Sterile neutrino searches at tagged kaon beams

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(Dated: October 21, 2020)

Tagged kaon beams are attractive neutrino sources, which would provide flavor pure $\nu_\tau$-beams with exactly measured normalization. We point out that this also leads to an anti-tagged flavor pure $\bar{\nu}_\tau$-beam, with equally well known normalization. Exposing a 1kt liquid argon detector at a baseline of 1km to this combination of unique beams allows to decisively test recent indications by IceCube and Neutrino-4 of sterile neutrino oscillations in the multi-eV range.

INTRODUCTION

The decisive measurement of a nonzero reactor mixing angle [1–3] has marked the beginning of an era of precision neutrino mixing measurements. The current neutrino oscillation data have determined the neutrino mass squared differences, $\Delta m^2_{31}$ and $|\Delta m^2_{31}|$, and the mixing angles $\sin^2(\theta_{ij})$ (with $ij = \{12, 13, 23\}$) of the lepton mixing matrix [4]. Nevertheless, there exist persistent hints from different experiments, notably LSND [5] and MiniBooNE [6], as well as reactor experiments [7–11] that may indicate the existence of a fourth neutrino species, a sterile neutrino $\nu_s$ with a mass of $O(1)$ eV mixing with active neutrinos. For a review on global sterile neutrino oscillations see e.g. [12] and references therein. While sterile neutrino oscillation would be a simple explanation, if applied to both the $\nu_\mu$-appearance results (LSND, MiniBooNE) and the reactor indications, it also would predict the disappearance of $\nu_\mu$, which has not been observed. On the contrary, strong limits have been placed on this mode over the years and thus a sterile neutrino interpretation of all these anomalous results seems unlikely. For masses of the new state above an eV, also cosmological bounds become an issue and direct bounds from KATRIN apply as well [13]. More recently two experiments provide indications of multi-eV scale oscillations. Specifically, the Neutrino-4 experiment reports a best-fit $\Delta m^2 \approx 7\, eV^2$ [14] and IceCube reports a best fit value of $\Delta m^2 \approx 4.5\, eV^2$ [15, 16]. The multi-eV region is difficult to access for reactor neutrino experiments due to the smearing out of oscillations because of the reactor core size. It is not yet clear if these new indications are compatible with the other eV-scale indications and if they will persist with increased statistics and/or a more careful assessment of systematic uncertainties. In this paper we will investigate tagged kaon beams [17], to study multi-eV scale neutrino oscillation directly and with extremely well constrained systematics.

A recent example of a proposal to build a tagged kaon beam is the ENUBET (Enhanced NeUtrino BEams from kaon Tagging) beamline technology [18] based on the reconstruction of positrons from the three-body semi-leptonic $K^+ \to e^+\nu_\tau\pi^0$ decay, aimed to determine the absolute $\nu_\tau/\nu_\mu$ flux at 1% level. The positrons are identified in the decay tunnel by calorimetric techniques and the beam-line is optimized to enhance the $\nu_\tau$-component from the three-body semi-leptonic decay and suppress to a negligible level the $\nu_\tau$-contamination from muon decays [18]. In ENUBET, the rate of positrons provides a direct measurement of the $\nu_\tau$ produced in the tunnel.

Neutrinos from this type of source will oscillate as usual, since the precision of neither the time nor the energy measurement on the positron will allow to determine the mass eigenstate produced and thus all that tagging does is to fix the beam normalization and baseline travelled.

The Neutrino-4 indication is observed in the $\bar{\nu}_e \to \bar{\nu}_\tau$ channel and the IceCube indication is observed in the $\nu_\mu \to \nu_\tau$ channel only, thus no specific prediction for an effect in $\nu_\mu \leftrightarrow \nu_\tau$ channels arises. A direct test of those indications is therefore best obtained by using the same channels as the original results[1]. Therefore, we will focus the analysis here on these two disappearance channels.

EXPERIMENTAL FRAMEWORK

In this section we describe the experimental set up and the assumptions that we use in the present analysis. The predicted event rates were calculated based on neutrino fluxes provided by the ENUBET collaboration [18, 19]. We consider a 1kt liquid argon detector with energy resolution which follows a Gaussian distribution. All calculations are performed with GLoBES [21, 22] using the N-flavor oscillation engine of Refs. [23, 24].

The signal is obtained from the survival probability of electron neutrinos ($\nu_e \to \nu_e$) stemming from the $K^+$ in the beam that decay into $e^+ + \nu_\tau$, which then interact in the liquid argon detector through the weak charged current. The yields of kaons transported to the entrance of the decay tunnel is $1.69 \times 10^{-3} \, K^+/PoT$ for 120 GeV

1 Note, that as long as CPT symmetry holds $\bar{\nu}_\alpha \to \bar{\nu}_\alpha$ has to have the same oscillation probability as $\nu_\alpha \to \nu_\alpha$. 
protons. The tagged $\nu_e$-flux is assumed to be 99% pure. The largest source of beam related background in the detector is due to neutral current coherent $\pi^0$ production: The $\pi^0$ decays into two photons and for pion energies below $\sim 1$ GeV the opening angle is large enough to cleanly reconstruct both photons and thus no confusion with a $\nu_e$ charged current event arises. At higher energies, however, the two photons are more collinear and may no longer be reconstructed as two particles, hence these neutral currents events may be misidentified as charged current $\nu_e$ events. Liquid Argon (LAr) detectors have very fine granularity and as a result very good particle identification. In particular photon-induced showers can be recognized by the gap between the vertex and the start of the shower. Without going into the details of event reconstruction, we estimate the rate of coherent, neutral current $\pi^0$ production. The cross section for neutral current coherent $\pi^0$ production has been measured by MINOS on iron [25] and by NOvA on carbon [26]; we use a theory-derived scaling factor of $(A/12)^{2/3}$ to translate these results for argon in accordance with the Berger-Sehgal model [27]. Expected $\pi^0$ rates were found to be of order 0.1% compared to our signal $\nu_e$ events and thus can be neglected for this analysis. The beam normalization is know at the 1%-level due to the high kaon tagging efficiency [18].

Similarly, muon neutrinos can be selected at the neutrino detector using radius-energy correlations. We performed a 5 GeV energy cut to avoid contributions from un-tagged $\pi^+$; since the the branching ratio for the semi-leptonic decay $K^+ \to e^+ \nu_e \pi^0$ is well known, 5%, and the number of kaon decays in this mode is fixed by tagging, we can use the equally well-know branching ratios for the muon neutrino generating decay modes $K^+ \to \mu^+ \nu_\mu$ (60%) and $K^+ \to \mu^+ \nu_\tau \pi^0$ (3%) to know the muon neutrino flux with the same accuracy as the electron neutrino flux. Final states here are charged current $\nu_\mu$ interactions with the detector. As in the electron neutrino case, neutral current background events were found to be of order 0.1% compared to signal and thus, negligible.

Placing a 1 kt liquid argon detector at a distance of 1 km from the decay pipe we obtain 1568 $\nu_e$ events and 24603 $\nu_\mu$ events/year\(^2\). Detection efficiencies in this type of detector are close 100% and for simplicity we neglect them, a simple increase of running time or detector mass by 10-20% will be required to compensate for this approximation. For a few-GeV beam, a distance of $L = 1$ km yields $L/E_\nu \simeq 0.2$ [km/GeV], which corresponds to an oscillation with $\Delta m^2 \simeq 5$ eV\(^2\). The $\nu_\mu$ energy $E_\nu$ spectrum peaks at approximately 7 GeV, while the $\nu_e$ energy spectrum peaks around 4 GeV as shown in Fig. [1]. We do not include the appearance channels in our analysis

\(^2\) This includes cuts on the beam radius with acceptances of 24% for $\nu_e$ and 34% for $\nu_\mu$, respectively [28].

![Expected event rates assuming a 1kt liquid argon detector at baseline $L = 1$ km for 120 GeV protons with a power beam of $10^{20}$ PoT/yr.](image)

Figure 1. Expected event rates assuming a 1kt liquid argon detector at baseline $L = 1$ km for 120 GeV protons with a power beam of $10^{20}$ PoT/yr.

and have confirmed that their inclusion would not impact our results in an appreciable manner.

**STERILE NEUTRINO SEARCHES**

Our treatment of the $3+1$ framework of neutrino oscillations follows the leptonic mixing matrix parameterization [12]

$$U = R(\theta_{34}) \bar{U}(\theta_{24}, \delta_{24}) R(\theta_{14}) R(\theta_{23}) \bar{U}(\theta_{13}, \delta) \bar{U}(\theta_{12}, \delta_{12}),$$

where $R(\theta_{i,j})$ are orthogonal $4 \times 4$ matrices on the $(i,j)$-plane, $\bar{U}(\theta_{i,j}, \delta_{i,j})$ are $4 \times 4$ unitary matrices on the $(i,j)$-plane and $\delta$ is the standard Dirac CP violating phase, under the short baseline approximation all extra phases are zero i.e. there will be no additional CP violation in the $3+1$ scenario. The probability for a neutrino produced in the flavor eigenstate $\nu_\alpha$ to be observed as flavor $\nu_\beta$ after traveling some distance $L$ in vacuum and having energy $E$ is:

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} R^*_{\alpha i} U_{\alpha i} U_{\beta i} U_{\beta j} \sin^2 \left( 1.27 \Delta m^2_{ij} \frac{L}{E} \right) + 2 \sum_{i>j} T_{\alpha i} U_{\alpha j} U_{\beta j} \sin \left( 2.54 \Delta m^2_{ij} \frac{L}{E} \right),$$

where $U_{\alpha i}$ ($\alpha = e, \mu, \tau, s; i = 1, 2, 3, 4$) are the elements of the leptonic mixing matrix, $E$ is the neutrino energy, $L$ is the beam to detector distance, $\Delta m^2_{ij}$ are the squared mass splittings between the standard neutrino mass eigenstates $\nu_1$, $\nu_2$, $\nu_3$ and a $\nu_4$ sterile state.
We consider different null hypotheses which is not quite the same case as considered here, but ance searches with free beam normalization see Ref. [30], about the limitations of Wilks’ theorem in disappear-

We computed data assuming the best fit of Neutrino-4 results [14] and IceCube results [15, 16]. Sensitivity contours were calculated based on the $\Delta \chi^2$ value for each parameter pair $(\Delta m^2_{31}, \sin^2 2\theta_{14})$ and by determining the boundary of the corresponding exclusion/allowed regions by translat-

Based on our simulated charged current event rates and assuming a $10^{20}$ PoT/yr beam power on a 1kt LAr detector, we obtain sensitivities for the hypothesis of sterile neutrino oscillation under a (3+1) scenario assuming five years of beam operation. Interpretation of the ENUBET experimental data in terms of sterile neutrino oscillations allows to test large values of $\Delta m^2_{31}$ and relatively sizable mixing between $\nu_e$ and $\nu_x$ states. This corresponds well with the parameter space regions indicated by the gallium results [29], Neutrino-4 results [14] and IceCube results [15, 16]. Sensitivity contours were calculated based on the $\Delta \chi^2$ value for each parameter pair $(\Delta m^2_{31}, \sin^2 2\theta_{14})$ and by determining the boundary of the corresponding exclusion/allowed regions by translating the $\Delta \chi^2$ to confidence levels using a $\chi^2$-distribution with two degrees of freedom. For a recent discussion about the limitations of Wilks’ theorem in disappearance searches with free beam normalization see Ref. [30], which is not quite the same case as considered here, but gives an indication of the size of the resulting corrections.

We consider different null hypotheses $H_0$:

- $H_0$: no oscillation. We compute data assuming no disappearance and fit the resulting Asimov data set with finite value of $\Delta m^2$ and $\sin^2 2\theta$. The result is a sensitivity limit, shown as dashed lines.

- $H_0$: oscillation according the RAA best fit. We compute data assuming the best fit of the RAA is true and fit the resulting Asimov data set with different value of $\Delta m^2$ and $\sin^2 2\theta$. The result are allowed regions (with closed contours), shown as solid lines.

- $H_0$: oscillation according the Neutrino-4 best fit. We compute data assuming the best fit of Neutrino-4 is true and fit the resulting Asimov data set with different value of $\Delta m^2$ and $\sin^2 2\theta$. The result are allowed regions (with closed contours), shown as solid lines.

- $H_0$: oscillation according the IceCube best fit. We compute data assuming the best fit of IceCube is true and fit the resulting Asimov data set with different value of $\Delta m^2$ and $\sin^2 2\theta$. The result are allowed regions (with closed contours), shown as solid lines.

For all cases we consider a combined fit of muon and electron neutrino disappearance and profile over the not-shown $\theta_{14}$ mixing angles.

Here, the normalization error of the signal becomes important, while the beam flux is very well know due to tagging the signal charged current cross sections are subject to large uncertainties. We assume, that the main physics program of ENUBET, which are cross section measurements, have reduced the resulting effective signal uncertainty to either 1%, 2% or 5%, where we take 2% as default unless stated otherwise.

The effective two-flavor limit in the electron disappearance channel yields this simple oscillation probability:

$$P_{ee} = 1 - 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \sin^2 \left(1.27 \Delta m^2_{41} \frac{L}{E}\right), \quad (3)$$

and according to the parameterization Eq.(1) this case reduces to the effective two flavor oscillation.

$$P_{ee} = 1 - \sin^2 2\theta_{ee} \sin^2 \left(1.27 \Delta m^2_{41} \frac{L}{E}\right), \quad (4)$$

where $\sin^2 2\theta_{ee} = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right)$ and $\theta_{ee} = \theta_{14}$ is the angle that encodes mixing.

Figure [2] shows the sterile neutrino oscillation sensitivity at ENUBET in the $\sin^2 2\theta_{ee} - \Delta m^2_{41}$ plane at 99% C.L. for an exposure of 1 kt assuming five years of beam operation. The blue, magenta and red dashed-dotted lines account for 1%, 2% and 5% signal normalization systematic. Also shown the 1$\sigma$, 2$\sigma$, 3$\sigma$ preferred regions for the best fit RAA [7] and Neutrino-4 [31] assuming 2% signal normalization systematic.

Until recent results from IceCube [15, 16] no indication for sterile neutrino oscillation in the muon disappearance channel had been found. In the 3+1 scenario with short baseline approximation, the muon neutrino disappearance probability is given by

$$P_{\mu\mu} = 1 - 4|U_{\mu4}|^2 \left(1 - |U_{\mu4}|^2\right) \sin^2 \left(1.27 \Delta m^2_{41} \frac{L}{E}\right)$$

$$= 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \left(1.27 \Delta m^2_{41} \frac{L}{E}\right), \quad (5)$$

where $|U_{\mu4}| = \cos \theta_{14} \sin \theta_{24}$ and the effective mixing angle $\theta_{\mu\mu}$ depends on both $\theta_{14}$ and $\theta_{24}$

$$\sin^2 2\theta_{\mu\mu} = 4 \cos^2 \theta_{14} \sin^2 \theta_{24} \left(1 - \cos^2 \theta_{14} \sin^2 \theta_{24}\right). \quad (6)$$

Figure [3] shows the sterile neutrino oscillation sensitivity at ENUBET in the $\sin^2 2\theta_{24} - \Delta m^2_{41}$ plane at 99% C.L. for an exposure of 1 kt assuming five years of beam operation. The blue, magenta and red dashed-dotted lines account for 1%, 2% and 5% signal normalization systematic. Also shown the 1$\sigma$, 2$\sigma$, 3$\sigma$ preferred regions assuming 2% signal normalization systematic for true $\sin^2 2\theta_{24} = 0.1$ and $\Delta m^2_{41} = 4.5$ eV$^2$ from IceCube [15, 16]. For comparison we also show the sensitivity of

| Table I. Relevant oscillation parameters in the 3+1 scenario used in this analysis. |
|---------------------------------|---------------------------------|---------------------------------|
| standard PMNS value [NO] | sterile parameter | value |
| $\theta_{12}$ | 33.2$^\circ$ | $\theta_{24}$ | 0 |
| $\theta_{23}$ | 45.8$^\circ$ | $\theta_{12}$ | 0 |
| $\theta_{13}$ | 9$^\circ$ | $\theta_{34}$ | 0 |
| $\Delta m^2_{21}$ [10$^{-5}$eV$^2$] | 7.5 | $\theta_{24}$ | free |
| $|\Delta m^2_{31}|$ [10$^{-3}$eV$^2$] | 2.6 | $\theta_{14}$ | free |
Figure 2. Comparison of the expected sensitivities in the $\sin^2 2\theta_{ee} - \Delta m^2_{41}$ plane. The blue, magenta and red dashed-dotted lines correspond to a 1%, 2% and 5% signal systematics at baseline length of $L = 1$km. The black diamond point represents the best fit point from Neutrino-4 [31], star represents the best fit of the reactor anti-neutrino anomaly RAA [7]. In addition we show 90% C.L. allowed region (purple shaded area) of the gallium anomaly JUN45 [29].

Figure 3. Comparison of the expected sensitivities in the $\sin^2 2\theta_{24} - \Delta m^2_{41}$ plane. The blue, magenta and red dashed-dotted lines correspond to a 1%, 2% and 5% signal systematics at baseline length of $L = 1$km. The black diamond point represents the best fit point 90% C.L. from IceCube [15, 16], shaded purple/brown areas are excluded by IceCube and MINOS [32] respectively.

another kaon decay based proposal, called Kpipe [33]: Kpipe is a proposed experiment to investigate sterile neutrinos from kaon decay at rest and is aimed to set the strongest limits in the muon neutrino disappearance channel. The expected number of $\nu_\mu$ events is $1.02 \times 10^5$ events/year in a 684 ton liquid scintillator detector, which comes in the shape of 120m long pipe. Kpipe would have about an order of magnitude more signal events than the proposal we consider here and thus in principle has the potential to provide excellent sensitivity in this channel.

CONCLUSIONS

In this letter we test different hypotheses regarding simulated experimental data of the ENUBET beamline technology, we demonstrate the capabilities of tagged kaon beams in the electron and neutrino disappearance channel to investigate intriguing indications from the Neutrino-4 and IceCube collaborations. The strength of the setup considered is the vanishingly small systematic errors from the beam flux and a virtually background free measurement. The drawback is the relatively low beam luminosity, as result of the need to tag kaon decays individually. The proposed setup is envisioned as add-on measurement to the cross section program of ENUBET. The physics case arises mainly from the Neutrino-4 result, which is in a $\Delta m^2$-region which ultimately may be hard for reactor neutrino experiments to test decisively. The proposed setup could decisively test either indication, IceCube at the 5 $\sigma$ level and Neutrino-4 at the 10 $\sigma$ level. This setup is not unique in this capability and of course dedicated facilities like nuSTORM [34] would provide superior sensitivity. In the hunt for the sterile neutrino, opportunistic measurements always have played a major role and we point out that if ENUBET is built and the Neutrino-4 indication persists, the setup in this paper would present such an opportunity.
ACKNOWLEDGMENTS

We acknowledge useful discussions with R. Pestes and J. M. Berryman. This work was supported by the U.S. Department of Energy Office of Science under award number DE-SC00018327.

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