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Symmetry Studies in Flavor Changing Processes

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In searching for new physics beyond the standard model, the importance of symmetry studies, in particular in the flavor changing processes of both quarks and leptons, is stressed. As examples in this talk, for the quark sector, a search for violation of the time reversal invariance in K^+ decays is presented, whereas for the lepton sector a search for violation of the lepton flavor conservation in rare muon decays is discussed.

1. INTRODUCTION

The standard model in particle physics has been successful to explain all the experimental data obtained so far. However, it is known to be incomplete, since it can not answer some basic questions, such as particle masses, the generation problem, the hierarchy problem, and so on. To understand these problems, new physics beyond the standard model is definitely required.

How is it possible to obtain clues of new physics beyond the standard model? Now, if new-physics contribution is small and coexists with the dominant standard-model contribution, it might be difficult to detect its contribution in their amplitudes. In such a case, symmetry studies would be quite useful, since new physics might bring a relative imaginary phase with respect to the standard model. This relative phase can in turn manifest itself, through its interference term, as the violation of the fundamental symmetries (in particular CP and T violation) which is not expected by the standard model alone. Thereby, searches for the violation of the fundamental symmetries would herald a clean signal of physics beyond the standard model.

In this talk, we will take one topic from the quark-flavor changing processes and another one from the lepton-flavor changing processes. Both of them are the processes from the second generation to the first generation. The first one is search for violation of the time-reversal invariance in $K^+ \rightarrow \pi^0 \mu^+ \nu$ decay, and the second one is a search for violation of the lepton flavor violation in rare muon decay such as $\mu^+ \rightarrow e^+ \gamma$ decay. For the former, on-going experiment at KEK 12-GeV PS, E246, is presented and for the latter an experimental idea using muon polarization in a $\mu^+ \rightarrow e^+ \gamma$ search is shown.

2. SYMMETRY STUDIES IN QUARK FLAVOR CHANGING PROCESSES

The measurement of triple vector correlations is known to give a promising search for T-violation. One such example concerning K decay is the transverse muon spin polarization $P_\mu^\perp$ in $K^+ \rightarrow \pi^0 \mu^+ \nu$ ($K_{\mu 3}^+$) decay,[1] where $P_\mu^\perp$ is defined as the spin polarization component normal to the decay plane, determined by the μ^+ and π^0 momentum vectors. It is given by

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

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 T-reversal operation changes the sign of $P_\mu^\perp$, a non-zero value of $P_\mu^\perp$ would signal T-violation. If CPT invariance is imposed, T-violation implies CP-violation.

2.1. $P_\mu^\perp$ in $K_{\mu 3}^+$ Decay

As a clean search for T-violating phenomena, the measurement of $P_\mu^\perp$ in $K_{\mu 3}^+$ decay has several striking advantages. First, the final-state electromagnetic interaction (FSI), which would otherwise mimic a fake T-odd effect, is negligibly small, of the order of 10^{-6} , in $K_{\mu 3}^+$ decay [4]. This is owing to the fact that only one charged particle exists in the final state. However, this small FSI is not always the case; for instance, in triple correlations in nuclear β decays and $P_\mu^\perp$ in $K_L^0 \rightarrow \pi^- \mu^+ \nu$ ($K_{\mu 3}^0$) decay, FSI is predicted to be as large as 10^{-3} [5]. This advantage in $K_{\mu 3}^+$ decay allows a wider window to search for T-violation mechanisms, free of FSI-induced background.

Second, $P_\mu^\perp$ in $K_{\mu 3}^+$ decay has no contribution from the KM phase in the minimal 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 $P_\mu^\perp$ value would be a definite signature of new physics beyond the minimal standard model.

In $K_{\mu 3}^+$ decay, the hadronic matrix element can be described as

$$\langle \pi | J | K \rangle = f_+^K(q^2)(\vec{p}_K + \vec{p}_\pi) + f_-^K(q^2)(\vec{p}_K - \vec{p}_\pi) \quad (2)$$

where $\vec{p}_K$ and $\vec{p}_\pi$ are the four momenta of the kaon and pion, respectively. $f_+^K(q^2)$ and $f_-^K(q^2)$ are the form factors of the hadronic matrix elements as a function of momentum transfer squared (q^2). The time-reversal invariance requires that the phases of f_+^K and f_-^K are relatively the same; in another words, if the parameter $\xi^K(q^2) \equiv f_-^K(q^2)/f_+^K(q^2)$ is defined, ξ^K should be a real number. Conversely, a non-zero value of $\text{Im}\xi^K$ would indicate T-violation. Based on eq.(2), $P_\mu^\perp$ can be calculated as a function of the energies of the muon (E_μ) and neutral pion (E_{π^0}) [6]. $P_\mu^\perp$ is given by [7]

$$P_\mu^\perp \cong \text{Im}\xi^K \left(\frac{m_\mu}{m_K} \right) \frac{|\vec{p}_\mu|}{[E_\mu + |\vec{p}_\mu| \vec{n}_\mu \cdot \vec{n}_\nu - m_\mu^2/m_K]} \quad (3)$$

in the K^+ rest frame. It can be seen, as expected, that $P_\mu^\perp$ is proportional to $\text{Im}\xi^K$.

The present experimental upper limit on $P_\mu^\perp$ in $K_{\mu 3}^+$ decay is, in the K^+ rest frame, $P_\mu^\perp = (-3.1 \pm 5.3) \times 10^{-3}$, which was obtained from the previous experiment at Brookhaven

National Laboratory (BNL) which used in-flight K^+ decays [8]. After the kinematic factor was corrected, $\text{Im}\xi^K = -0.017 \pm 0.025$ ¹ is quoted in the Particle Data Group [9].

2.1.1. Theoretical Predictions of $P_\mu^\perp$ in $K_{\mu 3}^+$ Decay

Three Higgs Doublet Models

Among the possible interactions of new physics which is sensitive to $P_\mu^\perp$ in $K_{\mu 3}^+$ decay, it has been discussed in general [10] that neither an effective vector (V) nor an axial-vector (A) interaction introduce $P_\mu^\perp$, but that only a scalar (S) or a pseudoscalar (P) interaction gives a non-zero $P_\mu^\perp$.

It implies that the search is sensitive to the extension of the Higgs sectors. Among the promising models are multi Higgs-doublet models in which at least three Higgs-doublets are needed to generate CP violation [11]. The three Higgs-doublet model (3HDM) has two charged Higgs particles $H_i^\pm$ ($i=1,2$). $P_\mu^\perp$ in $K_{\mu 3}^+$ decay arises from the interference between the W^+ -exchange and H^+ -exchange diagrams. The former contributes mostly to $f_+(q^2)$ and the latter only to $f_-(q^2)$. $\text{Im}\xi^K$ in $K_{\mu 3}^+$ decay is calculated in 3HDM and is given by [7]

$$\text{Im}\xi^K = \text{Im}(\alpha_1\beta_1^*) \cdot \left(\frac{v_2}{v_3}\right)^2 \cdot \left(\frac{m_K}{m_{H_1^+}}\right)^2, \quad (4)$$

where $\text{Im}(\alpha_1\beta_1^*)$ is a measure of the magnitude of CP-violation in 3HDM. m_K and $m_{H_1^+}$ are the masses of the kaon and charged Higgs, respectively. v_i ($i = 1, 2, 3$) are the three Higgs vacuum-expectation-values (V.E.V.). Although there have been no estimations of the magnitudes of the V.E.V.s, some possible patterns have been discussed. One scenario [12] is that the three V.E.V.s are proportional to the fermion masses which they couple to: i.e. $v_1 : v_2 : v_3 \sim m_b : m_t : m_\tau$. This scenario gives a large $P_\mu^\perp$ in semileptonic K decays because of a large value of v_2/v_3 ($\sim m_t/m_\tau$) of about 100. The present experimental constraints on the CP-violating parameters of $\text{Im}(\alpha_1\beta_1^*)$ versus (v_2/v_3) in 3HDM are shown for $m_{H_1^+} = \frac{1}{2}m_Z$ and $m_{H_1^+} = 2m_Z$ in Fig.1. The details are described elsewhere [13]. As seen in Fig.1, for the case of a large value of v_2/v_3 , $P_\mu^\perp$ in $K_{\mu 3}^+$ decay is the most sensitive among the other observables.

Supersymmetric models with squark family mixings

It has been pointed out that the supersymmetric (SUSY) contribution to $P_\mu^\perp$ in $K_{\mu 3}^+$ could be significant [14]. It would happen when the squark family mixing at the quark-squark-gluino couplings is large. In general, there are four squark-flavor mixing matrices, which are the couplings of squarks ($\tilde{u}_L, \tilde{u}_R, \tilde{d}_L, \tilde{d}_R$) and their corresponding quarks. They contribute to $K_{\mu 3}^+$ decay to produce $P_\mu^\perp$ if their relative phase is not zero. They are experimentally constrained by the other FCNC processes, such as $K\bar{K}$, $D\bar{D}$ and $B\bar{B}$ mixing, ε_K , ε'_K and $b \rightarrow s\gamma$. Considering these experimental constraints, if taking the

¹Since the $P_\mu^\perp$ measurements in $K_{\mu 3}^0$ decay might have FSI effects, only the $K_{\mu 3}^+$ data is used here instead of the combined result.

Figure 1. Constraints on $\text{Im}(\alpha_1\beta_1^*)$ vs. (v_2/v_3) : The left and right figures are for the cases of $m_{H_1^+} = (1/2)m_Z$ and of $m_{H_1^+} = 2m_Z$ respectively. In the figures, (a) constraint from the neutron electric dipole moment; (b) from $b \rightarrow s\gamma$; (c) from $P_\mu^\perp$ in $K_{\mu 3}$ decay; and (d) from $b \rightarrow \tau \bar{\nu}_\tau X$ decay. A shaded area is excluded. A dot line shows a sensitivity aimed at in E246

maximally-allowed values, they found that $P_\mu^\perp$ can be as high as 7×10^{-3} . Thereby, any new measurements of $P_\mu^\perp$ would place the most stringent constraints on the couplings. It should be noted that the prediction is much higher than the cases without squark family mixing of 10^{-6} [15].

Leptoquark models or Supersymmetric model with R -parity breaking

Since the excess was observed by H1 and ZEUS at HERA in deep-inelastic e^+p scattering at very large Q^2 [16], leptoquark models are attracting much theoretical and experimental attention as a potential candidate of new physics beyond the standard model [17,18]. One of the manifestation of leptoquark models is supersymmetric extension of the standard model with R -parity breaking. In SUSY with R -parity breaking, the superpotential can be written in the form of

$$W = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k \quad (5)$$

where λ_{ijk} , λ'_{ijk} , λ''_{ijk} are coupling constants with i, j, k being family indices. L_i , E_i , Q_i , $(\bar{U}_i, \bar{D}_i)$ denote superfields of the left-handed lepton doublets, lepton singlets, left-handed quark doublets and singlets, respectively. $P_\mu^\perp$ in $K_{\mu 3}$ decay can be introduced by slepton

Figure 2. Constraints of leptoquark (or SUSY with R -parity breaking) models as a function of mass of leptoquark. The shaded area is excluded experimentally. A new constraint expected from E246 is shown.

($\tilde{l}_i$) or squark ($\tilde{d}_i$) exchange. For the squark exchange case, $\text{Im}\xi^K$ can be given by

$$\text{Im}\xi^K = \sum_k \frac{\text{Im}[\lambda'_{21k}(\lambda'_{22k})^*]}{4\sqrt{2}G_F \sin\theta_c (m_{\tilde{d}_k})^2} \cdot \frac{m_K^2}{m_\mu m_s} \quad (6)$$

where G_F is the Fermi coupling constant, θ_c is the Cabbibo angle, and m_s is a strange quark mass. In this case, $\text{Im}[\lambda'_{21k}(\lambda'_{22k})^*]$ is a measure of CP violation in this model.² In Fig.2, the present experimental constraints (from the previous experiment) is shown, together with the expected bounds aimed by E246.

2.2. $P_\mu^\perp$ in $K^+ \rightarrow \mu^+ \nu \gamma$ Decay

$P_\mu^\perp$ in the radiative K^+ decay, $K^+ \rightarrow \mu^+ \nu \gamma$ (branching ratio = 5.5×10^{-3}), is also T-violating, where the decay plane is determined by the muon and the photon momentum vectors. One of the advantages in $P_\mu^\perp$ in $K^+ \rightarrow \mu^+ \nu \gamma$ is that it could have more variety of new-physics contributions such as effective pseudoscalar (P), vector (V) and axial vector (A), whereas $K_{\mu 3}^+$ decay has only new effective scalar interaction (S). It is because $K^+ \rightarrow \mu^+ \nu \gamma$ has structure-decay (SD) contributions (effective V and A currents) together with inner bremsstrahlung (effective P current). $P_\mu^\perp$ in $K^+ \rightarrow \mu^+ \nu \gamma$ arises from interference between those contributions. The charged Higgs contribution in 3HDM models was calculated [21] and its effect is almost comparable to that in $K_{\mu 3}^+$ decay, namely

²For the slepton exchange case, it can be replaced by $\text{Im}[\lambda'_{112}(\lambda'_{212})^*]$.

at an order of 10^{-3} . Furthermore, the SUSY contribution with squark family mixing to $P_\mu^\perp$ in $K^+ \rightarrow \mu^+ \nu \gamma$ has been discussed [22]. It is pointed out that the SUSY-induced right-handed quark current from W_R boson exchange gives an upper limit of $P_\mu^\perp$ as large as a few per cent, whereas with exchange of charged Higgs in SUSY, $P_\mu^\perp$ is no larger than a few tenths of a per cent. Also, they found that the signs of $P_\mu^\perp$ in $K^+ \rightarrow \mu^+ \nu \gamma$ and in $K^+_{\mu 3}$ would be the same for 3HDM models (effective S interaction), whereas they are opposite for exchange of charged Higgs introduced by SUSY (effective P interaction).

One of the disadvantages is FSI, which was estimated by C.Q. Geng to be as large as 10^{-3} [23]. It is, however, argued that since FSI can be calculated reliably, it could be used as a very useful calibration source of the apparatus when no true T-violation effect is found down to the level of FSI. So far, the measurement of $P_\mu^\perp$ in this decay has not been done yet.

2.3. KEK Experiment E246

KEK-PS E246³ employs K -decays at rest, in contrast to the previous experiments which used in-flight K decays. There are several advantages of the use of the K -decays at rest. For instance, it allows K -decay kinematics to be precisely determined. This, together with the carefully-designed detector, will reduce systematic errors.

Schematic side and end views of the E246 detector are shown in Fig.3. Incident K^+ s of 650 MeV/c 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 256 plastic-scintillating fibers with $5 \times 5 \text{ mm}^2$ square cross-section. After exiting the target, the muons from K^+ decays enter the spectrometer using a superconducting toroidal magnet, where their momenta are analyzed. The magnet has 12 identical magnet-gaps with the accurate 30° rotational symmetry. To track the muons, four sets of wire chambers are installed, one of which is located at the entrance and two at the exit of each of the 12 magnet gaps. The fourth one is a cylindrical drift chamber surrounding the target. In addition to those, there is an array of 32 thin ring-shaped plastic scintillators which surrounds the target to provide additional coordinate of the track along the beam axis.

Photons from the π^0 decays are detected with a highly-segmented photon detector, consisting of 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. The assembly covers about 75 % of 4π and has a beam hole for allowing the K^+ s into the target, and 12 holes for μ^+ s going out into the magnetic spectrometer.

The μ^+ s exiting the spectrometer are stopped in a muon polarimeter installed at the exit of each magnet gap. The muon polarimeter consists of a muon stopper made of pure aluminum, and e^+ counters located at clockwise and counter-clockwise sides from the stopper. The e^+ counters detect e^+ s in $\mu^+ \rightarrow e^+ \nu \bar{\nu}$ decay ($\tau_\mu = 2.2 \text{ } \mu\text{sec}$). The muon polarization is deduced from the asymmetric angular distribution of e^+ s, which are emitted preferentially along the μ^+ spin direction. The direction of the fringing magnetic field is parallel to $P_\mu^\perp$ so as to hold $P_\mu^\perp$, and at the same time it precesses the in-plane

³The E246 collaboration is formed by KEK, University of Tsukuba, University of Tokyo, Tokyo Institute of Technology, Osaka University, INR/Russia, Yonsei University, Korea University, University of Saskatchewan, University of Montreal, TRIUMF, University of British Columbia, Virginia Polytechnic Institute and State University, Princeton University, National Taiwan University.

Figure 3. Schematic (a) side and (b) end views of the E246 detector

polarization components to wash out.

2.3.1. Sensitivity to $P_\mu^\perp$ in E246

In E246, the $K_{\mu 3}^+$ events which have the π^0 moving along the detector axis, either forward or backward from the target, will be accepted as “gold-plated events” For those events, the decay plane can be set radially from the detector axis. $P_\mu^\perp$ is directed azimuthally in a *screw-sense* around the detector axis.

$P_\mu^\perp$ would then manifest itself as a difference in the e^+ counts between the clockwise (*cw*) and counter-clockwise (*ccw*) counters from the muon stopper. By summing the *cw*- and *ccw*- counts of all the 12 sectors, $P_\mu^\perp$ is given by

$$\frac{\sum_{i=1}^{12} N_i(cw)}{\sum_{i=1}^{12} N_i(ccw)} \cong 1 \pm 2AP_\mu^\perp, \quad (7)$$

where $N_i(cw)$ and $N_i(ccw)$ are total e^+ counts at the *cw* and *ccw* counters at the *i*th sector, respectively. A is the effective analyzing power. Since the same e^+ detector acts as the *cw* counter in one magnet-gap, as well as the *ccw* counter in the neighboring magnet-gap in the toroidal geometry, any fake asymmetries resulting from the efficiency of the e^+

counters would have opposite signs in these two adjacent magnet gaps, and thereby be canceled in the first order.

Since the direction of $P_\mu^\perp$ is opposite between the $K_{\mu 3}$ samples with forward-going π^0 s and with backward-going π^0 s, their comparison enables us to reduce systematic errors significantly. Further, a double ratio can be formed by these two samples as follows:

$$\frac{[\sum_{i=1}^{12} N_i(cw) / \sum_{i=1}^{12} N_i(ccw)]_{fwd}}{[\sum_{i=1}^{12} N_i(cw) / \sum_{i=1}^{12} N_i(ccw)]_{bwd}} \cong 1 + 4AP_\mu^\perp. \quad (8)$$

By taking this double ratio, we can increase the asymmetry by a factor of two. In addition, by using the $K_{\mu 3}^+$ events with the π^0 s moving transverse to the detector axis, we will be able to examine the zero-asymmetry level and also to determine the analyzing power of each e^+ counter by using the in-plane muon polarization.

Using the estimated μ^+ acceptance of 5% at the spectrometer and the reconstructed forward/backward going π^0 acceptance of 20% together with the detection efficiency of $\mu^+ \rightarrow e^+ \nu \bar{\nu}$ decay of about 10%, the total acceptance of the $K_{\mu 3}$ events is estimated to be 1×10^{-3} . Assuming a K^+ stopping rate of about 100 k/3-sec spill and a 10^7 -sec running time, we might collect a total of about 1×10^7 “gold-plated” $K_{\mu 3}^+$ events. The statistical error can be estimated by

$$\Delta P_\mu^\perp \sim \frac{1}{A} \cdot \sqrt{\frac{1}{\sum_{i=1}^{12} N_i}}, \quad (9)$$

where A is the analyzing power, which is expected to be about 0.2 from Monte-Carlo calculations. Using a total of $\sum_{i=1}^{12} N_i > 1 \times 10^7$ events, we estimate $\Delta P_\mu^\perp \sim 1.5 \times 10^{-3}$. Using the average value of $P_\mu^\perp / \text{Im}\xi^K \sim 0.3$, a sensitivity to $\text{Im}\xi^K$ of about 5×10^{-3} is expected. The systematic errors were estimated by using Monte-Carlo calculations, and are found to be smaller than the expected statistical sensitivity.

The experimental sensitivity to $P_\mu^\perp$ 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 that would introduce an additional acceptance loss. We are thus expecting a sensitivity of an order of per cent.

E246 has started physics-data taking since spring in 1996. We have already accumulated about 2 M gold-plated $K_{\mu 3}$ events. The analysis of the 1996 data is being undertaken. We are expected to run for two more years with higher acceptance in 1997 and 1998.

3. SYMMETRY STUDIES IN LEPTON FLAVOR CHANGING PROCESSES

Lepton flavor violation (LFV) has been attracting much attention recently, since several extensions to the standard model predict large LFV rates. Among the various theoretical models with LFV, models of supersymmetric grand unification (SUSY GUT) in particular predict a branching ratio only one or two order magnitudes lower than the current experimental limits [24,25]. A search for LFV in low energy processes would have the potential to test unification at very high energy. Compared to other LFV processes of interest, $\mu^+ \rightarrow e^+ \gamma$ is known to have a higher sensitivity to supersymmetric unification. The prediction of SU(5) SUSY GUT models can be given approximately by [24]

$$\Gamma(\mu \rightarrow e \gamma) \approx \frac{\alpha}{4} |V_{31}^* V_{32} I(y_i)|^2 \frac{m_\mu^5}{m_{\tilde{t}}^4} \quad (10)$$

where V_{ij} is KM *quark* matrix elements (at GUT scale), $I(y_t)$ is a function of the top Yukawa coupling (y_t). m_μ and m_τ are masses of muons and selectrons. The predicted branching ratio ranges from 10^{-15} to 10^{-13} for the singlet selectron mass of $m_{\tilde{e}_R}$ of 100 to 300 GeV, and the SO(10) SUSY GUT models give an even larger value of 10^{-13} to 10^{-11} by an enhancement of $(m_\tau/m_\mu)^2$ [25].

The event signature of $\mu^+ \rightarrow e^+\gamma$ is that a e^+ and a photon are in coincidence, and moving collinear back-to-back with their energies equal to a half of the muon mass ($m_\mu/2 = 52.8$ MeV). The current experimental upper limit is 4.9×10^{-11} at 90% confidence level [26]. Recently, the MEGA experiment at LAMPF, which aims at a sensitivity of 7×10^{-13} , completed data taking and is now analyzing their data [27].

There are two major backgrounds to the search for $\mu^+ \rightarrow e^+\gamma$. One is a physics (prompt) background from a radiative muon decay $\mu^+ \rightarrow e^+\nu\bar{\nu}\gamma$ when e^+ and photon are emitted back-to-back with two neutrinos carrying off little energy. The other background is an accidental coincidence of a e^+ in a normal muon decay, $\mu^+ \rightarrow e^+\nu\bar{\nu}$, accompanied by a high energy photon. The sources of a high energy photon might be either that in $\mu^+ \rightarrow e^+\nu\bar{\nu}\gamma$ decay, or external bremsstrahlung or annihilation-in-flight of e^+ s in the normal muon decay.

For polarized muons, a right-handed e^+ (e_R^+) in $\mu^+ \rightarrow e_R^+\gamma$ decay follows a $(1 - P_\mu \cos \theta_e)$ distribution, whereas a left-handed e^+ (e_L^+) in $\mu^+ \rightarrow e_L^+\gamma$ does a $(1 + P_\mu \cos \theta_e)$ distribution, where θ_e is an angle of the e^+ emission with respect to the muon polarization (P_μ). This angular distribution is known to be useful to discriminate different models since the helicity of e^+ in $\mu^+ \rightarrow e^+\gamma$ is sensitive to the mechanism of lepton flavor mixing. More importantly, it is shown in the following that the experimental backgrounds could be potentially further reduced by polarized muons. In the following, it is discussed how these backgrounds could be suppressed by using polarized muons to aim at a sensitivity of an order of 10^{-14} .

3.1. Physics Background to $\mu^+ \rightarrow e^+\gamma$ Search

The radiative muon decay, $\mu^+ \rightarrow e^+\nu\bar{\nu}\gamma$ (branching ratio equal to 1.4% for $E_\gamma > 10$ MeV), would become a background when the e^+ and photon are emitted back to back with two neutrinos carrying off little energy. The differential decay width of this radiative decay was calculated [28]. Given the detector resolution, the sensitivity limitation from this physics background can be estimated by integrating the differential decay width over the kinematic signal box. It is given by [29]

$$dB(\mu \rightarrow e\nu\bar{\nu}\gamma) \cong \frac{\alpha}{16\pi} [J_1(1 - P_\mu \cos \theta_e) + J_2(1 + P_\mu \cos \theta_e)] d(\cos \theta), \quad (11)$$

where J_1 and J_2 are given as a function of sizes of the kinematic signal box for the e^+ and photon energies. The sizes of the signal box are determined by the detector resolutions. It is found that the above distribution follows approximately a $(1 + P_\mu \cos \theta_e)$ distribution (i.e. $J_2 \gg J_1$) when the energy resolution of photon detection is worse than that of e^+ [29]. They imply that the selective measurement of e^+ s antiparallel to the muon polarization direction would suppress the physics background, improving a sensitivity of the search for $\mu^+ \rightarrow e_R^+\gamma$.

3.2. Accidental Background to $\mu^+ \rightarrow e^+\gamma$ Search

It turns out that the accidental background becomes more important than the physics background in a new generation experiment with a very high rate of stopped muons. The angular distribution of the sources of accidental background are examined for polarized muons [30]. It is known that e^+ s in the normal Michel muon decay follows a $(1 + P_\mu \cos \theta_e)$ distribution. We have studied the inclusive angular distribution of a high energy photon (e.g. ≥ 50 MeV) from $\mu^+ \rightarrow e^+\nu\bar{\nu}\gamma$. It is found to be emitted preferentially along the muon spin direction; namely follows a $(1 + P_\mu \cos \theta_\gamma)$ distribution, where θ_γ is an angle of the photon direction with respect to the muon spin direction. It should be noted that this inclusive angular distribution was obtained after the integration of energy and direction of e^+ s, which is in contrast to the case of physics background where only the extreme kinematics of e^+ and photon being back-to-back in $\mu^+ \rightarrow e^+\nu\bar{\nu}\gamma$ decay is relevant. It is further noted that the other sources of high energy photons such as external bremsstrahlung and annihilation-in-flight of e^+ s in the normal muon decay also follow a $(1 + P_\mu \cos \theta_\gamma)$ distribution.

This inclusive angular distribution of a high energy photon in $\mu^+ \rightarrow e^+\nu\bar{\nu}\gamma$ implies that the accidental background could be suppressed for $\mu^+ \rightarrow e_L^+\gamma$ where high energy photons must be detected at the opposite direction to the muon polarization. A similar suppression mechanism of accidental background can be seen for $\mu^+ \rightarrow e_R^+\gamma$ when high energy positrons are detected at the opposite direction to the muon polarization. As a result, the selective measurements of either e^+ s or photons antiparallel to the muon spin direction would give the same accidental background suppression for $\mu^+ \rightarrow e_R^+\gamma$ and $\mu^+ \rightarrow e_L^+\gamma$ decays respectively. This favorable situation comes from the fact that the inclusive distributions of both high energy e^+ s and photons, respectively in the normal and radiative muon decays, follow a $(1 + P_\mu \cos \theta)$ distribution, where θ is either θ_e or θ_γ .

The rate of the accidental background (B_{acc}) normalized to the total decay rate can be estimated by

$$B_{acc} = R_\mu \cdot f_e^0 \cdot f_\gamma^0 \cdot (\Delta t) \cdot \left(\frac{\Delta\omega}{4\pi}\right) \cdot \eta \quad (12)$$

where R_μ is an instantaneous muon intensity. f_e^0 and f_γ^0 are an integrated fraction of the spectrum (with their branching ratios) of e^+ in the normal muon decay and that of photon in $\mu^+ \rightarrow e^+\nu\bar{\nu}\gamma$ decay within the signal region for unpolarized muons, respectively. Δt and $\Delta\omega$ are respectively a full width of the signal regions for timing coincidence and angular constraint of the back-to-back kinematics. η is a suppression factor of the accidental background. $\eta = 1$ for the case of unpolarized muons. For instance, take some reference numbers such as the e^+ energy resolution (FWHM) of 1%, the photon energy resolution of 6%, $\Delta\omega = 3 \times 10^{-4}$ steradian, $\Delta t = 1$ nsec, and $R_\mu = 3 \times 10^8 \mu^+/\text{sec}$, B_{acc} is 3×10^{-13} . Unless there are significant improvements made on the detector resolution, the accidental background might appear at a level of 10^{-13} .

As explained before, the selective measurement of either e^+ s or photons antiparallel to the muon spin direction would provide a large background suppression factor. By taking account of the angular distributions of the $\mu^+ \rightarrow e^+\gamma$ signal, the suppression factor η is calculated for polarized muons by

$$\eta \equiv \frac{\int_{\cos \theta_D}^1 d(\cos \theta)(1 + P_\mu \cos \theta)(1 - P_\mu \cos \theta) / \int_{\cos \theta_D}^1 d(\cos \theta)}{(1 - P_\mu^2) + \frac{1}{3}P_\mu^2(1 - \cos \theta_D)(2 + \cos \theta_D)} \quad (13)$$

where θ_D is a half opening angle of detection with respect to the muon polarization direction. For instance, for $\theta_D = 300$ mrad, an accidental background can be suppressed down to about 1/20 (1/10) when P_μ is 100 (97)%. Note that an opening angle of $\theta_D = 300$ mrad give a geometrical solid angle coverage of 2.3%. Therefore, with a reasonable detector acceptance, a suppression of an order of magnitude could be achieved. Thus, a search for both $\mu^+ \rightarrow e_L^+ \gamma$ as well as $\mu^+ \rightarrow e_R^+ \gamma$ has the potential for an improved sensitivity (to an order of 10^{-14}) with polarized muons. The suppression in the search for $\mu^+ \rightarrow e_R^+ \gamma$ decay comes from the angular distribution of e^+ s in the normal muon decay, whereas that for $\mu^+ \rightarrow e_L^+ \gamma$ decay is due to the distribution of high energy photon in $\mu^+ \rightarrow e^+ \nu \bar{\nu} \gamma$ decay. It would be possible to aim for a sensitivity of 10^{-14} level.

Figure 4. Accidental background suppression as a function of (half) detector opening angle.

4. CONCLUSION

It has been shown that symmetry studies would be very powerful in searching for new physics beyond the standard model. In particular, T (or CP) violation in the quark flavor changing processes and LFV in the lepton flavor changing processes are very interesting

and important on this regard. The author is grateful to all the members in the KEK-PS E246 collaboration for the first subject and to Profs. Y. Okada and A. Maki for their useful discussions on the second subject.

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