Evidence for a 17-keV Neutrino

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(Received 23 January 1991)

A search for neutrinos of mass 10–40 keV has been made by studying the internal-bremsstrahlung spectrum of ^{71}Ge. We find evidence for a 17.2-keV neutrino with a mixing ratio of 1.6%.

PACS numbers: 23.40.Bw, 14.60.Gh, 27.50.+e

In 1985 Simpson [1] claimed that (2–4)% of neutrinos emitted in tritium β decay have a mass of 17 keV. Other β-decay investigations gave negative results, as did searches with internal bremsstrahlung in electron capture (IBEC) [2–4]; these investigations, and other possible explanations of Simpson's result, have been recently reviewed [3,4]. Recently, Simpson and Hime found new evidence for 17-keV neutrinos and observed a relative intensity of 0.73% with ^{35}S, and (0.6–1.6)% with tritium [5,6]. A recent investigation [7] of IBEC from ^{55}Fe could not exclude the recent results of Simpson and Hime in the 15–20-keV mass range. We have studied IBEC with ^{71}Ge and find evidence for a 17-keV neutrino; preliminary results were reported [8,9].

Assuming both light and heavy neutrinos the IBEC spectrum involves contributions from both types and is given by

$$\frac{dW(k)}{dk}=\frac{dW(k,m_L)}{dk}\cos^2\vartheta+\frac{dW(k,m_H)}{dk}\sin^2\vartheta\,, \qquad (1)$$

where k is the photon energy, m_L and m_H are the masses of the two neutrinos, and the fraction R of heavy neutrinos is given by $R=\sin^2\vartheta$. We searched for heavy neutrinos in the 10–40-keV mass region and we took m_L as zero.

A comprehensive review of IBEC is available [10]. IBEC associated with capture from initial S states is given by

$$\frac{dW_{nS}(k,m_\nu)}{dk}\propto k[Q-B(nS)-k] \times\{[Q-B(nS)-k]^2-m_\nu^2c^4\}^{1/2}R_{nS}(k) \qquad (2a)$$

and for initial P states by

$$\frac{dW_{nP_j}(k,m_\nu)}{dk}\propto k[Q-B(nP_j)-k] \times\{[Q-B(nP_j)-k]^2-m_\nu^2c^4\}^{1/2}Q_{nP_j}^2(k)\,, \qquad (2b)$$

where Q is the transition energy and $B(nS)$ and $B(nP_j)$ are the binding energies of the respective S and P states. $R_{nS}(k)$ describes modifications of the Coulomb-free results and exact expressions were developed by Intemann [11]. $Q_{nP_j}(k)$ was introduced by Glauber and Martin [12] and calculated in greater detail by De Rújula [13]. All the quantities in Eqs. (2a) and (2b) are known and the shape of the IBEC spectra can be calculated for different heavy neutrino masses, and for different R values. However, in order to increase the accuracy of our own determination we remeasured Q for the ^{71}Ge decay.

Heavy neutrino emission will produce a kink, or distortion, in the IBEC spectrum. The decay of ^{71}Ge is an allowed transition, 100% to the ground state of ^{71}Ga. There is excellent general agreement between theory and experiment for allowed decays [2,14]. In our technique it is only necessary that the theory is sufficiently well known that we can be confident there are no kinks in the IBEC spectrum, other than those associated with heavy neutrino emission. The theoretical distributions were calculated for IBEC associated with capture of S and P initial states. Kinks can be associated with capture from different initial atomic states but capture from the $1S$ state is dominant for the mass range investigated, and we searched for kinks at the $Q-B(1S)-m_Hc^2$ position. Our measured Q value was $229^{+1.1}_{-0.9}$ keV (95% C.L.) and $B(1S)=10.367$ keV. The $R_{nS}(k)$ function involved in $1S$ capture has smooth energy dependence and it can be calculated exactly [11] and the other terms in Eq. (2a) are phase-space contributions; one can be confident that there are no kinks in the internal-bremsstrahlung (IB) spectrum region analyzed unless there are contributions from heavy neutrinos.

A 10-mCi ^{71}Ge source ($T_{1/2}\simeq 11$ d) was made by the (n,γ) reaction on natural germanium. Radioactive impurities of ^{46}Sc, ^{55}Cr, ^{60}Co, ^{75}Se, ^{77}As, ^{124}Sb, and ^{137}Cs were identified. Radiochemical techniques were used to reduce these impurities to $<10^{-7}$ of the ^{71}Ge activity. The GeO$_2$ source was 3 mm thick and had a 14-mm-diam, 0.6-mm-thick Plexiglas window. Gamma rays were detected in a 47-mm-diam, 36.5-mm-thick HPGe detector which had a measured resolution of

$$[0.75\pm0.01+(0.00237\pm0.00005)k]^{1/2}\,,$$

where k is in keV and the uncertainties are at the 1σ level. The source and detector were shielded by 6 cm of lead and data were accumulated in a 4096 channel multichannel analyzer with an energy dispersion of 0.157 keV/channel. Data were recorded for about 8 d with an equal time for the background measurement. The energy calibration was checked every day and drifts were $< \pm 2$ channels.

A sum of five functions was used to describe the detector response: two Gaussians, an arctangent plateau, an arctangent multiplied by a Gaussian (to describe Compton backscattering), and another arctangent multiplied by the Compton cross section to describe the Compton plateau [15]. The response function has twelve parameters and they were determined using such standard sources as ^{57}Co, ^{133}Ba, ^{137}Cs, and ^{241}Am. Our response function f_{resp} is in general agreement with other analyses [16,17]. The efficiency ε_{PS} for carrier-free point sources was investigated using standard ^{57}Co, ^{60}Co, ^{133}Ba, ^{137}Cs, and ^{152}Eu sources and was found to be accurately represented by a function which is proportional to $k^{-A}\exp(Bk^{-D})$, where A, B, and D are constants. Values of $A = 1.030 \pm 0.011$, $B = -9318 \pm 50$, and $D = 2.16 \pm 0.01$ were found, with uncertainties being at the 1σ level. In order to allow for the source thickness ε_{PS} was multiplied by a polynomial P, where $P = a + bn + cn^2$, with a, b, and c being constants and n is a channel number. P is a smooth function of energy. Both ε_{PS} and P are reasonably standard expressions [18].

A corrected experimental spectrum N_{expt} was prepared for the fitting procedure by subtracting room background, contributions from radioactive impurities, and pileup contributions. The pileup contributions were estimated by separate measurements with a variety of radioactive sources. An IB spectrum, with background, impurity, and pileup contributions, is shown in Fig. 1. In a 5-keV interval near 200 keV, the IB contributions were 682000 counts, the background contributions were 6.8%, the pileup contributions were 3.1%, and contributions from impurities were 0.3%. There were no impurity peaks in the region of interest, which was on the downward slope between 155 keV and the IB end point. The kink for 17.2 neutrinos is at 201.6 keV.

The basis of our technique has been described previously [3,4]. In the region above a possible kink position (which depends on the m_H being investigated) N_{expt} was divided by the theoretical spectrum N_{IBEC}, which had been modified by multiplying by ε_{PS} and had been convoluted with f_{resp}. The width of that energy region was linearly increased with m_H value and was about 10 keV for m_H in the 15–20-keV range. In this region above the kink there is no influence of heavy neutrinos (except from electron capture involving higher atomic states which could be neglected). A, B, and D had already been fixed in the carrier-free source investigation and the coefficients a, b, and c adjusted to give the best fit to the ratio of the experiment to theory by fitting P with

$$(N_{\text{expt}}/N_{\text{IBEC}}\varepsilon_{\text{PS}}f_{\text{resp}})_{\text{above}}\,.$$

This allows an accurate determination of a, b, and c in the region where there is no heavy neutrino contribution.

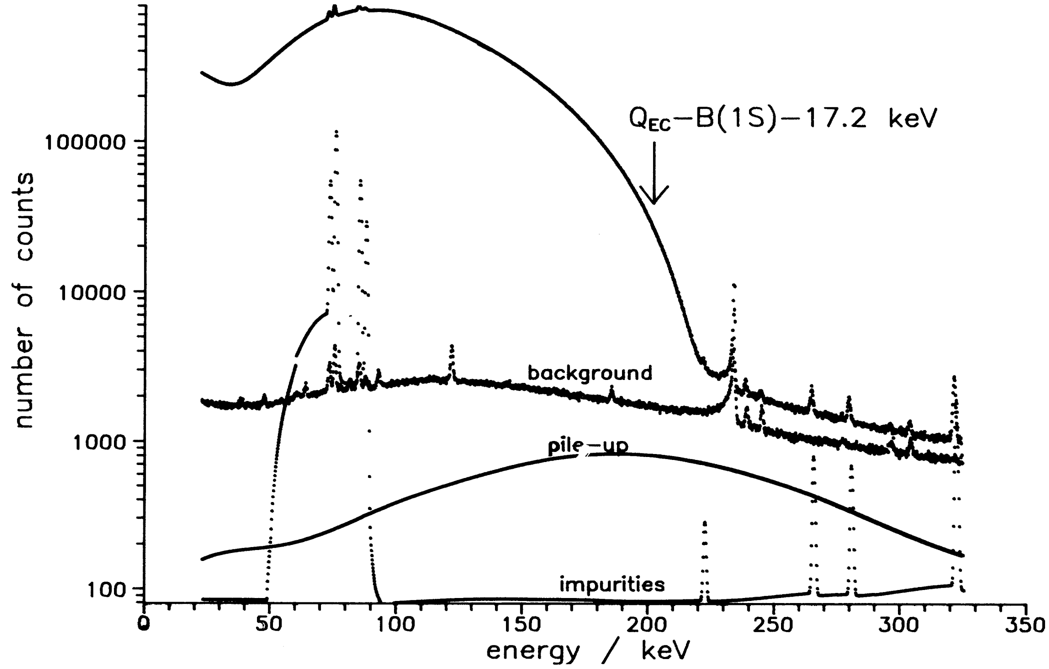

FIG. 1. The IB spectrum along with the contributions from room background, radioactive impurities, and pileup.

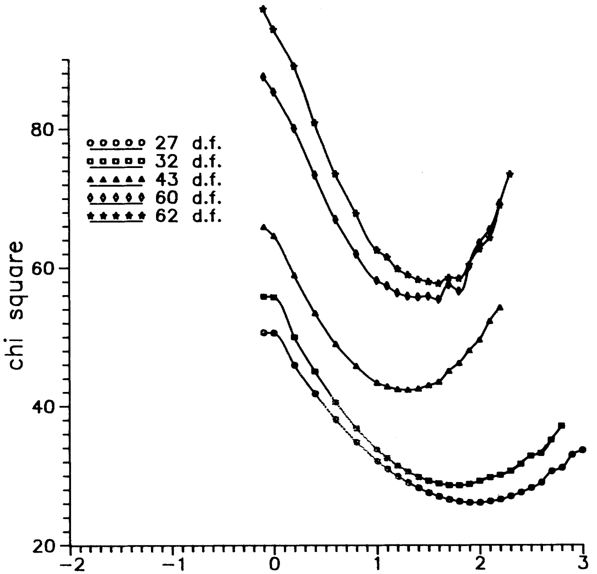

FIG. 2. χ^2 distributions for $m_H = 17.2$ keV. The five distributions are for five different degrees of freedom (d.f.), corresponding to using different numbers of channels in analysis.

Values of $a = 3.881 \pm 0.002$, $b = (-4.198 \pm 0.001) \times 10^{-3}$, and $c = (1.8256 \pm 0.0014) \times 10^{-6}$ were obtained with uncertainties being at the 1σ level.

The possible existence of heavy neutrinos was then investigated by extrapolating P below the kink position (for the same number of channels as used above the kink) and a χ^2 comparison was made between the extrapolated P and $(N_{\text{expt}}/N_{\text{IBEC}}\varepsilon_{\text{PS}}f_{\text{resp}})_{\text{below}}$ in this region for different values of R, introduced in N_{IBEC}. As the best values of a, b, and c had been determined in the region where there are no massive-neutrino contributions, only R was varied in the χ^2 comparison in the region where massive neutrinos can contribute. For each m_H investigated R was varied from -1% to $+2\%$ in steps of 0.1%; the significance of possible negative R values has been discussed previously [3].

In order to reduce any arbitrariness in choosing the number of channels used in the analyses, five different numbers of channels were used for each m_H value investigated. The final R value in each case was the average of the values which corresponded to minima in χ^2. Our procedure involved 100 χ^2 analyses for the m_H range investigated. In the case of $m_H = 17.2$ keV the 5 χ^2 distributions for the different numbers of channels (and degrees of freedom) are shown in Fig. 2. The minimum reduced χ^2 values are about 1.

A χ^2 analysis was also used to determine Q. Our value of $229.2^{+1.1}_{-0.9}$ keV is smaller than the best-fit value of 235.7 ± 1.8 keV obtained by Wapstra *et al.* [19]. However, our value is in agreement with 231 ± 3 keV obtained in the most accurate IB measurement [20]. If IB analyses have some bias to smaller Q values, we assume it would also reduce the position of the kink. In that case, it would not alter the value of R and we would still expect our estimate of m_H to be accurate.

The evidence for a small kink is not apparent in a visu-

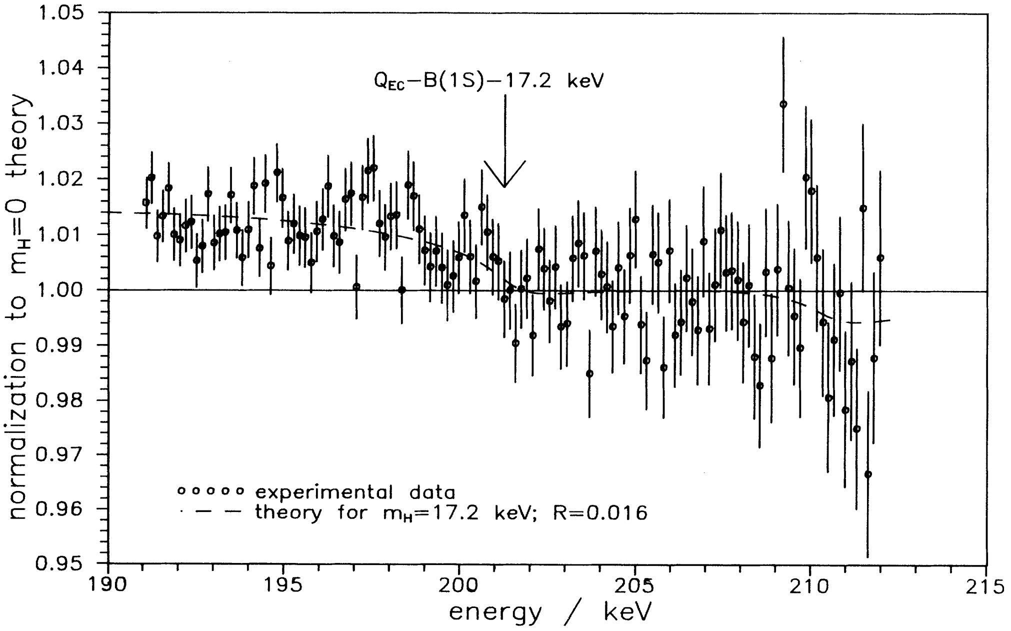

FIG. 3. The experimental corrected IB spectrum divided by the theoretical spectrum which assumes $m_H = 0$, normalized to the region just above the expected kink. The dashed line represents the theory for $m_H = 17.2$ keV and $R = 1.6\%$.

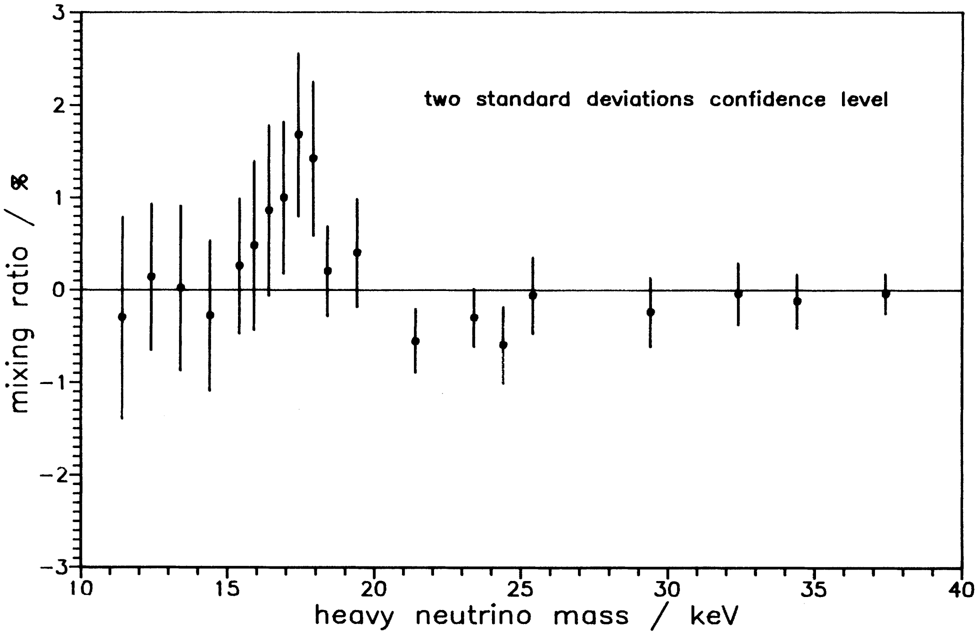

FIG. 4. The mixing ratio R obtained for possible heavy neutrino masses m_H in the 10–40-keV mass range; the values correspond to a 2-standard-deviation confidence level.

al inspection of the IB spectrum. However, if we normalize the spectrum to a spectrum which assumes $m_H=0$, the kink becomes visible at $Q-B(1S)-m_Hc^2$ corresponding to 201.6 keV. This is illustrated in Fig. 3.

The uncertainty in R has three components: (a) the uncertainty associated with the χ^2 analysis, (b) the dispersion associated with using five different numbers of channels for each m_H value, and (c) the error involved in projection of P into the region below the kink. At the 1σ level the uncertainties are 0.51%, 0.12%, and 0.1%, respectively. If the errors are added quadratically, this gives $R=(1.60\pm0.53)\%$. At the 3σ level the uncertainties are 0.89%, 0.35%, and 0.3%, respectively; this results in $R=(1.60\pm1.01)\%$ (99.7% C.L.).

The R values for m_H in the 10–40-keV mass range are shown in Fig. 4. There is clear evidence for a nonzero m_H value. We obtain $m_H=17.2^{+1.3}_{-1.1}$ keV (95% C.L.) and an R value of $(1.6\pm0.79)\%$ (95% C.L.).

Our result, which is obtained for a decay process different from β decay and involves using a different experimental technique, is in general agreement with that of Simpson and Hime and confirms the existence of the heavy neutrino. It is also supported by the recent results of Norman *et al.* [21].

One of the authors (B.A.L.) thanks the Natural Sciences and Engineering Research Council of Canada for financial support.

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