KamLAND-Zen: A Multi-Stage Program Searching for Neutrinoless Double-Beta Decay

Brian K. Fujikawa[1, 2, *] and Lindley Winslow[1, 3, †]
[1] *For the KamLAND-Zen Collaboration*
[2] *Nuclear Science Division Lawrence Berkeley National Laboratory*
[3] *Massachusetts Institute of Technology and University of California Los Angeles*

KamLAND-Zen is a multi-staged program that uses the kiloton-scale liquid scintillator detector KamLAND, retrofitted with a mini-balloon containing xenon-doped liquid scintillator, to search for the neutrinoless double-beta decay of ^{136}Xe. The experiment provides one of the world's best limits on neutrinoless double-beta decay with $T_{1/2} > 2.6 \times 10^{25}$ yrs at 90% C.L. obtained with a preliminary analysis of $\sim$350 kg of ^{136}Xe. The next phase of the experiment will increase this mass to 600 kg contained in a new low-background mini-balloon. Following the 600k kg phase, a major upgrade of the detector will take place. The upgrades will include improvements in the photon collection and the liquid scintillator in addition to increasing the mass to 1 ton or more. This detector, KamLAND2-Zen, will have the sensitivity to search for neutrinoless double-beta decay throughout the full inverted neutrino mass hierarchy region.

I. EXCECUTIVE SUMMARY

The discovery of the massive neutrino has opened the door to the even more tantalizing question of the Majorana or Dirac nature of the neutrino. Of the Standard Model particles, the neutrino is the only particle which could be its own antiparticle, a Majorana particle, and through models of Leptogenesis, could explain the bigger issue of the matter-antimatter asymmetry in the universe. The only feasible experiments to determine the Majorana nature of the neutrino are searches for neutrinoless double-beta decay (NDBD). This is why the 2007 NSAC Long Range Plan and last year's National Academy report on nuclear physics[1] highlight NDBD searches as high priority experiments.

KamLAND was one of the key experiments to show that neutrinos oscillate and therefore have mass[2]. Monolithic liquid scintillators like KamLAND provide full energy containment which allows for a full spectral fit, position reconstruction, and significant self-attenuation of external gamma-rays and neutrons. The scintillator is intrinsically pure and can be purified further through distillation. These techniques were key for the success of the oscillation analysis and are equally powerful in reducing backgrounds for the NDBD experiment KamLAND-Zen. The weakness of this technique for NDBD searches is the comparatively poor energy resolution which causes significant backgrounds from the two neutrino double-beta decay process. The strength of this technique is the straight-forward scaling to large volumes. KamLAND-Zen currently has the largest amount of isotope instrumented at 350kg of ^{136}Xe.

The US portion of the collaboration is small but active. The main hardware contribution is maintenance of the electronics and upgrades and maintenance to the calibration system. There is also a U.S.-based R&D effort to integrate sub-nanosecond photodetectors with novel scintillators to extract additional signals, like the direction of particles, to reduce backgrounds. A prototype will be constructed at MIT during Summer 2015. The US group is streamlining their analysis efforts for a sustained contribution. This is in addition to the writing and editing of publications.

The next few years will be exciting for the KamLAND-Zen Program. The construction of the new mini-balloon will begin in the Summer 2015 and is followed by the refurbishment of the water Cherenkov veto. Detector running will commence in 2016 with 600 kg of ^{136}Xe, with the possibility of increasing to the full inventory in the mine of 800 kg within a few months. The results of this run will educate the final design decisions in the major upgrade to the main detector KamLAND2-Zen. These upgrades will focus on improving the energy resolution from 4% to <2.5% at the endpoint. This will be achieved with a combination of increasing the light collection with light concentrators, increasing the light yield of the scintillator and higher quantum efficiency PMTs. This stage of the programs will increase the mass to >1 ton of ^{136}Xe, with the final mass increasing to allow the experiment to gain sensitivity to NDBD throughout the full inverted neutrino mass hierarchy region.

This schedule ensures that KamLAND-Zen will continue to have the largest mass of instrumented isotope and therefore one of the most competitive sensitivity's to NDBD. This technique is now proven to be very powerful,

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[*] Electronic address: `bkfujikawa@lbl.gov`
[†] Electronic address: `lwinslow@mit.edu`

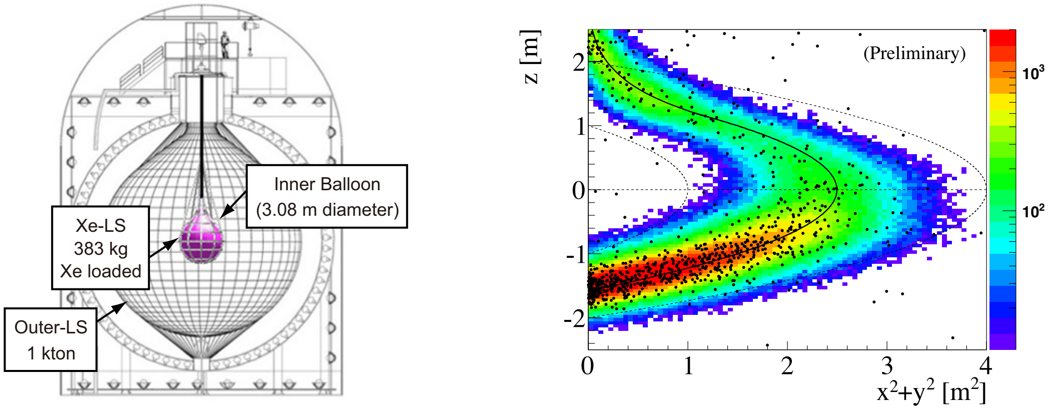

FIG. 1: Schematic view of the KamLAND-Zen detector. It shows the xenon loading for the current data set 350 kg ^{136}Xe. (left) Vertex distribution of candidate events (black points) and expected ^{214}Bi background events from a MC simulation (color histogram) for 2.3<E<2.7MeV. The normalization of the MC event histogram is arbitrary. The solid line indicates the shape of the balloon film. (right) From [4]

especially when combined with other techniques[3]. The data is a rich source of thesis topics and the upgrades provide unique experiences retrofitting a large-scale detector for students. A small US contribution especially manpower would allow this very successful collaboration to continue.

II. KAMLAND, BACKGROUNDS, AND THE FUTURE

The KamLAND detector is a monolithic liquid scintillator detector located in the Kamioka mine in Japan. A balloon R=6.5 m containing $\sim$ 1 kton of scintillator is observed with 1879 PMTs. Between the PMTs and the balloon, plain mineral oil is used to attenuate gamma-rays from the PMTs and stainless steel sphere to which they are mounted. The stainless steel sphere is surround by a water Cherenkov muon veto detector. For the KamLAND-Zen NDBD program, a second mini-balloon containing xenon-doped liquid scintillator is installed in the center, as is shown in Fig. 1 (left). The mini-balloon concentrates the isotope in a smaller volume which reduces the impact of backgrounds that are uniformly distributed in the analysis volume. The liquid scintillator can also be circulated and purified if necessary, as was done between the current data set phase-2 and the previous data set phase-1.

The size and geometry of this type of detector allows for complete energy containment and reconstruction of the position of events. This is a powerful tool for identifying backgrounds like that from ^{214}Bi, which is concentrated on the mini-balloon film Fig. 1 (right). The other main backgrounds for the NDBD analysis are uniformly distributed throughout the fiducial volume. They are the muon spallation product ^{10}C and the combination of four isotopes ^{110m}Ag, ^{88}Y, ^{208}Bi and ^{60}Co. These four isotopes may be spallation products or the result of fallout from the Fukushima reactor. The characteristic energy and position distribution of these backgrounds can be exploited in a combined fit for the NDBD rate. The results of this fit is shown in Fig. 2 for two example regions and correspond to a NDBD limit of $T_{1/2} > 1.3 \times 10^{25}$ yrs at 90% C.L.. This result can be combined with the first KamLAND-Zen result[3] to obtain $T_{1/2} > 2.6 \times 10^{25}$ yrs at 90% C.L. [4].

The KamLAND-Zen sensitivity to NDBD will improve through Summer 2015 when the new mini-balloon will be installed and data taking will commence with 600 kg of ^{136}Xe. Following a two-year run, the sensitivity of the experiment will reach $T_{1/2} > 2 \times 10^{26}$ yr. This corresponds to grazing the top of the parameter space corresponding to the inverted hierarchy with $\langle m_{\beta\beta} \rangle = 50$ meV for the largest NME in the (R)QRPA models[5]. Fig. 3 illustrates the evolution of the experiment's sensitivity given this schedule.

In order to push into the inverted hierarchy, the energy resolution of the experiment will need to be improved. This is the focus of the major upgrade to KamLAND2-Zen. R&D is underway by our Japanese colleagues on all components of the light collection from light concentrators which are expected to increase light output by a factor of 1.8, new liquid scintillator expected to contribute another factor of 1.4 and finally PMTs with higher quantum efficiency photocathodes expected to contribute a factor of 1.9. Together these factors should allow an improvement from 4% to the required resolution of 2.5%. In addition, an imaging system and a scintillating balloon film is being developed to discriminate different background event types from the NDBD signal.

The differentiation of signal and background using direction reconstruction is the goal of the U.S. R&D project. It is

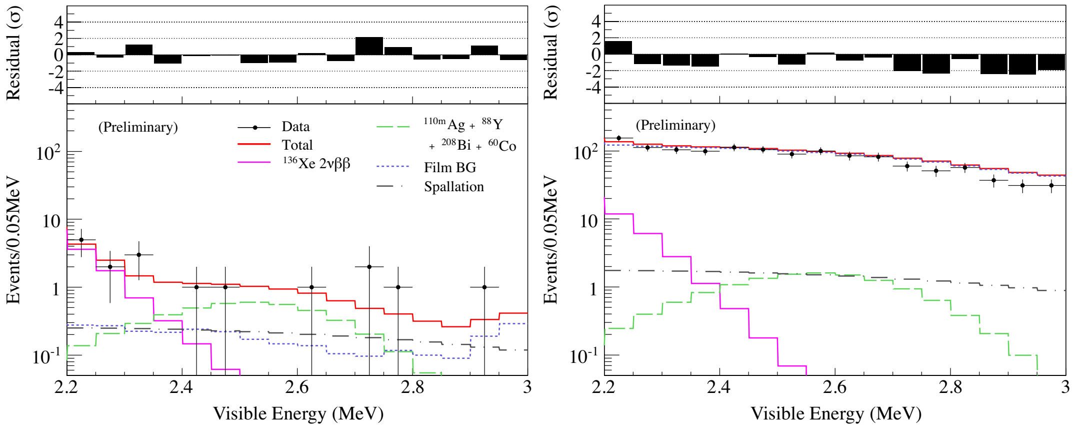

FIG. 2: Preliminary energy spectra of selected NDBD candidates within the radius cuts, R < 1.0m (left) and 1.0< R < 2.0m (right). The best-fit spectra correspond to the 2-dimensional energy-volume analysis fit results described in the text. The residuals from the best-fit are shown in the upper panels. From [4]

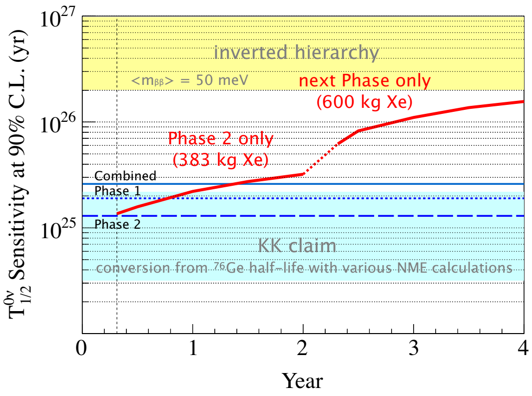

FIG. 3: Expected $T_{NDBD_{1/2}}$ sensitivity at 90% C.L. in the near future for KamLAND-Zen. The red line at less than 2 years corresponds to extending the current data set and not combining with previous data sets; the following red line is next phase only. The three horizontal lines indicate the lower $T_{NDBD_{1/2}}$ limits reported here (phase-2), the previous dataset's results (phase-1)[3], and the combined result (phase-1 + phase-2). From [4]

a close collaboration between the Large Area Picosecond Photodetector (LAPPD) group at the University of Chicago, and the UCLA KamLAND-Zen, now MIT, group. The scintillation light produced when a charged particle moves through scintillating liquid is isotropic and any Cherenkov light produced at wavelengths shorter than the absorption cutoff of the scintillator will be re-emitted isotropically. However, any Cherenkov light produced above this cutoff will propagate across the detector to the photodetectors retaining its directional information. This light will be at longer wavelengths and therefore travels at a slightly higher velocity. It will arrive slightly before the bluer scintillation light, which is also slowed by the scintillation process itself. With sub-nanosecond timing, like that provided by the LAPPD, one can separate the two types of light as shown in Fig. 4 (left). This information can then be input to a direction reconstruction algorithm like those developed for water Cherenkov detectors, and a good reconstruction is possible at energies relevant to NDBD Fig. 4 (right). A prototype detector based on this work is in the final design stages and will be constructed during Summer 2015.

Looking farther into the future, the liquid scintillator detector is the most straight forward technology to scale to the masses needed to explore NDBD in the parameter space corresponding to the normal hierarchy for neutrino mass[7]. At these masses, the backgrounds due to ^{8}B become significant. Techniques like those being developed for KamLAND-Zen will be key to mitigating all backgrounds for the next-next generation of experiments. The vision for the next-next generation of experiments exists within the KamLAND-Zen program with the possibility to convert the Super Kamiokande detector into a NDBD detector.

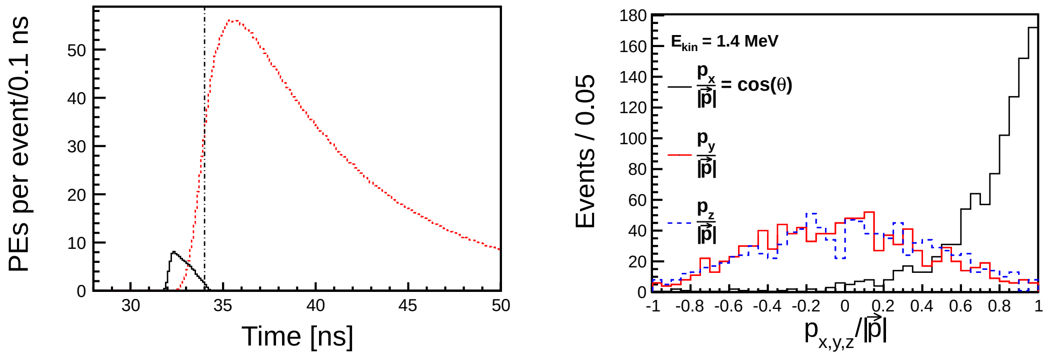

FIG. 4: Simulation of photoelectron arrival times after application of the photodetector transit-time spread (TTS) for the simulation of 1000 single electrons (5 MeV) moving along the x-axis of a 6.5 m sphere with TTS=0.1 ns and wavelength response. PEs from Cherenkov light (black, solid line) and scintillation light (red, dotted line) are compared (left). The results of this simulation can be input into simple Cherenkov reconstruction algorithm for direction. The reconstruction algorithm worked in the range of interest for NDBD, 1.4 MeV results are shown (right). From [6]

The U.S. KamLAND-Zen group has become small but has been productive considering the minimal support. Slightly more robust funding would allow the US analysis group to incorporate students and perform a truly independent NDBD analysis starting from the reconstructed data. Considering that KamLAND-Zen will be the most massive experiment with one of the best limits on NDBD for many years to come and its importance in planning the goals of other experiments, this is a logical strategy to ensure the best analysis. Furthermore, the KamLAND-Zen program has proven it's ability to consistently produce cutting-edge physics while nurturing R&D efforts for quick transitions to the next phase of the program. A small investment in the U.S. group would yield excellent returns.

Acknowledgments

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