EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/87-177
29 September 1987

CP VIOLATION IN K DECAY

I. Mannelli

Invited talk given at the
International Symposium on
Lepton and Photon Interactions at High Energies
DESY, Hamburg, 27 July-3 August 1987

CP VIOLATION IN K DECAY

Italo MANNELLI

NA31 Collaboration^{*)}, CERN, Geneva, Switzerland, and
 Dipartimento di Fisica, Università di Pisa and INFN Sezione di Pisa, Pisa, Italy

Since the original discovery¹ in 1964 that both K_S and K_L decay into $\pi^+\pi^-$, which represents clear evidence for CP violation, the challenge has been to devise experiments and theoretical models that could elucidate the nature of this phenomenon and its source. A number of implications have been analysed²: for example, it was pointed out in 1967³ that CP violation, combined with a very small baryon instability, could have produced, in the early explosive development of the Universe, the matter-antimatter imbalance as manifested today by the measured ratio $N_{\text{baryons}}/N_{\text{photons}} \approx 10^9$.

Despite intensive research efforts, no CP-violation effects have been detected outside the neutral K system. In addition to the two-pion channel, CP violation is detected in the charge asymmetry of semileptonic K_L decays. All results appear to be consistent with CPT invariance and what is clearly demonstrated is that in $K^0 \rightarrow \bar{K}^0$ mixing the amplitude for the transition $K^0 \rightarrow \bar{K}^0$ is different from the amplitude for the time-reversed transition $\bar{K}^0 \rightarrow K^0$. The superweak model⁴, linking CP violation to $|\Delta S| = 2$ transitions, is empirically still valid⁵. In this model, the K_L decay to two pions is due only to the impurity ϵ of the eigenstate K_1 with CP = + in the composition of the $K_L = (K_2 + \epsilon K_1) \cdot (1 + |\epsilon|^2)^{-1/2}$ itself (K_2 is the eigenstate with CP = -), and A_0 and A_2 , the amplitudes for K^0 to decay to two pions in isotopic spin $I = 0$ and $I = 2$ respectively, are relatively real. The ratios of the amplitudes for K_L and K_S decay to two pions

*) The members of the NA31 Collaboration are: *CERN*: H. Burkhardt, P. Clarke, D. Coward, D. Cundy, V. Gibson, N. Doble, L. Gatignon, R. Hagelberg, G. Kessler, J. van der Lans, T. Miczaika, H.G. Sander, A.C. Shaffer, P. Steffen, J. Steinberger, H. Taureg, H. Wahl, C. Youngman; *Dortmund*: G. Dietrich, F. Eisele, W. Heinen; *Edinburgh*: R. Black, D.J. Candlin, J. Muir, K.J. Peach, B. Pijlgrims, I. Shipsey, B. Stephenson; *Mainz*: H. Blümer, M. Kasemann, K. Kleinknecht, B. Panzer, B. Renk, S. Röhn; *Orsay*: E. Auge, R.L. Chase, M. Corti, L. Feyard, D. Fournier, P. Heusse, A.M. Lutz; *Pisa*: L. Bertanza, A. Bigi, M. Calvetti, M. Carosi, R. Casali, C. Cerri, R. Fantechi, S. Galeotti, I. Mannelli, E. Massa, A. Nappi, D. Passuello, G. Pierazzini; *Siegen*: C. Becker, D. Heyland, M. Holder, G. Quast, M. Rost, W. Weihs, G. Zech. Their dedication and hard work has made possible the performance of the experiment, the results of which on ϵ'/ϵ are reported here for the first time.

$$\eta_{+-} = \langle \pi^+ \pi^- | T | K_L \rangle / \langle \pi^+ \pi^- | T | K_S \rangle = \epsilon \quad \text{and} \quad \eta_{00} = \langle \pi^0 \pi^0 | T | K_L \rangle / \langle \pi^0 \pi^0 | T | K_S \rangle = \epsilon$$

are hence both equal to ϵ , and $\eta_{+-}/\eta_{00} = 1$. The phase of ϵ is fixed by the mass and total decay rate of K_S and K_L : $\arg(\epsilon) = \tan^{-1} 2(m_L - m_S)/(\Gamma_S - \Gamma_L) = 43.7^\circ$. In the more general case, where CP-violating amplitudes could be present in the K two-pion decay, to a good approximation

$$\eta_{00} = \epsilon - 2\epsilon' \quad , \quad \eta_{+-} = \epsilon + \epsilon'$$

with $\epsilon' = i/\sqrt{2} \operatorname{Im}(A_2/A_0) \exp[i(\delta_2 - \delta_0)]$, where δ_0 and δ_2 are the $\pi\pi$ phase shifts for $l = 0$ and $l = 2$, at $\sqrt{s} = m_K$. Experimentally, $\delta_2 - \delta_0 = -53 \pm 5^\circ$ and hence $\arg(\epsilon') = \delta_2 - \delta_0 + \pi/2 = 37 \pm 5^\circ$. Therefore taking ϵ' and ϵ as relatively real and for $|\epsilon'/\epsilon| \ll 1$

$$|\eta_{00}/\eta_{+-}|^2 = 1 - 6\epsilon'/\epsilon$$

with*) $\arg \eta_{+-} \sim \arg \eta_{00}$.

It was first realized in 1973⁷ that it is possible to incorporate CP violation into the standard electroweak gauge theory if three generations of quarks exist, as now appears very plausible. From this point of view only an accidental cancellation could produce $\epsilon' = 0$.

Also CP-violation phenomena could be expected in cases similar to the neutral K, in particular for the neutral B mesons, for which $B^0 \rightarrow \bar{B}^0$ mixing, a prerequisite for CP violation, has recently been observed by the UA1 Collaboration at the CERN Collider⁸ and by ARGUS at DORIS⁹.

The results of the first attempts to measure $|\eta_{00}/\eta_{+-}|$ are reported in Table 1 together with more accurate results published in 1985¹⁰.

The main features of the 1985 experiments are summarized in Table 2.

More recently¹¹ the Chicago-Fermilab-Princeton-Saclay Collaboration (experiment E731 at Fermilab) have given a preliminary result,

$$\epsilon'/\epsilon = 0.0035 \pm 0.003 \text{ (stat.)} \pm 0.002 \text{ (syst.)} \quad ,$$

based on a sample of 6738 $2\pi^0$ decays, obtained from an improved set-up at Fermilab which is ultimately expected to yield some 100,000 $2\pi^0$ decays and reach an accuracy of $\pm 1 \times 10^{-3}$ for ϵ'/ϵ .

At CERN the NA31 experiment has now produced its first result,

*) The experimental value for $\arg \eta_{00} - \arg \eta_{+-} = 9.8^\circ \pm 5.4^\circ$ is 2 standard deviations from zero⁵. A difference from zero would imply CPT non-invariance⁶.

$$\epsilon'/\epsilon = (3.5 \pm 1.4) \times 10^{-3},$$

and most of the remainder of this paper will be concerned with this experiment.

The principle is to measure

$$\epsilon'/\epsilon = (1 - R)/6,$$

where R is the double ratio of the decay rates

$$R = [\Gamma(K_L \rightarrow 2\pi^0)/\Gamma(K_L \rightarrow \pi^+\pi^-)]/[\Gamma(K_S \rightarrow 2\pi^0)/\Gamma(K_S \rightarrow \pi^+\pi^-)].$$

Charged and neutral decays are detected at the same time, alternatively for K_L and K_S . Switching from K_L to K_S was done with a periodicity of about a day. The overall stability of the detection system was checked in several ways. In particular, the ratio of charged to neutral decays for K_S changed by less than $\pm 1.5\%$ over a time equal to 20

Table 1

Measurements of $\epsilon'/\epsilon = [1 - (|\eta_{00}/\eta_{+-}|^2)]/6$

Year	Authors	$ \eta_{00}/\eta_{+-} $
1972	Holder et al.	1.00 ± 0.06
1972	Banner et al.	1.03 ± 0.07
1979	Christenson et al.	1.00 ± 0.09
Average		1.01 ± 0.04
$R = \eta_{00}/\eta_{+-} ^2 = 1.02 \pm 0.08$		
Year	Authors	ϵ'/ϵ
1985	Black et al.	$0.002 \pm 0.007 \pm 0.004$
1985	Bernstein et al.	$-0.005 \pm 0.005 \pm 0.002$
Average		-0.003 ± 0.005
$R = \eta_{00}/\eta_{+-} ^2 = 1.015 \pm 0.03$		

Table 2a

BNL–Yale Experiment
(Black et al., 1985)

No. of events	Background (%)
$K_L \rightarrow 2\pi^0$	17.5 ± 3
$K_S \rightarrow 2\pi^0$	1.2 ± 0.2
$K_L \rightarrow \pi^+ \pi^-$	2.0 ± 1
$K_S \rightarrow \pi^+ \pi^-$	20960
$\epsilon'/\epsilon = 0.0017 \pm 0.0082$ $ \eta_{00}/\eta + - ^2 = R = 0.990 \pm 0.043 \pm 0.026$	
Backgrounds: $K_L \rightarrow 3\pi^0 \rightarrow 6\gamma$ n interactions in He K_L semileptonic decays	
Incoherent K_S : $1.5 \pm 0.5\%$ of $K_S \rightarrow 2\pi^0$ 0.2% of $K_S \rightarrow \pi^+ \pi^-$	

Table 2b

Chicago–Saclay Experiment
(Bernstein et al., 1985)

No. of events	Background (%)	Inelastics (%)	Systematics (%)
$K_L \rightarrow 2\pi^0$	8.4 ± 0.4	2.9 ± 0.3	± 0.6
$K_S \rightarrow 2\pi^0$	0.6 ± 0.1	14.9 ± 0.5	± 1.0
$K_L \rightarrow \pi^+ \pi^-$	3.1 ± 0.2	0.4 ± 0.1	± 0.2
$K_S \rightarrow \pi^+ \pi^-$	0.2	1.7 ± 0.1	± 0.1
Acceptance correction K_L/K_S for $2\pi^0$ for $\pi^+ \pi^-$			
Total systematic error			
$\epsilon'/\epsilon = -0.0046 \pm 0.0053 \pm 0.0024$ $R = 1.028 \pm 0.032 \pm 0.014$			
Main systematics: uncertainties in background ($K_L \rightarrow 3\pi^0$, n interaction) inelastic regeneration of K_S acceptance correction (K_L upstream of K_S regenerator)			

so-called miniperiods, i.e. sets of K_L and K_S data takings, each one sufficient to give a value of ϵ'/ϵ independently of any change of acceptance between miniperiods. Binning the events in momentum p_K and decay vertex longitudinal position Z_v , for small enough bins (10 GeV/c was used for p_K and 1.2 m for Z_v), the relative acceptances cancel out in the double ratio to better than 1%, so the ratio of the number of reconstructed events needs only a small Monte Carlo computed correction in order to represent the ratio of decay rates.

The experimental set-up¹² is sketched in Fig. 1, where transverse dimensions are enhanced by a factor of 50 relative to the longitudinal ones.

The K_L beam is produced by 450 GeV/c protons at 3.6 mrad. The K_L intensity is such that in total about 10^5 decays (to any final state) occur per SPS pulse, over the 120 m following the beginning of the useful decay region. Once collimated, 48 m after the production target, the neutral beam remains in vacuum up to the dump which follows the whole set-up.

For K_S an attenuated proton beam is brought to a target, located on a train supporting also suitable deflecting magnets, proton beam dump, and a K_S beam-defining collimator, which can move in steps of 1.2 m over 48 m so as to imitate the flat K_L longitudinal decay distribution. An anticoincidence counter, preceded by 7 mm of Pb, is normally inserted in the K_S beam to define precisely the beginning of the decay region.

As shown in Fig. 2 the evacuated decay volume is terminated by a thin [4×10^{-3} radiation lengths (r.l.)] Kevlar window and followed by a helium tank, at the

FIGURE 1
Overall schematic view of the NA31 experimental set-up

FIGURE 2
The detector region of the NA31 set-up

$$M = \left[\sum_i^n E_i / Z_v \right] [\langle x^2 \rangle - \langle x \rangle^2 + \langle y^2 \rangle - \langle y \rangle^2]^{1/2}$$

with

$$\langle x^2 \rangle = \sum_i^n E_i x_i / \sum_i^n E_i, \quad \langle x \rangle = \sum_i^n E_i x_i / \sum_i^n E_i$$

and similarly for $\langle y^2 \rangle$ and $\langle y \rangle$.

Assuming that a K decay into $2\pi^0$ produced four detected photons, its longitudinal decay vertex position is obtained from

$$Z_v = \left[\sum_i^4 E_i / m_K \right] [\langle x^2 \rangle - \langle x \rangle^2 + \langle y^2 \rangle - \langle y \rangle^2]^{1/2}.$$

FIGURE 3

- a) Measured energy resolution for electrons in the NA31 liquid-argon calorimeter,
 b) Linearity of calorimeter response

Figures 4a and b show the precision with which the beginning of the decay region, typically 120 m in front of the calorimeter, is reconstructed for $\pi^0\pi^0$ and $\pi^+\pi^-$ events. The curves are simple Monte Carlo predictions incorporating the measured resolution. It should be noticed that, for example, a shift of 0.8% in the absolute energy calibration of the calorimeter would result in a shift of 1 m in Z_v . In fact, knowing the longitudinal geometry of the detector with about 1 cm accuracy, checking that the same position of the K_S anticounter is reconstructed from the neutral and from the charged decays, and that the transverse geometrical scale is the same for the chambers and the liquid-argon calorimeter, the momentum scale for p_K as reconstructed for $\pi^0\pi^0$ and $\pi^+\pi^-$ (see later the method of measurement for $\pi^+\pi^-$, which depends essentially on geometry and known values of masses) can be fixed to better than 0.4×10^{-3} .

As an illustration of the quality of the photon detection in this experiment, we have determined, from a sample of $K_S \rightarrow 2\pi^0$ decays with a particularly good geometrical configuration and a photon energy in a restricted range, the ratio of the mass of the K^0 to that of the π^0 .

FIGURE 4

Distribution of the distance of the reconstructed decay vertex from the position of the counter defining the beginning of the accepted decay region: a) for $K_S \rightarrow \pi^0\pi^0$ and b) for $K_S \rightarrow \pi^+\pi^-$

Taking

$$m_{\pi^0} = 134.964 \pm 0.004 \text{ (Ref. 5)}$$

we find

$$m_{K^0} = 497.56 \pm 0.01 \text{ (stat.)} \pm 0.03 \text{ (syst.)} ,$$

to be compared with the present world average

$$m_{K^0} = 497.72 \pm 0.07 \text{ (Ref. 5)}$$

which is due mostly to an $e^+e^- \rightarrow \phi \rightarrow K_1 K_2$ experiment⁵.

Of course, out of the three possible pairings of the four photons one can choose the one which is the best fit to the assumption that the photons come from $2\pi^0$. Within the resolution of the system the invariant mass of the two pairs would coincide with the π^0 mass for true $K \rightarrow 2\pi^0$ decays.

This appears to be precisely the case for K_S (Fig. 5). For K_L the plot of the masses of two pairs shows some background (Fig. 6). The curves traced in the figure are elliptical rings of fixed area. The ratio of the axes of the ellipses is determined by the different

FIGURE 5

Lego plot for the invariant mass of the 2γ pairs for $K_S \rightarrow \pi^0 \pi^0$

FIGURE 6

Density distribution for $K_L \rightarrow \pi^0 \pi^0$, as a function of the mass of the 2γ pairs

resolution in the sum and in the difference of the masses of the pairs, due to the constraint of the K mass imposed on the four photons.

Except for the first rings, the population is almost exactly constant (Fig. 7a), a fact expected from Monte Carlo for $K_L \rightarrow 3\pi^0$ events for which two photons have escaped detection. The comparison with K_S , where no such background is visible (Fig. 7b), and the flat dependence with respect to the number of the ring, allow for a precise background subtraction. It should be noticed in Fig. 8 that the background is a strong function of the distance of the decay vertex from the beginning of the K_L decay region, which coincides with the end of the K_L cleaning collimator. In fact, the reconstructed distance of the K decay vertex from the detector is equal to the true distance multiplied by the ratio of the invariant mass of the photons detected to the mass of the K. This is the reason for the shift in Z_v for the background, which is of the order of 25 m for the case when one of the π^0 's from $K_L \rightarrow 3\pi^0$ is missed by the detector.

For the energy determination of the π^+ and π^- , the experiment again employs calorimetry rather than magnetic deflection. This improves the acceptance while, in the 70 to 170 GeV/c K momentum range used in the experiment, it is quite possible, as we

FIGURE 7

a) Number of events $K_L \rightarrow 4\gamma$ as a function of the number of the elliptical ring in which they fall according to the values of the invariant mass of 2γ pairs. b) Same for $K_S \rightarrow 4\gamma$.

FIGURE 8

Dependence of the background from $K_L \rightarrow 3\pi^0$ decays on the distance of the decay vertex from the end of the K_L cleaning collimator

will show, to obtain good K momentum determination and background rejection. For this purpose the liquid-argon calorimeter is followed by an iron-plastic scintillator sampling calorimeter which, in conjunction with it, gives an energy resolution of $\simeq 65\%/\sqrt{E}$ (GeV) as shown in Fig. 9.

The position of the decay vertex is found directly from extrapolation of the tracks in the chambers; the momentum of K is determined using the relation

$$p_K = (1 + 1/R_E) [R_E m_K^2 - (1 + R_E)^2 m_\pi^2]^{1/2} / \theta,$$

where θ is the angle between the two pions and R_E is the ratio of the higher to the lower of the two pion energies. The above relation is remarkably accurate in our range of application. It is interesting to point out that p_K changes by only 5% when $1 < R_E <$

FIGURE 9

Energy resolution versus hadron energy for charged pions in the NA31 calorimetric measurement

5.6 and we in fact (also to reject $\Lambda \rightarrow p\pi^-$ decays) only accept $1 < R_E < 2.5$. In this way the resolution in p_K is typically 1%.

In order to reject background it is necessary to compute the $\pi^+\pi^-$ invariant mass, using the calorimetric measured energy for each pion. Figure 10a shows the K_S reconstructed mass. An analogue plot for K_L , Fig. 10b, shows a very similar peak, with however a secondary peak at its left, interpreted as misidentified $K_L \rightarrow \pi^+\pi^-\pi^0$ decays with the π^0 missed by the detector.

In order to appreciate more generally the problem of backgrounds, Table 3 summarizes the size of the two-pion signal for K_L and the main background sources, the importance of the latter relative to the signal, and the amount of background we finally had to subtract, after employing all rejection criteria that we found useful. These criteria give for both decay modes a rejection factor of about 5000.

We have already briefly discussed the criteria used for subtraction of the background induced by $K_L \rightarrow 3\pi^0$. For the charged decay modes we illustrate the main points in the following.

For $\pi^+\pi^-\pi^0$, with both photons from the π^0 escaping the detector, the reconstructed invariant mass is too low to contribute to the accepted $K_L \rightarrow \pi^+\pi^-$ region. Occasionally one of the photons could, however, closely overlap with the π^+ or π^- and be added to it, giving a higher invariant mass. The number of these events is estimated by looking at the photon density in events detected as $\pi^+\pi^-\gamma$ and normally rejected.

For $K \rightarrow \pi e \nu$ decays, the rejection comes mostly from the fact that an electron produces a shower which is almost always fully absorbed in the 27 r.l. thick

FIGURE 10

a) Invariant mass distribution for $\pi^+ \pi^-$ pairs in K_S decays. b) Same in K_L decays.

liquid-argon calorimeter. That rejection criteria, based only on shower development, still leave a small residue of electrons is shown in Figs. 11a and b, where we compare the distributions of the events for K_S and K_L in the distance, d_{target} , from the K production target to the reconstructed decay plane, suitably normalized to take into account the different extrapolation distances from the wire chambers to the K_S and K_L targets. The rather flat tail for K_L is interpreted as residual $K \rightarrow \pi e \nu$, as supported by a detailed examination of the events and Monte Carlo simulation for the shape of the distribution.

Looking at the distribution of large- d_{target} events as a function of the distance Z_v of the decay vertex from the end of the K_L cleaning collimator (Fig. 12) a peak is seen at small Z_v , which, after detailed study, can be attributed to inelastic regeneration in the collimator itself. Although we can calculate, from this regenerated K_S , the number of scattered K_L , which turns out to be negligible, we decided for this preliminary analysis simply to reject both $\pi^+ \pi^-$ and $\pi^0 \pi^0$ decays with $Z_v < 10.5$ m, because it is rather difficult to ensure the same dependence of the acceptance for the two decay modes as a function of the scattering angle.

The decays $K \rightarrow \pi \mu \nu$ are rejected, at trigger level, by the veto counters following the iron walls behind the calorimeters; at the reconstruction stage, they are rejected by the

Table 3

K_L signal and background sources

Decay modes	Branching ratios (%)	Ratios relative to $\pi\pi$	Background to signal ratio (%)
$K_L \rightarrow 2\pi^0$	0.094		
$3\pi^0$	21.5	230	4
$K_L \rightarrow \pi^+\pi^-$	0.203		
$\pi e \nu$	38.7	190	} 0.7
$\pi \mu \nu$	27.1	130	
$\pi^+\pi^-\pi^0$	21.5	110	0.1
$\pi e \nu \gamma$	1.3	6	~ 0
$\pi \pi \gamma$	4.4×10^{-3}	0.02	~ 0

FIGURE 11

a) Distribution of $K_L \rightarrow \pi^+\pi^-$ reconstructed events as a function of the distance, d_{target} , of the K-production target from the reconstructed decay plane. b) Same for $K_S \rightarrow \pi^+\pi^-$.

FIGURE 12
Distribution of large- d_{target} events as a function of the decay vertex distance from the end of the K_L cleaning collimator

requirements on the energy ratio of the two tracks, on their invariant mass, and on other kinematical quantities.

The background subtraction has been carried out bin by bin. The data analysed consist of 32 self-contained K_S and K_L data sets, or miniperiods, during which the experimental set-up and running conditions were kept as stable as possible. The double ratio R of the final number was calculated miniperiod by miniperiod for each of 10×32 bins of p_K and Z_v , for $70 < p_K < 170$ GeV/c and $10.5 < Z_v < 48.9$ m.

Given the measured resolution in p_K and Z_v , and the chosen bin sizes, the effects of the different beam sizes, different beam divergences, and momentum spectra between K_L and K_S are such that the double ratio of the numbers of reconstructed events, as shown by Monte Carlo studies, cannot possibly differ by more than 1% from the double ratio of the rates of decay, implying a total Monte Carlo correction on ϵ'/ϵ of $\sim 1 \times 10^{-3}$.

About 200,000 $K_L \rightarrow \pi^0 \pi^0$, 10^6 $K_L \rightarrow \pi^+ \pi^-$, and 12×10^6 $K_S \rightarrow 2\pi$, i.e. more than 20 times the integrated number of $K_L \rightarrow \pi^0 \pi^0$ events of all previous experiments, were collected in 1986 and a large fraction of them are used for the analysis.

The high statistics allow us to study the dependence of the result on various parameters. As an illustration, the double ratio R is given in Figs. 13a, b, and c as a function of Z_v , of p_K , and of the chronological number of the miniperiods. Our work is still in progress regarding the degree of possible systematic distortions. Up to now we have evaluated, in a preliminary fashion, the differential effect on the four types of

FIGURE 13

a) Double ratio: $[N(K_L \rightarrow 2\pi^0)/N(K_L \rightarrow \pi^+\pi^-)]/[N(K_S \rightarrow 2\pi^0)/N(K_S \rightarrow \pi^+\pi^-)]$ as a function of decay vertex position; b) Same as a function of momentum; c) Same as a function of time.

events selected due to all sources we could think to be relevant. The most important of them are briefly described below:

a) Trigger efficiency

By looking at a sample of events recorded with a much looser trigger requirement than the standard one, we have continuously monitored the trigger efficiency and found it to be, on an average: in the $2\pi^0$ mode, $(99.87 \pm 0.25)\%$ for the K_L trigger and $(99.76 \pm 0.04)\%$ for the K_S one; in the $\pi^+\pi^-$ mode, $(100 \pm 0.008)\%$ for the K_L trigger and $(99.99 \pm 0.003)\%$ for the K_S one. This implies $\Delta R = (0.11 \pm 0.27)\%$ for the double ratio.

b) Event losses by accidental events

By overlapping with normal events the content of events taken in correspondence with a random trigger, adjusted to occur during the burst at a frequency proportional to the instantaneous beam intensity, we have determined the fraction of events which have been lost because of the disturbance induced by an accidental event. We have decided, for the moment, to apply no correction and to assign an error on R of 0.5% (0.8×10^{-3} on ϵ'/ϵ), i.e. 2.5 times the statistical uncertainty of the effect measured, to cover possible imperfections of the method.

We have also other ways of studying the effect of accidentals, because for each event we have recorded the instantaneous beam intensity and the time history, in 64 time slices of 50 ns each, centred around the time of occurrence of the event, for 96 channels comprising all relevant detector elements.

c) Relative energy scale for $\pi^+\pi^-$ and $\pi^0\pi^0$

This could, in principle be an important effect, but a good understanding of the geometry allows sufficient precision to be achieved.

d) Uncertainty in background subtraction

The largest background subtracted is in $K_L \rightarrow 2\pi^0$, where it amounts to 4%. The procedure to estimate it is, however, straightforward and we estimate that we have determined it to an accuracy of $\pm 5\%$. The subtraction of the background for $\pi^+\pi^-$ is much smaller (0.7%), but only known with 50% uncertainty.

The summary of the systematic uncertainties and our present result for ϵ'/ϵ are given in Table 4 and shown in Fig. 14.

In Fig. 14, in addition to comparing our results with all previous determinations, we indicate¹³ the most recent best guess on the value of ϵ'/ϵ as $(2 \pm 1) \times 10^{-3}$, according to the Standard Model.

Combining quadratically the statistical error with the present limit on the systematic uncertainties, the result for ϵ'/ϵ is 2.5 standard deviations from zero. Given

Table 4

Summary of systematic uncertainties

$2\pi^0$	energy scale	$\pm 0.4 \times 10^{-3}$
	background	$\pm 0.3 \times 10^{-3}$
$\pi^+ \pi^-$	stability K_S/K_L	$\pm 0.4 \times 10^{-3}$
	background	$\pm 0.6 \times 10^{-3}$
K_S/K_L	beam divergence	$\pm 0.1 \times 10^{-3}$
	accidentals	$\pm 0.8 \times 10^{-3}$
K_S	scattering	$\pm 0.2 \times 10^{-3}$
	anticounter inefficiency	$\pm 0.1 \times 10^{-3}$
Total systematic error		$\pm 1.2 \times 10^{-3}$
Preliminary result $\epsilon'/\epsilon = (3.5 \pm 0.7 \text{ statistical error}$ $\pm 0.4 \text{ Monte Carlo statistical error}$ $\pm 1.2) \text{ systematic error}$ $\times 10^{-3}$		

this result we plan, in addition to completing in its final form the analysis of the present data, to apply for a new SPS run in 1988 with improvement to the experimental equipment, in particular to the veto coverage close to the beam pipe, a better K_L cleaning collimator system, and additional electron identification. We plan also to take data in a wider range of instantaneous intensities and to introduce some refinements in monitoring and data-taking procedure. At present we are running in order to measure $\arg \eta_{00} - \arg \eta_+ -$ with a projected accuracy of $\sim 1^\circ$.

Concerning future developments in this field by other groups, the E731 experiment is running already with an improved, higher-acceptance detector, in a beam with better K_L /neutron ratio, with an 'active' regenerator, a faster and more selective data-acquisition system, and finally with better calibration and resolution for the Pb-glass calorimeter. It is conceivable that ultimately a precision of 1×10^{-3} on ϵ'/ϵ , with 100,000 $K_L \rightarrow 2\pi^0$, will be reached.

FIGURE 14

Present preliminary result of the NA31 experiment for ϵ'/ϵ . In the error indicated, we have combined quadratically statistical and systematic errors.

An experiment (PS 195) based on quite different principles is in preparation at the CERN Low-Energy Antiproton Ring (LEAR)¹⁴. It is aimed at an accuracy of 1.5×10^{-3} for ϵ'/ϵ , while detecting CP-violation effects in other channels such as $K \rightarrow 2\gamma$ and $K \rightarrow 3\pi$, and checking various aspects of discrete symmetries.

By detecting the sign of the charged kaon produced in association with a neutral one in antiproton-proton annihilations at rest,

$$p\bar{p} \rightarrow K^+\pi^-\bar{K}^0 \quad \text{and} \quad p\bar{p} \rightarrow K^-\pi^+K^0,$$

the strangeness at $t = 0$ of the neutral K is determined and, for instance, an integrated asymmetry can be defined from the probability of an initial K^0 and $\bar{K}^0$ decaying into 2π within a time interval t_0 :

$$A_{2\pi} = \left[\int_0^{t_0} (K^0 \rightarrow 2\pi) - \int_0^{t_0} (\bar{K}^0 \rightarrow 2\pi) \right] / \left[\int_0^{t_0} (K^0 \rightarrow 2\pi) + \int_0^{t_0} (\bar{K}^0 \rightarrow 2\pi) \right].$$

For $t_0 \approx 20\tau_s$

$$A_{+-} = 2 \operatorname{Re} \epsilon + 4 \operatorname{Re} \epsilon' ,$$

$$A_{00} = 2 \operatorname{Re} \epsilon - 8 \operatorname{Re} \epsilon' ,$$

from which we get

$$\epsilon'/\epsilon \simeq [1 - (A_{00}/A_{+-})]/6 .$$

More than 10^9 $K \rightarrow \pi^0\pi^0$ decays will have to be collected to reach the required statistical accuracy, and a good fraction of the events will have to be analysed in detail to check sources of systematic distortion.

A recent Letter of Intent has been submitted at Brookhaven (No. 749) by the BNL-Yale Collaboration, which needs a primary proton beam of such intensity that will only become available with the future AGS Booster. The neutral K beam would be produced by charge exchange from a charged K beam and the coherent mixture of K_L and K_S could be altered, with hopefully no effect on the detecting apparatus, in such a way as to enhance or reduce the normal K_2 component of K_L and hence the ratio of $\pi^0\pi^0$ to $\pi^+\pi^-$ decays in case ϵ'/ϵ is different from zero. The sensitivity is again estimated to be 1×10^{-3} .

In conclusion, the present experiment and those which will give results in the next few years may reasonably be expected to definitely settle the question of the existence of direct CP violation in weak interactions, according to the Standard Model.

REFERENCES

- 1) J.H. Christenson, J.W. Cronin, V.L. Fitch and R. Turlay, Phys. Rev. Lett. 13 (1964) 138.
- 2) See, for example,
V.L. Fitch, Rev. Mod. Phys. 53 (1981) 367;
J.W. Cronin, Rev. Mod. Phys. 53 (1981) 373;
L. Wolfenstein, Annu. Rev. Nucl. Part. Sci. (1986).
- 3) A. Sakharov, Zh. Exp. Teor. Fiz. Pis'ma v Red. 5 (1967) 32 [Transl.: JETP Lett. 5 (1967) 24].
- 4) L. Wolfenstein, Phys. Rev. Lett. 13 (1964) 569.
- 5) Review of Particle Properties, Phys. Lett. 170B (1986) 1.
- 6) V.V. Barmin et al., Nucl. Phys. 247B (1984) 293.
- 7) M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49 (1973) 652.
- 8) C. Albajar et al., Phys. Lett. 186B (1987) 247.
- 9) H. Albrecht et al., Phys. Lett. 192B (1987) 245.
- 10) M. Holder et al., Phys. Lett. 40B (1972) 141.
M. Banner et al., Phys. Rev. Lett. 28 (1972) 1597.
J.A. Christenson et al., Phys. Rev. Lett. 43 (1979) 1209.
J.K. Black et al., Phys. Rev. Lett. 54 (1985) 1628.
R.H. Bernstein et al., Phys. Rev. Lett. 54 (1985) 1631.
- 11) B. Winstein, CP and other tests of the Standard Model, to appear in Proc. APS-DPF Meeting, Salt Lake City, January 1987.
- 12) H. Burkhardt et al., The beam and detector for a high energy measurement of CP violation in neutral kaon decays, CERN-EP/87-166 (1987) submitted to Nucl. Instrum. Methods.
- 13) M. Shifman, Theoretical status of weak decays, Report to this Symposium.
- 14) L. Adiels et al., Test of CP violation with K^0 and $\bar{K}^0$ at LEAR, Proposal CERN/PSCC/85-6, January 1985.