Low-energy Inelastic Neutrino Cross Sections

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☐ (NF1) Neutrino oscillations
☐ (NF2) Sterile neutrinos
☐ (NF3) Beyond the Standard Model
☐ (NF4) Neutrinos from natural sources
☐ (NF5) Neutrino properties
■ (NF6) Neutrino cross sections
☐ (NF7) Applications
■ (TF11) Theory of neutrino physics
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Abstract: Inelastic neutrino-nucleus scattering at tens-of-MeV energies has a variety of exciting applications, including detection of supernova and solar neutrinos, studies of stellar nucleosynthesis, and searches for physics beyond the Standard Model, among others. After reviewing physics opportunities related to low-energy inelastic neutrino-nucleus scattering, we consider current capabilities to (1) simulate these processes with a neutrino event generator, and (2) obtain needed measurements of the relevant interaction cross sections.

I. MOTIVATIONS

At supernova (~ 10 MeV) and solar ($\lesssim 10$ MeV) energies, the interactions of neutrinos with matter are dominated by scattering on atomic nuclei. Coherent elastic neutrino-nucleus scattering (CEvNS), a neutral-current process in which the final-state nucleus is left in its ground state, is considered at length in multiple LOIs. In this document, we consider the related *inelastic* charged-current and neutral-current processes.

While charged-current interactions on nuclei enable detectors such as DUNE [1] and HALO [2] to be sensitive to the ν_e component of supernova neutrino flux, modeling the nuclear response to these neutrinos is a challenging and necessary step to interpret detector signals. For instance, interpreting results from supernova neutrinos in DUNE will depend on understanding the complexity of the interactions [3]. For supernova burst neutrinos, the key information is encoded in the flavor composition and energy spectrum as a function of time. To fully exploit the physics potential of the next galactic core-collapse supernova, DUNE will need to be capable of disentangling the flavor components of the supernova flux. In order to develop such interaction channel tagging, simulations accurately representing the true distribution of interaction products as a function energy are critically needed. DUNE may also be sensitive to neutral-current interactions and charged-current interactions with electron antineutrinos, which require similar theoretical approaches. Similarly for HALO, which relies on neutrino-induced neutron production, a model of inelastic neutrino-nucleus scattering that includes subsequent de-excitations is necessary to achieve its supernova physics potential.

These reactions also play a role in supernova dynamics and nucleosynthesis of ejected matter in a neutrino-driven wind [4]. There are indications that inelastic neutrino-nucleus events emitting neutrons play a role in observed isotopic abundances formed during supernova nucleosynthesis [5], compete with β-decay in r-process nucleosynthesis [6], and add processing effects to the r-process abundances post-freeze-out [7]. In the neutron-rich environments described above, it may be possible for neutrino-induced fission to alter isotopic abundances and r-process rates [6].

Inelastic charged-current and neutral-current interactions have also been proposed as a means to access the low-energy portion of the solar neutrino spectrum. Detection schemes based on iodine [8], lithium [9], and boron [10] have been proposed, as has looking for solar neutrino signatures in future neutrinoless double beta decay experiments [11–13]. A recent study [14] also found that solar neutrino detection with DUNE has the potential to make unique contributions to the field.

Searches for low-energy physics beyond the Standard Model (BSM) will also benefit from an improved understanding of inelastic neutrino-nucleus scattering. An example is the possible absorption of fermionic dark matter by nuclei [15], which might produce experimental signatures similar to charged- or neutral-current neutrino-nucleus interactions. A detailed understanding of inelastic neutrino-nucleus cross sections is useful to searches for these absorption processes in two ways: scattering of solar neutrinos on nuclei will likely produce an important background, and similar nuclear modeling is needed to predict the BSM signal.

Although a suitable detector is not currently installed at the right distance from an existing neutrino production facility, opportunities exist for oscillation measurements using tens-of-MeV neutrinos which could provide a useful cross-check for other approaches. A scenario requiring the use of inelastic scattering on a complex nuclear target, a study of $\nu_\mu \to \nu_e$ appearance using a pion decay-at-rest (πDAR) source, was recently considered in ref. [16]. That analysis found that a large liquid-argon-based detector, such as a liquid argon time projection chamber (LArTPC), could provide constraints on δ_{CP} using πDAR neutrinos which would be complementary to those obtained from accelerator and atmospheric neutrinos.

Finally, measurements of low-energy inelastic neutrino-nucleus cross sections will provide an important constraint on nuclear physics modeling for other processes. For example, the nuclear matrix elements describing inelastic (anti-)neutrino-nucleus scattering, muon capture, and single beta decay are closely related to those needed to describe neutrinoless double beta decay. A theoretical model which provides a reliable description of the other processes may be used to predict neutrinoless double beta decay rates with increased confidence [17]. A second application is to cross section modeling for accelerator neutrino experiments. At forward scattering angles, which correspond to low momentum transfer, the neutrino-nucleus cross section at accelerator energies is impacted by the same nuclear physics effects that are important for the low-energy case more generally [18]. At these kinematics, differences between final-state lepton masses become vital and affect the ratio of the charged-current ν_μ and ν_e cross sections — an observation which might have important implications for neutrino oscillation experiments [19, 20].

II. SIMULATION CAPABILITIES

Inelastic neutrino-nucleus cross sections in this energy range have been studied in the theory literature over several decades [21, 22]. However, in contrast to neutrino interactions at accelerator energies ($\sim$100 MeV to $\sim$10 GeV), for which several modern Monte Carlo event generators [23–26] are widely used, relatively little attention has been paid to simulations of tens-of-MeV neutrino-nucleus reactions. A major challenge is that, for inelastic reaction modes, the standard approximations used at higher energies become inadequate: excitation of discrete nuclear levels and giant resonances can no longer be neglected via use of a Fermi gas model of the nucleus, and hadronic final-state interactions are thought to be dominated by compound evaporation instead of direct knockout [27]. Incorporation of a model for low-energy inelastic scattering into one of the general-purpose neutrino generators is therefore difficult due to the very different theoretical assumptions that must be made.

A recent attempt to create a dedicated low-energy neutrino event generator is MARLEY [28, 29]. Initial development of MARLEY has focused on simulations of the reaction $^{40}\mathrm{Ar}(\nu_e, e^-)^{40}\mathrm{K}^*$ using a simple, partially data-driven [30] model of the inclusive cross section. Nuclear de-excitations are simulated using nuclear level data and a statistical model treatment [31] that readily extends to many nuclei. Several MARLEY-based studies of solar and supernova neutrino interactions in argon have already been carried out [3, 32, 33], and first steps have begun toward the inclusion of other reaction modes and nuclear targets (see, e.g., ref. [34]).

Detecting solar and supernova neutrinos using inelastic scattering on complex nuclear targets shares a key similarity with accelerator-based neutrino oscillation experiments: the neutrino energy is of primary interest, but its reconstruction is very challenging due to the intricacies of nuclear physics [35]. Just as event generators are an indispensable tool for the accelerator neutrino oscillation community [36], an event generator which implements an appropriate set of physics models will be essential to the analysis and interpretation of low-energy neutrino data collected by DUNE, HALO, and similar detectors. Development of MARLEY and/or competing low-energy neutrino generators must therefore continue. Detailed measurements of neutrino-nucleus cross sections, widely recognized as essential for precision oscillation experiments [37], will also become a crucial need at tens-of-MeV energies to benchmark and improve low-energy neutrino generators in the coming years.

III. FACILITIES AND DETECTORS FOR CROSS SECTION MEASUREMENTS

While the physics potential of low-energy neutrino measurements is sufficient to justify dedicated cross section experiments, e.g., the proposed measurement of ν_e absorption on argon by CAPTAIN [38], a number of existing experimental facilities and detectors could be used to obtain much-needed data. In this section we briefly list a few of the possibilities. Snowmass discussions on this topic should consider these and possible future facilities, e.g., construction of a beta-beam [39, 40] that could be used to produce low-energy neutrinos.

COHERENT The COHERENT experiment [41] has several detectors in its suite with some capability for these measurements using the high-quality stopped-pion neutrino source at the Oak Ridge National Laboratory Spallation Neutron Source. Current targets are Pb, Fe, and I, with future detectors potentially measuring interactions on O and Ar [42]. At the future Second Target Station, 10-tonne scale detectors may be possible [43].

Fermilab Both of Fermilab's two currently-operating neutrino beams, the Neutrinos at the Main Injector (NuMI) beam [44] and the Booster Neutrino Beam (BNB) [38, 45], may be used as a source of low-energy neutrinos. Existing Fermilab LArTPC experiments, such as MicroBooNE [46], may have some sensitivity to low-energy charged-current scattering of ν_e on argon. Reconstruction of MeV-scale physics, including Michel electrons [47] and neutrino-induced nuclear de-excitation products [48], has recently been demonstrated in multiple LArTPCs designed for detection of accelerator neutrinos. Follow-up studies of this capability, e.g., refs. [33, 49, 50], continue to show promise for low-energy neutrino detection.

LANSCE The Los Alamos Neutron Science Center (LANSCE) operates an 800 MeV proton beam at its Lujan Center which serves as a 100-kW stopped pion source for low-energy neutrinos. Coherent CAPTAIN-Mills (CCM), a 10-ton detector which uses a liquid argon target instrumented with photomultiplier tubes, is operating at LANSCE to perform measurements of coherent elastic neutrino-nucleus scattering (CEvNS) on argon [51]. The CCM detector may also be suitable for inelastic neutrino scattering measurements on argon.

MLF The Material and Life Science Experimental Facility (MLF) at J-PARC provides a stoppped-pion neutrino source that is being used by the JSNS^2 experiment to search for sterile neutrinos [52]. The JSNS^2 detector, which employs a 17-ton fiducial volume filled with Gd-loaded liquid scintillator, will also be used to pursue measurements of tens-of-MeV neutrino scattering on ^{12}C.

Reactors Nuclear reactors may serve as a useful source of very low-energy $\bar{\nu}_e$ for studying inelastic antineutrino-nucleus cross sections, both for monitoring reactors [53] as well as for calibrating detectors for other low-energy neutrino sources [54].

[1] DUNE collaboration, *Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume II: DUNE Physics*, *arXiv preprint* (2020) [2002.03005].
[2] C. A. Duba, F. Duncan, J. Farine, A. Habig, A. Hime, R. G. H. Robertson et al., *HALO – the helium and lead observatory for supernova neutrinos*, *Journal of Physics: Conference Series* **136** (2008) 042077.
[3] DUNE collaboration, B. Abi, R. Acciarri, M. A. Acero, G. Adamov, D. Adams, M. Adinolfi et al., *Supernova Neutrino Burst Detection with the Deep Underground Neutrino Experiment*, 2020.
[4] K. Balasi, K. Langanke and G. Martínez-Pinedo, *Neutrino–nucleus reactions and their role for supernova dynamics and nucleosynthesis*, *Progress in Particle and Nuclear Physics* **85** (2015) 33 .
[5] G. V. Domogatskii and D. K. Nadezhin, *Neutrino production of bypassed isotopes, and the possible role of neutrinos in nucleosynthesis*, **22** (1978) 297.
[6] G. C. McLaughlin and G. M. Fuller, *Evidence for an intense neutrino flux during [ITAL]r[/ITAL]-process nucleosynthesis?*, *The Astrophysical Journal* **464** (1996) L143.
[7] Y.-Z. Qian, W. C. Haxton, K. Langanke and P. Vogel, *Neutrino-induced neutron spallation and supernova r-process nucleosynthesis*, *Phys. Rev. C* **55** (1997) 1532.
[8] W. C. Haxton, *Radiochemical neutrino detection via* ^{127}I$(\nu_e,e^-)^{127}$Xe, *Phys. Rev. Lett.* **60** (1988) 768.
[9] N. Shul'gina and B. Danilin, *Charged- and neutral-current disintegration of the 6li nucleus by solar neutrino and reactor antineutrino*, *Nuclear Physics A* **554** (1993) 137 .
[10] R. S. Raghavan and S. Pakvasa, *Probing the nature of the neutrino: The boron solar-neutrino experiment*, *Phys. Rev. D* **37** (1988) 849.
[11] H. Ejiri and S. R. Elliott, *Charged current neutrino cross section for solar neutrinos, and background to* $\beta\beta(0\nu)$ *experiments*, *Phys. Rev. C* **89** (2014) 055501.
[12] H. Ejiri and S. R. Elliott, *Solar neutrino interactions with the double-*β *decay nuclei* ^{82}Se,^{100} Mo*, and* ^{150}Nd, *Phys. Rev. C* **95** (2017) 055501.
[13] S. R. Elliott and H. Ejiri, *Solar neutrinos as background to neutrinoless double-beta decay experiments*, *AIP Conference Proceedings* **1894** (2017) 020008 [1708.00927].
[14] F. Capozzi, S. W. Li, G. Zhu and J. F. Beacom, *DUNE as the next-generation solar neutrino experiment*, *Phys. Rev. Lett.* **123** (2019) 131803.
[15] J. A. Dror, G. Elor and R. McGehee, *Directly detecting signals from absorption of fermionic dark matter*, *Phys. Rev. Lett.* **124** (2020) 181301 [1905.12635].
[16] R. Harnik, K. J. Kelly and P. A. N. Machado, *Prospects of measuring oscillated decay-at-rest neutrinos at long baselines*, *Phys. Rev. D* **101** (2020) 033008 [1911.05088].
[17] H. Ejiri, J. Suhonen and K. Zuber, *Neutrino–nuclear responses for astro-neutrinos, single beta decays and double beta decays*, *Physics Reports* **797** (2019) 1 .
[18] V. Pandey, N. Jachowicz, M. Martini, R. González-Jiménez, J. Ryckebusch, T. Van Cuyck et al., *Impact of low-energy nuclear excitations on neutrino-nucleus scattering at miniboone and t2k kinematics*, *Phys. Rev. C* **94** (2016) 054609 [1607.01216].
[19] M. Martini, N. Jachowicz, M. Ericson, V. Pandey, T. Van Cuyck and N. Van Dessel, *Electron-neutrino scattering off nuclei from two different theoretical perspectives*, *Phys. Rev. C* **94** (2016) 015501 [1602.00230].
[20] A. Nikolakopoulos, N. Jachowicz, N. Van Dessel, K. Niewczas, R. González-Jiménez, J. M. Udías et al., *Electron versus Muon Neutrino Induced Cross Sections in Charged Current Quasielastic Processes*, *Phys. Rev. Lett.* **123** (2019) 052501 [1901.08050].
[21] J. Walecka, *Semileptonic weak interactions in nuclei*, in *Muon Physics*, V. W. Hughes and C. S. Wu, eds., pp. 113 – 218, Academic Press, (1975), https://doi.org/10.1016/B978-0-12-360602-0.50010-5.
[22] T. Donnelly and R. Peccei, *Neutral current effects in nuclei*, *Physics Reports* **50** (1979) 1 .
[23] C. Andreopoulos et al., *The GENIE Neutrino Monte Carlo Generator*, *Nuclear Instruments and Methods* **A614** (2010) 87 [0905.2517].
[24] O. Buss, T. Gaitanos, K. Gallmeister et al., *Transport-theoretical description of nuclear reactions*, *Physics Reports* **512** (2012) 1.
[25] Y. Hayato, *A neutrino interaction simulation program library NEUT*, *Acta Physica Polonica B* **40** (2009) 2477.
[26] T. Golan, J. Sobczyk and J. Żmuda, *NuWro: the Wrocław Monte Carlo generator of neutrino interactions*, *Nuclear Physics B - Proceedings Supplements* **229-232** (2012) 499.
[27] K. Kim and M.-K. Cheoun, *Roles of one-step process on neutrino scattering off* ^{12}C, *Physics Letters B* **679** (2009) 330 .
[28] S. Gardiner, *Nuclear Effects in Neutrino Detection*, Ph.D. thesis, University of California, Davis, 2018. 10.5281/zenodo.3903986.
[29] S. Gardiner, "MARLEY User Guide." https://www.marleygen.org, 2020.
[30] M. Karakoç, R. G. T. Zegers, B. A. Brown, Y. Fujita et al., *Gamow-Teller transitions in the* $A = 40$ *isoquintet of relevance for neutrino captures in* ^{40}Ar, *Physical Review C* **89** (2014) 064313.
[31] W. Hauser and H. Feshbach, *The inelastic scattering of neutrons*, *Physical Review* **87** (1952) 366.
[32] A. de Gouvêa, I. Martinez-Soler and M. Sen, *Impact of neutrino decays on the supernova neutronization-burst flux*, *Phys. Rev. D* **101** (2020) 043013 [1910.01127].
[33] W. Castiglioni, W. Foreman, I. Lepetic, B. R. Littlejohn, M. Malaker and A. Mastbaum, *Benefits of MeV-scale*

reconstruction capabilities in large liquid argon time projection chambers, *arXiv preprint* (2020) [2006.14675].

[34] COHERENT collaboration, S. Hedges, "Electron neutrino charged-current interactions on I-127 in the COHERENT NaIvE detector." https://nusoft.fnal.gov/nova/nu2020postersession/?posterID=420.

[35] L. Alvarez-Ruso, M. Sajjad Athar, M. Barbaro, D. Cherdack, M. Christy, P. Coloma et al., *NuSTEC white paper: Status and challenges of neutrino–nucleus scattering*, *Progress in Particle and Nuclear Physics* **100** (2018) 1 [1706.03621].

[36] U. Mosel, *Neutrino event generators: foundation, status and future*, *Journal of Physics G: Nuclear and Particle Physics* **46** (2019) 113001 [1904.11506].

[37] O. Benhar, P. Huber, C. Mariani and D. Meloni, *Neutrino–nucleus interactions and the determination of oscillation parameters*, *Physics Reports* **700** (2017) 1 [1501.06448].

[38] CAPTAIN collaboration, *The CAPTAIN detector and physics program*, *arXiv preprint* (2013) [1309.1740].

[39] C. Volpe, *What about a beta-beam facility for low-energy neutrinos?*, *Journal of Physics G: Nuclear and Particle Physics* **30** (2004) L1.

[40] N. Jachowicz and G. C. McLaughlin, *Reconstructing supernova-neutrino spectra using low-energy beta beams*, *Phys. Rev. Lett.* **96** (2006) 172301 [nucl-th/0604046].

[41] D. Akimov, J. Albert, P. An, C. Awe, P. Barbeau, B. Becker et al., *COHERENT 2018 at the Spallation Neutron Source*, *arXiv preprint* (2018) [1803.09183].

[42] COHERENT collaboration, *COHERENT LOI 4: Inelastic Neutrino-Nucleus Interaction Measurements with COHERENT*, .

[43] *Neutrino Opportunities at the ORNL Second Target Station*, .

[44] C. Grant and B. Littlejohn, *Opportunities with decay-at-rest neutrinos from decay-in-flight neutrino beams*, *arXiv preprint* (2015) [1510.08431].

[45] S. Brice et al., *A method for measuring coherent elastic neutrino-nucleus scattering at a far off-axis high-energy neutrino beam target*, *Phys. Rev. D* **89** (2014) 072004 [1311.5958].

[46] R. Acciarri, C. Adams, R. An, A. Aparicio, S. Aponte, J. Asaadi et al., *Design and construction of the MicroBooNE detector*, *Journal of Instrumentation* **12** (2017) P02017 [1612.05824].

[47] R. Acciarri, C. Adams, R. An, J. Anthony, J. Asaadi, M. Auger et al., *Michel electron reconstruction using cosmic-ray data from the MicroBooNE LArTPC*, *Journal of Instrumentation* **12** (2017) P09014 [1704.02927].

[48] ArgoNeuT collaboration, *Demonstration of MeV-scale physics in liquid argon time projection chambers using ArgoNeuT*, *Phys. Rev. D* **99** (2019) 012002 [1810.06502].

[49] A. Friedland and S. W. Li, *Understanding the energy resolution of liquid argon neutrino detectors*, *Phys. Rev. D* **99** (2019) 036009 [1811.06159].

[50] MicroBooNE collaboration, A. Bhat, "Mev-scale physics in microboone." https://nusoft.fnal.gov/nova/nu2020postersession/?posterID=4.

[51] A. Aguilar-Arevalo, J. Asaadi, J. Bacon, J. Boissevain, M. Boswell, J. Conrad et al., "Fundamental Neutrino Physics at the Lujan Center." https://p25ext.lanl.gov/~lee/CaptainMills/Documentation/CCM_Proposal_Lujan_2018_V1.pdf.

[52] JSNS^2 collaboration, *Technical Design Report (TDR): Searching for a Sterile Neutrino at J-PARC MLF (E56, JSNS2)*, *arXiv preprint* (2017) [1705.08629].

[53] *Measuring inelastic charged- and neutral-current antineutrino-nucleus interactions with reactor neutrinos*, *Snowmass LOI* (2020) .

[54] L. M. Krauss, S. L. Glashow and D. N. Schramm, *Antineutrino astronomy and geophysics*, *Nature* **310** (1984) 191.