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Exploring Solar Neutrinos through Charged Current Reactions in ^{136}Xe with Delayed Coincidence Measurement using KamLAND-Zen

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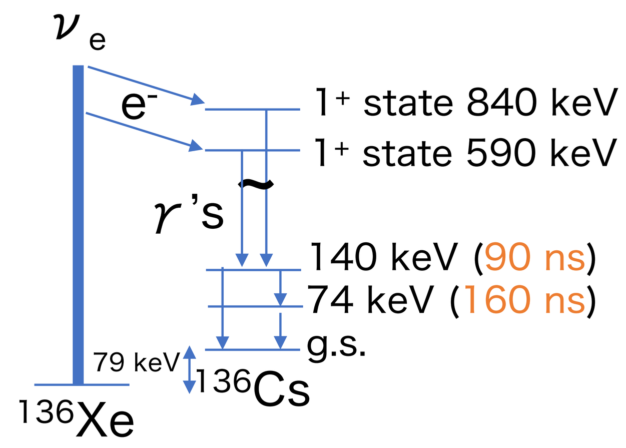
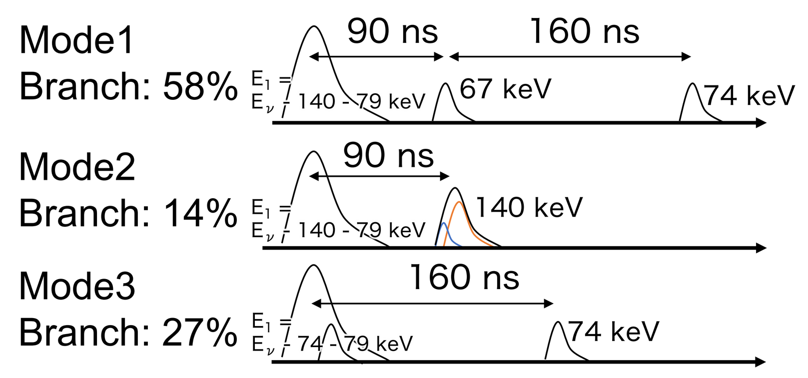
Introduction: CC reaction of ^{136}Xe (XeCC)

- Charged current reaction of ^{136}Xe and ν_e (XeCC): $^{136}\text{Xe} + \nu_e \rightarrow {}^{136}\text{Cs}^* + e^-$
  - Mostly goes to 1^+ (590 keV or 840 keV) states of ^{136}Cs
  - Sensitive to $E_\nu > 79$ (Q-value[1]) + 590 = 670 keV
- Recently low-lying isomeric states in ^{136}Cs with O(100) ns lifetimes were found[2, 3].
- With ns-resolution detectors, we can measure ν_e using ^{136}Xe through delayed coincidence.



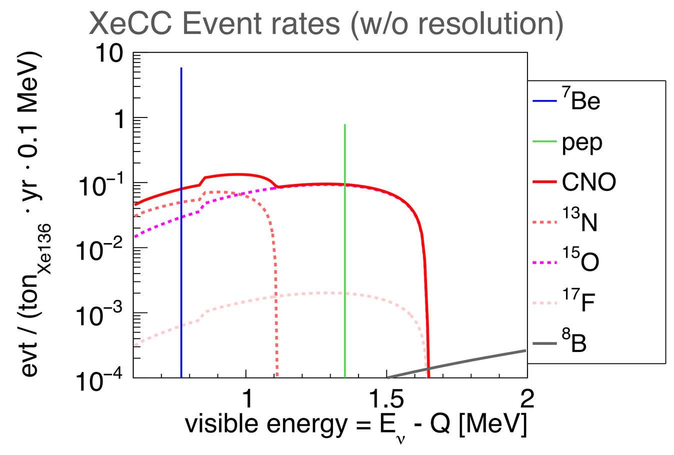


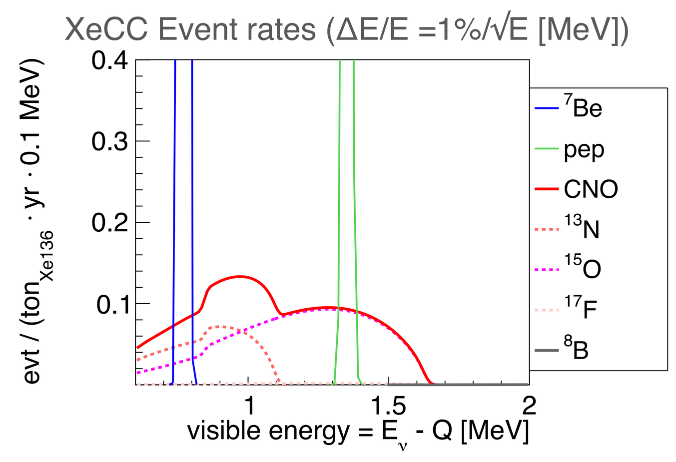
[1]: PRC 108, 045502 (2023). [2]: PRL 131, 052502 (2023). [3]: PRL 131, 052501 (2023).

Application to solar neutrino measurements

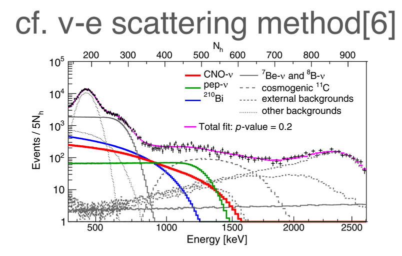
- Solar models: High-metallicity (GS98)[4] vs Low-metallicity (AGSS09)[5]
- CNO solar neutrino flux is sensitive to the metallicity.
- Current situation:
  - Borexino's measurement favors high metallicity models[6]
  - Uncertainties of the models and the measurement are all at ~15%.
- Toward higher precision?
  - Traditional method (ν-e scattering) faces challenges in BG control.
  - Advantages of XeCC:
    - Potentially BG free delayed coincidence measurement
    - 1:1 energy reconstruction allows distinction from other solar-ν's
- Expected XeCC rates (B16-GS98 [7], oscillated)
  - ^{7}Be: 5.9/yr/ton, pep: 0.79/yr/ton, CNO: 0.92/yr/ton
- ^{7}Be-ν's are within the reach of current sub-ton scale detectors
- 100 ton exp. to reach smaller uncertainty than models

[4]: Spa. Sci. Rev. 85, 161—174 (1998). [5]: Annu. Rev. Astro. 47, 481—522 (2009). [6]: PRD 108, 102005 (2023). [7]: ApJ 835, 202 (2017).



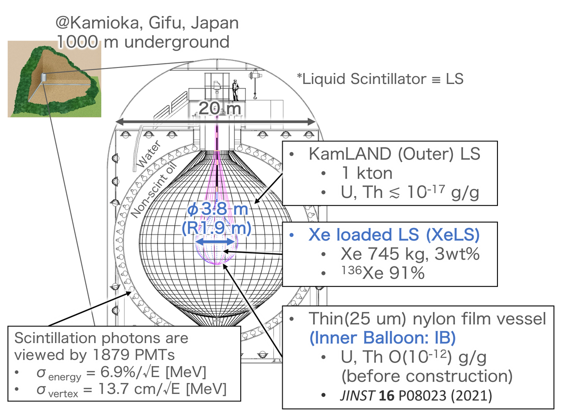


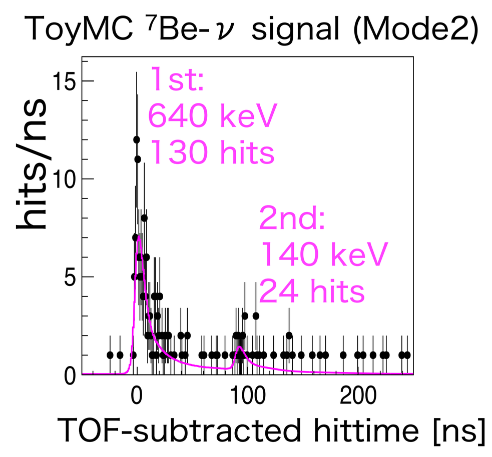
cf. ν-e scattering method[6]



	^{136}Xe mass [ton]	CNO-ν flux unc. [%] (5yr obs.)	Target
KamLAND-Zen 800	0.68	-	^{7}Be-ν (Proof of concept)
KamLAND2-Zen	1.0	40%	CNO-ν (a few events)
Future 5 ton exp.	5.0	20%	^{13}N/^{15}O separation
Future 10 ton exp.	10	15%	Unc. same level as models
Future 100 ton exp.	100	5%	Far better unc. than models. New implication?

Feasibility of KamLAND-Zen

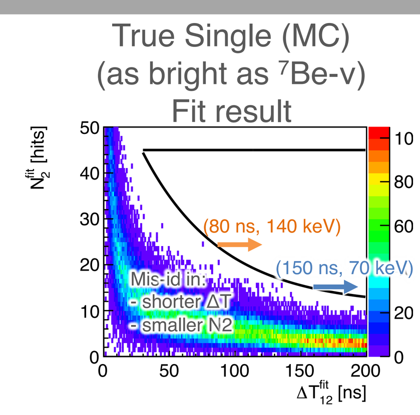


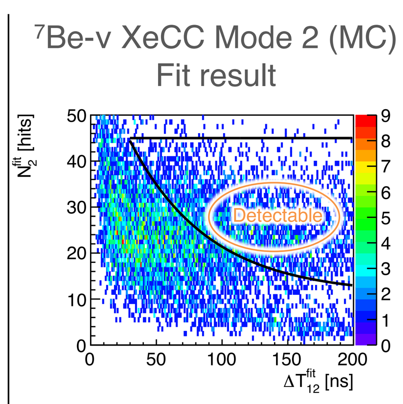


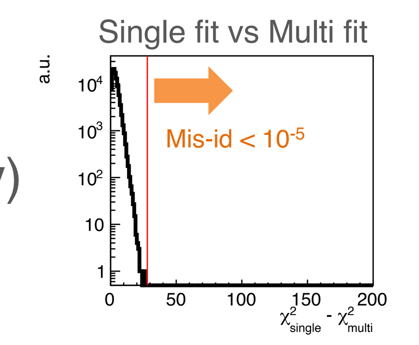
- Detector
  - Xe gas dissolved organic liquid scintillator
  - World's largest ^{136}Xe exposure: 0.68 ton x 5 yrs.
  - Scint. decay time ~5 ns.
  - Photons detected by 1879 PMTs (240 p.e./MeV)
  - Dark hits: 0.04 p.e./ns ~ 10 keV equiv. per event.
- DAQ
  - Trigger threshold: ~0.3 MeV
    - Only 1st pulse can be triggered
  - Event window: ~200 ns
    - 2nd (and 3rd) pulses can be detected if in the event window of the 1st pulse
- Expected ^{7}Be-ν signal in KamLAND-Zen
  - Mode 2 (double pulses) is most promising
    - E_1 = 860 - 140 - 79 = 640 keV ~ 130 hits
    - $E_2 + E_3$ = 66 + 74 = 140 keV ~24 hits

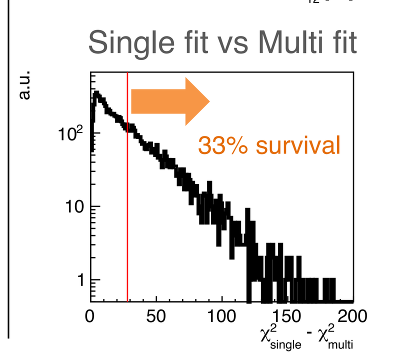
Challenges

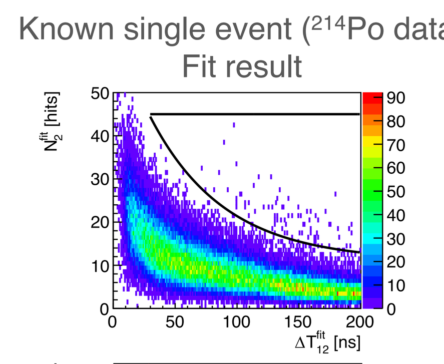
- Single vs Multi pulse discrimination
  - Multi pulse fit
    - Hits: N_1, N_2 (,N_3)
    - Time diff.: ΔT_{12} (,ΔT_{23}) [ns]
  - The discrimination power depends on (N_1, N_2, ΔT_{12})
  - Mis-id of single pulse required to be < 10^{-5}
    - (2νββ rate) > 10^5 x (^{7}Be-ν rate)
    - Fractions satisfy the condition (at ^{7}Be-ν energy)
      - Mode 1: 18%
      - Mode 2: 33%
      - Mode 3: 7.3%
  - Larger 1st pulse makes it harder to find delayed pulses
    - CNO-ν detection is difficult for KamLAND-Zen 800
- Accidental BG: Anything + 2νββ
  - Total single rate in the detector (> 10 hits): ~5 kHz
    - ^{14}C(Q_β = 156 keV) rate in the LS (r < 6.5 m): ~1 kHz
    - Others in the buffer (6.5 < r < 8.5 m): ~4 kHz
  - Accidental coincidence probability: ~10^{-3}/event
    - 10^2 reduction required to reach ^{7}Be-ν rate
    - Vertex reconstruction on delayed pulses in development

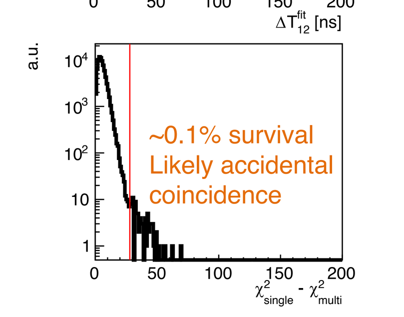






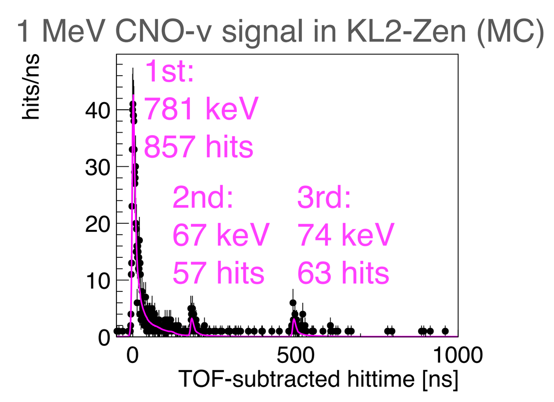


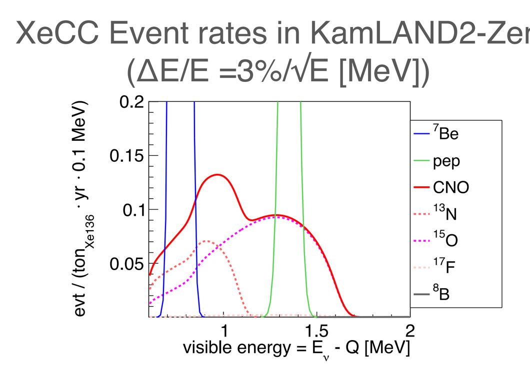




Prospects

- [Current] KamLAND-Zen 800: ^{7}Be-ν detection?
  - (If accidental BGs are successfully mitigated)
  - ^{7}Be-ν original number of events (0.68 ton x 5yr): 20 evt
  - Fiducial volume ratio: 40%
  - Signal efficiency: 17%
    - Mode 1: 58%(branch) x 18% (single/multi discri.)
    - Mode 2: 14%(branch) x 33% (single/multi discri.)
    - Mode 3: 27%(branch) x 7.3% (single/multi discri.)
  - Expected number of events (after cuts): 1.4 evt
- [Future] KamLAND2-Zen: CNO-ν detection?
  - x5 light yield to bring better single/multi pulse discrimination
    - Delayed 70 keV → ΔT > 50 ns
    - Delayed 140 keV → ΔT > 10 ns
  - Scintillating inner balloon: Full Xe (~1 ton) available
  - Event window enlargement (200 ns → 1000 ns)
    - >90% multi pulses containment
    - Clear detection of the 3-fold coincidence (Mode 1)
  - Expected number of events (5yr, ~90% eff.)
    - ^{7}Be: 27 evt, pep: 3.6 evt
    - CNO (energy selection eff. 58%): 1.4 evt





Summary

- $^{136}\text{Xe} + \nu_e \rightarrow {}^{136}\text{Cs}^* + e^-$: Potential new way to detect ν_e
- 100 ton ^{136}Xe detector to perform CNO-ν flux meas. at 5% unc.
- Feasibility of KamLAND-Zen (800)
  - Single/multi pulse separation ability is not perfect, but ok
  - Accidental BG: Vertex recon. on a delayed pulse is necessary
    - If achieved, ^{7}Be-ν detection is possible.
- KamLAND2-Zen
  - Possible CNO-ν detection