A short history of CP violation with neutral kaons

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Outline

• Introduction: reminder of CP
• Discovery at BNL ? \( \varepsilon \)
• Search for direct CP: \( e'/e \)
• Results from CERN and FNAL
• Conclusions
The story starts in the 1940's

- strangeness
- Quark model
- $t$-? Puzzle
- $K^0 - \bar{K}^0$ mixing

$V$ particles in cloud chamber

$K_L$ prediction by Pais + Gell Man

July 6th, 2004

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CP Violation with neutral kaons
**CP violation in K decays**

**Weak and CP eigenstates:**

\[ K_S \sim K_1 + \epsilon K_2 \quad \text{CP}(K_1) = +1 \quad K_1 = (K_0 + \bar{K}_0)/\sqrt{2} \]

\[ K_L \sim K_2 + \epsilon K_1 \quad \text{CP}(K_2) = -1 \quad K_2 = (K_0 - \bar{K}_0)/\sqrt{2} \]

**Indirect CP violation** comes from mixing of CP eigenstates \( K_1 \) and \( K_2 \) in weak eigenstates \( K_S \) and \( K_L \)? **mixing parameter** \( \epsilon = (2.28 \pm 0.02) \times 10^{-3} \)

**Direct CP violation** results from asymmetric decay amplitudes

\[ \Gamma(K_0 \rightarrow \pi\pi) \neq \Gamma(\bar{K}_0 \rightarrow \pi\pi) \] **parameter** \( \epsilon' \)

**CP violation parameters:**

\[ \eta^+ = \frac{A(K_L \rightarrow \pi^+\pi^-)}{A(K_S \rightarrow \pi^+\pi^-)} = \epsilon + \epsilon' \]

\[ \eta^0 = \frac{A(K_L \rightarrow \pi^0\pi^0)}{A(K_S \rightarrow \pi^0\pi^0)} = \epsilon - 2\epsilon' \]

**Direct CP violation** \( \epsilon' \) = **penguin diagrams in SM**

\[ \epsilon' = \frac{i}{\sqrt{2}} \text{Im} \left( \frac{A_\gamma}{A_0} \right) \exp^{i(\delta_2 - \delta_0)} \]

**Theoretical calculations** of \( \epsilon'/\epsilon \) within SM

range \([4-30] \times 10^{-4}\)

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CP Violation with neutral kaons
Direct CPT violation \( \delta = \frac{A_0 - \overline{A}_0}{A_0 + \overline{A}_0} \)

Direct CP violation \( \varepsilon' = \frac{1}{\sqrt{2}} \frac{A_2 - \overline{A}_2}{A_2 + \overline{A}_2} e^{i(d_2 - d_0)} \)

\( \Phi_\varepsilon \approx 43.49 \pm 0.08^\circ \)

\( \eta_{+-} = (\varepsilon + \Delta + \delta) + \varepsilon' \) \( \varepsilon : \text{CP, CPT in } K^0 - \overline{K}^0 \text{ mixing} \)

\( \eta_{00} = (\varepsilon - \Delta + \delta) - 2\varepsilon' \) \( \Delta : \text{CP, CPT in } K^0 - \overline{K}^0 \text{ mixing} \)
CP violation: is it a mystery?

- Unexpected phenomenon
- Disturbing discovery of $K_L$? $pp$ at BNL by Christenson, Cronin, Fitch, Turlay
- Kobayashi and Maskawa give a modern explanation
- Sakharov’s conjecture for baryon asymmetry of the universe
- $CP$ violation = matter-antimatter asymmetry $\sim 3 \times 10^{-10}$
- Need also thermal non-equilibrium and processes with $\Delta B \neq 0$
- $CP$ violation from CKM not sufficient
- Phase transition not strong enough
- CKM too cool
- New source(s) needed
I. INTRODUCTION

The present proposal was largely stimulated by the recent anomalous results of Adair et al. on the coherent regeneration of \( K_2 \)'s, neutrals. It is the purpose of this experiment to check these results with a precision far transcending that attained in the previous experiment. Other results to be obtained will be a new and much better limit for the partial rate of \( K_2^0 \rightarrow \pi^+ \pi^- \), a new limit for the presence (or absence) of neutral currents as observed through \( K_2^0 \rightarrow \pi^+ \pi^- \). In addition, if time permits, the coherent regeneration of \( K_2^0 \)'s in dense materials can be observed with good accuracy.

II. EXPERIMENTAL APPARATUS

Purposely the equipment of this experiment already exists in operating condition. We propose to use the present 30° neutral beam at the A.O.S. along with the di-pion detector and hydrogen target currently being used by Cronin et al. at the Cosmotron. We further propose that the experiment be done during the forthcoming \( \mu^-p \) scattering experiment on a parasitic basis.

The di-pion apparatus appears ideal for the experiment. The energy resolution is better than 4 Mev in the \( \pi^- \) or the Q value measurement. The origin of the decay can be located to better than 0.1 inches. The 4 Mev resolution is to be compared with the 20 Mev in the Adair bubble chamber. Indeed it is through the greatly improved resolution (coupled with better statistics) that one can expect to get improved limits on the partial decay rates mentioned above.

III. COUNTING RATES

We have made careful Monte Carlo calculations of the counting rates expected. For example, using the 30° beam with the detector 60-ft. from the A.O.S. target we could expect 0.6 decay events per \( 10^{11} \) circulating protons if the \( K_2 \) went entirely to two pions. This means that one can set a limit of about one in a thousand for the partial rate of \( K_2^0 \rightarrow 2\pi^0 \) in one hour of operation. The actual limit is set, of course, by the number of three-body \( K_2 \) decays that look like two-body decays. We have not as yet made detailed calculations of this. However, it is certain that the excellent resolution of the apparatus will greatly assist in arriving at a much better limit.

If the experiment of Adair et al. is correct the rate of coherently regenerated \( K_2 \)'s in hydrogen will be approximately 50/hour. This is to be compared with a total of 20 events in the original experiment. The apparatus has enough angular acceptance to detect incoherently produced \( K_2 \)'s with uniform efficiency to beyond 15°. We emphasize the advantage of being able to remove the regenerating material (e.g., hydrogen) from the neutral beam.

IV. POWER REQUIREMENTS

The power requirements for the experiment are extraordinarily modest. We must power one 18-in. x 36-in. magnet for sweeping the beam of charged particles. The two magnets in the di-pion spectrometer are operated in series and use a total of 20 kw.

July 6th, 2004

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CP Violation with neutral kaons
BNL 1963: the experiment

- Letter of Intent by J. Cronin, V. Fitch, R. Turlay: April 1963
- Agreement of BNL directorate: May 1963
- Apparatus ready: June 2\textsuperscript{nd} 1963

- 40 days of running: end of July 1963

\begin{enumerate}
\item regeneration on C, Cu, Pb 70000 triggers
\item CP limit 47000 triggers
\item Adair effect on H2 23000 triggers
\end{enumerate}

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CP Violation with neutral kaons
BNL 1963: the first hint

R. Turlay's first notice
fall 1963

Peak at 0° for
events @ K mass

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CP Violation with neutral kaons
BNL 1963: the experiment

Figure 7: Page from the data book at the beginning of the CP violation run, June.

Page from data book @ beginning of CP violation run

Figure 9: Page from notebook of J. W. Cronin with comment on the first results of the analysis of the CP events measured with the angular encoder.

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CP Violation with neutral kaons
Short bibliography on $CP$ discovery and early experiments

- R. Turlay, CP Violation, Int. Conf. on History of original ideas and basic Discoveries in Particle Physics, Erice. Plenum (1996) Nato ASI B352
- J. Steinberger, experimental status of CP violation.
Why measure $\varepsilon'/\varepsilon$?

Unitarity triangle
Constraints on models
(SM, SUSY ...)

$\frac{\varepsilon'}{\varepsilon} \propto \text{Im} \lambda_t \left( \frac{110 \text{ MeV}}{m_s(2 \text{ GeV})} \right)^2 \left[ 0.75 \cdot B_\beta - 0.4 \cdot B_\beta \left( \frac{m_t}{165 \text{ GeV}} \right)^{\frac{5}{3}} \right] \frac{\Lambda^{(4)}}{340 \text{ MeV}}$

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CP Violation with neutral kaons
January 1979: Proposal

A Study of Direct CP Violation in the Decay of the Neutral K0 via a Precision Measurement of \(|v_\mu/v_\tau|\)

R. Bernstein, J.W. Cronin, and B. Welnhofer
University of Chicago, Enrico Fermi Institute, Chicago, Illinois
L. Cousins, J. Greenhalgh, and M. Schwartz
Stanford University, Department of Physics, Stanford, California
D. Hendin and G. Thomson
University of Wisconsin, Department of Physics, Madison, Wisconsin

Abstract

In this proposal, we describe an experiment to measure the ratio \(R\) of the CP violating amplitudes \(|v_\mu|\) and \(|v_\tau|\) to a precision of better than 1\% thereby improving the present results by about one order of magnitude. If the CP violation is confined to the mass matrix, \(R = 1.0\) exactly. Recent theoretical considerations which unify the CP violating interactions with the CP conserving weak and electromagnetic interactions among six quarks predict \(R\) differing from 1.0 by stable amounts.

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CP Violation with neutral kaons

\(K_L\)\(^2\pi^0\) mass peak BKG \(\sim 8\%\)

\(K_S\)\(\pi^+\pi^-\) inelastic BKG \(\sim 1.7\%\)

\(K_L\)\(\pi^0\) inelastic BKG \(\sim 14.6\%\)
Basic principles

E731 uses regeneration

NA31 uses movable target

CERN-Edinburgh-Mainz-Orsay-Pisa-Siegen Collaboration
Proposal 22 Dec 1981
Approved 16 Sep 1982
Data taking 1986 – 1989
Final result 1993

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E731 at Fermilab 1985-1990

Pb glass calorimeter

Regenerator in vacuum

Poor linearity

$K_L \rightarrow \pi^0 \pi^0$

$K_S \rightarrow \pi^0 \pi^0$

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CP Violation with neutral kaons
December 1980: Proposal

3 December, 1980

To: CERN-Dortmund-Heidelberg-Faehn Collaboration
From: J. Steinberger and H. Ruhl

Subject: $|\eta_{\sfrac{2}{3}}/\eta_{\sfrac{1}{3}}|$ experiment

As is well known, SU(2) x U(1) with six flavours provides a "natural" way to CP violation, and deviations from 1 in $|\eta_{\sfrac{2}{3}}/\eta_{\sfrac{1}{3}}|$ of the order of <1%, and consequently of the order of 3% in the double ratio

$$\frac{\Gamma(K_\mu - 2\pi)}{\Gamma(K_\pi^+ - \pi^-)}$$
$$\frac{\Gamma(K_\mu - 3\pi)}{\Gamma(K_\pi^+ - 2\pi)}$$

can be expected. An experiment by Cronin et al. to measure this accuracy is in progress at TOTEM.

We have been thinking about how one might best do this measurement and think we have found a way in which one might hope to get an accuracy of the order of 0.003 in $|\eta_{\sfrac{2}{3}}/\eta_{\sfrac{1}{3}}|$. The general idea is shown on the sketch. Neutral and charged are measured simultaneously in a detector which consists of:

1) Proportional chambers to measure the charged directions;
2) A y calorimeter with $dE/dx \simeq 0.1/E$, and $dE/dx \simeq 3$ mm;
3) A hadron calorimeter with $dE/dx \simeq 3.4/E$, and rather coarse grain;
4) Mucu counters.

It is intended to work in the range 100 < $E < 200$ GeV. Short and long-lived kaons are obtained alternately by a change in target position.

The chief backgrounds for the neutral mode is the $3\pi^0$ decay, and the position and energy information should be sufficient to get rid of all these. The resolution of the reconstructed $f^0$ is $2\pm\Delta f^0$, and the resolution in the reconstructed $f^0$ mass for the neutral decay should be <1%. The background for the charged mode is presumably chiefly $K_\pi$, and $K_\mu$, decay. It should be possible to reject
Status in 1989

CP violation: where we stand 25 years later

\[ \varepsilon'/\varepsilon = (33 \pm 11) \times 10^{-4} \, (\text{NA31}) \]

\[ \varepsilon'/\varepsilon = [(-10 \text{ to } 10) \pm 15] \times 10^{-4} \, (\text{E731, very preliminary}) \]

The E731 result does not confirm the non-zero result of NA31 nor does it significantly disagree with it.

What are we to conclude from these experiments? The most important conclusion is that they must be continued to still higher accuracy. The point is not to find the exact value of \( \varepsilon' \); the point is to make absolutely sure that \( \varepsilon' \) is non-zero. The NA31 experiment has wounded the superweak theory. The time has come to really kill it. I remember in 1968 in Moscow discussing the death of the superweak theory based on an experiment ... The superweak theory does not die easily.

L. Wolfenstein, Concluding talk

CP violation in particle physics and astrophysics, Chateau de Blois 1989
Final results in 1996

\( \epsilon' \epsilon \) Status: ... The final results from NA31 and E731 are well known:

\[
\text{NA31: } \Re \epsilon'/\epsilon = (23 \pm 6.5) \times 10^{-4}, \\
\text{E731: } \Re \epsilon'/\epsilon = (7.4 \pm 5.9) \times 10^{-4}.
\]

The NA31 result is more interesting in that it tends to disagree with the latest predictions from the Standard Model. On the other hand, the E731 result is in the range favored by the Standard Model and as well it doesn’t quite rule out the Superweak Model \((\Re \epsilon'/\epsilon = 0)\) with any confidence. The results differ by about two standard deviations; nevertheless, the conclusions are sufficiently different that it would not be appropriate to average the results prior to the establishment of a non-zero effect.\(^{\text{HW}}\)

B Weinstein, Summary (Experiments)
Workshop on K physics, Orsay 1996

R. Turlay reviewed the status of our present knowledge on CP/CPT violation for the kaon case. A new interest has arisen in recent years in connection with the successful 6-quark Kobayashi and Maskawa model (which includes CP violation in a "natural" way) and with astrophysics problems. The two planned experiments, at CERN and Fermilab, aim for $\sim 10^5$ events in 1985-87 with an accuracy of $\sim 0.1\%$ on $|\epsilon'/\epsilon|$, whereas in 1974 the errors were at the level of 1%. Why then LEAR? In the referee’s opinion LEAR can do as well in the $|\epsilon'/\epsilon|$ measurement or better in other parameters. Even if the statistical accuracy is comparable, the systematic errors would be of a completely different origin. Also one would explore the kaons in $K^0$ and $\bar{K}^0$ states with the possibility to study the $K_{e3}$ channel and improve the measurement on CP and CPT. However, one should go for a long-term programme ($\sim 5$ years)

The Committee agreed that a CP/CPT experiment could be an interesting ingredient in the second-generation LEAR programme, but in view of the large effort involved it was clearly too early to take any commitment.
Strangeness $K^\circ$ ( $\bar{K}^\circ$) signed at $t=0$ by $K^+(K^-)$

Direct observation of time evolution $K^0(t) \Rightarrow \bar{K}_0(t)$

Strangeness of decay signed with $K_{e3}$

$T$ invariance $\Rightarrow K^\circ(t)$ observed from $\bar{K}_0(t=0)$ identical to $\bar{K}_0(t)$ observed from $K^\circ(t=0)$.

Measurement of $T$ invariance without CPT hypothesis

$T$ violation: $A_T \approx 4\text{Re}(\varepsilon)$ if CPT invariance holds
**First observation of T from time conjugate processes**

\[
A_T^{\exp}(\tau) = \frac{\eta N(K_{l=0}^0 \rightarrow e^+ \pi^- \nu_{l=\tau}) - \xi N(K_{l=0}^0 \rightarrow e^- \pi^+ \bar{\nu}_{l=\tau})}{\eta N(K_{l=0}^0 \rightarrow e^+ \pi^- \nu_{l=\tau}) + \xi N(K_{l=0}^0 \rightarrow e^- \pi^+ \bar{\nu}_{l=\tau})}
\]

\[
\langle A_T^{\exp}\rangle_{(1-20)\tau_s} = (6.6 \pm 1.3) \times 10^{-3}
\]

\[
\chi^2/\text{d.o.f.} = 0.54
\]

**Systematic errors on \( A_T^{\exp} \)**

<table>
<thead>
<tr>
<th>Source</th>
<th>( A_T^{\exp} ) [10^{-3}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>background level</td>
<td>±0.03</td>
</tr>
<tr>
<td>background asymmetry</td>
<td>±0.02</td>
</tr>
<tr>
<td>( \xi )</td>
<td>±0.2</td>
</tr>
<tr>
<td>( \eta )</td>
<td>±1.0</td>
</tr>
<tr>
<td>decay-time resolution</td>
<td>negligible</td>
</tr>
<tr>
<td>regeneration</td>
<td>±0.1</td>
</tr>
<tr>
<td>Total syst.</td>
<td>±1.0</td>
</tr>
</tbody>
</table>
**CPLEAR Results**

- **CP Violation**
  
  \[ K^0 \rightarrow \pi^+ \pi^- \]

  \[
  |\eta_{\pi\pi}| = (2.286 \pm 0.023_{\text{stat}} \pm 0.026_{\text{syst}} \pm 0.067_{\text{sys}}) \times 10^{-3} \\
  \phi_{\pi\pi} = 43.19^\circ \pm 0.53_{\text{stat}} \pm 0.28_{\text{syst}} \pm 0.42_{\Delta m} \\
  K^0 \rightarrow \pi^0 \pi^0 \\
  |\rho_{\pi^0\pi^0}| = (2.47 \pm 0.31_{\text{stat}} \pm 0.24_{\text{syst}}) \times 10^{-3} \\
  \phi_{\pi^0\pi^0} = 42.0^\circ \pm 5.6_{\text{stat}} \pm 1.9_{\text{syst}} \\
  K^0 \rightarrow \pi^+ \pi^- \pi^0 \\
  \text{Re}(\eta_{\pi^+\pi^-}) = (-2 \pm 7_{\text{stat}} \pm 6_{\text{syst}}) \times 10^{-3} \\
  \text{Im}(\eta_{\pi^+\pi^-}) = (-2 \pm 9_{\text{stat}} \pm 7_{\text{syst}}) \times 10^{-3} \\
  K^0 \rightarrow \pi^0 \pi^0 \pi^0 \\
  \text{Re}(\rho_{\pi^0\pi^0\pi^0}) = 0.18 \pm 0.14_{\text{stat}} \pm 0.06_{\text{syst}} \\
  \text{Im}(\rho_{\pi^0\pi^0\pi^0}) = 0.15 \pm 0.20_{\text{stat}} \pm 0.03_{\text{syst}}
  
  \text{(direct)} \quad \text{(unitarity)}
  
  \text{PLB 458 (1999) 545} \quad \text{PLB 420 (1998) 191} \quad \text{EPI CS (1998) 191}
  
  \text{PLB 425 (1998) 391} \quad \text{PLB 444 (1998) 43} \quad \text{PLB 444 (1998) 52} \quad \text{PLB 444 (1998) 43}
  
  \text{PLB 444 (1998) 38} \quad \text{PLB 444 (1998) 38} \quad \text{PLB 444 (1998) 52} \quad \text{PLB 444 (1998) 43}
  
  \text{PLB 407 (1997) 193} \quad \text{PLB 413 (1997) 232}
  
  \text{PLB 413 (1997) 422}

- **Other parameters of the neutral kaon system**

  \[ \Delta m = (529.5 \pm 2.0_{\text{stat}} \pm 3.0_{\text{syst}}) \times 10^{-7} \text{ keV} \]

  \[ \Delta S = \Delta Q \text{ rule:} \]

  \[ \text{Re}(\xi) = (-1.8 \pm 4.1_{\text{stat}} \pm 4.5_{\text{syst}}) \times 10^{-3} \]

  \[ \text{Re}(\xi) = (2.0 \pm 5.3_{\text{stat}} \pm 0.3_{\text{syst}}) \times 10^{-2} \]

  \[ \text{Im}(\xi) = (1.2 \pm 1.9_{\text{stat}} \pm 0.3_{\text{syst}}) \times 10^{-3} \]

  \[ \text{BR}(K \rightarrow \pi^+ \pi^- \pi^-) = 0.5 \pm 1.3_{\text{stat}} \pm 1.5_{\text{syst}} \times 10^{-7} \]

  \[ \text{BR}(K \rightarrow \pi^0 \pi^0 \pi^0) < 4 \times 10^{-7} \]

  \text{Koan scattering amplitudes in Carbon}

- **Other tests of fundamental physics**

  \[ \text{Test of quantum mechanics coherence} \]

  \[ \text{EPR test with } \Phi \rightarrow K^0 \bar{K}^0 \]

  \[ \text{Test of equivalence principle} \]

- **T Violation**

  \[ \text{Re}(\xi) = (1.65 \pm 0.33_{\text{stat}} \pm 0.25_{\text{syst}}) \times 10^{-3} \]

  \[ \text{Re}(\xi) = (1.649 \pm 0.025) \times 10^{-3} \]

  \text{PLB 444 (1998) 43} \quad \text{PLB 456 (1999) 297}

- **CPT Violation**

  \[ \text{Re}(\delta) = (3.0 \pm 3.3_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-4} \]

  \[ \text{Im}(\delta) = (-1.5 \pm 2.3_{\text{stat}} \pm 0.3_{\text{syst}}) \times 10^{-3} \]

  \[ \text{Im}(\delta) = (-2.4 \pm 5.0) \times 10^{-5} \]

  \[ M_{K_{L0}} - M_{K_{S0}} = (-1.5 \pm 2.0) \times 10^{-18} \text{ GeV} \]

  \[ M_{K_{L0}} - M_{K_{S0}} = (3.9 \pm 4.2) \times 10^{-18} \text{ GeV} \]

  \text{PLB 364 (1995) 239} \quad \text{PLB 422 (1998) 339} \quad \text{PLB 452 (1999) 425}

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CP Violation with neutral kaons
Double $K_L$ beams ($<p>=70$ GeV/c)  
Regenerator for $K_S$  
Pure CsI calorimeter  
$K_S/K_L$ by event position  
MC acceptance correction  
Maximize statistics
KTeV at Fermilab 1992-2002

The Regenerator

π⁺ π⁻ Data/MC ratios

π⁰ Data/MC ratios

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Simultaneous near/far targets
Converging beams ($<p>=100$ GeV/c)
Liquid Kr calorimeter
Tagging by time-of-flight
Lifetime weighting to minimize acceptance correction
The weighting method used by NA48 at CERN

At the same $z \Rightarrow$ Acceptance $K_S = K_L$
But very different decay lengths: $\tau_{K_L} \approx 600 \times \tau_{K_S}$
$\Rightarrow$ Different total acceptance for $K_S$ and $K_L$
$\Rightarrow$ large correction on $R$
Solution: Weight $K_L$ events with:

$$w = \frac{\pi \pi \text{ decay rate in } K_S}{\pi \pi \text{ decay rate in } K_L} \approx e^{-z/(\beta\gamma c)(1/\tau_{K_S} - 1/\tau_{K_L})}.$$  

Same decay vertex distribution for $K_S$ and weighted $K_L$
Acceptance correction cancels
Price: Increase in statistical error ($\approx 35\%$)
## Data Taking Periods

<table>
<thead>
<tr>
<th>Year</th>
<th>NA48: $\varepsilon'/\varepsilon$</th>
<th>NA48/1: $K_S$</th>
<th>NA48/2: $K^\pm$</th>
<th>$K_L \rightarrow \pi^0\pi^0$</th>
<th>Total: 5.3M $K_L \rightarrow \pi^0\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>$\varepsilon'/\varepsilon$</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td>$\varepsilon'/\varepsilon$</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>1998</td>
<td>$\varepsilon'/\varepsilon$</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>1999</td>
<td>$\varepsilon'/\varepsilon$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>$\varepsilon'/\varepsilon$</td>
<td>$K_S$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>$\varepsilon'/\varepsilon$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>$\varepsilon'/\varepsilon$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>$\varepsilon'/\varepsilon$</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

**CERN-NA48**

July 6th, 2004

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CP Violation with neutral kaons
Experimental results on $\text{Re}(\varepsilon'/\varepsilon)$

- Final result (1997-2001)
  \[ \Gamma(K^0 \rightarrow \pi^+\pi^-) - \Gamma(\bar{K}^0 \rightarrow \pi^+\pi^-) \]
  \[ \Gamma(K^0 \rightarrow \pi^+\pi^-) + \Gamma(\bar{K}^0 \rightarrow \pi^+\pi^-) = (5.04 \pm 0.82) \times 10^{-6} \]

- Half statistics (1997)

- More results expected from KTeV and KLOE

Direct CP violation observed with neutral K, i.e. 2 numbers for CP

Average: $(16.7 \pm 2.3) \times 10^{-4}$

$\chi^2 = 6.2/3$

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CP Violation with neutral kaons
Despite huge efforts, $\epsilon'/\epsilon$ not yet computed reliably
Measured value is roughly compatible with the SM
Expect improvements from lattice
Yields and background for $K_L \to 2\pi^0$

<table>
<thead>
<tr>
<th>Year</th>
<th>Experiment</th>
<th>$K_L \to 2\pi^0$</th>
<th>Background</th>
<th>Data volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985</td>
<td>E617-FNAL Chicago-Saclay</td>
<td>3,152</td>
<td>~11.3%</td>
<td>10 GB</td>
</tr>
<tr>
<td>1985</td>
<td>Yale-BNL</td>
<td>1,361</td>
<td>~17.6%</td>
<td></td>
</tr>
<tr>
<td>1988</td>
<td>E731-Test-FNAL</td>
<td>6,950</td>
<td>~5.0%</td>
<td></td>
</tr>
<tr>
<td>1988</td>
<td>NA31-CERN</td>
<td>109,000</td>
<td>~4.0%</td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td>E731A-FNAL</td>
<td>52,200</td>
<td>~5.0%</td>
<td></td>
</tr>
<tr>
<td>1993</td>
<td>E731-FNAL Final</td>
<td>410,326</td>
<td>~5.0%</td>
<td>100 GB</td>
</tr>
<tr>
<td>1993</td>
<td>NA31-CERN Final</td>
<td>428,000</td>
<td>~2.7%</td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>KTeV-FNAL</td>
<td>10,000,000</td>
<td>~0.48%</td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>NA48-CERN</td>
<td>5,000,000</td>
<td>~0.16%</td>
<td>100 TB</td>
</tr>
</tbody>
</table>

July 6th, 2004
B. Peyaud
CP Violation with neutral kaons
The experimental results have higher precision than current calculations.

The fine cutting is left to theory ...

The legacy of ~2 decades of experiments

Direct CP violation has received experimental evidence in $K^0$ system

$\varepsilon'/\varepsilon = (16.7 \pm 2.3) \times 10^{-4}$

The holy grail measurements: $K_L \rightarrow \pi^0 \bar{\nu}$, $K^+ \rightarrow \pi^+ \bar{\nu}$

BNL E926 (KOPIO), KEK E391?  M. Sozzi’s talk

hopefully the harvest of the next decade

July 6th, 2004

B. Peyaud

CP Violation with neutral kaons
René Turlay: a gentleman dedicated to physics and to people

A true leader in physics
A grand master in understanding human beings

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