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MUON POLARIZATION IN KAON DECAYS

G. BÉLANGER and C. Q. GENG
Laboratoire de Physique Nucléaire, Université de Montréal,
C.P. 6128, Succ. A, Montréal, Québec, Canada H3C 3J7

ABSTRACT

Thr muon polarization in Kaon decays could give indirect information on the CKM matrix as well as new signals of direct CP violation. The standard model prediction for polarization measurements and the effects of new physics are presented.

1. Introduction

There has been strong interests in both theoretical and experimental studies of rare Kaon decays. Improvements of present experiments are under way and proposals for even more precise ones are made. These are pursued with the goal of elucidating the mystery of CP violation and of checking the consistency of the standard model description of both CP violation and the closely related phenomenon of quark mixing. After all, the only signal of CP violation has been observed in Kaons and rare Kaon decays will eventually become precise enough to determine indirectly the last unknown in the CKM quark mixing matrix, the element V_{td}. What is less well known is that there are many more possibilities of measurements with Kaons than just decay rates. Valuable information on CP violation, the CKM matrix or new physics can be gathered by measuring various polarizations in K decays. These can either be CP conserving, e.g $P_L(K^+ \to \pi^+\mu^+\mu^-)$[1]or CP violating such as the two-spin correlation $P_2(K^+ \to \pi^+\mu^+\mu^-)$,[2] the transverse polarization $P_T(K^+ \to \pi^0\mu^+\nu)$[3]and the longitudinal polarization $P_L(K_L \to \mu\bar{\mu})$.[4] We will describe here all but the last process and show that such measurements could in the first case give indirect information on the CKM matrix or in the second case give a new signal of direct CP violation. In all cases hints of what lies beyond the standard model could be found.

2. CP conserving process

The $K^+ \to \pi^+\mu^+\mu^-$ decay offer many interesting possibilities. It is best analysed when working with the general amplitude

$$\mathcal{M} = \bar{u}[F_S + iF_P\gamma_5 + F_V p_K^\mu \gamma_\mu + F_A p_K^\mu \gamma_\mu \gamma_5]v \tag{1}$$

The rate for this decay is dominated by the one photon exchange diagram with charm quark which contribute to F_V. In order to avoid ambiguities from the long-distance effects, it is preferable to simply use the experimental value to evaluate the vector form factor. Since the rate for this decay has not been measured yet (the present limit is

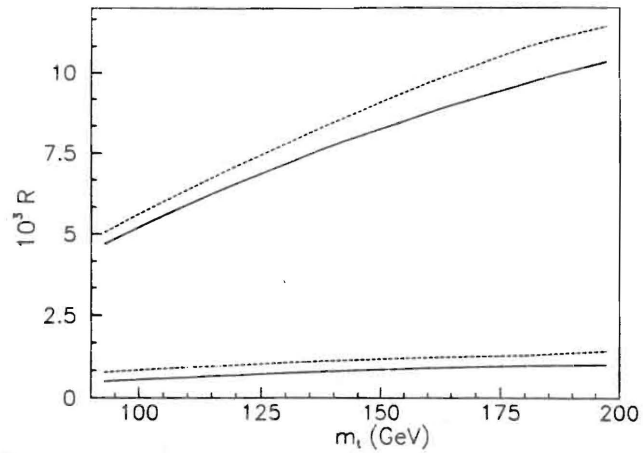

Fig. 1. R as a function of m_t in the standard model (full) and the two-Higgs doublet model (dashed)

$BR(K^+ \to \pi^+\mu^+\mu^-) < 2.3 \times 10^{-7})$[5] we will use the value from $K^+ \to \pi^+e^+e^-$ to extract F_V^{exp}. In due time our prediction will be revised. The other form factors are easily calculated in the standard model. F_P and F_A come from the Z penguin and W box diagrams while F_S is negligible in the SM. The polarization occurs from the interference between the photon penguin and the one-loop electroweak diagrams with the top quark.[6] The longitudinal polarization can easily be calculated and is given by

$$P_L(K^+ \to \pi^+\mu^+\mu^-) = R\ \Psi(E_\mu \bar{E}_\mu) \tag{2}$$

where $\Psi(E_\mu \bar{E}_\mu)$ is a phase space factor that will be taken to be ≈ 10. R is the short-distance contribution[1]

$$R = (1.2 \pm .1) \times 10^{-3} A^2 (1-\rho) C_\mu(x_t) \tag{3}$$

where A, ρ are the parameters of the CKM matrix in the Wolfenstein parametrization and $C_\mu(x_t)$ is a top quark mass dependent function. The interesting point to note here is that we find the same m_t and CKM dependence as for $K_L \to \mu\bar{\mu}$. In fact the two are simply related by

$$\frac{P_L(K^+ \to \pi^+\mu^+\mu^-)}{Br(K_L \to \mu\bar{\mu})^{1/2}} = (60 \pm 6)\Psi(E_\mu, \bar{E}_\mu) \tag{4}$$

The advantage of using the polarization is that the prediction is much more reliable since the ambiguities due to long distance effects are under control. Extracting

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the short-distance contribution to $K_L \to \mu\bar{\mu}$ is model dependent and can lead to large uncertainties,[7] on the other hand a precise measurement of $K_L \to \mu\bar{\mu}$ is easier. The results for R as a function of m_t are shown in Fig. 1, these imply a polarization of a few percent. The standard prediciton will be checked eventually since P_L could be measured at the percent level at BNL or at a future Kaon factory.[8] Also shown in Fig. 1 are the predictions in the charged Higgs model for $\xi = v_d/v_u = 1$ and $m_H = 200GeV$. One sees that the polarization is insensitive to the charged Higgs. This is a common feature of CP conserving processes with charged Higgs and is explained by the fact that the effect of a new particle in the loop is compensated by the higher value of $(1-\rho)$ needed to fit the $B_d^0 - \bar{B}_d^0$ mixing parameter.

In models such as the Left-Right symmetric (LR) model and in the minimal susy model, we do not expect much enhancement over the standard prediction. In fact a significant effect could occur only in models where the F_S form factor is not negligible. For example, leptoquark models which could contribute at the tree-level to this decay, lead to a polarization which is basically unconstrained and could be $P_L \approx 1$.

3. CP violating processes

The various polarizations listed below are classified according to the symmetry they violated.

Correlation	*Symmetries violated*	*Decays*
$\vec{s}_\mu \cdot \vec{p}_\mu$	P	$K_L \to \mu\bar{\mu}$
$\vec{s}_\mu \cdot (\vec{p}_1 \times \vec{p}_2)$	T	$K_{\mu 3}$, $K^+ \to \pi^+\mu^+\mu^-$
$\vec{p}_i \cdot (\vec{s}_\mu \times \vec{s}_{\bar{\mu}})$	P, T	$K^+ \to \pi^+\mu^+\mu^-$

where $\vec{s}_{\mu(\bar{\mu})}$ is the muon (anti-muon) spin vector and $\vec{p}_i$ some momentum. The last row includes generically any observable where both spins enter. All of these polarizations can be used to test the standard model and beyond.

3.1. $P_T(K^+ \to \pi^0\mu^+\nu)$

The transverse polarization is unmeasurably small in the standard model so this process will provide a good testing ground for new physics.[3] Note that there is a small polarization which is induced by electromagnetic final state interactions even in the absence of CP violation however it turns out to be very small (10^{-6} for the charged Kaon decay considered here). We can simply classify the models of new physics according to whether or not they could give a measureable polarization. Many authors[9] have shown that the transverse polarization vanishes in any model with effective V or A interactions. These include LR models, horizontal symmetries as well as certain SUSY and GUT models. A large polarization is possible only in models with effective S, P or T interactions. Examples of these are multi-Higgs models with spontaneous CP violation where P_T can be 10^{-3} (for $m_H \approx 50GeV$) or as usual leptoquark models where it could be much larger due to the weak constraints on the Yukawa couplings in that type of model.

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

The so-called two-spin correlation includes all possible observables where the spins of both leptons are measured. Like the longitudinal polarization, the two-spin correlation comes from the interference between the one photon exchange diagram with charm and the Z penguin and W box diagrams with the top quark.[10] Again the analysis is best performed in terms of the general amplitude (1). The polarization is given by

$$P_2(K^+ \to \pi^+\mu^+\mu^-) = R_2\Phi(E_\mu, \bar{E}_\mu) \tag{5}$$

where Φ is a phase space factor and R describes the short-distance contribution which is directly proportionnal to the CP violation parameter in the Wolfenstein parametrization of the CKM matrix. In the Standard model, one predicts

$$R_2 = (.3 - 2.1) \times 10^{-3} \tag{6}$$

for $m_t = 100 - 200GeV$. This value of R_2 implies a polarization of 10^{-2} with an average phase space factor ≈ 10. It should be emphasized that this decay is very clean since most uncertainties from long-distance effects are absorbed when taking the experimental value for F_V. Furthermore it was shown that the final state interactions between pions and muons should be 10^{-3}. Therefore a measurement at the level 10^{-2}, as planned,[8] will probe the standard model. Furthermore, there are possible enhancements to the two-spin correlation coming from new physics.

In the two-Higgs doublet model the charged Higgs in loops leads to a possible factor of 1.8 enhancement of the polarization even though in such models there are no new source of CP violation. It was also shown that in leptoquark models with the quantum numbers $\phi = (3, 2, 1/3)$ there is a contribution to the F_S form factor leading to possibly very large polarizations. On the other hand in models like LR models and minimal SUSY models we do not expect much enhancement over the standard model.

TABLE 1. Predictions for various rare decays.

Model	$K_L \to \mu\bar{\mu}$ P_L	$K^+ \to \pi^0\mu^+\nu$ P_T	$K^+ \to \pi^+\mu^+\mu^-$ P_T	$K^+ \to \pi^+\mu^+\mu^-$ P_2
Charged Higgs	small	8×10^{-3}	small	10^{-1}
Neutral Higgs	1×10^{-2}	small	small	small
Leptoquarks	small	large	10^{-2}	large
SUSY	7×10^{-2}	small	10^{-3}	10^{-3}
Left-Right	2×10^{-2}	0	10^{-3}	8×10^{-4}
Reference	4	3	2	2

The predictions of various models for the CP violating polarizations in Kaon decays are summarized in Table 1. A small polarization indicates that the predictions will not be measurable and a large polarization means that there are no significant constraints on that type of model. Note that the leptoquark, charged Higgs and susy

models could be different for the various processes considered, full details are given in Ref. 2-4. From this table it is clear that new physics can lead to measurable signals of CP violation and furthermore there is the possibility of distinguishing between the models. It is therefore essential to perform as many of these measurements as possible.

To conclude, the CP conserving polarization P_L would provide some very reliable information on the CKM matrix. In order to eventually understand CP violation, efforts should be made to obtain new information from as many different processes as possible. The search for CP violating polarizations in Kaon decays offer an interesting possibility to do this. Finally these polarizations might eventually give hints of some underlying new physics.

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