New Limit on the T-Violating Transverse Muon Polarization in $K^+ \to \pi^0 \mu^+ \nu$ Decays

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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 value $P_T = -0.0017 \pm 0.0023(\text{stat}) \pm 0.0011(\text{syst})$ was obtained giving an upper limit $|P_T| < 0.0050$. The T-violation parameter was determined to be $\text{Im}\xi = -0.0053 \pm 0.0071(\text{stat}) \pm 0.0036(\text{syst})$ giving an upper limit $|\text{Im}\xi| < 0.016$.

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The transverse muon polarization, P_T, in the $K^+ \to \pi^0 \mu^+ \nu$ ($K^+_{\mu 3}$) decay is one of the observables of CP violation beyond the standard model (SM). CP violation in general is a subject of continuing interest in K and B meson decays. P_T, defined as the polarization component perpendicular to the decay plane, is an obvious signature of a violation of time reversal (T) invariance, since the spurious effect from final state interactions is very small ($< 10^{-5}$) [1]. P_T is almost vanishing ($\sim 10^{-7}$) in the SM with the Kobayashi-Maskawa scheme [2]; it is therefore a very sensitive probe of CP violation mechanisms beyond the SM and new physics along with B physics such as $b \to s\gamma$ and some other decays [3]. Models [4] such as those with multi-Higgs doublets or leptoquarks, or some supersymmetry (SUSY) may give rise to P_T 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 was published [5] 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. Further runs provided a cumulative data sample with 3 times more events. This Letter constitutes our final result from all the data with an improved analysis. The present result supersedes all our earlier reports.

The principle of the experiment was the same as described before [5]. A kaon beam with an average intensity of 1.0×10^5/s was produced at the 12 GeV proton synchrotron from 3×10^{12} protons per spill of 0.7 s duration with a 2.7 s repetition time. The detector setup (Fig. 1) using stopped kaons at a 12-sector magnet is described in detail in [6]. The muon polarization consists of 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 (ϕ or y component in Fig. 1) of μ^+ emitted radially (in the r direction) and stopped in the Al stoppers when a π^0 was tagged in the forward (fwd) or the backward (bwd) direction relative to the detector axis. The spin depolarization during flight and in the stopper was estimated to be negligible. This azimuthal polarization was measured as an asymmetry between clockwise (cw) and counterclockwise (ccw) emitted Michel e^+, N_{cw}, and N_{ccw}. Summation over the 12 sectors with 12-fold azimuthal symmetry played an important role in reducing systematic errors. Events from fwd and bwd π^0's have opposite asymmetries. We exploit this feature to double the signal and also as a powerful means to cancel the systematic errors.

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 amount of data. As was described in [5], two completely independent analy-

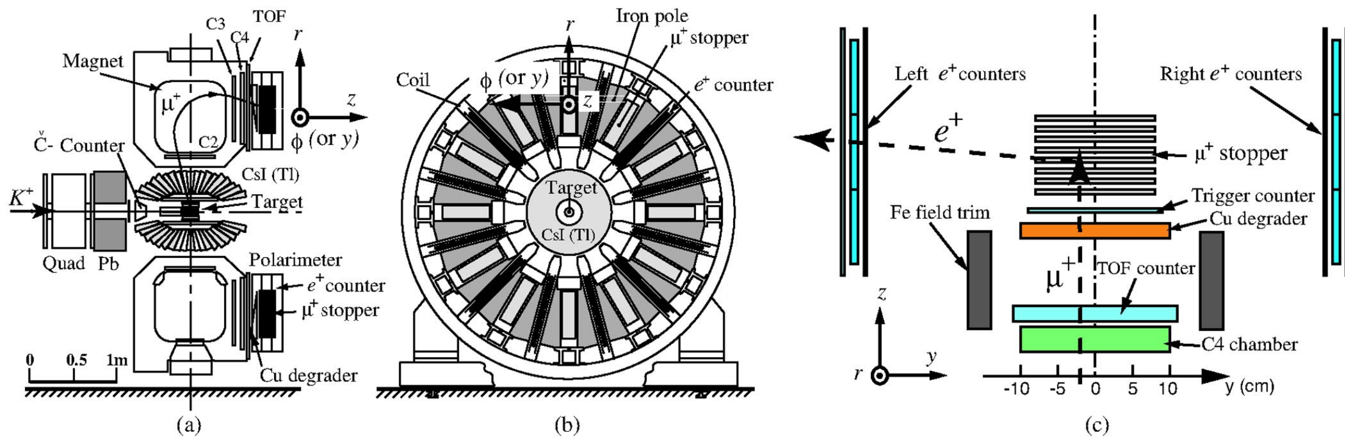

FIG. 1 (color online). Experimental setup. (a) Cross section side view, (b) end view, and (c) cross section view of the muon polarimeter of one sector at a certain radial position r with the tilted positron counters. The y direction is also shown. See [6] for details.

ses, A1 and A2, pursued their own best offline event selections with their own analysis policies. This approach provided a cross-check of the quality of selected events and also an estimate of the systematic errors in the analysis. Basic event selection criteria were same in both analyses. The π^0's were identified not only as two photons (2γ) but also as one photon (1γ) with energy $E_\gamma > 70$ 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 corrected for muon direction. 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. In total, 6.3×10^6 and 5.5×10^6 good events were obtained for 2γ and 1γ, respectively. The fraction of 2γ and 1γ mismatch events between A1 and A2 was only 1.5% and these were rejected. 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. The only significant background to muon stopping and its decay was due to π^+ decay in flight from $K^+ \to \pi^+\pi^0$; its contamination effect was estimated and included in the systematic errors.

In [5], the T-violating asymmetry A_T was calculated as $A_T = (R_f/R_b - 1)/4$, where $R_{f(b)} = (N_{\rm cw}/N_{\rm ccw})_{f(b)}$ for the π^0-fwd (bwd) region, using the total positron cw and ccw counts. Then, P_T was calculated as $P_T = A_T/(\alpha_{\rm int}\langle\cos\theta_T\rangle)$ using an average analyzing power $\alpha_{\rm int}$ and the angular attenuation factor $\langle\cos\theta_T\rangle$ with θ_T being the angle of decay plane normal vector relative to the y axis. However, 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 were employed. A 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, in which we use the y muon stopping point from the C4 tracking chamber located just in front of the stopper, was employed. For the r direction, an integration was used because the change of geometrical asymmetry is much smaller (about 1/10 of y dependence), and because its determination from tracking was poor. 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 as

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

where $w(y)$ is the weight function proportional to $1/\sigma^2_{P_T}(y)$ (here, $\sigma_{P_T}(y)$ is the error distribution) and normalized to 1, and $P_T(y)$ is

$$P_T(y) = \frac{A_T(y)}{\alpha(y)\langle\cos\theta_T\rangle}, \tag{2}$$

with the y-dependent asymmetry $A_T(y)$ and analyzing power $\alpha(y)$. The definition of $A_T(y) = [A_f(y) - A_b(y)]/2$ assured that it was free from the geometrical asymmetry and from muon stopping densities, and canceled the systematic errors common for fwd/bwd. Here, $A_f(y)$ and $A_b(y)$ were calculated as $A_{f(b)}(y) = \{[N_{\rm cw}(y)/N_{\rm ccw}(y) - 1]/2\}_{\rm fwd(bwd)}$. The y dependence of analyzing power could be calibrated using the positron asymmetry $A_N(y)$ associated with the normal polarization P_N as $A_N(y)$ is proportional to $\alpha(y)$. A_N was measured by rearranging the fwd and bwd events into left and right categories of π^0 directions and calculating $A_N = (A_{\rm left} -$

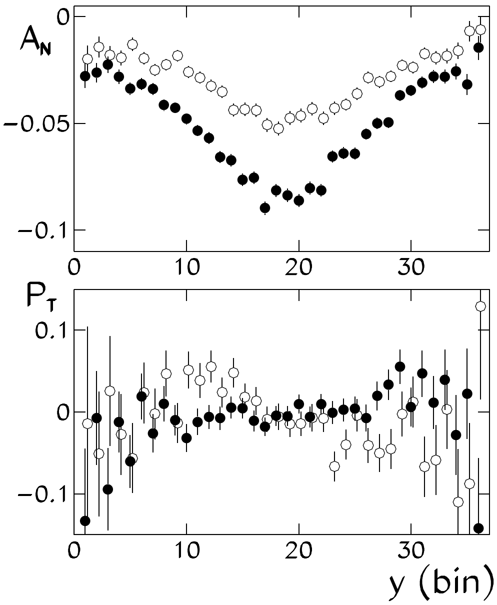

FIG. 2. Measured A_N (upper) and P_T (lower) as functions of y. Black dots (•) are 2γ events and open circles (∘) are 1γ events. Each bin is 0.5 cm wide with the center ($y = 0$ cm) at between 18 and 19 bins.

$A_{\rm right})/2$. This has a maximum at the center of the stopper (Fig. 2). The absolute value of α was calibrated by a Monte Carlo simulation as $\alpha = A_N^{\rm MC}/P_N^{\rm MC}$. 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. The obtained $\alpha(y)$ function corresponded to $\alpha_{\rm int} = 0.271 \pm 0.027$, which is significantly higher than our previous estimate of $\alpha_{\rm int} = 0.197 \pm 0.005$ [5] deduced as $\alpha = A_N^{\rm exp}/P_N^{\rm MC}$ and thus less reliable. P_T thus obtained in Eq. (1) is regarded as the average value of P_T distribution in 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 the data set. 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. Figure 2 shows $P_T(y)$ thus calculated which is nearly constant with slight but opposite-sign gradients for 2γ and 1γ. This is due to different muon stopping distributions along the r direction for fwd and bwd events with an opposite tendency of $\delta\langle r\rangle = \langle r\rangle_{\rm fwd} - \langle r\rangle_{\rm bwd}$ for 2γ and 1γ due to kimematics. P_T was calculated, for the integration Eq. (1), by summation over the 36 bins from $y = -9.0$ cm to $+9.0$ cm. The effect of the r origin $P_T(y)$ gradients is eliminated since the effect cancels between $+y$ and $-y$, and the y distribution is symmetric. The average values of y, weighted by the statistical significance of respective $P_T(y)$, were $\langle y\rangle = 0.007$ mm and 0.020 mm for 2γ and 1γ, respectively. These small $\langle y\rangle$'s confirm an excellent C4/stopper alignment and justify this analysis. The factor $\langle \cos\theta_T\rangle$ was evaluated for each data set by using a Monte Carlo calculation taking into account realistic background conditions to be typically 0.7 and 0.6 for 2γ and 1γ, respectively.

Data quality checks were performed for the 18 data sets of the three groups with six data categories each. First the null asymmetry was calculated as the asymmetry of all the fwd and bwd events added, using the total cw and ccw counts integrated over y and it was confirmed that there was no significant bias. Next, A_N were compared. Although there was a slight difference among the 1γ data sets due to different cut criteria of the event selection, we decided to use all the 1γ data. Then the distribution of decay plane normal $(\vec{n}_{\pi^0} \times \vec{n}_{\mu^+})$ with its θ_r and θ_z components [5] was studied to check for any possible kinematical phase space distortions, and no significant offsets were found. Finally, the 18 P_T values (Table I) which are consistent with each other (a fit to a constant gives $\chi^2/\nu = 0.78$, where ν is the degree of freedom), yielded the average of $P_T = -0.0017 \pm 0.0023$, being consistent with zero. The sector dependence of P_T is plotted in Fig. 3 with $\chi^2/\nu = 0.69$ for 2γ data and $\chi^2/\nu = 1.97$ for 1γ data, showing that the latter is slightly inferior. The P_T's were converted to the T-violating physics parameter Imξ [7] with the conversion coefficients $\Phi = 0.327$ and 0.287 for 2γ and 1γ,

TABLE I. T-violating polarization P_T 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. For the definitions of event categories, see the text.

Data category	I(1996-1997)	II(1998)	III(1999-2000)
$2\gamma[A1 \cdot A2]$	0.00112 ± 0.00667	-0.00317 ± 0.00729	-0.00596 ± 0.00711
$2\gamma[\bar{A}1 \cdot A2]$	-0.00735 ± 0.01022	0.01225 ± 0.00858	-0.00037 ± 0.00754
$2\gamma[A1 \cdot \bar{A}2]$	-0.00385 ± 0.00899	0.00640 ± 0.01268	-0.00473 ± 0.01201
$1\gamma[A1 \cdot A2]$	-0.01393 ± 0.00956	-0.01366 ± 0.01042	0.01113 ± 0.01035
$1\gamma[\bar{A}1 \cdot A2]$	0.01014 ± 0.01069	-0.01114 ± 0.01280	-0.01088 ± 0.01022
$1\gamma[A1 \cdot \bar{A}2]$	0.00228 ± 0.01134	-0.01660 ± 0.01531	0.00951 ± 0.01195

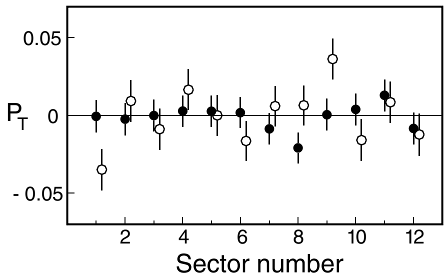

FIG. 3. Dependence of P_T on the sector number. Black dots (•) are 2γ events and open circles (∘) are 1γ events.

respectively, deduced from a Monte Carlo simulation [5]. The ideogram of Imξ (Fig. 4) shows that there is significant overlap among the different data sets. The average is found to be Im$\xi = -0.0053 \pm 0.0071$. It is noteworthy that the analysis by the previous method gives consistent central values of $P_T = -0.0018$ and Im$\xi = -0.0063$.

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 spurious A_T or a small admixture of P_N resulting in a spurious P_T effect (Table II). The contribution of misalignments of detector elements and the muon spin rotation field remained as in [5]. The small mean values of 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 of fwd and bwd, in particular, in the y distribution even for a measured y at C4, producing a spurious A_T through the geometrical asymmetry along y. This effect, inadvertently omitted in our previous analysis, was carefully estimated in the present analysis to be $\delta P_T = 7.1 \times 10^{-4}$. The small effect due to $P_T(y)$ gradients and finite $\langle y \rangle$ values was treated as a systematic error ($\delta P_T = 2 \times 10^{-5}$) and included in the item "Analysis" together with other analysis uncertainties [5]. The total systematic error was calculated as the quadratic sum of all the

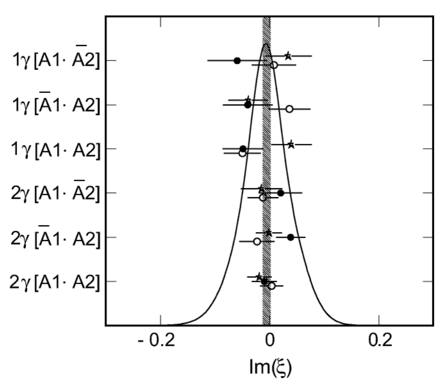

FIG. 4. Ideogram of Im(ξ). Black dots (•) are data sets I, open circles (∘) are II, and stars (⋆) are III. $\chi^2/\nu = 0.78$.

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 on the stopper	6.1
K^+ stopping distribution	<3.0
Decay plane rotations (θ_r and θ_z)	1.4
μ^+ multiple scattering	7.1
Backgrounds (including π^+ decay from $K^+_{\pi 2}$)	<2.0
Analysis (including P_T gradients)	4.0
Total	<11.4

contributions resulting in $\Delta P_T = 1.1 \times 10^{-3}$, which is much smaller than the statistical error.

In conclusion, we obtained the values of $P_T = -0.0017 \pm 0.0023(\mathrm{stat}) \pm 0.0011(\mathrm{syst})$ and Im$\xi = -0.0053 \pm 0.0071(\mathrm{stat}) \pm 0.0036(\mathrm{syst})$ with no indication of 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 experiment [8] and it may constrain the lightest Higgs boson mass and/or other parameters in the framework of non-SM models [4] better than or complementary to the neutron electric dipole moment d_n and B meson decays. For example, our result gives a stronger constraint to the three Higgs doublet model than the similar semileptonic decay $B \to X\tau\nu_\tau$ [9] and implies in one of the multi-Higgs doublet models ([4] Garisto and Kane) that the down quark contribution to d_n should be more than a factor 10 less than the current experimental limit of $d_n^{\mathrm{exp}} < 6.3 \times 10^{-26} e$ cm; our $|\mathrm{Im}\xi|$ 90% limit corresponds to $0.5 \times 10^{-26} e$ cm.

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[1] A. R. Zhitnitskii, Yad. Fiz. **31**, 1024 (1980) [Sov. J. Nucl. Phys. **31**, 529 (1980)]; V. P. Efrosinin *et al.*, Phys. Lett. B **493**, 293 (2000).

[2] I. I. Bigi and A. I. Sanda, *CP Violation* (Cambridge University Press, Cambridge, England, 2000); E. Golowich and G. Valencia, Phys. Rev. D **40**, 112 (1989).
[3] See, for example, T. Hurth, Rev. Mod. Phys. **75**, 1159 (2003); Y. Grossman, Int. J. Mod. Phys. A **19**, 907 (2004).
[4] R. Garisto and G. Kane, Phys. Rev. D **44**, 2038 (1991); G. Bélanger and C. Q. Geng, Phys. Rev. D **44**, 2789 (1991); M. Kobayashi, T.-T. Lin, and Y. Okada, Prog. Theor. Phys. **95**, 361 (1995); M. Fabbrichesi and F. Vissani, Phys. Rev. D**55**, 5334 (1997); G.-H. Wu and J. N. Ng, Phys. Lett. **B392**, 93 (1997).
[5] M. Abe *et al.*, Phys. Rev. Lett. **83**, 4253 (1999).
[6] J. A. Macdonald *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 60 (2003).
[7] N. Cabibbo and A. Maksymowicz, Phys. Lett. **9**, 352 (1964); **11**, 360(E) (1964); **14**, 72(E) (1966).
[8] S. R. Blatt *et al.*, Phys. Rev. D **27**, 1056 (1983).
[9] Particle Data Group, S. Eidelman *et al.*, Phys. Lett. **B592**, 1 (2004); Y. Grossman, Nucl. Phys. **B426**, 355 (1994).