THE PHYSICS OF KAON DECAYS: CP VIOLATION AND LEPTON FLAVOR NONCONSERVATION

William R. Molzon

University of California, Irvine, CA 92717

Bruce D. Winstein

University of Chicago, Chicago, IL 60637

AT03-76ER11019

The participants in the working group were: K. Arisaka, UCLA, G. Bock, Fermilab, S. Childress, Fermilab, R. Coleman, Fermilab, T. Diehl, Rutgers, R. Ford, Fermilab, G. Gollin, Illinois, A. Heinson, Irvine, B. Hsiung, Fermilab, D. Jensen, Massachusetts, E. Ramberg, Fermilab, W. Slater, UCLA, S. Somalwar, Chicago, G. Thomson, Rutgers, R. Tschirhart, Fermilab, T. Yamanaka, Fermilab.

ABSTRACT

We discuss here the research that is likely to be done in the 1990's in the study of kaon decays. We concentrate on searches for direct CP violation and for the violation of electron- and muon-number, including approved and proposed experiments at existing facilities, and those which could be done at a facility using the proposed Fermilab Main Injector.

I. INTRODUCTION

The working group on the physics which could be done with kaons in the 1990's focused largely on prospects for improving our knowledge of CP violation and electron- and muon-number conservation. Specifically, the group studied various aspects of the following experiments:

- a measurement of ϵ'/ϵ to a precision below 10^{-4} ,
- a search for the lepton-flavor-violating decays $K_L^0 \rightarrow \mu^\pm e^\mp$ and $K_L^0 \rightarrow \pi^0 \mu^\pm e^\mp$ with a sensitivity below 10^{-13} ,
- a search for the decays $K_L^0 \rightarrow \pi^0 e^+ e^-$ and $K_L^0 \rightarrow \pi^0 \mu^+ \mu^-$ to a sensitivity below 10^{-13} ,
- a search for the decay $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ to a sensitivity below 10^{-12} .

There will be significant improvement in our present knowledge of these processes in the next five years from running or proposed experiments at Brookhaven, Fermilab, CERN and KEK. Approaching the sensitivities mentioned above will probably need the higher luminosities and/or energies of new accelerators. Two such machines could be used in the next decade for these experiments: the KAON facility at TRIUMF and the

new Main Injector at Fermilab. In the near term, improvements will come from a number of detectors separately optimized for each study. Really significant advance in these modes will require ambitious experiments involving technologies approaching those needed for SSC experiments. It may be that the best chance for progress will come in a facility capable of doing many experiments without significantly compromising any of them.

In this report, we will discuss the motivation for this continuing series of experiments, review the status of approved and planned experiments, and discuss the technical issues and possible implementations for a facility capable of doing many of the measurements discussed above. Additional information can be found in the proceedings of the Fermilab Workshop on Physics at the Main Injector¹, the Vancouver Workshop on Science at KAON², and the Breckenridge Workshop on Physics at Fermilab in the 1990's³. Information on approved experiments can be found in the proposals to the laboratories^{4,5,6,7,8,9}.

II. PHYSICS MOTIVATION AND STATUS

The physics motivation for a continued study of CP violation in the kaon system is well documented, and we will summarize it here only briefly. After 25 years of study, our total knowledge of CP violation can be ascribed to the fact that the linear combinations of $K^0 \bar{K}^0$ with definite mass and lifetime (the K_L^0 and K_S^0) are not eigenstates of the CP operator. The underlying cause of the observed CP violation is unknown. It could be due to a non-zero phase in the CKM quark mixing matrix, in which case other manifestations would be found in kaon and other systems. Alternatively, it could be due to a superweak interaction in which case the observable effects could be

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Figure 1. ϵ'/ϵ vs. M_T from Buchalla, Buras, and Harlander. The curves represent the "standard" range of ϵ'/ϵ values while the dashed curves represent the allowed range when all parameters ($\bar{R}$, s_{23} , Λ_{QCD} , B_K , and m_t) take their extreme values. Also shown are the measurements by E731 (for their 20% data sample) and NA31. Parts a) and b) are for δ , the phase of V_{ub} in the first and second quadrant, respectively.

limited to what we have already seen.

Additional information will come from more precise determinations of the ratio ϵ'/ϵ and measurements of the branching ratios $K_L^0 \rightarrow \pi^0 e^+ e^-$, $K_L^0 \rightarrow \pi^0 \mu^+ \mu^-$, and $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$. Also, high statistics studies of B mesons, where relatively large effects are expected, may help aid in the study of CP violation. One could also study CP violation in the K system using new kaon sources; i.e. by producing ϕ mesons in e^+e^- collisions and using the $K^0 \bar{K}^0$ or $K^+ K^-$ decay modes to produce a well defined initial state in which to study decays¹⁰.

The most precise determinations of ϵ'/ϵ are from NA31¹¹ at CERN and E731¹² at Fermilab. Their results are shown in figure 1, superimposed on a plot of the most recent calculations¹³ of the expected value if the observed CP violation is due to a non-zero phase in the CKM matrix. The expectation depends on the top quark mass, and for sufficiently large t-quark mass, the value could be zero or even negative. Clearly, a more precise determination is needed. E731 has in hand data to determine this parameter to a statistical precision of .0006, and NA31 has additional data which will yield a significant improvement in their statistical precision. On a longer time scale, both groups have proposals to improve their measurements^{5,6}, and a precision approaching 0.0001 in the next 4-5 years is possible. As seen in figure 1, even this may not be sufficient to unambiguously determine if the standard model prediction for this parameter is correct, and more precise determinations will be of use.

Closely coupled with the issue of a non-zero ϵ'/ϵ is the branching ratio for the $K_L^0 \rightarrow \pi^0 e^+ e^-$ mode, which is expected to be of the order of 10^{-11} . A

substantial fraction of this decay should be direct CP violation, arising from contributions with virtual top quarks. The direct branching ratio has been calculated¹⁴ to be

$$B(K_2 \rightarrow \pi^0 e^+ e^-) = 10^{-5} \times (s_2 s_3 s_\delta)^2 G(M_T),$$

where G is a function of the top quark mass of order unity and the original CKM matrix element notation is used. Using the constraint on the CKM mixing angles provided by the observation of $B\bar{B}$ mixing, this can be expressed in terms of β , one of the angles of the CKM unitarity triangle, B_B , the bag factor for the K meson system, and f_B , the B meson decay constant, and another function of M_t of order unity:

$$B(K_L^0 \rightarrow \pi^0 e^+ e^-) = 5 \times 10^{-13} \sin^2 \beta / (B_B f_B^2 F(M_t)),$$

Given the possible values of the constants in the above expression, the value for the direct branching ratio could range from about 10^{-12} to 10^{-11} with a central value of 3×10^{-12} .

The limits on this mode come from experiments at BNL E845, Fermilab 731, and CERN NA31. E851 was optimized for this experiment, and achieved a limit of 5.5×10^{-9} , while E731 set a limit of 7.5×10^{-9} . E799, a follow-on experiment to E731, proposes to reach a sensitivity of the order of 10^{-10} in their 1991 run, while an experiment at KEK⁹ proposes to reach 10^{-11} .

The difficulty lies in isolating the contribution from the diagram of interest from three other contributions: an indirect term, coming from the $K_1 \rightarrow \pi e e$ transition, a CP conserving term coming from the $K_2 \rightarrow \pi^0 \gamma \gamma$ intermediate state, and a background coming from the $K_L \rightarrow e^+ e^- \gamma \gamma$ radiative decay. Based upon the use of chiral perturbation theory, the prediction¹⁵ for the branching ratio for the indirect term has a two-fold ambiguity: the value should be either 1.5×10^{-10} or 2.4×10^{-11} . This should be directly determined, but for now the ambiguity can be broken by a study of the similar decay $K^+ \rightarrow \pi^+ e^+ e^-$. Experiment E777 at Brookhaven has about 700 of these events¹⁶ with relatively high ee invariant mass and their spectrum favors a distribution for the $e^+ e^-$ mass peaked at the high end of the allowed range; this strongly suggests the lower value for the corresponding K_1 transition.

For the CP conserving transition, there are competing theories which give values between 10^{-14} and 10^{-11} for the two photon (CP conserving) K_2 transition to $\pi^0 ee$. There are now two observations^{17,18} of the $K_L^0 \rightarrow \pi^0 \gamma \gamma$ branching ratio and high values for the $\gamma \gamma$ invariant mass are strongly favored in both observations. This again favors the chiral perturbation theory prediction for the lower branching ratio.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

It was recently realised¹⁹ that an essential background to this mode results from the decay $K_L^0 \rightarrow \gamma\gamma e e$ decays in which the two photons have an invariant mass equal to the π^0 mass within the resolution of the detector. This makes it unlikely that this mode will be seen in a background free experiment. Even so, one should be able to isolate the direct contribution given a superb photon calorimeter and sufficient experimental sensitivity. These points are further discussed in section VII. Similar considerations apply to the decay $K_L^0 \rightarrow \pi^0 \mu^+ \mu^-$.

The mode $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ is yet another possibility for observing direct CP violation²⁰. It is thought to be completely dominated by direct CP violation. There are no contributions due to either one or two photon intermediate states. The direct CP violating rate is expected to be a factor of 5-6 higher than that for $K_L^0 \rightarrow \pi^0 e^+ e^-$; a factor of three in this ratio is due to the existence of three neutrino species in the final state. Discovering this decay requires detecting a single isolated π^0 in an environment of K_L^0 decays with 2 and 3 neutral pions in the final state. Little is presently known about this mode. Some progress will come in the next few years as a by-product of other experiments, but sensitivities near the theoretical expectation will require a completely new experiment operating at high rates.

The apparent conservation of additive quantum numbers associated with each type of lepton continues to hold despite sensitive searches in kaon decay experiments^{21,22,23}, muon decay experiments^{24,25}, and attempts to observe muon to electron conversion in the field of heavy nuclei²⁶. No clear theoretical prediction exists for the level at which one would expect to see muon and electron number violation. Within specific models, one or another of the possible ways of detecting violations of muon- and electron-type lepton number may be more or less favored. In a model in which the decay is mediated by a new gauge boson coupling to μe and $s\bar{d}$, muon decay experiments impose stringent constraints on the lepton vertex, while the smallness of the K_L-K_S mass difference imposes severe constraints on the hadron vertex. For some models in which there are selection rules (i.e. conservation of additive quantum numbers associated with the three generations of quarks and leptons), neutral kaon decay may be the most sensitive probe available.²⁷ In any event, assuming that coupling constants are equal to the electroweak coupling constant, the mass range probed by these experiments is of the order of a few hundred TeV/c^2 for sensitivities of order 10^{-13} .

The best limits on $K_L^0 \rightarrow \mu^\pm e^\mp$ have been set at

BNL by E791. The current limit on $B(K_L^0 \rightarrow \mu^\pm e^\mp)$ is 6.4×10^{-11} based on about half of their data. In the next few years, the sensitivity should improve by roughly an order of magnitude in an experiment proposed by many of the E791 collaborators (BNL P871). With a detector better optimized for high rates and a kaon decay rate of 2×10^7 , two years (4000 hours) of running should result in a sensitivity below 10^{-12} by 1995.

Two decays complementary to this one are $K^+ \rightarrow \pi^+ \mu^\pm e^\mp$ and $K_L^0 \rightarrow \pi^0 \mu^\pm e^\mp$. The former has been searched for at BNL by E777¹³ to a sensitivity of 2.1×10^{-10} , and a new experiment is being mounted (E851) which should improve this by more than a factor of 10. These decays involve axial vector or tensor interactions while $K_L^0 \rightarrow \mu^\pm e^\mp$ would be mediated by a scalar or vector interaction. Since the Lorentz structure of the decay process is undetermined, either the three body or two body decay modes may be suppressed or non-existent. From the present $K^+ \rightarrow \pi^+ \mu^\pm e^\mp$ limit, one can infer a limit on the decay $K_L^0 \rightarrow \pi^0 \mu^\pm e^\mp$ of about 10^{-9} , where the increase in the limit is due to the difference in lifetimes of the K^+ and K_L^0 . There are no approved experiments to search for $K_L^0 \rightarrow \pi^0 \mu^\pm e^\mp$. As we will discuss in section VIII, a facility operating at the main injector could have sufficient rate to reach a sensitivity in the range of 10^{-13} .

In the remainder of this report, we will discuss the technical issues to be solved to make substantial progress after the current round of approved experiments are finished in the mid 1990's. In this discussion, we concentrate on a facility which could be built at the main injector.

III. MAIN INJECTOR AS KAON FACTORY

In many respects, the Fermilab main injector would be close to an ideal accelerator at which to further explore rare and CP violating decays of neutral kaons. The results from the high intensity, good duty factor, and the 120 GeV operating energy. We here discuss these attributes in comparison with the accelerators used to produce the best previous experiments.

The best e'/e measurements have been done at high energy machines using modest kaon fluxes. These experiments reached a single event sensitivity below 10^{-9} . Since the fractional energy resolution scales as $1/\sqrt{E}$, high kaon energy is an advantage. Also, a relatively small fraction of the photons of interest have energy less than or equal to that deposited in the photon detector by minimum ionizing particles, thus minimizing backgrounds from this source. The main injector will provide the additional flux needed to reach signifi-

icantly higher precision. The photon energies will be somewhat lower, necessitating improved calorimetry. However, new total absorption scintillating detectors promise improved resolution, and the lower average energy is not expected to be a disadvantage.

For the decay $K_L^0 \rightarrow \pi^0 e^+ e^-$, comparable results have been achieved by experiments at both high and low energies: BNL E845 and Fermilab E731. The requirements of this experiment are similar to those of the e'/e experiment, with the increased flux being even more critical in achieving the improved sensitivity.

The best limits on lepton flavor violating decays have been set at low energy machines. These experiments benefitted from the higher kaon fluxes obtainable with the high repetition rate and large current (1.6×10^{13} protons every 3 seconds in a 1.2 second spill) of the BNL synchrotron. Even the KEK synchrotron, with its lower current ($\approx 2 \times 10^{12}$ protons every 2.5 seconds) coupled with a good experiment was competitive with the BNL effort. Additional benefits accrued from the relative ease of triggering on electrons using threshold Cerenkov counters and the ability to determine the approximate energy of the muon by measuring its range in matter. Disadvantages resulted from the relatively worse K_L^0/n flux ratio at low energies and the large flux of kaons at energies below that for which the detectors had acceptance. The kaon spectrum at the main injector will be better matched to the experimental techniques and will have a larger kaon flux and a reduced n/K_L^0 flux ratio.

Table 1 presents typical characteristics of the proton beam which could be used to produce a neutral beam. With this beam incident on a 1A Be or BeO target,

Table 1
Main Injector Proton Beam

Energy	120 GeV
Intensity	3×10^{13}
Spill Length	1.9 sec
Repetition Rate	3.8 sec
Structure	debunched

a flux of order of a few times 10^{11} kaons would be produced at 0° production angle in a beam of $36 \mu\text{str}$. The proton beam energy is high enough that a large fraction of the kaon flux is in the energy interval of use. The cycle time of the machine is comparable to that at BNL and large currents will be available.

For the e'/e experiment, it is particularly important that the proton beam spot on the target be precisely positioned and stable. The proton transport has been designed for stability, and with active feedback on the

position, it is anticipated that stability could be maintained at the $10 \mu\text{m}$ level.

In order to reduce the contamination of neutrons in the beam, one would choose a beam at non-zero targeting angle, and preferentially absorb the neutrons with a low atomic number material. To minimize the flux of photons, they would be converted in a high-Z material and the resulting electrons swept from the beam. Using a photon converter of 12 radiation lengths of lead and a neutron moderator of 45 cm of beryllium results in the kaon beam shown in table 2, for different production angles. Figure 2 shows the momentum

Table 2
Main Injector Proton Beam

θ (mrad)	Kaon Flux (GHz)	Neutron Flux (GHz)	Decays (MHz)
0	4.9	76.0	174
8	3.8	14.0	158
16	2.7	3.2	139
20	2.2	1.9	130
24	1.9	1.3	120
32	1.5	0.7	104

spectrum at different production angles derived from protons of 24 and 120 GeV energy.

Figure 2. The flux of kaons decaying in an 18m long decay channel. The flux shown is for a beamline without a neutron moderator.

Significant work has gone into designing the neutral beam elements necessary to produce such a beam. In particular, the problem of reducing the muon flux in the spectrometer has been extensively studied with GEANT simulations. These techniques have also been used to study neutron and photon contamination in the kaon beam channel. Targets capable of handling fluxes of up to 3×10^{13} protons per pulse have been designed.

Figure 3 shows a possible design for the neutral

good acceptance, one would attempt to construct the chambers without a hole for the beam. About 0.1% of the beam would interact in the chambers, but the total rate would still be dominated by particles from kaon decays. It would be advantageous to have the left and right sides separated to minimize the rate per wire and simplify the triggering.

Following the charged particle spectrometer are detectors for identifying leptons and measuring photon and electron energies. Electron identification at the trigger level is done with either transition radiation detectors or threshold gas Cerenkov counters. For the $K_L^0 \rightarrow \pi^0 e^+ e^-$ experiment, which concentrates on kaon energies above 15 GeV/c, one is mostly interested in electrons above 2 GeV/c where TRD's can be made with relatively high efficiency. For the $K_L^0 \rightarrow \mu^\pm e^\mp$ and $K_L^0 \rightarrow \pi^0 \mu^\pm e^\mp$ searches, which use the large kaon flux down to 3-4 GeV, one would want to use electrons down to 1 GeV/c or less, and a Cerenkov counter may be needed for that.

Electromagnetic energy would be measured in a scintillating total absorption detector, probably an array of undoped CsI crystals. The most stringent constraints on the performance of this device are imposed by the e'/e experiment in terms of understanding of the resolution and energy scale in the device, particularly the linearity and the tails of the energy resolution, as discussed in section VII. The resolution is extremely important for the $K_L^0 \rightarrow \pi^0 e^+ e^-$ search, since the level of background from the primary source is proportional to the resolution. Present thinking centers on either a tower arrangement or alternating layers of X and Y slats.

Muon identification would be done with scintillation counters following passive absorber sufficient to fully absorb the showers from electrons and nearly all the pions from kaon decay. A rangefinder consisting of passive absorber and active readout layers would be used to measure the energy of muons below 12 GeV by range. This would aid in identifying muons from pion decay and eliminating accidental coincidences in the muon scintillators giving a fake muon signature.

We next discuss some of the specifics of the various measurements.

V. e'/e MEASUREMENT

As was discussed in section II, we will likely know the value of this parameter by the mid 1990's to a precision approaching 10^{-4} as a result of ongoing efforts at Fermilab and CERN. However, there is no guarantee that a non-zero effect will be seen and therefore one

would like to improve our knowledge by another order of magnitude if possible. The flux is available at the Main Injector to make such a measurement and there are a few possible techniques that could be attempted. Here we will describe one of them.

For the accurate determination of e'/e , one must obtain very high statistics as well as reduced systematic uncertainty. At the Main Injector, the flux is great enough that one can still accumulate the required level of statistics while employing a small target and very small solid angle beams to reduce the level of systematic uncertainty. Very likely a variation of the double beam method of E731 will be employed. A regenerator is used for making the K_S^0 's so that the coherent K_S^0 and K_L^0 have identical beam shapes. Since the regeneration power is greater at lower energies, relatively less flux on the regenerator is required, lowering the ambient rate in the apparatus.

Table 3 gives some properties of the beam and characteristic rates of a possible experiment. The singles rates in the detectors are modest and are dominated by the interaction rate in the regenerator. The decay rate shown is only for K_L^0 decays within a fiducial decay volume of about 18m. The acceptance shown is for the four body $K_L \rightarrow \pi^0 \pi^0$ and it is large for the momentum range indicated. This range is also favorable since the gamma energy resolution improves with energy and, to accurately compare the decay rates into $2\pi^0$ and $\pi^+ \pi^-$, the best possible energy resolution is needed. An important feature is that in the analysis only 2 pion decays in a 2m region around the regenerator for both beams are used for this measurement; as a result systematic uncertainty from any acceptance difference between the two beams becomes small. In calculating the sensitivity here and in subsequent sections, we assume the accelerator and detector will be up 35% of the year, or very close to the 10^7 second "Snowmass" year.

Table 3
Beam Properties and Detector Rates
for e'/e Experiment

Beam Flux	3×10^{13} protons/pulse
Target length	8cm
Solid angle (each beam)	$1 \mu\text{sr}$
Momentum range	10-50 GeV/c
Decay rate (K_L^0)	0.6 MHz
$2\pi^0$ acceptance (18m region)	35%
Singles rate (from regenerator)	7.5 MHz
Sensitivity per year (35% efficiency)	2×10^{-3}

The final source of systematic error will be the un-

beam. It includes a large sweeping magnet immedi-

Figure 3. The neutral beam channel.

ately downstream of the target, a second magnet with field rotated by 90° to sweep muons produced in the beam dump away from the detector, and a third magnet to remove charged particles produced in the final beam defining collimator. GEANT modelling has been used to optimize the design. The beam impinges on the target at an angle of 20 mrad from the horizontal. The noninteracting protons are transported away from the neutral channel to a dump. Muons produced in this dump are swept horizontally away from the detectors.

The final collimation is done at a station 14 meters from the production target. It is envisaged that this collimator would be replacable; different inserts would be used to produce beam configurations optimized for each experiment. The region beginning at the first collimator and extending through the decay region would be evacuated.

IV. EXPERIMENTAL FACILITY

Figure 4 shows a possible experimental layout. It consists of the beam defining elements discussed above, a 20m long evacuated neutral decay channel, a charged particle spectrometer with two sequential analysing magnets and five planes of multilayer precision tracking devices, a high resolution photon calorimeter, and trigger counters and other lepton identifying detectors. In addition, for the $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ experiment, there exists a hermetic veto system surrounding the evacuated decay region. For this experiment, the apparatus would be reconfigured with the electromagnetic calorimeter following immediately downstream of the vacuum decay region.

The detector is required to perform the following functions:

Figure 4. A plan view of a kaon decay facility for the Main Injector.

- measure photon energies with a precision of $\sigma(E)/E < 0.5\%$ at 5 GeV, primarily for the e^+e^- and $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ experiments,
- measure charged particle momenta to a precision of 0.3% for momenta up to 15 GeV/c, and detect pion decays in the spectrometer with high efficiency, primarily for the $K_L^0 \rightarrow \mu^\pm e^\mp$ and $K_L^0 \rightarrow \pi^0 \mu^\pm e^\mp$ searches,
- detect photons above 200 MeV/c from $K_L^0 \rightarrow \pi^+ \pi^-$ decays with very high efficiency, to reduce background in the $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ search,
- identify electrons and muons with high efficiency while rejecting contamination from other particle types to below 10^{-4} ,
- operate in a charged particle flux above $10^8/\text{m}^2/\text{sec}$, and a similar flux of photons.

The apparatus envisaged has five planes of high precision tracking devices, either small-cell drift chamber or thin-walled straw tubes around two analysing magnets with 300 MeV/c transverse momentum kick. To reduce the probability of multiple hits in the same cell, the maximum drift distance is about 3mm and a gas such as argon-CF₄ with a drift velocity of roughly 100 $\mu\text{m}/\text{nsec}$ would be used. The maximum rate per wire would be about 10^6 , with a probability of about 3% of having a hit in each cell in the maximum drift time. We assume a resolution of 150 μm would be achieved, somewhat worse than has been achieved in large chambers using argon-ethane gas. To preserve

certainty in the residual background. There are effects arising from scattering in the regenerator where a K_S^0 decay can wind up in the vacuum beam (in the neutral mode). With the small beams used and with a fully active regenerator in vacuum (i.e. one made entirely of scintillator), this effect is less than 1% and more importantly is identical for charged and neutral decays so that it both largely cancels and can be very well determined. The background from $3\pi^0$ decays which fake $2\pi^0$ decays is at the 0.4% level in E731; this background is not as easy to simulate and thus it should be lowered significantly. This will be accomplished with a fine grained, high precision electromagnetic calorimeter (CsI or BaF₂) and an additional extensive anti-counter system surrounding the decay region to catch missing gammas from this mode. Thus it appears that a determination with nearly 10^{-5} precision could be performed.

VI. $K_L^0 \rightarrow \pi^0 \mu^+ \mu^-$ and $K_L^0 \rightarrow \pi^0 e^+ e^-$

With an extracted beam from the Main Injector, the flux necessary to permit sensitivities to this and other modes in the range of 10^{-10} per hour of running are obtainable. This will be the best place to perform such experiments of any presently existing or planned facility. The acceptance of the detector for the $K_L^0 \rightarrow \pi^0 e^+ e^-$ mode is about 15% with the requirement that both photons exceed 1 GeV. The decay rate for kaons greater than 10 GeV is about 33×10^6 per spill. As discussed in section II, the difficulty lies in isolating the contribution from various backgrounds.

Two of these are irreducible, depending only on the amplitude for the CP conserving 2γ intermediate state decay mode and the state mixing contribution. The background from $K_L^0 \rightarrow \gamma \gamma e e$ decays has recently been determined to be at the level of 5×10^{-7} , depending upon cutoff energy for the lower energy γ in the kaon rest frame. These decays tend to have one very low energy gamma and a very low mass $e^+ e^-$ pair. Even after reasonable cuts on these quantities, a sizable background remains and one has only the π^0 mass as a final constraint. With the high precision calorimeter, this background is at the 10^{-11} level and one will probably have to live with it at this level. For the apparatus shown, one should have about 4000 such background events, implying a 3σ sensitivity for a residual branching ratio of about 5×10^{-13} , where a direct CP violating signal should be seen.

Another way to see direct CP violation in $K_L^0 \rightarrow \pi^0 e^+ e^-$ decays is to observe the interference between K_S^0 and K_L^0 near the target. The CP conserving term does not contribute to the interference, and because the K_S^0 branching ratio is about a factor of 300 larger

than that of the K_L^0 , the $e^+ e^- \gamma \gamma$ background is less of a problem. Thus the result would be much easier to interpret. One way to quote the sensitivity of such an interference experiment is to say that if the branching ratio for the direct CP violating term in the K_L^0 decay were 10^{-12} , we would measure it to 30% precision. The same detector would be used for the interference measurement but with a modified beam. It would require extending the proton beam transport through the first collimator to impinge on a target just upstream of the beam defining collimator. This would allow the observation of decays within about 6m of the target and allow the measurement of the interference.

VII. $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

As discussed above, this decay mode is particularly simple from a theoretical point of view since it is dominated by short distance contributions which are nearly completely due to direct CP violation. Clearly, the difficulty arises in detecting the events and ensuring they are free from background.

The background originates from decays with two and three neutral pions, and the principal means of rejecting it relies on detecting the photons originating from the extra pions. The $3\pi^0$ pion final state is easier to suppress, since it has four extra photons. This mode occurs with a branching ratio of 12%. The CP violating $2\pi^0$ final state is suppressed by about 2 orders of magnitude, but the two extra photons are more easily missed.

Various ways of achieving the background rejection are possible. For modest sensitivities, one can measure the π^0 by either converting the photons or using only Dalitz decays and then require its transverse momentum with respect to the kaon direction to be larger than that allowed for the background sources. For higher sensitivities, too much acceptance is lost by these techniques, and one must use the 2γ decays of pions at all transverse momenta. For events with two detected photons, the kaon decay vertex must still be determined to reconstruct the π^0 mass. This could be done by measuring the photon directions in a directional calorimeter and determining the vertex from the intersection of the (small) neutral beam and the photon trajectories. If two photon directions are determined, the vertex is overconstrained using the two photon trajectories and the beam. Table 4 gives estimates of the sensitivities which would be achieved in different scenarios for the background rejection.

To get the best sensitivity, the clear technical challenge is to build a photon detector in which the probability of missing the two photons from a second neutral

Table 4
 $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ Experimental Sensitivities

Detection Technique	Sensitivity
E731 2 γ conversions $P_T > 200$ MeV/c	10^{-4}
E799 $\pi^0 \rightarrow e e \gamma$, $P_T > 200$ MeV/c	$10^{-3} - 10^{-6}$
Main Injector $\pi^0 \rightarrow e e \gamma$, $P_T > 200$ MeV/c	10^{-3}
Main injector, γ veto 10^{-3}	10^{-11}
Main injector, γ veto 10^{-4}	10^{-12}

pion is sufficiently small. The apparatus shown above would be modified by moving the photon calorimeter to a position immediately following the vacuum decay region. A set of charged particle detectors would be placed immediately upstream of the photon detectors. A hermetic veto system would completely surround the decay region and the end of the neutral beam line just upstream of it.

Detecting low energy photons and ensuring that the veto system is truly hermetic are most important. The primary inefficiency for low energy photons is due to photonuclear absorption, in which the photon is absorbed in a heavy nucleus with no prompt emission. E787 at BNL has achieved efficiencies of .999 in detecting photons down to 20 MeV. In the Main Injector facility, the photon energies are nearly always larger than 200 MeV, and their detection will be easier. A number of possible designs have been explored. One possibility is a layer of plastic scintillator 50 cm thick followed by a lead-scintillator sandwich totalling 4 radiation lengths. This detector would have to operate inside the vacuum tank, to avoid loss of photons in the vacuum tank walls, and would have to operate in charged and neutral fluxes of greater than 1 MHz/m². It would have an inefficiency for detecting photons above 200 MeV of below 10^{-3} .

VIII. $K_L^0 \rightarrow \mu^\pm e^\mp$ AND $K_L^0 \rightarrow \pi^0 \mu^\pm e^\mp$ SEARCHES

A new experiment to search for $K_L^0 \rightarrow \mu^\pm e^\mp$ and $K_L^0 \rightarrow \pi^0 \mu^\pm e^\mp$ should aim for sensitivities below 10^{-13} in order to significantly improve on measurements which we will likely have by 1995 or so. The low energy experiments which have set the best limits benefited from high kaon flux obtained with high rep rate and high current accelerators. Additional benefits accrued from the relative ease of triggering on electrons using threshold Cerenkov counters, and the ability to determine the approximate energy of the muon by measuring its range in absorbers. These advantages (and even higher fluxes with the AGS booster) will continue to be exploited.

Further improvement will require a more ambitious detector and even higher rates. The principal require-

ments are:

- suppression of backgrounds from the copious decay $K_L^0 \rightarrow \pi e \nu$,
- ability to work with rates of order 100 MHz in a detector of a few square meters,
- ability to select and write to tape candidate events from a rate of order 1 MHz of two body K_L^0 decays containing an apparent muon and electron.

The background results from two mechanisms: $K_L^0 \rightarrow \pi e \nu$ decay in which the pion decays or is misidentified as a muon and $K_L^0 \rightarrow \pi e \nu$ decay in which the electron is misidentified as a muon and the pion as an electron. The first mechanism leads to the requirement of redundant measurement of the muon momentum to insure that the apparent muon momentum is not significantly higher than the original pion momentum due to a decay in the analysing magnet. Even with redundant momentum analysis, it is difficult to estimate the level at which background will fake the signal. Effects which are not easily calculable, such as pattern recognition errors, or not understood tails in the resolution of the spectrometer could well be the limiting factor. Based on the experience of E791, it is plausible to expect that the background will be near a sensitivity of 10^{-13} . Further studies will be required to make a compelling argument that background rejection below 10^{-13} is possible.

The decay $K_L^0 \rightarrow \pi^0 \mu^\pm e^\mp$ is expected to have background from the analogous decay $K_L^0 \rightarrow \pi^0 \pi^\pm e^\mp \nu$. This would be much suppressed due to the relatively smaller branching ratio for this mode (6×10^{-5} vs. 0.39). Three pion decays would not be a significant source of background for the same reason that the π pion decay does not contribute to $K_L^0 \rightarrow \mu^\pm e^\mp$: when the parent mass is calculated assigning the electron mass to a pion, the shift in parent mass is sufficiently large as to be displaced from the kaon mass by many times the detector resolution. Again, detailed simulations of background processes have not been done, but they are not expected to be a problem.

The detector as envisaged would have momentum resolution somewhat better than that achieved in E791, due to the somewhat longer lever arms in the spectrometer and the more uniform and better understood magnetic fields which should be achievable. That experiment had a calculated background level below 10^{-12} , and the experiment was able to achieve background levels in nearby kinematic regions within a factor of two of the expectation²⁸. Figure 5 shows the

Figure 5. Calculated and measured $K_L^0 \rightarrow \mu^\pm e^\mp$ background levels for E791.

comparison of expected and measured levels. What remains to be shown is that one can achieve improved background rejection in a high rate environment.

The second objective of the design is to be able to tolerate the large flux of charged particles in the detector. Even if the flux is dominated by particles from kaon decays, the rates are formidable—more than 100 MHz per m^2 in drift chamber modules, with rates on individual wires exceeding 1 MHz. While detectors have been operated at these rates, it has not to our knowledge been demonstrated that one can maintain good resolution and high pattern recognition efficiency at these rates in a large system with minimal redundancy in the measurements.

Finally, the third major challenge is in the online event selection. The rate of events with two charged particles in the spectrometer and signals indicating the presence of a muon and an electron will exceed 1 MHz, primarily from $K_L^0 \rightarrow \pi e \nu$ decays with a decaying pion. This could be reduced with a selection based on the apparent transverse momentum of the particles by looking for appropriate patterns in the trigger scintillation counters and drift chambers. It is estimated that this could reduce the trigger rate by a factor of about three, while maintaining good efficiency for the signal. Further background suppression will likely require pattern recognition and kinematical analysis. E791 typically analysed 10,000 events per spill (with a 3 second repetition rate). This was limited by the online processing power of about 30 MIPs. The bandwidth of the data acquisition (100 Mbyte/sec) was not a limit

since the average event size was 600 bytes. Assuming an event size of 2 kbytes and a readout rate of 300,000 events per spill, the bandwidth required would be about a factor of 6 larger, which could be accommodated with a wider readout bus and a faster clock speed. The requisite increase in processing speed is already commercially available, with thirty 30MIP RISC processors, for example.

Many of the same considerations apply to the decay $K_L^0 \rightarrow \pi^0 \mu^\pm e^\mp$. The low level trigger would be a simple adaptation of that for $K_L^0 \rightarrow \mu^\pm e^\mp$. An additional requirement of two photon showers in the calorimeter would be added to the requirement of a muon and an electron, presumably reducing the low level rate to a fraction of that for the two body decay. The high level trigger would require an invariant mass calculation including the two photons in addition to the two charged leptons.

IX. CONCLUSIONS

The working group has examined the motivation for continuing studies of rare decays of neutral kaons through the 1990's in light of ongoing experiments and the possibility of further substantial improvements in experimental sensitivity. Several modes show promise for exciting discoveries. It appears possible to make significant advances in the precision of an ϵ'/ϵ measurement to a level below 10^{-4} . Coupled with a better determination of standard model parameters, including the top quark, this measurement may show whether CP violation is due to a non-zero phase δ in the CKM matrix. In any event, a definitive non-zero measurement of ϵ'/ϵ would be the first qualitatively new positive result on CP violation in many years.

It is also possible to significantly improve on the current sensitivity to $K_L^0 \rightarrow \pi^0 e^+ e^-$ and $K_L^0 \rightarrow \pi^0 \mu^+ \mu^-$. Due to the recent realization that $K_L^0 \rightarrow \gamma \gamma e e$ contributes background at a level above the standard model prediction, it is unlikely that these modes will be discovered in a background free experiment. Nonetheless, it may be possible to isolate a signal above background at the standard model level. The background level can be normalized internal to the experiment. Decay rates significantly above the standard model should be readily seen. It may also be possible to see the mode $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$. The prediction for this rate is reliable; its detection at the SM level requires a superb photon detector, but the promise of a definitive test of the standard model prediction warrants the effort.

Finally, the question of muon and electron number conservation will continue to be of fundamental importance. Experiments in the next few years may push

limits in kaon decays to the 10^{-12} level, and limits in purely leptonic modes to the 10^{-13} level. Until evidence of violation of these conservation laws is found, efforts at improving the experimental sensitivity will be valuable, and the main injector may well be the best place to do that in the next ten years.

X. ACKNOWLEDGEMENTS

We thank M. Crisler, E. Swallow, R. Wands, R. Fast and S. Cihangier who have contributed to this report through their efforts on the preparation of a conceptual design report²⁹ for a kaon decay experimental facility at the Fermilab main injector.

XI. REFERENCES

- [1] *Proceedings of the Workshop on Physics at the Main Injector*, Batavia, IL, May 1989.
- [2] *Proceedings of the Workshop on Physics at Fermilab in the 1990's*, Breckenridge, Colorado, August, 1989.
- [3] *Proceedings of the Workshop on Science at Kaon*, Vancouver, British Columbia, August 1990.
- [4] A. Heinson et al., Brookhaven Proposal 871, September, 1990.
- [5] A. Barker et al., Fermilab Proposal 799, September, 1989.
- [6] K. Arisaka et al., Fermilab Proposal 832, 1990.
- [7] G.D. Barr et al., CERN/SPSC/90-22, 1990.
- [8] H. Gordon et al., Brookhaven Proposal 851, 1990.
- [9] K. Miyake et al., KEK Proposal 162, September, 1988.
- [10] G. Barbiellini and C. Santoni, CERN-EP/89-88
- [11] H. Burkhardt, et al., *Phys. Lett.* 206B, 169 (1988).
- [12] R. Patterson et al., *Phys. Rev. Lett.* 42, 3724 (1989).
- [13] G. Buchalla, A.J. Buras, M. Harlander, MPI-PAE-PTh-30/90, (1990).
- [14] C.O. Dib, I. Dunietz, F.J. Gilman, *Phys. Rev. D* 39, 2639, (1989).
- [15] G. Ecker, A. Pich, E. de Rafael, *Nuc. Phys.* B291, 692, (1987).
- [16] M. Zeller, private communication.
- [17] G.D. Barr et al., *Phys. Lett.* 242B, 523 (1990)
- [18] A. Barker et al., EFI 91-1, Submitted to *Phys. Rev. D*.
- [19] H.B. Greenlee, *Phys. Rev. D* 42, 3724 (1990).
- [20] L. Littenberg, *Phys. Rev. D* 39, 3322 (1989)
- [21] A.M. Lee et al., *Phys. Rev. Lett.* 64, 165 (1990).
- [22] C. Mathiazhagan et al., *Phys. Rev. Lett.* D42, 3724 (1990). W. Molzon, "Improved Upper Limits on $B(K_L^0 \rightarrow \mu^\pm e^\mp)$ and $B(K_L^0 \rightarrow ee)$ and New Value for $B(K_L^0 \rightarrow \mu\mu)$ ", in *Proceedings of the 25th International Conference on High Energy Physics*, Singapore, August 1990.
- [23] T. Inagaki et al., *Phys. Rev. D* 40, 1712 (1990) and M. Kuze "Search for Rare Decays $K_L^0 \rightarrow \mu^\pm e^\mp$ and $K_L^0 \rightarrow ee$ ", University of Tokyo, Ph.D. dissertation, 1989.
- [24] U. Bellgardt et al., *Nucl. Phys.* B299, 1 (1988).
- [25] R. Bolton et al., *Phys. Rev. Lett.* 56, 2461 (1986).
- [26] D.A. Bryman et al., *Phys. Rev. Lett.* 55, 485 (1985).
- [27] P. Langacker, "Rare Kaon Decays as a Probe of New Physics," these proceedings.
- [28] J. Urheim, "Experimental Search for the Decay $K_L^0 \rightarrow \mu^\pm e^\mp$ ", University of Pennsylvania, Philadelphia, PA, Ph.D. dissertation, 1989.
- [29] *Conceptual Design Report for a Kaon Facility at the Main Injector*, in preparation.