Limits on Neutrinoless $\beta\beta$ Decay Including That with Majoron Emission

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Neutrinoless double-β decay would require two new phenomena, of which one is lepton-number nonconservation. Among several candidates for the other are nonzero neutrino mass and the emission of a Goldstone boson, such as the majoron. For the former possibility our Ge-detector array now sets a limit for the $0^+ \to 0^+$ transition in ^{76}Ge of $T_{1/2} > 5\times10^{23}$ yr from the fluctuation in the background or almost a factor of 2 longer by maximum likelihood at the 68% confidence level (C.L.). For the latter process we have a 90%-C.L. limit of 1.4×10^{21} yr, a result in disagreement with a recent possible observation of majoron emission.

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If neutrinoless double-β decay ($\beta\beta_{0\nu}$) were observed,[1-3] it would provide information on physics beyond the standard model in at least two areas: violation of lepton-number conservation plus one or more of a list which includes light neutrino mass, right-handed currents, heavy neutrino mass, supersymmetric particles with R-parity nonconservation,[4] and the existence of a massless Goldstone boson such as the majoron.[5] The last of these would have particularly wide-ranging consequences, since the majoron would result from the spontaneous breaking of baryon- minus lepton-number symmetry, a process also giving mass to light majorana neutrinos. Thus the recent reports[6] of the possible observation of neutrinoless $\beta\beta$ decay induced by majoron emission have aroused widespread interest. We present here results in conflict with those reports, based on an experiment with about an order of magnitude more sensitivity and with lower backgrounds.

The nucleus ^{76}Ge is a candidate for $\beta\beta$ decay and constitutes 7.8% of normal Ge, which can be made into an excellent detector of electron energy. The $\beta\beta$ decay would then be observed as the sum of the energies of the two electrons emitted. The $\simeq$0.1% energy resolution of a Ge detector is particularly useful in the search for the $\beta\beta_{0\nu}$ decay, $^{76}\text{Ge} \to {}^{76}\text{Se} + 2e^-$, which would give a spike at the end-point energy of 2.041 MeV. The energy resolution of the Ge is of little use in searching for $\beta\beta_{2\nu}$ decay, $^{76}\text{Ge} \to {}^{76}\text{Se} + 2e^- + 2\bar{\nu}_e$, which has a four-body decay spectrum peaking at about 0.65 MeV, or the $\beta\beta_{0\nu,B}$ decay, $^{76}\text{Ge} \to {}^{76}\text{Se} + 2e^- + B$, giving a three-body spectrum which peaks at about 1.55 MeV. Here B is the massless Goldstone boson which we shall hereafter refer to as a majoron.

Meaningful results for the $\beta\beta_{0\nu,B}$ decay are possible since remarkably low backgrounds have been achieved by placing the experiments underground with good passive shields and making strong efforts of varying success to reduce intrinsic radioactivities. The main distinction in method of background suppression is whether or not an active NaI shield is used. The experiments of Leccia *et al.*,[7] Ejiri *et al.*,[8] and Caldwell *et al.*[9] use NaI, and those of Forster *et al.*,[10] Fisher,[10] Simpson *et al.*,[11] Fiorini and co-workers,[12] and Avignone[13] do not. NaI and associated phototubes are not as free of radioactivity as other materials near the Ge detectors, and despite the self-vetoing, systems with NaI tend to display more and larger full-energy peaks than do those without NaI. However, the peaks themselves do not interfere with observing $\beta\beta$ decay. Rather it is the low-energy tails from those peaks which raise backgrounds, and the NaI provides typically an order of magnitude suppression of the Compton tail. This comes about not only because the Compton scattered photon in most cases exits from the Ge and enters the NaI to veto the event, but also because many of the initial photons are part of a cascade decay, and any of the other time-coincident photons can also veto the event. This suppression is important because the number of counts in a Compton tail can be many times the number of counts in the peak, and this peak/Compton ratio is difficult to model, since it is very dependent on the location of the source relative to the Ge and the presence of any intervening material.

In addition to the Compton tail, there is another source of counts below each peak which should also be taken into account and is easily confused with multiple Compton scattering because of its shape. This effect occurs in a closed-end coaxial cylindrical Ge detector of the type used in $\beta\beta$-decay studies because it has a large exposed open surface at one end of the cylinder which is usually protected by a coating,[14] resulting in a surface which is generally not electrically neutral and thus distorts the internal electric field lines. If any of the γ-ray interactions occurs in the region of distorted field, incomplete charge collection results.[15–17] While only (10–20)% of signals from single interactions would be degraded in this manner, a typical high-energy γ ray undergoes $\simeq 3$ interactions in the detector, so that around half the signals may correspond to energies which are too low. Caldwell *et al.* have made extensive measurements with sources in different locations with respect to the Ge to determine the shapes of the low-energy tails of peaks resulting from both Ge detector charge-collection inefficiencies and Compton scattering.

The Caldwell *et al.* experiment,[9] 200 m underground in the powerhouse of the Oroville, California, Dam, has used between four and eight Ge detectors, averaging about 160 cm^3 (0.9 kg) of fiducial volume each, inside a 15-cm-thick complete NaI shield, which in turn is inside borated polyethylene surrounded by a 20-cm-thick Pb shield. The data presented here for the majoron-induced decay represent a total mass times livetime of 6.7 kg yr. This is by far the largest data sample available for studying this process.

The recording of background events in a Ge detector in which energy is deposited in a NaI crystal or a second Ge detector provides a powerful diagnostic tool. As an example important to the results presented here, we have found in this way that ^{68}Ga provides a significant source of background. The ^{68}Ga activity probably originates from ^{70}Ge$(n,3n)\,^{68}$Ge, produced by cosmic rays when the Ge is above ground or from used Ge detectors going back into the pool of starting material. The ^{68}Ge decays by electron capture (280-day half-life), giving a characteristic Ga x ray. The daughter, ^{68}Ga, decays with a 68-min half-life, emitting a 1.89-MeV β^+. If the positron's annihilation γ's are also absorbed in the Ge detector, a spectrum extending to 2.91 MeV is produced. The ^{68}Ga decay dominates from 0.8 to 1.7 MeV the spectrum which results when the annihilation γ's escape and are registered in the NaI. Confirmation of this important source of background is obtained from (1) the size of the Ga x-ray peak, and (2) the rate at which the background level has decreased since the detectors were placed underground. The quantity of ^{68}Ga will vary from detector to detector, but all detectors used in $\beta\beta$ decay experiments in which sufficiently low-energy measurements have been recorded show the characteristic Ga x-ray peak.

In the energy region of major interest, 1.5 to 3.0 MeV, our data can be accounted for mainly by ^{68}Ga activity and the tails of identified peaks. Since the ^{40}K peak at 1.461 MeV is an order of magnitude larger than any other peak, it is safer to confine the analysis to energies above that peak. Furthermore, the main sensitivity to majoron-induced decay is above 1.5 MeV. However, we can model the ^{40}K tail sufficiently well that the results obtained below do not change appreciably if a wider energy region is included. We have accumulated sufficient counts that 33 γ-ray lines can be identified with known nuclides between 1.5 and 3.0 MeV. Many of these are small and might be ascribed to background fluctuations in data sets with fewer counts, or without Compton suppression. If peaks are not identified and data are averaged over large energy intervals, as is done in looking for majoron-induced decays, then not only are the peak counts subsumed into the average background, but also the far larger number of counts in the tails are not properly identified. In our fit to the data with the peaks subtracted, the tail contributions provide roughly half the background, while the ^{68}Ga activity supplies about $\frac{1}{5}$, although this contribution is both energy and time dependent. The remainder of the background we take as a constant, although replacing it by a term linear or even exponential in energy does not change the results significantly. This $\frac{1}{4}$ to $\frac{1}{3}$ of the data represents our ignorance. With more statistics we would very likely identify other peaks or β spectra.

The resulting fit is shown as a solid curve in Fig. 1, where the data minus peaks are plotted in 50-keV bins. The agreement with the data is good, considering the complexity of the background, the difficulty in modeling the low-energy continuum below each subtracted peak, and the possibility of small peaks that are missed. *Thus no majoron-induced decay is needed to explain the data.* If we fix the contributions from the radioactive backgrounds and allow the number of events in the majoron term to vary, the result is 0 ± 200 events. The error here is purely statistical, however, and does not reflect the uncertainty in the background size and shape. The error in the normalization of the continuous background below peaks is $\pm 10\%$. In addition, different shapes for this

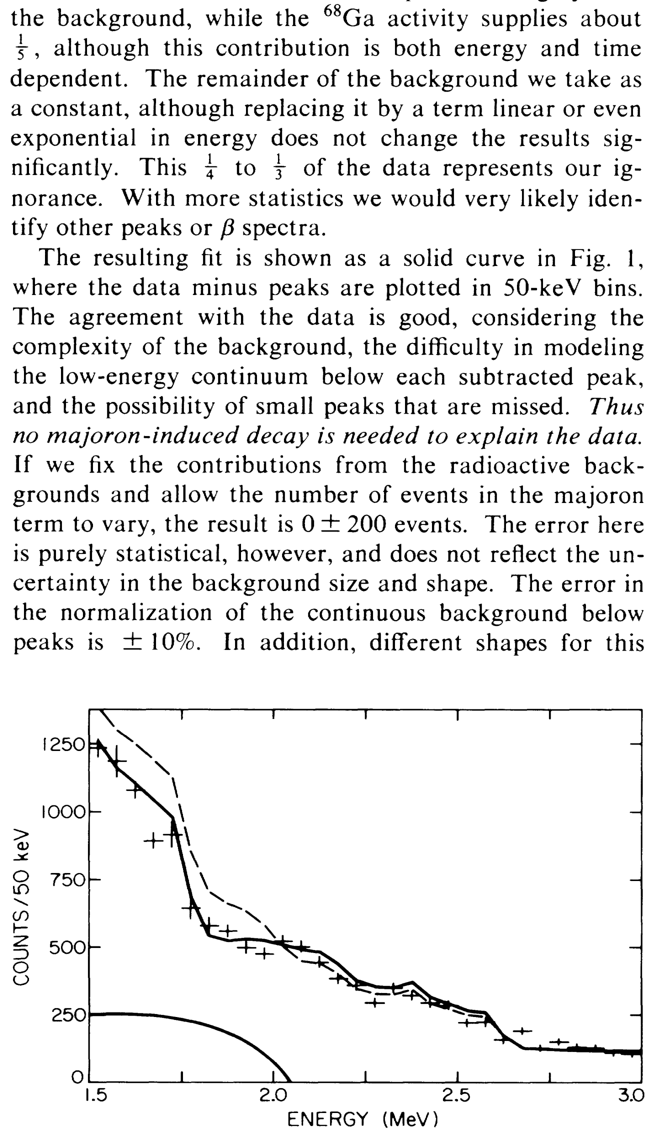

FIG. 1. Data from this experiment averaged over 50-keV bins with a fit (solid line) to the known backgrounds plus a constant term. The dashed curve shows the spectrum including a majoron-induced decay of $T_{1/2} = 6 \times 10^{20}$ yr, with the two background terms fixed at the low end of their allowed range. The other curve shows the expected size and shape of the majoron-induced decay alone.

background were tried in the fit. The effect of these uncertainties is a systematic error of ± 1200 events in the majoron spectrum. The error in the normalization of the ^{68}Ga contribution is $\pm 20\%$, corresponding to an error in the majoron component of ± 500 events.

The systematic error in the majoron term is ± 1300 events, and the total error, including statistical, is ± 1320 events. The systematic error dominates with this amount of data. This is also reflected in the fact that the errors would need to be increased from the statistical by a factor of about 2 to give a χ^2 per degree of freedom of 1. Using the total error, including systematic, we get a 90%-confidence-level upper limit of 2200 events, which yields $T_{1/2}(\beta\beta_{0\nu,B}) > 1.4\times 10^{21}$ yr. This would correspond[3] to a limit on the coupling of the majoron to the electron neutrino of $< 7\times 10^{-4}$ with use of the matrix elements of Ref. 2 and $< 3\times 10^{-4}$ with use of those of Grotz and Klapdor.[18] These limits on the coupling are probably more stringent than those from ^{48}Ca,[19] ^{82}Se,[20] ^{130}Te,[3] and ^{150}Nd,[21] but uncertainties in nuclear matrix elements make comparisons difficult.

If we try to fit the data by including a contribution of majoron-induced decay at the level of $T_{1/2}(\beta\beta_{0\nu,B}) = 6\times 10^{20}$ yr suggested by the data of Ref. 6, we get the dashed curve of Fig. 1. However, this requires that the ^{68}Ga and tail contributions be as small as the errors allow. Even taking into account the systematic errors in these backgrounds, the probability for the fit with a majoron-induced component corresponding to $T_{1/2} = 6\times 10^{20}$ yr is 10^{-4}.

Our result is clearly in disagreement with that of Ref. 6. It is interesting that one of our eight detectors considered alone shows a spectrum remarkably similar to that of Ref. 6. In both cases there is prominent evidence for an α at 5.3 MeV, which gives a large continuum extending down to the vicinity of 2 MeV. By comparing this spectrum with that for our other detectors with much lower α background, we see that the degraded α's provide a contribution to the background which gradually falls toward lower energies, combining with the normal rising background seen in Fig. 1 to produce an almost flat background down to about 2 MeV. The rise in counts toward lower energy then appears significant. This detector has a considerably larger level of background than any of our others, and data from it were not included in the majoron analysis.

In addition to the misleading flat background at higher energies making the rise at lower energies look more important in the data of Ref. 6, we believe that the authors are also being misled by believing that "the only background in the spectrum above the 1461-keV γ-ray peak is the broad 5.3-MeV α peak and its degraded continuum." While they exclude ^{68}Ga as being the *sole* source of the rise in the spectrum, they certainly have some of this activity. They also may not identify other γ-ray peaks because of insufficient statistics, and in their case with no Compton suppression the tails of those peaks would contribute many more counts than the peaks themselves. One other issue is that the data do not show the steep rise from the end point toward lower energies expected from majoron-induced decay, as shown by the curve in Fig. 1. This is the case for both the data of Ref. 6 (although the statistics in this case obscure the point) and our own, which has an order of magnitude more mass times lifetime in this energy range.

The $\beta\beta_{0\nu}$ decay, which would give a spike at 2.041 MeV, is much easier to observe and to interpret than the spectrum of the $\beta\beta_{0\nu,B}$ decay. Because our limit for this decay has improved considerably since our latest publication,[9] which then gave the most stringent limit from any experiment, we also present this new result here. For a data sample of 8.4 kg yr, the time and detector averaged background in the vicinity of 2.04 MeV is now 1.4 counts/keV·kg·yr. On the basis of the fluctuation allowed in the background around the expected peak, for which our FWHM resolution is 3.36 keV, we get a 68%-confidence-level lifetime limit $T_{1/2}(\beta\beta_{0\nu}) > 5\times 10^{23}$ yr, using the analysis described previously.[9] It is conventional to use instead a maximum-likelihood analysis, but there is a significant dip in the energy region where the peak is expected, so that using the analysis procedure recommended by Aguilar-Benitez *et al.*,[22] we obtain a much larger lifetime limit of 9×10^{23} yr.

These results are to be compared with the best published result from a single experiment[12] of 3.3×10^{23} yr by maximum likelihood. Even 5×10^{23} is a factor of about 2 better than a recently published[13] "world limit" which includes some of our data. For the present result, adding the data from all other experiments changes the limit by less than the uncertainty in assigning a limit from our experiment alone.

The interpretation of this limit in terms of physically interesting quantities will be left to a subsequent publication, except to indicate the sensitivity of the result by its effect on a limit for light majorana neutrino mass. This result gives a *lower* limit on the effective mass of the neutrino for the $\beta\beta_{0\nu}$ process, but were a positive result observed at this lifetime value (and we choose to use 5×10^{23} yr to be conservative), then a neutrino would have to exist with this or a *larger* neutrino mass.[23] To show the effect of using different nuclear matrix elements (calculated in the references given) to interpret the result, we give the neutrino-mass limits to more significant figures than the uncertainty in the lifetime warrants: $\langle m_\nu \rangle <$ 1.8,[2] 1.3,[24] and 0.7 eV.[18]

This result for light neutrino mass emphasizes the power of double-β decay for probing physics beyond the standard model. Unfortunately, so far only minimum lifetime limits have been obtained, and our results do not support a discovery as exciting as neutrinoless double-β decay induced by majoron emission. Fisher *et al.*[25] have reached a similar negative conclusion.

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