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Task J

**A High Sensitivity Search for CP Violating Rare  $K_L$  Decays  
and  
Precision Measurement of the Direct CP Violation Parameter  $\epsilon'/\epsilon$   
via the four  $K \rightarrow 2\pi$  decay modes**

**Progress Report  
for period May 1, 1992 - April 30, 1993**

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## Introduction

Fermilab experiments E731, E773, E799, and E832 are a series of experiments to investigate the physics of CP violation, CPT violation, and rare decays of the neutral kaon system.

E731 finished data taking in 1988 and many results has been published between then and now. During past year, we finished and published the full data set analysis of the goal of the experiment which is  $(\epsilon'/\epsilon)_{2\pi} = (7.4 \pm 5.2 \text{ [stat]} \pm 2.9 \text{ [syst]}) \times 10^{-4}$ . The value favors a high top quark mass value within the Standard Model. It should be noted that a total of five Physical Review Letter papers has been published in the past one year from this data.

E773 tests CPT violation by determining  $(\Delta\phi)_{2\pi}$  with an accuracy of about  $0.5^\circ$ , and data were taken during the last Fermilab Fixed Target run period between September and November 1991. It is anticipated the data analysis will be finished within a year.

E799 with the primary goal of observing direct CP Violation via searching for the rare decay  $K_L \rightarrow \pi^0 l^+ l^-$  (where  $l = e, \mu, \nu$ ) took test data between November 1991 and January 1992 (Phase I). Because of the varieties of trigger implemented, the data is rich and diverse in physics and will have many first observations and best limits for various kaon decays. Some preliminary results are shown here. The first result from this data was submitted and accepted by Physical Review Letter in April 1993 while at least four other results will be submitted for publication in the coming fiscal year.

E799 (Phase II) and E832 (a follow up experiment of E731) are scheduled to take data after the current Fermilab collider run with a new facility and detector.

Much progress has been made in the physics of CP violation and rare decay of kaon since the discovery of  $K_L$ . With a sample of 23 semi-leptonic events observed (single event sensitivity of about  $10^{-2}$ ) in 1956, the neutral kaon system has become one of the most fertile ground for experimentation. With a sample of about 50 events of  $K_L \rightarrow \pi^+ \pi^-$  observed (single event sensitivity of about  $10^{-4}$ ) in 1964, the 'indirect' CP violation was discovered. The sensitivity of various rare kaon decay search reached about  $10^{-6}$  in the seventies. During the past decade, the 'direct' CP violation parameter  $(\epsilon'/\epsilon)_{2\pi}$  of the neutral kaon system has been measured

with an accuracy of about  $\sim 10^{-3}$  and various rare kaon decay has reached single event sensitivity of  $10^{-8} - 10^{-10}$ .

#### Results from E731 data set:

$(\epsilon'/\epsilon)_{2\pi}$ , if non-zero will be a signal for 'direct' CP violation. Experimentally it can be determined from the double ratio  $R$  of the two pion decay rates of  $K_L$  and  $K_S$ ,  $R = \Gamma(K_S \rightarrow \pi^+\pi^-) / \Gamma(K_L \rightarrow \pi^+\pi^-) / \Gamma(K_S \rightarrow 2\pi^0) / \Gamma(K_L \rightarrow 2\pi^0) \sim 1 - 6 \text{Re}(\epsilon'/\epsilon)$ . The major challenge of the experiment then involves, a) collection of very high statistics of each decay mode and, b) minimization of systematic errors throughout the collection and analysis of the data. At a function of proper time  $t$  from the regenerator, the  $\pi\pi$  decay rates in the vacuum and regenerated beams are proportional to  $|\eta|^2$  and  $|\rho \exp(-t/2\tau_S + i\Delta m t) + \eta|^2$  respectively;  $\rho$  is the coherent regeneration amplitude,  $\tau_S$  the  $K_S$  lifetime,  $\Delta m$  the  $K_L$ - $K_S$  mass difference and  $\eta$  the appropriate ratio of  $K_L$  to  $K_S$  decay amplitudes. Because  $|\rho| \gg |\eta|$ , the ratio of the total number of regenerated to vacuum charged (neutral) decay,  $R_{+-}(\infty)$ , is proportional to  $|\rho/\eta_{+-}(\infty)|^2$ . Thus  $R \sim R_{+-}/R_{00}$ .

In 1991, we announced results from the entire data set in the Geneva Lepton-Photon Conference in. Before that, we had published a result [Patterson et. al.; Phys. Rev. Lett. 64,1491(1990)] based upon 20% of the data set which was  $(\epsilon'/\epsilon)_{2\pi} = (-4 \pm 14(\text{stat.}) \pm 6(\text{syst.})) \times 10^{-4}$  (E731, 20% sample), in agreement with a class of super-weak models. Since the first publication, much better understanding of the acceptance, energy resolution, and the backgrounds have allowed major reductions in the systematic error. This was accomplished by detailed studies of a sample of about 100 million  $K_{e3}$  decays recorded with little bias. First, the 20% sample was reanalyzed and the central value became  $-1 \times 10^{-4}$ : the result moved by only 1/2 of the old systematic error even though nearly every aspect of the analysis was improved. The final FULL E731 results were published in the 1st March 1993 issue of Phys. Rev. Lett. and the result is  $(\epsilon'/\epsilon)_{2\pi} = [7.4 \pm 5.2(\text{stat.}) \pm 2.9(\text{syst.})] \times 10^{-4}$ . The value is consistent with zero.

Table 1 : Recent  $(\epsilon'/\epsilon)_{2\pi}$  results (in units of  $10^{-4}$ ) from E731 and NA31

Data Set	$\epsilon'/\epsilon$	Statistical Error	Systematic Error
NA31 '86	33	7	8++
E731 20%	-4	14	6
NA31 '88	17	7	7++
E731 20% reanalysis	-1	14	3.2
<b>E731 Full</b>	<b>7.4</b>	<b>5.2</b>	<b>2.9</b>
NA31 '89+	21	5	6.5++
<b>NA31 Full+</b>	<b>23</b>	<b>3.4</b>	<b>6.5</b>
+Preliminary			
++Correlated errors			

NA31 also announced a new result in the 1991 Geneva Lepton-Photon Conference and a listing of all of the recent results is given in Table-1 as shown above. It is seen that there is still a disagreement (at the  $2\sigma$  level) and that while NA31 is dominated by (common) systematic uncertainties, E731 is statistically dominated.

Our group has also made very precise determinations of other parameters of the neutral kaon system with the same  $2\pi$  data samples, using exactly the same techniques of background subtraction and acceptance corrections. The results published in 1st March 1993 issue of Phys. Rev. Lett. are:

$$\tau_S = (0.8929 \pm 0.0016) \times 10^{-10} \text{ sec};$$

$$\Delta\phi = (0.5286 \pm 0.0028) \times 10^{10} \text{ sec}^{-1};$$

$$\phi_{+-} = (42.2 \pm 1.4)^\circ;$$

$$\Delta\phi = \phi_{+-} - \phi_{00} = (-1.6 \pm 1.2)^\circ.$$

These results are either comparable to or exceed in precision the best previous determinations. In particular, the value for  $\phi_{+-}$  is in good agreement (as expected from CPT symmetry) with the expected "superweak phase",  $43.5^\circ \pm 0.14^\circ$ , unlike the PDG value of  $46.0^\circ \pm 1.2^\circ$ , which is largely based upon an NA31 result. The result for  $\tau_S$  is three times better than the best previous determination, and the value for  $\Delta\phi$  is a factor of two better than earlier results of both E731 and NA31.

We have as well made other measurements with this data set, some of which are given in the following Table:

Table 2 : Some rare decay results from E731 data		
PROCESS	RESULT	COMMENT
$K_L \rightarrow \pi^0 e e$	$br < 7.5 \times 10^{-9}$ (90%)	published (1990)
$K_L \rightarrow \pi^0 \gamma \gamma$	$br = (1.86 \pm 0.85) \times 10^{-6}$	published (1991)
$K_L \rightarrow \pi^+ e^- \pi^0 \nu$	$br = (5.16 \pm 0.20 \pm 0.22) \times 10^{-5}$	729 events; published (1993)
$K_L \rightarrow \pi^+ \pi^- \gamma$	$br = (23.0 \pm 0.7) \times 10^{-3}$ $\times Br(K_L \rightarrow \pi^+ \pi^-)$	published (1993)
$K_S \rightarrow \pi^+ \pi^- \gamma$	$br = (7.1 \pm 0.22) \times 10^{-3}$ $\times Br(K_S \rightarrow \pi^+ \pi^-)$	published (1993)
$K_L \rightarrow \pi^0 \nu \nu$	$br < 2.2 \times 10^{-4}$ (90%)	published (1992)
$\eta \rightarrow \gamma$	$(2.15 \pm 0.26 \pm 0.20) \times 10^{-3}$	published (1993)
$\phi \rightarrow \gamma$	$(72 \pm 23 \pm 17)^0$	published (1993)

In the past one year, as indicated in the table above, we have published three other results from E731 data, (i) " Study of the Decay  $K_L \rightarrow \pi^+ e^- \pi^0 \nu$  " Phys. Rev. Lett. vol.70,1591(1993); (ii) " Simultaneous Measurement of  $K_S$  and  $K_L$  Decays into  $\pi^+ \pi^- \gamma$  " Phys. Rev. Lett. vol.70, 2525(1993) ; and (iii) " Measurement of the CP-Violation Parameter  $\eta \rightarrow \gamma$  in Neutral Kaon Decays " Phys. Rev. Lett. vol.70, 2529(1993). Except for one more result, the analysis of the E731 data is declared finished and the experiment complete.

#### Status of the dedicated rare kaon decay experiment E799:

In 1989, we proposed to perform Fermilab E799 which is a high sensitivity search for rare kaon decays, in particular, the  $K_L \rightarrow \pi^0 l^+ l^-$  (where  $l = e, \mu$ ) modes. These  $K_L$  decay modes has both direct and indirect CP violating contributions, such that  $\epsilon'/\epsilon$  is of order of unity! The interesting direct piece is primarily a short-distance effect which can be fairly reliably calculated. The indirect CP amplitude (the  $\epsilon$  piece) and the CP conserving amplitude from a  $\pi^0 \gamma \gamma$  intermediate state need to be measured or calculated reliably so that the direct CP effect, if observed, could be interpreted correctly. Latest round of Brookhaven and CERN kaon results (i.e. the Mee spectrum of the  $K^+ \rightarrow \pi^+ e^+ e^-$  and the  $M_{\gamma\gamma}$  spectrum of the  $K_L \rightarrow \pi^0 \gamma \gamma$

together with Chiral Perturbation Theory seems to support that these two amplitudes are small. Thus an observation of  $K_L \rightarrow \pi^0 l^+ l^-$  will be an very exciting opportunity to look into direct CP violation effect. It should be cautioned that one may need to subtract a potential irreducible background from radiative Dalitz decays,  $K_L \rightarrow l^+ l^- \gamma \gamma$ .

We finished a six week data taking test run on 8th of January 1992. The data taken could be classified by the following:

- (i)  $\epsilon'$  physics data :  $K_L \rightarrow \pi^0 e^+ e^-$ ,  $K_L \rightarrow \pi^0 \mu^+ \mu^-$ , and  $K_L \rightarrow \pi^0 \nu \nu$ ;
- (ii)  $\gamma\gamma^*$  physics data :  $K_L \rightarrow \mu^+ \mu^- \gamma$ ,  $K_L \rightarrow e^+ e^- \gamma$ ; and  $\pi^0 \rightarrow e^+ e^- \gamma$ ;
- (iii)  $\gamma^* \gamma^*$  physics data :  $K_L \rightarrow e^+ e^- e^+ e^-$ ;  $\pi^0 \rightarrow e^+ e^- e^+ e^-$ ; and  $K_L \rightarrow \mu^+ \mu^- e^+ e^-$ ;
- (iv)  $\mu e$  physics data :  $K_L \rightarrow \pi^0 \mu^+ e^-$ ;  $\pi^0 \rightarrow \mu^+ e^-$ ;
- (v)  $\pi^+ \pi^- \gamma^*$  physics data :  $K_L \rightarrow \pi^+ \pi^- e^+ e^-$ ;

A new technique using "tagged"  $\pi^0$  from the copious  $K_L \rightarrow 3\pi^0$  decay was used to measure the  $\pi^0 \rightarrow e^+ e^-$  branching ratio which has a contentious history. A signal of 9  $\pi^0 \rightarrow e^+ e^-$  events with no Dalitz  $\gamma$  is detected. In figure 4 of the appendix, crosses are the Monte Carlo simulation of the Dalitz background and is absolutely normalized with twenty five times higher statistics. Other backgrounds with two single Dalitz, double Dalitz, and external conversion are negligible. Systematic studies included momentum scale and shifts, calorimeter energy smearing and shifts. Radiative corrections are taken into account. Based on the nine observed events with one background, we determined  $BR(\pi^0 \rightarrow e^+ e^-) = (8.0 \pm 4.1 \pm 2.9) \times 10^{-8}$ . This result was submitted to Phys. Rev. Lett. for publication and was accepted in April 1993.

With the same sample, a high statistics (300K events;  $\times 10$  world's sample) measurement of the  $\pi^0$  Dalitz form factor will be performed also. The detector has high acceptances for multibody final states, typically of 10% due to high kaon energy.

Within the coming fiscal year, numerous results from this test run of E799 data will be submitted for publication (partially listed above). In Chicago for this task, two graduate students (Kevin McFarland and Debra Harris) are writing their PhD thesis on the  $K_L \rightarrow \pi^0 e^+ e^-$ ,  $K_L \rightarrow \pi^0 \mu^+ \mu^-$ .



,  $\pi^0 \rightarrow e^+e^-$  results. Two senior undergraduates are working on the lepton number violation decay mode searches.

### E799 Phase II / E832

E832 aims to measure of  $(\epsilon'/\epsilon)_{2\pi}$  with a precision of  $1 \times 10^{-4}$  or a factor of about 6 better than that of E731. Same technique (two beams simultaneous with regenerator) with a new detector and beamline will be used. The most important detector upgrade will be the electromagnetic calorimeter which will be a fly's eye geometry CsI crystal array. The same detector will be used for rare decay studies (E799 Phase II), reaching a sensitivity for 4-body decays of  $10^{-11}$ . This program is nicknamed 'KTeV' (by Doug Jensen of Fermilab) and we plan to take data after the current Fermilab Collider run period. CERN NA48 plans to measure  $(\epsilon'/\epsilon)_{2\pi}$  better. In order to control the systematics, they switched from the NA31 one beam to the two beam simultaneous technique which is possibly the most important ingredient for such precise measurement.

The KTeV project has been given an experimental site and facility (NM2 in Fermilab) to be ready to take data possibly in 1995. Various parts of the detector are well on its way to be built. Currently the collaboration includes Chicago, Fermilab, Rutgers, Osaka, Rice, Colorado, UCLA, and Elmhurst. This task, together with Fermilab, is responsible for the large scale Transition Radiation Detector which is essential to the rare decay searches. We have already prototype several small ones and a beam test has been scheduled in KEK in mid-June to elucidate the performance of foam radiator. A full size prototype is currently being built in Fermilab. This task is responsible for the design electronics and trigger of the TRD system in the coming fiscal year.

## SUMMARY OF THE PROGRESS REPORT OF TASK J

Much happens during the last grant year as described above. We have published five Phys. Rev. Lett. papers and one has been accepted. Two PhD students and one senior undergraduate has been working on their thesis analysis which will result in five publications in the coming year. Both PhD students will defend their thesis soon.

Two new graduate students joined the task J effort recently, one in late 1992, and one in spring 1993. Both will participate in the TRD project and will do thesis research on KTeV.

We expect many kaon and pion decay results in coming years before KTeV starts to take data. This task will be the major part of the data analysis efforts of the E799-I data taken in 1991-1992.

List of publications in the past year:

- 1) "New Measurements of the Neutral Kaon Parameters  $\Delta m$ ,  $\tau_s$ ,  $\phi_{00}$ - $\phi_{+-}$ , and  $\phi_{+-}$ ", L. Gibbons et. al., Phys. Rev. Lett. vol 70, 1199(1993).
- 2) "Measurement of the CP-Violation Parameter  $\text{Re}(\epsilon'/\epsilon)$ ", L. Gibbons et. al. Phys. Rev. Lett. vol 70, 1203(1993).
- 3) "Study of the Decay  $K_L \rightarrow \pi^+ e^- \pi^0 \nu$ ", G. Makoff et. al. Phys. Rev. Lett. vol 70, 1591(1993).
- 4) "Simultaneous Measurement of  $K_S$  and  $K_L$  Decays into  $\pi^+ \pi^- \gamma$ ", E. Ramberg et. al. Phys. Rev. Lett. vol 70, 2525(1993).
- 5) "Measurement of the CP-Violation Parameter  $\eta_{+-\gamma}$  in Neutral Kaon Decays", E. Ramberg et. al., vol 70, 2529 (1993).
- 6) "A Measurement of the Branching ratio of  $\pi^0 \rightarrow e^+ e^-$  Using decays in flight of  $K_L \rightarrow 3\pi^0$ ", K. McFarland et. al., Accepted by Phys. Rev. Lett.
- 7) "Results and Plans for the Fermilab Kaon Decay Program", Y. Wah, Proceeding of the Dallas Int. Conf. of High Energy Physics 1992.

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