Search for heavy neutrino in leptonic decays of $K^+$

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Abstract. A high statistics data sample of the $K^+ \rightarrow \mu^+ \nu_\mu$ decay was recorded in 2012 by the OKA collaboration. The missing mass analysis was performed to search for a decay channel $K^+ \rightarrow \mu^+ \nu_H$ with a stable heavy neutrino in the final state. The obtained missing mass spectrum did not reveal statistically significant peaks corresponding to stable heavy neutrinos in the mass range $(220 < m_{\nu_H} < 375)$ MeV/c$^2$. Instead, we update upper limits on the branching ratio and on the value of the mixing element $|U_{\mu H}|^2$.

1. Introduction
It was proposed several decades ago [1], that experimental investigation of two body weak leptonic decays of charged kaons (and pions) could provide sensitive test for neutrino mass and mixing with help of peak search method on a missing mass plot, especially in hypothetical cases in which the spectrum of neutrino masses can be thought to be extended up to several MeV/c$^2$. Several approaches were exploited to search for heavy neutrinos (HN): via modification of beta decay spectrum, attempts to measure an excess in yield due to possible decay products of HN (or appearance in beam dump experiments), with the peak search at missing mass distributions, see reviews [2,3]; they gave negative results on admixture of heavy neutrinos to either electron or to muon neutrinos. A revised view on cosmological considerations [4] consistent with observed non zero masses and oscillations of active neutrinos put new arguments to search for heavy (sterile) neutrinos with emphasis to the mass range from $\sim 150$ MeV/c$^2$ to $100$ GeV/c$^2$ [5, 6]. Two nowadays experiments [7, 8] analyzed their data on $K \rightarrow \mu\nu$ decay to search for stable heavy neutrino in mass range of few hundred MeV/c$^2$ and improved upper limit on the $|U_{\mu H}|^2$ known from the early experiment [9]. To contribute to this series of investigations we analyzed large data sample obtained in 2012 by the OKA experiment.

2. The OKA setup
The OKA is a fixed target experiment dedicated to investigation of kaon decays it is located at NRC "Kurchatov Institute"-IHEP in Protvino (Russia). A secondary hadron beam with enhanced fraction of kaons is obtained from the U-70 Proton Synchrotron through the beam line equipped by two (obtained from CERN SPS [11]) RF separator cavities according to Panofsky scheme [10].

The OKA setup makes use of two magnetic spectrometers placed along the beam line with an $11$ m long Decay Volume (DV) enclosed between them, see figure 1. The DV is filled with helium

1 Or assuming "disappearance" decay modes like $\nu_H \rightarrow \nu_e \nu_\mu \bar{\nu}_e$ into active neutrinos ($\nu_e, \nu_\mu, \nu_\tau$ instead of $\nu_\xi, \nu_\epsilon$).
and contains 11 rings of guard system (GS) at its outer surface, made of 670 Lead-Scintillator sandwiches. It is complemented by an electromagnetic calorimeter BGD (with a central opening).

![Figure 1. Schematic elevation view of the OKA setup. See text for details.](image)

The first magnetic spectrometer measures incoming beam particles. It consists of magnet $M_1$ surrounded by a set of (beam) proportional chambers $BPC_{(1Y,2Y,2X,3X,3Y,4X,4Y)}$. The second spectrometer is dedicated to charged decay products. It consists from a wide aperture $200 \times 140$ cm² spectrometric magnet and surrounded by tracking stations: proportional chambers $PC_{(1,...,8)}$, straw tubes $ST_{(1,2,3)}$ and by drift tubes $DT_{(1,2)}$. In addition a matrix hodoscope $HODO_{(matrix)}$ is used to improve time resolution and to link $x$–$y$ projections of a track.

At the end of the setup there are two calorimeters: the electromagnetic one (GAMS-2000 – made of lead glass blocks), and the hadron one (HCAL$_{(GDA)}$ – made of 100 iron-scintillator sandwiches) and, finally, four partially overlapping ($1 \times 1$ m² scintillator plate each) muon counters $\mu C$ behind the HCAL.

Trigger logic used in the analysis is organized upon a following set of detectors:
- beam trigger part is based on four scintillation counters $S_{1} \cdot S_{2} \cdot S_{3} \cdot S_{4}$ (200 $\times$ 200 $\times$ 1 mm³ each), and a thicker one, 60 $\times$ 85 $\times$ 6 mm³, delivering timing, $S_{(3)}$;
- the identification of beam kaon is done with a set of two threshold Cherenkov counters $\tilde{C}_{1} \cdot \tilde{C}_{2}$, while $\tilde{C}_{3}$ was not used in this run;
- suppression of events with undecayed beam particles is done in anti-coincidence with one of two scintillator counters $S_{bk1} \cdot S_{bk2}$ (80 mm and 90 mm in diameter).

More details on the OKA setup can be found elsewhere [12–14].

3. Event selection

As already mentioned, to search for heavy neutrino we follow well established strategy [1][7–9]. We perform peak search (at few hundreds MeV/c² range) on the squared missing mass spectrum from the $K^+ \rightarrow \mu^+ \nu_\mu$ exclusive decay channel. In this report we discuss measurements performed in November 2012 run with the momentum of secondary hadron beam of 17.7 GeV/c. Beam intensity ($S_{1} \cdot S_{2} \cdot S_{3} \cdot S_{4}$) was $\sim 2 \cdot 10^6$ per spill. The fraction of kaons in the beam after kaon separators was $\sim 12.5\%$. An average absolute number of kaons is $\sim$250k/spill.

One of the tasks persuaded during data taking was connected to the Primakoff effect; for that a thin copper target was installed inside the DV near its exit for the half time of the run. This part of the run was included in analysis for the sake of statistics, hence dedicated Monte-Carlo simulation (MC) for that period was performed.

Two prescaled triggers are used for further analysis. The first one selects beam kaons which decay in the vicinity of the DV, $Tr_{K\text{decay}} = S_{1} \cdot S_{2} \cdot S_{3} \cdot S_{4} \cdot \tilde{C}_{1} \cdot \tilde{C}_{2} \cdot S_{bk}$. The second one, $Tr_{K\rightarrow\mu X} = Tr_{K\text{decay}} \cdot \mu C$, additionally requires secondary muon by inclusion of signal from muon.
counters $\mu C$. The prescale factors for $T_{K_{\text{decay}}}$ and $T_{K_{\rightarrow \mu X}}$ are 1/10 and 1/4, while the proportion between numbers written with these two triggers turned out to be equal. The total number of $\sim 1.6 \times 10^{10}$ events with kaon decays are logged.

The event selection for $K^+ \rightarrow \mu^+ \nu$ decay channel chosen in off-line analysis such as to select events with single beam track and single secondary reconstructed track (both with measured momentum). The sole secondary segment after the second magnet SM is well matched to showers of the muon type (i.e. one or two adjacent cells with the MIP energy deposition) in both GAMS-2000 and HCAL calorimeters. The missing mass resolution is obtained with the sufficiently high number of points on the four track segments in two magnetic spectrometers. The measured momentum of incoming into the OKA setup kaon is consistent with $\approx 17.7$ GeV/c (beam setting). The required momentum of a secondary muon required to be below 16.4 GeV/c. To ensure good decay vertex reconstruction, there are requirements for $a)$ minimal angle between vertex segments of 3 mrad, and $b)$ minimal (matching) distance between them < 1 cm. The vertex position is required to be inside the DV situated by 2.5$\sigma$ margins (in terms of z-vertex resolution) between the entrance foil of the DV and the position of the copper target. Other decay channels are suppressed by requiring the total energy deposition in GS to be below 50 MeV/c² and to be below 100 MeV/c² in BGD, respectively, while the total energy deposition in GAMS-2000 and HCAL should be consistent with that of a single muon. After applying these cuts, $25.7 \times 10^6$ $K^+ \rightarrow \mu^+ \nu$ decays were selected for subsequent analysis.

4. Search for heavy neutrino

Search for peaks in the missing mass distribution, $m_{\mu}^2 = m_{miss}^2 = (p_K - p_{\mu}) \cdot (p_K - p_{\mu})^i$, $i = 1, 2, 3, 4$, which may be responsible for heavy neutrino in the final state of the $K^+ \rightarrow \mu^+ \nu_H$ decay requires description of the expected signal shape. For that a detailed GEANT-3.21 Monte-Carlo simulation (MC) is done with the subsequent off-line reconstruction and analysis. It provides realistic background description, from which the expected signal must be distinguished. Noticeable background processes were simulated with the MC and weighted according to their matrix elements and branching ratios: $K^+ \rightarrow \mu^+ \nu_H$, $K^+ \rightarrow \mu^+ \nu_\mu \gamma$, $K^+ \rightarrow \mu^+ \nu_\mu \pi^0$, $K^+ \rightarrow \pi^+ \pi^0$, $K^+ \rightarrow e^+ \nu_e \pi^0$, also processes when kaon either scatters or interacts while passing the setup. A series of heavy neutrino masses were simulated to parametrize the detector response.

The experimental data and main backgrounds from MC, passing the reconstruction and selections cuts, are shown in the $(m_{miss}^2, p_{\mu})$ plots of figure 2 additionally MC signals from five different cases of assumed heavy neutrino mass are shown superimposed. The $K^+ \rightarrow \mu^+ \nu_\mu \gamma$ and $K^+ \rightarrow \mu^+ \nu_\mu \pi^0$ can not be suppressed without significant loss in statistics for $K^+ \rightarrow \mu^+ \nu_H$. However, it is evident that any features of background processes like peaks or abrupt changes in population of distribution over $m_{miss}^2$ would introduce bias to the result of peak search procedure, contaminating possible signal from heavy neutrino by its shape. The abrupt drop of the $m_{miss}^2$ distribution from the $K^+ \rightarrow \pi^+ \pi^0$ can be eliminated, to a large extent, by introducing kinematic acceptance limits with a smooth curve in $p_{\mu}$: $m_{miss}^2$, as indicated at figure 2(a). The selection of these limits partially improves the resolution at $m_{miss}^2 = 0$. The corresponding $m_{miss}^2$ distributions are shown in figure 2(a). The normalization is done to the experimental data at $m_{miss}^2 = 0$, relative normalization of different MC background processes are done according to known branching ratios with respect to the $K^+ \rightarrow \mu^+ \nu_H$. A set of reconstructed heavy neutrino signals was produced by the MC simulation with a neutrino mass step of 20 MeV/c². It was found that the signal, as a function of $m_{miss}^2$ is well approximated by the Gaussian shape, with an integral error of $\sim 2\%$. An interpolation between the generated set of masses is done with polynomial curves for the obtained signal width and for the total efficiency $\varepsilon_H$ (including acceptance), which are shown at the right chart of figure 3.

Three approaches were used to extract possible signal from heavy neutrino.

The first approach does not use information from MC background processes, but the
Figure 2. The distribution of $p_\mu$ vs. $m_{\text{miss}}^2$ obtained from the analysis of the experimental data (plot a) and from MC simulation of background channels (plots b, ..., g). Distributions (MC) from a set of possible signals for $m_{\nu_H} = \{200, 240, 280, 320, 360\}$ MeV/c$^2$ are also shown superimposed on each other (plot h). Note logarithmic scale for the third dimension. Event entries passing all selections are shown. In case of MC, the initial statistics is also indicated.

Figure 3. (a): the $m_{\text{miss}}^2$ distribution for the data and MC events inside kinematic limits, indicated in figure 2 (a). The normalization is relative to the experimental data. (b): efficiency and signal width parameterization for the set of HN masses, obtained with MC.

parameterization of the expected (HN) signal width only: a bin by bin scan is done within $0.05 < m_{\text{miss}}^2 < 0.14$ GeV/c$^2$ interval in which a common fit with Gaussian shape for the signal of interest and polynomial approximation for the background, obtained from a wider region of $m_{\text{miss}}^2 > 0.04$ GeV/c$^2$ from the data events (selected as already described above).

The second approach explicitly uses information about MC background processes and the signal width parameterization. It does bin by bin data scan (within the same range of interest $0.05 < m_{\text{miss}}^2 < 0.14$ GeV/c$^2$) in which for every assumed $m_{\text{miss}}^2$ we do a common fit of signal (with known width) and each background process (except for the $K^+ \rightarrow \mu^+ \nu_\mu$) with a free scaling parameter. This multiplier is introduced for suppressed background channels because of very strong background suppression applied, hence one may assume that the obtained efficiency can be inaccurate by some factor of $\sim 2$ (e.g. relative suppressions for two most pronounced channels, $K^+ \rightarrow \mu^+ \nu_\mu \gamma$ and $K^+ \rightarrow \mu^+ \nu_\mu \pi_0^0$, in comparison to the main decay channel $K^+ \rightarrow \mu^+ \nu_\mu$ are in
the order of $10^{-1}$ and $10^{-2}$ correspondingly). I.e. in this approach the MC shape of background processes is used explicitly (within the high mass range $m_{\text{miss}}^2 > 0.05 \text{ GeV/c}^2$), while their magnitude is adjusted during fit procedure at each mass of interest.

The third approach is a reduced version of the second one. It uses distributions for each background process obtained from MC. On the first stage the efficiency for each background shape (except for the $K^+ \rightarrow \mu^+ \nu_H$) are refined by the fit of (sum of) the MC distributions to the experimental distribution, hence the best background model is obtained with refined efficiencies for each background process in the mass range of interest (ignoring possible local contributions from NH signal). After that the bin by bin fit of signal with the Gaussian shape and known width is done in order to find possible local excess in data yield compared to the MC distribution (which is fixed at the first stage before the mass scan).

![Figure 4](image.png)

**Figure 4.** Upper limit on branching (a) and on the mixing matrix element $|U_{\mu H}|^2$ (b) at 90% CL as a function of a heavy neutrino mass for three procedures of the fit. $|U_{\mu H}|^2$ is shown in comparison with preceding experiments, see text for details.

The fit procedure for the signal number estimate in all three approaches is not bound to positive values, the bin content is $\sim 10^2$, hence, the Wald approximation \[15,16\] for the upper limit estimate can be used. No (statistically significant) indications of signal from $\nu_H$ are found in the considered mass region \[14\]. The upper limit at 90% CL is obtained for on branching of $K^+ \rightarrow \mu^+ \nu_H$ and on the mixing parameter $|U_{\mu H}|^2$ between muon neutrino and one of heavy sterile neutrinos $\nu_H$, see figure 4. The systematcal error of around 10% to be added. We extend the result \[7\] (red dashed curve) obtained with stopped kaons toward higher masses and we update upper limit from \[8\] (dash-dotted green curve), also the old limit from \[9\] is shown (black solid curve).

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