Dedicated to the Memory of
JOHN BAHCALL
Flag Bearer First & Last, of the Quest for pp Neutrinos

Measuring the
Neutrino Luminosity of the Sun
-- LENS-Sol --

TAUP 05, Zaragoza, Spain
September 12, 2005

R. S. Raghavan
Virginia Tech
LENS (Indium): SCIENCE GOAL
Precision Measurement of the Neutrino Luminosity of the Sun

**LENS-Sol**

To achieve Goal → Measure low energy nu spectrum (pp, Be, CNO)
→ ± ~3% pp flux
→ Exptl Tool: Tagged CC Neutrino Capture in $^{115}\text{In}$

$$\nu_e + ^{115}\text{In} \rightarrow e^- + \text{(delay)} 2\gamma + ^{115}\text{Sn}$$

**LENS-Cal**

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

R.S. Raghavan/VT/Aug05
LENS-Sol / LENS-Cal Collaboration
(Russia-US: 2004---)

Russia:
INR (Mosow):  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. North Carolina: A.Champagne
ORNL:  J. Blackmon, C. Rascoe, A. Galindo-Urribari
Princeton U. : J. Benziger
Virginia Tech:  Z. Chang, C. Grieb, M. Pitt,
R.S.Raghavan*, R.B. Vogelaar

*raghavan@vt.edu

NEW COLLABORATORS (US & INTERNATIONAL)
CORDIALLY WELCOME!

R.S.Raghavan/VT/Aug05
The Indium Low Energy Neutrino Tag

CC Nu Capture in $^{115}\text{In}$ to excited isomeric level in $^{115}\text{Sn}$

3 Unique Features:
- **Tag:** Delayed emission of 2 $\gamma$'s
- **Threshold:** 114 keV $\rightarrow$ pp Nu
- $^{115}\text{In}$ abundance: $\sim$96%

Basic Bgd Challenge:
- Indium Nu target is radioactive! ($\tau = 6 \times 10^{14}$ y)
- $^{115}\text{In}$ $\beta$-Spect. overlaps pp signal

Basic bgd discriminator: Tag Energy:
$E(\text{Nu tag}) = E(\beta_{\text{max}}) + 116$ keV

Be, CNO & LENS-Cal signals not affected by Indium bgd

R.S. Raghavan/VT/Aug05
**Expected Result:**

**Low Energy Solar Neutrino Spectrum**

**LENS-Sol Signal =** [SSM(low CNO)+LMA] x Detection Efficiency: pp 64%; Be 85%; pep 90%

→ Rate: pp 40 /y /t In
→ 2000 pp ev. / 5y → ±2.5%
→ Design Goal: S/N ≥ 3

Signal in LENS is a *coincidence* event--extracted from fit of coincidence time spectrum to [isomeric exp. decay + Random Coinc. Bgd]

**Detector Resolution** (800 pe/ MeV)

**Random coinc bgd**

Rate: pp 40 /y /t In

**S/N=1**

**S/N=3**

**Design Goal:** S/N ≥ 3

**With currently achieved energy resolution,** access to pp Spectral *Shape* for the first time.

R.S.Raghavan/VT/Aug05
NEW SCIENCE—Discovery Potential of LENS
Massive Nu’s Open Door for probing a series of fundamental Questions
APS Nu Study 2004 → Lo Energy Solar Nu Spectrum: one of 3 Priorities

Phased yield of Unique Results
In First Two years (No Calibration with Nu Source needed)

• Test of MSW LMA Physics --no proof yet!
  no B8 d/n effect, spectral shape?)
  \[ P_{ee} (pp) = P_{ee} (vac) \approx (1 - 0.5 \sin^2 2\theta_{12}) \? \]

• Non-standard Fundamental Interactions?
  \[ P_{ee} (Be) / P_{ee} (pp) < \approx 1 \? \quad P_{ee} (pep)/P_{ee} (pp) < \approx 1 \? \]

• Mass Varying Neutrinos? (ditto)
• CPT Invariance of Neutrinos?
  \[ \text{If not LMA for } \nu \text{'s (contra } \bar{\nu} \text{'s), what else?} \]
  Oscillations in pp spectrum? (RSR JCAP 2003)

• RSFP/ Nu magnetic moments
  \[ \text{Time Variation of pp and Be signals? (No Var. of } ^8 \text{B nus !)} \]
  (Chauhan et al JHEP 2005)

Lo Nu
Only way to answer these questions!

R.S.Raghavan/VT/Aug05
In Five Years (with source Calib):

→ **Absolute** pp, Be, pep nu fluxes at earth
→ **Measured Neutrino Luminosity (~4%)**

Neutrino-Sun Dichotomy in solar nu data
Use Photon output of sun to standardize neutrino output

*Photon Luminosity* ↔ *Neutrino Luminosity*

“External” Test of our best knowledge of the Neutrino & the Sun
Exptl. Status (after 6 expts/40 y) --No useful constraint!

\[
\frac{L(\nu \text{ inferred})}{L(\nu)} = 1.4^{+0.2}_{-0.3}^{+0.7}_{-0.6}
\]

Precise *L(ν)* at earth → Nu parameters → Precise *L(ν)* in Sun → *L(ν)* in Sun?

→ **Neutrino Physics:**

→ Precision Values of $\theta_{12}, \theta_{13}$, sterile neutrinos?

→ **Astrophysics:**

*L(ν)* > *L(hν)* Is the Sun getting Hotter?

*L(ν)* < *L(hν)* Sub-dominant non-nuclear source of energy of Sun?

**Answers for Big Questions with Small L(ν)≠L(hν)**

R.S.Raghavan/VT/Aug05
**In-LENS: Studied world wide since 1976! - Decisive Progress in 2005-**

### Status Fall 2003

- Longit. modules + hybrid (InLS + LS)

**InLS:** 5% In; L(1/e)=1.5m; 230 pe/MeV In:
- Total mass LS: 6000 ton
- 30 ton for 1900 pp’s /5
- PMTs: ~200,000
- Detection Efficiency: ~20%
- S/N~1 (single decay BS only ~1/ 25 (All In decay modes)

(MPIK Talk at DPG 03/2004)

### Status Summer 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 : 125 to 190 ton
- In:10-15 ton for 1970 pp’s /5y
- PMTs: 13300 (3”)-- 6,500 ( 5”)
- Detection Efficiency: 64-45%
- S/N ~3 (ALL In decay modes)

R.S.Raghavan/VT/Aug05
**InLS Status (Aug ‘05 Summary)**

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

- Milestones unprecedented in metal LS technology
- LS technique relevant to many other applications

- Basic Bell Labs Patent
  - Filed: 2001; awarded: 2004
### NEW DETECTOR CONCEPT—
**SCINTILLATION LATTICE CHAMBER**

- **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 bgd**
  - Hit localizability independent of event energy
- **HE particle (e.g. µ) tracks, γ- shower structure directly seen**

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![Concept/test model](image1)

Optical segmentation by double foils with airgap

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

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R.S. Raghavan/VT/Aug05
Effect of non-smooth foil assembly on hit definition
12.5 cm cells in 4x4x4m cube; 100 keV event; /9000 hv/MeV; Signal=6x20 pe

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

Conclude:
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 at intervening air gaps

**pe yield (400 cm detector)**

- **1700 pe/MeV (L=10m) via antireflecting coating on films?**

**4x4x4m Cube**

- **Adopt 1020 pe/MeV 7.5cm 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.

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Hi pe/MeV in LENS? → New Window into the Sun’s Interior Direct Measurement of Central Temperature of Sun

Central Temp. in Sun shifts energy of Be line by $\Delta E$ (Sun-Lab)
Can one detect $\Delta E$ in the observed energy of Be line 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) $\Delta E$(Sun-Lab): +1.29 keV

$\delta E(1\sigma) = 0.5$ keV

R.S. Raghavan/VT/Aug05
Complexity of Indium radioactivity background

In\textsuperscript{115} \(\beta\), \(\gamma\) (BS) \((E_{\text{max}} = 498\text{ keV})\)

\(\beta\) \((E_{\text{max}} < 2\text{ keV})\) \((1.2 \times 10^{-6})^*\)

\(\text{BGD}\)

\(\text{SIGNAL}\)

Basic tag candidate: Shower with \(N_{\text{hit}} \geq 3\)

BGD tag: shower near vertex -- chance coincident with In \(\beta\) in vertex

Multiple In decays simulate tag candidate in many ways

One In decay: \(\rightarrow A_1 = \beta + BS \gamma \ (E_{\text{tot}} = 498\text{ keV})\) \((x1)\)

\(\rightarrow A_2 = 498 \gamma\) \((x1)\)

Two In decays: \(\rightarrow B = \beta + BS\) or \(498\gamma\) in any combination from each decay \((x10^{-8})\)

Three In decays: \(\rightarrow C = 3 \beta\)-decays All combinations \((x10^{-16})\)

Four In decays: \(\rightarrow D = 4 \beta\)-decays All combinations \((x10^{-24})\)

Only single decay - BS (A1) considered up to 2004!

* Cattadori et al: 2003

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Indium bgd Simulations and Analysis

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

Analysis-- Basics
- Primary selection -- tag candidate shower events with Nhit ≥ 3
- Every hit in the bgd shower is a possible tag vertex in random coincidence (10µs) with a previous β in that cell

ANALYSIS STRATEGY (NEW)
- Classify all eligible events (Nhit ≥ 3) according to Nhit
- Optimize cut conditions individually for each Nhit class

→ Leads to significantly higher overall detection efficiency than with old method of same cuts for all Nhit

R.S.Raghavan/VT/Aug05
## Role of Experimental Tools in Bgd Suppression

### Basic task: Analysis of tag candidate

<table>
<thead>
<tr>
<th>RAW (singles)</th>
<th>Signal /t ln/y</th>
<th>Bgd tot /t ln/y</th>
<th>Bgd A1 - BSγ /t ln/y</th>
<th>Bgd A2 -498γ /t ln/y</th>
<th>Bgd B-β1+BSγ2 /t ln/y</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>62.5</td>
<td>79 x10^{11}</td>
<td>“Free”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valid tag (Energy, branching, shower coinc, hits &gt; 3 pe) in Space/Time delay coinc with prompt event in vertex</td>
<td>50</td>
<td>2.76x10^5</td>
<td>8.3x10^4</td>
<td>2.8x10^3</td>
<td>1.9x10^5</td>
</tr>
<tr>
<td>+ ≥3 Hits in Tag shower</td>
<td>46</td>
<td>2.96x10^4</td>
<td>2.6x10^4</td>
<td>2.5x10^3</td>
<td>1.4x10^3</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 ± 0.6</td>
<td>0.57</td>
<td>4.0</td>
<td>8.35</td>
</tr>
</tbody>
</table>

→ Tag analysis must suppress bgd by ~2x10^4--NOT 10^{11}

→ Sufficient to Generate ~4x10^6 ntuples for analysis

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**Final Result:** Overall Bgd suppression >10^{11}
At the cost of signal loss by factor~1.6

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Typical LENS-Sol: DESIGN FIGURES OF MERIT
Preliminary!---Work in Progress
InLS: 8% In; L(1/e) =1000cm; Y (InLS) = 9000 hv/MeV; Hits > 3pe

<table>
<thead>
<tr>
<th>Cell Size mmx mmx mm</th>
<th>Det Eff %</th>
<th>Nu Rate /T In/y</th>
<th>Bgd Rate /T In/y</th>
<th>S/N</th>
<th>Mass for 2000pp/5y (ppflux3%)</th>
<th>T (In)</th>
<th>T (InLS)</th>
<th>PMT’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 10^3 pe/MeV 4x4x4</td>
<td>64</td>
<td>40</td>
<td>13</td>
<td>3</td>
<td>10</td>
<td>125</td>
<td>13300 (3”)</td>
<td></td>
</tr>
<tr>
<td>125 950 pe/MeV 5x5x5</td>
<td>41.8</td>
<td>26</td>
<td>9</td>
<td>2.9</td>
<td>15.3</td>
<td>190</td>
<td>6500 (5”)</td>
<td></td>
</tr>
<tr>
<td>180 1000 p/MeV 6x6x6</td>
<td>33.1</td>
<td>20.7</td>
<td>22</td>
<td>1</td>
<td>19.3</td>
<td>240</td>
<td>3300 (8”)</td>
<td></td>
</tr>
</tbody>
</table>

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Vertex energy
No cut applied

nu events
BS >450 kev
498

Total Tag Energy
Before cut

Nu
Bgd
After cut

Nhit dist
Before Cuts
After Cuts

Nu
Bgd
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 det. efficiency → low detector Tonnage
  - Good S/N

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

Next Steps

• Chemical Technology of large scale InLS production
• Detector construction technology for Scintillation Chamber
• Aim at Proposal for full scale LENS-Sol in late 2006

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Space (10x10x10m) Adequate for full scale LENS-Sol

- Electric service
- Gravel berm
- Steel reinforcement for possible gutter to be installed later
- Truck access to front and back area
- Tank access
- Main drain
- NRL Lab
- Overhead lighting
- 3 1/2 pairs on separate switches

Unfinished Space for future use

Tank I: Fresh water supply, above ground, 500 Gallons
Tank II: Sewage collection, below ground, 700 Gallons
Tank III: Spill collection, below ground, 500 Gallons

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ADDITIONAL SLIDES
CPT violation!  \( \nu \neq \bar{\nu} \)

If not LMA for \( \nu \), What else?

Best fit model, solar neutrino data only—LWO, long wavelength vacuum oscillations
(upper panel)

Detect LWO via fast oscillations in pp spectrum (lower panel)

(RSR JCAP 2003)
Non-Std Fundamental Interactions
---LE window unique probe
(not hi energy or Kamland)

FIG. 2: Regions of $\Delta m^2$ and $\tan^2 \theta$ allowed at 90, 95, 99, 99.73% C.L. (2 dof) for SM interactions (left) and the NSI scenario (right) described by Eqs. (3-6). For the latter we used $\epsilon_{11}^u = \epsilon_{11}^d = 0.065, \epsilon_{12}^u = \epsilon_{12}^d = -0.15$.

Penya -Garay et al
hep-ph 0402266

FIG. 3: The predicted KamLAND spectrum (top) and the time-averaged solar neutrino survival probability (bottom) for the LMA-0 best-fit point. For comparison, the standard LMA-I survival probability is also given. Refer to the text for details.

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### Error Budget for pp nu flux measurement with 2000 events/5y at S/N=3

<table>
<thead>
<tr>
<th>Item</th>
<th>Percent Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal/Bgd Statistics ( \Delta S/S% )</td>
<td>2.5</td>
</tr>
<tr>
<td>Coinc. Detection Efficiency ( \Delta \varepsilon/\varepsilon % )</td>
<td>0.7</td>
</tr>
<tr>
<td>No. of Target Nuclei ( \Delta N/N% )</td>
<td>0.3</td>
</tr>
<tr>
<td>Cross Section (Q value) ( \Delta I/I% )</td>
<td>0.3</td>
</tr>
<tr>
<td>Cross Section (B(GT)) ( \Delta M/M% )</td>
<td>1.8</td>
</tr>
<tr>
<td>Total Flux Uncertainty ( \Delta \phi/\phi% )</td>
<td>3.2</td>
</tr>
</tbody>
</table>
### Example of Detailed results:

75x75x75mm Cells; (2x[4x4x4m Cube]
L(1/e) = 10m;  Y = 9 hv/keV;  pe/keV = 1.0;  Hits ≥ 3 pe

<table>
<thead>
<tr>
<th>Bgd Type</th>
<th>A1</th>
<th>C</th>
<th>D</th>
<th>A2</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events before Cuts</td>
<td>500000</td>
<td>20000</td>
<td>1000</td>
<td>2000000</td>
<td>3x10^6</td>
</tr>
<tr>
<td>Rate before Cuts</td>
<td>6.17.10^8</td>
<td>14.6</td>
<td>2.24.10^-3</td>
<td>6.17.10^8</td>
<td>9.49.10^4</td>
</tr>
<tr>
<td>Rate After Cuts</td>
<td>5.7(23).10^-1</td>
<td>9.5(26).10^-3</td>
<td>0(2).10^-6</td>
<td>4.03(12)</td>
<td>8.3(5)</td>
</tr>
<tr>
<td>Events After Cuts</td>
<td>6</td>
<td>13</td>
<td>0</td>
<td>1088</td>
<td>264</td>
</tr>
</tbody>
</table>

**Neutrino detection efficiency:**  64%
**Neutrino Event rate:**  40 solar pp per ton In per year
**Indium Background rate:**  13.0 (6) per ton In per year
**S/B-ratio:**  3.08
Indium-115 Beta Spectrum (Pfeiffer et al. PR 1979)

\[ \sim 2.08 \times 10^6 \text{ In decays} \]
Bremmstrahlung Spectrum of 100,000 In decays with energy > 450 keV (1/111)+ at least one photon >40 keV (1/116)
Corresponding total In decays = $10^5 \times 111 \times 116 = 1.29 \times 10^9$
(GEANT IV--; Pfeiffer In-beta spectrum)
LONG TERM (Yrs) STABILITY--CHEM, OPT, SCINTILLATION

**Long term Stability in typical samples (BNL & Bell Labs)**

- All samples above were made at low pH-Hi HMVA and stored without special precautions on air exposure
- Light yield very stable
- \( L(1/e) \) degrades somewhat (see band)
- Traced to HMVA degradation from air exposure (left)
- Present InLS contains no HMVA
  - higher stability over several years expected

R.S. Raghavan/VT/Aug05
InLS Status (Aug ‘05)

Summary

1. Indium conc. ~8 wt% (higher may be viable)
2. Scintillation signal efficiency (typical): 9000 hv/MeV
3. Transparency at 430 nm: L(1/e) (typical): 10 m
4. Chemical and Optical Stability: ~2 years
5. InLS Chemistry—Robust

• Milestones unprecedented in metal LS technology
• LS technique relevant to many other applications

• Basic Bell Labs Patent
  Filed: 2001; awarded: 2004
\[ K = \frac{P_{ee}}{1 - 0.5 \sin^2 2\theta_{12}} \]

Current LMA 95\% c.l. area

\[ \Delta m^2 (x10^5) \text{eV}^2 \]
Current limits from 7 experiments

\[ P_{ee}(pp:LMA) = 0.985(1 - 0.5\sin^2 2\theta_{12}) \]