S

UdeM-LPN-TH-79

Fermilab Library
0 1160 0013452 2

UdeM-LPN-TH-79
Jan. 1992

T VIOLATION IN $K^+ \to \pi^0\mu^+\nu$ AND $K^+ \to \pi^+\mu^+\mu^-$ DECAYS[a]

C. Q. GENG

Laboratoire de Physique Nucléaire, Université de Montréal
C.P. 6128, Succ. A, Montréal, PQ, Canada H3C 3J7

FERMILAB
JUN 3 1992

ABSTRACT

T violating muon spin involved correlations in $K^+ \to \pi^0\mu^+\nu$ and $K^+ \to \pi^+\mu^+\mu^-$ decays are discussed. The predictions on these effects in various CP violation models are presented.

One of the most intriguing and fascinating phenomena in particle physics is T-violation or CP-violation. In the framework of local quantum field theories, with Lorentz invariance and the usual spin-statistics connection, T-violation implies CP-violation (and vice versa), because of the CPT invariance of such theories. Experimentally, only CP-violation has been observed so far and this only in the neutral kaon system. But the origin of this violation remains unclear. In the standard model the phenomenon arises from a unique physical phase in the Kobayashi-Maskawa (KM) quark mixing matrix.[1] To ensure that this phase is indeed the source of CP violation or T violation, one needs to look for new decay modes, especially that outside K^0 system. It would be particularly interesting if the time reversal symmetry is directly violated in these modes, rather than inferring it as a consequence of CP violation, since outside the framework of local quantum field theories there is no reason for the two symmetries to be linked although our discussion is within the context of such theories and therefore we shall not make any distinction between the CP- and T-violation. Within kaon physics, the most promising T violating effects which would be accessible to future experiments are muon polarizations in $K^+ \to \pi^0\mu^+\nu$ and $K^+ \to \pi^+\mu^+\mu^-$. In this talk, I will present recent studies on these effects.[2-4]

We start by writing the decays as

$$K^+(p_K) \;\to\; \pi^0(p_\pi)\,\mu^+(p_\mu, s_\mu)\,\nu(p_\nu) \qquad (1)$$

and

$$K^+(p_K) \;\to\; \pi^+(p_\pi)\,\mu^+(p_\mu, s_\mu)\,\mu^-(p_{\bar\mu}, s_{\bar\mu}) \qquad (2)$$

[a]Talk presented at the *KEK workshop on rare kaon decays*, KEK, Dec. 10-11, 1991.

ROUTE TO
NAME | LOCATION

Table 1: T violating correlations in (1) $K^+ \to \pi^0\mu^+\nu$ and (2) $K^+ \to \pi^+\mu^+\mu^-$ decays.

Type	Correlations	*Symmetries violated*	Decays
a	$\vec{s}_\mu \cdot (\vec{p}_i \times \vec{p}_j)$	T	(1) and (2)
b	$\vec{p}_i \cdot (\vec{s}_\mu \times \vec{s}_{\bar\mu})$	P , T	(2)
c	$(\vec{s}_\mu \cdot \vec{p}_\mu)\vec{s}_{\bar\mu} \cdot (\vec{p}_\mu \times \vec{p}_{\bar\mu})$	P , T	(2)

where p_i ($i = K^+$, π, $\mu(\bar\mu)$, ν) and $s_{\mu(\bar\mu)}$ are the four-momentum and muon spin polarization vectors, respectively. There are three possible typies of T violating correlations in $K^+ \to \pi^0\mu^+\nu$ and $K^+ \to \pi^+\mu^+\mu^-$ decays as shown in Table 1 where the momentum and spin vectors are in the rest frame of K^+.[b] The muon polarizations in (a), so called transverse muon polarizations, involve only one muon spin while those in (b) and (c) both μ^+ and μ^- spins. To study these T violating muon polarization effects we first carry out a general analysis based on Lorentz invariance. The most general invariant amplitudes can be written as

$$\mathcal{M} = (\bar v(p_\nu),\, \bar v(p_{\bar\mu}, s_{\bar\mu}))\,[F_S + iF_P\,\gamma_5 + F_V\, p_K{}^\mu\gamma_\mu + F_A\, p_K{}^\mu\gamma_\mu\gamma_5]u(p_\mu, s_\mu) \qquad (3)$$

for (1) and (2), where F_S, F_P, F_V and F_A are scalar, pseudo-scalar, vector and axial-vector form factors, respectively. If we define P^k_{TV} ($k = a$, b and c) to be the coefficients of the T violating correlations in Table 1 in the differential decay rates, respectively, we find that

$$P^a_{TV} \;\propto\; m_K[-Im(F_S F_V^*) + Re(F_P F_A^*)], \qquad (4)$$

$$P^b_{TV} \;\propto\; [-\frac{E_{\bar\mu}}{m_\mu}(Re(F_S F_P^*) + m_K^2 Im(F_V F_A^*)) - m_K(Im(F_S F_A^*) + Re(F_P F_V^*))], \qquad (5)$$

$$P^c_{TV} \;\propto\; [-(Re(F_S F_P^*) - m_K^2 Im(F_V F_A^*)) + m_K(Im(F_S F_A^*) - Re(F_P F_V^*))]. \qquad (6)$$

We now explore P^a_{TV} in $K^+ \to \pi^0\mu^+\nu$ and P^{a-c}_{TV} in $K^+ \to \pi^+\mu^+\mu^-$ in the standard model and its various extensions.

[b]The P and T violating triple correlations $\vec{p}_i \cdot (\vec{p}_j \times \vec{p}_k)$ do not exist for 3-body decays because $\vec{p}_i + \vec{p}_j + \vec{p}_k = 0$ ($i \neq j \neq k$).

$$K^+ \to \pi^0\mu^+\nu$$

The decay has been well measured[5] with $Br(K^+ \to \pi^0\mu^+\nu)_{expt} = (3.18 \pm 0.08)\%$. The three possible tree-level contributions, through s, t and u channels, to the decay correspond to intermediate bosons of electric charges 1, $\frac{2}{3}$ and $-\frac{1}{3}$, respectively. The standard, left-right-symmetric, and horizontal-symmetry and the multi-Higgs models which can have gauge boson and scalar charged Higgs exchanges, respextively are the examples of s-channel contributions while the t, u-channel diagrams arise only in leptoquark models with intermediate leptoquark exchanges. It is easy to see that among the various models the standard contribution to the decay branching ratio dominates.

For the standard model the transverse muon polarization is expected to be zero because of the absence of the KM phase in the diagram. This can be shown in terms of Eq. (4). The $V-A$ structure of the standard model gives

$$\begin{aligned} F_S &= iF_P = \frac{1}{2}G_F sin\theta_c m_\mu\,, \\ F_V &= -F_A = G_F sin\theta_c \end{aligned} \tag{7}$$

which leads to

$$Im(F_S F_V^*) = Re(F_P F_A^*) = 0\,, \tag{8}$$

and therefore $P^a_{TV}(K^+ \to \pi^0\mu^+\nu) = 0$. It is straightforward to extended this result to arbitrary models with effective V or A interactions such as the left-right-symmetric and horizontal-symmetry models. Hence, the existence of a non-zero value of $P^a_{TV}(K^+ \to \pi^0\mu^+\nu)$ will be a definite signature of new physics beyond these models.

However, $P^a_{TV}(K^+ \to \pi^0\mu^+\nu)$ is sensitive to some multi-Higgs and leptoquark models. For the Weinberg three Higgs doublets model in which CP violation arises purely from a phase in the charged Higgs boson mixing, we find[2]

$$P^a_{TV}(K^+ \to \pi^0\mu^+\nu) \simeq \frac{|Im(\alpha_1\beta_1^*)|}{M_H^2}\frac{v_2^2}{v_3^2}m_\mu m_K \frac{|\vec{p}_\mu|}{[E_\mu + |\vec{p}_\mu|\vec{n}_\mu\cdot\vec{n}_\nu - \frac{m_\mu^2}{m_K}]} \tag{9}$$

estimated to be

$$P^a_{TV}(K^+ \to \pi^0\mu^+\nu) \sim 2.6\times 10^{-4}\,\frac{v_2^2}{v_3^2} \tag{10}$$

which yields an upper bound around 8.4×10^{-3}. For the multi-Higgs models in which the KM matrix has a non-zero phase we find that it can easily reach a level of 10^{-3} without conflicting with experimental constraints. In some classes of leptoquark models a large $P^a_{TV}(K^+ \to \pi^0\mu^+\nu)$ would also be achieved.

The muon polarization effects predicted from these models are accessible to the recently approved experiment: E246 at KEK[6] in which a sensitivity of 0.09% in $P^a_{TV}(K^+ \to \pi^0\mu^+\nu)$ will be obtained[c] and future experiments in a kaon factory.[7]

Finally we remark that the theoretical backgrouds, i.e., *Final-state-interaction* (FSI), to the polarization effect, can be ignored since they are expected to be $O(10^{-6})$ arising from two-loop diagrams.[8]

$$K^+ \to \pi^+\mu^+\mu^-$$

This decay has not been observed yet and the current experimental limit[5] is $Br(K^+ \to \pi^+\mu^+\mu^-) < 2.3\times 10^{-7}$. In the standard model it occurs at the one-loop level via the electroweak penguin and box diagrams. As is well known, the decay is dominated by the one-photon piece, which has large albeit uncertain long-distance corrections. The decay branching ratio is around 5×10^{-8} determined by the measurement of $K^+ \to \pi^+e^+e^-$ mode. The form factors in Eq. (3) are found to be

$$\begin{aligned} F_S &\sim 0\,, \\ F_V &\sim F_V^{expt} = (9\pm 1)\times 10^{-15}\ MeV^{-2}\,, \\ iF_P = m_\mu F_A &\sim m_\mu V_{ts}V_{td}^*\frac{G_F}{\sqrt{2}}\alpha L^{Z+B}(m_t^2/M_W^2)\,. \end{aligned} \tag{11}$$

Here the contribution to F_S from two photon intermediate states has been neglected and those to F_V and F_A (F_P) are dominated by the one photon exchange diagram which is fixed by the measurement of $K^+ \to \pi^+e\bar{e}$ and by the Z-penguin and W-box diagrams involving t-quark, respectively. From Eqs. (4)-(6) and (11) we find that $P^a_{TV}(K^+ \to \pi^+\mu^+\mu^-)$ is vanishingly small whereas $P^{b,c}_{TV}$ could be large depending on the parameters m_t and η. For example, we get[4]

$$\begin{aligned} P^c_{TV}(K^+ \to \pi^+\mu^+\mu^-) &= (4.1\pm 0.3)\times 10^{-3}A^2\eta L^{Z+B}(m_t^2/M_W^2) \\ &\quad\cdot\left(\frac{2|\vec{p}_{\bar{\mu}}||\vec{p}_\mu|\sin\theta_{\mu\bar{\mu}}}{(E_{\bar{\mu}}+m_\mu)(E_\mu E_{\bar{\mu}} + \vec{p}_\mu\cdot\vec{p}_{\bar{\mu}} - m_\mu^2)}\right) \end{aligned} \tag{12}$$

reaching a maximum value 7.5×10^{-2} for $m_t = 200\ GeV$ and some particular area of phase space as shown in Ref. 4.

The contributions to $P^{a-c}_{TV}(K^+ \to \pi^+\mu^+\mu^-)$ from the final state electromagnetic interactions between the pion and the muons at one loop level have been examined. We find that the one-spin correlations in (a) receive significant contribution from FSI and we estimated $P^a_{TV}(K^+ \to \pi^+\mu^+\mu^-)|_{FSI} \simeq O(10^{-3})$. However, the contributions to the two-spin correlations in (b) and (c) are much smaller than that in the standard model.

[c] The current upper limit is about 10^{-2} from BNL experiments.[5]

The muon polarization effects have been also studied in various CP violation theories beyond the standard model. We find that in the extensions of the Standard Model, $P^a_{TV}(K^+ \to \pi^+\mu^+\mu^-)$ is not enhanced significantly. However, the polarizations involving two-spin could reach a value of $O(1)$ in the leptoquark models with the present constraints on the parameters. They are also enhanced by the charged Higgs effect. Other CP violation models such as the multi-Higgs doublet, supersymmetry, and left-right symmetric models predict unmeasurably small values for $P^{b,c}_{TV}(K^+ \to \pi^+\mu^+\mu^-)$.

Clearly, to test the KM mechanism in the standard and charged Higgs models and/or leptoquark, the measurement of the polarizations of both μ^+ and μ^- in $K^+ \to \pi^+\mu^+\mu^-$ is required. These effects could be measured in a kaon factory experiment.[9]

We conclude the talk as follows:

♠ The muon polarizations can directly test T violation.

♣ The processes are outside the neutral K-system.

◇ Measuring the transverse muon polarization in $K^+ \to \pi^0\mu^+\nu$ will be a clear indication of CP violation beyond the standard model and test CP violation in the multi-Higgs and leptoquark models.

♡ Measuring the muon polarizations involving two-spin in $K^+ \to \pi^+\mu^+\mu^-$ will test the KM phase in the standard and charged Higgs models and CP violating leptoquark models.

Acknowledgements

The author would like to thank the organizers of the workshop for their invitation and hospitality. The author would also like to thank G. Bélanger, P. Agrawal, and J. Ng for collaborations and J. Imazato, T. Inagaki, Y. Kuno, T. Shinkawa and S. Sugimoto for discussions.

References

1. M. Kobayashi and T. Maskawa, *Prog. Theor. Phys.* 19 (1973) 652.
2. G. Bélanger and C. Q. Geng, *Phys. Rev.* **D44** 2789 (1991).
3. P. Agrawal, J. N. Ng, G. Bélanger and C. Q. Geng, *Phys. Rev. Lett.* **67** (1991) 537.
4. P. Agrawal, J. N. Ng, G. Bélanger and C. Q. Geng, *TRI-PP-91-76* and *UdeM-LPN-TH-65*, *Phys. Rev.* **D45** (1992), (in press).
5. Particle Data Group, *Phys. Lett.* **B239** (1990) 1.
6. KEK E246 Collaboration, J. Imazato *et al.*, *KEK-PS Research Proposal.*
7. Y. Kuno, Talk presented at the Workshop on Science at the Kaon Factory, Vancouver, 1990.
8. A. R. Zhitnitskii, *Sov. J. Nucl. Phys.* **31** (1980) 529.
9. Y. Kuno, these proceedings.