A new limit of T-violating transverse muon polarization in the $K^+ \rightarrow \pi^0\mu^+\nu$ decay

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Abstract

A search for T-violating transverse muon polarization (P_T) in the $K^+ \to \pi^0 \mu^+ \nu$ decay was performed using kaon decays at rest. A new improved P_T value was obtained to be $P_T = -0.0017 \pm 0.0023(stat) \pm 0.0011(syst)$ giving an upper limit, $|P_T| < 0.0050$. The T-violation parameter was determined to be $\text{Im}\xi = -0.0053 \pm 0.0071(stat) \pm 0.0036(syst)$ giving an upper limit, $|\text{Im}\xi| < 0.016$.

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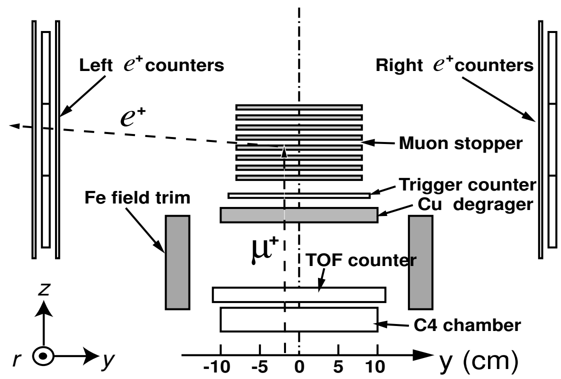

FIG. 1: Muon polarimeter of one sector and y direction. The figure is a cross section at a certain radial position r with the tilted positron counters. See [9] for details.

The transverse muon polarization, P_T, in the $K^+ \to \pi^0\mu^+\nu$ ($K^+_{\mu 3}$) decay, which is defined as the polarization component perpendicular to the decay plane, is an obvious signature of a violation of time reversal (T) invariance [1], since the spurious effect from final state interactions is very small ($< 10^{-5}$) [2]. P_T is almost vanishing ($\sim 10^{-7}$) in the standard model (SM) with the Kobayashi-Maskawa scheme [3]; it is therefore a very sensitive probe of CP violation mechanisms beyond the SM, in contrast to the T violation so far found in the K^0 system [4]. Models [5] such as those with multi-Higgs doublets or leptoquarks, or a class of SUSY are able to give rise P_T with a significant size as large as 10^{-3}.

At the High Energy Accelerator Research Organization (KEK) the E246 collaboration has been performing a search for P_T in $K_{\mu 3}$. In 1999, the first result, $P_T = -0.0042 \pm 0.0049(stat) \pm 0.0009(syst)$ was published [6] based on $\sim 3.9 \times 10^6$ good $K^+_{\mu 3}$ events from the data taken during 1996 and 1997, indicating no evidence for T violation. The T-violating parameter Im(ξ) [7] was then extracted as $\text{Im}(\xi) = -0.013 \pm 0.016(stat) \pm 0.003(syst)$. Since then we have been improving the statistical accuracy by accumulating more data. Further runs provided a cumulative data sample of $\sim 11.8 \times 10^6$ good $K^+_{\mu 3}$ events. Meanwhile we also reported the transverse muon polarization in the decay $K^+ \to \mu^+\nu\gamma$ for the first time [8]. This Letter constitutes our final result from all the data. During these data analyses we also developed an improved scheme to obtain higher statistical sensitivity and to better control the systematics. The entire data sets were subjected to the same analyses. The present result supersedes all our earlier reports.

The principle of the experiment was the same as described before [6]. It was performed by means of the detector setup [9] at a 12-sector superconducting toroidal magnet using stopped kaons. The muon polarization is decomposed into three components a) longitudinal, $P_L = \vec{s}_\mu \cdot \vec{p}_\mu / |\vec{p}_\mu|$ parallel to the muon momentum $\vec{p}_\mu$, b) normal, $P_N = \vec{s}_\mu \cdot (\vec{p}_\mu \times (\vec{p}_\pi \times \vec{p}_\mu))/|\vec{p}_\mu \times (\vec{p}_\pi \times \vec{p}_\mu)|$ normal to $\vec{p}_\mu$ in the decay plane, and c) transverse, $P_T = \vec{s}_\mu \cdot (\vec{p}_\pi \times \vec{p}_\mu)/|\vec{p}_\pi \times \vec{p}_\mu|$ perpendicular to the decay plane. P_T was searched for as the azimuthal polarization (y component in Fig.1) of μ^+ emitted radially (in the r direction) and stopped in the stoppers when a π^0 was tagged in the forward (fwd) or the backward (bwd) direction relative to the detector axis. This 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) emitted Michel e^+, N_{cw} and N_{ccw}. The setup was constructed with 12-fold azimuthal symmetry and with polar symmetry with respect to fwd and bwd π^0's. Summation over the twelve sectors played an important role in reducing systematic errors. As follows from the P_T definition, events from fwd and bwd π^0s have opposite asymmetries. By looking at their difference, we profited not only from the doubled signal but also from the powerful cancellation of the systematic errors. A kaon beam with an average intensity of 1.0×10^5/s was produced at the K5 channel of the 12 GeV proton synchrotron from 3×10^{12} protons per spill of 0.7 s duration with a 2.7 s repetition time. We ran the experiment under almost the same condition since 1996, although the beam intensity and conditions changed slightly from time to time.

The two analysis method described in the previous paper [6] was followed in the off-line event selection. Two completely independent analysis teams, A1 and A2, pursued their own best event selections with their own analysis policies. This method provided the means of a data quality cross-check of the selected events and the estimation of systematic errors associated with the analysis. The basic selections of good $K^+_{\mu 3}$ events in the initial stage of both analyses were not changed significantly. The π^0's were identified not only as two photons (2γ) but also as one of the photons (1γ) with energy E_γ >70 MeV. The maximum sensitivity to P_T is provided by the fwd and bwd regions of π^0 (2γ) or photons (1γ) with $|\cos\theta_{\pi^0(\gamma)}| > 0.342$, where $\theta_{\pi^0(\gamma)}$ is the polar angle.

Details of the event selection were optimized according to the data. Slight differences between the two analyses led to a non-negligible amount of uncommon good events in each analysis. All the selected events were categorized into the common ($A1 \cdot A2$) events and two sets of uncommon events ($\overline{A1} \cdot A2$ and $A1 \cdot \overline{A2}$) separately for 2γ and 1γ, providing 6

TABLE I: T-violating polarization P_T and null asymmetry A_0 of the 18 data sets of 2γ and 1γ events from the two analyses of A1 and A2 for three experimental periods of I, II and III. The errors are only statistical ones.

Data set		I(1996-1997)	II(1998)	III(1999-2000)
2γ [A1 $\cdot$ A2]	P_T	0.00112 ± 0.00667	-0.00317 ± 0.00729	-0.00596 ± 0.00711
	A_0	-0.00041 ± 0.00139	-0.00193 ± 0.00150	-0.00464 ± 0.00146
2γ [$\bar{\text{A1}}\cdot$ A2]	P_T	-0.00735 ± 0.01022	0.01225 ± 0.00858	-0.00037 ± 0.00754
	A_0	-0.00503 ± 0.00191	0.00002 ± 0.00166	-0.00065 ± 0.00139
2γ [A1 $\cdot\bar{\text{A2}}$]	P_T	-0.00385 ± 0.00899	0.00640 ± 0.01268	-0.00473 ± 0.01201
	A_0	0.00191 ± 0.00174	-0.00296 ± 0.00216	-0.00134 ± 0.00196
1γ [A1 $\cdot$ A2]	P_T	-0.01393 ± 0.00956	-0.01366 ± 0.01042	0.01113 ± 0.01035
	A_0	-0.00201 ± 0.00160	-0.00433 ± 0.00172	-0.00215 ± 0.00160
1γ [$\bar{\text{A1}}\cdot$ A2]	P_T	0.01014 ± 0.01069	-0.01114 ± 0.01280	-0.01088 ± 0.01022
	A_0	-0.00199 ± 0.00176	-0.00258 ± 0.00184	-0.00101 ± 0.00149
1γ [A1 $\cdot\bar{\text{A2}}$]	P_T	0.00228 ± 0.01134	-0.01660 ± 0.01531	0.00951 ± 0.01195
	A_0	0.00162 ± 0.00190	-0.00104 ± 0.00223	-0.00174 ± 0.00181

final data sets. In total 6.3 million and 5.5 million good events were obtained for 2γ and 1γ, respectively. The background contamination was almost same as before [6]. The data quality check was done for these 6 data sets. The positron yield was extracted from the time spectra by integrating from 20 ns to 6.0 μs after subtraction of the constant background deduced from fitting between 6.0 μs to 19.5 μs.

In our previous paper the T-violating asymmetry A_T was calculated as $A_T = (R_{fwd}/R_{bwd}-1)/4$, where $R_{fwd(bwd)} = (N_{cw}/N_{ccw})_{fwd(bwd)}$ for π^0-fwd (bwd) region, using the total positron cw and ccw counts. Then, P_T was calculated as $P_T = A_T/(\alpha_{int} < \cos\theta_T >)$ using an average analyzing power α_{int} and the kinematical angular attenuation factor $< \cos\theta_T >$. It is however easily realized that this method is prone to a systematic error due to potentially different muon stopping distributions of fwd and bwd events. To obtain a finite stopping efficiency, muon stoppers with finite size in the y and r directions (Fig.1) were employed. An intrinsic geometrical asymmetry appears for muons at (y, r) off center which, in turn, can induce a fake A_T if the muon stopping distribution is different between fwd and bwd events, in particular in the y direction. In the current analysis an exact treatment was employed in which we use the y muon stopping distribution information from the C4 tracking chamber located just in front of the stopper.

In the new analysis the transverse polarization P_T for each data set was evaluated as the average of contribution $P_T(y)$ from each part of the stopper using the C4 y coordinate from y=-9.0 cm to +9.0 cm as;

$$P_T = \int P_T(y)w(y)dy \tag{1}$$

where $w(y)$ is the weight of $\sim 1/\sigma^2_{P_T}$, and $P_T(y)$ is

$$P_T(y) = \frac{A_T(y)}{\alpha(y) < \cos\theta_T >} \tag{2}$$

with the y-dependent asymmetry $A_T(y)$ and analyzing power $\alpha(y)$. The definition of $A_T(y) = [(A_{fwd}(y) - A_{bwd}(y)]/2$ assured that the analysis was free from the intrinsic geometrical asymmetry and from muon stopping densities, and canceled the systematic errors common for fwd/bwd events. Here, $A_{fwd}(y)$ and $A_{bwd}(y)$ were calculated as $A_{fwd(bwd))}(y) = [(N_{cw}(y)/N_{ccw}(y) - 1)/2]_{fwd(bwd)}$. The analyzing power y dependence could be calibrated using the positron asymmetry $A_N(y)$ associated with the normal polarization P_N as $\alpha(y) \sim A_N(y)$. A_N could be measured by rearranging the fwd and bwd events into $left$ and $right$ categories of π^0 directions, and calculating $A_N = (A_{left} - A_{right})/2$. This has a maximum at the center of the stopper. The absolute value of α was calibrated by a Monte Carlo simulation. The obtained $\alpha(y)$ function corresponded to $\alpha_{int} = 0.271 \pm 0.027$, which was significantly higher than our previous estimate of $\alpha_{int} = 0.197 \pm 0.005$ [6]. The coefficient $\alpha(y)$ included the effects of intrinsic muon decay asymmetry, muon spin precession around the field, positron interactions, and the finite counter solid angle. P_T thus obtained in Eq.(1) is regarded as the average value of P_T distribution due to the finite kinematical acceptance of $K_{\mu 3}$ in the stopper. The validity of applying the proportionality relation $P_T(y) \sim A_T(y)/A_N(y)$ in Eq.(2) was carefully checked under the actual trigger condition. In order to increase the statistical accuracy of $\alpha(y)$, A_N of all the data sets was summed since $\alpha(y)$ is only dependent on y and should not depend significantly on data set. Fig.2 shows $A_N(y)$ for all the data plotted for 36 bins from y=-9.0 cm to +9.0 cm. In the actual analysis, the averaging of $+i$ and $-i$ bins was used because the shape of $\alpha(y)$ should be symmetric in the first order approximation also in the presence of the magnetic field. $P_T(y)$

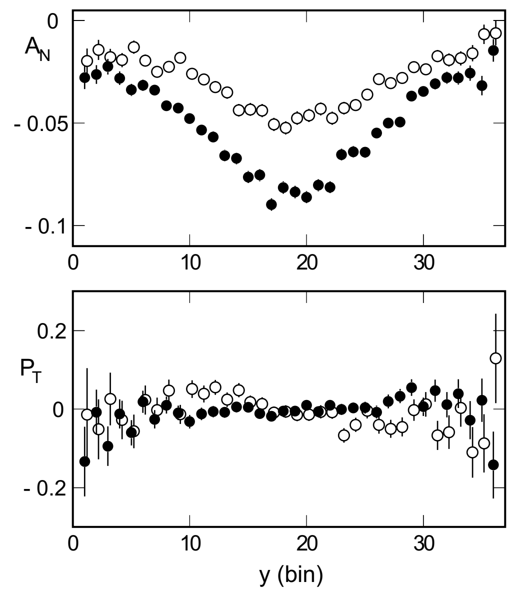

FIG. 2: Normal asymmetry A_N (upper) and obtained P_T (lower) as functions of y. Black dots (•) are 2γ events and open circles (∘) are 1γ events. One bin is 0.5 cm and the range is from -9.0 to +9.0 cm.

thus calculated is nearly constant with slight gradients both for 2γ and 1γ. This is due to the different muon stopping distributions in r direction between fwd and bwd events. P_T was calculated by summation of the integrand of Eq.(2) over these 36 bins. 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 defined for the angle θ_T of the decay plane normal vector relative to the y-axis of the polarimeter and evaluated for each data set by using a Monte Carlo calculation taking into account realistic background conditions for each data set.

The total data were grouped into three 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 18 data sets. A null asymmetry check was performed first with $A_0 = [(N_{cw}/N_{ccw})_{fwd+bwd} - 1]/2$ for each data set using the total cw and ccw counts integrated over y and it was confirmed that there was no significant bias (Table 1). Next, A_N were compared among the data sets. Although there was a slight difference among the 1γ data sets due to different tightness of the event selection we decided to use all the 1γ data. The distribution of decay plane normal $(\mathbf{n}_{\pi^0} \times \mathbf{n}_{\mu^+})$ with its θ_r and θ_z components [6] was studied in order to check for any possible kinematical phase space distortions in each data set. No

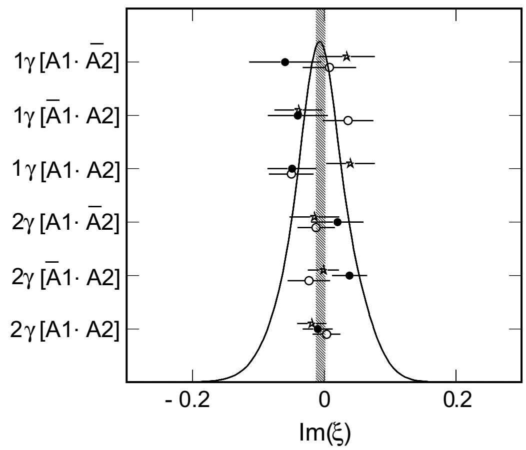

FIG. 3: Ideogram of Im(ξ). Black dots ($\bullet$) are data sets I, open circles ($\circ$) are II, and stars ($\star$) are III. $\chi^2/\nu = 0.78$.

significant offsets were found. Finally, the 18 P_T values, which are consistent each other (with a fit to a constant with $\chi^2/\nu = 0.78$, where ν is the degree of freedom), allowed us to use all the 18 data sets. They are summarized in Table 1. The transverse polarization was computed as the average of the 18 values giving $P_T = -0.0017 \pm 0.0023$, which is consistent with zero. The conversion to the T-violating physics parameter Imξ was done using the same conversion coefficients $\Phi = 0.327(0.287)$ as in the previous analysis [6] from a Monte Carlo simulation for $2\gamma(1\gamma)$. Its ideogram is shown in Fig.3 with the average of Im$\xi = -0.0053 \pm 0.0071$. It is noted that the analysis by the previous method using total *cw* and *ccw* counts gives consistent central values of $P_T = -0.0018$ and Im$\xi = -0.0063$.

Possible systematic errors were thoroughly examined and their summary is listed in Table II. Although almost all the systematics were canceled due to the summation of the 12 sectors and the double ratio between fwd and bwd events, a few errors remain giving rise to a small admixture of P_N resulting in a spurious P_T effect. The contribution of misalignments of detector elements and the muon spin rotation field remained as in [6]. The small shifts of the decay plane normal distribution, θ_r and θ_z, were treated as an error. The effect of muon multiple scattering through the Cu degrader may cause a difference in the actual muon stopping distribution, in particular in the y distribution due to statistical fluctuation even for a measured y at C4. The different distribution may produce a spurious A_T through the intrinsic geometrical asymmetry. This effect, inadvertently omitted in our previous analysis, was carefully estimated in the present analysis. It contributes as large as $\delta P_T =$

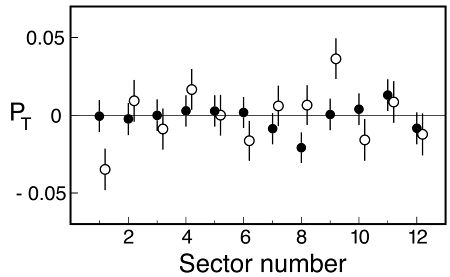

FIG. 4: Dependence of P_T on the sector number. Black dots (•) are 2γ events and open circles (∘) are 1γ events.

TABLE II: 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
μ^+ multiple scattering	7.1
Backgrounds	< 2.0
Analysis	4.0
Total	< 11.4

7.1×10^{-4}. The effect of small $P_T(y)$ gradients along y had nearly perfect cancellation but it was limited by the small asymmetry of muon distributions about $y = 0$. Its effect was treated as a systematic error and included in the item "Analysis" together with other analysis uncertainties [6]. 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. The sector dependence of P_T is also plotted in Fig.4 with $\chi^2/\nu = 0.69$ for 2γ data and $\chi^2/\nu = 1.97$ for 1γ data showing a slight inferior behavior for the 1γ data.

In conclusion we obtained the values of

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

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

giving no evidence for T violation. The 90% confidence limits are given as $|P_T| < 0.0050$ and $|\mathrm{Im}\xi| < 0.016$ by adding statistical and systematic errors quadratically. This result is a factor 3 improvement over the last BNL-AGS experiment [10] and it may constrain the lightest Higgs mass and/or other parameters in the framework of non-SM models [5] better than or complementary to the neutron electric dipole moment d_n and B meson decays. For example, our result implies in one of the multi-Higgs models ([5] Garisto and Kane) that the down quark contribution to d_n should be less than $7 \times 10^{-27}e$-cm, a factor 9 less than the current experimental limit of $d_n^{exp} < 6.3 \times 10^{-26}e$-cm.

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