LENS
Measuring the Neutrino Luminosity of the Sun

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Christian Grieb
Virginia Tech
## LENS-Sol / LENS-Cal Collaboration (Russia-US: 2004-)

### Russia:
- **INR (Moscow):** I. Barabanov, L. Bezrukov, V. Gurentsov, V. Kornoukhov, E. Yanovich;
- **INR (Troitsk):** V. Gavrin et al., A. Kopylov et al.;

### U. S.:
- **BNL:** A. Garnov, R. L. Hahn, M. Yeh;
- **U. N. Carolina:** A. Champagne;
- **ORNL:** J. Blackmon, C. Rasco, A. Galindo-Uribarri;
- **Princeton U.:** J. Benziger;
- **Virginia Tech:** Z. Chang, C. Grieb, M. Pitt, R.S. Raghavan, R.B. Vogelaar;
LENS-Indium: SCIENCE GOAL

Precision Measurement of the Neutrino Luminosity of the Sun

**LENS-Sol:**
→ Measure the low energy solar ν spectrum (pp, $^7$Be, CNO)
→ ± ~3% pp- ν flux
→ Experimental tool: Tagged CC Neutrino Capture in Indium

\[ \nu_e + ^{115}\text{In} \rightarrow e^- + \gamma + (\gamma/e^-) + ^{115}\text{Sn} \]
- solar signal
- delayed tag ($\tau=4.76 \mu s$)

**LENS-Cal:**
→ Measure *precise* B(GT) of $^{115}$In CC reaction using MCi $^{51}$Cr neutrino source at BAKSAN
→ Tagged ν-capture to *specific* level of $^{115}$Sn
→ *Note:* B(GT) = 0.17 measured via (p,n) reactions
Solar Neutrinos

Extraordinary Neutrino Beam Free of Charge

For NEUTRINO PHYSICS:

- WELL DEFINED HIGHEST FLUX (pp)
- FLAVOR PURE - $\nu_e$ only
- LONGEST BASELINE
- LARGEST MASS OF HIGH DENSITY
- LOWEST ENERGIES (keV to MeV)
- LOW ENERGY SPECTRUM - ENERGY DEP. EFFECTS

Best tools for investigating neutrino flavor phenomena in Vacuum and in Matter

For ASTROPHYSICS:

Best tool for unprecedented look at how a real Star works - in the past, present and future
Solar Neutrinos

What we know:

- **Standard Solar Model**
- Missing $\nu_e$ (Cl, Ga, SK, SNO)
- Flavor mixing happens (SNO)
Solar Neutrinos

What we know:

- Standard Solar Model
- **Missing $\nu_e$ (Cl, Ga, SK, SNO)**
- Flavor mixing happens (SNO)

![Diagram showing Total Rates: Standard Model vs. Experiment](image)
Solar Neutrinos

What we know:

- Standard Solar Model
- Missing $\nu_e$ (Cl, Ga, SK, SNO)
- Flavor mixing happens (SNO)
Neutrino Mixing Parameters

**MSW explanation:**

Solar data: $\Delta m_{12}^2, \theta$

(assumes CPT): $\Delta m_{12}^2, \theta$

add anti-neutrinos (Kamland)

MSW-LMA is based on the combined results from many complimentary experiments
Solar $\nu$-Luminosity

Three main contributions:

<table>
<thead>
<tr>
<th>Process</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp$</td>
<td>0.925</td>
</tr>
<tr>
<td>$^7\text{Be}$</td>
<td>0.075</td>
</tr>
<tr>
<td>$^8\text{B}$</td>
<td>0.00009</td>
</tr>
</tbody>
</table>

- $^8\text{B}$ (SK, SNO)
- $^7\text{Be} + ^8\text{B}$ (Cl)
- $pp + ^7\text{Be} + ^8\text{B}$ (Ga)
- $^7\text{Be}$ (Borexino, Kamland -future)

$\Rightarrow$ in principle can deduce pp-$\nu$ flux

**Problem**: yield weighted by cross-section

$\Rightarrow$ poor sensitivity of Gallium experiments to pp-$\nu$
Solar Luminosity: Neutrino vs. Photon

With added Luminosity constraint:

\[
\frac{L_v}{L_{hv}} = 1 \quad \frac{\phi_{pp}}{\phi_{pp-SSM}} = 1.01 \pm 0.02
\]

Without Luminosity constraint:

\[
\frac{L_v(\text{inferred})}{L_{hv}} = 1.4 \begin{pmatrix} 0.2 \\ 0.3 \end{pmatrix}_{1\sigma} \begin{pmatrix} 0.7 \\ 0.6 \end{pmatrix}_{3\sigma}
\]

Experimental status –
No useful constraint!
NEW SCIENCE - Discovery Potential of LENS

In 5 years (with ν- source calibration):

pp, $^7$Be $\nu$-fluxes at earth ±3% $\Leftrightarrow$ Measured Neutrino Luminosity ~4%

$\Rightarrow$ Ultimate test of the Neutrino & the Sun

$\Rightarrow$ Test solar model and neutrino oscillations with one measurement

$\Rightarrow$ Astrophysics: $L_\nu > L_{hv}$ Is the sun getting hotter?
$\quad L_\nu < L_{hv}$ Cooling or a sub-dominant non-nuclear source of energy in the sun?

$\Rightarrow$ Precision values of $\theta_{12}$, $\theta_{13}$

$\Rightarrow$ Sterile Neutrinos?
NEW SCIENCE - Discovery Potential of LENS
APS Nu Study 2004 ➔ Low Energy Solar Nu Spectrum: one of 3 Priorities

In the first 2 years (no calibration with ν-source needed):

- **Test of MSW LMA physics** - *no specific physics proof yet!*
  \[ P_{ee}(pp)=0.6 \text{ (vac. osc.)} \quad P_{ee}(^8B)=0.35 \text{ (matter osc.)}, \quad \text{as predicted?} \]
- **Non-standard Fundamental Interactions?**
  Strong deviations from the LMA profile of \( P_{ee}(E) \) ?
- **Mass Varying Neutrinos?**
  (see above)
- **CPT Invariance of Neutrinos?**
  so far LMA only from Kamland\( \bar{\nu}_e \), is this true also for \( \nu_e \) ?
- **RSFP/ Nu magnetic moments**
  Time Variation of pp and \(^7\text{Be}\) signals? (No Var. of \(^8\text{B}\) nus !)
  (Chauhan et al JHEP 2005)

Low Energy Neutrinos:
Only way to answer these questions!
Science from Relative Fluxes

MSW-LMA Profile

Deviations from standard $P_{\nu_e \rightarrow \nu_e}$ survival probability in various new scenarios

Mass-varying neutrinos

Non-standard interactions

LENSS

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

**Tag:** Delayed emission of (e/γ)+ γ

**Threshold:** 114 keV $\rightarrow$ pp-ν’s

**$^{115}$In abundance:** ~ 96%

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

**Basic background discriminator:**
- Time/space coincidence tag
- Tag energy: $E_{\nu-tag} = E_{\beta max} + 116$ keV

$^7$Be, CNO & LENS-Cal signals not affected by Indium-Bgd!
**Expected Result: Low Energy Solar ν-Spectrum**

**LENS-Sol Signal**

\[
\text{LENS-Sol Signal} = SSM(\text{low CNO}) + \text{LMA} \times \text{Detection Efficiency } \varepsilon
\]

pp: \( \varepsilon = 64\% \)

\(^7\text{Be}: \varepsilon = 85\% \)

pep: \( \varepsilon = 90\% \)

→ Rate: pp 40 /y/t In
→ 2000 pp ev. / 5y \( \pm 2.5\% \)
→ Design Goal: S/N \( \geq 3 \)

Access to pp spectral *Shape* for the first time

**LENS**

In-LENS: Studied Worldwide Since 1976!
Dramatic Progress in 2005

Status Fall 2003

Longit. modules + hybrid (InLS + LS)
InLS: 5% In, L(1/e)=1.5m, 230 pe/MeV
Total mass LS: 6000t
In: 30t for 1900 pp \(\nu\)’s /5y
PMTs: ~200,000
pp-\(\nu\) Detection Efficiency: ~20%
S/N~1 (single decay BS only)
~1/ 25 (All In decay modes)
(MPIK Talk at DPG 03/2004)

Status Fall 2005

• In Liq. Scint.
• New Design
• Bgd Structure
• New Analysis Strategy

Cubic Lattice Non-hybrid (InLS only)
InLS: 8% In, L(1/e)>10m, 900 pe/MeV
Mass InLS : 125t to 190t
In: 10t-15t for 1970 pp \(\nu\)’s /5y
PMTs: 13,300 (3”) - 6,500 (5”)
pp-\(\nu\) Detection Efficiency: 64-45%
S/N ~3 (ALL In decay modes)
1. Indium concentration ~8%wt (higher may be viable)
2. Scintillation signal efficiency (working value): 9000 hν/MeV
3. Transparency at 430 nm: L(1/e) (working value): >10m
4. Chemical and Optical Stability: at least 2 years
5. InLS Chemistry - Robust

Basic Bell Labs Patent, filed 2001, awarded 2004
New Detector Concept - The Scintillation Lattice Chamber

Light propagation in GEANT4

Concept

Test of double foil mirror in liq. @~2bar

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
100 keV event in 4x4x4m cube, 12.5cm cells

**Perfect optical surfaces**: 20 pe (per channel)

**Rough optical surfaces**: 20% chance of non-ideal optics at every reflection
12 pe in vertex + ~8 pe in “halo”

**Conclusion** - Effect of non-smooth segmentation foils:
- No light loss - (All photons in hit and halo counted)
- Hit localization accuracy virtually unaffected
Light loss by Multiple Fresnel Reflection

Upper limit ~1700pe/MeV (L=10m) - reach via antireflective coating on films?

Adopt 1020 pe/MeV 7.5 cm cells

4x4x4m Cube Absorption length = 10m
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
Indium Radioactivity Background

**BGD**

\(^{115}\text{In}\)

\(\beta_0 + n\gamma\) (BS) 
\(E_{\text{max}} = 499\text{ keV}\)

\(115\text{In} \rightarrow 115\text{Sn}\)

**SIGNAL**

\(E(\nu) - 114\text{ keV} \) (e1)

\(115\text{In} \rightarrow e/\gamma \)  
\(116\text{ keV} \) (g2)

\(115\text{Sn} \rightarrow 498\text{ keV} \) (g3)

* Cattadori et al: 2003

Multiple \(^{115}\text{In}\) decays simulate tag candidate in many ways

- e1 = signal electron
- g2 = 116 conv. Electron
- g3 = 498 keV \(\gamma\)-ray
- Creates shower around vertex
- Tag = g2 + g3 in prompt
- Coincidence = shower
- \(E(g2+g3) = 620\text{ keV}\)
- \(N\text{hit} = 3\)
Indium Radioactivity Background

Background categories

n $^{115}$In $\beta$-decays in (quasi) prompt coincidence produce a tag:

Basic tag candidate: Shower near vertex ($N_{hit} \geq 3$) - chance coincident with $^{115}$In $\beta$ in vertex

Type A: $A_1 = \beta + BS \gamma (E_{tot} = 498 \text{ keV}) \ (x1)$
$A_2 = \gamma (498 \text{ keV}) \ (x1)$

Type B: 2 $\beta$-decays ($x10^{-8}$)
Type C: 3 $\beta$-decays ($x10^{-16}$)
Type D: 4 $\beta$-decays ($x10^{-24}$)

$\{ \}$ Suppression via tag topology

Strong suppression via energy
Indium Background Simulations and Analysis

Data: Main Simulation of Indium Events with GEANT4
- ~ 4x10^6 In decays in one cell centered in ~3m^3 volume (2-3 days PC time)
- Analysis trials with choice of pe/MeV and cut parameters (5' /trial)

Analysis Strategy
- Primary selection - tag candidate shower events with Nhit ≥ 3
- Classify all eligible events (Nhit ≥ 3) according to Nhit
- Optimize cut conditions individually for each Nhit class

Main Cuts
- Total energy: g2+g3
- Tag topology: Distance of lone β from shower
## Background Suppression - Analysis of Tag Candidates

<table>
<thead>
<tr>
<th></th>
<th>Signal /y /t In</th>
<th>Bgd tot /y /t In</th>
<th>Bgd A1 /y /t In</th>
<th>Bgd A2 /y /t In</th>
<th>Bgd B /y /t In</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RAW</strong></td>
<td>62.5</td>
<td>$79 \times 10^{11}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valid tag (Energy, Branching, Shower) in Space/Time delayed coinc. with prompt event in vertex</td>
<td>50</td>
<td>$2.76 \times 10^5$</td>
<td>$8.3 \times 10^4$</td>
<td>$2.8 \times 10^3$</td>
<td>$1.9 \times 10^5$</td>
</tr>
<tr>
<td>$\geq 3$ Hits in tag shower</td>
<td>46</td>
<td>$2.96 \times 10^4$</td>
<td>$2.6 \times 10^4$</td>
<td>$2.5 \times 10^3$</td>
<td>$1.4 \times 10^3$</td>
</tr>
<tr>
<td>$+Tag$ Energy = 620 keV</td>
<td>44</td>
<td>306</td>
<td>0.57</td>
<td>4.5</td>
<td>293</td>
</tr>
<tr>
<td>$+Tag$ topology</td>
<td>40</td>
<td>$13 \pm 0.6$</td>
<td>0.57</td>
<td>4.0</td>
<td>8.35</td>
</tr>
</tbody>
</table>

→ Tag analysis must suppress Background by $\sim 2 \times 10^4$
→ Sufficient to generate $\sim 4 \times 10^6$ n-tuples for the analysis

**Final Result:** Overall Background suppression $> 10^{11}$
At the cost of signal loss by a factor $\sim 1.6$
### Typical LENS-Sol Design Figures of Merit – Work in Progress

**Scintillator properties:**

- InLS: 8% In
- $L(1/e) = 1000\text{cm}$
- $LY (\text{InLS}) = 9000\text{ hv/MeV}$

**Detector Design:**

<table>
<thead>
<tr>
<th>Cell Size mm</th>
<th>Cube size m</th>
<th>Pe yield /MeV</th>
<th>Det Eff %</th>
<th>pp-ν /t In/y</th>
<th>Bgd /t In/y</th>
<th>S/N</th>
<th>M (In)* ton</th>
<th>M (InLS) ton</th>
<th>PMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>4</td>
<td>1000</td>
<td>64%</td>
<td>40</td>
<td>13</td>
<td>3</td>
<td>10</td>
<td>125</td>
<td>13300 (3”)</td>
</tr>
<tr>
<td>125</td>
<td>5</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”)</td>
</tr>
</tbody>
</table>

LENSS

MINILENS

Final Test detector for LENS

- \text{InLS} : 128 \text{ L}
- \text{PC Envelope} : 200 \text{ L}
- 12.5\text{cm pmt’s} : 108
MINILENS: Global test of LENS R&D

• Test detector technology
  → Large Scale InLS
  → Design and construction

• Test background suppression of In radiations by $10^{-11}$

• Demonstrate In solar signal detection in the presence of high background

Direct blue print for full scale LENS
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-$\nu$ events

→ Demonstrate In-$\nu$ Signal detection even in MINILENS

**Cosmogenic production of In ($p,n$) Isomers**

Taggable via $\mu$, $p$, $n$ (via In, gamma) and delayed coincidence

Rate @ 1400 mwe VT-NRL Kimballton lab $l=3\,y/t\,ln$;
Rate @ surface laboratory: $900/\,t\,ln/\,y$
Summary

Major breakthroughs:

- In LS Technology
- Detector Design
- Background Analysis

→ Basic feasibility of In-LENS-Sol secure
  - extraordinary suppression of In background
    (all other Bgd sources not critical)
  - Scintillation Chamber – InLS only
  - High detection efficiency → low detector mass
  - Good S/N

IN SIGHT: Simple Small LENS (~10 t In /125 t InLS)

Next Step
Test of all the concepts and the technology developed so far:

MINI-LENS - 130 liter InLS scintillation lattice detector