Low energy inelastic neutrino-nucleus interactions at the SNS

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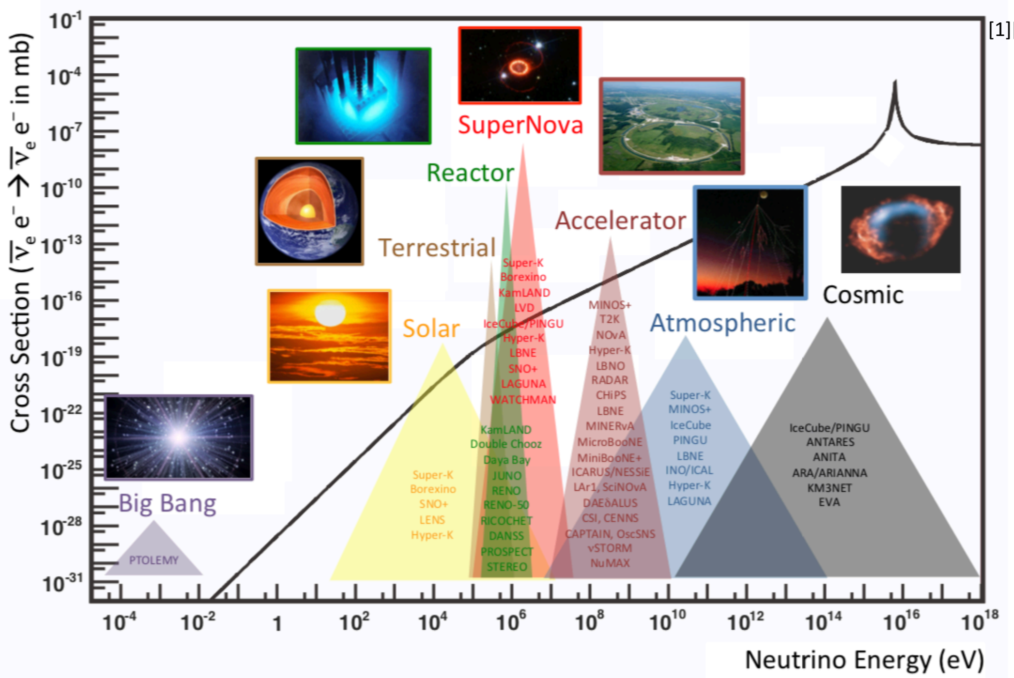
NuFact 2018
8/16/2018

Outline

1. Motivation
2. COHERENT Collaboration
3. The Spallation Neutron Source
4. Inelastic Measurements at the SNS:
    1. ^{208}Pb
    2. ^{56}Fe
    3. ^{127}I
5. Summary and Outlook

Low Energy Neutrino-Nucleus Interactions

- Many sources can produce neutrinos with energies less than a few hundred MeV
  - Accelerator
  - Supernova
  - Reactor
  - Terrestrial
  - Solar
- Can have large fluxes through detectors, but cross sections low
- Neutrino-nucleus interactions can be a useful tool to study these sources



[1][2]

Low Energy Neutrino-Nucleus Interactions

- Neutrino-nucleus interactions important for:
  - Understanding supernova dynamics
  - Supernova detection
  - Interpreting oscillation experiments
  - Tests of nuclear models, g_A quenching
- Only a handful of low energy neutrino-nucleus measurements have been made

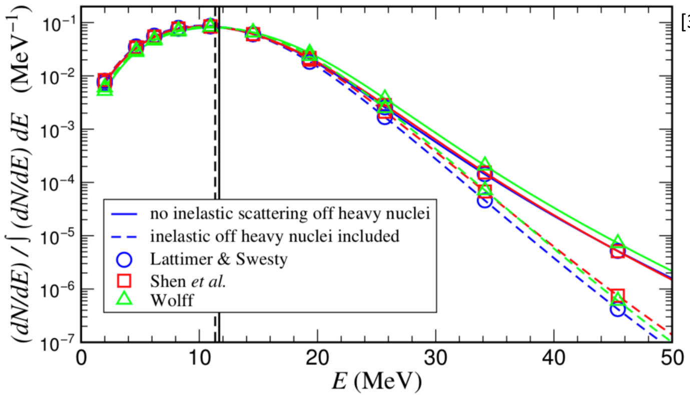
Measured neutrino-nucleus cross sections,
$E_\nu < 300$ MeV, terrestrial sources

[1]

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

Supernova Dynamics

- Neutrino-nucleus interactions can:
  - Cause nuclei to emit particles (protons, neutrons, alphas) altering nuclear abundances generated in a supernova
  - Contribute to neutrino thermalization rate
  - Modify neutrino spectrum emitted by supernova



[3]

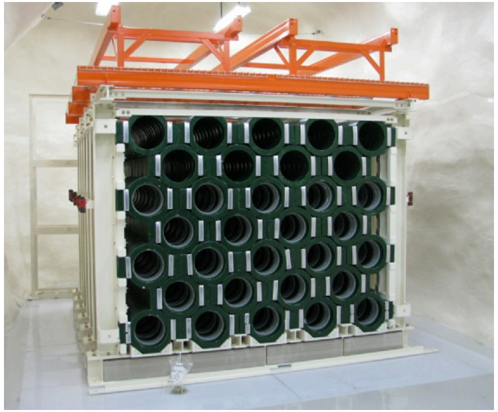
Material	$\langle\sigma\rangle$ (10^{-42} cm^2) With IS	$\langle\sigma\rangle$ (10^{-42} cm^2) Without IS	Reduction
e	0.114	0.123	7%
d	5.92	7.08	16%
^{12}C	0.098	0.17	43%
^{12}C (N_{gs})	0.089	0.15	41%
^{16}O	0.013	0.031	58%
^{40}Ar	17.1	21.5	20%
^{56}Fe	8.81	12.0	27%
^{208}Pb	147.2	201.2	27%

[3]

Supernova Detection

- Supernova interactions can be studied with nuclei in current, future detectors:

HALO—^{208}Pb

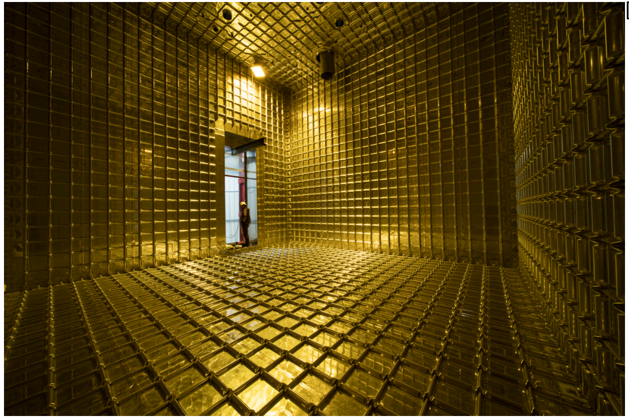


[4]

LVD—^{56}Fe

[5]

DUNE—Ar



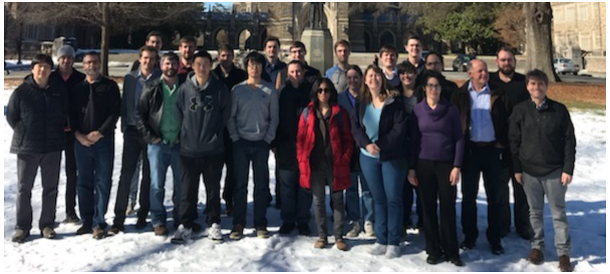
[6]

  – Also water cerenkov detectors (^{16}O), LS detector (^{12}C)

COHERENT

The COHERENT Collaboration

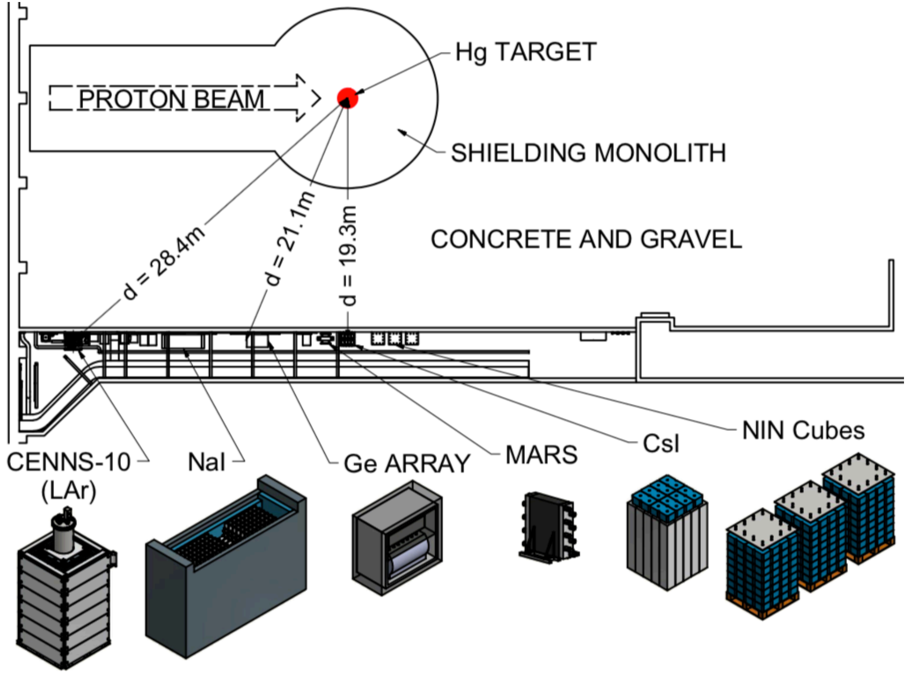
- ~80 members from 18 institutions in 4 countries
- Formed to observe CEνNS in a variety of targets: CsI, Na, Ar, Ge
  - Also measuring charged-current interactions on Pb, Fe, I, …
- Uses neutrinos produced at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL), Tennessee



The COHERENT Collaboration

- Detectors located 20-30m from the liquid Hg target at the SNS
  - Much of the space between filled with concrete/gravel, reduces neutron background
  - Several past and current detectors deployed measuring neutron background

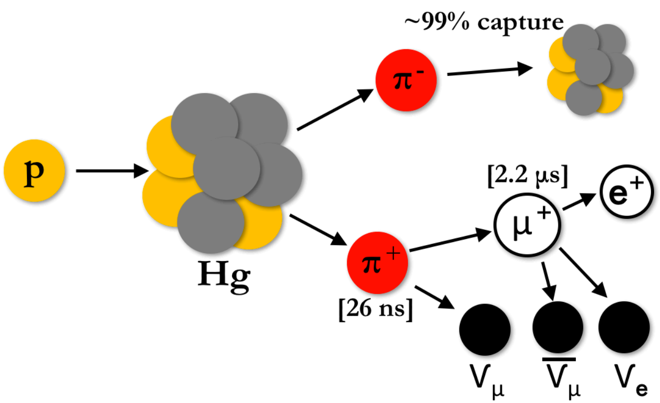
[7]

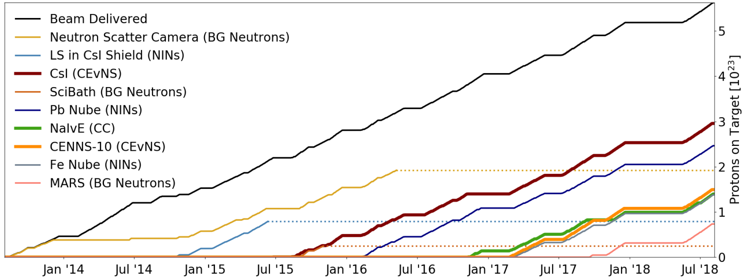


The Spallation Neutron Source (SNS)

The Spallation Neutron Source

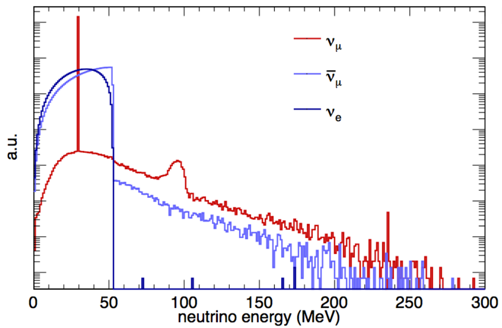
- Stopped-pion source
  - Electron, muon, and anti-muon neutrinos
- High neutrino flux
  - COHERENT's detectors get ~$4.3 \times 10^7\ \nu/\mathrm{cm}^2/\mathrm{sec}$ (20 m from source)
  - In 308.1 live-days, 1.76 x 10^{23} protons-on-target (~1/3 g)





The Spallation Neutron Source

- Energy in similar range as supernova neutrino spectrum
- Electron and anti-muon neutrino timing dictated by muon decay
  - Reduces beam-related backgrounds
- ~1 μs proton pulses with 60 Hz repetition rate reduces backgrounds



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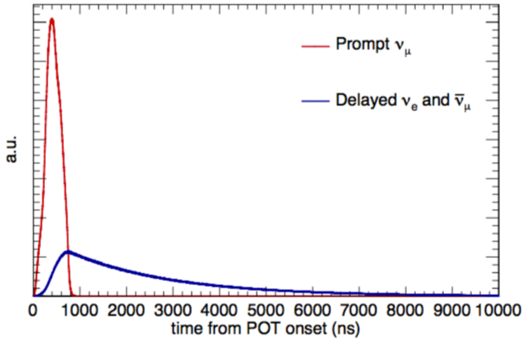
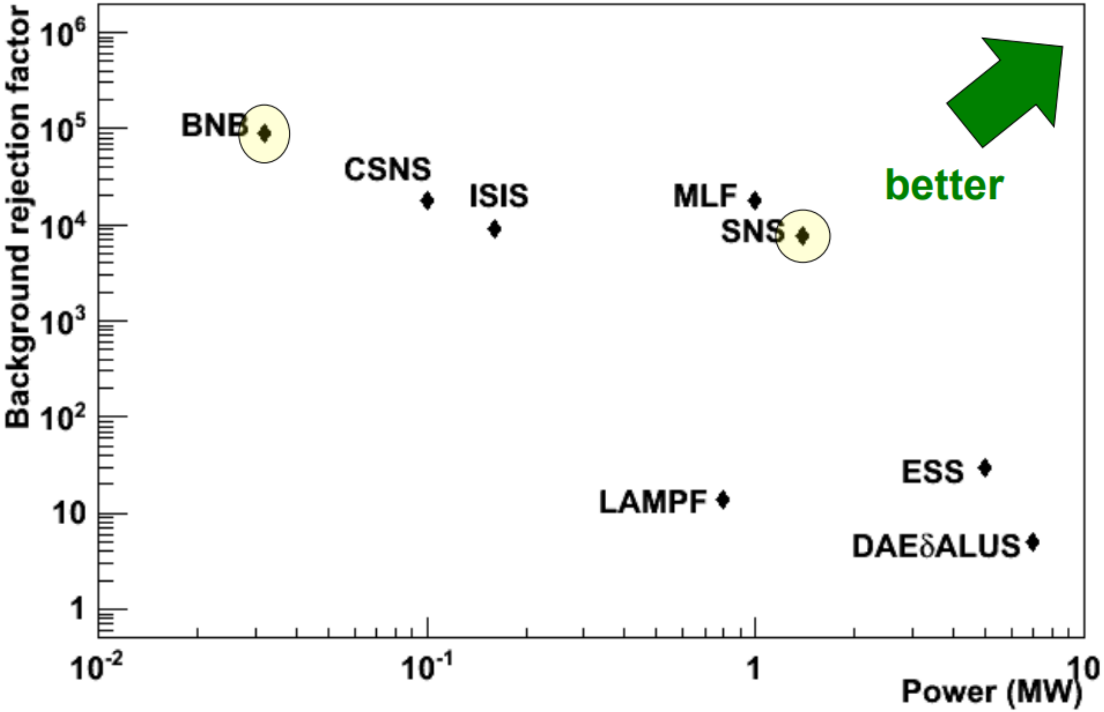


The Spallation Neutron Source



Neutrino-Nucleus Interactions on ^{208}Pb

Neutrino-Nucleus Interactions on ^{208}Pb

- Original interest for COHERENT to study neutrino-induced neutrons background from lead:
  - Lead a common shielding material in low-background experiments
  - Neutrinos can interact in lead can produce excited nuclei that can de-excite through neutron emission
  - Neutrons will have timing structure of neutrinos, similar energy depositions
- Calculated 1n and 2n cross sections (in units of 10^{-42} cm^2) as a function of neutrino energy from [9], but never measured

$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Bi}^{*} + e^{-}$$ [8]

$$\Downarrow$$

$$^{208-y}\mathrm{Bi} + x\gamma + yn$$

$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Pb}^{*} + \nu_x'$$

$$\Downarrow$$

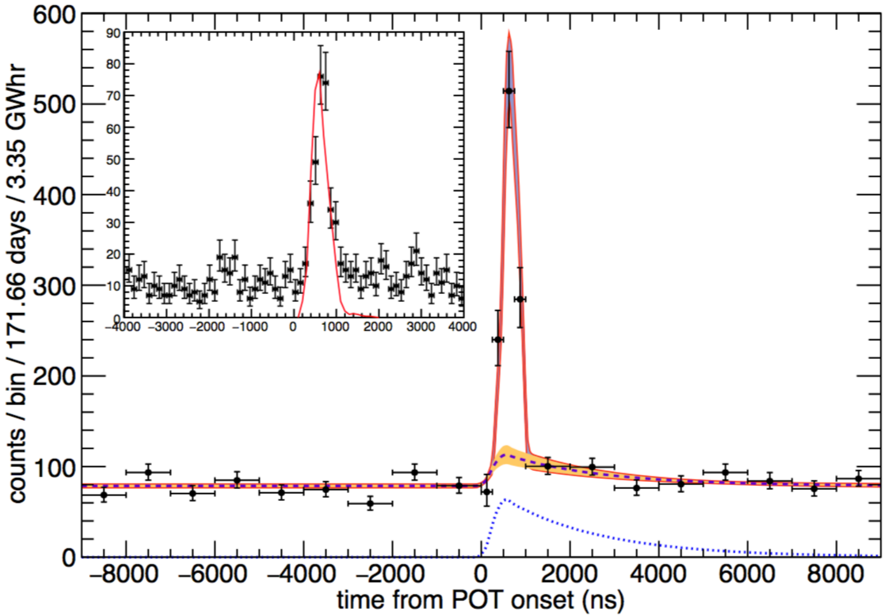
$$^{208-y}\mathrm{Pb} + x\gamma + yn$$

[9]

E_ν	$\nu_e \to e$			$\nu \to \nu$		
	1n	2n	total	1n	2n	total
5	—	—	0.39E-07	—	—	0.67E-11
10	0.29E-11	—	0.09	0.002	—	0.007
15	0.91	—	1.54	0.06	—	0.08
20	4.96	—	6.51	0.20	—	0.27
25	14.66	0.45	17.63	0.46	0.03	0.62
30	25.05	3.15	32.22	0.87	0.15	1.22
35	29.27	10.85	45.37	1.44	0.42	2.15
40	33.56	23.68	64.10	2.15	0.93	3.48
45	37.91	38.97	85.33	2.97	1.74	5.25
50	42.54	53.79	106.16	3.86	2.93	7.50
55	47.17	71.63	130.09	4.79	4.56	10.24

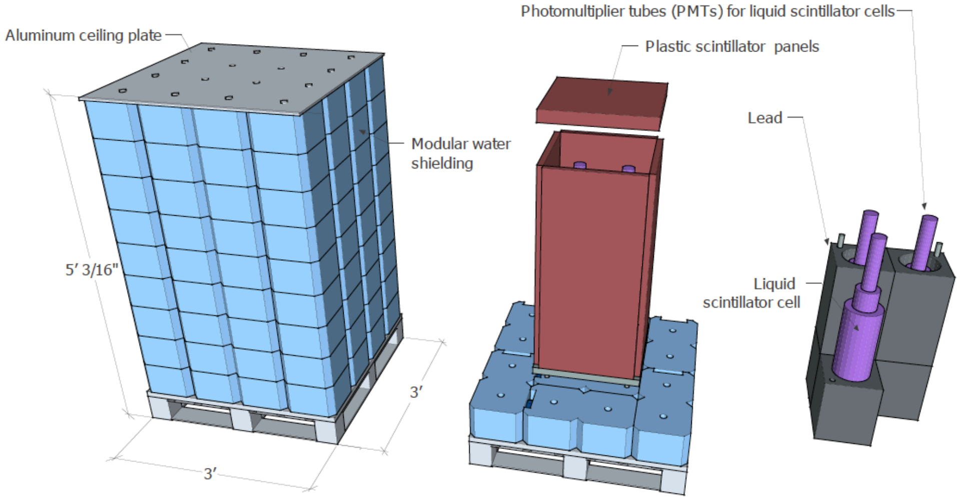
Neutrino-Nucleus Interactions on ^{208}Pb

- Originally deployed LS cell in shielding to be used by CsI detector (2.2 tons lead)
- Best fit of the excess due to neutrino-induced neutrons was 0.97 ± 0.33 n/GWHr/kg of Pb
  - Factor ~1.7 smaller than calculated in [11]
  - Additional neutron shielding deployed around the CsI detector
  - Dedicated experiment designed to study interaction



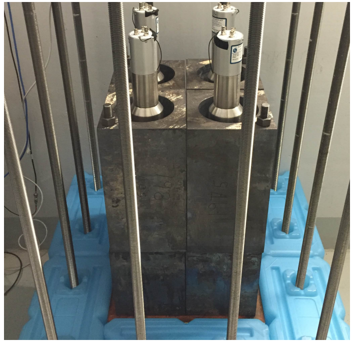
Lead Neutrino Cube

- Nearly 1-ton of ^{208}Pb, four LS cells (EJ-301)
  - PSD to identify neutron events
  - Muon vetos to reject muon-induced backgrounds
  - Water shielding to reduce environmental, beam-related neutron backgrounds
- Data collection began in 2016
- Designed to be portable, easy to switch targets

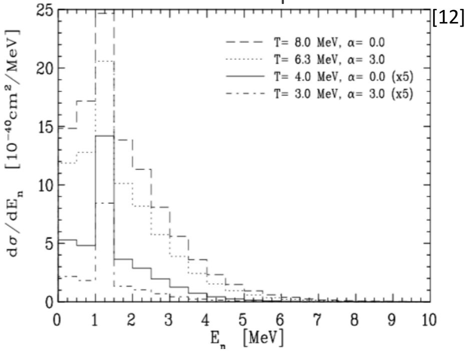


Lead Neutrino Cube

- Looking for excess of neutron events from charged-current interactions in delayed window following POT
  - Also measure neutron spectrum
  - Also look for coincidences between cells for 2n events
- Data collection ongoing



Predicted n spectrum for CC events from supernova



Neutrino-Nucleus Interactions on ^{56}Fe

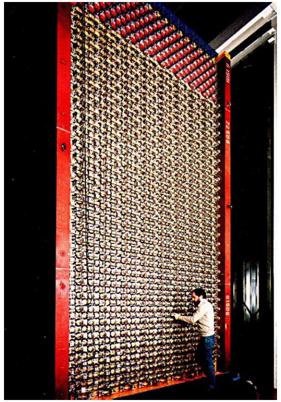
Neutrino-Nucleus Interactions on ^{56}Fe

- Iron is a common shielding material
- Previous flux-averaged measurement by KARMEN[13]:

  $2.51 \pm 0.83 \pm 0.42 \times 10^{-40}$ cm^2
- Proposed as target for supernova neutrino detectors such as OMNIS
- LVD sensitive to supernova neutrino-Fe interactions through NC channel

$$\nu_e + {}^{56}\mathrm{Fe} \rightarrow {}^{56}\mathrm{Co}^* + e^-$$
$$\Downarrow$$
$$ {}^{56-y}\mathrm{Co} + x\gamma + yn$$

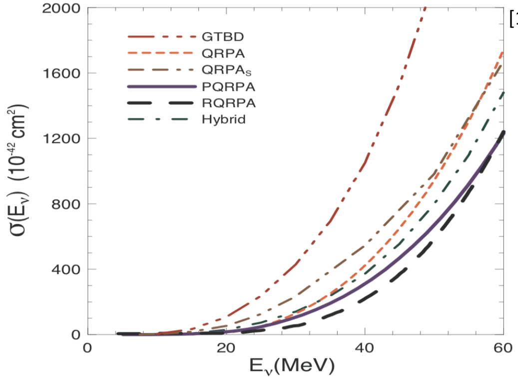
$$\nu_X + {}^{56}\mathrm{Fe} \rightarrow {}^{56}\mathrm{Fe}^* + \nu_X'$$
$$\Downarrow$$
$$ {}^{56-y}\mathrm{Fe} + x\gamma + yn$$



[14]

Iron Neutrino Cube

- Partial deployment in February 2017, full configuration in July 2017
- Nearly 700 kg of iron
- Inclusive charged-current cross sections shown from calculations in [15]
- Neutron emission cross sections for supernova neutrinos from [12]



[15]

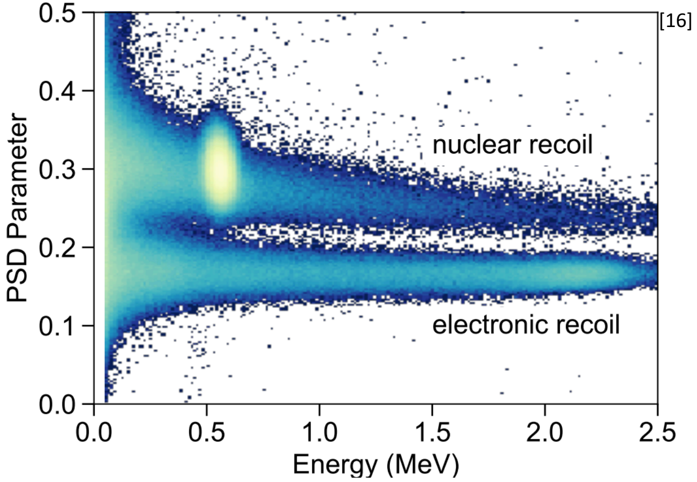
[12]

(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)

Neutrino Cube Upgrades

- PSD difficult for lowest energy neutrons
  - A ^{6}Li-loaded LS could look for neutron captures, improving neutron identification
- Additional nuclear targets being considered

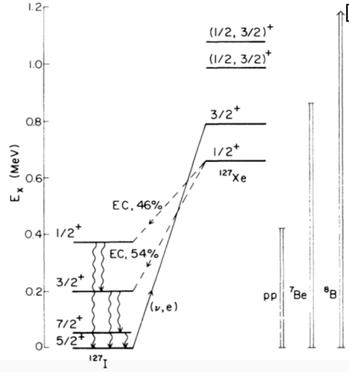


Neutrino-Nucleus Interactions on ^{127}I

Neutrino-Nucleus Interactions on ^{127}I

- ^{127}I proposed[17] as potential for a solar/supernova neutrino detector
  - Utilized similar to radiochemical approach used at Homestake with ^{37}Cl[18]
  - Charged-current threshold of 789 keV, used to determine ratio of ^{7}Be to ^{8}B solar neutrino flux
  - Larger cross section
- Work done to understand GT strength distribution for ^{127}I in (p,n)[19], (He,t)[20], angular correlation[21] experiments
- Inclusive cross section calculated by Mintz and Pourkaviani[22]

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



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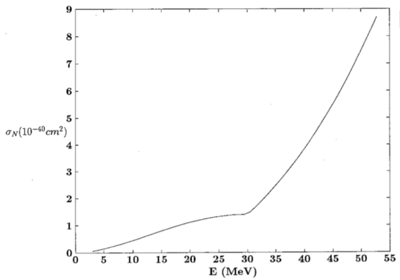


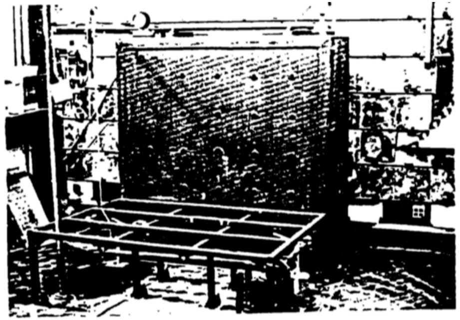
[22]

^{127}I Measurement at LAMPF

- Radiochemical approach used at LAMPF[23] to measure exclusive flux-averaged cross section

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

- ^{127}Xe bubbled out of tank, decays counted (half-life of 36.4 days)
- Exclusive measurement
  - ^{127}Xe can de-excite through n, p, or α emission
  - Particle emission threshold in ^{127}Xe is 7.23 MeV, most of the electron neutrinos produced are more energetic
- No energy dependence, flux-averaged measurement
- Suggested repetition with electronic NaI detectors to measure energy dependence



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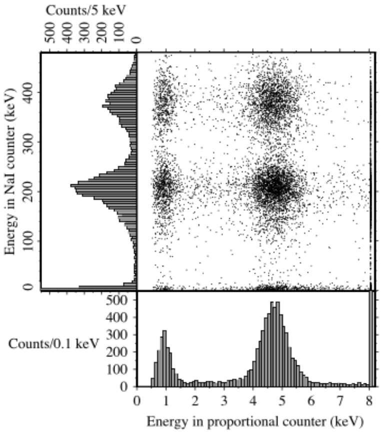
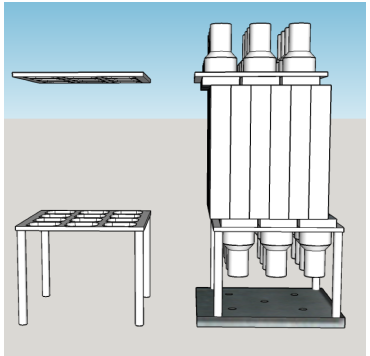
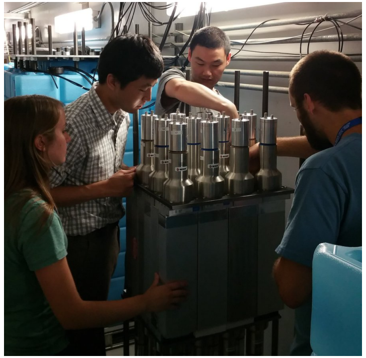


[23]

NaIνE

- Prototype detector consisting of 24 NaI[Tl] scintillators with a total mass of 185 kg
- Goal is to measure inclusive charged-current cross section on ^{127}I as a function of neutrino energy
- Originally deployed in 2016, upgraded in 2017

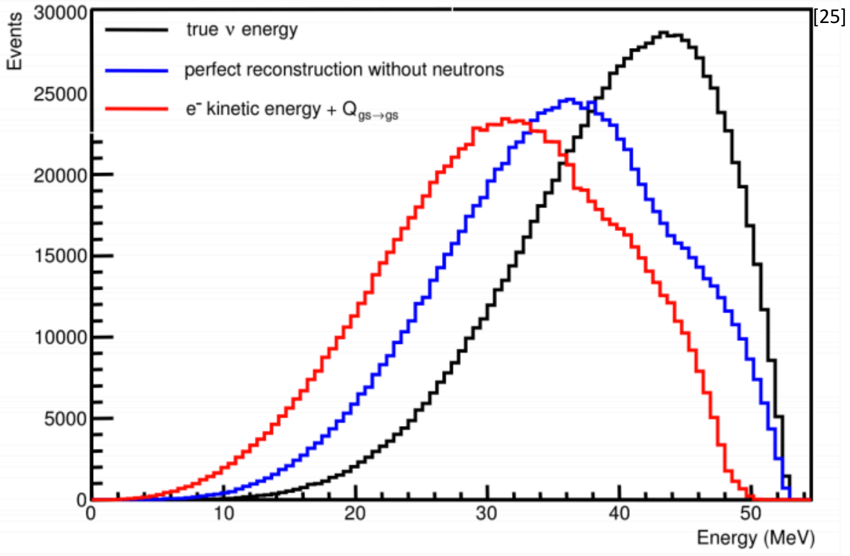




NaIνE

- Detector will see scintillation from products of charged-current interaction (electrons, protons, neutrons, alphas, gammas)
- Detector coarsely segmented
- Use simulations such as MARLEY[26] to generate expected output

Muon decay at rest ν_e spectrum for Argon



Ton-Scale NaI Detector

- Several hundred more NaI[Tl] scintillators available to make measurement
- Plan to simultaneously observe CC interactions on ^{127}I and CEνNS interactions on ^{23}Na, using a dual-gain base
- Test production of bases completed, testing in progress
- Simulations underway to determine shielding requirements, finalize detector support structure

Summary and Outlook

- Few low-energy neutrino-nuclear measurements exist, despite their use for understanding supernovae, fundamental physics
  - Theoretical predictions for these cross sections, scaling with energy, particle emission
- Detectors currently deployed to SNS to study neutrino-nucleus interactions in Pb, Fe, I
  - SNS provides large neutrino flux to make these measurements possible
- Interest in measurements on other targets (Ar for DUNE, ^{16}O to improve flux normalization, other metals for neutrino cubes)

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