Charged-Current Interactions
at the SNS

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8/22/17
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

$$\nu_e + n \xrightarrow{w} p + e^-$$
Existing low-energy (1-300 MeV) $\nu$-A measurements with terrestrial neutrino sources

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Reaction Channel</th>
<th>Source</th>
<th>Experiment</th>
<th>Measurement (10$^{-42}$ cm$^2$)</th>
<th>Theory (10$^{-42}$ cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^2$H*</td>
<td>$^2\text{H}(\nu_e, e^-)$pp</td>
<td>Stopped $\pi/\mu$</td>
<td>LAMPF</td>
<td>52 ± 18 (tot)</td>
<td>54 (1A) (Tatara et al., 1990)</td>
</tr>
<tr>
<td>$^{12}$C</td>
<td>$^{12}\text{C}(\nu_e, e^-)^{12}\text{N}_{\text{g.s.}}$</td>
<td>Stopped $\pi/\mu$</td>
<td>KARMEN</td>
<td>9.1 ± 0.5 (stat) ± 0.8 (sys)</td>
<td>9.4 [Multipole] (Donnelly and Peccei, 1979)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stopped $\pi/\mu$</td>
<td>E225</td>
<td>10.5 ± 1.0 (stat) ± 1.0 (sys)</td>
<td>9.2 [EPT] (Fukugita et al., 1988)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stopped $\pi/\mu$</td>
<td>LSND</td>
<td>8.9 ± 0.3 (stat) ± 0.9 (sys)</td>
<td>8.9 [CRPA] (Kolbe et al., 1999b)</td>
</tr>
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<td></td>
<td>$^{12}\text{C}(\nu_e, e^-)^{12}\text{N}^*$</td>
<td>Stopped $\pi/\mu$</td>
<td>KARMEN</td>
<td>5.1 ± 0.6 (stat) ± 0.5 (sys)</td>
<td>5.4-5.6 [CRPA] (Kolbe et al., 1999b)</td>
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<tr>
<td></td>
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<td>Stopped $\pi/\mu$</td>
<td>E225</td>
<td>3.6 ± 2.0 (tot)</td>
<td>4.1 [Shell] (Hayes and S, 2000)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stopped $\pi/\mu$</td>
<td>LSND</td>
<td>4.3 ± 0.4 (stat) ± 0.6 (sys)</td>
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<tr>
<td></td>
<td>$^{12}\text{C}(\nu_{\mu}, \nu^-)^{12}\text{C}^*$</td>
<td>Stopped $\pi/\mu$</td>
<td>KARMEN</td>
<td>3.2 ± 0.5 (stat) ± 0.4 (sys)</td>
<td>2.8 [CRPA] (Kolbe et al., 1999b)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stopped $\pi/\mu$</td>
<td>KARMEN</td>
<td>10.5 ± 1.0 (stat) ± 0.9 (sys)</td>
<td>10.5 [CRPA] (Kolbe et al., 1999b)</td>
</tr>
<tr>
<td></td>
<td>$^{12}\text{C}(\nu_{\mu}, \mu^-)^X$</td>
<td>Decay in Flight</td>
<td>LSND</td>
<td>1060 ± 30 (stat) ± 180 (sys)</td>
<td>1750-1780 [CRPA] (Kolbe et al., 1999b)</td>
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<td>1380 [Shell] (Hayes and S, 2000)</td>
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<td>1115 [Green’s Function] (Meucci et al., 2004)</td>
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<td></td>
<td>$^{12}\text{C}(\nu_{\mu}, \mu^-)^{12}\text{N}_{\text{g.s.}}$</td>
<td>Decay in Flight</td>
<td>LSND</td>
<td>56 ± 8 (stat) ± 10 (sys)</td>
<td>68-73 [CRPA] (Kolbe et al., 1999b)</td>
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<td>56 [Shell] (Hayes and S, 2000)</td>
</tr>
<tr>
<td>$^{56}$Fe</td>
<td>$^{56}\text{Fe}(\nu_e, e^-)^{56}\text{Co}$</td>
<td>Stopped $\pi/\mu$</td>
<td>KARMEN</td>
<td>256 ± 108 (stat) ± 43 (sys)</td>
<td>264 [Shell] (Kolbe et al., 1999a)</td>
</tr>
<tr>
<td>$^{71}$Ga</td>
<td>$^{71}\text{Ga}(\nu_e, e^-)^{71}\text{Ge}$</td>
<td>$^{51}$Cr source</td>
<td>GALEX, ave.</td>
<td>0.0054 ± 0.0009 (tot)</td>
<td>0.0058 [Shell] (Haxton, 1998)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{51}$Cr</td>
<td>SAGE</td>
<td>0.0055 ± 0.0007 (tot)</td>
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<tr>
<td></td>
<td></td>
<td>$^{27}$Ar source</td>
<td>SAGE</td>
<td>0.0055 ± 0.0006 (tot)</td>
<td>0.0070 [Shell] (Bahcall, 1997)</td>
</tr>
<tr>
<td></td>
<td>$^{127}$I</td>
<td>$^{127}\text{I}(\nu_e, e^-)^{127}\text{Xe}$</td>
<td>Stopped $\pi/\mu$</td>
<td>LSND</td>
<td>284 ± 91 (stat) ± 25 (sys)</td>
</tr>
</tbody>
</table>

* Many more measurements on deuterium with reactor neutrinos
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
Charged-current reaction in $^{127}$I

\[ \nu_e + ^{127}\text{I} \rightarrow ^{127}\text{Xe} + e^- \]

- $^{127}$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

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

- 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
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:
  $^{127}$Xe $\rightarrow$ $^{127}$I $^*$ + $\gamma$ (203, 375 keV)
  $^{127}$I $^*$ $\rightarrow$ $^{127}$I + $e^-$ ($\sim$0.9, 4.7 keV)
• Background processes also produce $^{127}$Xe: cosmic rays, fast/slow neutrons, energetic alphas

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
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

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

- 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 $\nu_e > 14.98$ MeV

http://www.triumf.ca/research-highlights/experimental-result/halo-operational-snoblab
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
Charged-Current reaction in $^{56}$Fe

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

- 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

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

<table>
<thead>
<tr>
<th>((T, \alpha))</th>
<th>((4, 0))</th>
<th>((6, 0))</th>
<th>((8, 0))</th>
<th>((10, 0))</th>
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<th>((4, -3))</th>
<th>((6.26, -3))</th>
</tr>
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<tbody>
<tr>
<td>(56\text{Fe}(\nu_e, e^- \gamma)^{56}\text{Co})</td>
<td>9.8 (0)</td>
<td>3.1 (1)</td>
<td>6.1 (1)</td>
<td>1.3 (2)</td>
<td>7.7 (0)</td>
<td>2.1 (1)</td>
<td>7.5 (1)</td>
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<td>(56\text{Fe}(\nu_e, e^- n)^{56}\text{Co})</td>
<td>7.5 (–1)</td>
<td>8.0 (0)</td>
<td>3.2 (1)</td>
<td>8.1 (1)</td>
<td>2.5 (–1)</td>
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<td>(56\text{Fe}(\nu_e, e^- p)^{55}\text{Fe})</td>
<td>5.4 (0)</td>
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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:** $\nu_e + ^{12}\text{C} \rightarrow ^{12}\text{N} + e^-$
  - Useful for normalizing neutrino cross sections, flux
  - $^{12}\text{N}$ 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:** $\nu_e + ^{16}\text{O} \rightarrow ^{16}\text{F} + e^-$
  - Light nuclei, useful for SN dynamics, existing/future detectors, directional information
  - $^{16}\text{F}$ 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 $^{15}\text{F}$ or $^{15}\text{O}$ decay with high energy gammas
  - Sensitive to isotope abundance: 0.2% $^{18}\text{O}$ makes ~10% of total cross section for solar neutrinos

- **Sodium:** $\nu_e + ^{23}\text{Na} \rightarrow ^{23}\text{Mg} + e^-$
  - Less theoretical work done for this, may be capable of measuring in 2-ton NaI[Tl] detector
  - 11 second decay time of $^{23}\text{Mg}$, ~3 MeV positron followed by annihilation—help determine detector efficiency at identifying CC produced leptons

- **Argon:** $\nu_e + ^{40}\text{Ar} \rightarrow ^{40}\text{K} + e^-$
  - 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!