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Bachelor of Science

A Study of the Properties of KamLAND Photodetectors

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UT-ORNL Summer Research Program

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Introduction

Neutrino physics is one of the forefront topics of modern physics research. Neutrinos are present in many key nuclear reactions, and thus can tell us a great deal about precisely what goes on in these reactions.

Neutrinos are of a class of particles known as "leptons." Neutrinos have very low mass and a neutral charge, and are thus virtually unaffected by both gravity and electromagnetism. The only real interactions neutrinos have with other forms of matter occur during their creation, and when they interact with atomic nuclei, one of the few particle systems dense enough to have any chance of actually intersecting a neutrino's path. Even these interactions are extremely rare, and neutrinos have an outstanding capacity to travel completely through quantities of matter as large as stars and planets.

The sun is our largest source of neutrinos, showering the earth with trillions upon trillions of neutrinos every second, the vast majority of which pass completely through and continue out into space. It is fortunate for life on earth that these neutrinos have such low rates of interaction with matter because if this rate were much higher, life on earth would be quite impossible. Because solar neutrinos are predicted as the most common type, scientists have taken to studying the phenomenon of solar neutrino production extensively.

Solar neutrinos are produced by nuclear reactions within the solar core. Since they are so copiously emitted by these reactions, and are able to so easily penetrate the solar material around them, we can use the neutrinos that we detect to peer directly into the heart of the sun, in order to more completely understand the nuclear processes that take place there. This gives us the capacity to more adequately compare our theoretical Standard Solar Model to actual observation, which in turn allows us to fine-tune our theory, and supplements our ability to predict solar behavior.

The Standard Solar Model represents everything we know, and can predict about the sun. It allows us to describe everything from solar mass, to solar energy output, radius, age, and even predicted neutrino output, or "neutrino flux". In recent years, however, it has been discovered that the neutrino flux predicted by the Standard Solar Model is inconsistent with values that we obtain through observation. The phenomenon developed to explain this inconsistency is known as "neutrino oscillation". This theory predicts that neutrinos have, at any given moment, a chance to oscillate to another form of matter, which therefore renders them invisible to detectors built to detect only a certain type of matter.

Because neutrinos are produced by nuclear reactions, they can effectively be produced by nuclear power plants. Neutrinos produced in this fashion are qualitatively different from solar neutrinos, because of the method of nuclear reaction involved. Such neutrinos are actually anti-neutrinos, which share many of the traits of normal neutrinos, and allow scientists to have a more controlled source from which to study neutrino interaction.

Several collaborative efforts have been made to study neutrino phenomena. One of the most promising of these is the KamLAND project. KamLAND stands for Kamioka Liquid-Scintillator Anti-Neutrino Detector. It is located on the main island of Honshu, Japan, and is buried deep inside Mt. Ikenoyama. This location places the detector in a prime location for detecting anti-neutrinos, because it places the detector within 150-200 km from the majority of Japan's nuclear reactors. It operates as a low energy anti-neutrino detector on a scale of 1.8 MeV to approximately 10 MeV. It is capable of precise anti-neutrino flux measurements originating from the surrounding reactors, and can also detect beryllium-7 and boron-8 solar neutrino events. This in turn increases the possibility of detecting neutrino oscillation.

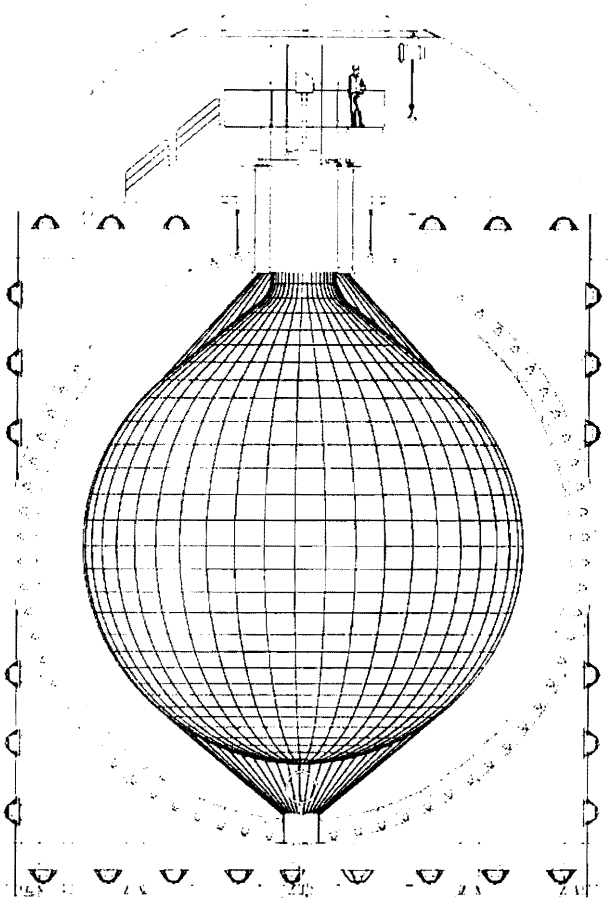


Fig. 1

Figure 1 is a side view of the KamLAND detector. The detector is dominated by a centrally located scintillator-filled balloon. This location is where the actual reactions between neutrinos and the scintillator take place. Around the balloon, arranged in a sphere, are a series of photomultiplier tubes, or “PMTs”, which detect light coming from the balloon, amplify the signals generated by the light, and send these signals to a computer.

The process of detection involves two stages of signal emission. Upon entering the liquid scintillator, the anti-neutrino may be captured by a proton, resulting in a neutron and a positron. The positron is quickly annihilated, yielding two gamma rays at 511 keV each. These represent the first signals picked up by the PMTs from a given reaction. Meanwhile, the neutron is thermalized, encountering a proton and emitting a gamma ray at approximately 2.2 MeV. These gamma rays are detected by the PMTs and registered in the computer. The time delay between the gamma rays from positron annihilation and that of the neutron-proton interaction is a distinctive signature occurring only during anti-neutrino reactions. By making sure that this time delay is in evidence, the computer is able to determine that it has truly witnessed an anti-neutrino reaction.

The KamLAND detector is also able to detect solar neutrinos, though with far less accuracy. This limitation is due to the nature of the solar neutrino reaction in the detector, which is a single ionization event and generates only a single signal, making it very hard to detect among background signals. Scientists at KamLAND persist in studying these neutrinos, however, because of their value in directly measuring solar neutrino flux.

Background signals are a big problem in such a sensitive instrument as the Kamioka detector and have many contributors. Cosmic ray muons release enormous amounts of energy when they enter the liquid scintillator. Additionally, the natural radioactivity of the surrounding environment can contribute false signals. The KamLAND detector is reasonably protected from cosmic rays by the mountain. Additional protection is afforded by a veto counter system, which consists of a layer of ultra-pure water surrounding the scintillator balloon and monitored by additional PMTs. These PMTs detect the Cherenkov light emitted when a muon passes through the water. When this light is detected, the computer knows to filter out the corresponding large signal generated within the scintillator. However, the natural radiation of both the surrounding rock and the material of the detector itself generate a background that is more difficult to filter.

The low interaction rates of neutrinos with more ordinary matter makes them very hard to detect, even with such a sophisticated detector as the one at KamLAND. Even with roughly trillions of neutrinos passing through the detector every second, the detector only manages roughly 2 events per day, with an average of .7 background signals per day. With so few detectable signals to work with, it is necessary to make sure each signal is detected and measured as precisely as possible.

One of the contributors to error in the measurement of the signal is due to the nature of the photomultiplier tubes themselves. Photomultiplier tubes contribute several problems that necessitate extensive study and attempts at correction. My project this summer has dealt primarily with the study of the 17" and 20" photomultiplier tubes used in the KamLAND project. The balloon of the scintillator is viewed by 1879 PMTs altogether, of which 554 are 20" tubes and 1325 of which are the newer, 17" tubes. The tubes are essentially identical in their light-gathering abilities, with the 17" being somewhat more precise than the 20", though their more specific differences necessitate further study. The distinguishing measurements represent the diameter of the photomultiplier face over which light is successfully gathered.

The method by which the PMT multiplies the signal with which it is supplied is called the dynode system. Figure 2 is a cut-away of a 17" photomultiplier tube. The photocathode is a photo-emissive surface consisting of alkali metals with very low work functions, meaning that their electrons are easily liberated by passing photons. Our particular PMTs are sensitive to ultra-violet through blue light and emits only very little dark current as a background. When a photon enters the photocathode, it is absorbed and the photocathode emits a photoelectron into the interior of the PMT. The photoelectron is, in turn, focused by electrodes and passes into the dynode system. This system serves to multiply the number of photoelectrons at each subsequent dynode such that by the time the photoelectrons reach the anode, they are able to generate an interpretable signal. The amount by which the dynode system is able to magnify the photoelectron signal is known as the dynode gain. For our PMT, the gain was ~10^7.

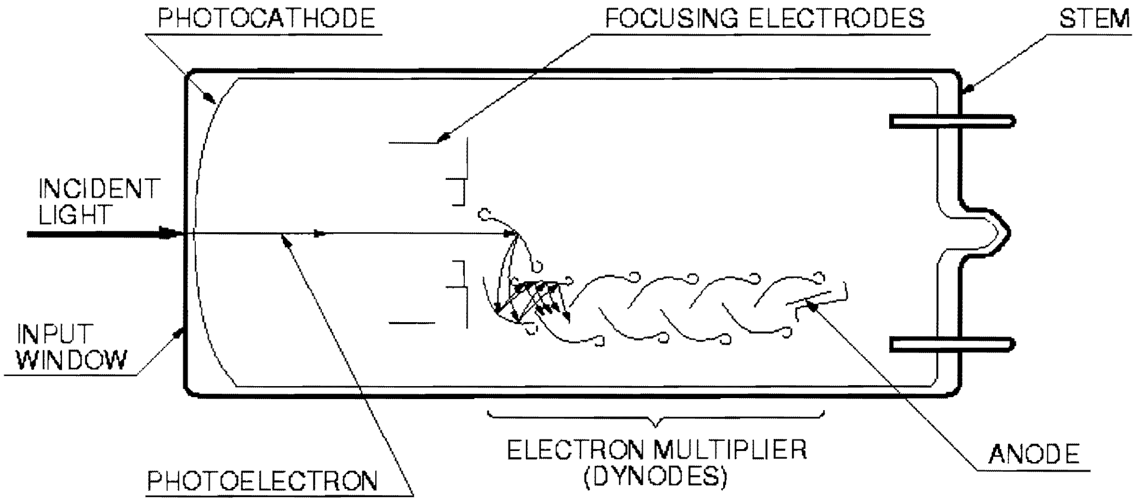


Fig. 2

A large contribution to signal error, and the main subject of my summer research, was abnormal pulsing within the photomultiplier signals. These abnormal pulses result from erratic photoelectron behavior during signal generation. The main types of abnormal pulsing include prepulsing, late-pulsing, and after-pulsing. My main data gathering focused on the effects of after-pulsing and late-pulsing, but prepulsing information is also included here for the purpose of completeness.

Prepulsing occurs when a photon passes completely through the photocathode and directly strikes the first dynode, producing a cascade of photoelectrons which then continue through the dynode system as normal. The prepulses come before the main pulse because normal photoelectrons produced at the photocathode have some drift time between the photocathode and the first dynode, whereas a prepulse photon travels from the photocathode to the first dynode at the speed of light. A diagram of what happens during prepulsing is shown in Figure 3.

After-pulses are produced by imperfections in the electric field inside the PMT. Because of these imperfections, secondary photoelectrons produced at any given dynode have some chance to travel backward through the tube and hit the dynode that generated them again, producing a new cascade of electrons that results in a new signal detected at a time separation from the original signal equal to the flight time of the errant electron. This type of after-pulsing is also called an "induced afterpulse". Figure 4 demonstrates this type of after-pulsing. The second possibility for after-pulsing can occur when photoelectrons that should hit a particular dynode, are instead completely reflected from it, travel back, and hit the dynode again, only then producing secondary photoelectrons, which continue on to the anode. This form of after-pulsing is also called a delayed pulse.

Late-pulsing is the result of gas inside the photomultiplier tube. After the initial photoelectron is produced by the photocathode, it has a chance, during its drift to the dynode system, to ionize some of the residual gas inside the PMT. The ionized molecule may then drift to the photocathode, producing new electrons which then proceed to the dynode system and generate a new signal. This process is visualized in Figure 5. Because of the time scale involved with the drift of the ionized molecule, late-pulses occur much later than the other abnormal pulse types and are harder to recognize.

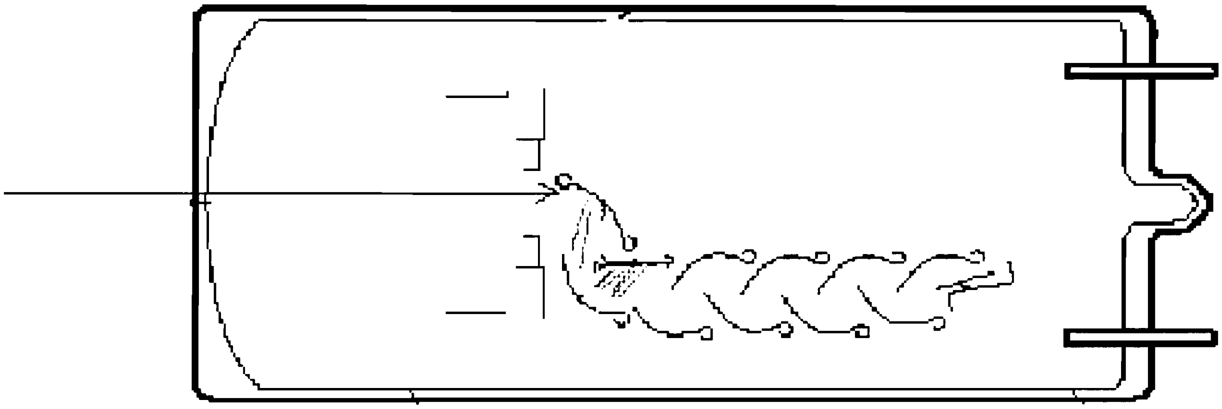


Fig 3. “Prepulsing”

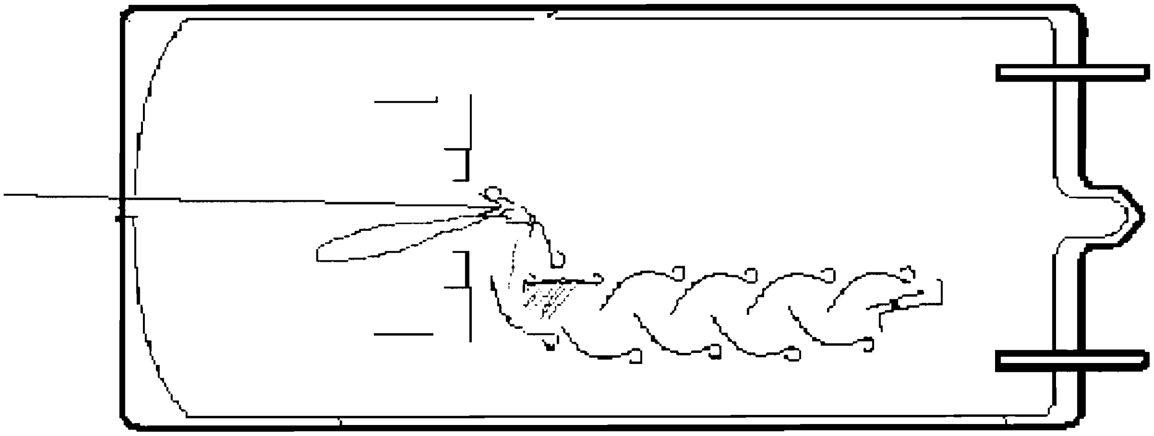


Fig. 4 “After-pulsing”

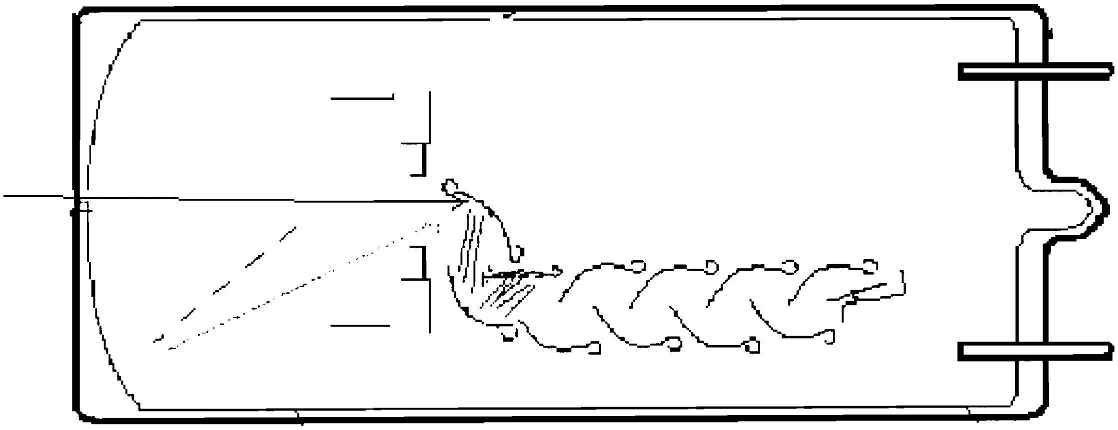


Fig. 5 “Late-pulsing”

After-pulses and late-pulses can prove a nuisance to scientists trying to study the main signal because they can overlap and distort the primary signal, or generate false positive signals, ultimately decreasing the accuracy with which scientists can detect neutrinos. If we could allow the computer to ignore these abnormal pulses or filter them out, it would have significant effect in decreasing error in neutrino detection. In addition, a continuing goal of the KamLAND project is to gather the necessary data to make an effective Monte-Carlo simulation. This would be an entirely computer-based simulation of neutrino detection that would enable us to perform experiments away from the actual detector, and may allow for experiments deemed too unwieldy, complicated, or time-consuming to be performed at the detector itself. Such a simulation, however, necessitates extremely exact data from the real detector, including an understanding of the abnormal pulsing effects.

Experiment

All of my experiments were conducted using a NIM electronics system for transmission of the LED pulse to the PMT. Data was gathered through the use of a CAMAC data acquisition system run by a computer programmed using LabVIEW software. The PMT itself sat in a covered box which prevented outside light from entering and disrupting the measurements. The PMT LED, controlled by our NIM-based electronic pulser, pulsed at a steady rate of 23 Hz. By altering the power to the LED we controlled the amount of light produced and, consequently, the number of single photoelectrons, or “SPEs”, generated. This setup enabled us to acquire data on the signal based on the number of “hits” received by the ADC/TDC system, as shown in Figure 6. The system uploaded the information as a data set to a text file that was later analyzed using a histogram generator programmed in FORTRAN. This setup served as our primary data acquisition system. Supplementing this system was an analysis of oscilloscope waveforms generated by the PMT. The oscilloscope used was the Tektronix THS730A and the images were captured using the computer-based oscilloscope program Wavestar. Wavestar data was interpreted using Microsoft Excel spreadsheets.

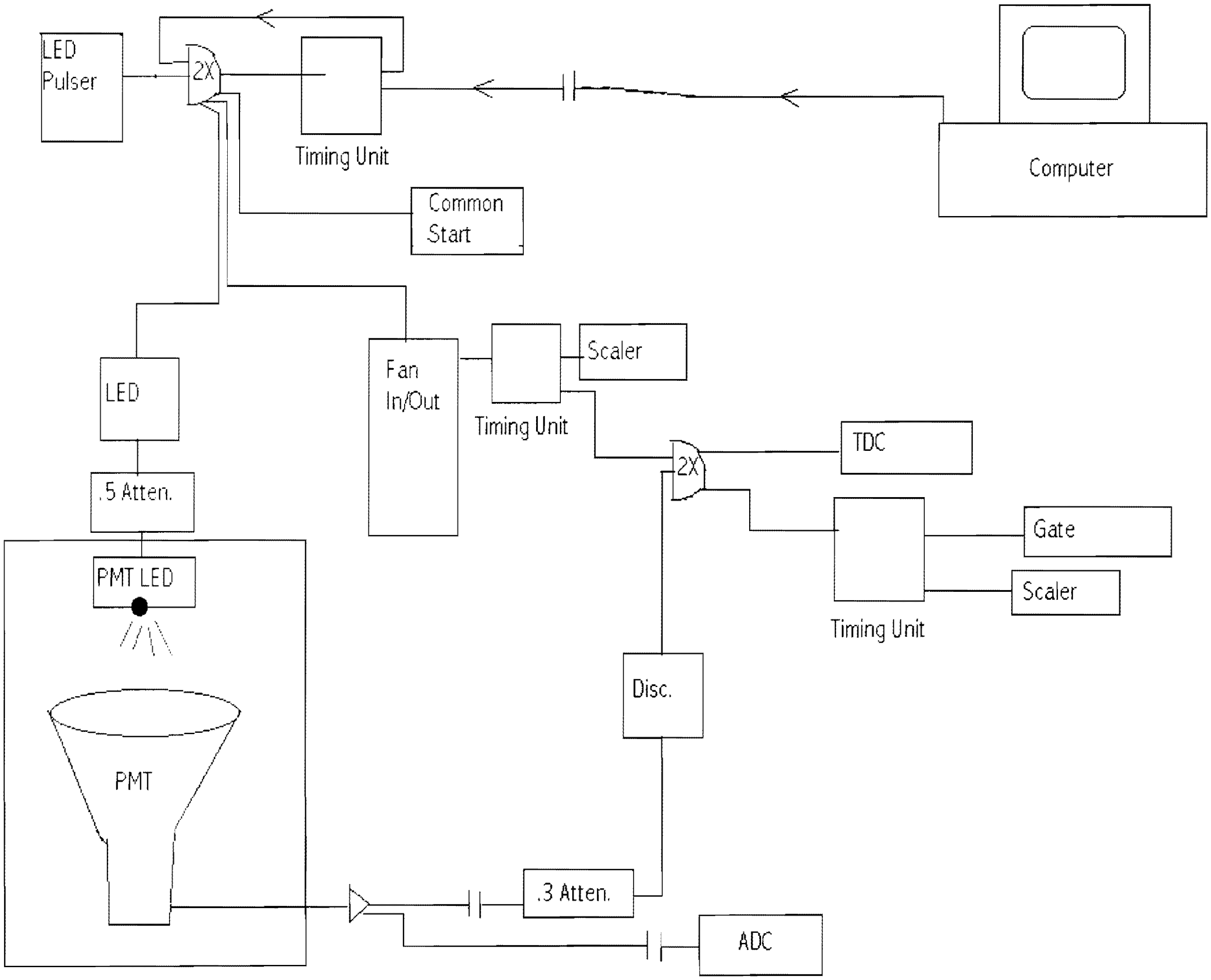


Fig. 6 "NIM/CAMAC-based Data Acquisition"

Data

The results of the experiment can be seen in the following tables and graphs. Table 1 represents those experiments performed on the 17" tube using the NIM/CAMAC system only. Table 1 has two measurements for a single photoelectron, a measurement at ~5 SPE, and one at ~10 SPE. It is important to notice that the data for the other columns represent the effect from abnormal pulsing per SPE, rather than the cumulative effect of all photoelectrons entering the tube. According to Table 1 and Graph 1, the effect of abnormal pulsing per single photoelectron remains the same, no matter the number of photoelectrons entering the tube.

An analysis of the 20" PMT provides a somewhat different conclusion. This PMT was measured primarily using the oscilloscope program. Using this system, we were able to generate images of much higher SPE concentrations, though it made it very difficult to pinpoint late-pulses and delayed pulses, and so the measurements focused primarily on the induced after-pulses. As expected, the 20" tube was less precise than the 17" and seemed to generate after-pulses much more frequently. We determined that for SPE counts of 1-10, and, to some degree, up to 100, the relationship of SPE count to after-pulse rate stayed linear, with the probability of after-pulsing per SPE staying roughly constant. However, at much higher SPE counts, the percentage began to rise per SPE, until it was over 100% per SPE! Though attempts were made to measure the PMT signals using the NIM/CAMAC system, they yielded suspicious results which we discounted. It is worth mentioning however, that these values yielded much lower percentages for after-pulse rates, than those detected using the oscilloscope method.

Table 1, Graph 1

17" Probability of Appearance of Afterpulses and Late-Pulses per SPE

Prompt LED Signal (SPE)	Delayed Prompts	Induced After-pulses	Late Pulses
1.0235	4.5	3.1	20.5
1.092	3.93	3.1	20.9
5.4	0.2	3.2	19.6
10	0	3.1	19.6

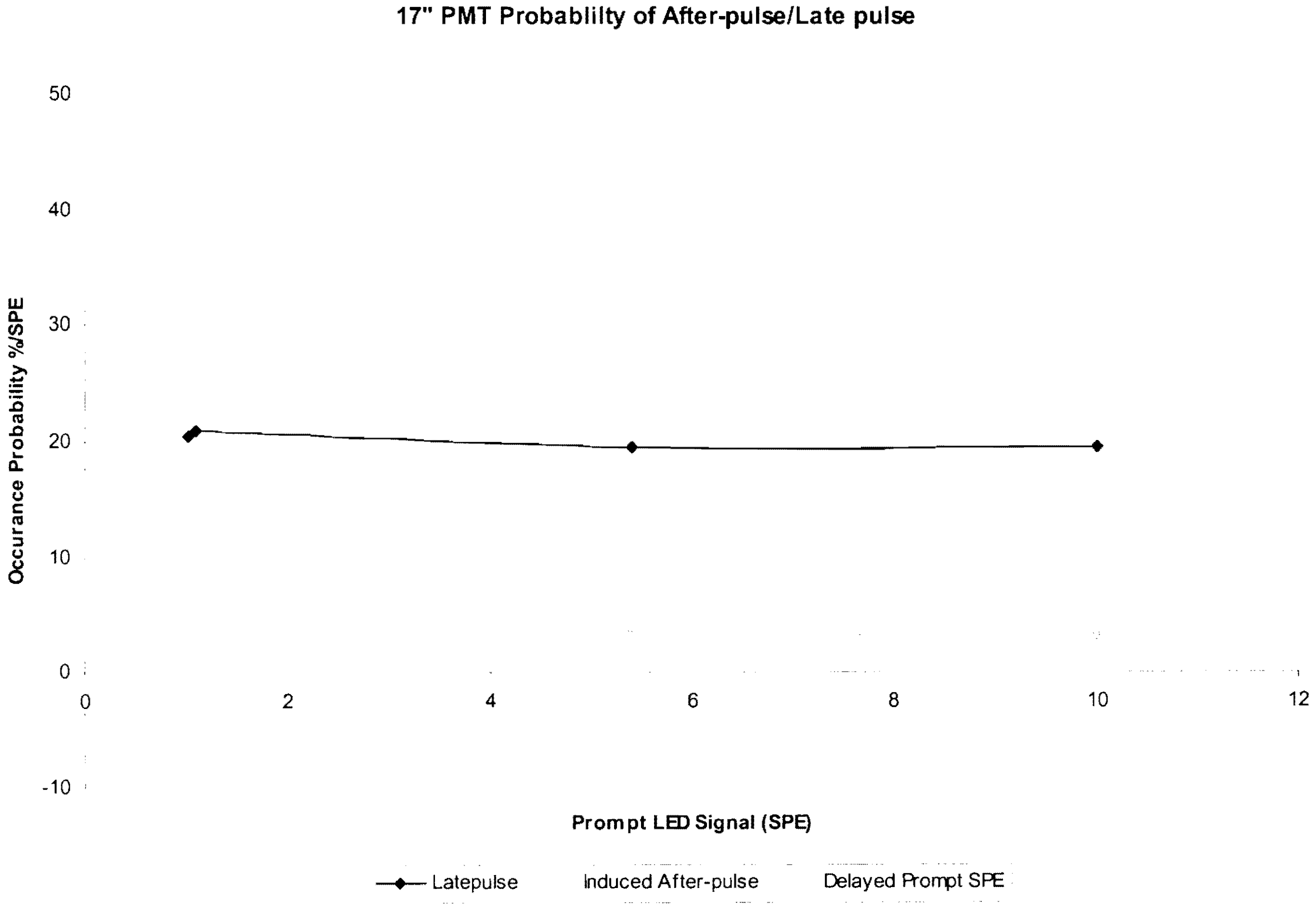
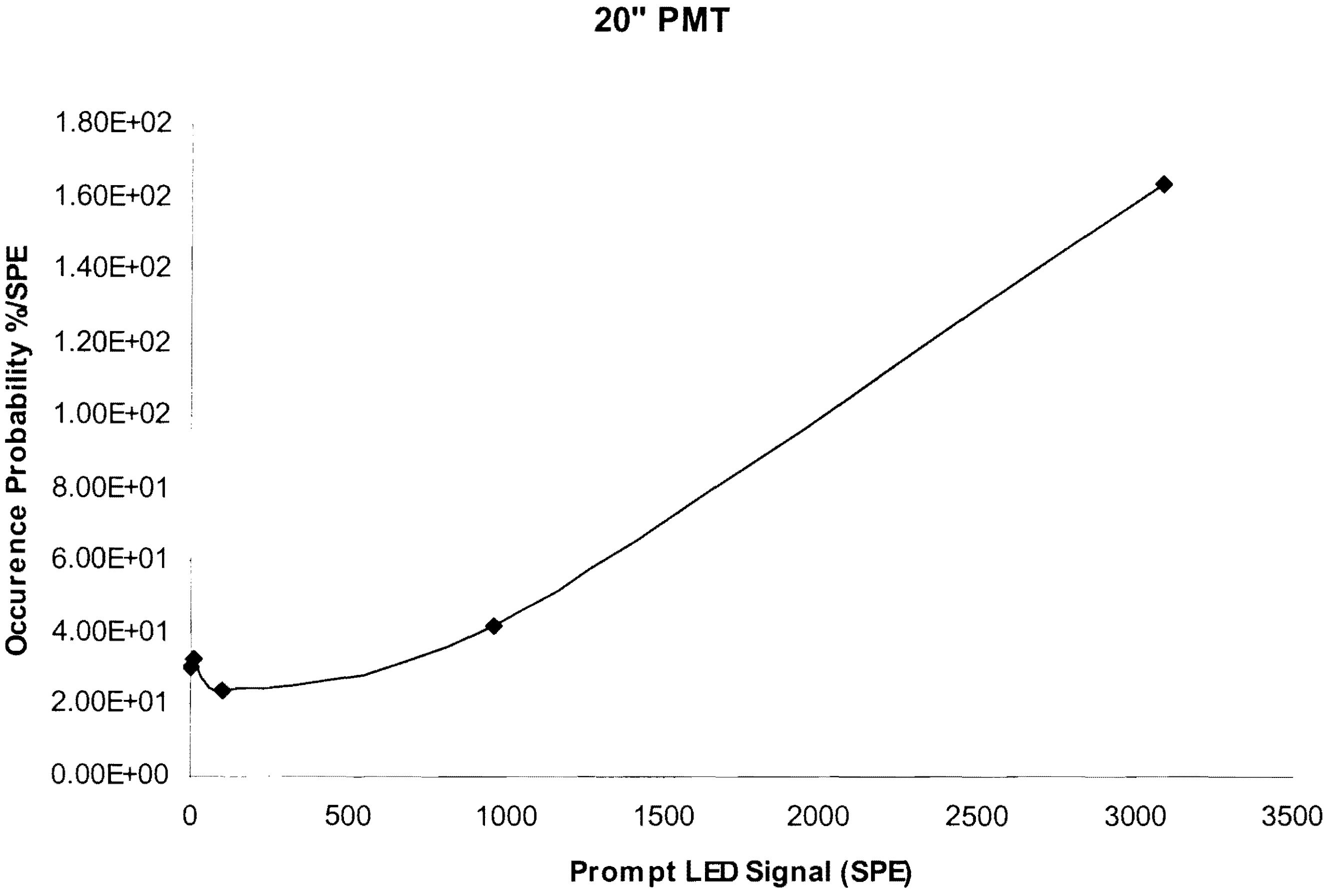


Table 2, Graph 2

20" Probability of Appearance of Afterpulses and Late-Pulses

Prompt LED Signal (SPE)	Delayed Prompts(%)	Induced After-pulses (%)	Late Pulses (%)
1.08	~	3.08E+01	~
2.16	~	30.27401783	~
5.04	~	32.9642644	~
10	~	32.4556213	~
100	~	23.82937414	~
960	~	41.93747683	~
3080	~	163.969709	~



Conclusion

In the course of our experiments, we observed a constant value for SPE contribution to after-pulsing in both the 20" and 17" PMTs for SPE counts between 1 and 10. To some degree this constant value was maintained in the 20" PMT up to a scale of ~100 SPE. After that point however, the after-pulse rate per SPE began to increase linearly, even to the point that the after-pulse signal was apparently larger than the initial signal. This suggests that perhaps after a certain SPE count, SPEs are able to create constructively interfering after-pulses, which can not only support themselves, but can grow exponentially, rendering the PMT blind to any useful signal. This theory needs to be thoroughly tested with the 17" tube as well, to determine if the effect occurs in both tubes, or if it is merely an effect of the 20" tube's construction. However, for small SPE counts, we see that both PMTs maintain a predictable, linear rate for abnormal pulsing. This linearity apparently applies to all tested forms of abnormal pulses.

This is an ongoing research project with the ultimate goal of generating a Monte-Carlo simulation of KamLAND neutrino detection. Future research will involve a thorough study of the behavior of the 17" tube at high SPE counts. Additionally, the 20" tube will be reanalyzed in order to double check the validity of our initial testing due to questionable initial data. We will also supplement our current data with new measurements taken for late-pulsing and after-pulsing in the 20" tube.

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