Residual Nucleus Tagging for the Study of Neutrino-Nucleus Interactions

Tomohiro Eda for KamLAND collaboration, RCNS, Tohoku Univ. e-mail : eda@awa.tohoku.ac.jp

P6

1. Research Motivation

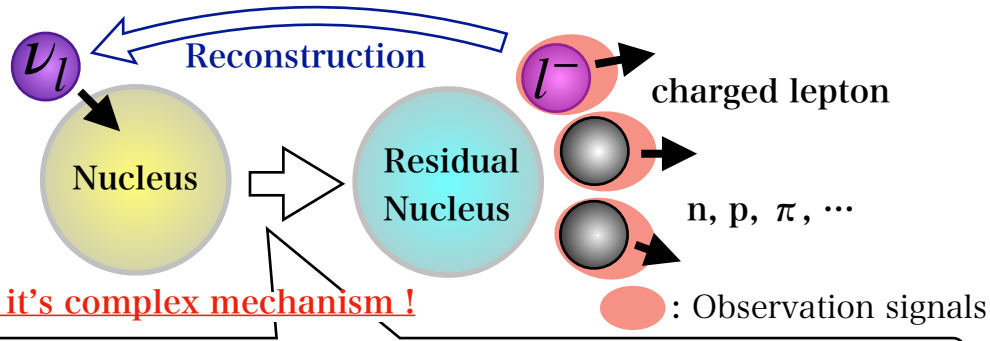
- Neutrino is indirectly reconstructed from observed particles

➡ So, we **need to model it properly** for the precise measurements

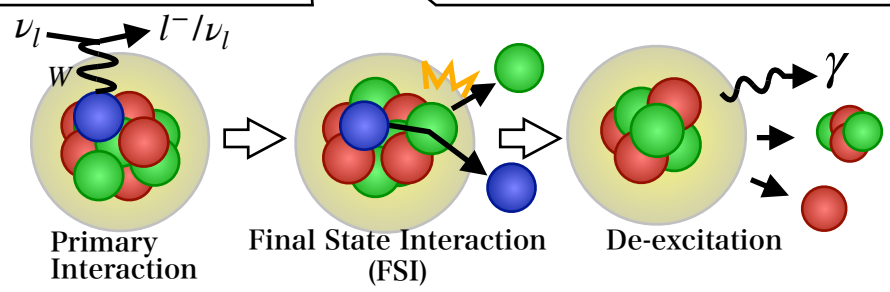
ex) ν CPV search, DSNB search etc.

Residual Nucleus

$$\nu + N \rightarrow l + \text{hadrons} + N'(Z, A)$$



But it's complex mechanism !



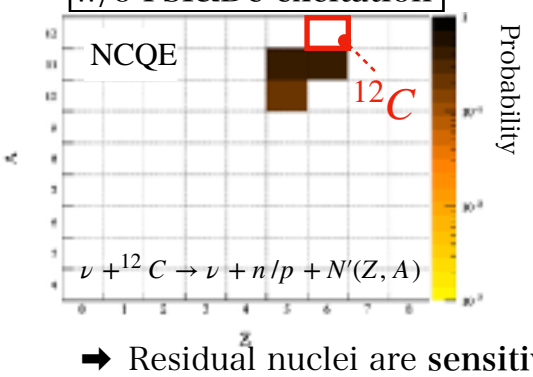
Large model dependence exists in among MC generators

➡ The differences appear in the species and number of final-state particles

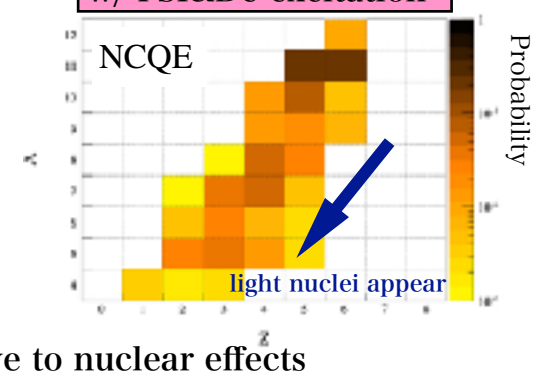
$\nu + N \rightarrow [l + \text{hadrons}] + [N'(Z, A)]$ not experimentally confirmed yet (sub-GeV region)

Abundant experimental data

w/o FSI&De-excitation



w/ FSI&De-excitation

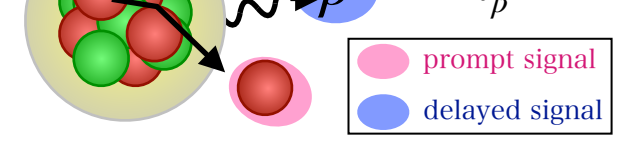


➡ Residual nuclei are **sensitive to nuclear effects**

Residual Nucleus can be a new prob for ν N interactions

2. Residual Nucleus Tagging and KamLAND

- Residual nuclei are tagged by the beta decay signal
  - unique time and space correlation, energy spectrum



[1]

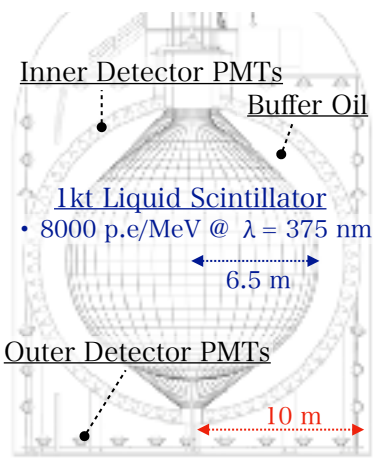
	Lifetime in KamLAND LS	Radiation energy (MeV)
^{12}B	29.1 ms	13.4 (β^-)
^{12}N	15.9 ms	17.3 (β^+)
^{8}Li	1.21 s	16.0 ($\beta^-\alpha$)
^{8}B	1.11 s	18.0 ($\beta^+\alpha$)
^{9}C	182.5 ms	16.5 (β^+)
^{9}He	171.7 ms	10.7 ($\beta^-\gamma n$)
^{9}Li	257.2 ms	13.6 ($\beta^-\gamma n$)
^{11}C	29.4 min	1.98 (β^+)
^{10}C	27.8 s	3.65 ($\beta^+\gamma$)
^{11}Be	19.9 s	11.5 (β^-)
^{6}He	1.16 s	3.51 (β^-)

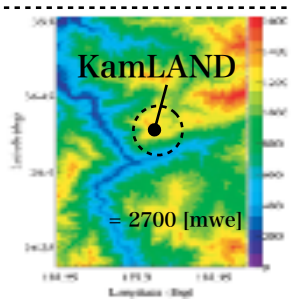
[1] PHYSICAL REVIEW C 81, 025807 (2010)

➡ Spallation products from cosmic-μ become main BG due to long-time delayed coincidence

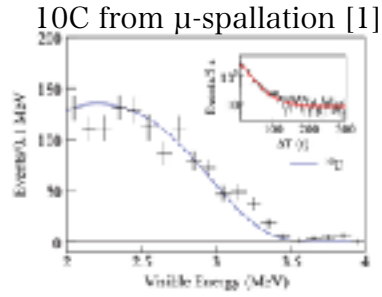
Data-taking Period
2002 - 2024

KamLAND Detector





10C from μ-spallation [1]

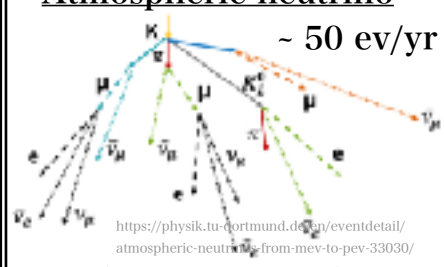


Advantages of KamLAND

- **Significant suppression of cosmic-μ flux** due to the underground environment
  - ~1/100,000 of that at ground level
- **Excellent reconstruction performance** for low-energy events
  - Vertex resolution : 13 cm/√E [MeV]
  - Energy resolution : 7%/√E [MeV]
- **An established method** for identifying residual nuclei from cosmic-μ spallation
  - well-known detector response to the signals

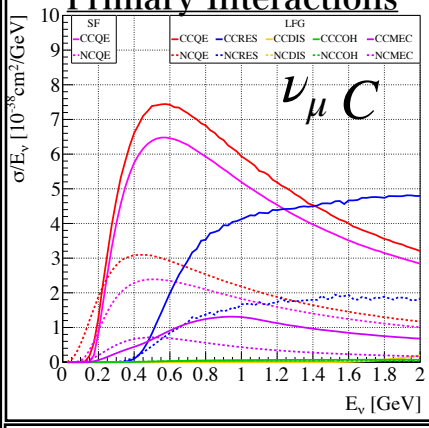
3. Neutrino Source and MC Settings

Atmospheric neutrino



~ 50 ev/yr

Primary Interactions



Atm ν flux
- Honda flux
  http://www-rccn.icrr.u-tokyo.ac.jp/mhonda/public/nflx2014/index.html

ν N Interaction MC
- NuWro v25.11
  - 10 interactions
  https://github.com/NuWro/nuwro

De-excitation MC
- NucDeEx v2.2.2
  - only CC/NCQE
  https://github.com/SeishoAbe/NucDeEx

Detector MC
- KLG4 (Geant4-based)
  - period : 2003 - 2018
  - livetime : 11.2 yr

Event Reconstruction & Event Selection

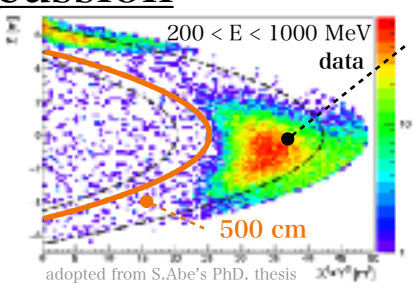
Oscillation effect
- Prob3++ v3.1
  https://webhome.phy.duke.edu/~raw22/public/Prob3++/

MC prediction

4. Results and Discussion

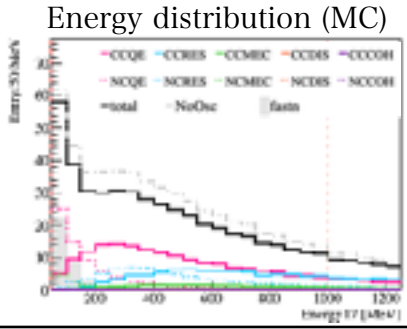
Selection Criteria for atm. ν

- $50 < E < 1000$ MeV
- $R < 500$ cm
- OD PMT cut



untagged μ & fast neutrons

Energy distribution (MC)

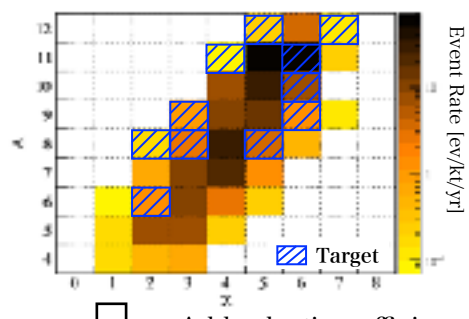


Expected : 458 events (BG : 34)

Exposure : 4.6 [kt•yr]

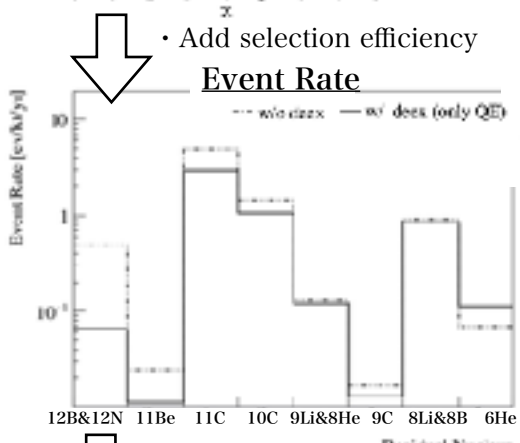
- fast-neutron is considered as BG
  - Not fully rejected by radius cut alone
- QE (52%) and RES (32.3%) are dominant interactions in the window

Prediction of Residual Nuclei Distribution



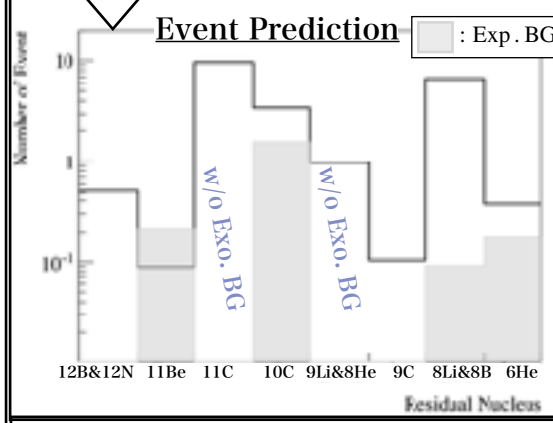
・Add selection efficiency

Event Rate



・Consider exposure [kt•yr]
・Add Exp. BG

Event Prediction

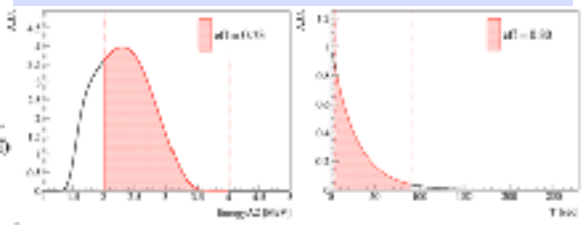


Selection Criteria for Residual Nuclei (e.g. 10C)

- $2 < E < 4$ MeV
- $R < 450$ cm
- $5 < dT < 90$ [sec] ($5 < dT < 105$ [min])
- $dR < 150$ [cm]
- no muon 2ms before

off-time time window (used for BG estimation)

100% efficiency is assumed in this study



- The accidental BG is estimated from off-time data samples
- Redistribution to light nuclei (A≤8) can be seen by the de-excitation
- 11C and 9Li&8He are plotted w/o BG. The estimation is in progress
- Tens of events are expected in the KamLAND data-taking period
- Model verification can be done by signal dominant species, marked ▭

	Expo.	#Ev (MC)	Exp. BG
12B+12N	8.0	0.52	(1.6±0.2)E-03
11Be	8.0	0.10	0.22 ± 0.04
11C	3.3	9.60	-
10C	3.3	3.45	1.56 ± 0.15
9Li+8He	8.0	0.97	-
9C	8.0	0.10	(2.0±1.2)E-04
8Li+8B	8.0	6.71	0.09 ± 0.01
6He	3.3	0.37	0.17 ± 0.01

5. Prospects

- Investigate the impact of model dependence in ν interactions and de-excitation processes on residual nucleus distributions
  – NEUT, GENIE: ν N MC × G4PreCompound: de-excitation MC
- Evaluate the scale of changes in residual nucleus distributions induced by ν-correlated signals (charge-exchange reactions with nuclei)
- Construct a β-decay signal model based on cosmic μ–induced spallation and evaluate the likelihood of candidate events following atm. ν signals