Recent results from KamLAND-Zen experiment



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KamLAND-Zen Collaboration KamLAND/KamLAND-Zen in-person/online hybrid collaboration meeting last week



> 50 researchers from Japan, USA and the Netherlands



















Since this is very rare decay ($T_{1/2}^{0\nu} > 10^{26}$ yr for ¹³⁶Xe), a large amount of target isotopes & ultra low BG environment are required

DVBBBBB



if $0\nu\beta\beta$ decay observed :

- lepton number violation
- neutrino is Majorana particle ($\nu = \bar{\nu}$)
- gives effective Majorana mass, neutrino mass hierarchy information





KamLAND experiment







Liquid scintillator (~1 kton)



In operation since 2002

• well known detector response

· Ultra low BG liquid scintillator in the wide energy range

- •²³⁸U ~ 5.0×10⁻¹⁸ g/g
- ·²³²Th ~ 1.3×10⁻¹⁷ g/g

Many physics targets (Followings are recent publications)

- Geo-neutrino : <u>https://doi.org/10.1029/2022GL099566</u>
- Astrophysical neutrino :
 - <u>https://iopscience.iop.org/article/</u>
 - <u>10.3847/1538-4357/ac4e7e</u>
 - <u>https://doi.org/10.3847/1538-4357/ac32c1</u>
 - https://doi.org/10.3847/1538-4357/ac35d1





KamLAND-Zen experiment Zen : Zero neutrino double beta decay search



¹³⁶Xe enriched Xenon loaded LS (Xe-LS) into KamLAND center within inner balloon

utilize KamLAND ultra-low BG environment

•Xenon characteristics : •Chemically stable noble gas • Dissolved into LS : ~3.1 wt% •Enrichment : 90.8% ¹³⁶Xe, 8.8% ¹³⁴Xe

•136Xe:



•Q-value : 2.458 MeV, Low BG region in KamLAND ·Slow ¹³⁶Xe $2\nu\beta\beta$ decay (T_{1/2} = 2.2 x 10²¹ year, ~2600 events per in inner balloon per day) \rightarrow less $2\nu\beta\beta$ tail due to energy resolution





 $T_{1/2} > 1.07 \times 10^{26}$ yr (90% C.L.)



- Data taking started Jan. 2019

from KamLAND-Zen 400 to KamLAND-Zen 800



KamLAND-Zen 400:

- Mini-balloon radius = 1.54 m
- Xenon mass = 320 ~ 380 kg
- Duration: 2011 ~ 2015

about factor of 2 Xenon mass ass scaling. but also



	Period-1		Period-2			
	(270.7 days)		(263.8 days)			
nts	22		11			
l	Estimated	Best-fit	Estimated	Best-fit		
3	-	5.48	-	5.29		
Residual radioactivity in Xe-LS						
ries)	0.23 ± 0.04	0.25	0.028 ± 0.005	0.03		
ries)	-	0.001	-	0.001		
	-	8.5	-	0.0		
External (Radioactivity in IB)						
ries)	-	2.56	-	2.45		
ries)	-	0.02	-	0.03		
	-	0.003	-	0.002		
Spallation products						
	2.7 ± 0.7	3.3	2.6 ± 0.7	2.8		
	0.07 ± 0.18	0.08	0.07 ± 0.18	0.08		
	0.15 ± 0.04	0.16	0.14 ± 0.04	0.15		
	0.5 ± 0.2	0.5	0.5 ± 0.2	0.4		

KamLAND-Zen 800:

- Mini-balloon radius = 1.90 m
- <u>Xenon mass = 745±3 kg</u>
- Data taking starts Jan. 2019

Not only the mass scaling, but also hardware/software improvement are achieved





Hardware improvement Ultra-clean inner-balloon fabrication



details can be found : JINST 16, P08023 (2021) and NOW 2018 presentation (Y. Gando)



Gore × 24

> $\cdot 25 \,\mu \text{m}$ thickness nylon film components are welded to make 3.8 m diameter inner balloon





Hardware improvement Ultra-clean inner-ballon fabrication





3He leak test + repair





All fabrication work were done in class 1 clean room in Sendai, Japan.

details can be found : JINST 16, P08023 (2021) and NOW 2018 presentation (Y. Gando)







Hardware improvement Ultra-clean inner-ballon fabrication



The contamination levels in the IB : ^{238}U : $(3 \pm 1) \times 10^{-12} \text{ g/g}_{Film}$ ^{232}Th : $(3.8 \pm 0.2) \times 10^{-11} \text{ g/g}_{Film}$ \rightarrow factor of 10 reduction from KamLAND-Zen 400 \rightarrow We set a fiducial volume cut of 1.57 m

details can be found : JINST 16, P08023 (2021) and NOW 2018 presentation (Y. Gando)

Vertex distribution of data in ROI overlaid on ²¹⁴Bi MC







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 To remove carbon spallation & ¹³⁷Xe (¹³⁶Xe neutron capture) $\cdot \Delta T < 150$ ms after passing through the LS

- \cdot New!) a likelihood method based on muon energy deposition (dE/dX)

· Triple coincidence $(1)\mu$, (2)n-capture γ , $(3)\Delta R < 160$ cm from neutron capture γ -ray)

along the μ track based on the timing of all the photons.

μ track length [cm]

newly developed shower reconstruction tool to calculate light intensity profiles <u>Rejection efficiencies for ${}^{10}C$, ${}^{6}He$ and ${}^{137}Xe$ are > 99.3%, (97.6±1.7)%, and (74±7%)</u>

Long-lived isotopes from xenon spallation many candidate isotopes whose individual yields are too small to be decomposed

- Total yield becomes one of the main BG

- half life : (~hours to ~days)
- Primary contributions :
 - 1321, 1301, 1241, 1221, 118Sb, 110In and 88Y
- Xe spallation :
 - characterized by detecting multiple neutrons

Perform MC simulation (Spallation : FLUKA, Subsequent decay : Geant4)

Long-lived isotopes from xenon spallation

- Traced decay chain using Geant4
 - Checked decay database consistency with ENSDF
- Expected event rate :
 - 0.082±0.006 event/day/Xe-ton/ROI
 - ~90% from major 32 nuclei
- A new likelihood method is developed
 - Parameters :
 - $\ \ \, \Delta T \ from \ \ \mu$

 - neutron multiplicity

 Data which is classified as long-lived background is also used for simultaneous fitting

42.0 ± 8.8% rejection efficiency (8.6% signal sacrifice)

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- R < 2.5 m from the center and > 0.7 m from the bottom
- $\cdot \Delta T > 2 \text{ ms from } \mu$
- Radioactive decays rejection
- $\cdot \bar{\nu}_{o}$ event rejection by inverse β -decay coincidence
- Poorly reconstructed event rejection

· (214Bi-214Po, 212Bi-212Po by coincidence & double pulse veto, spallation veto)

- Combined energy spectra Internal 10 volume bins 3 time bins
- KamLAND-Zen800 523 days livetime data set

- Best fit of $0 \nu \beta \beta$ rate : 0
- Upper limit on ¹³⁶Xe 0 $\nu \beta \beta$ < 7.9 events, < 15.5 (ton yr)⁻¹ in units of ¹³⁶Xe exposure

Obtained spectrum

Combined analysis & Xe spallation result

- $\cdot 0\nu\beta\beta$ rate v.s. long-lived RI rate scan
- Long-lived rate in 2.35 < E < 2.70 MeV : 0.111 ± 0.019 events/day/Xe-ton
- FLUKA prediction
- . Scanned result of Long-lived RI tagging eff :40.1 $^{+10.2}_{-8.2}$ % : consistent with the estimation

consistent within 1.5σ $: 0.082 \pm 0.006 \text{ events/day/Xe-ton}$

Limit on half-life

KL-Zen 400 : reanalyzed with updated rejection techniques

KL - Zen 800 result : $T^{1/2} > 2.0 \times 10^{26} \text{ yr}$ (90% C.L.) KL - Zen 400 + KL - Zen 800

Combined result : $T^{1/2} > 2.3 \times 10^{26} \text{ yr}$ (90% C.L.)

Sensitivity :

 $T^{1/2} > 1.5 \times 10^{26} \text{ yr}$ (90% C.L.)

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Prediction :

- (a) : Phys. Rev. D 86, 013002
- (b) : Phys. Lett. B 811, 135956
- : Euro. Phys. J C 80, 76 (C)

Experiment :

(Ge) : GERDA, Phys. Lett. 125 252502 (Te): CUORE, Nature 604, 53

Further improvement for KamLAND-Zen 800

KamNet : An Integrated Spatiotemporal Neural Network

Toward KamLAND2-Zen

High QE PMT, Winstone cone

and LAB base brighter LS

Improve light collection efficiency (x1.9), photo coverage (x1.8), and photon yield (x1.4)

HPGe measurement (226,228Ra etc.)

Scintillation inner balloon

Purpose: reduce backgrounds originating from balloon.

https://doi.org/10.1093/ptep/ptz064 https://doi.org/10.1088/1742-6596/1468/1/012136

Material screening using ultra-low BG HPGe and ICP-MS

ICP-MS measurement (238U, 232Th etc.)

R & D are ongoing toward KamLAND2-Zen (Target : ~20 meV/5 yr)

Summary

- · The latest result of KamLAND-Zen $0\nu\beta\beta$ search : hardware improvement (cleaner inner balloon) software improvement (spallation veto, understanding the long-lived)
 - spallation products)

 $\Rightarrow T_{1/2}^{0\nu} > 2.3 \times 10^{26}$ year (90% C.L., KL—Zen400, 800 combined analysis) $\Rightarrow <m_{\beta\beta} < 36 - 156$ meV, first search in the inverted mass order region. · arXiv: 2203.02139

experiment, many new ongoing R & D projects

 Analysis tool improvement is ongoing (ex: PID w/ NN, arXiv:2203.01870) To explorer deeper into inverted hierarchy region with KamLAND2-Zen

Backup

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BG budget

TABLE I: Summary of the estimated and best-fit background contributions for the frequentist and Bayesian analyses in the energy region 2.35 < E < 2.70 MeV within the 1.57-m-radius spherical volume. In total, 24 events were observed.

Background	Estimated	Best-fit			
		Frequentist	Bayesian		
136 Xe $2\nu\beta\beta$	_	11.98	11.95		
	Residual radioactivity	in Xe-LS			
238 U series	0.14 ± 0.04	0.14	0.09		
232 Th series	-	0.84	0.87		
External (Radioactivity in IB)					
238 U series	_	3.05	3.46		
232 Th series	-	0.01	0.01		
Neutrino interactions					
$^8{\rm B}$ solar $\nu~e^-$	ES 1.65 ± 0.04	1.65	1.65		
Spallation products					
Long-lived	7.75 ± 0.57 †	12.52	11.80		
^{10}C	0.00 ± 0.05	0.00	0.00		
⁶ He	0.20 ± 0.13	0.22	0.21		
137 Xe	0.33 ± 0.28	0.34	0.34		

[†] Estimation based on the spallation MC study. This event rate constraint is not applied to the spectrum fit.

solar ν : ⁸B solar ν elastic scattering & CC interaction of ⁷Be + ¹³⁶Xe \rightarrow ¹³⁶Cs is producted, and its β decay.

- Shell Model
- 2.28, 2.45 -- J. Phys. G 45, 014003 (2018) 1.63, 1.76 -- Phys. Rev. C 93, 024308 (2016) 2.39 -- Phys. Rev. C 101, 044315 (2020)
- QRPA
- 1.55 -- Phys. Rev. C 87, 064302 (2013) 2.91 -- Phys. Rev. C 91, 024613 (2015) 2.72 -- Phys. Rev. C 98, 064325 (2018) 1.11, 1.18 -- Phys. Rev. C 97, 045503 (2018) 3.38 -- Phys. Rev. C 102, 044303 (2020)
- EDF
- 4.20 -- Phys. Rev. Lett. 105, 252503 (2010) 4.77 -- Phys. Rev. Lett. 111, 142501 (2013) 4.24 -- Phys. Rev. C 95, 024305 (2017)
- IBM
 - 3.25 -- Phys. Rev. C 91, 034304 (2015) 3.40 -- Phys. Rev. D 102 (9), 095016 (2020)

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