The KamLAND-Zen Electronics Upgrade

Updating the search for neutrinoless double beta decay

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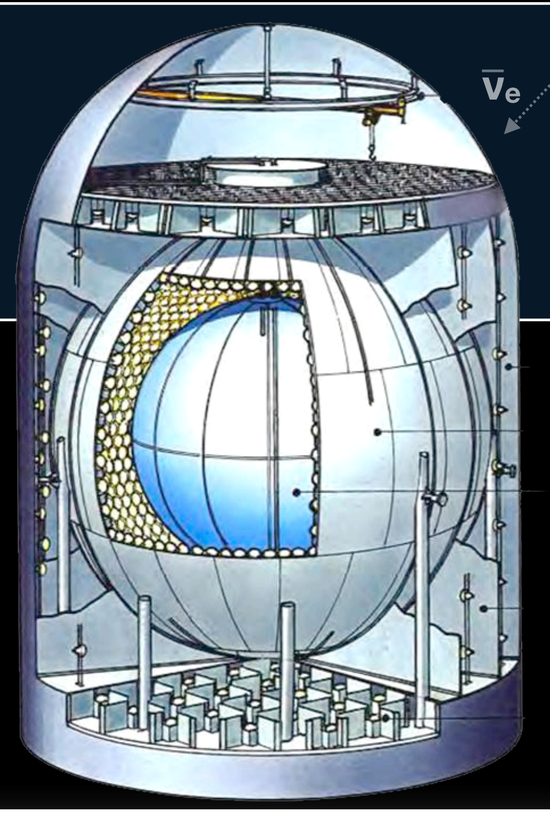
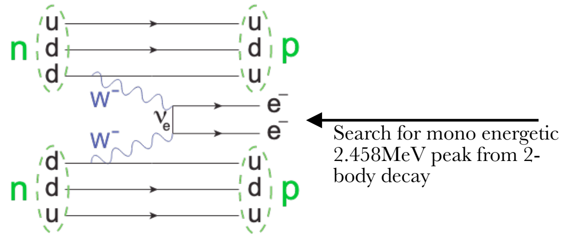


The KamLAND-Zen ("Zero neutrino") program has recently set the worlds most stringent limit on neutrinoless double beta decay (0νββ), being the first experiment excluding a half-life less than 10^{26} years at the 90% C.L. The next push will be to upgrade the detector hardware, increase the amount of dissolved ^{136}Xe gas, and update the readout system in order to probe the inverted hierarchy region. This is the KamLAND2-Zen experiment. Below, we discuss the upgrade to the electronics system.

1. Neutrinoless double beta decay (0νββ)

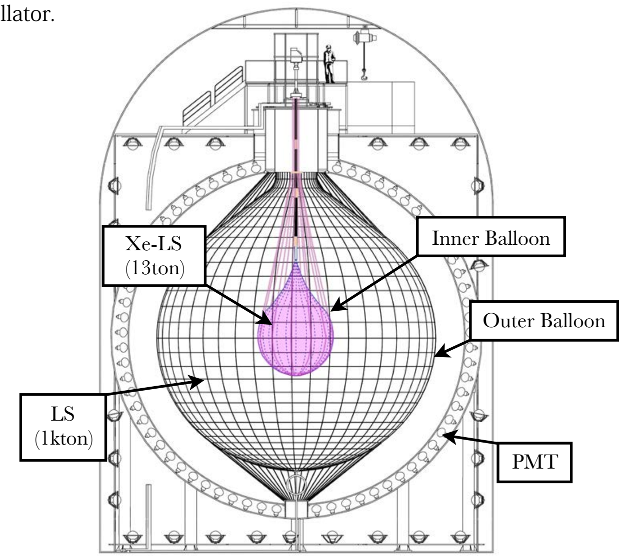
Is the neutrino its own antiparticle?



The only viable experiments to determine the Majorana nature of the neutrino are searches for the unobserved nuclear process of neutrinoless double beta decay.

2. The current detector and readout electronics

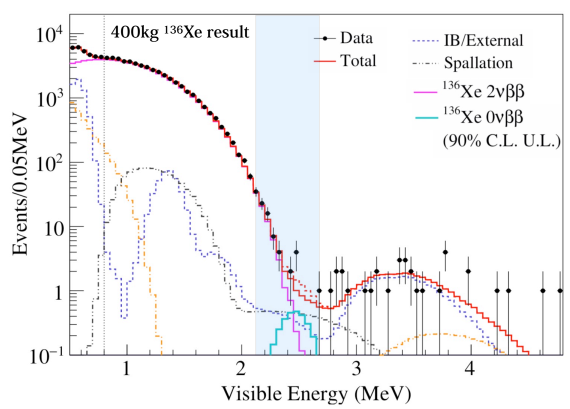
The ultra-low background detector consists of a 13m diameter spherical balloon consisting of 1 kiloton of liquid scintillator (LS), imaged by 1,879 photomultiplier tubes (17" and 20" PMTs). A smaller 3m diameter inner balloon contains nearly 800kg of xenon, doped in liquid scintillator.

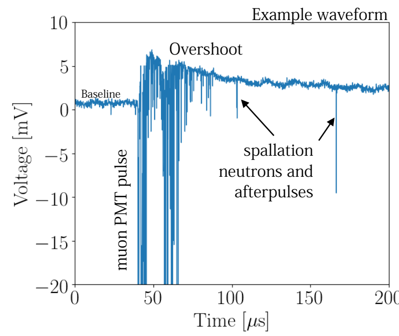


Each PMT readout channel is equipped with four 8-bit flash ADCs (one 1GSPS plus three 200 MSPS each with a different level of gain). The dynamic range utilizing all four ADCs extends from 0.01mV to 8 V. A digital discriminator sets the trigger threshold to approximately 1/3PE. RMS electronic noise level is measured to be 0.14mV.

3. Motivation for KamLAND2-Zen upgrade

Backgrounds pose a limiting constraint on the sensitivity of KamLAND-Zen to a 0νββ signal. In the **region of interest** (blue region below), spallation isotopes generated from cosmic ray muon interaction represent the dominant background.



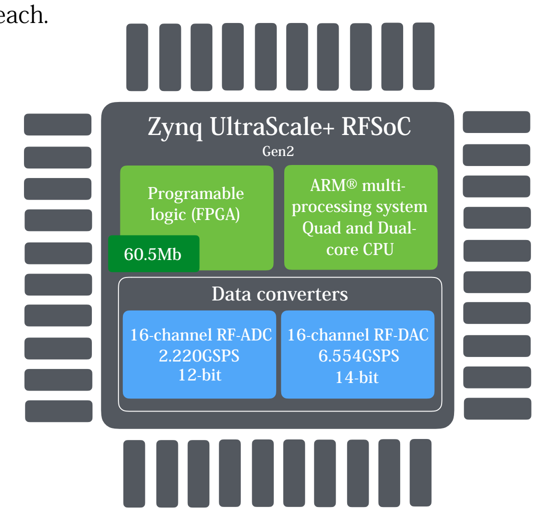


- Neutrons can be used to tag spallation products generated from cosmic ray muons. All of which must be tagged. The overshoot introduced by the PMT AC coupling makes this difficult with the current electronics.
- The current electronics have limited maximum trigger rates, reducing the potential of capturing a nearby supernova event.
- Modern techniques for improving the light-yield of the detector an improve the energy resolution by a factor of two in the region of interest. These include introducing HQE PMTs and Winston cones.

4. Electronic readout system upgrade: introducing a System-on-Chip (SoC)

The electronics upgrade introduces a **flexible software-based trigger system** with **zero dead time** and **active baseline restoration**, along with an extended physics reach.

- Continuous 1GSPS digitization of each PMT's analog waveform is accomplished using the **Zynq UltraScale+ RFSoC.** All signal processing is in the digital domain, where the trigger can be set via software. The powerful on-chip programable logic performs the PMT pulse extraction.
- The integrated deep memory buffers enable the capability of fully recording a nearby super nova event.
- The RF-DAC provides the possibility for active baseline restoration after a high-charge event. This removes the overshoot introduced by the AC coupling, allowing neutrons to be tagged after a muon passes through the detector, reducing backgrounds and dead time.
- Frequency selection can now occur in the digital domain allowing for flexibility and optimization of the system.
- Digital noise reduction as well updates to the front-end analog electronics is expected to bring the electronics noise level down to 0.1mV.



The electronics upgrade would allow us to extract the maximum amount of information from this simple but powerful detector. Given the digitization rates expected from two gain channels per PMT, we estimate the the total data rate input to the FPGAs to be 3.6 TB/s.

5. Anticipated physic reach

The electronics upgrade, along with increased ^{136}Xe doping, and an improved light collection system enables KamLAND2-Zen to:

- explore the inverted neutrino mass hierarchy, $\langle m_{\beta\beta} \rangle$ ~20meV,
- provide the capability of recording the entire event record from a galactic supernova,
- improve measurements related to reactor neutrino studies, geophysics and astrophysics measurements
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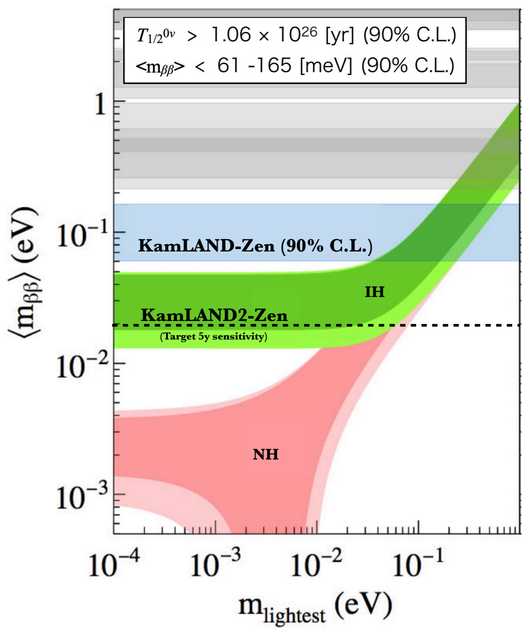

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