Opportunities with stopped-pion neutrinos at the SNS

J. C. Blackmon, Physics Division, ORNL
on behalf of the $\nu$SNS collaboration

1. Stopped-pion neutrinos
2. Supernovae and neutrinos
3. $\nu$SNS overview
4. Potential instruments & physics
   - $\nu A$ coherent scattering
   - $\nu$ reaction cross sections I: liquids
   - Other standard model physics
   - $\nu$ reaction cross sections II: solids
   - Prototype testing
5. Backgrounds
6. Outlook
LSND at LANSCE (LANL)

800 MeV protons

26 ns

2.2 μs

Very small $\bar{\nu}_e$ component ($\sim 10^{-4}$)

Sterile neutrinos?

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\Delta m^2 = 0.2 - 10$ eV$^2$

$\sigma^{(12C)}$ [Auerbach et al. (2001)]

OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY
KARMEN at ISIS (RAL)

- KARMEN and LSND used similar techniques
  Liquid scintillator
  $\nu_e + p \rightarrow n + e^+$
  Prompt signal $\otimes$ correlated neutron capture

<table>
<thead>
<tr>
<th></th>
<th>LSND</th>
<th>KARMEN</th>
</tr>
</thead>
<tbody>
<tr>
<td># protons</td>
<td>28.9 C</td>
<td>9.4 C</td>
</tr>
<tr>
<td>Pulse width</td>
<td>600 $\mu$s</td>
<td>0.5 $\mu$s</td>
</tr>
<tr>
<td>In-flight</td>
<td>3%</td>
<td>Very low</td>
</tr>
<tr>
<td>baseline</td>
<td>30 m</td>
<td>18 m</td>
</tr>
<tr>
<td>events</td>
<td>32$\pm$9</td>
<td>$&lt; 5$ (90%)</td>
</tr>
<tr>
<td>fraction ($10^{-3}$)</td>
<td>2.64$\pm$0.67$\pm$0.45</td>
<td>$&lt; 0.85$</td>
</tr>
</tbody>
</table>

- $\sigma_{cc}^{(^{12}\text{C})} = (8\pm1) \times 10^{-42}$ cm$^2$
  [Bodmann et al. (1992)]
- Also $\nu$+Fe ($\sim$40%) [Maschuw (1998)]

Drexlin, NPB118 (2003)
Currently operating at low power
100kW in FY07

Eventual operation > 1 MW (~FY09)

~7x10^{12} \pi / \text{spill}
(~10x \text{ISIS})

Similar pulse structure to ISIS \rightarrow greatly suppressed backgrounds

LINAC:
Repeat 60/sec.

Accumulator Ring:

1 GeV

Oak Ridge National Laboratory
U. S. Department of Energy
Core-collapse supernovae

- Destruction of massive star initiated by the Fe core collapse
  - $10^{53}$ ergs of energy released
  - 99% carried by neutrinos with energies close to that from $\mu$ decay
- A few happen every century in our Galaxy, but the last one observed was over 300 years ago
- Dominant contributor to Galactic nucleosynthesis
- Neutrinos and the weak interaction play a crucial role in the mechanism, which is not well understood
Electron capture and core collapse

- Electron capture and the charged-current $\nu_e$ reaction are governed by the same nuclear matrix element:
  \[ \nu_e + A(Z,N) \leftrightarrow A(Z+1,N-1) + e^- \]

- What are the rates?
  - Gamow-teller strength distributions
  - First-forbidden contribution
  - $g_A/g_V$ modifications by nuclear medium

- New calculations using a hybrid model of SMMC and RPA predict significantly higher rates for N>40
  - Mixing and temperature unblock $f_{5/2}$

- Supernovae models w/ new rates:
  - Shock starts deeper and weaker
  - But less impedance

The weak interaction plays a crucial role in establishing the dynamics of the supernova shock wave
\( \nu \) opacities

- Prompt supernova mechanism fails
- Neutrinos interactions are believed to be crucial in the delayed mechanism
- Realistic treatment of \( \nu \) opacities is required for supernova models

- Many ingredients
  - Charged-current reactions on free nucleons (and nuclei)
  - Neutral-current scattering
  - \( \nu_e \)-e scattering
  - Inelastic processes
  - \( \nu \nu \) scattering
  - \( \nu - \nu \) annihilation
Neutrino reactions and nucleosynthesis

- Neutrino reactions with nuclei ahead of the shock may alter the entropy & composition of infall → less resistance [Bruenn & Haxton (1991)].

- Neutrino reactions will alter distribution of iron peak elements. Cross sections are important for interpreting observations in metal-poor stars [Fröhlich et al., astro-ph/0410208 (2005)].

- In the outer layers, neutrino reactions may be the dominant source for boron & fluorine [Woosley et al. (1990)] and rare isotopes like $^{138}$La and $^{180}$Ta [Heger et al. (2005)]. Observed abundances may provide constraints on supernovae.

- Neutrino reactions may have an important influence on nucleosynthesis in the $r$ process: setting the neutron-to-proton ratio and altering the abundance pattern [Haxton et al. (1997)]. Light p-process nuclei [Meyer et al. (2003)]?

$v$-nucleus cross sections are important for understanding the supernova explosion mechanism and nucleosynthesis
**Supernova observations**

- Observations of supernova neutrinos provide us with a window into the conditions deeper within the explosion, i.e. below the photosphere.

- Measurement of the neutrino energy spectra from a Galactic supernova would provide a wealth of information on the conditions in supernovae, neutrino oscillations, etc.

- Nuclei of interest: $^2$H, C, O, Pb

- An accurate understanding of neutrino cross sections is important for designing and interpreting measurements of neutrinos from supernovae.
A neutrino facility at the Spallation Neutron Source

proposed νSNS site

20 m² x 6.5 m (high)

Close to target ~ 20 m
→ 2x10⁷ ν/cm²/s

θ=165° to protons
→ lower backgrounds

The SNS
Target hall

OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY
**ν–SNS facility overview**

- Total volume = 130 m$^3$
  - 4.5m x 4.5m x 6.5m (high)
- Heavily-shielded
- 60 m$^3$ steel ~ 470 tons
  - 1 m thick on top
  - 0.5 m thick on sides
- Active veto
- ~70 m$^3$ instrumentable
- Configured to allow 2 simultaneously operating detectors of up to 40 tons
  - νA coherent scattering
  - 43 m$^3$ liquid detector
  - Segmented detector for solids
  - Prototypes
Coherent Scattering

Never measured
Only observable is low energy (~10keV) nuclear recoil


Straight-forward to calculate
Huge cross section > $10^{-39}$ cm$^2$

Important for supernova dynamics (neutrino opacity)

\[
\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1+\cos\theta) \frac{(N-(1-4\sin^2\theta_w)Z)^2}{4} F^2(Q^2)
\]
CLEAN

McKinsey et al.

Very high purity liquid Ne or Ar (scintillators)
Good recoil/electron discrimination
100 ton device under development (SNO-Lab or DUSEL)

Micro-CLEAN

Mini-CLEAN under construction

3 liters

65 liters

OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY
νA scattering using mini-CLEAN at νSNS

Scholberg et al.

Mini-CLEAN event rate above 20 keV threshold

900 /yr in Ar

400 /yr in Ne

Background rates at E~10 keV at the SNS?
Substantial improvements in the limits on certain nonstandard interactions can be obtained with 10% measurements of the coherent scattering cross section.
Homogeneous detector

- 3.5m x 3.5m x 3.5m steel vessel (43 m³)
- 600 PMT’s (8” Hamamatsu R5912)
  → Fiducial volume 15.5 m³ w/ 41% coverage
- Robust well-understood design
  LSND
  MiniBoone

- Potential experiments
  - 1300 events/yr $\nu_e + ^{12}\text{C}\rightarrow ^{12}\text{N} + e^{-}$ (mineral oil)
  - 450 events/yr $\nu_e + ^{16}\text{O} \rightarrow ^{16}\text{F} + e^{-}$ (water)
  - 1000 events/yr $\nu_x + ^2\text{H} \rightarrow p + n + \nu_x$ (heavy water)
Performance

Geant4 Monte Carlo simulations ongoing

• $\delta E/E \sim 6\%$

• $\delta x \sim 15\text{-}20\ cm$

• $\delta \theta \sim 5^\circ\text{-}7^\circ$

• Neutron discrimination?

• Layout and coverage

• More compact photosensors
  60\% of mass lost to fiducial cut
Other standard model tests

- Shape of the $\nu_e$ spectrum from $\mu$ decay is sensitive to scalar and tensor components of the weak interaction

\[ dN_{\nu_e}/dx = \frac{G_F^2 m_\mu^5}{16\pi^3} Q_L'(G_0(x) + G_1(x) + \omega_L G_2(x)) \]

$\omega_L = 0.11$ KARMEN upper limit
Armbruster et al., PRL81 (1998)

- We should substantially improve the limit on $\omega_L$ with only 1 year of data
Other standard model tests

- Some models predict muon decay branches that violate lepton flavor-number conservation at the levels of up to $10^{-4}$

- Such decays could account for a fraction of the LSND signal.

\[ \mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu \]

**Simulated \(\bar{\nu}_e\)SNS rate with b.r.=1**

<table>
<thead>
<tr>
<th>Target material:</th>
<th>Mineral oil</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\bar{\nu}_e) events/year</td>
<td>31400</td>
<td>32300</td>
</tr>
<tr>
<td>with fiducial cut</td>
<td>12900</td>
<td>13200</td>
</tr>
<tr>
<td>and combined efficiency</td>
<td>3200</td>
<td>3300</td>
</tr>
</tbody>
</table>

- Simulations indicate the background rate at the SNS may be substantially lower than at KARMEN
  - \(^{12}\text{C}(\nu_e, e)^{12}\text{N}\) eliminated with H\(_2\)O
  - \(\bar{\nu}_e\) background reduced ~2x.

- Expect branching ratio limit to be reduced by ~2x in 2 years

\(\bar{\nu}_e\) branching ratio \((10^{-3})\)

- LSND: \(2.65 \pm 0.67 \pm 0.45\)
- KARMEN: \(< 0.85\)
Segmented detector

- Target - thin corrugated metal sheet (e.g. 0.75 mm-thick iron)
  Total mass ~14 tons, 10 tons fiducial
  Other good metal targets: Al, Ta, Pb
- Detector
  1.4x10^4 gas proportional counters (strawtube)
  3m long x 16mm diameter
- 3D position by Cell ID & charge division
- PID and Energy by track reconstruction
- Expected Precision
  1100 events/yr $\nu_e$+Fe→Co+e^{-}
  1100 events/yr $\nu_e$+Al→Si+e^{-}
  4900 events/yr $\nu_e$+Pb→Bi+e^{-}
Strawtube R&D

- Currently testing prototypes
  - Diameters between 10-16 mm
  - Lengths ranging up to 2 m
  - Gases (Ar-CO₂, Isobutane, CF₄)
- Measure resolution with cosmic muons
  - Energy, position, time
- How much can time resolution be improved using pulse shape information?
- Simulations to improve the fast neutron discrimination.
Backgrounds

• Uncorrelated
  – Cosmic rays
    • Muons \rightarrow neutrons
    • Neutrons
  – Cosmogenic activity
  – SNS activation
  – Natural radioactivity

• Correlated prompt
  – Beam loses in RTBT
  – From the SNS target
  – Neighboring instruments

• Multiply-scattered neutrons

Reduced by $\sim 6 \times 10^{-4}$

$(60 \text{ Hz} \times 10 \mu\text{s})$
Cosmic rays

- Problem: $\mu + Fe \rightarrow n + X$
  
  $2900 \mu/s \times 6 \times 10^{-4} \rightarrow 1.7$ Hz coincident
  
  99% efficient veto $\rightarrow$ 3% of beam spills vetoed

  **Untagged muons:**
  
  63 untagged muons/hour in coincidence
  
  $\sim 2\%$ produce fast neutrons traversing detector
  
  30 fast neutrons/day (11000/year)
    
    Must be further reduced by detector signatures
    
    Can be very accurately characterized

- Cosmic ray neutrons
  
  $\sim 60$ n/s $\times 6 \times 10^{-4} \rightarrow 3100$ /day coincident
  
  Only reduced by shielding $\rightarrow$ sets scale for bunker
  
  1-m-thick steel ceiling reduces flux by $10^2$
    
    $\rightarrow$ 30 fast neutrons/day
    
    leaves $\sim 40$ m$^3$ of shielding for sides
      
      $\rightarrow$ 0.5-m-thick walls on average

  **Need high efficiency veto**
Cosmic ray veto

- 1.5 cm iron
- Extruded scintillator 1 cm x 10 cm x 4.5 m

Wave-length shifting fibers read out by multi-anode PMT

Efficiencies
- Muons ~99% muons
- Gamma = 0.005%
- Neutron = 0.07%
November 2005 production

- In collaboration with MECO
  100 x 4.5-m planks extruded for νSNS
SNS Neutrons

- Three sources considered:
  - Direct neutrons from SNS target
  - Scattered neutrons from BL17/18
  - Neutrons from beam losses in the RTBT
Segmented Performance: $\nu_e + \text{Fe} \rightarrow \text{Co} + e^-$

- Total rate
- $t < 10\mu s$ & no veto (98%)
- Fiducial cut
- $(\Delta E/\text{cell})_{\text{ave}} < 10$ keV
- 57% $\nu$ efficiency
- Cosmics eliminated
- Neutrons little reduced
**Time cut**

- Negligible fast neutron background expected after ~ 1 μs

**Crucial to understand neutron background, especially for t=1-10μs**

<table>
<thead>
<tr>
<th>Time cut (μs)</th>
<th>ν efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2-10.0</td>
<td>43</td>
</tr>
<tr>
<td>1.5-10.0</td>
<td>37</td>
</tr>
<tr>
<td>1.8-10.0</td>
<td>34</td>
</tr>
<tr>
<td>2.0-10.0</td>
<td>30</td>
</tr>
</tbody>
</table>

**Neutrino interactions**
- SNS neutrons
- Cosmic muons
- Cosmic hadrons
Background Studies Layout

- 60 tons of steel installed
- 2 stacks of shield block
- 52” x 52” x 60” high
- 4 Detector stations
- 5” liquid scintillator
- $^3$He counters

Open for prototype testing
Installation

- Block installation complete
- Detectors and data acquisition system now being installed
- Expect to be ready for SNS run cycle in October 2006
ν–SNS Collaboration

http://www.phy.ornl.gov/nusns

• Active, diverse collaboration
  – 20 institutions

<table>
<thead>
<tr>
<th>System</th>
<th>Lead</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project manager</td>
<td>Efremenko (Tenn)</td>
</tr>
<tr>
<td>Bunker</td>
<td>Cianciolo (ORNL)</td>
</tr>
<tr>
<td>Segmented Detector</td>
<td>Hungerford (Houston)</td>
</tr>
<tr>
<td>Homogeneous Detector</td>
<td>Stancu (Alabama)</td>
</tr>
<tr>
<td>νA Scattering</td>
<td>Scholberg (Duke)</td>
</tr>
<tr>
<td>Veto</td>
<td>Greife (Mines)</td>
</tr>
<tr>
<td>SNS &amp; Backgrounds</td>
<td>Blackmon (ORNL)</td>
</tr>
<tr>
<td>Theory</td>
<td>McLaughlin (NCSU) Hix (ORNL)</td>
</tr>
</tbody>
</table>
**Timeline**

- **March 2004**
  - Study report completed
  - Letter of Intent to SNS

- **August 2004**
  - “Green light” from SNS

- **October 2004**
  - Neutrino Matrix

- **August 2005**
  - Proposal submitted
  - Likely withdrawn

- **FY 2007**
  - NSAC LRP

- **FY 2010-FY2011**
  - Construction

---

**Project Cost**

<table>
<thead>
<tr>
<th>Item</th>
<th>$M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunker</td>
<td>2.3</td>
</tr>
<tr>
<td>Veto</td>
<td>1.1</td>
</tr>
<tr>
<td>Segmented Detector</td>
<td>1.2</td>
</tr>
<tr>
<td>Homogeneous Detector</td>
<td>1.2</td>
</tr>
<tr>
<td>Mini-CLEAN</td>
<td>0.5</td>
</tr>
<tr>
<td>Cont. &amp; Escl. (FY06$)</td>
<td>+50%</td>
</tr>
</tbody>
</table>

---

2. The precise determination of neutrino cross sections is an essential ingredient in the interpretation of neutrino experiments and is, in addition, capable of revealing exotic and unexpected phenomena, such as the existence of a neutrino magnetic dipole moment. Interpretation of atmospheric and long-baseline accelerator-based neutrino experiments, understanding the role of neutrinos in supernova explosions, and predicting the abundances of the elements produced in those explosions all require knowledge of neutrino cross sections. New facilities, such as the Spallation Neutron Source, and existing neutrino beams can be used to meet this essential need.
Summary & Outlook

• Neutrino scattering and reactions are important for understanding supernovae
  – Influence core collapse
  – Affect shock dynamics
  – Modify the distribution of iron-peak elements
  – May be the dominant source of B, F, $^{138}\text{La}$, $^{180}\text{Ta}$
  – Affect r process nucleosynthesis

• The combination of high flux and favorable time structure at the SNS can allow a diverse program of measurements
  – High statistics in less than 1 year of operation

• We have a strong collaboration of experimentalists and theorists

• We welcome new ideas and participation

• νSNS must figure into the NSAC Long-Range Plan if we are to capitalize on this opportunity

• See http://www.phy.ornl.gov/nusns