RESULT OF T-VIOLATING MUON POLARIZATION MEASUREMENT IN
THE \( K^+ \rightarrow \pi^0 \mu^+ \nu \) DECAY

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A search for T-violating muon polarization in the \( K^+ \rightarrow \pi^0 \mu^+ \nu \) decay has been performed at
KEK using stopped kaons. A new improved limit was obtained, \( P_T = -0.0017 \pm 0.0023 \) (stat) \( \pm 0.0011 \) (syst), corresponding to a 90 % confidence limit of \( |P_T| < 0.0050 \). The T-violating parameter was also determined to be \( \text{Im} \xi = -0.0053 \pm 0.0071 \) (stat) \( \pm 0.0036 \) (syst), and \( | \text{Im} \xi | < 0.016 \) (90 % CL).

1 Transverse Muon Polarization

Experiment E246∗ has searched for a violation of time-reversal invariance (T-violation) by means
of a precise measurement of the transverse muon polarization, \( P_T \), in \( K^+ \rightarrow \pi^0 \mu^+ \nu \) decay (\( \mathcal{K}_{\mu3}^+ \)) at KEK. This polarization is defined as the component of the muon polarization perpendicular to
the decay plane, namely \( P_T = \vec{s}_\mu \cdot (\vec{p}_\pi \times \vec{p}_\mu) / |\vec{p}_\pi \times \vec{p}_\mu| \), and its non-zero value is a clear signature
of T-violation with T-odd character because of the negligible level of any spurious final-state interaction effects of less than \( 10^{-5} \). T-violation is itself an important symmetry violation to be tested, since, at the same time, it provides knowledge of CP-violation through the CPT theorem.

The important feature in the present case is the fact that the contribution from the standard model (SM) Kobayashi-Maskawa scheme is negligibly small \(^2 \) (\( \sim 10^{-7} \)). Thus, an observation of

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$P_T$ above the level of $10^{-5}$ uniquely signifies the discovery of a CP violation mechanism other than the SM. Several theoretical models, eg, three-Higgs-doublet models, leptoquark models, and some class of supersymmetric models with R-parity violation or squark mixing, have been considered and they can produce $P_T$ as large as $10^{-3}$ without conflicting with other experimental constraints. The $K_{\mu3} P_T$ measurement has a long history both in $K_L$ and $K^+$ decays including the most recent $K^+$ at BNL-AGS about 20 years ago. All of them, however, ended with upper limits. E246 aimed for improving the limit further in statistical accuracy as well as in the systematic errors. The final result of this experiment has recently been obtained, and it is presented in this talk.

2 E246 Experiment

2.1 Progress

The main feature of the E246 experiment is the use of kaon decays at rest in contrast to all the previous experiments which used kaon decays in flight. This enabled a measurement of all decay kinematic directions, and, in this way, a double ratio measurement with suppressed systematic errors was realized. After the detector construction between 1992 to 1995, data taking was performed for 5 years from 1996 to 2000. In 1999 we published the first result from the first 25% of the data, giving $\text{Im}\xi = -0.013 \pm 0.016(\text{stat}) \pm 0.003(\text{syst})$, where $\text{Im}\xi$ is the T-violating physics parameter in $K_{\mu3}$ decay. $\xi$ is defined as the form factor ratio, $\xi = f_-/f_+$. A complete analysis of the entire data set has been done carefully after the completion of the data acquisition. The E246 data also contained several byproduct physics results, such as the $P_T$ measurement in $K^+ \rightarrow \mu^+\nu\gamma$ and decay-form-factor related physics.

2.2 Experimental Setup

The experimental setup and the principle of the experiment have been well described. A schematic view of the setup is shown in Fig.1. The detector system consists of a charged particle tracking system, a CsI(Tl) calorimeter with 762 segmented crystals for $\pi^0$ detection,
and a muon polarimeter to measure the decay positron asymmetry. Incoming kaons, triggered by a Cherenkov counter, were stopped in an active fiber target where $K_{\mu 3}$ decay takes place with a branching ratio of 3.2%. $P_T$ was searched for as the azimuthal ($\phi$) polarization ($y$ component in Fig.2) of $\mu^+$ emitted radially (in the $r$ direction) and stopped in the pure Al stoppers when a $\pi^0$ was tagged in the forward ($fwd$) or the backward ($bwd$) direction relative to the detector ($z$) axis; events from $fwd$ and $bwd$ $\pi^0$s have $P_T$ with opposite signs.

### 2.3 Muon Polarimeter

A schematic view of the polarimeter and its cross section are shown in Fig.2. Muons entering the polarimeter are slowed down through a degrader and stopped in stack of pure Al plates, with spacing in-between to reduce scattering and absorption of decay positrons. A flux of magnetic field was guided by iron plates to apply a field on the stopper with strength of 200-300 Gauss to hold the azimuthal component while rotating the other components. There is neither spin relaxation nor initial loss in the pure Al. The azimuthal polarization was measured as an asymmetry $A = [N_{cw} - N_{ccw}]/[N_{cw} + N_{ccw}] \sim (N_{cw}/N_{ccw} - 1)/2$ between clockwise ($cw$) and counter-clockwise ($ccw$) $e^+$ counts, $N_{cw}$ and $N_{ccw}$.

### 3 Analysis

#### 3.1 $K_{\mu 3}$ Event Selection

$K_{\mu 3}^+$ events were selected in terms of 1) the charged-particle momentum $p_\mu$, 2) the charged particle mass from the time-of-flight measurement $m_\mu$, and 3) the CsI(Tl) information on the $\pi^0$ ($m_{\gamma\gamma}$ for 2-photon events and $E_\gamma$ for one-photon events: the CsI(Tl) has 12 holes for muons to pass into the spectrometer as well as two beam in/out holes. $\pi^0$s were identified not only with 2 photons but also as one photon with relatively high energy). Necessary conditions for the active kaon target, the kinematics, and veto counters etc. were also imposed. The most significant background was from $\pi^+$ in-flight decay muons, but this could be suppressed down to a level less than several % after the tracking quality cuts such as the fit $\chi^2$. Thanks to the very good timing performance of the CsI(Tl) crystals, the accidental backgrounds in the calorimeter could be very efficiently suppressed.
Figure 3: Time spectra of decay positrons (left) and result of $P_T$ as a function polarimeter axis $y$ (right). In the upper part the asymmetry $A_N$ which represents the analyzing power is also plotted. Black dots (●) are $2\gamma$ events and open circles (○) are $1\gamma$ events.

3.2 Two-Analysis Method

We employed the two-analysis method, namely two completely independent analyses, A1 and A2, pursued their own best event selection conditions with their own analysis criteria. The basic selections of good $K^{+}\mu^-\nu_\mu$ events were almost common, but details of 1) charged particle tracking, 2) CsI(Tl) clustering, cut variables and the cut points were generally different. This method provided the means of a data quality cross-check of the selected events. All the selected events were then sorted into common (A1 · A2) events and two sets of uncommon events (A1 · A2 and A1 · A2) separately for $2\gamma$ and $1\gamma$, thus providing 6 final data sets. Slight differences between the two analyses led to a non-negligible amount of uncommon good events in each analysis. The maximum sensitivity to $P_T$ is provided by the $fwd$ and $bwd$ regions of $\pi^0$ ($2\gamma$) or photons ($1\gamma$) with $|\cos \theta_{\pi^0(\gamma)}| > 0.342$, where $\theta_{\pi^0(\gamma)}$ is the polar angle, and $A$ for $fwd$ and $bwd$ were calculated as $A_{fwd}$ and $A_{bwd}$, respectively.

3.3 Data Quality Check

The data were grouped into three experimental periods of (I) 1996-1997, (II) 1998, and (III) 1999-2000, each having nearly the same beam conditions and almost the same amount of data, giving $3 \times 6 = 18$ data sets. First, the null asymmetry $A_0 = (A_{fwd} + A_{bwd})/2$ was confirmed to be close to zero for each data set. Next, the polarimeter sensitivity was checked by means of the asymmetry associated with the large in-plane polarization $P_N$. The selected events were rearranged into “left” and “right” categories instead of $fwd$ and $bwd$ and the asymmetry $A_N = (A_{left} - A_{right})/2$ was calculated. The quantity $A_N/P_N < \cos \theta$ represents the sensitivity to the polarization measurement, where $< \cos \theta$ is the kinematical attenuation of $P_N$. The third data quality check was done by means of the distribution of the decay plane angles relative to the polarimeter axis. The asymmetry of this distribution would induce an admixture of an in-plane polarization. All the data sets passing these tests were then used for $P_T$ extraction.
3.4 Polarimeter Analysis

The muon stoppers had finite sizes in the $y$ and $r$ directions (Fig. 2). In order to remove the intrinsic geometrical asymmetry we employed the distribution information from the C4 tracking chambers located in front of the stopper. $P_T$ for each data set was evaluated as the average of the contributions $P_T(y)$ from each part of the stopper from $y = -9.0$ cm to $+9.0$ cm as:

$$P_T = \int P_T(y)w(y)dy$$

where $w(y)$ is the weight and $P_T(y) = A_T(y)/[\alpha(y) < \cos \theta_T >]$ with the $y$-dependent asymmetry $A_T(y)$ and analyzing power $\alpha(y)$. $A_T(y)$ defined as $A_T(y) = [(A_{fwd}(y) - A_{bwd}(y))/2$ was free from the intrinsic geometrical asymmetry and from the muon stopping densities, and therefore cancelled the systematic errors common for $fwd/bwd$ events. The analyzing power $y$ dependence could be calibrated using the positron asymmetry $A_N(y)$ associated with the normal polarization $P_N$ as $\alpha(y) \sim A_N(y)$. The absolute value of $\alpha$ was calibrated by a Monte Carlo simulation. Fig. 3 shows $A_N(y)$, and $P_T(y)$ thus calculated which is nearly constant with only slight gradients for both $2\gamma$ and $1\gamma$ events. This is due to the different muon stopping distributions in the $r$ direction between $fwd$ and $bwd$ events. $P_T$ was calculated by averaging $P_T(y)$. The effect of the $P_T(y)$ gradients could be eliminated due to the symmetric nature about $y = 0$ in this summation. The factor $< \cos \theta_T >$ was evaluated for each data set by a Monte Carlo calculation taking into account realistic background conditions for each data set.

4 Result and Systematic Errors

The transverse polarization $P_T$ was calculated as the average of the 18 values to be $P_T = -0.0017 \pm 0.0023$. Thus, no $T$ violation was observed. The conversion to the $T$-violating physics parameter $\text{Im} \xi_2$ was done using a conversion coefficients $\Phi = 0.327(0.287)$ from a Monte Carlo simulation for $2\gamma(1\gamma)$. Its ideogram is shown in Fig. 4 with the average of $\text{Im} \xi_2 = -0.0053 \pm 0.0071$.

The major systematic errors are listed in Table I. Almost all the systematics were cancelled due to the summation of the rotationally symmetric 12 sectors and the double ratio between $fwd$ and $bwd$ events. The few remaining errors give rise to a small admixture of $P_N$ resulting in a spurious $P_T$ effect. There are some contributions from misalignments of detector elements and the muon spin rotation field. The small shifts of the decay plane normal distribution, $\theta_r$ and $\theta_z$, were treated as an error. The effect of muon multiple scattering through the Al degrader...
Table 1: Summary of systematic errors.

| Source                                      | $\delta P_T \times 10^4$ |
|---------------------------------------------|---------------------------|
| $e^+$ counter misalignment                  | 2.9                       |
| Misalignments of other counters             | 2.6                       |
| Misalignment of $\vec{B}$ field             | 6.1                       |
| $K^+$ stopping distribution                 | <3.0                      |
| Decay plane rotations                       | 1.4                       |
| $\mu^+$ multiple scattering                | 7.1                       |
| Backgrounds                                 | <2.0                      |
| Analysis                                    | 4.0                       |
| Total                                       | <11.4                     |

can cause a difference in the actual muon stopping distribution, and thus produce a spurious $A_T$ through the intrinsic geometrical asymmetry as large as $\delta P_T = 7.1 \times 10^{-4}$. The total size of the systematic error was calculated as the quadratic sum of all the contributions resulting in $\delta P_T = 1.1 \times 10^{-3}$ which is much smaller than the statistical error. Finally, the ideogram of 18 Im$\xi$ values shows a good behavior with a fit to a constant with $\chi^2/\nu = 0.78$.

5 Summary

The KEK E246 experiment has obtained the improved limits of

$$ P_T = -0.0017 \pm 0.0023(\text{stat}) \pm 0.0011(\text{syst}) $$

$$ \text{Im}\xi = -0.0053 \pm 0.0071(\text{stat}) \pm 0.0036(\text{syst}), $$

showing no evidence for $T$ violation. The 90% CL’s are given as $|P_T| < 0.0050$ and $|\text{Im}\xi| < 0.016$ by adding statistical and systematic errors quadratically. This limit of Im$\xi$ is a factor 3 improvement over the last BNL-AGS experiment$^4$. Our results constrain the lightest Higgs mass and other parameters in the framework of non-SM models$^3$ better than or complementary to other constraints such as the neutron electric dipole moment $d_n$ and $B$ meson decays.

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