PROCEEDINGS OF SCIENCE

Explaining the MiniBooNE Excess Through a Mixed Model of Oscillation and Decay

S. Vergani,[a,*] **N.W. Kamp,**[b] **A. Diaz,**[b] **C.A. Argüelles,**[c] **J.M. Conrad,**[b] **M.H. Shaevitz**[d] **and M.A. Uchida**[a]

[a] *University of Cambridge, Cambridge CB3 0HE, United Kingdom*

[b] *Dept. of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

[c] *Dept. of Physics, Harvard University, Cambridge, MA 02138, USA*

[d] *Dept. of Physics, Columbia University, New York, NY, 10027, USA*

E-mail: sv408@hep.phy.cam.ac.uk, nwkamp@mit.edu, diaza@mit.edu, carguelles@fas.harvard.edu, conrad@mit.edu, shaevitz@nevis.columbia.edu, mauchida@hep.phy.cam.ac.uk

This poster presents a model of the electron-like excess observed by the MiniBooNE experiment comprising of oscillations involving two new mass states: ν_4, at $O(1)$ eV, that participates in oscillations, and $\mathcal{N}$, at $O(100)$ MeV, that decays to $\nu + \gamma$ via a dipole interaction. Short-baseline oscillation data sets, omitting MiniBooNE appearance data, are used to predict the oscillation parameters. We simulate the production of $\mathcal{N}$ along the Booster Neutrino Beamline via both Primakoff upscattering ($\nu A \rightarrow \mathcal{N} A$) and Dalitz-like neutral pion decays ($\pi^0 \rightarrow \mathcal{N}\nu\gamma$). The simulated events are fit to the MiniBooNE neutrino energy and visible scattering angle data separately to find a joint allowed region at 95% CL. A point in this region with a coupling of 3.6×10^{-7} GeV^{-1}, $\mathcal{N}$ mass of 394 MeV, oscillation mixing angle of 6×10^{-4} and mass splitting of 1.3 eV^2 has $\Delta\chi^2/dof$ for the energy fit of 15.23/2 and 37.80/2. This model represents a significant improvement over the traditional single neutrino oscillation model.

**** The European Physical Society Conference on High Energy Physics (EPS-HEP2021), ****
**** 26-30 July 2021 ****
**** Online conference, jointly organized by Universität Hamburg and the research center DESY ****

*Speaker

PoS(EPS-HEP2021)208

1. Evidences for Neutrinos Beyond Standard Model

Over the last 25 years, anomalies have been observed in short-baseline (SBL) neutrino oscillation experiments. A model called "3+1" has been proposed which introduces a new non-interacting, "sterile", state with mass of $O(1\text{ eV})$, in addition to the three Standard Model (SM) neutrino states. In this model, $\nu_\mu \to \nu_e$ appearance, ν_e disappearance, and ν_μ disappearance searches should all point to neutrino oscillations at $L/E \sim 1$ m/MeV, where L is the distance a neutrino of energy E travels, with a consistent set of flavor mixing parameters [1–3]. While the data seem to fit oscillations when analyzed individually, global fits find a small probability that the same parameters explain all of the relevant data sets [2], as measured by the Parameter Goodness of Fit (PGF) test [4]. Notably, MiniBooNE appearance data creates large tension between appearance and disappearance in the 3+1 model. This is because the 3+1 best-fit parameters from the other data sets yield a poor fit to the lowest energy range of the MiniBooNE anomaly [5]. For this is reason, the explanations for MiniBooNE beyond the 3+1 model are of great scientific interest. The MiniBooNE anomaly is a 4.8σ excess of electron-like events observed in interactions from a mostly muon neutrino beam in a Cherenkov detector [6], which cannot distinguish between photons and electrons in electromagnetic showers. Thus, a favored alternative to the 3+1 model has been to introduce MeV-scale heavy neutral leptons (HNLs) that decay via $\mathcal{N} \to \nu\gamma$ within the detector, where the photon is subsequently wrongly identified as an electron [7–9]. The MiniBooNE energy distribution is well described by these initial studies of $\mathcal{N}$-decay models, but the 3+1 oscillations predicted from fits to the other anomalies are omitted.

2. New Model: the Heavy Neutral Lepton Dipole

We propose [10] a combination of the two explanations by fitting the MiniBooNE energy and angle distributions using a combined model called 3+1+$\mathcal{N}$-decay or dipole model. We obtained the 3+1 oscillation component by fitting SBL data sets without MiniBooNE appearance. This model explains the data well and identifies a highly limited range for the four model parameters: the mixing angle, $\sin^2 2\theta$, and mass splitting, Δm^2, for the oscillation; and the HNL mass, $m_\mathcal{N}$, and photon coupling, d, for the decay. In order to test the model, we wrote a Monte Carlo simulation for the production and decay of $\mathcal{N}$ in the Booster Neutrino Beam in neutrino mode. Dalitz-like π^0 decay and Primakoff upscattering $\nu A \to \mathcal{N} A$ were the two processes included in the production, but we found that the latter is by far the dominant $\mathcal{N}$-production mode for $10\,\text{MeV} < m_\mathcal{N} < 1000\,\text{MeV}$. Simulated $\mathcal{N}$ entered the MiniBooNE detector and were forced to decay into a photon and a neutrino, taking into account polarization, and were weighted by the decay probability. The detector efficiency, eff, was given by a linear fit to the reconstructed gamma-ray efficiency as a function of true energy [11], $eff = (-0.12\,\text{GeV}^{-1}) * E_{true} + 0.29$, which we used to weight the $\mathcal{N} \to \nu\gamma$ events. The true energy and angle of the photons were smeared independently according to the resolution given by the MiniBooNE collaboration.

3. Fitting MiniBooNE Excess

This analysis employed the 3+1 global fitting code described in Ref. [2] and we found that the best-fit parameters (without MiniBooNE) are $\Delta m^2 = 1.32\,\text{eV}^2$ and $\sin^2 2\theta_{e\mu} = 6.9{\times}10^{-4}$. Removing

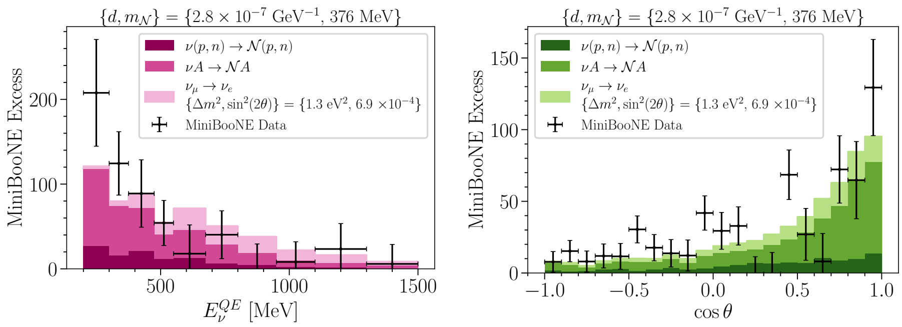

Figure 1: E_ν^{QE} (left) and $\cos\theta$ (right) distributions of the MiniBooNE excess for a representative point of the $3+1+\mathcal{N}$-decay model. The error bars on the energy distribution include systematic and statistical errors, while for the angular distribution only statistical errors are included. Taken from [10].

MiniBooNE appearance from the fit increases the probability to 7×10^{-3} (2.5σ). Therefore, the tension is, mostly, due to the MiniBooNE appearance data set. We hypothesize that it has the additional component of $\mathcal{N}$-decay, and, thus, poor agreement with 3+1-only. In order to isolate the decay component, we subtracted from the MiniBooNE excess the predicted contribution of the oscillation component, which was determined from the $3+1$-only global fit without MiniBooNE data. The remaining excess was fit to the model for dipole production, decay, and observation in the detector. Results are shown in Fig. 1. Good agreement is observed for both distributions.

4. Results and Conclusion

Fig. 2 shows confidence regions for both fits in $\{d, m_\mathcal{N}\}$ parameter space and we found a region consistent with both distributions at the 95% CL near $d = 3 \times 10^{-7}$ GeV^{-1} and $m_\mathcal{N} = 400$ MeV. We consider an example HNL decay contribution for $d = 2.8 \times 10^{-7}$ GeV^{-1} and $m_\mathcal{N} = 376$ MeV, indicated by the star in Fig. 2. This corresponds to the best fit to the E_ν^{QE} distribution within the joint 95% CL allowed region from the E_ν^{QE} and $\cos\theta$ fits. Table 1 shows the χ^2 values for the $3+1$ and $3+1+\mathcal{N}$-decay fits to both distributions, indicating significant improvement for the $3+1+\mathcal{N}$-decay model. In conclusion, we have presented a new physics model including neutrino-partners with masses of $\mathcal{O}(1$ eV) that participate in oscillations and $\mathcal{O}(100$ MeV) that decay to single photons. This model can simultaneously explain the MiniBooNE anomaly and relieve tension in the global experimental picture for 3+1 oscillations. The results indicate very narrow ranges of HNL decay and oscillation parameters; thus, this is a highly predictive result that can be further tested by existing experiments in the near future.

PoS(EPS-HEP2021)208

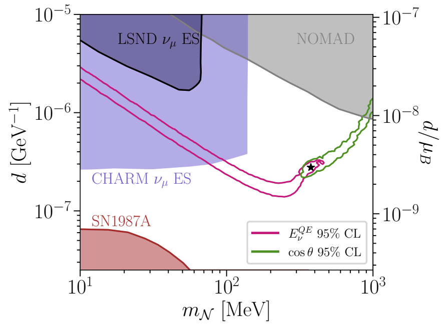

Figure 2: Preferred regions to explain the MiniBooNE excess in E_ν^{QE} (pink) and $\cos\theta$ (green) as a function of dipole coupling and $\mathcal{N}$ mass. The black star indicates $\{d,\ m_\mathcal{N}\} = \{2.8 \times 10^{-7}\ \text{GeV}^{-1},\ 376\ \text{MeV}\}$, which lies in the joint 95% CL allowed region for both distributions. Constraints from other experiments are also shown at the 95% CL. Taken from [10].

Parameters	χ^2/dof			
($\sin^2 2\theta, d, m_\mathcal{N}$)	$3+1+\mathcal{N}$		$3+1$	
	E_ν^{QE}	$\cos\theta$	E_ν^{QE}	$\cos\theta$
(0.30, 3.1, 376)	5.7/8	32.1/18	30.5/10	86.4/20
(0.69, 2.8, 376)	7.9/8	31.4/18	27.3/10	71.8/20
(2.00, 5.6, 35)	20.2/8	36.7/18	27.6/10	40.8/20
(0, 0, 0)	34.1/10	99.4/20	same	same

Table 1: χ^2/dof values for 3 + 1 and 3 + 1 + $\mathcal{N}$-decay models obtained by comparing expectations to the MiniBooNE excess in E_ν^{QE} and $\cos\theta$. The parameters in column one refer to ($\sin^2 2\theta_{\mu e} \times 10^{-3}$, $d \times 10^{-7}$ [GeV^{-1}], $m_\mathcal{N}$ [MeV]). The mass splitting is 1.32 eV^2 in all cases. The null case (no oscillations and no HNL decay) is also shown in the last row. Taken from [10].

References

[1] G. Collin, C. Argüelles, J. Conrad and M. Shaevitz, *First Constraints on the Complete Neutrino Mixing Matrix with a Sterile Neutrino*, *Phys. Rev. Lett.* **117** (2016) 221801 [1607.00011].

[2] A. Diaz, C. Argüelles, G. Collin, J. Conrad and M. Shaevitz, *Where Are We With Light Sterile Neutrinos?*, *Phys. Rept.* **884** (2020) 1 [1906.00045].

[3] S. Böser, C. Buck, C. Giunti, J. Lesgourgues, L. Ludhova, S. Mertens et al., *Status of Light Sterile Neutrino Searches*, *Prog. Part. Nucl. Phys.* **111** (2020) 103736 [1906.01739].

[4] M. Maltoni and T. Schwetz, *Testing the statistical compatibility of independent data sets*, *Phys. Rev. D* **68** (2003) 033020 [hep-ph/0304176].

[5] C. Giunti, M. Laveder, Y.F. Li and H.W. Long, *Pragmatic View of Short-Baseline Neutrino Oscillations*, *Phys. Rev. D* **88** (2013) 073008 [1308.5288].

[6] MiniBooNE collaboration, *Updated MiniBooNE neutrino oscillation results with increased data and new background studies*, *Phys. Rev. D* **103** (2021) 052002 [2006.16883].

[7] C. Dib, J.C. Helo, S. Kovalenko and I. Schmidt, *Sterile neutrino decay explanation of LSND and MiniBooNE anomalies*, *Phys. Rev. D* **84** (2011) 071301 [1105.4664].

[8] S. Gninenko, *New limits on radiative sterile neutrino decays from a search for single photons in neutrino interactions*, *Phys. Lett. B* **710** (2012) 86 [1201.5194].

[9] G. Magill, R. Plestid, M. Pospelov and Y.-D. Tsai, *Dipole Portal to Heavy Neutral Leptons*, *Phys. Rev. D* **98** (2018) 115015 [1803.03262].

[10] S. Vergani, N.W. Kamp, A. Diaz, C.A. Argüelles, J.M. Conrad, M.H. Shaevitz et al., *Explaining the MiniBooNE Excess Through a Mixed Model of Oscillation and Decay*, 2105.06470.

[11] Z. Pavlovic, R. Van de Water and S. Zeller, *Miniboone gamma-ray and electron efficiencies*, Tech. Rep. (2012).