Decays in Flight of Heavy Sterile Neutrinos in the MiniBooNE Detector

Mark Ross-Lonergan

1 Institute of Particle Physics Phenomenology, University of Durham, Durham UK
E-mail: mark.ross-lonergan@durham.ac.uk

Abstract. Heavy sterile neutrinos in the \( O(10) \) MeV mass range would be produced in neutrino superbeams, from pion and kaon decays. In short-baseline experiments and for sufficiently long lifetimes, such steriles can propagate to the detector and decay to electrons or photons, leading to signatures which may be mis-identified for oscillation driven electron quasi-elastic charged current events. Some generic features of the production and decay of such steriles are mentioned, and the particular case study of the low energy excess at the MiniBooNE detector is studied for possible signals. We show that angular data heavily constraints the amount of events that could be from such decays to at most 50 % of the excess.

The MiniBooNE experiment was proposed and built due to the anomalous results obtained during the running of the LSND experiment[1], which could be interpreted as neutrino oscillations with a mass difference of approximately \( \Delta m^2 \approx 1 \text{ eV}^2 \), requiring an additional sterile neutrino when combined with the limits on active neutrinos from Z decay precision measurements[2]. Although no conclusive evidence exists, the MiniBooNE data alongside the previous results from LSND and reactor anomalies [3] represent a hint of new physics at the eV scale. The excess low-energy \( (< 400 \text{ MeV}) \) events observed in MiniBooNE, however, do not agree well with standard 3+1 or 3+2 explanations for the anomalies.[4]

As such, alternative explanations are sought for the low-energy excess in isolation, and in these proceedings the possibility of a signal being generated by a MeV scale sterile neutrino decaying in flight is investigated. Although no evidence currently exists to suggest new particles at such an energy scale, MeV sterile neutrinos would naturally be produced at neutrino beam facilities around the world through standard meson decay, with an extra factor of the appropriate mixing element suppressing the production, allowing for a rich phenomenology in many present and future experiments.

A common method in the literature to estimate the expected flux of such sterile neutrinos contained in a standard neutrino beam, is by modifying the known neutrino flux by the mixing element \( |U_{\mu 4}|^2 \). This method does not lend itself to the study of any spectral information as the difference in the kinematical production of a massless and MeV state can be significant, as described by Asaka et al [5]. Other effects such as the removal of helicity suppression in the \( \pi^+ \rightarrow e^+ \nu_e \) channel if the electron neutrino is replaced by a MeV sterile \( \pi^+ \rightarrow e^+ \nu_s \), can greatly enhance fluxes and must be taken into account.
Sterile Production at MiniBooNE
In this work we investigate the behaviour of such MeV range sterile neutrinos in modern short-baseline experiments, and for the purpose of this proceedings, we use as a case study the possibility that the MiniBooNE low-energy excess[6] is the result of decaying heavy steriles in flight.

In order to more accurately account for the kinematics of the production mechanism we follow the methods laid out by Asaka et al. in which the steriles fluxes are calculated by integrating the parent meson spectrum (e.g Pions) over all kinematical variables such that the resultant sterile successfully impinges on the MiniBooNE detector approximately $R = 550m$ downstream of the proton beam target. This includes the effects of a line source of decays, from a parent flux $\phi_{\pi}$, as estimated from the HARP and E910 experiments [7].

$$\phi_s(E_s) \propto \int_0^{50m} dl \int_0^{1} d \cos \theta \int_0^{\infty} dp_\pi \phi_\pi(p_\pi) \exp \left( \frac{-l \Gamma_{\pi m_\pi}}{p_\pi} \right) \frac{d^2 \Gamma(\pi \rightarrow \nu_s \mu)}{dE_\gamma d \cos \theta} \left( \frac{m_\pi}{p_\pi} \right),$$

(1)

with $\cos \theta^-$ forming a geometric acceptance cone given by the point of pion decay $l$ and the radius of the MiniBooNE detector $r$, $\cos \theta^- = \cos \left( \frac{r}{R-l} \right)$.

Although the total decay width $\Gamma(\pi \rightarrow \mu \nu_s)$ indeed approaches 0 as the sterile’s mass approaches the kinematic boundary $m_\pi - m_\mu$, the doubly differential decay width $\frac{d^2 \Gamma}{dE_\gamma d \cos \theta}$ at values such that the angle is within the acceptance cone, increases until a turnover very close the boundary ($\ll 1$ MeV from boundary). This is easily understood from within the pion rest frame; as one approaches the kinematic boundary the sterile is being produced with vanishing velocity. When then boosted back into the lab frame, this corresponds to a lab velocity increasingly parallel to the parent pion. As the pions are focused to the detector this means that there is little spread outside $\cos \theta^-$ when compared to lighter neutrino behaviour. Such a boost further increases the estimated sterile flux at the detector over that naively expected from a $|U_{\mu 4}|^2$ scaling.

Sterile Decay
Once produced, and if the lifetime is sufficiently large, the steriles propagate the baseline length and their decays can be observed inside the detector. A decay such as the radiative $\nu_s \rightarrow \nu_f \gamma$ channel gives rise to a individual photon inside the detector, whose EM shower is indistinguishable from that of an electrons, in the water based cherenkov detector. As such it is mid-identified as an electron from an oscillated quasi-elastic charged current event. To keep this model independent as possible the exact method of decay is keep arbitrary and is quantified by an effective decay width $\Gamma_{\text{eff}}$. The flux of observed photons for a given visible energy $E_\gamma$ and total sterile decay width $\Gamma_{\text{tot}}$ is

$$\phi_\gamma(E_\gamma) = \Gamma_{\text{eff}} \int_{E_0}^{\infty} \phi_s(E_s) \exp \left( \frac{-(R-l) \Gamma_{\text{tot}} m_s}{p_s} \right) \frac{m_s}{p_s^2},$$

(2)

with $E_0$ being the kinematic threshold $E_0 = E_\gamma (1 - m^2_\gamma/4E^2_\gamma)$.

Energy and Angular Spectrums at MiniBooNE
Quantitatively, from a fit to the energy spectrum only, the significance for rejecting the background only model in favour of that of a decaying sterile is approximately 3$\sigma$ with systematic errors in the 5-10% level, if the sterile is from a parent pion. Steriles with a kaon origin, however, never exceed 2$\sigma$ due to the heavier parent smearing the spectrum to higher energies.
Figure 1: Energy spectrum for a 25 MeV sterile, with $|U_{\mu 4}|^2\Gamma_{\text{eff}} = 10^{-29.4}$ GeV in comparison to MiniBooNE low-energy excess.

Figure 2: Energy spectrum for a 300 MeV sterile, with $|U_{\mu 4}|^2\Gamma_{\text{eff}} = 10^{-30.51}$ GeV in comparison to MiniBooNE low-energy excess.

MiniBooNE does not just report on the energy spectrum, however, is also has angular information for its events. The decay in flight mechanism produces decay products which are naturally boosted forward significantly. Hence the angular spectrum generated by such processes is a much better variable to constrain the amount that such decays can contribute to the observed low-energy excess. The heavier steriles from parent kaons actually fit the angular spectrum better due to possibility of much heavier daughter particles not being boosted to such a degree.

A conservative estimate using angular data is that, at the 90% C.L, the fraction of excess events that can originate from such sterile decays at $\approx 50\%$, with the significance of rejecting a background only model over such a scenario alone dropping to $\approx 1\sigma$. As such we conclude that the simplest model of single photons from heavy sterile decays cannot adequately explain the low-energy excess, due to the interplaying kinematics that mean a better energy fit requires regions of parameter space that directly leads to a worse angular spectrum, and vice versa.

Although the simplest model fails to reproduce the MiniBooNE excess, it highlights the phenomenology of such decays in modern experiments, and also raises the possibility that one could use such decays to place bounds on sterile-active mixing combinations such as $|U_{\tau 4}| |U_{\mu 4}|$, which currently suffers from lack on knowledge on $U_{\tau 4}$. Furthermore, by considering more complicated decays, as well as the possibility of decays before the detector one may be able to modify the final state kinematics so that a more isotropic spectrum is generated, easing tension between the MiniBooNE angular and energy data. Further work is undergoing.
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