New Results on Low-Energy Inelastic Neutrino-Nucleus Scattering from COHERENT

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Fermilab Joint Experimental-Theory Physics Seminar

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Lawrence Livermore National Laboratory

COHERENT SNS

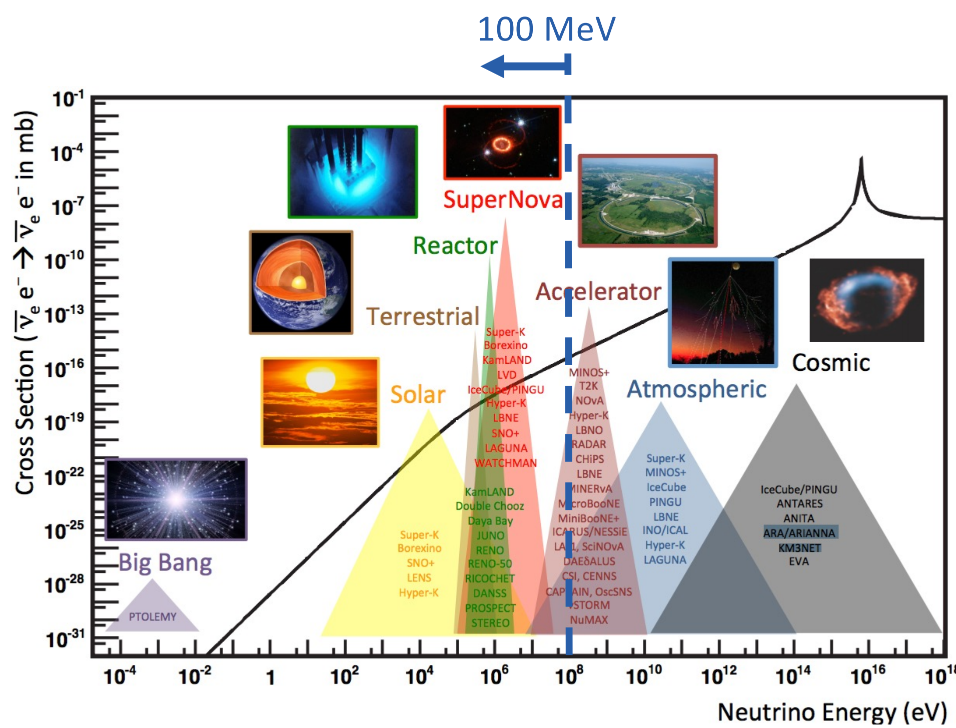
Outline

- Motivation for studying low energy neutrino-nucleus interactions
- The COHERENT collaboration & neutrino production at the SNS
- The lead neutrino cube—neutrino-induced neutrons on lead
- The NaIvE-185 detector—inclusive electron-neutrino charged-current measurement on ^{127}I
- Ongoing efforts and future inelastic COHERENT measurements

Motivation for Studying Low Energy Neutrino-Nucleus Interactions

Low-Energy Neutrino-Nucleus Interactions

- Many sources produce exclusively low energy (< 100 MeV) neutrinos
- Neutrinos reveal key information about processes generating them
  - Sources can be used to study fundamental properties of neutrino
  - Cross sections are small
- Typical detectors use large amounts of water, liquid or plastic scintillator
  - Rely on neutrino-electron scattering or inverse-β decay
- An alternate channel is neutrino-nucleus interactions
  - Larger cross sections, lower thresholds, denser targets, different detector technologies



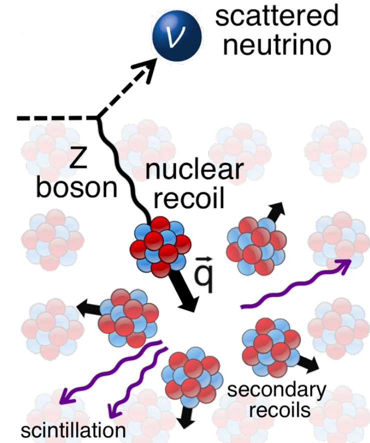
[A. de Gouvea, et al., arxiv:12104340 (2013)]
[J. A. Formaggio & G. P. Zeller, Rev. Mod. Phys **84** (2012)]

Neutrino-Nucleus Interactions

- Coherent elastic neutrino-nucleus scattering (**CEvNS**)
  - Mediated by Z^0
  - Large cross section ($\propto N^2$), ~threshold-less
  - Nucleus in same state before & after interaction (no particles emitted)
    - Only signature is low-energy nuclear recoil
  - Momentum transfer comparable to size of nucleus

$$qR \leq 1$$

CEvNS:



[D. Akimov, et al., Science 357 (2017)]

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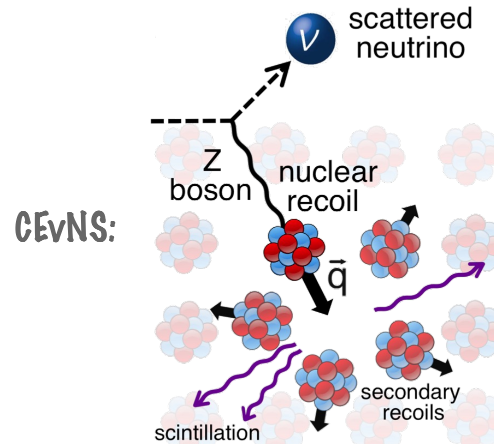
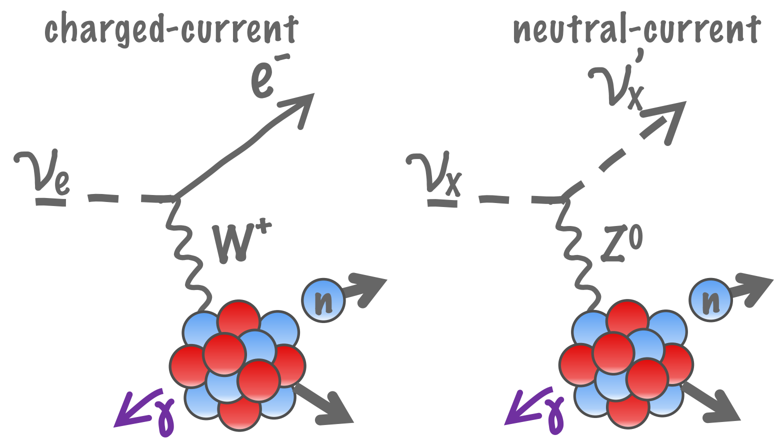


[D. Akimov, et al., Science 357 (2017)]

- Inelastic charged-current (**CC**) and neutral-current (**NC**) scattering
  - Mediated by $W^{\pm}$, Z^0
  - Cross section, threshold varies with different nuclei
  - Nucleus emits secondary particles (protons, neutrons, gammas, …) as a result of interaction
  - Focus of this talk



Existing Low-Energy Neutrino-Nucleus Measurements

List of <300 MeV neutrino-nucleus measurements with terrestrial sources

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$_{\text{g.s.}}$	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$_{\text{g.s.}}$	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)

[J. A. Formaggio & G. P. Zeller, Rev. Mod. Phys **84** (2012)]

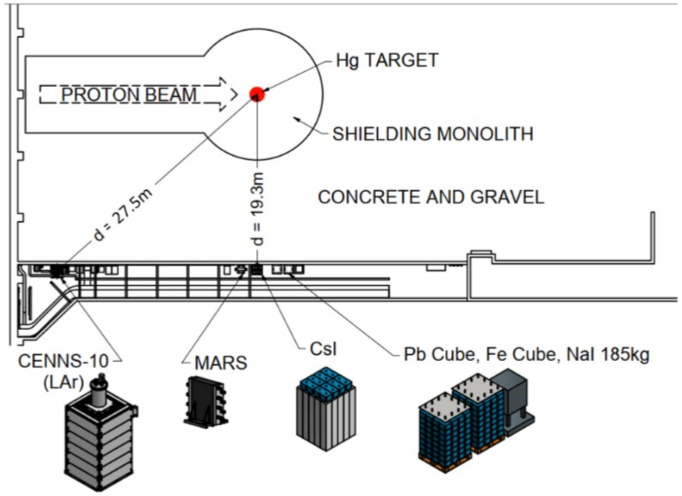
The COHERENT Collaboration & Neutrino Production at the SNS

The COHERENT Collaboration

- ~80 members, 20 institutions
- Formed to observe CEvNS, study physics in multiple targets, including N^2 scaling of cross section
- Use neutrinos produced by the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL)
- Intense flux of low-energy pulsed neutrinos useful for studying inelastic neutrino-nucleus interactions as well

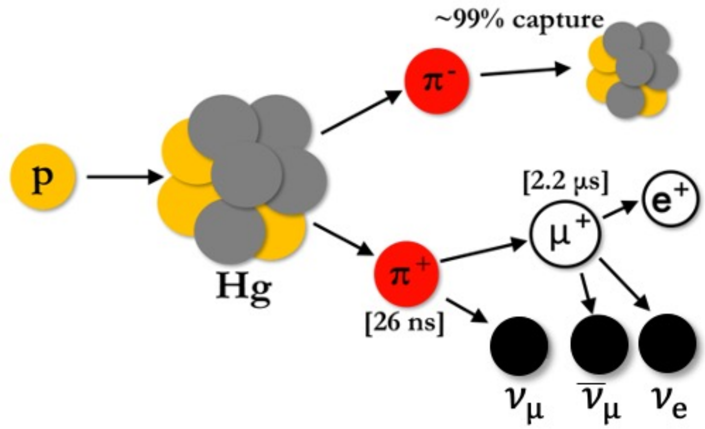
Neutrino Alley

- COHERENT's detectors in "Neutrino Alley" at the SNS
  - 25m long hallway, 20-30m from target
  - Not designed for neutrino detectors
  - Concrete and gravel reduce beam neutrons
- Dedicated detectors for measuring neutrons
- Take advantage of timing structure of neutrinos produced at the SNS

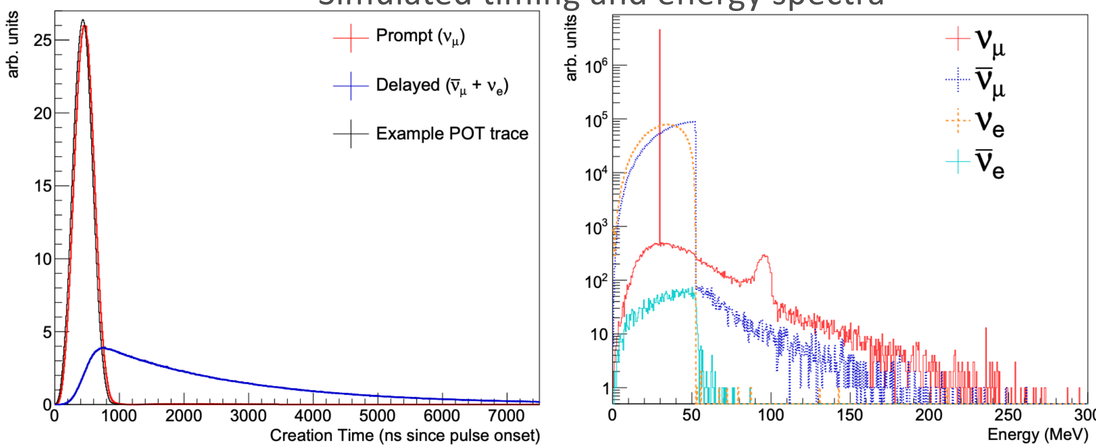


Neutrinos at the SNS

- 1 GeV protons strike Hg target at the SNS at 60Hz
  - 350ns FWHM of proton pulse
- Produces π^- and π^+ (and neutrons)
  - Neutrons are a background for our detectors, we refer to them as beam-related neutrons (**BRNs**)
- π^+decay in ~26ns, leading to prompt ν_μ and μ^+
- μ^+ decay with lifetime of 2.2μs, producing delayed ν_e and $\bar{\nu}_\mu$

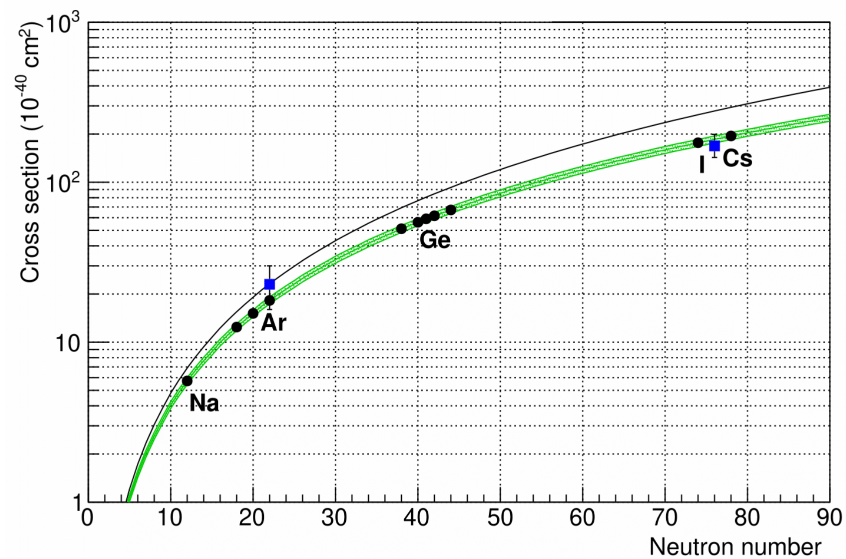


Simulated timing and energy spectra



[D. Akimov, et al., arXiV:2109.11049 (2021)]

COHERENT's CEvNS Detectors

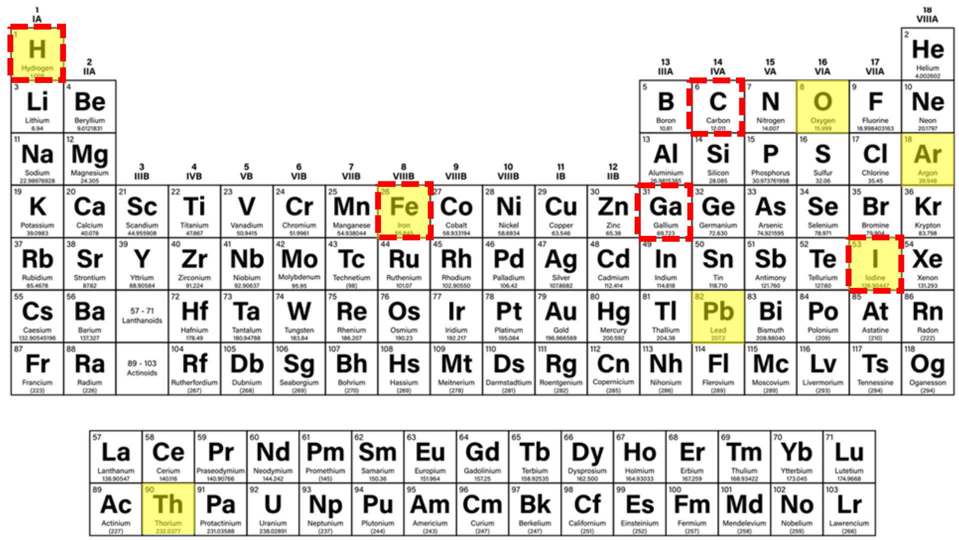


Target	Technology	Mass (kg)	Threshold (keV_{nr})	Date
CsI	CsI[Na] scintillator	14.6	6.5	6/2015
Ar	Single-phase liquid argon	24	20	12/2016
Na	NaI[Tl] scintillator array	185/2,425	13	2016/2022
Ge	p-type point contact Ge	16	3	2022

COHERENT's Inelastic Detectors

= existing measurements for low-energy (<300 MeV) neutrinos from terrestrial sources

= COHERENT's current & planned detectors



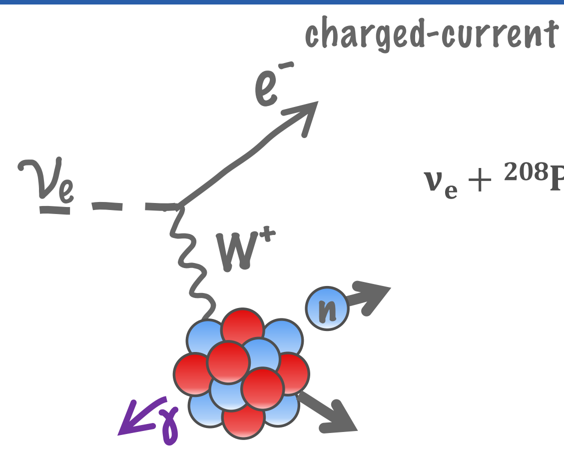
Name	Target	Channel	Deployment Date
Lead Neutrino Cube	Lead	$\mathrm{Pb}(\nu_e, e^- + xn)$	1/2016
Iron Neutrino Cube	Iron	$\mathrm{Fe}(\nu_e, e^- + xn)$	2/2017
Na$I\nu$E (COH-NaI-185)	$^{127}\mathrm{I}$	$^{127}\mathrm{I}(\nu_e, e^- + x)$	6/2016
CENNS-10 (COH-Ar-10)	Argon	$\mathrm{Ar}(\nu_e, e^- + x)$	2017
νThor	Thorium	$\mathrm{Th}(\nu_e, e^- + x)$	2022
CENNS-750 (COH-Ar-750)	Argon	$\mathrm{Ar}(\nu_e, e^- + x)$	future
D_2O	$^2\mathrm{H/O}$	$^2\mathrm{H/O}(\nu_e, e^- + x)$	future

Results presented today!

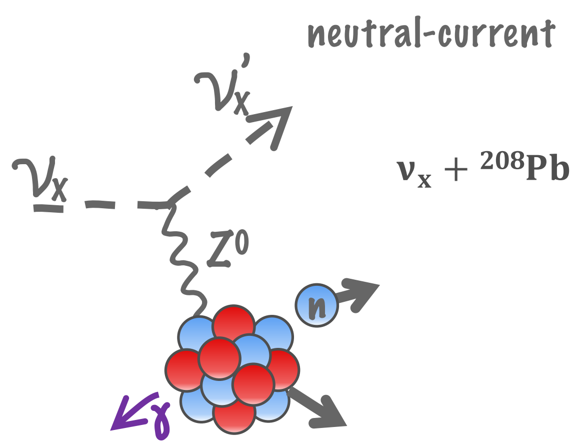
The Lead Neutrino Cube

Motivation for Measuring NINs

- Neutrino interactions in shielding of COHERENT's detectors could present beam-related background
  - Neutrino interactions can generate excited nuclei that de-excite by emitting neutrons
  - Produced neutrons follow the timing distribution of the neutrinos, and can produce low energy nuclear recoils in detectors



$$\nu_e + {}^{208}\text{Pb} \rightarrow {}^{208}\text{Bi}^* + e^-$$
$$\Downarrow$$
$${}^{208-y}\text{Bi} + x\gamma + yn$$



$$\nu_x + {}^{208}\text{Pb} \rightarrow {}^{208}\text{Pb}^* + \nu_x'$$
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$${}^{208-y}\text{Pb} + x\gamma + yn$$

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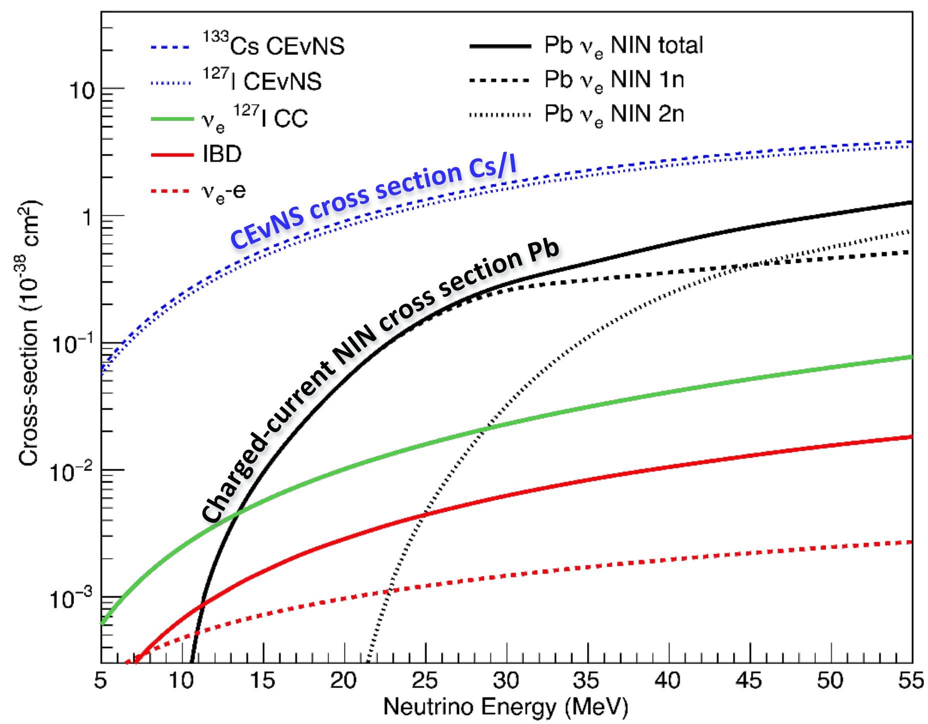

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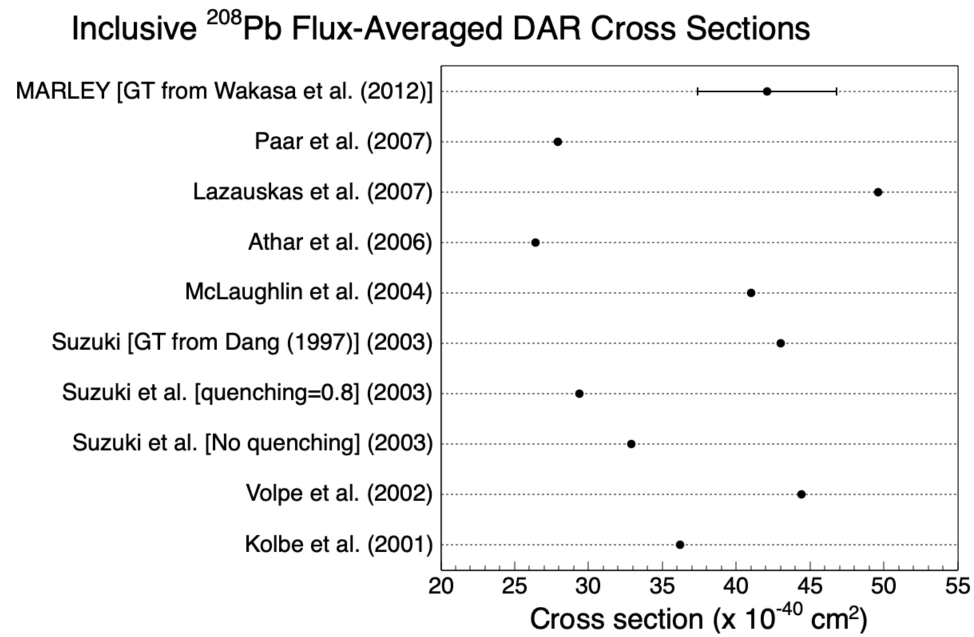

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- Cross section expected to be lower than CEvNS, but previously unmeasured
  - Variations in calculations
  - Much greater mass of shielding than CEvNS detectors themselves

CEvNS Target	Shielding
14.6 kg CsI[Na]	2,200 kg lead
24 kg liquid argon	11,000 kg lead
16 kg Ge	3,400 kg lead
2,425 kg NaI	17,000 kg iron and lead

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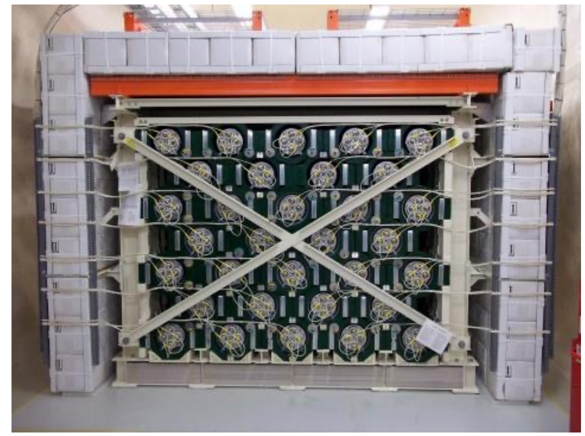
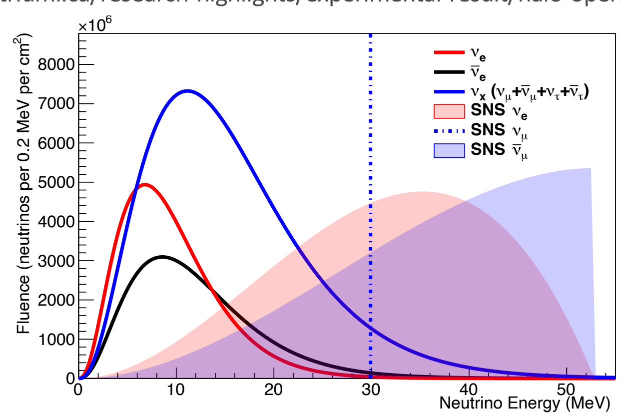
  - Variations in calculations
  - Much greater mass of shielding than CEvNS detectors themselves
- Primary mechanism for HALO to detect supernova neutrinos



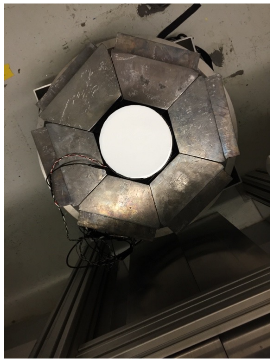
[https://www.triumf.ca/research-highlights/experimental-result/halo-operational-snolab]

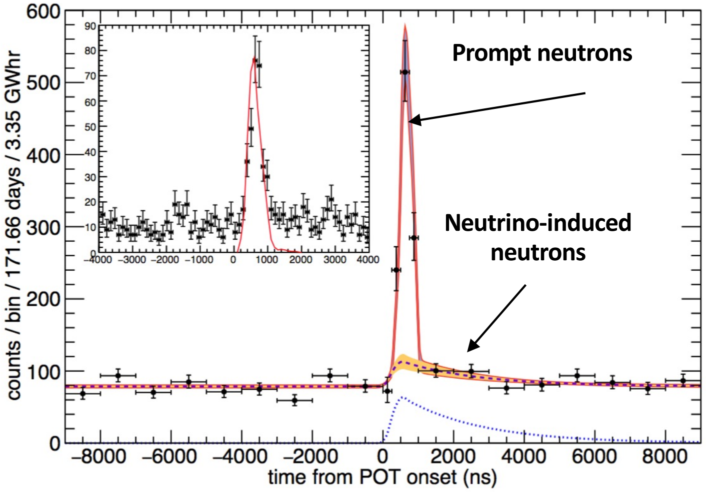


[image courtesy of K. Scholberg]

Initial Attempt—Eljen Cell Detector

- In 2015, prior to deployment of CsI[Na] CEvNS detector, two 1.5-L liquid scintillators deployed inside its shielding
  - 2,200kg of Pb shielding ~20m from target
  - Exposure of 171.7 days (3.35 GWhr)
  - Threshold of 30 keVee
- Best fit of non-zero NIN component at 2.9σ
  - 0.97 ± 0.33 neutrons produced/GWhr/kg of Pb
  - ~1.7x lower than predicted in McLaughlin, G.C. Phys. Rev. C **70** 4 (2004)
- Not a major background for CEvNS in CsI
  - With additional HDPE shielding added inside lead, ~47x lower than CEvNS signal!

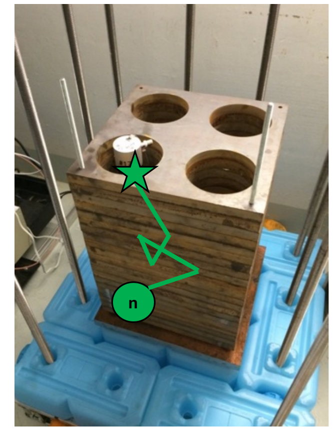


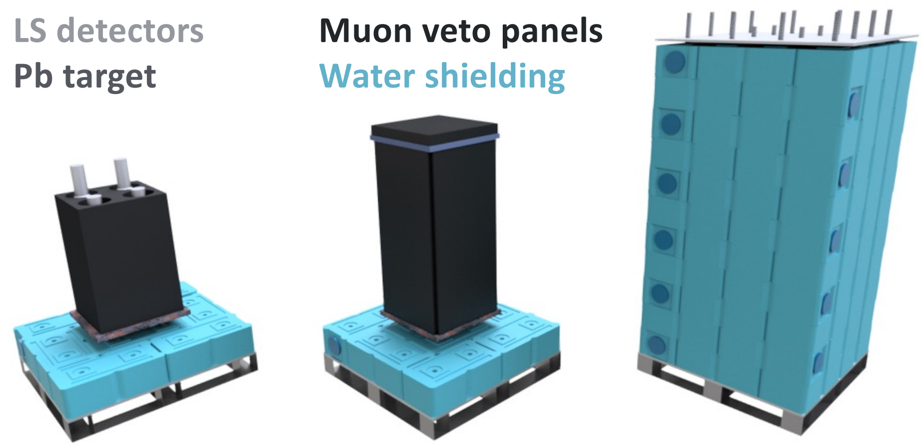


[D. Akimov, et al., Science 357 (2017)]

The Lead Neutrino Cube

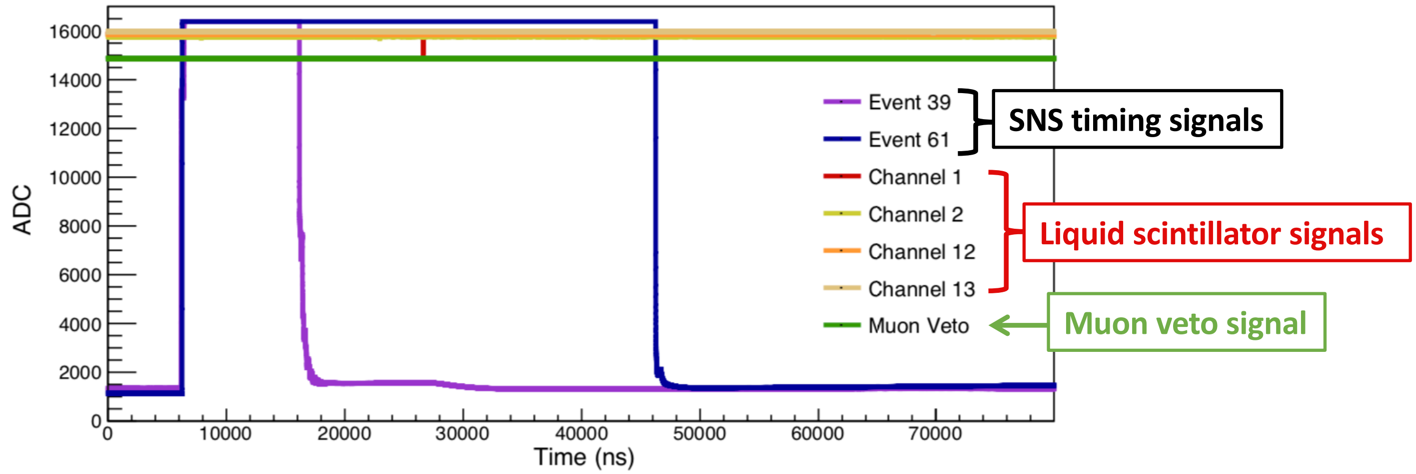
- Two dedicated NIN detectors at SNS
  - 900-kg Pb—deployed in 2015
  - 700-kg Fe—deployed in 2017
- NINs produced in lead/iron have small but non-zero efficiency to make their way to LS cells, identified as neutrons using PSD
- Muon veto panels surround targets to reject muon-induced neutrons
- Water shielding reduces steady-state, beam-related neutrons
- Focus on delayed neutrino window, CC cross section expected to be larger than NC, free of prompt beam-related neutron (BRN) background





Data Acquisition Scheme

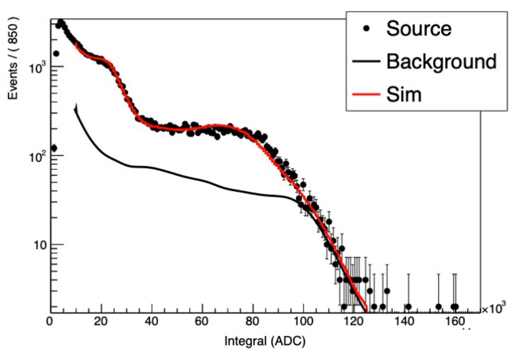
- DAQ record coincidences between SNS timing signals and internal triggers within 20µs window, record all channels
- Waveform reconstruction code:
  - Filter waveforms to remove long-timescale oscillations in baseline
  - Identify pulses, integrate for energy and PSD parameter
  - Hold-off time to remove electronic ringing artifacts
  - In software, correlate LS pulses with vetoes, SNS timing pulses
- Events within a 14µs window around the SNS timing signal blinded



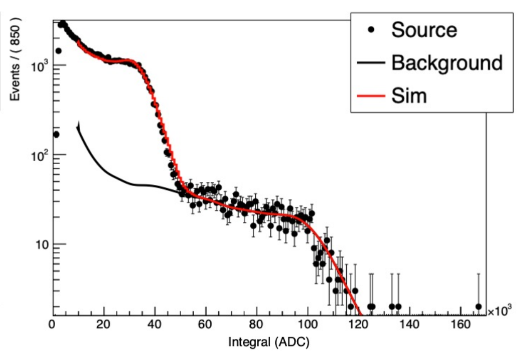
Gamma Calibrations

- Calibrations performed with gammas source (^{22}Na, ^{137}Cs, ^{133}Ba, ^{60}Co) several times throughout detector operations
- Source and detector simulated in MCNP, fit to data allowing energy-resolution and ADC-to-keV calibration parameters to float
- Between calibrations, background spectrum fit (largely due to ^{40}K) to track gain on shorter time scales

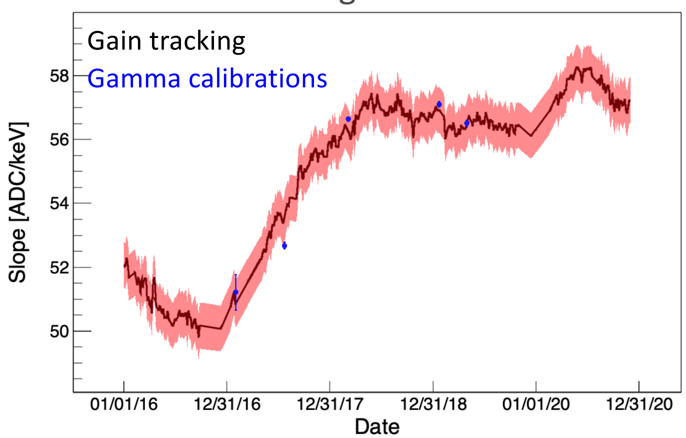
^{22}Na calibration



^{137}Cs calibration

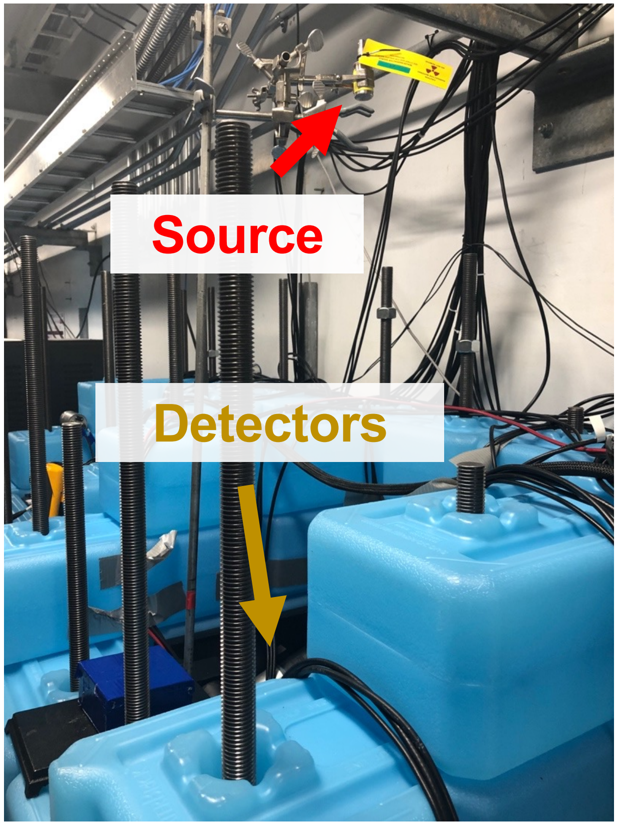


Gain changes over time



Neutron Calibrations

- *in-situ* run performed with time-tagged ^{252}Cf neutron source
- Time-tagged signal replaced SNS timing signal in DAQ, shielding removed to expose detectors to source, otherwise identical to running configuration



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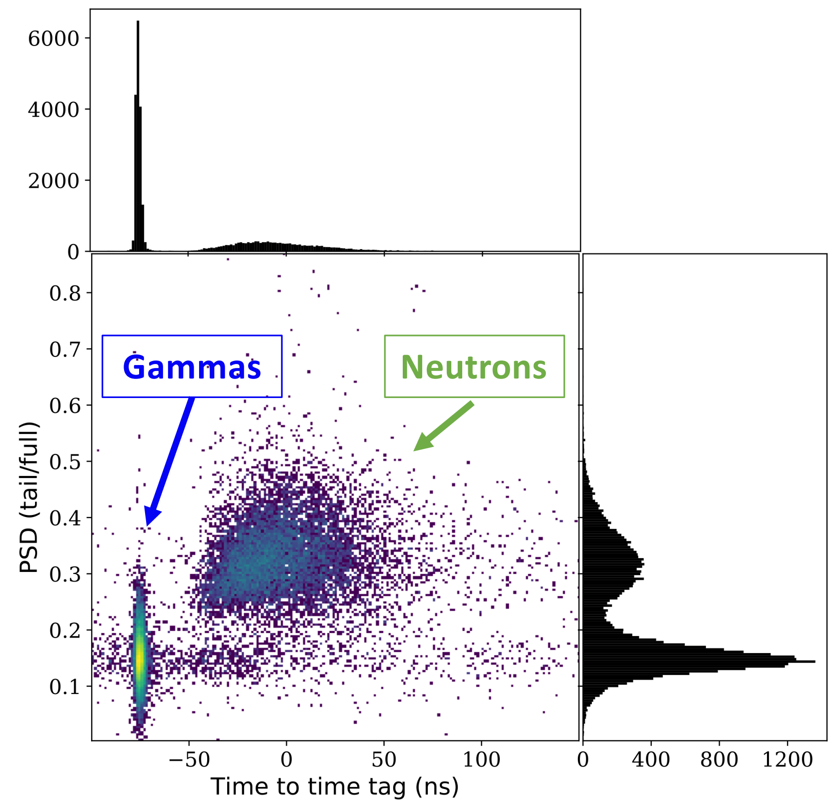

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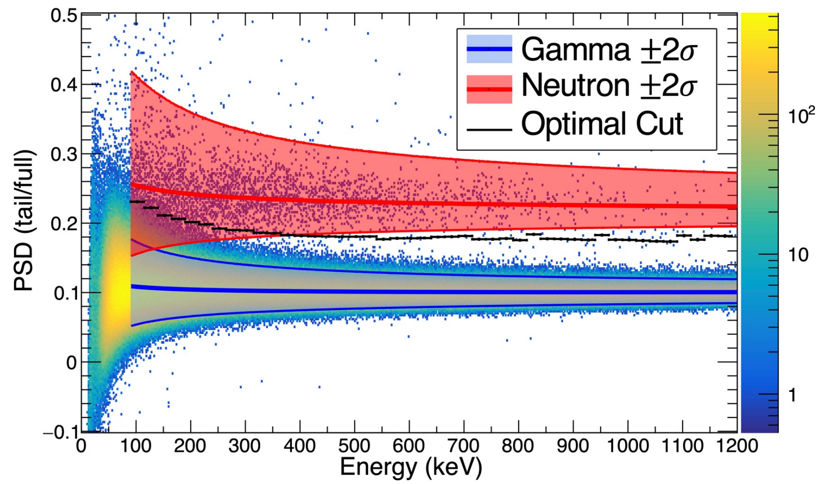
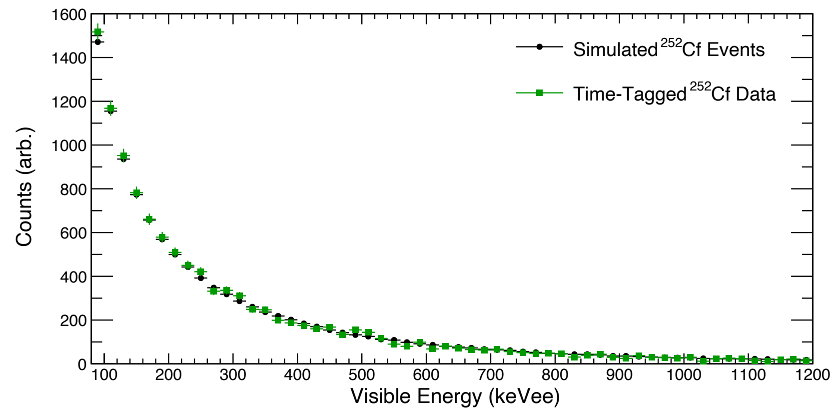
- Time-tagged signal replaced SNS timing signal in DAQ, shielding removed to expose detectors to source, otherwise identical to running configuration
- Produced clean population of gammas, neutrons for understanding thresholds, optimizing PSD parameter
- Develop neutron PSD cut
- Compare data to simulation to ensure we understand energy response





MARLEY

- Used MARLEY* to generate signal predictions for inelastic neutrino-nucleus interactions at the SNS
- **M**odel of **A**rgon **R**eaction **L**ow **E**nergy **Y**ields—originally designed for ^{40}Ar, but can be used with other nuclei
- Handles allowed components of inelastic neutrino-nucleus reactions at low energies
  - Forbidden transitions play larger role at higher energies

$$\frac{d\sigma}{d\cos\theta_\ell} = \frac{G_F^2 |U_{ud}|^2}{2\pi} F_C \left[\frac{E_i E_f}{s}\right] E_\ell |\vec{p}_\ell| \left[(1+\beta_\ell \cos\theta_\ell)\, B(F_-) + \left(1 - \frac{1}{3}\beta_\ell \cos\theta_\ell\right) B(GT_-)\right]$$

- Inputs are Gamow-Teller strength distributions
  - Calculate theoretically or measure via charge-exchange reactions–(p,n) or (^{3}He,t)

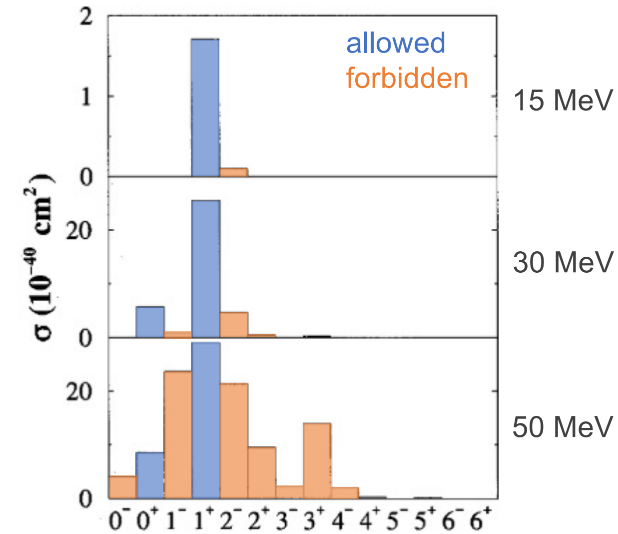


FIG. 3. Contribution of the different multipolarities to the differential ^{208}Pb(ν_e,e^-)^{208}Bi cross section (10^{-40} cm^2) of Fig. 1 for E_{ν_e} = 15 MeV (up), 30 MeV (middle), 50 MeV (bottom).

[C. Volpe, et al., Phys. Rev. C **65** (2002)]

*S. Gardiner, Simulating low-energy neutrino interactions with MARLEY, Comput. Phys. Commun. 269, 108123

MARLEY for ^{208}Pb

- Gamow-Teller strengths obtained from (p,n) measurement
  - Input B(GT⁻) and B(F) values into MARLEY along with electron neutrino DAR spectrum

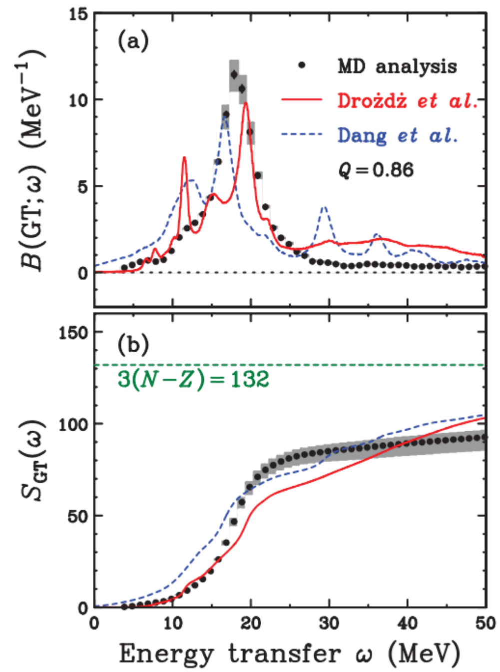
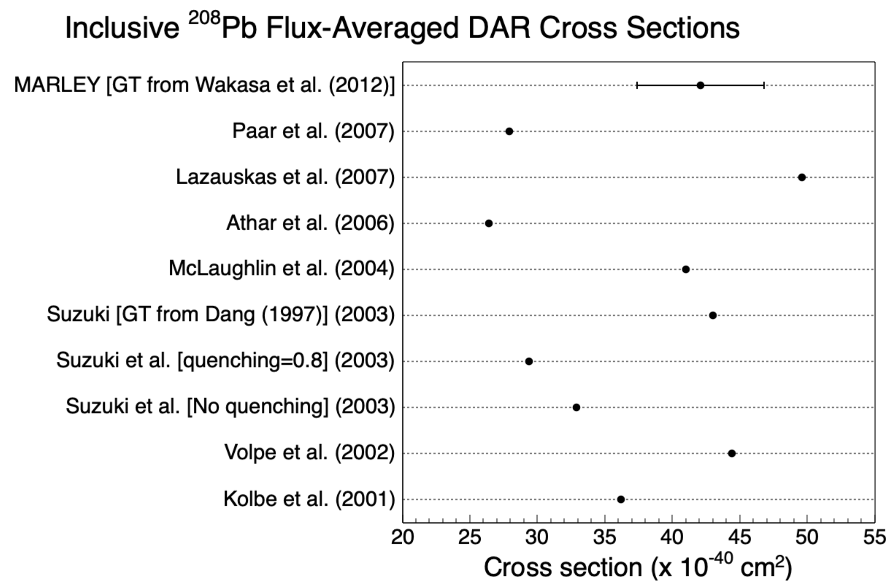


FIG. 16. (Color online) (a) The GT strength $B(\mathrm{GT};\omega)$ and (b) its integrated $S_{\mathrm{GT}}(\omega)$ distributions obtained by MD analysis of the ^{208}Pb(p,n) reaction. The bands represent the uncertainties arising from the selection of α in Eq. (18). The solid and dashed curves are the theoretical predictions reported by Drożdż *et al.* [18] and Dang *et al.* [62], respectively, with a quenching factor $Q = 0.86$ [13].

[T. Wakasa, et al., Phys Rev. C **85** (2012)]

MARLEY for ^{208}Pb

- Gamow-Teller strengths obtained from (p,n) measurement
  - Input B(GT^{-}) and B(F) values into MARLEY along with electron neutrino DAR spectrum
- MARLEY outputs cross sections, energies and multiplicities of emitted particles
  - Cross section for lead agrees well with existing theoretical calculations
  - Provides calculations for specific channels

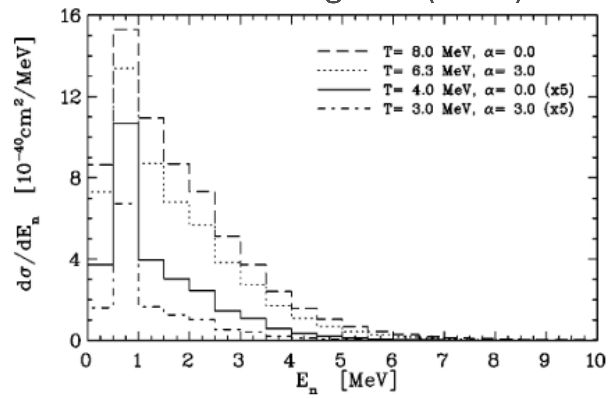


Channel	Cross section $(\times 10^{-40}\mathrm{cm}^2)$
$^{208}\mathrm{Pb}(\nu_e, X)$	42.1
$^{208}\mathrm{Pb}(\nu_e, e^- + n)^{207}\mathrm{Bi}$	31.6
$^{208}\mathrm{Pb}(\nu_e, e^- + 2n)^{206}\mathrm{Bi}$	7.7
$^{208}\mathrm{Pb}(\nu_e, e^- + 3n)^{205}\mathrm{Bi}$	0.4

MARLEY for ^{208}Pb

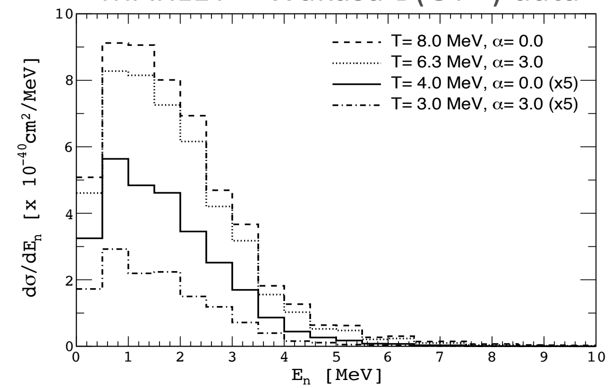
- Gamow-Teller strengths obtained from (p,n) measurement
  - Input B(GT⁻) and B(F) values into MARLEY along with electron neutrino DAR spectrum
- MARLEY outputs cross sections, energies and multiplicities of emitted particles
  - Cross section for lead agrees well with existing theoretical calculations
  - Provides calculations for specific channels
- Similar neutron energy spectrum as E. Kolbe & K. Langanke, Phys. Rev. C **64** (2001) for supernova neutrinos
  - No published neutron spectrum from DAR neutrinos w/o MARLEY

Kolbe & Langanke (2001)



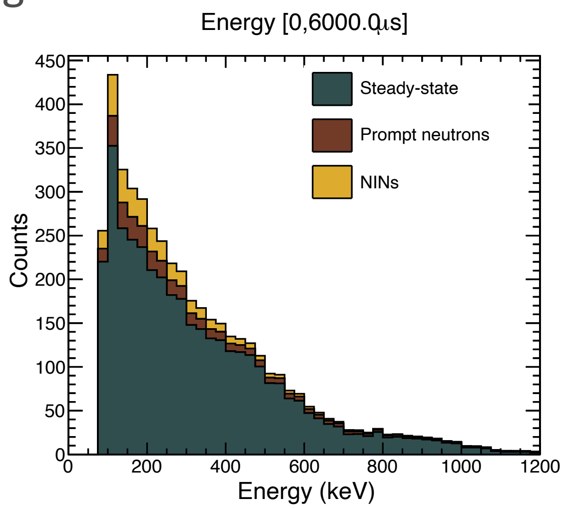
[E. Kolbe & K. Langanke, Phys. Rev. C **64** (2001)]

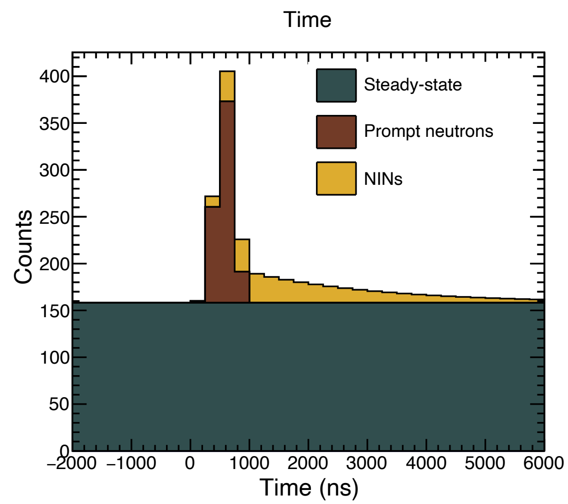
MARLEY + Wakasa B(GT⁻) data



PDFs

- MARLEY events simulated in MCNP, GEANT4 to determine efficiency for NINs arriving in detector of 18.8%
- Apply measured trigger threshold, energy resolution, PSD cut, to arrive at an efficiency of detecting NINs of 3.3%
- One-dimensional (time-only) fit to data
- Using MARLEY's predictions, expect 346 charged-current NIN events with cuts
  - Approx. 5σ significance with nominal cross section





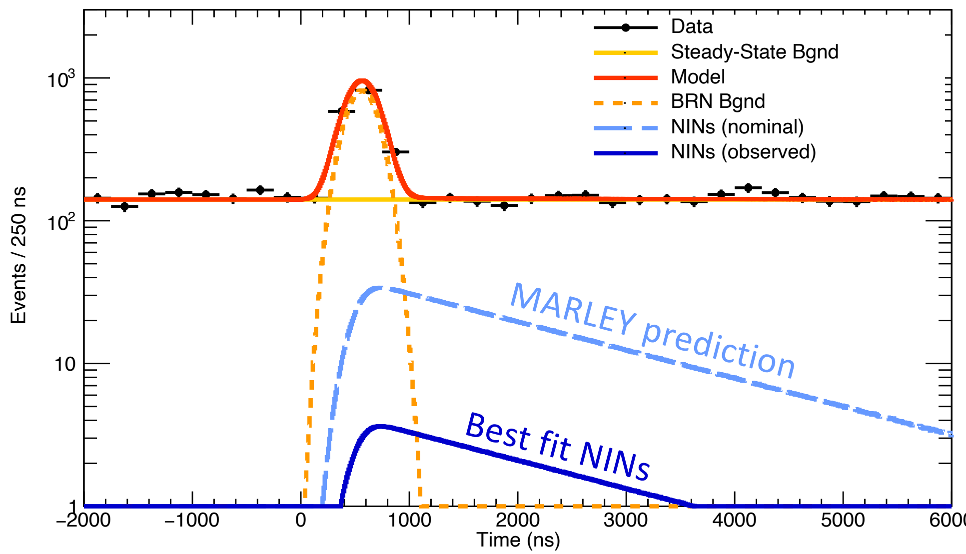
Uncertainties

- Largest source of uncertainty (10%) due to uncertainty in neutrino flux
  - D_2O detector being deployed to SNS to measure flux via the electron neutrino charged-current cross section on ^2H
  - 2-3% theoretical uncertainty
- Second largest uncertainty due to quenching factor of nuclear recoils in EJ-301 liquid scintillator
  - Members of collaboration measured this at low recoil energies at TUNL

Source	NIN uncertainty (%)
Neutrino flux	± 10
Quenching factor	± 2.7
Software threshold	$+0.2$ / -0.4
PSD selection	± 1.0
Calibration	$+2.1$ / -2.2
Energy resolution	$+1.7$ / -0.5
Muon veto	$+0.4$ / -0.3
Lead target mass	± 0.6
MARLEY NC prediction	$+0/-1.6$
Total:	$+10.8$ / -10.8

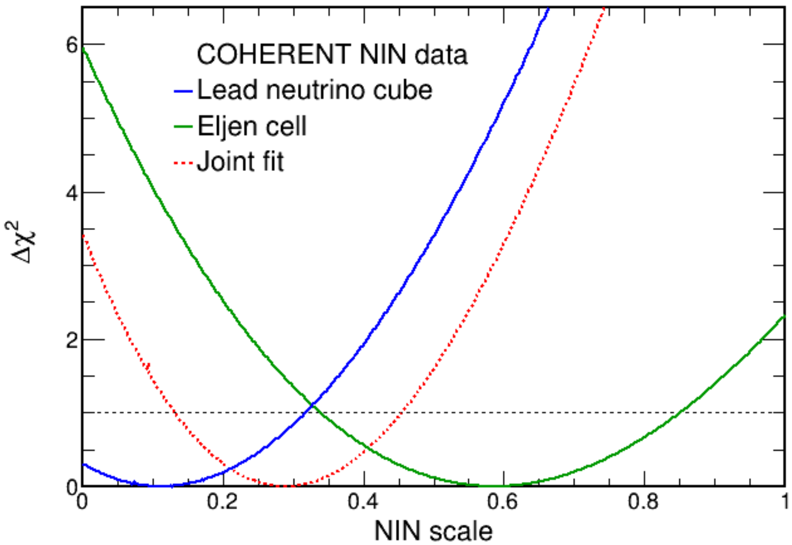
Unblinded Results

- Best fit of 36^{+72}_{-36} events compared to expected 346 events
  - Cross section lower than expected
- Post-unblinding checks:
  - Purity of lead target—stamped as >99.99% pure, density consistent with lead
  - Detector sensitivity to neutrons over lifetime—BRNs compared to delivered beam power show excellent agreement
  - PSD cut extended to lower energies where uncertainties more difficult to quantify due to presence of Cherenkov events—increased number of events, but suppression of cross section still observed



Combined Fit with Eljen Cell Data

- Data from Eljen-cell detector reanalyzed
  - Used MARLEY framework for generating predictions
  - Allowed additional smearing term for BRN timing due to dispersion effects (included in lead neutrino cube fit)
  - Improved predictions for neutrino flux based on beam power and energy (D. Akimov, et al., arXiV:2109.11049 (2021))
- Combined fit yields MARLEY cross section suppressed by a factor of $0.29^{+0.17}_{-0.17}$
  - 1.8σ significance, >4σ disagreement with MARLEY model
- Open questions:
  - Is neutron emission channel suppressed?
    - Study inclusive lead charged-current cross section
    - Can do within COHERENT, also external plans (arXiv:2205.11769)
  - Are emitted neutrons lower in energy than predicted?
    - Study lead NIN cross section with capture-gated detector
  - Is the NIN cross section suppressed for other targets?
    - Study NIN cross section with different target (Fe neutrino cube)



The NaIvE-185 Detector

Motivation for Measuring ^{127}I CC Interactions

- Initial motivation from W. C. Haxton, Phys. Rev. Lett **60** (1988), proposing radiochemical experiment using ^{127}I for solar neutrino detection

$$\nu_e + {}^{127}\mathrm{I} \rightarrow e^- + {}^{127}\mathrm{Xe}^*$$

  - Low threshold gives access to ^{7}Be solar neutrinos, larger cross section than for ^{37}Cl
  - Resulting ^{127}Xe has long half-life, use similar radiochemical technique as used for ^{37}Cl
- Engel, et al. pointed out the cross section depends on g_A
  - Suppression of g_A important for interpreting $0\nu\beta\beta$ matrix elements, half-lives
  - Can potentially test quenching at momentum transfer not available through beta-decay experiments

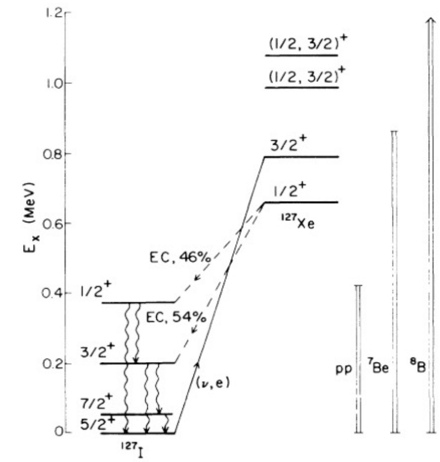


FIG. 1. Level scheme showing weak transitions between ^{127}I and ^{127}Xe.

[W. C. Haxton, Phys. Rev. Lett **60** (1988)]

J^π	$g_A = -1.0$	$g_A = -1.26$
0^+	0.096	0.096
0^-	0.00001	0.00002
1^+	1.017	1.528
1^-	0.006	0.008
2^+	0.155	0.213
2^-	0.693	1.055
3^+	0.149	0.171
3^-	0.017	0.025
total	2.098	3.096

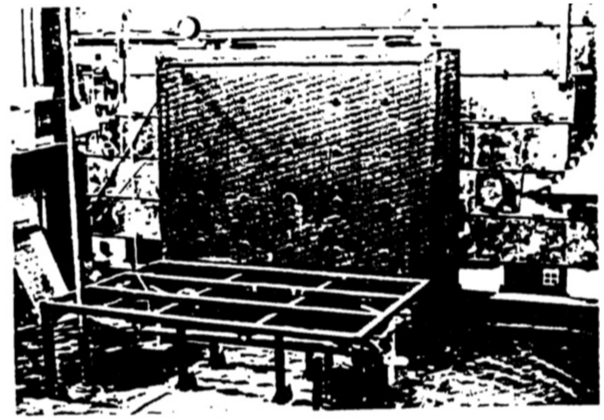
[J. Engel, S. Pittel, & P. Vogel, Phys. Rev. C **50** (1994)]

Motivation for Measuring ^{127}I CC Interactions

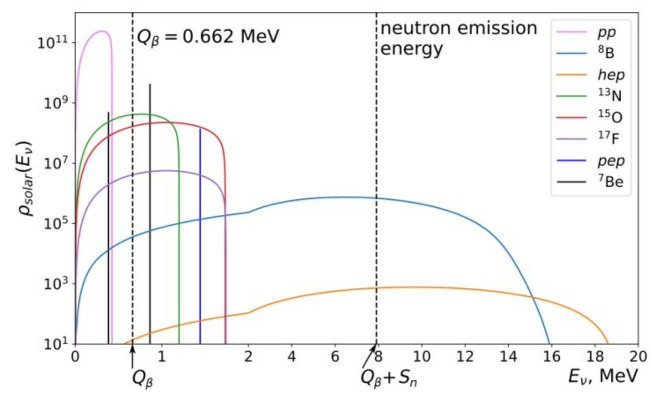
- Exclusive cross section to $^{127}Xe_{bound}$ measured at LAMPF in the 1990s with radiochemical approach
- Reported flux-averaged cross section of

$$\sigma = 2.84 \pm 0.91(stat) \pm 0.25(sys) \times 10^{-40}\ \mathrm{cm}^2$$

  - Only measured cross section to bound states of ^{127}Xe—majority of neutrinos at DAR sources have energy above neutron emission threshold
- Suggested repetition with electronic NaI detector to measure energy-dependence of cross section
- Recently interest in looking at ^{126}Xe/^{127}Xe ratio for comparing ^{7}Be to ^{8}B/HEP neutrinos



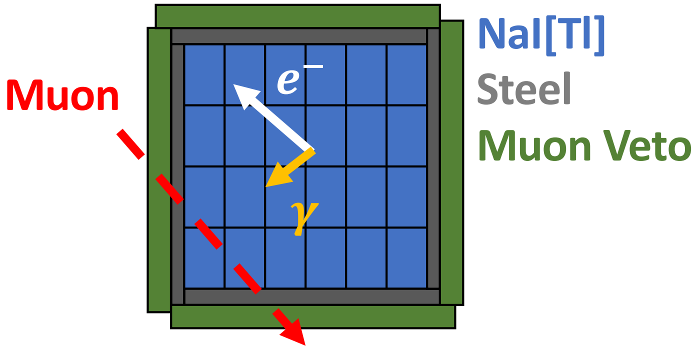
[B. T. Cleveland, et al., 23rd Int. Cosmic Ray Conf. **3** (1993)]



[Y. S. Lutostansky, et al., arXiv:2103.12325 (2021)]

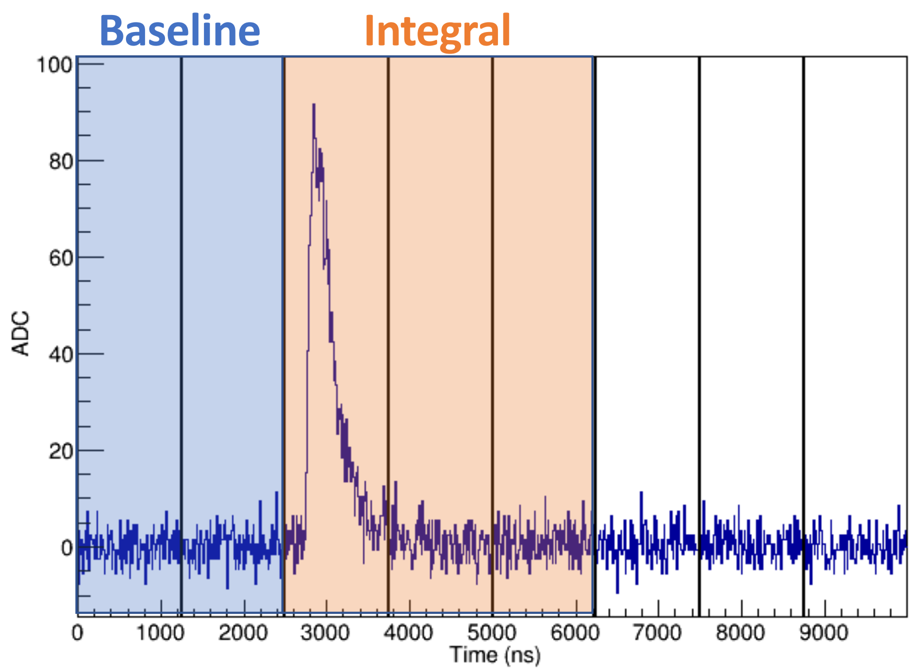
NaIvE-185 Detector

- NaI neutrino Experiment (**NaIvE**) designed to measure the inclusive charged-current cross section, energy-dependence
- Twenty-four 7.7-kg NaI[Tl] scintillator detectors (185-kg mass), deployed 2016
- Signal is “large-energy” (10-55 MeV) depositions in delayed neutrino window
- Muon veto panels to reduce cosmic muons
- 1.5” steel between NaI and veto panels to avoid vetoing signal
- Detector also used as prototype for ton-scale NaI CEvNS detector



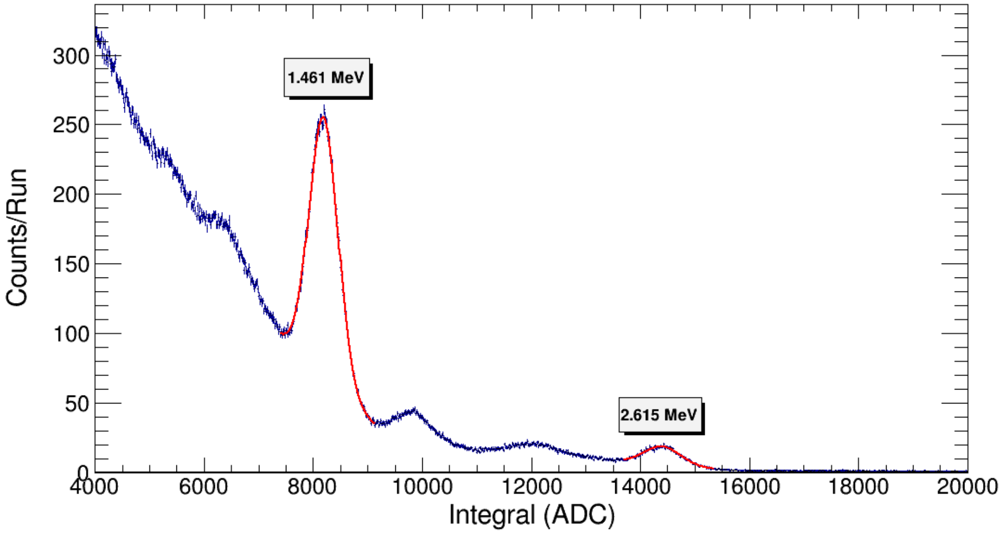
Data Acquisition System

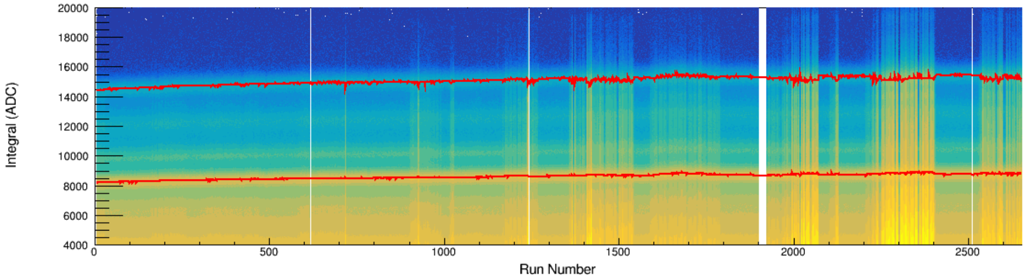
- Detector uses digitizer trigger to record scintillation in any NaI channel above a threshold (500-900 keV)
- Integrated PMT charge recorded in eight timing windows (accumulators) around the pulse to determine baseline, integral
- Muon veto panels, SNS timing pulses trigger independently, timing correlation done in software
  - Data within -2µs to +20µs of SNS timing signal blinded



Intrinsic Background Calibrations

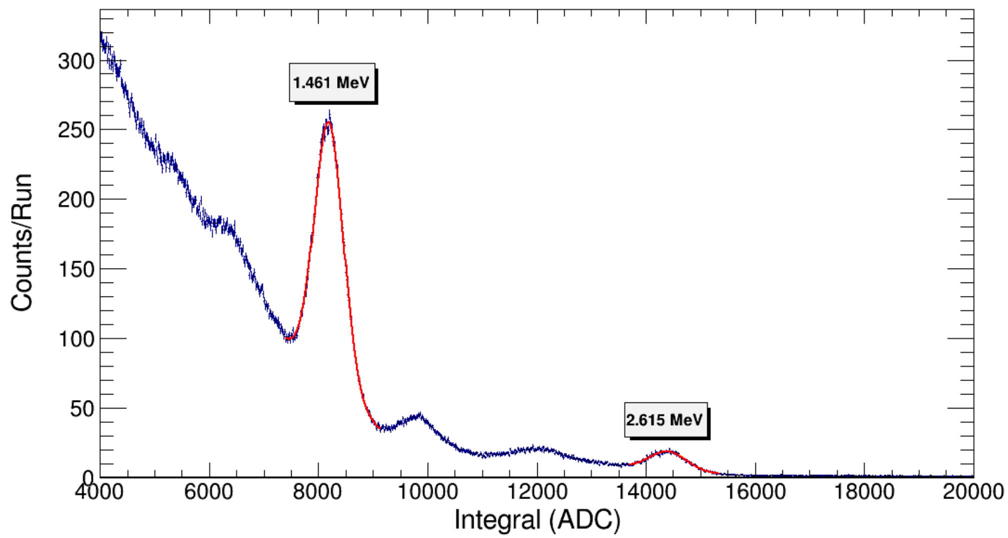
- Calibrate each NaI channel based on ^{40}K and ^{208}Tl intrinsic backgrounds
  - Track gain changes over time, measure energy resolution in crystals

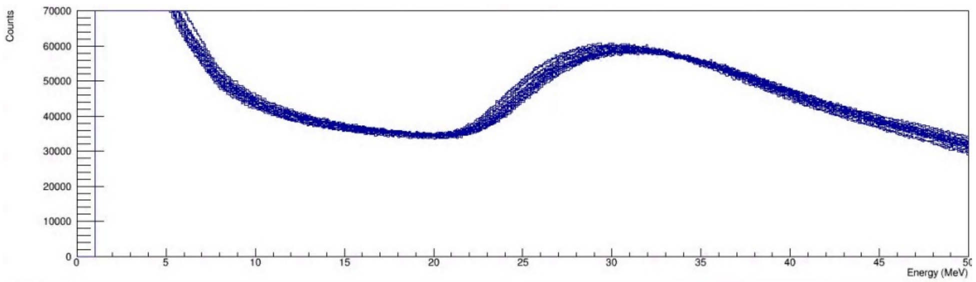


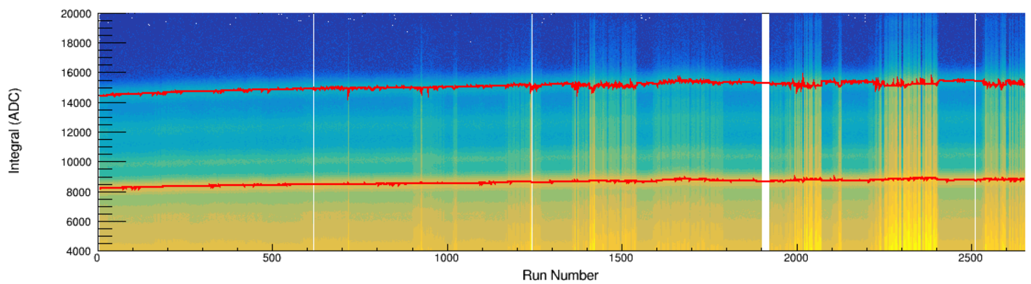


Intrinsic Background Calibrations

- Calibrate each NaI channel based on ^{40}K and ^{208}Tl intrinsic backgrounds
  - Track gain changes over time, measure energy resolution in crystals
- Extending calibration to higher-energies leads to small discrepancies in high energy background (muon) spectrum in each crystal

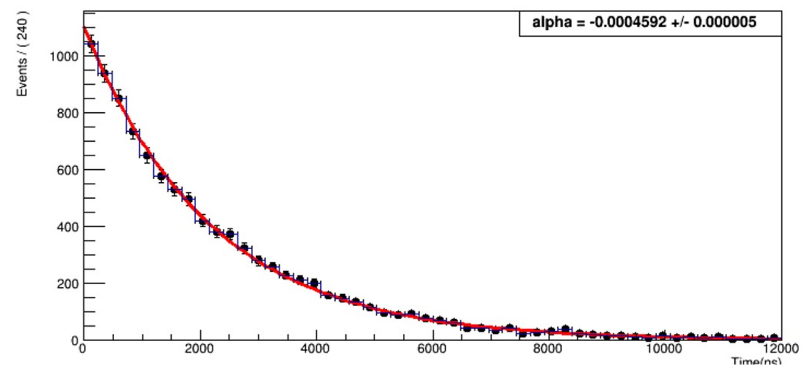


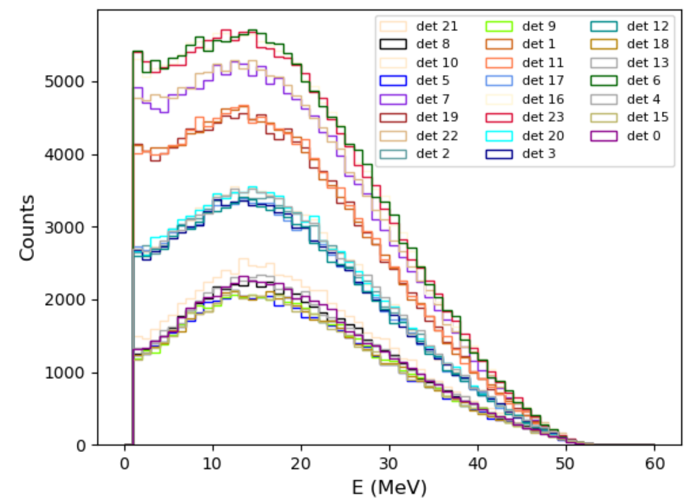




Michel Positron Correction

- Use Michel positrons to correct calibration
- Collect population of Michel events by looking for large energy depositions in crystals after a muon event (tagged with veto panels)
  - Fitting data gives anti-muon mean lifetime of $2.172 \pm 0.024 \mu s$
- Simulate positrons in GEANT4, matching data selection criteria
- Fit quadratic calibration function to data that preserves low energy calibrations





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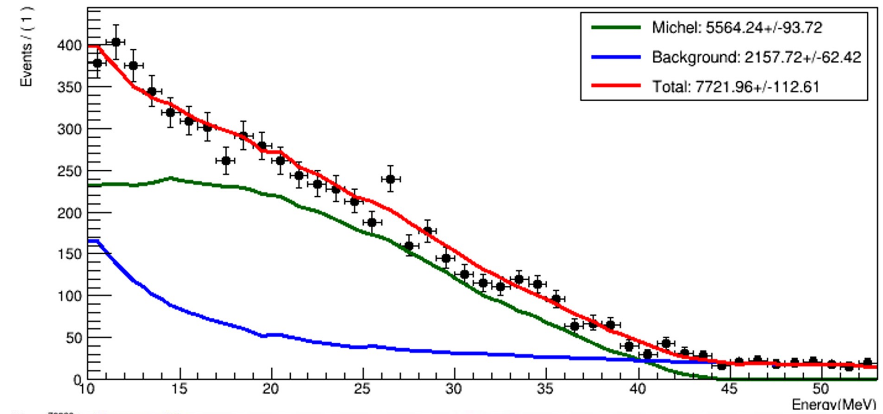
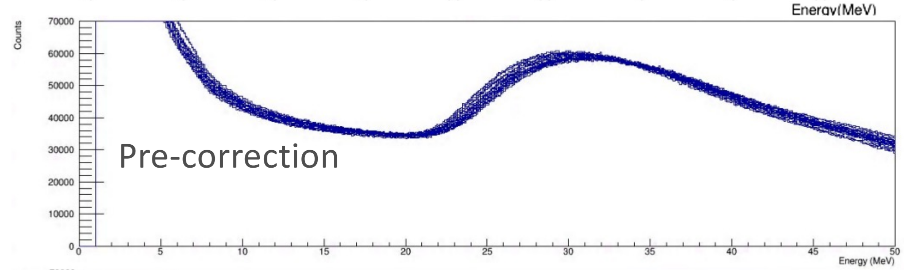
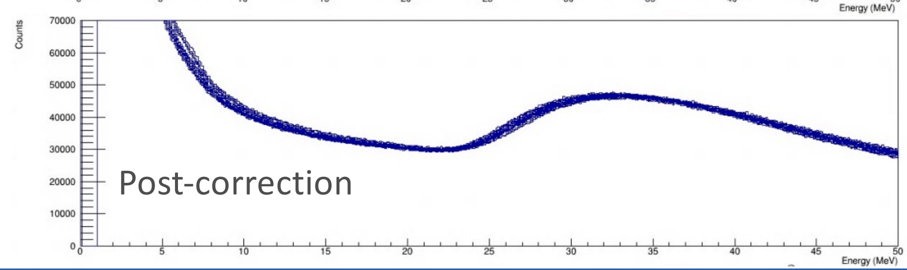
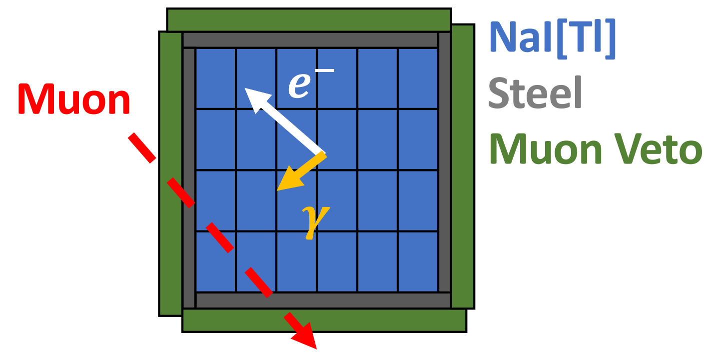


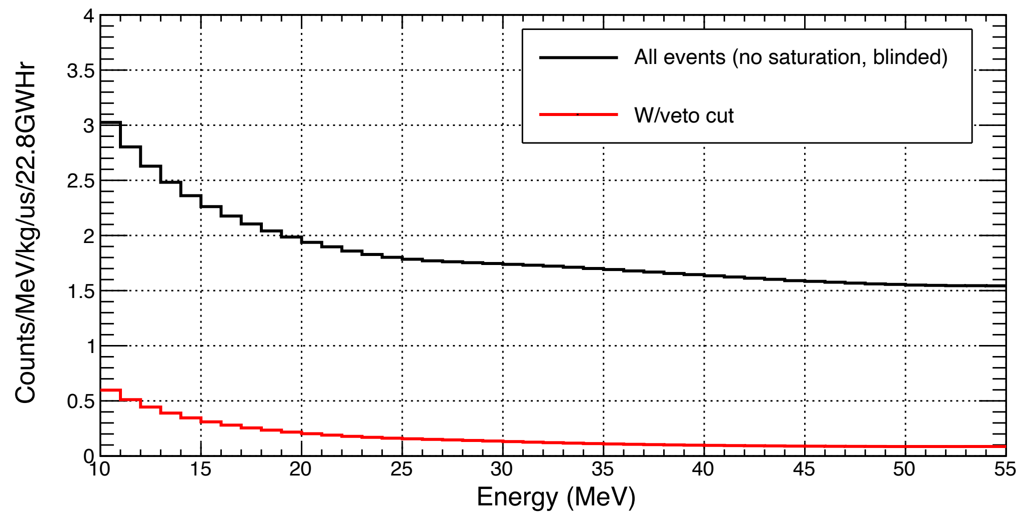




Muon Veto Cut

- Cosmic muons the largest source of backgrounds for charged-current signal
- Tag NaI events close in time to muon veto panel PMT events above threshold
  - 1.5” steel between NaI crystals and veto panels to avoid vetoing signal
  - Systematic incorporated into analysis to account for uncertainty in veto thresholds
- Veto rejects ~93% of cosmic muon backgrounds between 10-55 MeV
  - Additionally benefit from looking in a small (several microsecond) window around SNS timing signal to reduce backgrounds

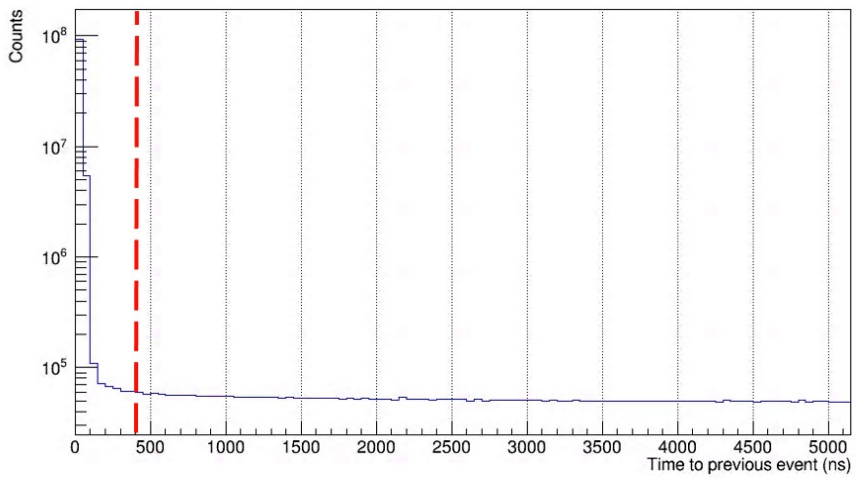




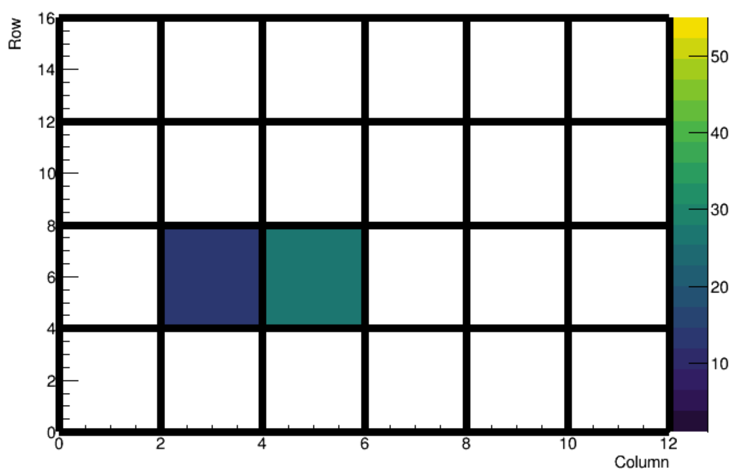
Event Reconstruction

- Energy from all NaI channels (above 1 MeV threshold) summed together if occur within 400ns window
  - Topology not currently used in analysis, something to study further
- Correlate timing of events with muon veto signals, SNS timing signals

Time between events in NaI detectors



Tagged Muon, t=2133 ns, E=40.39 MeV



MARLEY predictions for ^{127}I

- MARLEY used for ^{127}I charged-current predictions along with (p,n) charge-exchange data
- MARLEY's inclusive cross section for DAR neutrinos:

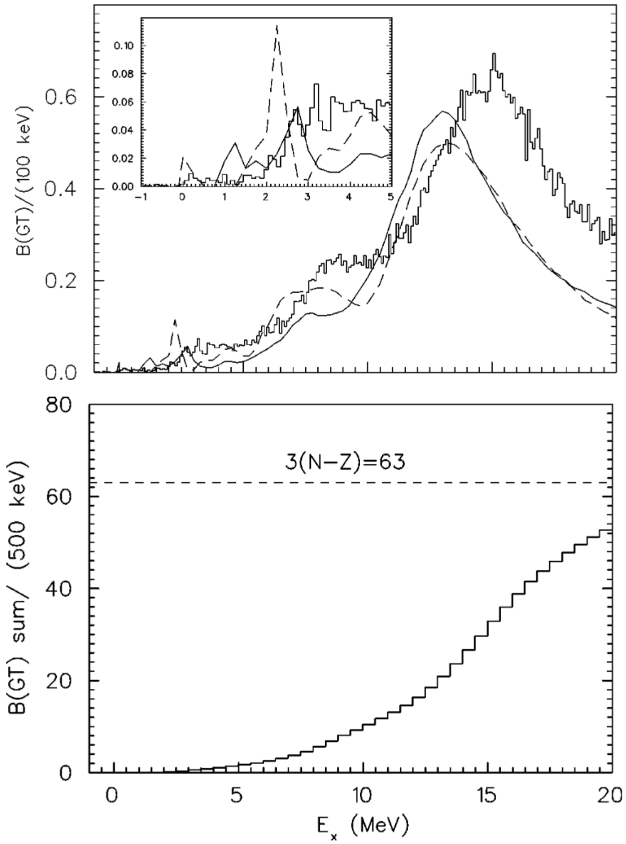
$$22.5^{+1.2}_{-6.5} \times 10^{-40}\ \mathrm{cm}^2$$

  - Uncertainty from B(GT$^-$) normalization uncertainty
- Cross section for exclusive channel to $^{127}Xe_{bound}$:

$$2.5^{+0.3}_{-0.6} \times 10^{-40}\ \mathrm{cm}^2$$

  - Good agreement with LAMPF measured value of

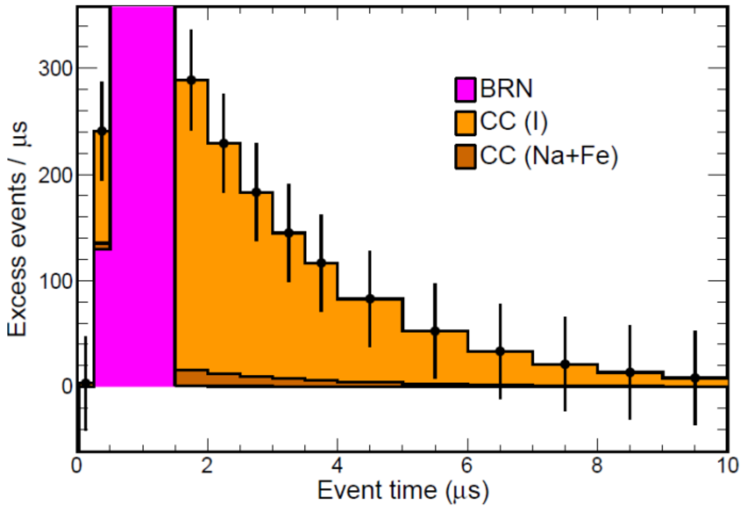
$$2.84 \pm 0.91(stat) \pm 0.25(sys) \times 10^{-40}\ \mathrm{cm}^2$$



[M. Palarczyk, et al., Phys. Rev. C 59 (1999)]

PDFs

- Simulate charged-current events in GEANT4, process matching analysis cuts to arrive at signal PDF predictions
  - Restrict to 10-55 MeV where most of signal expected to reside, above neutron capture energy on ^{23}Na and ^{127}I
  - Expect 1,320 CC events on ^{127}I
  - ~61 events from CC on sodium, iron shielding
- Three main results:
  - Inclusive cross-section: 1D fit in time
  - Spectrum of charged-current events: 1D fits in time in 5 MeV energy bins
  - Zero-neutron emission (0*n*) cross section and one-neutron emission (1*n*) cross sections within MARLEY model: 2D fit in energy and time



Uncertainties

- Largest uncertainty is neutrino flux (again!)
- Second largest uncertainty is due to unknown veto threshold, non-uniformity of light collection from muon veto panels
  - Even with 1.5” steel between NaI detector and veto panels, some charged-current signal triggers veto system in simulation
- Signal mostly at higher energies, uncertainties in calibration, energy resolution, trigger efficiency have little effect on number of counts in energy region-of-interest

Quantity	I-CC Unc [%]	Na-CC Unc [%]	Fe-CC Unc [%]
Neutrino flux	±10.0	±10.0	±10.0
Trigger Efficiency	+0.0 -0.3	+0.0 -0.1	+0.0 -1.0
Calibration	+0.0 -0.0	+0.0 -0.0	+0.1 -0.3
Energy Resolution	+0.0 -0.0	+0.0 -0.0	+0.2 -0.2
Muon Veto Threshold	+2.8 -5.1	+1.1 -2.0	+2.0 -3.7
Total:	+10.4 -11.2	+10.1 -10.2	+10.2 -10.7

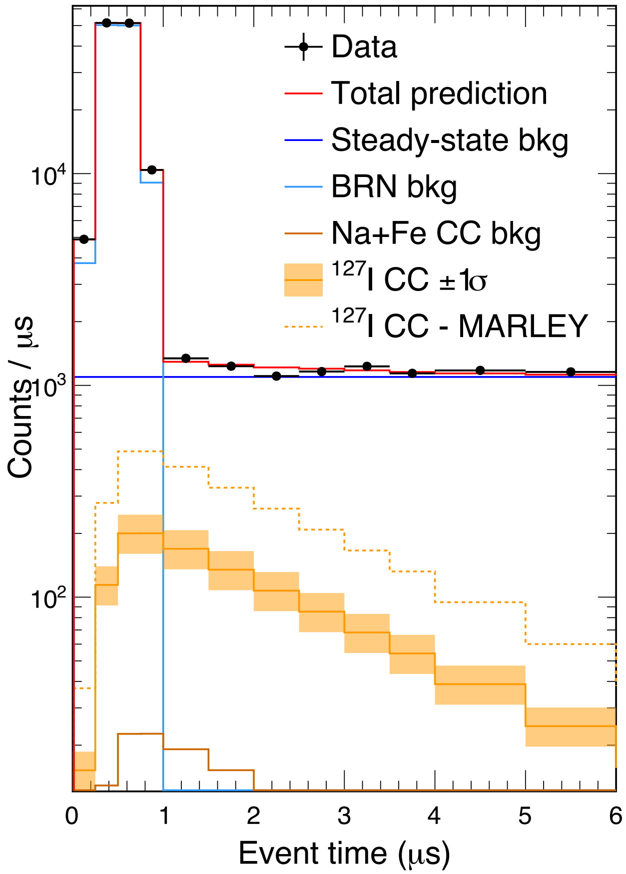
Event Type	nTargets ($\times10^{26}$)	MARLEY σ ($\times10^{-40}$cm^2)	Eff.	Unc.	Number
I-CC	7.4	22.5	0.758	+10.4-11.2	1320^{+148}_{-137}
Na-CC	7.4	0.5	0.793	+10.1-10.2	31^{+3}_{-3}
Fe-CC	50.0	2.9	0.021	+10.2-10.7	31^{+3}_{-3}

Results: Inclusive Cross Section

- Best fit gives 541^{+121}_{-108} events
  - 5.8σ evidence of CC events
  - χ^2 of 13.1, 12 d.o.f.
- Corresponds to cross section of

$$\mathbf{9.2^{+2.1}_{-1.8} \times 10^{-40}\ cm^2}$$

  - 40.9% MARLEY cross section



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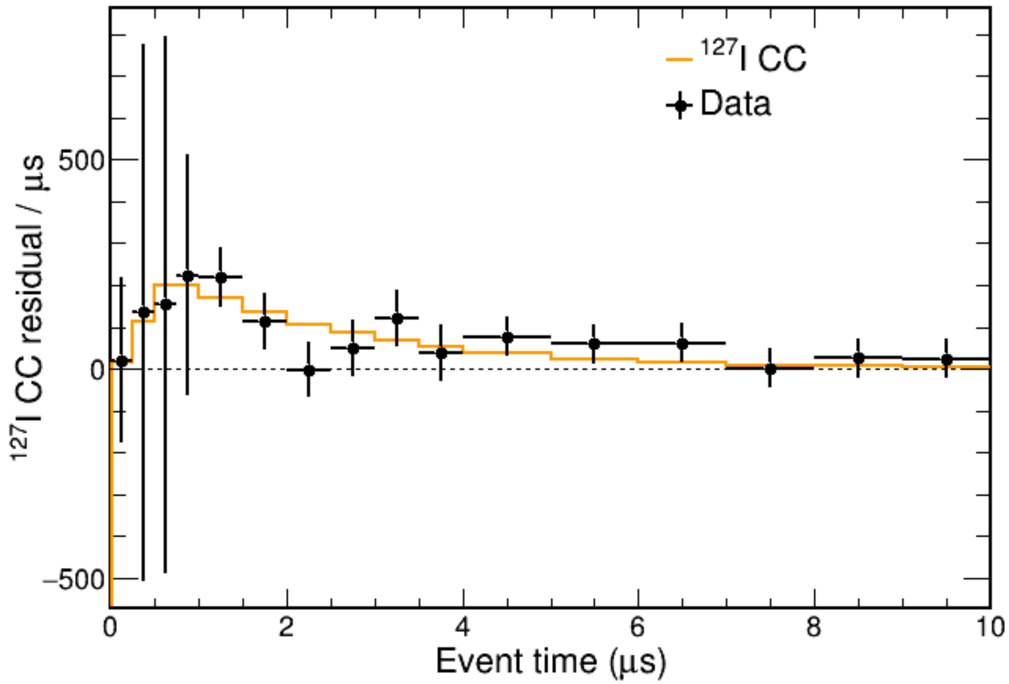
  - χ^2 of 13.1, 12 d.o.f.
- Corresponds to cross section of

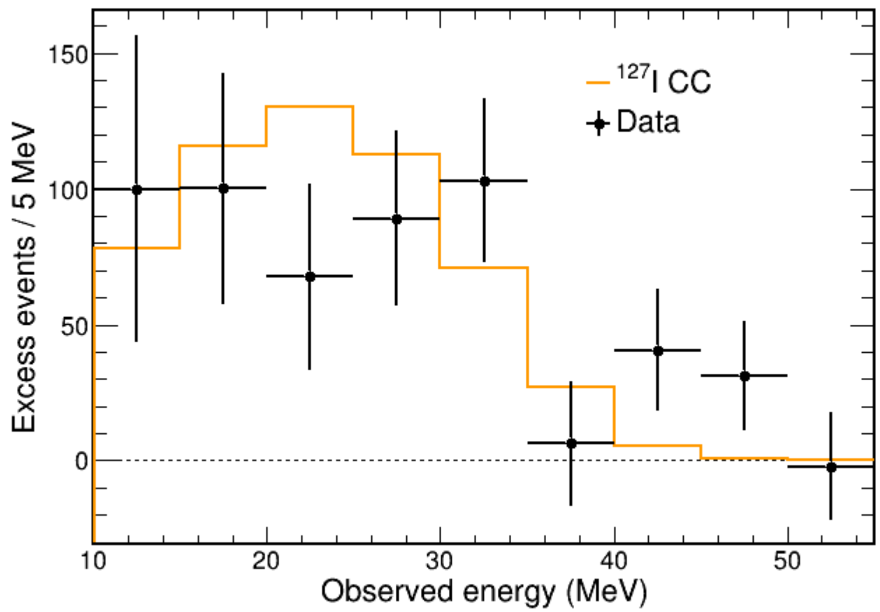
$$\mathbf{9.2^{+2.1}_{-1.8} \times 10^{-40}\ cm^2}$$

  - 40.9% MARLEY cross section
- Subtract off steady-state, BRN backgrounds to form signal residuals for 1D timing fit across 10-55 MeV range



Results: ^{127}I Charged-Current Spectrum

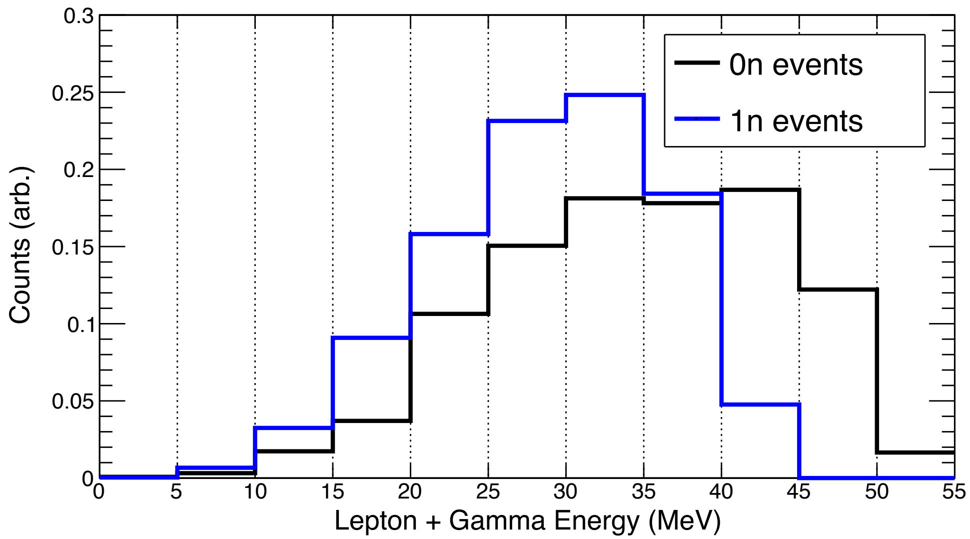
- Fit 1D timing spectrum in 5 MeV bins from 10-55 MeV to generate an energy spectrum
  - In each bin, independent fits to timing to estimate BRN and CC amplitudes
- Does not show great agreement with scaled MARLEY model, but two caveats
  - Large error bars on due to low statistics
  - Forbidden transitions not incorporated in MARLEY predictions



Result: 0*n*/1*n* Cross Sections

- Different spectrum of visible energy (gammas + lepton) for events with neutron emission (1*n*) compared to those without (0*n*)
  - Threshold for 1*n* emission events is 7.9 MeV compared to 0*n* threshold of 0.7 MeV
  - Plot intended to demonstrate difference in spectral shape, amplitudes arbitrary

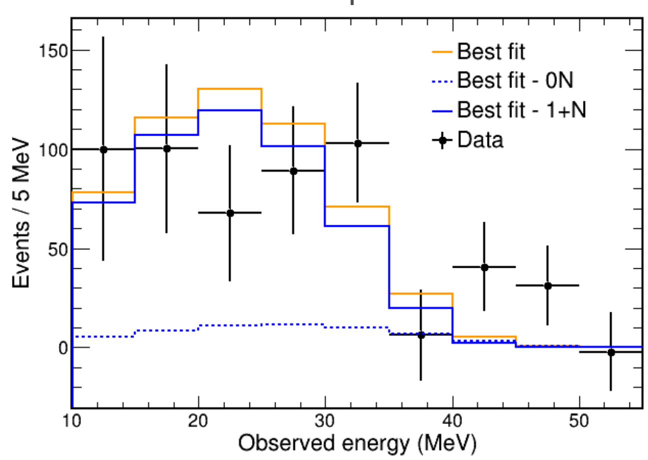
Sum energy of lepton + gamma from MARLEY (no detector effects)



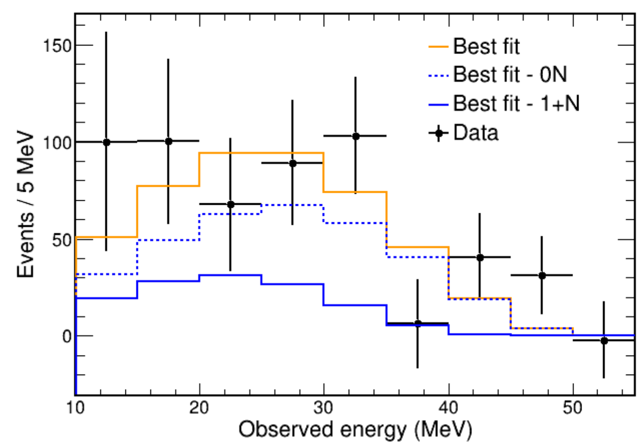
Result: 0*n*/1*n* Cross Sections

- After simulating events in detector geometry, 2D fit in energy and time allowing 0*n* and 1*n* amplitudes to float freely
- MARLEY predicts 10.6% events are 0*n*, data favors larger fraction (72.3%) of events are 0*n*
- 0*n* cross section: $\mathbf{5.2^{+3.4}_{-3.1} \times 10^{-40} cm^2}$
  - Compare to LAMPF measured value: $\mathbf{2.84 \pm 0.91}(\boldsymbol{stat}) \pm \mathbf{0.25}(\boldsymbol{sys})\times\mathbf{10^{-40}\,cm^2}$
- 1*n* cross section: $\mathbf{2.4^{+3.3}_{-2.4} \times 10^{-40} cm^2}$

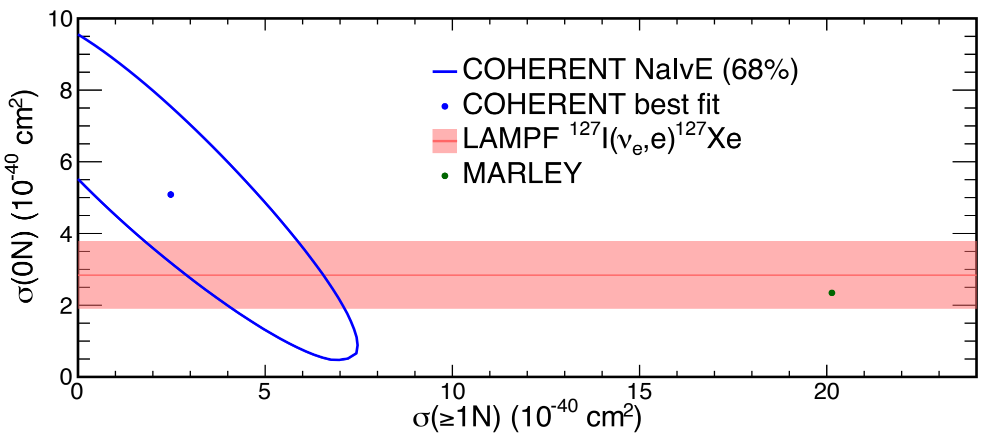
Nominal scaled MARLEY prediction: 10.6% 0*n* events

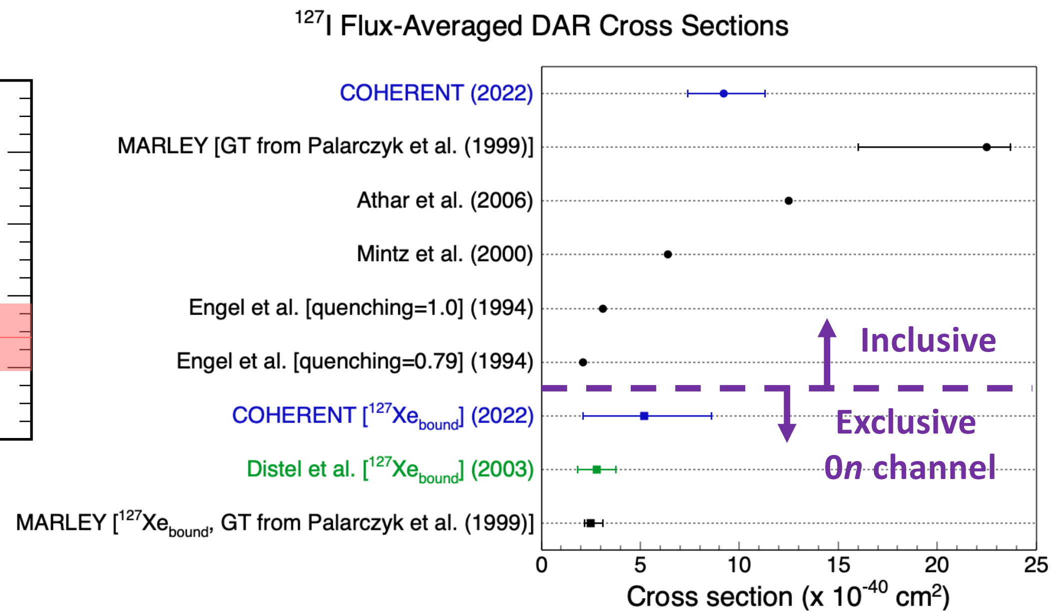


Best fit: 72.3% 0*n* events



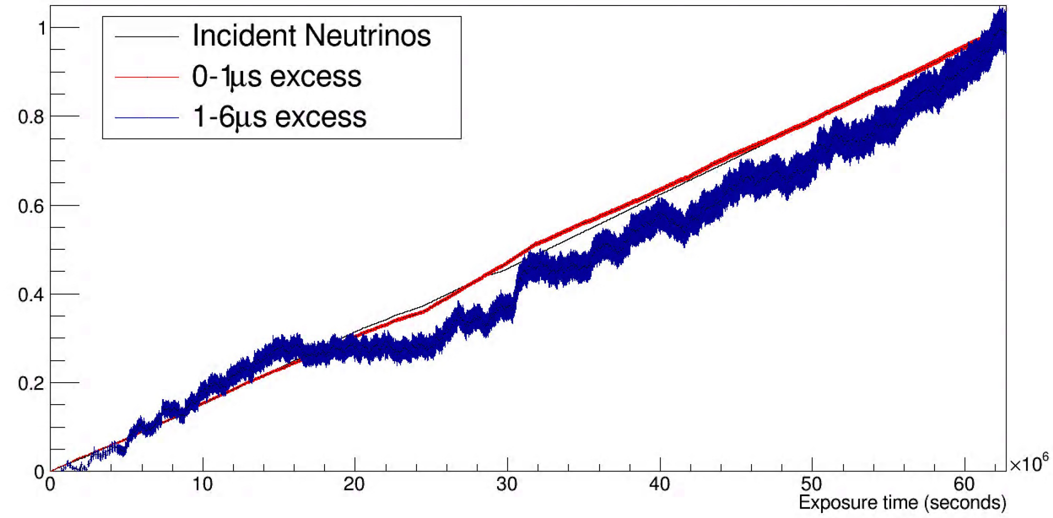
Comparison of Results





Post-Unblinding Checks

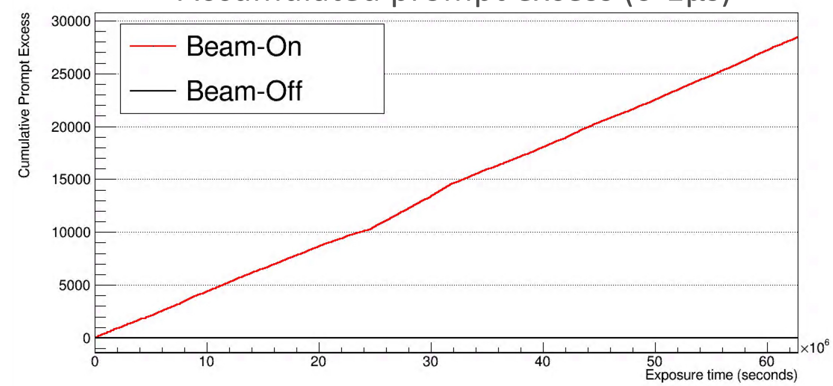
- K-S test shows good agreement between prompt and delayed excesses and delivered beam
  - With 1000 pseudo-experiments, K-S probabilities are 1.000 and 0.987 from prompt and delayed excesses



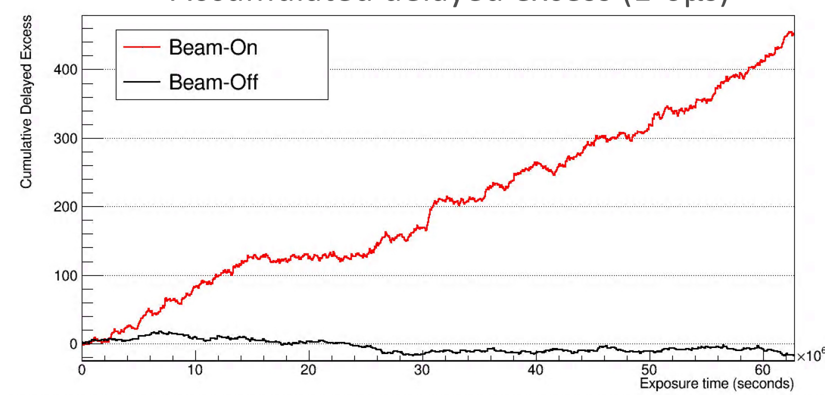
Post-Unblinding Checks

- K-S test shows good agreement between prompt and delayed excesses and delivered beam
  - With 1000 pseudo-experiments, K-S probabilities are 1.000 and 0.987 from prompt and delayed excesses
- No excess observed in prompt/delayed windows when beam not on target

Accumulated prompt excess (0-1μs)



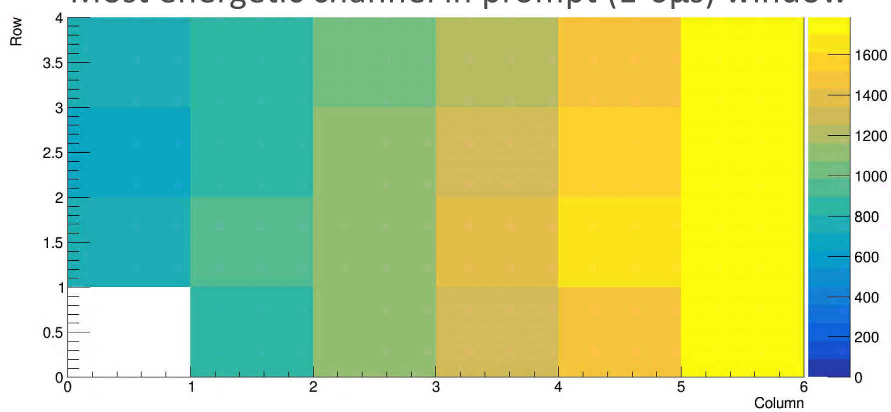
Accumulated delayed excess (1-6μs)



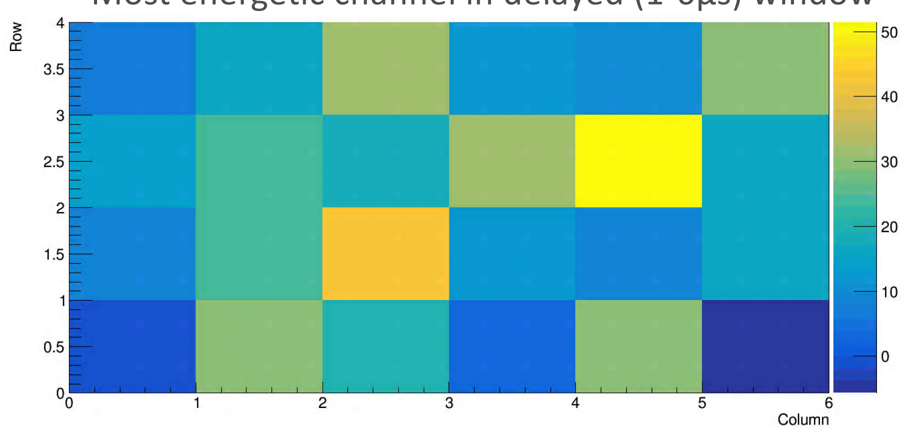
Post-Unblinding Checks

- K-S test shows good agreement between prompt and delayed excesses and delivered beam
  - With 1000 pseudo-experiments, K-S probabilities are 1.000 and 0.987 from prompt and delayed excesses
- No excess observed in prompt/delayed windows when beam not on target
- Some initial topology studies show neutrons incident on detector from side, do not see same pattern for delayed events
  - Helps understand BRN background for COHERENT's other detectors

Most energetic channel in prompt (1-6μs) window



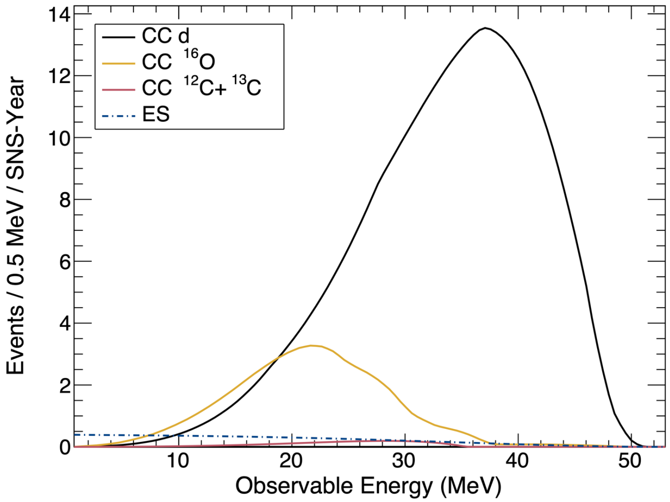
Most energetic channel in delayed (1-6μs) window



Future COHERENT Measurements

D_2O for Flux Normalization

- Neutrino flux one of largest uncertainties at SNS, ~10%
  - ν_e CC cross section on ^2H calculated to within 2-3%
- Deploying 600-kg D_2O detector measure flux, reduce uncertainties
- May also be able to measure ^{16}O charged-current events
  - Potentially useful for understanding supernova neutrinos interacting via this channel in large water detectors



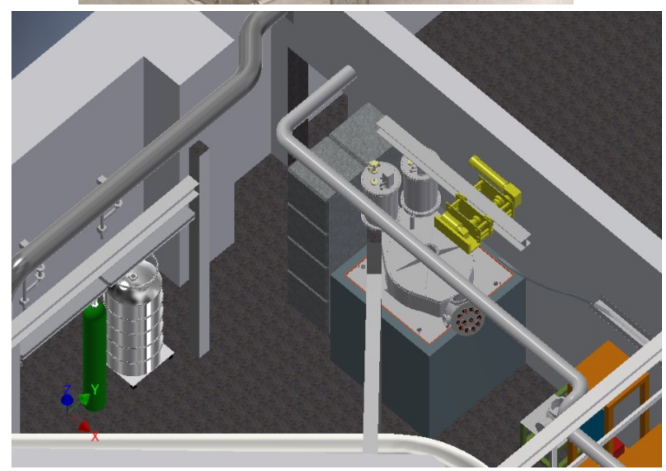
[arxiv:1910.00630.pdf]

CENNS-10/CENNS-750

- CENNS-10 single-phase liquid argon detector with 24-kg fiducial volume, deployed in 2016
  - Primary goal to measure CEvNS, data being studied to see what can be said about inelastic events on ^{40}Ar
- CENNS-750 upgrade in development, increase statistics and go after charged-current interactions on ^{40}Ar
  - Recent funding from Korea National Research Foundation (Jun 1, 2022)
  - Will study CEvNS, charged-current, and dark matter

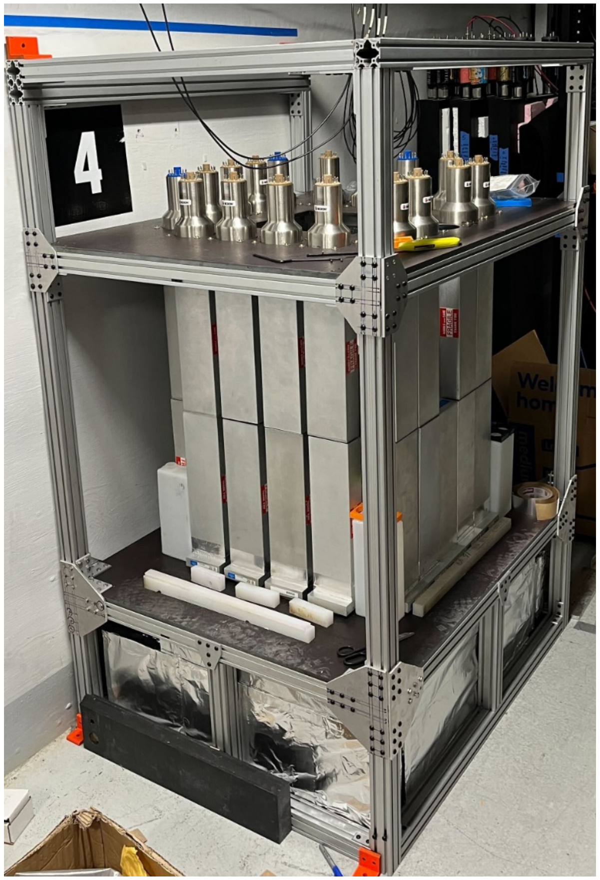
CENNS-10:

CENNS-750:



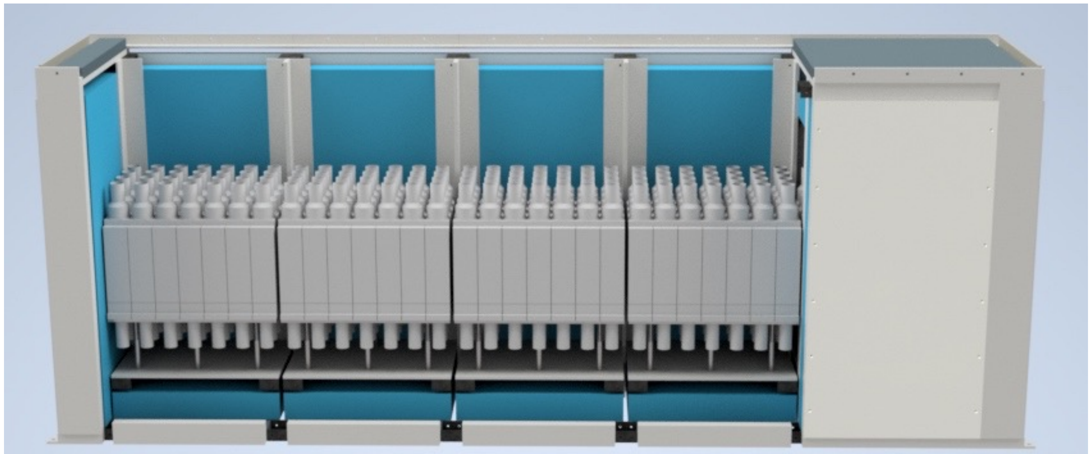
NuThor: Neutrino-Induced Fission

- Detector designed to study neutrino-induced fission, a long-theorized but never observed process
- Looks for neutrons from neutrino-induced fission through capture of gadolinium-doped water
- Initial data collection has started!



NaIvETe

- NaI neutrino Experiment TonnE-scale (**NaIvETe**)
- Ton-scale version of NaIvE-185, consisting of 315 NaI detectors (2,425 kg)
- Main goal is to measure CEvNS on ^{23}Na
- Space left in design to implement muon veto panel to enable charged-current measurement
- Better gamma shielding, water shielding, and improved statistics from larger mass, may be able to go after CC on ^{23}Na/^{27}Al as well



Summary

- COHERENT has results from its first searches for inelastic neutrino-nucleus scattering at the SNS
  - Lead neutrino cube reports NIN cross section on lead suppressed by factor $0.29^{+0.17}_{-0.17}$ compared with MARLEY model
  - NaIvE-185 reports cross section 40.9% lower than predicted
  - Shows need for improved understanding of uncertainties in nuclear models
- More analysis to be done on existing datasets:
  - 2*n* emission events for lead neutrino cube
  - NIN analysis for iron neutrino cube
  - Machine learning approach for NaIvE-185
- Suite of other detectors coming online in the next few years, should expand existing low-energy inelastic neutrino-nucleus measurements
  - D_2O for reducing flux uncertainty, ^{16}O CC events
  - NuThor for neutrino-induced fission on ^{232}Th
  - NaIvETe increase stats on ^{127}I CC, potentially $^{23}Na/^{27}Al$ CC as well
  - CENNS-750 for ^{40}Ar

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Thank you for your attention!