Single photon background to ν_e appearance at MiniBooNE

Richard J. Hill*

Enrico Fermi Institute and Department of Physics, The University of Chicago, Chicago, Illinois, 60637, USA

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Neglected single-photon processes are compared to an excess of electronlike events observed in a predominantly ν_μ beam at MiniBooNE. Predictions are given for analogous events in antineutrino mode.

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I. INTRODUCTION

The MiniBooNE experiment was designed to test the indication of a $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation signal at LSND [1,2]. MiniBooNE data for ν_e appearance in a ν_μ beam [3], when restricted to the range of 475–1250 MeV reconstructed neutrino energy, refute a simple two-neutrino oscillation interpretation for the LSND signal. However, the results indicate an excess of signal-like events at low energy, which has persisted at the 3σ level after various refinements to the analysis [4]. First results from MiniBooNE for $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam do not show a significant excess [5], but are inconclusive with respect to the LSND signal.

Because electromagnetic showers instigated by electrons and photons are not distinguishable at MiniBooNE, neutral current events producing single photons are an irreducible background to the charged current $\nu_e n \to e^- p$ signal. This note presents flux-averaged cross sections for the dominant sources of single-photon backgrounds, some of which were not incorporated in the MiniBooNE analysis. These standard model processes must be well-understood and accounted for before appealing to more exotic interpretations of the electronlike signal.

II. SINGLE-PHOTON PROCESSES

The $\sim$1 GeV energy range is unfortunately not well suited to precise analytic results, since there is no obvious small expansion parameter for this regime of QCD [6]. At low energy, contributions to the process of interest can be tabulated in the rigorous language of a chiral lagrangian expansion. Extrapolation to moderate energy can then be performed by explicitly including the lowest-lying resonances in each channel, and adopting phenomenological form factors to mimic the effects of higher resonances. This methodology was discussed in detail in [7]. This study was motivated by the search for low-energy remnants of the baryon current anomaly, such as the coherent coupling of weak and electromagnetic currents to baryon density [8,9].

In terms of the chiral lagrangian expansion, the production of single photons in neutrino scattering on nucleons begins at order $1/M$ [10]. The $1/M$ contributions represent offshell intermediate nucleon states or Compton-like scattering, including bremsstrahlung corrections to elastic scattering. At the next order there appears a term that derives from s-channel $\Delta(1232)$ production and t-channel $\omega(780)$ exchange. Exchange of π^0 in the t-channel is naively of similar size but is suppressed by an amplitude factor $1\text{–}4\sin^2\theta_W \approx 0.08$ [11]. Similarly, exchange of isovector $\rho(770)$ is suppressed relative to isoscalar $\omega(780)$ by a factor $\sim(1/3)^2$ from quark counting rules. The Δ and ω contributions are spin-independent interactions at low energy, and can also give rise to coherent scattering on compound nuclei such as ^{12}C in the MiniBooNE detector. The coherent contribution from bremsstrahlung emission on the nucleus is numerically small.

In what follows, the coherent bremsstrahlung process, and the incoherent π^0 and ρ^0 processes, are neglected. The remaining contributions are computed using the parameter values and form factor models from [7] and the published MiniBooNE fluxes in both neutrino and antineutrino modes [12]. A simple ''impulse approximation'', ignoring nuclear corrections, is employed for the incoherent cross sections. The incoherent Δ contribution was studied in the MiniBooNE analysis, with normalization constrained by comparison to observed π^0 production and a model of final state interactions [13].

III. MINIBOONE ν CROSS SECTIONS

Figure 1 displays flux-integrated cross sections, presented as events per MeV of reconstructed neutrino energy [15]. The normalization corresponds to a detector mass of 800×10^6 g, and 6.46×10^{20} protons on target for the updated analysis of ν_e charged current quasielastic (CCQE) events in a primarily ν_μ beam [4]. A cut $E_\gamma \geq$ 140 MeV is placed on the photon energy, in accordance with the experimental selection.

To compare to the MiniBooNE data in the absence of a dedicated efficiency analysis, the number of events has been multiplied by an efficiency factor of 25% and detector resolution/smearing effects have been neglected. For comparison, the original MiniBooNE analysis quotes an

*richardhill@uchicago.edu

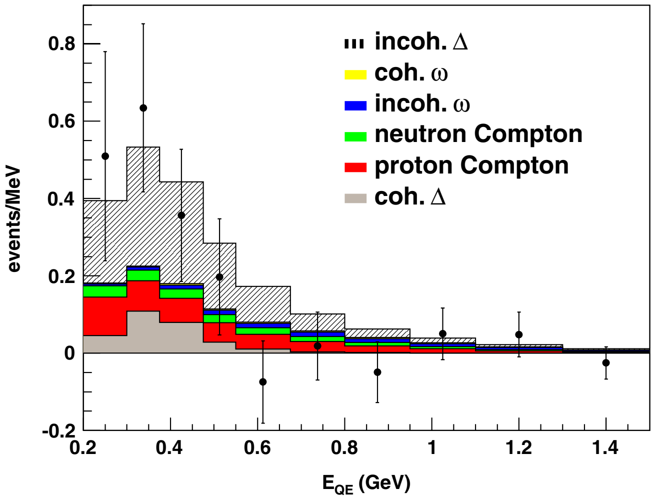

FIG. 1 (color online). Single-photon events at MiniBooNE for 6.46×10^{20} protons on target in neutrino mode. A 25% efficiency is assumed. The hatched line represents the difference between the direct calculation and MiniBooNE π^0-constrained incoherent $\Delta \to N\gamma$ background. Data points correspond to the excess events reported in [4], Fig. 2.

efficiency of $30.6 \pm 1.4\%$ for reconstructing signal-like ν_e CCQE events [3]. As can be seen from Table I, after selection cuts the efficiency for events with similar signatures, $\nu_\mu e^- \to \nu_\mu e^-$ and $\nu_e n \to e^- p$, fall in the range 20%–30% [16]. It can also be seen from this table that the direct estimate of the number of single-photon events mediated by $\Delta(1232)$ is larger than the π^0-constrained background estimate of MiniBooNE by a factor ≈ 2 [18]. The effects of a larger incoherent $\Delta \to N\gamma$ background are illustrated by the hatched area in Fig. 1, computed by adding 0.5 times the direct estimate (i.e., effectively doubling the MiniBooNE background). Under the assumption of a constant 25% efficiency, the fit of these additional single-photon events to the MiniBooNE excess yields $\chi^2 = 10.3$ for 10 d.o.f. Theoretical errors are discussed at the end of this note and have not been included in the fit. Assuming a lower 20% efficiency and taking the difference between the estimates of $\Delta \to N\gamma$ events from the table, the remaining excess would be 15 ± 26, 23 ± 25 and -47 ± 36 in the 200–300, 300–475 and 475–1250 MeV bins, respectively. If no additional incoherent $\Delta \to N\gamma$ events are included, these numbers become 29 ± 26, 55 ± 25 and -9 ± 36. The neutron/proton Compton backgrounds were estimated by MiniBooNE to be small or negligible [14].

TABLE I. Single-photon and other backgrounds for MiniBooNE ν-mode in ranges of E_{QE}. Ranges in square brackets are the result of applying a 20%–30% efficiency correction.

process	200–300	300–475	475–1250
1γ, non-Δ	85[17–26]	151[30, 45]	159[32, 48]
$\Delta \to N\gamma$	170[34–51]	394[79–118]	285[57–86]
$\nu_\mu e \to \nu_\mu e$	14[2.7–4.1]	20[4.0–5.9]	40[7.9–12]
$\nu_e n \to ep$	100[20–30]	303[61–91]	1392[278–418]
MB excess	45.2 ± 26.0	83.7 ± 24.5	22.1 ± 35.7
MB $\Delta \to N\gamma$	19.5	47.5	19.4
MB $\nu_\mu e \to \nu_\mu e$	6.1	4.3	6.4
MB $\nu_e n \to ep$	19	62	249

The most significant excess in the updated MiniBooNE analysis occurred in the $E_{QE} = 300$–475 MeV bin. The distributions in reconstructed Q^2 [19], and cosine of the angle, $\cos\theta$, of the electromagnetic shower with respect to the beam direction, are displayed for this energy range in Fig. 2. The normalization assumes an energy- and angle-independent efficiency of 25%, and includes 0.5 times the incoherent $\Delta \to N\gamma$ background as in Fig. 1. A χ^2 fit yields 10.9/10 d.o.f. for $\cos\theta$ and 2.6/7 d.o.f. for Q^2_{QE}.

Note that in the accounting method here, it does not matter whether the MiniBooNE $\Delta \to N\gamma$ background

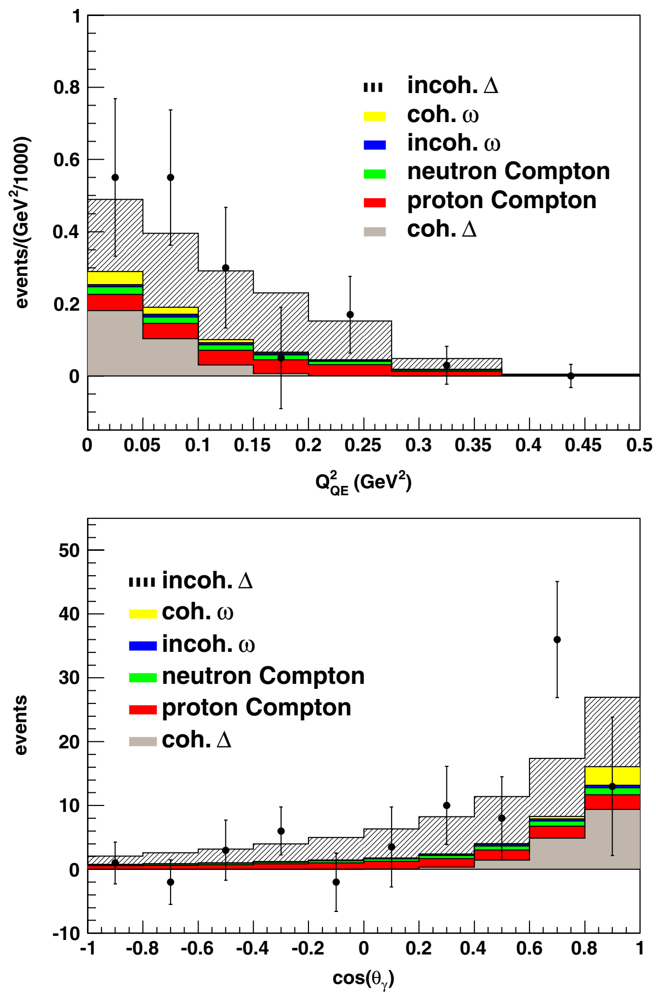

FIG. 2 (color online). Distributions in Q^2_{QE} and $\cos\theta$ for the events displayed in Fig. 1 for $E_{QE} = 300$–475 MeV. Data points correspond to Figs. 4 and 5 of [4].

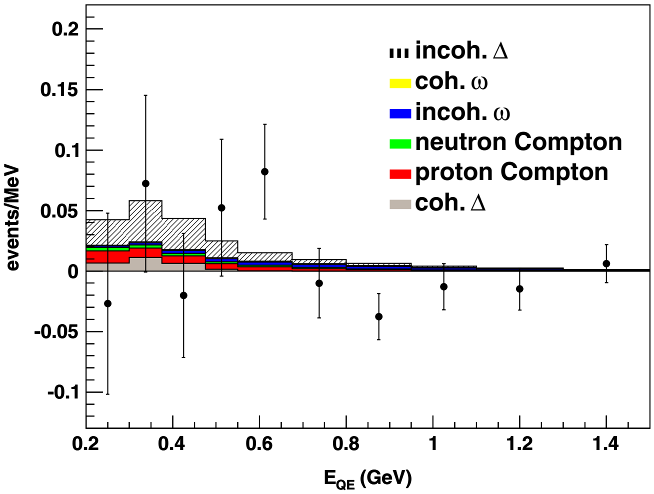

FIG. 3 (color online). Comparison of single-photon events to MiniBooNE data [5] with other backgrounds subtracted in antineutrino mode.

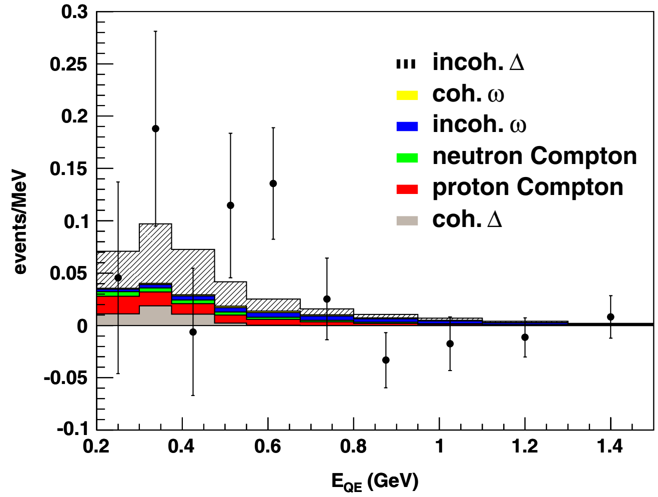

FIG. 4 (color online). Comparison of single-photon events to MiniBooNE data [28] with other backgrounds subtracted in antineutrino mode.

estimate represents just the incoherent, or the sum of incoherent plus coherent processes. In the latter case, the difference between the π^0-constrained background and the direct estimates given here would be larger; the "Δ" and "coherent Δ" regions in the figures would contribute different amounts but with the same total.

From the estimates presented here, it may be difficult to extract the coherent component from other backgrounds. Doing so would represent the first signal for coherent single-photon production by the weak neutral current above the nuclear scale [20].

IV. MINIBOONE $\bar{\nu}$ CROSS SECTIONS

The above procedure may be repeated for antineutrinos. Figure 3 displays flux-integrated cross sections normalized according to 3.39×10^{20} protons on target from the search for $\bar{\nu}_e$ CCQE events in a primarily $\bar{\nu}_\mu$ beam [5]. A cut $E_\gamma \geq 140$ MeV is applied, and a 25% efficiency has been assumed, in accordance with a comparison to MiniBooNE backgrounds in Table II [24]. Again, the direct estimate of $\Delta \to N\gamma$ events is ≈ 2 times larger than the MiniBooNE estimate; the difference is illustrated in the figure by including 0.5 times the direct estimate for these events. The resulting fit for the $E_{\rm QE}$ distribution yields $\chi^2 = 13.3$ for 10 d.o.f. Assuming a 20% efficiency and taking the difference between the estimates of $\Delta \to N\gamma$ events from the table, the excess becomes -11.5 ± 11.7 and -2.8 ± 10.0 in the 200–475 and 475–1250 MeV bins, respectively. If no additional incoherent $\Delta \to N\gamma$ events are included, these numbers become -6.1 ± 11.7 and -0.2 ± 10.0.

TABLE II. Single-photon and other backgrounds for MiniBooNE $\bar{\nu}$-mode in ranges of $E_{\rm QE}$. Ranges in square brackets are the result of applying a 20%–30% efficiency correction.

process	200–475	475–1250
1γ, non-Δ	28[5.6–8.4]	17[3.4–5.2]
$\Delta \to N\gamma$	58[12–17]	23[4.6–6.9]
$\bar{\nu}_e/\nu_e$ CCQE	81[16–24]	261[52–78]
MB excess	-0.5 ± 11.7	3.2 ± 10.0
MB $\Delta \to N\gamma$	6.6	2.0
MB $\bar{\nu}_e/\nu_e$ CCQE	18	43

V. SUMMARY

Neglected single-photon events give a significant contribution to the MiniBooNE low-energy excess. If the excess is interpreted as photon events, fits to the data appear to indicate an enhanced resonant $\Delta \to N\gamma$ contribution (either incoherent or coherent) relative to MiniBooNE estimates based on π^0 production [25]. Such an enhancement is suggested by the model estimates in this paper, and is consistent with the absence of a significant excess in the MiniBooNE antineutrino results. A dedicated efficiency analysis would constrain the overall normalization error. Examination of processes such as $\nu_\mu n \to \mu^- p\gamma$ could be used to test other sources of uncertainty [27]. More definitive conclusions would require better understanding of uncertainties including nuclear corrections. An enhanced coupling of the neutral weak current and electromagnetic current to baryons may have interesting astrophysical implications [8].

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Note added.—After this paper was submitted, an updated search for $\bar{\nu}_e$ appearance in MiniBooNE appeared, with a dataset 1.7 times larger compared to [5]. An update of Fig. 3 is shown in Fig. 4. The histogram in the figure amounts to 22 events in the range 200–475 MeV, and 12 events in the range 475–1300 MeV, compared to 18.1 ± 14.3 and 20.9 ± 13.9 excess events reported in [28].

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[9] In terms of the baryon chiral lagrangian, the operator induced by t-channel ω exchange (considered in [8]) also receives contributions from s- and u-channel Δ. The amplitudes constructively interfere at energies $E \ll m_\omega$, $m_\Delta - m_N$, with Δ appearing to give the larger contribution. Further discussion, including extrapolation to larger energy and kinematic distributions for different photon production mechanisms, can be found in [7].

[10] $M \sim m_N \sim 4\pi f_\pi \sim 1$ GeV.

[11] The 1–4$\sin^2\theta_W$ factor results from a near cancellation between isoscalar and isovector components of the weak current. The cancellation is rigorously valid at low energy where the pion chiral lagrangian is valid. Avoiding the cancellation at higher energy would require dramatic violation of vector meson dominance. This possibility was considered in: J. Jenkins and T. Goldman, Phys. Rev. D **80**, 053005 (2009).

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[14] W. C. Louis (private communication).

[15] The reconstructed neutrino energy assumes charged current quasielastic scattering on a stationary nucleon to an electron final state. Neglecting the electron mass, we have $E_{\rm QE} \equiv E_{\rm vis}/[1 - (E_{\rm vis}/m_N)(1 - \cos\theta)]$.

[16] For the CCQE events, the small $\bar{\nu}_e$ contamination in the beam is neglected and the cross section is calculated in a standard relativistic Fermi gas model of Smith and Moniz [17], with model parameters $\epsilon_b = 27$ MeV and $k_F = 225$ MeV.

[17] R. A. Smith and E. J. Moniz, Nucl. Phys. **B43**, 605 (1972); **B101**, 547(E) (1975).

[18] Using the energy-dependent Breit-Wigner width gives a lower total cross section and pulls events to lower energy: with the same form factors the number of events would be 217, 363 and 175 in the 200–300, 300–475 and 475–1250 MeV bins, respectively. For definiteness, we focus on the default cross sections from [7].

[19] The reconstructed Q^2 variable is defined, neglected electron mass, as $Q^2_{\rm QE} \equiv 2E^2_{\rm vis}(1 - \cos\theta)/[1 - (E_{\rm vis}/m_N) \times (1 - \cos\theta)]$.

[20] Nuclear excitation yields coherent photon production at the ~MeV energy scale, e.g. [21]. While some hints of single-photon events were discussed in previous high-energy experiments, these were not definitively isolated as being due to single photons as opposed e.g. to π^0 production with a missed photon [22,23].

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[25] The ratio of photon events to π^0 events in neutral current scattering on a ^{12}C nuclear target is subject to significant, $\mathcal{O}(100\%)$, nuclear modeling corrections, see e.g. [26]. Reference [4] assigns $\lesssim 20\%$ uncertainty to the single-photon background prediction after applying final state interaction corrections.

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