Measuring the Neutrino Luminosity of the Sun & Search for Sterile Neutrinos

LENS & MINILENS

International Workshop on "Double Beta Decay and Neutrinos"
Osaka, June 12, 2007

Christian Grieb for the LENS Collaboration
Virginia Tech
LENS-Indium: Foundations

**CC ν-capture in $^{115}$In to excited isomeric level in $^{115}$Sn**

$$\nu_e + ^{115}\text{In} \rightarrow e^- + \gamma + (\gamma/\nu) + ^{115}\text{Sn}$$

Tag: Delayed emission of $(\nu/\gamma)+\gamma$
Threshold: 114 keV → pp-ν’s
$^{115}$In abundance: ~ 96%
CC-capture: Faithful reproduction of ν spectrum

Background Challenge:
- Indium-target is radioactive! ($t = 6 \times 10^{14}$ y)
- $^{115}$In β-spectrum overlaps pp-ν signal

Basic background discriminator:
Time/space coincidence tag
Tag energy: $E_{\nu\text{-tag}} = E_{\beta\text{max}} + 116$ keV
Requires spatial resolution of < 10 cm

$^7$Be, CNO & LENS-Cal signals not affected by Indium-Bgd!
Indium $\beta^-$-Background Structure – Space / Time coincidence

Signal

$^{115}\text{In}$

$^{115}\text{Sn}$

$E(\nu\nu\nu) - 114\text{ keV}$

$116\text{ keV}$

$497\text{ keV}$

$\tau = 4.76\mu\text{s}$

$
e/\gamma$ 116 keV

$\gamma$ 497 keV

Signal Signature:

Prompt $e^-$ (🌟) followed by low energy $(e^-/\gamma)$ (🌟) and Compton-scattered $\gamma$ (🌟)

-> time/space coincidence

-> tag fixed energy 613 keV

-> Compton scattered shower

Background:

Random time and space coincidence between two $\beta$-decays (🌟);

Extended shower (🌟) can be created by:

a) 498 keV $\gamma$ from decay to excited state;

b) Bremsstrahlungs $\gamma$-rays created by $\beta$;

c) Random coincidence (~10 ns) of more $\beta$-decays;

Or any combination of a), b) and c).

$\beta_1 (E_{\text{max}} < 2\text{ keV})$

$(b = 1.2\times10^{-6})^*$

$\beta_0 + n\gamma (\text{BS})$

$(E_{\text{max}} = 499\text{ keV})$

$498\text{ keV}$

$\gamma$

$^{115}\text{Sn}$

*Cattadori et al: 2003
3D Digital Localizability of Hit within one cube

- ~75mm precision vs. 600 mm (±2σ) by TOF in longitudinal modules
- x8 less vertex vol. → x8 less random coinc. → Big effect on Background
- Hit localizability independent of event energy
Background rejection steps:

1. Time/space coincidence in the same cell required for trigger;
2. Tag requires at least three ‘hits’;
3. Narrow energy cut;
4. Tag topology: multi-β vs. Compton shower;

Classification of events according to hit multiplicity;
Cut parameters optimized for each event class → improved efficiency;

\[ E_{\text{tag}} \] [keV] \[ N \text{ year}^{-1} t \text{ In}^{-1} \]

Black: pp-ν events
Blue: A1 Bkgd
Green: A2 Bkgd
Red: B Bkgd

\[ ^{115}\text{In} \rightarrow \beta_1 (E_{\text{max}} < 2 \text{ keV}) \quad (b = 1.2 \times 10^{-5})* \]
\[ ^{115}\text{Sn} \rightarrow \beta_0 + n\gamma (BS) \quad (E_{\text{max}} = 499 \text{ keV}) \]

*\text{Cattadori et al: 2003}
## Indium $\beta^-$-Background Rejection - MC Results

Results of GEANT4 Monte Carlo simulation (cell size = 7.5cm)

<table>
<thead>
<tr>
<th>RAW rate</th>
<th>Signal (pp) $\text{y}^{-1} \times \text{t ln}^{-1}$</th>
<th>Bgd (In) $\text{y}^{-1} \times \text{t ln}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
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<td>62.5</td>
<td>$79 \times 10^{11}$</td>
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<td>with prompt event in vertex</td>
<td>50</td>
<td>$2.76 \times 10^{5}$</td>
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<td>B. $\geq$3 Hits in tag shower</td>
<td>46</td>
<td>$2.96 \times 10^{4}$</td>
</tr>
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<td>C. +Tag Energy = 613 keV</td>
<td>44</td>
<td>306</td>
</tr>
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<td>D. +Tag topology</td>
<td>40</td>
<td>$13 \pm 0.6$</td>
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 نيوزelin β⁻-Background Rejection - MC Results

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- Signal / Background ~3 with pp-v event detection efficiency 64%
- **Remember**: only pp-v events affected by Indium Background, $^7$Be, pep and CNO Background-free
- LENS is a feasible detector:
  - 125t of liquid scintillator for ~2000 pp-v events in 5 years with full spectroscopic information plus $^7$Be, pep and CNO
**Indium Liquid Scintillator Status**

1. Indium concentration ~8%wt (higher may be viable)
2. Scintillation signal efficiency (working value): 9000 $h\nu/MeV$
3. Transparency at 430 nm: $L(1/e)$ (working value): 10m
4. Chemical and Optical Stability: at least 1 year
5. InLS Chemistry - Robust

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**Milestones unprecedented in metal LS technology**

**LS technique relevant to many other applications**

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Basic Bell Labs Patent, filed 2001, awarded 2004
LENS Expected Result: Low Energy Solar $\nu$-Spectrum

$>98\%$ Flux $<2\text{MeV}$

LENS-Sol Signal

$= \ \text{SSM(low CNO) + LMA}$

$\times$

Detection Efficiency $\varepsilon$

$\text{pp: } \varepsilon = 64\%$

$\text{7Be: } \varepsilon = 85\%$

$\text{pep: } \varepsilon = 90\%$

$\rightarrow$ Rate: pp $40 \text{ pp ev./y/t ln}$

$\rightarrow$ 2000 pp ev./5y/10t ln $\rightarrow$

$\pm 2.5\%$

$\rightarrow$ Design Specification: S/N $\geq 3$

Access to pp $\nu$ spectral $shape$ for the first time

Fitted Solar $\nu$-Spectrum

Signal + Background (S/N = 3)

Signal ($\tau = 4.76 \mu s$)

Time Spectrum (S/B = 3)
Solar Luminosity: Neutrino vs. photon

Energy Balance:

\[ L_{\nu-\text{inferred}} = L_{h\nu} \]

Solar luminosity as measured by photon flux

Measured neutrino fluxes at earth
+ oscillation physics
\Rightarrow\text{ nuclear reaction rates}
\Rightarrow\text{ energy release in the sun}

Will be met under these conditions:
1. Fusion reactions are the sole source of energy production in the sun
2. The sun is in a quasi-steady state (change in 40,000 years is negligible)
3. The neutrino oscillation model is correct & no other physics involved;

From a single detector:

Test of astrophysics, solar model;
Test of neutrino physics (LMA-MSW at low E, NSI, mass-varying vs, \( \Theta_{13} \), ...);
Neutrino inferred Luminosity of the Sun - Experimental Status

**Predicted** relative neutrino fluxes at the sun (SSM):

Main contributions:

- \( \text{pp} \) 0.91
- \( \text{\( ^7 \)Be} \) 0.074
- \( \text{(CNO)} \) 0.014
- \( \text{\( ^8 \)B} \) 0.00009

**Measured** neutrino fluxes at the earth:

- \( \text{\( ^8 \)B} \) (SK, SNO) known very well
- \( \text{\( ^7 \)Be} + \text{\( ^8 \)B} \) (Cl) sensitive mostly to \( \text{\( ^8 \)B} \)
- \( \text{pp} + \text{\( ^7 \)Be} + \text{\( ^8 \)B} \) (Ga)
- \( \text{\( ^7 \)Be} \) (Borexino, Kamland – in the future)

\( \Rightarrow \) in principle can deduce pp-\( \nu \) flux

**Problem**: disentangling fluxes from individual neutrino sources

\[
\frac{L_{\nu(\text{inferred})}}{L_{h\nu}} = 1.4 \begin{pmatrix} 0.2 \\ 0.3 \end{pmatrix} \sigma \begin{pmatrix} 0.7 \\ 0.6 \end{pmatrix} \sigma
\]


\[
\frac{L_{\nu(\text{inferred})}}{L_{h\nu}} = 1.2(0.2)
\]


**Experimental status** – No useful constraint!
Probing the Temperature Profile of Energy Production in the Sun with LENS

Neutrino Production

Temperature Profile

Temperature in the Solar Core impacts Neutrino Energies, not just relative fluxes

Relative kinetic particle energies add to the Q-value of capture and fusion reactions. Not all energies contribute evenly:

**pp-fusion:**
Gamow Peak at
\[ E_0 = 5.91 \text{keV} \cdot (T / 1.5 \cdot 10^7 \text{ K})^{\frac{2}{3}} \]

Maxwellian energy distribution
\( \times \)
Tunneling probability

pp endpoint shifted up by \( \sim 5.2 \text{keV} \)

\( \Delta <E> \sim 1.29 \text{ keV} \)

**7Be electron capture:** maxwellian energy distribution shifts mean energy of \( ^7\text{Be} \) \( \nu \) line by \( \Delta <E> \sim 6.6 \text{ keV} \)

**hep:**
\[ E_0 = 10.73 \text{keV} \cdot (T / 1.5 \cdot 10^7 \text{ K})^{\frac{2}{3}} \]

\( \Delta <E> \sim 6.6 \text{ keV} \)

**pp- and pep neutrino production temperature and related Gamow peak energy:**


Probing the Temperature Profile of Energy Production in the Sun with LENS

Top: \( pp-\nu \) spectrum with/without Gamow shift

Bottom: Signal spectrum in LENS with/without Gamow shift

12t Indium - 6 years - \( \delta E/E=6\% \) at 300keV

Measured Gamow shift in improved LENS: 10000 simulations with ~3000 pp \( \nu \) events each \( \sigma=1.62 \text{keV} \)

Conclusion: Slightly improved LENS can detect the predicted Gamow shift in the \( pp-\nu \) endpoint \( \Delta E=5.2\text{keV} \) with 95% confidence.

# LENS-Cal Neutrino Sources

<table>
<thead>
<tr>
<th>Source</th>
<th>DecayMode /Produced by</th>
<th>$\tau$</th>
<th>$E_\nu$ (keV)</th>
<th>$E_e = E_\nu - 0.114$ keV</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{37}$Ar</td>
<td>EC/ (n, $\alpha$)</td>
<td>50.5 d</td>
<td>814 (100%)</td>
<td>700</td>
<td>Int. Bremss. 0-814; ~$\Sigma$5x10^{-4} $h$/decay</td>
</tr>
<tr>
<td>Haxton</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{51}$Cr</td>
<td>EC/ (n,$\gamma$)</td>
<td>40.1 d</td>
<td>751 (90%)</td>
<td>637</td>
<td>320$\gamma$ (10%)</td>
</tr>
<tr>
<td>RSR Kuzmin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Imp. $\gamma$'s (MeV) %??</td>
</tr>
<tr>
<td>$^{65}$Zn</td>
<td>EC($\beta^+$)/ (n,$\gamma$)</td>
<td>353 d</td>
<td>1350 (50%)</td>
<td>1236</td>
<td>1115 $\gamma$ (50%); 511 $\gamma$ (2%); Imp. $\gamma$'s.</td>
</tr>
<tr>
<td>Louis Alvarez</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Neutrino Energy typically 700 keV
Sterile Neutrinos – Physics beyond the Standard Model

• Fourth (fifth) mass state with high mass splitting triggered by LSND appearance of $\bar{\nu}_e$ from $\nu_\mu$ beam at short base line ~30m!

• Implies $\Delta m^2 \sim 1\text{eV}^2$

• Also motivated from cosmology

\[
\begin{align*}
(3+1) & \quad (3+2) \\
\Delta m^2_{\text{LSND}} & \quad \Delta m^2_{\text{LSND}} \\
\Delta m^2_{\text{atm}} & \quad \Delta m^2_{\text{atm}} \\
\Delta m^2_{\text{solar}} & \quad \Delta m^2_{\text{solar}}
\end{align*}
\]

Already planned: LENS-Cal
MCi Cr Source in LENS to calibrate $\nu_e$ capture cross section on $^{115}$In

Parasitic measurement
For sterile neutrinos

Active - Sterile oscillation of monochromatic 753 keV pure e-flavored neutrinos via
Spatial distribution of flavor survival in ~5 m

Active-Sterile Oscillations
Active - Sterile Neutrino Oscillations in LENS

Survival probability of $\nu_e$:

$$P_{ee} \approx 1 - 4U_{e4}^2 (1 - U_{e4}^2) \sin^2 x_{41} - 4U_{e5}^2 (1 - U_{e5}^2) \sin^2 x_{51}$$

- Cross terms such as $U_{e4}^2 U_{e5}^2$ are neglected

$$x_{ij} = 1.27 \Delta m_{ij}^2 (eV^2) L(m) / E_{\nu}(MeV)$$

<table>
<thead>
<tr>
<th>Model</th>
<th>$\Delta m_{ij}^2 (eV^2)$</th>
<th>$U^2$</th>
<th>$\sin^2 2\theta_{ee}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3+1</td>
<td>0.9214</td>
<td>0.0185</td>
<td>0.073</td>
</tr>
<tr>
<td>3+2a</td>
<td>0.9214</td>
<td>0.0146</td>
<td>0.057</td>
</tr>
<tr>
<td></td>
<td>22.15</td>
<td>0.0013</td>
<td>0.005</td>
</tr>
<tr>
<td>3+2b</td>
<td>0.4614</td>
<td>0.0081</td>
<td>0.032</td>
</tr>
<tr>
<td></td>
<td>0.8915</td>
<td>0.0156</td>
<td>0.062</td>
</tr>
</tbody>
</table>

With $\Delta m^2 \sim 1 \text{ eV}^2$ and $E_{\nu} \sim 0.753 \text{ MeV}$ (from $^{51}\text{Cr}$), **full flavor recovery occurs in $\sim 2m$, directly observable in a lab-scale detector.**

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$\rho_{In}$ (wt. %)</th>
<th>$d_{detector}$ (meters)</th>
<th>$m_{In}$ (tons)</th>
<th>$m_{total}$ (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A - LENS-Sol</td>
<td>8</td>
<td>5.1</td>
<td>9.9</td>
<td>125</td>
</tr>
<tr>
<td>B - LENS-Sterile</td>
<td>15</td>
<td>3.3</td>
<td>5.1</td>
<td>34</td>
</tr>
</tbody>
</table>

Design options for LENS
Statistical precision of oscillation parameter measurement in LENS
Active – Sterile Oscillation Sensitivity with LENS
Final Test detector for LENS
- NSF funded

- InLS : 128 L
- Liquid Scintillator Buffer
- 3” pmt’s : ~150

- Test detector technology
  → Medium Scale InLS production
  → Design and construction

- Test background suppression of In raditions by $10^{-11}$
  Expect ~ 5 kHz In $\beta$-decay singles rate; adequate to test trigger design, DAQ, and background suppression schemes

- Demonstrate In solar signal detection in the presence of high background (via “proxy”)

- Direct blue print for full scale LENS
Proxy pp-ν events in MINILENS

Proxy pp nu events in MINILENS from cosmogenic $^{115}\text{In}(p,n)^{115}\text{Sn}$ isomers

- Pretagged via $\mu$, $p$ tracks
- Post tagged via $n$ and 230 $\mu$s delay

→ Gold plated 100 keV events (proxy pp), Tagged by same cascade as In-ν events

→ Demonstrate In-ν Signal detection even in MINILENS
MINILENS concept
MINILENS Electronics

PMTs

0 ns
40 ns
80 ns
120 ns
x10

quad fan in/out

150 → 38
38 → 10
10 → 3
3 → 1

threshold
discriminator

trigger (2.5 kHz In)

transient
digitizer
(2 ns, 8 bit)

computer
200 ns
read per event

high voltage

LENS
Christian Grieb, Virginia Tech, June 2007
Options for Lattice Structure

Single Foil

Solid teflon segmentation

Double Foil

Double-layer (air-gap) lattice
Summary

Major breakthroughs in LENS:
- Indium liquid scintillator synthesis
- New detector technology (Scintillation Lattice Chamber)
- GEANT4 Simulation of Indium $\beta^-$ background

$\rightarrow$ Basic feasibility of In-LENS-Sol secure (10t In, 125t In-LS)

Science in LENS:
- Measure solar $\nu$-spectrum below 2MeV
- $\nu$ Luminosity of the sun
- Gamow shift of pp-$\nu$ spectrum probes the T profile
- Search for active - sterile neutrinos
- Test of Astrophysics & $\nu$ physics in one experiment

Now:
- Build MINI-LENS - 130 liter InLS detector
- Test all the concepts and the technology developed so far
  & demonstrate Indium solar signal detection
LENS-Sol / LENS-Cal Collaboration
(Russia-US: 2004-)

Russia:

INR (Moscow): I. Barabanov, L. Bezrukov, V. Gurentsov, V. Kornoukhov, E. Yanovich;
IPC (Moscow): N. Danilov, G. Kostikova, Y. Krylov
INR (Troitsk) I: J. Abdurashitov, V. Gavrin. et al.
II: V. Betukhov, A. Kopylov, I. Oriachov, E. Solomontin

U. S.:

BNL: R. L. Hahn, M. Yeh;
U. N. Carolina: A. Champagne, H. Back;
ORNL: J. Blackmon, C. Rascoe, A. Galindo-Uribarri, Q. Zeng;
Princeton U.: J. Benziger;
SCSU: Z. Chang;
Virginia Tech: C. Grieb, J. Link, M. Pitt, R. S. Raghavan, D. Rountree, R. B. Vogelaar;
Additional Slides
Signal Reconstruction

- Event localization relies on PMT hit pattern (NOT on signal timing)

- Algorithm finds best solution for event pattern to match PMT signal pattern

- System is overdetermined, hardly affected by unchannelled light

- Timing information + position $\Rightarrow$ shower structure
## LENS Design Figures of Merit

<table>
<thead>
<tr>
<th>Cell Size [mm]</th>
<th>Cube size [M]</th>
<th>pe/MeV</th>
<th>Det. Eff [%]</th>
<th>Nu/t In/y</th>
<th>Bgd/t In/y</th>
<th>S/N</th>
<th>M (In) [tons]</th>
<th>M (InLS) tons</th>
<th>PMTs</th>
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<tr>
<td>75</td>
<td>5</td>
<td>900</td>
<td>64</td>
<td>40</td>
<td>13</td>
<td>3</td>
<td>10</td>
<td>125</td>
<td>13300* (3&quot;)</td>
</tr>
<tr>
<td>125</td>
<td>~6</td>
<td>950</td>
<td>40</td>
<td>26</td>
<td>9</td>
<td>2.9</td>
<td>15.3</td>
<td>190</td>
<td>6250* (5&quot;)</td>
</tr>
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*PMT’s on three sides only

LENS is a feasible detector,

125t of liquid scintillator and ~13300 photomultiplier channels

for ~2000 pp-ν events in 5 years with full spectroscopic information plus $^7$Be, pep and CNO
Test of Solar Models

Solar models predict relative intensities in the pp-chain.

Reaction rates depend on temperature profile and abundances.

Cross check with measured fluxes (using neutrino oscillation physics)

Neutrino Inferred Solar Luminosity

Nuclear reactions in the pp-chain:

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Number</th>
<th>Q (MeV)</th>
<th>(\langle q_{\text{ne}}\rangle) (MeV)</th>
<th>(S_0) (keV barns)</th>
<th>((dS/dE)) (barns)</th>
<th>Lifetime (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^1\text{H}(p, e^+ \nu_e)^2\text{H})</td>
<td>1</td>
<td>1.442</td>
<td>0.285</td>
<td>4.07(1 ± 0.051) \times 10^{-22}</td>
<td>4.52 \times 10^{-24}</td>
<td>10^{10}</td>
</tr>
<tr>
<td>(^1\text{H}(p, e^- \nu_e)\text{H})</td>
<td>2</td>
<td>1.442</td>
<td>1.442</td>
<td>[see Eq. (5), Paper I]</td>
<td></td>
<td>10^{12}</td>
</tr>
<tr>
<td>(^3\text{He}(p, \gamma)^4\text{He})</td>
<td>3</td>
<td>5.494</td>
<td></td>
<td>2.5 \times 10^{-1}</td>
<td>7.9 \times 10^{-6}</td>
<td>10^{-8}</td>
</tr>
<tr>
<td>(^3\text{He}(p, e^+ \nu_e)^4\text{He})</td>
<td>4</td>
<td>19.795</td>
<td>9.625</td>
<td>8 \times 10^{-20}</td>
<td></td>
<td>10^{12}</td>
</tr>
<tr>
<td>(^4\text{He}(p, 2p)^4\text{He})</td>
<td>5</td>
<td>12.860</td>
<td></td>
<td>5.15(1 ± 0.17) \times 10^3</td>
<td>-0.9</td>
<td>10^{5}</td>
</tr>
<tr>
<td>(^6\text{He}(4\text{He}, \gamma)^7\text{Be})</td>
<td>6</td>
<td>1.586</td>
<td></td>
<td>0.54(1 ± 0.06)</td>
<td>-3.1 \times 10^{-4}</td>
<td>10^{6}</td>
</tr>
<tr>
<td>(^7\text{Be}(p, \nu_e)^7\text{Li})</td>
<td>7</td>
<td>0.862</td>
<td>0.862</td>
<td>[see Eq. (9), Paper I]</td>
<td></td>
<td>10^{-1}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.384</td>
<td>0.384</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^7\text{Li}(p, \alpha)^4\text{He})</td>
<td>8</td>
<td>17.347</td>
<td></td>
<td>52(1 ± 0.5)</td>
<td>0</td>
<td>10^{-5}</td>
</tr>
<tr>
<td>(^7\text{Be}(p, \gamma)^8\text{B})</td>
<td>9</td>
<td>0.137</td>
<td></td>
<td>0.0243(1 ± 0.22)</td>
<td>-3 \times 10^{-5}</td>
<td>10^{2}</td>
</tr>
<tr>
<td>(^8\text{B}(e^+ \nu_e)^8\text{Be*})</td>
<td>10</td>
<td>17.980</td>
<td>6.710</td>
<td></td>
<td></td>
<td>10^{-8}</td>
</tr>
</tbody>
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