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A $^{13}C(\alpha, n)^{16}O$ calibration source for KamLAND

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Abstract

We report on the construction and performance of a calibration source for KamLAND using the reaction $^{13}C(\alpha, n)^{16}O$ with ^{210}Po as the alpha progenitor. The source provides a direct measurement of this background reaction in our detector, high energy calibration points for the detector energy scale, and data on quenching of the neutron visible energy in KamLAND scintillator. We also discuss the possibility of using the $^{13}C(\alpha, n)^{16}O$ reaction as a source of tagged slow neutrons.

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1. Introduction

The reactor phase of the Kamioka Liquid scintillator Anti-Neutrino Detector (KamLAND) detects the interaction

$$\bar{\nu} + p \rightarrow n + e^{+} \tag{1}$$

by observing the delayed coincidence between the positron and the subsequent capture of the neutron [1]. A trigger can be generated by any reaction which produces a prompt signal above threshold and a free neutron.

A particular background in KamLAND results from the presence of ^{210}Po (a daughter of ^{222}Rn present in quantities governed by the ^{210}Pb concentration), which decays by emitting a 5.304 MeV α particle, allowing the alpha capture reaction

$$\alpha + {}^{13}C \rightarrow n + {}^{16}O. \tag{2}$$

This reaction has been studied since the 1950s [2–5] and Harrisopulos et al. recently measured the cross-section to 4% [6]. However, the current theoretical understanding of the reaction was insufficient to describe the response of KamLAND to the reaction in Eq. (2) due to uncertainties in the neutron spectrum and the poorly known excited state branching fractions.

We have produced and deployed a calibration source utilizing the reaction in Eq. (2) to carry out a direct measurement of the background rate and the energy spectrum for this reaction in KamLAND. Similar sources reported in the extant literature [7–9] use different progenitor isotopes and were constructed as gamma calibration sources for germanium detectors, while we are as interested in the neutron as the decay gamma.

2. Design and construction

To obtain an accurate measurement of the prompt neutron energy spectrum in KamLAND requires either ^{210}Pb or ^{210}Po as the progenitor—other isotopes generate different alpha energies. Despite the short half-life of the Polonium isotope—138.4 days—we judged it feasible to construct a source, certify it for use in the detector, and deploy it on a time scale comparable with the ^{210}Po half-life. After our attempts to obtain ^{210}Pb in sufficient quantities were unsuccessful, we decided to build a source with ^{210}Po.

The strongest design constraints were imposed by the stringent local regulatory limits on contained activity and

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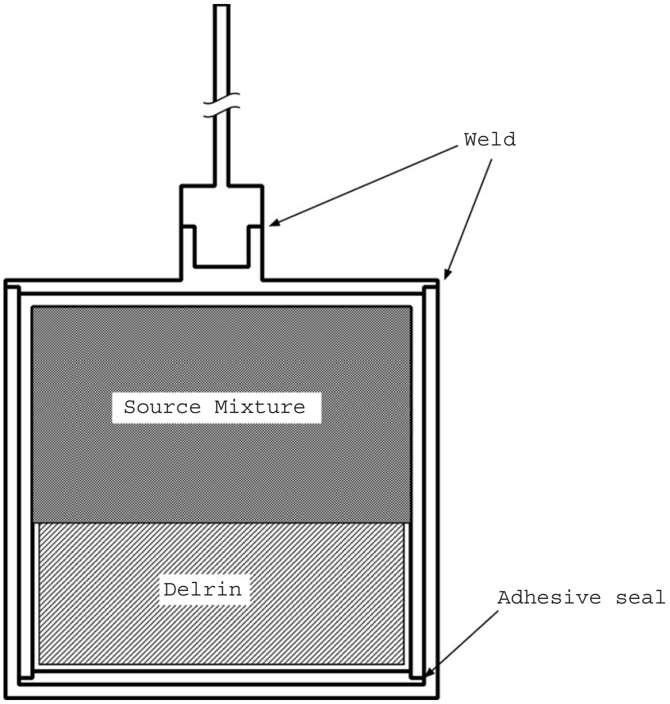

Fig. 1. Construction of the source capsule. The chamber is 13 mm in diameter and 13 mm in height. Both capsules have 1 mm thick walls. The inner capsule was inserted with the lid away from the joint in the outer capsule to protect the adhesive from the heat of welding.

the very low capture fraction for alpha particles. We were limited to an initial contained activity of 100 μCi of ^{210}Po. Assuming this limit and computing the expected capture fraction (see Section 6.3) we could estimate a neutron rate of the source no higher than 30 Hz.

We were able to obtain ^{210}Po in a 4 M hydrochloric acid solution and high purity ^{13}C in powder form. The source was constructed by filling the capsule with approximately 0.3 g of ^{13}C powder, dripping the Polonium solution into the carbon powder, and allowing the whole to dry thoroughly before tamping the powder with a Delrin spacer and closing the system. A heat lamp was used to speed the evaporation, which required two days. Our design called for a total contained activity of 95 μCi on the day of assembly.

The source capsule—shown in Fig. 1—was constructed of stainless steel for ease of manufacture. The inner capsule was constructed of series 316 L stainless steel for acid resistance, and series 304 stainless steel was used in the outer capsule for its good welding properties. Both materials are known to be compatible with KamLAND liquid scintillator (LS).

Despite the use of low carbon stainless steel in the inner capsule, tests showed that it would nonetheless develop gas bubbles in the presence of HCl that threatened to spatter our alpha source around the fume hood. To prevent this, we painted the inside of the capsule with four thin coats of a clear acrylic paint obtained at a local craft store. This treatment provided adequate acid resistance.

The inner capsule was sealed using a structural adhesive,[1] wiped clean, and inserted in the outer capsule, which was welded shut using an electron beam technique.

3. Certification

Objects to be deployed in KamLAND must first be certified as both chemically compatible with the LS and radiologically clean. In particular, it is necessary to show that radiological sources are properly sealed and do not leak.

Following standard KamLAND procedure, we thoroughly cleaned the source, and then soaked it in 0.1 M nitric acid for four days, pressure cycling to five atmospheres three times in the course of the soak. The soak liquid was counted in a high sensitivity germanium detector to exclude gamma radio-contamination. Special attention was paid to the possible presence of ^{40}K, and the daughters of ^{238}U and ^{232}Th.

Because ^{210}Po does not have a significant gamma line, this method is not well suited to detecting a low activity Polonium leak. Instead we introduced a sample of the soak liquid into a cuvet full of acid tolerant LS,[2] which was subsequently placed between two PMTs and the signal from any alpha activity observed directly. Understanding this device required calibration data with several gamma sources to establish the energy response; with a clean control sample to understand the shape of the background (mostly cosmic rays and ambient radioactivity); and with a ^{210}Po doped sample to establish the quenching behavior of the LS. A null result was obtained for measured ^{210}Po leakage with a 90% C.L. upper limit of 0.3 Bq, and the source was certified for use in KamLAND.

4. Source physics

KamLAND signals from the source arise from three mechanisms: prompt activity from the alpha progenitor, prompt activity from the alpha capture reaction, and delayed activity from the capture of the thermalized neutron.

At the alpha energy of ^{210}Po, Eq. (2) can proceed not only to the ground state of ^{16}O, but also to the first two excited states. See Table 1 for thresholds and decay products.

4.1. Progenitor activity

The ^{210}Po progenitor decays primarily by

$$^{210}\mathrm{Po} \to {}^{206}\mathrm{Pb} + \alpha\,(5.304\,\mathrm{MeV})$$

but has a $(1.21 \pm 0.04) \times 10^{-5}$ branch to

$$^{210}\mathrm{Po} \to {}^{206}\mathrm{Pb} + \alpha\,(4.517\,\mathrm{MeV}) + \gamma\,(0.803\,\mathrm{MeV}). \quad (3)$$

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[1] 3M Scotch Grip 1357.

[2] Packard Ultima Gold AB.