifact peculiar to the use of a silicon detector. The second experiment was a more conventional beta decay study utilizing a radioactive source external to the detector. In this experiment, a source of ^{35}S (sulfur-35) was put on a thin backing and the beta particles were observed in a cooled silicon detector. Both of these experiments provided further evidence that a neutrino with a mass of 17 keV is mixed with about 1% probability with the massless neutrino.

These new claims have prompted another round of experiments to be performed by physicists all around the world - but this time the results are different. New studies of the beta decays of ^{14}C (carbon-14) and ^{35}S and a study of the electron-capture decay of ^{71}Ge (germanium-71) all indicate that a neutrino with a mass of 17 keV is emitted approximately 1% of the time when these nuclei decay. The recent ^{14}C experiment was similar to Simpson's tritium experiments in that the radioactive source was inside the detector. In this case, however, the detector was made from a crystal of germanium grown with ^{14}C inside it. This avoided the problem of the radiation damage produced by an implantation process. The results of this study are shown in Fig. 2. The spectral distortion which appears 17 keV below the ^{14}C endpoint energy is the signature of the heavy neutrino. The new ^{35}S experiment improved on Simpson's version by utilizing collimators and baffles to prevent scattered electrons from reaching the silicon detector. The results of this experiment also showed a clear distortion of the ^{35}S beta spectrum characteristic of a neutrino with a mass of 17-keV and an emission probability near 1%. The ^{71}Ge experiment differs from others in that what was detected were photons given off in radiative electron capture (inner bremsstrahlung). These photons share the available decay energy with the neutrino, much like the electron and anti-neutrino do in ordinary beta decay. Thus, if a massive neutrino is sometimes emitted in electron capture, a "kink" should appear in the inner bremsstrahlung spectrum. Such a feature 17-keV below the endpoint is just what was observed in this recent study. Thus, three additional groups using quite different techniques have now reported evidence for the existence of the 17-keV neutrino.

Implications of a 17-keV Neutrino. If these new results prove to be true, they will have profound implications for both particle physics and astrophysics. In the so-called Standard Model of elementary particles, neutrinos are taken to be massless. While some extensions of the Standard Model allow for neutrino masses on the order of an electron volt or so, 17 keV is far heavier than had been expected. From experiments performed at high energy accelerators, it is now known that there are only the three types of neutrinos mentioned earlier, and thus the question arises as to which one has a mass of 17 keV? The limit on the mass of the electron-type neutrino mentioned previously eliminates the possibility that it is the 17-keV neutrino. From so-called neutrino oscillation experiments, in which one looks for neutrinos of one type to convert into another, the μ-type neutrino is also ruled out. This leaves open the possibility that the tau neutrino is the object with a mass of 17 keV that is being observed in these beta decay experiments.

Such a heavy neutrino might be expected to play a major role in a number of astrophysical problems, such as the solar neutrino problem (i.e. the deficit of neutrinos reaching us from the Sun) and the problem of dark matter (the fact that the universe seems to contain far more matter than we can directly see). The 17-keV neutrino appears to be too heavy to help resolve the solar neutrino problem. Its effect would be to decrease the flux of electron-type neutrinos reaching the Earth by only about 2% which hardly makes a dent in the factor of 2-3 discrepancy between theory and experiment. Regarding the dark matter problem, the situation is not so clear. Neutrinos were produced in huge numbers in the Big Bang. If these particles are stable, then there are hundreds of neutrinos per cubic centimeter everywhere in the universe today. If neutrinos have a rest mass energy of approximately 100 eV, they would provide a high enough matter density to eventually halt the universal expansion and close the universe. A 17-keV neutrino is a problem in this regard. If it were stable, it would provide about 200 times the required closure density. Thus, the universe should have long ago collapsed under the weight of its neutrinos. Since this did not happen, the conclusion is that the 17-keV neutrino must be unstable and have a lifetime less than a million years or so. If its lifetime is near this upper limit, the decay products of the 17-keV neutrino could be the sought-for dark matter. Just what these decay products might be is an open question.

Conclusions. It is quite suggestive that a number of very different recent experiments have observed "kinks" in beta decay spectra 17 keV below whatever the endpoint energy is for the nucleus being studied. Furthermore, it is significant that all of these experiments yield consistent mixing probabilities of approximately 1%. It is hard to find a common error that might be plaguing all of the experiments. However, it should be pointed out that all positive reports of such "kinks" come from experiments performed with solid-state ionization detectors of either silicon or germanium. To date, no magnetic spectrometer or gas detector experiments have seen a "kink". Clearly, if this object is a neutrino, it must show up in every beta spectrum. Thus, at the present time there are many very careful experiments being performed at a number of different laboratories to help clarify the intriguing puzzle of the 17-keV neutrino.

References

A. Hime and N. A. Jelley, New evidence for the 17 keV neutrino,
Phys. Lett. B 257:441- 449 , 1991.

R. Shrock, New tests for and bounds on neutrino masses and lepton mixing,
Phys. Lett. B 96: 159-164, 1980.

J. J. Simpson, Evidence of heavy-neutrino emission in beta decay,
Phys. Rev. Lett. 54: 1891-1893 , 1985.

B. Sur et al., Evidence for the emission of a 17-keV neutrino in the beta decay of ^{14}C,
Phys. Rev. Lett. 66:2444-2447, 1991.

I. Zlimen et al., Evidence for a 17-keV neutrino,
Phys. Rev. Lett. 67: 560-563, 1991.

Figure Captions

Figure 1. The beta spectrum that would be observed in nuclear beta decay studies if a massless neutrino were emitted 99% of the time and a neutrino of mass m_ν were emitted 1% of the time. The "kink" occurs at the energy where the spectrum associated with the emission of the heavy neutrino ends.

Figure 2. The ratio of the observed beta spectrum of ^{14}C to that expected if the neutrino were massless. The shape of the spectrum expected for massless neutrinos was determined from the observed data above 140 keV. The change in this ratio from 1.0 that begins to occur at 138 keV is well fitted by the smooth curve through the data points, which shows the deviation expected if a 17-keV neutrino is emitted 1% of the time in the beta decay of ^{14}C. (After B. Sur et al., Evidence for the emission of a 17-keV neutrino in the beta decay of ^{14}C, *Phys. Rev. Lett.* 66:2444-2447, 1991).

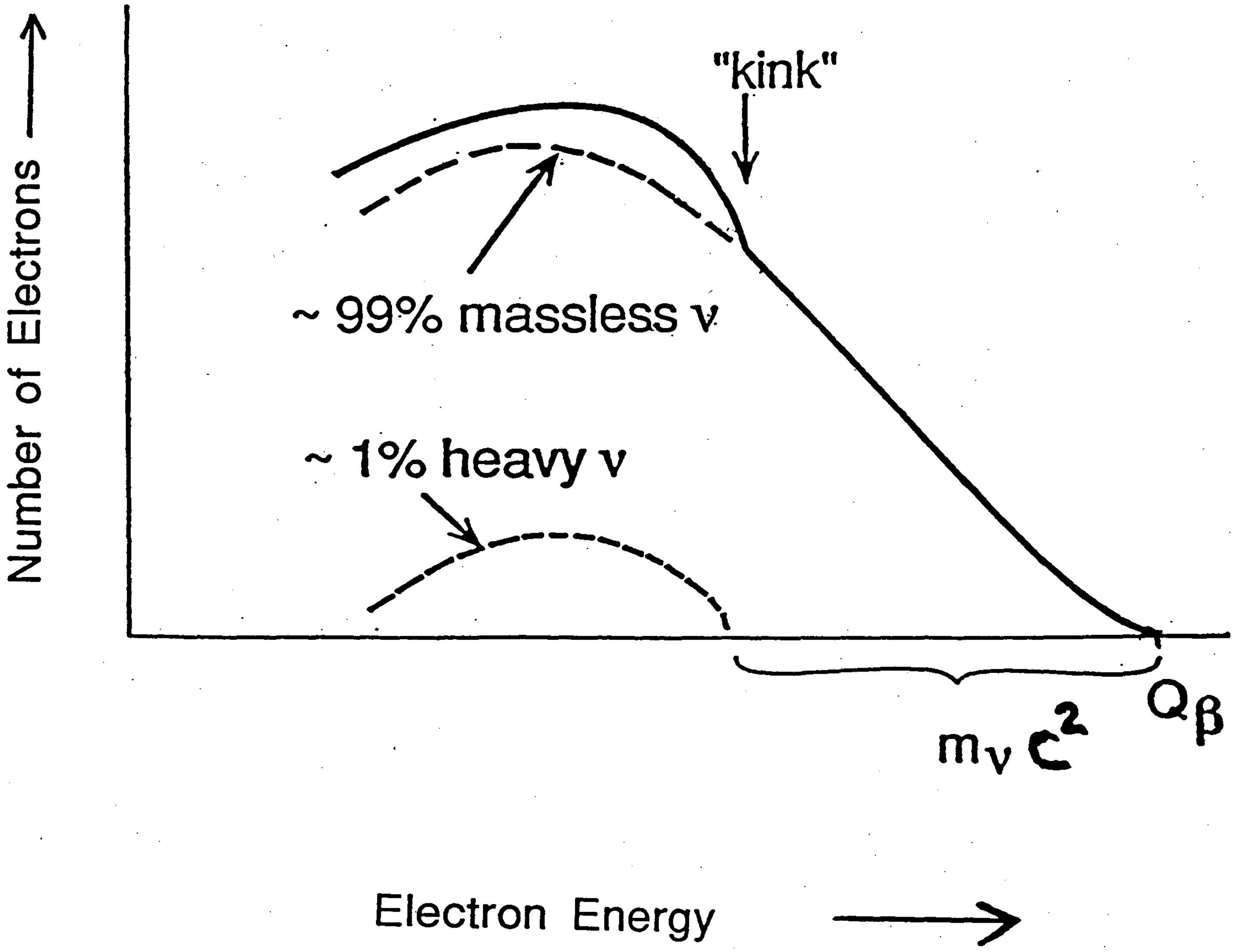
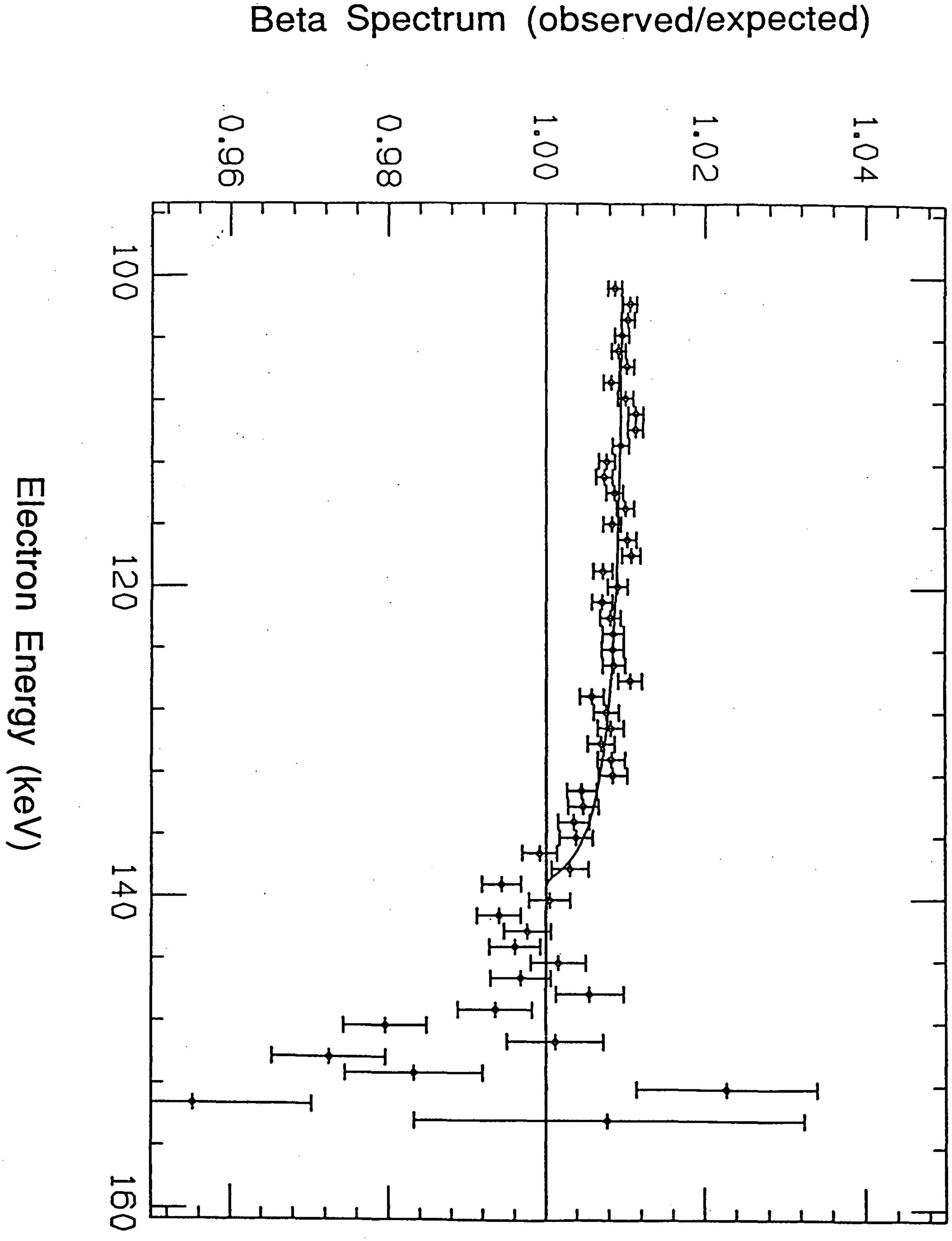

Number of Electrons
"kink"
~ 99% massless ν
~ 1% heavy ν
$m_\nu c^2$
Q_β
Electron Energy

Figure 1

Figure 2.


Beta Spectrum (observed/expected)
1.04
1.02
1.00
0.98
0.96
100
120
140
160
Electron Energy (keV)

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