Search for Excited-State Double Beta Decay of ^{136}Xe in KamLAND-Zen 800

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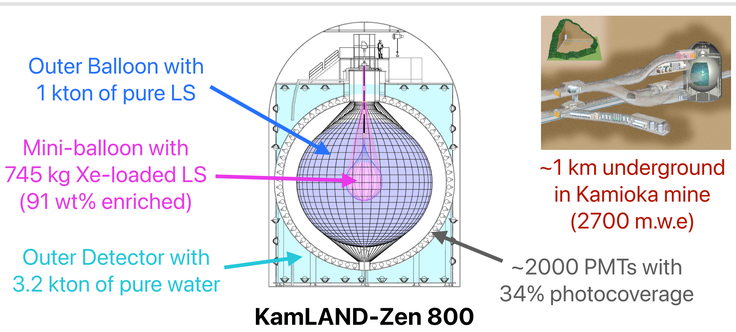
KamLAND-Zen 800 Detector

Liquid Scintillator (LS) detector searching for **Neutrinoless Double Beta Decay** ($0\nu\beta\beta$) in **^{136}Xe**



~1 km underground
in Kamioka mine
(2700 m.w.e)

KamLAND-Zen 800

Holds current world-leading lower limit on the $0\nu\beta\beta$ half-life of ^{136}Xe at **3.8×10^{26} years** at 90% C.L [1]

Excited State Double Beta Decay

Standard Model double beta decay to **excited states** of daughter nucleus

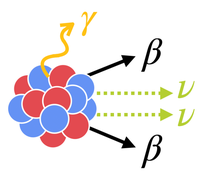
- Rate suppressed due to reduced phase space from lower Q values
- Has not been directly measured for ^{136}Xe → ^{136}Ba*
  - KamLAND-Zen 400 set a half-life limit of 8.3×10^{23} yr (2016) [2]
  - EXO-200 set a half-life limit of 14×10^{23} yr (2023), challenging theoretical values predicted by QRPA [3]

Why do we care?

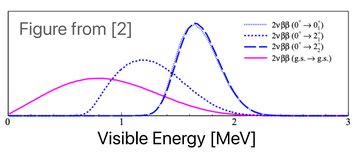
- **Irreducible background** for $0\nu\beta\beta$ analysis
- Measurement of the rate is a valuable experimental input for **nuclear matrix element (NME) calculations of $2\nu\beta\beta$ & $0\nu\beta\beta$**
  - Same initial and final nucleus → correlated NMEs
  - Can help reduce theoretical uncertainties in $0\nu\beta\beta$ search

Event Signature

- **Double beta decay** followed by **gamma cascade** from de-excitation to ground state
- Decay to the 1st excited state of the 0+ state is the dominant decay mode for ^{136}Xe → ^{136}Ba*
  - Q-value = 879 keV, 2 γ's at 760.5 and 818.5 keV

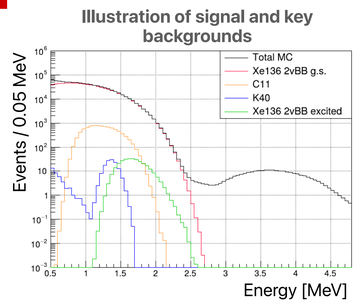


- Seen as a small spectral distortion relative to the dominant ground-state $2\nu\beta\beta$ background, with potentially more multi-site-like topology from the de-excitation gamma cascade.



Analysis Strategy

- **Signal**: a small distortion in the dominant ^{136}Xe $2\nu\beta\beta$ spectrum
- Dedicated region of interest (ROI) and background model needed
- **Key backgrounds**: ^{136}Xe $2\nu\beta\beta$, ^{40}K, ^{11}C
- **Main challenge**: control spectral degeneracies and detector-response effects



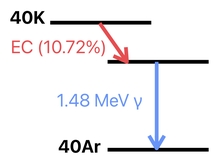
Analysis Workflow

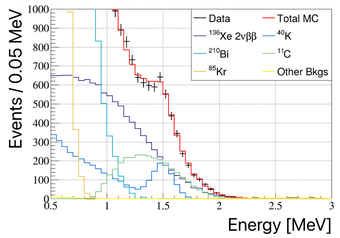
Prepare MC templates for signal and background → **Apply external constraints** on ^{40}K, ^{11}C, and detector response → **Perform profile likelihood fit** → **Validate fit results** through closure tests, systematic studies, etc. → **Final Result**

^{40}K film background

The ^{40}K background is dominated by the contribution from the surface of mini-balloon film. Analyzing radial shells around mini-balloon film provides a handle on activity as the 1.46 MeV peak can be resolved above the $2\nu\beta\beta$ continuum in this region.

^{40}K constraint must be included in likelihood fit consistently without double-counting.





Detector-response modeling

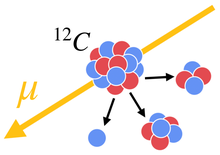
The ^{136}Xe excited-state signal is a small spectral distortion of the ground-state spectrum. As such, energy scale and nonlinearity can introduce distortions that mimic signal.

Energy response parameters enter as constrained nuisances in the likelihood fit. Calibration and control samples from intrinsic backgrounds such as spallation products, ^{40}K, or ^{214}Bi-Po events will be used to validate the energy response model.

Birks' Law

$$\frac{dL}{dx} = S\frac{\frac{dE}{dx}}{1 + k_B\frac{dE}{dx}}$$

^{11}C spallation background



^{11}C is produced by cosmic-ray muons spallating carbon nuclei inside the detector. It is the most dominant of such carbon spallation backgrounds. The ^{11}C background overlaps the low to mid-energy search region.

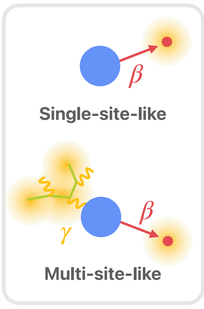
Its production rate was measured in KamLAND with pure LS to be 973 ± 10 events/kton-days [4]. A renewed measurement in KamLAND-Zen may provide more accurate constraints. Muon-correlated candidate samples provide an independent constraint on the rate, which can be included as a nuisance parameter in the likelihood.

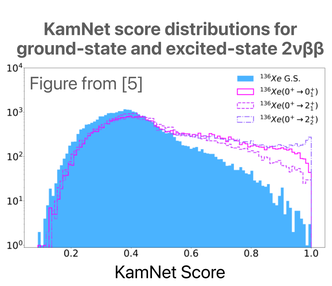
Using ML to capture topology information

^{136}Xe excited-state decays include gamma cascades that produce more multi-site-like events than ground-state $2\nu\beta\beta$.

KamNet [5] is a spatiotemporal deep neural network designed for KamLAND-Zen that discriminates between different event topologies. Utilizing KamNet can provide additional topological information that help distinguish between our signal and the dominant ground-state $2\nu\beta\beta$ background.

Control samples are needed to validate the score distributions for $2\nu\beta\beta$, ^{11}C, and other gamma-like backgrounds.





Summary and Outlook

- Excited-state $2\nu\beta\beta$ of ^{136}Xe is an unobserved Standard Model process
- KamLAND-Zen 800 enables a renewed search
- Main challenge: dominant $2\nu\beta\beta$ background and detector-response systematics
- Strategy: constrained likelihood with ^{40}K, ^{11}C, and detector-response inputs
- Final result will follow full validation and collaboration review

References

[1] S. Abe *et al.* (KamLAND-Zen), Phys. Rev. Lett. **135**, 262501 (2025).
[2] K. Asakura *et al.* (KamLAND-Zen), Nucl. Phys. A **946**, 171 (2016).
[3] S. Al Kharusi *et al.* (EXO-200), Chinese Phys. C **47**, 103001 (2023).
[4] A. Gando *et al.* (KamLAND), Phys. Rev. C **92**, 055808 (2015).
[5] A. Li, Z. Fu, L. A. Winslow, C. Grant, H. Song, H. Ozaki, I. Shimizu, and A. Takeuchi, Phys. Rev. C **107**, 014323 (2023).