EXPERIMENTAL STUDY OF WEAK INTERACTIONS BY PRECISION MEASUREMENT OF RARE KAON DECAY

PROGRESS REPORT
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PROGRESS REPORT

Task B: Experimental Study of Weak Interactions by Precision Measurement of Rare Kaon Decays

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I. OVERVIEW

The long-term interest of this group is to carry out incisive and precise measurements which seek to clarify how hadrons interact weakly. At the present time this understanding can be summarized remarkably succinctly by the the Cabibbo-Kobayashi-Maskawa (CKM) parametrization. In the early 80's we were part of a collaboration that carried out the first precise measurement of polarized $\Sigma^-\beta$ decay (Fermilab Experiment #715). Our results (Publication 1) settled a long-standing experimental controversy as to the sign of A/V, the ratio of axial vector and vector form factors in this process. As is now well-known, the controversy was resolved in favor of the "standard model" CKM parametrization. But it is important to recall that this "A/V test" was, at the time regarded as crucial to establishing the CKM picture. In addition, we collected enough statistics to obtain a reasonably accurate measurement of "weak magnetism" and further, to hint that "weak electricity" which is first-order forbidden, may in fact be larger than expected.

In 1984 we joined Bruce Winstein's NSF funded group studying decays of long-lived neutral kaons (Fermilab Experiment # 731). The main physics thrust of E731 is to investigate the existence of direct CP violation in the 2π decay modes of K^0_L by measuring the quantity Real(ϵ'/ϵ). Twenty-five years after the discovery of CP violation, its origin still remains a mystery. So far, CP violation has been observed in the two pion decays of the K^0_L and in the charge asymmetry of its semi-leptonic decays. To the extent of our current knowledge, these instances of CP violation can be totally ascribed to the CP impurity in the weak interaction eigenstate K^0_L. Direct CP violation, i.e., CP change in the decay process rather than from the initial state impurity, appears to be rare, if it exists at all. The issue is far from resolved as there is an apparent discrepancy at approximately the two standard deviation level between this experiment, which finds no evidence for direct CP violation, and a CERN experiment # NA-31 which claims an effect. Clearly, more

work is needed to settle the matter. Some clarification may emerge when we complete analysis of our entire data set, but it is becoming increasingly clear that a further generation of more precise ϵ'/ϵ experiments will be required.

Another way that direct CP violation could be observed is through the study of certain very rare K^0_L decays. One such experiment, Fermilab E799, the search for $K^0_L \rightarrow \pi^0 e^+ e^-$, has already been proposed and approved. This and other rare decay modes will be discussed subsequently.

II. E731 RESULTS

[In collaboration with Bruce Winstein's NSF funded group and Yau Wah (DOE Task J) at the University of Chicago, Elmhurst College, University of Illinois, Fermilab, and Saclay].

The principal physics goal of E731 is to investigate the existence of direct CP violation in the 2π decay modes of K_L by measuring the quantity $\text{Real}(\epsilon'/\epsilon)$.

The incorporation of CP violation in the Standard Model is done via the Cabibbo-Kobayashi-Maskawa (CKM) mixing formalism. The CKM formalism ties together the two current unknowns of the Standard Model, namely, the top quark mass and the magnitude of the direct CP violation. The Standard Model requires the existence of direct CP violation, but depending on the top quark mass, its magnitude can be quite small. Thus, a definitive measurement of the ϵ'/ϵ parameter along with a measurement of the top quark mass would provide a very powerful check of the Standard Model. A significant inconsistency between the values (or limits) of these two parameters would signal a problem with the Standard Model and would be very interesting indeed.

The current status of the ϵ'/ϵ measurement is as follows. In 1988, the CERN-NA31 group published a 3 standard deviation non-zero measurement of ϵ'/ϵ [$(+33\pm11)\times10^{-4}$]. Our group has published a lower value that is consistent with zero value [$(-3\pm14 \pm 6)\times10^{-4}$] based upon

20% of the E731 data (Publication 2).   Ours is the first determination
in which all four $K_{L,S} \rightarrow \pi\pi$ decay modes were recorded simultaneously,

allowing us to achieve the smallest systematic error ($\pm 6 \times 10^{-4}$).
The NA-31 central value lies somewhat above the current Standard Model
prediction for all values of the top quark mass, but the discrepancy
decreases for small values of the top-quark mass. Our value is
consistent with current Standard Model prejudices. At this point, the
only safe conclusion that one can draw is that more precise
measurements as well as further improvements in the theoretical
framework for predicting ϵ'/ϵ are needed. We have also extracted a
number of other important physics results from our E731 data. These
will be mentioned briefly .

(a) ϵ'/ϵ

We completed data taking on E-731 on February 15, 1988. The run
was highly successful in terms of apparatus and accelerator performance.
Our entire data set (some 5,000 tapes) contains approximately 300,000
$K^0_L \rightarrow 2\pi^0$ events. By July 1988 we had reduced 20% of our total data to

200 data summary tapes. This reduction factor of 5 was greatly
facilitated by use of the Fermilab ACP (Advanced Computer Program)
parallel processor. Over the last two years, the E731 group has
successfully understood the characteristics of the apparatus and the
data. The ϵ'/ϵ result based on 20% of the data has been published
(Publication 2).
Given the importance of knowing the ϵ'/ϵ parameter and the
apparent 2 sigma disagreement with the CERN NA31 result, analysis of the
rest of the data is the top priority of the group. The result from the total
data set should improve the error on the ϵ'/ϵ parameter to $\pm .0007$. So
far, there are no indications of any surprises in the data and we
anticipate that the final result should be ready by the end of 1990. A
substantial part of the analysis, specially for the high statistics K_{e3} and

$3\pi^0$ modes, has been carried out on a 30-node, 2 M-byte ACP I system
based at Chicago.

b) CPT violating phase difference $\phi_{00} - \phi_{+-}$

From the same 20% of the E731 data , our group has published a new measurement of the CPT violating phase difference $\Delta\Phi = \phi_{00} - \phi_{+-}$ (Publication 3). The result is $\Delta\Phi = -0.9^0 \pm 2.2^0 \pm 0.7^0$. No evidence for CPT violation was found. This result is significant in light of the earlier measurement, $12^0 \pm 6^0$, a two standard deviation departure . The total data set will provide a precision of 1.5^0. CERN NA-31 also finds that $\Delta\Phi = +0.2 \pm 2.8^0$. Our group is about to run Fermilab experiment773 with the goal of measuring this phase difference to half a degree.

(c) $K_L \rightarrow \pi^0 e^+ e^-$

The amplitude for $K_L \rightarrow \pi^0 e^+ e^-$ is composed of a CP conserving part and a CP violating part. The leading CP-conserving amplitude proceeds through two-photon exchange while the CP-violating one may proceed via one-photon exchange. Within the framework of the Standard Model where CP violation comes from the phase δ in the Kobayashi-Maskawa matrix, $K_L \rightarrow \pi^0 e^+ e^-$ may have a sizable $\Delta S = 1$ CP-violating component $(\epsilon'_{\pi ee}/\epsilon)$.

In contrast, the Superweak Model predicts $\epsilon'_{\pi ee}$ to be zero.
In terms of the CP eigenstates K_1 (even) and K_2(odd), K_L is written as

$(K_2 + \epsilon K_1)$ and one may describe the contributions to the $K_L \rightarrow \pi^0 e^+ e^-$ decay amplitude as follows: (a) the CP conserving amplitude via two photons exchange $K_2 \rightarrow \pi \gamma^* \gamma^*$, where γ^* is an off-shell photon; (b) the mass matrix "indirect" CP violation amplitude which comes from the small K_1 impurity in K_L; and (c) the "indirect" CP violation amplitude ϵ' from the one photon exchange $K_2 \rightarrow \pi^0 \gamma^*$ part of K_L. Within the Standard

Model, part (c) can be described by the "electromagnetic penguin" diagram and is comparable to or larger than part (b) in magnitude. Theoretical estimation of the "size" of this penguin is under active pursuit by our theoretical colleagues. While the predictions of the branching ratio in general are around 10^{-11}, the Weinberg Model predicts a branching ratio as high as 0.6×10^{-9}. The $K_L -> \pi^0 e^+ e^-$ decay is an attractive alternative avenue for the observation of 'direct' CP violation, particularly if the studies of the 2π decays of neutral kaon (ϵ'/ϵ) should prove inconclusive.

A limit of B.R. ($K_L -> \pi^0 e^+ e^-$) < 7.5×10^{-9} (90% C.L.) has been obtained from the complete E-731 data set. This is in agreement with the BNL E-845 result, B.R. ($K_L -> \pi^0 e^+ e^-$) < 5.0×10^{-9} (90% C.L.). E-799 at Fermilab, an experiment dedicated to search for this decay mode with a Phase I sensitivity of 2×10^{-10} will take data in early 1991. There is also keen competititon from KEK.

(d) $K_L -> \pi^0 \gamma\gamma$

$K_L -> \pi^0 \gamma\gamma$ is of current interest for several reasons. It provides an opportunity to test the Standard Model in the context of chiral symmetry: at the one-loop level in chiral perturbation theory, the decay has a predicted branching ratio of 6.8×10^{-7} with a characteristic $\gamma\gamma$ mass distribution having a peak at about 325 MeV^2. This decay also provides a CP conserving intermediate state for the $K_L -> \pi^0 e^+ e^-$ decay. One needs to measure $K_L -> \pi^0 \gamma\gamma$ well so that the interpretation of direct CP violation in $K_L -> \pi^0 e^+ e^-$ can be unambiguous. For our 20% data analysis, a result of B.R. ($K_L -> \pi^0 \gamma\gamma$) < 2.7×10^{-6} (90% C.L.) was published in 1989 (Publication 5). Our current 100% data analysis shows that with $M_{\gamma\gamma} > 300$ MeV, B.R.($K_L -> \pi^0 \gamma\gamma$) < 1.3×10^{-6} (90% C.L.). With $M_{\gamma\gamma} > 280$ MeV, B.R.($K_L -> \pi^0 \gamma\gamma$) = $(1.7 \pm 0.7) \times 10^{-6}$. This is in agreement with the recent CERN NA31

result,B.R.($K_L \to \pi^0 \gamma\gamma$) = (2.1± .6) x 10^{-6} for the same mass region. This is the subject of a Ph.D. thesis by V. Papadimitriou.

(e) $\pi^0 \to e^+ e^-$

Basically this decay can be described by a fourth order electromagnetic diagram and the branching ratio is calculated to be > 4.8x10^{-8} (the unitarity limit). The world average B.R.($\pi^0 \to e^+ e$)=(1.8± 0.7)x10^{-7} comes from two measurements, but there is some controversy concerning the validity of the results. A new technique was used to search for this decay in the current E-731 data. We have collected about 15 million reconstructed $K \to 3\pi^0$ decays. The signature of $\pi^0 \to e^+ e^-$ is then two tracks matched with leadglass showers and reconstructed as a π^0, the four extra showers reconstructed as $2\pi^0$, and all six clusters reconstructed as a kaon coming from the target. The total sample corresponds to a limit of <2.0 x10^{-7} (90% confidence). There is no background at this level. We believe this "tagged pion" technique can be exploited much further and a definite measurement can be made in the upcoming E799.

(f) $K_{L,S} \to \pi^+ \pi^- \gamma$

The radiative decay of $K_{L,S} \to \pi^+ \pi^- \gamma$ can originate from (a) inner bremsstrahlung from the virtual pions and (b) direct emission from the $K\pi\pi$ vertex. The inner bremsstrahlung is common to both K_L and K_S decays with a CP-even final state. For decays arising from direct emission the final state is CP-odd, and therefore allowed only in the K_L and suppressed in K_S decays. The 2π radiative events were selected by requiring two charged tracks and one photon shower in the leadglass calorimeter. The K_S decays has the characteristic 1/k spectrum of inner bremsstrahlung. The K_L decays have both the 1/k and the CP-allowed direct emission.

Results for these 2π radiative decays from E731 are:

B.R. $(K_S \to \pi^+\pi^-\gamma, E_\gamma > 50 \text{MeV}) = (2.41 \pm 0.06) \times 10^{-3} \times$ B.R.$(K_S \to \pi^+\pi^-)$,

B.R. $(K_L, \to \pi^+\pi^-\gamma, E_\gamma > 20 \text{MeV}) = (1.45 \pm 0.09) \times 10^{-5}$.

These represent major improvements from previous results. Also from the K_S decays, one can extract from the proper time distribution behind the regenerator, the parameter $\eta_{+-\gamma}$. It is measured to be $\eta_{+-\gamma} = (2.0 \pm 0.2) \times 10^{-3}$. This is the 4th unambiguously non-zero CP violation parameter ever measured joining η_{+-}, η_{00} and δ.

(g) K_{e_4}

Before this experiment, only 15 events had been observed. We have a total of 780 events observed yielding a branching ratio of

B.R. $(K_L \to \pi^\pm\pi^0 e^\pm \upsilon) = (5.6 \pm 0.2 \pm 0.4) \times 10^{-5}$. This decay mode, unlike its charged partner K^+_{e4} is p-wave dominated rather than s-wave. Further angular distribution analysis may also test various form factor contributions. One of them could be direct CP violated.

(h) K_{23}

Since the ϵ'/ϵ measurement requires a very thorough understanding of the detector acceptance, we collected approximately 100 million K_{e3} events during the E731 run in order to monitor the charged mode acceptance. This is the largest sample of K_{e3} events ever collected and not surprisingly, is an avenue for independent physics measurements. We expect to measure the CP violating semi-leptonic asymmetry parameter δ to a precision of $\pm 0.008\%$; the current world average has a precision of $\pm 0.012\%$. These data may also yield a new measurement of the K_{e3} form factor.
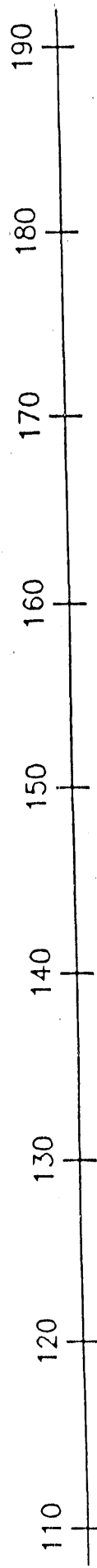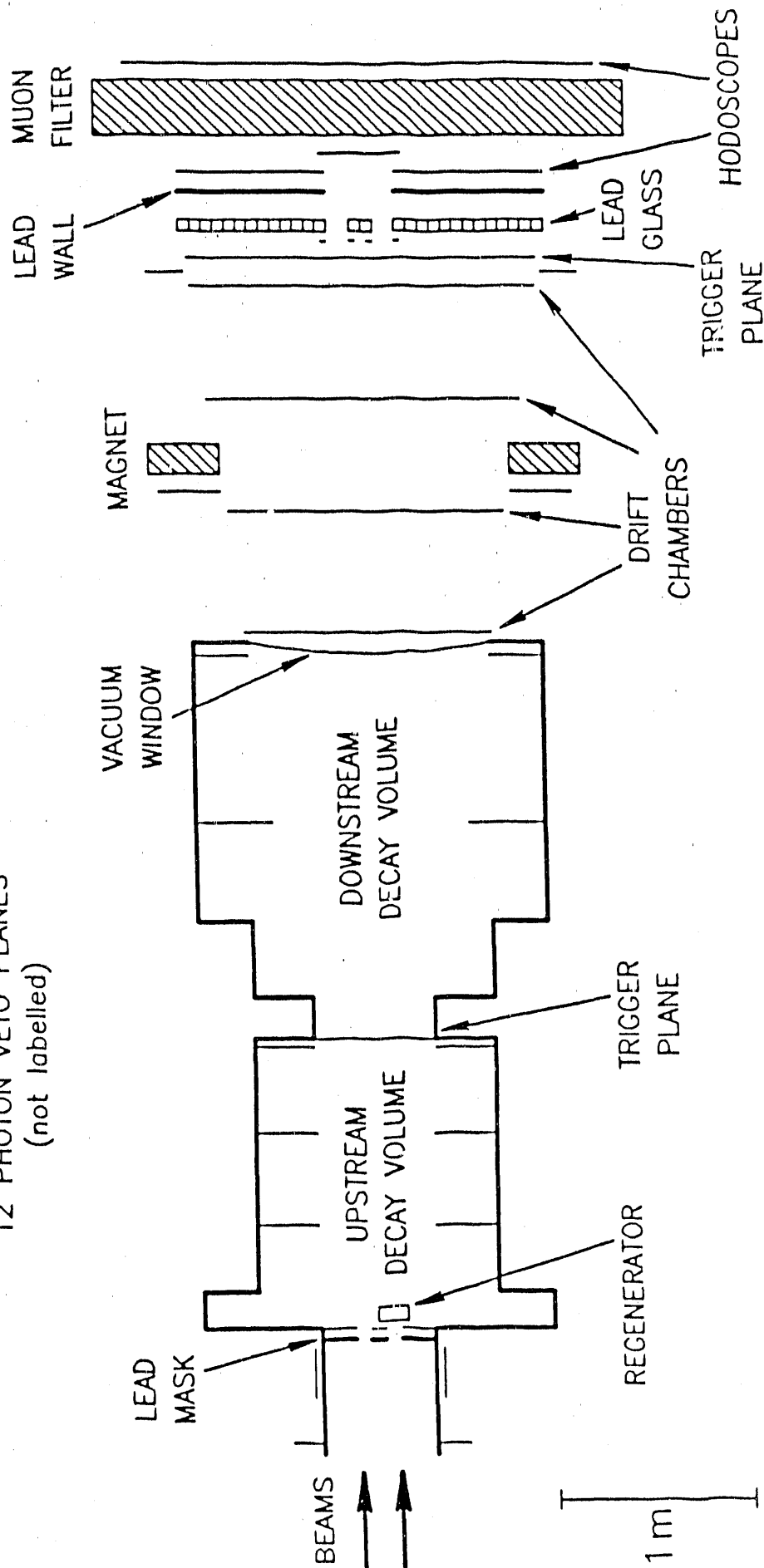
(i) $K_L \rightarrow 3\pi^0$ decay constant

In a similar fashion, we wrote approximately 15 million $K_L \rightarrow 3\pi^0$ decays to tape during E731 to monitor the neutral mode acceptance of the detector. Again, this is the largest $3\pi^0$ sample to date. We expect to publish the first-ever measurement of the quadratic slope term in the $3\pi^0$ Dalitz plot. This quantity is closely tied to the second order term in the Chiral Lagrangian, and can be used to confront the Lattice Gauge calculations. The $3\pi^0$ mode offers a very clean way of measuring the quadratic slope term of the Dalitz plot since there are no charged particles in the final state. Also, because of the three-fold symmetry, only the $3\pi^0$ decay has an identically zero linear slope term, and as a result, the quadratic term has no corrections. For a decay such as $K_L \rightarrow$

$\pi^+\pi^-\pi$, the quadratic slope term is dominated by the square of the linear term. From the same data sample, we are in the process of measuring the K_S CP violation parameter η_{000}. Barring major surprises, we expect to improve the current limit on η_{000} by a factor of two or so.

III. PREPARATION FOR FERMILAB E-773.

Neutral Kaons offer one of the most sensitive ways of investigating the possibility of CPT violation in nature. Assuming CPT symmetry, our current experimental knowledge of the phase and magnitude of ϵ, the values of the strong $\pi\pi$ phase shifts, and the ratio η_{00}/η_{+-} dictate that the phase difference $\Delta\Phi$ between η_{00} and η_{+-} must be less than a fraction of a degree. A value of $\Delta\Phi$ larger than this would clearly signal a violation of CPT invariance and its measurement would occasion considerable excitement. Fermilab experiment 773 is designed to determine $\Delta\Phi$ to an accuracy of half a degree. This experiment is scheduled to begin taking data at Fermilab near the end of 1990. The apparatus for E773 (Fig. 1) consists of the E731 spectrometer with

12 PHOTON VETO PLANES (not labelled)

BEAMS

1 m

LEAD MASK

UPSTREAM DECAY VOLUME

REGENERATOR

TRIGGER PLANE

DOWNSTREAM DECAY VOLUME

VACUUM WINDOW

DRIFT CHAMBERS

MAGNET

TRIGGER PLANE

LEAD WALL

LEAD GLASS

HODOSCOPES

MUON FILTER

HODOSCOPES

Distance from production target [m]

FIGURE 1. SCHEMATIC OF E-731 SPECTROMETER

appropriate modifications. These modifications involve changes in the beamline, a new configuration with two regenerators instead of one, and improvement in tracking capabilities at the trigger level.

A major new feature of the experiment is the presence of a fully active downstream regenerator which moves periodically between the two Kaon beams. Unlike its E731 counterpart, the new regenerator is made entirely out of plastic scintillator material instrumented with photomultiplier tubes. This feature allows one to study and reject the K_S events arising from non-coherent regeneration. It also allows the rejection of events that produce cross-over between the two Kaon beams, thus reducing the systematic error. Due to a very high hadronic shower background rate, observing the very small signals resulting from diffractive regeneration in the scintillator is a challenging task. In addition, the signals have to be delayed significantly prior to digitization in order to be in time with the rest of the detector. The active regenerator overcomes these challenges by employing fast scintillator and photomultiplier tubes, active voltage dividers and shaping amplifiers. The regenerator was designed and built last year, and is currently in the beamline. A more detailed description of the active regenerator is given in Appendix A.

The regenerator was successfully tested during the two E773 test runs during the Summer of 1990 . The regenerator was able to tolerate the high rates produced by 3×10^{12} protons per pulse without excessive PMT anode current. We find that the coherent peak ($p_t^2=0$) is reduced by only 2% after background subtraction, whereas the background events are reduced by an enormous 68%. The active regenerator has clearly performed very well during the test runs, and we are eagerly looking forward to the data from the full E773 run toward the end of the year.

IV. PREPARATION FOR FERMILAB E-799, PHASE 1

E799 which has an ultimate goal of observing $K_L \rightarrow \pi^0 e^+ e^-$ with a sensitivity of $< 1 \times 10^{-11}$ (90% C.L.), was approved by the Fermilab PAC in

June 1989 for two fixed target runs. Phase I (with a goal of 2×10^{-10} will start in early 1991 for two months according to the most recent Fermilab schedule. Besides the necessary beam-line work (mostly rigging of vacuum pipes) to change over from E-773, three modules of TRD (Transition Radiation Detector) will be installed.

A full size TRD module was constructed during 1990. It is essentially a longitudinal drift chamber with 200 sense wires. It was moved into the beamline and was tested comprehensively during a 2 week hadron beam period. The chamber together with a newly developed Xe-recirculating gas system, worked satisfactorily and provides a π/e rejector of about 4.5 per module. With a total of three modules at Phase I, a rejector factor of 70 is anticipated.

V. Publications

1. High-precision measurement of polarized-Σ^- beta decay, S.Y. Hsueh, D. Muller, J. Tang, R. Winston, G. Zapalac, E.C. Swallow, et al., Phys. Rev. D. <u>38</u>, 2056, (1988).

2. Determination of $Re(\epsilon'/\epsilon)$ by the simultaneous detection of the four $K_{L,S} \to \pi\pi$ decay modes, J.R. Patterson, A. Barker, R.A. Briere, L.K. Gibbons, G. Makoff, V. Papadimitriou, S. Somalwar, Y.W. Wah, B. Wiknstein, R. Winston, M. Woods, H. Yamamoto, E. Swallow, et al., Phys. Rev. Lett. <u>64</u>, 1491, (1990).

3. A test of CPT symmetry through a determination of the difference in the phases of η_{00} and η_{+-} in $K \to 2\pi$ decays, M. Karlsson, G. Gollin, J. Okamitsu, R. Tschirhart, A. Barker, R.A. Briere, L.K. Gibbons, G. Makoff, V. Papadimitriou, J.R. Patterson, S. Somalwar, Y.W. Wah, B. Winstein, R. Winston, M.Woods, H. Yamamoto, E. Swallow, et al., Phys. Rev. Lett <u>64</u>, 2976 (1990).

4. New limit on $K_L \to \pi^0 e+e-$, A. Barker, R. Briere, L.K. Gibbons, G.

Makoff, V. Papadimitrious, J.R. Patterson, S. Somalwar, Y.W. Wah, 3. Winstein, R. Winston, M. Woods, H. Yamamot, E. C. Swallow, et al., Phys. Rev. D. 41, 3546, (1990).

5.   Search for $K_L \rightarrow \pi^0 \gamma \gamma$, V. Papadimitriou, L.K. Gibbons, J.R. Patterson, Y. Wah, B. Winstein, R. Winston, M. Woods, H. Yamamoto, E.C. Swallow, et al., Phys. Rev. Lett. 63, 28, (1989).

APPENDIX

ACTIVE REGENERATOR FOR E773

The active regenerator consists of a total of 0.4 meters of plastic scintillator in the Kaon beamline. Its purpose is to regenerate a K_S beam from the K_L beam. The scintillator is viewed by photomultiplier tubes in order to distinguish the coherent regeneration from the ineleastic and diffractive regeneration. Since the presence of a signal in the PMT is caused by a localized interaction, such a signal implies non-coherent regeneration. The length of the regenerator was decided on the basis of an optimization study of the E773 experiment.

The background light in the scintillator is produced mostly by the charged particles produced in hadronic showers. Due to the high rate of hadronic showers, pulse pile-up is expected to be a problem, especially since the signal size from a typical diffractive event can be as small as a few photoelectrons. On the other hand, a hadronic shower can create as many as 20,000 photoelectrons in a 1" thick scintillator. If the shower occurs in the accelerator rf bucket previous to the one in which the signal occurs, the PMT has to recover completely in approximately 20 nsec. In addition, the PMT output has to be delayed by approximately 500nsec to give the trigger enough time to make the digitizing decision.

The dispersion in the delay cable exacerbates the signal pile-up.

A possible solution is to have individual scintillator blocks much smaller than 1", which is clearly impractical. The proposed solution to avoid the pile-up is to use fast scintillator in conjunction with fast PMT's, and shape the tube output with a high-pass filter in order to eliminate the slow components entirely. The price one pays is in the attenuation of the signals. This attenuation is in addition to the attenuation due to the delay cable. Because of the average anode current limitation ($<100\,\mu A$), one cannot increase the PMT gain enough to compensate for the attenuation due to the delay cable and shaping circuit. As a result, one has to resort to low-noise external amplification of the PMT signal.

One additional problem encountered in a high rate PMT environment is that of random after pulsing due to the residual gas in the PMT. The amount of after pulsing depends on the total PMT activity, which, as stated above, is very large in our case. As a result, the probability of seeing a random afterpulse of expected signal size in at least one of the channels of the detector is significant. For example, with the expected hadronic shower background in E773, one would, on an average, get afterpulses bigger than ten photoelectrons in at least one of the channels in the regenerator once in 5 pulses. The Carbon diffractive signal is then simply washed out. The after pulsing probability is eliminated to a large degree by having more than one PMT look at the same scintillator, and demanding multiple coincidence.

Finally, one also needs excellent optical collection in order to see the very small signals that one expects from diffractive events. The PMT is mounted directly on the scintillator. Teflon tape normally used as a pipe sealant works as an efficient diffuse reflector for wrapping the scintillator.

The regenerator relies very heavily on the electronics to overcome the severe environmental conditions described above. To this end, we designed and custom-made the amplifiers for the PMT's.

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