First Measurement of Monoenergetic Muon Neutrino Charged Current Interactions

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We report the first measurement of monoenergetic muon neutrino charged current interactions. MiniBooNE has isolated 236 MeV muon neutrino events originating from charged kaon decay at rest ($K^+ \rightarrow \mu^+ \nu_\mu$) at the NuMI beamline absorber. These signal $\nu_\mu$-carbon events are distinguished from primarily pion decay in flight $\nu_\mu$ and $\bar{\nu}_\mu$ backgrounds produced at the target station and decay pipe using their arrival time and reconstructed muon energy. The significance of the signal observation is at the 3.9σ level. The muon kinetic energy, neutrino-nucleus energy transfer ($\omega = E_\nu - E_\mu$), and total cross section for these events are extracted. This result is the first known-energy, weak-interaction-only probe of the nucleus to yield a measurement of $\omega$ using neutrinos, a quantity thus far only accessible through electron scattering.

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A charged kaon decays to a muon and a muon neutrino ($K^+ \rightarrow \mu^+ \nu_\mu$) 63.6% of the time [1]. In the case that the kaon is at rest when it decays, the emitted muon neutrino is monoenergetic at 236 MeV. The kaon decay at rest (KDAR) neutrino has been identified as a gateway to a number of physics measurements, including searches for high-$\Delta m^2$ oscillations [2,3] and as a standard candle for studying the neutrino-nucleus interaction, energy reconstruction, and cross sections in the hundreds of MeV energy region [4]. There are other ideas for using this neutrino, including as a source to make a precision measurement of the strange quark contribution to the nucleon spin ($\Delta s$) [4] and as a possible

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signature of dark matter annihilation in the Sun [5,6]. Despite the importance of the KDAR neutrino, it has never been isolated and identified.

In the charged current (CC) interaction of a 236 MeV νμ (νμ,C → μ−X), the muon kinetic energy (Tμ) and closely related neutrino-nucleus energy transfer (ω = Eν − Eμ) distributions are of particular interest for benchmarking neutrino interaction models and generators, which report widely varying predictions for kinematics at these transition-region energies [7–14]. Traditionally, experiments are only sensitive, at best, to total visible hadronic energy since invisible neutrons and model-dependent nucleon removal energy corrections prevent the complete reconstruction of energy transfer [16]. The measurements reported here, therefore, provide a unique look at muon kinematics and the relationship to neutrino energy in the few hundreds of MeV range, highly relevant for both elucidating the neutrino-nucleus interaction and performing low energy precision oscillation measurements at short [17–19] and long baselines [20].

The MiniBooNE detector uses 445 tons (fiducial volume) of mineral oil and 1280 photomultiplier tubes (PMTs), with an additional 240 PMTs instrumenting a veto region, to identify neutrino events originating from the Booster Neutrino Beamline (BNB) and Neutrinos at the Main Injector (NuMI) neutrino sources. The experiment has reported numerous oscillation and cross section measurements and new physics searches since data taking began in 2002 [17]. For this analysis, we consider the charge and time data of PMT hits collected during the NuMI beam spill. NuMI provides an intense source of KDAR neutrinos at MiniBooNE in a somewhat indirect way. The 96 cm, 2.0 interaction length NuMI target allows about 84% of the total KDAR neutrinos that reach MiniBooNE (dashed lines). The signal KDAR neutrinos (solid line) originate mainly from the absorber.

antineutrino modes, since KDAR production from the absorber is not dependent on the polarization of the horns. However, the background νμ and ¯νμ event rate is predicted to be about 30% lower in the antineutrino mode. We use data taken in this configuration from 2009–2011, corresponding to 2.62 × 1020 protons on the NuMI target.

The focus of this analysis is on reconstructing KDAR-like low energy νμ CC events. A simple detector observable, PMThits5ns, defined as the number of PMT hits multiplied by the fraction of light detected in the first 5 ns after correcting for vertex position, is used to reconstruct Tμ in selected events featuring (1) an electron from muon decay, noting that about 7.8% of μ− capture on nuclei [26], (2) a lack of veto activity, and (3) a reconstructed distance between the end point of the primary track and the muon decay vertex of < 150 cm. This detector observable is meant to isolate the muon via its characteristic prompt Čerenkov light, as compared to the delayed scintillation-only light (r = 18 ns) from the below-threshold hadronic part of the interaction. According to the NuWro neutrino event generator [12], only 14% of muons created in 236 MeV νμ CC events are expected to be produced with energy less than 39 MeV, the Čerenkov threshold for muons in MiniBooNE mineral oil. KDAR-induced muons are expected to populate a “signal region,” defined as 0–120 PMThits5ns, and representing Tμ in the range 0–115 MeV. Because of the kinematics of 236 MeV νμ CC events, no signal is expected elsewhere, which is considered the “background-only region” (>120 PMThits5ns). Although the signal muon energy range considered for this measurement is lower than past MiniBooNE cross section analyses featuring νμ/¯νμ [27–33], the energy and timing distributions of MiniBooNE’s vast calibration sample of 0–53 MeV electrons from muon decay provide a strong benchmark for understanding the detector’s response to low energy muons in terms of both scintillation and Čerenkov light. Further, a scintillator “calibration cube” in the MiniBooNE volume at a 31 cm depth, used to form a very pure sample of tagged 95 ± 4 MeV cosmic ray muons, shows excellent agreement between data and Monte Carlo

![FIG. 1. The NuMI beamline and various sources of neutrinos that reach MiniBooNE (dashed lines). The signal KDAR neutrinos (solid line) originate mainly from the absorber.](image-url)
simulations in terms of timing, Čerenkov angle, and energy reconstruction [17]. The energy resolution for 95 MeV muons is measured to be 12%; a detailed detector simulation agrees and predicts that the muon energy resolution in low energy $\nu_\mu$ CC events drops gradually to about 25% for 50 MeV muons. The detection efficiency for KDAR $\nu_\mu$ CC events is $> 50\%$ for events containing muons with energy $> 50$ MeV.

It is challenging to isolate the KDAR neutrino signal in MiniBooNE among the significant backgrounds. Even after optimizing event selection cuts and reconstruction, the signal-to-background ratio in the signal region is expected to only be $\sim 1:1$. Along with the difficulty in identifying KDAR events based on neutrino energy, another issue is that reconstructing them as coming from the absorber is not possible because the muon and neutrino directions are poorly correlated at these low energies. Simply convolving a flux prediction with a neutrino cross section to form a background rate prediction is also not feasible. Although a reliable background flux prediction is available [34], the rate and kinematics of such events in MiniBooNE are also determined by the relevant total and differential $\nu_\mu$ and $\bar{\nu}_\mu$ cross sections for neutrino energies in the hundreds of MeV region. The rapid turn on of the $\nu_\mu$ CC cross section above the mass of the muon and almost complete lack of data below 400 MeV [35,36] would make any kind of background prediction near KDAR energies arbitrary and highly uncertain.

In order to mitigate the issues associated with the background prediction near KDAR energies, we use a timing-based in situ background measurement technique which relies on the fact that KDAR $\nu_\mu$ CC events from the absorber arrive at MiniBooNE $\sim 200$ ns after background $\nu_\mu$ and $\bar{\nu}_\mu$ CC events originating from the target station and decay pipe. The background neutrinos simply take a more direct route to MiniBooNE as compared to their signal counterparts from the absorber: the distance from the target to the absorber plus the distance from the absorber to MiniBooNE is $725 + 86 = 811$ m, while the distance from the target to MiniBooNE is $749$ m. Although the beam window is $\sim 9 \mu$s, this timing difference provides a “background-enhanced” period at the beginning of the window, where background $\nu_\mu$ and $\bar{\nu}_\mu$ CC events are expected to dominate, and a “signal-enhanced” period at the end of the window, where signal KDAR $\nu_\mu$ CC events from the absorber dominate. Considering the neutrino event timing resolution and the timing uncertainties due to various sources, we define the first and last $600$ ns of the beam window as background and signal enhanced, respectively. The inset of Fig. 2 shows the relative event rate in the enhanced regions compared to a high-statistics region in which signal and background remain constant (referred to as “normal time” and discussed later in detail). Most notably, there is a $2.4 \sigma$ ($2.1 \sigma$) excess (deficit) of KDAR-like events ($0-120$ PMThits$_{5ns}$) at late (early) times.

In the absence of a reliable background prediction, we employ a template-based analysis which tests the consistency of various candidate KDAR signal $T_\mu$ distributions with data. We consider a broad and well-defined set of possible $T_\mu$ signal shapes and determine how well each matches the data. This procedure can be thought of as the reverse of the usual differential cross section measurement extraction. Instead of starting from a detector observable and turning it into a measure of $T_\mu$, for example, we start with a candidate “true” $T_\mu$ distribution and map (or “fold”) it into a detector observable distribution in PMThits$_{5ns}$. The candidate true $T_\mu$ signal shapes are based on a beta distribution. This carefully chosen function, with only two parameters characterizing its shape, is meant to cover all physical and continuous shapes that the true KDAR-induced $T_\mu$ distribution can take, noting that we are not sensitive to few-MeV-scale resonance features (e.g. as predicted by continuum random phase approximation calculations [7]). The shape of the signal model ($T_\mu$ spectrum) is defined by two parameters, $a$ and $b$, according to the beta distribution: $x^{a-1}(1-x)^{b-1}/B(a, b)$, where $B(a, b) = \Gamma(a)\Gamma(b)/\Gamma(a+b)$ and $x = T_\mu/T_{\mu_{\text{max}}}$. After correcting for detector efficiency, each candidate $T_\mu$ distribution is folded into the corresponding PMThits$_{5ns}$ distribution and compared to data as a function of time. The normalization of signal and background are expected to change at early and late times, but the shapes of each stay nearly constant.

The analysis proceeds in four steps. (1) The data sample is broken up into seven time bins within the 9200 ns beam window: three early-time bins (200 ns each), one “normal-time” (NT) bin (8000 ns), and three late-time bins (200 ns bins).
Signal region data are distributed into 12 candidate signal shapes, normalizations, and end points. The procedure is then repeated for various combinations of regions of the three early-time and three late-time bins. Figure 3 shows an example set of constant-shaped background templates for each of the early-time and late-time bins, the normalization of each background template is adjusted so that it is consistent with the number of events observed in each time bin’s background-only region. Figure 3 shows an example set of constant-shaped background templates for each of the early-time and late-time bins. (2) Using the following procedure, signal and background templates in PMThitsSns are formed using the high-statistics NT region distribution as a reference, where signal and background are expected to be constant. The candidate signal template is drawn from a large number of possible shapes and normalizations within reasonable physical limits. In the signal region (0–120 PMThitsSns), the background template is defined such that the candidate signal plus background distribution is equal to the NT data. Figure 2 shows an example set of templates overlaid on data in NT. (3) In each of the three early-time and three late-time bins, the normalization of each background template is adjusted so that it is consistent with the number of events observed in each time bin’s background-only region. Figure 3 shows an example set of constant-shaped background templates for each of the early-time and late-time bins. (4) A Poisson extended maximum likelihood $\chi^2$ statistic [1,37,38] is formed from a comparison between the signal + background templates and data in the signal regions of the three early-time and three late-time bins. This treatment is studied later with Monte Carlo simulations. The procedure is then repeated for various combinations of candidate signal shapes, normalizations, and end points.

For a particular time bin $(i)$, excluding the NT bin, the signal region data are distributed into 12 PMThitsSns bins $(j)$ from 0–120. A $\chi^2$ for a Poisson-distributed variable is then formed by comparing the data $(d_{i,j})$ and a prediction $(P_{i,j,a})$ based on the signal model $(T_{j,a})$ with signal normalization $\alpha$ plus the background $(B_{i,j})$ such that

$$P_{i,j,a} = T_{j,a} + B_{i,j},$$

$$\chi^2_{i,a} = 2\sum_j \left\{ \frac{P_{i,j,a} - d_{i,j} + d_{i,j} \ln(d_{i,j}/P_{i,j,a})}{P_{i,j,a}} \right\} d_{i,j} > 0,$$

$$d_{i,j} = 0.$$

We then marginalize over the signal normalizations in each time bin to produce $\chi^2 = \min_{\alpha} (\chi^2_{i,a})$.

No KDAR signal events from the absorber are expected in the first 200 ns time bin. This time period, therefore, contains the expected PMThitsSns shape of the background distribution in the signal region. In the first time bin, the measured ratio of data events in the 0–120 PMThitsSns signal region (28) to total number of events (118) is compared to the equivalent ratio for the current candidate model’s background prediction to form an uncertainty weighted pull term $(f_{\text{pull}})$. This pull term penalizes candidate models that produce background templates inconsistent with the first time bin. Finally, the total $\chi^2$ for a particular model shape and normalization is given by $\chi^2 = \sum_i \chi^2_{i} + f_{\text{pull}}$.

We test a set of physically allowed and reasonable models with the parameter sets $a \in [2.0, 8.0], b \in [0.0, 6.0]$. Models with $0 < a < 2.0$ are considered unphysical and inconsistent with all predictions since they are initially concave down or do not go to zero at $T_{\mu} = 0 \text{ MeV}$. We also test a range of muon kinetic energy “effective end points,” $T_{\mu}^{\text{max}} = 95–115 \text{ MeV}$. Although the separation energy in $^{13}\text{C}$ is 17 MeV, corresponding to a $T_{\mu}$ end point of 112 MeV, we consider this range of effective end points for capturing the characteristic behavior of the distribution near threshold, limited by the coarse sensitivity of a two-parameter model.

The best fit model parameters found are $a = 2.0, b = 0.88$, with a signal normalization of $3700 \pm 1250$ events ($\chi^2_{\text{min}} = 72.6$ with 64 degrees of freedom). The NT data and best fit signal and background distributions are shown in Fig. 2, and the corresponding results for each early- and late-time bin are shown in Fig. 3. The extracted $T_{\mu}$ and $\omega = 236 \text{ MeV} - m_{\mu} - T_{\mu}$ distributions with 1σ ($\chi^2_{\text{min}} + 2.3$) shape-only allowed bands are shown in Fig. 4. The result is shown with $T_{\mu}^{\text{max}} = 95 \text{ MeV}$, representing the best fit effective end point, noting that $T_{\mu}^{\text{max}}$ values up to the physical limit of 112 MeV are not strongly disfavored. A simulation with events distributed according to the best fit shape and data normalizations in each time bin confirms that the size of the 1σ allowed region is reasonable, with 61% (65%) of best fit values falling in the 2 (3) parameter shape-only (rate + shape) contour. In the case that the end point is included as an additional shape parameter, we find that 66% of best fit values fall in the three parameter shape + end point contour.
in approximately one year [39].

In summary, MiniBooNE has performed the first measurement of monoenergetic $\nu_\mu$ CC events. The 236 MeV KDAR neutrinos, originating at the NuMI absorber 86 m from MiniBooNE, are distinguished from background neutrinos created at the NuMI target station and decay pipe using muon energy reconstruction and timing. We have employed a somewhat unconventional analysis, which relies on a parametrized $T_\mu$ prediction and subsequent comparison to data, for extracting the result. This data-driven measurement does not rely on unfolding and is largely independent of both cross section and kinematic predictions from neutrino event generators and a flux determination. These results provide a standard candle benchmark, in terms of a variable historically unavailable to neutrino scattering experiments ($\omega$), for modeling the relationship between lepton kinematics and neutrino energy, elucidating the neutrino-nucleus to neutrino-nucleon transition region, and using the associated predictions to inform oscillation measurements at short and long baselines.

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FIG. 4. The best fit $T_\mu$ (red-dashed) and $\omega$ (blue-dashed) spectra with shape-only 1\sigma error bands, given a fixed end point of $T_\mu = 95$ MeV. The distributions are fully correlated.
[1] J. Beringer et al. (Particle Data Group), Phys. Rev. D 86, 010001 (2012).
[2] J. Spitz, Phys. Rev. D 85, 093020 (2012).
[3] S. Axani, G. Collin, J. M. Conrad, M. H. Shaevitz, J. Spitz, and T. Wongjirad, Phys. Rev. D 92, 092010 (2015).
[4] J. Spitz, Phys. Rev. D 89, 073007 (2014).
[5] C. Rott, S. In, J. Kumar, and D. Yaylali, J. Cosmol. Astropart. Phys. 11 (2015) 039.
[6] C. Rott, S. In, J. Kumar, and D. Yaylali, arXiv:1710.03822.
[7] V. Pandey, N. Jachowicz, T. Van Cuyck, J. Ryckebusch, and M. Martini, Phys. Rev. C 92, 024606 (2015).
[8] M. Martini, M. Ericson, G. Chanfray, and J. Marteau, Phys. Rev. C 80, 065501 (2009).
[9] M. Martini, M. Ericson, and G. Chanfray, Phys. Rev. C 84, 055502 (2011).
[10] F. Akbar, M. Sajjad Athar, and S. K. Singh, J. Phys. G 44, 125108 (2017).
[11] D. Casper, Nucl. Phys. B, Proc. Suppl. 112, 161 (2002).
[12] C. Juszczak, Acta Phys. Pol. B 40, 2507 (2009); T. Golan, C. Juszczak, and J. T. Sobczyk, Phys. Rev. C 86, 015505 (2012).
[13] C. Andreopoulos et al., Nucl. Instrum. Methods Phys. Res., Sect. A 614, 87 (2010).
[14] We have compiled a number of predictions for the KDAR neutrino’s outgoing muon kinetic energy in the data release associated with this measurement [15].
[15] https://www-boone.fnal.gov/for_physicists/data_release/ kdar/.
[16] P.A. Rodrigues et al. (MINERvA Collaboration), Phys. Rev. Lett. 116, 071802 (2016).
[17] A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 599, 28 (2009).
[18] R. Acciarri et al. (MicroBooNE Collaboration), J. Instrum. 12, P02017 (2017).
[19] R. Acciarri et al., arXiv:1503.01520.
[20] K. Abe et al. (T2K Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 659, 106 (2011).
[21] P. Adamson et al., Nucl. Instrum. Methods Phys. Res., Sect. A 806, 279 (2016).
[22] A. Ferrari, P. R. Sala, A. Fasso, and J. Ranft, Reports No. CERN-2005-010, SLAC-R-773, INFN-TC-05-11.
[23] T. T. Böhlen, F. Cerutti, M. P. W. Chin, A. Fassò, A. Ferrari, P. G. Ortega, A. Mairani, P. R. Sala, G. Smirnov, and V. Vlachoudis, Nucl. Data Sheets 120, 211 (2014).
[24] N. V. Mokhov, Report No. FERMILAB-FN-628, 1995; O. E. Krivosheev and N. V. Mokhov, Report No. Fermilab-Conf-00/181, 2000; O. E. Krivosheev and N. V. Mokhov, Report No. Fermilab-Conf-03/053, 2003; N. V. Mokhov, K. K. Gudima, C. C. James et al., Report No. Fermilab-Conf-04/053, 2004.
[25] S. Agostinelli et al., Nucl. Instrum. Methods Phys. Res., Sect. A 506, 250 (2003).
[26] J. Grange, Ph.D. thesis, University of Florida, 2013.
[27] A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), Phys. Rev. Lett. 100, 032301 (2008).
[28] A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), Phys. Rev. Lett. 103, 061802 (2009).
[29] A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), Phys. Rev. Lett. 103, 081801 (2009).
[30] A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), Phys. Rev. D 81, 092005 (2010).
[31] A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), Phys. Rev. D 83, 052007 (2011).
[32] A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), Phys. Rev. D 83, 052009 (2011).
[33] A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), Phys. Rev. D 88, 032001 (2013).
[34] L. Aliaga Soplin, Ph.D. thesis, College of William and Mary, 2016.
[35] S. J. Barish et al., Phys. Rev. D 16, 3103 (1977).
[36] L. B. Auerbach et al., Phys. Rev. C 66, 015501 (2002).
[37] G. Cowan, Statistical Data Analysis (Clarendon, Oxford, 1998).
[38] B. Roe, Probability and Statistics in Experimental Physics (Springer, New York, 2001).
[39] S. Ajimura et al., arXiv:1705.08629.