Letter of Intent
Measurement of $\Gamma(K^+ \rightarrow e^+\nu)/\Gamma(K^+ \rightarrow \mu^+\nu)$
and
Search for heavy sterile neutrinos
at J-PARC

TREK Collaboration*

December 25, 2009

1 Introduction

In this Letter of Intent we express our strong commitment to engage in the commissioning of the K1.1Br line at J-PARC, develop the components of the high precision T-violation experiment (TREK) [1] and engage in K-decay physics parameter studies during this period. Below, we present the rationale and strategy leading up to the TREK experiment.

It has become clear that, at this time, the low intensity of the hadron beams is a major limiting factor to begin the TREK experiment at J-PARC. It is expected that it might be a few years before we will see intensities greater than 100 kW. Bearing this in mind, we have examined the experimental and physics options to maintain and even enhance the momentum towards the realization of the TREK experiment while J-PARC is ramping up the beam intensity.

1.1 Physics topics

It turns out that we can actively participate in the development of the beamline while producing K^+ decay physics of much interest. Even at an early stage, we can engage in a high precision measurement of the ratio of the $K_{\mu 2}$ and K_{e2} decays, which serves as a test of μ-e universality [2]. Details of this study are described in section 2. Thus far, the best results have been obtained from decay-in-flight measurements using highly relativistic kaons by the NA48 and Daphne groups [3, 4]. While their measurements are consistent with the Standard Model predictions [5], there is still

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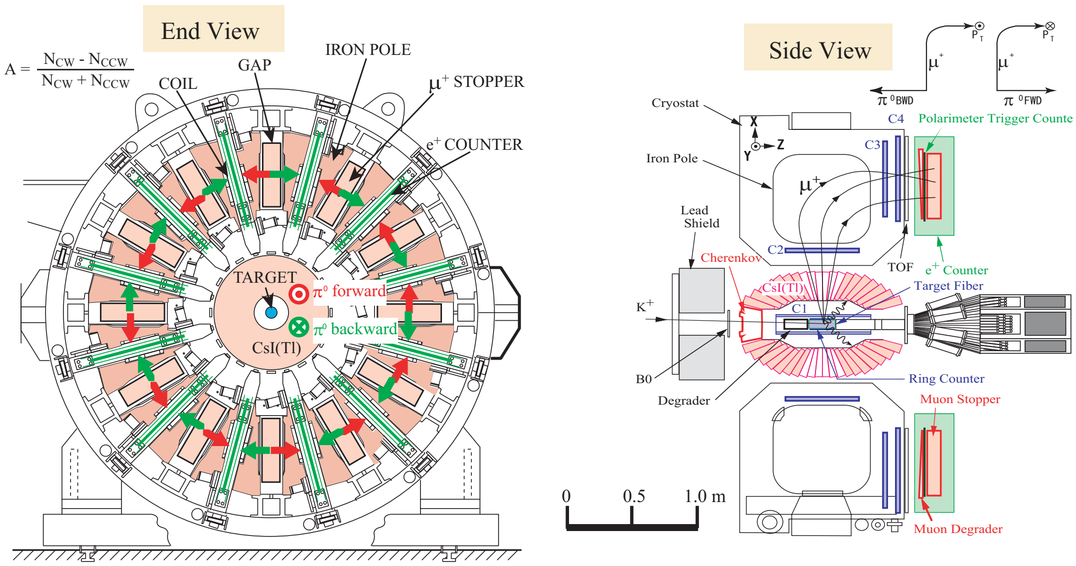

Figure 1: Cross sectional end and side views of the TREK setup. The momentum vectors of charged particles and π^0s are determined by the Toroidal spectrometer and the CsI(Tl) calorimeter, respectively. The muon polarization is measured as the decay e^+ asymmetry.

room for improvement as the current data is only at the one percent level. Our data will be obtained in the very early phases of the commissioning when the beam power will be $\leq$30 kW. The fact that we will work with stopped kaons, where the kaon beam history does not contribute to the systematics, makes our result a valuable supplement to the literature data. It should be remarked that a few theses works of E246 [6] were related to this subject and thus we have very considerable in-house expertise on this subject.

We will be able to test the predictions of some exotic models introducing heavy neutrinos below the kaon mass. Recently, Shaposhnikov and collaborators presented arguments that right handed weak currents might manifest themselves as heavy neutrinos [7]. Earlier searches by Hayano et al [8] yielded lower/upper limits for 70 $< m_\nu(MeV/c^2) <$ 300. We will be able to measure longitudinal polarization and look for correlations between the polarization and missing mass/momentum plots which provides an additional sensitivity to the test. In the experiment to search for heavy neutrinos, the normal and longitudinal μ^+ polarizations in $K^+ \rightarrow \mu^+\pi^0\nu$ and $K^+ \rightarrow \mu^+\nu\gamma$ can be simultaneously measured. These polarizations, thus far inaccessible to experiment, provide the decay form factor information. Details of these studies are described in section 3.

1.2 Game plan

We will participate in the beamline tuning of the K1.1-BR, whose beam optics was designed by the TREK group. We propose to set up the toroidal spectrometer and CsI(Tl) calorimeter (See Fig. 1) during the years 2010 through 2011. We expect that the low intensity beamline will be ready for use by the end of 2011 at the spectrometer. We would like to have the toroidal spectrometer in place and furnished with a charged particle setup using with the old E246 components (target, drift chambers, and TOF system) before the planned TREK detector upgrade takes place. Eventually we will realize the upgrade item-by-item as the funding profile permits. We plan to implement a GEM detector to improve the vertex reconstruction. Because of the rotational symmetry of the 12 identical gaps in the spectrometer and the large directional acceptance of the calorimeter, the distortion of the K^+ decay spectra due to instrumental misalignments are drastically reduced. This feature will allow us to study the $K^+ \to e^+\nu$ and $K^+ \to \mu^+\nu$ decays to very high precision. As a bonus, we will also obtain data which will serve as a test of the μ-e universality.

By the Spring 2011, we will gain a good understanding of the kaon beam characteristics (beam profile, K/π ratio etc.). We can then freeze the TREK target size and expect to have it ready by the Summer 2012. We will setup and commission the active polarimeters which will enable us to measure the normal, longitudinal and the transverse polarization of the decay muons in the K. This task is essential for us to calibrate the polarimeter for the TREK experiment. Simultaneously, we will obtain the data for the heavy neutrino search and the form factor measurement. We anticipate that the years 2012 and 2013 will be spent commissioning the entire system while collecting the data mentioned above.

If the J-PARC intensities reach their design values sooner, we will reconsider this strategy and begin the TREK experiment at the earliest possible date. A ten-fold increase in the beam intensity will make these initial experiments much faster and this physics can still be addressed.

We expect that our involvement in the K1.1-BR is to the mutual advantage of both J-PARC and our experimental group. There is the potential for several M.Sc. and Ph. D theses for Japanese students as well as students from abroad. There is also room for several undergraduate students' projects in the commissioning stage. This will enhance the visibility of J-PARC among the young scientists abroad and contribute to the training of highly qualified personnel.

We are planning to submitting a full proposal at the J-PARC PAC's Summer 2010 meeting.

2 Measurement of $\Gamma(K^+ \to e^+\nu)/\Gamma(K^+ \to \mu^+\nu)$ ratio

2.1 μ-e universality and LFV effect in SUSY models

High precision electroweak tests represent a powerful tool to probe the Standard Model (SM) and to obtain indirect hints of new physics. The $K^+ \to l^+\nu_l$ decay (K_{l2}) is one of the best channels to perform such tests. The hadronic form factor in $K_{l\nu}$ decay can be canceled out by making the ratio of the electric and muonic decay modes as,

$$R_K^{SM} = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)} = \frac{m_e^2}{m_\mu^2}[\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}](1+\delta_r) = (2.472 \pm 0.001) \times 10^{-5}. \quad (1)$$

As a result, the SM prediction of R_K^{SM} are known with excellent accuracy ($\sim 10^{-3}$) and this makes it possible to search for new physics effects using a precise measurement of this BR.

Recently, a minimal SUSY extension of the SM (MSSM) with R parity was considered as a candidate for the new physics to be tested by R_K [2]. A possible mechanism to detect the Lepton Flavor Violation (LFV) SUSY effect through a deviation from the μ-e universality in K_{l2} was discussed. A charged Higgs-mediated SUSY LFV contribution, as shown in Fig. 2, can be strongly enhanced by emitting a τ neutrino. This effect can be described as,

$$R_K^{LFV} = R_K^{SM}[1 + \frac{m_K^4}{M_{H^+}^4}\frac{m_\tau^2}{m_e^2}\Delta_{13}^2 \tan^6\beta], \quad (2)$$

where M_H is charge Higgs mass and Δ_{13} is the term induced by the exchange of a Bino and a slepton. Taking $\Delta_{13} = 5 \times 10^{-4}$, $\tan\beta = 40$, and $M_H = 500$ GeV, we can obtain $R_K^{LFV} = 1.013 \times R_K^{SM}$. Thus, it is possible to reach a contribution at the percent level thanks to the possible LFV enhancements arising in SUSY models.

2.2 Experimental situation

In the KAON09 conference, the NA48 and KLOE groups reported the latest results of the R_K values, as follows [9, 10].

2.2.1 NA48/2 and NA62

Two preliminary results of NA48/2 were reported based on the 2003 and 2004 data sets [3]. After the NA48/2 measurements, NA62 data-taking in 2007/08 was optimized for the R_K measurement. The NA62 K_{e2} sample is about 10 times larger than the world sample. Preliminary result based on 40% of the NA62 K_{e2} sample were reported as,

$$R_K = (2.500 \pm 0.016) \times 10^{-5}, \Delta R_K/R_K = 0.7\%, \quad (3)$$

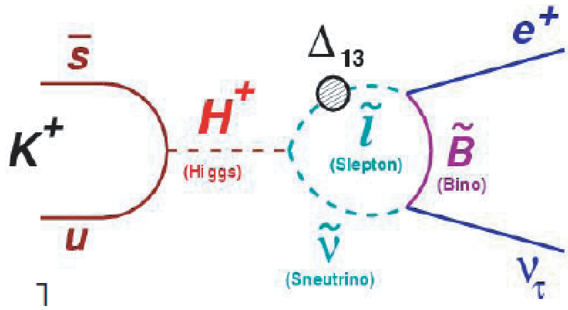

Figure 2: Contribution from LFV effect arising in SUSY.

which is compatible with the SM prediction at the 2σ level. Using the full NA62 data sample (150k), the precision is expected to be improved to about $\Delta R_K/R_K = 0.5\%$ [9].

2.2.2 KLOE

Recently, the final KLOE result was published [4, 10], They collected about 14k $K^{\pm}_{e2}$ samples and obtained

$$R_K = (2.493 \pm 0.031) \times 10^{-5}, \Delta R_K/R_K = 1.0\%(stat.) + 0.8\%(syst.) = 1.3\%. \quad (4)$$

The result does not depend upon the kaon charge, and agrees with the SM prediction.

2.3 R_K measurement using the TREK apparatus at J-PARC

Here, we will discuss the significance to perform the $K_{e2}/K_{\mu 2}$ experiment using a stopped K^+ beam at J-PARC during the low intensity period. Since the NA62 and KLOE groups adopted an in-flight-kaon method, the detection mechanism is different than the J-PARC experiment and it is worth checking the R_K value using a different kinematical approach. Such independent measurements are complimentary and comprehensive studies are very important to achieve an experimental sensitivity better than 10^{-3}.

Assuming 30 kW operation and 50 days data collection, the number of K_{e2} events is estimated to be 250×10^3 which is about twice the NA62 data, corresponding to a statistical error of R_K is $\Delta R_K = 0.0054$ ($\Delta R_K/R_K = 0.2\%$). The key to success in the R_K determination using the TREK apparatus is the separation of the following 3 processes: (1) K_{e2} with real bremsstrahlung generated in the stopper, (2) $K_{e2\gamma}$ internal bremsstrahlung (IB), and (3) $K_{e2\gamma}$ structure dependent term (SD), because the width of the radiative corrected $K_{l2} + K^{IB}_{l2\gamma}$ has to be compared with the theoretical calculation. In general, since decay particles are essentially affected by interaction with the target material in the stopped K^+ experiment, the K_{e2} with a bremsstrahlung photon generated through the interaction between e^+ and stopper material would deform the K_{e2} spectra.

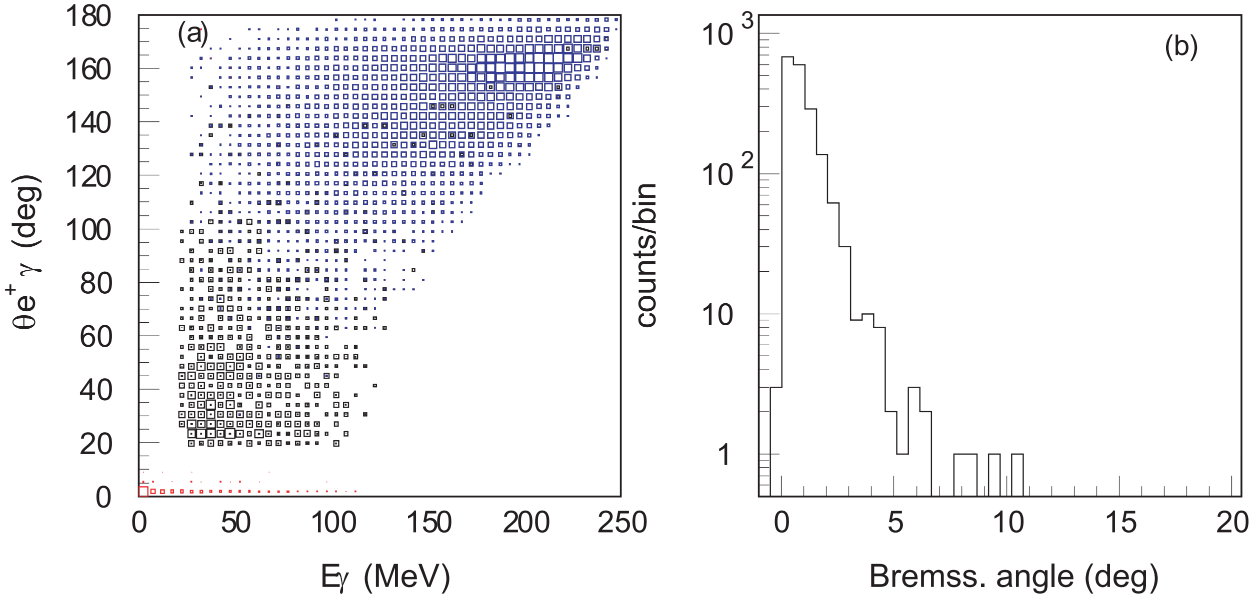

Figure 3: (a) correlation plot for E_γ and $\theta_{e^+\gamma}$ for SD (blue), IB (black), K_{e2} with bremsstrahlung photon (red) and (b) $\theta_{e^+\gamma}$ for real bremsstrahlung. Real bremsstrahlung gammas pass through the hole without hitting the calorimeter. The events due to the IB and SD processes have distinct structure and it is possible to separate them.

A Monte Carlo simulation was carried out for both the e^+ measurement by the spectrometer and the γ measurement by the CsI(Tl) calorimeter in order to check the separation of the above 3 processes. Fig. 3(a) shows the correlation plot for E_γ and $\theta_{e^+\gamma}$, where E_γ is photon energy and $\theta_{e^+\gamma}$ is opening angle between the e^+ and the photon. Real bremsstrahlung gammas are nearly parallel to the e^+ direction and they pass through the holes without hitting the calorimeter, although these events are overlaid in the figure. Fig. 3(b) shows the $\theta_{e^+\gamma}$ distribution of real bremsstrahlung. As a result, the spectral shapes are distinct and the separation of these three processes is quite feasible. Fig. 4 shows the expected constraints in the tanβ-M_H correlation at the 90% confidence level. They were obtained using only the statistical uncertainty.

The following discussion concerns the SD events in the $K_{e2\gamma}$ decay, which are simultaneously recorded in this measurement. The form factors of the $K^+ \to e^+\nu\gamma$ transition have been studied in the light-front quark model and the chiral perturbation theory of $O(p^6)$. Due to the helicity suppression of the K_{e2} decay, the SD component gives the dominant contribution to their spectra shapes. Therefore, the precise measurement of $K_{e2\gamma}$ will offer a good testing ground for these theories [13].

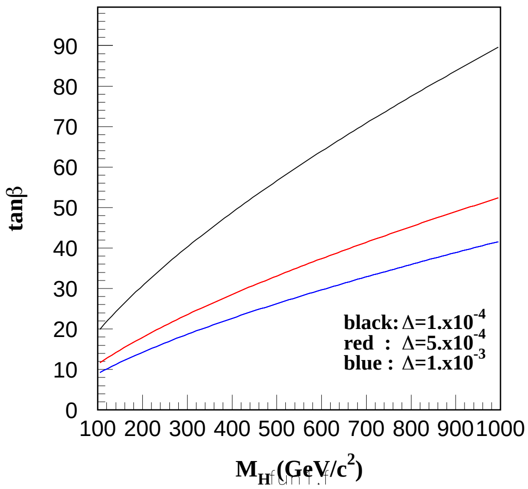

Figure 4: Constraint to M_H and tanβ. The constraint curves at the 90% confidence level are obtained by assuming typical Δ_{13} values.

3 Search for heavy neutrino in $K^+ \to \mu^+ N$ decay

3.1 Introduction

In a search for physics beyond the Standard Model one can use different types of guidelines. A possible strategy is to attempt to explain the phenomena that cannot be fit to the SM by minimal means, that is by introducing the smallest possible number of new particles without adding any new physical principles or a new energy scale. An example of such a theory is the renormalizable extension of the SM, the νMSM (neutrino Minimal Standard Model) [11, 12], where three light singlet right-handed neutrinos (sterile neutrinos) are introduced. The leptonic section of this theory has the same structure as the quark section, i.e. every left-handed fermion has its right-handed counterpart. If the sterile neutrinos are lighter than the kaons, they can give rise to leptonic and semileptonic decay with relatively large branching ratios. This gives a possibility to prove or rule out νMSM with light sterile neutrino.

The predictions of the branching ratio in two-body decays $K^+ \to \mu^+ N$ were obtained to be BR$< 10^{-6}$, as shown in Fig. 5 [11, 12]. This decay has some very important features, such as,

- μ^+ momentum generated from the $K^+ \to \mu^+ N$ decay is monochromatic. A peak structure is formed in the momentum spectrum.
- Since the μ^+s are generated through right-handed current, the μ^+ polarization is 100% and opposite that from the normal $K^+ \to \mu^+ \nu$ decay.

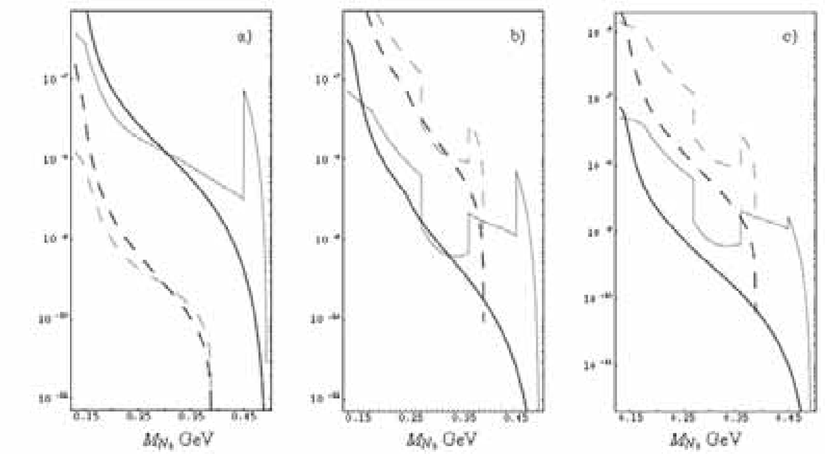

Figure 2: Branching ratios of decays $K \to eN_I$ (solid lines) and $K \to \mu N_I$ (dashed lines) at varios heavy neutrino masses M_N in models: a) I, b) II, c) III. In a phenomenologically viable model the branching ratios are confined between corresponding thin and thick lines which show upper and lower limits on U^2 from Fig. 1b, respectively.

Figure 5: $K^+ \to e^+N$, $K^+ \to \mu^+N$ branching ratio calculated as a function of sterile neutrino mass in the framework of νMSM.

We can improve the sensitivity for the sterile neutrinos by measuring both the μ^+ momentum and the μ^+ polarization simultaneously. On the other hand, the main background is the $K^+ \to \pi^0\mu^+\nu$ decay with two photon escape from the CsI(Tl) calorimeter. A dedicated photon veto system is necessary for $K_{\mu 3}$ suppression.

3.2 Experimental situation

The muon momentum spectrum in $K_{\mu 2}$ decay was measured using a high-resolution magnetic spectrograph to look for a discrete muon peak associated with heavy-neutrino emission [8]. The momentum resolution at 236 MeV/c was 2.1 MeV/c FWHM (0.9%) with a perfectly Gaussian line shape, and it decreased gradually toward lower momenta. Backgrounds due to the $K_{\mu 3}$ decays were suppressed by detecting the photons using the veto counter system surrounding the K^+ stopper.

No distinct peak was observed in the muon momentum spectrum except for the normal one at 236 MeV/c. They set the upper limit on the mass and mixing of heave neutrinos. The 90% confidence-level limit was set to be 10^{-5} for the $m_\nu = 100$ MeV/c^2 and 10^{-6} for the $m_\nu = 200 - 300$ MeV/c^2.

3.3 Heavy neutrino search at J-PARC

A Monte Carlo simulation was performed to study the experimental sensitivity using the TREK apparatus to heavy neutrinos. Fig. 6 show the simulation results obtained by assuming (a) Br($K^+ \to \mu^+N$)=1×10^{-8}, (b) 30kW beam power and 50 days data collection, (c) 99.9% π^0 veto efficiency, and (d) μ^+ monoenergy peak at $P_\mu = 170$

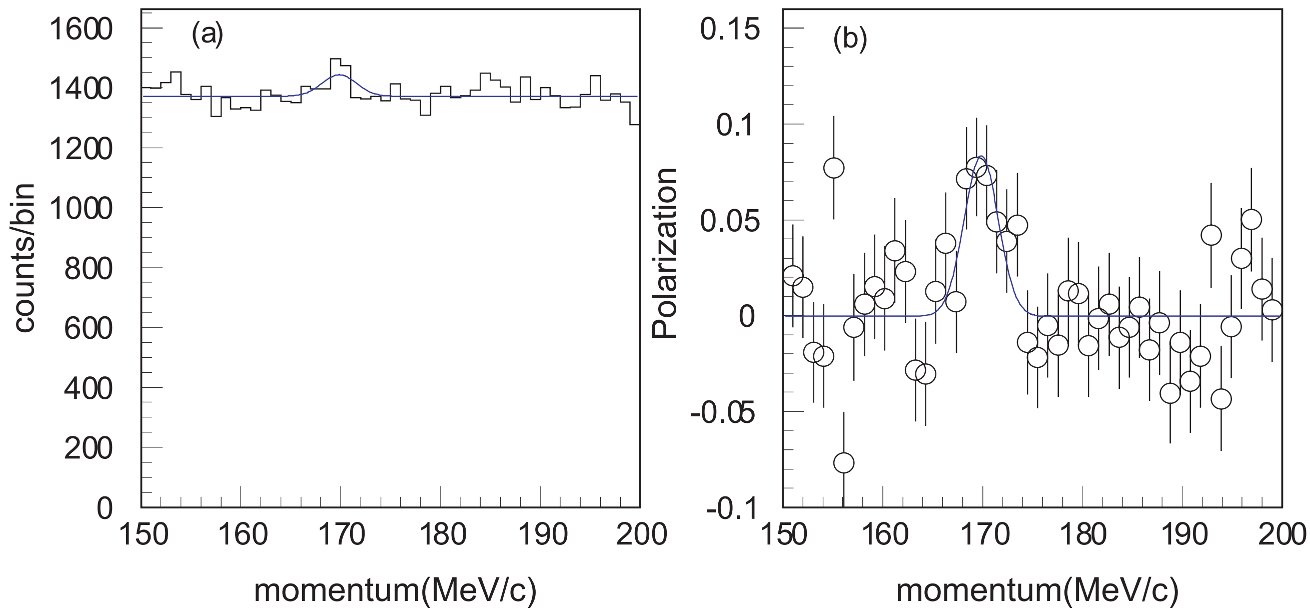

Figure 6: Distributions of (a) μ^+ momentum and (b) μ^+ polarization obtained in the simulation under the assumption mentioned in the text. The heavy neutrino signal can be determined at the 10σ level by fitting the μ^+ momentum and the μ^+ polarization simultaneously.

MeV/c and a flat distribution from the $K_{\mu 3}$ backgrounds. The heavy neutrino signal can be determined with 10σ level by fitting the μ^+ momentum and the μ^+ polarization simultaneously. This result indicates the attainable sensitivity is higher than 10^{-8} with reasonable beam power and time.

3.4 In-plane component of μ^+ polarization in $K^+ \to \mu^+\nu\gamma$ and $K^+ \to \mu^+\pi^0\nu$

In the experiment to search for heavy neutrinos, the μ^+ polarizations in $K^+ \to \mu^+\pi^0\nu$ and $K^+ \to \mu^+\nu\gamma$ can be simultaneously measured. These polarizations provide the decay form factors as follows.

3.4.1 The $K^+ \to \mu^+\nu\gamma$ decay

The decay $K^+ \to \mu^+\nu\gamma$ ($K_{\mu 2\gamma}$) can proceed via two distinct mechanisms. The first is the internal bremsstrahlung (IB) process which is a radiative version of the familiar $K_{\mu 2}$ decay. Its Feynman diagram has a photon emitted from the external kaon or muon line. The second is the structure-dependent radiative decay (SD), which involves the emission of a photon from intermediate states. The structure-dependent component in the decay $K_{\mu 2\gamma}$ was observed by BNL E787 group [14]. Using the kinematic region where the muon kinetic energy is greater than 137 MeV and the photon energy is greater than 90 MeV, the sum of the vector and axial-vector form factors was extracted.

In the TREK experiment, as well as these spectroscopic studies, the μ^+ polarization from the SD effect can be measured. The SD term is sensitive to the electroweak structure of the kaon and has been the subject of chiral perturbation theory (ChPT) [15]. The μ^+ polarization has been calculated using the theoretically predicted SD amplitude [16]. Therefore, a precise measurement of μ^+ polarization in $K_{\mu 2\gamma}$ will offer a strict testing ground for the ChPT prediction by comparing with the results obtained from spectroscopic studies.

3.4.2 The $K^+ \to \mu^+\pi^0\nu$ decay

In $K_{\mu 3}$ decays, the matrix element is written as [17]

$$\begin{aligned} M &\propto f_+(t)[(P_K + P_\pi)_\mu \bar{l}\gamma_\mu(1+\gamma_5)\nu] + f_-(t)[m_l\bar{l}(1+\gamma_5)\nu] \quad (5)\\ &\propto f_+(t)[[(P_K + P_\pi)_\mu \bar{l}\gamma_\mu(1+\gamma_5)\nu + \xi(t)[m_l\bar{l}(1+\gamma_5)\nu]], \quad (6)\end{aligned}$$

where P_K and P_π are the four-momenta of the K and π mesons, m_l is the lepton mass, and f_+ and f_- are dimensionless form factors which can depend only on $t = (P_K - P_\pi)^2$, the square of the four-momentum transfer to the leptons. $\xi(t)$ is the ratio of $f_-(t)$ and $f_+(t)$ and $Re(\xi)$ is related to the the muon polarization. The μ is expected to be polarized in the direction $\vec{A}$ with $\vec{P} = \vec{A}/|\vec{A}|$, where $\vec{A}$ is given by [18],

$$\begin{aligned} \vec{A} = &\quad a_1(\xi)p_\mu - a_2(\xi)[\frac{p_\mu}{m_\mu}(m_K - E_\pi + \frac{p_\pi p_\mu}{|p_\mu|^2}(E_\mu - m_\nu)) + p_\pi] \quad (7)\\ &+ \quad Im(\xi)(p_\pi \times p_\mu). \quad (8)\end{aligned}$$

The form factors can be deduced by fitting the in-plane μ^+ polarization distribution. There are three published results but they have fairly large errors [19, 20, 21]. Needless to say the last term in Eq.(8) corresponds to the T-violating muon polarization being pursued in the TREK experiment.

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