Snowmass2021 - Letter of Interest

Measuring Inelastic Charged- and Neutral-Current Antineutrino-Nucleus Interactions with Reactor Neutrinos

NF Topical Groups:

☐ (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
■ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
☐ (Other) *[Please specify frontier/topical group(s)]*

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Abstract: The intense flux of antineutrinos provided by a reactor make it an ideal environment to study low-energy inelastic charged- and neutral-current neutrino-nucleus interactions. Applications of these measurements include monitoring reactors, searching for sterile neutrinos, calibrating antineutrino detectors for other low-energy neutrino sources, as well as studying fundamental physics of neutrino-nucleus interactions. The first step toward designing an experiment to measure these processes is surveying candidate materials and detection schemes. There are few previous experimental attempts to measure these cross sections, and existing theoretical studies of charged- and neutral-current interactions on nuclei with reactor neutrinos are limited in scope. Taking advantage of increased computational power, improvements in detector technology, and new nuclear physics data, a modern study of candidate nuclei and detector schemes would provide the basis for designing detectors to measure these processes. Once target materials and detection technologies are chosen, detailed studies can be performed on the physics sensitivity of these detectors.

I. INTRODUCTION

There have been few experimental efforts to measure low-energy ($\lesssim$ 10 MeV) inelastic antineutrino-nucleus interactions [1–6]. The intense flux of antineutrinos produced at reactors provides an ideal source to study inelastic low-energy charged-current (CC) and neutral-current (NC) neutrino-nucleus interactions. Inelastic neutrino interactions are accompanied by emission of one or more particles (gammas, nucleons, etc.), providing unique experimental observables. Measurements of these interactions have applications in monitoring reactors, searching for sterile neutrinos, calibrating detectors from other low-energy neutrino sources, and studying the physics of neutrino-nucleus interactions.

Existing calculations of cross sections and detector signatures for low-energy CC and NC neutrino-nucleus scattering are limited in scope, reflecting knowledge and technology available at the time of publication [7, 8]. Advances in detector technology, computational power, and nuclear data motivate a reexamination of materials and schemes to measure these processes. A more complete modern study of candidate nuclei and detector schemes would provide a basis for more detailed studies with specific detector designs, backgrounds, and the physics that could be accomplished with a detector sensitive to these channels.

II. MOTIVATION

Monitoring reactors. The majority of existing reactor neutrino detectors rely on electron antineutrino CC interactions, in liquid or plastic scintillator, through inverse-beta decay on protons (IBD). IBD is a powerful tool for studying reactor neutrinos–the coincidence between the prompt positron and delayed neutron capture reduces backgrounds, and the 1.022 MeV signal from positron annihilation and MeV-scale signal from neutron-capture abate the need for low threshold detectors.

While IBD-based detectors are a mature technology, there are limitations. A significant portion of the reactor neutrino flux lies below the IBD threshold of 1.8 MeV (see calculations [9–12]). This threshold limits the ability of IBD technology to detect breeding blankets [13]. There are ongoing experimental efforts to access lower energy reactor neutrinos, such as neutrino-electron scattering [14], or coherent elastic neutrino-nucleus scattering (CEνNS) [15]. Inelastic neutrino-nucleus interactions provide another means to access reactor neutrinos below the IBD threshold, and can potentially benefit from background rejection through coincidence-schemes, for example, the emission of multiple gammas or timing coincidences between prompt signals and nuclear de-excitations or decays.

IBD detectors typically use liquid or plastic scintillator, which have low densities and small mass fractions of hydrogen. A detector utilizing inelastic neutrino-nucleus interactions can benefit from targets of higher density, leading to a more compact detector. An open problem is the identification of beta branches contributing to the reactor neutrino spectrum [16]; the improved energy resolution of inorganic scintillators compared to plastic and liquid scintillators could benefit this effort.

Reactor flux anomalies and sterile neutrinos. A deficit in the overall reactor neutrino flux is observed in IBD detectors compared to theoretical calculations. One explanation of this discrepancy is the existence of a sterile neutrino [17]. Inelastic neutrino-nucleus interactions provide an alternate channel to test this hypothesis, and have the additional benefit of potentially simultaneously measuring CC and NC interactions [18].

An excess in the reactor neutrino spectrum above $\sim$4 MeV has been observed by multiple IBD detectors [19–22]. There have been suggestions that this excess could be related to inelastic neutrino-nucleus scattering on the small amount of ^{13}C present in liquid and plastic scintillator in IBD detectors [23]. Neutrino-nucleus interactions could test this by measuring the reactor neutrino spectrum with a carbon-free detector.

Application for studying other neutrino sources. Low-energy neutrino CC and NC channels have been proposed for use in detecting solar [18, 24–27], supernova [8, 28, 29], and geoneutrinos [8]. Inelastic CC and NC interactions on nuclei potentially offer lower thresholds than commonly used channels, accessing lower energy neutrinos from these sources. For these proposals, measurements with reactor neutrinos would provide a calibration scheme [8].

An additional benefit of using low-energy CC neutrino-nucleus interactions for this purpose is the enhancement of the cross section near the Q-value as a result of resonant orbital electron capture (ROEC) [30]. Suggested for use in detecting geoneutrinos [8], this process has yet to be measured. The cross section for ROEC with different targets could be measured using reactor antineutrinos to test the benefits in using this process for measuring neutrinos from other sources.

Neutrino-nucleus interactions and nuclear physics. For specific NC targets, cross sections can be sensitive to the strange axial-vector form factor of the nucleon [31]. NC interactions can also test axial isoscalar neutral current interactions, which would lead to an increase in the cross sections [32]. Studying these effects for various candidate nuclei would help to quantify their sensitivities.

Comparing measurements of antineutrino-nucleus cross sections with theoretical predictions from Shell Model, Random Phase Approximation (RPA), and ab-initio approaches can test the validity of these calculations. This can provide an experimental test of techniques used to calculate matrix elements for neutrinoless double beta decay searches.

III. PREVIOUS STUDIES

Charged current reactions. The most thorough existing catalog of low-energy antineutrino CC reactions was published in 1984 [8]. While the focus of that study was geoneutrinos, the large overlap in the energies of geoneutrinos and reactor neutrinos make it a useful starting point. One limitation of that study is the focus on a radiochemical detection approach, which may be well suited for geoneutrinos but not necessarily ideal for reactor neutrinos. In addition to calculating cross sections for the reactor neutrino spectrum, an updated study would look at additional targets, using new nuclear physics data, and considering a variety of detection schemes.

Neutral current reactions. A detailed catalog of NC cross sections at reactor neutrino energies was published in 1978, containing cross sections and predicted experimental signatures for 23 isotopes [7]. The limitations of this survey are the focus on NC excitations above $\sim$600 keV, citing growing backgrounds at lower energies, as well as the restriction to targets with A $<$ 100, due to the lack of available experimental data at the time. The use of recent nuclear data, as well as advanced computational power to generate predictions when no data is available, would extend a modern study of NC cross sections to additional targets. Improvements in reducing detector backgrounds make it worthwhile to extend this search to signatures lower than 600 keV. This initial survey was the foundation for more detailed studies with specific targets, including ^{6}Li [18, 33–35], ^{7}Li [34–39], ^{9}B/^{10}B [40], ^{19}F [37], ^{23}Na [35].

Experimental efforts. There have been limited experimental efforts to measure inelastic neutrino-nucleus cross sections with reactor neutrinos. For both CC and NC processes, the heaviest nuclei for which measurements have been made using reactor neutrinos is ^{2}H [2–5]. Other efforts have attempted to measure CC interactions on ^{37}Cl [1], and CC and NC interactions on ^{73}Ge [6] and ^{133}Cs/^{127}I [41]. With modern advances, there is potential to make the first measurements of these processes with heavier targets, an important first step toward future applications.

IV. IMPROVEMENTS OF A MODERN STUDY

Improvements in detector technology. Since initial studies of the 1970s/1980s, detector technology has improved significantly. This includes reducing backgrounds by eliminating impurities and radioactive components in detectors (for example, [42, 43]) and improving tracking capabilities of low-energy particles with time-projection chambers (for example [44]). Commercial production of new scintillators such as CeBr$_3$ has also made the use of certain isotopes more viable. Recent work dissolving targets in liquid scintillator [45, 46] or using thin sheets of passive material [47] can extend the list of candidate materials beyond what was previously considered, potentially including radioactive isotopes at targets [48].

Improvements in measurements and calculations of nuclear matrix elements. Pioneering work in the 1980s has furthered the capability to experimentally measure Gamow-Teller strength distributions through (p,n) and (n,p) scattering [49, 50], and more recently through (^{3}He,t) and (t,^{3}He) scattering [51]. Understanding these strength distributions are important for evaluating CC cross sections for neutrino-nucleus scattering, as well as population of excited states from these interactions. Similarly, experimental measures of M1 strength distributions through (p,p'), $(n,n'\gamma)$, or $(\vec{\gamma},\gamma)$ [52] scattering provide information on the nuclear response to NC interactions. Where experimental data is not available, Shell Model, RPA, or ab-initio calculations can be used to predict these strengths, taking advantage of modern computational power.

Improvements in computational power and simulation. Modern computational power exceeds what was available at the time of previous studies, improving theoretical predictions, detector simulations, and data analysis. Machine learning approaches have been employed for rejecting backgrounds in dark matter experiments [53], and could be utilized to identify unique signatures from low-energy inelastic neutrino-nucleus reactions. Additionally, open source software MARLEY enables calculations of cross sections and nuclear responses, provided experimental nuclear physics data exists or can be calculated [54, 55].

V. CONCLUSION

Offering lower thresholds, increased densities, and improved energy resolution, detectors based on inelastic neutrino-nucleus scattering provide a complementary channel to existing reactor neutrino detectors, and have a variety of other applications. There is limited past experimental effort toward measuring these processes, and previous calculations of targets and observables are limited in scope. Advances in detector technology, computational power, and nuclear data have made it worthwhile to revisit materials and detection schemes that could be used to study these processes, as the first step toward designing a detector to measure them. A modern study would provide a basis for more detailed calculations of specific detection schemes, detector designs, backgrounds, and physics sensitivities.

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[1] R. Davis, Attempt to Detect Antineutrinos from a Nuclear Reactor by the Cl^{37}(v,e)A^{37} Reaction, Physical Review **97**, 766 (1955).

[2] T. L. Jenkins, F. E. Kinard, and F. Reines, Electron Antineutrino Interaction With Deuterons, Physical Review **185**, 1599 (1969).

[3] E. Pasierb, H. S. Gurr, J. Lathrop, F. Reines, and H. W. Sobel, Detection of Weak Neutral Current Using Fission ν_e on Deuterons, Physical Review Letters **4**, 96 (1979).

[4] G. S. Vidyakin and V. N. Vyrodov, Observation of a weak charged current in the interaction of reactor antineutrinos with a deuteron, JETP Sov. Phys. **49**, 130 (1988).

[5] G. S. Vidyakin and I. I. Vyrodov, Observation of weak neutral current in interaction of fission antineutrinos with deuterons, JETP Sov. Phys. **51**, 245 (1990).

[6] H. Y. Liao, Production and decay of the ^{73}Ge*(1/2-) metastable state in a low-background germanium detector, Journal of Physics G: Nuclear and Particle Physics **35**, 077001 (2008).

[7] H. C. Lee, Neutral current and the nuclear scattering of reactor antineutrinos, Nuclear Physics, Section A **294**, 473 (1978).

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

[9] F. T. Avignone and Z. D. Greenwood, Calculated spectra of antineutrinos from the fission products of ^{235}U, ^{238}U, and ^{239}Pu, and antineutrino-induced reactions, Phys. Rev. C **22**, 594 (1980).

[10] T. A. Mueller *et al.*, Improved predictions of reactor antineutrino spectra, Phys. Rev. C **83**, 054615 (2011).

[11] A. C. Hayes and P. Vogel, Reactor neutrino spectra, Annual Review of Nuclear and Particle Science **66**, 219 (2016).

[12] X. Qian and J.-C. Peng, Physics with reactor neutrinos, Reports on Progress in Physics **82**, 036201 (2019).

[13] B. K. Cogswell and P. Huber, Detection of breeding blankets using antineutrinos, Science & Global Security **24**, 114 (2016).

[14] M. Askins *et al.* (WATCHMAN Collaboration), The Physics and Nuclear Nonproliferation Goals of WATCHMAN: A WAter CHerenkov Monitor for ANtineutrinos (2015), 1502.01132.

[15] *Proceedings of The Magnificent CEνNS Workshop 2018* (Zenodo, 2019) Available on arXiv: https://arxiv.org/abs/1910.07450.

[16] A. A. Sonzogni, M. Nino, and E. A. McCutchan, Revealing fine structure in the antineutrino spectra from a nuclear reactor, Phys. Rev. C **98**, 014323 (2018).

[17] J. M. Berryman and P. Huber, Reevaluating reactor antineutrino anomalies with updated flux predictions, Phys. Rev. D **101**, 015008 (2020).

[18] N. B. Shul'gina and B. V. Danilin, Charged- and neutral-current disintegration of the ^{6}Li nucleus by solar neutrino and reactor antineutrino, Nuclear Physics, Section A **554**, 137 (1993).

[19] Y. J. Ko *et al.*, Sterile neutrino search at the NEOS experiment, Phys. Rev. Lett. **118**, 121802 (2017).

[20] G. Bak *et al.* (RENO Collaboration), Measurement of reactor antineutrino oscillation amplitude and frequency at RENO, Phys. Rev. Lett. **121**, 201801 (2018).

[21] H. de Kerret *et al.* (The Double Chooz Collaboration), Nature Physics **16**, 558 (2020).

[22] D. Adey *et al.* (Daya Bay Collaboration), Extraction of the ^{235}U and ^{239}Pu antineutrino spectra at daya bay, Phys. Rev. Lett. **123**, 111801 (2019).

[23] J. M. Berryman, V. Brdar, and P. Huber, Particle physics origin of the 5 MeV bump in the reactor antineutrino spectrum?, Physical Review D **99**, 55045 (2019).

[24] Q. R. Ahmad *et al.* (SNO Collaboration), Direct evidence for neutrino flavor transformation from neutral-current interactions in the sudbury neutrino observatory, Phys. Rev. Lett. **89**, 011301 (2002).

[25] T. Kovacs *et al.*, Borex: Solar neutrino experiment via weak neutral and charged currents in boron-11, Solar Physics **128**, 61–65 (1990).

[26] C. Grieb and R. S. Raghavan, Probing the temperature profile of energy production in the sun, Phys. Rev. Lett. **98**, 141102 (2007).

[27] D. McKinsey and K. Coakley, Neutrino detection with CLEAN, Astroparticle Physics **22**, 355 (2005).

[28] C. A. Duba *et al.*, HALO: The helium and lead observatory for supernova neutrinos, Journal of Physics: Conference Series **136**, 042077 (2008).

[29] R. N. Boyd and A. S. J. Murphy, Omnis, the observatory for multiflavor neutrinos from supernovae, AIP Conference Proceedings **533**, 132 (2000), https://aip.scitation.org/doi/pdf/10.1063/1.1361735.

[30] L. A. Mikaelyan, B. G. Tsinoev, and A. A. Bereyai, Induced capture of orbital electron, Soviet J. nucl. Phys. **6**, 254 (1968).

[31] T. Suzuki, Y. Kohyama, and K. Yazaki, Study of the isoscalar weak neutral current by inelastic ν scattering from ^{12}C and ^{10}B, Physics Letters B **252**, 323 (1990).

[32] J. Bernabéu, T. E. Ericson, E. Hernández, and J. Ros, Effects of the axial isoscalar neutral-current for solar neutrino detection, Nuclear Physics, Section B **378**, 131 (1992).

[33] T. W. Donnelly and R. D. Peccei, Neutral current effects in nuclei, Physics Reports **50**, 1 (1979).

[34] J. Bernabeu, Elementary particle approach to neutral current processes in nuclei, Nuclear Physics A **324**, 365 (1979).

[35] L. M. Sehgal, Neutral currents, theory and application, Progress in Particle and Nuclear Physics **14**, 1 (1985).

[36] S. S. Gershtein, N. V. Hieu, and R. A. Eramzhyan, Possibility of observing neutral currents in neutrino experiments, JETP Sov. Phys. **16**, 1097 (1963).

[37] T. W. Donnelly, D. Hitlin, M. Schwartz, J. D. Walecka, and S. J. Wiesner, Nuclear excitation by neutral weak currents, Physics Letters B **49**, 8 (1974).

[38] F. T. Avignone and T. W. Donnelly, A computer study of the experimental feasibility of observing the nuclear excitation of ^{7}Li by reactor antineutrinos, Nuclear Instruments and Methods **179**, 163 (1981).

[39] J. Bernabeu, Neutral currents in atomic and nuclear physics, Nuclear Physics A **518**, 317 (1990).

[40] H. T. Wong and J. Li, A Pilot Experiment with Reactor Neutrinos in Taiwan, Recent advances and cross-century outlooks in physics. Proceedings, Conference, Atlanta, USA, March 18-20, 1999 , 136 (1998).

[41] H. T. Wong *et al.*, Prospects of scintillating crystal detector in low-energy low-background experiments, Astroparticle Physics **14**, 141 (2000).

[42] J. Amaré *et al.*, Analysis of backgrounds for the ANAIS-112 dark matter experiment, The European Physical Journal C **79**, 412 (2019).

[43] S. I. Alvis *et al.* (Majorana Collaboration), Search for neutrinoless double-β decay in $^{76}\mathrm{Ge}$ with 26 kg yr of exposure from the Majorana Demonstrator, Phys. Rev. C **100**, 025501 (2019).

[44] N. Phan *et al.*, GEM-based TPC with CCD imaging for directional dark matter detection, Astroparticle Physics **84**, 82 (2016).

[45] R. S. Raghavan (The LENS Collaboration), LENS, MiniLENS—status and outlook, J. Phys.: Conf. Ser. **120**, 052014 (2008).

[46] D. Bergeron, H. Mumm, M. Tyra, J. La Rosa, S. Nour, and T. Langford, Optimum lithium loading of a liquid scintillator for neutron and neutrino detection, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **953**, 163126 (2020).

[47] F. Piquemal, The SuperNEMO project, Physics of Atomic Nuclei **69**, 10.1134/S1063778806120131 (2006).

[48] A. G. Cocco, G. Mangano, and M. Messina, Low energy antineutrino detection using neutrino capture on electron capture decaying nuclei, Phys. Rev. D **79**, 053009 (2009).

[49] T. Taddeucci and othersr, The (p, n) reaction as a probe of beta decay strength, Nuclear Physics A **469**, 125 (1987).

[50] K. Jackson *et al.*, The (n, p) reaction as a probe of gamow-teller strength, Physics Letters B **201**, 25 (1988).

[51] G. Perdikakis *et al.*, Gamow-teller unit cross sections for (t,^{3}He) and (^{3}He,t) reactions, Phys. Rev. C **83**, 054614 (2011).

[52] J. Birkhan *et al.*, Electromagnetic $M1$ transition strengths from inelastic proton scattering: The cases of $^{48}\mathrm{Ca}$ and $^{208}\mathrm{Pb}$, Phys. Rev. C **93**, 041302 (2016).

[53] J. Renner *et al.*, Background rejection in NEXT using deep neural networks, Journal of Instrumentation **12** (01), T01004.

[54] S. Gardiner, *Nuclear Effects in Neutrino Detection*, Ph.D. thesis, University of California, Davis (2018).

[55] Low-energy inelastic neutrino cross sections, Snowmass LOI (2020).