Designing a High Acceptance Detector for a CP Violation Experiment

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Abstract

A collaboration of universities including The University of Chicago is in the middle of an experiment to measure the branching ratio of the $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ decay. This rare decay is being studied because it is a direct violation of charge conjugate and parity symmetry, and the branching ratio is precisely predicted by the Standard Model. If the branching ratio measured by this experiment is significantly less than or greater than the predicted ratio, then the Standard Model is wrong.

The neutral pion created by this decay immediately decays into two photons, and the detector measures the position and energy of these photons. However, the current detector for this experiment has a small efficiency because the barrel of the detector is not able to detect individual photons as signal. A simulation was created in GEANT3 to model this decay, and an analysis program analyzed 10,000 events to calculate the acceptance with the improved detector as compared to the acceptance using the current detector. As hypothesized, the acceptance increased substantially with the improvements to the detector.

1 Introduction

1.1 CP Violations

Symmetries are operations to a system under which the system remains unchanged. In the Standard Model all physical systems must obey the CPT theorem, which states that CPT symmetry must be preserved. CPT symmetry requires that a physical system must remain unchanged under the simultaneous inversion of charge, parity, and time. Each of these operations is a symmetry in its own right. Under charge symmetry a system remains unchanged when an antiparticle is exchanged for a particle. Parity symmetry requires a system to remain the same when a particle is exchanged with an identical mirror image particle. Time symmetry is obeyed when a system remains invariant under the forward and backward flow of time. Although once thought to be universal symmetries, weak interactions have been directly observed to violate parity symmetry since 1955. In 1964 James W. Cronin and Val L. Fitch observed the rare $K_L^0 \rightarrow \pi^+ \pi^-$. Because this decay is prohibited by CP symmetry, its observation implies a simultaneous violation of charge and parity symmetry[1]. In 1980 Cronin and Fitch won the Nobel Prize for their discovery[2]. This discovery allows for the postulation that T-symmetry is not universal, because CPT symmetry cannot be violated. However, there is not direct observation of this phenomenon.

There have been many experiments since then to study CP violations. In 2001, CP violations in the decay of B mesons were observed[3]. Currently Arizona State University, The University of Chicago, Dzhelepov Laboratory of Nuclear Problems, High Energy Accelerator Research Organization, Kyoto University, National Defense Academy, National Taiwan University, Osaka University, Pusan National University, Saga University, Tbilisi State University, TRIUMF, and Yamagata University have formed an collaboration to directly observe CP violations through the rare $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$.

1.2 Kaon Long Decay Modes

The decay modes of the Kaon-Long particle are the focus of this experiment. The most prevalent of which are $K_L^0 \rightarrow \pi^\pm e^\mp \nu_e$ with a branching ratio of 38.78 ± 0.28 %, $K_L^0 \rightarrow \pi^\pm \mu^\mp \nu_\mu$ with a branching ratio of 27.18 ± 0.25 %, $K_L^0 \rightarrow \pi^0 \pi^0 \pi^0$ with a branching ratio of 21.13 ± 0.27%, and $K_L^0 \rightarrow \pi^+ \pi^- \pi^0$ with a branching ratio of 12.55 ± 0.20 %. Another important K-long decay mode is $K_L^0 \rightarrow \pi^0 \pi^0$ with a branching ratio on the order of 10^{-3} [4]. The decay that is being studied in this experiment is the "Golden Mode Decay," $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$, which exhibits CP symmetry. The branching ratio of this decay is $2.8 \pm 0.4 \times 10^{-11}$ as predicted by the Standard Model. Since CP violations have already been directly observed, the main goal of this experiment is measuring the branching ratio within 10% accuracy[5]. If the measured branching ratio is significantly less than or greater than the above prediction, the Standard Model is not an adequate theory for describing the interactions of subatomic particles.

2 Experimental Setup

2.1 CPV Experimental Setup

In order to produce the K-Long particles, protons are shot at a platinum target. When the proton hits the platinum nucleus, a shower of particles is produced. These particles are deflected 16°, due to space limitations in the experimental hall. Figure 1 shows the layout of the beamline. Collimators are used to focus the beam into a narrow "pencil beam"[6].

[1] James W. Cronin, *Science New Series*, 122 (1981)
[2] Gloria B. Lubkin, *Phys. Today*, 17 (1980)
[3] Phil Schewe, James Riordon, and Ben Stein, *Am. Institute of Phys. News Update*, 547 (2001)
[4] *European Physical Journal*, 514 (2000)
[5] *Proposal for KL → π0vv Experiment at J-Parc*, 5 (2006)
[6] *Proposal for KL → π0vv Experiment at J-Parc*, 23 (2006)

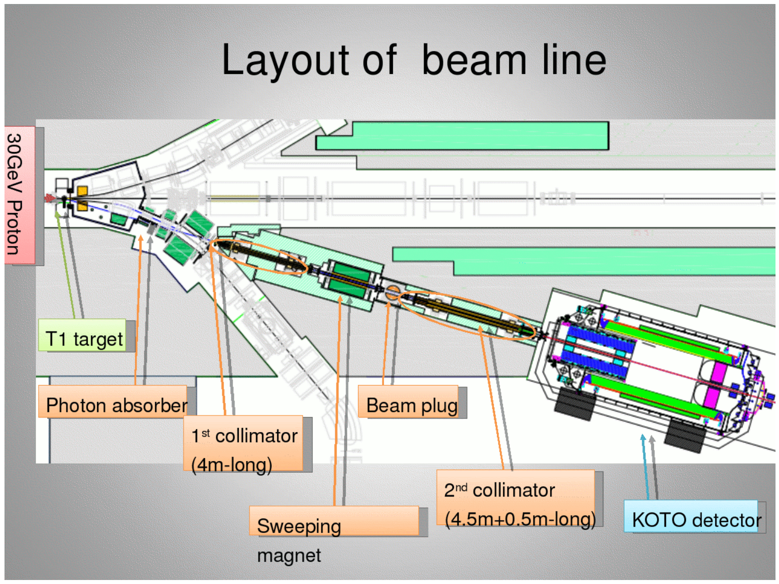

Figure 1: Layout of the beam line

The K-Long beam is focused into the detector, where each K-Long particle decays. Figure 2 shows a diagram of the detector. Each K-Long particle decay is an event. In this experiment only the K-Long particle decay into a neutral pion, neutrino and anti-neutrino is of interest. Neutral pions immediately decay into two photons, so a Golden Mode Decay will be identified by the detection of two photons and no other particles.

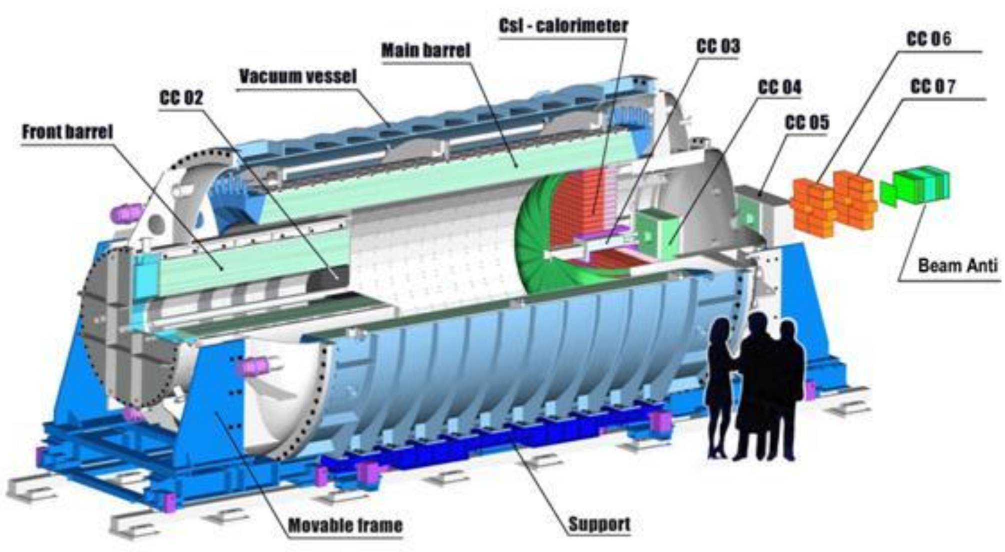

Figure 2: Diagram of the CPV Detector

All other events in which the K-Long particle does not decay in the Golden Mode can be rejected by various elements of detector. The other K-long decay modes either result in a charged particle or more than one neutral pion. The main barrel of the detector is a lead scintillator, which can detect both photons and charged particles. The end of the main barrel, a cesium iodide (CsI) calorimeter, can detect photons, and two layers of plastic scintillator covering the CsI can detect charged particles. If these elements detect a charged particle, that event is rejected. If these elements detect more than two photons, that event is rejected.

The lead scintillator is assembled in long strips that are the entire length of the detector (refer to Figure 3). This makes it impossible for one section of the scintillator to distinguish between a photon that hit at one end of the barrel and one that hits at the other end. Therefore, all events in which photons hit the sides of the detector are rejected, due to the inability to know exactly how many photons were produced in that event.

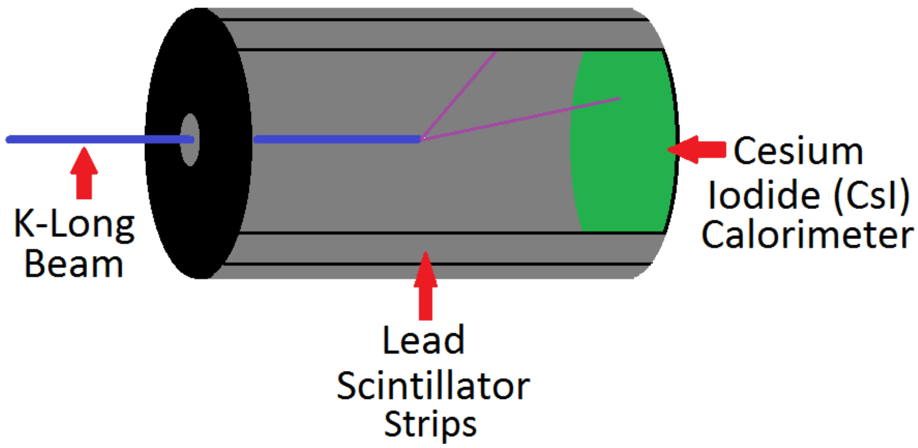

Figure 3: Schematic diagram of the main barrel of the detector. This diagram shows the CsI calorimeter and the lead scintillator. Notice that the lead scintilator is assembled in long strips.

The CsI calorimeter is constructed of 2,700 square CsI crystals. These crystals can accurately measure the position and energy of photons. Because there are so many crystals, the energy and position of each individual photons can be detected[7]. In order to detect photons that escape down the hole of the detector, several collar counters (CC04, CC05, and CC06) as well as the Beam Hole Veto counters (BHCV and BHPV) are placed downstream of the calorimeter as shown in Figure 2[8].

The amount of Golden Mode Decays that are detected is measured by acceptance. Acceptance is the number of accepted events—the number of events in which only two photons are detected—over the total number of events.

2.2 GEANT3 Simulation

In order to calculate the acceptance of a detector in which the main barrel can also measure the position and energy of individual photons, GEANT3[9] is used to simulate the geometry and kinetics of the above experimental setup.

The main barrel is specified to be 5.2 meters long and 2 meters tall. The K-Long beam enters through a 6 centimeter diameter hole in the front and exits through a 20 centimeter diameter hole in the CsI. The K-Long beam decays in a 2 meter region inside the detector. Figure 4 shows the geometry of the detector as simulated by GEANT3.

[7] *Proposal for KL → π0νν Experiment at J-Parc*, 40 (2006)
[8] *Proposal for KL → π0νν Experiment at J-Parc*, 27 (2006)
[9] CERN (1993)

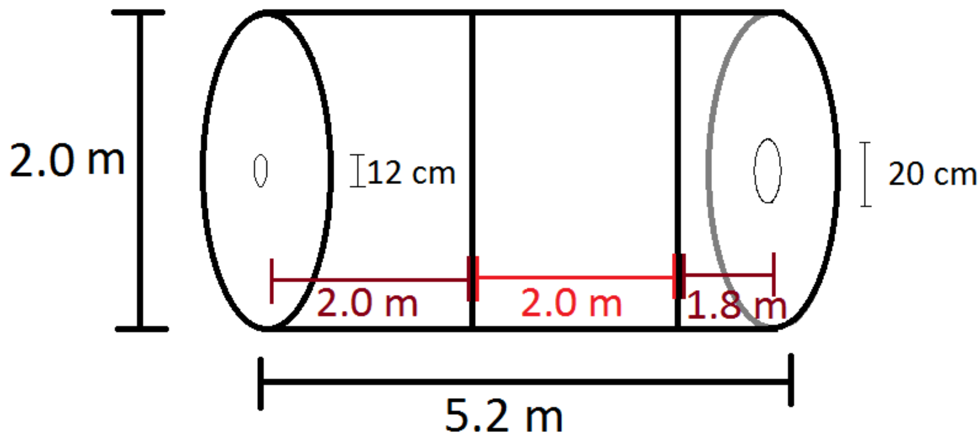

Figure 4: Schematic diagram of the geometry of the detector as simulated in GEANT3. The bright red region is the area in which the K-Long particle is allowed to decay.

The kinetic properties of the incoming K-Long beam are specified in GEANT3. The K-Long beam is simulated to decay in the Golden Mode with a momentum distribution shown in Figure 5. The peak momentum is around 0.6 GeV/c.

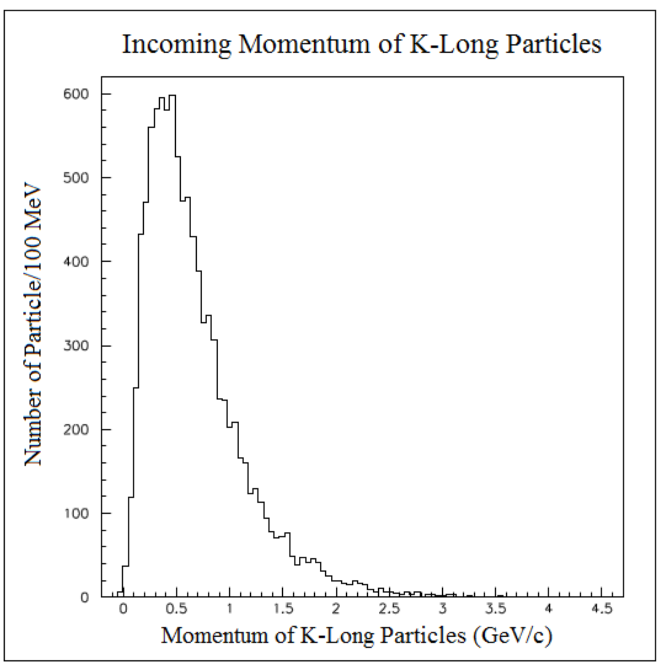

Figure 5: Incoming K-Long beam momentum distribution

The vertex at which each particle decays follows an exponential distribution. The lifetime of the K-long particle is very long, so distance over which it decays is very large. Figure 6 shows the distribution of the K-Long beam over 700 meters. However, the distance over which the K-Long particle decays in the detector is only two meters. Therefore, the distribution over this distance appears to be flat as seen in Figure 7.

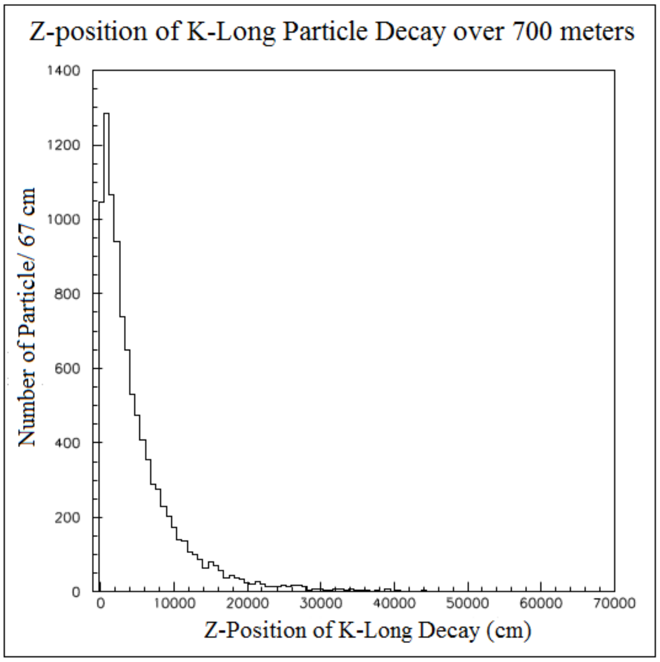

Figure 6: Distribution of K-Long particle decay vertex over 700 m

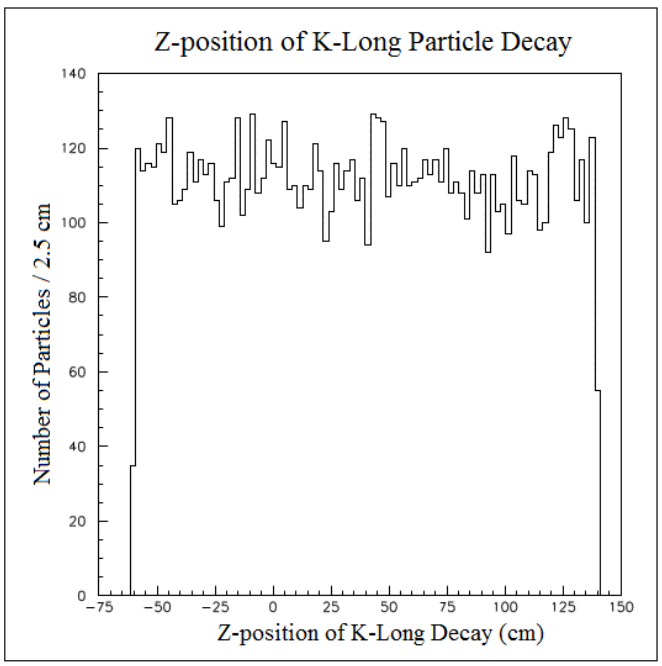

Figure 7: Distribution of K-Long particle decay vertex over 2 m

2.3 Analysis Program

An analysis program was created to analyze the data produced by the GEANT3 simulation. This program examines each event to ascertain whether the neutral pion decayed into two photons. A neutral pion will decay into a photon, an electron, and a positron 1.2% of the time. The program also determines if these two photons hit anywhere on the detector, if the two photons hit more than 15 cm apart, and if both photons had an energy over 50 MeV. All the events that met these requirements were accepted. The number of accepted events is divided by the total number of events to calculate the acceptance. The acceptance in the whole detector is compared to the acceptance of events in which both photons hit the CsI. In order for an event to be accepted by the CsI detector, an event had to meet all the above conditions as well as both photons had to hit the CsI within an 80 centimeter radius.

2.4 Background

Events that decay in modes other than $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ are considered background, and sometime these events can be detected as the Golden Mode Decay. The $K_L^0 \rightarrow \pi^0 \pi^0$ results in a four photon signal. If two of these photons are to leave through the hole at the end of the detector or if the photons are to land too closely to each other, then the detector will only record the position and energy of two photons. The branching ratio for this decay is on the order of 10^{-3}, which is 10^8 times more likely to happen then the Golden Mode Decay. In order to measure this background a new GEANT3 simulation was set up. This simulation was almost identical to original program except that instead of decaying in the Golden Mode, the K-Long particles decayed into two neutral pions. The geometry of the detector was also slightly altered; the hole in the CsI calorimeter was closed.

An analysis program was created to calculate the background from this particular decay. This program handles four different situations: four photons hitting the detector, three photons hitting the detector, two photons hitting the detector, and one photon hitting the detector. If four photons hit the detector, the program determines which two photons have the lowest energies. An inefficiency function shown in Equation 1 calculates the inefficiency of the detector to measure background estimations for each low energy photon. The inefficiency values for the two low energy photons in each event are multiplied together to give an inefficiency value for the event.

$$f = \begin{cases} 1 & (E < 1.4\ MeV) \\ 3.54 \times 10^{-7} * E^{-2.23} & (1.4\ MeV < E < 2.0\ GeV) \\ 7.30 \times 10^{-8} & (2.0\ GeV < E) \end{cases}$$

Equation 1: The inefficiency equation is a stepwise function. If the energy of the photon is less than 1.4 MeV, then the detector is completely inefficient at measuring the background. If the energy of the photon is higher than 2 GeV, then the inefficiency of the detector is a constant and very small value. This inefficiency function determines the inefficiency of a CsI calorimeter. However, it is being used for the whole detector because an inefficiency function for the lead scintillator has not yet been determined[10].

If any two of the four photons that hit the detector land within five centimeters of each other, the two close photons are assigned a fusion probability. Two photons are considered to be fused if the detector cannot distinguish between them. Consequently, the detector records their position and energy as one photon. Equation 2 calculates the probability of two photons appearing as one.

[10] *Proposal for KL → π0νν Experiment at J-Parc*, 89 eq 6 (2006)

$$f = \begin{cases} 1 & (d < 1.5\ cm) \\ -0.475 * d + 1.7125 & (1.5\ cm < d < 3.5\ cm) \\ -0.0333 * d + 0.1667 & (3.5\ cm < d < 5\ cm) \end{cases}$$

Equation 2: The probability function for two photons being fused comes from the fit for a graph that plots data from a Monte Carlo study of fusion probability as a function of distance[11].

Once this fusing probability is assigned to the photons, a random number between zero and one is drawn. If this random number is less than the fusing probability, the two photons will appear to the detector as one photon. The energy of this photon is the sum of the energies of the two photons that hit close together. Because two photons have been fused, the detector only records the energy of three photons: the energies of the two photons that hit far apart and the combined energy of the photons that hit close together. The two lowest energies of these three photons are found. Equation 1 calculates the inefficiency value for these two photons. The product of the inefficiencies is the inefficiency value for that event.

The analysis program next considers any event in which three photons hit the detector and one escapes through the hole. The program determines the energy of the lowest energy photon that hits the detector. An inefficiency value is calculated for this photon by Equation 1. The hole in the CsI was closed so that the radius of the photon that escapes can be recorded. As mentioned above in section 2.1 there are five detectors located beyond the CsI. These detectors will record the position and energy of any photons that exits the hole in the CsI. When the escaped photon hits the CsI detector within a five centimeter radius, in reality (if the hole in the CsI was there) these photons will hit a detector downstream of the CsI that has an inefficiency function calculated by Equation 3.

$$f = 10^{-3} + e^{-6.9*E}$$

Equation 3: Inefficiency function for photons that hit a detector downstream of the CsI

When the photon hits the CsI at a radius between five and ten centimeters, in actuality the photons will hit a detector with an inefficiency function calculated by Equation 4.

$$f = \begin{cases} 1 & E < 0.5\ MeV \\ p_1 e^{p_2 * E} & 0.5\ MeV < E < 5\ MeV \\ 4.37 * E^{-1.83} + p_3 e^{p_4 * E} & 5\ MeV < E < 2.0\ GeV \\ 1.23\ X\ 10^{-7} & 2.0\ GeV < E \end{cases}$$

Equation 4: Inefficiency function for photons that hit a detector downstream of the CsI. Values p_1, p_2, p_3, and p_4 are determined by Table 1[12].

[11] *Proposal for KL → π0vv Experiment at J-Parc*, 60 figure 37 (2006)
[12] *Proposal for KL → π0vv Experiment at J-Parc*, 89 equation 7 (2006)

θ (deg)	p_1	p_2	p_3	p_4
5	1.13	-248	0.491	-85.4
15	1.13	-238	0.645	-130
25	1.13	-245	0.729	-162
35	1.13	-249	0.784	-180
45	1.13	-251	0.822	-192
55	1.14	-253	0.845	-199
65	1.14	-255	0.861	-204
75	1.14	-256	0.869	-207
85	1.14	-256	0.873	-208

Table 1: Parameters for the inefficiency function given by Equation 4. θ is the incident angle of the photon to the detector[13].

The inefficiency value for the event is the product of the inefficiency value of the photon that escaped down the hole and the inefficiency value of the lowest energy photon that hits the detector. If two photons in the detector hit within five centimeters of each other, then the above procedure is used to determine whether the photons are fused. If the photons are fused, then their energies are summed. The lowest energy between the fused photon and the other photon that hits the detector is determined and assigned an inefficiency value calculated by Equation 1. This inefficiency value is multiplied by the inefficiency value for the photon that escaped through the hole in the CsI to determine the inefficiency value for the event.

If only one or two photons hit the detector, then the detector is completely inefficient and $f = 1$. If the event does not result in four photons, then the event will be rejected and $f = 0$. The total inefficiency for the detector measuring $K_L^0 \rightarrow \pi^0\pi^0$ is the sum of the inefficiency values for each event.

3 Results and Discussion

3.1 Acceptance

The analysis program calculated the total acceptance in the whole detector for signal to be 77.30%, while the acceptance at the CsI was 27.78%. Improving the barrel of the detector increased the acceptance. However, the calculated acceptance at the CsI is much higher than in previous simulations, where it was closer to 15%. Further analysis will be performed to understand the disagreement in these calculations.

The events that were not accepted were rejected for several reasons. In some cases two photons did not hit anywhere in the detector. Table 2 shows the number of events in which two photons hit the detector, the number of events in which only one photon hits the detector, the number of events in which no photons hit the detector, and the number of events in which the neutral pion decayed into a positron and an electron.

[13] *Proposal for KL → π0νν Experiment at J-Parc*, 90 table 13 (2006)

Events in which…	Number of events	Percent of total events
…two photons hit the detector	9234	92.34%
…one photon hit the detector and the other escaped through the hole in the CsI	643	6.43%
…both photons escaped through the hole in the CsI	1	0.01%
…the neutral pion decayed into a photon, a positron, and an electron	122	1.22%

Table 2: Break down of how many photons hit the detector

Overall, 7.66% of the events were rejected because two photons did not hit the detector. In 1.22% of the events, the neutral pion decayed into a photon, an electron, and a positron, which agrees with the probability for this decay mode.

Of the accepted events in the whole detector there are three possibilities for the detection of the two photons: both photons could hit the barrel of the detector, one photon could hit the barrel and one photon could hit the CsI, or both photons could hit the CsI. Table 4 show the acceptance and reason for rejected events in each of the above cases.

	Two photons hit in the barrel	One photon hits in the barrel and one photon hits the CsI	Two photons hit at the CsI	Whole detector
Two photons hit within 15 cm	0	0	0	0
One of both photon have an energy less than 50 MeV	1504	0	0	1504
Number of accepted events	1000	3101	2778	7730
Acceptance	10%	31.01%	27.78%	77.3%

Table 3: Acceptance and reasons for rejected events when two photons hit in the barrel, one photon hits in the barrel and one photon hits at the CsI, two photons hit at the CsI, and two photons hit anywhere in the detector.

The acceptance in the middle three columns does not sum to the acceptance in whole detector because events in which both photons hit at the CsI were only accepted if both photons hit within an 80 centimeter radius.

The energies of the accepted photons are shown in Figures 8 and 9. Figure 8 shows the distribution of energies of the accepted photons that hit anywhere in the detector. Figure 9 only shows the energy distribution of accepted photons that hit the CsI.

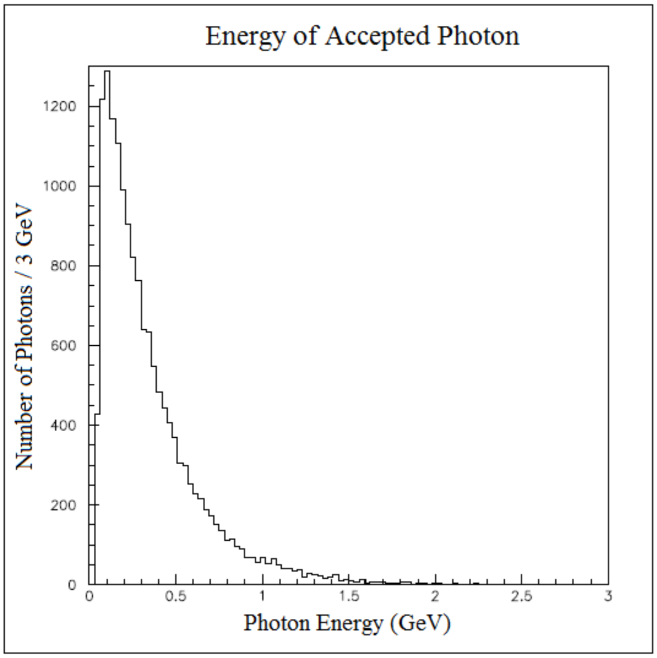

Figure 8: Energy distribution of accepted photons

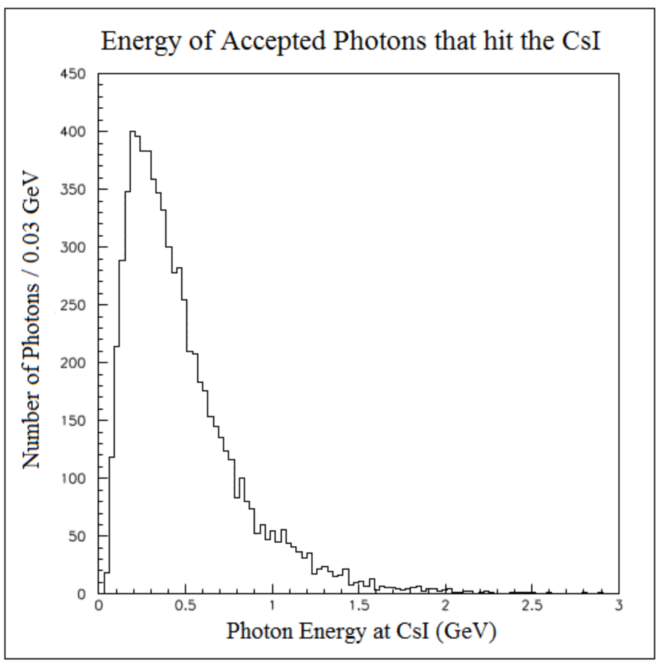

Figure 9: Energy distribution of accepted photons that hit the CsI

The distribution for the energy of photons hit in the whole detector shows a much greater number of low energy photons than the distribution for the energy of photon that only hit at the CsI. It can be inferred that low energy photons are more likely to hit the barrel of the detector than the CsI. This deduction can further be confirmed by Table 3. Only in events where both photons hit in the barrel were any events not accepted because either photon had energy less than 50 MeV. The improvement of the detector will allow for the detection of lower energy photons.

The radius of the accepted events in which both photons hit the CsI was also calculated and a distribution of the radiuses can be seen in Figure 10. In all events where the two accepted photons did not hit the CsI, the detected z-position of where the photon hit the detector was plotted in Figure 11.

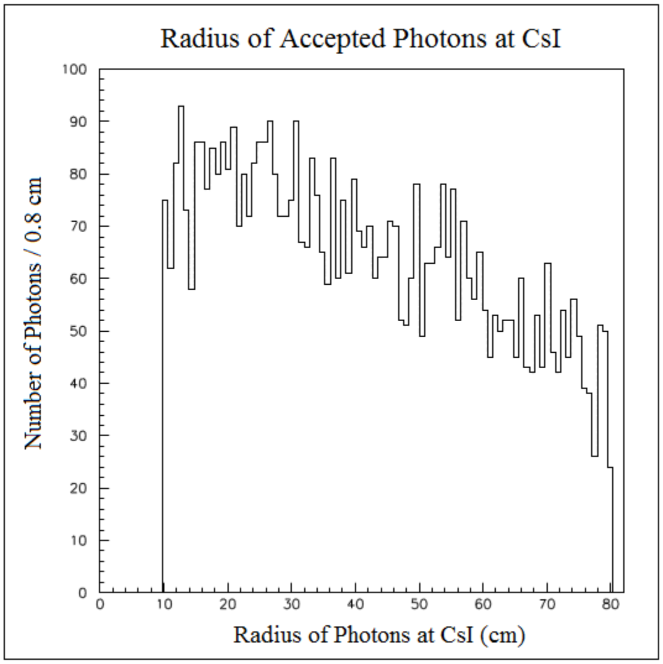

Figure 10: Radius distribution of accepted events in which both photons hit at the CsI

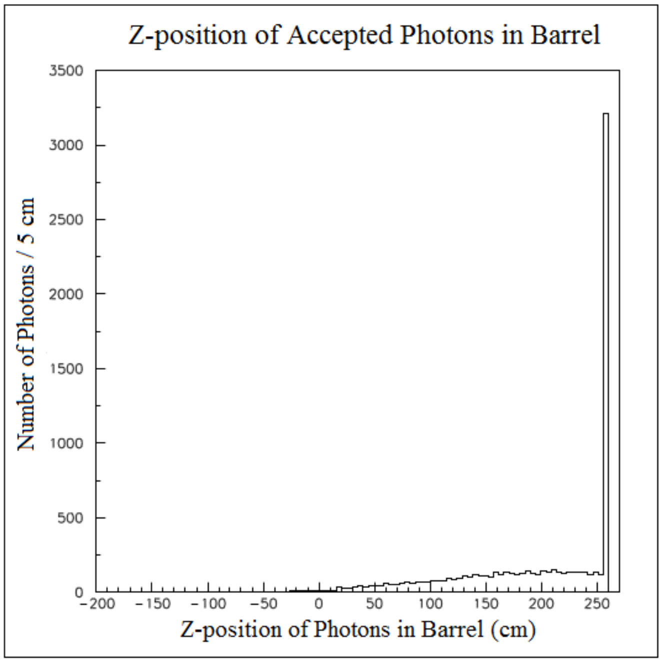

Figure 11: Distribution of the detected z-position where accepted events hit the detector. Only the accepted events in which either both photons hit the barrel or one photon hit the barrel and the other photon hit the CsI are plotted in this graph.

Many photons hit the detector at 2.6 meters as show in Figure 11. This distance corresponds to the end of the detector, which means that the photons hit at the CsI. The graph only plots photons where either both accepted photons hit in the barrel or one photon hits in the barrel and one hits at the CsI. Table 3 shows explicitly the number of events in which both photons hit in the barrel is 1000, while the number of events in which one photon hits in the barrel and the other photon hits at the CsI is 3101. The ratio these two cases of accepted events is about 1:3.

3.2 Increasing the barrel length

The barrel length of the detector was increased by three meters over two equal intervals. The corresponding acceptances in the whole detector and at the CsI are recorded in Table 4.

Barrel Length (cm)	Acceptance (Whole Detector)	Acceptance (CsI)
520	77.30%	27.78%
670	79.56%	19.30%
820	80.51%	14.81%

Table 4: Increasing the barrel length data

As the barrel is increased the acceptance in the whole detector increases and the acceptance at the CsI decrease. This is exactly what was expected. As the barrel length increases the vertex where the K-Long particles decay is further away from the CsI, so less particles make it all the way there.

3.3 Background

The analysis program for background inefficiency due to $K_L^0 \rightarrow \pi^0\pi^0$ decay calculated the background in the whole detector to be 6084.05. In comparison, if the inefficiency value for every event had been one, meaning that the detector was completely inefficient at measuring the background estimation, then the background inefficiency would be 10,000. The background inefficiency due to the same decay for the current detector that can only detect individual photons at the CsI is 9421.15. The improved detector decreased the background by about one-third.

4 Conclusion

The initial simulation of improving the detector so that the barrel can detect individual photons definitely increases the acceptance. Low energy photons are more likely to hit the barrel of the detector rather than the CsI. Improving this detector will allow for the lower energy photons to be accepted. Furthermore, currently the most common occurrence for how photons hit in the detector is one photon hits the CsI and one photon hits the detector. These events are not being accepted because both photons did not hit the CsI. However, if the detector is improved, these events will be accepted and greatly increase acceptance. Not only will the improved detector increase the signal, but the improved detector decreases inefficiency due to background. A new detector in which the main barrel is capable of detecting individual photons will greatly improve the detection of the Golden Mode Decay.