Double Beta Decay of $^{136}$Xe with KamLAND

Sei Yoshida
Research center for Neutrino Science, Tohoku University
for the KamLAND collaboration
KamLAND Collaboration

S. Abe¹, T. Ebihara¹, S. Enomoto¹, K. Furuno¹, Y. Gando¹, H. Ikeda¹, K. Inoue¹, Y. Kibe¹, Y. Kishimoto¹, M. Koga¹, Y. Minekawa¹, T. Mitsui¹, K. Nakajima¹, K. H. Nakajima¹, K. Nakamura¹, M. Nakamura¹, K. Owada¹, I. Shimizu¹, Y. Shimizu¹, J. Shirai¹, F. Suekane¹, A. Suzuki¹, Y. Takemoto¹, K. Tamae¹, A. Terashima¹, H. Watanabe¹, E. Yonezawa¹, S. Yoshida¹, A. Kozlov², J. Busenitz³, T. Classen³, C. Grant³, G. Keefer³, D. Leonard³, D. MaKee³, A. Piepke³, M. P. Decowski⁴, J. A. Detwiler⁴, S. J. Freedman⁴, B. K. Fujikawa⁴, F. Gray⁴, E. Guardincerri⁴, L. Hsu⁴, K. Ichimura⁴, R. Kadel⁴, K.-B. Luk⁴, H. Murayama⁴, T. O’Donnell⁴, H. M. Steiner⁴, L. A. Winslow⁴, D. A. Dwyer⁵, C. Jillings⁵, C. Mauger⁵, R. D. McKeown⁵, C. Zhang⁵, B. E. Berger⁶, C. E. Lane⁷, J. Maricic⁷, T. Miletic⁷, M. Batygov⁸, J. G. Learned⁸, S. Matsuno⁸, S. Pakvasa⁸, J. Foster⁹, G. A. Horton-Smith⁹, A. Tang⁹, S. Dazeley¹⁰, K. Downum¹¹, G. Gratta¹¹, K. Tolič¹¹, W. Bugg¹², Y. Efremenko¹², Y. Kamyshev¹², O. Perevozchikov¹², H. J. Karwowski¹³, D. M. Markoff¹³, W. Turnow¹³, K. M. Heeger¹⁴, F. Piquemal¹⁵, and J. -S. Ricol¹⁵

¹. Research Center of Neutrino Science, Tohoku University
². IPMU, The University of Tokyo
³. Department of Physics and Astronomy, University of Alabama
⁴. Physics Department, University of California Birkeley/ Lawrence Berkeley National Laboratory
⁵. W. K. Kellogg Radiation Laboratory, California Institute of Technology
⁶. Department of Physics, Colorado State University
⁷. Physics Department, Drexel University
⁸. Department of Physics and Astronomy, University of Hawaii at Manoa
⁹. Department of Physics, Kansas State University
¹⁰. Department of Physics and Astronomy, Louisiana State University
¹¹. Physics Department, Stanford University
¹². University of Tennessee
¹³. Triangle Universities of Nuclear Laboratory/Physics Department, Duke University
¹⁴. Department of Physics, University of Wisconsin
¹⁵. CEN Bordeaux-Gradignan, IN2P3-CNRS and University Bordeaux I

Joint Meeting of APS/JPS @Hawaii  October 13th, 2009
Geological anti-neutrinos


Reactor anti-neutrinos

PRL 100, 221805 (2008)
PRL 94, 081801 (2005)
PRL 90, 021802 (2003)

n-Disappearance, anti-neutrino from the Sun and other sources

PRL 96, 101802 (2006)
PRL 92, 071301 (2004)

Solar neutrino

Current target

Next physics target:
Neutrinoless double beta decay
KamLAND Detector

- Kamioka mine overburden: 2700 m.w.e.
- Muon rate: 0.33 Hz
- 1000 tons of Liquid Scintillator
- Mineral Oil: Buffer against external BG
- 1979 PMTs (17” 1325 + 20” 554)
- Photocathod coverage: 34%
- Outer water Cherenkov detector for muon veto

KAMioka Liquid scintillator Anti-Neutrino Detector

Dodecane (C12H25): 80%
Pseudocumene: 20%
(1,2,4-Trimethyl Benzene)
PPO: 1.36 g/l
(2,5-Diphenyloxazole)
2νββ half-life; Not yet observed
- Best experimental limit: > 1.0 x 10^{22} yr R.Bernabei et al.
- Theoretical expectation: ~ 10^{21} - a few x 10^{22} yr

Advantages of $^{136}$Xe
- Q-value: valley of natural RI background
- Gaseous isotope can be purified during the experiment
- No long lived unstable Xe isotopes
- Easy to enrich

Q_{ββ} = 2.479\text{MeV}
$0\nu\beta\beta$ in KamLAND

- Low-background condition
- Large volume detector $\rightarrow$ high scalability
- Well-understood (measured) background model
- Liquid detector allows for additional in-situ purification
- No further modification to the detector
  $\leftrightarrow$ dissolve/load $\beta\beta$ isotope in LS
- Anti-neutrino measurements; simultaneously

$^{136}\text{Xe}$ in KamLAND

- Easy to dissolve; more than 3 wt%
- Easy to extract
- $T_{1/2}^{2\nu\beta\beta} > 10^{22}$ yr $\Rightarrow$ require modest energy resolution

High sensitivity with low cost
1st Phase

- Install mini-balloon into KamLAND.
- 250 ~ 400 kg of enriched $^{136}$Xe loaded liquid scintillator
- Explore KKDC claimed region; down to 60meV
- Keyword=Quickness; Start data taking 2011/Spring

 KKDC claim

$^{136}$Xe : 250~400kg mini-Balloon

(Final Xe volume depends on the budget.)
Milestone in KamLAND $\beta\beta$ decay (2)

**2nd Phase**

- 1000 kg of enriched $^{136}$Xe loaded liquid scintillator
- Brighter LS development (target: ~40% increase L.Y.)
- Light concentrator (target: ~80%)
- Explore the inverted hierarchy region; down to 25 meV
R&D for 1st Phase

- Development of Xe loaded liquid scintillator
- Development of mini-balloon
- Construction of Xe gas handling system
- Minor modification of chimney region to install mini-balloon

Software development
  - Simulation for the background study
  - Data taking for new electronics
Density control:

- Density of KamLAND LS = 777.2 kg/m³ @15 °C
- KamLAND LS components:

To dissolve Xe into LS → Lighten LS density:

- Decrease PC amount → decrease light output
- Similar chemical & optical property with lighter density
  
  Dodecane (C₁₂H₂₆) → Decane (C₁₀H₂₂)

Dodecane (C₁₂H₂₆) : 80 wt%
Pseudocumene : 20 wt%
1,2,4-Trimethylbenzene
PPO (C₁₅H₁₁NO) : 1.36 g/l
2,5-Diphenyloxazole

Density ; 0.75
Density ; 0.88
Density ; 0.735
**Xe loaded LS for $\beta\beta$ decay (2)**

- **Xe solubility measurement**
  - Controlling LS temperature (Solubility depends on temp.)

![Diagram of solubility setup](image)

- **Set point = 2.5 wt%**
  - T @ center of KamLAND
    - 10 ~ 13°C
  - There is enough margin if temp. would be fluctuated.

![Graph showing solubility vs temperature](image)

3.0 wt% @~15 °C
Xe loaded LS for $\beta\beta$ decay; Summary

**LS candidate composition**
- Density control
- Solubility
- Light yield $\rightarrow$ increase PPO

81.8 wt%

Decane ($C_{12}H_{26}$)

18.2 wt%

Pseudocumene
1,2,4-Trimethylbenzene

2.7 g/l

PPO ($C_{15}H_{11}NO$)
2,5-Diphenyloxazole

**Xe**
- 2.5 wt%

Light emission ratio with KamLAND LS

Goal of light yield with Xe

w/o Xe

KLLS = 1.0

96%

after Xe dissolving
Experience of 13mφ KamLAND Balloon

To reduce background from mini-balloon materials
- Without using lamination glue
  → only use heat connection
- Using much thinner films

KamLAND balloon structure

Image of mini-Balloon (2.7 ~ 4 mφ)

KamLAND balloon film (135 μm)

Ny (25 μm)×3  \( \rightarrow \)  EVOH(EF-XL) (15 μm)×2  \( \rightarrow \)  Rn-barrier

Film connection is made by sandwiching an EVOH film (no-extended type) and heat welding with microwave.
**Development of mini-Balloon**

**Requirements for Materials**
- Low background
  - Radio-purity: $10^{-13} \text{g/g for U/Th}$
  - Less volume $\rightarrow$ thin film ($\sim 25 \mu\text{m}$)
- Transparency to PPO emission wavelength ($350 \text{nm} \sim 450 \text{nm}$)
- Non-permeability for Xe gas
- Chemical compatibilities: against PC, Decane and Dodecane
- Mechanical strength
- Without aging effect

**Candidate Film**
- Several kinds/thickness of films are tested:
  - EVOH (extended, non-extended)
  - Nylon
  - Multi-layer
- **Good Candidates**: EVOH with heat connection
  $\rightarrow$ 1st test mini-balloon will be made in October!
R&D of Balloon Films(1)

- Xe gas permeability measurement
  - Enriched Xe gas is so expensive. → to avoid loosing gas

Film sample

~45 °C

KamLAND LS

Xe gas leakage through films: less than a few kg/5 yr for every film samples

Chemical compatibility/ Aging effect
- Checking color, weight, chemical components in soaked liquid, .......
R&D of Balloon Films (2)

Optical transparency measurement
- Using spectro-photometer

Aging effect was also investigated by acceleration method with conditions of 45 deg.C, 40 days.

\[ \text{OK (Transparency, Mechanical strength, Weight)} \]

Almost no absorption of scintillation light!

Compared with KamLAND-LS

PPO emission wavelength: 350 ~ 500 nm

Ratio; with/without film

EF-XL 12 \( \mu \text{m} \)

Set the film in a cell.
R&D of Balloon Films (3)

- Mechanical strength test
  - Before/after soaking test in LS

- Radioactive impurity measurement
  - Detection limit of ICP-MS: ~ a few \times 10^{-11} \text{ g/g} for U/Th
  - Requirement: ~ 10^{-13} \text{ g/g}
  - Not achieved the required level.

→ planning the Neutron Activation Analysis
Xenon Gas Handling System

- **Requirements for Xe gas system**
  - Repetition to dissolve/extract Xe gas into/from LS for ex., if BG of mini-balloon is above the required level,
  - Radio-pure system against $^{222}$Rn emanation

  **Enriched $^{136}$Xe (~92 %) is expensive,**
  - Small dead volume of Xe gas
  - Large extraction efficiency → **loss-less extraction system**
  - Without leakage; < $10^{-5}$ Pa.m$^3$/sec for whole system

- **Quality Control**
  - Dissolved Xe concentration
  - Temperature control of Xe-LS, Transparency, Density control, Chemical composition of LS, etc......
  - Impurity measurement ($O_2$ contents, RI’s)

We have experience in the construction and operation of the distillation system.
Xenon Gas Handling System

Conceptual design of Xe handling system

Xe Storage Tank

LS Buffer Tank

N2 Gas

mini-Balloon

KamLAND Detector

Xe Storage

Tank

PC

Density Control

LS Cooling dev.

(Heat Exchanger)

Bypass Tank

Glove Box

Xe Compressor/

Cooling device

Press. Offset

balloon

LS Cooling dev.

(LS/Xe Mixer)

LS/LS

Xe/N2 Separator

Gas

Exhaust

LS Degas Tank

LS/Xe

Mixer

Bubbling

Flow control

valve

Press. Control

valve

Reverse valve

Glove Box

Vacuum pump

Bolower

Bubbling

Press. Control

valve

Flow control

valve

ON-OFF valve

Reverse valve

LS Condenser

LS trans. pump

Joint Meeting of APS/JPS @Hawaii

October 13th, 2009
Xenon Gas Handling System

We have much experience in

- LS/Xe dissolve system → purge tower system
- Gas handling → pure Nitrogen generator
Background Studies for $\beta\beta$ decay

**Background Candidates in 1st Phase**

1. Cosmic-muon induced background; $^{10}$C, $^{11}$Be
   - tagging with new electronics

2. $^{8}$B solar neutrino → unavoidable in KamLAND

After installing mini-balloon & Xe loaded LS

3. $2\nu\beta\beta$ decay of $^{136}$Xe
   - E-resolution: 7.8%/\sqrt{E}

4. $^{214}$Bi, $^{208}$Tl in mini-balloon
   - by delayed coincidence

5. $^{208}$Tl in KamLAND-LS & Xe-LS
   - tagging by delayed coin.
Spallation background: $^{10}$C

- **New dead time free** electronics for tagging neutron after muon
- New electronics is being installed.

**Factor ~20 reduction** by tagging neutrons
Toward spallation background rejection

- New electronics MOGURA installation

- Ready to start data taking at ~ the end of this year.
Background Studies (3)

214Bi, 208Tl in mini-balloon

- Rejection by delayed coincidence
- Range of α-particle in materials ~ short; rejection efficiency is expected to be small, relatively (~ 70%).
  ⇒ also use 214Pb - 214Bi coincidence

- 208Tl; energy deposition above 2.6MeV
  but if light yield of Xe-LS is different with KamLAND-LS, ⇒

\[ 212\text{Po} \quad 0.3 \, \mu s \]
\[ 212\text{Bi} \quad 61 \, m \]
\[ 208\text{Pb} \quad \text{stable} \]
\[ 208\text{Tl} \quad 3.05 \, m \]
\[ 214\text{Po} \quad \text{tag} \]
\[ 214\text{Bi} \quad 19.9 \, m \]
\[ 214\text{Pb} \quad 26.8 \, m \]
\[ 218\text{Po} \quad 214\text{Bi} \text{ r } Q_{\beta} \text{ = 3.27 MeV} \]
Backgrounds are expected far below the $^{136}$Xe $0\nu\beta\beta$ peak.

Sensitivity of 1st phase: below KKDC claim
Time Table of the $\beta\beta$ Project

1st phase; start data taking 2011 spring

Physics targets

0$\nu+2\beta$ 250–400 kg

Important demonstration for the continuous funding

0$\nu+2\beta$ 1000 kg

Aggressive estimation
3 month drain & dry
3 month deconstruction
2 month chimney modification
3 month construction
3 month LS filling
Next physics target of KamLAND: $0\nu\beta\beta$ decay

Enriched $^{136}$Xe dissolved liquid scintillator

Milestone

1. **1st phase:** 250 ~ 400 kg of Xe $\rightarrow$ 60 meV (KKDC claim, degenerate)
2. **2nd phase:** 1000 kg of Xe with increasing L.Y. $\rightarrow$ 25 meV (inverted hierarchy)

R&D items for 1st phase

- Xe-LS development; already finished
- Development of mini-balloon; making 1st text balloon
- Xe gas handling system & quality control system; designing & development
- Background study; simulation studies are finished, New electronics is being installed.

1st Phase; start data taking on 2011/spring