Delayed coincidence with a day-scale window for tagging ^{232}Th series isotopes in KamLAND

Takahiko Hachiya for the KamLAND collaboration
Research Center for Neutrino Science, Tohoku University, Sendai 980-8578, Japan
E-mail: takahiko@awa.tohoku.ac.jp

Abstract. Decays of ^{232}Th series isotopes such as ^{212}Bi^{212}Po and ^{208}Tl form background events for underground physics experiments. In this study, we performed new delayed coincidence with a day-scale window using data of KamLAND, a 1 kton liquid scintillator detector. We firstly searched for a coincidence of ^{220}Rn–^{216}Po ($T_{1/2}$ = 0.15 s), prompt coincidence (PC), and then searched for events of ^{212}Bi^{212}Po or ^{208}Tl decays within 2 day from PC. It yields ∼80% tagging efficiency with modest, ∼10%, deadtime despite the requirement of long time correlation thanks to low accidental coincidence rate of PC. This method will be newly introduced to analyses of solar neutrino measurement at 3 MeV region with KamLAND and neutrinoless double-beta decay search with KamLAND-Zen to reduce the backgrounds.

1. Introduction

Decays of ^{232}Th series daughters form background events for underground physics experiments such as solar neutrino measurement and neutrinoless double-beta decay search. The delayed coincidence (DC) method with μs time window has been commonly used for tagging part of the decay sequence: ^{212}Bi($Q_\beta = 2.25$ MeV, $T_{1/2} = 60.6$ m)–^{212}Po($Q_\alpha = 8.95$ MeV, $T_{1/2} = 299$ ns).

In this study, we tried applying DC with a day-scale time window to ^{232}Th series isotopes using data of a large liquid scintillator (LS) detector, KamLAND. We firstly tagged prompt coincidence (PC) of ^{220}Rn($Q_\alpha = 6.41$ MeV)–^{216}Po($Q_\alpha = 6.91$ MeV, $T_{1/2} = 0.145$ s) and searched for associated ^{212}Bi–^{212}Po pair decay or ^{208}Tl($Q_\beta = 5.00$ MeV, $T_{1/2} = 3.05$ m) decay within ∼2 day from PC. The long coincidence time comes from lifetime of ^{212}Pb($T_{1/2} = 10.6$ h).

KamLAND consists of 1-kton LS contained in 6.5-m-radius-balloon made from nylon/EVOH multilayered film, non-scintillating oil which holds the balloon, 1325 17-inch photo-multiplier-tubes (PMTs) and 554 20-inch PMTs. The energy resolution and vertex resolution are $6.9\%/\sqrt{E(\mathrm{MeV})}$ (σ), and 13 cm$/\sqrt{E(\mathrm{MeV})}$ (σ), respectively [1].

2. Analysis

2.1. Event selection

We used data collected during period from 7th, Apr., 2009 to 12th, Aug., 2011. Note that before this period we performed LS purification campaign which reduced radioactive impurities below 1 MeV energy region by ∼5 orders of magnitude [1] and there was no inner balloon for neutrinoless double-beta decay search, KamLAND-Zen [3], inside the detector in this period. ^{232}Th activity in LS of this period was estimated from ^{212}Bi–^{212}Po DC events as (59 ± 4) nBq/m^3 [2].

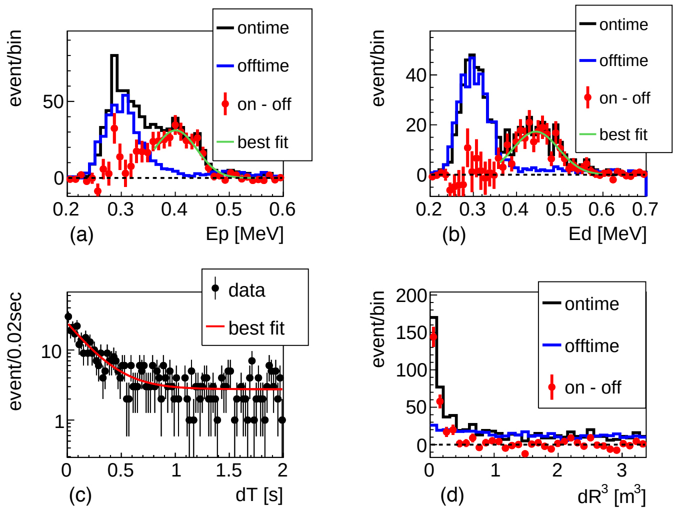

Figure 1. Distributions of delayed coincidence (DC) parameters of prompt coincidence (PC).

We required that the events of interest should occur after more than 2 ms from previous muon and within 5 m from the detector center. We removed short-time (< 2 ms) DC events for PC and ^{208}Tl decay candidate selection. The exposure after the selections was 265 kton-day.

2.2. Prompt Coincidence (PC)

We set ontime and offtime windows for time difference (dT) between prompt event, ^{220}Rn α decay, and delayed event, ^{216}Po α decay, as < 200 ms and 1.5–2.0 s, respectively. We also set criterion for extracting pure PC events as follows: $0.4 < \mathrm{Ep} < 0.5$ MeV, $0.42 < \mathrm{Ed} < 0.55$ MeV, $\mathrm{dR}^3 < 0.1$ m^3, where Ep is visible energy of prompt event, Ed is visible energy of delayed event, and dR is the distance between prompt event and delayed event. Figure 1 shows distributions of each parameter after applying selections other than the parameter's one. Figure 1(a) shows Ep spectra and Figure 1(b) shows Ed spectra. Peak structures at $\sim$0.4 MeV in ontime-minus-offtime spectra (red points) correspond to quenched visible energy signals of the α decays. Results of Gaussian fit to them (solid green lines) were as follows: (mean [MeV], sigma [MeV]) $= (0.401 \pm 0.007, 0.039 \pm 0.005)$ for Ep and $(0.445 \pm 0.006, 0.053 \pm 0.005)$ for Ed. Decay of ^{210}Po($Q_\alpha = 5.41$ MeV) in LS is background for the signals. The contribution can be seen as $\sim$0.3 MeV peak in offtime spectra (solid blue lines). Figure 1(c) is dT distribution. We obtained halflife it as (0.15 ± 0.02) s by fitting with exponential (solid red line). This agrees with $T_{1/2}$ of ^{216}Po. We can see clear event excess in the region of small dR^3 in Figure 1(d).

2.3. Day-scale delayed coincidence

Since the lifetimes of ^{212}Pb and ^{212}Bi are long, a day-scale time window is needed for tagging decay sequences of PC–^{212}Bi–^{212}Po and PC–^{208}Tl. We firstly confirmed validity of matching PC with ^{212}Bi–^{212}Po by applying relatively tight windows as follows: $0.37 < E_{^{220}\mathrm{Rn}} < 0.6$ MeV, $0.4 < E_{^{216}\mathrm{Po}} < 0.6$ MeV, $\mathrm{dR}^3_{^{220}\mathrm{Rn}^{216}\mathrm{Po}} < 0.2$ m^3, $\mathrm{dT}_{^{220}\mathrm{Rn}^{216}\mathrm{Po}} < 1.0$ s, $0.45 < E_{^{212}\mathrm{Bi}} < 2.5$ MeV, $0.7 < E_{^{212}\mathrm{Po}} < 1.0$ MeV, $\mathrm{dR}_{^{212}\mathrm{Bi}^{212}\mathrm{Po}} < 2$ m, $0.4 < \mathrm{dT}_{^{212}\mathrm{Rn}^{212}\mathrm{Po}} < 2.5$ μs. Figure 2(a) shows space and time correlation of the matched events, where $\mathrm{dR}_{\mathrm{PC-BiPo}}$ is distance between ^{220}Rn^{216}Po combined position and one of ^{212}Bi^{212}Po and $\mathrm{dT}_{\mathrm{PC-BiPo}}$ is time difference between PC and ^{212}Bi^{212}Po. We can find clustered events at low $\mathrm{dR}_{\mathrm{PC-BiPo}}$ and short $\mathrm{dT}_{\mathrm{PC-BiPo}}$ region. The projected $\mathrm{dT}_{\mathrm{PC-BiPo}}$ distribution with selection of $\mathrm{dR}^3_{\mathrm{PC-BiPo}} < 2$ m^3 is shown in Figure

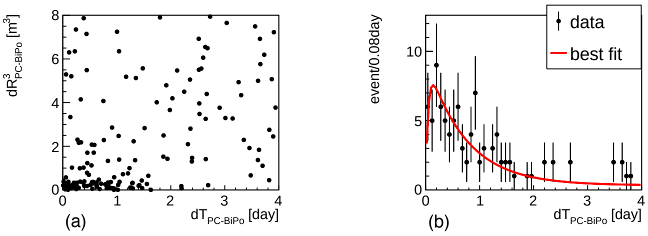

Figure 2. (a): Space and time correlation of PC–^{212}Bi^{212}Po candidates. (b): dT distribution of PC–^{212}Bi^{212}Po candidates with $\mathrm{dR}^3_{\mathrm{PC-BiPo}} < 2$ m^3.

2(b). We fitted it with sequential decay model (solid red line) and obtained halflives as (11.9 ± 2.7) h and (0.76 ± 0.71) h and they agree with $\mathrm{T}_{1/2}$ of ^{212}Pb and ^{212}Bi, respectively.

2.4. Selections for veto purpose
In order to apply the tagging for veto purpose, we applied enlarged selection for PC as follows: $0.36 < \mathrm{Ep} < 0.6$ MeV, $0.36 < \mathrm{Ed} < 0.65$ MeV, $\mathrm{dT} < 1.0$ s, $\mathrm{dR} < 1.0$ m, and estimated their efficiencies as (84.9 ± 7.4)%, (94.6 ± 3.2)%, 99.2%, (100 ± 8.9)%, respectively. The total efficiency is (80 ± 13)%. ^{232}Th activity in LS was derived from the efficiency and the remaining events after the selection as (59 ± 10) nBq/m^3. It agrees with the estimation obtained from ^{212}Bi–^{212}Po DC events. We estimated the fraction of deadtime due to accidental coincidence using space-time uniform events as (9.4 ± 0.8)% assuming we require $\mathrm{dT}_{\mathrm{PC-BiPo}} < 2$ day (95% selection efficiency) and $\mathrm{dR}^3_{\mathrm{PC-BiPo}} < 2$ m^3.

2.5. Limit on loss of tagging efficiency due to convection
It is possible that isotopes move farther than the space correlation requirement due to convection of LS. Such an effect is not clear from Figure 2(a). We calculated the loss of tagging efficiency by comparing tagged event numbers of PC–^{212}Bi^{212}Po and PC–^{208}Tl with expected numbers under the no-loss hypothesis as (6 ± 14)% and (12 ± 15)%, respectively. Here we required $\mathrm{dR}^3_{\mathrm{PC-BiPo(Tl)}} < 2$ m^3 ($\mathrm{dR} < 1.26$ m). Their combined upper limit is < 22% (90% C.L.).

3. Summary
We performed day-scale delayed coincidence tagging of decays of ^{232}Th series isotopes in LS detector. We found that $\sim$80% of the tagging efficiency is achievable with modest $\sim$10% deadtime. Loss of the efficiency due to convection of LS was not so significant and we set an upper limit on it. This tagging method can be widely applied to low background experiments. It will be introduced to analyses of solar neutrino measurement at 3 MeV energy region in KamLAND to suppress ^{208}Tl events and neutrinoless double-beta decay search of KamLAND-Zen to reduce ^{212}Bi^{212}Po pile-up backgrounds. It may be also possible to use the present data for tracking convection effects.

Acknowledgments
This work was supported by JSPS KAKENHI Grant Number 18J10498.

References
[1] A. Gando *et al.* (KamLAND Collaboration) 2015 *Phys. Rev. C* **92** 055808.
[2] Y. Takemoto 2014 *Observation of* ^{7}*Be Solar Neutrinos with KamLAND* Doctorial Dissertation (Graduate School of Science, Tohoku University).
[3] A. Gando *et al.* (KamLAND-Zen Collaboration) 2016 *Phys. Rev. Lett.* **117** 082503.