A Study of Signal/Noise Improvement of the CsI Array for the Search of Rare Kaon Decay K_L-> p^0 nu nubar

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Abstract: One method of testing the Standard Model is by determining dimensions of the unitarity triangle. The decay of k-long to pi0 nu nubar would give the height of this triangle, however, detection of this decay is very difficult due to background decay present. Using a Monte Carlo to simulate k-long to $2p^0$ to 4γ decay, the separations of the photons on the CsI array were calculated to determine the rate of single and double fusion on 7x7 cm crystals and 2.5x2.5 crystals, and found the size decrease lessened the single fusion by at least one order of magnitude and double fusion by two orders of magnitude. This has determined that the switch from the current crystals in use at KEK for those used in KTeV to be a highly beneficial effort.

Introduction:

The Cabibbo-Kobayashi-Maskawa (CKM) Matrix represents the nine transitions between any two of the quarks, three with charge +2/3 e (up, charm, and top) and three with charge -1/3 e (down, strange, and bottom). These nine constants due to the quark transitions are distinct. The imaginary part of these matrix elements forms the height of what is known as the “unitarity triangle”.

By experimentally determining the branching ratio of k-long to pi0 nu nubar, the height of the triangle, known as η, can be determined as the branching ratio is proportional to η squared. This would test the Standard Model.

The dilemma here is that this decay is predicted to have a branching ratio of $3x10^{-11}$. While a large enough sample size would make such events highly probable, detection is complicated. The only aspect of the decay seen by the detector is the two gamma particles immediately yielded from the neutral pion. A very large background, camouflaging the desired decay, is the double fusion of two gamma particles after a kaon decays into two neutral pions. This fusion occurs when two gammas hit close enough on the decay that the resultant electromagnetic showerings overlap, yielding the detection of a single photon instead of two.

A way to possibly decrease this background detected is to exchange the current CsI crystals for those used in the KTeV experiment. The KTeV experiment was the most comprehensive kaon experiment to date, and used crystals smaller in dimension. The current experiment searching for the aforementioned decay is being conducted at KEK, but the proposed new experiment would be conducted at JPARC starting in the year 2006. The current crystals at KEK are 7x7x30 cm in dimension, while those used in at KTeV are 2.5x2.5x50 cm.

Content:

In order to determine how much better the noise would be eliminated in the search for rare kaon decay by the suggested dimension reduction, a Monte Carlo simulated a k-long decaying into two neutral pions, which then decay immediately into four gamma particles, as this is the most prominent kaon background. This simulation was run initially for five different kaon momentums (1,2,3,4, and 5 GeV/c), each simulation containing **one hundred thousand** events.

For each of the one thousand events, there were six permutations of separations of the four photons. The function separation.f was written, returning the smallest of these six separations. Functions sep1.f, sep2.f, sep3.f, sep4.f, sep5.f, and sep6.f were written, returning the first permutation, the second, the third, etc., respectively. These functions allowed for the graphing the individual separations, and combined to allow for the viewing of the full distribution of photon separation distances.

Programs Tally3.f and Tally10.f were written in order to compute the number of times of the 100,000 events for each of the momentum, one of the separations, of the six possible permutations, and only one was less than or equal to three and ten centimeters, respectively. These simulate the number of times four gamma particles would be mistaken for three, called a 4 -> 3 fusion.

Three and ten centimeters are approximated maximum distances two photons could have landed from each other on the CSI array and still be confused as one. This number was approximated based on the length of the diagonals on the square face of each crystal, and the number of other blocks that would be in proximately to the showering. An additional reason for using three centimeters is its proximity to the Moliere radius.

Tabulate.cc was also written to compute the probabilities of there being an event where four gamma particles would be mistaken as two, using a Poisson distribution, and numbers of total separations less than or equal to three and ten centimeters.

The following table provides the probabilities yielded from the Tabulate.cc program at the different momentums, and a comparison of the two.

Momentum (GeV/c)	Probability for double fusion at 3cm	Probability for double fusion at 10cm	P(10cm) / P(3cm)
1	1.57646 E-7	1.6589 E-5	105.229
2	1.3340 E-7	1.2829 E-5	96.169
3	1.3949 E-7	1.3236 E-5	94.889
4	1.36867 E-7	1.4279 E-5	104.328
5	1.769 E-7	1.804 E-5	101.979

Each of the five probabilities at the two different distances differs by a factor of approximately one hundred. This implies the chance of a four gamma being mistaken for two in the 2.5 X 2.5 centimeter system is two orders of magnitude less likely than in the 7 x 7 centimeter system.

Momentum (GeV/c)	Tally3.F results	Total # of Separations 3 cm or less	Tally10.F	Total # of Separations 10 cm or less
1	337	337	3423	3466
2	310	310	2999	3047
3	317	317	3063	3095
4	314	314	3179	3215
5	357	357	3593	3615

This table shows that for every separation less than or equal to three centimeters it is a possible situation where four photons will be mistaken for three. This is also important to consider, because experimentally there is a probability of not detecting one of the photons. The most common instances of this occur when one of the photons hitting the CsI is very soft, appearing to just be noise within the crystal, and in the case of a photo-nuclear interaction between the photon and a nucleus inside the surrounding scintillator, producing light not in the visible spectrum, and thus not detected.

Momentum (GeV/c)	Ratio of Tally3.f Results to Tally10.f Results
1	10.157
2	9.674
3	9.662
4	10.124
5	10.064

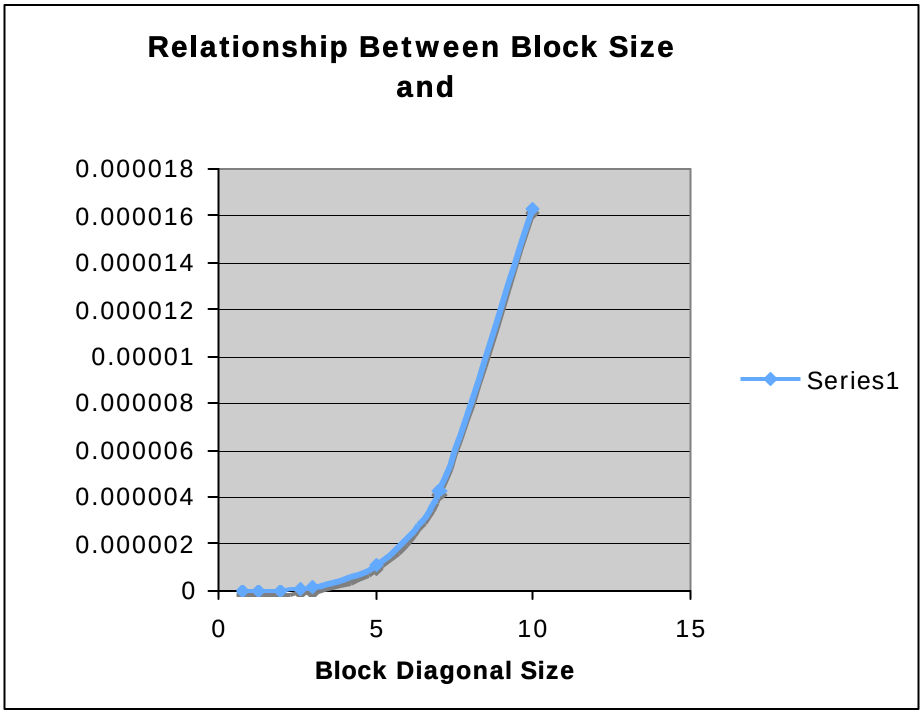
The table above shows that it is approximately ten times less common for a 4 -> 3 fusion to occur when the calorimeter comprised of the smaller KTeV crystals. Something to note here is that the ratios of the results appear to be momentum independent.

However, outside of the idealized world, kaons do not all have the same momentum, ensured by a delta function. In order to explore a more realistic scenario, the Monte Carlo was run for the E391A momentum spectrum. Additionally, Tally functions were written for blocks of size 2 cm, 1.5 cm, 1 cm, and .5 cm. This action was performed to provide information about the ideal size of crystals in the calorimeter for maximum noise reduction. The method of determining the number for each of these block size's respective tally number involved looking at the sizes are of these blocks' diagonal and rounding down based on the number of other blocks in close proximity. Tally functions tally5.f and tally7.f were also written in order to give a more thorough view of the relationship between block size and the probability of double fusion.

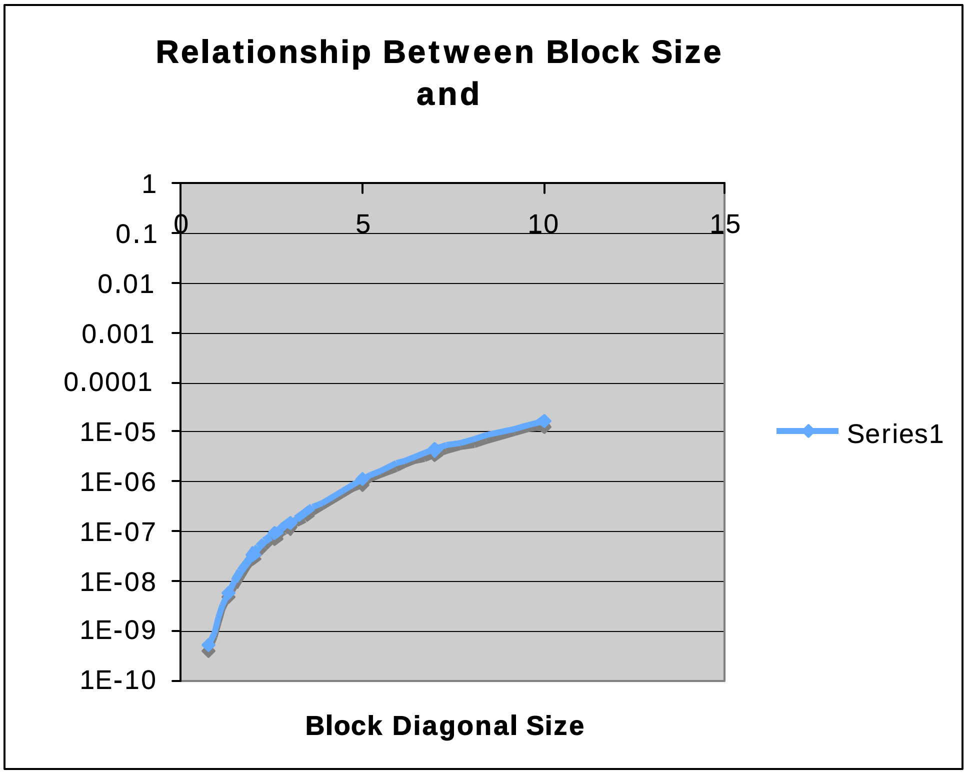
The following table shows the relationship between separation, frequency, and the probability of double fusion:

Separation	Tally Count	Total Frequency	Probability of Double Fusion
.75	19	19	5.0137 E-10
1.3	65	65	5.8674 E-9
2	157	157	3.4226 E-8
2.6	255	255	9.0274 E-8
3	325	325	1.4662 E-7
5	890	890	1.0985 E-6
7	1741	1751	4.275 E-6
10	3388	3437	1.6313 E-5

Theoretically, were the size of the block infinitely small, the probability of double fusion would be zero. This chart supports this, as the probability for double fusion gets significantly smaller as the maximum separation gets smaller. Again, these probabilities were determined using a Poisson distribution, taking under consideration the total number of separations and the total frequency in the specified ranges. The graph below shows the steep increase in the probability of four to two fusions

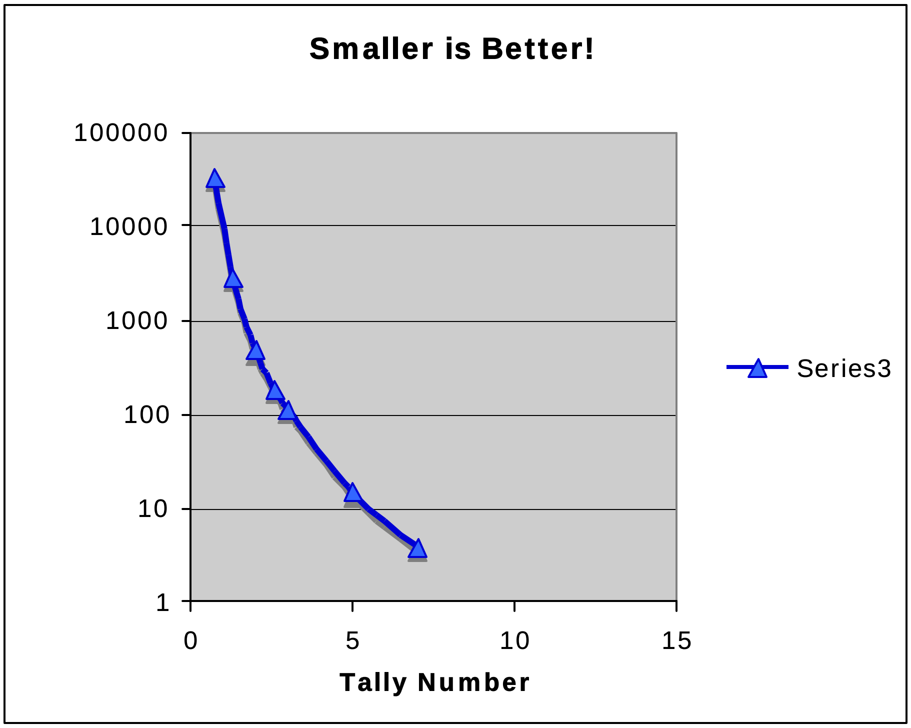


after a block size of approximately 2.5 x 2.5 cm, coincidentally the same the size of the blocks used in the KTeV CsI calorimeter. A linear scale was used, giving a false impression of the noise decrease experienced in by the further decrease of the block size. The following graph presents the same information logarithmically, to broaden our perspective of the noise behavior.



This logarithmic view more accurately shows the way in which the probability steeply approaches zero as the size of the block approaches zero. An important thing to note is the increase of the error as the tally functions search for smaller separations, since the sample size of each of these sets gets smaller as well. The error for these is approximately equal to one divided by the square root of the observed frequently in the separation range. So, for the tallyp75 function, which represents the block of size .5x.5 cm, the error is nearly twenty percent as only nineteen events in this range were observed. The error for the tally ten range, on the other hand, is approximately two percent.

An “improvement factor” is defined as the ratio between the probability of double fusion between the current crystals in use at KEK and the smaller crystals. The chart below shows the steep improvement as you make the crystals smaller and smaller, even when displayed on a logarithmic scale.



Summary/Conclusion:
The probability for double fusion is approximately a hundred times greater when using the KEK crystals than when using those employed by KTeV's calorimeter. Making this change before the start of the next generation of the experiment at JPARC in 2006 will significantly increase the visibility of the decay from k-long to pi0 nu nubar.
It is now very clear that more the size of the dimensions of the crystals on the CsI calorimeter are decreased, the less noise will be encountered. It has been illustrated graphically that the limit of the probability of double fusion as the diagonal of the face of the crystal approaches zero, is in fact zero. Also, the limit of the improvement factor as the diagonal of the face of the crystal approaches zero, is infinity. However, reducing the size of the crystals beyond the 2.5 x 2.5 cm crystals used at KTeV is in many ways not necessary, as clarity in the calorimeter's detection is not the only method of fighting this common kaon background.