DOUBLE BETA DECAY: PRESENT AND FUTURE

David O. Caldwell
University of California, Santa Barbara, California 93106

Summary

Neutrinoless double beta decay provides a window onto the new physics the SSC hopes to explore, requiring lepton nonconservation, which is outside the standard model. It then gives limits on light and heavy Majorana neutrino masses, right-handed currents, and the existence of Majorons and supersymmetric particles. The experimental status of double beta decay is reviewed briefly, and current best limits are given on these interesting quantities. Prospects for future experiments are also surveyed.

Introduction to Double Beta Decay

At this Workshop devoted mainly to an accelerator motivated by the need to explore beyond the standard model, it is quite fitting to discuss double beta decay. If neutrinoless double beta decay ($\beta\beta_{0\nu}$) should be observed, it would violate lepton number, which is conserved in the standard model, and hence this would similarly probe new physics. So far no positive effect has been seen, but the limits obtained already are very constraining on theories and set goals for the SSC. In depth reviews[1-4] of double beta decay are available, and here only a few relevant points will be discussed.

Double beta decay of the form $(A,Z)\rightarrow(A,Z+2)+2e^-+2\bar{\nu}_e$, or $\beta\beta_{2\nu}$, surely occurs as a second-order weak transition between even-even nuclei when this is energetically possible, since the intermediate odd-odd nucleus is generally of higher mass, making a single β transition impossible. The effect of this decay has been observed by geochemical experiments using billion-year-old rocks. The $\beta\beta_{0\nu}$ decay, $(A,Z)\rightarrow(A,Z+2)+2e^-$ would be much more likely than $\beta\beta_{2\nu}$ because of a factor $\sim 10^6$-10^8 greater phase space were it not that there are two inhibiting conditions: (1) lepton number must be violated, and (2) there must be a helicity reversal. To explain the latter in terms of a conventional picture for $\beta\beta_{0\nu}$ decay, when a neutron turns into a proton with the emission of an e^-, a virtual $\bar{\nu}_e$ of positive helicity would be emitted, but to produce a second e^- from another neutron, the virtual particle must be absorbed as a ν_e of negative helicity. For this to be possible $\nu_e \equiv \bar{\nu}_e$, or the neutrino must be of the Majorana type, and the wrong helicity admixture must be present, which can occur if the neutrino has mass or if right-handed currents exist. Indeed, the neutrino could be one of extremely large mass with some coupling to the very light or massless ν_e. The decay could also be mediated by the existence of supersymmetric particles (gluino, zino, and photino exchange) or of massless bosons, such as Majorons[5] (χ^o) in the process $(A,Z)\rightarrow(A,Z+2)+2e^-+\chi^o$, which we designate $\beta\beta_{0\nu,\chi}$. Many of these processes are experimentally distinguishable, if the summed energy of the two e^- is observed, since $\beta\beta_{2\nu}$ gives a four-body spectrum, $\beta\beta_{0\nu,\chi}$ gives a three-body spectrum, and $\beta\beta_{0\nu}$ gives a spike. Even the presence of right-handed currents can in principle be singled out because that mechanism permits a $0^+\rightarrow 2^+$ transition to the first excited state as well as the $0^+\rightarrow 0^+$ transition, which is the only one allowed for $\beta\beta_{0\nu}$ decay driven by neutrino mass alone.

Double Beta Decay Experiments

With so much to be learned from double beta decay, it is not surprising that experiments searching for it are going on all over the world. While much reanalysis of the geochemical experiments has been taking place lately with somewhat changed $\beta\beta_{2\nu}$ lifetimes, space does not permit discussing these or the laboratory experiments on the verge of detecting this process. However, mention must be made of a possible resolution of the previous one-to-two order of magnitude discrepancy between calculated $\beta\beta_{2\nu}$ lifetimes and measurements or limits on these quantities. The calculable $\beta\beta_{2\nu}$ process provides some check on the interpretation of $\beta\beta_{0\nu}$ lifetime limits in terms of parameters of physical interest. Vogel and Zirnbauer[6] have found cancellations can occur if the previously neglected particle-particle component of the spin-isospin polarization force is included. This is capable of bringing experiment and theory into agreement but makes calculations very uncertain. It is not yet known whether there is a similar effect on calculated $\beta\beta_{0\nu}$ lifetimes.

While work with other nuclei such as ^{100}Mo, ^{136}Xe, and ^{150}Nd is underway, the important limits at present on $\beta\beta_{0\nu}$ come from ^{76}Ge experiments. High-purity Ge can be made into a high-resolution ($\sim$0.1%) detector of electron energies, and 7.8% of Ge is the $\beta\beta$ nucleus ^{76}Ge. To summarize these experiments, information will be given on the groups involved, the location of the experiment, the quantity of Ge currently used, background levels achieved around 2 MeV (in units of counts/keV·year·kg of Ge), and the $0^+\rightarrow 0^+$ lifetime limit reached at last reporting. The Zaragosa-Bordeaux-Strasbourg group[7] with 2.2 kg of Ge in the Frejus tunnel has reached 2.2×10^{22}y in 2252 hours with a rather high background of 40 because not all of their NaI counters have arrived, and the substitute counters have been irradiated. The Caltech-SIN-Neuchatel group[8] in the St. Gotthard tunnel obtained a lifetime of 6.2×10^{22}y after 6728 hours with 0.48 kg of Ge and a background of 4, but they are installing 6 kg of Ge, as well as building a TPC to use ^{136}Xe. The Osaka group[9] located in the Kamioka mine and using 0.88 kg of Ge with a background of 6 for 8621 hours achieved a limit of 7.4×10^{22}y and have since replaced the Ge with ^{100}Mo and Si detectors. The Pacific Northwest Laboratory, University of South Carolina group[10] in the Homestake mine operated 0.67 kg of Ge for 8089 hours with a background of 2.4 to reach 1.4×10^{23}y, and they are now assembling a 3.9 kg detector, which will eventually be doubled. The Guelph-Aptec-Queens group[11] is currently using 3.0 kg of Ge in a salt mine near Windsor, Ontario and has achieved 1.6×10^{23}y in a 3200 hour run with a background of roughly 2. The Milan group, which was the first[12] to use Ge, has more recently[13] operated two Ge detectors in the Mt. Blanc tunnel, one of 0.62 kg with a background of 24 when run for 21,000 hours gave a limit of 1.2×10^{23}y, and the other of 0.74 kg with a background of 4 gave a slightly better limit of 1.3×10^{23}y in 10,000 hours. The combined limit from these two is 1.8×10^{23}y. They are now developing a MWPC for ^{136}Xe.

Finally, the University of California at Santa Barbara, Lawrence Berkeley Laboratory experiment[14] has been operating in the power house of the Oroville, California

dam. Because the current best limits are from this experiment, a little more information will be given about those limits. Initially 3.5 kg of Ge were used for 3550 hours with a time-averaged background (which dropped a factor of two in 6 months) of 2.2 to achieve a limit of 2.5×10^{23}y. Using 2456 hours of those data, a 90% C.L. limit for $\beta\beta_{2\nu}$ of 8×10^{19}y was reached, as well as a 90% C.L. limit of 6×10^{20}y for $\beta\beta_{0\nu,\chi}$. After adding more detectors for a total of 5.3 kg, there was an additional 5000 hour run. Combining the data of the two runs gave a time-averaged background of 1.7 and limits for the $0^+\to0^+$ transition of 4.1×10^{23}y and for the $0^+\to2^+$ decay to the first excited state of 1.3×10^{23}y (by using the NaI surrounding the Ge in coincidence to be sensitive to the 559 keV deexcitation γ, instead of using the NaI in anticoincidence to reduce backgrounds). More recently all 8 detectors (7.1 kg) have been used for some additional running, and the current $0^+\to0^+$ limit is 4.5×10^{23}y. This last value is the $\beta\beta_{0\nu}$ limit which will be used below for setting limits on quantities of interest.

Interpretation of the $\beta\beta_{0\nu}$ Results

The limit[14] for $\beta\beta_{0\nu,\chi}$ decay of 6×10^{20}y has been evaluated[3] to give 90% C.L. limits for the coupling of the Majoron to the electron neutrino. The result depends on the matrix elements used, varying from $<1.1\times10^{-3}$ for the Los Alamos[2] matrix elements to $<4.1\times10^{-4}$, using those from Heidelberg.[15]

This variation in matrix element calculations is not as large as the uncertainty resulting from the disagreement between experiment and theory in the $\beta\beta_{2\nu}$ case, but the possible resolution of that problem already alluded to would make the $\beta\beta_{2\nu}$ matrix elements difficult to predict reliably. It is far from clear whether that problem even applies to the short-range $\beta\beta_{0\nu}$ case, so it will be ignored here, as will another potentially serious issue: if the neturino involved is actually a mixture, it may consist of neutrinos of opposite CP eigenstates, producing a cancellation which would make the effective neutrino mass, $<m_\nu>$, in $\beta\beta$ decay less than in, say, single β decay.[16] The quantity $<m_\nu>$ will be given below ignoring these problems and also as if it were the only effect contributing to $\beta\beta_{0\nu}$ decay. Right-handed current (RHC) effects could be present at the same time, for example, but these will also be treated as if they occurred alone. Actually, if RHC were present, any gauge theory would require $<m_\nu>\neq0$ as well,[17] but by stating limits as if only one cause is operative, one gets a better feeling for the relative sensitivity of the limits to $\beta\beta_{0\nu}$ lifetimes. The RHC parameters are interpreted most easily in terms of the simplified Hamiltonian,

$$H_W=-2^{-1/2}G_F\cos\theta_C[j_L^\mu(J_{L\mu}^\dagger+\eta_{LR}J_{R\mu}^\dagger)+j_R^\mu(\eta_{RL}J_{L\mu}^\dagger+\eta_{RR}J_{R\mu}^\dagger)]+\text{h.c.},$$

where the j's (J's) are components of the leptonic (hadronic) currents, with L and R standing for left- and right-handedness. The $<m_\nu>$, $<\eta_{RR}>$, and $<\eta_{RL}>$ parameters given below display more significant figures than are warranted to show the effects of different calculations. The more recent Tübingen-Jülich calculation[18] of $<\eta_{RL}>$ includes the effects of using a relativistic p-wave electron wave function and of including nucleon recoil, giving an impressively small number. This is many orders of magnitude[3] more stringent than those of other experiments for the case of neutrino mass generation by the see-saw mechanism.[19]

Table I: Neutrino Mass and RHC Parameter Limits for $T_{1/2}>4.5\times10^{23}$y

Parameter	Los Alamos[2]	Tübingen-Jülich[18]	Heidelberg[15]
$<m_\nu>$ eV	1.9	1.4	0.76
$<\eta_{RR}>$	3.2×10^{-6}	2.7×10^{-6}	--
$<\eta_{RL}>$	4.7×10^{-6}	3.4×10^{-8}	--

If instead of the above mechanisms for $\beta\beta_{0\nu}$ decay, it were engendered by the mixing of a heavy Majorana neutrino (mass M_ν) with the electron neutrino, which then could be effectively massless, the lifetime limit can be used to provide constraints on M_ν for a given coupling, $(U_e^L)^2$, of the heavy neutrino to the light one. For the case in which only left-handed W bosons are involved, the limits on M_ν vs. $(U_e^L)^2$ are given in Fig. 1, using the Haxton-Stephenson calculations.[2] The constraints on these parameters (values below and to the right of the lines are allowed) from $\beta\beta_{0\nu}$ (the diagonal line) are generally much more stringent than from other experiments.[20] A heavy neutrino could be a fourth-generation particle, which might be of the Majorana or Dirac type, but extra neutrinos, such as are required in the low-energy limit of string theories or in left-right symmetric models, are most likely Majorana particles. For the left-right symmetric theories right-handed W bosons are also involved, giving a different sort of limit.[21]

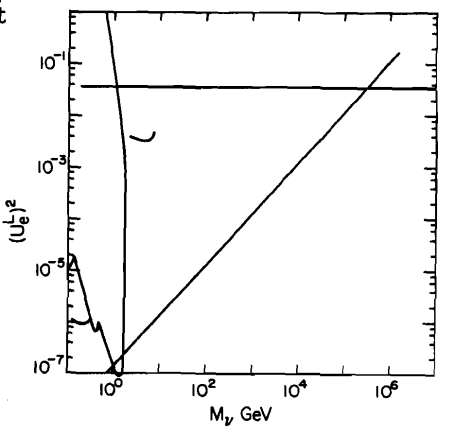

Fig. 1. Limit on the mass of a heavy Majorana neutrino as a function of its probability for mixing with an electron neutrino.

Recently, Mohapatra[22] has found a new use for $\beta\beta_{0\nu}$ results, namely setting a limit on supersymmetric particle masses. Instead of the exchange of Majorana neutrinos, various gauginos can be exchanged, and in supersymmetric theories with R-parity violation this sets a limit on the mass of the squark ($\tilde{U}$) involved as a function of gaugino mass. The exchange of zino plus photino would 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. 2 as a function of gaugino mass.

While the constraints $\beta\beta_{0\nu}$ places on $<m_\nu>$ are relatively well known, those it imposes on RHC are not so known, and the limitations placed on M_ν vs. U_e^L are practically not known at all. Now there are the new constraints on supersymmetric particles, further showing the sensitivity of this second-order weak process to

new physics, and it is hoped that the usefulness of double beta decay will be noticed more widely.

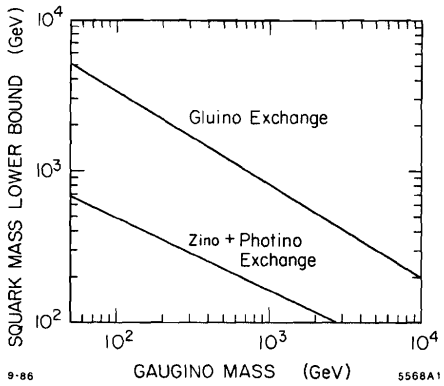

Fig. 2. Lower limit from $T_{1/2} > 4.5\times10^{23}$y for $\beta\beta_{0\nu}$ imposed on the mass of the $\tilde{u}$ squark as a function of the mass of the gaugino exchanged, with zino plus photino exchange surely allowed, and gluino exchange subject to some conditions.

Future Prospects

Since this process is so important in seeking clues to physics beyond the standard model, what are the prospects for further improvements and the hopes for seeing a positive effect? In the short term the UCSB-LBL experiment should achieve a limit of around 10^{24}y in two years time. That doubling of the lifetime limit is an improvement in limits on $\langle m_\nu \rangle$, $\langle \eta_{RR} \rangle$, and $\langle \eta_{RL} \rangle$ by only a factor of $\sqrt{2}$, so no positive effect is expected.

The significant change which could occur in that time scale is the advent of Soviet experiments using large quantities of separated isotopes. There are two of these now being developed. One by a Moscow group has 10 kg of separated ^{136}Xe, and they are building a 3m× 3m×1.5m TPC to use this gas. The TPC is expected to be completed by the end of 1986, and then there will be the usual shakedown period to get the apparatus working and particularly to reduce backgrounds. It is not clear at this point how free the Xe is of contaminants. The second experiment by a Moscow-Leningrad-Heidelberg group will use 15 kg of separated ^{76}Ge, of which they have about half now. That quantity of material would give them a factor of 20 advantage over the UCSB-LBL experiment, provided it could all be used and similar backgrounds are achieved. Normally there is a large loss of material in making the crystal and some loss in making detectors from the crystal. Again, separated materials also tend to have radioactive contamination. However, if these problems can be overcome, there will be from either experiment an order of magnitude improvement in the $\beta\beta_{0\nu}$ lifetime limit.

Since these quantities of separated isotopes would cost several hundred million dollars in the West, if they could be obtained at all, Western physicists will have to either give up this field or try a different approach. The most promising new technique is the use of low-temperature quasi-particle/phonon detectors, which are described elsewhere[23] in these Proceedings. If these can be implemented, one or even two orders of magnitude improvement in the $\beta\beta_{0\nu}$ lifetime limit appears possible. Then there will be a new era in double beta decay with renewed hope of a positive effect, but even negative results will impose severe and very important constraints on new physics.

REFERENCES

1. H. Primakoff and S.P. Rosen, Ann. Rev. Nucl. Part. Sci. 31, 145 (1981).
2. W.C. Haxton and G.J. Stephenson, Jr., Progr. in Part. and Nuc. Phys. 12, 409 (1984).
3. M. Doi, T. Kotani, and E. Takasugi, Prog. of Theo. Phys. Supp. No. 83 (1985).
4. J.D. Vergados, Phys. Rep. 133, No. 1 and 2 (1986).
5. Y. Chikashige, R.N. Mohapatra, and R.D. Peccei, Phys. Lett. 98B, 265 (1981); G.B. Gelmini and M. Roncadelli, Phys. Lett. 99B, 411 (1981).
6. P. Vogel and M.R. Zirnbauer, California Institute of Technology preprint MAP-78 (submitted to Phys. Rev. Lett. 1986).
7. F. Leccia, Ph. Hubert, D. Dassie, P. Mennrath, M.M. Villard, A. Morales, J. Morales, and R. Nunez-Lagos, Nuovo Cimento 78A, 50 (1983) and 85A, 19 (1985).
8. A. Forster, H. Kwon, J.K. Markey, F. Boehm, and H.E. Henrikson, Phys. Lett. 138B, 301 (1984); P. Fisher, Caltech Preprint, to appear in the Proceedings of the 1986 Moriond Conference.
9. H. Ejiri, N. Takahashi, T. Shibata, Y. Nagai, K. Okada, N. Kamikubota, T. Watanabe, T. Irie, Y. Itoh, and T. Nakamura, Nuc. Phys. A448, 271 (1986).
10. F.T. Avignone, III, R.L. Brodzinski, D.P. Brown, J.C. Evans, Jr., W.K. Hensley, J.H. Reeves, and N.A. Wogman, Phys. Rev. Lett. 50, 721 (1983) and 54, 2309 (1985); Phys. Rev. C34, 666 (1986).
11. J.J. Simpson, P. Jagam, J.L. Campbell, H.L. Malm, and B.C. Robertson, Phys. Rev. Lett. 53, 141 (1984).
12. E. Fiorini, A. Pullia, G. Bertolini, F. Cappelani, and G. Restelli, Phys. Lett. 25B, 602 (1967) and Nuovo Cimento 13A, 747 (1973).
13. E. Bellotti, O. Cremonesi, E. Fiorini, G. Ligouri, A. Pullia, P. Sverzellati, and L. Zanotti, Phys. Lett. 146B, 450 (1984).
14. D.O. Caldwell, R.M. Eisberg, D.M. Grumm, D.L. Hale, M.S. Witherell, F.S. Goulding, D.A. Landis, N.W. Madden, D.E. Malone, R.H. Pehl, and A.R. Smith, Phys. Rev. Lett. 54, 281 (1985) and Phys. Rev. D33, 2737 (1986).
15. K. Grotz and H.V. Klapdor, Phys. Lett. 153B, 1 (1985)
16. M. Doi, T. Kotani, H. Nishiura, K. Okuda, and E. Takasugi, Phys. Lett. 102B, 323 (1981) and Prog. Theo. Phys. 69, 602 (1983); L. Wolfenstein, Phys. Lett. 107B, 77 (1981) and Nuc. Phys. B186, 147 (1981); B. Kayser and A.S. Goldhaber, Phys. Rev. D28, 2341 (1983).
17. B. Kayser, S.T. Petcov, and S.P. Rosen, to be published.
18. T. Tomada, A. Faessler, K.W. Schmidt, and F. Grümmer, Nuc. Phys. B153, 1 (1985).
19. M. Gell-Mann, P. Raymond, and R. Slansky in "Supergravity" (North-Holland, Amsterdam, 1979), p. 317; T. Yanagida, Proc. Workshop on Unifed Theory and Baryon Number in the Universe (KEK, 1979).
20. F.J. Gilman and S.H. Rie, Phys. Rev. D32, 324 (1985)
21. R.N. Mohapatra, Phys. Rev. D34, 909 (1986).
22. R.N. Mohapatra, University of Maryland preprint (1986, unpublished).
23. B. Cabrera, B. Sadoulet, and D. Caldwell, these Proceedings.