CP VIOLATION IN $K^0$ DECAYS

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In this lecture, I will review recent results on the study of “direct” CP violation, where the violation occurs in a particle decay rather than in particle-antiparticle mixing. Brief comments on rare decays, particularly those with a CP reach, will be made. Finally, I will indicate how the community would like to see the field evolve.

1 MOTIVATION

There are a few reasons why pursuit of experimental studies of CP violation are important. The first is that we only have one established effect. There are many manifestations, all in the decays of the neutral kaon: $2\pi, \pi\nu, \pi\pi\gamma,$ and, most recently in $\pi\pi\ee$. But these are all traceable to the $\epsilon$ impurity in the $K_L$ state: the sizes of the asymmetries are precisely predicted and this effect is dubbed “indirect” in that it arises from a (presumably) second order CP- and T- violating interaction in the K-K transition.

The effect is also of cosmological significance. We live in a world of matter: we find no anti-planets, no significant component of anti-matter in extra-galactic cosmic rays, and no evidence for anti-galaxies. In our galaxy, there are approximately $10^{69}$ protons and $10^{79}$ photons whereas, if we extrapolate this volume back to a time of $10^{-6}$ sec from the big-bang, its temperature was about $10^{13}$ degrees and it would have contained $10^{79}$ protons, anti-protons, and gammas. Nevertheless, it is thought that the baryon asymmetry was present even at this early time so the question remains as to its origin, and whether the CP violation we see in the neutral kaon decays is at all connected.

The standard model “explanation” of the effect (in the kaon system) is compelling and it predicts a direct effect in K decays as well as larger effects in the mixing and decays of B mesons. Now, we have one effect and one parameter ($\delta$, the phase in the CKM matrix, or $\eta$, the Wolfenstein parameter); we badly need more effects, both within the K and B systems, to see if the model is consistent. Indeed the future of K decay experiments is aimed at such studies as we will see later.
2 MEASURING $\epsilon'/\epsilon$

The best avenue to see direct CP violation is the study of $\epsilon'/\epsilon$ in the neutral kaon decays to two pions. All four modes need to be studied and the double ratio,

$$R = \frac{\Gamma(K_L \rightarrow 2\pi^0)/\Gamma(K_S \rightarrow 2\pi^0)}{\Gamma(K_L \rightarrow \pi^+\pi^-)/\Gamma(K_S \rightarrow \pi^+\pi^-)},$$

gives $\epsilon'/\epsilon$ through the relation $\epsilon'/\epsilon = (1-R)/6$.

The experimental situation in the early 1990's led to three new efforts to further search for direct CP violation, these being KTeV at Fermilab (an evolution of the E731 experiment), NA48 at CERN (an evolution of the NA31 experiment), and KLOE at DAΦNE, an entirely new effort. At the present time, there are first results from both KTeV and NA48, and KLOE is just beginning to take data.

For the present generation of experiments, there are certain common features:

- collection of all four modes simultaneously by means of two beams, one with $K_L$ decays and the other with $K_S$
- use of high-precision electromagnetic calorimetry for excellent reconstruction of the $2\pi^0$ decays
- precision magnetic spectrometry.

This leads to relatively low and understandable backgrounds as well.

The areas where there remain differences are the following:

- how do the experiments make $K_S$?
- how do the experiments account for the acceptance difference (arising from the differing lifetimes) between $K_S$ and $K_L$?
- is the analysis done blind?

3 KTEV

The first result from KTeV has been published\[a\] so here I will just briefly discuss some of its key features. The KTeV apparatus is shown schematically in Figure 1.

KTeV uses a regenerator to derive its $K_S$ beam. Shown in Figure 2 is the reconstructed decay distribution for $\pi^+\pi^-$ decays downstream of the regenerator, for events with momentum between 30 and 35 GeV/c. In this bin, the $K_S$ lifetime is only about 1.7 m so that, to normalize the $\epsilon'/\epsilon$ measurement, only a few meters would be needed. As the $K_S$ component decays, it becomes of comparable magnitude to that of the much smaller $K_L$ component and their interference is most noticeable, at about 15 m downstream of the target. Thus using all the decays downstream of the regenerator gives access to the $K_S$ lifetime, the mass difference between $K_S$ and $K_L$, and the phase difference between the two decays, this for both $\pi^+\pi^-$ and $2\pi^0$ decays. And the ability to understand these distributions gives confidence that the detector and beam are well understood.

There are two drawbacks to the use of a regenerator. The first is the ambient rate that it causes in the detector. Essentially all the kaons and neutrons incident upon it interact\[b\] and therefore potentially spray unwanted “accidental” particles into the detection elements. The beam which strikes the regenerator is filtered and attenuated to enhance the $K/n$ ratio and to reduce the overall rate. Nevertheless, the interaction rate in the regenerator is about 1.5 MHz and this source contributes the majority of the ambient rate in the detectors.

This turns out to not be a major problem for several reasons. The first is that the regenerator is fully active, consisting of 85 separate scintillator pieces each read out by two photomultipliers. The

\[a\] A. Alavi-Harati et al., Phys. Rev. Lett. 83, 22 (1999)

\[b\] The KTeV regenerator is about 1.8 kaon interaction lengths and about 3.5 neutron interaction lengths.
FNAL beam structure is 53 MHz, meaning that approximately 3% of the buckets are occupied, with either a neutron or a kaon, or, rarely, more than one such particle. Whenever there is an inelastic interaction producing particles that could hit the detector, it is effectively vetoed by the signals in the regenerator. So the activity will be “out of time.”

The KTeV detector with the longest latency, and therefore most sensitive to such activity, is the drift chamber system where drifts up to approximately 200 ns occur. Out-of-time activity can

\[ \text{It is important that the intensity from bucket to bucket be uniform so attention must be paid to monitoring beam microstructure.} \]
interfere with the real track information if it occurs on the relevant wires. This effect has been extensively studied and to a very high order is properly simulated by simply superimposing accidental events upon monte-carlo generated “pure” events. By such studies, we have determined that the overall effect of the ambient rate from the regenerator shifts the ratio of $K_S$ to $K_L$ (“single ratios”) by less than 0.001 in each $(\pi^+\pi^-, 2\pi^0)$ case. There is a loss of events, at the level of 2%, due to such accidental activity in the chambers, but the loss is quite symmetric between the two beams. The main reason for this is that the “spray” from the regenerator is broad enough that it effectively is uniform over the drift chambers; were the ambient particles confined to a small region about the (regenerator) beam region, the difference would be greater.

The second drawback from the use of the regenerator is incoherent scattering of $K_S$. When such scatters produce extra particles (inelastic events), they are effectively self-vetoed. But elastic scattering off Carbon nuclei produce negligible recoil energy so that these events smear out the coherently regenerated beam and even can “cross-over” to the vacuum side. Figure 3 shows this effect for neutral events at the calorimeter.

\[ \text{Figure 3: Reconstructed transverse position of neutral events at the calorimeter. The regenerator (which normally moves from side-to-side) is for this figure always on the right.} \]

Fortunately this effect can be directly measured using the $\pi^+\pi^-$ events themselves. For the angular distribution of this process is independent of how the kaon decays. Hence the distribution is determined with the charged sample (using the magnetic spectrometer) and this can be used to accurately give the effects in the neutral decays. Small uncertainties in the charged acceptance for this scattered component, however, give a systematic uncertainty of order 0.0005 in the double ratio.

We show in the table below the performance of each of the KTeV systems in comparison to that for the previous generation of experiments at FNAL. The calorimeter, made of pure CsI, has achieved a resolution of 0.75% averaged over the momentum spectrum.

The Monte-Carlo simulation in KTeV is most important because the vertex distributions are so different between $K_S$ and $K_L$. Accepted $K_S$ events reconstruct on average about 5m upstream of $K_L$ so, to control the ratio of recorded events to better than 0.001 means that we should understand any instrumental induced “slope” in the acceptance at the level of about 0.02% per meter.

The best means to study the acceptance in the data is by using the high statistics decay modes that are taken simultaneously with the $2\pi$ decays. Figure 4 shows the decay distribution for about 40 million $Ke_3$ decays together with the monte-carlo simulation. Fitting the ratio of the two to a linear departure shows that the distributions match at the level of about 0.005% per meter. It is relevant
| Parameter                                                                 | E731/E773/E799                  | KTeV                  |
|--------------------------------------------------------------------------|---------------------------------|-----------------------|
| Pressure in decay region                                                 | 500 $\mu$Torr                   | 1 $\mu$Torr           |
| $\mu$ flux per proton on target                                          | $4 \times 10^{-5}$              | $2 \times 10^{-7}$    |
| Max. proton flux/spill                                                   | 2.0E12                          | 5.0E12                |
| Calorimeter radiation exposure (E799)                                    | 450 rad/E12/week                | 50 rad/E12/week       |
| $\gamma$ energy resolution at 20 GeV/c                                   | 3.5%                            | 0.65%                 |
| calorimeter nonlinearity (3-75 GeV/c)                                    | 10%                             | 0.4%                  |
| $\pi/e$ rejection, calorimeter                                           | $\sim$ 50                      | $\sim$ 400            |
| Magnetic field ($p_t$ kick)                                              | 200 MeV/c                       | 400 MeV/c             |
| Magnetic field nonuniformity                                             | 5%                              | 1%                    |
| Material in spectrometer (rl)                                            | $\sim$ 0.87%                    | $\sim$ 0.35%          |
| Single wire plane resolution                                             | $\sim$ 85$\mu$m                 | $\sim$ 100$\mu$m      |
| Track momentum resolution at 20 GeV/c                                    | 0.5%                            | 0.25%                 |
| $2\mu$ efficiency                                                        | 82%                             | 99%                   |
| Regenerator: Inelastic background in vac. beam                           | $\sim$ 1.8%                     | $\sim$ 0.3%           |
| $\gamma$ veto performance (p.e. / MeV)                                  | 0.02                            | 0.2                   |
| $\pi/e$ rejection, TRD system                                            | NA                              | $\sim$ 150            |
| Level 2 clustering-trigger time                                          | 30 $\mu$s                       | 2 $\mu$s              |
| Level 2 tracking-trigger time                                            | 3 $\mu$s                       | 1.5 $\mu$s            |
| Level 2 TRD-trigger time                                                 | NA                              | 1 $\mu$s              |
| Level 3 complete event reconstruction                                    | NA                              | 200k events/spill     |
| DAQ output                                                               | $\sim$ 20 MB / spill            | $\sim$ 300 MB/spill   |
| Livetime                                                                 | 0.7 at 0.8E11 p/spill           | 0.7 at 3.5E12 p/spill |
| Offline $\pi^0\pi^0$ mass resolution (MeV/c$^2$)                        | 5.5                             | 1.5                   |
| Offline $\pi^+\pi^-$ mass resolution (MeV/c$^2$)                        | 3.5                             | 1.6                   |

Table 1: Comparison between E731/E773/E799 and KTeV.
to point out that the lifetime of the $K_L$ itself would contribute a slope in this plot of about 0.05% per meter. However, the same distribution for our $\pi^+\pi^-$ sample shows a slope three times greater, about a 2.5 standard deviation effect; accordingly, we use this larger slope as a measure of the possible systematic uncertainty associated with acceptance.

![Graph showing $K_L \rightarrow \pi^+e^+\nu$ decay]

Figure 4: Comparison of data and monte-carlo for $Ke^-\nu$ events. Lower plot shows the ratio of the two.

Making the acceptance corrections, we then look at the momentum dependence of the “regeneration” amplitude for each of the modes. This is expected to exhibit a power-law behaviour and a very important check is that the power be the same for the two modes. We find indeed that the regeneration amplitude can be well represented by the form $|f - f| / k \propto p^{-\alpha}$ and for the parameter $\alpha$, we find 0.5890(15) and 0.5884(19) for the charged and neutral modes respectively.

We fit for the $K_S$ lifetime and find consistent results for each mode. The KTeV (preliminary) value is $0.8967(7) \times 10^{-10}$ s and this is shown in comparison with other recent measurements in Figure 5. Again, in fitting for the mass difference, we again find internally consistent values with the KTeV value being 0.5280(13) which is shown in the Figure. Finally, we determine the potentially CPT violating phase difference between the two CP violating amplitudes, finding $\Delta \Phi = 0.09(46)^0$, as is shown in Figure 6. And, at the suggestion of Alan Kostelecky, we have examined our data for a diurnal variation in $\Phi^+\pi^-$ as might be predicted in certain CPT and Lorentz violating interactions, finding no day-night effect at the level of about 1/3 degree.

### 3.1 Looking at the Answer

The $\epsilon'/\epsilon$ analysis is done blind in KTeV.

We use as much as possible the high statistics modes for study of the detector and to improve our modeling of it, rather than the $2\pi$ modes from which the answer is calculated. The acceptance calculations are validated using $Ke^-\nu$ and $3\pi^0$ decays. Then the $2\pi$ samples are examined and the $\tau_s$ and $\Delta m$ parameters are determined and with high precision are found to be consistent between the two modes. A precision CPT test is done, to the level of 1/2 degree. And the regeneration powers are

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*Sensitivity of CPT Tests with Neutral Mesons, V.A. Kostelecky, Phys. Rev. Lett. 80, 1818 (1998).*

*To report a value for $\Phi^+\pi^-$, one needs to worry about certain systematic uncertainties in the phase of the regeneration amplitude. But such are irrelevant if one is just interested in the time dependence of $\Phi^+\pi^-$.***
found to be equal with high precision. Finally, all systematic studies are completed and the value for each error is tabulated.

It is only after all of these checks, studies, and evaluations that the answer is uncovered – the decision to commit to a result is made beforehand.

The result was \( \text{Re}(\epsilon'/\epsilon) = (28.0 \pm 4.1) \times 10^{-4} \) where the statistical error was 0.0003 and the systematic 0.00026. At nearly seven standard deviations, this establishes direct CP violation.

4 NA48

The NA48 experiment has given its first preliminary result very recently. A sketch of their very elegant beam arrangement is shown in Figure 7. They too use two beams but the \( K_S \) beam is derived from a small fraction of the primary beam that is diverted and then targeted upon a close-by target. The two beams have different angular divergences but cross at the detector. (In KTeV, the beams are precisely the same divergence but are separated at the detector.)

The performance of the NA48 calorimeter is excellent, allowing 0.7% resolution at high energies.

In NA31, the \( K_S \) target was serially stepped through the decay region to approximate \( K_L \) decays; in this way, acceptance corrections were minimal. NA48 does not use this technique but rather has elected to weight their \( K_L \) events according to the distribution of \( K_S \) events. This results in a
significant statistical loss but has the advantage that the corrections that need to be applied, now to the weighted event ratios, are less than 1% whereas those for KTeV are of order 5%.

One potential problem that the group has studied extensively is an energy dependence in the double ratio. When fit for a linear slope, a 3 standard deviation departure is found with the value changing by about 5% over the span of energies from 70 to 170 GeV/c. But extensive studies of the data, including examining the double ratio in energy bins beyond their nominal fiducial region, has convinced the group that this is a statistical fluctuation.

The preliminary result they report, based upon about 10% of their anticipated sample, is: \( \text{Re}(ε'/ε) = (18.5 \pm 7.3) \times 10^{-4} \) where the systematic error is larger than the statistical one. However, most of the systematic error is dominated by statistics so that, for awhile anyway, the total error will roughly scale with added data.

5 THE GRAND AVERAGE

The most recent results are shown graphically in Figure 8. The grand average of these last measurements is \( (21.2 \pm 2.8) \times 10^{-4} \), with a confidence level of about 7%.

The KTeV result is in better agreement with that from NA31 rather than from E731 but the experimenters have not found any reason other than a fluctuation to account for this difference. The E731 beam, detector, and analysis were extensively documented in a long article\(^{a}\) for Physical Review D. At present the NA48 result is in good agreement with those from E731, KTeV, and NA31.

The theoretical situation is still developing. Figure 9 shows this grand average along with some recent predictions. It is still too early to say if the rather large value points to new physics or to inadequacies in the standard model calculations. The goals of the next round of lattice calculations, aiming at 10% determinations of the matrix elements, would mean that \( ε'/ε \) would become a “powerful precision test and new physics probe”\(^{b}\).

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\(^{a}\)CP and CPT Symmetry Tests from the Two-Pion Decays of the Neutral Kaon with the Fermilab E731 Detector with L.K. Gibbons et al., Physics Review D55, 6625 (1997)

\(^{b}\)Bill Marciano, summary talk of the Chicago Kaon Conference, June 1999, editors Jon Rosner and Bruce Winstein, to be published by the University of Chicago Press.
In this section, I will briefly mention other studies of rare K decays that have an implication for CP violation.
6.1 $K_L \to \pi^0\nu\bar{\nu}$

A theoretically clean channel is the decay of the long-lived Kaon to a neutral pion, neutrino, anti-neutrino pair. This is mediated by the $Z$-penguin, with a branching ratio given by

$$BR(K_L \to \pi^0\nu\bar{\nu}) = 8 \times 10^{-11} (M_t/M_W)^2 A^4 \eta^2$$

where $\eta$ is the parameter in the CKM matrix.

This mode has been the by-product of a number of searches by Fermilab experiments. The latest result comes from the KTeV experiment which reports

$$BR(K_L \to \pi^0\nu\bar{\nu}) < 5.9 \times 10^{-7} (KTeV, 90\% confidence).$$

Less clean but still interesting is the $ee$ mode. The KTeV 90% confidence value is $6.64 \times 10^{-10}$ and the similar limit for the $\mu\mu$ mode is $3.4 \times 10^{-10}$. These are both an order of magnitude improved over the corresponding E731 results and while not quite at the level expected in the Standard Model, are beginning to rule out certain parameter regions in an extended SUSY scheme.

7 FUTURE RARE DECAY STUDIES

The prime goal, now that direct CP violation has been seen, in the K system is the study of the $\pi^0\nu\nu$ decay and there are several groups seriously considering this mode. Many institutions in KTeV have written an expression of interest to pursue this mode at Fermilab, using the much higher intensity of the Main Injector. There is a similar proposal at BNL. The goal is the collection of about 100 events. The idea is that with this mode and the corresponding $K^+$ decay, one can accurately determine the angle $\beta$ of the unitarity triangle in the K sector and this can be compared to a similar determination in the $B$ sector.

The E787 experiment at Brookhaven has the best information on the $K^+$ decay: they have seen one unambiguous event which corresponded to a branching ratio in the range of about $2 \times 10^{-10}$. They have a proposal to increase their sensitivity to allow about 10 events to be collected. And the CKM proposal at Fermilab would collect about 100 such events.

These experiments, if successful, would allow a test at the level of a few degrees and thus will be quite sensitive to any new physics.

8 CONCLUSION

KTeV has reported on just 20% of the data collected in 1996/7. And more data is being collected now in the 1999 run, with a variety of systematic checks, so that the accuracy on $\epsilon'/\epsilon$ should improve significantly.

NA48 has also collected more data and should run as well in 2000. And KLOE is collecting its first samples now. So, during the next few years, we should see several high precision determinations of $Re(\epsilon'/\epsilon)$. The theorists are actively looking to improve their predictive power so that we should know on that time scale if we are seeing new physics. One thing is certain: a new CP violating effect has been established. It will be quite interesting to see if such an effect can be isolated in B decays and in any case new CP violating signatures in that sector, in comparison with studies to be made in the kaon decays, will tell us if the CKM picture is complete, or if new mechanisms are needed.

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