A NEW DETERMINATION OF THE $K^0 \rightarrow \pi^+ \pi^-$ DECAY PARAMETERS

C. GEWENIGER*1, S. GJESDAL*2, G. PRESSER*1, P. STEFFEN, J. STEINBERGER, F. VANNUCCI*3 and H. WAHL,
CERN, Geneva, Switzerland

F. EISELE*1, H. FILTHUTH, K. KLEINKNECHT*1, V. LÜTH and G. ZECH*4
Institut für Hochenergiephysik, Heidelberg, Germany

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In a short neutral beam we have measured the proper time-dependence of the decay $K^0 \rightarrow \pi^+ \pi^-$. This time structure exhibits the interference between the short- and long-lived states and is in agreement with the general expectations of the $\mathcal{CP}$ violation phenomenology.

This experiment gives new and more precise measurements of the following three parameters:

i) the decay width of the short-lived $K_S$ component: $\Gamma_S = (1.119 \pm 0.006) \times 10^{10} \text{ sec}^{-1}$;

ii) the modulus of the $\mathcal{CP}$ violating parameter $\eta_{\pi^+}$: $|\eta_+| = (2.30 \pm 0.035) \times 10^{-3}$;

iii) the phase of $\eta_{\pi^+}$ as a function of the $K_S - K_L$ mass difference $\Delta m$: $\phi_{\pi^+} = (49.4 \pm 1.0) + [(\Delta m - 0.540)/0.540] \times 305^\circ$.

The result of $|\eta_{\pi^+}|$ may be compared with the result of the foregoing letter on Re $\epsilon$ in the frame of the superweak model. Good agreement is observed.

The experiment presented here studies the time dependence of the $\pi^+\pi^-$ decay mode of the $K^0$ meson in a short neutral beam. This time dependence has been previously studied [1, 2] and the main purpose of this experiment is to improve the precision, statistically as well as systematically, in order to provide a more accurate measure of the amplitude ratio

$$\frac{\langle \pi^+\pi^- | T | K_L \rangle}{\langle \pi^+\pi^- | T | K_S \rangle} = |\eta_{\pi^+}| \exp (i\phi_{\pi^+}).$$

There is a substantial interest in experimental precision, because of the predictions of the superweak [3] and other models. If $\mathcal{CPT}$ is assumed to be conserved and if $\epsilon$ is the admixture of the $\mathcal{CP}$ odd ($\mathcal{CP}$ even) state in the dominantly $\mathcal{CP}$ even ($\mathcal{CP}$ odd) decay state, then the superweak model predicts

$$\eta_{\pi^+} = \epsilon. \quad (1)$$

Together with unitarity the model further specifies the phase of both parameters:

*1 Now at Universität Dortmund, Abteilung Physik, Germany.
*2 Now at Distriktshøgskolen, Stavanger, Norway.
*3 Now at Institut de Physique Nucléaire, Orsay, France.
*4 Now at Gesamthochschule, Siegen, Germany.

$$\phi = \tan^{-1} \frac{2\Delta m}{\Gamma_S - \Gamma_L}.$$ 

A whole class of other models is less specific in its predictions, but deviations from eq. (1) are expected to be of the order of the admixture of the $I = 2$ isospin state in the dominantly $I = 0$, $K_S \rightarrow \pi^+\pi^-$ decay. The smallness of this admixture ($\sim 4\%$) explains the interest in precision in the experimental verification of eq. (1).

This experiment presents a very substantial effort over a number of years, and all the relevant details of apparatus and analyses unfortunately cannot be included in this letter. The interested reader must be referred to a future, more detailed publication elsewhere.

The apparatus has been presented in the preceding letter [4]. Without going into details we point out its important properties.

The decay region which extends from 2.2 m to 11.6 m after the target permits detection in the proper time interval

$$3.5 \times 10^{-10} \text{ sec} < \tau < 30 \times 10^{-10} \text{ sec}.$$ 

The use of multiwire proportional chambers allows
a high data-taking rate and limits the amount of matter in the beam.

The spectrometer section is followed by a trigger plane of twelve thin (1.6 mm) counters. A right-left coincidence in this plane is required to initiate an event, and the final read-out system requires two — and only two — hits in each plane of the multiwire proportional chambers.

The following requirements are imposed on the selection of events:

i) each chamber must have exactly two vertical and two horizontal wires hit;

ii) a $\chi^2$ deviation, formed of the vertical kink angle of each track (after correction for vertical focusing) and of the skewness of the vertex, must be less than 12;

iii) there must be no signal in the Čerenkov counter and no coincidence between the two muon counter planes;

iv) the longitudinal distance target-decay vertex must be greater than 2.2 m;

v) the momenta of both charged secondaries must lie in the interval 1.50 GeV/c to 8.50 GeV/c (the minimum range for traversal of the muon detector is 1.45 GeV/c and the threshold for pion detection in the Čerenkov is 8.40 GeV/c);

vi) only events with inwards bending in the magnet are retained;

vii) events for which simultaneously $m_{\pi\pi}$ is within 10 MeV of the $\Lambda^0$ mass, and $p_+/p_-/(p_++p_-)$ is greater than 0.74, are withdrawn from the sample to reduce the $\Lambda$ contamination.

These criteria are designed to select $K^0 \rightarrow \pi^+\pi^-$ decays and reject other decays as cleanly as necessary.

The remaining sample is plotted in the histograms of figs. 1a and 1b as a function of the invariant mass $m_{\pi\pi}$ and of $\rho_T^2$, the squared distance of the reprojected momenta in the target plane, from the target centre.

A two-dimensional linear background subtraction in $m_{\pi\pi}$ and $\rho_T^2$ was performed in each momentum bin ($\Delta p = 0.5$ GeV/c) and each proper time bin ($\Delta \tau = 0.5 \times 10^{-10}$ sec). The amount of subtracted events varies from 2.2% for $K_S$ to 7.3% for $K_L$ of the accepted events.

The final data sample is accumulated in a two-dimensional histogram in the kaon proper time and momentum. There are 6 million events in total and perhaps more significantly ~5000 events per $10^{-10}$ sec time bin at long times. The momentum distribution of the observed events is shown in fig. 2.

Extraction of the information from the experi-

![Fig. 1. (a) $m_{\pi\pi}$ distribution. (b) $\rho_T^2$ is the squared distance of the reprojected momenta in the target plane, from the target centre.](image-url)
mental curve demands a good knowledge of the acceptance of the apparatus. This was achieved by simulating 6.6 million decays with a Monte Carlo program. These events were treated in the same way as the data. Fig. 3 shows the acceptance curves for different momenta as well as a weighted acceptance for events with momentum between 5 and 12.5 GeV/c.

The time distribution of events summed over the momentum interval 5–12.5 GeV/c with limits im-
posed by the decay volume is shown as the histogram a in fig. 4. The curve b of fig. 4 shows the data corrected for the detection efficiency.

Fig. 2. Kaon momentum spectrum of the accepted events.

Fig. 4. Time distribution of $K \rightarrow \pi^+\pi^-$ events. a) Events (histogram) and fitted distribution (dots). b) Events corrected for detection efficiency (histogram), fitted distribution with interference term (dots) and fitted distribution without interference term (solid line). Insert: Interference term as extracted from data (dots) and fitted term (line).

Fig. 3. Acceptance curves for different kaon momenta. The dashed line represents the average acceptance of the apparatus.
The theoretically expected distribution in proper time is:

\[ I_{2n}(r) = [S(p) + S(p)] \{ \exp (-\Gamma_S r) + 2A(p) \eta_{\pm} \exp \left[ -\left( \Gamma_L + \Gamma_S \right) r/2 \right] \cos (\Delta m r - \phi_{\pm}) \} \]

where \( S(p) \) and \( S(p) \) are the production intensities of \( K^0 \) and \( \bar{K}^0 \) and \( A(p) \) measures the initial admixture of \( K^0 \) and \( \bar{K}^0 \):

\[
A(p) = \frac{S(p) - S(p)}{S(p) + S(p)}.
\]

This expression is fitted to the data in 0.5 GeV/c momentum bins to find \( \Gamma_S, |\eta_{\pm}|, \phi_{\pm} \) and unparameterized \( S(p) \) and \( \bar{S}(p) \) assuming \( \Delta m \) and \( \Gamma_L \) to be known. The experimentally-determined phase \( \phi_{\pm} \) is a linear function of \( \Delta m \).

The \( \chi^2 \) of the fit is 421 for 444 degrees of freedom. The result of the fit is shown as the dots in figs. 4a and 4b. The cosine part of the interference term is extracted from the full curve as presented in the insert of fig. 4.

The final results are the following:

\[ \Gamma_S = (1.119 \pm 0.006) \times 10^{10} \text{ sec}^{-1} \]

\[ |\eta_{\pm}| = (2.30 \pm 0.035) \times 10^{-3} \]

\[ \phi_{\pm} = (49.4 \pm 1.0) + \left( \frac{\Delta m - 0.540}{0.540} \right) \times 305^\circ. \]

The stability of the results was checked by varying the momentum range and the time interval used in the fit, as well as by changing the positions of the cuts mentioned previously. Also different background subtractions gave consistent results. The stated errors include estimated systematic uncertainties. The correction on the phase \( \phi_{\pm} \) amounts to \( (0.4 \pm 0.3)^\circ \) for the effects of a \( \gamma \)-ray absorber following the target, the scattering on the collimator walls, the \( K^0 \)'s produced by the nucleons absorbed in the collimator and the regeneration in the helium. A 0.5% uncertainty in the magnetic field is also taken into account.

The value of \( \Gamma_S \), although in disagreement with earlier results [5], agrees with the most recently reported measurement [6].

The value of \( |\eta_{\pm}| \), in disagreement with earlier results [7] has been confirmed [8] since it was first reported by this group [9]. A check measurement was made in order to confirm the result on \( |\eta_{\pm}| \) by comparing the rates of the processes \( K_L \rightarrow \pi^+\pi^- \) and \( K_L \rightarrow \pi^0\nu \). This result, which is systematically less reliable, is \( |\eta_{\pm}| = (2.30 \pm 0.06) \times 10^{-3} \).

The measurement of \( \Delta m \), undertaken with the same apparatus, is close to completion and we prefer to wait for this result before drawing a conclusion on the compatibility of the phase measurement with the superweak model.

In any case, the new value of \( |\eta_{\pm}| \), together with the more precise charge asymmetry measurements of the previous letter, can be compared with the prediction of the superweak model supplemented with unitarity:

\[ |\eta_{\pm}| = \frac{\Gamma_S - \Gamma_L}{\sqrt{(\Gamma_S - \Gamma_L)^2 + (2\Delta m)^2}} = \text{Re } \epsilon. \]

In the foregoing letter it is found that \( \text{Re } \epsilon = (1.67 \pm 0.08) \times 10^{-3} \).

This has to be compared with the result of this letter:

\[
|\eta_{\pm}| \times \frac{\Gamma_S - \Gamma_L}{\sqrt{(\Gamma_S - \Gamma_L)^2 + (2\Delta m)^2}}
= (2.30 \pm 0.035) \times \frac{0.721 \pm 0.005}{\times 10^{-3}}
= (1.66 \pm 0.03) \times 10^{-3}.
\]

The agreement is very good, the precision being approximately 5%.

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