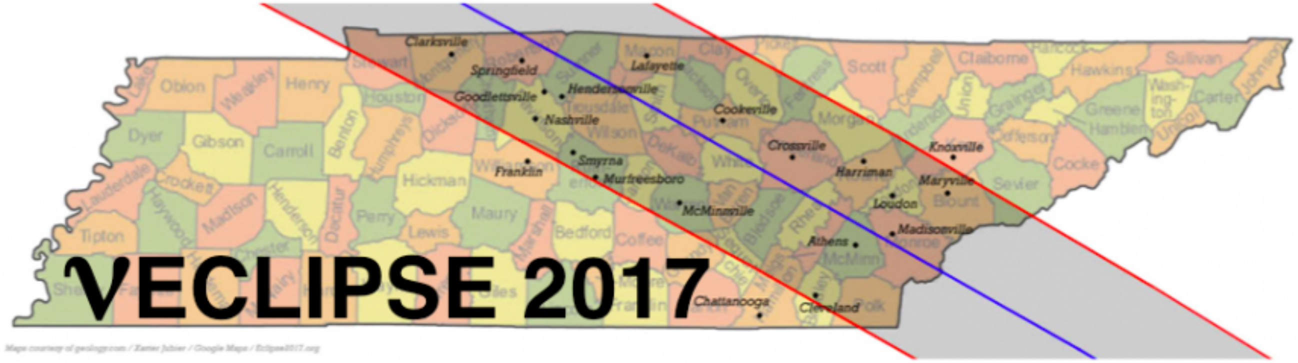


Charged-Current Interactions at the SNS

Samuel Hedges

8/22/17

Duke UNIVERSITY

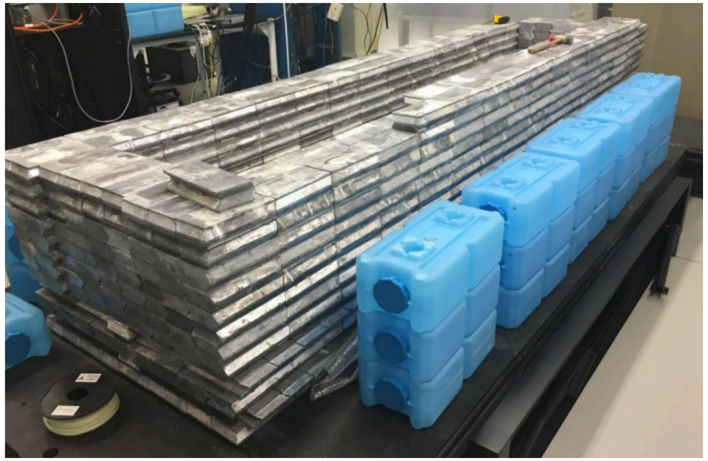
TUNL

COHERENT SNS

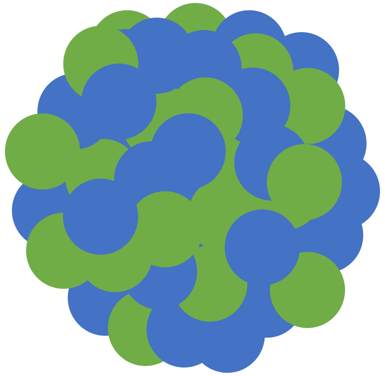
Motivation for studying charged-current interactions

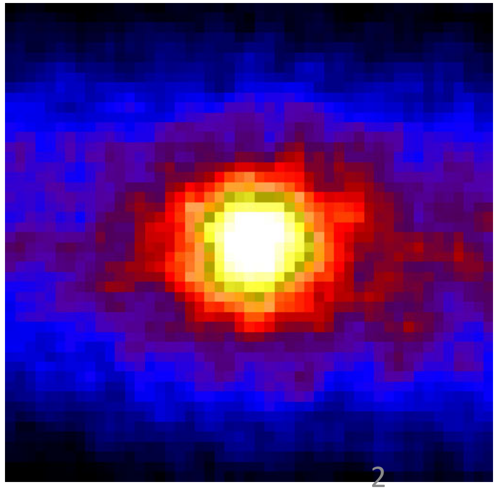
- Backgrounds induced in shielding
- Understanding supernova dynamics and nucleosynthesis
- Tests of nuclear models and excitations
- Evaluating materials for supernova and solar neutrino detection
- Limited number of similar measurements

$$\nu_e + \mathrm{n} \xrightarrow[\mathrm{W}^-]{} \mathrm{p} + \mathrm{e}^-$$



ESA/Hubble & NASA





R. Svoboda, K. Gordan, Super-K

Existing low-energy (1-300 MeV) υ-A measurements with terrestrial neutrino sources

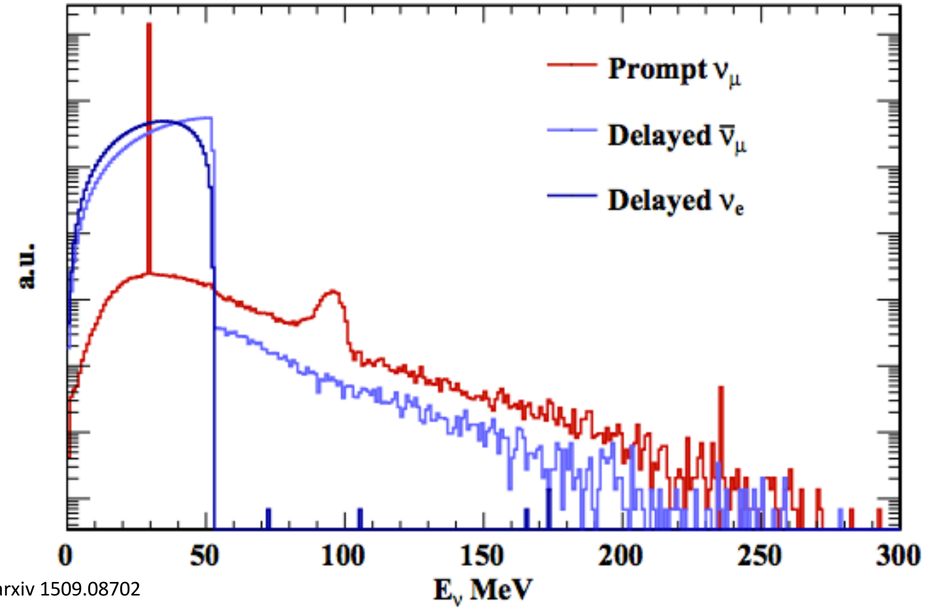
Isotope	Reaction Channel	Source	Experiment	Measurement (10^{-42} cm^2)	Theory (10^{-42} cm^2)
^{2}H*	$^2\mathrm{H}(\nu_e, e^-)pp$	Stopped π/μ	LAMPF	52 ± 18(tot)	54 (IA) (Tatara *et al.*, 1990)
^{12}C	$^{12}\mathrm{C}(\nu_e, e^-)^{12}\mathrm{N}_{\mathrm{g.s.}}$	Stopped π/μ	KARMEN	9.1 ± 0.5(stat) ± 0.8(sys)	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)
	$^{12}\mathrm{C}(\nu_e, e^-)^{12}\mathrm{N}^*$	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)	
	$^{12}\mathrm{C}(\nu_\mu, \nu_\mu)^{12}\mathrm{C}^*$	Stopped π/μ	KARMEN	3.2 ± 0.5(stat) ± 0.4(sys)	2.8 [CRPA] (Kolbe *et al.*, 1999b)
	$^{12}\mathrm{C}(\nu, \nu)^{12}\mathrm{C}^*$	Stopped π/μ	KARMEN	10.5 ± 1.0(stat) ± 0.9(sys)	10.5 [CRPA] (Kolbe *et al.*, 1999b)
	$^{12}\mathrm{C}(\nu_\mu, \mu^-)\mathrm{X}$	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)
	$^{12}\mathrm{C}(\nu_\mu, \mu^-)^{12}\mathrm{N}_{\mathrm{g.s.}}$	Decay in Flight	LSND	56 ± 8(stat) ± 10(sys)	68-73 [CRPA] (Kolbe *et al.*, 1999b)
					56 [Shell] (Hayes and S, 2000)
^{56}Fe	$^{56}\mathrm{Fe}(\nu_e, e^-)^{56}\mathrm{Co}$	Stopped π/μ	KARMEN	256 ± 108(stat) ± 43(sys)	264 [Shell] (Kolbe *et al.*, 1999a)
^{71}Ga	$^{71}\mathrm{Ga}(\nu_e, e^-)^{71}\mathrm{Ge}$	^{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	$^{127}\mathrm{I}(\nu_e, e^-)^{127}\mathrm{Xe}$	Stopped π/μ	LSND	284 ± 91(stat) ± 25(sys)	210-310 [Quasi-particle] (Engel *et al.*, 1994)

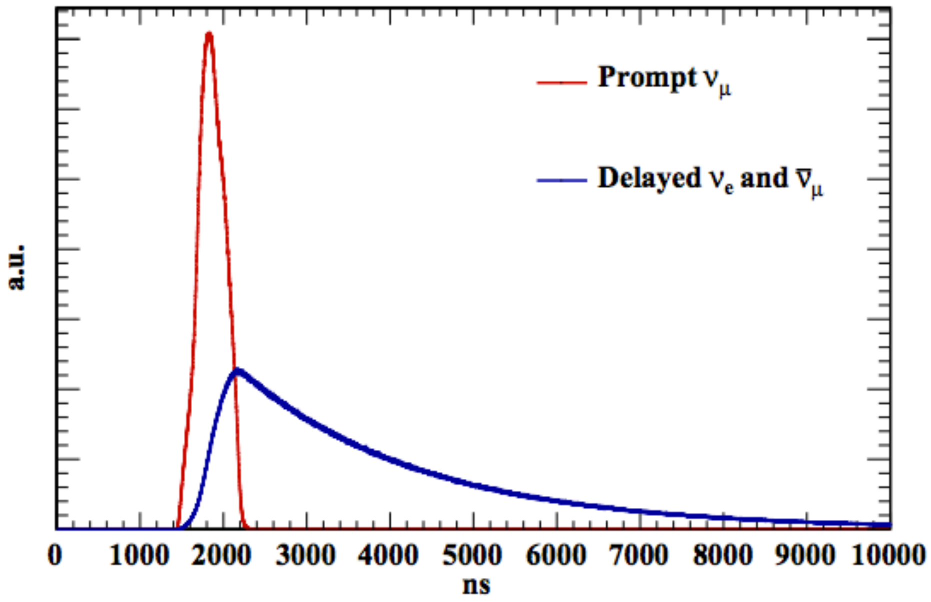
* Many more measurements on deuterium with reactor neutrinos

J. A. Formaggio and G. P. Zeller Rev. Mod. Phys. 84, 1307

Charged-current interactions at the SNS

- Neutrino energy at SNS comparable to supernova energies
- Timing distribution helps reduce backgrounds
- Can study both charged-current and neutral-current interactions
- High flux source of neutrinos
- Not the first to suggest these types of measurements at the SNS
- COHERENT collaboration has deployed three experiments to study these interactions





The COHERENT collaboration arxiv 1509.08702

Charged-current reaction in ^{127}I

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

- ^{127}I as potential for a solar/supernova neutrino detector (Haxton 1988)
- Experimental test of low energy CC interactions in a medium-heavy size nucleus
- Neutrino energy threshold of 789 keV
- Radiochemical approach used at LAMPF to measure flux-averaged cross section of

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

- Particle threshold in ^{127}I of 7.23 MeV
    - Can't use radiochemical approach to detect CC interaction on ^{127}I when final state not ^{127}Xe

W. C. Haxton Phys. Rev. Lett. 60, 768

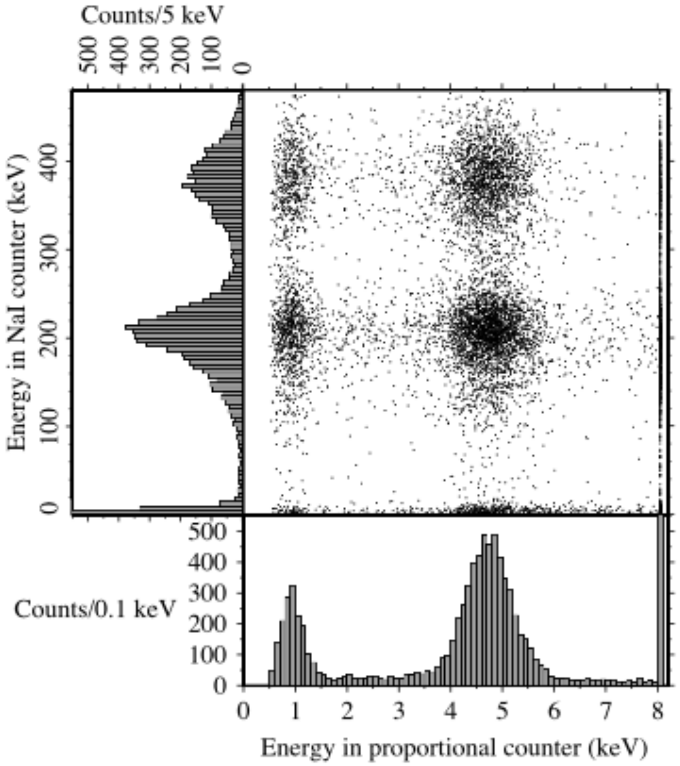
J. R. Distel, B. T. Cleveland, K. Lande, C. K. Lee, P. S. Wildenhain, G. E. Allen, and R. L. Burman Phys. Rev. C 68, 054613

LAMPF measurement

- Similar to Homestake radiochemical approach for measuring CC on ^{37}Cl from solar neutrinos
- Tank of NaI (1540kg of ^{127}I) 8.5m from beam stop, 300+ day exposure
- ^{127}Xe decays exclusively to excited ^{127}I states:

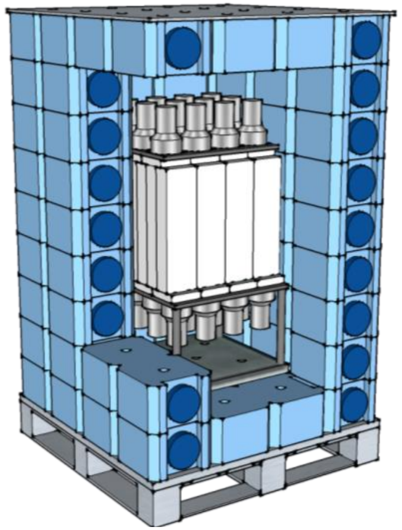
$$^{127}\mathrm{Xe} \rightarrow {}^{127}\mathrm{I}^{*} + \gamma \text{ (203, 375 keV)}$$
$$^{127}\mathrm{I}^{*} \rightarrow {}^{127}\mathrm{I} + e^{-} \text{ (~0.9, 4.7 keV)}$$

- Background processes also produce ^{127}Xe: cosmic rays, fast/slow neutrons, energetic alphas

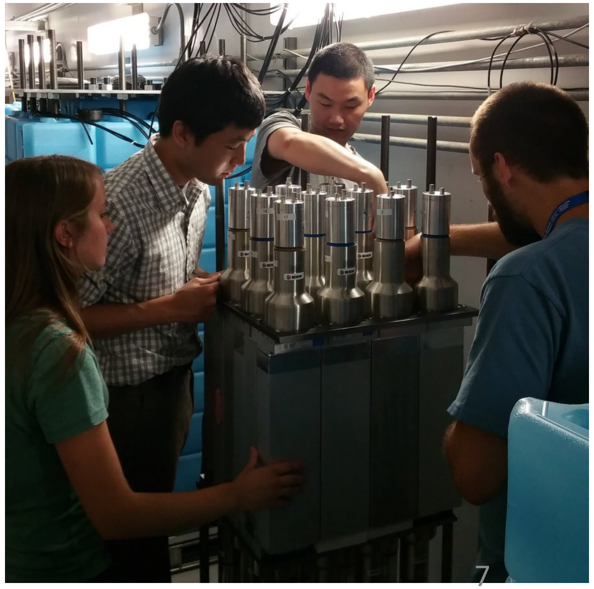


J. R. Distel, B. T. Cleveland, K. Lande, C. K. Lee, P. S. Wildenhain, G. E. Allen, and R. L. Burman Phys. Rev. C 68, 054613

NaIνE—A 185kg prototype detector



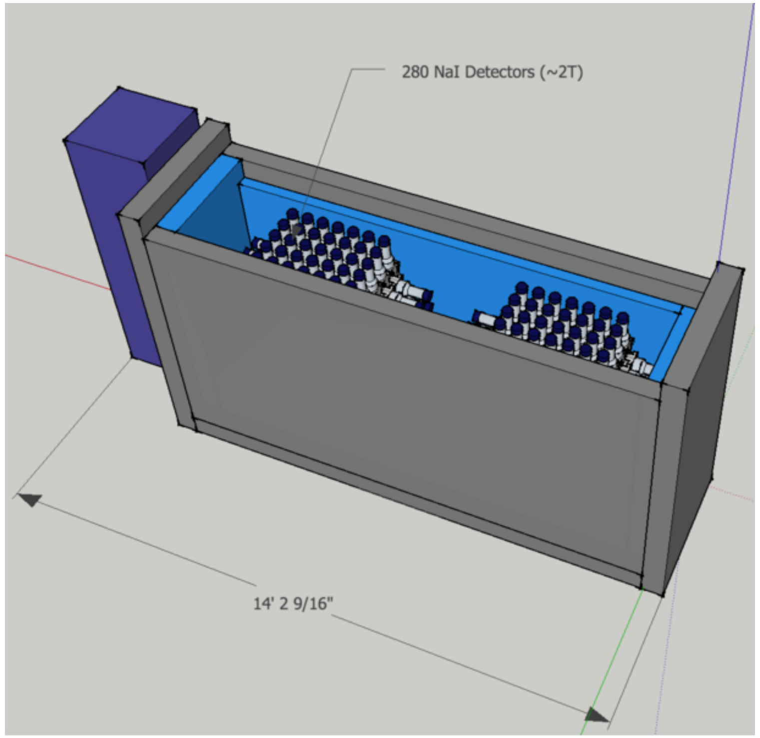
- Development of detector was thesis project of Ben Suh
- Measures outgoing lepton in CC interactions in energy range of interest (~1-52 MeV)
    - Segmented design can give some positional information
    - No requirement on final state of ^{127}I nucleus
    - Uses timing, energy, detector multiplicity to reject backgrounds (muons)
- Running in production mode since November 2016
- 0.25 counts/crystal/month predicted
- Currently operating in self-vetoing configuration: identify muons as high-multiplicity events, look at central 8 detectors for CC interaction
    - Deployment of muon vetos will reduce backgrounds, include all 24 crystals as fiducial mass



Ben Suh, Measuring the 127I, ν_e Charged-Current Cross-Section of NaI[Tl], 2016

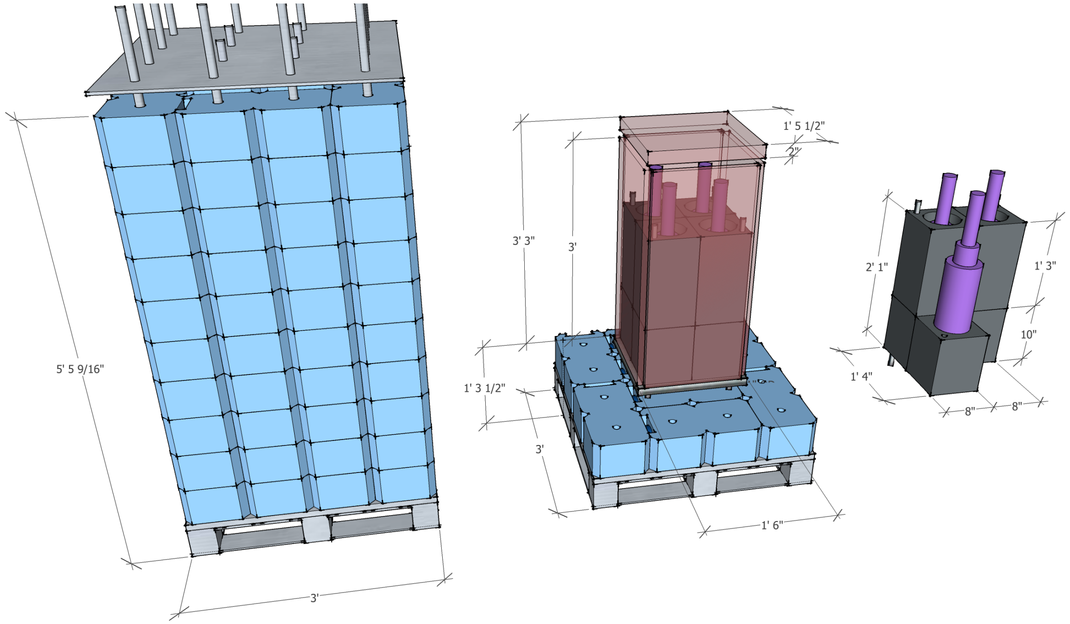
Opportunities with a larger detector: NaI 2-ton

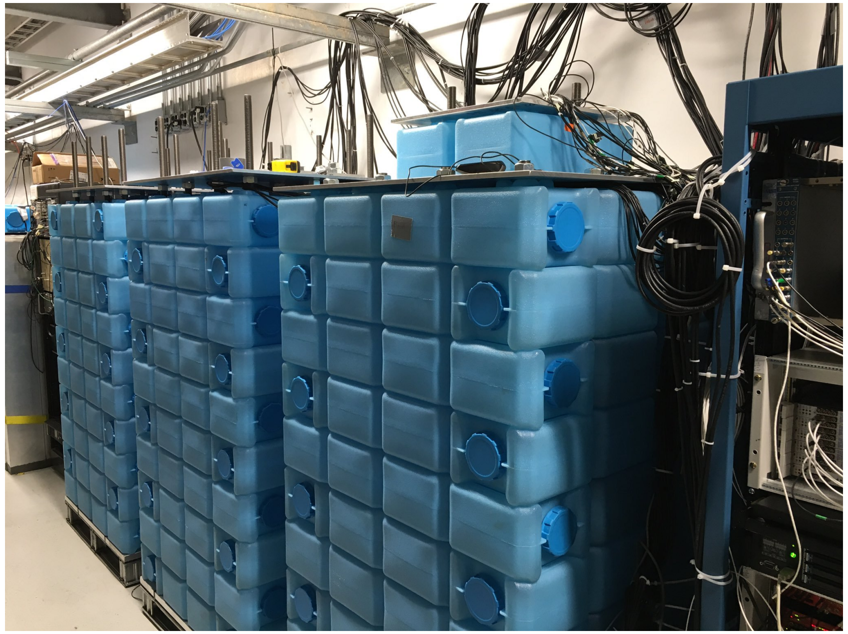
- Dual outputs allow observation of low energy CEvNS events (~3-100 keV) and higher energy charged-current events (<52.8 MeV)
- Allows dual measurement of electron-neutrino process and flavor-blind process
- ^{127}Xe decays with half-life of 36.4 days, may not be useful for tagging CC events
  - Should be able to measure ^{127}Xe content from decays, but need to understand production from background sources, DAQ considerations



The Neutrino Cubes: CC and NC Interactions

- Designed by Grayson Rich, palletized neutrino detectors with switchable targets
- PSD capable liquid scintillators surrounded by target mass
- Look for neutrons produced in CC and NC events above particle threshold
- Muon vetos reduce backgrounds, water shielding reduces thermal neutrons

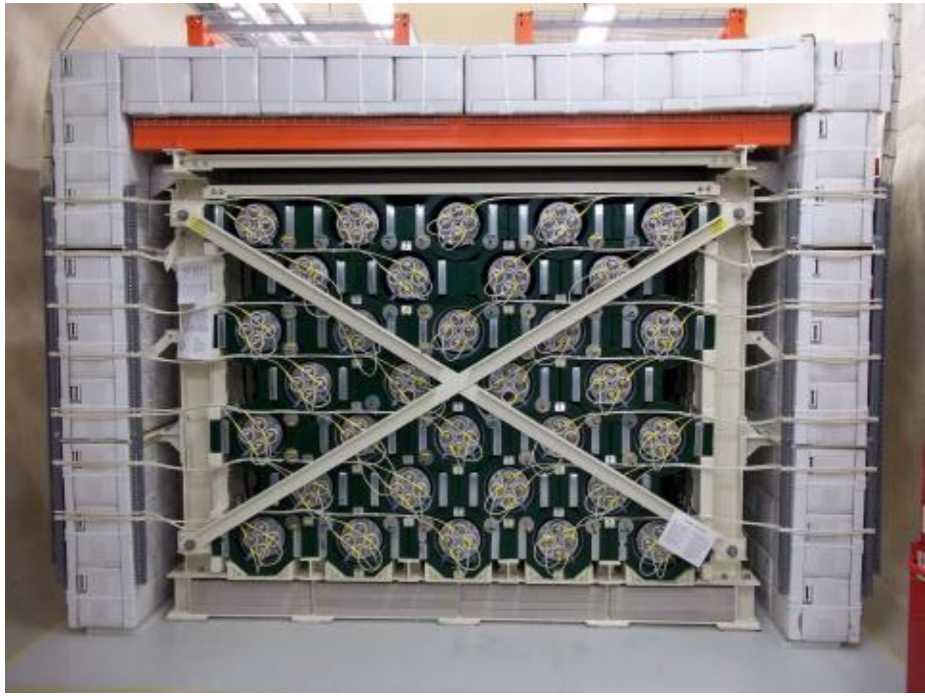




Charged-Current reaction in ^{208}Pb

$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Bi}^{*} + e^{-}$$

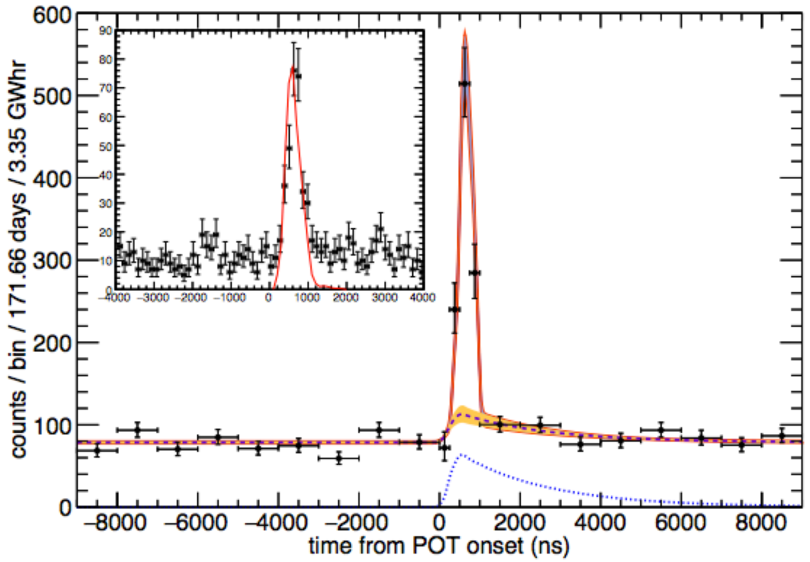
- Bi^* can de-excite via emission of gammas, neutrons, protons
- Common shielding material
- High Z, expected large CC cross-section
- Test nuclear models for heavy nucleus
- Improve understanding of SN dynamics
- Spectroscopic information about neutrino energy may be possible from number of neutrons
    - Never measured, important for existing experiments
- Neutron emission threshold of 6.9 MeV in ^{208}Bi
- Two neutron emission possible for ν_e > 14.98 MeV

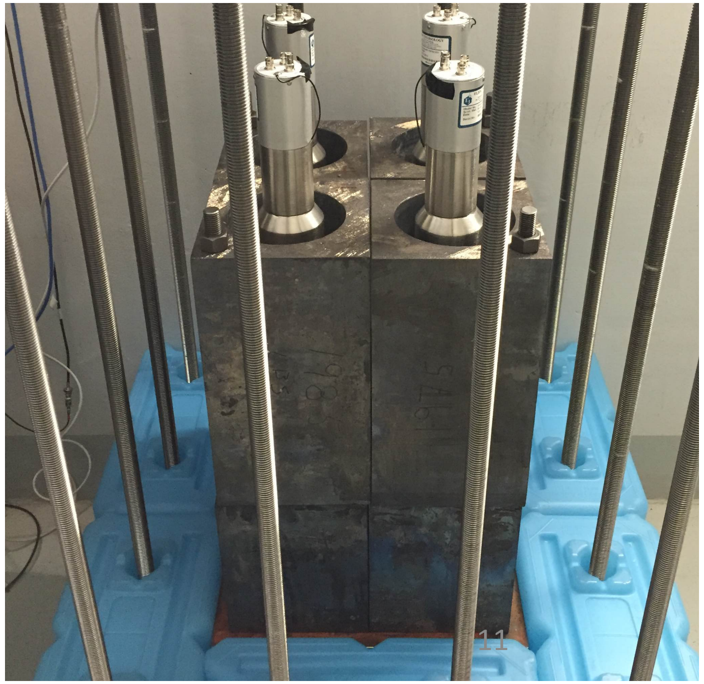


http://www.triumf.ca/research-highlights/experimental-result/halo-operational-snolab

The Lead Neutrino Cube

- Nearly 1-ton of ^{208}Pb
- Data acquisition started in early 2016, ongoing
- Expect most of signal to come from CC interaction, neutrons in delayed window
- Try to reconstruct neutron spectrum, 1n vs 2n events
- COHERENT has preliminary measurement from LS cell in CsI detector's shielding





(T,α)	(4,0)	(6,0)	(8,0)	(10,0)	(3,3)	(4,3)	(6.26,3)
$^{208}\mathrm{Pb}(\nu_e,e^-\gamma)^{208}\mathrm{Bi}$	4.7 (1)	1.3 (2)	2.5 (2)	4.0 (2)	3.5 (1)	7.6 (1)	2.2 (2)
$^{208}\mathrm{Pb}(\nu_e,e^-\mathrm{n})^{207}\mathrm{Bi}$	2.3 (2)	9.9 (2)	2.3 (3)	4.0 (3)	1.2 (2)	4.2 (2)	1.9 (3)
$^{208}\mathrm{Pb}(\nu_e,e^-\mathrm{p})^{207}\mathrm{Pb}$	1.8 (-2)	1.1 (-1)	3.3 (-1)	6.9 (-1)	7.2 (-3)	3.3 (-2)	2.3 (-1)
$^{208}\mathrm{Pb}(\nu_e,e^-\alpha)^{204}\mathrm{Tl}$	2.1 (-2)	2.6 (-1)	1.1 (0)	3.0 (0)	4.7 (-3)	4.1 (-2)	6.0 (-1)
$^{208}\mathrm{Pb}(\nu_e,e^-)\mathrm{X}$	2.8 (2)	1.1 (3)	2.5 (3)	4.5 (3)	1.6 (2)	4.9 (2)	2.1 (3)

E Kolbe, K Langanke, G Martínez-Pinedo, and P Vogel Journal of Physics G: Nuclear and Particle Physics, Volume 29, Number 11
D. Akimov, et al. COHERENT collaboration 2017

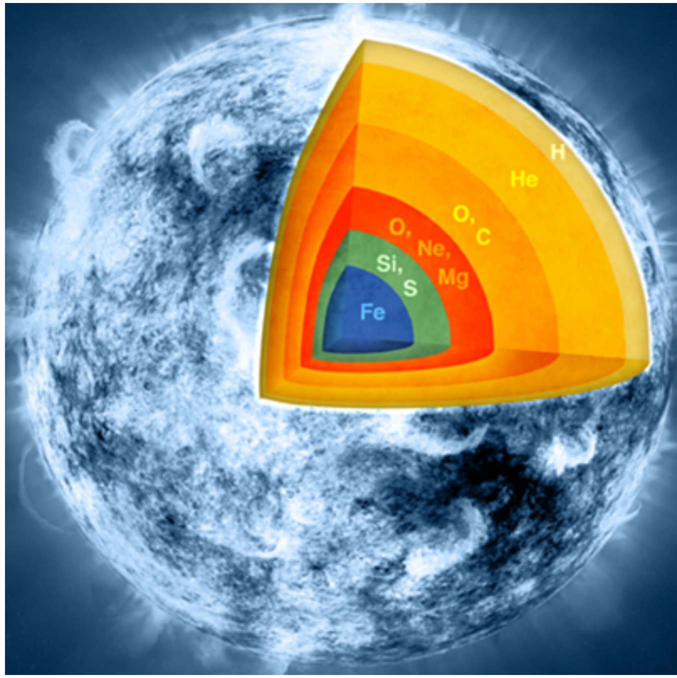
Charged-Current reaction in ^{56}Fe

$$\nu_e + {}^{56}\mathrm{Fe} \rightarrow {}^{56}\mathrm{Co}^* + e^-$$

- Co^* can de-excite via emission of gammas, neutrons, protons
- Important for supernova dynamics during core collapse
- Use as a supernova neutrino detector
  - Neutron production rate can provide information on SN neutrino energy
  - Understanding response to CC and NC interactions useful for identifying neutrino flavor
- Common shielding material
  - KARMEN saw bremsstrahlung of charged-current lepton interacting in their shielding
  - Report cross section of

$$2.51 \pm 0.83 \pm 0.42 \times 10^{-40}$$

- For CC, proton threshold of 5.85 MeV, neutron threshold of 10.08 MeV
  For NC, proton threshold of 10.18 MeV, neutron threshold of 11.2 MeV



http://insider.si.edu/2012/03/remains-of-exploded-star-indicate-supernova-turned-it-inside-out/

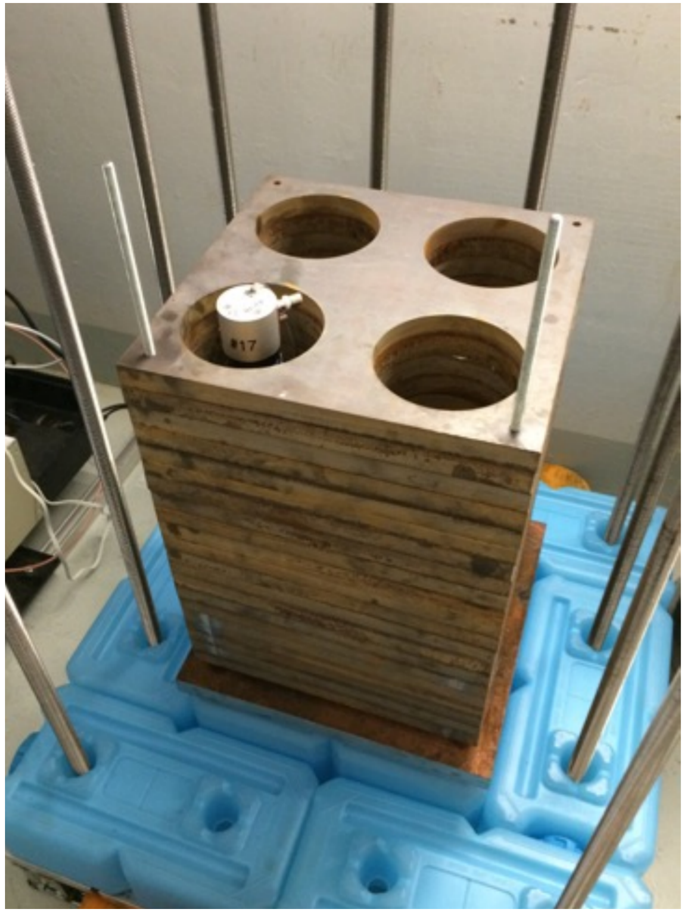
R.Maschuw, et al., KARMEN collaboration Progress in Particle and Nuclear Physics Volume 40, 1998

The Iron Neutrino Cube

- Nearly 700kg of iron
- Liquid scintillators with PSD looking for low energy neutrons
- Partial deployment in February 2017, full configuration in July 2017
- Looking for gammas/neutrons produced in CC, NC interactions
  - May be able to see bremsstrahlung gammas for events near liquid scintillators

(T, α)	(4, 0)	(6, 0)	(8, 0)	(10, 0)	(3, −3)	(4, −3)	(6.26, −3)
^{56}Fe(ν_e, e$^-\gamma$)^{56}Co	9.8 (0)	3.1 (1)	6.1 (1)	1.3 (2)	7.7 (0)	2.1 (1)	7.5 (1)
^{56}Fe(ν_e, e$^-$ n)^{55}Co	7.5 (−1)	8.0 (0)	3.2 (1)	8.1 (1)	2.5 (−1)	1.7 (0)	2.0 (1)
^{56}Fe(ν_e, e$^-$ p)^{55}Fe	5.4 (0)	3.2 (1)	9.7 (1)	1.7 (2)	9.2 (−1)	5.1 (0)	4.7 (1)
^{56}Fe(ν_e, e$^-\alpha$)^{52}Mn	6.1 (−2)	9.7 (−1)	4.8 (0)	1.5 (1)	3.0 (−2)	2.1 (−1)	2.9 (0)
^{56}Fe(ν_e, e$^-$)X	1.6 (1)	7.2 (1)	1.9 (2)	4.0 (2)	8.9 (0)	2.8 (1)	1.4 (2)

(T, α)	(4, 0)	(6, 0)	(8, 0)	(10, 0)	(3, −3)	(4, −3)	(6.26, −3)
^{56}Fe(ν, $\nu'\gamma$)^{56}Fe	2.5 (0)	9.8 (0)	1.7 (1)	2.8 (1)	1.2 (0)	4.4 (0)	1.6 (1)
^{56}Fe(ν, ν' n)^{55}Fe	8.9 (−1)	6.7 (0)	2.2 (1)	5.0 (1)	2.8 (−1)	1.7 (0)	1.4 (1)
^{56}Fe(ν, ν' p)^{55}Mn	1.2 (−1)	1.0 (0)	3.6 (0)	9.3 (0)	3.4 (−2)	2.3 (−1)	2.2 (0)
^{56}Fe(ν, $\nu'\alpha$)^{52}Cr	2.4 (−2)	1.9 (−1)	6.6 (−1)	1.7 (0)	6.4 (−3)	4.4 (−2)	4.0 (−1)
^{56}Fe(ν, ν')X	3.6 (0)	1.8 (1)	4.3 (1)	8.9 (1)	1.5 (0)	6.3 (0)	3.3 (1)



E Kolbe, K Langanke, G Martínez-Pinedo, and P Vogel Journal of Physics G: Nuclear and Particle Physics, Volume 29, Number 11

Future Prospects for the Neutrino Cubes

- Data collection, analysis, and simulation ongoing
  - Students at Duke, UNC, UT Knoxville
- Increase neutron detection rate with more mass and detectors
- Explore other configurations to gain information from CC lepton as well as nuclear de-excitations
- Neutrino cubes designed to have target material be switchable, cost of material and scientific relevance to dictate future measurements

Potential future CC measurements at the SNS

- Carbon: $\nu_{\mathrm{e}} + {}^{12}\mathrm{C} \ \rightarrow {}^{12}\mathrm{N} + e^{-}$
  - Useful for normalizing neutrino cross sections, flux
  - ^{12}N decays with half-life of 11ms via high energy positron emission
  - Neutrino energy threshold high, but possible at SNS
  - Neutral current interaction has excited state emitting 15.11 MeV gamma
- Oxygen: $\nu_{\mathrm{e}} + {}^{16}\mathrm{O} \ \rightarrow {}^{16}\mathrm{F} + e^{-}$
  - Light nuclei, useful for SN dynamics, existing/future detectors, directional information
  - ^{16}F decays with beta or beta + gamma with half-life of 7.13 seconds
  - Neutrino energy threshold high, but possible at SNS
  - In NC interaction, following particle emission (n, p) have ^{15}F or ^{15}O decay with high energy gammas
  - Sensitive to isotope abundance: 0.2% ^{18}O makes ~10% of total cross section for solar neutrinos
- Sodium: $\nu_{\mathrm{e}} + {}^{23}\mathrm{Na} \ \rightarrow {}^{23}\mathrm{Mg} + e^{-}$
  - Less theoretical work done for this, may be capable of measuring in 2-ton NaI[Tl] detector
  - 11 second decay time of ^{23}Mg, ~3 MeV positron followed by annihilation—help determine detector efficiency at identifying CC produced leptons
- Argon: $\nu_{\mathrm{e}} + {}^{40}\mathrm{Ar} \ \rightarrow {}^{40}\mathrm{K} + e^{-}$
  - Useful for DUNE
  - See previous talks
- …

Conclusion

- SNS an ideal source of neutrinos for CC and NC interactions near supernova energies
- Three experiments running looking at non-CEvNS neutrino interactions at the SNS
  - Neutrino cubes: Brandon Becker (UT Knoxville), Mayra Cervantes (Duke), Justin Raybern (Duke), Grayson Rich (UNC), Gleb Sinev (Duke)
  - Sodium Iodide: Abasi Brown (NCCU), Eric Erkela (UW), Shalane Hairston (NCCU), Daniel Salvat (UW), Benjamin Suh (U. Indiana)
- Many ideas for future measurements
- SNS and ORNL a big help in getting these deployed

Thank you!