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2017 J. Phys.: Conf. Ser. 800 012020

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Search for the rare decays $K^+ \rightarrow \mu^+ X$ in E949 experiment

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Abstract. The existence of a heavy neutrino, ν_H , in the $K^+ \rightarrow \mu^+ \nu_H$ decays was tested using the E949 experimental data with an exposure of 1.70×10^{12} stopped kaons. The allowed heavy neutrino mass region for the analysis is from $175 \text{ MeV}/c^2$ to $300 \text{ MeV}/c^2$. With major background from the radiative $K^+ \rightarrow \mu^+ \nu_\mu \gamma$ decay understood and suppressed, the preliminary new upper limits (90% C.L.) on the neutrino mixing matrix element between muon and heavy neutrino, $|U_{\mu H}|^2$, were set at the level of 10^{-8} to 10^{-9} . New limit on the $K^+ \rightarrow \mu^+ \nu \bar{\nu} \nu$ branching ratio assuming Standard Model muon spectrum is set to be 2.4×10^{-6} .

1. Introduction

The Standard Model (SM) has been tested experimentally with high precision, but some phenomena cannot be explained in the SM framework: the neutrino oscillations experiments [1] confirm that neutrino have a mass and undergo mixing (while in the SM all neutrinos, ν_e , ν_μ , ν_τ , are massless). In other words, the weak eigenstates ν_e , ν_μ , ν_τ are linear superposition of the mass eigenstates ν_1 , ν_2 , ν_3 . The SM also cannot explain baryon asymmetry of the Universe and dark matter. So far we know that there is a new physics beyond the SM, but we do not know exactly what is it. To search for new physics we are able either search for new particles (unpredicted by the SM) or search for rare processes and compare measured probabilities of these processes with the SM predicted ones.

An extension of the SM by three singlet fermions with masses smaller than the electroweak scale without adding any new physical principles (such as supersymmetry or extra dimensions) or new energy scales (like Grand Unified scale) allows to explain simultaneously the phenomena that cannot be fit to the SM. An example of such a theory is the renormalizable extension of the SM, the ν MSM (neutrino Minimal Standard Model) [2, 3]. In this model, the lightest sterile neutrino, ν_{H1} , is likely to have a mass in the $\mathcal{O}(10) \text{ keV}/c^2$ region and is sufficiently stable to be a viable dark matter candidate. The masses of ν_{H2} and ν_{H3} should lie in the range from $\sim 150 \text{ MeV}/c^2$ to $\sim 100 \text{ GeV}/c^2$ and should be degenerate ($\Delta M_{2,3} \ll M_{2,3}$) to generate baryon asymmetry of the Universe.

Two strategies can be used for the experimental search of these particles. The first one is related to their production. Since they are massive, the kinematics of two body decays $K^\pm \rightarrow \mu^\pm \nu_\mu$ and $K^\pm \rightarrow \mu^\pm \nu_H$ is not the same. So the study of kinematics of rare meson decays can constrain the strength of the coupling of heavy leptons using the following expression [4]:

$$\Gamma(M^+ \rightarrow l^+ \nu_H) = \rho \Gamma(M^+ \rightarrow l^+ \nu_l) |U_{lH}|^2, \quad (1)$$



where $M = \pi, K$; $l = e, \mu, \rho$ is a kinematical factor and lies in the range from 1 to 4 for $0 < m_{\nu_H} < 300 \text{ MeV}/c^2$. The second strategy is to look for the decays of heavy leptons to hadrons and leptons.

The best constraints in the small mass region $m_{\nu_H} < 450 \text{ MeV}$ are coming from CERN PS191 experiment [5], giving roughly $|U_l H|^2 < 10^{-9}$ in the region $250 \text{ MeV}/c^2 < m_{\nu_H} < 450 \text{ MeV}/c^2$. The successful predictions of the Big Bang Nucleosynthesis (BBN) allow to establish a number of lower bounds on the couplings of neutral leptons [6, 7] which decrease considerably the admitted window for the couplings and masses of the neutral leptons.

The $K^+ \rightarrow \mu^+ \nu \bar{\nu} \nu$ decay involves four fermions and cannot occur in first order in the SM. Therefore, its investigation provides information about higher-order weak effects. The most recent calculation of this process in the framework of the SM has been done by D. Gorbunov and A. Mitrofanov [8]. The SM predicts an extremely low total rate for this process ($\mathcal{O}(10^{-16})$) and any observed signal would be a clear evidence of new physics. This decay has been searched by one only experiment in 1973 [9], no evidence was found and upper limit $BR(K^+ \rightarrow \mu^+ \nu \bar{\nu} \nu) < 6.0 \times 10^{-6}$ at 90% C.L. was set.

In this paper, we present result of a search for heavy neutrinos in $K^+ \rightarrow \mu^+ \nu_H$ decays from the inclusive muon spectrum of $K^+ \rightarrow \mu^+ + \text{nothing}$ decays and search for rare decay $K^+ \rightarrow \mu^+ \nu \bar{\nu} \nu$ using the kaon decay-at-rest data from the E949 experiment [10].

2. E949 experiment

The E949 K^+ beam was produced by a high-intensity proton beam from the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory (BNL). Protons were accelerated to a momentum of 21.5 GeV/c and hit a platinum production target.

The E949 detector had axial symmetry in beam direction (z -axis) and consisted of several components. Kaons were identified by the Čerenkov counter before the target. Incoming 710 MeV/c kaons stopped and decayed in scintillating fiber target. The momentum and trajectory of the outgoing charged particles were measured in drift chamber. These particles came to rest in a Range Stack (RS) of 19 layers of plastic scintillator. The primary functions of the RS were energy and range measurements of charged particles and their identification. The detection of any activities coincident with the charged track was very important for suppressing the backgrounds for $K^+ \rightarrow \mu^+ \nu_H$ decay. Photons from $K_{\pi 2}$, $K_{\mu \nu \gamma}$, $K_{\mu 3}$ and other radiative decays were detected by hermetic photons detectors with $\simeq 4\pi$ solid angle coverage.

2.1. The trigger

The experimental signature of the $K^+ \rightarrow \mu^+ \nu_H$ and $K^+ \rightarrow \mu^+ \nu \bar{\nu} \nu$ decays is the same as for the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay (one single charged track with no any detector activity). That's why we decided to use the main E949 trigger. It consisted of several requirements. First of all, a kaon must enter the target. To be sure that the kaon decayed at rest, the secondary charged particle must leave the target at least 1.5 ns later than the kaon hit in the Čerenkov detector. The 3-body K^+ decays were suppressed by the RS layer requirements. The charged particle must reach at least the sixth layer of the RS. The long tracks (in general, $K_{\mu 2}$ decay) were suppressed by the layer 19 veto requirement. There were also additional refined requirements of the charged track range taking into account the number of target fiber hits and the track's downstream position (z -coordinate) in RS layers 3, 11, 12, 13 as well as the deepest layer of penetration (refined range). The charged track must be within the fiducial region of all traversed RS layers.

The main E949 trigger included the online pion identification in the RS. It required a signature of $\pi^+ \rightarrow \mu^+$ decay in the online-selected stopping counter. The μ^+ from the $\pi^+ \rightarrow \mu^+ \nu_\mu$ decay at rest had the kinetic energy of 4 MeV (few mm equivalent range in plastic scintillator) and rarely exited the stopping counter. So, pion pulses in the stopping counter recorded by the

transient digitizers (TDs) had a double-pulse structure. Despite the online pion identification requirement, some muons remained in the final sample due to inefficiency.

Events were rejected if any activity in the photon detectors with energy above a threshold was detected. This condition removed events with photons. A similar requirement in the RS was also applied. The 24 sectors of the RS are conventionally grouped into six; a group of 4 sectors is called a "hexant". Only one hexant was allowed to have hits or two hexants if they were adjacent. This rejected events with multiple tracks and events with photon activity in the RS.

More detail description of the E949 experiment may be found in [10].

3. Data analysis

3.1. Total acceptance

In addition to the trigger requirements described above, we used several groups of offline cuts to select single muon track. The kinematic cuts were used to select events in the detector fiducial volume. Beam cuts were applied to identify incoming particle as a kaon and suppress extra beam particles at the track time. To suppress kaon decay-in-flight we applied delay coincidence cut. Numerous requirement were placed on the activity in the target to suppress background and ensure a reliable determination of the kinematic properties of the charged muon. Range-momentum cut was changed to select muons. In the main E949 analysis it was designed to check whether the range of a charged track is consistent with that for pions. To suppress photon activity in the detector we applied photon veto cut (loose for the background study and tight for the final result).

Acceptance for the $K^+ \rightarrow \mu^+ \nu_H$ decay was measured using Monte-Carlo simulation and monitor triggers. The single event sensitivity (S.E.S.) for the heavy neutrino with mass $m_{\nu_H} = 250 \text{ MeV}/c^2$ can be calculated as

$$S.E.S. = \frac{1}{Acc \times N_K} = 7.35 \times 10^{-10}, \quad (2)$$

where Acc is the total acceptance efficiency and N_K is the total number of stopped kaons. This sensitivity is roughly constant for the whole investigated region (Fig. 1).

To verify our acceptance measurement we calculated $K_{\mu 2}$ and $K_{\mu \nu \gamma}$ branching ratios. The $K_{\mu 2}$ branching ratio was measured to be 0.54 ± 0.15 and it is consistent with PDG value (0.6355 ± 0.0011) within the error [1]. The $K_{\mu \nu \gamma}$ branching ratio was measured to be $(1.3 \pm 0.4) \times 10^{-3}$ for $140 < p_\mu < 200$ and is also consistent with PDG value $((1.4 \pm 0.2) \times 10^{-3})$ for the same muon momentum region [1].

3.2. Residual background

The search for $K^+ \rightarrow \mu^+ \nu_H$ consists in a searching for additional peak below $K_{\mu 2}$ peak. So we should well understand all background sources that can fake or cover our signal. We simulated the main background sources, $K_{\mu \nu \gamma}$, $K_{\mu 3}$ and $K_{\pi 2 \gamma}$ decays. After trigger requirements and offline selection criteria the $K_{\mu 3}$ contribution in the total number of background events is less than 1% of the $K_{\mu \nu \gamma}$ contribution due to two photons in the final state. The $K^+ \rightarrow \pi^+ \pi^0 \gamma$ decay can be ignored due to three photons in the final state and large range-momentum pion rejection. Therefore, the $K^+ \rightarrow \mu^+ \nu_\mu \gamma$ is the dominant background source for the search of the $K^+ \rightarrow \mu^+ \nu_H$ decay.

Given the agreement between the PDG values and our $K^+ \rightarrow \mu^+ \nu_\mu$ and $K^+ \rightarrow \mu^+ \nu_\mu \gamma$ branching ratio measurements, the experimental muon momentum spectra and the simulated $K_{\mu 2} + K_{\mu \nu \gamma}$ muon momentum spectra can be compared. To add $K_{\mu 2}$ and $K_{\mu \nu \gamma}$ decays together we take into account their branching ratios and the number of simulated events.

The dependence of acceptance after all cuts on the muon momentum and comparison between experimental (5% all data) and simulated muon momentum shape are shown in Fig. 1. There

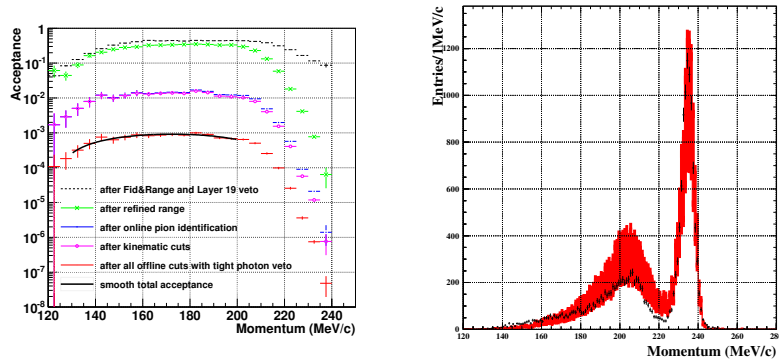


Figure 1. (Left) The dependence of acceptance on the muon momentum for the $K^+ \rightarrow \mu^+ \nu_H$ decay. (Right) Comparison between experimental (5% all data) and simulated muon momentum shape (in color).

are some discrepancies between data and MC in the muon momentum spectrum. Between 200 MeV/c and 220 MeV/c, the radiative gamma energy is low, the difference is caused by the difficulty in simulating detector activity or electronic noise of the low photon veto cut threshold. Beyond 220 MeV/c, it is caused by the uncertainty of layer 19 and refined range cuts.

Below 200 MeV/c, the simulated and experimental spectra are consistent, but MC is not the best fit of the data. Since the simulated shape does not show obvious bumps or valleys, we assume that the experimental background shape is also smooth.

3.3. Results

To search for additional peaks below the main $K_{\mu 2}$ peak we used asymptotic formula for the distribution of a test statistic, which was derived using the results of Wilks and Wald [11]. The method is a frequentist approach which is free of computationally expensive Monte Carlo calculations and is able to consider the shape of the signal. It thus avoids the ambiguity of selecting a signal region. Besides the mean value of the upper limit, an error band of the upper limit can be also calculated. The main feature of this approach is artificial data set (Asimov). An Asimov data set was used to evaluate the expected upper limit and its error band. For the heavy neutrino searching in this paper, the Asimov data set is the background-only expectation assuming no heavy neutrino signal in the region under test. The background shape was determined directly by fitting the momentum spectrum of data after all criteria. To avoid artificial peaks or valleys in the signal region, the range $\pm 6\sigma$ (the σ is the momentum resolution which is known from MC simulation) around the point of interest was chosen to fit for background with a second order polynomial function. With known background shape we are able to estimate expected number of background events in each bin in the testing region.

The muon momentum spectrum for the full data sample after all cuts and peak search result are shown in Fig. 2.

Since the observed upper limit is within the error band of the expected upper limit there is no evidence for a heavy neutrino signal.

The preliminary upper limit on mixing matrix element $|U_{\mu H}|^2$ set by this experiment is shown in Fig. 3. More details about heavy neutrino search in E949 experiment can be found in [13].

The final data set (Fig. 2 (left)) can be also used to constrain any decays $K^+ \rightarrow \mu^+ X$, where X is invisible (not detectable) set of neutral particles. Unfortunately, we cannot predict number

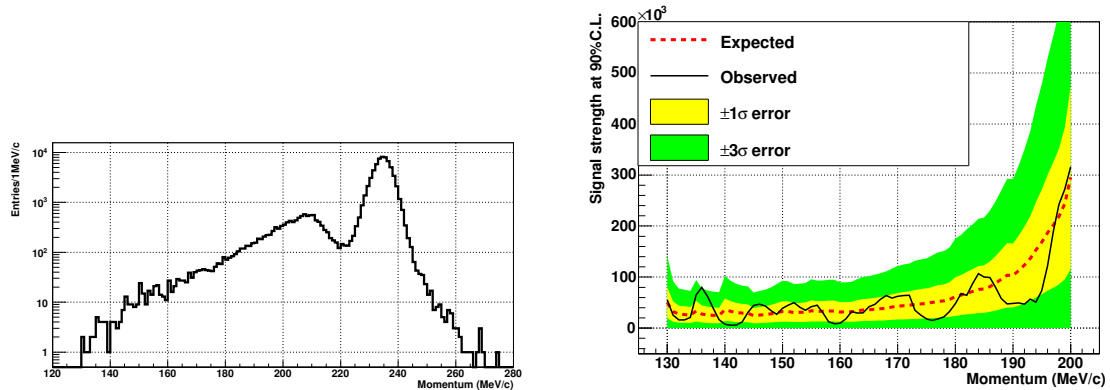


Figure 2. (Left) Muon momentum spectrum for the full data after all cuts applied. (Right) 90% C.L. expected upper limit with a $\pm 1\sigma$ error band and 99.8% C.L. error band. The black line is the observed upper limit result.

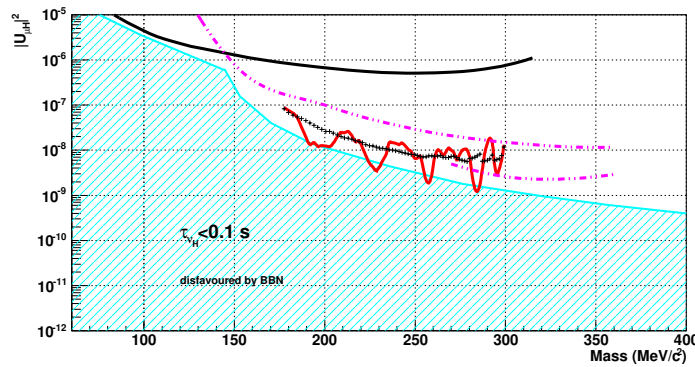


Figure 3. The preliminary upper limits on the mixing matrix element $|U_{\mu H}|^2$ set by this experiment (solid red curve, black crosses show expected upper limit) and others. Solid smooth black line shows the result of the peak search in kaon decays [12], dotted magenta lines show the results of the heavy neutrino decay experiment CERN PS191 [5] in two modes: top dotted line is derived from $K^+ \rightarrow \mu^+ \nu_H \rightarrow \mu^+ (\mu^- e^+ \nu_e) + c.c.$, bottom dotted line is derived from $K^+ \rightarrow \mu^+ \nu_H \rightarrow \mu^+ (\mu^- \pi^+) + c.c.$ The shaded region shows one of the possible BBN lower bounds [6, 7].

of background events with high precision, so we extract upper limit on the $K^+ \rightarrow \mu^+ X$ branching ratio assuming that all observed events is a signal (zero expected background). Acceptance for the single muon for different momentum is already known (Fig. 1 (left)). The lowest bound of the signal region, 130 MeV/c, was selected due to the acceptance drop off. The number of observed events is drastically increased with muon momentum. So, the upper bound of the signal region, 175 MeV/c, was selected to correspond to the previous experimental search for the decay $K^+ \rightarrow \mu^+ \nu \bar{\nu}$ ([9]). We get the following upper limit on the partial $K^+ \rightarrow \mu^+ X$ branching ratio:

$$BR(K^+ \rightarrow \mu^+ + X, 130 < p_\mu < 175 \text{ MeV/c}) < 7.5 \times 10^{-7} \quad (3)$$

For any assumed muon spectrum the total decay rate on the $K^+ \rightarrow \mu^+ \nu \bar{\nu}$ decay (or any other decay with single muon and set of invisible neutral particles) can be calculated using the

following expression:

$$\frac{\Gamma(K^+ \rightarrow \mu^+ \nu \bar{\nu} \nu)}{\Gamma(K^+ \rightarrow \text{all})} = 7.5 \times 10^{-7} \times \frac{\int_0^{p_\mu^{\max}} (d\Gamma/dp_\mu) dp_\mu}{\int_{130}^{175} (d\Gamma/dp_\mu) dp_\mu} \quad (4)$$

where p_μ^{\max} is the maximum muon momentum defined by kinematics ($p_\mu^{\max} = (m_K^2 - m_\mu^2)/2m_K$). Using the SM spectrum [8] we get the following 90% C.L. upper limits on the total decay rate for $K^+ \rightarrow \mu^+ \nu \bar{\nu} \nu$ decay:

$$\frac{\Gamma(K^+ \rightarrow \mu^+ \nu \bar{\nu} \nu)}{\Gamma(K^+ \rightarrow \text{all})} < 2.4 \times 10^{-6} \quad (5)$$

More details about search for the $K^+ \rightarrow \mu^+ \nu \bar{\nu} \nu$ decay in E949 can be found in [14].

4. Conclusion

The result of the search for heavy neutrinos in the $K^+ \rightarrow \mu^+ \nu_H$ decay channel using the E949 data sample in an exposure of 1.70×10^{12} stopped kaons is presented. Since no evidence for extra peaks below the main $K^+ \rightarrow \mu^+ \nu_\mu$ peak was found we set preliminary upper bounds on the mixing matrix element $|U_{\mu H}|^2$ in the mass region 175–300 MeV/ c^2 . In contrast to the CERN PS191 or BBN bounds our result is model-independent because we did not make any assumptions about heavy neutrino decay rates or couplings. Using the same data sample the upper limit on the $K^+ \rightarrow \mu^+ \nu \bar{\nu} \nu$ branching ratio in the SM framework was set to be 2.4×10^{-6} which is about factor of 3 better than the current results from [9].

Acknowledgments

This research was supported in part by Grant #14-12-00560 of the Russian Science Foundation, the U.S. Department of Energy, the Ministry of Education, Culture, Sports, Science and Technology of Japan through the Japan-U.S. Cooperative Research Program in High Energy Physics and under Grant-in-Aids for Scientific Research, the Natural Sciences and Engineering Research Council (Grant no. 157985) and the National Research Council of Canada, National Natural Science Foundation of China, and the Tsinghua University Initiative Scientific Research Program.

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