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Search for Time-Reversal Violation in K^+ decays

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A search for the violation of time-reversal invariance in K^+ decays is described. In particular, a new experiment, E246, which is being prepared at KEK to measure the transverse muon polarization in K^+ decays is discussed. The search is sensitive to T (or new CP) violation mechanisms beyond the standard model. Particular emphasis is being placed on theoretical models with extended Higgs sectors.

1. Introduction

It is known that the triple-vector correlation is odd under the time-reversal operation. The measurement of such correlations would give a promising testing ground to scrutinize time-reversal invariance. In four-body decay, a triple correlation of three-momentum vectors, such as $\vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3)$, can be formed for three of the four decay products. In three-body decay, at least one spin vector has to be included, such as $\vec{s}_1 \cdot (\vec{p}_1 \times \vec{p}_2)$. One such example concerning K decay is the transverse muon polarization (P_T) in $K^+ \rightarrow \pi^0 \mu^+ \nu$ ($K_{\mu 3}^+$) decay [1], where P_T is defined as the muon polarization component transverse to the decay plane, determined by the μ^+ and π^0 momentum vectors. It is given by

$$P_T \equiv \frac{\vec{s}_{\mu^+} \cdot (\vec{p}_{\mu^+} \times \vec{p}_{\pi^0})}{|\vec{p}_{\mu^+} \times \vec{p}_{\pi^0}|}, \quad (1)$$

where $\vec{s}_{\mu^+}$ is the muon spin vector; $\vec{p}_{\mu^+}$ and $\vec{p}_{\pi^0}$ are the momentum vectors of the muon and neutral pion, respectively. Since the time-reversal operation changes the sign of P_T , a non-zero value of P_T would signal T violation.

If CPT invariance is imposed, T violation is equivalent to CP violation. Since the first discovery of CP violation in $K_L^0 \rightarrow 2\pi$ decay [2], more than a quarter of a century has passed. However, the origin of CP violation has not yet been completely understood. Among various models proposed to explain observed CP-violation phenomena in K^0 decay, the most promising is the standard model with an imaginary phase in the

Cabbibo-Kobayashi-Maskawa (CKM) matrix elements [3]. Although two experiments were carried out at FNAL and CERN to measure ε'/ε in K^0 decay in order to verify the non-zero CKM phase, no conclusive results have been obtained. New experiments are now being prepared at each of the laboratories. Further intensive studies of the standard-model CP violation are expected to be carried out at future B factories at KEK and SLAC.

However, it is difficult to understand why the CKM phase should be the only source for CP violation. In fact, the observed baryon asymmetry in the universe (BAU) is used to argue that an additional CP violation mechanism beyond the standard model is necessary. The ratio of the observed baryon number to the entropy in the universe is $n_B/s \sim (0.6-1.0) \times 10^{-10}$ [4]. It is known that only the CKM phase in the minimal standard model gives values that are too small, such as $n_B/s \sim 10^{-20}$, due to its small couplings and mixing angles [5].¹ Furthermore, recent progress concerning anomalous baryon-number nonconservation in the standard model of electroweak interactions at high temperature raises the possibility that BAU was generated at the electroweak scale (electroweak baryogenesis) [5,6], and suggests that the original scenario of GUT baryogenesis does not easily fit, since the pre-existing GUT BAU might be washed out at the electroweak scale. It seems quite likely that new

¹Shaposhnikov has however argued for some enhancements of CP violation in the minimum standard model [6].

source(s) of CP violation beyond the standard model could exist, and that electroweak baryogenesis requires new CP violation source(s) on the electroweak scale which can be accessible experimentally. This would open up exciting *experimental* possibilities and prospects to understand the CP violation necessary for BAU.

As a background-free clean search for new CP violation mechanism(s), the measurement of P_T in $K_{\mu 3}^+$ decay has two striking virtues. First, P_T in $K_{\mu 3}^+$ decay has no contributions from the CKM phase in the minimum standard model at the tree level, and higher-order contributions are extremely small ($\sim 10^{-6}$). This implies that the observation of a non-zero P_T value would be a definite signature of new physics beyond the standard model. Also, there have been general discussions [7,8] that neither an effective vector (V) nor an axial-vector (A) interaction (such as in the minimum standard model and the left-right symmetric model) introduce P_T , but that only a scalar (S) or a pseudoscalar (P) interaction gives a non-zero P_T . Therefore, P_T can be regarded as being one of the best observables to definitely examine the extended Higgs sector and the scalar leptoquark model.

Second, it is known that a fake T-odd effect could be introduced by a final-state electromagnetic interaction (FSI) besides the true T-violating interaction. In fact, the FSI effects for nuclear β decays and for P_T in $K_L^0 \rightarrow \pi^- \mu^+ \nu$ decay, for instance, are predicted to be as large as 10^{-3} [9]. However, FSI for P_T in $K_{\mu 3}^+$ decay was calculated to be negligibly small (on the order of 10^{-6}), since only one charged particle exists in the final state [10]. This allows a wider window to search for new CP violation mechanism(s).

In the following section the kinematics of $K_{\mu 3}^+$ decay and P_T are discussed. In a subsequent section, theoretical predictions of P_T in $K_{\mu 3}^+$ decay are discussed. Although no models on T violation exist, some extended models on CP violation predict P_T . In particular, the multi-Higgs-doublet model (MHDM) is discussed in some detail. The other models, such as the leptoquark model, are also briefly mentioned. In section 4, P_T in another K^+ decay, such as $K^+ \rightarrow \mu^+ \nu \gamma$

decay, is discussed. Finally, a new experiment, E246, at KEK to measure P_T in $K^+ \rightarrow \pi^0 \mu^+ \nu$ and $K^+ \rightarrow \mu^+ \nu \gamma$ decays is described in section 5.

2. Kinematics of $K_{\mu 3}$ Decay and its T-violating correlation

The matrix element of $K_{\mu 3}$ decay can be described as

$$M = \frac{G_F}{2} \sin \theta_c \left[f_+(q^2) (\tilde{p}_K + \tilde{p}_\pi)^\lambda + f_-(q^2) (\tilde{p}_K - \tilde{p}_\pi)^\lambda \right] [\bar{u}_\mu \gamma_\lambda (1 - \gamma_5) u_\nu], \quad (2)$$

where G_F is the Fermi coupling constant, and θ_c is the Cabbibo angle. $\tilde{p}_K$ and $\tilde{p}_\pi$ are the four momenta of a kaon and a pion, respectively. $f_+(q^2)$ and $f_-(q^2)$ are the form factors of the hadronic matrix elements as a function of the four-momentum transfer squared; $q^2 = (\tilde{p}_K - \tilde{p}_\pi)^2$. Using $\tilde{p}_K = \tilde{p}_\pi + \tilde{p}_\mu + \tilde{p}_\nu$, eq.(1) can be rewritten as

$$M = \frac{G_F}{2} \sin \theta_c \cdot f_+(q^2) \left[2 \tilde{p}_K^\lambda \cdot \bar{u}_\mu \gamma_\lambda (1 - \gamma_5) u_\nu + (\xi(q^2) - 1) m_\mu \bar{u}_\mu (1 - \gamma_5) u_\nu \right], \quad (3)$$

where the parameter $\xi(q^2) = f_-(q^2)/f_+(q^2)$ is defined. The first term corresponds to the vector amplitude and the second term corresponds to the scalar amplitude. The T-invariance places a constraint that the relative phases of f_+ and f_- are the same; in another word, the parameter ξ should be a real number. Conversely, a non-zero value of $\text{Im} \xi$ would signal a violation of T-invariance.

The muon-polarization vector can be decomposed into three orthogonal components: the longitudinal polarization (P_L), the normal polarization (P_N) and the transverse polarization (P_T), where P_L is the component of the muon-polarization vector along the muon momentum and P_N is the component normal to the $\tilde{p}_\mu$ in the decay plane. They were calculated based on eq.(2) as functions of the kinetic energies of μ^+ (E_μ) and π^0 (E_{π^0}) and $\xi(q^2)$ [11,12]. P_T is given by [13]

Figure 1. $P_T/\text{Im}\xi$ as functions of E_μ and E_π in $K_{\mu 3}$ decay

$$P_T \cong \text{Im}\xi \left(\frac{m_\mu}{m_K} \right) \frac{|\vec{p}_\mu|}{[E_\mu + |\vec{p}_\mu| \vec{n}_\mu \cdot \vec{n}_\nu - m_\mu^2/m_K]} \quad (4)$$

in the K^+ rest frame. It can be seen that P_T is proportional to $\text{Im}\xi$. It is noted that since P_T is proportional to the lepton mass, K_{e3} is not sensitive to $\text{Im}\xi$. The kinematic factor of $P_T/\text{Im}\xi$ in eq.(4) is plotted in Fig.1 as functions of E_μ and E_π with the $\xi(q^2)$ value in the Particle Data Group [14]. The sensitivity of P_T to $\text{Im}\xi$ becomes higher if $E_{\mu+}$ is higher, although the density (N) is lower. A figure of merit defined by $P_T/\text{Im}\xi \times \sqrt{N}$ is plotted in Fig.2. E246 will cover the kinematic region of $40 < E_{\mu+} < 110$ MeV. The average kinematic factor is obtained by integrating over the kinematics region of interest. The radiative corrections to the muon polarization was calculated and found to be small, generally being less than a few % level [15]

3. Multi Higgs Doublet Model

Naive extensions of the Higgs sector in the standard model are models having multi Higgs doublets. They automatically meet the experimental fact that $\rho \equiv m_W^2/(m_Z^2 \cos^2 \theta_W) = 1$ at a tree level [16]. Furthermore, to satisfy the

Figure 2. Figure of merit as functions of E_μ and E_π in $K_{\mu 3}$ decay

other experimental fact concerning the absence of favor-changing neutral currents (FCNC), Weinberg [17] proposed natural flavor conservation (NFC), which demands that all fermions of a given electric charge couple to only one Higgs doublet. In MHDM, it is also known that at least three Higgs doublets are needed to generate CP violation [17]. In the following, a three Higgs doublet model (3HDM) with NFC is considered [18].

The three Higgs doublets are given by

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \phi_i^0 \end{pmatrix} \quad (i = 1, 2, 3), \quad (5)$$

$$\langle \phi_i^0 \rangle = v_i e^{i\theta_i}, \quad \text{and} \quad (6)$$

$$(v_1^2 + v_2^2 + v_3^2) = (2\sqrt{2}G_F)^{-1}, \quad (7)$$

where v_i are the vacuum expectation values (V.E.V.). Φ_1 , Φ_2 , and Φ_3 can couple to right-handed down-type quarks (D_R), up-type quarks (U_R) and charged leptons (E_R), respectively. There are 6 charged and 6 neutral scalar fields, corresponding to the 12 degrees of freedom. After spontaneous symmetry breaking, two charged scalars and one neutral scalar are absorbed into the $W^\pm$ and the Z , and four charged ($H_1^\pm$ and $H_2^\pm$) and five neutral physical Higgs particles remain. The physical particles in the mass eigen-

state comprise a mixture of six original scalar fields.

In the original Weinberg's model of spontaneous CP violation, it arises solely due to the complex vacuum expectation values (V.E.V.) of the Higgs fields, and the CKM phase is forced to vanish [17]. This model might have difficulties with the experimental constraints, as is shown later. Instead, we are considering another mechanism in which the Yukawa couplings have explicit complex phases together with the non-vanishing CKM phase. In this model, there are three potential sources of CP violation: one is the complex CKM matrix elements; the second is the complex charged-Higgs mixing matrix elements; and the third is the complex neutral Higgs mixing matrix elements. Among them, the first and second are relevant to K -decay physics. The charged Higgs mixing matrix is given by

$$\begin{pmatrix} \phi_1^+/v_1 \\ \phi_2^+/v_2 \\ \phi_3^+/v_3 \end{pmatrix} = \begin{pmatrix} 1 & \alpha_1 & \alpha_2 \\ 1 & -\beta_1 & -\beta_2 \\ 1 & \gamma_1 & \gamma_2 \end{pmatrix} \begin{pmatrix} G^+ \\ H_1^+ \\ H_2^+ \end{pmatrix}, \quad (8)$$

where α_i , β_i and γ_i ($i = 1, 2$) are the mixing matrix elements. Then, the Lagrangian of the charged-Higgs Yukawa interaction is given by

$$L = (2\sqrt{2}G_F)^{\frac{1}{2}} \sum_{i=1}^2 [\alpha_i U_L K M_D D_R + \beta_i U_R M_U K D_L + \gamma_i M_E E_R] H_i^+, \quad (9)$$

where K is the CKM matrix and M_j ($j = U, D, E$) are the quark mass matrix elements. CP violation in this charged-Higgs sector results from the imaginary part of the off-diagonal Higgs mixing matrix elements. Thereby, CP violation appears in such combinations as $\text{Im}(\alpha_i \beta_i^*)$, $\text{Im}(\beta_i \gamma_i^*)$ or $\text{Im}(\gamma_i \alpha_i^*)$. They can be considered to be a measure of the magnitude of CP violation. They have the following relations:

$$\frac{\text{Im}(\alpha_2 \beta_2^*)}{\text{Im}(\alpha_1 \beta_1^*)} = \frac{\text{Im}(\beta_2 \gamma_2^*)}{\text{Im}(\beta_1 \gamma_1^*)} = \frac{\text{Im}(\gamma_2 \alpha_2^*)}{\text{Im}(\gamma_1 \alpha_1^*)} = -1 \quad (10)$$

and

$$\frac{\text{Im}(\alpha_1 \beta_1^*)}{v_3^2} = \frac{\text{Im}(\beta_1 \gamma_1^*)}{v_1^2} = -\frac{\text{Im}(\gamma_1 \alpha_1^*)}{v_2^2}. \quad (11)$$

Although there has been no estimation of the magnitudes of the three V.E.V.'s, some possible patterns have been discussed [19]. One scenario is that the three V.E.V.'s are roughly comparable in magnitude, namely

$$v_1 \sim v_2 \sim v_3. \quad (12)$$

Since the physical particle masses are expressed by the product of the V.E.V. and its relevant Yukawa coupling constant, in this scenario different magnitudes of the Yukawa couplings should generate the observed mass hierarchies between down- and up-type quarks and leptons.

The second scenario [20] is that the V.E.V.s would be attributed to the mass hierarchies, rather than the Yukawa couplings. Namely, the magnitudes of the V.E.V.s are proportional to the particle masses which they couple. Namely,

$$v_1 : v_2 : v_3 \sim m_b : m_t : m_\tau, \quad (13)$$

It gives $v_1, v_3 \ll v_2$. As shown in later, T or CP violation in semileptonic K decays in 3HDM is expected to be enhanced in the second scenario, since the Yukawa coupling to leptons is very large, as shown by eq.(11).

In the following, the experimental constraints on 3HDM are surveyed. For simplicity, it is assumed that the masses of two charged-Higgs particles are not degenerate. The lightest Higgs particle is called H_1^+ ; the other is H_2^+ . Namely, $m_{H_1^+} \ll m_{H_2^+}$.

3.1. Constraints due to the neutron electric dipole moment

A non-vanishing value for the neutron electric dipole moment (d_n) violates T invariance and, thus, CP invariance. In 3HDM, it could have several contributions [21]. Among them are those due to a charged-Higgs exchange, a neutral-Higgs exchange and the Weinberg's three-gluonic operators. For simplicity, d_n due to only a charged-Higgs exchange is considered here. In the non-relativistic approximation d_n can be simply expressed in terms of the electric dipole moments of down (d_d) and up quarks (d_u) by

$$d_n = \frac{4}{3}d_d - \frac{1}{3}d_u \sim \frac{4}{3}d_d. \quad (14)$$

In the above, $d_d \gg d_u$ is used. At the one-loop level of a charged-Higgs exchange contribution, d_d is given by [22]

$$d_d = \frac{\sqrt{2}G_F}{(12\pi^2)} m_d \text{Im}(\alpha_1 \beta_1^*) \sum_i^{u,c,t} K_{id}^2 I(x_i), \quad (15)$$

where K_{ij} are the CKM matrix elements. $I(x_i)$ is a function of $x_i \equiv (m_i/m_{H_1^+})^2$, where m_i is a (current) mass of charge 2/3 quarks ($i = u, c, t$). Among them, the charm quark contribution is the largest [18].

The present experimental upper bound of the 95% confidence level (C.L.) is [23]

$$d_n < 1.2 \times 10^{-25} e \cdot \text{cm}. \quad (16)$$

From eq.(15), the upper limits of

$$\text{Im}(\alpha_1 \beta_1^*) < 12 \quad \text{for} \quad m_{H_1^+} = \frac{1}{2} m_Z \quad (17)$$

and

$$\text{Im}(\alpha_1 \beta_1^*) < 64 \quad \text{for} \quad m_{H_1^+} = 2m_Z \quad (18)$$

are obtained [13].

3.2. Constraints from ε in $K^0 \rightarrow 2\pi$ decay

In the original Weinberg's 3HDM with spontaneous CP violation [17], it was assumed that all of the CKM matrix elements are real and that no CKM phase exists. In this model, to reproduce ε in $K^0 \rightarrow 2\pi$ decay ($|\varepsilon| = 2.26 \times 10^{-3}$), it was shown by Cheng [24] that

$$\frac{\text{Im}(\alpha_1 \beta_1^*)}{m_H^2} \left[\ln \frac{M_H^2}{m_c^2} - \frac{3}{2} \right] = \frac{(0.024 - 0.027)}{\text{GeV}^2} \quad (19)$$

should be satisfied. It gives $\text{Im}(\alpha_1 \beta_1^*) = 9.2$ for $m_{H_1^+} = \frac{1}{2} m_Z$ and $\text{Im}(\alpha_1 \beta_1^*) = 96.2$ for $m_{H_1^+} = 2m_Z$. These values are slightly large and might conflict with the other experimental constraints.

However, it seems more natural and reasonable to have complex CKM matrix elements, as discussed before. In this model, it can be assumed that ε is dominated by the (short-distance) contribution from the non-zero CKM phase. In this case, no strong constraints to $\text{Im}(\alpha_1 \beta_1^*)$ can be applied from ε and ε'/ε in $K^0 \rightarrow 2\pi$ decay.

3.3. Constraints from B decay

Since the Yukawa coupling of a charged Higgs particle is proportional to the mass of a right-handed quark, useful constraints can be obtained from B -meson decay, even in CP-conserving processes [25]. One of these decays is inclusive $b \rightarrow s\gamma$ decay. The latest experimental upper limit on $b \rightarrow s\gamma$ decay reported by CLEO [26] is

$$B(b \rightarrow s\gamma) < 5.4 \times 10^{-4} \quad (20)$$

at the 90% C.L. On the other hand, the standard model prediction is about $(2.5 - 4) \times 10^{-4}$. This stringent upper limit reduces the window for new physics. Grossman and Nir calculated the upper bounds on $\text{Im}(\alpha_1 \beta_1^*)$ as a function of $m_{H_1^+}$ for different top-quark masses [27]. In the case of $m_t = 140 \text{ GeV}/c^2$, it gives

$$\text{Im}(\alpha_1 \beta_1^*) < 2 \quad \text{for} \quad m_{H_1^+} = \frac{1}{2} m_Z \quad (21)$$

and

$$\text{Im}(\alpha_1 \beta_1^*) < 4 \quad \text{for} \quad m_{H_1^+} = 2m_Z. \quad (22)$$

It is noted that although in the two Higgs-doublet model (2HDM) the upper limit of $b \rightarrow s\gamma$ simply gives a lower bound on m_{H^+} , $m_{H^+} = \frac{1}{2} m_Z$ is still allowed in 3HDM.

The other decay mode which can place constraints is an inclusive semileptonic B decay with τ in the final state, $b \rightarrow X \tau \nu_\tau$. The branching ratio for $b \rightarrow X \tau \nu_\tau$ has been measured by the ALEPH collaboration [28], which is

$$B(b \rightarrow X \tau \nu_\tau) = (4.08 \pm 0.76 \pm 0.62) \times 10^{-2}. \quad (23)$$

The standard-model prediction is $(2.30 \pm 0.25) \times 10^{-2}$. The difference in the branching ratios places a limit on the possible charged Higgs contribution in 3HDM, which constrains $\text{Im}(\gamma_1 \alpha_1^*)$. Grossman [29] calculated its upper bound as

$$\text{Im}(\gamma_1 \alpha_1^*) < 0.23 \times m_{H_1}^2 \quad (\text{GeV}^{-2}) \quad (24)$$

for $m_{H_1} < 370 \text{ GeV}/c^2$. This bound is obtained when the real part of the charged-Higgs contribution destructively interferes with the W -diagram contribution and the imaginary part (which is

proportional to $\text{Im}(\gamma_1 \alpha_1^*)$) becomes dominant in the decay width. However, from this decay, unless the real part is determined elsewhere, the constraint on $\text{Im}(\gamma_1 \alpha_1^*)$ cannot be significantly improved once the branching ratio reaches the standard-model value.

3.4. Constraints from P_T in $K_{\mu 3}$ decay

P_T arises from interference between the W^+ -exchange and charged Higgs exchange diagrams, as shown in Fig.3. The former contributes mostly to f_+ and the latter only to f_- . As can be seen in eq.(4), P_T is proportional to $\text{Im}\xi$ with an additional kinematic factor. $\text{Im}\xi$ in $K_{\mu 3}^+$ decay is calculated in 3HDM and is given by

$$\text{Im}\xi = \text{Im}(\gamma_1 \alpha_1^*) \cdot \left(\frac{m_K}{m_{H_1^+}} \right)^2 \quad (25)$$

$$= -\text{Im}(\alpha_1 \beta_1^*) \cdot \left(\frac{v_2}{v_3} \right)^2 \cdot \left(\frac{m_K}{m_{H_1^+}} \right)^2. \quad (26)$$

In eq.(25), since $K_{\mu 3}^+$ decay is a semi-leptonic decay, it involves the mixing parameter of γ_1 as in $b \rightarrow X \tau \nu_\tau$ decay. In eq.(26), $\text{Im}(\gamma_1 \alpha_1^*)$ is translated into $\text{Im}(\alpha_1 \beta_1^*)$ by using eq.(11). It introduces an additional factor of $(v_2/v_3)^2$ which has no experimentally-available constraints. It could be as large as about $90^2 \sim (m_t/m_\tau)^2$ if the second scenario of V.E.V.s discussed above is correct. In this case, a large enhancement of P_T can be expected.

The present experimental upper limit on P_T in $K_{\mu 3}^+$ decay is, in the K^+ rest frame,

$$P_T = (-3.1 \pm 5.3) \times 10^{-3}, \quad (27)$$

which was obtained from a previous experiment at Brookhaven National Laboratory (BNL) about ten years ago [30]. After the kinematics factor is corrected, $\text{Im}\xi$ can be obtained. The Particle Data Group [14] quoted

$$\text{Im}\xi = -0.017 \pm 0.025. \quad (28)$$

From this, a 90% confidence-level limit of $|\text{Im}\xi| < 0.058$ can be obtained.² It yields

²Since the P_T measurements in $K_{\mu 3}^0$ decay might have FSI

Figure 3. Diagrams contributing to $K_{\mu 3}^+$ decay. (a) is a W exchange and (b) is a charged-Higgs exchange.

$$\text{Im}(\gamma_1 \alpha_1^*) < 0.24 \times m_{H_1^+}^2 \quad (\text{GeV}^{-2}), \quad (29)$$

which should be compared with eq.(24). This polarization data in $K_{\mu 3}^+$ decay taken ten years ago gives an almost comparable limit to the recent data of $B(b \rightarrow X \tau \nu_\tau)$ from ALEPH in eq.(24) in spite of the larger Yukawa coupling constant in B decay. It is a consequence that the polarization measurement is *more sensitive* to the charged-Higgs contribution than to a branching-ratio measurement.³

3.5. Summary of Constraints in 3HDM

To summarize the experimental constraints on the CP-violating parameters in 3HDM, Figs.4 and 5 show constraint plots of $\text{Im}(\alpha_1 \beta_1^*)$ versus (v_2/v_3) for the case $m_{H_1^+} = \frac{1}{2}m_Z$ and for $m_{H_1^+} = 2m_Z$, respectively. As can be seen, $\text{Im}\xi$ obtained from P_T in $K_{\mu 3}^+$ decay and a measurement of $B(b \rightarrow X \tau \nu_\tau)$ place the most stringent limit on $\text{Im}(\alpha_1 \beta_1^*)$ for a large value of (v_2/v_3) .

As shown later, the new experiment E246 at KEK-PS is aiming at a sensitivity to $\text{Im}\xi$ down to the order of 10^{-3} . The regions which would be covered by E246 are shown in Figs.4 and 5 as dot lines. The more general constraints including

effects, only the $K_{\mu 3}^+$ data is used here instead of using the combined result.

³A similar argument that the polarization asymmetry is enhanced over rates in *top* decays for 3HDM was discussed in reference [31].

Figure 4. Constraints on $\text{Im}(\alpha_1\beta_1^*)$ vs. (v_2/v_3) for $m_{H_1^+} = \frac{1}{2}m_Z$. (a) constraint from the neutron electric dipole moment; (b) from $b \rightarrow s\gamma$; (c) from P_T in $K_{\mu 3}$ decay; and (d) from $b \rightarrow X\tau\nu$ decay. A shaded area is excluded. A dot line shows a sensitivity aimed at in E246

Figure 5. Constraints on $\text{Im}(\alpha_1\beta_1^*)$ vs. (v_2/v_3) for $m_{H_1^+} = 2m_Z$. (a) constraint from the neutron electric dipole moment; (b) from $b \rightarrow s\gamma$; (c) from P_T in $K_{\mu 3}$ decay; and (d) from $b \rightarrow X\tau\nu$ decay. A shaded area is excluded. A dot line shows a sensitivity aimed at in E246

CP-conserving decays in 3HDM can be found in reference [29].

3.6. Other Theoretical Models

Bélanger and Geng [13] considered leptoquark models that give contributions to P_T in $K_{\mu 3}^+$ decay with the assumption of a non-vanishing CKM phase. It would appear through scalar leptoquark exchanges at the tree level. Among the four scalar leptoquark models that they considered, two of them could lead to a large P_T ; however there are basically no direct experimental constraints on these models, except for the polarization measurement itself.

Christova and Fabbrichesi [32] calculated the contribution from the minimal supersymmetric model to P_T in $K_{\mu 3}^+$ decay. They considered the gluino penguin diagram and found that the effect is on the order of 10^{-6} , which is too small for the current experiment to observe.

Geng [38] considered the contribution of a possible tensor interaction to P_T in $K_{\mu 3}^+$ decay [38]. The effect could be large and the measurement of P_T would give strong constraints on the tensor interaction.

4. P_T in $K^+ \rightarrow \mu^+\nu\gamma$ Decay

The transverse muon polarization (P_T) in a radiative K^+ decay, $K^+ \rightarrow \mu^+\nu\gamma$, is another T-violating triple correlation, where the decay plane is determined by the muon and photon momentum vectors. A long time ago, it was discussed in terms of old motivations, such as a search for T- (or C-) violation in the electromagnetic interaction occurring in the structure-decay (SD) contribution [33–35]. Recently, Marciano [36] argued that the charged-Higgs exchange diagrams with an inner-Bremsstrahlung photon interfere with the SD diagrams, yielding a non-zero phase with respect to the normal interference term with W^+ exchange. It introduces P_T , whose magnitude is almost comparable to that in $K_{\mu 3}^+$ decay. Some calculations based on 3HDM are being undertaken [37] and the sensitivity of $P_T/\text{Im}\xi$ for $K^+ \rightarrow \mu^+\nu\gamma$ decay is shown in Fig.6. In addition, Geng [38] calculated the contribution of a tensor interaction to P_T in $K^+ \rightarrow \mu^+\nu\gamma$ decay,

similarly to $K_{\mu 3}^+$ decay. He found that it could be at most 10^{-2} . In general, this decay has a hadronic axial-vector current as well as a vector current, in contrast to $K_{\mu 3}^+$ decay which has only a vector current. Therefore, this decay could have potentially more sources of T (or new CP) violation.

On the other hand, FSI was estimated by Geng [38], who found that it could be as large as 10^{-3} . It is, however, argued that since FSI can be calculated reliably, it could be used as a useful calibration source of the apparatus, even if no true T-violation effect can be found down to the level of FSI.

No experimental limit on P_T in $K^+ \rightarrow \mu^+ \nu \gamma$ decay exists so far. E246 will attempt to measure P_T in this decay.

Figure 6. $P_T / \text{Im}\xi$ as functions of E_{μ^+} and E_γ in $K^+ \rightarrow \mu^+ \nu \gamma$ decay

5. KEK E246 Experiment

The new E246 experiment [39], which is aimed at a search for P_T with higher sensitivity, is being prepared at the KEK 12-GeV proton synchrotron (KEK-PS). In E246, K^+ -decays at rest will be employed in contrast to the previous experiments

which used in-flight K^+ decays. The adaption of K^+ decays at rest would provide several advantages over in-flight experiments. First, an apparatus can detect and reconstruct π^0 s (in $K_{\mu 3}^+$ decay) moving in any direction with high and uniform efficiency. This allows us to compare two groups of $K_{\mu 3}^+$ events with the π^0 s going forward and backward along the detector axis to reduce any systematic errors (as described later). Second, since the apparatus can be more compact, it is easier to achieve a reliable relative-alignment of each of the sub-detector systems, which is necessary to eliminate any systematic errors. Third, an isotropic decay from K^+ decays at rest is free from any influence from the beam history in the transporting system. Fourth, a muon polarimeter to measure the μ^+ polarization can be located far off from the beam, so that the background from a beam can be avoided.

5.1. E246 detector

Schematic side and end views of the E246 detector being constructed are shown in Fig. 7.

Incident K^+ s (of about 650 MeV/c) from the K5 beam channel at the KEK-PS are slowed down in the degrader, and are stopped in a target located at the center of the detector. The K^+ stopping target consists of an array of about 300 plastic-scintillating fibers with a square cross section. The fibers are arranged so as to be parallel to the beam direction. This provides a precise determination of the K^+ -decay vertex positions and tracking of muons from $K_{\mu 3}^+$ decay inside the target.

After exiting the target, the muons enter a spectrometer using the superconducting toroidal magnet, where their momenta are analyzed. The magnet, which can produce a magnetic field of up to 1.85 T, has 12 identical magnet-gaps with accurate 30° rotational symmetry, and covers about 12% of a 4π solid angle. It has been installed at the K5 beam channel at the KEK-PS and is already operating. In E246, a magnetic field of about 1 T will be used. To track muons from K^+ decay, four sets of chambers have been instrumented. Three of them are a multiwire proportional chamber with a bi-dimensional cathode-strip readout, one of which is placed at the en-

Figure 7. Schematic side and end views of the E246 detector

trance and the other two at the exit of each of the 12 magnet gaps. The fourth one is a cylindrical drift chamber surrounding the target, which has four-layers of anodes and two cathode planes with helical strips. The expected momentum resolution is about 0.5% in σ .

The π^0 s in $K^+_{\mu 3}$ decay are detected by a highly-segmented photon detector by measuring photons in $\pi^0 \rightarrow \gamma\gamma$ decay. The photon detector comprises 768 of thallium-doped CsI crystals with a silicon PIN photodiode readout. They form a tower structure in which each crystal points to the K^+ stopping target. Each crystal module covers 7.5 degrees in both the polar and azimuthal directions. The photon detector has a large geometrical solid angle of about 75 % of 4π , covering other than beam holes for K^+ s coming in and 12 holes for μ^+ s going out into the magnetic spectrometer. A prototype test has shown that an energy resolution of 2 – 3% can be achieved. A photon directional resolution of about 3 degrees and a re-

constructed π^0 mass resolution of 5 MeV/ c^2 are expected based on Monte Carlo calculations.

The μ^+ s exiting the spectrometer are stopped in a muon polarimeter installed at the exit of each magnet gap. It comprises of a muon stopper and counters surrounding it. In front of the muon stopper, a muon degrader made of copper will be placed to decelerate the muons. The muon stopper will be made of either aluminum or graphite, which are known to be able to completely preserve the muon polarization. The counters are used to detect e^+ s in $\mu^+ \rightarrow e^+ \nu \bar{\nu}$ decay ($\tau_\mu = 2.2 \mu\text{sec}$). The muon polarization is measured by detecting the asymmetric angular distribution in e^+ s, which are emitted preferentially along the μ^+ spin direction. As mentioned later, E246 will accept $K_{\mu 3}$ events in which P_T is azimuthally directed. This implies that the direction of P_T is parallel to a fringing magnetic field of the toroidal magnet. This magnetic field will hold P_T against any disturbances (such as a stray field) which

would otherwise depolarize P_T . In addition, since the in-plane muon polarization (P_L and P_N) is to be precessed around a magnetic field, after time-integration of the e^+ counts, an effective asymmetry from the inplane polarization could be reduced. This would eliminate any potential spurious asymmetry due to inplane polarization. This configuration used in E246 is also in remarkable contrast to the previous experiments, in which a magnetic field was applied perpendicular to P_T and P_N and the both polarization components were rotated.

5.2. P_T measurement in the E246 detector

In E246, the $K_{\mu 3}^+$ events which have π^0 moving along the detector axis, either forward or backward from the target, will be accepted as “good events”. For those events, the decay plane can be set radial, including the detector axis, and P_T is directed azimuthally in a *screw-sense* around the detector axis, as shown in Fig.8. P_T would be manifest as a difference in the e^+ counts of the counters located at the clockwise (*cw*) and counter-clockwise (*ccw*) sides (from the muon stopper where the μ^+ is stopped). By summing the *cw*- and *ccw*- counts of all the 12 magnet gaps, P_T is given by

$$\frac{\sum_{i=1}^{12} N_i(cw)}{\sum_{i=1}^{12} N_i(ccw)} \cong 1 \pm 2AP_T, \quad (30)$$

where $N_i(cw)$ and $N_i(ccw)$ are the total number of e^+ counts at the *cw*- and *ccw*- side counters from the muon stopper in the i th magnet gap, respectively. A is the effective analyzing power of the polarization measurement, which could be dependent on the solid angle of the counters, the e^+ energy threshold, etc. P_T is obtained based on a deviation of eq.(30) from unity.⁴

To measure the polarization to high precision, some careful considerations have to be made in the detector design so as to avoid any potential sources of spurious asymmetries. E246 has adopted the following two guiding principle: (a)

⁴The other way to deduce P_T is to take the following ratio of $\sqrt[12]{\prod_i N_i(cw)/N_i(ccw)} = 1 \pm 2AP_T$. This has an advantage to cancel possible difference of the counter efficiencies out since they appear both in the numerators and denominators

a (12-fold) toroidal symmetry (achieved by the toroidal spectrometer) and (b) use of kaon decays at rest.

The toroidal symmetry will cancel any fake asymmetries arising from, for instance, a K^+ beam shift or unequal e^+ counter efficiencies, and so on. First, the K^+ -beam shift from the target center would introduce an asymmetric distribution of muons stopped in the muon stoppers, producing spurious asymmetries in each magnet gap. It, however, has an opposite sign at different hemispheres separated by a line along the beam-shifting direction. It thus does not generate a screw-sense asymmetry and is cancelled by combining all of the 12 toroidal-magnet gaps. Second, suppose one of the e^+ counters obtains a poor detection efficiency, another fake asymmetry could be introduced. However, since the same e^+ counter is used to detect the *cw*-side e^+ detection in one magnet-gap, as well as the *ccw*-side e^+ detection in the neighboring magnet-gap, the fake asymmetries thus introduced would have opposite signs in these two magnet gaps, and no screw-sense asymmetry would be generated. Again, after combining all of the sectors, this fake asymmetry would be cancelled.

The use of $K_{\mu 3}^+$ decay at rest allows one to detect π^0 s moving forward and backward along the beam line with high and uniform efficiency, as described before. It can be seen in Fig.8 that the sign of P_T for the $K_{\mu 3}^+$ events with forward-going π^0 is opposite to that with the backward-going π^0 . The $\pm$ signs in eq.(30) correspond to either of those. The comparison between these two groups of events will remarkably reduce spurious asymmetries, since their signs could be the same. Combining them, a double ratio can be formed as

$$\frac{[\sum_{i=1}^{12} N_i(cw)/\sum_{i=1}^{12} N_i(ccw)]_{fwd}}{[\sum_{i=1}^{12} N_i(cw)/\sum_{i=1}^{12} N_i(ccw)]_{bwd}} \cong 1 + 4AP_T. \quad (31)$$

By taking such a double ratio, we can obtain an enhancement factor of four in the asymmetry measurement.

In addition, by using the $K_{\mu 3}^+$ events with π^0 moving transverse to the detector axis, we will be able to examine the zero-asymmetry level and

Figure 8. Direction of P_T in a schematic end view of the detector with the 12 sectors. (a) is for $K_{\mu 3}$ events with forward-going π^0 s and (b) is for those with backward-going π^0 s.

to further reduce any spurious asymmetries. For those events, the decay plane is set transverse to the detector axis and the in-plane μ^+ polarization can be measured. Since the amount of inplane polarization of the cw and ccw directions are in equal, a null asymmetry should be detected. This fact could be used to monitor and correct for any systematics at the same time as taking data for a long-run period.

6. Sensitivity to P_T in $K^+ \rightarrow \pi^0 \mu^+ \nu$ Decay

To reduce the background from other major decay modes, the $K_{\mu 3}^+$ events whose μ^+ momentum is above 100 MeV/c and below the $K^+ \rightarrow \pi^+ \pi^0$ ($K_{\pi 2}$) peak (of 205 MeV/c) will be taken. It covers about 65% of the total $K_{\mu 3}^+$ spectrum. One of the major background events in this kinematic region comes from in-flight π^+ decays in $K_{\pi 2}$ decay. It can be discriminated by cuts on the angle between μ^+ and π^0 and on the total π^0 energy. It should be noted that most of the background events never introduce spurious asymmetry, but just dilute the true asymmetry.

Using the estimated μ^+ acceptance of 5% at the spectrometer and the reconstructed π^0 acceptance of 20% together with the detection efficiency of $\mu^+ \rightarrow e^+ \nu \bar{\nu}$ decay of about 20%, the total acceptance of the $K_{\mu 3}$ events is estimated to be 2×10^{-3} . Assuming an average K^+ stopping

rate of about 100 k/sec and a 10^7 -sec running time, we might be able to obtain a total of 65 M “good” $K_{\mu 3}^+$ events.

The statistical error of P_T can be estimated by

$$\begin{aligned} \Delta P_T &= \frac{1}{4A} \\ &\times \Delta \left(\frac{[\sum_{i=1}^{12} N_i(cw) / \sum_{i=1}^{12} N_i(ccw)]_{fwd}}{[\sum_{i=1}^{12} N_i(cw) / \sum_{i=1}^{12} N_i(ccw)]_{bwd}} \right) \\ &\sim \frac{1}{A} \cdot \sqrt{\frac{1}{\langle \sum_{i=1}^{12} N_i \rangle}}, \end{aligned} \quad (32)$$

where A is the analyzing power, which is expected to be about 0.25 from Monte-Carlo calculations. Using a total of $\langle \sum_{i=1}^{12} N_i \rangle \sim 65$ M events, we estimate $\Delta P_T \sim 5 \times 10^{-4}$. Using the average value of $P_T / \text{Im}\xi \sim 0.25$, estimated from Monte-Carlo calculations, a sensitivity to $\text{Im}\xi$ of about 2×10^{-3} is expected. An estimation of the systematic errors was made by using Monte-Carlo calculations. They might be smaller than the expected statistical sensitivity.

The experimental sensitivity to P_T in $K^+ \rightarrow \mu^+ \nu \gamma$ decay in KEK-PS E246 is presently being estimated. Although its branching ratio is lower than $K_{\mu 3}^+$, it does not need a π^0 reconstruction, which introduces an additional acceptance loss in the case of $K_{\mu 3}^+$ decay. We are thus expecting the sensitivity not to be significantly worse than that of $K_{\mu 3}^+$ decay.

Since the E246 detector has a large solid-angle magnetic spectrometer with good momentum resolution, a photon detector with good energy and directional resolutions and a capability of the muon polarization measurements, it can be used to study other interesting physics. Possible shopping lists are: (1) a test of the disputable tensor interaction in $K^+ \rightarrow \mu^+ \nu \gamma$ decay [40] and in $K^+ \rightarrow \pi^0 e^+ \nu$ (K_{e3}) decay [41] by precise spectrum measurements; (2) a search for sterile (right-handed weak isosinglet) massive neutrinos in $K_{\mu 2}$ decay with μ^+ helicity tagging [42] and so on.

The first engineering run is planned to start in 1995.

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