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Observed Event Excess in the MiniBooNE Search for $\bar{\nu}_\mu \to \bar{\nu}_e$ Oscillations

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The MiniBooNE Collaboration reports results from a search for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, using a data sample corresponding to 5.66×10^{20} protons on target. An excess of events is observed which, when constrained by the observed $\bar{\nu}_\mu$ events, has a probability for consistency with the background-only hypothesis of 0.5% in the oscillation-sensitive energy range of $475 < E_\nu^{QE} < 1250$ MeV. The data are consistent with $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations with Δm^2 ranging from 0.1 to 1 eV^2 and with the evidence for antineutrino oscillations from the Liquid Scintillator Neutrino Detector at Los Alamos National Laboratory.

The MiniBooNE experiment has published searches for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, motivated by the LSND 3.8σ excess of events [1]. In the $\nu_\mu \to \nu_e$ study, MiniBooNE found no evidence for oscillations within a two neutrino mixing model at 98% C.L.; however, a 3.0σ excess of electron-like events was observed below 475 MeV [2, 3]. The source of the excess remains unexplained [3], although several hypotheses have been put forward [4–10], including, for example, anomaly-mediated neutrino-photon coupling and sterile neutrino oscillations with CP or CPT violation. Initial results from the $\bar{\nu}_\mu \to \bar{\nu}_e$ study were reported in [11]. A search in antineutrino mode provides a more direct test of the LSND signal, which was observed with antineutrinos. Due to limited statistics, the initial MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ search was inconclusive with respect to two-neutrino oscillations at the LSND mass scale, although a joint analysis reported compatibility between the LSND, KARMEN [12, 13], and MiniBooNE antineutrino experiments [4]. In this paper, we report an updated analysis of the $\bar{\nu}_\mu \to \bar{\nu}_e$ search with 1.7 times more protons on target (POT) than reported in [11].

This analysis uses the same technique that was reported earlier [11] and assumes only $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations with no significant $\bar{\nu}_\mu$ disappearance and no ν_μ oscillations. In addition, no contribution from the observed neutrino mode low energy excess has been accounted for in the antineutrino prediction. These simplifications may change the fitted $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation probability by 10-20%.

The antineutrino flux is produced by 8 GeV protons from the Fermilab Booster interacting on a beryllium target inside a magnetic focusing horn. Negatively charged mesons produced in p-Be interactions are focused in the forward direction and subsequently decay primarily into

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$\bar{\nu}_\mu$. The flux for neutrinos and antineutrinos of all flavors is calculated with a simulation program using external measurements [14]. In antineutrino mode, the ν_μ, $\bar{\nu}_e$, and ν_e flux contaminations at the detector are 15.7%, 0.4%, and 0.2%, respectively. The $\bar{\nu}_\mu$ flux peaks at $\sim$ 400 MeV and has a mean energy of $\sim$ 600 MeV.

The MiniBooNE detector has been described in detail elsewhere [15]. The detector location was chosen to satisfy $L[\mathrm{m}]/E[\mathrm{MeV}] \sim 1$, similar to that of LSND, which maximizes the sensitivity to oscillations at $\Delta m^2 \sim 1$ eV^2. The detector consists of a 40-foot diameter sphere filled with pure mineral oil ($\sim CH_2$). Neutrino interactions in the detector produce final state electrons or muons, which produce scintillation and Cherenkov light detected by the 1520 8-inch photomultiplier tubes (PMTs) that line the interior of the detector.

The signature of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations is an excess of $\bar{\nu}_e$-induced charged-current quasi-elastic (CCQE) events. Reconstruction [16] and selection requirements of these events are identical to those of the previous neutrino and antineutrino mode analyses [3, 11]. The detector cannot differentiate between neutrino and antineutrino events on an event-by-event basis. To help constrain the $\nu_e/\bar{\nu}_e$ candidate events, a $\nu_\mu/\bar{\nu}_\mu$ sample is formed. The separation of ν_μ from $\bar{\nu}_\mu$ in this large CCQE sample is accomplished by fitting the observed angular distribution of the outgoing muons to a linear combination of the very different CCQE angular distributions for μ^+ and μ^-. Relative to the Monte Carlo prediction, the μ^+ yield required an increase of 1.20 to the rate of π^- decays ($\bar{\nu}_\mu$), while the μ^- yield was 0.99 of its predicted rate. Overall, the normalization required a 13% increase, which is compatible with the combined neutrino flux and cross section uncertainties. A sample of 24,771 data events pass the $\bar{\nu}_\mu$ CCQE selection requirements. The neutrino and antineutrino content of the sample are 22% and 78%, respectively.

The oscillation parameters are extracted from a combined fit to the $\bar{\nu}_e$ CCQE and $\bar{\nu}_\mu$ CCQE event distributions. Any possible $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal, as well as some $\bar{\nu}_e$ backgrounds interact through the same process as $\bar{\nu}_\mu$ CCQE events and are related to the $\bar{\nu}_\mu$ CCQE events through the same π^- decay chain at production. These correlations enter through the off-diagonal elements of the covariance matrix used in the χ^2 calculation, relating the contents of the bins of the $\bar{\nu}_e$ CCQE and $\bar{\nu}_\mu$ CCQE distribution. This procedure maximizes the sensitivity to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations when systematic uncertainties are included [17].

The number of predicted $\bar{\nu}_e$ CCQE background events for different ranges of E_ν^{QE} is shown in Table I. The background estimates include both antineutrino and neutrino events, the latter representing $\sim$ 44% of the total background. The predicted backgrounds to the $\bar{\nu}_e$ CCQE sample are constrained by measurements at MiniBooNE and include neutral current (NC) π^0 events [18], $\Delta \rightarrow N\gamma$ radiative decay, and external events from neutrino interactions outside the detector. Other backgrounds from mis-identified ν_μ or $\bar{\nu}_\mu$ [19, 20] and from intrinsic ν_e and $\bar{\nu}_e$ events from the $\pi \rightarrow \mu$ decay chain receive the $\bar{\nu}_\mu$ CCQE normalization correction according to their parentage at production (π^+ or π^-). The expected excess of low-energy events from the neutrino component of the beam [2] is about 12 events for $200 < E_\nu^{QE} < 475$ MeV.

TABLE I: *The expected number of events for different E_ν^{QE} ranges from all of the backgrounds in the $\bar{\nu}_e$ appearance analysis and for the LSND expectation (0.26% oscillation probability averaged over neutrino energy) of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, for 5.66×10^{20} POT.*

Process	200 – 475 MeV	475 – 1250 MeV
$\overset{(-)}{\nu}_\mu$ CCQE	4.3	2.0
NC π^0	41.6	12.6
NC $\Delta \rightarrow N\gamma$	12.4	3.4
External Events	6.2	2.6
Other $\overset{(-)}{\nu}_\mu$	7.1	4.2
$\overset{(-)}{\nu}_e$ from $\mu^\pm$ Decay	13.5	31.4
$\overset{(-)}{\nu}_e$ from $K^\pm$ Decay	8.2	18.6
$\overset{(-)}{\nu}_e$ from K_L^0 Decay	5.1	21.2
Other $\overset{(-)}{\nu}_e$	1.3	2.1
Total Background	99.5	98.1
0.26% $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	9.1	29.1

Systematic uncertainties are determined by considering the predicted effects on the $\bar{\nu}_\mu$ and $\bar{\nu}_e$ CCQE rate from variations of actual parameters. These include uncertainties in the flux estimate, uncertainties in neutrino cross sections, most of which are determined by in-situ cross-section measurements at MiniBooNE, and uncertainties in detector modeling and reconstruction. By considering the variation from each source of systematic uncertainty on the $\bar{\nu}_e$ CCQE signal, background, and $\bar{\nu}_\mu$ CCQE prediction as a function of E_ν^{QE}, a covariance matrix in bins of E_ν^{QE} is constructed. This matrix includes correlations between $\bar{\nu}_e$ CCQE (signal and background) and $\bar{\nu}_\mu$ CCQE and is used in the χ^2 calculation of the oscillation fit.

Fig. 1 (top) shows the E_ν^{QE} distribution for $\bar{\nu}_e$ CCQE observed data and background. A total of 277 events pass the $\bar{\nu}_e$ event selection requirements with $200 < E_\nu^{QE} < 3000$ MeV, compared to an expectation of 233.8 ± 22.5

TABLE II: *The number of data, fitted background, and excess events in the $\bar{\nu}_e$ analysis for different E_ν^{QE} ranges. The uncertainties include both statistical and constrained systematic errors.*

E_ν^{QE} Range	Data	Background	Excess
200 – 475 MeV	119	$100.5 \pm 10.0 \pm 10.2$	18.5 ± 14.3
475 – 675 MeV	64	$38.3 \pm 6.2 \pm 3.7$	25.7 ± 7.2
475 – 1250 MeV	120	$99.1 \pm 10.0 \pm 9.8$	20.9 ± 14.0
475 – 3000 MeV	158	$133.3 \pm 11.5 \pm 13.8$	24.7 ± 18.0
200 – 3000 MeV	277	$233.8 \pm 15.3 \pm 16.5$	43.2 ± 22.5

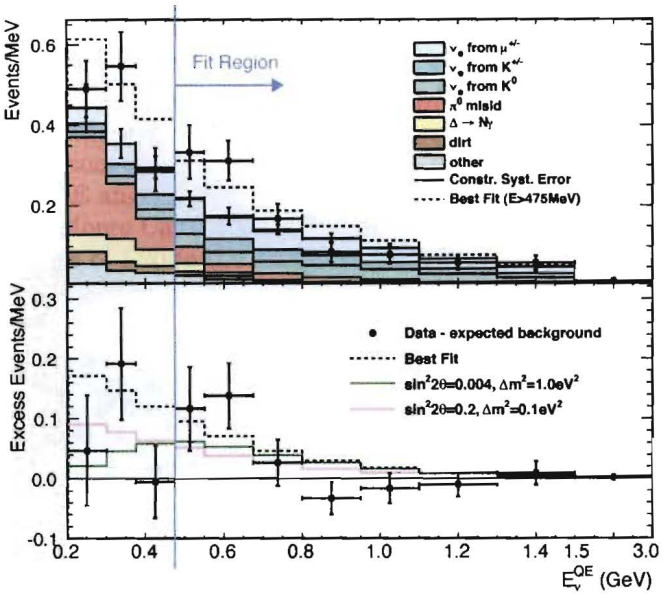

FIG. 1: Top: The E_ν^{QE} distribution for $\bar{\nu}_e$ CCQE data (points with statistical errors) and background (histogram with systematic errors). Bottom: The event excess as a function of E_ν^{QE}. Also shown are the expectations from the best oscillation fit with $E_\nu^{QE} > 475$ MeV, where the prediction is extrapolated below 475 MeV, and from neutrino oscillation parameters in the allowed region.

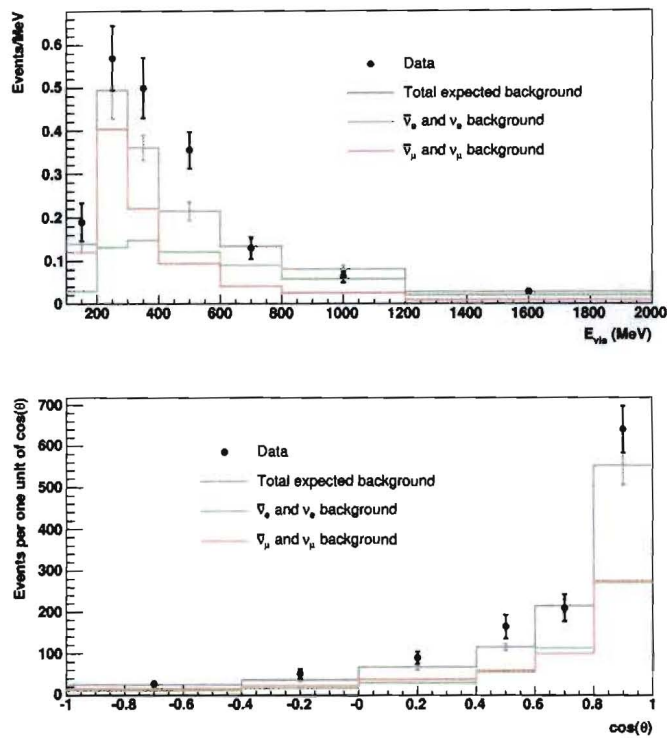

FIG. 2: The E_{vis} (top panel) and $\cos(\theta)$ (bottom panel) distributions for data (points with statistical errors) and backgrounds (histogram with systematic errors) for $E_\nu^{QE} > 200$ MeV.

events. This corresponds to an excess of 43.2 ± 22.5 events. In the previous neutrino run analysis, event totals were considered in two energy regions: 200 - 475 MeV and 475 - 3000 MeV, which is the energy range for the neutrino oscillation search. For the antineutrino data, the excess for $475 < E_\nu^{QE} < 3000$ MeV is 24.7 ± 18.0 events. In the oscillation sensitive region of $475 < E_\nu^{QE} < 1250$ MeV, the observed $\bar{\nu}_e$ events, when constrained by the $\bar{\nu}_\mu$ data events, have a $\chi^2/DF = 18.5/6$ and a probability of 0.5% for a background-only hypothesis. For the combined $\bar{\nu}_\mu$ and $\bar{\nu}_e$ data in the energy range $475 < E_\nu^{QE} < 3000$ MeV, the background-only hypothesis yields a $\chi^2/DF = 26.8/14.9$ with a χ^2-probability of 3.0%. (DF is the effective number of degrees of freedom from frequentist studies.) This is higher than the 0.5% probability found for the $\bar{\nu}_e$ signal region due to the inclusion of $\bar{\nu}_\mu$ and higher-energy $\bar{\nu}_e$ bins, where no signal is expected. The number of data, fitted background, and excess events for different E_ν^{QE} ranges are summarized in Table II.

Fig. 2 shows the observed and predicted event distributions as functions of reconstructed E_{vis} and $\cos(\theta)$ for $200 < E_\nu^{QE} < 3000$ MeV. E_{vis} is the measured visible energy, while θ is the scattering angle of the reconstructed electron with respect to the incident neutrino direction. The shape-only background only χ^2 values from the $\bar{\nu}_e$ and $\bar{\nu}_\mu$ combined fit are $\chi^2/DF = 23.8/13$ and $\chi^2/DF = 13.6/11$ for E_{vis} and $\cos(\theta)$, respectively. Therefore, the E_{vis} distribution does not match well the shape of the estimated backgrounds, while the $\cos(\theta)$ distribution matches the background (and signal) shape.

Many checks were performed on the data to ensure that the backgrounds were estimated correctly. Beam and detector stability checks showed that the neutrino event rate was stable to $< 2\%$ and that the detector energy response was stable to $< 1\%$. In addition, the fractions of neutrino and antineutrino events were stable over energy and time, and the measured external event rates were similar in both neutrino and antineutrino modes. Furthermore, any single background would have to be increased by more than 3 σ to explain the observed excess of events. An additional check comes from the data in neutrino mode, which has a similar background to antineutrino mode and where good agreement was obtained between the data and Monte Carlo simulation for $E_\nu^{QE} > 475$ MeV. Finally, the event rate of candidate $\bar{\nu}_e$ events in the last 2.27×10^{20} POT is found to be 1.9σ higher than the candidate event rate in the first 3.39×10^{20} POT [11].

Fig. 1 (bottom) shows the event excess as a function of E_ν^{QE}. Also shown are the expectations from the best oscillation fit with $E_\nu^{QE} > 475$ MeV and from neutrino oscillation parameters in the allowed region. The energy range $E_\nu^{QE} > 475$ MeV has been chosen for the fit as this is the energy range MiniBooNE used for searching

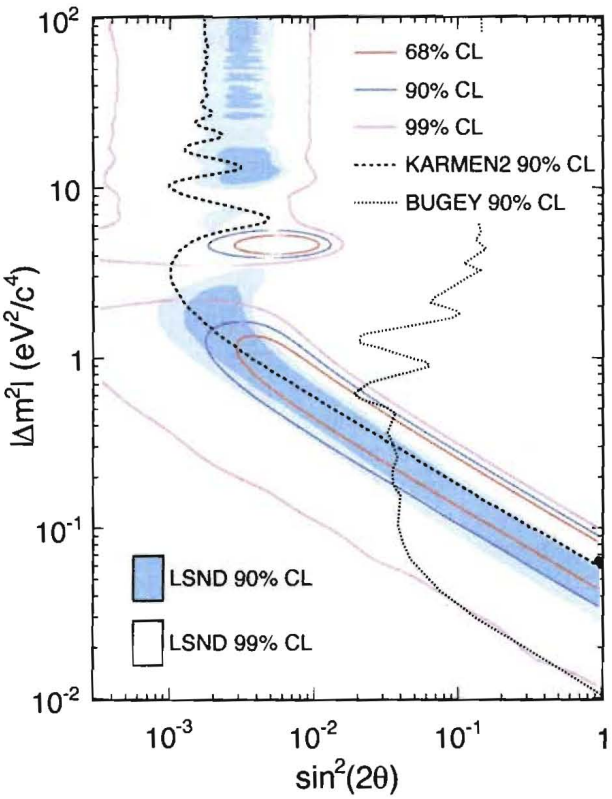

FIG. 3: MiniBooNE 68%, 90%, and 99% C.L. allowed regions for events with $E_\nu^{QE} > 475$ MeV within a two neutrino $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation model. Also shown are limits from KARMEN [12] and Bugey [21]. The Bugey curve is a 1-sided limit for $\sin^2 2\theta$ corresponding to $\Delta\chi^2 = 1.64$, while the KARMEN curve is a "unified approach" 2D contour. The shaded areas show the 90% and 99% C.L. LSND allowed regions.

for neutrino oscillations.

Using a likelihood-ratio technique, the best oscillation fit for $475 < E_\nu^{QE} < 3000$ MeV occurs at (Δm^2, $\sin^2 2\theta$) = (0.064 eV^2, 0.96) and has a χ^2 of 16.4 for 12.6 DF, corresponding to a χ^2-probability of 20.5%. For the oscillation-sensitive energy range of $475 < E_\nu^{QE} < 1250$ MeV, the best oscillation fit has a χ^2 of 8.0 for 6 DF, corresponding to a χ^2-probability of 23.4%. The ratio of the likelihood of the background only fit divided by the likelihood of the best oscillation fit is 0.6%. Fig. 3 shows the 68%, 90%, and 99% C.L. closed contours for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, where frequentist studies were performed to determine the C.L. regions. The allowed regions are in agreement with the LSND allowed region.

In summary, the MiniBooNE experiment observes an excess of $\bar{\nu}_e$ events in the energy region above E_ν^{QE} of 475 MeV for a data sample corresponding to 5.66×10^{20} POT. A model independent hypothesis test gives a probability of 0.5% for the data to be consistent with the expected backgrounds in the oscillation-sensitive energy range of $475 < E_\nu^{QE} < 1250$ MeV, and a likelihood-ratio fit gives a 0.6% probability for background only relative to the best oscillation fit. The allowed regions from the fit, shown in Fig. 3, are consistent with $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations in the 0.1 to 1 eV^2 Δm^2 range and consistent with the allowed region reported by the LSND experiment [1]. Additional running in antineutrino mode is expected to approximately double the current number of POT.

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