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$U(1)'$ mediated decays of heavy sterile neutrinos in MiniBooNE

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The MiniBooNE low-energy excess is a long-standing problem which has received further confirmation with a reanalysis using newly collected data, with the anomaly now at the 4.8σ level. In this paper we propose a novel explanation which advocates a low-energy sector containing Z' bosons with GeV-scale masses and sterile neutrinos with masses around 100–500 MeV. We show that this scenario provides excellent spectral agreement with the MiniBooNE low-energy excess in the form of Z'-mediated neutral current production of heavy sterile states, a fraction of whose subsequent decay to e^+e^- pairs are misidentified as single electronlike electromagnetic showers. Our model inscribes itself in the broad class of models in which sterile neutrinos are charged under new interactions, allowing new couplings to hidden-sector physics. Alongside the electronlike MiniBooNE signature this model also predicts a novel, low-background, signal in LArTPC detectors such as MicroBooNE consisting of two distinguishable electronlike electromagnetic showers originating from a single vertex.

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I. INTRODUCTION

The MiniBooNE low-energy excess (LEE) [1] is a long-standing anomaly which has received renewed attention thanks to a recent analysis [2], which doubled the amount of data in neutrino mode sample, raising the significance of the anomaly to 4.8σ. The excess of approximately 460 low-energy electronlike (e-like) events was observed in both neutrino and, to a lesser extent, antineutrino channels with 12.84×10^{20} protons on target with the Booster beam in neutrino mode, and 11.27×10^{20} protons on target in antineutrino mode [2]. The events are almost entirely contained within the lowest energy bins, $E \lesssim 0.6$ GeV visible energy, and their angular distribution is relatively flat, with a slight preference to being forward [2].

These events have yet to receive a satisfactory explanation, be it through conventional or unconventional physical mechanisms. One of the most popular interpretations is as the oscillation $\nu_\mu \to \nu_e$, driven by a novel mass-squared splitting $\Delta m^2 \approx \mathcal{O}(1)$ eV^2, requiring the existence of a sterile neutrino. This solution furthered the intrigue around a collection of anomalous short-baseline oscillation results, possibly relating them [3,4]. The LEE spectrum agrees with that of an oscillatory solution [2] and is consistent with the LSND anomaly; however, such an explanation remains controversial for two main reasons. Firstly, significant tension exists with the null results of ν_μ disappearance searches, mainly by MINOS+ and IceCube; see [5,6,7] for overviews of the global situation. Secondly, such a light nearly-sterile neutrino is at odds with cosmological observations unless its production in the early Universe is suppressed e.g. by secret interactions [8,9]; however, despite being reduced, some cosmological tension remains in such models [10,11].

Nonoscillatory explanations of the excess have also been suggested [12–14] which postulate the production of heavy sterile neutrinos with masses $\mathcal{O}(10\text{–}100)$ MeV in scattering events *inside* the detector and their radiative decay [12,13]. As a mineral oil Čerenkov detector, MiniBooNE lacked any capability for separation of electrons and photons [15]. In the first version of this explanation [12,13], heavy sterile neutrino production is mediated by Standard Model (SM) weak neutral-current (NC) and suppressed by sterile mixing angles, necessitating very large mixing angles, $10^{-3} \lesssim |U_{\mu4}|^2 \lesssim 10^{-2}$, which sit very uneasily with the bounds from prior experiments and from subsequent radiative muon capture rates measured at TRIUMF [16] and of rare kaon decays by the ISTRA + Collaboration [17]. A variant was proposed which evaded some of these constraints by using the neutrino-photon vertex to drive both the initial production and subsequent decay of the heavy states [14] but resulted in events strongly clustered around the beam line [18], in contrast to the flatter angular distribution of the LEE. Recent work on neutrino dipole portals have placed further constraints on these models [19].

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In this paper, we discuss a novel explanation of the excess, based on the idea of heavy nearly-sterile neutrino production *in situ*, that combines the kinematic behavior of production by a heavy mediator with an enhanced decay rate. The core idea is that neutrinos have NC interactions mediated by a new GeV-scale boson such that sterile neutrinos with masses $100\ \text{MeV} \lesssim m_4 \lesssim 500\ \text{MeV}$ are produced by neutrino beam interactions with the nuclei in the detector. These subsequently decay into e^+e^- pairs giving rise to the signal through misreconstruction. The introduction of a new boson significantly enhances the production cross section if its mass is below 10 GeV, allowing for smaller values of $U_{\mu 4}$, while avoiding the problem encountered by explanations based on photon exchange of failing to well reproduce the angular spectrum [18]. Another crucial aspect of our work is the reinterpretation of the excess as an e^+e^- pair, as we will discuss in more detail. With this novel interpretation of the excess, we open up the possibility that a NC process drives both the production and decay of heavy sterile neutrinos inside the detector.

For simplicity, we assume that the heavy sterile neutrino's enhanced production and decay rate come from just one novel interaction. This assumption is not essential to our proposal, but we leave the discussion of variants to future work.

II. THE PHENOMENOLOGICAL MODEL

We assume that the SM gauge group is extended by a new factor $\mathrm{U}(1)'$ [20] which kinetically mixes with a hypercharge with a mixing parameter χ. We assume that the new gauge symmetry is broken at low energies and include a mass for the X boson without detailing its provenance. The low-scale Lagrangian is then given by

$$\mathcal{L} = \mathcal{L}_{\nu\mathrm{SM}} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\sin\chi}{2}X_{\mu\nu}B^{\mu\nu} + \frac{\mu^2}{2}X_\mu X^\mu, \quad (1)$$

where $\mathcal{L}_{\nu\mathrm{SM}}$ denotes an extension of the SM incorporating neutrino masses, $F_{\mu\nu} \equiv \partial_\mu F_\nu - \partial_\mu F_\nu$ with B_μ and X_μ denoting the $\mathrm{U}(1)_\mathrm{Y}$ and $\mathrm{U}(1)'$ gauge fields, respectively, the latter with a mass μ. As usual, the kinetic mixing term between B_μ and X_μ can be removed by a field redefinition [21,22], and we further identify the states of definite mass (denoted A, Z and Z') by performing a change of basis between these fields and the third generator of the $\mathrm{SU}(2)_\mathrm{L}$ group. After electroweak symmetry breaking, the mass of the photon (denoted by A) vanishes exactly, while the Z has the SM expression for its mass and the Z' has a mass given by μ.

We assume that none of the SM field content is charged under the novel $U(1)'$. Working to first order in χ and μ/v, the coupling between a SM fermion f and the Z' is purely vectorial and proportional to both χ and the particle electric charge q_f,

$$\mathcal{L} \supset -eq_f \cos\theta_\mathrm{W}\chi\bar{f}\gamma^\mu f Z'_\mu,$$

with $\tan\theta_\mathrm{W} \equiv g'/g$.

We also introduce SM-gauge singlets which are charged under the new $\mathrm{U}(1)'$, and assume that they mix with the SM neutrinos. In our simplified scheme, which captures the essential phenomenology, we work with a single right-handed neutrino but the extension to include multiple states is unproblematic. We denote the neutrino flavor states as ν_α $\alpha=\{e,\mu,\tau,s\}$ and the mass eigenstates as ν_i, $i = 1, 2, 3, 4$. These are related via a 4×4 Pontecorvo-Maki-Nakagawa-Sakata(PMNS)-like matrix U as $\nu_\alpha = U_{\alpha i}\nu_i$. The nearly-sterile massive neutrino ν_4 is assumed to have a small mixing with the lighter states and will be referred to as a "sterile neutrino".

Neutrino mixing mediates the $U(1)'$ interaction to the light neutrinos, and we find the following neutrino-Z' vertices to leading-order in χ and the small elements of the PMNS-like matrix:

$$\mathcal{L} \supset U^*_{\alpha 4} g'\bar{\nu_\alpha}\gamma^\mu P_\mathrm{L}\nu_4 Z'_\mu + U^*_{\alpha 4}U_{\beta 4}g'\bar{\nu_\alpha}\gamma^\mu P_\mathrm{L}\nu_\beta Z'_\mu + g'\bar{\nu_4}\gamma^\mu P_\mathrm{L}\nu_4 Z'_\mu, \quad (2)$$

where g' is the coupling constant of the new force. Provided that $|U_{\alpha 4}|^2 \ll 1$, we can expect sterile-active-Z' interactions to occur at a higher rate than active-active-Z' interactions ensuring that SM processes are largely unaffected. The novel interactions have a number of consequences for both sterile neutrino and Z' phenomenology. Firstly, we expect heavy neutrino production inside neutrino detectors via Z'-mediated upscattering. Secondly, these heavy states will have shorter lifetimes from enhanced NC decays. This could occur via either an on shell or off shell Z', e.g. $\nu_4 \to \nu_\alpha Z'$ or $\nu_4 \to \nu_\alpha e^+e^-$, depending on the hierarchy of the Z' and heavy neutrino masses. Here, for definiteness, we focus on the case $m_4 < m_{Z'}$. Although dependent on the precise values of kinetic and neutrino mixing parameters (and the possible presence of other particles in the model), order one branching fractions to $\nu_\alpha e^+e^-$ are attainable, with the other likely decays being to invisible multineutrino final states.[1] Finally, for $m_{Z'} > 2m_4$ the Z' will have a dominant decay into two sterile neutrinos. Although the latter are unstable, this unconventional final state will impact the constraints from previous experiments.

While ours is a phenomenological explanation, it is possible to incorporate it in theoretically consistent models. Typical examples include inverse and extended seesaw models in which two sterile neutrinos are introduced, one of which is neutral with respect to all gauge symmetries and couples to the Higgs and leptonic doublets through a Yukawa interactions and the other is mainly charged under the new symmetry and has a sizable mixing angle with the

[1] Although kinematically possible for heavy neutrinos with masses above 135 MeV, decays into pseudoscalar mesons are not enhanced by the Z' due to is vectorial coupling to quarks.

active neutrinos. The latter would play the role of the sterile neutrino ν_4 in our phenomenological explanation. It should be pointed out that models of this kind are also compatible with the bounds from neutrino masses.

III. THE MINIBOONE LOW ENERGY EXCESS

The analysis in this paper depends on both the production of a heavy neutrino via Z' mediated quasielastic scattering and the subsequent decay of the heavy neutrino into an electron-positron pair and a light neutrino. In the first step, the light neutrino flux, produced by meson decay inside the decay pipe of the Booster Neutrino beam [23], upscatters to produce the heavy neutrinos inside the detector via the Z'-mediated production process $\nu_\mu + \mathcal{N} \to \nu_4 + \mathcal{N}$ for a target hadron $\mathcal{N}$. For this to give a number of events comparable to few percent of the NC ones due to ν_μ interactions, we require that $|U_{\mu 4}|^2 \chi^2 (m_Z/m_{Z'})^4 \sim 0.01$, which suggests a scale for the new Z' of below 10 GeV. We include both coherent scattering off of carbon and incoherent scattering off the constituent protons of the detector medium. The coherent cross section is computed using an analytical approximation of a Woods-Saxon form factor [24,25] based on the symmetrized Fermi function [26,27]. The hadronic current in the neutrino-proton cross section is parametrized by the electromagnetic form factors of the proton [28], as the Z' only couples to SM particles via its electric charge.

In our model, the subsequent decay of these heavy neutrinos produces the MiniBooNE excess events. The dominant visible decay rate is to e^+e^- pairs mediated by the new boson $\nu_4 \to \nu_\alpha e^+ e^-$.

It is necessary to estimate the amount of e^+e^- events which would be misidentified as signal by the experiment. The MiniBooNE analysis made significant efforts to remove NC π^0 events in which there were two distinct Čerenkov rings. To this end, every event was fitted both with the single-shower (e) and two-shower ($\gamma\gamma$) hypothesis, and the log-likelihood ratio being used in the final selection. To help prevent cases in which the algorithm finds a better two shower fit in the case of true electron events, an additional requirement was included that ensured the invariant mass of the two shower candidates was less than the pion mass. MiniBooNE's detailed optical model [15] and the use of electron and π^0 likelihood functions in the final selection are difficult to reproduce externally, and instead we estimate the thresholds at which we expect these distinctions to be possible. First, we exclude all events with $m_{\gamma\gamma} > 0.08$ GeV, the upper bound of the range excluded in the MiniBooNE analysis [29]. For events passing this cut, we assume that the e^+e^- pair misidentification as a single Čerenkov shower can be achieved in one of two ways: i) events with sufficiently overlapping e^+e^- Čerenkov rings such that the final state is indistinguishable from a single e-like event, and ii) highly energy-asymmetric e^+e^- pairs, in which one lepton is of sufficiently low energy as not to be resolved consistently. To estimate the rate of "overlapping" and "asymmetric" events, we refer to MiniBooNE's own analysis. Although the CCQE selection includes a cut of > 200 hits in the main detector tank (180 hits is approximately the Michel electron upper bound, 52.8 MeV), this applies to the event as a whole, and provided that the most energetic shower is above this then it is possible to find a significantly lower energy shower alongside it. In the final π^0 selection the lowest events which MiniBooNE successfully detected had a second shower with ≈30 MeV reconstructed energy [30], albeit at a low efficiency. In parallel, the most recent MiniBooNE data show that the observed excess is solely contained in a single bin of angular separation between the electrons [31]. As such we take a conservative definition of an e^+e^- pair to be overlapping when the true angular separation between the fermions is small, $\theta_{\rm sep} < 5°$, and asymmetric events being those for which the softest particle of the e^-e^+ pair carries less than 30 MeV true total energy.

The degree at which an e^+e^- pair from a three-body decay meets our misreconstruction criteria depends predominantly on the boost factor of the parent heavy neutrino. We have studied this via a dedicated Monte Carlo simulation of decay events, confirming that the percentage of e^+e^- decays in our model which are classified as asymmetric or overlapping events is mostly insensitive to the Z' mass, with typical values ranging from 40% (for m_4 of 50 MeV) to below 10% (for $m_4 \geq 200$ MeV). The decays which do not satisfy our conditions would appear as a diffuse background to two shower events, such as the abundant NC-induced $\pi^0 \to \gamma\gamma$ events. Although it is possible these excess events could be resolved if they lie away from the π^0 peak, it is unclear without knowledge of the MB likelihood functions in which analysis region they would fall. We note that MiniBooNE did observe a slight excess in NC π^0 events relative to their Monte Carlo predictions [32], although this was corrected for in the CCQE ν_e analysis.

In order to identify the parameter space favored by our explanation of the LEE, we have performed a Monte Carlo simulation of the both the scattering and subsequent decay process, obtaining the visible energy and angular distribution of e-like events which meet our misreconstruction criteria. We fully incorporate the MiniBooNE detector and selection efficiencies for the CCQE ν_e analysis, as published in the data release for [33]. We show the allowed regions of parameter space that can explain the MiniBooNE LEE in Fig. 1. The left (right) panel shows the result of a shape only $\Delta\chi^2$ fit to the energy (angular) distributions of the LEE [2]. The angular and visible energy spectra have been fitted separately, as we do not have access to the fully correlated distributions, although their strong agreement in the preferred region leads us to expect such correlations will not significantly alter our result. The goodness of our fit can be seen in Fig. 2 where the predictions of a representative model is shown for both reconstructed visible energy and shower angle. This figure assumes a sterile neutrino of mass 0.14 GeV and a Z' of mass 1.25 GeV. Excellent agreement is

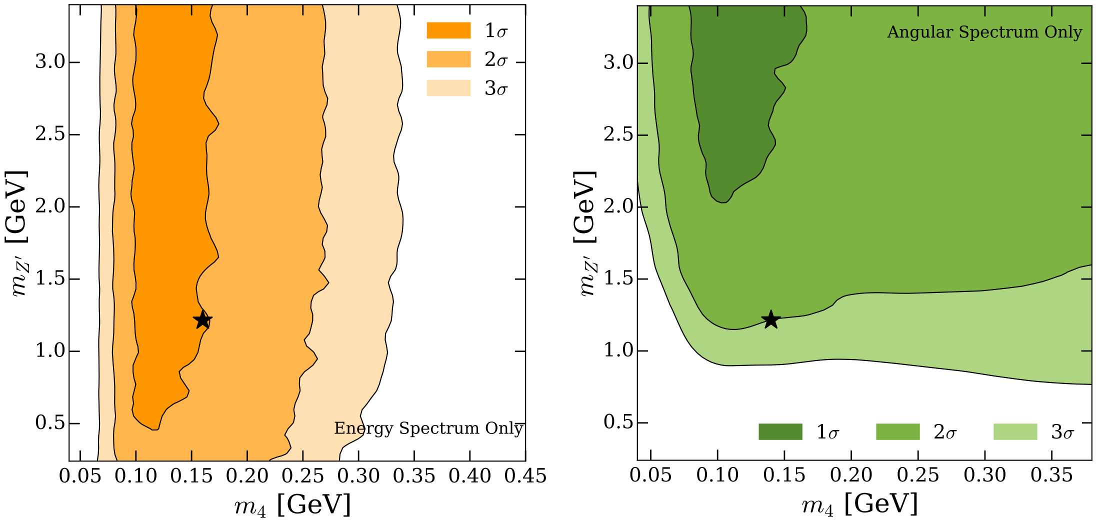

FIG. 1. Results of parameter scan in m_4 and $m_{Z'}$ fitting the shape of our model signal to reconstructed visible energy spectrum (left) and the reconstructed shower angle (right). The energy spectra is sensitivity only to m_4, requiring 100 MeV $\lesssim m_4 \lesssim$ 200 MeV to produce an excess with low enough energy, where as the angular spectrum puts a lower bound on the Z' mass below which the signal events are too forward going. The black star shows a representative point, detailed in Fig. (2). The values of the remaining parameters $U_{\mu4}$, $U_{\tau4}$, and kinetic mixing χ are marginalized over.

seen in both, with the Z' being heavy enough to produce a sufficiently isotropic signal, and the sterile neutrino mass allowing for the correct, steeply rising, visible energy spectra that was observed.

These figures report a shape-only analysis which mainly depends on the masses of the new particles. The total event rate is instead controlled by the specifics of the decay and by the allowed values of χ and $|U_{\alpha4}|$, factors which can change significantly from model to model. Deferring a thorough exploration of these issues to future work, we present here a concrete minimal realization of our explanation. As a representative value, we find that we can explain the MiniBooNE LEE with neutrino mixing angles of $|U_{\mu4}|^2 = 1.5 \times 10^{-6}$ and $|U_{\tau4}|^2 = 7.8 \times 10^{-4}$, a kinetic mixing strength of $\chi^2 = 5 \times 10^{-6}$ and a coupling of $g' = 1$. In this case, the hierarchy in mixing angles leads to a dominant visible decay of $\nu_\tau e^+ e^-$ with a total decay length of $\mathcal{O}(1)$ m. We find an expected event rate of 430 LEE events produced from scattering inside the detector.

Finally, we note that our estimates are based only on production from scattering inside the detector. As the MiniBooNE analysis does not rely on the reconstruction

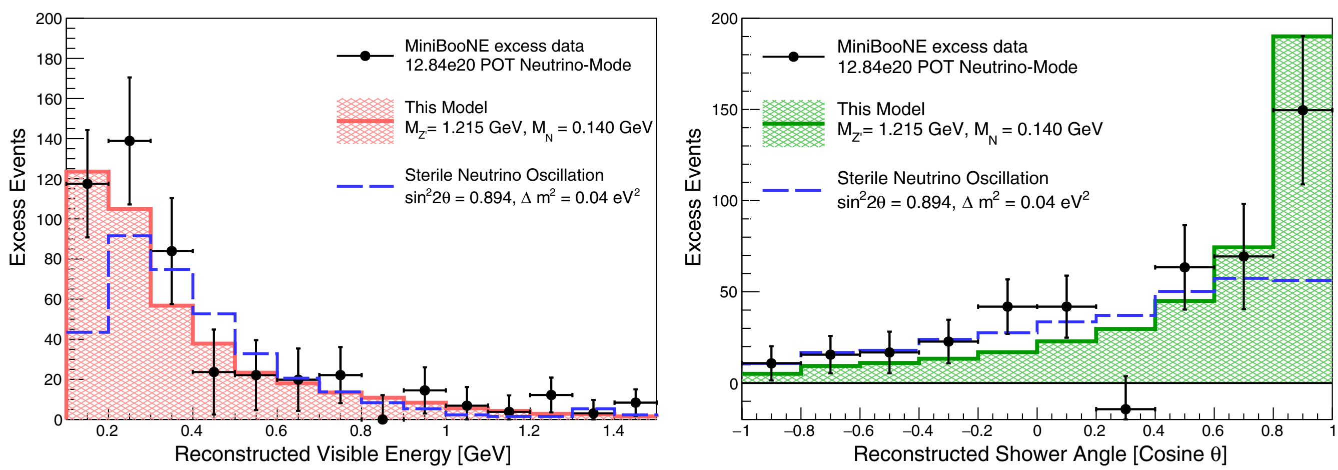

FIG. 2. Our model predictions in relation to the MiniBooNE excess, after subtracting predicted backgrounds, in both reconstructed visible energy (left) and reconstructed shower angle (right), for a 0.14 GeV sterile neutrino and 1.25 GeV Z'. In a minimal realization, this requires neutrino mixings of $|U_{\mu4}|^2 = 1.5 \times 10^{-6}$, $|U_{\tau4}|^2 = 7.8 \times 10^{-4}$ and kinetic mixing $\chi^2 = 5 \times 10^{-6}$, corresponding to a total decay length of 1 m. Excellent agreement is observed in both spectrums. MiniBooNE's best-fit sterile neutrino oscillation model is shown for comparison (blue dashed line).

of the scattering vertex, the potential exists for additional dirt events to contribute to our signal. These are expected to have the same kinematic properties as those simulated above and will generally increase our event rates, moving our estimated values of χ^2 and $|U_{\alpha 4}|^2$ to lower values.

A. Constraints on a minimal realization

In this section we will show that our minimal realization based on a hierarchical mixing pattern can produce a sufficient rate of signal events whilst satisfying all current bounds.

Both the kinetic mixing, χ^2, and active-sterile mixing elements, $|U_{\alpha 4}|^4$, have been bounded by many experiments in the past but these bounds need to be reconsidered in our model. Specifically, we need to take into account that: we have (i) large invisible and nearly invisible branching ratios for the Z' and (ii) an unstable heavy neutrino which decays within distances of the order 1–10 m. Any experiment which looked for the visible decays of on shell Z' particles must be reconsidered taking into account the visible branching fraction suppressed by χ^2. Published bounds subject to this weakening include *BABAR* [34], KLOE [35] and A1/MAMI [36], which searched for final state electrons, by approximately a factor of a χ. For a Z' of mass 1.25 GeV the most stringent bound, *BABAR*, becomes $\chi^2 \leq 7 \times 10^{-4}$ at the 90% C.L., allowing for kinetic mixings sufficiently large to produce enough events as required in Fig. 2.

The semi-invisible decays of the Z' into two sterile neutrinos and their subsequent decay into multileptons and missing energy might offer a novel means to test this model. The most promising signature would be two dilepton pairs at displaced vertices, neither pointing to a common origin. To the best of our knowledge, this has not been picked up in existing analyses.

Experimental bounds on active-heavy neutrino mixing will also be affected by the new interactions. Enhanced decay rates of the sterile neutrino naively increase the sensitivity of beam dump experiments, e.g. PS191 [37] or NuTeV [38]. However, once the rate increases sufficiently, sterile neutrinos produced in the beam will decay before reaching the detector, removing the bounds. For the parameters of our minimal realization, the sterile neutrino has a decay length of 1 m, severely weakening the bounds for $U_{\mu 4}$ set by PS191 (baseline: 128 m) and also $U_{\tau 4}$ set by experiments such as NOMAD [39] (835 m) and CHARM [40] (487 m).

Peak search experiments have no dependence on the subsequent decay and fully apply in our model [41] but are compatible with our benchmark point. Neutrino trident production could also place bounds on our new mediator [42]. Having provided a benchmark point in agreement with all experimental bounds, we leave an exhaustive scan of the whole parameter space to a future study.

IV. SUMMARY AND PREDICTIONS FOR MICROBOONE

We have discussed a novel explanation of the MiniBooNE low-energy excess based on heavy sterile neutrino production and decay inside the detector. The explanation hinges on the misidentification of the EM shower by a combination of highly asymmetric and overlapping e^+e^- pairs, which we argue happens for a sufficient fraction of decays in the sterile neutrino and Z' mass regions highlighted. We have shown a specific phenomenological model based on a sterile neutrino coupled to a hidden-sector $U(1)'$, which provides an excellent fit to both the energy and angular spectra of the LEE. This spectral agreement favors sterile masses of $100 \lesssim m_4 \lesssim 250$ MeV and Z' masses above 1 GeV. We have stressed that the event rate itself is dependent on the other parameters and on specific assumptions made on the model. We have presented a minimal realization requiring no additional particles beyond the sterile and Z', but with a hierarchy in the sterile-active mixing angles. This model can produce the correct number of events while maintaining the excellent spectral agreement with the LEE as in our more general model. Interestingly, the interplay between $U(1)'$ kinetic mixing and neutrino mass mixing leads to crucial model-dependent reinterpretations of the bounds on conventional $\mathcal{O}(100)$ MeV heavy neutrinos so that the values of the parameters required to explain the MiniBooNE LEE are allowed. We emphasize that this is only a minimal realization, and there are many variants on the core mechanism of this interpretation. For example, the production and decay could proceed via different light mediators, or the decay rate could be enhanced in a model with two sterile neutrinos where the heavier subsequently decays into the lighter one, as can arise in linear/extended seesaw models.

Our explanation can be falsified at contemporary short-baseline experiments such as MicroBooNE, whose liquid argon technology will crucially have access to topological and calorimetric means to distinguish electromagnetic showers of electrons from those of photons. We estimate that MicroBooNE would see around 150 (75) LEE signal-like events in the planned 6.6×10^{20} POT exposure, assuming a selection and reconstruction efficiency of 80% (40%) [43]. These signallike events are highly asymmetric or overlapping and would be split between MicroBooNE's γ-like LEE search (overlapping) and their e-like search (asymmetric). The model presented here has the unique feature that accompanying the 150 LEE events will be a novel signal of around 500[2] two e-like showers originating from a single vertex with no directly connected

[2] Due to the higher atomic mass of argon, this would be further enhanced by an proportional increase in coherent events, although these additional events would favor forward-going and overlapping electron pairs.

hadronic activity, but potentially with some protons from the initial scattering nearby. The only other common interactions that produces two electromagnetic showers in MicroBooNE are NC π^0 events in which both photons convert to e^+e^- pairs within a centimeter in conjunction with failing the electron-photon separation dE/dx calorimetric cuts [44]. As such we believe this is an extremely clean signal channel, allowing for the direct test of this class of models at MicroBooNE.

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Note added.—Recently, an explanation [45] for the MiniBooNE LEE appeared which also invokes a light Z' and a sterile neutrino. The latter is produced in Z'-enhanced NC interactions in the detector and subsequently decays into a light neutrino and an on shell Z' which itself decays rapidly into an e^+e^- pair. The signature is two strongly overlapping electrons. Although such explanation can also be achieved in our model if $m_{Z'} < m_4$, we focus here on the alternative case of $m_{Z'} > m_4$ and defer a more in-depth analysis of other variants of the explanation to future work.

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