Charge Asymmetry in the Muonic Decay of the $\mathrm{K}_{2}{ }^{\circ}{ }^{*}$
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We report herewith the observation and measurement of a charge asymmetry in the muonic decay of the long-lived neutral K meson ( $\mathrm{K}_{2}{ }^{\circ}$ ). In particular we find the decay rate into $\pi^{-} \mu^{+} V\left(R_{\mu^{+}}\right)$to be larger than the decay rate into $\pi^{+} \mu^{-} \bar{v}\left(R_{\mu^{-}}\right)$with the ratio determined as

$$
R \equiv \frac{R_{\mu^{+}}}{R_{\mu^{-}}}=1.0081 \pm .0027
$$

This result, obtained at the Stanford Linear Accelerator Center (SLAC), is a prima facie demonstration of CP non-invariance in $\mathrm{K}_{2}{ }^{\mathrm{O}}$ decay. It is consistent with theoretical expectations based upon an analysis of experimental data which has been obtained since the first such demonstration by Christenson, Cronin, Fitch and Turlay. ${ }^{(1)}$

The analysis of $\mathrm{K}_{2}{ }^{\mathrm{O}}$ decay in terms of parameters characterizing the CP violation has been carried out by a number of authors. ${ }^{(2,3,4)}$ It is most convenient to make use of the four parameters $\eta_{+}, \eta_{00}, \epsilon$ and $\epsilon$ ' as follows:

1. $\eta_{+-}=\frac{\text { Amplitude }\left(K_{2}{ }^{0} \rightarrow \pi^{+} \pi^{-}\right)}{\text {Amplitude }\left(K_{1}{ }^{0} \rightarrow \pi^{+} \pi^{-}\right)} \quad$ 2. $\quad \eta_{00}=\frac{\text { Amplitude }\left(K_{2}{ }^{0} \rightarrow \pi^{0} \pi^{0}\right)}{\text { Amplitude }\left(K_{1}{ }^{0} \rightarrow \pi^{0} \pi^{0}\right)}$

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3. $\epsilon$ determines the extent to which $\mathrm{K}_{2}{ }^{\circ}$ is not an eigenstate of CP viz.
$$
\mathrm{K}_{2}^{\circ}>=\frac{\left.(1+\epsilon)\left|\mathrm{K}^{\circ}>-(1-\epsilon)\right| \overline{\mathrm{K}}^{\circ}\right\rangle}{\sqrt{2\left(1+|\epsilon|^{2}\right)}} \quad \text { where }\left|\overline{\mathrm{K}}^{\circ}>=\mathrm{CPT}\right| \mathrm{K}^{\circ}>
$$
4. $\epsilon^{\prime}=\frac{1}{\sqrt{2}} \frac{\operatorname{Im} A_{2}}{A_{0}^{0}} e^{i\left(\frac{\pi}{2}-\delta_{0}+\delta_{2}\right)}$
where $A_{2}=\left\langle 2 \pi^{\prime}\right.$ s in stationary $I=2$ state $| H_{w k}\left|K^{0}\right\rangle$ $A_{0}=\left\langle 2 \pi^{\prime}\right.$ s in stationary $I=0$ state $| H_{w k}\left|K^{\circ}\right\rangle$
and $\delta_{0}$ and $\delta_{2}$ are the appropriate $\pi \pi$ phase shifts.
$\eta_{+-}$and $\eta_{00}$ can be expressed in terms of $\epsilon$ and $\epsilon$ ' as follows:
$$
\eta_{+-}=\epsilon+\epsilon^{\prime} \quad ; \quad \eta_{O O}=\epsilon-2 \epsilon^{\prime}
$$

To the extent that the $\Delta T=3 / 2$ decay of the $K_{I}{ }^{\circ}$ and the $C P$ violating amplitudes for decays into states other than two pions can both be ignored, we can obtain the phase of $\epsilon$ from the relation:

$$
\tan \epsilon=2 \frac{\left[\mathrm{~m}_{\mathrm{K}_{2}} 0-\mathrm{m}_{\mathrm{K}_{1}} \circ\right]}{\gamma_{\mathrm{K}_{1}} 0-\gamma_{\mathrm{K}_{2}}{ }^{\circ}}
$$

In this relation, $\mathrm{m}_{\mathrm{K}_{1}}$ o and $\mathrm{m}_{\mathrm{K}_{2}} \mathrm{O}$ are the masses of the $\mathrm{K}_{1}{ }^{\circ}$ and $\mathrm{K}_{2}{ }^{\circ}$ respectively. $\gamma_{\mathrm{K}_{1}} 0$ and $\gamma_{\mathrm{K}_{2}} 0$ are their decay rates.

In the event that the weak interactions obey the $\Delta S=\triangle Q$ rule, the charge ratio is given by

$$
R=I+4 \operatorname{Re} \in
$$

From the measured intensity of the two pion decay of the $\mathrm{K}_{2}{ }^{0}(1,6,7,8,9)$ and from studies of the interference of this decay with regenerated $\mathrm{K}_{1}{ }^{0}{ }^{(10,11)} \Lambda^{\text {it }}$ is possible to obtain two solutions for $\epsilon$. They yield two possible charge ratios

$$
R_{a}=1.0064 \pm .0014 \quad R_{b}=0.9997 \pm 0003
$$

The error in $R_{a}$ is largely attributable to uncertainty in the phase of $\eta_{+}$which we have taken as $80^{\circ} \pm 15^{\circ}$. We have taken the values for the other
measured parameters as follows:

$$
\eta_{+-}=1.96 \pm 0.09 \times 10^{-3} \quad \eta_{00}=4.4 \pm 0.3 \times 10^{-3}
$$

$\arg \epsilon=42.5^{\circ}$
The experimental arrangement for producing a beam of $\mathrm{K}_{2}{ }^{\circ}$ 's is shown
in Fig . la. The electron beam at 15 GeV with an average intensity of 1.5 microamps is allowed to impinge on a 30 cm beryllium target. A hole through a 12 -foot thick shielding wall at $3^{\circ}$ to the electron beam allows the passage of secondary particles produced in the target. In order to remove the large electromagnetic component characteristic of electron machines we place 12 inches of lead in the beam just before an $18^{\prime \prime} \times 72^{\prime \prime}$ sweeping magnet. A second sweeping magnet is located as shown. At this point the neutral beam is collimated to a vertical size of 6 inches and a horizontal size of 9 inches. The experimental apparatus, shown in Fig. Ib, begins at a distance of 230 feet from the target.

An anti-coincidence counter (A), $20^{\prime \prime} \times 20^{\prime \prime} \times 1 / 4^{\prime \prime}$, precedes a $2-1 / 2$ meter decay region and serves to eliminate counts caused by charged particles originating either in the shielding walls or from decays prior to the decay region. The decays of interest take place in a helium filled bag to reduce interactions of primary beam particles. Following the decay region are a series of counters and spark chambers to enable identification of a decay of interest. In sequence, the instrumentation includes the following.

1. A hodoscope consisting of eight horizontal scintillation counters, each having a height of 2 inches, a horizontal width of 20 inches and a thickness of I/4 inch. These counters (called $S_{1}$ through $S_{8}$ ) serve to identify the simultaneous presence of two particles emerging from the decay region.
2. A thin plate spark chamber of 30 inch height, 26 inch width, and having a total of 17 plates in the beam direction. Each plate is constructed of $1 / 4$-inch polyurethane foam faced with .002 inch aluminum foil. The total thickness of the chamber is. $1.5 \mathrm{gms} / \mathrm{cm}^{2}$.
3. A l6-inch wide aperture magnet bending in a vertical plane. The pole face of the magnet is 29 inches in height and 36 inches along the beam direction. Data were taken at various current settings corresponding to field integrals of $9.4,11.3$ and 13.1 kilogauss meters.
4. Another thin plate spark chamber of 54 -inch height, 36-inch width and identical thickness to the first.
5. A large scintillation counter (T) covering the exit aperture of the magnet. For the first half of the experiment the counter was 30 inches high, 32. inches wide, $1 / 2$ inch thick, and was viewed by eight 2 -inch phototubes. For the second half of the experiment the height was increased to 40 inches and the scintillator was viewed by one 5 -inch phototube.
6. Two large, 5 ton, aluminum spark chambers. These chambers are each constructed of eleven l-inch plates with effective area of 91 inches by 91 inches.
7. A 30-inch thick lead wall. The purpose of this wall is to supply the bulk of the material necessary to remove the pions through nuclear interactions. Muons with momentum of more than about $1.55 \mathrm{BeV} / \mathrm{c}$ will, on the other hand, penetrate the shield unaffected except for energy loss and coulomb scattering.
8. Another 5-ton spark chamber similar to those described above.
9. Eight pairs of scintillation counters ( $M_{1}$ through $M_{8}$ ), each 11 inches high and 48 inches wide. The counters are set as shown with one inch of plywood between the two counters in each pair. Muons which have succeeded in penetrating the spark chambers and lead wall will thus produce a coincidence count within the struck pair.

An event of interest is characterized by the time coincidence of two or more $S$ counters, the $T$ counter and an $M$ pair. For all magnet settings used, a muon arriving at counters $M_{1}, M_{2}, M_{3}, M_{6}, M_{7}$ or $M_{8}$ has uniquely determined sign, and so
those counters can be used for a rigorous sign decision. Muons arriving at $M_{4}$ or $M_{5}$ have their sign determined with 91.7 percent accuracy as determined through a study of typical pictures taken with the spark chambers when triggered by the above counter conditions (see Fig. 2). The accuracy of sign decision results from the fact that the transverse momentum transfer in the magnet is more than the maximum transverse momentum of the muon.

It should also be pointed out that the dimensions of the $M$ counter bank are such as to intercept more than 98 percent of those muons entering the apparatus which have sufficient energy to meet the range requirement.

The function of the spark chambers as such was largely one of calibration and diagnosis. By taking a relatively small number of pictures, it was possible to determine the nature of spurious triggers and to investigate quantitatively various sources of potential bias.

Normal operation of the SIAC machine yields 360 bursts of beam per second, each 1.6 microseconds long. This rather poor duty cycle leads to a number of accidentals which must be subtracted from the data. The dominant source of accidentals in this experiment is the chance coincidence of a real $\mathrm{K}_{2}{ }^{\circ}$ decay where no muon penetrates the apparatus with an $M$ pair triggered by an unrelated track. The majority of the latter arise from $\mathrm{K}_{2}{ }^{\circ}$ and neutron interactions in the heavy spark chambers and lead wall. For each $\mathrm{K}_{2}{ }^{\circ}$ which decays and initiates a trigger in the $S$ and $T$ counters, we expect about 2000 interactions in the aluminum or lead with an average of many thousand secondaries. The measured accidental rate in counters $M_{4}$ and $M_{5}$ is about 15 percent of the real rate in those counters, reasonably consistent with the expected flux. Counter $M_{1}$ has a high accidental rate caused by unrelated particles coming over the lead shield. These and other significant accidentals are continuously monitored and subtracted out for each M pair individually.

Inasmuch as the data has been logged in eight bins, corresponding to the eight $M$ counter pairs, we can in principle make seven independent determinations of the charge asymmetry by normalizing to the same total number of events for each magnet polarity. In Table 1 we tabulate the number of counts in each bin, after subtraction of accidentals, for each magnet polarity. The "down" runs are then corrected proportionally to yield the same total number of events as the "up" runs. Asymmetries are then calculated by taking the ratio (or inverse ratio) of "up" to "down" counts in each bin and correcting for the fraction of wrong decisions. Combining all of the data yields a charge ratio before further correction of $1.0095 \pm .0026$. The statistical error has been appropriately increased due to the statistical nature of the subtraction of accidentals.

It should be noted here that essentially the same result is obtained from each magnet polarity individually by just taking the ratio of $M_{1}+M_{2}+M_{3}+M_{4}$ to $M_{5}+M_{6}+M_{7}+M_{8}$. This is the result of the geometric symmetry of the apparatus about the beam line.

Potential sources of systematic error and corrections to the asymmetry are discussed later. The only corrections which appear necessary are due to the charge asymmetry in the small number of false events corresponding to an interaction in the $S$ counter bank and to the washing out of the asymmetry due to pion decays in flight. These corrections change the final charge ratio to

$$
R=1.0081 \pm .0027
$$

We have explored experimentally a number of sources of potential systematic error. Inefficiency in the anti-coincidence counter A, can lead in principle to the acceptance of "events" which originate as interactions in the shielding wall preceding the decay region. We can study any bias this introduces by examining in detail only those "events" which trigger A. We find that only about 25 percent
of all possible triggers originate before $A$ and that they have an asymmetry of $1.02 \pm .02$. Inasmuch as A is determined experimentally to be no more than 4 percent inefficient at 300 volts below its normal operating point, we conclude that the potential bias here is less than two hundredths of a percent.

Bias due to interactions in the helium was investigated by replacing the helium bag with 6 inches of carbon, increasing its effect by a factor of 250 and observing a charge ratio of $1.029 \pm .030$. The effect of the helium is thus negligible.

A small systematic shift in the charge ratio due to the interaction of neutrons and kaons in the $S$ bank scintillator is anticipated. In order that we obtain a trigger one of the particles emerging from the interaction mast either decay to a muon or penetrate the shield and another particle must activate a second $S$ counter. The systematic shift results from the charge asymmetry in the emitted prongs (more $\mathrm{K}^{+}$than $\mathrm{K}^{-}$, for example) and differential penetration of $\mathrm{K}^{+}$and $\mathrm{K}^{-}$. We have studied and corrected for this bias as follows.
a. Data was accumulated with two inches and with three inches of additional scintillator placed just before the $S$ counter bank. The probability of any given interaction triggering two $S$ counters is much higher, for geometrical reasons, in this configuration than if the interaction actually took place within an $S$ counter itself. We observed an increase of 14 percent in the "event" rate for two inches of scintillator and 24 percent for three inches of scintillator. The charge ratio in the scintillator induced events was determined to be $1.34 \pm 0.11$. b. Through a study of 24,000 pictures taken with the spark chambers we determined that 0.70 percent of the triggers were due to interactions in the $S$ bank. Of these events, 51 gave positive triggers and 47 gave negative triggers.

Combining the information obtained from the above two measurements reduces the charge ratio by $0.0017 \pm .0006$.

Occasionally we expect an unaccompanied muon, presumably from a $\mathrm{K}_{2}{ }^{\circ}$ decay where the pion missed the $S$ bank, to eject a delta ray as it traverses an $S$ counter. This delta ray will bend back in the fringing field and trigger a neighboring $S$ counter, giving rise to an "event". A study of the sample pictures indicates that .89 percent of our triggers arise from this source. We have measured independently the charge ratio corresponding to unaccompanied muons without delta rays and find it to be $1.009 \pm .014$. We have calculated the extent to which a bias is introduced because of the unique sign of the delta ray and have found it to be negligible. Furthermore, of the 124 events in the sample pictures which fit this hypothesis, we find 61 positive muons and 63 negative muons.

We conclude that these "events" do not constitute a significant bias.
We have studied the extent to which positive and negative pions, arising from various decay modes of the $\mathrm{K}_{2}{ }^{\mathrm{o}}$ can differentially penetrate the shielding wall giving rise to an apparent charge asymmetry.

A study of the 14,000 sample photographs of decay "events" yielded 176 examples of such penetrations, with no statistically significant difference between positive and negative pions. Furthermore, these pions gave wrong sign decisions 30 percent of the time, washing out, to this extent, any possible asymmetry. This indicates a contribution of less than 0.08 percent to the final charge ratio from pion penetration. As a confirmation we performed the following subsidiary experiment.

Identical beams of positive and negative pions of $4.5 \mathrm{BeV} / \mathrm{c}$ momentum were introduced into the apparatus. Two feet of iron followed by a bank of additional
counters were placed behind the $M$ bank to act as vetoes for any high energy muons in the beam. Positive and negative pions were determined to penetrate equally to .06 percent from this measurement.

A 1 percent difference between the energy loss per unit path lengtis of positive and negative muons passing through matter could account for our asymmetry. Although this difference is completely unreasonable theoretically, we have carried out a subsidiary experiment to investigate its possibility.

A beam of muons, either positive or negative, with momentum spread of $\pm 8$ percent was introduced into the apparatus. The mean momentum was chosen so as to just barely enable the penetration of the chambers and lead wall. The magnet polarity was then chosen so as to bend the muons downward and the magnitude of the field was made identical for each polarity. A photograph was taken of each muon which succeeded in triggering the $M$ bank. A study of the low momentum cutoff imposed by the range requirement for 1000 penetrating muons of each sign indicated that the energy loss of positive and negative muons is identical to within 0.3 percent.

We have studied experimentally the extent to which positive and negative muons scatter differently in passing through our lead shield and have concluded that there can be no bias due to this effect.

The experiment is completely insensitive to the accuracy with which the magnetic field is reversed. This is the result of the fact that essentially every muon with momentum sufficient to penetrate the shield is logged in the $M$ counters with its sign determined almost unambiguously.

The pulse height distributions on the $M$ counters were carefully checked for variation with magnetic field and none was found.

The experiment is almost completely insensitive to field dependent efficiency variations in the $S$ counters or the $T$ counters. In any case, no such variations were found.

The singles rates in the $M$ counters, largely due to the residue of the $\mathrm{K}^{\prime}$ s and neutrons which interact in the chamber, show no significant change upon field reversal.

In conclusion, we have determined that the $\mathrm{K}_{2}{ }^{\circ}$ and $\mathrm{K}_{2}{ }^{\circ}$ are non-ortrofonal to the extent that

$$
\operatorname{Re} \epsilon=(2.0 \pm 0.7) \times 10^{-3}
$$

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TABLE 1.

Tabulation of Data after Subtraction of Accidentals

| M Counter | No. of events <br> Magnet <br> Polarity up | No. of events <br> Magnet | Normalized <br> Nolarity down <br> Nof events <br> Magnet |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 14,500 | 14,125 | 14,008 | Percentage of <br> Polarity down | Wrong Decision $^{+} / \mu^{-}$ratio |
| 2 | 42,141 | 41,881 | 41,535 | 0 | $1.0351 \pm .0174$ |
| 3 | 74,188 | 74,300 | 73,685 | $0.6 \pm 0.2$ | $1.0069 \pm .0056$ |
| 4 | 65,902 | 66,217 | 65,669 | $7.8 \pm 0.7$ | $1.0041 \pm .0070$ |
| 5 | 63,706 | 64,599 | 64,065 | $8.8 \pm 0.6$ | $1.0065 \pm .0074$ |
| 6 | 74,218 | 75,854 | 75,226 | $0.6 \pm 0.2$ | $1.0137 \pm .0056$ |
| 7 | 43,136 | 43,939 | 43,575 | 0 | $1.0102 \pm .0071$ |
| 8 | 13,811 | 13,954 | 13,839 | 0 | $1.0020 \pm .0129$ |

* We define magnet polarity up as the polarity which gives the upward bend to particles of positive charge.
$\dagger$
Normalized to the total number of events with magnet polarity up.


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la. Beam Layout at SIAC

lb. Arrangement of Experimental Equipment



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