Neutrino Interactions in the few-GeV region and the MiniBooNE anomaly

L Alvarez-Ruso¹, J Nieves¹, and E Saúl Sala¹ and E Wang²
¹Departamento de Física Teórica and Instituto de Física Corpuscular
Centro Mixto Universidad de Valencia-CSIC, 46071 Valencia, Spain
²Department of Physics, Zhengzhou University, Zhengzhou, Henan 450001, China
E-mail: Luis.Alvarez@ific.uv.es

Abstract. The MiniBooNE experiment reported results from the analysis of \( \nu_e \) and \( \bar{\nu}_e \) appearance searches, which showed an excess of signal-like events at low reconstructed neutrino energies with respect to the expected background. The origin of this anomaly could reside in poorly understood neutrino interactions in the detector, leading to unaccounted backgrounds. We discuss photon emission in neutral current interactions with nucleons and nuclei, finding it insufficient to explain the observed event excess. A proposed alternative scenario in which photons arise from the radiative decay of heavy (\( \sim 50 \) MeV) sterile neutrinos produced by \( \nu_\mu \) electromagnetic and weak interactions in the detector is also considered. We have calculated the expected signal at MicroBooNE. The distinctive shape and total number of photon events from this mechanism makes its experimental investigation appealing.

1. The MiniBooNE anomaly
The paradigm of three mixing neutrino flavors emerges from oscillation experiments with solar, atmospheric, reactor and accelerator neutrinos in which the square-mass differences and mixing angles have been determined with ever growing precision. Nevertheless, a number of anomalies that challenge this picture has been observed. One of them, reported by MiniBooNE, has found an excess of electron-like events over the predicted background in both \( \nu \) and \( \bar{\nu} \) modes [1, 2]. The excess is concentrated at \( 200 < E_{QE}^\nu < 475 \) MeV, where \( E_{QE}^\nu \) is the neutrino energy reconstructed assuming a charged-current quasielastic (QE) nature of the events.

Existing analyses struggle to accommodate this result together with world oscillation data, even in presence of one or more families of sterile neutrinos [3, 4]. The effect of multinucleon interactions in \( E_{QE}^\nu \) reconstruction is insufficient to remove the tension in global analyses [5], pointing at an explanation that does not invoke oscillations.

2. Photon-emission backgrounds in the Standard Model
One of the possible origins of the MiniBooNE anomaly resides in poorly understood backgrounds. At low \( E_{QE}^\nu \) the background is dominated by photon emission because Cherenkov detectors like MiniBooNE cannot distinguish electrons from single photons. The largest source of single photons is NC\( \pi^0 \) production where one of the photons from the \( \pi^0 \rightarrow \gamma \gamma \) decay is not identified. This background has been constrained by the MiniBooNE’s NC\( \pi^0 \) measurement [6]. The second most important process is photon emission induced by NC interactions (NC\( \gamma \)), which can take
place on single nucleons
\[ \nu(\bar{\nu}) N \rightarrow \nu(\bar{\nu}) \gamma N, \]  
and on nuclear targets
\[ \nu(\bar{\nu}) A \rightarrow \nu(\bar{\nu}) \gamma X \]  
\[ \nu(\bar{\nu}) A \rightarrow \nu(\bar{\nu}) \gamma A \]  
via incoherent [Eq. (2)] or coherent [Eq. (3)] scattering. This background could not be directly measured in the experiment. Instead, it was estimated using the NC\(\pi^0\) measurement, assuming that NC\(\gamma\) events come from the radiative decay of weakly produced resonances, mainly \(\Delta \rightarrow N\gamma\) \([1, 2]\). This procedure neither takes into account the existence of non-resonant terms (first and second diagrams in figure 1 with virtual nucleons in the intermediate state), nor the coherent channel. If the NC\(\gamma\) emission estimate were not sufficiently accurate, this would be relevant to track the origin of the observed excess.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{feynman_diagrams.png}
\caption{Feynman diagrams for NC photon emission considered in the literature. The first two diagrams stand for direct and crossed baryon pole terms with nucleons and baryon resonances \(\Delta(1232), N^*(1440), N^*(1520), N^*(1535)\) in the intermediate state. The third diagram represents \(t\)-channel meson \((\pi, \rho, \omega)\) exchange contributions.}
\end{figure}

Theoretical models for the reaction of Eq. (1) in the few-GeV region have been developed in Refs. \([7, 8, 9]\). These calculations incorporate \(s\)- and \(u\)-channel amplitudes with nucleons and \(\Delta(1232)\) in the intermediate state (see figure 1). The structure of nucleon pole terms at threshold is fully determined by the symmetries of the Standard Model. The extension towards higher energy transfers required to make predictions for neutrino cross sections is performed by the introduction of phenomenological parametrizations of the weak and electromagnetic form factors. The same strategy has been followed for the resonance terms. The \(\Delta(1232)\) excitation followed by its radiative decay is the dominant mechanism. The contribution from the \(D_{13}(1520)\) on proton targets is sizable above \(E_\nu \sim 1.5\) GeV while \(P_{11}(1440)\) and \(S_{11}(1535)\) are negligible (see figure 5 of Ref. \([9]\)). The pion-pole mechanism, which originates from the \(Z^0\gamma\pi\) vertex, fixed by the axial anomaly of QCD, is nominally of higher order \([10]\) and, indeed, gives a very small contribution to the cross section. Among the terms with heavier meson \(t\)-channel exchange, the \(\omega\) one was proposed as a solution for the MiniBooNE anomaly \([11]\) because of the rather large (although uncertain) couplings and the \(\omega\) isoscalar nature, which enhances its impact on the coherent reaction of Eq. (3). However, actual calculations found this contribution small compared to \(\Delta(1232)\) excitation \([7, 12]\).

The incoherent NC\(\gamma\) reaction on nuclear targets, Eq. (2), has been studied in Refs. \([13, 9]\) using the relativistic local Fermi gas approximation to take into account Fermi motion and Pauli blocking. The broadening of the \(\Delta\) resonance in the medium has also been incorporated using a spreading potential in Refs. \([13, 8]\), while Ref. \([9]\) uses the parametrization of the imaginary part of the in-medium \(\Delta\) selfenergy as a function of the local nuclear density derived in Ref. \([14]\). The
neglect of nuclear medium corrections is a poor approximation: by taking into account Fermi motion and Pauli blocking, the cross section already goes down by more than 10%. With the full model the reduction is of the order of 30% (see figure 9 of Ref. [9]). Coherent photon emission [Eq. (2)] is computed in Refs. [15, 9] using the same microscopic input as for the incoherent process. The sum of amplitudes over all nucleons leads to the Fourier transform of different operators proportional to the nuclear density. The resulting integrated cross sections are about a factor 10-15 smaller than the incoherent ones.

The NC\(\gamma\) model outlined above has been applied to calculate the number and distributions of single photon events at MiniBooNE [16], using the available information about the detector mass and its composition (CH\(_2\)), the total number of protons on target (POT), [2], the flux prediction [17] and photon detection efficiency [18]. The yields from the incoherent channel are the largest ones. Those from the coherent channel and the reaction on protons, which are comparable, are smaller but significant. The coherent contribution is particularly important for antineutrinos and in the forward direction (see the plots in figure 3 of Ref. [16]).

Our results for the \(E_{QE}^{\nu}\) distributions are shown in figure 2. The error bands correspond to a 68 % confidence level according to the error budget in Table 1 of Ref. [16]. The comparison with the MiniBooNE in situ estimate [2, 18] shows a good agreement: the shapes are similar and the peak positions coincide. The largest discrepancy is observed in the lowest energy bin. In the two bins with the largest number of events, the two calculations are consistent within our errorbars. The overall agreement is also good in comparison to the result of Zhang and Serot [8]. Therefore,

we conclude that neutral current photon emission from single-nucleon currents is insufficient to explain the event excess observed by MiniBooNE in both neutrino and antineutrino modes.

3. Photons from radiative decay of heavy neutrinos

Gninenko proposed that additional photons could originate in the weak production of a heavy \((m_\nu \approx 50\) MeV) sterile neutrino slightly mixed with muon neutrinos, followed by its radiative decay [19]. In Ref. [20] it was pointed out that the \(\nu_h\) could also be electromagnetically produced, alleviating tensions in the original proposal with other data such as those from radiative muon capture measured at TRIUMF.

We have revisited the scenario presented in Ref. [20] using present understanding of electromagnetic (EM) and weak interactions on nucleons and nuclei [21, 22]. For a more detailed analysis, we compare to the MiniBooNE excess of events in the originally measured electron-like energy and angle [18] (being the photon ones in our case) rather than in \(E_{QE}^{\nu}\). We have studied

![Figure 2. \(E_{QE}^{\nu}\) distributions of total NC\(\gamma\) events for the \(\nu\) (left) and \(\bar{\nu}\) (right) modes. The “MB” histograms display the MiniBooNE estimates [18].](image-url)
\( \nu_h \) EM and weak production in the following processes

\[
\nu_\mu, \bar{\nu}_\mu(k) + N(p) \rightarrow \nu_h, \bar{\nu}_h(k') + N(p'), \quad (4)
\]

\[
\nu_\mu, \bar{\nu}_\mu(k) + A(p) \rightarrow \nu_h, \bar{\nu}_h(k') + A(p'), \quad (5)
\]

\[
\nu_\mu, \bar{\nu}_\mu(k) + A(p) \rightarrow \nu_h, \bar{\nu}_h(k') + X(p'). \quad (6)
\]

Reaction (5) is coherent while (6) is incoherent; excited states \( X \) include any number of knocked out nucleons but no meson production.

In the EM case, following Ref. [20], we have adopted the effective interaction

\[
\mathcal{L}_{\text{eff}} = \frac{1}{2} \mu_\nu^i \left[ \bar{\nu}_h \sigma_{\mu\nu} (1 - \gamma_5) \nu_i + \bar{\nu}_i \sigma_{\mu\nu} (1 + \gamma_5) \nu_h \right] \partial^\nu A^\nu, \quad (7)
\]

in terms of a real transition coupling \( \mu_\nu^i \); \( \nu_h \) is assumed to be a Dirac fermion of mass \( m_h \).

In the weak case, the neutrino vertex has the same structure as in the Standard Model and is proportional to the mixing \( U_{\mu h} \). The EM (NC) hadronic tensors are the same probed in the corresponding electron (neutrino) scattering processes. For the nucleon, it is given in terms of electromagnetic and axial form factors, for which we have adopted dipole parametrizations. For coherent scattering (5), the tensor is proportional to the square of the nuclear form factor, obtained as the Fourier transform of the empirical charge-density distribution. For the incoherent reaction, as in the previous section, we take into account particle-hole excitations in infinite nuclear matter, adapted to finite nuclei using the local density approximation.

With the parameters of Ref. [20], \( m_h = 50 \text{ MeV} \), \( \mu_\nu^e = 2.4 \times 10^{-9} \mu_B \), and \( |U_{\mu h}|^2 = 0.003 \), the EM cross section on nuclei is dominated by the coherent mechanism, while the incoherent one is suppressed by Pauli blocking at low four-momentum transfers, where the amplitude is enhanced by the photon propagator. On the contrary, the incoherent reaction is the largest contribution to the weak NC part (figure 1 of Ref. [21]). Interference terms between the EM and NC amplitudes are allowed but negligible.

We have investigated the \( \nu_h \) propagation and radiative decay inside the MiniBooNE detector, obtaining the photon energy and angular distributions. We have taken advantage of the fact that, as pointed out in Ref. [20], the beam energies are large compared to \( m_h \) and only an insignificant amount of the electromagnetically (weakly) produced heavy neutrinos have the spin against (aligned with) its momentum. Radiative decay photons are emitted predominantly in the direction opposite to the \( \nu_h \) spin. The \( \nu_h \) lifetime in its rest frame \( \tau = 5 \times 10^{-9} \text{ seconds} \) [20].

To compare to the measured excess of events, the detection efficiency [18] has to be taken into account. The number of low energy events is underestimated in \( \nu \)-mode, while the agreement is good in \( \bar{\nu} \)-mode. The predominantly EM coherent contribution is strongly forward peaked. This leads to a very narrow angular distribution not observed in the experiment as can be seen in figure 2 of Ref. [21]. This result is in line with the findings of Ref. [23].

The agreement can be improved by fitting the parameters in the allowed range established in Ref. [24]. With these values, \( m_h = 68.6 \text{ MeV} \), \( \mu_\nu^e = 6.4 \times 10^{-10} \mu_B \), \( |U_{\mu h}|^2 = 0.01 \) and \( \tau = 2.5 \times 10^{-9} \text{ seconds} \), the resulting event energy and angular distributions are given in figure 3. The MiniBooNE excess of events is now better described, particularly the angular distributions.

This better agreement is obtained at the price of reducing the EM strength, while increasing the NC one by setting \( |U_{\mu h}| \) to its maximal allowed value; this upper limit in \( |U_{\mu h}| \) prevents from obtaining a more satisfactory description of the data.

4. Single-photon events at MicroBooNE

The radiative decay hypothesis can be further tested at the Short Baseline Neutrino (SBN) detectors at Fermilab: SBND, MicroBooNE (currently taking data) and ICARUS, with liquid...
Figure 3. Photon events from radiative decay of $\nu_h$, $\bar{\nu}_h$ at the MiniBooNE detector in $\nu$-mode (top) and $\bar{\nu}$-mode (bottom) compared to the MiniBooNE excess [18].

Argon targets. Our predictions for the photon distributions at MicroBooNE, with the flux in $\nu$-mode [25] and assuming $N_{\text{TOT}} = 6.6 \times 10^{20}$, are displayed in figure 4. The shape and number of events appears distinctive from those from conventional photon emission mechanisms shown in figure 5. In particular, events from $\nu_h$ decay are clearly more forward-peaked.

Figure 4. Photon events from radiative decay of $\nu_h$ at MicroBooNE in $\nu$-mode.

Acknowledgments
Work supported by the Spanish Ministerio de Economía y Competitividad and European Regional Development Fund under Contracts FIS2014-51948-C2-1-P, FIS2014-51948-C2-2-P, FIS2017-84038-C2-1-P, FIS2017-84038-C2-2-P and SEV-2014-0398, and by Generalitat Valenciana under contract PROMETEOII/2014/0068.
Figure 5. NC\(\gamma\) events at MicroBooNE in \(\nu\)-mode predicted with the model of Ref. [9] described in Sec. 2. The (negligible) contribution from \(\bar{\nu}\) in the flux is also shown in the bottom panels.

References
[1] Aguilar-Arevalo A et al. (MiniBooNE Collaboration) 2009 Phys. Rev. Lett. 102 101802 (Preprint 0812.2243)
[2] Aguilar-Arevalo A et al. (MiniBooNE Collaboration) 2013 Phys. Rev. Lett. 110 161801 (Preprint 1207.4809)
[3] Giunti C, Laveder M, Li Y F and Long H W 2013 Phys. Rev. D88 073008
[4] Garayzio S, Giunti C, Laveder M and Li Y F 2017 JHEP 06 135 (Preprint 1703.00860)
[5] Ericson M, Garzelli M V, Giunti C and Martini M 2016 Phys. Rev. D93 073008
[6] Aguilar-Arevalo A A et al. (MiniBooNE Collaboration) 2010 Phys. Rev. D81 013005 (Preprint 0911.2063)
[7] Hill R J 2010 Phys. Rev. D81 013008 (Preprint 0905.0291)
[8] Zhang X and Serot B D 2013 Phys. Lett. B719 409–414 (Preprint 1210.3610)
[9] Wang E, Alvarez-Ruso L and Nieves J 2014 Phys. Rev. C89 015503 (Preprint 1311.2151)
[10] Serot B D and Zhang X 2012 Phys. Rev. C86 015501 (Preprint 1206.3812)
[11] Harvey J A, Hill C T and Hill R J 2014 Phys. Rev. C89 015503 (Preprint 1311.2151)
[12] Rosner J L 2015 Phys. Rev. D91 093001 (Preprint 1502.01704)
[13] Zhang X and Serot B D 2012 Phys. Rev. C86 035502 (Preprint 1206.6324)
[14] Oset E and Salcedo L 1987 Nucl. Phys. A468 631–652
[15] Zhang X and Serot B D 2012 Phys. Rev. C86 035504 (Preprint 1208.1553)
[16] Wang E, Alvarez-Ruso L and Nieves J 2015 Phys. Lett. B740 16–22
[17] Aguilar-Arevalo A et al. (MiniBooNE Collaboration) 2009 Phys. Rev. D79 072002 (Preprint 0806.1449)
[18] Miniboone collaboration: https://www.boone.fnal.gov/for physicists/data release/
[19] Gninenko S N 2009 Phys. Rev. Lett. 103 241802
[20] Masip M, Masjuan P and Meloni D 2013 JHEP 1301 106
[21] Alvarez-Ruso L and Saul-Sala E 2017 Proceedings, Prospects in Neutrino Physics (NuPhys2016): London, UK, December 12-14, 2016 (Preprint 1705.00353)
[22] Alvarez-Ruso L and Saul-Sala E in preparation
[23] Radionov A 2013 Phys. Rev. D88 015016
[24] Gninenko S N 2011 Phys. Rev. D83 015015 (Preprint 1009.5536)
[25] Pavlovic Z and Palamara O private communication