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Antineutrino Charged-Current Reactions on Hydrocarbon with Low Momentum Transfer

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We report on multinucleon effects in low momentum transfer (< 0.8 GeV/c) antineutrino interactions on plastic (CH) scintillator. These data are from the 2010–2011 antineutrino phase of the MINERvA experiment at Fermilab. The hadronic energy spectrum of this inclusive sample is well described when a screening effect at a low energy transfer and a two-nucleon knockout process are added to a relativistic Fermi gas model of quasielastic, Δ resonance, and higher resonance processes. In this analysis, model elements introduced to describe previously published neutrino results have quantitatively similar benefits for this antineutrino sample. We present the results as a double-differential cross section to accelerate the investigation of alternate models for antineutrino scattering off nuclei.

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Current and future accelerator-based neutrino oscillation experiments analyze flavor oscillations based on distortions of reconstructed antineutrino energy spectra. These measurements require models for both the lepton energy and angle, and for the hadronic system. Experiments using calorimetric reconstruction [1,2] are especially sensitive to the presence of neutrons in the final state. To probe for charge-parity (CP) violation in the lepton sector [3–5], models of antineutrino processes require similar accuracy to the corresponding neutrino processes. Otherwise, model uncertainties limit the sensitivity to, or possibly mimic, a CP-violating effect.

We present the first antineutrino analysis of inclusive charged-current reactions to isolate multinucleon effects in the quasielastic (CCQE) and $\Delta$ resonance kinematic regions. We reconstruct the hadronic system using calorimetry and obtain an estimate of the three-momentum transfer for each event. The data are subdivided into six subranges of momentum transfer up to 0.8 GeV/$c$, and within each range, we present the observed hadronic energy in the detector. To describe these data, a component of the event rate could be attributed to many-body effects like a two-particle, two-hole ($2p2h$) process [6–16]. Also, suppression of CCQE interactions is preferred, such as provided by a random phase approximation (RPA) calculation [7,17–19] applied to a Fermi gas model [20].

The data were taken with the NuMI beam [21] operating in antineutrino mode. The primary beam of 120 GeV protons interacts in a graphite target, producing mesons. A pair of magnetic horns focuses negatively-charged mesons toward a decay pipe where their decay leads to an antineutrino spectrum in the MINERvA detector peaking near 3.0 GeV. We use a GEANT4-based [22,23] prediction for the flux with central values and uncertainties adjusted [24] using thin-target hadron production data [25–28] and an in situ neutrino-electron scattering constraint [29].

A sample of charged-current $\bar{\nu}_\mu$ interactions are selected from MINERvA’s 5.3 ton fiducial volume by requiring that a muon track leaves the MINERvA detector and has its positive charge and momentum identified in the MINOS magnetized iron spectrometer [30] located 2 m downstream. The fiducial volume is both an active tracker and a calorimeter, built from planes of scintillator (CH) strips with a triangular shaped 3.3 cm base and 1.7 cm height. Alternating and nesting the triangles gives light-sharing information that improves tracking resolution. Each hexagonal plane contains 127 strips of up to 245 cm in length. The planes are installed with strips oriented vertically or rotated $\pm 60^\circ$, ensuring the precise reconstruction of the interaction point and muon track angle, even when hadronic activity partially obscures the muon. The target mass consists of 8.2%, 88.5%, and 2.5% hydrogen, carbon, and oxygen, respectively, plus small amounts of heavier nuclei.

Particles leaving the active tracking region pass into the electromagnetic calorimeter (ECAL), where thin sheets of lead are epoxied to each scintillator plane. Farther downstream are layers of hadronic calorimetry using alternating planes of scintillator and passive steel. The calorimetric and tracking capabilities of MINERvA are constrained relative to GEANT4 v.9.4.p2 (with the Bertini Cascade option) using in situ [31] and hadron test beam measurements [32]. With no test beam measurements, the neutron response and its uncertainties come after adjusting the cross section to match the data from [33] as used by later versions of GEANT4.

The kinematics of each event are reconstructed using the measured muon energy and angle, and measured energy deposits attributed to hadrons. The technique is nearly identical to [6]. A full simulation of the reconstructed sample with a calibrated detector response is made using the GEANT4 simulation and genie version 2.8.4 neutrino event generator [34]. This simulation is used to obtain a correction [35], as a function of the calorimetrically measured hadronic energy, to estimate the energy transfer $q_0$. This correction is applied identically to the reconstructed simulation and data. In both cases, the calorimetric neutrino energy estimate is $E_\nu = E_\mu + q_0$, where $E_\mu$ includes the muon rest mass $M_\mu$. The square of the four-momentum transfer is $-q^2 = Q^2 = 2E_\mu(E_\mu - p_\mu \cos \theta_\mu) - M_\mu^2$, and the three-momentum transfer is simply $q_3 = \sqrt{Q^2 + q_0^2}$. In this Letter, the kinematics of the analysis sample are limited to $q_3 < 0.8$ GeV/$c$. There are no other requirements on reconstructed hadronic topologies for this inclusive sample.

The measured energy deposits are used to form another calorimetric estimator, the available energy $E_{\text{avail}}$ [6]. This is energy due to particles that deposit most or all of their energy in the detector: proton kinetic energy, charged pion kinetic energy, electrons, positrons, and photons, including those from neutral pion and eta decays. These momentum transfers are too low for the production of heavier mesons and baryons.

When $E_{\text{avail}}$ is formed from a model, it does not include neutrons that leave a small fraction of their energy in the detector or the energy used to unbind nucleons. In the neutrino case [6], where outgoing protons far outnumber neutrons, this is a good approximation. In the simulation of this antineutrino subsample, 70% of interactions have more than half of the energy transfer going to neutrons, including 40% which have neutron-only final states. Up to 60% of neutrons at these energies leave reconstructed energy deposits in the detector, so neutrons can contribute significantly to the hadronic energy deposits. Despite this, reconstructed or model distributions of $E_{\text{avail}}$ vs. $q_3$ retain the ability to separate CCQE and $\Delta$ resonance kinematics and the region between them. Because the analysis is limited to interactions with little energy in the recoil system, only the energy deposits in the tracker and downstream ECAL regions are considered. The backgrounds
from unrelated beam activity are higher and the calorimetric resolution is worse for energy deposits in the other regions, degrading the sensitivity to multinucleon effects.

While $E_{\text{avail}}$ is defined assuming neutrons have a negligible calorimetric response, the actual situation is more complex. Interactions that have only neutrons in the final state are most likely to have reconstructed hadronic energy between 0 and 10 MeV. Figure 1 shows the reconstructed energy deposits from the GENIE-produced hadronic energy between 0 and 10 MeV. The three curves also illustrate the relative abundance of lower kinetic energies in the selected MC sample. Neutrons in this energy range typically leave small isolated energy deposits, uncorrelated with the neutron kinetic energy.

The selected inclusive sample is compared to the Monte Carlo simulations. The gg transmission model is used for the selected events, the unfolded distribution, and the true distribution of MC simulations compared to the latter.

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Because this is an analysis of an inclusive sample, event selection is minimal. We only create a boundary for unfolding the data into a double differential cross section that can be reproduced by external event generators, and we exclude regions of kinematic space that do not have good acceptance. The muon momentum is required to be above 1.5 GeV/c and an angle less than 20 degrees with respect to the beam direction. We further limit the reconstructed antineutrino energy to between 2 and 6 GeV, which spans the peak of this beam and allows a direct comparison to the neutrino results. These selections are used for the reconstructed events, the unfolded distribution, and the true distribution of MC simulations compared to the latter.

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We have modified the default GENIE version 2.8.4 to include advances in modeling the important processes. The CCQE process is modified to include RPA screening based on the IFIC Valencia model [17,45], implemented by weighting GENIE CCQE events [46]. A CCQE-like two-particle, two-hole process “2p2h,” from the model by the same group [8,45], is implemented in GENIE [15].

The IFIC Valencia 2p2h model increases the predicted event rates, but not enough. This process is increased further with an empirical enhancement [47] based on MINERvA inclusive neutrino data [6]. The additional events are from weighting up the generated 2p2h events according to a two-dimensional Gaussian in true $q_0$, $q_3$, whose six parameters are fit to the neutrino data version of these distributions. This enhancement adds 50% to the predicted 2p2h strength, but it targets the event rate in the kinematic region between the CCQE and $\Delta$ peaks where the rate doubles. The collection of changes in this and the preceding paragraphs are referred to as “MnvGENIE-v1” and are the central, tuned model for many recent analyses [48–51].

The resulting description of the antineutrino data is much improved, as illustrated in Fig. 3 and summarized in Table I using a standard $\chi^2$ test on the reconstructed samples. These models also improve the description of muon-only kinematic distributions of an overlapping subset of the same data set [50], selected with no pions in the final state.

For this model comparison to reconstructed data, the largest systematic uncertainties include flux, hadron energy scale, and GENIE resonance interaction and final-state rescattering model uncertainties. The GENIE uncertainty on the CCQE axial form factor is reduced to $\pm9\%$ following the analysis of [54]. An uncertainty on the RPA CCQE suppression [46,52] is added, most significantly from comparison to muon capture data. No single uncertainty dominates the model prediction for the reconstructed distributions.

The antineutrino sample retains a discrepancy just beyond the error band in the four second-lowest $E_{\text{avail}}$ bins within the range $0.3 < q_3 < 0.8 \text{ GeV/c}$. These bins are dominated by events with neutron-only final states, including feed-down from higher energy transfer CCQE and 2p2h reactions. Limited to the models available for this analysis, both the CCQE RPA and the tuned 2p2h component each have a 10% to 30% effect on these bins. The comparison of the first two rows of Table I is subtle; the first does not contain additional uncertainty from the RPA model. Applying an estimate for the uncertainty to both rows also yields a worse $\chi^2$ for the lower $q_3$ range for neutrino when RPA is added. RPA reduces some bins where the MC simulation is already under predicting the data. However, the RPA model produces a better agreement with the data. The right-most columns are made using the neutrino data [6] though the models being tested in this Letter have advanced since that earlier publication.
details of the CCQE vs. 2p2h processes not yet exposed within the available models, details such as those [18,19,55] that go beyond the Fermi gas.

This 2p2h tune comes with three other variations that treat the final state nucleon content as uncertain. Instead of enhancing all 2p2h events, the first variation enhances only those generated for pn initial state nucleon pairs, which translate to pp final states for the neutrino case in the fit and nn for the antineutrino case where we apply the tuned parameters. The next variation enhances reactions that are not on pn initial state pairs, which lead to pn final states. Finally, the third variation enhances CCQE events at these kinematics. In addition to testing these variations against the reconstructed data, they are used as an uncertainty applied later when producing a double-differential cross section.

This sample also includes a significant component at and beyond the Δ resonance peak, which remains poorly described by these model variations. The shortcoming of the model for these low $Q^2 = q_3^2 - q_0^2 \approx 0$ events shows up on the far right of the distributions in Fig. 3. Similar mismodeling of the resonance-region rate has been previously reported in measurements on mineral oil by MiniBooNE [56,57], in MINERvA’s pion final state samples [49,58,59], in the neutrino version of this analysis [6], and in a resonance-rich neutrino + Fe sample from MINOS [53]. The latter used a calorimetric sample as a sideband and tuned an ad hoc, low $Q^2$ suppression to the data in order to improve the estimate of the resonance background in their CCQE analysis. At $Q^2 = 0$, the rate is 40% of nominal and becomes no suppression by $Q^2 = 0.7 \ (\text{GeV}/c)^2$. Applying the MINOS parametrization improves the description of these MINERvA data for some of those bins at high $q_3$, but the suppression goes too far and produces a model deficit in the highest energy bins of the low $q_3$ panel. These bins in Fig. 3 were already well described, and the $\chi^2$ reflects that the agreement worsens. Either the single-parameter $Q^2$ weight or the tuning to neutrino + Fe data is not adequate to describe the two dimensional kinematics of these antineutrino + CH samples.

To allow the development and testing of improved models, this distribution is unfolded to produce a double differential cross section $d^2\sigma/dE_{\text{avail}}dq_3$, shown in Fig. 4 and tabulated in the Supplemental Material [60]. The procedure is the same as in [50], Secs. VIIB and VIII, and it uses [61–63] but with three iterations. The resolution for $q_3$ in Fig. 2 is with an rms near 23% throughout and slowly changing with $q_0$. The reconstructed available energy is the sum of a component from charged hadron and electromagnetic energy deposits with a central peak of 30% resolution but a rms of 40% as in the neutrino case [6]. Then, the random tens of MeV energy from about half of the final state neutrons further degrade the resolution to

![FIG. 4. Unfolded $d^2\sigma/dE_{\text{avail}}dq_3$ cross section per nucleon compared to the model with RPA and tuned 2p2h components. The breakdown of the predicted QE (dashed), 2p2h (dot-dashed), and Δ resonance (dotted) portions are shown. To show the detail, the data and model prediction for the first bin (dominated by neutron-only final states) are not shown; they are far off the top of the plot with values between 9 and $17 \times 10^{-42} \text{cm}^{-2}/\text{GeV}^2$ per nucleon.](http://example.com/figure4.png)
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