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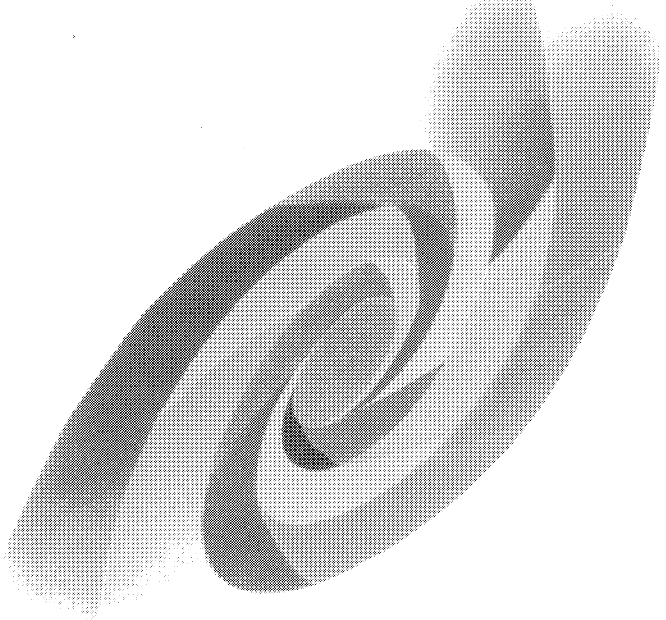

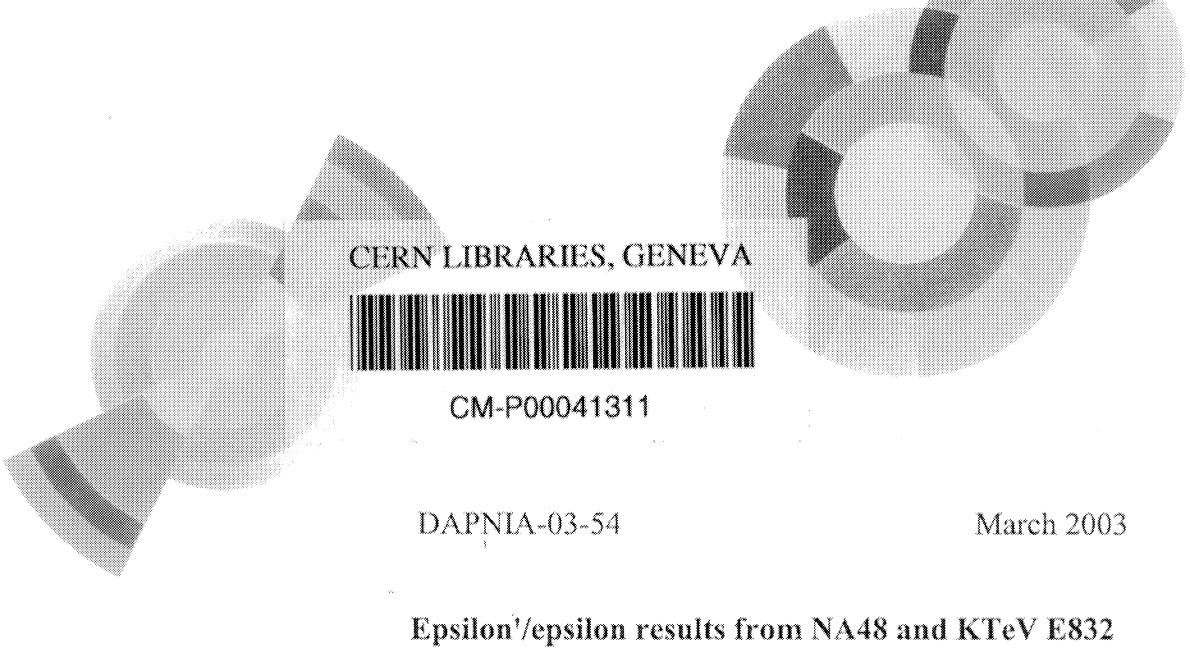

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ε'/ε results from *NA48* and *KTeV E832*

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After more than 25 years of intense experimental effort, the parameter $Re(\varepsilon'/\varepsilon)$ which characterizes *direct* $\mathcal{CP}$ violation in the neutral kaon system has been accurately measured by both the *Fermilab KTeV E832* and the *Cern NA48* experiments. The latest results presented here demonstrate unambiguously the existence of *direct* $\mathcal{CP}$ violation.

The experimental challenge is reviewed, and the techniques used to extract the parameter are discussed. The current situation is given and future propects are briefly sketched.

1. Introduction

1.1. $\mathcal{CP}$ violation in the $K^0 - \overline{K^0}$ system

$\mathcal{CP}$ violation was discovered in 1964 by *Christenson, Cronin, Fitch* and *Turlay* [1], in the decay of the long-lived neutral kaon (called until then 'K_2^0') in two charged pions, with a branching ratio close to 2×10^{-3}. This discovery showed that the long-lived neutral kaon could not be a pure $\mathcal{CP}$ eigenstate. As early as 1964, *Wu* and *Yang* [2] introduced a new formalism to describe the neutral kaon system, with K_S and K_L states, and the '*impurity parameter*' ε_K :

$\mathcal{CP}$ **symmetry being not conserved**, the strong hamiltonian eigenstates K_S (S=*Short*) and K_L (L=*Long*) are no more pure $\mathcal{CP}$ eigenstates (K_1 resp. K_2), but contain a small contribution of the opposite $\mathcal{CP}$ eigenstate (K_2 resp. K_1), parametrized by ε_K (in the hypothesis of $\mathcal{CPT}$ invariance) :

$$|K_S\rangle = \frac{1}{\sqrt{1+|\varepsilon_K|^2}}(|K_1\rangle + \varepsilon_K|K_2\rangle) \ ; \ |K_L\rangle = \frac{1}{\sqrt{1+|\varepsilon_K|^2}}(|K_2\rangle + \varepsilon_K|K_1\rangle) \tag{1}$$

It then clearly appears that the parameter ε_K describes the $\mathcal{CP}$ violation resulting from an asymmetric mixing between the K^0 and $\overline{K^0}$ states, the decay process itself being $\mathcal{CP}$ conserving. This kind of $\mathcal{CP}$ violation in the **mixing** is called **indirect $\mathcal{CP}$ violation**.

$\mathcal{CP}$ violation can also arise as a consequence of the decay of the K_2 component of the K_L into two pions. This kind of $\mathcal{CP}$ violation in the **decay** is called **direct $\mathcal{CP}$ violation**. It is linked to the phase difference between weak transitions amplitudes of the $|K^0\rangle$ and $|\overline{K^0}\rangle$ to a two pions final state of defined isospin I. The relevant parameter in the kaon system is ε' which can be written as :

$$\varepsilon' = \frac{\varepsilon_K}{\sqrt{2}}\left\{\frac{\langle\pi\pi_{I=2}|H|K_L\rangle}{\langle\pi\pi_{I=0}|H|K_L\rangle} - \frac{\langle\pi\pi_{I=2}|H|K_S\rangle}{\langle\pi\pi_{I=0}|H|K_S\rangle}\right\} \tag{2}$$

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*Invited talk on behalf of the NA48 collaboration.

This expression immediately shows the smallness of ε', since $\varepsilon = (2.28 \pm 0.02) \times 10^{-3}$ and because of the empirical $\Delta I = 1/2$ selection rule, and the value of $Re(\varepsilon'/\varepsilon)$ is expected in the $\mathcal{O}(10^{-3})$ range. The smallness of *direct* $\mathcal{CP}$ violation effects has required a tremendous experimental effort over the last 2 decades to establish that ε' is different from zero, opposed to the *superweak* model [3] prediction. The theoretical interest is twofold : *first* assert whether a $\mathcal{CP}_{odd}$ state can decay to a $\mathcal{CP}_{even}$ final state, which would immediately rule out the *superweak* model, and *second* put constraints on the parameters of the *Cabibbo-Kobayashi-Maskawa* V^{CKM} matrix [4].

The ratio of the $\mathcal{CP}$ violating to the $\mathcal{CP}$ conserving kaon decay amplitudes to a $\pi\pi$ final state is different for $\pi^0\pi^0$ and $\pi^+\pi^-$ final states, because of their different decomposition on isospin eigenstates of $I = 0$ and $I = 2$. In other words, the two $\mathcal{CP}$ violating neutral kaon decay amplitudes into two pions :

$$\eta^{+-} \equiv \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \simeq \varepsilon + \varepsilon' \ ; \ \eta^{00} \equiv \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} \simeq \varepsilon - 2\,\varepsilon' \tag{3}$$

contain different admixture of the two $\mathcal{CP}$ violating processes in charged and in neutral mode. This small difference is used by fixed target experiments to search for *direct* $\mathcal{CP}$ violation in a significant difference from 1 of the double ratio of decay rates R :

$$R \equiv \frac{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)} = \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2 \approx 1 - 6Re\left(\frac{\varepsilon'}{\varepsilon}\right) \tag{4}$$

1.2. Sketch of the double ratio method

As can be seen from equation 4, the experimental challenge is then the precise **event counting** in four decay modes. In fact, if the aimed accuracy for $Re(\varepsilon'/\varepsilon)$ is below the per-mil, the double ratio R and *a fortiori* each of the numbers entering in R should be known to better than 0.6 %. The experimental constraints are derived from the simple expression of the double ratio :

- the experiment has to measure both K_L and K_S decays.
- the experiment has to measure both neutral $\pi^0\pi^0$ and charged $\pi^+\pi^-$ decay modes, and to be able to reject parasitic modes exhibiting the same experimental signature. Those backgrounds mainly affect the K_L decays : in neutral mode, the signal has a branching ratio of $BR(K_L \to \pi^0\pi^0) = 9.14 \times 10^{-4}$ far below the $3\pi^0$ background with $BR(K_L \to 3\pi^0) = 21.6\%$; in the charged mode as well, the signal has a branching ratio of $BR(K_L \to \pi^+\pi^-) = 2.03 \times 10^{-3}$ and one has to get rid of semi-leptonic backgrounds $K_L \to \pi^\pm l^\mp \nu$ (K_{e3} and $K_{\mu 3}$) which represent 65.7% of all K_L decays. K_S decays counting is affected by hyperon decays in case of a close target, or by incoherent regeneration in case a regenerator is used. In addition, all modes can suffer from the scattering of the neutral beams on collimators. The identification of these modes has to allow a substantial reduction of the backgrounds to a few % if the uncertainty associated to background subtraction is to be kept below 1 %.
- to reach 10^{-3} on $Re(\varepsilon'/\varepsilon)$, the statistics in each decay mode has to exceed 10^5 events : with such a number of events in each of the modes, the statistical error on R would be 0.632 % and the one on $Re(\varepsilon'/\varepsilon)$ six times smaller, say $\sim$ 1 per

mil. Experimentaly the limitation comes from the $\mathcal{CP}$ violating modes, mainly $K_L \to \pi^0\pi^0$ which is suppressed by a factor 4 due to acceptance and BR compared to $K_L \to \pi^+\pi^-$. The statistical issue was the strongest limitation of the experiments of the first generation.

- last, but not least, the extraction of a decay rate from a number of events observed in a **precisely defined fiducial volume** requires in principle the knowledge of the incoming kaon **flux**, of the detection **efficiency**, of the **dead time** and **acceptance** associated to the decay mode.

We will see in the next section that each of the two experiments *E731* and *NA31* has chosen to measure **simultaneously** two modes, in order to avoid the precise determination of all the ingredients listed in the last item.

The statistical issue will be solved by selective triggers, fast data acquisition and long running periods. The background issue requires high resolution detectors for both neutral and charged modes.

Let us now address to question of having K_L and K_S in an experiment. Consider the instantaneous K^0 ($\overline{K^0}$) to $\pi\pi$ decay rate downstream a target, consisting of a K_S decay term, a K_L decay term and an interference term :

$$\frac{d\Gamma(\overset{(-)}{K^0} \to 2\pi)}{d\tau} \propto \frac{1}{|1 \pm \varepsilon|^2} \left[e^{-\frac{\tau}{\tau_S}} + |\eta|^2 e^{-\frac{\tau}{\tau_L}} \pm 2|\eta| \cos(\Delta m\tau - \phi_\eta) e^{-\frac{\tau}{2}(\frac{1}{\tau_S}+\frac{1}{\tau_L})} \right] \tag{5}$$

where τ is the kaon proper time and $\eta = A(K_L) \to 2\pi)/A(K_S) \to 2\pi)$. Due to the smallness of $|\eta|$ ($\sim 0.23\%$), the 2π sample in a detector close to the target will be dominated by K_S decays. In a region where the contributions of the K_S term and the interference term are comparable (at $\tau \sim 12\tau_S$), we might think to extract η_{+-} and η_{00} provided the relative K^0 and $\overline{K^0}$ amounts are precisely known. This turns out to be difficult in practice, and therefore experimentalists prefer to use different K_S and K_L sources, one close to the detector to collect the K_S sample and the other much farther for the K_L sample. All precision experiments are using, each in its manner, this principle.

2. The heritage from the first precision measurements

In the mid '80's, two experiments allowed a quantitative step towards the determination of ε'/ε. The *NA31* experiment at *CERN* made the choice of measuring simultaneously neutral and charged kaon decays using detection elements mainly based on precise calorimetry. In order to symmetrize the detector acceptance for K_L and K_S decays, and therefore minimize the acceptance correction, a complicated beam layout was used : the K_L originated from a far target, while the K_S were created on a close target, moveable over the common decay distance. As a result, the longitudinal decay vertex distributions of K_S decays were made identical to the *flat* ones of K_L decays. *NA31* reported a first evidence of *direct* $\mathcal{CP}$ violation : $Re(\varepsilon'/\varepsilon) = (23 \pm 6.5) \times 10^{-4}$ [5].

The *E731* at *Fermilab* chose instead to measure simultaneously K_L and K_S decays using a *double-beam* from a unique far target. In the path of one of the 2 K_L beams, a thick regenerator was used to create a K_S component. The regenerator position was alternating between the 2 beams every accelerator spill in order to symmetrize the K_L and K_S acceptances. The detector setup was slightly different in neutral and charged modes because of dedicated trigger schemes. The neutral mode detection was based on calorimetry, while a precise magnetic spectrometer was used in charged mode. The *E731* result : $Re(\varepsilon'/\varepsilon) = (7.4 \pm 5.2 \pm 2.9) \times 10^{-4}$ [6] gave no sign of *direct* $\mathcal{CP}$ violation.

The marginal agreement between the 2 values resulted in a global penalty for the 2 groups, since the *PDG* value : $Re(\varepsilon'/\varepsilon) = (15 \pm 8) \times 10^{-4}$ was less than 2 sigma from zero, and could not disqualify the superweak model. Clarifying the situation with a much better accuracy was one of the main motivations of new experiments in both laboratories. The methods of *NA31* and *E731* were radically different, as well as their limitations. *E731* was statistically limited, and therefore used at best the statistical power of K_L decays, at the price of a strong dependence upon the MonteCarlo simulation. On the other hand, the simultaneous collection of K_L and K_S decays allowed natural cancellations in single ratios of decay rates. *NA31* appears more systematically limited, because of distinct K_L and K_S data taking periods, resulting in quite different accidental activities. Among the strong points of *NA31*, we have to quote the absence of backgrounds for K_S decay modes due to the use of a target, unlike *E731* which uses a regenerator. In addition, the similarity of the energy and vertex position distributions results in a very small differential acceptance correction and MonteCarlo dependence.

Even before the discovery of the top quark, experimentalists of both collaborations decided for a new experimental '*round*', in the light of the experience acquired with *E731* and *NA31*, with a new goal accuracy of $1 - 2 \times 10^{-4}$ on $Re(\varepsilon'/\varepsilon)$. This kind of precision was largely motivated by the theoretical predictions of those days which, even if they did not discard the *NA31* value, had a tendancy to prefer values of a few 10^{-4} and therefore made the experimental challenge harder.

In the proposals of the third generation of experiments which went out in the early '90's (*KTeV*, *NA48*), there are many common features :

- use of much more intense kaon beams to collect ten times bigger data samples,
- simultaneous collection of the four modes which enter in the double ratio,
- symmetrization of the K_L and K_S beam acceptances,
- use of a magnetic spectrometer for the measurement of charged particles momenta,
- use of a better electromagnetic calorimeter for photon or electron detection and background rejection.

It could then seem that the same experiment is being designed on either side of the Atlantic Ocean. We will see in the following section that it is far from being the case, and that each collaboration preserved its cultural identity, both in the beam layout and in the analyzing technique.

3. The last generation of experiments

The *NA48* experiment at *Cern* makes use of a sophisticated beam line designed having in mind the minimization of the corrections to the double ratio of number of events from the four decay modes in a common fiducial region. Two quasi-colinear K_L and K_S beams are formed, and their 2π decays are collected simultaneously in order to maximize the cancellations of beam fluxes, efficiencies, experimental acceptances and losses due to accidental activity in the double ratio. The convergence of the beams at the detectors makes it impossible to recognize the beam origin of $2\pi^0$ decays. Therefore a tagging counter is placed in the attenuated proton beam going to the K_S target in order to identify the beam from which a decay originates by a time of flight technique between the protons and the kaon decay products. In the same spirit than *NA31* which mimicked the 'flat' K_L distribution, *NA48* applies lifetime weighting to the K_L events to make similar distributions and therefore minimize the differential acceptance correction in both neutral and charged modes. As a consequence, the decay region is limited to $3.5\tau_s$ from the K_S target corresponding to $\sim 40m$, and about 2/3 of otherwise good K_L decays are rejected *online* by a lifetime cut. An additional increase of the statistical error of $\sim 40\%$ is due to the weighting procedure, so that 3 years of high intensity proton beams are required to reach the aimed accuracy of $\sim 2\times10^{-4}$ on ε'/ε. The *NA48* dataset of 5.3×10^6 $K_L \to \pi^0\pi^0$ recorded from '97 to 2001 results in the final value of the direct $\mathcal{CP}$ violation parameter [7] :

$$Re(\varepsilon'/\varepsilon) = (14.7 \pm 1.4(stat) \pm 1.7(syst)) \times 10^{-4} \tag{6}$$

The *KTeV E832* experiment at *Fermilab* makes use of a setup similar to the one of *E731*, with improved components mainly in the beam definition, fully active regenerator to kill the background from inelastic regeneration, and highly segmented pure *CsI* electromagnetic calorimeter. The improvement in experimental resolution allow a substantial reduction of the physical backgrounds. Similar to *E731*, the *E832* analysis makes full use of the statistical power of the data. The Monte Carlo technique is used to determine precisely the acceptances and reproduce the detectors responses in the four decay modes. A large number of $\pi e\nu$ and $3\pi^0$ events have been collected in order to understand precisely the acceptances with independant samples. The $Re(\varepsilon'/\varepsilon)$ determination resulted from a '*blind*' analysis, in the sense that the value of the parameter was affected by an unknown offset in the fitting procedure, and this until the systematic studies were finalized. About 3.4×10^6 $K_L \to \pi^0\pi^0$ from the '96+'97 dataset are used for the measurement [8] :

$$Re(\varepsilon'/\varepsilon) = (20.7 \pm 1.48(stat) \pm 2.39(syst)) \times 10^{-4} \tag{7}$$

An equivalent dataset is available from the '99 data taking period, and will allow to reduce the statistical uncertainty to $\sim 1\times10^{-4}$, while improvements on the neutral reconstruction are expected to reduce the systematic uncertainty as well. A very important cross-check comes from a reweighting analysis similar to the one of *NA48*, and leads to a compatible result at the price of a statistical uncertainty worse by a factor 1.7.

Together, *NA48* and *KTeV E832* experiments have established the existence of *direct* $\mathcal{CP}$ violation. Using the results from the four precise experiments discussed in this paper, the world average is : $Re(\varepsilon'/\varepsilon) = (16.6 \pm 1.6) \times 10^{-4}$, which definitely rules out the *superweak* model, and supports the *CKM* picture of the standard model.

4. Putting constraints on CKM parameters

In the framework of the *Standard Model*, an approximate 'pedagogical' formula (*Buras* [9]) shows the relationship between ε'/ε and the V^{CKM} coefficients :

$$\frac{\varepsilon'}{\varepsilon} \approx Im\lambda_t \cdot 13 \left(\frac{110MeV}{m_s(2GeV)}\right)^2 \left[B_6^{(1/2)}(1-\Omega_{IB}) - 0.4 \cdot B_8^{(3/2)} \left(\frac{m_t}{165GeV}\right)^{2.5}\right] \frac{\Lambda^{(4)}_{\overline{MS}}}{340MeV} \quad (8)$$

with $Im\lambda_t \equiv ImV^*_{ts}V_{td} = A^2\lambda^5\eta$ in the Wolfenstein parameterization. Therefore, the measurement of ε'/ε can in principle be turned into a measurement of the *CKM* parameter η. Unfortunately the theoretical uncertainties on the matrix element $B_6^{(1/2)}$ - reflecting the effect of the *Electro Weak* penguins, and $B_8^{(3/2)}$ - corresponding to the *strong* penguins, are such that a quantitative estimate of η can hardly be extracted presently from the precise measurement of ε'/ε. The challenge is now for the theorists, to provide precise estimates of the matrix elements.

Going one step further to derive *CKM* parameters from kaon physics will require the precise measurement of the branching ratio of theoretically clean decay modes, in other words with errors of a few percent from theory. The so-called '*golden kaon decay modes*' $K^+ \to \pi^+\nu\overline{\nu}$ and $K^0_L \to \pi^0\nu\overline{\nu}$ which will be measured at *Fermilab*, *BNL* and *JHF* in the next decade, will allow a determination of both ρ and η parameters of the *CKM* unitarity triangle complementary to the precision measurements in the B system with similar accuracy. They can therefore be considered as key tools to troubleshoot the standard model and possibly point to some new physics beyond the standard model.

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