LENS
Measuring the Neutrino Luminosity of the Sun

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**LENS-Indium: SCIENCE GOAL**

**Precision Measurement of the Neutrino Luminosity of the Sun**

**LENS-Sol:**
- Measure the low energy solar $\nu$ spectrum (pp, $^7$Be, CNO)
- $\pm \sim 3\%$ pp- $\nu$ flux
- Experimental tool: Tagged CC Neutrino Capture in Indium

\[
\nu_e + ^{115}\text{In} \rightarrow e^- + \gamma + \left(\gamma / e^-\right) + ^{115}\text{Sn}
\]

- 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 $\nu$-capture to *specific* level of $^{115}$Sn
- *Note:* $B(GT) = 0.17$ measured via (p,n) reactions
Tag: Delayed emission of (e/γ)+ γ
Threshold: 114 keV → pp-ν’s

115In abundance: ~ 96%

Background Challenge:
- Indium-target is radioactive! (τ = 6x10^{14} y)
- 115In β-spectrum overlaps pp-ν signal

Basic background discriminator:
Tag energy: E_{ν-tag} = E_{β_{max}} + 116 keV

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

LENS-Sol Signal
= SSM(low CNO) + LMA x Detection Efficiency $\varepsilon$

pp: $\varepsilon = 64\%$
$^7$Be: $\varepsilon = 85\%$
pep: $\varepsilon = 90\%$

$\rightarrow$ Rate: pp 40 /y /t In
$\rightarrow$ 2000 pp ev. / 5y $\rightarrow$ ±2.5%
$\rightarrow$ Design Goal: S/N $\geq$ 3

Access to pp spectral Shape for the first time

Detector Resolution 800 pe / MeV

Signal extracted from fit of coinc. time spectrum to isomeric exp. decay + Random Coinc. Bgd

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

Random coinc. Bgd

S/N=1

S/N=3

LENS
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!*
  \( P_{ee}(pp) = 0.6 \) (vac. osc.) \( P_{ee}(^{8}\text{B}) = 0.35 \) (matter osc.), 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 \( \overline{\nu} \), 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)
NEW SCIENCE - Discovery Potential of LENS

In 5 years (with ν- source calibration):

→ Absolute pp, $^7$Be nu fluxes at earth ± 3%
→ Measured Neutrino Luminosity (~4%)

Photon Luminosity $\leftrightarrow$ Neutrino Luminosity
Ultimate test of the neutrino & the sun
Experimental status - No useful constraint!

\[
\frac{L_{\nu \text{ (inferred)}}}{L_{h\nu}} = 1.4 \left[ \frac{0.2}{0.3} \right]_{1\sigma} \left[ \frac{0.7}{0.6} \right]_{3\sigma}
\]

→ Test solar model and neutrino oscillations with one measurement
→ Astrophysics: $L_\nu > L_{h\nu}$ Is the sun getting hotter?
    $L_\nu < L_{h\nu}$ Cooling or a sub-dominant non-nuclear source of energy in the sun?
→ Precision values of $\theta_{12}$, $\theta_{13}$; Sterile Neutrinos?
In-LENS: Studied Worldwide Since 1976!
Dramatic Progress in 2005

Status Fall 2003
- In Liq. Scint.
- New Design
- Bgd Structure
- New Analysis Strategy

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 ν’s /5y
- PMTs: ~200,000
- pp-ν 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
- 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 ν’s /5y
- PMTs: 13,300 (3”) - 6,500 (5”)
- pp-ν Detection Efficiency: 64-45%
- S/N ~3 (ALL In decay modes)
Indium Liquid Scintillator Status

Milestones unprecedented in metal LS technology

LS technique relevant to many other applications

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 Stabililty: at least 2 years
5. InLS Chemistry - Robust

Basic Bell Labs Patent, filed 2001, awarded 2004

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

Adopt 1020 pe/MeV 7.5 cm cells

Black: L=10m with foil imperf.
Pink: L=10m without foil imperf.
Blue: L=7m with foil imperf.
Red: L=7m without foil imperf.
Indium Radioactivity Background

\[ \beta_{1} (E_{\text{max}} < 2 \text{ keV}) \quad (b = 1.2 \times 10^{-6})^{*} \]

\[ \beta_{0} + n\gamma \quad (\text{BS}) \quad (E_{\text{max}} = 498 \text{ keV}) \]

\[ ^{115}\text{In} \quad \beta_{0} + n\gamma \quad (\text{BS}) \quad \gamma \quad 498 \text{ keV} \quad (\text{g3}) \]

\[ ^{115}\text{Sn} \]

\[ ^{115}\text{In} \quad e/\gamma \quad 116 \text{ keV} \quad (\text{g2}) \]

* Cattadori et al: 2003

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

\[ e_{1} = \text{signal electron} \]
\[ g_{2} = 116 \text{ conv. Electron} \]
\[ \text{Both in vertex cell} \]

\[ e_{1} - \text{Tag delay coinc} \]
\[ \text{Within 10 \mu s} \]

\[ g_{3} = 498 \text{ keV } \gamma\text{-ray} \]
\[ \text{Creates shower around vertex} \]

\[ \text{Tag} = g_{2} + g_{3} \text{ in prompt} \]
\[ \text{Coincidence} = \text{shower} \]
\[ E(g_{2} + g_{3}) = 620 \text{ keV} \]
\[ \text{Nhit} = 3 \]
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: $A_1 = \beta + BS \gamma (E_{tot} = 498$ keV) $^{(x1)}$

Type B: 2 $\beta$-decays ($x10^{-8}$)

Type C: 3 $\beta$-decays ($x10^{-16}$)

Type D: 4 $\beta$-decays ($x10^{-24}$)

Strong suppression via energy

Suppression via tag topology
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>Condition</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>RAW</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>+ ≥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 ~$2 \times 10^4$
- Sufficient to generate ~$4 \times 10^6$ n-tuples for the analysis

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**Final Result:** Overall Background suppression > $10^{11}$

At the cost of signal loss by a factor ~ 1.6
Scintillator properties:

- InLS: 8% In
- L(1/e) = 1000 cm
- LY (InLS) = 9000 hν/MeV

Detector Design:

<table>
<thead>
<tr>
<th>Cell Size mm</th>
<th>Cube size cm</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>
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 - 200 liter InLS scintillation lattice detector
VT-NRL Low Bgd Laboratory @ Kimballton
Limestone Mine VA

30 min by car from Virginia Tech
Direct Measurement of the Central Temperature of the Sun with High pe/MeV in LENS

Expected precision of centroid energy of $^7$Be Line in LENS (Statistics only, 2000 events, 1700 pe/MeV): $\delta E(1\sigma) \pm 0.5$ keV
Predicted solar shift (Bahcall 1993) $\delta E = +1.29$ keV

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