Cross section measurements with monoenergetic muon neutrinos

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The monoenergetic 236 MeV muon neutrino from charged kaon decay at rest ($K^+ \to \mu^+ \nu_\mu$) can be used to produce a novel set of cross section measurements. Applicable for short- and long-baseline accelerator-based neutrino oscillation experiments, among others, such measurements would provide a "standard candle" for the energy reconstruction and interaction kinematics relevant for charged current neutrino events near this energy. This neutrino can also be exercised as a unique known-energy, purely weak interacting probe of the nucleus. A number of experiments are set to come online in the next few years that will be able to collect and characterize thousands of these events.

I. INTRODUCTION

The muon neutrino charged current (ν_μ CC) interaction is central to accelerator-based neutrino physics. However, despite the recent rapid progress in detection technology and analysis techniques, it is still quite difficult to measure the energy of ν_μ CC events, especially in the case of an interaction with a nuclear target. Final state interactions (FSIs), Fermi momentum, short-range correlations between nucleons, and the usually undetectable potential outgoing nuclear deexcitation gammas and neutrons can all work to convolute the reconstructed neutrino energy. This is before detector limitations, such as resolution, blindness to hadrons due to (e.g.) Cerenkov threshold, and event classification errors or ambiguity are even considered. Although a detector sensitive to the low-energy hadronic component of the final state can alleviate this at some level, many of these complications are simply inherent to the neutrino-nucleus system itself. As an example, a perfect detector's reconstruction of a 1 GeV ν_μ-nucleus CC quasielastic (CCQE, $\nu_\mu n \to \mu^- p$) event in terms of muon kinematics only provides an expected neutrino energy resolution of ~20%, with significant non-Gaussian asymmetric tails on either side of the true energy [1–4]. Although there are a number of predictions for the spectral smearing due to nuclear effects and the general direction of the convolution is understood, it is still highly nontrivial to correctly transform a reconstructed neutrino energy distribution into a true energy distribution with proper correlations and uncertainty estimates. Differences between neutrino and antineutrino events in terms of the nuclear physics that affects each can also be difficult to quantify.

A substantial amount of experimental effort has recently been directed toward measuring CC and neutral current (NC) neutrino cross sections at the hundreds of MeV and GeV scale [5,6]. These measurements are interesting for the study of the neutrino-nucleus interaction itself, the neutrino as a probe of the nucleus (e.g. the strange spin component

of the nucleon, Δ_s [7,8]), and, perhaps most importantly, are essential for long-baseline neutrino oscillation programs and informing the simulations [9–11] that such experiments rely on. The interaction cross section has also garnered a great deal of interest recently from theorists at the intersection of neutrino and nuclear physics, especially in the context of meson exchange currents and short-range correlations between nucleons [12–18].

The decay at rest of a positively charged kaon ($K^+ \to \mu^+ \nu_\mu$, BR = 63.6% [5]) produces a 236 MeV muon neutrino. A large sample of these monoenergetic neutrinos, interacting via the CC channel $\nu_\mu\,^{12}\mathrm{C} \to \mu^- X$, where X is a proton and/or an excited nucleus, can be recorded to produce a standard candle for the ν_μ and its interaction kinematics at and near this energy. As discussed in Ref. [19], these charged kaon decay-at-rest neutrinos can also be used for a sensitive probe of high-Δm^2 oscillations indicative of a sterile neutrino. Unfortunately, these measurements are only really possible with neutrinos, rather than both neutrinos and antineutrinos, because of nuclear capture for negatively charged kaons.

This article serves to point out the importance of measuring the differential and total cross sections associated with this unique, monoenergetic neutrino. For intense kaon decay-at-rest neutrino sources in general, a determination of the monoenergetic ν_μ flux is complicated as the kaon production rate is difficult to accurately simulate and measure. Therefore, a precision, absolutely normalized cross section measurement is challenging. As discussed later, however, an exclusive interaction channel (for a carbon target, at least) can be used to determine the flux at the 10% level in the case that enough events are collected. Either way, a single differential or double differential cross section measurement in terms of outgoing muon angle and/or momentum, with detailed shape information, is valuable. Given a known neutrino energy, a precision differential cross section measurement in energy transfer, as is common for electron scattering experiments, is also available. No such measurement exists for ν_μ CC

interactions. After discussing the relevance of these measurements in a number of physics applications, a set of potential experimental locations and detection technologies are considered.

II. PHYSICS WITH NEUTRINOS FROM KAON DECAY AT REST

Along with using the known-energy neutrinos as a unique probe of the nucleus, and as a test of our theoretical description of neutrino-nucleus interactions at this energy, a set of 236 MeV ν_μ CC cross section measurements can be utilized in a number of ways.

Long-baseline neutrino oscillation experiments employ near and far detectors for measuring the L/E-dependent mixing probability of a beam of originally ν_μ or $\bar{\nu}_\mu$. These experiments are able to run in either neutrino or antineutrino mode by changing the polarization of their beamline magnets to focus $\pi^+(\rightarrow \mu^+\nu_\mu)$ or $\pi^-(\rightarrow \mu^-\bar{\nu}_\mu)$. The near detector, typically hundreds of meters from the source, provides a description of the initial, preoscillation composition of the mostly pure ν_μ or $\bar{\nu}_\mu$ beam. The far detector, typically hundreds of kilometers from the source, probes the beam for ν_μ and $\bar{\nu}_\mu$ disappearance as well as ν_e and/or ν_τ appearance. These experiments are sensitive to the θ_{23} octant, the orientation of the mass hierarchy, and the neutrino CP-violating phase δ_{CP}, among other physics.

The ν_μ or $\bar{\nu}_\mu$ CCQE interaction is often utilized both as the signal channel for the disappearance measurements and to constrain predictions relevant for the appearance channels. Given the L/E oscillation dependence, reconstructing the energy of these neutrinos is obviously vital to extracting the mixing parameters. Further, an appropriate comparison between the near and far detector event rate as a function of reconstructed neutrino energy (and/or lepton kinematics, as in Ref. [20]) requires knowledge of the interaction cross section because the energy composition of the beam is different at each site, even in the case that both detectors are on axis. Along with near-far flux differences due to oscillations, this is due to the fact that the near detector is exposed to a range of incident neutrino angles (and corresponding kinematics) from pions decaying in flight at different locations in the decay pipe, while the far detector is effectively exposed to a point source of neutrinos. The possibility of systematic differences between the near and far sites in composition, size, detection technology, etc., can lead to further reliance on knowledge of the underlying cross section as well.

As an example, the uncertainties associated with the neutrino interaction dominate the systematics on the predicted number of signal ν_e events in the T2K long-baseline neutrino oscillation experiment [20,21]. These uncertainties, especially those related to the ν_μ/ν_e ($\bar{\nu}_\mu/\bar{\nu}_e$) cross section ratio [22], will likely be among the leading sources of systematic uncertainties in future δ_{CP}

programs, and there are multiple experiments around the world with the goal of improving our knowledge of the kinematics of the outgoing charged lepton and the neutrino/antineutrino cross section on various nuclear targets in the long-baseline energy regime. The situation is such that it may be advantageous for future long-baseline experiments to tune their characteristic neutrino fluxes to better align with regions of low cross section and/or energy reconstruction uncertainty.

The few-hundreds-of-MeV neutrino energy range is an interesting possible place of emphasis for future long-baseline experiments for a number of reasons. Along with tuning closer to the second or third oscillation maxima, depending on baseline, in an attempt to better distinguish between different δ_{CP} scenarios and perhaps moving toward a more well-understood cross section and neutrino energy reconstruction region, given a precise set of (e.g.) 236 MeV-based measurements, emphasizing a lower beam energy can also prove advantageous because of the smaller resonant background and reduction of complications due to short-range correlations. Short-range correlations are not expected to play a large role at these relatively low neutrino energies [2,3]. However, in the case of a statistics-limited measurement, as compared to a background- or interaction-systematics-dominated one, a lower energy may not be optimal due to the reduction in cross section, and therefore event rate, as well as the lack of muon reconstruction abilities below 54 MeV for water-based Cerenkov detectors such as SuperK/HyperK. Further, it is not clear if the benefit of the cross section measurements outlined here, in a move to lower energy, can outweigh the comparatively poor theoretical understanding of the ν_μ/ν_e cross section ratio in this low energy part of the QE regime.

Beyond the general comments above, the impact of a set of 236 MeV cross section measurements is potentially wide ranging, especially in the case of a future experiment that relies on cross section knowledge in the few-hundred-MeV neutrino energy region. As an example, the European Spallation Source Neutrino Super Beam (ESSνSB) long-baseline neutrino oscillation project aims to produce a 5 MW, 2 GeV proton beam and combine it with a water Cerenkov based detector 300–600 km away in order to measure δ_{CP} [23]. In neutrino mode, the ν_μ flux peaks at about 225 MeV. There is also an idea to employ simultaneous, high power 8- and 60-GeV proton beams with a 200 kt water Cerenkov detector to obtain sensitivity to "low" energy (0.2–1.5 GeV) $\nu_\mu \rightarrow \nu_e$ oscillations at the second oscillation maximum at a distance of 1300 km. Such an experiment would provide a precise determination of δ_{CP} that is largely independent of the mass hierarchy orientation [24]. A cross section measurement with kaon-induced neutrinos is also quite relevant for a future β beam with a γ near 100 and/or a 3.5 GeV Super Proton Linac (SPL) superbeam from CERN; both sources will produce neutrino fluxes in the few-hundred-MeV range [25].

The β-beam-SPL combination has been identified as a future option that will have greater sensitivity to δ_{CP} than any other superbeam or β-beam concept, second only to a neutrino factory [26].

As is true for all neutrinos in the long-baseline energy regime, nuclear effects play a large role for 236 MeV ν_μ interactions and, despite the value in the cross section measurements outlined, it should be stated that this neutrino energy is a challenging one to deal with theoretically. The neutrino energy, or rather the characteristic energy transfer, is right at the transition between our neutrino-on-nucleus and neutrino-on-nucleon frameworks. The impulse approximation, in which it is assumed that the neutrino interacts with a single nucleon, breaks down at these lower energies and the distinction between a pre-FSI pure CCQE interaction ($\nu_\mu n \rightarrow \mu^- p$) and an "absorption" interaction (on carbon, for example, $\nu_\mu {}^{12}C \rightarrow \mu^- X$) becomes blurred. Indeed, measurements of the monoenergetic neutrino may shed light on this important transition and inform the theoretical representations.

III. EXPERIMENTAL LOCATIONS

There are a number of proton fixed target experimental locations around the world where these cross section measurements are possible. The main requirement, other than a capable existing or planned detector, is that the primary proton energy exceed ~3 GeV for adequate kaon production. The 1.4 MW, 1 GeV Spallation Neutron Source at Oak Ridge and the future 5 MW, 2 GeV European Spallation Source are therefore not considered here. In addition, given that a decay-at-rest source produces an isotropic flux of neutrinos, the detector needs to be reasonably close ($\lesssim 100$ m) to the source. The NuMI beam dump at Fermilab and the JPARC Materials and Life Science Facility (MLF) spallation source, in combination with a set of nearby planned detectors, are considered as possible experimental locations here.

The 120 GeV NuMI beam line terminates for all non-neutrinos at a beam dump, 720 m downstream of the target [27]. Given the target's two interaction lengths, as much as 14% of the beam is passed on to this beam stop. The NuMI beam dump therefore provides a significant source of kaon decay-at-rest neutrinos and there are a set of nearby detectors that are sensitive to the ν_μ CC interaction at 236 MeV: MiniBooNE, running since 2002 and located about 85 m from the NuMI dump, is a Cerenkov- and scintillation-based mineral oil detector [28], and MicroBooNE, running in 2014 and located about 102 m from the dump, is a liquid argon time projection chamber (LArTPC) [29]. While MiniBooNE has probably collected thousands of these from-NuMI events [30], it is likely difficult to unambiguously identify them as monoenergetic ones given the detector's propensity for lepton-only reconstruction for this class of interactions. Further, the

pion decay-in-flight ν_μ "background," largely coming from the NuMI decay pipe, likely makes the bump difficult to pick out. However, MiniBooNE+, an experimental proposal to add liquid scintillator to the existing MiniBooNE detector [31], may be able to enhance the energy reconstruction abilities enough to resolve the from-kaon peak. With full kinematic reconstruction abilities, as with the MicroBooNE LArTPC, the decay-in-flight background can be reduced significantly with reconstructed neutrino energy and direction requirements; this experiment is an attractive future location for these measurements.

It is worth noting that the SciBooNE experiment has also likely collected a significant number of these monoenergetic neutrinos, originating at the booster neutrino beam line (BNB) dump, but the decay-in-flight ν_μ flux from the BNB decay pipe is more than an order of magnitude higher in the relevant energy region [32]. This will also be true for the future LAr1-ND experiment [33], proposed to be located at the SciBooNE hall in the BNB.

The JPARC-MLF is host to another intense source of kaon decay-at-rest neutrinos coming from 3 GeV protons on a mercury target. The eventually 1 MW source features only a small decay-in-flight background component as it is nominally used for spallation neutron production rather than as a conventional neutrino beam line. The mercury target is basically surrounded on all sides by concrete and iron, and the large majority of pions, muons, and kaons created quickly come to rest and capture or decay. Currently, there are plans to place a 50 ton fiducial volume gadolinium-loaded liquid scintillator (LS) neutrino detector 17 m from the source for a sterile neutrino search there [34]. Such a detector can also be used to perform the measurements described here.

IV. DETECTION

We survey the detection technologies associated with the JPARC-MLF (LS) and MicroBooNE (LArTPC) experiments when considering these cross section measurements. Although a Cerenkov-based detector with muon-only reconstruction proficiency could potentially pick out the monoenergetic bump in reconstructed energy due to the 236 MeV neutrino, especially in the absence of a significant nonmonoenergetic background, both technologies considered here have better neutrino energy reconstruction capabilities, mainly because of their ability to reconstruct the low-energy nucleonic component of these events; LS and LArTPC technology are simply more suitable for making sure that the events being evaluated are indeed coming from charged kaon decay at rest. Of course, what is learned from these measurements as well as their applicability toward future oscillation programs is highly dependent on which nuclear target is chosen.

The detection of ν_μ CC events up to ~260 MeV with LS in the Liquid Scintillator Neutrino Detector (LSND) experiment is discussed at length in Ref. [35]. A combination of both

scintillation and Cerenkov light signals can provide directional, calorimetric, and particle identification information for reconstructing the events. The muon is identified by requiring a delayed coincidence with a characteristic decay electron and can also be distinguished with a Cerenkov signal since nearly 90% of monoenergetic events produce a muon above the 36 MeV kinetic energy threshold (in the commonly used linear alkyl-benzene based LS). Stopping μ^- are captured 8% of the time on carbon in the LSND detector [35]. A veto, in combination with beam timing, can render the steady state background, mainly coming from cosmic ray muon decay in the detector, negligible. Notably, the JPARC-MLF source features an extremely tight beam window with two 80 ns wide pulses of protons 540 ns apart at 25 Hz, resulting in a steady state rejection factor of 4×10^{-6}. It is also expected that the JPARC-MLF LS detector will feature faster electronics than LSND, although it is difficult to estimate the achievable muon momentum and angular resolutions until the detector parameters, such as photocoverage and time resolution, are finalized. For reference, LSND's 25% photocoverage resulted in a muon directional reconstruction resolution of about 12° for muons above threshold and an energy resolution of better than 10% at $T_\mu = 100$ MeV [35,36].

In a best case scenario, the contributions of the scintillation- and (usually) Cerenkov-ring-producing muon and scintillation-only proton (or protons, since FSIs and correlations can result in multiple ejected nucleons), can be separated in LS for a more precise measurement of the differential cross sections, especially in terms of reconstructing the momentum of the muon. In practice, however, this is difficult and will likely require successfully modeling the light production of both the outgoing proton(s) and nuclear deexcitation gammas.

In a LArTPC, the charged particles created in a neutrino interaction, the reconstruction of which is required in order to infer the energy and flavor of the neutrino itself, propagate through the liquid argon medium and create trails of ionization along their paths. An electric field is imposed in the liquid argon volume and the trails are drifted through the noble liquid toward a set of sensing electrodes. The signals in time captured by the electrodes, usually in the form of a set of wire planes oriented at an angle with respect to one another, provide a complete three-dimensional image of the neutrino event. Calorimetric information is available as the ionization collected by the electrodes is related to the amount of energy deposited along the charged particle tracks. Scintillation light (128 nm) is also produced readily as the charged particles ionize atoms; argon's high scintillation yield is useful for detecting this aspect of the interaction as well, although a wavelength shifter is required in conjunction with photomultiplier tubes to shift the light into the visible spectrum and detect it. With sensitivity to deexcitation gammas, neutrons, protons down to the few-tens-of-MeV level, and precise calorimetric reconstruction abilities, LArTPC technology is attractive for detecting and characterizing 236 MeV ν_μ CC events.

Table I shows the expected number of monoenergetic ν_μ CC events in both MicroBooNE and the LS detector at the JPARC-MLF. The MicroBooNE event rate estimate assumes 2 years of running NuMI in neutrino mode at 700 kW (6×10^{20} POT/year), consistent with the Fermilab road map. Interestingly, NuMI neutrino mode and antineutrino mode each provide a similar flux of monoenergetic neutrinos. The JPARC-MLF event rate estimate assumes 4 years of running with a 1 MW beam and 4000 hours/year of operation, or 3×10^{22} POT/year, consistent with Ref. [34]. The neutrino flux at each location has been determined using GEANT4 [37] (and FLUKA [38] also, in the case of NuMI) simulations of the sources, noting that kaon production is highly uncertain at both locations. As an example, the kaon-induced monoenergetic ν_μ production at the 3 GeV JPARC-MLF source is 0.0035 ν_μ/proton with GEANT4 but is found to be about 75% higher with the LAQGSM/MARS (MARS15) software package [39]. The GEANT4 results are used here in order to be conservative. The event rate estimates also assume a ν_μ CC cross section of 1.3×10^{-39} cm²/neutron, consistent with the NuWro neutrino event generator for interactions on both carbon and argon at 236 MeV [9] and the theoretical predictions [40]. The expected neutrino flux from the JPARC-MLF source in all directions, without regarding potential detector location, in the energy range 100–300 MeV can be seen in Fig. 1. The 236 MeV ν_μ and three-body kaon decay "K_{e3}^+" ($K^+ \rightarrow \pi^0 e^+ \nu_e$, BR = 5.1%) ν_e distributions are obviously quite prominent.

The NuWro neutrino event generator has been used here in order to simulate 236 MeV ν_μ CC interactions on carbon and argon. The simulation provides an idea of what can be expected from these neutrinos, although the employed impulse approximation is known to simulate neutrinos, especially ν_μ, poorly at these relatively low energies. NuWro is used because it contains a spectral-function-based

TABLE I. The expected monoenergetic ν_μ CC event rate at two experimental locations along with the beam exposure and detector assumptions.

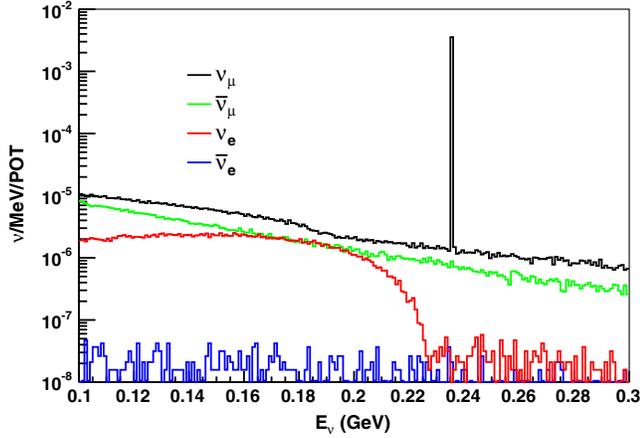| Detector (source)	Target (mass)	Exposure	Distance from source	236 MeV ν_μ CC events
MicroBooNE (NuMI dump)	LAr (90 ton)	1.2×10^{21} POT (2 years)	102 m	2300
Liq. scint. (JPARC-MLF)	Gd-LS (50 ton)	1.2×10^{23} POT (4 years)	17 m	194000

FIG. 1 (color online). The neutrino flux from 100–300 MeV provided by the 3 GeV proton-on-mercury JPARC-MLF source. The 236 MeV charged kaon decay-at-rest daughter ν_μ is easily seen.

simulation for both nuclei [41]. The results of the neutrino-on-carbon simulation are shown in Fig. 2. The kinetic energy of the muon is seen along with a Gaussian smeared energy, given an arbitrary 10% detection resolution. Also, the post-FSI reconstructed neutrino energy $\bar{E}_\nu$ $(= E_\mu + \sum_i^n T_{i,\mathrm{proton}} + S_p$, where n is the number of protons and $S_p = 16$ MeV is the proton separation energy for ^{12}C) with a perfect detector, after considering neutron and deexcitation gammas nonreconstructable, is shown. The separation energy for a single proton only is used for simplicity. The apparent bimodal shape of the distribution is due to the shell structure of the nucleus and the energy levels of the neutron within the spectral function
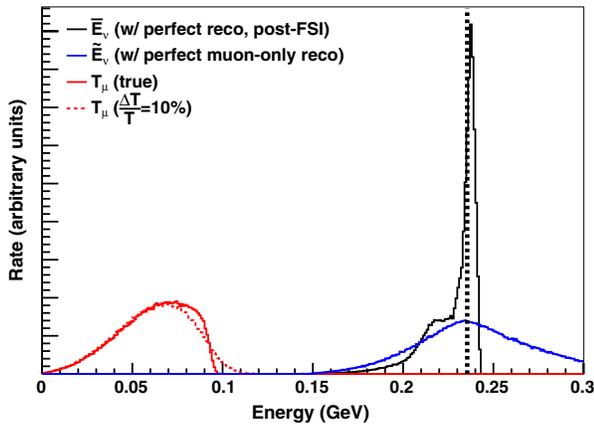

FIG. 2 (color online). The NuWro simulation results of 236 MeV ν_μ (from $K^+ \to \mu^+\nu_\mu$) CC interactions on carbon. The kinetic energy of the outgoing muon, given a set of detector resolution assumptions, is shown. The reconstructed neutrino energy available with a perfect detector is also visible, noting that deexcitation gammas and neutrons are considered missing energy here. The reconstructed neutrino energy with perfect muon-only tracking is also shown for reference.

implementation. The reconstructed energy with a perfect muon-only detector $\tilde{E}_\nu$, given the usual two-body kinematics CCQE formula, assuming target nucleon at rest and a binding energy of 34 MeV, is also shown for reference. The shape of the expected 236 MeV ν_μ CC event rate distribution in muon angle and kinetic energy, as simulated with NuWro, is shown in Fig. 3.

The main requirement for a valuable monoenergetic ν_μ cross section measurement is that the signal interaction is properly identified as such. This determination relies on the ability to precisely reconstruct the energy of the neutrino, with the actual energy resolution needed depending on the background nonmonoenergetic ν_μ flux in the energy region of interest. In the case of the JPARC-MLF source, for example, the monoenergetic cross-section-weighted flux, without regard for detector location, will be a factor of $\sim$30 times higher than the integrated background in an arbitrary true energy window of 80 MeV around 236 MeV. The actual signal to background at the detector location will likely be significantly higher than this, given the tentative backward orientation of the detector relative to the primary proton beam direction, according to Ref. [34], and resulting decrease in the decay-in-flight component at the detector. For example, the ratio increases to $\sim$180 in the case that only neutrinos with $\cos\theta_z < 0$ (where $+z$ is the primary proton direction) are considered. Regardless, if a ν_μ CC event is identified from this source, with even modest energy resolution, one can be fairly confident that it is monoenergetic.

The favorable signal-to-background ratio at the JPARC-MLF may afford the ability to perform these cross section measurements with a water Cerenkov detector, capable of providing lepton-only kinematic reconstruction, for a cross section measurement directly applicable to the Super-K and Hyper-K detectors [42] within the T2K long-baseline program, and water-based devices in general. However, the 236 MeV ν_μ is at the low end of neutrino energies relevant for T2K ($E_\nu^{\mathrm{peak}} \sim 600$ MeV). Further, the water
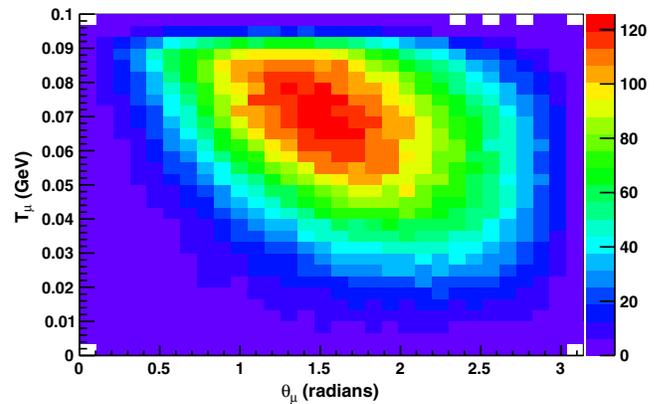

FIG. 3 (color online). The kinematics of the muon from 236 MeV ν_μ CC interactions on carbon according to NuWro. The z-axis units are arbitrary.

Cerenkov threshold for muons is 54 MeV in kinetic energy so one-third of the signal is nominally irretrievable (see Fig. 2) and, when considering muons in the T2K ν_μ disappearance analysis, Super-K's threshold (200 MeV/c, due to particle identification requirements at low energy) is above the characteristic momenta for monoenergetic events [43].

The large JPARC-MLF signal-to-background ratio in an arbitrary true neutrino energy window of 80 MeV around 236 MeV decreases to $\sim$1 in the case of the NuMI beam dump source given the substantial pion decay-in-flight background ν_μ flux. Along with precisely reconstructing the neutrino energy in order to reduce background, this issue can be mitigated somewhat with the ability to reconstruct the direction of the incoming neutrino since the large majority of monoenergetic ν_μ will be coming directly from the dump rather than the NuMI decay pipe or target station. This requires the ability to reconstruct the low-energy hadronic component of the interaction at a reasonable level as the outgoing muon and incoming neutrino direction are rather poorly correlated. Notably, the ArgoNeuT LArTPC detector has demonstrated the ability to reconstruct protons down to 21 MeV kinetic energy [44]. While it is currently not clear exactly how well MicroBooNE will be able to reconstruct the direction of 236 MeV events, especially given that nuclear effects can distort the direction of the outgoing nucleon(s), the detector's orientation relative to the NuMI beam line and dump, with the NuMI target and dump separated by about 110°, will make it easier to distinguish between neutrinos from the different sources. Even if this is not achievable, the decay-in-flight background contribution to a monoenergetic ν_μ measurement can be constrained by considering events outside of the relevant energy region. Data collection with a proton beam plug or lengthened target, which would substantially reduce the monoenergetic flux at MicroBooNE, could also allow for an *in situ* measurement of the background component.

V. OTHER OPPORTUNITIES WITH KAON DECAY-AT-REST NEUTRINOS

Aside from measurements of the ν_μ CC differential and total cross sections described above, from-kaon neutrinos provide a number of other physics opportunities as well. Two of these are described below: (i) A measurement of an exclusive channel can deliver a precise determination of the neutrino flux at 236 MeV, and (ii) the charged kaon decay K_{e3}^+ can provide a significant sample of ν_e events in an energy range relevant for accelerator-based oscillation measurements.

Despite the complications discussed above with regard to the transition between neutrino-on-nucleon and neutrino-on-nucleus scattering, the contribution from the absorption part of the inclusive interaction can be seen as something of a windfall, at least when considering a carbon target, given

the significant $\nu_\mu {}^{12}\mathrm{C} \to \mu^- {}^{12}\mathrm{N_{gs}}$ exclusive cross section at this energy. This exclusive reaction, which can be purely identified with a triple coincidence of the muon, the decay daughter electron, and the positron from the β decay of ${}^{12}\mathrm{N_{gs}}$ has a well-predicted cross section at 236 MeV of $\approx 7 \times 10^{-41}$ cm^2/nucleus [45] which results in an event rate of about 1% relative to the inclusive channel. Although this rate is comparatively low, it still would provide nearly 2000 monoenergetic events in 4 years of running with the JPARC-MLF detector. While the theoretical cross section prediction for the inclusive channel is highly uncertain, with models differing by up to $\sim$25% for LSND's flux-averaged cross section ($\langle E_\nu \rangle = 156$ MeV) [35,40,46,47], the exclusive channel is well known, with differences between the various shell-model-based predictions at the level of only 10% at 250 MeV [35,45]. The exclusive prediction is more precise because it relies on form factors arrived at with measured values of the related electroweak transition probabilities (β decay and muon capture) [40]. Given the reliable cross section prediction, this exclusive channel can be used for the absolute flux determination at this energy and therefore for reporting precisely normalized differential and total cross section measurements.

Along with the monoenergetic ν_μ, kaons yield another potentially important source of neutrinos as well. While ν_μ CC cross section measurements in the energy range 53–500 MeV are quite sparse [32,35,48,49], ν_e cross section measurements above 53 MeV are nonexistent. A significant number of ν_e CC events can be collected from the JPARC-MLF source (via K_{e3}^+), noting that the ν_e cross section is about 25% higher than ν_μ at these energies and the ν_e cross section has a significantly lower energy threshold due to the muon-electron mass difference. Although the ν_e are not monoenergetic, the flux does cut off sharply at $\approx$225 MeV and has a characteristic energy shape. With regard to applying such a measurement to T2K, the neutrino energy is low but well within relevance, given that T2K requires the reconstructed electron momentum to exceed 100 MeV/c in their appearance analysis [20]. Indeed, one of T2K's ν_e appearance candidates has a reconstructed energy of $\approx$150 MeV [20]. Since there are no ν_e CC measurements at these energies and this channel, along with its antineutrino analog, represents the actual signal for a long-baseline neutrino oscillations experiment's δ_{CP} measurement, as well as numerous short-baseline electron-flavor appearance searches, this sample might prove quite useful.

About 6500 ν_e CC events are expected from 100–225 MeV in true neutrino energy in 4 years of running the JPARC-MLF 50-ton LS experiment. This estimate uses the ν_e cross section prediction from Ref. [46]. This sample may also be important as an experimental check of the ν_μ/ν_e cross section ratio, recalling that ν_μ events are used to constrain the ν_e appearance expectation in both short- and long-baseline experiments. Notably, this ratio has been
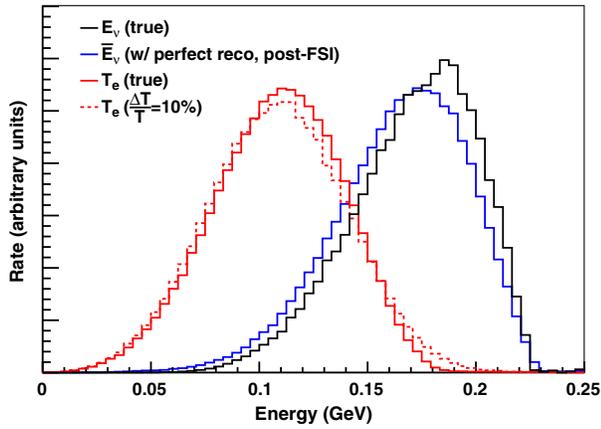
FIG. 4 (color online). The NuWro simulation results of ν_e (from $K^+ \to \pi^0 e^+ \nu_e$) CC interactions on carbon. The kinetic energy of the outgoing electron, given a set of detector resolution assumptions, is shown. The true neutrino energy and reconstructed neutrino energy available with a perfect detector $(\bar{E}_\nu = E_e + \sum_i^n T_{i,\text{proton}} + S_p)$ are also visible.

identified as one of the keys to improving sensitivity to δ_{CP} in future long-baseline experiments [22] and our knowledge of it is weakest at low energy where the lepton mass difference and nuclear form factors contribute more. Measurements of these cross sections are also applicable in understanding the MiniBooNE low-energy excess at 250–475 MeV [50] and for informing MicroBooNE's study of this energy region and below, given the low(er) energy reconstruction capabilities of LArTPC technology. The results of a simulation of the ν_e from the JPARC-MLF source (shown in Fig. 1), which is basically the flux exclusively coming from $K^+ \to \pi^0 e^+ \nu_e$, on a carbon target are shown in Fig. 4. The true neutrino energy, reconstructed neutrino energy available with a perfect detector $\bar{E}_\nu$ $(= E_e + \sum_i^n T_{i,\text{proton}} + S_p)$, and electron kinetic energy with two different detection resolution scenarios are shown. LS, LArTPC, and water Cerenkov technology are all capable of efficiently reconstructing ν_e CC events in this energy range.

It is also worth briefly mentioning that monoenergetic ν_μ-induced NC events may offer an interesting physics sample as well, especially since NC measurements are always flux integrated; these may be useful for measuring Δ_s and/or isovector couplings in elastic scattering.

VI. CONCLUSION

Measurements of the monoenergetic 236 MeV ν_μ from charged kaon decay at rest may be quite valuable for probing the nucleus using neutrinos and accelerator-based oscillation experiments. A number of experiments coming online in the next few years, including MicroBooNE at Fermilab and the LS-based experiment at JPARC's MLF facility, will be able to make precise cross section measurements of this unique known-energy channel. In particular, the MLF experiment will see close to 200000 236 MeV ν_μ CC events in 4 years of running along with 6500 ν_e CC events coming from a well-understood flux shape in the 100–225 MeV range. In the future, it seems pertinent to develop a quantitative understanding of the role these measurements can play in reducing the systematics associated with both energy reconstruction and cross sections in accelerator-based oscillation experiments, and perhaps even informing decisions related to the development of these programs.

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