REVIEW OF DOUBLE BETA DECAY

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The search for neutrinoless double beta decay, which is more than three decades old, has undergone widely revived interest because of its unique ability to test (1) lepton number conservation, (2) whether the electron neutrino has a mass, and (3) whether right-handed currents exist. These issues have attained new importance not only as tests of theories which unite the strong, electromagnetic, and weak interactions, but also in the case of neutrino mass because of a need to explain the missing dark mass of galaxies, provide a mechanism for galaxy formation, and give stability to galaxies.

The possibility for double beta decay arises because the pairing energy in nuclei with even numbers of neutrons and protons provides tighter binding than the adjacent odd-odd nuclei. Thus in many instances an even-even nucleus is energetically forbidden to decay to the neighboring odd-odd nucleus, but it may have an energetically possible decay to the next even-even nucleus via the second-order weak interaction,

$$[A, Z] \rightarrow [A, Z+2] + 2e^- + 2\bar{\nu}\ , \qquad (1)$$

where the symbol ν is always used here to mean ν_e. Although there has been geochemical evidence for this decay, its direct observation has been reported only recently. Moe and Lowenthal[1] give a lifetime of $(1.0 \pm 0.4) \times 10^{19}$ years for Se^{82}.

However, the really interesting possible $\beta\beta$ decay would be

$$[A, Z] \rightarrow [A, Z+2] + 2e^- . \qquad (2)$$

This 0ν decay obviously violates lepton number conservation, requiring that the virtual $\bar{\nu}$ from the first e^- emission be reabsorbed as a ν to permit a second e^- to be emitted. This means that $\bar{\nu} \equiv \nu$, or the neutrino is of the Majorana type for reaction (2), whereas (1) can occur for Dirac or Majorana neutrinos. Originally, it was believed that aside from possible inhibitions due to lepton number violation, the 0ν decay should be much more favored than the 2ν one because of the very large phase space factor ($\sim 10^6$). Thus the lack of $\beta\beta$ decay of $T_{1/2} \lesssim 10^{15}$ years was taken as evidence for the Dirac nature of the neutrino. However, the discovery in 1957 of maximal parity violation in β decay means that (2) was absolutely forbidden even for Majorana neutrinos unless at least one of the following were true: right-handed currents exist, or the neutrino has a mass. In the first case, a small component of the wrong helicity in the weak current would spin some neutrinos the opposite way, permitting the reaction to proceed. In the second case ($m_\nu \neq 0$), the $\bar{\nu}$ velocity is less than c, making it possible to reverse the helicity by a coordinate transformation.

Either or both of these helicity-breaking mechanisms could be at work, and they have extremely different implications for cosmology and grand unified theories. Fortunately, it is possible to distinguish between them experimentally. Since the ground states of even-even nuclei are 0^+, the usually expected $\beta\beta$ transition is $0^+ \rightarrow 0^+$. While a $\bar{\nu}$ mass can cause only this $0^+ \rightarrow 0^+$ transition, the "wrong" helicity current can give transitions to the first excited state, generally 2^+, as well. The ν mass mechanism ejects two electrons with identical helicities in a relative S-wave, giving the selection rule $\Delta J^P = 0^+$, whereas the right-handed current mechanism ejects electrons of opposite helicity in a relative P-wave, allowing $\Delta J^P = 0^+, 1^+, 2^+$. Thus if the $0^+ \rightarrow 2^+$ transition is not observed, but the $0^+ \rightarrow 0^+$ is, then the $0^+ \rightarrow 0^+$ rate gives a measure of neutrino mass. If both transitions are observed, then a comparison of the two rates in principle permits measuring the strength of right-handed currents, as well as the neutrino mass. Figures will be given later, but it should be noted at this point that the limits on the mass of a right-handed W boson which can be set by $\beta\beta$ decay are about two orders of magnitude greater than given by any other known experiment, but this $\beta\beta$ test exists only for Majorana neutrinos, while others are independent of neutrino type.

Turning now to the $\beta\beta$ experiments, we find they are of two general types, the geochemical and the laboratory. The former has produced indirect evidence for $\beta\beta$ decay in both Te and Se. However, the geochemical method, which seeks a noble gas decay product in rocks of $\sim 10^9$-year age, gives a lifetime[2] for ^{82}Se which is ~ 20 times that of the direct observation of Ref. 1. It is difficult to fault the geochemical results. For example, measurements on rocks from four continents give the same result to a factor 3-4. Measurement uncertainties, especially those due to ore age and some effects of Xe diffusion, are reduced by comparing rates for ^{128}Te and ^{130}Te decays, as was first suggested by Pontecorvo.[3] In addition, theoretical uncertainties are reduced by the probable cancellation of nuclear matrix elements. Since the energy release in ^{130}Te is almost three times larger than that in ^{128}Te, the ratio of their lifetimes is very sensitive to the number of leptons in the final state. Thus for 2ν decay, the ^{128}Te to ^{130}Te rate ratio is expected to be 2×10^{-4}, while for 0ν it is about 4×10^{-2} for no right-handed currents, but with RHC this number could be as low as 3×10^{-3}. The published experimental result[4] of $(6.29 \pm 0.02) \times 10^{-4}$ has led to considerable speculation that 0ν must occur as well as 2ν. However, this experiment gets a ^{130}Te half-life differing by a factor of 2 or 3 from other geochemical determinations, and a recent result[5] gives the rate ratio as $(1.0 \pm 1.1) \times 10^{-4}$. This result from the Heidelberg group[5] was made with relatively young ore and thus has a large statistical error, but there is reason to believe that the systematic uncertainties may be better than those of the Missouri group.[4]

Adding to the conclusion that there is no present evidence for 0ν decays are theoretical objections[6] that the ^{128}Te and ^{130}Te matrix elements may not be equal and that the calculated absolute lifetimes differ drastically from experimental ones, although the calculated[7] ^{82}Se rate agrees with the laboratory experiment.[1] If the Heidelberg result[5] is correct, then $m_\nu < 5$eV, but if the Missouri result is right, $m_\nu \simeq 10$eV for no right-handed currents.

It is worth noting that the Los Alamos-Purdue calculation[6] which gives 10eV treats the relativistic phase space more exactly and gives a more careful treatment of the radial dependence of the 0ν operators. This result differs from previous calculations which yielded[8] 30eV and[9] 1eV. Very recently there has been resolution of these differences and a convergence of the calculational details.[10] However, there is still important disagreement on nuclear matrix elements and hence ν mass values, except for this ratio case.

Turning now to the laboratory experiments looking for 0ν decays, we note first that these are very difficult, since one is looking for a process with a lifetime probably exceeding 10^{23} years in a background of many competing processes. This requires of the order of 10^2 grams of an isotope, usually not having a very large abundance, to get a few counts per year. Thus the source must be large, and yet the β energies are low ($\sim$1 MeV), so ranges are short. All materials have some natural radioactivity which give confusing backgrounds, and in addition, cosmic ray interactions can cause problems.

To overcome these difficulties, two techniques are used: (1) tracking devices look for two electrons, and (2) energy measuring devices look for a peak due to the summed electron energies. The more copious 2ν decay would, of course, give a broad energy spectrum below that peak and a different energy and angular distribution of electrons.

To compare the accuracies of different experiments, one can give the results in terms of limits on m_ν and the RHC, both being desirable because the processes have a different dependence on the energy available in the decay. For $m_\nu \neq 0$, $\Gamma(0\nu) \sim (m_\nu/m_e)^2$, but if $m_\nu = 0$ and the leptonic current is $J = J_L + \eta J_R$, then $\Gamma(0\nu) \sim \eta^2 = \left[\frac{M_{W_L}}{M_{W_R}}\right]^4$, where W_L is the usual intermediate vector boson and W_R would be that giving a right-handed current.

The best published measurements are given below, along with the Los Alamos-Purdue calculated[7] limits on m_ν (for $\eta = 0$) and for η (with $m_\nu = 0$). Note that the matrix elements used by the Japanese group[10] give m_ν and η values about three times larger, because these are based on the geochemical lifetimes.

Source	$T_{\frac{1}{2}}(0\nu) >$	$m_\nu >$	$\eta <$	Exp. Ref.
^{48}Ca	$10^{21.3}$y	30 eV		11
^{76}Ge	$10^{21.7}$y	15 eV	3×10^{-5}	12
^{82}Se	$10^{21.5}$y	12 eV	1×10^{-5}	13

For the Ca and Se measurements, a thin source in a spark chamber was placed between two counters. The β's hitting the counters were to trigger the spark chamber which could measure the curvature of the tracks in a magnetic field. The Se measurement[1] which detected the 2ν decay had a thin source in a cloud chamber. Incidentally, the Ca decay is especially favorable energetically, but the nuclear matrix element is apparently unusually small because of a K selection rule, so that the expected rate is about the same for Ca and Se or Ge.

The Ge measurement utilizes an energy determination, since Ge makes an ideal β counter. The Milan[12] group had 0.2% resolution in energy in a 69 cm^3 counter which had 7.67% ^{76}Ge, the apparatus being located in the Mt. Blanc tunnel.

With the recent revived interest in the questions that $\beta\beta$ decay can give answers to, it is natural that a number of new experiments are underway or being planned. A brief description will be given here of work going on, starting with the USSR. At INR (Moscow) the $0^+ \rightarrow 0^+$ 0ν and 2ν decays have been searched for using thin, planar sources of ^{58}Ni, ^{124}Sn, ^{130}Te, and ^{150}Nd sandwiched between hodoscoped scintillation counters which give coincidence information, as well as electron energies and spatial positions. To look for $0^+ \rightarrow 2^+$ decays a NaI well counter is used to detect the de-excitation γ-ray in separate experiments. The limits set so far are in the 10^{19} to a few times 10^{20} year range.

In Japan work is going on at Tokyo Metropolitan University on Ca^{48} and at Osaka on ^{100}Mo and ^{150}Nd.

Turning now to the Western Hemisphere, we discuss the experiments according to the decay, starting with ^{82}Se. The University of California at Irvine group (A. Hahn, M. Moe, and F. Reines) is replacing the cloud chamber with a Time Projection Chamber (TPC) and expects to get serious data within a year. They hope to reach a 0ν lifetime of 3×10^{22} years, limited by practical source size. A quite different kind of experiment is being planned by the Brookhaven-SUNY-Oak Ridge group (W. Chen, B. Cleveland, S. Hurst, and J. Ullman) which will do a radiochemical experiment using 10 kg of Se, by means of single-atom counting of ^{82}Kr. This should settle the question of the lifetime of the 2ν decay, but it will require somewhat uncertain calculation to extract any 0ν contribution.

The second decay is ^{136}Xe $\rightarrow$ ^{136}Ba, which has not previously been utilized. The Xe has the interesting advantage that it scintillates and hence can provide some energy measurement suitable for triggering, and yet it can be used as the working substance in a TPC. Thus, except for expense, the source volume is not a problem. The U.C. Irvine group of H.H. Chen, P.J. Doe, and H.J. Mahler, plans to use one liter of liquid xenon, and they have already made a liquid argon TPC function. Their feasibility studies should be completed by about the end of 1982. A Lawrence Berkeley Laboratory group (R. Muller, R. Tripp, R. Kenney, etc.) investigated using a high-pressure gas TPC. Their measurements of backgrounds on the TPC at PEP this summer were discouraging. Now they are considering using separated ^{100}Mo as a very thin source between counters capable of giving energy, position, and timing information. Fortunately two moles of ^{100}Mo are available from Oak Ridge, giving a factor of ten enhancement.

The most popular $\beta\beta$ source is ^{76}Ge, with the Milan group (E. Bellotti, E. Fiorini, C. Liguori, A. Pullia, Q. Sarracino, and L. Zanotti) again putting a shielded Ge crystal in the Mt. Blanc tunnel. This one is twice as big (135 cm^3) as in their previous experiment, and they have also made some improvement in the materials so as to reduce radioactivity in the cryostat which keeps the Ge at liquid nitrogen temperature. In September 1982, they had been counting for 3000 hours, getting a lifetime limit of 1.8×10^{22} years, or a neutrino mass limit in the absence of right-handed currents of about 10 eV. They also set a limit of 1.5×10^{22} years on the lifetime of the electron. Their future plans probably involve building a gas Xe TPC, but if tests are not encouraging, they will go in the direction of increased quantities of Ge.

The CEN group (Bordeaux-Gradignan) use a 110 cm^3 Ge counter with 6 NaI crystals in coincidence to look for the $0^+ \rightarrow 2^+$ transition. In September, after 900 hours of counting they had a limit $T_{\frac{1}{2}} = 1.0\times10^{21}$ years.

An experiment which probably will be counting in Fall 1982 is that of F. Boehm's group at Caltech. They have a 100 cm^3 Ge detector surrounded by an active plastic scintillator shield and plan to reach a limit of 5×10^{22} years.

The collaboration of South Carolina (F.T. Avignone) and Batelle Pacific Northwest (R. Brodzinski and W. Wogman) has been using an existing Ge low-level counting facility to reach a limit comparable to that of the original Milan experiment. They plan to obtain a large Ge crystal (perhaps 250 cm^3), place it in an active NaI shield, and locate it in a deep mine.

The group at Guelph (J.L. Campbell, P. Jagam, and J.J. Simpson) is collaborating with a maker of Ge detectors (H. Malm of Aptec, Toronto) and has obtained a 200 cm^3 crystal with which they plan to achieve a lifetime limit of 3×10^{22} years (at the 95% confidence level). They have hopes of using up to 500 cm^3 of Ge, possibly with active shielding.

Finally, there is the collaboration of the University of California at Santa Barbara group (D.O. Caldwell, R.M. Eisberg, and M.S. Witherell) with the Ge experts of the Instrumentation Science Division of Lawrence Berkeley Laboratory (F. Goulding, N. Madden, R. Pehl and A. Smith). Already ordered are about 1400 cm^3 of Ge (eight 170 cm^3 crystals in a close-packed array) and sufficient NaI to provide a 6"-thick shield surrounding it, so it is a bigger scale experiment than the others. Considerable development work has also been done on finding materials with a low level of radioactivity and in improving the information obtained from the Ge detector.

It is worth mentioning the advantages this experiment will have over the 1973 Milan work, and some of these apply to other new experiments as well. First, there is 20 times as much Ge, providing a proportional increase in lifetime limit. Second, there is an active NaI shield to veto the largest source of background, the 2.6 MeV γ in ^{208}Pb at the end of the ^{228}Th decay chain. This γ (and a few others of less importance) can deposit a 2.041 MeV in the Ge by Compton scattering, but if the rest of the γ energy goes into the NaI (or another Ge detector), that background can be vetoed. This is one reason inert material between the Ge and NaI must be kept to a minimum. Note that the NaI shield (or again some other Ge detector) is very useful in providing a coincidence signal when trying to detect the $0^+ \to 2^+$ transition, since one looks for 1.486 MeV in one Ge detector from the 2 β's and 0.555 MeV from the de-excitation γ in the NaI (or sometimes in another Ge detector). The third advantage is that materials can be used, particularly inside the NaI well containing the Ge, which have lower natural radioactivity. We have done extensive counting of materials and find zone-refined Si, quartz, Mg and BeO particularly useful, especially as we want low-Z materials to avoid absorbing background γ's which would otherwise be vetoed. Note that the zone-refined Ge in the detector has impurities at the 10^{-13} level. A fourth advantage is a factor of two improvement in resolution (2.5 KeV full width at 2.041 MeV), which reduces the background by that factor. A fifth advantage is that we have learned how to discriminate against β's that come from outside the Ge and against multiple γ interactions in the Ge. These advances, which have surprisingly not been known before, will be of use in many low-level counting applications.

With these advantages, we should reach a lifetime limit of about 10^{24} years in one year of counting, but the old Milan result can be reached in a couple of days. If the lifetime were 3×10^{23} years, we would get about a count a month. If the results are negative, this will provide a limit of $\sim$1 eV on the neutrino mass for no right-handed currents, or $\sim$60 TeV for the mass of the right-handed W boson, based on Ref. 7. For reaching these limits, it is important that for Ge the $0^+ \to 0^+$ and $0^+ \to 2^+$ transitions have about equal probabilities, as some calculations indicate, although this is still being investigated. It is also interesting to note that the present limit on M_{W_R} is about 210 GeV, but as stated before that applies to Dirac or Majorana neutrinos, while the $\beta\beta$ limit exists only if neutrinos are of the Majorana type.

These are rather impressive limits on m_ν and M_{W_R}, as well as on lepton-number conservation, and one might question whether pushing further is necessary. If there is reason to, what are the prospects of doing so? It is too early to tell how low background can be reduced by using lower radioactivity materials, active shielding, and some discrimination on event topology. However, if this is not sufficient, then further utilization of a hybrid of energy measurement and the tracking technique looks promising. For example, the Xe TPC's can be exploited in this way. They may, however, have much larger intrinsic radioactivity backgrounds than the ultra-pure Ge, and they can never achieve precise energy determinations. There is a possibly promising development of a TPC made from Ge. This has been done by our LBL collaborators in conjunction with the Pisa group. If one can get some tracking and energy-loss information without sacrificing the energy resolution, then the backgrounds can surely be reduced to zero. Then the lifetime limit would depend simply on how much Ge and electronics one could afford to buy. It would take about a million dollars of Ge to get to a 10^{25}-year limit, but that would give only about 0.3 eV for the m_ν limit. From the economics alone it is to be hoped that a positive result will be found from present efforts, and we will have answered by this means these important questions about the neutrinos and weak interactions.

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