NEW LIMITS ON PHYSICS BEYOND THE STANDARD MODEL FROM DOUBLE BETA DECAY

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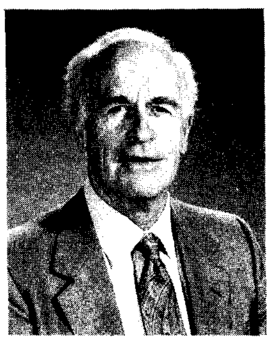

Neutrinoless double beta decay ($\beta\beta_{0\nu}$) would require two pieces of new physics, one of which is lepton number nonconservation. Among candidates for the other are light electron neutrino mass, the admixture of a very heavy neutrino, and supersymmetric particles with R-parity violation. Applicable to these is a new limit from the UCSB/LBL Ge detector array for the $0^+\rightarrow0^+$ transition in ^{76}Ge of $T_{1/2}>6\times10^{23}$y from the fluctuation in the background or 8×10^{23}y by maximum likelihood at the 68% C.L. This result also sets limits on right-handed currents, as does the result for the $0^+\rightarrow2^+$ transition, $T_{1/2}>2\times10^{23}$y. A limit of $T_{1/2}>1.4\times10^{21}$y at the 90% C.L. is set on $\beta\beta_{0\nu}$ induced by a Goldstone boson, such as a Majoron. The last result is in disagreement with a recently reported possible observation of Majoron emission.

If neutrinoless double beta decay[1,2] ($\beta\beta_{0\nu}$) were observed, 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 violation,[3] and the existence of a massless Goldstone boson such as the Majoron.[4] 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[5] of the possible observation of neutrinoless $\beta\beta$ decay induced by Majoron emission have aroused widespread interest. The results presented here are based on an experiment with almost an order of magnitude more data and lower backgrounds and disagree with those reports.

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 $\sim$0.1% energy resolution of a Ge detector is particularly useful in the search for the $\beta\beta_{0\nu}$ decay, $^{76}Ge \rightarrow {}^{76}Se + 2e^-$, the evidence for which would be 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, $^{76}Ge \rightarrow {}^{76}Se + 2e^- + 2\bar{\nu}_e$, which gives a four-body decay spectrum peaking at about 0.65 MeV, or the $\beta\beta_{0\nu,B}$ decay, $^{76}Ge \rightarrow {}^{76}Se + 2e^- + B$, 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. The main reason any meaningful result can be presented for the $\beta\beta_{0\nu,B}$ decay is that remarkably low backgrounds have been achieved with the Ge detectors.

Among the Ge experiments the main distinction in method of background suppression is whether or not an active NaI shield is used. 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 is not generally taken into account, and which, due to its shape, is easily confused with multiple Compton scattering. This effect occurs in all semiconductor detectors because of the existence of regions in the device where there is incomplete charge collection due to distortions in the electric field. While only 10-20% of signals from single interactions would be degraded in this manner, a typical high-energy γ-ray undergoes $\sim$3 interactions in the detector. If any one of these interactions occurs in the region of distorted field, a degraded signal results, so that typically around half the signals correspond to energies which are too low. The UCSB/LBL group has 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 UCSB/LBL experiment[6)] 200m underground in the powerhouse of the Oroville, California Dam has used between 4 and 8 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 $\times$ live-time of 7.1 kg·y. 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, with the ^{68}Ge decaying by electron capture (280-day half-life) and 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. This background source 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, this being consistent with a 280-day half-life. All Ge detectors must have this background activity, since it is produced both by cosmic rays when the Ge is above ground, and probably also because old neutron-damaged Ge detectors may go back into the pool of starting material and contaminate newly produced crystals. 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 one-fifth, although this contribution is both energy and time dependent, earlier data showing more than later. 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 one-fourth to one-third of the data represents our ignorance. With more statistics we would very likely identify other peaks or beta spectra.

The resulting fit shown as a solid curve in Fig. 1, where the data minus peaks is plotted in 50 keV bins, is surprisingly good considering the complexity of the quite irregular background, the difficulty in modeling the low-energy tails of peaks, and the likelihood that small peaks are still being missed. Thus no Majoron-induced decay is needed to explain the data. To take into account the fact that the systematic errors in describing the background are somewhat larger than the statistical errors, we scale up the statistical errors by a factor of 2.0, which would make the χ^2 per degree of freedom equal to 1. Using these conservatively inflated errors we get a 90% confidence level upper limit for $T_{1/2}(\beta\beta_{0\nu,B}) > 1.4\ 10^{21}$y. This would

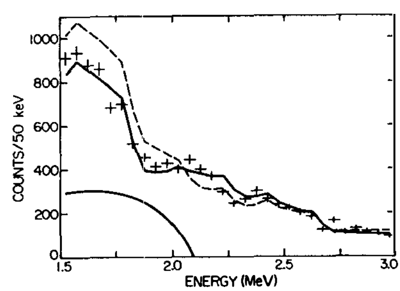

Fig. 1. Data from this experiment averaged over 50 keV bins with a fit (solid line) to the known background plus a constant term. The dashed curve is a fit requiring the addition of a Majoron-induced decay of $T_{1/2} = 6{\times}10^{20}$y. The other curve shows the expected shape of the latter decay alone.

correspond[2] to a limit on the coupling of the Majoron to the electron neutrino of $<7\times10^{-4}$ using the matrix elements of Ref. 1 and $<3\times10^{-4}$ using those of Ref. 7.

If we try to fit the data by including a contribution of Majoron-induced decay at the level of $T_{1/2}(\beta\beta_{0\nu,B}) = 6\times10^{20}$y suggested by the data of Ref. 5 we can get the dashed curve of Fig. 1. However, this requires that the tail contribution be as small as the errors on the peak heights allow and that the ^{68}Ge contribution go to zero, whereas we know this activity exists. Even with these unrealistic conditions the probability of this curve fitting the data is 10^5 times smaller than the fit with no Majoron-induced decay component.

Our result is clearly in disagreement with that of Ref. 5. It is interesting that one of our 8 detectors considered alone shows a spectrum remarkably similar to that of Ref. 5, as shown in Fig. 2. 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 comoaring 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 low energies and which combines with the normal rising background seen in Fig. 1 to produce an almost flat background down to about 2 MeV. Thus the subsequently rising background appears more significant in this particular detector, which has a considerably larger level of background than any of our other detectors.

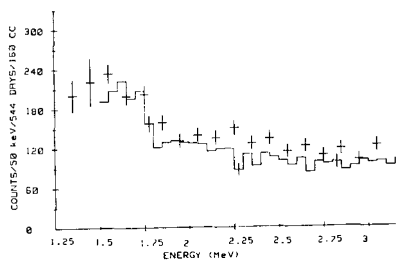

Fig. 2. Data from the UCSB/LBL detector with the largest α background compared to the PNL/USC data normalized to the same counting time and mass of Ge. The PNL/USC data are shown with error bars, whereas for clarity only one typical error bar is shown for the UCSB/LBL data, which are plotted as a histogram.

In addition to the misleading flat background at higher energies making the rise at lower energies look more important in the data of Ref. 5, we suggest 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," as can be seen in Fig. 3, in which our data are compared with theirs properly normalized to the same counting time and quantity of Ge. While they exclude ^{68}Ga as being the sole source of the rise in the spectrum, they certainly have some of this activity, as seen by the Ga X-ray in their low-energy data. 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

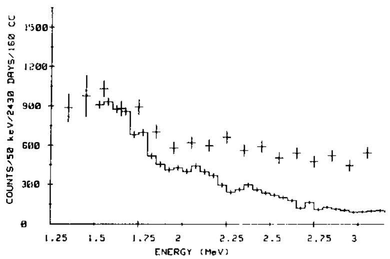

Fig. 3. Data from the UCSB/LBL detectors (with the one eliminated which was used for Fig. 2) shown as a histogram compared with the PNL/USC data normalized to the same counting time and mass of Ge. The latter is plotted in 100 keV bins and the former in 50 keV bins.

other issue is that the data do not show the steep rise from the endpoint 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. 5 (although the statistics in this case obscures the point) or our own, which has an order of magnitude more kg·y 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. The limit for this decay has improved considerably since our previous publication.[6] For a data sample of 7.75kg·y, the time and detector averaged background in the vicinity of 2.04 MeV is now 1.4 counts/keV·kg·y. On the basis of the fluctuation allowed in the background in an energy region around the expected peak we get a 68% C.L. lifetime limit $T_{1/2}(\beta\beta_{0\nu})>6\times10^{23}$y. However, there is a dip in the energy region where the peak is expected, so a maximum likelihood analysis results in a larger lifetime limit. Using the analysis procedure recommended by the Particle Data Group,[8] we obtain a limit of 8×10^{23}y.

The difference in these two results for a lifetime limit points up the futility of trying to produce a "world limit". Although attempts have been made at doing so by adding the spectra of different experiments, this is a dubious procedure, particularly since the energy resolution differs from one experiment to another. For the result given above, adding the data from all other experiments only changes the limit by about 10%, which is less than the uncertainty in assigning a limit from our experiment alone.

This result may be interpreted as a limit on light Majorana neutrino mass, giving a lower limit on the effective mass of the neutrino in the $\beta\beta_{0\nu}$ process. However, if a positive result were observed at this lifetime value (and we choose 6×10^{23}y to be conservative), then a neutrino would have to exist with this or a larger neutrino mass.[9] 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: $\langle m_\nu \rangle < 1.7$ (Ref. 1), 1.2 (Ref. 10), 0.66 (Ref. 7) eV. These values apply to the case in which this is the only contributor to $\beta\beta_{0\nu}$.

If instead the decay occurred because of the mixing with a probability $(U_e^L)^2$ of the electron neutrino with a heavy Majorana neutrino, M_ν, a limit can be set

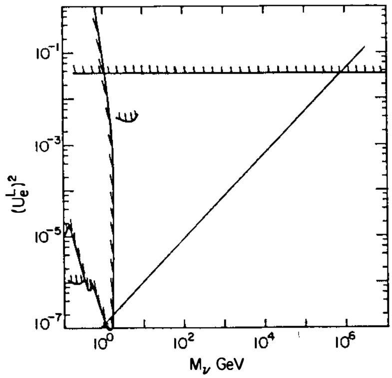

Fig. 4. Limits on the mass of a heavy Majorana neutrino coupled to a left-handed W boson as a function of its probability for mixing with an electron neutrino.

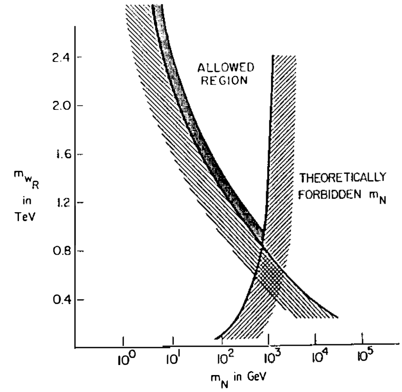

Fig. 5. Limits on the mass of a heavy Majorana neutrino coupled to a right-handed W boson as a function of the mass of that boson. Increasing the double beta decay limit from 2.5×10^{23}y to 6×10^{23}y has added the dotted region.

on M_ν for a given $(U_e^L)^2$, as shown in Fig. 4. Values above and to the left of the diagonal line (which uses the calculation of Ref. 1) are excluded, and these are generally much better limits than those from other experiments, also shown in the figure. This neutrino would be coupled to a left-handed W boson, but if instead it were coupled to a right-handed W boson, W_R, such as appears in left-right symmetric models, then the limit on neutrino mass (now given as m_N in Fig. 5) becomes a function of the mass of W_R, as shown in the figure mainly taken from Mohapatra.[11)]

One other use of this lifetime limit is to constrain the $\tilde{u}$ squark mass as a function of gaugino mass for supersymmetric theories with R parity violation.[3)] One limit is given by zino plus photino exchange, which should surely occur, but an even more stringent limit is set if gluino exchange involves essentially a point interaction so that a Fierz transformation is allowed and colored intermediate states are not required. Both limits are shown in Fig. 6, which again depends on the calculation of Ref. 1. It will be noticed that these are generally well beyond values which can be reached with present accelerators.

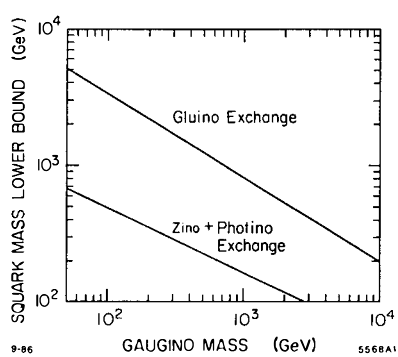

Fig. 6. Lower limit on the $\tilde{u}$ squark mass as a function of the mass of the gaugino exchanged.

Finally, limits may be set on the existence of right-handed currents (RHC). The transition to the first excited state of ^{76}Se (i.e., $0^+ \to 2^+$) can occur only by RHC, and hence searching for it would be of great importance if any positive effect were detected. This is carried out using the NaI in coincidence with the Ge signal to detect the 0.559-MeV deexcitation γ-ray. The lifetime limit on this process set by the background fluctuations is $T_{1/2} > 2\times10^{23}$y. Using, however, the limit from the $0^+ \to 0^+$ transition, which is more restrictive, constraints can be set on the RHC coupling parameters, η_{RR} and η_{RL}. These are the coefficients in the Hamiltonian of the right-handed leptonic current and the right- or left-handed hadronic current. The effective values of η_{RR} and η_{RL} are given in Table I under the assumption that one or the other of these is the sole contributor to $\beta\beta_{0\nu}$, in order to show the sensitivity of each parameter to the lifetime limit. Not only might both be involved, but also in any gauge theory if RHC exist, then $m_\nu \neq 0$.[9] Table I also gives unjustified significant figures to show the effect of different calculations.

TABLE I: Limits on RHC Parameters for $T_{1/2} > 6 \times 10^{23}$y

Parameter	Ref. 2 and 3	Ref. 24
$< \eta_{RR} >$	3.2×10^{-6}	$2.4\times^{-6}$
$< \eta_{RL} >$	3.0×10^{-7}	$2.9\times^{-8}$

These various results emphasize the power of double beta 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 beta decay induced by Majoron emission.

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