Increasing Acceptance in the KOTO Detector

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Abstract

The KOTO experiment is a collaboration involving the University of Chicago that intends to measure the branching ratio of the $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$. This particular decay demonstrates direct CP violation; the Standard Model provides a theoretical value for the branching ratio. However, this value is also sensitive to physics beyond the Standard Model, such as supersymmetry. By accurately measuring this value, it is possible to test the Standard Model and search for evidence of physics beyond it.

In order to accurately measure this value, it is important to measure a number of these rare decays. The current detector design only has an acceptance of 9.4%[1]; previous research has shown that by recording events incident on the side of the detector, the acceptance could be increased up to 77.3% [2]. However, these events may also veto themsevles, due to a secondary signal produced by the electromagnetic shower in the detector. A model was created of a photon incident on the side of the detector. It showed that events could indeed produce such a secondary signal; however, it also showed that this was dependant on the incident angle, and that many such events could be recouperated. Thus, this method would still provide a significant increase in acceptance for the KOTO detector.

1 KOTO Experiment

1.1 Theory

Symmetries are operations under which a system remains invariant. Charge conjugation symmetry, or C-symmetry, requires that a system remain the same if all particles are switched with their antiparticles; parity or P-symmetry requires that a system remain the same if all spatial coordinates are mirrored; time or T-symmetry requires that the system remain the same under time reversal. It has been discovered that these symmetries are not universally conserved; for example, weak interactions breaks both C- and P- symmetry. It had been proposed that all systems demonstrated CP-symmetry, that is, that if both charge and parity are switched, all systems remain the same. This was disproved in 1964 by James Cronin and Val Finch through the observation of the $K_L^0 \rightarrow \pi^+\pi^-$, a discovery which won them the Nobel Prize [4]. Because of this, it is now theorized that CPT symmetry cannot be violated; the existence of CP violation is explained in the Standard Model through a imaginary term in the CKM matrix that describes quark mixing [6].

The decay observed by Cronin and Finch shows an indirect CP violation; The $K_L^0 \rightarrow \pi^0\nu\bar{\nu}$ decay demonstrates direct CP violation. The experiment hopes to measure the branching ratio of this "golden mode" decay with a sensitivity better than 3×10^{-13}, which will allow the measurement of the imaginary term in the CKM matrix to within 5% [1]. By comparing the experimental values for the branching ratio and imaginary term of the CKM matrix with the theoretical values predicted by the Standard Model, this experiment will provide both an important test of the Standard Model and probe for the existance of physics beyond it.

1.2 Detector

The neutrinos produced in the $K_L^0 \rightarrow \pi^0\nu\bar{\nu}$ decay are, like all neutrinos, very difficult to detect. Thus, data related to the π^0 is used to examine the event. However, the π^0 itself decays very quickly; fortunately, 98.8% of these undergo the $\pi^0 \rightarrow \gamma\gamma$ decay [5]. Because of this, the detector has been designed to detect these two photons. The core of the Detector for the KOTO experiment is a tube with a diameter of 2 meters and a length of 3 meters (Fig. 1. At one end, there is a 2 meter diameter CsI calorimeter, composed of 2700 individual channels. The sides of the detector are 32 lead scintillator strips, extending lengthwise along the barrel. The CsI calorimeter is located directly behind a plastic scintillator. The CsI calorimeter exists to detect the hits of the two photons from the π^0

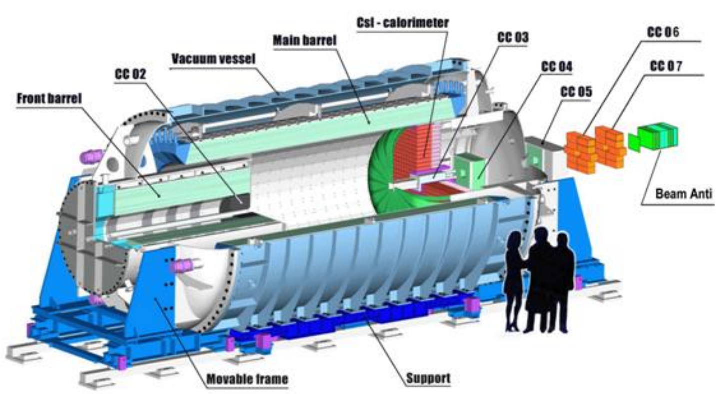

Figure 1: KOTO Detector Configuration

decay. The calorimeter is also designed to veto events where it detects more than two hits. The plastic scintillator located in front of the calorimeter is the charge veto; it will veto all events where a charged particle passes through it. The lead scintillators exist to veto events that impact the side of the chamber; any time that a particle is detected in it, it will veto the event.

1.3 Acceptance

Acceptance is defined as the number of detected events over the total number of events that occur. The current acceptance of the KOTO detector is 9.4% [1].At this acceptance, and given the infrequency of golden mode decays, it is expected that, in order to observe the more than 100 such events, the experiment will have to be run for several years.A significant number of the rejected events occur under circumstances like the one shown in Figure 2; as one of the photons produced by the π^0 decay hit the lead scintillator strips, the event was rejected. A preceding REU project was to study a method of increasing acceptance [2].

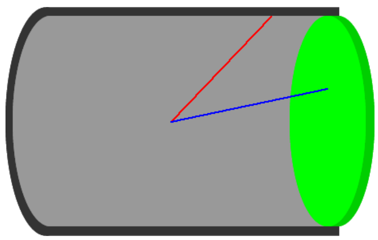

Figure 2: Event vetoed by lead scintillator

The specific method studied was the installation of a calorimeter in the barrel of the detector. This would allow the acceptance of events where one or both of the photons produced in the π^0 decay hits the side of the detector. With this addition to the detector,it was discovered that the acceptance could be raised up to 77.3% [2]. Such an increase in acceptance would significantly decrease the time necessary to record the desired number of events.

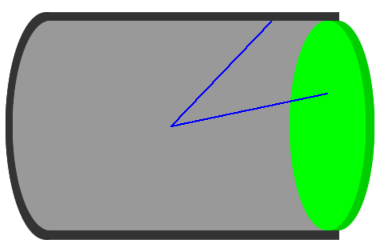

Figure 3: Event accepted due to calorimeter in side of detector

1.4 Electromagnetic Shower

When the photons interact with the material of the calorimeter, they produce an electromagnetic shower. This is occurs when an incident photon of high energy experiences the phenomena of bremsstrahlung and pair production; as the photons and e^+e^- pairs radiate and produce new pairs and photons in turn, a cascade effect occurs [6]. The energy deposited by this shower is what the calorimeter eventually reads out.

When the incident angle is near 90°, the EM shower is completely contained within the calorimeter. However, when the incident angle of the photon is shallower, the shower may not be completely contained (Fig. 4). If a photon or positron/electron produced in the EM shower hits the CsI calorimeter, then it might be register as an additional photon or charged particle, either of which would then cause the event to be vetoed.

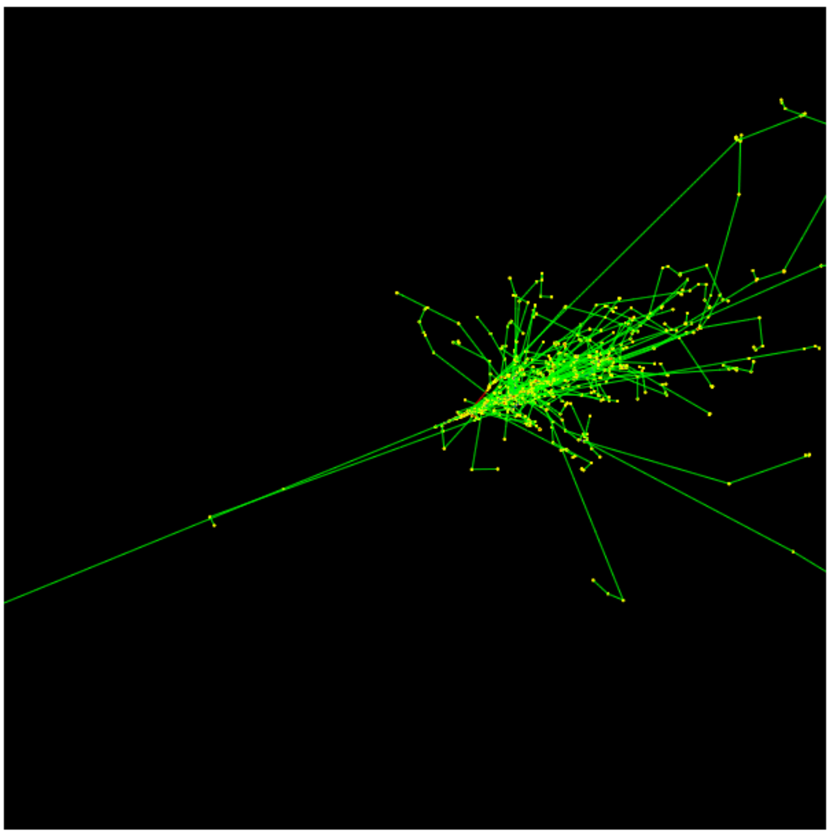

Figure 4: EM shower produced by photon incident at 30°

2 REU Project

2.1 Motivation

The objective of this project was to study the effect that secondary hits from the EM shower would have on the acceptance of the Detector. Self-veto events would necessarily reduce the acceptance; if these type of events make up a sufficiently large percentage of those produced, then the advantages of adding calorimeters in the side of the detector might be reversed. Currently, as such events are rejected under all circumstances, the EM shower problem does not exist. The possibility of using the time of flight difference between EM shower photons and ones originating in the event to recover events that would otherwise be vetoed was also studied.

2.2 Geant4 Simulation

A simulation in Geant4 was used in order to determine the effects of the EM shower [3]. A model of the detector was created using the dimensions of the current configuration of the KOTO detector, but the sides were modeled using CsI like the calorimeter in the end, rather than layered plastic and lead. The standard model for EM showers within Geant4 was used to simulate the effects being searched for.

Photons were shot at a location on the side of the detector located 1 meter away from the CsI calorimeter in the end. They had initial energies randomly selected within the 100-1000 MeV range, a representation of the photon energies likely produced in the experiment. 10,000 such events were simulated for 10-degree increments between 10° and 90°. The same angles were then studied again, with 5,000 events being run, and with the impact site moved to 2 meters away from the CsI calorimeter.

2.3 Analysis

The data produced by the Geant4 simulation was then analyzed. The initial energy of the photon was recorded, as was the energy and type of all particles that hit the CsI calorimeter in the end of the detector. The energy deposited in the end was divided into 4916 channels composed of 2.5 cm squares; Each channel was numbered, and the energy deposited in each was written out. The same was done with the detectors in the side, which were divided angularly into 32 angular components. In the subsequent analysis, 1 MeV was used as the energy cut off; any channel with less energy deposited or charged particle that did not exceed this threshold was considered to have not been detected.

The data was then run through a number of programs. The number of channels were counted per event, as was the number of charged events. The location and angles of activated channels were calculated, as was the energy-weighted average locations for each and their average radius.

3 Results

3.1 Detected Events

From the data collected from the Geant4 simulation, a number of things can be seen. The first is that not all events result in energy deposition in the end calorimeter. This means that not all events lead to a secondary signal. This is useful, because it means that it is only a percentage of the total events that can self-veto. The number and percent of events that are detected by the CsI, and thus that self-veto, can be seen in Table 1.

Angle	Events	Percent
10°	9273	92.73%
20°	7159	71.59%
30°	4845	48.45%
40°	3027	30.27%
50°	1982	19.82%
60°	1374	13.74%
70°	1000	10.00%
80°	847	8.47%
90°	700	7.00%

Table 1: Events detected by CsI calorimeter

It can be seen that, as the angle increases to 90°, the percent of events that are detected decreases. This is as expected, since a hit at a right angle to the surface should be completely contained within the calorimeter. Furthermore, in most of the incident angles, the detected events are a minority of the overall events, which means that event without recovering any self-vetoes there would still be a significant improvement in acceptance.

3.2 Charged Events

The charge veto is designed to prevent decays where charged particles are produced from being recorded. Since these charged particles have mass and will thus travel at some unfixed speed, it will be impossible to reconstruct these events using the time of flight difference. It will prove impossible to concretely determine the source of any given particle, and identify if it is from an electron/positron pair produced in the EM shower, or if it arises from some other decay. Thus, all of these events will always be vetoed.

As can be seen in Table 2, however, the number of charged events drops quite dramatically when moving upwards from 10°. Indeed, the while the percentage when compared to the detected events (those where the CsI is triggered) never falls below 2%, CsI events decrease as the angle increases. Thus, when compared to the total events run, they remain mostly under 1%. As, in almost all cases a significant majority of the events can be reconstructed, the charged particles do not pose a serious problem to the increased acceptance detector.

Angle	Charge Events	Percent(Total)	Percent (Detected)
10°	3305	33.05%	35.64%
20°	637	6.37%	8.90%
30°	206	2.06%	4.25%
40°	95	0.95%	3.14%
50°	45	0.45%	2.27%
60°	32	0.32%	2.33%
70°	21	0.21%	2.10%
80°	24	0.24%	2.83%
90°	18	0.18%	2.57%

Table 2: Events vetoed by charge veto

3.3 Distribution of Hits

We can also examine the distribution of hits in the CsI from the EM Shower. In each of Figures 5-7, the number of times that a channel was triggered over the whole 10,000 event run is shown. The photon that strikes the wall of the chamber occurs one meter above the end of the positive x-axis. It can be seen that, while there are hits scattered about the entire CsI, these events are concentrated around that point, moving slightly inwards as the angle of incidence increases. From the distribution, we can see that there is no one location where the hits from a given event are more likely to occur than others; thus, the location of a hit cannot be used as a selection criteria for identifying events that come from an EM shower.

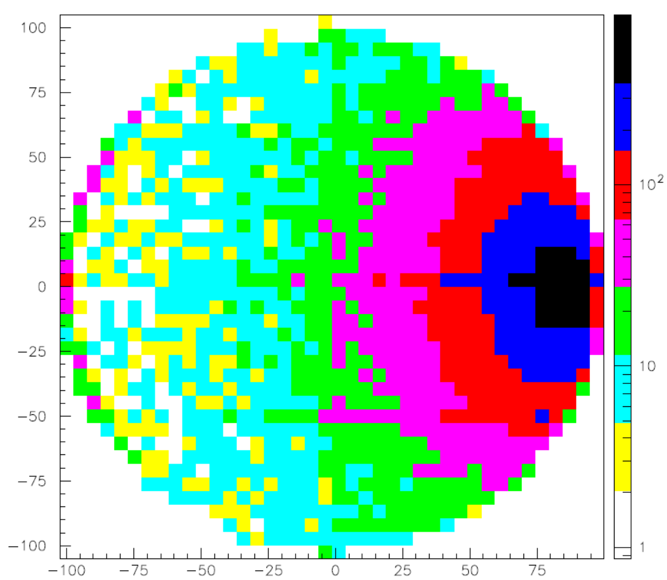

Figure 5: Triggered Channels, 10°

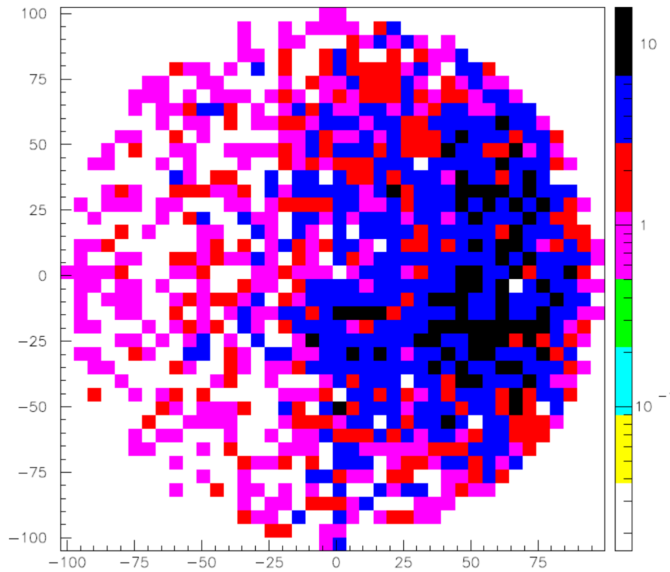

Figure 6: Triggered Channels, 50°

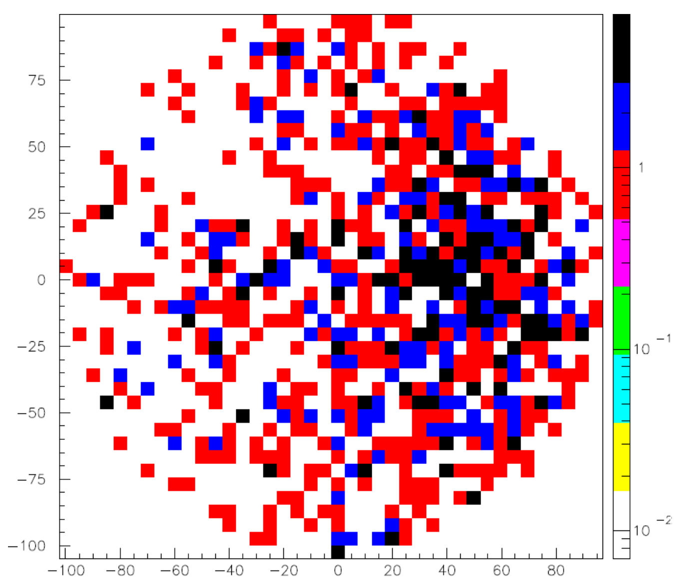

Figure 7: Triggered Channels, 80°

3.4 Time of Flight Difference

Geometry, however, gives us a method to differentiate between events caused by a decay, and those from an EM Shower. It is save to assume that the decays that are observed by the detector occur within the beam of K_L^0 in the center of a detector. From this and the location of any side and CsI hit, we can draw a triangle, as seen in Figure 8. Any photon originating in the event would follow a path along the side labeled "c". A photon from the EM shower, however, would have to follow a path along sides "a" and "b". Since this is a triangle, we know that $a + b > c$. As all photons will be traveling at c, the speed of light in a vacuum, this difference in path length will also be seen as a difference in time of flight.

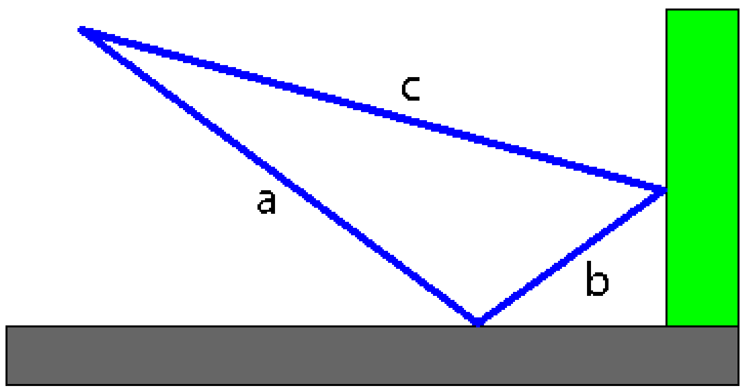

Figure 8: Triangle

This difference in can be seen in the histograms in Figure 9. It is important to note that all of these differences in time of flight exceed 0.2 ns, or 200 picoseconds. Since this is true, it will be possible to identify these events using the hardware in the detector. This is because the timing resolution of the detector is expected to be better than 200 picoseconds. While it will be impossible to use this method on charged particles, it will be possible to use the difference in time of flight to identify photons produced in an EM shower and ignore them, thus greatly increasing acceptance.

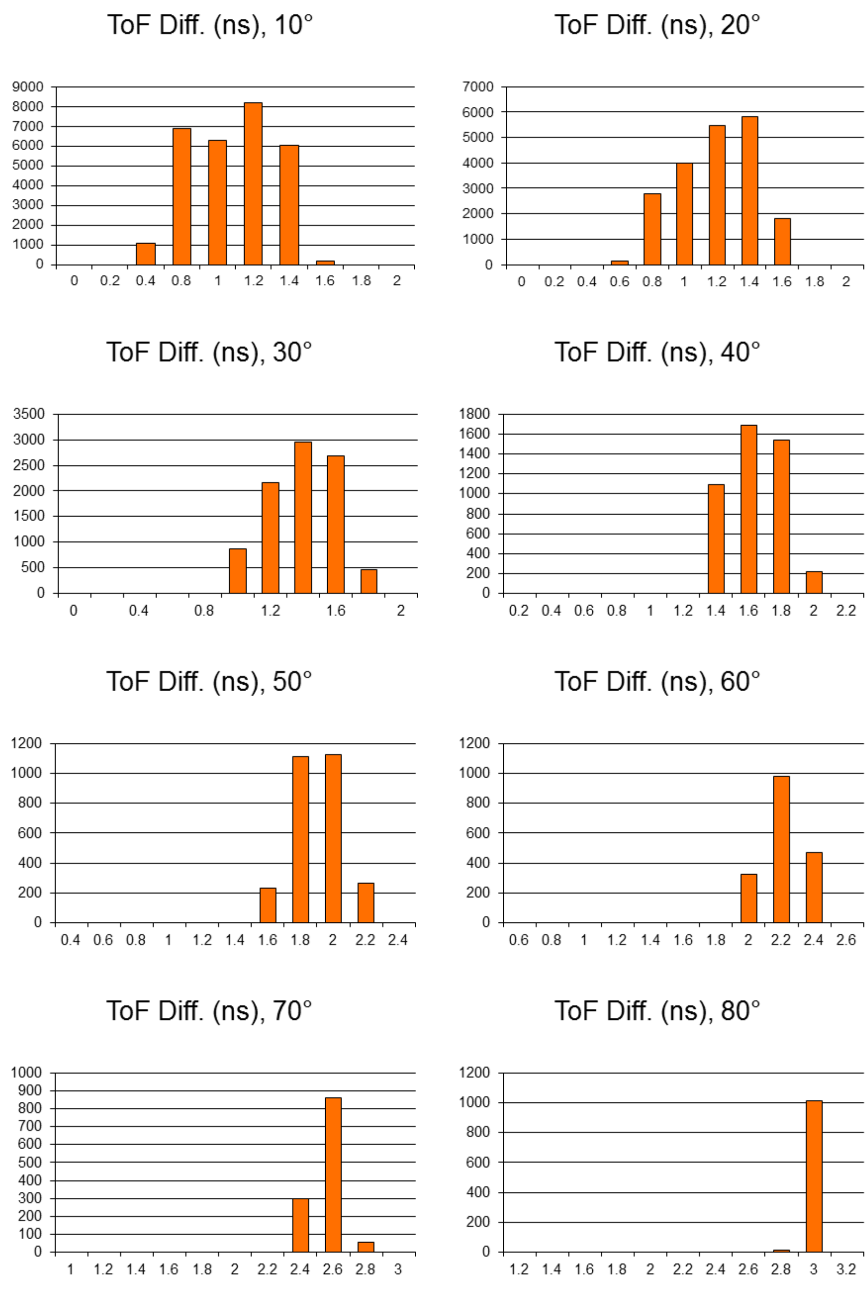

Figure 9: Time of Flight Difference

4 Conclusion

Using this simulation of the effects of an EM shower, it has been determined that the secondary hits in the CsI would not eliminate the increases in acceptance provided by detectors in the barrel. Furthermore, it has been shown that the difference in time of flight can be used to distinguish between EM shower events and original decay events in the CsI calorimeter, as long as the particles in question are photons. If we were to take the distribution of incident angles as flat across the angle studied, then we would only loose 4.87% of all events to charge veto, or, 95.13% of all events would be valid.

A linear distribution of angles, however, is extremely unlikely. In order to specifically determine the acceptance of this detector, further research is necessary. Future simulation should explore the acceptance of the detector using the actual decays of the K_L to determine the distribution of incident photon angles. Furthermore, it is necessary to determine the ideal z-resolution of the new calorimeters in the barrel of the detector.

Using this admittedly unlikely angular distribution, and the distribution of probabilities in [2], a new acceptance can be calculated. Given the results of the EM shower simulation, the detector has an acceptance of 64.5%, still a significant improvement over the 9.6% of the current KOTO Detector. Such an improvement to the existing detector would significantly decrease the runtime necessary to record sufficent events.

References

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