Neutrino Scattering Measurements 10s of MeV and KDAR (236 MeV)

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Snowmass21 NF06 Low Energy Neutrino and Electron Scattering Workshop

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Introduction

- Review the status and plans for 10s of MeV inelastic neutrino-nucleus and KDAR neutrino-nucleus scattering programs
- Past measurements
- Facilities and current experiments
- Apologies to efforts that I failed to mention

Motivation

- Understanding of tens of MeV neutrino-nucleus interactions important for
  - Interpreting the detection of supernova burst neutrinos by future experiments (e.g. DUNE and HALO)
  - Supernova dynamics and nucleosynthesis
  - Solar neutrino measurements
  - Beyond standard model searches
  - Interpreting short-baseline oscillation experiments

Status

Total cross sections: 10% uncertainties

Often measurements with several hundred events

Main systematic uncertainty from meson production

TABLE VII Experimentally measured (flux-averaged) cross-sections on various nuclei at low energies (1-300 MeV). Experimental data gathered from the LAMPF (Willis *et al.*, 1980), KARMEN (Armbruster *et al.*, 1998; Bodmann *et al.*, 1991; Maschuw, 1998; Ruf, 2005; Zeitnitz *et al.*, 1994), E225 (Krakauer *et al.*, 1992), LSND (Athanassopoulos *et al.*, 1997; Auerbach *et al.*, 2002, 2001; Distel *et al.*, 2003), GALLEX (Hampel *et al.*, 1998), and SAGE (Abdurashitov *et al.*, 2006, 1999) experiments. Stopped π/μ beams can access neutrino energies below 53 MeV, while decay-in-flight measurements can extend up to 300 MeV. The ^{51}Cr sources have several mono-energetic lines around 430 keV and 750 keV, while the ^{37}Ar source has its main mono-energetic emission at E_ν = 811 keV. Selected comparisons to theoretical predictions, using different approaches are also listed. The theoretical predictions are not meant to be exhaustive.

Isotope	Reaction Channel	Source	Experiment	Measurement (10^{-42} cm^2)	Theory (10^{-42} cm^2)
^{2}H	^{2}H(ν_e, e^-)pp	Stopped π/μ	LAMPF	52 ± 18(tot)	54 (IA) (Tatara *et al.*, 1990)
^{12}C	^{12}C$(\nu_e, e^-)^{12}$N$_{g.s.}$	Stopped π/μ	KARMEN	9.1 ± 0.5(stat) ± 0.8(sys)	9.4 [Multipole](Donnelly and Peccei, 1979)
		Stopped π/μ	E225	10.5 ± 1.0(stat) ± 1.0(sys)	9.2 [EPT] (Fukugita *et al.*, 1988).
		Stopped π/μ	LSND	8.9 ± 0.3(stat) ± 0.9(sys)	8.9 [CRPA] (Kolbe *et al.*, 1999b)
	^{12}C$(\nu_e, e^-)^{12}$N*	Stopped π/μ	KARMEN	5.1 ± 0.6(stat) ± 0.5(sys)	5.4-5.6 [CRPA] (Kolbe *et al.*, 1999b)
		Stopped π/μ	E225	3.6 ± 2.0(tot)	4.1 [Shell] (Hayes and S, 2000)
		Stopped π/μ	LSND	4.3 ± 0.4(stat) ± 0.6(sys)	
	^{12}C$(\nu_\mu, \nu_\mu)^{12}$C*	Stopped π/μ	KARMEN	3.2 ± 0.5(stat) ± 0.4(sys)	2.8 [CRPA] (Kolbe *et al.*, 1999b)
	^{12}C$(\nu, \nu)^{12}$C*	Stopped π/μ	KARMEN	10.5 ± 1.0(stat) ± 0.9(sys)	10.5 [CRPA] (Kolbe *et al.*, 1999b)
	^{12}C(ν_μ, μ^-)X	Decay in Flight	LSND	1060 ± 30(stat) ± 180(sys)	1750-1780 [CRPA] (Kolbe *et al.*, 1999b)
					1380 [Shell] (Hayes and S, 2000)
					1115 [Green's Function] (Meucci *et al.*, 2004)
	^{12}C$(\nu_\mu, \mu^-)^{12}$N$_{g.s.}$	Decay in Flight	LSND	56 ± 8(stat) ± 10(sys)	68-73 [CRPA] (Kolbe *et al.*, 1999b)
					56 [Shell] (Hayes and S, 2000)
^{56}Fe	^{56}Fe$(\nu_e, e^-)^{56}$Co	Stopped π/μ	KARMEN	256 ± 108(stat) ± 43(sys)	264 [Shell] (Kolbe *et al.*, 1999a)
^{71}Ga	^{71}Ga$(\nu_e, e^-)^{71}$Ge	^{51}Cr source	GALLEX, ave.	0.0054 ± 0.0009(tot)	0.0058 [Shell] (Haxton, 1998)
		^{51}Cr	SAGE	0.0055 ± 0.0007(tot)	
		^{37}Ar source	SAGE	0.0055 ± 0.0006(tot)	0.0070 [Shell] (Bahcall, 1997)
^{127}I	^{127}I$(\nu_e, e^-)^{127}$Xe	Stopped π/μ	LSND	284 ± 91(stat) ± 25(sys)	210-310 [Quasi-particle] (Engel *et al.*, 1994)

Table from Formaggio, J. A., and G. P. Zeller. Rev. Mod. Phys. 84 (2012) https://doi.org/10.1103/RevModPhys.84.1307.

Pass measurements on Carbon

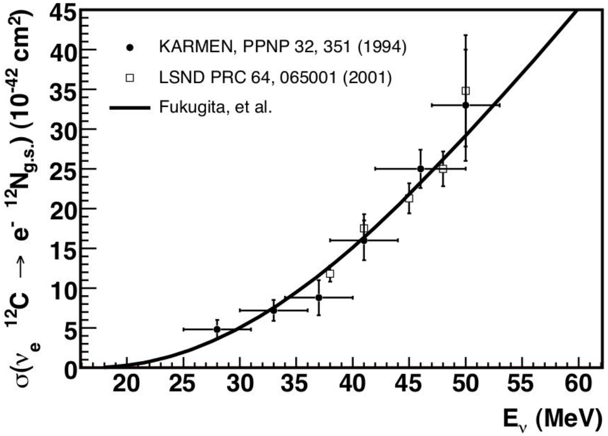


FIG. 6 Cross-section as a function of neutrino energy for the exclusive reaction $^{12}C(\nu_e, e^-)^{12}N$ from μ^- decay-at-rest neutrinos. Experimental data measured by the KARMEN (Zeitnitz *et al.*, 1994) and LSND (Athanassopoulos *et al.*, 1997; Auerbach *et al.*, 2001) experiments. Theoretical prediction taken from Fukugita *et al.* (Fukugita *et al.*, 1988).

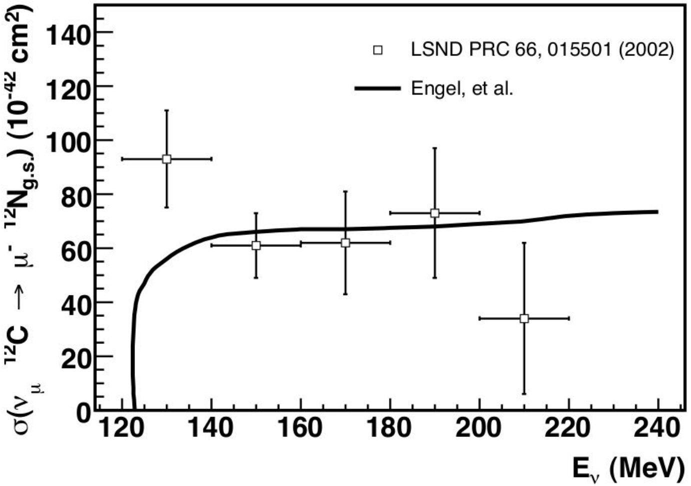
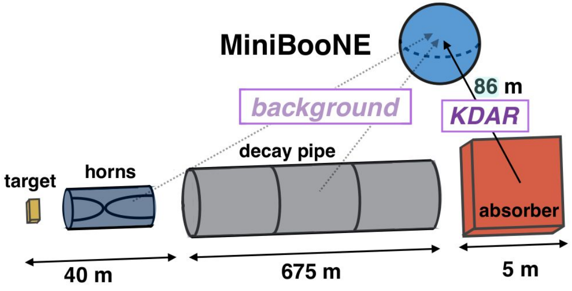


FIG. 7 Cross-section as a function of neutrino energy for the exclusive reaction $^{12}C(\nu_\mu, \mu^-)^{12}N$ measured by the LSND (Auerbach *et al.*, 2002) experiment. Theoretical prediction taken from (Engel *et al.*, 1996).

Figures from Formaggio, J. A., and G. P. Zeller. Rev. Mod. Phys. 84 (2012) https://doi.org/10.1103/RevModPhys.84.1307.

KDAR

Relatively recently, first measurement of mono-energetic neutrinos from KDAR by MiniBooNE



Measured total numu CC cross section to about ~30%

$\sigma = (2.7 \pm 0.9 \pm 0.8) \times 10^{-39}$ cm^2 /neutron.

Compared to NuWro[1] prediction:
$\sigma = 1.3 \times 10^{-39}$ cm^2 /neutron

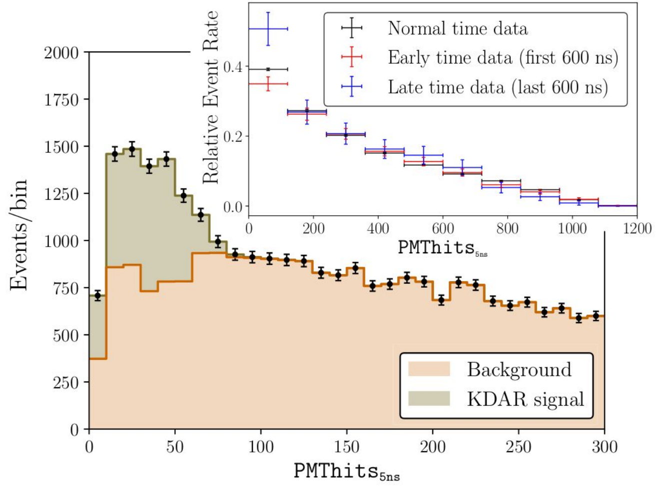


FIG. 2. The normal time data distribution (black points with error bars) with the best-fit signal template (green) stacked on the inferred background (orange). The inset shows the relative event rate for early time, late time, and normal time after normalizing the three distributions in the background-only region (PMThits$_{5ns}$>120). A deficit (excess) of KDAR-like events at early (late) times can be seen.

Figs. from MiniBooNE. PRL 120 **14** (2018)
https://doi.org/10.1103/PhysRevLett.120.141802.

[1] C. Juszczak, Acta Phys. Pol. B 40 2507 (2009);
T. Golan, C. Juszczak, and J. T. Sobczyk, Phys. Rev. C 86 015505

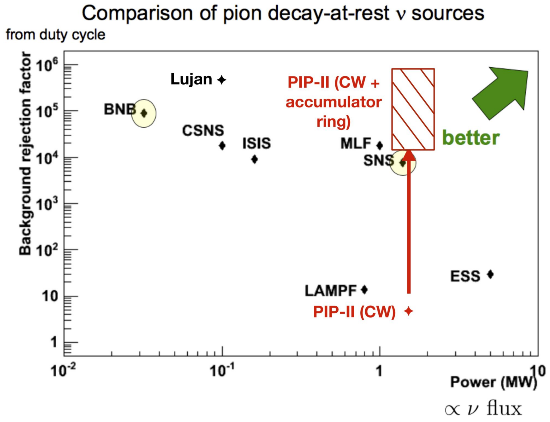
Facilities and Experiments to make further measurements

- Reactors
- IsoDAR/Daedalus
- Captain Mills @ Los Alamos Neutron Science Center (LANSC), LANL
- JSNS^2 @ Material Life Science Facility (MLF), J-PARC, Tokai, Japan
- SBN @ Fermilab, BNB and NUMI beam
- COHERENT @ Spallation Neutron Source (SNS), Oak Ridge National Lab

Sources often compared on two dimensions:

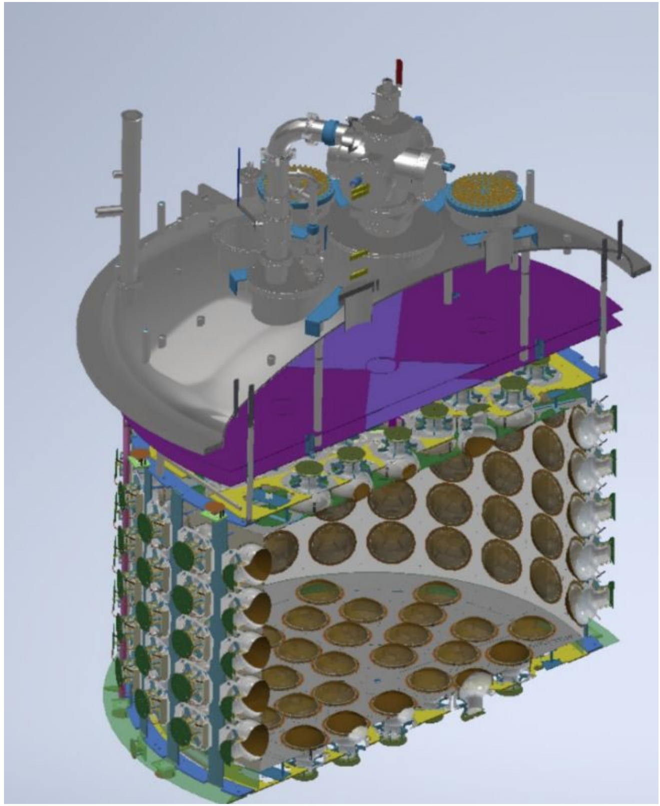
- Background rejection from duty cycle
- Power which is proportional to the neutrino flux

Other access might be proton energy, which determines amount of KDAR



LANSCE and CAPTAIN-Mills

- Los Alamos Neutron Science Center (LANSCE) operates an 800 MeV proton beam at its Lujan Center and produces a 100-kW stopped pion source
- Coherent CAPTAIN-Mills (CCM), a 10-ton detector which uses a liquid argon target instrumented with photomultiplier tubes
- CCM120 recently published search for dark matter [1]
- Could be used to measure inelastic events
- Improved detector, CCM200, with several upgrades, e.g. more PMTs and liquid filtration to improve light yield, running since Sept 2021 [2]



[1] CAPTAIN-Mills arXiv:2105.14020 (2021) http://arxiv.org/abs/2105.14020.
[2] E. Dunton. DPF2021. (2021)

CAPTAIN-Mills

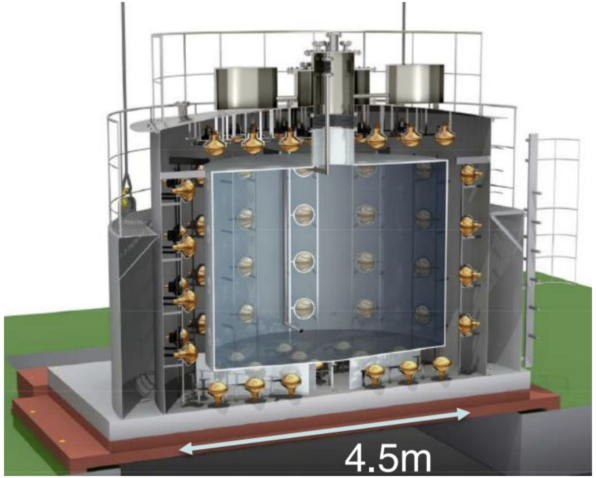
- Expect several hundred inelastic interactions per year

Reaction	L = 20 m (events/yr)	L = 40 m (events/yr)
Coherent ν_μ (E = 30 MeV)	2709	677
Coherent $\nu_e + \bar{\nu}_\mu$	9482	2370
Charged Current ν_e	257	64
Neutral Current ν_μ	36	18
Neutral Current $\bar{\nu}_\mu$	79	20

E. Dunton – Searching for Sterile Neutrinos with Coherent Captain Mills
Magnificent CEvNS 2019

JSNS^2 @ MLF

- J-PARC Materials and Life Science Experimental Facility (MLF) produces a 1 MW beam of 3 GeV protons
- JSNS^2 detector: 17 tonnes Gd-loaded Liquid Scintillator [1]
- Baseline: 24 m
- Aims to investigate LSND anomaly
- Can also measure reactions, e.g. C(nue,e-)N



[1] JSNS^2 Collaboration. NIM A (2021) https://doi.org/10.1016/j.nima.2021.165742.

KDAR with JSNS^2

- Estimated 30,000 and 60,000 (!) KDAR numu interactions will occur in the detector [1]
- Seen as two successive scintillation pulses from muon followed by michel electron
- Opportunity to make precision measurements

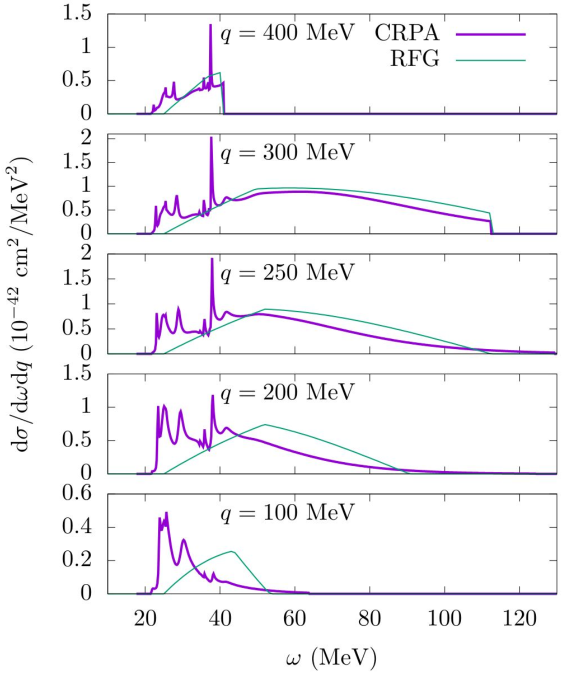
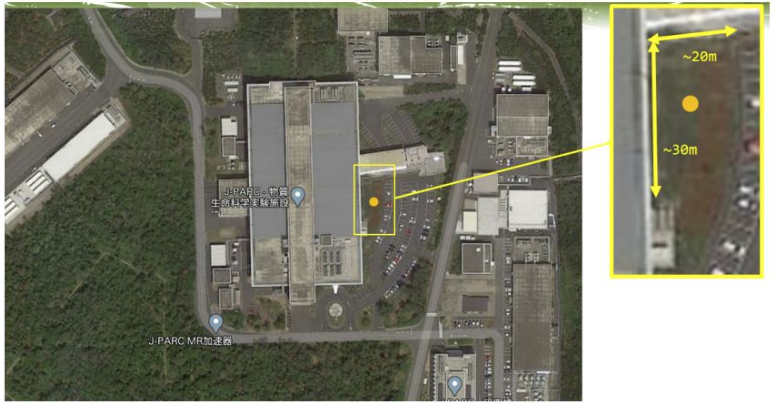


FIG. 2. Double differential cross section for the CC interaction of a 236-MeV ν_μ with carbon for different values of q.

[1] JSNS^2 Collaboration. arXiv:1705.08629 (2017). http://arxiv.org/abs/1705.08629
[2] Right-hand figure from Nikolakopoulos et al. Phys. Rev. C **103** 6 (2021): 064603. https://doi.org/10.1103/PhysRevC.103.064603.

JSNS^2-II

- Proposal to build a second 35 fiducial tonne detector [1]
- Located outside the MLF building with baseline of 48 m
- Received approval for 1st phase of 2-phase plan [2]

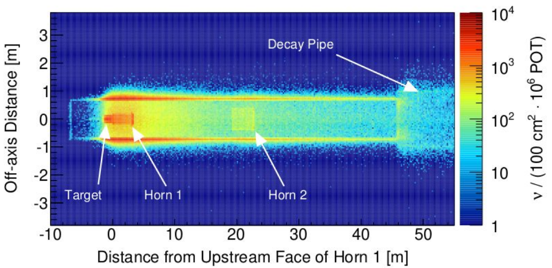


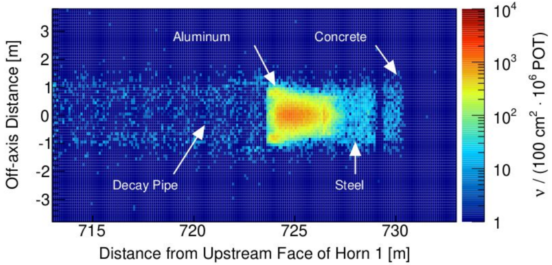
[1] JSNS2 Collab. arxiv:2012.10807 (2020) http://arxiv.org/abs/2012.10807.
[2] J. Park. WIN2021. Conference talk.

Fermilab

- FNAL's NuMI beam can provide a sizeable amount of DAR neutrinos
- Observable by nearby detectors: MiniBooNE and LArTPCs of the Short-Baseline Neutrino program (SBN)

Fermilab





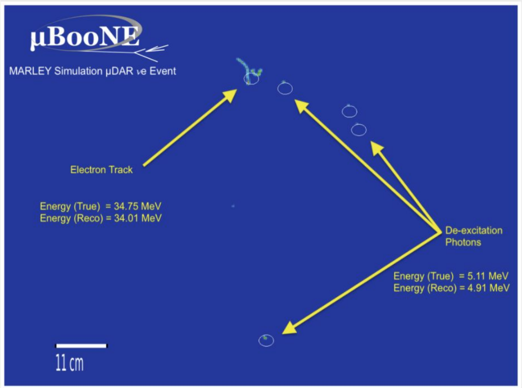
Location (x, y, z) [m]	LAr Mass [t]	CC ν_e	CC $\overline{\nu}_e$	NC ν_μ	NC $\overline{\nu}_\mu$	CC ν_μ (235.5 MeV)
$(15, 20, 0) \rightarrow$ 25 m from target	5.0	1.1×10^3	1.4	1.2×10^2	4.1×10^2	4.5×10^3
$(0, 40, 0) \rightarrow$ 40 m from target	5.0	4.9×10^2	0.6	5.0×10^1	1.8×10^2	2.0×10^3
$(15, -1, 753) \rightarrow$ 32 m from absorber	5.0	1.1×10^2	0.1	1.0×10^1	4.0×10^2	4.0×10^2
$(53, 76, 679) \rightarrow \mu$BooNE	60.4	1.8×10^2	0.3	1.9×10^1	6.5×10^1	6.9×10^2

- DAR neutrino interaction rate in existing detectors comparable to other experiments

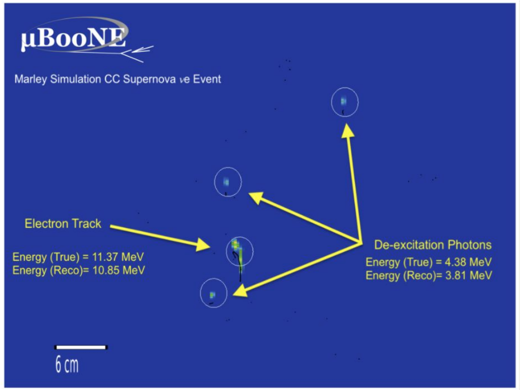
Table and Figures from Grant and Littlejohn. arXiv:1510.08431 (2016) http://arxiv.org/abs/1510.08431.

LArTPCs

- Measurement with LArTPC opportunity to measure lepton momentum, identify gammas
- Status of detectors
  - MicroBooNE: recently moved into dormant mode
  - ICARUS: taking physics data
  - SBND: still under construction with first fill sometime in 2022/early 2023
- For piDAR neutrinos, need to study if interaction can produce enough scintillation light to pass the PMT event trigger (necessary to keep data rate manageable)
- (Use convolutional neural nets [on GPU or FPGA] to implement online pattern-based trigger)



(a) μDAR event



(b) Supernova neutrino event

Figures from MicroBooNE public note 1076
https://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1076-PUB.pdf

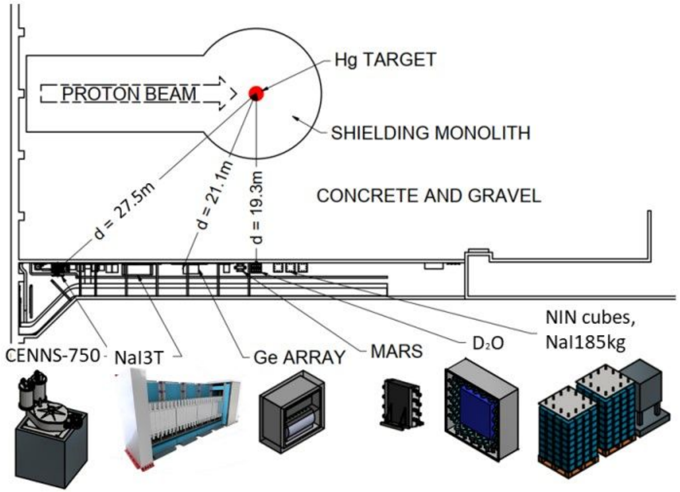
DAR neutrinos from PIP-II

- Protons for multi-MW DUNE beam supplied by PIP-II LINAC
- Continuous wave operation
- More ideal for DAR experiments if modifications can be made to bunch the protons
- Many physics opportunities, including inelastic measurements, with SBN detectors observing neutrinos from the beam dump station

https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF6_RF0-NF2_NF3-AF2_AF5-099.pdf

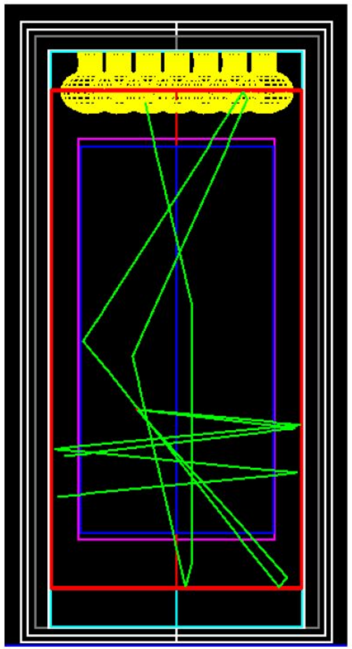
COHERENT @ Oak Ridge SNS

- Beam energy: 1 GeV
- Total power: 1.4 MW
- A collection of detector subsystems in "neutrino alley" with different nuclear targets observe DAR neutrinos
- First generation of detectors produced measurements. Starting to develop second generation.
- Targets for inelastic measurements -- current and proposed -- include Na, Pb, Fe, I, O, and Ar



COHERENT: D20 Target

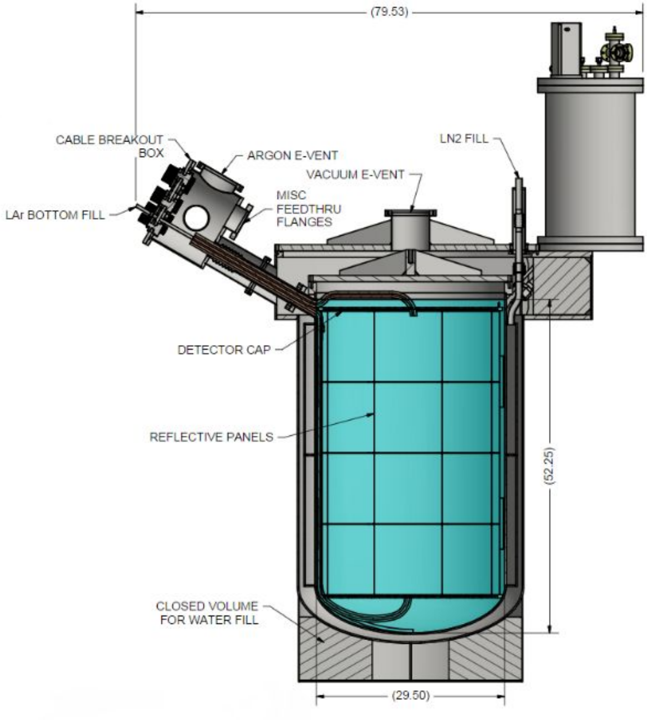
- Recently funded subsystem will consist of 592 kg D20 target [1]
- One goal is to provide measurement of the flux, reducing a major uncertainty in the measurements of all subsystems
- Goal is to reduce flux uncertainty to 5% stat in 2 years which approaches the ν_e + d cross section uncertainty



[1] COHERENT collaboration et al 2021 JINST 16 P08048. https://doi.org/10.1088/1748-0221/16/08/P08048.

COHERENT: COH-LAr-750

- A 10-kg LAr detector took data and published the first CEvNS measurement on Argon
- Next phase in LAr campaign is a proposed 750 kg single-phase liquid argon detector
- Expect about ~340 CC and ~100 NC events per year



LAr Detector Future R&D

- Investigating the possibility of incorporating detection of Cherenkov light
- Strategy is a dual-band detector where one set of sensors detects VUV scintillation, another set detects blue Cherenkov photons
- Goal is to provide electron kinematics data for modelers

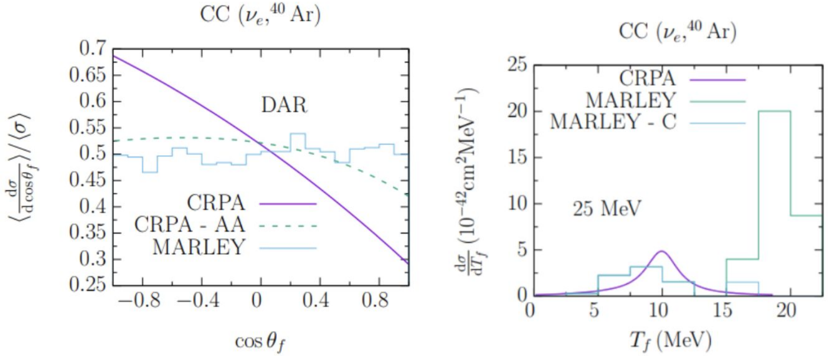
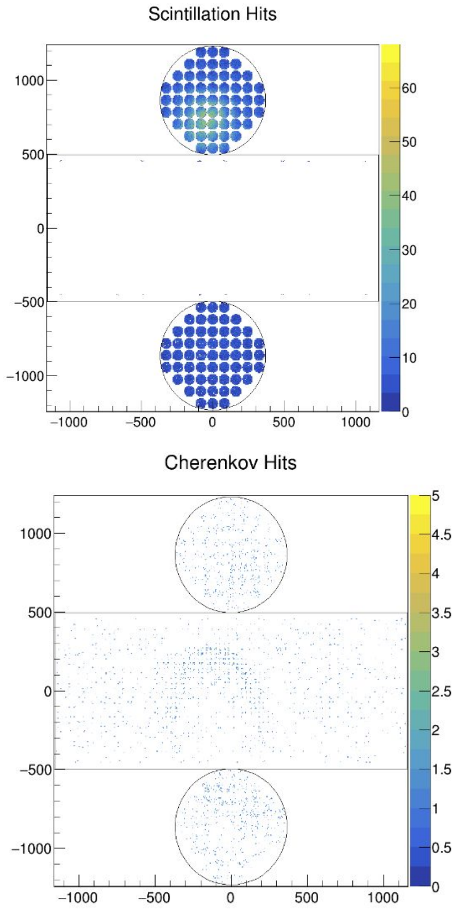


Fig. from Van Dessel et al. Phys. Rev. C **101** 4 (2020): 045502. https://doi.org/10.1103/PhysRevC.101.045502.

Simulated 20 MeV nue CC event



ORNL Beam Upgrade + Second Target Station

- ORNL is planning an upgrade to the current 1.4-MW beam.
- Proton Power Upgrade (PPU) project will double power to 2.8 MW, increase energy to 1.3 GeV
- Plan is also to build a second target station
- Preliminary studies suggest similar neutrino production from the STS as the FTS [1].
- New STS instrument hall could accomodate 10-ton-scale detectors with sufficient shielding and overburden.

Buildings highlighted in orange are the proposed STS hall

[1] R. Rapp. https://conference.sns.gov/event/171/attachments/258/1358/fpsts2019_rapp.pdf.

Summary

- Precision of existing measurements at 10s of MeV and for KDAR neutrinos between 10-50%
- Several facilities can host current and future experiments. By the next several years the community will hopefully have a handful of new measurements

Backups

Status

Reaction	Neutrino Source	Accuracy	Reference
$^{12}C(\nu_e,e^-)^{12}N_{g.s.}$	Accelerator ν	$\sim$10%	[22][23]
$^{12}C(\nu_e,e^-)^{12}N^*$	Accelerator ν	$\sim$15%	[22][23]
$^{12}C(\nu,\nu')^{12}C(1^+1)$	Accelerator ν	$\sim$20%	[22][23]
$^{13}C(\nu_e,e^-)^{13}N$	Accelerator ν	76%	[22]
$^{56}Fe(\nu_e,e^-)^{56}Ni$	Accelerator ν	37%	[22]
$^{71}Ga(\nu_e,e^-)^{71}Ge$	RI (^{51}Cr)	11%	[24][25]
$^{127}I(\nu_e,e^-)^{127}Xe$	Accelerator ν	33%	[26]

[22] R. Maschuw (KARMEN Collab.), Prog. Part. Nucl. Phys. 40, 183 (1998)
[23] L.B. Auerbach et al. (LSND Collab.), Phys. Rev. C64, 065501 (2001)
[24] J.N. Abdurashitov et al. (SAGE Collab.), Phys. Rev. C59, 2246 (1999)
[25] W. Hampel et al. (GALLEX Collab.), Phys. Lett. B420, 114 (1998);
F. Kaether et al. (GALLEX Collab.), Phys. Lett. B685, 47 (2010).
[26] J.R. Distel et al., Phys. Rev. C68, 054613 (2003)

COHERENT

The tonne-scale liquid argon (LAr) detector is expected to see ~340 veCC events per year, as 79 well as ~100 inelastic NC events. Another major unknown is the contribution of NC interactions

80 to the supernova burst yield in DUNE. An inclusive measurement in COHERENT's tonne-scale

81 LAr detector could be made to ~5% percent precision in three years.

Topics

- Status
    - Past measurements [done]
        - Review from papers
        - MiniBoonE KDAR
    - Current/future experiments
        - SBN
        - COHERENT: CsI, heavy water, LAr
        - CAPTAIN-MILLS: possible, CCM200
        - JSNS^2: KDAR events, C(nue,e)N possible
        - ISODAR:
    - Future, proposed
        - Differential cross section
        - Fermilab: possible

Hybrid crystals

https://iopscience.iop.org/article/10.1088/1361-6560/aa6a49

Cherenkov backgrounds

https://dataspace.princeton.edu/handle/88435/dsp01z316q436k

LSND Fact sheet

- The energy resolution was determined from the shape of the electron energy spectrum and was found to be 6.6% at the 52.8 MeV end point.
- The position and direction resolution obtained from the LSNDMC simulation are approximately 30 cm and 17°, respectively, for electrons in the energy region of interest, 16–35 MeV.
- From: https://journals.aps.org/prc/pdf/10.1103/PhysRevC.55.2078
- 500 events for measurement. Uncertainty in 10% range.

JSNS2 Fact sheet

- The energy resolution was determined from the shape of the electron energy spectrum and was found to be 6.6% at the 52.8 MeV end point.
- The position and direction resolution obtained from the LSNDMC simulation are approximately 30 cm and 17°, respectively, for electrons in the energy region of interest, 16–35 MeV.
- From: https://journals.aps.org/prc/pdf/10.1103/PhysRevC.55.2078

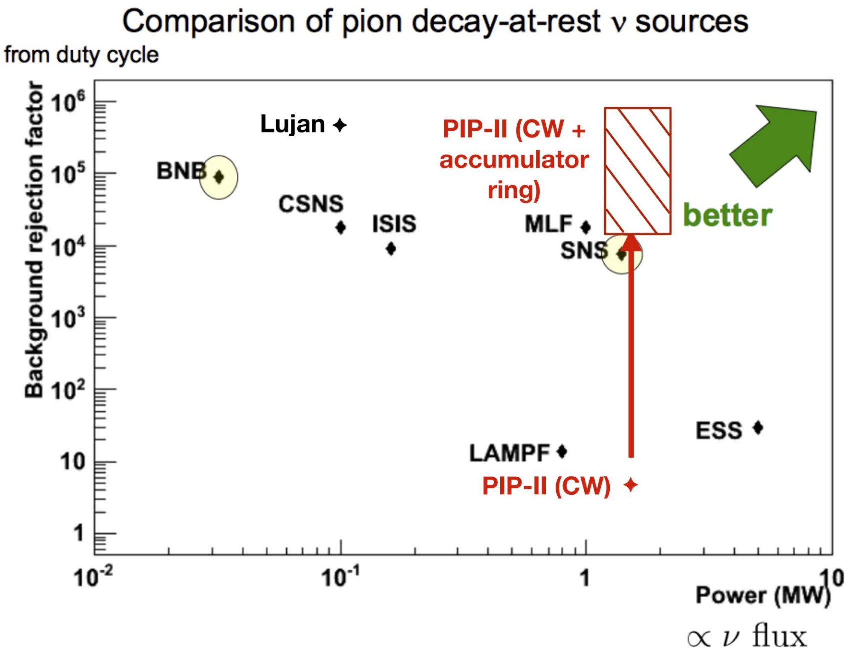
nue/numu cross section

- From
- At low energy, forward lepton angles, should expect numu cross section larger than nue cross section
- In this regime, momentum transfer q is actually proportional to lepton mass

PIP-II

Further improvements of the beam being explored.

One improvement is to better bunch the proton beam.



https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF6_RF0-NF2_NF3-AF2_AF5-099.pdf
https://indico.fnal.gov/event/44988/contributions/198373/attachments/135420/167922/Toups_NF3_Kickoff_Day2.pdf

Charge

Neutrino Scattering Measurements 10s of MeV and KDAR (236 MeV)

20m

Status and plans of worldwide 10s of MeV inelastic neutrino-nucleus and KDAR neutrino-nucleus scattering programs, needs of these measurements, how these measurements will help constrain low-energy neutrino-nucleus interaction physics for the worldwide neutrino program.

Questions to try and answer in my talk

- Main question how to improve current measurements
  - Stats or systematics limited?
  - Main source of uncertainty? I think the pion production
- How to improve? What to gain?
  - More stats, for fine grained differential measurements
  - Constraining the flux
  - Lepton angle