CURRENT STATUS OF CP VIOLATION IN K DECAYS

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In this lecture I will give a brief review of the experimental progress in the study of CP violation in the neutral K meson system. We will speak exclusively of the measurement of $|\eta_{oo}|^2/|\eta_{+-}|^2$ for which two new experimental results have been announced. A more complete discussion of other relevant experiments has been given in the lectures of Stan Wojcicki in this volume. A thorough discussion of the relation of ε and ε' to the Kobayashi-Maskawa (K-M) matrix has been given by Mark Wise in the preceding lecture. We will concentrate therefore on the experimental problems.

Before starting I would like to remind you of a fact that many of you may not have known. Pief Panofsky and my colleague, Val Fitch, were the first to electronically detect long-lived K mesons. Their experiment was the precursor of all the beautiful electronic experiments with the neutral K meson. This work was done during a brief sabbatical visit of Pief to Brookhaven in the summer of 1957. I was fortunate to share an office with Pief that summer. Although it was easier to quickly mount an experiment in those days, Pief's drive was spectacular. In no time Pief found an important project and an outstanding local collaborator. They obtained some large plastic scintillators from Allan Sachs at Columbia, cut them to shape and polished them with Colgate toothpaste! They did their own rigging at night, and within a few weeks were detecting K_L mesons. Figure 1 shows the title page of their paper. As a young witness, I could see that Pief was a very special individual; the extraordinary success of this laboratory under his guidance is easy to understand.

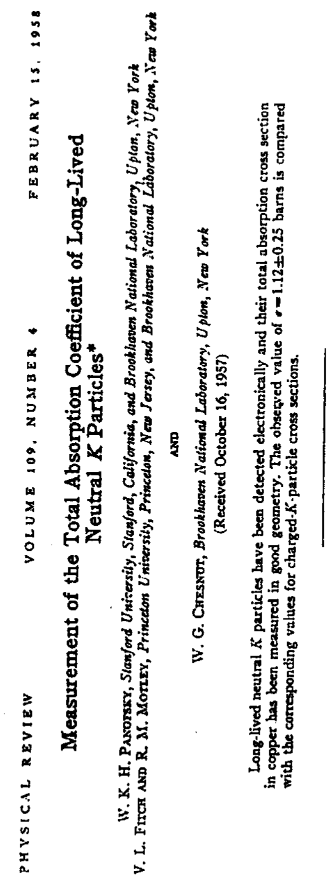
CP violation in the K system can have two sources.[1] The K_L meson is a superposition proportional to $(1+\varepsilon)|K\rangle + (1-\varepsilon)|\overline{K}\rangle$. The parameter ε is a measure of the CP "impurity" in the K_L state. A second type of CP violation, expressed by a parameter ε' =

$$\frac{i}{\sqrt{2}} \mathrm{Im}\left(\frac{A_2}{A_0}\right) e^{i(\delta_2-\delta_0)}$$

is a measure of "direct" CP violation resulting from a non-zero relative phase between A_2 and A_0, the I=0 and I=2 decay amplitudes to two pions. The values of the $\pi\pi$ scattering phase shifts and the phenomenological analysis of the decay parameters (assuming CPT invariance) lead to the phases of ε and ε' being the same (~45°) with a precision of 10°. The observed decay parameters are $|\eta_{+-}|^2 = \Gamma(K_L\to\pi^+\pi^-)/\Gamma(K_S\to\pi^+\pi^-)$ and $|\eta_{00}|^2 = \Gamma(K_L\to\pi^\circ\pi^\circ)/\Gamma(K_S\to\pi^\circ\pi^\circ)$. These are related (to a good approximation) to ε and ε' by $\eta_{+-} = \varepsilon+\varepsilon'$, and $\eta_{00} = \varepsilon-2\varepsilon'$. With the phase relation above, one finds $\varepsilon'/\varepsilon = (1-|\eta_{00}|^2/|\eta_{+-}|^2)/6$. Thus, a measurement of the ratio $|\eta_{00}|^2/|\eta_{+-}|^2$ measures rather directly the second parameter ε'.

Gilman and Wise[2] first pointed out that "penguin" diagrams and the K-M parameters place a lower limit on ε'/ε. Evaluation of this lower limit is difficult and has gone through many changes. At present the best estimate[3] is that $\varepsilon'/\varepsilon > 0.005$. Such a value would correspond to $|\eta_{00}|^2$ being 3% smaller than $|\eta_{+-}|^2$.

We have recently completed the analysis of an experiment carried out by a collaboration of the University of Chicago and Saclay. The table below lists the participants in this experiment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Measurement of the Total Absorption Coefficient of Long-Lived Neutral *K* Particles*

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(Received October 16, 1957)

Long-lived neutral *K* particles have been detected electronically and their total absorption cross section in copper has been measured in good geometry. The observed value of σ=1.12±0.25 barns is compared with the corresponding values for charged-*K*-particle cross sections.

Fig. 1. Title page of a paper with Panofsky as co-author which employed electronic detection of long-lived neutral K mesons for the first time.

which was performed at Fermilab.

Chicago	Saclay
R. Bernstein*	B. Peyaud
G. Bock†	R. Turlay
D. Carlsmith*	A. Zylberstejn
D. Coupal*	
J. Cronin	
G. Gollin††	
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We measured simultaneously K_L and K_S to $\pi^\circ\pi^\circ$, and in a modification of the apparatus we measured simultaneously K_L and $K_S \to \pi^+\pi^-$. Two separate beams were used. A meter-long-carbon regenerator was placed in one of the two beams to produce K_S mesons. The regenerator alternated between each beam on a pulse by pulse basis. As a practical matter the beam containing the regenerator was attenuated by a factor of 4 compared to the K_L beam. The $\pi^+\pi^-$ or $\pi^\circ\pi^\circ$ decays are observed in a 14 meter decay region downstream of the regenerator. The simultaneous observation of K_L and K_S eliminates corrections due to deadtime loss and unequal beam intensities. The detector is about 65 meters away from the decay region so that the efficiency for K_S and K_L decays is nearly the same. Then one measures rate $(K_L \to \pi^\circ\pi^\circ)$/rate $(K_S \to \pi^\circ\pi^\circ) \approx |\eta_{00}|^2/|\rho|^2$ and rate $(K_L \to \pi^+\pi^-)$/ rate $(K_S \to \pi^+\pi^-) \approx |\eta_{+-}|^2/|\rho|^2$ so the ratio of ratios is $|\eta_{00}|^2/|\eta_{+-}|^2$ the desired number. The effective regeneration amplitude is ρ.

There are a number of corrections that have to be made to the measurements. The efficiency of K_L and K_S are not quite the same because the Z (distribution) of K_S decays decreases with distance from the regenerator. The K_L decays are flat as a function of distance. Backgrounds are quite different for each of the decay modes. This problem was exacerbated by the fact that the regenerator and parts of the decay region were not placed in a vacuum.

Figure 2 shows a schematic plan view of the apparatus. For the neutral decays, the trigger required one of the four γ-rays to convert in a 0.1 radiation length lead sheet. This sheet was preceded by a 1.6 mm-thick scintillation counter in anti-coincidence and followed by 1.6 mm-thick horizontal and vertical hodoscopes made of 1.27 cm-wide strips. In addition, two tracks in the drift chamber spectrometer were required as well as $\geq$ 40 GeV of energy deposit in a lead glass γ-ray spectrometer. A number of anti-coincidence counters were installed to reduce triggers on $K_L \to 3\pi^\circ$ decays.

The γ-ray spectrometer consisted of 804 lead glass blocks 5.7 x 5.7 x 60 cm deep stacked in a 2.2 meter-wide by 1.2 meter-high array. The Cerenkov light was recorded by Amperex 2202 photomultipliers and read into LeCroy 2285 ADCs. For some of the data the trigger included a fast mass calculation. The spectrometer consisted of four 2 meter-wide x 1 meter-high drift chambers with a 100D40 magnet as shown in the figure. Properties of the detector are given in Table 1 below. A complete description of the detector can be found in the thesis of R. H. Bernstein.

For energies less than ~15 GeV the lead glass was calibrated by means of the converted electrons of the trigger. These were momentum analyzed by the drift chamber spectrometer before they entered the lead glass. For energies greater than 15 GeV the spectrometer was calibrated by a source of π°'s known to originate in the lead converter. These π°'s were produced by neutron interactions in the

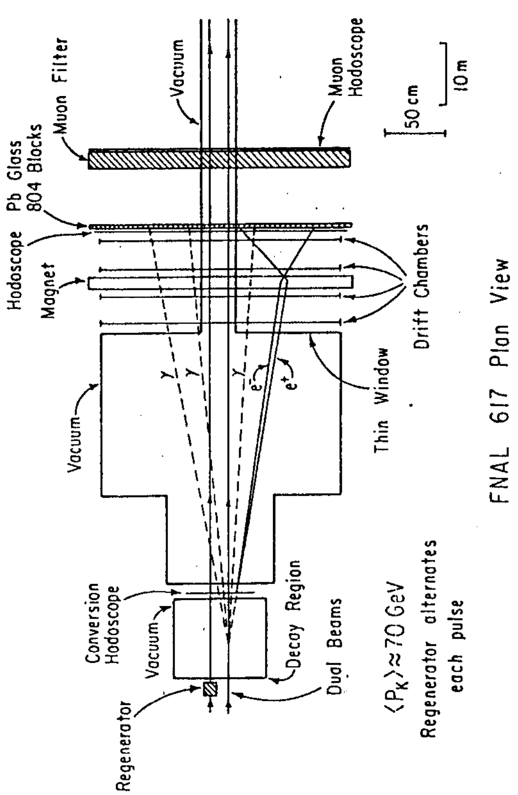

Fig. 2. Schematic plan view of the apparatus for the Fermilab experiment.

Table 1

<u>Properties of the Detector</u>

A. Drift chamber spectrometer

σ_x = 150μ/chamber

σ_p/P = 0.8%

B. Lead glass

$\sigma_E/E = \sqrt{(0.02)^2 + (0.06/\sqrt{E})^2}$

σ_x = 3 mm

C. Resolutions for $K\to\pi\pi$ decays

1. $K\to\pi^\circ\pi^\circ$

   σ_{M_K} = 6.5 MeV/c²

   P_T^2 distribution falls to 1/e at 500 (MeV/c)²

   σ_Z vertex = 1.7 meter

2. $K\to\pi^+\pi^-$

   σ_{M_K} = 4.0 MeV/c²

   P_T^2 distribution falls to 1/e at 100 (MeV/c)²

   σ_Z vertex = 0.4 meter

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lead converter. Precise knowledge of the origin of these π°'s allowed a calibration algorithm to be developed in which the energy scale was set by the π° mass. Each glass block had a relation between ADC counts and energy which was nonlinear and varied from block to block as well as with time. A xenon flasher system to monitor gain drifts was ineffective. The mass spectrum of the two photons was computed using the position of the lead sheet as a vertex and is plotted in Fig. 3. The mean mass of the distribution is 135.0 GeV/c², the standard deviation is 3.8 MeV/c² which is the expected width given the energy resolution. This source of π°'s

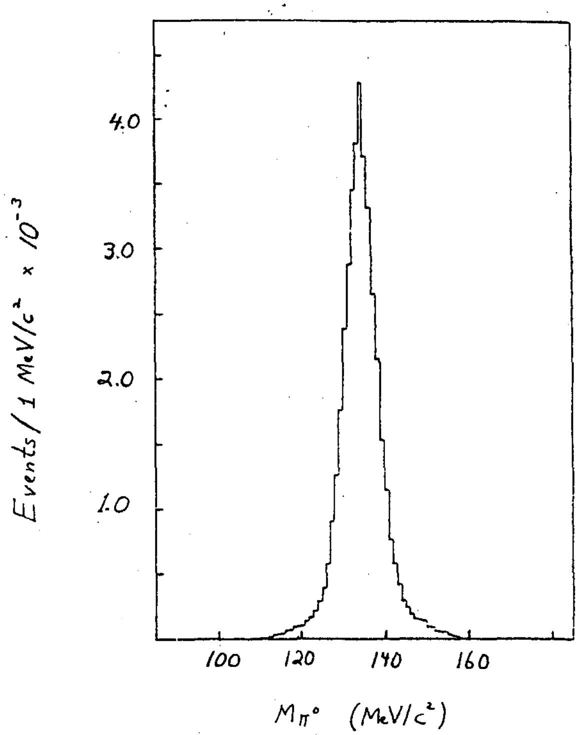

Fig. 3. Mass distribution of π° events produced at the converter sheet.

with a precise Z vertex provides an excellent absolute calibration of the lead glass spectrometer. For $K_L \to \pi^\circ\pi^\circ$ decays, the fractional error in the distance of the reconstructed vertex is equal to the fractional error in the absolute energy calibration. A 1% energy calibration error shifts a typical vertex position by 70 cm.

All events which have four γ-rays (one being the e^+e^- pair) were reconstructed. Let E_i be the energy of the i^{th} γ-ray and d_{ij} be the distance between the i^{th} and j^{th} γ-ray. If the two γ-rays come from a π° decay, its vertex (distance from the lead glass) is given by $Z_{ij} = \sqrt{E_i E_j}\ d_{ij}/M_{\pi^\circ}$. Let σ_{ij} be the expected error in Z_{ij}. Then we form a $\chi^2 - (Z_{ij}-Z_{k\ell})^2/(\sigma_{ij}^2 + \sigma^2_{k\ell})$. We use the minimum χ^2 to choose the best of the three possible ways to pair the 4 γ-rays. Events with $\chi^2 \leq 2$ are retained. The vertex is taken as the weighed average of Z_{ij} and $Z_{k\ell}$ for the best solution. There is no information on the position transverse to the beam.

It is essential to know the transverse position of the decay vertex to measure the transverse momentum (P_T^2) of the decay with respect to the incident beam direction. It is also necessary to determine which of the two beams contained the decay. The transverse position is found by the intersection of the e^+e^- conversion direction with the plane containing the Z vertex determined above. Then using this decay point the target position and the center of energy one can find the beam and the P_T^2 of the K decay. These relations are shown in Fig. 4.

Figure 5 shows the horizontal component of the reconstructed beam position. Figure 6 shows the traditional plot of mass versus P_T^2 for the K_L decay candidates. The backgrounds in Fig. 6 are $3\pi^\circ$ decays for which two photons were lost and for which a good χ^2 is retained. In addition, there is a long tail in P_T^2 of events with the correct mass. These events originate from inelastic production

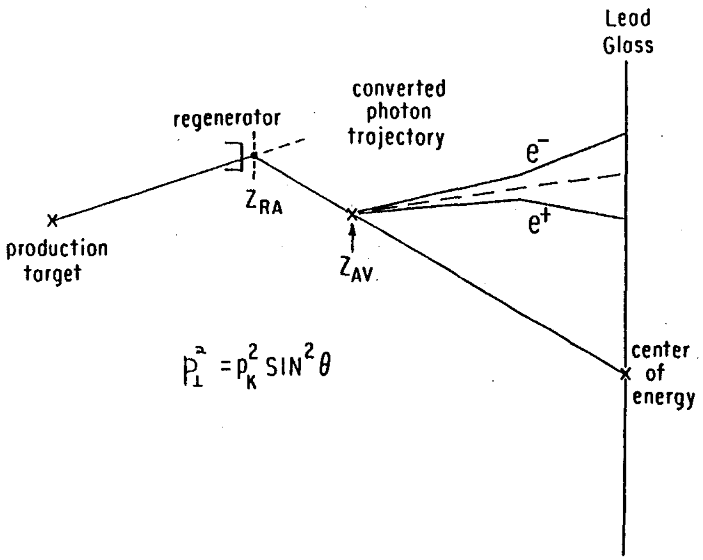

Fig. 4. Geometry for calculation of the $P_T{}^2$ of a K decay candidate and the beam of its origin.

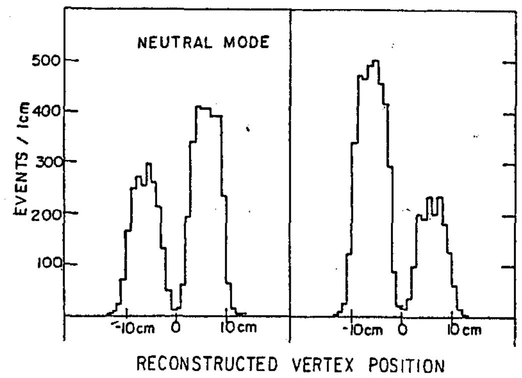

Fig. 5. Horizontal distribution of K mesons at the entrance to the decay region. The two distributions are for the regenerator in the right and in the left beam.

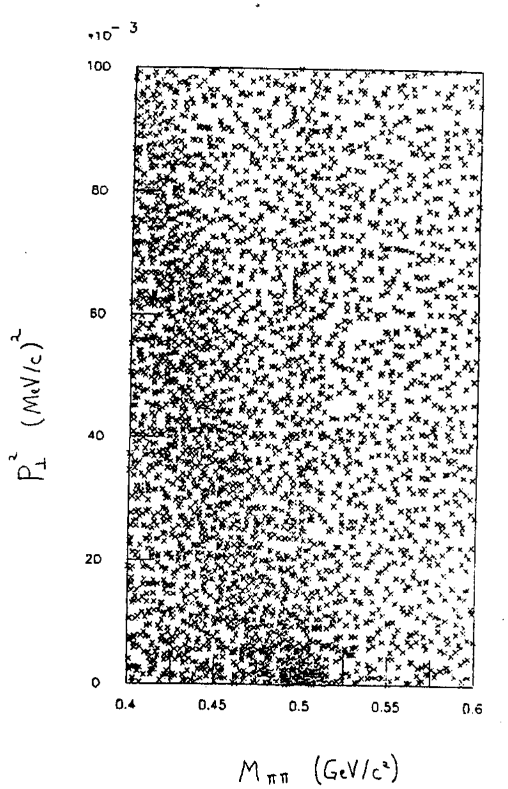

Fig. 6. Traditional plot of mass versus p_T^2 for the reconstructed $K_L \to \pi^\circ\pi^\circ$ events.

of K_S by K mesons and perhaps neutrons in the beam. A third component of the background comes from $\pi^\circ\pi^\circ$ events with a continuum mass distribution. These latter two backgrounds are produced by interactions in those parts of the free decay volume which are not evacuated.

Figure 7 shows $K_L \to \pi^\circ\pi^\circ$ events projected on the mass axis for P_T^2 <2500 $(GeV/c)^2$ and total energy of 85±5 GeV. The dashed line shows the background subtraction. The methodology of the $K_L \to \pi^\circ\pi^\circ$ background subtraction is too complex to discuss here.

The background in the K_S sample is almost entirely incoherent regeneration and inelastic production by incident K mesons and neutrons. Thus, projections on the P_T^2 axis for mass cuts between 480 and 520 MeV/c^2 are made. An exponential extrapolation is used to evaluate the background under the forward coherently regenerated peaks. Figure 8 shows these distributions for each momentum bin.

The amount of background in the charged decays is much less because of better resolution. For $K_L \to \pi^+\pi^-$ the background consists of unidentified K_{μ_3} and K_{e_3} decays as well as $K_S \to \pi^+\pi^-$ produced by K mesons and neutrons in the non-vacuum parts of the decay region. For the $K_S \to \pi^+\pi^-$ the subtraction is similar to the technique for $K_S \to \pi^\circ\pi^\circ$.

The table below gives some gross details of the event sample.

Mode	Raw Events	Corrected Events	Fraction Subtracted
$K_L \to \pi^\circ\pi^\circ$	3507	3150 ± 61	0.117 ± 0.006
$K_S \to \pi^\circ\pi^\circ$	6524	5663 ± 86	0.131 ± 0.010
$K_L \to \pi^+\pi^-$	11005	10638 ± 107	0.033 ± 0.002
$K_S \to \pi^+\pi^-$	26235	25751 ± 158	0.018 ± 0.001

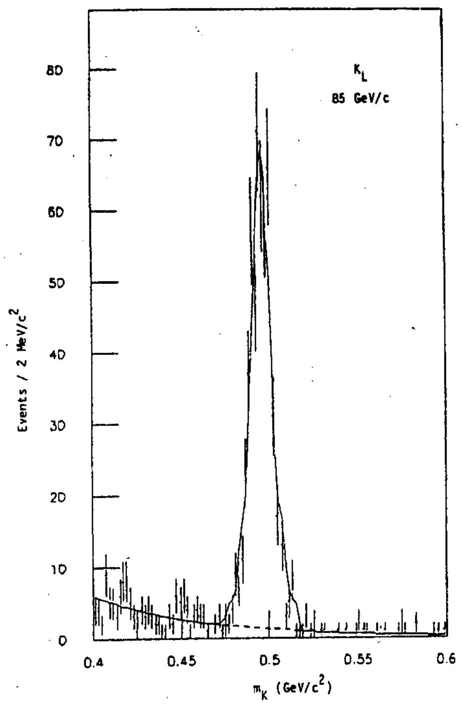

Fig. 7. Projection of events with energy 85±5 GeV and P_T^2<2500 $(GeV/c)^2$ onto the mass axis. The dashed line under the peak shows the background subtraction.

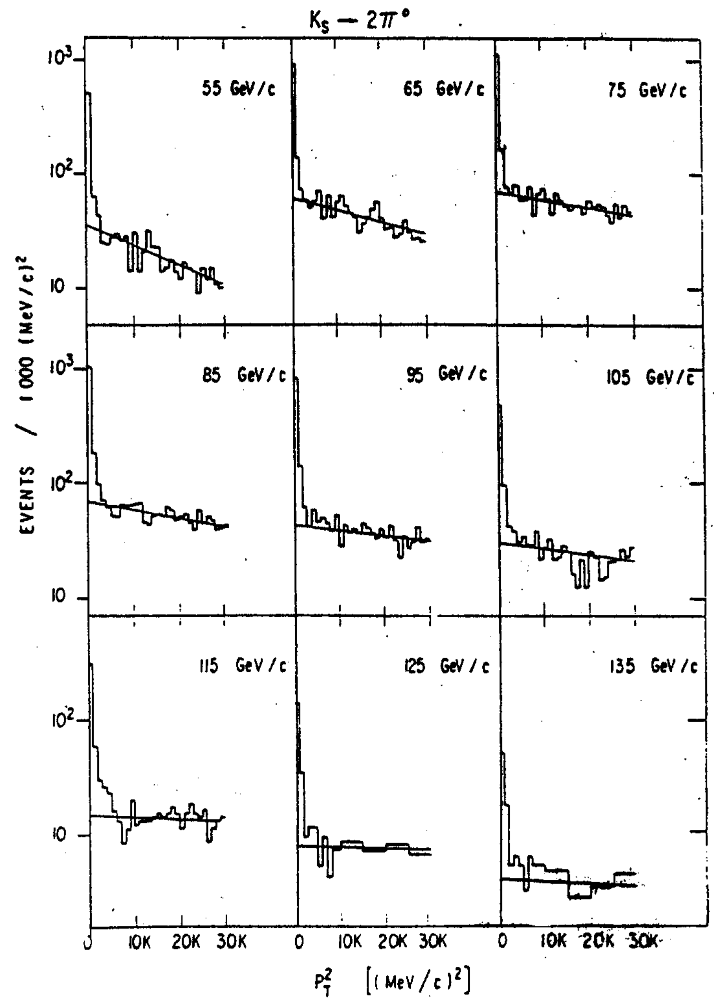

Fig. 8. Extrapolations in P_T^2 for $K_S \rightarrow \pi^\circ\pi^\circ$ background subtraction.

The relative efficiencies for the four different samples have been calculated by Monte Carlo techniques. These calculations are done as a function of momentum. Figure 9 shows schematically the Z distributions of the four samples. The $K_S \to \pi^0\pi^0$ sample begins sharply at a point defined by a piece of lead two radiation lengths thick. The $K_L \to \pi^0\pi^0$ sample extends upstream of this point. It was not possible to insert a similar piece of lead in the K_L beam because of background limitations.

A great deal of attention was given to the Monte Carlo. In the Monte Carlo for the neutral decay mode, one had to compute the relative efficiency over a decay region considerably larger than the region occupied by the regenerated events. There were some very powerful checks for the Monte Carlo calculation. There was a large sample of $K_L \to 3\pi^0$ events in which all six photons were detected. Figure 10 shows the distribution of Z vertices for $K_L \to 3\pi^0$ at 75±5 MeV energy. Also shown is the Monte Carlo calculation for the distribution. Comparisons of this kind give an estimated systematic error due to the Monte Carlo of ±0.5% and 0.2% for $|\eta_{00}|^2$ and $|\eta_{+-}|^2$. Additional systematic error is added for uncertainty in the background subtraction.

The extraction of $|\eta_{00}|^2/|\eta_{+-}|^2$ is not direct since the K_S source from the regenerator has a significant amplitude for K_L decays which interferes with the K_S decays. Typically just downstream of the lead plate the amplitude of K_S is 0.11 of K_L. On the assumption that $\eta_{+-}=\eta_{00}$ the regeneration amplitude for the carbon is extracted as a function of momentum for both the neutral and charge decays. Figure 11 shows the result for both neutral and charged decays. Since the regeneration amplitude is independent of decay mode, any difference is the result of $|\eta_{00}|^2/|\eta_{+-}|^2$ being different from 1. Actually an overall fit is made to the data with the quantity ε'/ε as the end result,[4] yielding

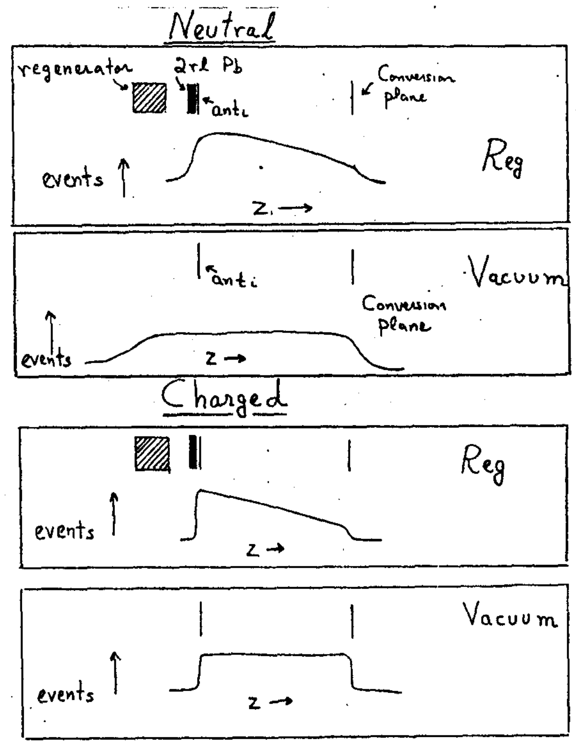

Fig. 9. Qualitative distribution of z-vertices for the four categories of events.

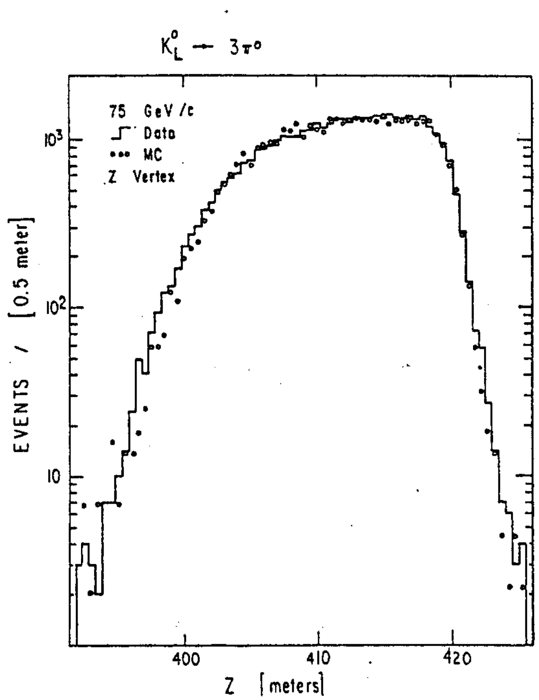

Fig. 10. Comparison of the vertex distribution of $K_L \to 3\pi^0$ events with the Monte Carlo distribution.

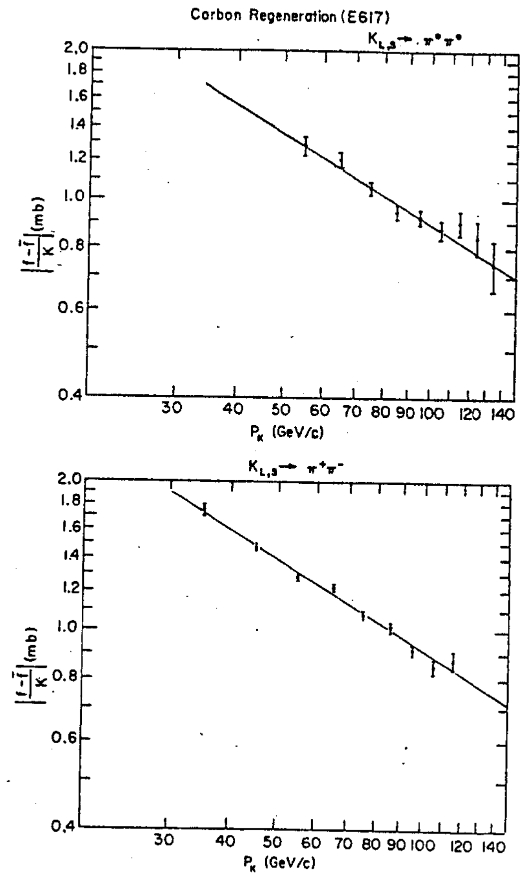

Fig. 11. Calculated regeneration amplitudes from $K_S \to \pi^0\pi^0$ and $K_S \to \pi^+\pi^-$ events. The solid line is the power law dependence as determined in Reference 4.

$$\varepsilon'/\varepsilon \;=\; -0.0046 \pm 0.0052 \pm 0.0024 \text{ (sys)}.$$

This result has been checked. One can cut the $K_L \to \pi^\circ\pi^\circ$ events at the position of the lead plate and reevaluate the result. This method is somewhat less sensitive to Monte Carlo errors but has a larger statistical error because of loss of events. This method yields a result

$$\varepsilon'/\varepsilon \;=\; -0.004 \pm 0.006.$$

A third method has been used by the author of this article. Here K_L events are weighted with decay factors and interference factors so that they have an identical distribution to the events in the regenerated beam. This method which has still poorer statistical power because events in the K_L beam with Z vertices far from the regenerator have very little weight. The method does not require a Monte Carlo acceptance calculation however. This result is

$$\varepsilon'/\varepsilon \;=\; -0.002 \pm 0.007.$$

Finally using the Monte Carlo to compute the relative acceptance for $K_L \to 2\pi^\circ$ and $K_L \to 3\pi^\circ$ we find $\Gamma(K_L \to 2\pi^\circ)/\Gamma(K_L \to 3\pi^\circ) = (4.54 \pm 0.10) \times 10^{-3}$. Using this value and appropriate branching ratios from the Particle Data Group[5] one finds,

$$\varepsilon'/\varepsilon \;=\; -0.008 \pm 0.010.$$

We stress that these various methods serve as checks. Our result is therefore -0.0046±0.0057 where we have added the systematic error in quadrature.

Very recently a result has been announced by the Yale-BNL group.[6] Figure 12 shows a schematic view of their apparatus. In this experiment charged and neutral decays were observed simultaneously, first for K_L decays and then for K_S decays produced in a carbon regenerator. The neutral decays were obtained with a trigger similar to the Chicago-Saclay experiment. A nice feature of the

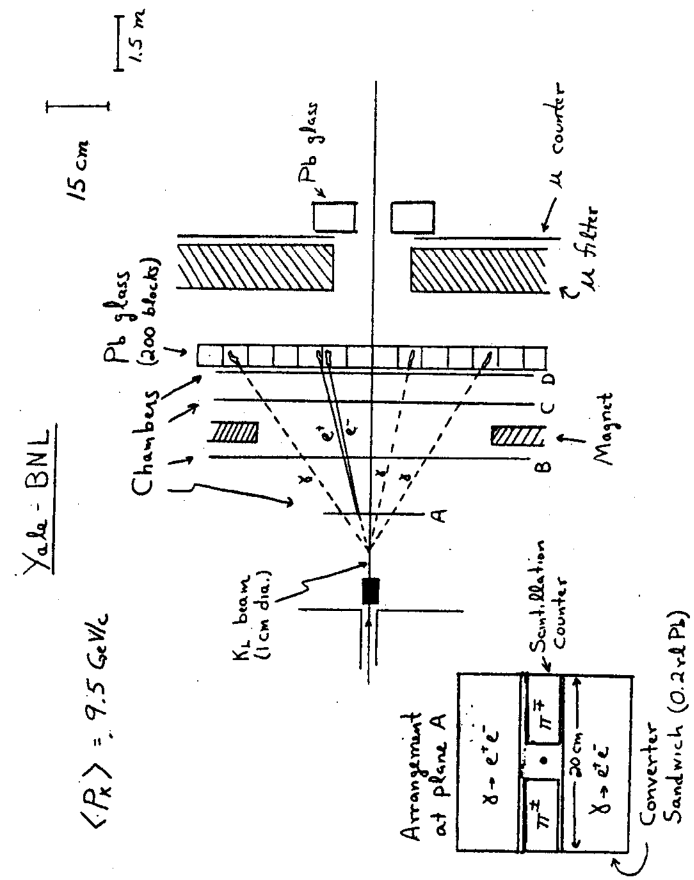

Fig. 12. Plan view of Yale-BNL apparatus.

arrangement was that the decay vertex was determined by the intersection of the converted pair and the 5 mm radius beam. The rather coarse segmentation of the lead glass spectrometer and the low energy ~10 GeV gave a much poorer performance of the γ-ray spectrometer compared to Chicago-Saclay.

The data sample, after background subtraction yielded 1122 $K_L\to\pi^\circ\pi^\circ$ events, 3537 $K_S\to\pi^\circ\pi^\circ$ events, 8680 $K_L\to\pi^+\pi^-$ events and 20963 $K_S\to\pi^+\pi^-$ events. Figure 13 shows mass plots of their data. The data were divided into bins of Z and P and the ratio of ratios calculated for each bin. The average of these values gave $|\eta_{00}|^2/|\eta_{+-}|^2$ = 0.990 ± 0.043 ± 0.026 sym. This gives ε'/ε = 0.0017 ± 0.0082. Figure 14 shows the results of the two recent experiments along with the previous experiments.

In Fig. 15 the plot from Gilman and Hagelin[3] is reproduced. With a top quark mass of 40 GeV one expects an ε'/ε value positive and greater than 0.005. Sadly all the work so far has not been of sufficient precision to establish or rule out the parameters of the K-M matrix as the description of CP violation.

Thus, further experiments are required. There are two of these which will occur in the next few years. The first is an upgrade of the Chicago-Saclay experiment at Fermilab with additional collaborators from Princeton and Fermilab. The experiment which will be designed to handle a higher rate, will have a larger acceptance, and lower backgrounds. Figure 16 shows a sketch of the new apparatus.

To survive a higher rate new drift chambers are being built with a 6 mm wire spacing. The duty cycle of the Tevatron with 800 GeV protons is 20 sec/60 sec cycle. This is a duty factor five times better than in the previous experiment. The increased beam energy of the Tevatron and a shorter K_L beam will provide a K_L flux per hour which is five times greater than the previous experiment.

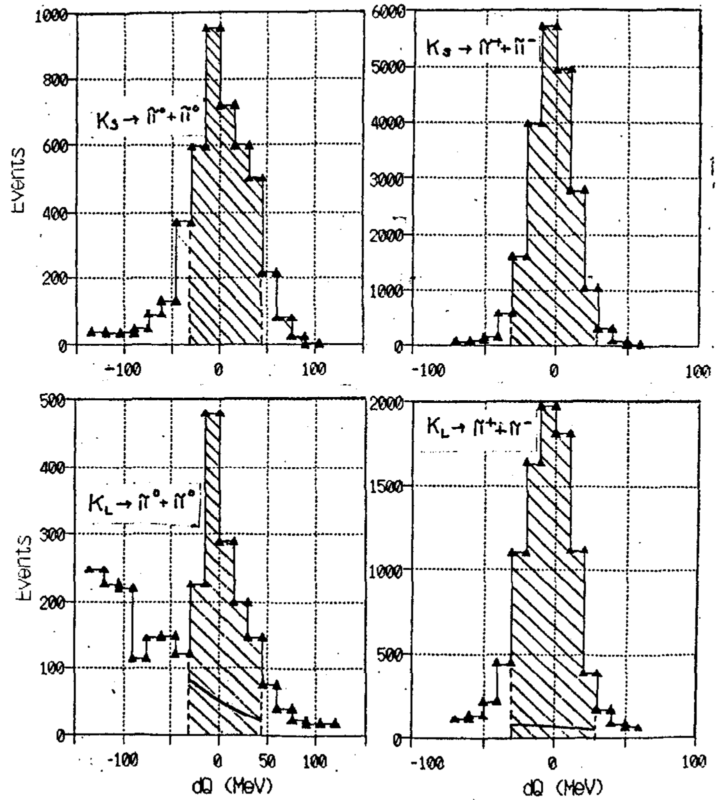

Fig. 13. Mass plots of the four categories of events in the Yale-BNL experiment.

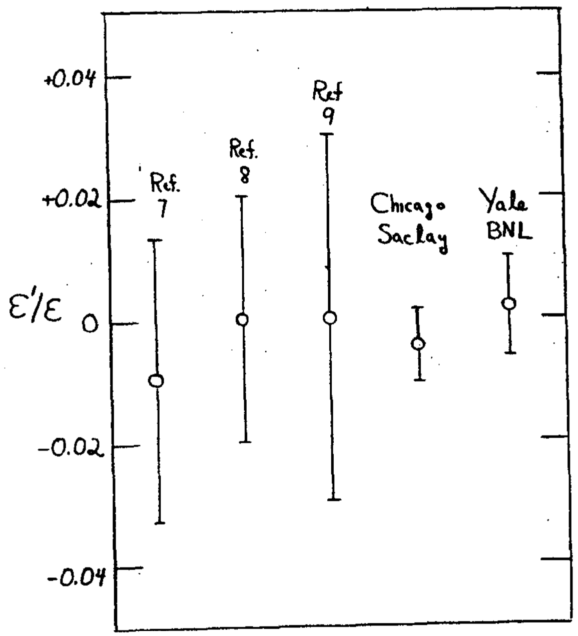

Fig. 14. Plot of measurements of ε'/ε.

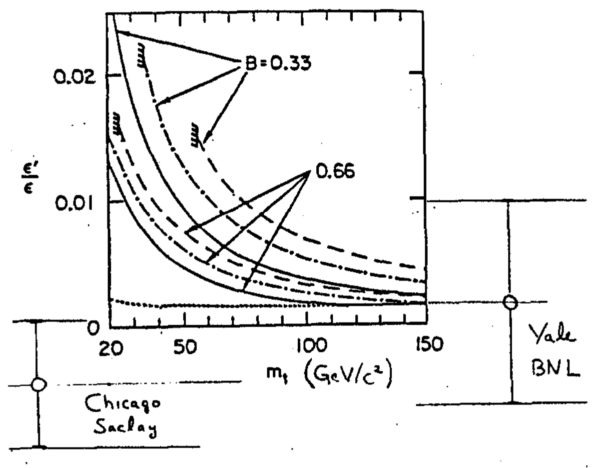

Fig. 15. Plot of the value of ε'/ε expected in the K-M model with top quark mass, "bag" factor and b lifetime as parameters. From Gilman and Hagelin, Reference 3.

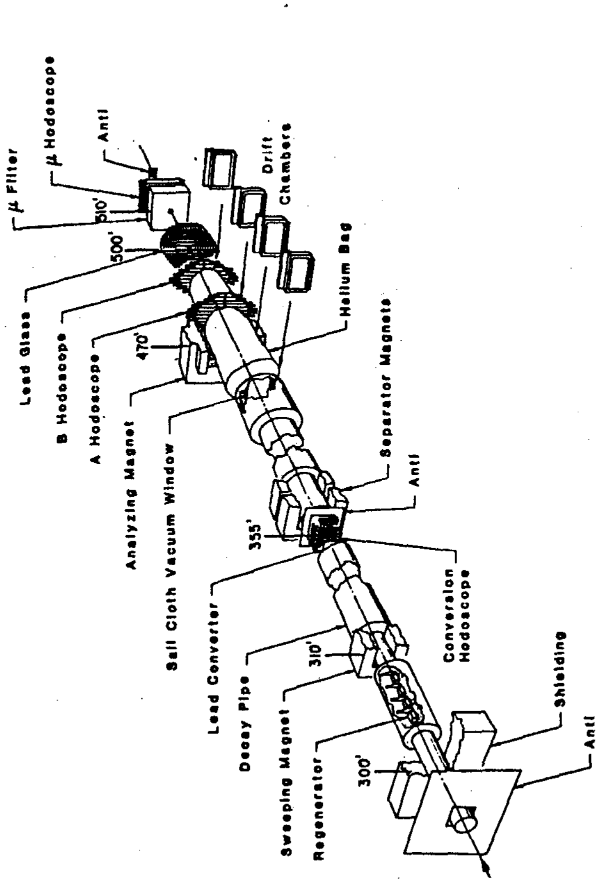

Fig. 16. Apparatus for the new Chicago-Fermilab-Princeton-Saclay experiment.

The acceptance of the new experiment has been increased. The decay region is somewhat closer to the detector. The magnet has been opened to an aperture of 1.5 meters. The lead glass is restacked in a circular pattern. The size of the holes in the lead glass has been reduced. All of these modifications result in an increase in acceptance by a factor five.

Steps have been taken to reduce the backgrounds. The most important of these has been the placement of the regenerator and all the decay volume in an unbroken vacuum. In Fig. 17 data are plotted from the Chicago-Saclay experiment which show the mass spectrum for $K_L \to \pi^\circ\pi^\circ$ with vertices in the air compared with the mass spectrum for vertices in vacuum. In the latter case the background is reduced by a factor three. The incoherent and inelastic background under the coherently regenerated peak is 13%. This background is almost entirely inelastic events. The true incoherent regeneration (with no nuclear breakup) is expected to be only ~1%. One will try to make the regenerator "active" by inserting a number of scintillators throughout its volume. These should veto a significant fraction of the inelastic events. One notes that the inelastic subtraction for $K_S \to \pi^+\pi^-$ is only 3.3%. The difference is due to the superior $P_T{}^2$ resolution in the charged mode. One cuts at $P_T{}^2 = 300$ $(MeV/c)^2$ in the charged mode, while one cuts the neutral mode at $P_T{}^2 = 2500$ $(MeV/c)^2$. One can expect some improvements in resolution of the lead glass spectrometer which will further reduce the background.

A total of 10^5 $K_L \to \pi^\circ\pi^\circ$ events should be collected and a precision of 0.001 is expected for ε'/ε. The reduced background should keep the systematic error at a level comparable to, or smaller than the statistical error. The experiment should be installed for testing during January-June 1985. Data taking would be expected in mid-1986.

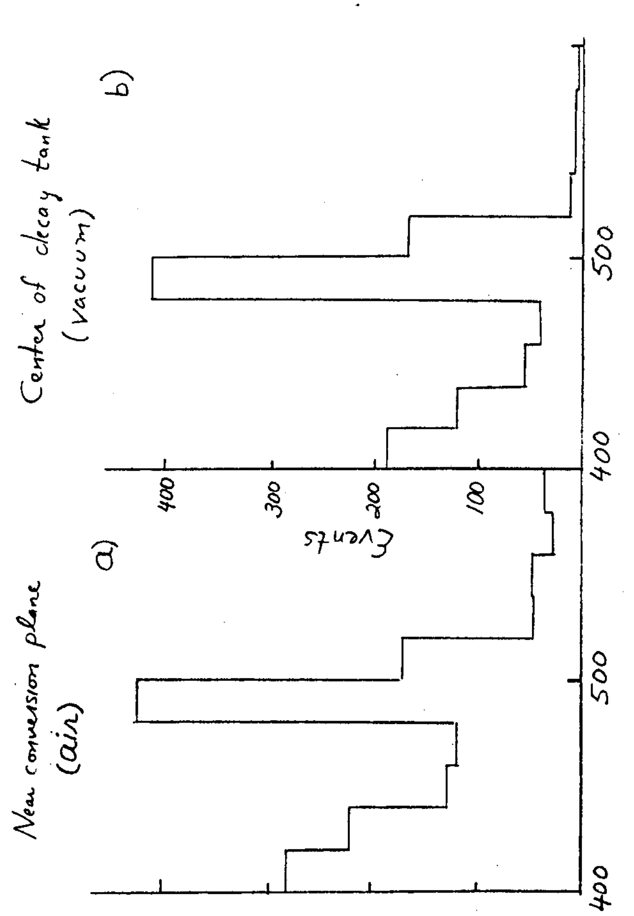

Fig. 17. Mass spectrum for $K_L \to \pi^\circ\pi^\circ$; (a) For events with decay vertex in air; (b) For events with decay vertex in vacuum.

At CERN an experiment (NA31) to measure ε'/ε is just beginning a period of testing. This is by a CERN, Dortmund, Edinburgh, Orsay, Pisa, and Siegen group. The experiment is characterized by a bold approach designed to have a very high data rate and relative simplicity of analysis. It uses an apparatus with no magnet, and no converter is used to trigger on $K_L \to \pi^\circ\pi^\circ$ decays. This gives the experiment a high intrinsic efficiency. A 50-meter decay volume will be used. The experiment views either a K_L beam or a K_S beam and records charged and neutral decays simultaneously. Figure 18 shows a schematic view of this experiment.

The K_S beam is produced by a magnet train inside the vacuum chamber. It can be moved so that the K_S's can be produced throughout the decay volume. The charged decays are detected by minidrift chambers. The $K_L \to \pi^+\pi^-$ decays are separated from the K_{e_3} and K_{μ_3} decays by a combination of high quality electromagnetic and hadron calorimeters. The properties of these calorimeters are

<u>Hadron Calorimeter</u>

$$\frac{\sigma_E}{E} = 0.6/\sqrt{E}$$

<u>Liquid Argon Electromagnetic Calorimeter</u>

$$\frac{\sigma_E}{E} = \sqrt{(0.08/\sqrt{E})^2 + (0.01)^2}$$

$$\sigma_x = 2 \text{ mm}$$

$$\sigma_{M_K} = 3 \text{ MeV/c}^2$$

The mass of the $K \to \pi^+\pi^-$ events are given by $M^2 = \frac{E^2\theta^2}{4}(1-x^2) + 2M_\pi^2$ where $X = (E_1-E_2)/(E_1+E_2)$, E_1 and E_2 being the energy of each hadron. The mass resolution needs only to be sufficient to remove $K_L \to \pi^+\pi^-\pi^\circ$ events where the π° is lost. Then the expression can be turned around, knowing $M = M_K$ to give a very precise energy since the

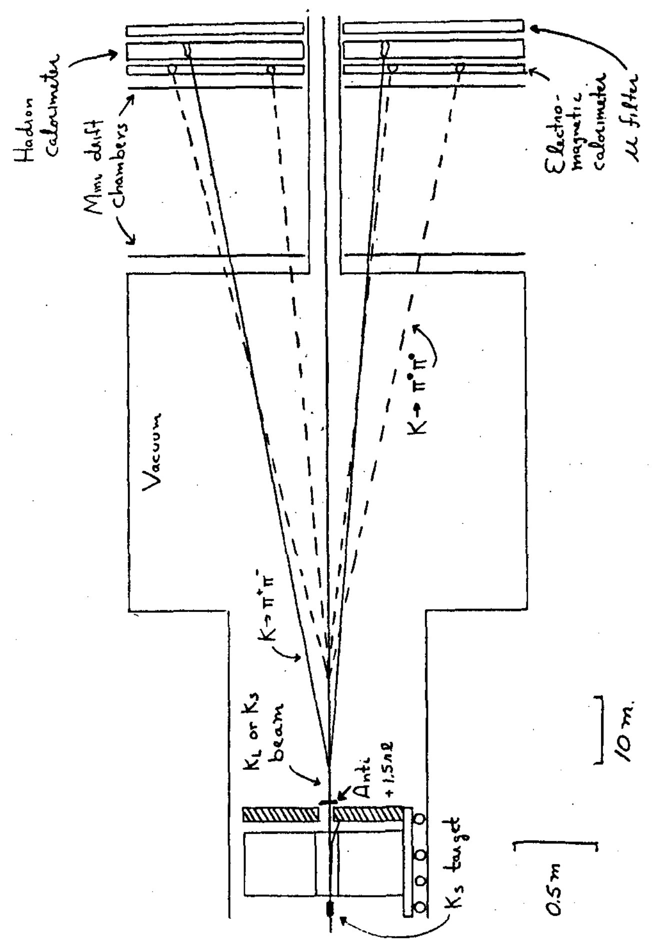

Fig. 18. Schematic view of CERN experiment (NA31).

opening angle θ is well measured. The K_{ℓ_3} are removed because of the excellent muon and electron identification of the calorimeters.

The $K \to \pi^\circ\pi^\circ$ events are reconstructed and the vertex located as in the Chicago-Saclay experiment. Again, no information exists concerning the transverse location of the vertex. The rates are large; one expects 2 x 10^4 $K_L \to \pi^\circ\pi^\circ$ and 7.5 x 10^4 $K_L \to \pi^+\pi^-$ each day. Furthermore the intrinsic efficiency is large, typically 30% within the 50-meter decay volume. This is ~10 times larger than the new Fermilab experiment which takes a loss because of the γ-ray conversion requirement.

A bold venture often has associated risks. What are the risks in the CERN experiment?

The conditions for the K_L and K_S data collecting are quite different. Backgrounds will be different and the momentum spectra will be quite different. A good control of the absolute calibration of the calorimeters will be required. Also, one must be sure that the relative efficiency for $\pi^\circ\pi^\circ$ and $\pi^+\pi^-$ decays remains the same for K_L and K_S running.

There is less information collected for each event than in the Fermilab experiment. In the neutral mode there is no measurement of the transverse momentum of the decay with respect to the beam direction. Only if the center of energy lies outside the beam does one know that the event is not acceptable. The transverse momentum resolution is quite poor for the charged mode, being roughly P_T^2 = 600 $(MeV/c)^2$ for the distribution of coherent events to drop to 1/e of the central value. It is inevitable that there will be some "non-forward" background that will have to be estimated from the P_T^2 distribution in the charged mode and the events with centers of energy outside the beam in the neutral mode.

In principle one expects very little such backgrounds because of the absence of a regenerator and the vacuum of the decay region. In the Fermilab experiment the measurement of P_T^2 is an extra constraint that this experiment will not have. This experiment has, however, a much superior mass resolution, which will help to compensate for the loss of information.

A long decay volume increases the $3\pi^\circ$ decay background. The background occurs for events where two γ-rays are lost. In order for the event to reconstruct with a K mass, the vertex is displaced closer to the apparatus than the true vertex. An example of this phenomenon is shown in Fig. 19. The $K_L \to 3\pi^\circ$ events were generated by Monte Carlo at a point 80 meters from the lead glass. We consider events with two γ-rays lost without hitting the anti-counters. We plot the vertex distribution of those which reconstruct with $M_X = 500 \pm 20$ MeV/c^2 and $P_T^2 < 2500$ (MeV/c)^2. One observes that the background lies substantially beyond the decay region of the Fermilab experiment, but would fall inside the decay region of an experiment such as the CERN experiment. This curve shows qualitatively the disadvantage of a long decay region.

The CERN experiment will take data in 1985 and 1986. The collaborators expect a precision of better than 0.001 on ε'/ε.

With improved electromagnetic detectors such as BGO or CsI one might some day want to reconsider an experiment at AGS energies[10] (10 GeV K mesons). At these lower energies the inelastic contribution to regeneration of K_S mesons at finite P_T is much smaller than at Fermilab energies. In the experience of the author the level of inelastic plus incoherent regeneration is about seven times less than at Fermilab. Furthermore, regeneration amplitudes are much larger; they vary as $P^{-.62}$. If in a few years there is still a need to repeat this experiment, I believe the high intensity, low energy machine is ideal, providing one is willing to invest in an adequate apparatus which will not be cheap.

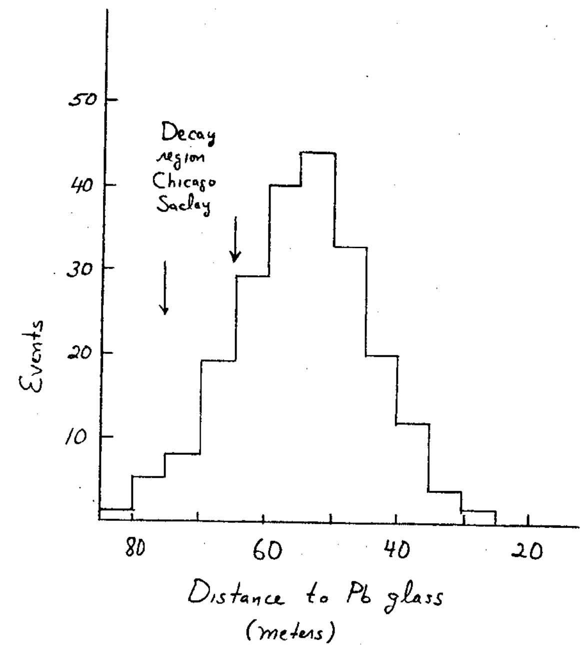

Fig. 19. Vertex distribution of $K_L \to 3\pi^\circ$ events that reconstruct as $K_L \to 2\pi^\circ$ for $K_L \to 3\pi^\circ$ decays at 80 meters from a lead glass detector.

In conclusion, we see that ε'/ε is very likely less than 0.01, and remains consistent with zero. Two new experiments, quite different in nature should give results with ~5 times greater precision than the Fermilab experiment. The hope that the K-M parameters can account for the observed CP violation remains unconfirmed.

REFERENCES

1. If the reader is not familiar with the phenomenology of CP violation, there are a number of reviews, e.g., J.W. Cronin, Rev. Mod. Phys. 53, 373 (1981); K. Kleinknecht, Ann. Rev. Nucl. Sci. 26, 1 (1976), Ling-Lie Chau, Phys. Reports 95, 1 (1983).
2. F. Gilman and M. Wise, Phys. Rev. Lett. 83B, 83 (1979).
3. F. Gilman and J. Hagelin, Phys. Lett. 133B, 443 (1983).
4. In the overall fit to the data, use has been made of precision measurements of K_L regeneration amplitudes and phases; A. Gsponer et al., Phys. Rev. Lett 42, 13 (1979).
5. Review of Particle Properties, Particle Data Group, Phys. Lett. 111B, (1982).
6. J. K. Black et al., Yale University Preprint, 1984.
7. M. Banner et al., Phys. Rev. Lett. 28, 1597 (1972).
8. M. Holder et al., Phys. Lett. 40B, 141 (1972).
9. J. H. Christenson et al., Phys. Rev. Lett. 43, 1209 (1979).
10. J. W. Cronin, Los Alamos Report LA-9566-MS, UC-34d, 1982.