Snowmass2021 - Letter of Interest

Prediction and Measurement of the Reactor Neutrino Flux and Spectrum

Neutrino Frontier Topical Groups:
(NF02) Sterile neutrinos
(NF03) Beyond the Standard Model
(NF07) Applications
(NF08/TF11) Theory of Neutrino Physics
(NF09) Artificial neutrino sources

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Abstract:

Nuclear reactors are essentially-pure sources of electron antineutrinos from the beta-decay of fission daughters. The intense, well-localized, controllable nature of these man-made neutrino sources has meant that they have played a central role in developing our current understanding of neutrinos. This will likely remain true as we continue into an age of precision measurement of neutrino properties. Nonetheless, the reactor neutrino spectrum is complicated, stemming from thousands of individual branches, and our current predictions are imperfect. Unlocking the full scientific potential of reactor neutrinos requires improving our current predictive capabilities. Here we outline the potential impacts of an improved understanding of the spectrum and the significant questions that must be answered. This program of scientific investigation cuts across multiple sponsor organizations (e.g. DOE Basic Energy Sciences, Nuclear Physics, High Energy Physics, NNSA Defense Nuclear Nonproliferation, etc..) and highlights the need for close coordination and mutual support between stakeholders.

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Scientific Motivation

A detailed understanding of reactor antineutrino fluxes and energy spectra significantly impacts a broad array of scientific and technological questions. These range from addressing fundamental questions about the nature of neutrinos to enabling precision tests of the Standard Model. Specific high-impact scientific goals include:

HEP Science Drivers

- Performing neutrino-based precision BSM searches at reactors (G1)
- Probing the existence of sterile neutrinos with reactor-based experiments (G2)
- Enabling precision CEvNS-based physics measurements at reactors (G3)
- Enabling an unambiguous reactor-based neutrino mass hierarchy measurement (G4)

Nuclear Science and Application Drivers

- Enabling nuclear reactor monitoring using $\overline{\nu}_e$ detectors (G5)
- Advancing nuclear databases and calculations used for nuclear science and nuclear energy (G6)

Required Enabling Capabilities

Achievement of these scientific goals will require the resolution of outstanding problems in reactor neutrino physics and the development of a more precise fundamental understanding of reactor antineutrino production. These essential enabling capabilities include:

- Generating precise data-driven and theory-based flux and spectrum models for all fission isotopes
- Resolving flux discrepancies between reactor antineutrino predictions and measurements
- Resolving spectral discrepancies between LEU antineutrino predictions and measurements

Specific Approaches to Address Modeling and Measurement Needs

A research program achieving all of these science goals and enabling capabilities will require effort from diverse scientific communities both within and beyond the Snowmass-focused field of high energy physics as well as effective coordination between organizations [1]. These research thrusts include measurements, data analysis, and data organization tasks to be performed primarily by neutrino experimentalists, new nuclear data and nuclear structure measurements to be performed primarily by nuclear experimentalists, and model development to be performed primarily by nuclear theorists and reactor modelling experts. These activities will require close collaboration and coordination between differing expert communities. Each research topic outlined below is also linked to the physics goal it enables.

Neutrino Measurements

- Through additional data analysis, improve precision of neutrino spectrum measurements in existing HEU and LEU experiments [2–5]. (G1, G2, G3)
- Precisely measure neutrino flux above 7 MeV with current and future experiments [6]. (G5)
- Perform new or improved flux measurements at LEU and HEU reactors [7–9]. (G1, G2, G3, G5)
- Perform new reactor $\overline{\nu}_e$ spectrum measurements at multiple reactor facilities with differing fuel compositions. In particular, systematics-correlated measurements between different reactors, or measurement at Pu-burning or fast reactors [10]. (G1, G2, G3, G5, G6)
- Perform improved analysis of flux and spectrum dependence on fission fractions with data from individual experiments (i.e. evolution analyses) [11–13]. (G4, G5)
- Perform a high-statistics, high-resolution (%-level) spectrum measurement [14]. (G4, G6)
- Perform joint analyses of data from experiments with differing fission fractions (All)
- Pursue reactor-based CEvNS measurements with existing technology, as well as R&D and measurements with next-generation low-threshold technology [15–17]. (G3, G5)
- Establish databases with standard data format and accompanying meta-data to share experimental and theoretical data for reliable data-data and data-model comparisons (All)

Nuclear Physics Measurements

- Continue re-evaluation of pandemonium-affected beta feeding measurements for isotopes with significant contributions to the antineutrino spectrum at high energies [18–27] (G6)
- Measure beta spectrum shape for forbidden decays providing out-sized contribution to the antineutrino spectrum at high energies [28]. (G6)
- Modern measurements of integral beta spectra from the three primary fission isotopes ^{235}U, ^{239}Pu, and ^{241}Pu. (All)

Theory and Modelling Improvements

- Re-evaluate experimental inputs, calibrations, and uncertainties in the thermal fission beta spectrum measurements of the 1980's [29] (G1, G2)
- Continual updates in *ab initio* and conversion predictions via incorporation of up-to-date nuclear data measurements/improvements, which enables improved data/model comparisons [30, 31] (All)
- Extension of 'reference' *ab initio* calculations below the 1.8 MeV IBD threshold [32] (G1, G3, G5)
- For diverse reactor designs, develop reactor simulations for robust modelling of fuel content evolution, non-linear or non-equilibrium $\overline{\nu}_e$ production, and $\overline{\nu}_e$ production by non-fuel isotopes [33–35]. (G1, G2, G3, G5)
- Improve uncertainty treatment in *ab initio* calculations (properly treat correlations) and conversion calculations (properly treat forbidden decay contribution uncertainties) [36, 37]. (G1, G2, G6)

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Popov,[85] P. Poussot,[57] W. Pratumwan,[84] E. Previtali,[66] F. Qi,[20] M. Qi,[51] S. Qian,[20] X. H. Qian,[20] H. Qiao,[108] Z. H. Qin,[20] S. K. Qiu,[101] M. Rajput,[58] G. Ranucci,[61] N. Raper,[24] A. Re,[61] H. Rebber,[96] A. Rebii,[71] B. Ren,[76] J. Ren,[38] T. Rezinko,[34] B. Ricci,[65] M. Robens,[94] M. Roche,[71] N. Rodphai,[62] A. Romani,[81] B. Roskovec,[28] C. Roth,[94] X. Ruan,[90] X. Ruan,[38] S. Rujirawat,[84] A. Rybnikov,[34] A. Sadovsky,[34]

P. Saggese,[61] G. Salamanna,[68] S. Sanfilippo,[68] A. Sangka,[113] N. Sanguansak,[84] U. Sawangwit,[113]
J. Sawatzki,[112] F. Sawy,[72] M. Schever,[93,69] J. Schuler,[57] C. Schwab,[57] K. Schweizer,[112] D. Selivanov,[34]
A. Selyunin,[34] A. Serafini,[65] G. Settanta,[93] M. Settimo,[100] Z. Shao,[99] V. Sharov,[34] J. Shi,[20] V. Shutov,[34]
A. Sidorenkov,[86] F. Simkovic,[64] C. Sirignano,[72] J. Siripak,[84] M. Sisti,[66] M. Slupecki,[88] M. Smirnov,[24]
O. Smirnov,[34] T. Sogo-Bezerra,[100] J. Songwadhana,[84] B. Soonthornthum,[113] A. Sotnikov,[34] O. Sramek,[30]
W. Sreethawong,[84] A. Stahl,[69] L. Stanco,[67] K. Stankevich,[85] D. Stefanik,[64] H. Steiger,[112] J. Steinmann,[69]
T. Sterr,[70] M. R. Stock,[112] V. Strati,[65] A. Studenikin,[85] G. X. Sun,[20] S. F. Sun,[25] X. L. Sun,[20] Y. J. Sun,[29]
Y. Z. Sun,[20] N. Suwonjandee,[62] M. Szelezniak,[57] J. Tang,[24] Q. Tang,[24] Q. Tang,[101] X. Tang,[20]
A. Tietzsch,[70] I. Tkachev,[86] T. Tmej,[30] K. Treskov,[34] A. Triossi,[57] G. Troni,[56] W. Trzaska,[88] C. Tuve,[59]
N. Ushakov,[86] S. van Waasen,[94] J. Vanden Boom,[94] G. Vanroyen,[100] N. Vassilopoulos,[20] V. Vedin,[110]
G. Verde,[59] M. Vialkov,[85] B. Viaud,[100] C. Volpe,[63] V. Vorobel,[30] D. Voronin,[86] L. Votano,[109] P. Walker,[56]
C. Wang,[76] C. H. Wang,[21] E. Wang,[87] G. Wang,[91] J. Wang,[29] J. Wang,[24] K. Y. Wang,[20] L. Wang,[20]
M. F. Wang,[20] M. Wang,[39] M. Wang,[101] R. G. Wang,[20] S. G. Wang,[108] W. Wang,[51] W. Wang,[24]
W. S. Wang,[20] X. Wang,[53] X. Y. Wang,[24] Y. F. Wang,[20] Y. G. Wang,[74] Y. Wang,[77] Y. Wang,[89]
Y. F. Wang,[20] Y. Q. Wang,[77] Y. Wang,[51] Z. Wang,[77] Z. Wang,[20] Z. M. Wang,[20] Z. Y. Wang,[77] M. Waqas,[58]
A. Watcharangkool,[113] L. H. Wei,[20] W. Wei,[20] Y. D. Wei,[76] L. J. Wen,[20] C. Wiebusch,[69] S. C. F. Wong,[24]
B. Wonsak,[96] D. Wu,[20] F. L. Wu,[51] Q. Wu,[39] W. J. Wu,[74] Z. Wu,[20] M. Wurm,[83] J. Wurtz,[57] C. Wysotzki,[69]
Y. F. Xi,[105] D. M. Xia,[55] Y. G. Xie,[20] Z. Q. Xie,[20] Z. Z. Xing,[20] B. Xu,[77] C. Xu,[101] D. L. Xu,[102,97]
F. R. Xu,[95] H. K. Xu,[20] J. L. Xu,[20] J. Xu,[35] M. H. Xu,[20] Y. Xu,[46] Y. Xu,[93,69] B. J. Yan,[20] T. Yan,[84]
W. Q. Yan,[20] X. B. Yan,[20] Y. P. Yan,[84] A. B. Yang,[20] C. G. Yang,[20] H. Yang,[20] J. Yang,[87] L. Yang,[76]
X. Y. Yang,[20] Y. . Yang,[82] Y. F. Yang,[20] H. F. Yao,[20] Z. Yasin,[58] J. X. Ye,[20] M. Ye,[20] Z. P. Ye,[102]
U. Yegin,[94] F. Yermia,[100] P. H. Yi,[20] X. W. Yin,[20] Z. Y. You,[24] B. X. Yu,[20] C. Y. Yu,[76] C. X. Yu,[46]
H. Z. Yu,[24] M. Yu,[74] X. H. Yu,[46] Z. Y. Yu,[20] C. Z. Yuan,[20] Y. Yuan,[108] Z. X. Yuan,[77] Z. Y. Yuan,[74]
B. B. Yue,[24] N. Zafar,[58] A. Zambanini,[94] S. Zeng,[20] T. X. Zeng,[20] Y. D. Zeng,[24] L. Zhan,[20] F. Y. Zhang,[97]
G. Q. Zhang,[20] H. Q. Zhang,[20] H. H. Zhang,[24] J. W. Zhang,[20] J. Zhang,[20] J. B. Zhang,[91] J. Zhang,[20]
P. Zhang,[20] Q. M. Zhang,[99] S. Zhang,[24] S. Zhang,[24] T. Zhang,[97] X. M. Zhang,[20] X. T. Zhang,[20]
Y. Zhang,[20] Y. H. Zhang,[20] Y. Y. Zhang,[20] Y. P. Zhang,[20] Y. Y. Zhang,[97] Y. M. Zhang,[24] Z. Y. Zhang,[74]
Z. J. Zhang,[76] F. Y. Zhao,[78] J. Zhao,[20] R. Zhao,[24] S. J. Zhao,[87] T. C. Zhao,[20] D. Q. Zheng,[95] H. Zheng,[76]
M. S. Zheng,[38] Y. H. Zheng,[103] W. R. Zhong,[95] J. Zhou,[38] L. Zhou,[20] N. Zhou,[29] S. Zhou,[20]
X. Zhou,[74] J. Zhu,[24] K. J. Zhu,[20] B. Zhuang,[20] H. L. Zhuang,[20] L. Zong,[77] and J. H. Zou[20]
(The JUNO Collaboration)

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(on behalf of The MTAS Collaboration)

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Y. D. Kim,[116,119,121] Y. J. Ko,[116] H. M. Lee,[115] M. H. Lee,[116,121] J. Lee,[116] C. S. Moon,[118] Y. M. Oh,[116]
H. K. Park,[122] K. S. Park,[116] S. H. Seo,[116] K. Siyeon,[117] G. M. Sun,[115] Y. S. Yoon,[123] and I. Yu[120]
(The NEOS Collaboration)

M. J. Borusinski,[124] R. Dorrill,[124] A. Druetzler,[124] J. Learned,[124] V. Li,[125] D. Markoff,[126]
J. Maricic,[124] S. Matsuno,[124] H. P. Mumm,[127] K. Nishimura,[124] A. Irani,[128] M. Pitt,[128]
C. Rasco,[129] B. Thibodeau,[128] G. Varner,[124] B. Vogelaar,[128] and T. Wright[128]
(The NuLat Collaboration)

M. Andriamirado,[33] A. B. Balantekin,[16] H. R. Band,[17] C. D. Bass,[130] D. E. Bergeron,[127] D. Berish,[42]
N. S. Bowden,[125] J. P. Brodsky,[125] C. D. Bryan,[131] R. Carr,[132] T. Classen,[125] A. J. Conant,[129] G. Deichert,[131]
M. V. Diwan,[18] M. J. Dolinski,[133] A. Erickson,[134] B. T. Foust,[17] J. K. Gaison,[17] A. Galindo-Uribarri,[114,135]

C. E. Gilbert,[114, 135] C. Grant,[136] B. T. Hackett,[114, 135] S. Hans,[18] A. B. Hansell,[42] K. M. Heeger,[17] D. E. Jaffe,[18] X. Ji,[18] D. C. Jones,[42] O. Kyzylova,[133] C. E. Lane,[133] T. J. Langford,[17] J. LaRosa,[127] B. R. Littlejohn,[33] X. Lu,[114, 135] J. Maricic,[124] M. P. Mendenhall,[125] A. M. Meyer,[124] R. Milincic,[124] I. Mitchell,[124] P. E. Mueller,[114] H. P. Mumm,[127] J. Napolitano,[42] C. Nave,[133] R. Neilson,[133] J. A. Nikkel,[17] D. Norcini,[17] S. Nour,[127] J. L. Palomino,[33] D. A. Pushin,[137] X. Qian,[18] E. Romero-Romero,[114, 135] R. Rosero,[18] P. T. Surukuchi,[17] M. A. Tyra,[127] R. L. Varner,[114] D. Venegas-Vargas,[114, 135] P. B. Weatherly,[133] C. White,[33] J. Wilhelmi,[17] A. Woolverton,[137] M. Yeh,[18] A. Zhang,[18] C. Zhang,[18] and X. Zhang[125]
(The PROSPECT Collaboration)

J. H. Choi,[138] H. I. Jang,[139] J. S. Jang,[140] S. H. Jeon,[120] K. K. Joo,[141] K. Ju,[142] D. E. Jung,[120] J. G. Kim,[120] J. H. Kim,[120] J. Y. Kim,[141] S. B. Kim,[120] S. Y. Kim,[143] W. Kim,[118] E. Kwon,[120] D. H. Lee,[120] H. G. Lee,[143] I. T. Lim,[141] D. H. Moon,[141] M. Y. Pac,[138] H. Seo,[143] J. W. Seo,[120] C. D. Shin,[141] B. S. Yang,[144] J. Yoo,[144, 142] S. G. Yoon,[142] I. S. Yeo,[141] and I. Yu[120]
(The RENO Collaboration)

C. Chang,[145] L. Bergé,[146] A. Broniatowski,[146] L. Dumoulin,[146] A. Giuliani,[146] M. Chapellier,[146] P. De Marcillac,[146] S. Marnieros,[146] E. Olivieri,[146] D. Poda,[146] M. Calvo,[147] J. Goupy,[147] A. Monfardini,[147] Q. Arnaud,[148] C. Augier,[148] J. Billard,[148] A. Cazes,[148] J. Colas,[148] J. Filippini,[148] J. Gascon,[148] M. De Jesus,[148] H. Lattaud,[148] A. Juillard,[148] T. Salagnac,[148] T. Soldner,[148] A. Lubashevskiy,[149] E. Yakushev,[149] S. Rozov,[149] J. Lamblin,[150] B. Mom,[150] A. Stutz,[150] J. A. Formaggio,[151] D. W. Mayer,[151] J. Johnston,[151] P. Harrington,[151] S. Heine,[151] V. Sibille,[151] R. Chen,[152] E. Figueroa-Feliciano,[152] H. Ziqing,[152] S. Hertel,[153] P. Patel,[153] D. Pinckney,[153] A. Serafin,[153] A. Shilcusky,[153] N. Decheine,[154] K. Palladino,[154] S. Weber,[155] and C. Hirjibehedin[155]
(The Ricochet Collaboration)

O. A. Akindele,[125] N. S. Bowden,[125] L. Carman,[125] T. Classen,[125] S. Dazeley,[125] M. Ford,[125] I. Jovanovic,[156] V. Li,[125] M. P. Mendenhall,[125] F. Sutanto,[156] N. Zaitseva,[125] and X. Zhang[125]
(The ROADSTR Near-Field Working Group)

W. Beaumont,[157] S. Binet,[158] I. Bolognino,[159] M. Bongrand,[159] J. Borg,[160] V. Buridon,[161] H. Chanal,[158] B. Coupé,[162] P. Crochet,[158] D. Cussans,[163] A. De Roeck,[157, 164] D. Durand,[161] M. Fallot,[159] D. Galbinski,[160] S. Gallego,[161] L. Giot,[159] B. Guillon,[161] D. Henaff,[159] S. Hayashida,[160] B. Hosseini,[160] S. Kalcheva,[162] G. Lehaut,[161] I. Michiels,[165] S. Monteil,[158] D. Newbold,[163, 166] N. Roy,[167] D. Ryckbosch,[165] H. Rejeb Sfar,[157] L. Simard,[167, 168] A. Vacheret,[160] G. Vandierendonck,[165] S. Van Dyck,[162] N. van Remortel,[157] S. Vercaemer,[157] M. Verstraeten,[157] B. Viaud,[159] A. Weber,[169, 166] M. Yeresko,[158] and and F. Yermia.[159]
(The SoLid Collaboration)

A. Bonhomme,[14, 170] C. Buck,[14] P. del Amo Sanchez,[171] I. El Atmani,[170] L. Labit,[171] J. Lamblin,[172] A. Letourneau,[170] D. Lhuillier,[170] M. Licciardi,[172] M. Lindner,[14] T. Materna,[170] H. Pessard,[171] R. Rogly,[170] V. Savu,[170] S. Schoppmann,[14] T. Soldner,[173] A. Stutz,[172] and M. Vialat[173]
(The STEREO Collaboration)

A. Algora,[174] A. Beloeuvre,[159] M. Estienne,[159] M. Fallot,[159] L. Giot,[159] R. Kean,[159] A. Porta,[159] and J. L. Tain[174]
(The Valencia-Nantes TAGS Collaboration)

I. Sidelnik

(on behalf of the vIOLETA Collaboration)

O. A. Akindele,[125] T. Anderson,[175] M. Askins,[176] Z. Bagdasarian,[176] A. Baldoni,[175] A. Barna,[177] T. Benson,[16] M. Bergevin,[125] A. Bernstein,[125] B. Birrittella,[16] S. Bogetic,[125] J. Boissevain,[178] J. Borusinki,[177] S. Boyd,[179] T. Brooks,[180] M. (Mat) Budsworth,[181] J. Burns,[181] M. Calle,[181] C. Camilo,[18] A. Carroll,[182] J. Coleman,[182] R. Collins,[182] C. Connor,[183] D. Cowen,[175] B. Crow,[177] J. Curry,[125] F. Dalnoki-Veress,[184, 185] D. Danielson,[186] S. Dazeley,[125] M. Diwan,[18] S. Dixon,[180] L. Drakopoulou,[187] A. Druetzler,[177] J. Duron,[177] S. Dye,[177] S. Fargher,[180] A. Fienberg,[175] V. Fischer,[188] R. Foster,[180] K. (Kat) Frankiewicz,[183] T. Gamble,[180] D. Gooding,[183] S. Gokhale,[18] C. Grant,[183] R. Gregorio,[180] J. Gribble,[181] J. Griskevich,[28] D. Hadley,[179] J. He,[188] K. Healey,[180] J. Hecla,[176] G. Holt,[182] C. Jabbari,[189, 190] K. Jewkes,[179] I. Jovanovic,[156] R. Kaiser,[191] M. Keenan,[175] P. Keener,[178] E. (Liz) Kneale,[180] V. Kudryavtsev,[180] P. Kunkle,[183] J. Learned,[177] V. Li,[125] P. Litchfield,[191] X. Ran Liu,[187] G. Lynch,[187] M. Malek,[180] J. Maricic,[177] P. Marr-Laundrie,[16] B. Masic,[187] C. Mauger,[178] N. McCauley,[182] C. Metelko,[182] R. Mills,[192] A. Mitra,[179] F. Muheim,[187] A. Mullen,[176] A. Murphy,[187] M. Needham,[187] E. Neights,[175] K. Nishimura,[177] K. Ogren,[156] G. Orebi Gann,[176] L. Oxborough,[16] S. Paling,[193] A. Papatyi,[194] B. Paulos,[16] T. Pershing,[188] L. Pickard,[188] S. Quillin,[181] R. Resoro,[18] B. Richards,[179] L. Sabarots,[16] A. Scarff,[180] Yan-Jie Schnellbach,[182] P. Scovell,[193] B. Seitz,[191] O. Shea,[187] V. Shebalin,[177] G. Smith,[187] M. Smy,[28] H. Song,[183] N. Spooner,[180] C. Stanton,[187] O. Stone,[180] F. Sutanto,[156] R. Svoboda,[188] S. Szoldos,[176] L. Thompson,[180] F. Thomson,[191] C. Toth,[193] M. Vagins,[28] R. (Rick) Van Berg,[178] G. Varner,[177] S. Ventura,[177] B. Walsh,[18] J. Webster,[187] M. Weiss,[175] D. Westphal,[125] M. Wetstein,[54] T. Wilson,[182] S. Wilson,[180] S. Wolcott,[16] M. Wright,[180] and M. Yeh[18]
(The WATCHMAN collaboration)

J. M. Berryman,[176, 195] J. I. Collar,[186] A. Erlandson,[196] S. Gariazzo,[197] M.V. Garzelli,[198] C. Giunti,[199] B. L. Goldblum,[176] A. Hayes,[200] S. Hedges,[1] C. Mariani,[3] D. Minic,[3] L.Miramonti,[201] X. Mougeot,[202] D. Naim,[203] J. Newby,[129] K. Ni,[204] T. O'Donnell,[3] S. Ozturk,[205] L. Périssé,[206] R. Pestes,[3, 18] A. A. Sonzogni,[207] Z. Tabrizi,[3] M. Vivier,[170] and K. Walkup[3]

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