The TREK Program at J-PARC

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Abstract

The TREK program at J-PARC in Japan consists of a series of experiments that have been proposed to use high-intensity kaon beams at the new J-PARC Hadron Facility and the upgraded apparatus of the E-246 experiment from KEK-PS. The low-energy positively charged kaons will be stopped, and their decays observed with a large acceptance toroidal spectrometer capable of tracking charged particles with high resolution, combined with a photon calorimeter and additional instrumentation with muon polarimeters. The first two experiments, requiring less beam intensity, aim to test lepton universality in the $K_{e2}/K_{\mu 2}$ ratio with $< 0.2\%$ statistical and $< 0.13\%$ systematic uncertainty, and to search for heavy sterile neutrinos (N) in two-body kaon decays $K^+ \to \mu^+ N$ with a sensitivity of $\mathrm{Br}(K^+ \to \mu^+ N)$ of 10^{-8}. As higher kaon intensity becomes available, the Time Reversal Experiment with Kaons (TREK) will be carried out aiming to find New Physics beyond the Standard Model by a precision measurement of the T-violating transverse polarization P_T of muons in the $K^+_{\mu 3}$ decay of stopped kaons. The sensitivity for P_T of 10^{-4} at J-PARC is improved by a factor of 20 compared to the current E-246 limit, well in the allowed range of various models involving New Physics from exotic scalar interactions. An overview of the planned experiments, the current project status and timeline will be discussed.

1 Search for Time Reversal Violation

The Standard Model is widely believed to be incomplete as it leaves several fundamental questions open such as the mechanisms of baryogenesis and electroweak symmetry breaking. Experimentally, it is of great interest to find evidence for New Physics beyond the Standard Model in accessible observables. To that extent, searches for violation of time reversal symmetry (T) have a long history. They provide an alternative means to search for violation of charge conjugation and parity (CP) based on the more general CPT theorem. New sources of CP violation beyond the existing ones in the neutral meson sector are a necessary condition for an explanation of the matter-antimatter asymmetry according to Sakharov's criteria [1].

Electroweak theory allows one to link T-odd observables (which change sign under time reversal transformation) to time reversal symmetry breaking, which can be interpreted as clear indication of New Physics. The transverse polarization P_T of muons in stopped K^+ decay in the $K^+_{\mu 3}$ mode ($K^+ \to \mu^+ \pi^0 \nu_\mu$) is such a long-recognized example [2] as depicted in Fig. 1. The matrix element for the semileptonic decay is written

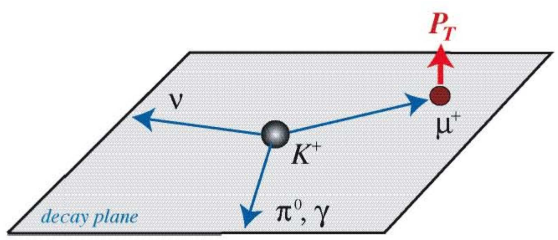

Figure 1: Transverse muon polarization P_T in $K^+_{\mu 3}$ decays at rest.

in $V - A$ theory as

$$M = \frac{G_F}{2} \sin\theta_c \; f_+(q^2) \left[2p_K^\lambda \cdot \bar{u}_\nu \gamma_\lambda (1-\gamma_5)\nu_\mu + (\xi(q^2) - 1) m_\mu \bar{u}_\nu (1-\gamma_5)\nu_\mu \right], \tag{1}$$

where the parameter $\xi(q^2)$ is defined as $\xi(q^2) = f_-(q^2)/f_+(q^2)$, involving the vector form factors f_+ and f_- which are functions of $q^2 = (p_K - p_\pi)^2$. If time reversal symmetry is conserved, $\xi(q^2)$ is real; the presence of T

violation gives rise to a non-vanishing imaginary part proportional to the T-odd transverse muon polarization

$$P_T \equiv \frac{\vec{\sigma}_\mu \cdot (\vec{p}_\pi \times \vec{p}_\mu)}{|\vec{p}_\pi \times \vec{p}_\mu|} = \mathrm{Im}\xi \cdot \frac{m_\mu}{m_K} \frac{|\vec{p}_\mu|}{E_\mu + |\vec{p}_\mu| \vec{n}_\mu \cdot \vec{n}_\nu - m_\mu^2/m_K}, \tag{2}$$

where $\vec{\sigma}_\mu$ is the polarization vector of the outgoing μ^+, and $\vec{p}_{\pi(\mu)}$ are the momenta of the outgoing π^0 and μ^+, respectively. The transverse muon polarization is maximal if the directions $\vec{n}_\mu$ and $\vec{n}_\nu$ are perpendicular.

The Standard Model prediction for P_T is extremely small, of order 10^{-7}, arising only from higher-order loop contributions [3]. Contributions from final-state interactions in the semi-leptonic mode are precisely calculable in terms of T-conserving multi-step processes and do not exceed 10^{-5} in the $K^+_{\mu 3}$ channel [4, 5]. On the other hand, models involving New Physics such as multi-Higgs doublet models, leptoquark models or supersymmetric models with R-parity breaking or s-quark mixing give rise to finite values of P_T ranging from 10^{-4} to 10^{-2} [6, 7, 8, 9].

The proposed Time Reversal Experiment with Kaons (TREK) at J-PARC [10] will be sensitive to P_T to the order 10^{-4}, thereby improving the current limit on P_T by a factor ~ 20 and probing deeply inside the window of New Physics in this channel, as illustrated in Fig. 2.

Experimentally, P_T can be measured by polarimetry of muons after identifying the $K^+_{\mu 3}$ decay mode in stopped K^+ decays. The proposed experiment TREK at J-PARC reuses most of the existing setup of the predecessor experiment E-246 at KEK-PS shown in Fig. 3, which had resulted in $P_T = -0.017 \pm 0.0023(stat) \pm 0.0011(syst)$ and $\mathrm{Im}\xi = -0.0053 \pm 0.0071(stat) \pm 0.0036(syst)$, corresponding to the current upper limits of $|P_T| < 0.005$ and $|\mathrm{Im}\xi| < 0.016$ (90% C.L.) [11].

For the experiment at J-PARC, a secondary K^+ beam with a momentum 0.8 GeV/c is stopped inside a scintillating fiber target. The kaons will be provided by the slowly extracted high-intensity proton beam of the J-PARC Proton Synchrotron impinging on a production target at the Hadron Facility. The design intensity of 9 μA of proton beam current at 30 GeV, corresponding to a beam power of $\sim$ 270 kW, will result in a flux of $\sim 2 \cdot 10^6$ kaons per second delivered to TREK, with a K/π ratio better than 1. The new secondary beamline was constructed and commissioned in fall 2010.

The kinematics of the $K^+_{\mu 3}$ decay mode is completely determined by measuring the energy and angle of the outgoing μ^+ (using a toroidal magnetic spectrometer and spatially sensitive tracking detectors) and the π^0 (using a large-acceptance CsI(Tl) calorimeter). The superconducting toroidal magnetic spectrometer has twelve sectors equally instrumented. The calorimeter is highly segmented, consisting of 768 crystals; it is used to reconstruct the π^0 from the angles and deposited energies of the two decay photons. It covers a solid angle of about 3π and is arranged with twelve slit openings aligned with each toroidal sector, to allow the outgoing charged muon to pass without any excessive materials along the track. In a second step, the polarization component of the outgoing μ^+ perpendicular to the decay plane (P_T) is determined in a muon polarimeter based on the measured direction of the emitted positrons in stopped $\mu^+ \rightarrow \mathrm{e}^+ \nu_e \bar{\nu}_\mu$ decays. The rotational symmetry of the arrangement helps reduce the systematic uncertainties.

The previous E-246 system will be upgraded to meet the requirements of statistical and systematic uncertainties of TREK. The higher kaon beam intensity at J-PARC in combination with an increased acceptance of the upgraded setup with a newly designed active muon polarimeter will improve the statistical error of P_T by a factor 20 to $\sim 10^{-4}$ in less than one year of running time. While the previous passive polarimeter consisted of a stack of muon stoppers between simple plastic scintillators to count the clockwise and counterclockwise emitted positrons, the new active muon polarimeter uses aluminum stopping plates parallel to

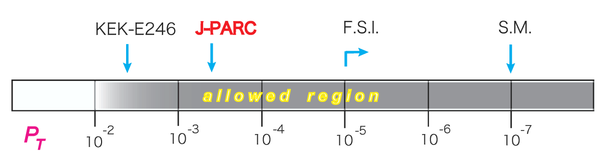

Figure 2: Sensitivity of P_T to New Physics. Also marked are the 90% confidence limits achieved by E-246 and projected for TREK at J-PARC.

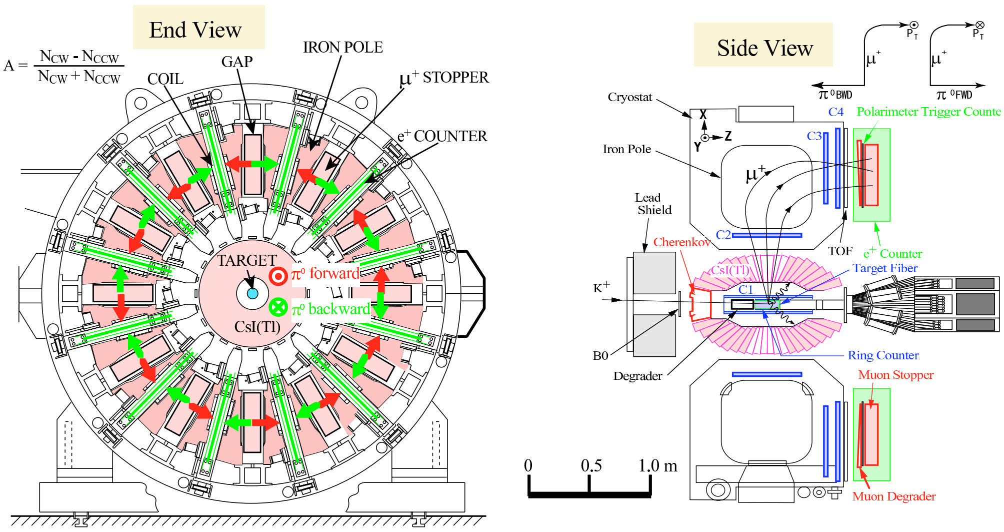

Figure 3: Schematic drawing of the E-246 apparatus to be reused by TREK in end view (left) and side view (right). The T-violating asymmetry is recorded from different positron count rates in clockwise and counterclockwise direction. Distinguishing between forward and backward pions corresponds to flipping of the decay plane, leading to a sign change of the asymmetry.

the muon path, with the intermediate space between the plates designed as a wire chamber. This design results in a substantially larger solid angle acceptance to detect the decay positrons with good angular and energy resolution. It also allows us to determine the position of the stopped muon and thereby to eliminate the previous systematic uncertainty of P_T due to the muon stopping distribution. In addition, a dedicated homogeneous holding field is used to ensure a polarization alignment relative to the field.

The higher count rates in TREK require a faster readout of the CsI(Tl) calorimeter, which will be based on avalanche photo diodes (APD) with new current amplifiers. The kaon stopping target has been redesigned with smaller diameter and higher segmentation by using a bundle of 492 scintillating fibers each 3 mm thick, resulting in a 7.5 cm diameter target. Promising tests of performance and radiation hardness have been conducted with multi-pixel photon counters (MPPC) as a novel fiber readout technology, which will be adopted for the new target.

It has been demonstrated with detailed simulations that the systematic uncertainties of P_T can be reduced to $< 10^{-4}$. Alignments of tracking elements and the polarimeter will be calibrated with real tracks. The tracking capability for charged particles will be improved near the target region in order to identify and suppress backgrounds from charged pion tracks decaying in flight which resemble true $K^+_{\mu 3}$ events and which can cause spurious asymmetries. Identifying this class of events is only possible by adding near-target tracking elements in the field-free inner region of the toroid, which requires robust technology in the high-rate environment expected at J-PARC. Therefore, the charged tracking upgrade will be based on the novel Gas Electron Multiplier (GEM) technology [12]. The anticipated tracking upgrade for TREK is illustrated in Fig. 4. It is envisioned to construct a cylindrical GEM tracking detector (C0), surrounding the target assembly inside the CsI(Tl) calorimeter barrel, as well as additional planar GEM elements (C1) to cover the muon gaps outside the barrel in each of the twelve sectors. In addition, it is planned to fill previous large air gaps with He bags to reduce multiple scattering effects.

In summary, a new generation of the experimental search for T-violating transverse muon polarization in the stopped-kaon decay has been proposed with TREK at J-PARC. The sensitivity of TREK will improve the current upper limit of P_T by at least a factor 20. The proposed experiment uses the previous E-246 apparatus after applying upgrades to various components.

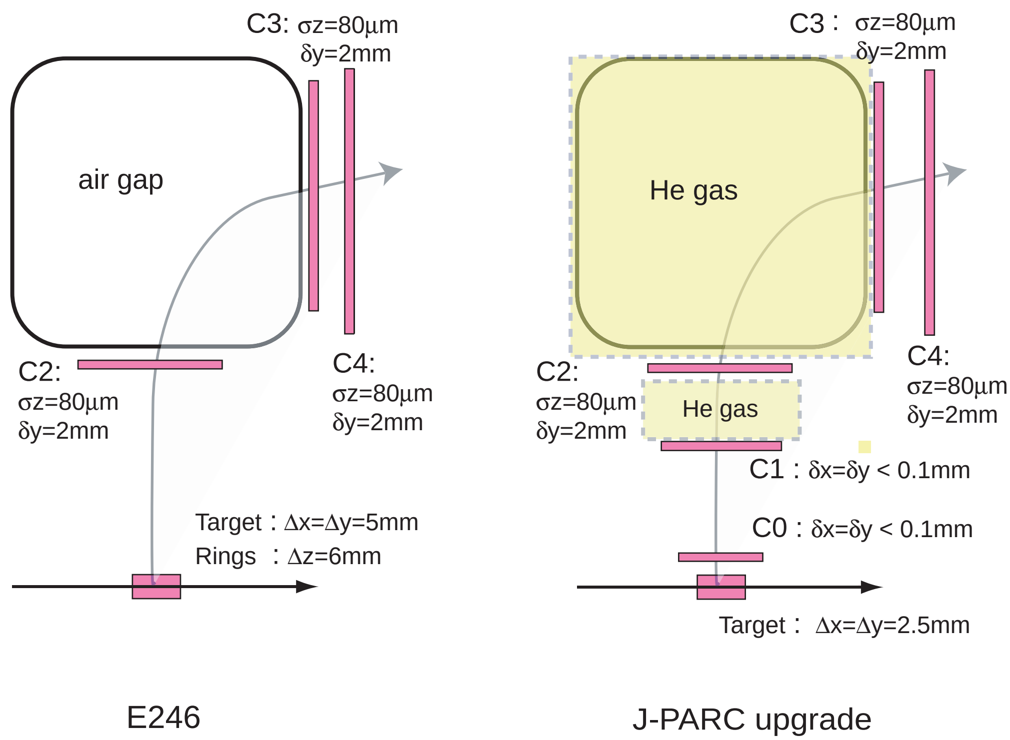

Figure 4: Proposed upgrade of the charged-particle tracking system.

2 Test of Lepton Flavor Universality by Precise Measurement of $\Gamma(K^+ \to e^+\nu)$ / $\Gamma(K^+ \to \mu^+\nu)$

High precision electroweak tests represent a powerful tool to test the Standard Model (SM) and to obtain indirect hints of new physics. The $K^+ \to l^+\nu_l$ decays (K_{l2}) are very well suited to perform such tests. Lepton universality, which is expressed as the identical coupling constant of the three lepton generations – the electron, muon, and tau – is a basic assumption in the SM. Violation of lepton universality clearly indicates the existence of new physics beyond the SM. The matrix element of K_{l2} decays can be described as

$$M = g_l \frac{G_F}{\sqrt{2}} q^\lambda f(q^2)[u_l \gamma_\lambda (1-\gamma_5) u_\nu] = g_l \frac{G_F}{\sqrt{2}} f_K m_l u_l (1-\gamma_5) u_\nu \tag{3}$$

where g_l is the coupling constant for the lepton current and g_e/g_μ should be unity under the assumption of lepton universality. The hadronic form factor $f(q^2)$ is a function of the momentum transfer squared (q^2). However, in the present case, $q^2 = m_K^2$ and $f(m_K^2) = f_K$ is a constant. The K_{l2} decay diagrams are shown

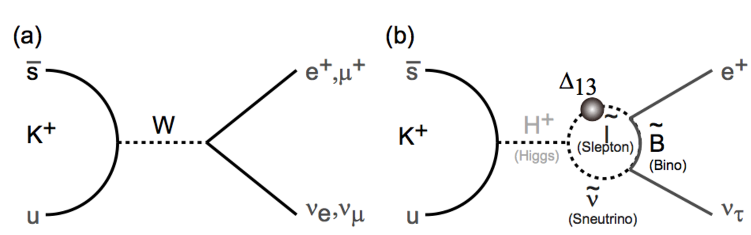

Figure 5: Contributions to R_K from (a) SM and (b) LFV SUSY effect. A charged Higgs-mediated LFV SUSY contribution can be strongly enhanced by emission of a τ neutrino.

in Fig. 5. The hadronic form factor is canceled in the ratio of the electric (K_{e2}) and muonic ($K_{\mu 2}$) decay modes as,

$$R_K^{SM} = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1+\delta_r) = (2.477 \pm 0.001) \times 10^{-5}, \quad (4)$$

under the assumption of $\mu - e$ universality. Conversely, this ratio can provide a test of $\mu - e$ universality as, $g_\mu/g_e = (R_K^{exp}/R_K^{SM})^{1/2}$. Here, the numerical value comes from inserting the particle masses into Eq. (2). The correction term δ_r is due to the internal bremsstrahlung process (IB) which is, unlike the structure dependent process (SD), by definition included in R_K. The factor $(m_e/m_\mu)^2$ accounts for the helicity suppression of K_{e2} decay due to the V-A structure of the charged weak current, and, in other words, enhances the sensitivity to effects beyond the SM. As a result, the SM prediction of R_K^{SM} is known with excellent accuracy ($\Delta R_K/R_K \approx 0.4 \times 10^{-3}$) and this makes it possible to search for new physics effects by a precise measurement of R_K . The current world average is $R_K = (2.488 \pm 0.010) \times 10^{-5}$ which is composed of the recent NA62 [13] and KLOE [14] experiments. In order to further improve the experimental precision, we have proposed a new experiment to measure R_K with an accuracy of $\Delta R_K/R_K = 0.2\%$ at J-PARC [15]. There is a good chance that the LHC will discover new elementary particles such as various supersymmetric (SUSY) particles soon. Recently, a minimal SUSY extension of the SM (MSSM) with R parity has been considered as a candidate for new physics to be tested by R_K [16]. In the case of K_{l2}, in addition to the normal $W^\pm$ exchange shown in Fig. 5, a possible mechanism to detect the LFV SUSY effect through a deviation from the $\mu - e$ universality has been discussed. A charged Higgs-mediated LFV SUSY contribution can be strongly enhanced by emitting a τ neutrino. This non-vanishing $e - \tau$ lepton mixing effect can be described as,

$$R_K^{LFV} = R_K^{SM}\left(1 + \frac{m_K^4}{m_{H^+}^4} \cdot \frac{m_\tau^2}{m_e^2}\Delta_{13}^2 \tan^6\beta\right), \quad (5)$$

where M_{H^+} is the mass of the charged Higgs. The term Δ_{13} is induced by the exchange of a Bino and a slepton, which represents the contribution of the LFV effect generated from the off-diagonal flavor changing entries of the slepton mass matrix. A large enhancement factor m_τ^2/m_e^2 can produce a sizable effect in R_K through a change of the K_{e2} decay width. Thus, it is possible to reach a contribution at the percent level thanks to the possible LFV enhancements arising in SUSY models.

The new experiment will be performed with the TREK apparatus at J-PARC employing a stopped K^+ beam. The technique is different from the NA62 and KLOE experiments which used the in-flight-kaon decay method. The K_{e2} ($p_{e+} = 247$ MeV/c) and $K_{\mu 2}$ ($p_{\mu^+} = 236$ MeV/c) events will be detected using the TREK toroidal spectrometer. In order to compare the experimental R_K value with the SM prediction, the internal bremsstrahlung process in radiative $K^+ \to e^+\nu\gamma$ ($K_{e2\gamma}^{IB}$ and $K^+ \to \mu^+\nu\gamma$ ($K_{\mu 2\gamma}^{IB}$ decays must be included into the K_{e2} and $K_{\mu 2}$ samples, respectively. The R_K value is derived from the number of the accepted K_{e2} and $K_{\mu 2}$ events by correcting for the detector acceptance. Charged particles from the kaon stopping target will be tracked and momentum- analyzed using one GEM detector and three multi-wire proportional chambers in each toroidal sector. The K_{e2}, $K_{\mu 2}$, and their radiative decays will be collected for a central magnetic field of the spectrometer, $B = 1.4$ T. In order to remove $K^+ \to \pi^0 e^+\nu(K_{e3})$ and $K^+ \to \pi^0\mu^+\nu(K_{\mu 3})$ backgrounds, the K_{e2} and $K_{\mu 2}$ events are identified by requiring the e^+ and μ^+ momentum to be higher than the K_{e3} and $K_{\mu 3}$ endpoints ($p_{max} = 228$ and 215 MeV/c). Particle discrimination between e^+ and μ^+ will be carried out using aerogel Cherenkov (AC) counters and by measuring the time-of-flight (TOF) between the TOF1 and TOF2 scintillation counters. The TOF1 and AC counters surround the fiber target, and the TOF2 counters are located at the exit of the spectrometer.

The $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$ ratio can be obtained from the number of accepted events (N), $\tilde{K}_{e2} = K_{e2} + K_{e2}^{IB}$ and $\tilde{K}_{\mu 2} = K_{\mu 2} + K_{\mu 2}^{IB}$, corrected for the detector acceptance. The acceptance ratio can be calculated by a Monte Carlo simulation. It is to be noted that the analysis procedure is exactly identical for both K_{e2} and $K_{\mu 2}$ except for the particle identification in order to reduce the systematic error due to the analysis. The statistical error of the R_K value will be dominated by that of the accepted K_{e2} events because the BR$(K_{\mu 2})/BR(K_{e2}) \approx 105$. Here, we assume 30 kW operation of the J-PARC Main Ring which corresponds to 220 kHz of kaon beam intensity at the K^+ target position. The number of K_{e2} events is estimated by assuming 50 days data collection as $\approx 250 \times 103$ corresponding to a statistical error of $\Delta R_K = 0.0054$ ($\Delta R_K/R_K = 0.2\%$). We considered systematic errors due to (1) uncertainty of the detector acceptance ratio, (2) imperfect reproducibility of the experimental conditions by a Monte Carlo simulation, (3) performance of particle identification, and (4) background contamination. The total systematic error is obtained to be $\Delta R_K/R_K = 0.13\%$ by adding all items in quadrature. We will make an effort to reduce the systematic uncertainties down to about half of the statistical uncertainty.

3 Search for Heavy Sterile Neutrinos Using the TREK detector

In the search for physics beyond the Standard Model (SM), one can use different types of guidelines. A possible strategy is the attempt to explain phenomena that are not described by the SM by minimal extensions, 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), where three light singlet right-handed neutrinos (sterile neutrinos) are introduced. The νMSM provides a framework to explain neutrino oscillations, dark matter as sterile neutrinos, and the baryon asymmetry induced from leptogenesis via sterile neutrino oscillation. The SM is originally formulated with massless neutrinos as components of the electroweak SU(2) doublets. To accommodate the neutrino masses, one can add several electroweak singlets to build the seesaw Lagrangian as, $L_{\nu MSM} = L_{SM} + N_I i d_\mu \gamma^\mu N_I - F\alpha I L_\alpha N_I \Phi - M N_2 N_3 - \Delta M_{IJ}/2N + IN_J$ + h.c., where N_I are the right-handed singlet leptons, Φ and L_α (α = e, μ, τ) are the Higgs and lepton doublet, F is the matrix of Yukawa couplings, and M is the common mass of two heavy neutral fermions. ΔM_{IJ} are related to the mass of the lightest sterile neutrino N_1 responsible for Dark Matter (DM). Also, Δ_{IJ} produces the small splitting of the masses of N_2 and N_3. 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. All of the sterile neutrinos have masses below the electroweak scale: one has a mass of the order of a few keV, while the two remaining sterile neutrinos are assumed to be closely degenerate at a scale of about 0.1-10 GeV. The lightest singlet fermion N_1 may have a lifetime greatly exceeding the age of the Universe and may thus play the role of a DM particle. The DM sterile neutrino is likely to have a mass in the keV region. Within the framework of the νMSM, the baryon asymmetry can be naively explained though CP-violating sterile neutrino oscillation in the Early Universe. The kinetics of these oscillations and the transfer of lepton number between active and sterile neutrino sectors has been considered. For masses of sterile neutrinos exceeding ≈ 20 GeV, the mechanism does not work as the sterile neutrinos equilibrate. 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 confirm or rule out the νMSM with light sterile neutrino by kaon decay experiments.

4 Timeline

J-PARC is in the process of recovering from the March 2011 earthquake. Beam operation of the main ring is scheduled to resume again in December 2011. It is anticipated that the 50 kW slowly extracted beam at 30 GeV will become available by 2014, and > 100 kW by 2015. The lepton flavor universality test and heavy sterile neutrino search will be carried out first, before the final upgrade of the TREK apparatus is implemented in preparation for the T-violation run at full intensity.

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