Preliminary White Paper

High Mass Indium Detector for Low Energy Solar Neutrinos:
Precision Measurements for Neutrino Physics & Astrophysics

R. S. Raghavan (raju@lucent.com)
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Overview-- LENS-Sol & LENS-Cal

Solar neutrinos oscillate! This recent fundamental result has opened an active exploration of neutrino physics and astrophysics of unprecedented breadth and detail. This White Paper surveys the potential of low energy solar neutrino spectroscopy using the Indium detector for definitive contributions to the program of establishing the precise structural basis of non-standard neutrinos as well as the astrophysics of the sun.

The low energy (<2 MeV) *spectrum* of solar neutrinos (ν) comprising the pp, ^{7}Be and CNO ν fluxes contains >99% of sun's neutrino output, yet it has never been directly observed. The global convergence of data from present solar ν experiments implies that such a program must meet not only the intrinsic technical challenge of observing low energy solar ν in real-time but accept the new one of measuring low energy ν fluxes to a *precision of a few percent* in order to impact and advance current neutrino and astrophysical theory [1].

One of the few means available for meeting this double challenge is the Indium neutrino detector.[2] This device is designed to measure in real-time, the low energy solar neutrino (ν_e) spectrum, based on charged current (CC) driven ν_e capture in ^{115}In (~96%). The reaction is uniquely suited for low energy solar neutrino research because of the low threshold (Q=114 keV) and a distinct reaction tag that can overcome the formidable background endemic to low energies in general and in the Indium case in particular. Recent progress in technology and design innovation indicates for the first time that a *high mass* detector with ~60 ton In aimed at high statistical precision in the measured ν_e event rates, may be technically viable. The project—named **LENS-Sol**--may be affordable (~$100M) in the class of large solar ν devices in Japan and Canada. This White Paper is a preliminary review of the basic considerations underlying LENS-Sol and the possible scientific impact of its results.

LENS-Sol is expected to be sited in the Kimballton (VA, USA) limestone mine[3] that offers *excavated, road accessible, Gran Sasso class* underground caverns and an infrastructure that allows rapid realization of an underground laboratory at relatively modest cost. The depth of the site, 1600 mwe, is adequate for the In detector with its reaction tag. VirginiaTech (30 min. by car from Kimballton) is working towards hosting the project with support from its campus facilities.

In order to derive absolute fluxes from signal rates, the CC ν_e capture cross-section in In (measured so far indirectly by (p,n) reactions) must be directly calibrated with *high precision* using MCi radio-active ν_e sources. For this purpose, **LENS-Cal**, a *separate,* smaller experiment (5 tons of In; cost $10M), will be performed concurrently in Russia.

Why is it important to carry out this program?

The pp solar neutrino beam, well characterized by its solar model-independence and its precise flux (~1%), is the most intense (6x10^{10}/cm^{2}s), continuous beam, available on earth. It offers an experimental baseline of 1AU, far beyond any terrestrial possibility. Its characteristics are unlikely ever to be matched by machines. *It is also free*. The only reason it is not regarded in the same light as machine-produced beams is that real-time *detection* of this beam is not yet demonstrated. If this problem is solved with LENS-Sol/Cal, it is no stretch to see that such a "ν_e facility" would be a premier laboratory for neutrino physics, available at far lower cost than an accelerator-neutrino beam-detector facility. Precise low energy solar ν_e fluxes from a single experiment, LENS-Sol, can establish the basis of ν flavor-physics over and beyond the global physics reach of seven different present solar neutrino experiments.

LENS-Sol aims at precision results on six observables: the absolute low energy fluxes from all the main solar sources, direct flux ratios (no CC calibration involved) and the shape of the pp ν_e spectrum. A global analysis of LENS-Sol results, possibly with extra data from the Standard Solar Model (SSM[4]), can determine or tightly constrain a wide range of neutrino and astrophysical parameters. Direct results are possible using the pp and pep fluxes (and flux ratios), since they are solar model independent. Such results lead directly to the ν parameters Δm^2 and $\sin^2 2\theta$ that tag the prevalent conversion scenario *ab initio.* If it is the current favorite-- the large mixing angle (LMA) model of conversion-- it will be specifically proved for the first time. In particular, $\sin^2 2\theta$ can be determined significantly more precisely than current limits. Consistency of LENS-Sol and SSM data could narrow the limits on the parameter θ_{13} in 3-ν mixing. Precise values of Δm^2 and $\sin^2 2\theta$ (and θ_{13}) are pivotal for assessing the rates of ββ-decay[5], currently the object of major experimental effort. With knowledge of the ν_e parameters, the validity of CPT, a topic of new interest from the neutrino standpoint[6], can be directly *tested* by independent data on $\bar{\nu}_e$ oscillations. At present it is an *assumption*[7] in global analysis of solar ν data. The CNO solar ν_e flux will be measured for the first time. From the analysis of the global LENS-Sol results and the resulting low energy ν_e fluxes and conversion parameters, new tests of solar structure can be expected, e.g., on the PPI–PPII termination ratio[1] and the neutrino–luminosity of the sun[1]. The former tests the backbone of the SSM structure and the latter, the basic astronomical idea of nuclear fusion as the *sole* origin of the sun's energy[1]. In summary, the scientific synergy of non-standard neutrinos and solar astrophysics can be decoupled with clarity and precision by LENS-Sol/Cal.

LENS-Sol is based on liquid scintillation (LS) technology in a modular hybrid design of In-loaded LS (InLS;~8%In) modules dispersed in a x4 larger volume of unloaded LS (ULS) modules (see below). The latter, employed as an internal active shielding, is a necessary construct of the design for In-solar ν_e detection, but it pays its own dividends by extending the scientific reach of the project considerably. As the largest device of this kind (3000 tons of LS), LENS-Sol would be the most powerful detector yet, for ν_e and $\bar{\nu}_e$ --especially at low energies, from nearby nuclear reactors, the earth's interior and supernovae. These topics are rich in potential for new discoveries in ν physics, geophysics and the astrophysics of stellar collapse.

Solar Neutrino Spectrum and Rates

The In detector measures solar neutrinos via ν_e capture: $\nu_e + {}^{115}In \rightarrow e^- + {}^{115}Sn$ by detecting the prompt electron e^- that is the basic ν_e signal in the device. The energy of the incident ν_e is measured by the energy of e^-: $E_e = E\nu_e - Q$ (=114 keV). Thus the solar ν_e spectrum from the pp (0-420 keV), ^{7}Be (862 keV), pep (1442 keV) and CNO (0-1700 keV) reactions in the sun can be well resolved. Fig. 1 illustrates such a result. Recent progress in InLS technology with 500-800 pe/MeV (better than the 300pe/MeV used in Fig. 1) promises the possibility of measuring the *shape* of the pp-continuum. Table 1 lists the breakdown of event totals in 5 years.

In principle, the only sources of systematic error are the corrections for background and for the energy-dependent detection efficiency. The background is explicitly measured *in vivo* with higher statistics than the signal (see below). The design aims for S/N~3 (for pp ν_e only; S/N>>3 for other solar ν_e) so that the statistical precision of the figures in Table 1 is substantially preserved. The detection efficiency depends on analysis cuts using measured singles spectra and monte-carlo analyses. It is thus realistic to use the statistical precision of the rates in Table 1 for preliminary estimates of physics impact.

Table 1. Event Rates in LENS-Sol (60 tons In; 5y Live Time). ε is the detection efficiency;

	pp	^{7}Be	pep	CNO
SSM	29540	9200	480	2050
Practical= SSM x ε	7385 ε =0.25	7360 ε =0.8	380 ε =0.8	1640 ε =0.8
LMA = Prac x δ	**4800 δ=0.65**	**4300 δ=0.58**	**220 δ=0.58**	**930 δ=0.58**

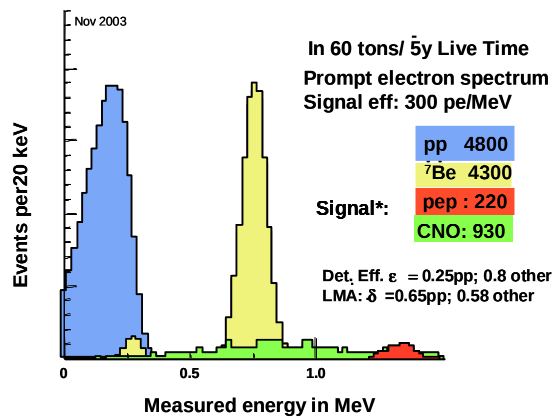

Fig. 1 Low energy solar neutrino spectrum observable by LENS-Sol assuming 300pe/MeV.

The basic results of LENS-Sol/LENS-Cal provide data on 6 observables-- 3 absolute fluxes using CC data from LENS-Cal (2%); 2 main flux ratios (No CC involved) and 1 spectral shape:

- the absolute ν_e fluxes (precision) from: pp (3%), ^{7}Be (3%); pep(7%) and CNO (5%);
- the signal ratios ^{7}Be/pp (2%) & pep/pp (7%);
- the spectral shape of the pp continuum (~5% /50 keV energy bin).

Impact: Particle Physics

So far, solar neutrino physics conclusions depend on seven different experiments: two spectral measure-

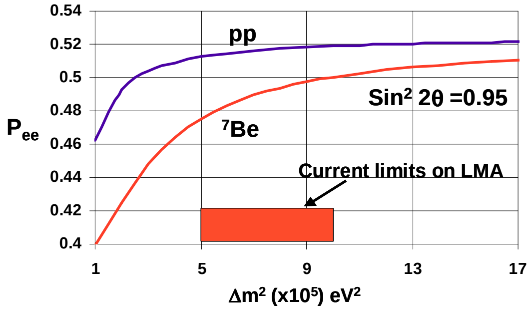

Fig. 2 Matter-vacuum transition at low energies revealed by the different variation of the flavor survival P_{ee} with Δm^2 for pp and ^{7}Be neutrinos

ments E(ν)>5 MeV (SK, SNO), three radiochemical activation measurements sensitive to low energies (Ga--SAGE, GALLEX/GNO; Cl--Homestake), one NC/CCmeasurement (SNO) and one reactor $\bar{\nu}_e$ experiment (KamLAND) that tacitly assumes the same mass-mixing structure for ν_e & $\bar{\nu}_e$ via CPT.

The basic conclusion that solar ν are flavor converted comes from SNO[8]. Indications for LMA as the particular type of conversion comes from the ν_e survival P_{ee}= 0.35 at $E\nu_e$>5 MeV and the energy independence of the conversion in the *>5MeV range* observed by SK [9] (both items are not unique to LMA[10]). LMA is strongly supported globally by all seven types of data[11]. Nevertheless, *no specific "smoking gun"* has yet been found for LMA. The role of LENS-Sol/Cal can be illustrated first by the direct results that specifically test the physics of LMA conversion.

Flavor conversion in the LMA has a characteristic profile in which high energy solar ν_e are converted by matter effects in the sun and low energy ν_e, mainly by vacuum oscillations[1]. While the high energy results are consistent with LMA, the clinching evidence resides (yet to be seen) in the low energy effects. The transition from matter to vacuum conversion is energy dependent via the parameter $\beta = 0.22\ \mu_\varepsilon\rho\ (E_\nu/\Delta m^2)$ [1] where $\mu_e\rho$ is the electron density at the site of neutrino production in the sun. β decides the predominance of matter (β>1) or vacuum (β<1) conversion. For pp ν_e (β<<1) matter effects are practically absent. For ^{7}Be ν_e (β<1), matter effects *persist* in the LMA regime (5 <Δm^2<10x 10^5 eV^2). Fig. 2 shows this effect in the variation of P_{ee} for pp and ^{7}Be neutrinos. The limiting ν_e survival is the vacuum value P_{ee}= 1– ½ $\sin^2 2\theta$, a deviation from which, such as a dependence on Δm^2, indicates matter effects. For pp ν_e, Pee is practically the vacuum value 0.525 (for $\sin^2 2\theta = 0.95$) in the entire LMA. However, ^{7}Be ν_e are still in transition as seen (in Fig.2) from the

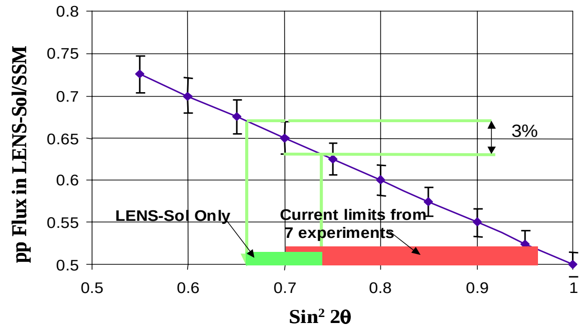

Fig. 3 Determination of $\sin^2 2\theta$ from the measured pp flux normalized by the SSM pp flux.

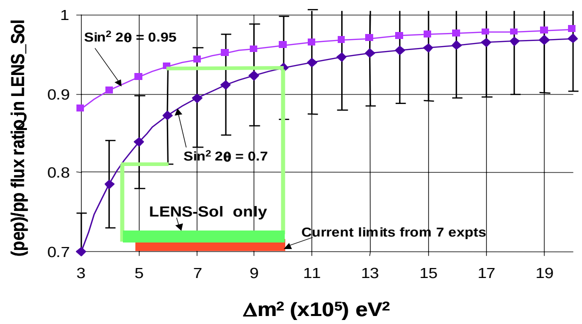

Fig. 4 Determination of Δm^2 from the measured signal ratio (pep/pp) normalized by the SSM ratio.

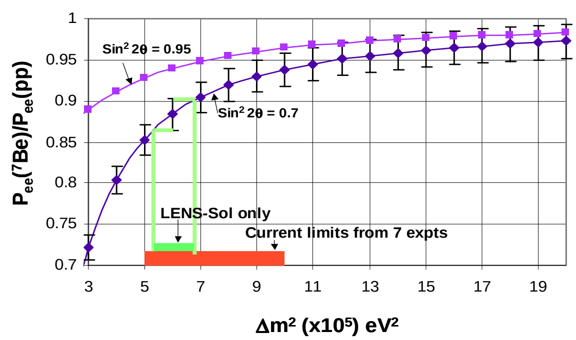

Fig. 5 Determination of Δm^2 from the measured signal ratio (^{7}Be)/(pp) normalized by SSM datum for ^{7}Be (the flux or the PPI-PPII ratio R, see text).

deviation (~10%) from the vacuum survival limit as a function of Δm^2 even for $\sin^2 2\theta = 0.95$. (For $\sin^2 2\theta \equiv 1$, both pp and ^{7}Be $P_{ee} \equiv 1/2$ flat). Thus, precise measurements of low energy solar ν_e fluxes can determine independently: 1) $\sin^2 2\theta$ from the pp flux result and 2) Δm^2 from the ^{7}Be or the pep flux or the flux ratios pep/pp and ^{7}Be/pp.

The practically constant P_{ee} for pp ν_e shown in Fig. 2 can first be verified in LENS-Sol by the undistorted shape of the pp ν_e continuum. The absolute total pp ν_e flux will be measured to ~ ±3% precision that directly leads to P_{ee} since the pp ν_e flux is solar model-independent and predicted to a precision of~1%. Fig. 3 shows the dependence of LENS-Sol ratio (pp ν_e flux/SSM ν_e flux) vs. $\sin^2 2\theta$ Thus $\sin^2 2\theta$ can be measured significantly more precisely than the current limits. *No other method is known for determining $\sin^2 2\theta$ with such precision*.

Fig. 4 illustrates the determination of Δm^2 via the pep signal for which the production location in the sun- and its ν_e energy-- result in a β very close to that for ^{7}Be ν_e. The pep flux is also independent of the solar model, especially the pep/pp flux ratio. Normalized with this, the signal ratio pep/pp (no CC calibration) in LENS-Sol leads directly to P_{ee}(pep)/(pp) in Fig 4 which shows its variation with Δm^2 in the LMA regime. A value of Δm^2 at least as precise as the current limits can be obtained despite the low intensity of the pep line. Fig. 5 shows a similar analysis of the ^{7}Be/pp signal ratio (= K). The strong ^{7}Be line can lead to a much more precise value of Δm^2 if the signal ratio K can be normalized absolutely (as above for the pep case). For this, at least one relatively precise but solar model-*dependent* datum such as the ^{7}Be flux *or* the PPI-PPII termination ratio R= 2K/1–K = 0.174 [1] is necessary.

The above analysis assumes 2ν mixing defined by the mixing parameter $\sin^2 2\theta = \sin^2 2\theta_{12}$. The parameter θ_{13} for 3ν mixing has assumed importance in recent years because of its role in the neutrino mass-mixing matrix. In the solar neutrino case, the effect of θ_{13} reduces simply to a renormalization of P_{ee}[12,1]: $P_{ee}(3\nu) = \cos^4\theta_{13} P_{ee}(2\nu)$. The current limit on θ_{13} is $\sin^2\theta_{13} < 0.05$ from ν_e oscillations in the CHOOZ experiment[13]. A combined analysis of CHOOZ and KamLAND suggests $\sin^2\theta_{13} < 0.01$.[14] These limits lead to $\cos^4\theta_{13} > 0.9$-0.98, implying a change of up to 10% in P_{ee} values. The absolute fluxes of pp (and other) ν_e measured in LENS-Sol/Cal are thus sensitive to θ_{13}. The flux *ratios* however, are independent of $\cos^4\theta_{13}$. A combined analysis for θ_{13}, θ_{12} and Δm^2 with LENS-Sol/Cal and SSM data (measured fluxes and flux ratios, the PPI-PPII ratio, neutrino luminosity) should lead to precise values for $\sin^2 2\theta_{12}$, Δm^2 and possibly good limits for θ_{13}.

Thus, a single experiment, LENS-Sol/Cal can determine the basic ν_e parameters more precisely than the current limits set by a consensus of 7 different experiments. Data on $\sin^2 2\theta_{12}$ and Δm^2 and tighter limits on θ_{13} from LENS-Sol/Cal will help establish the precise neutrino mass-mixing matrix and in particular, pivotally help in deriving the 'effective neutrino mass' that controls the rate of neutrino-less $\beta\beta$–decay[4]. Finally, note that all the ν_e parameters above are derived exclusively from LENS-Sol, making *no appeal to CPT invariance.* Thus these ν_e results on $\sin^2 2\theta$ and Δm^2 *as well as θ_{13}* can be confronted directly with future reactor $\bar{\nu}_e$ oscillation data with higher than present precision to *test CPT invariance* in the ν_e sector.

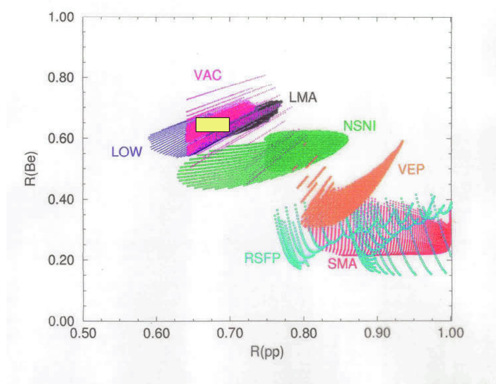

Fig. 6 Regions of validity of "exotic" neutrino scenarios locatable by measurement of the pp and Be fluxes (LOW: low mass MSW; VAC: vacuum oscillations; NSNI: Non-standard neutrino interactions: RSFP: resonant spin flavor precession; SMA: small mixing angle-MSW; VEP: violation of equivalence principle). The calculation is for *electron-scattering* (ES) The yellow box from LENS-Sol (CC onverted to ES equivalents) can severely limit the possible model(s). (Calculations from Ref. 15).

The pp and ^{7}Be fluxes from LENS-Sol can test many, possibly subdominant, ("exotic") neutrino scenarios besides the standard expectation of the LMA as discussed above. Fig. 6 shows these possibilities in a map of the ^{7}Be and pp fuxes (relative to the SSM fluxes) in an electron-scattering experiment[15]. The parameter box in Fig. 6 illustrates the severe limits on exotic models that can be set by LENS-Sol (CC converted to ES equivalents).

Solar Astrophysics

A measurement of the CNO flux (see above in list of results from LENS-Sol) would remove a major uncertainty in the predictions of the SSM. Present experimental results are said to be consistent with 0 to 8% of solar *energy* via CNO reactions[16]. The energy contribution of CNO, a longstanding question, can be clarified by LENS-Sol by determining the CNO *flux* with a precision of ~5% .

Since the ^{8}B branching is ~10^{-4} in the PP chain, the energy balance of the sun is determined dominantly by the pp, Be and CNO reactions. With the precise measured fluxes from all these sources and the ν conversion parameters, the *astrophysical* solar

ν_e fluxes become sufficiently precise to derive the *neutrino luminosity* of the sun. This allows a direct comparison of the ν_e and *optical* luminosities[1]. A *shortfall* of the ν_e luminosity is of fundamental interest since that could imply a hidden source of energy (black holes ? WIMPS? axions ?) in the sun. The combined analysis of LENS-Sol and SSM fluxes can probe a critical SSM feature—the branching of the PPI to PPII reaction chains directly from the measured signal ratio Be^7/pp. The coupled interplay of the ν and astrophysics aspects, the traditional problem in solar ν research, can thus be defined independently and self-consistently by a single experiment—LENS-Sol/Cal.

$\bar{\nu}_e/\nu_e$ from Reactors, Earth, Supernovae

The physical design of LENS-Sol will comprise not only the In-loaded LS part necessary for solar neutrino detection but also a larger volume of unloaded LS (ULS) (see below). The total mass of the ULS will be ~3000 tons, itself an active detector. With this, LENS-Sol will be the most powerful low energy antineutrino ($\bar{\nu}_e$) detector operated so far. The sensitivity to $\bar{\nu}_e$ arises from the $\bar{\nu}_e(p,n)e^+$ reaction whereby the n-tagged observation of the e^+ signal yields the incident $\bar{\nu}_e$ spectrum $\{E_{e+}= E(\bar{\nu}_e) - 1.8\text{MeV}\}$ as in KamLAND (1000 ton LS)[7]. A key advantage in LENS-Sol is the substantial presence of Indium, a powerful n-detector ($\sigma(n) = 3000$ b), that sets n-diffusion delay times shorter than those in the (n,p) reaction used in KamLAND. The background could thus be smaller. This capability extends the science reach of LENS-Sol to non-solar neutrino topics of current interest: reactor $\bar{\nu}_e$ physics, global trans-uranic radioactivity in the earth's interior and its role in geophysical structure and the physics of stellar explosions

Reactor Antineutrinos: There are several GW power reactors within 250-300 km of the LENS-Sol site. A preliminary signal estimate is ~200/y (cf.~1000/yr/kT in KamLAND) but possibly with lower background. Thus reactor $\bar{\nu}_e$ oscillation data could be enhanced in quality with new measurements in LENS-Sol set on a different baseline from that in KamLAND.

Geo-Neutrinos: A kiloton scale $\bar{\nu}_e$ detector is inherently sensitive to $\bar{\nu}_e$ from U and Th decay in the earth's interior, mainly the crust. A global measurement of such "geo-neutrinos" has been suggested with detectors at different strategic locations on the earth [17]. The KamLAND detector (Japan) and Borexino (Europe) are two such devices. LENS-Sol, on the North American plate can be an interesting addition to this network. It may indeed have the best location for a sensitive geo-neutrino measurement. The reactor background in KamLAND is high; that at Borexino is low but the detector mass is also low. The best compromise of high detector mass and low reactor $\bar{\nu}_e$ background may make LENS-Sol the most sensitive device for a definitive measurement of geo-neutrinos.

Supernovae (SN): SN1987A showed the astro-physical importance of observing ν emission from exploding stars. The next observation needs to be much more detailed with spectroscopic inventories of the different types of neutrino species emitted in these events. The large mass of LENS-Sol, its target composition and the neutron detection capability via In combine to make an ideal SN ν detector.

1) the In target with its low threshold can yield the complete ν_e spectrum with high sensitivity to the low energy part.
2) the ULS part can deliver the $\bar{\nu}_e$ component.
3) NC excitation to T=0 states in ^{12}C (15 MeV) in the LS as well as neutron unstable states in ^{115}In (~9 MeV) facilitate the detection of neutrinos of all types regardless of flavor.
4) ν-electron scattering (ES) provides a signal based on both NC and CC.

The SN burst is the overall tag for all these events. Individual tags available in the above reactions (except ES) help separate the flavor components of the neutrino emission. Thus a complete inventory of ν species can be made of a future SN event .

Neutrino Calibration--LENS-Cal[18]

Since LENS-Sol is a CC-based detector, a direct measurement of the ν_e capture cross section in In (instead of using the B(GT) matrix element of the In-Sn transition from (p,n) reaction results[19]) assumes a central role in the flux measurement. This consists of measuring the response of the In detector to a well characterized man-made MCi ν_e source. The technique has been previously applied in the Ga experiments in Russia[20] and in Italy[21]. The facilities and technology for making and handling such intense sources are available only in Russia.

The detection of ν_e via In is particularly clean because the solar ν_e response of In-Sn system is driven by a single level at 615 keV in ^{115}Sn (see Fig. 9), the only level <2.5 MeV with a measurable response. The most suitable ν_e source (see Table 2) is 50d-^{37}Ar (particularly because of its low background contamination). The technology for MCi sources of ^{37}Ar is in hand from the work of the Institute of Nuclear Research (INR) Moscow[22].

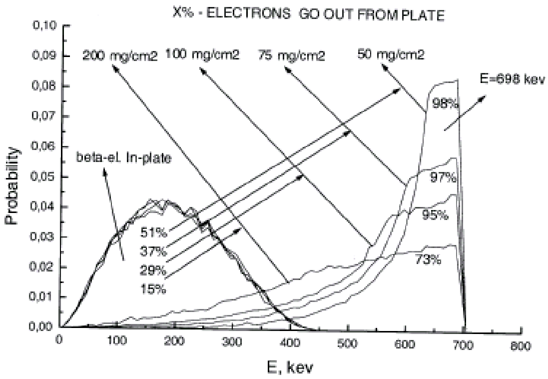

Fig 7 Energy profiles of the In β–spectrum (left) and a mono-energetic electron line at 700 keV (as from the capture of ^{37}Ar- ν_e in In) (right) emitted from In foils of different thickness.(From Ref. 18).

Table 2: Characteristics of ν_e Sources

	E_e keV	MCi	Shots #	In/Scin g/cc	M (Scin) (Ton)	Signal Events
^{37}Ar	**700**	**2**	**5**	**100/300 = 0.33**	**15**	**8750**
^{51}Cr	637	3	5	75/300 = 0.25	20	6100

Table 3. Signal Rates for Source Options**: 5 ton In**

	τ	E_ν keV	E_e	Background Sources
^{37}Ar	**50.5 d**	**0.814 (100%)**	**700**	**Int. Bremms. 0-814; ~5x10^{-4} hν/decay**
^{51}Cr	40.1 d	0.751 (90%)	637	320γ (10%) MeV γ's from contam. %??

The signal strength in LENS-Cal depends pivotally on the optimization of the source-detector geometry for the highest flux achievable from the source. Since the In reaction operates with a strong signature, arrangements are possible (design in progress) where the source assembly can be enclosed inside a hollow array (cube or sphere) of detector modules. The detector should be designed with the highest possible Indium density ρ (signal ∝ $\rho^{2/3}$). These requirements as well as the logistics suggest a specifically designed experiment–LENS-Cal, to be performed concurrently *in Russia.*

The design of LENS-Cal is different from that of LENS-Sol because its hybrid design results in low In density ρ (~0.02). LENS-Cal is based on a design of a sandwich stack of In metal foils and plastic or ULS detector layers. The electron signal from ^{37}Ar is 700 keV in the In foil. The energy is high enough

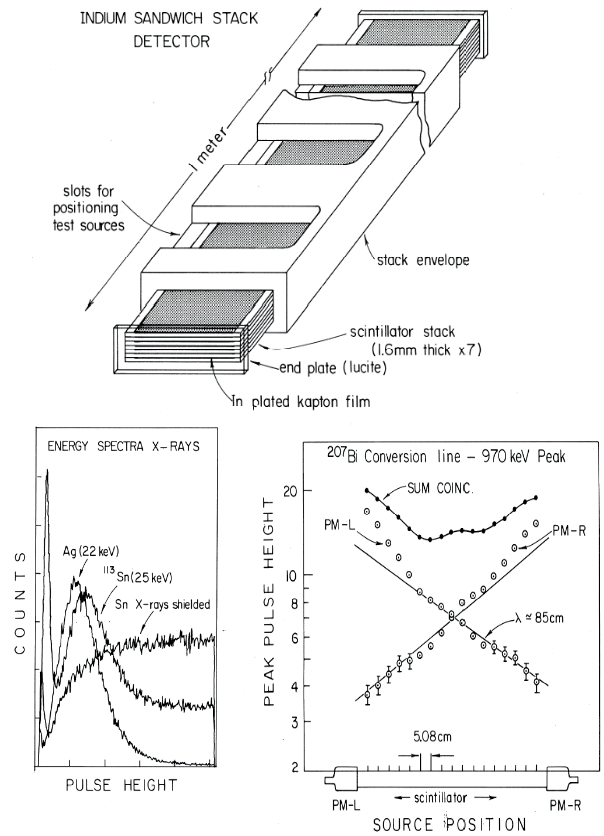

Fig. 8 In sandwich stack test detector (top) and typical results of spectroscopic measurements: low energy spectra (lower left) and signal attenuation (lower right) (ref.23).

to make the sandwich idea experimentally viable. Fig. 7 shows emission profiles of 700 keV electrons out of In foils of different thickness. The optimal thickness is 75-100mg/cm^2 and that of the plastic layers-- 3mm, the range of 700 keV electrons. The resulting In density is then ρ=0.33. The signal in LENS-Cal occurs at higher energies beyond the In decay spectrum. (see Fig. 7). Thus, the In-decay background, a major aspect in LENS-Sol design (see below), can be avoided entirely. Signal observation in LENS-Cal is thus basically simpler. Tests of the sandwich design were made by measurements on a 1-m long sandwich stack detector[23] (Fig. 8) constructed with 1.6mm plastic and 9 mg/cm^2 In layers. Light piping in this test detector is by total internal reflection only. The results (Fig. 8) show that the sandwich design, even with the severe problem of light-piping through 1.6mm x1000 mm plastic layers (intended originally for pp neutrinos!) is well suited to very low energy (~25 keV) spectroscopy. The use of 3mm scintillator layers (x2 that of Fig. 8) and new technology of light piping by specular reflecting foils (see below) promises significant improvement towards 2 to 3m modules. The overall design based on this technique calls for a relatively small detector with 5 ton In and 15 ton scintillator. Table 2 and 3 give parameter details and expected signal rates. The average event rate in such a detector during the 2τ life of the ^{37}Ar source will be ~*30 times* that of the solar rate. Table 3 shows that statistical precisions <2% can be attained with 5 shots of the Ar source irradiations.

LENS-Sol: Methodology

Fig. 9 displays the level scheme of ν_e capture in In which makes a transition to an excited isomeric state at 613 keV in ^{115}Sn. The basic tag is thus a delayed coincidence of the prompt signal electron e_1 in fig. 9 and a cascade of γ-rays e/γ_2 (115 keV) and γ_3 (498 keV). The time window of the delay is set by the signature lifetime of the capture state of τ = 4.76 μs. Thus, the main design objective is to realize in

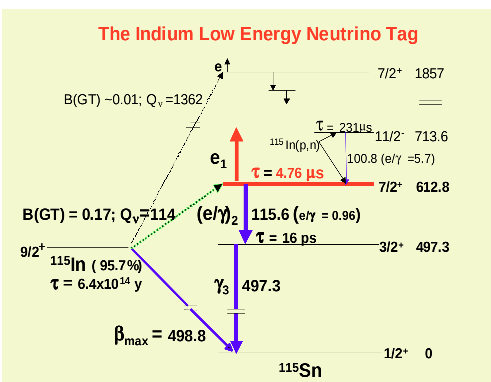

Fig. 9 Level scheme of the In neutrino tag

practice the full tag potential of the time and space coincidence as well the topology of the capture event as completely as possible. The main background which must be suppressed by the operation of the tag comes from the natural radioactivity of In itself (0.25 Hz/g In). The In β-decay, with an end-point of ~498 keV, completely overlaps the *pp signal* region. They create a random coincidence background not only by the presence of a high singles rate of localized electrons from the β–decay but more severely by bremmstrahlung (BS) radiation. The BS can reproduce the correlated cascade *exactly* similar to that in the ν_e tag via the emission of a low energy β~100 keV and a 400 keV γ. This BS cascade can randomly produce a delayed coincidence with another In decay electron and mimic the solar ν_e event. Although this process is extremely rare, $<10^{-9}$/In decay, the intensity of the In decay makes it the principal background. It is important to realize that the above problems are

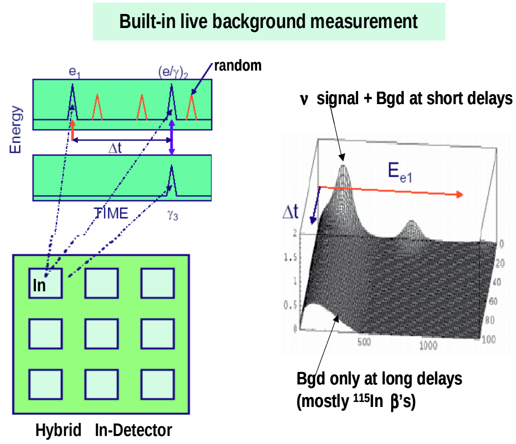

Fig. 10 Role of the In neutrino tag for signal and background measurement in granular In detector

present *only for pp ν_e spectroscopy.* All the other signal features occur beyond the In β-decay end-point of 498 keV, thus, they are free of the In decay background problems. Hence they are observable with significantly higher S/N as well as detection efficiency (see Table 1).

The design of the In detector has been studied for many years, especially in the last few years by the LENS R&D group[24]. As a result, a viable In detector should incorporate the following basic features :

- The In target should be embedded integrally in the detection medium to resolve the low energy prompt electron signal spectrum. The most practical solution is In-loaded LS technology with a loading of some 8-10 wt % In.
- The detector must be granular so that the vertex of the ν_e event, i.e. the delayed coincidence of e_1-$(e/\gamma)_2$ can be tightly localized[2]. The vertex cell should contain <50g of In.
- In order to suppress correlated random coincidence background from the In-BS a hybrid design should be adopted with In cells dispersed in In-free LS so that an In cell has only *In-free* neighboring cells[25]. The initial delayed coincidence in the vertex cell should be followed by a prompt coincidence with a 498 keV γ_3 observed in the *In-free* vicinity as shown schematically in the hybrid lattice in Fig. 10-11.
- The ensemble of tag conditions-- the delayed triple coincidence (e_1-(delay)-$(e/\gamma)_2$-(prompt)-γ_3 with the correct time order of events, overall event topology of the triple coincidence with spatial coincidence in the vertex cell and γ_3 in the nearby In-free LS and the energies of the gating and signal events –imposes an extremely stringent template that provides the discrimi-

nation of $\sim 10^{11}$ needed to suppress the In-decay background.

- The delayed coincidence is recorded in 3-d spectra of energy, time delay and number of events (see Fig. 10) so that at short delays the spectrum contains the solar signal plus random coincidence events (mostly from the In-β decay). At long delays $\Delta t >> \tau$ the tag lifetime, only random events with the In-β-spectrum are present. Thus the background is measured *in vivo*. The time window is much wider than the tag window τ so that the random background spectrum can be measured with higher statistical precision than the signal by a fit to the exponential isomeric decay plus the constant background.

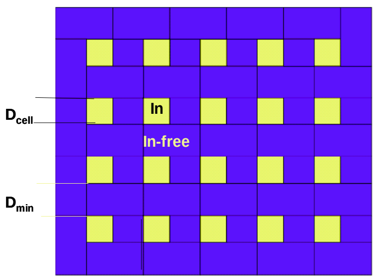

Fig. 11 Hybrid design concept for analysis

Hybrid Design Analysis

The effectiveness of the initial hybrid design of Fig. 10 and the cost of background suppression in terms of detection efficiency after the many spectroscopic analysis cuts that enforce the ν_e tag has been investigated by extensive monte carlo simulations [26]. The architecture visualizes a segmented array modular detector consisting of individual longitudinal modules with a wall thickness of 2mm containing the InLS and In-free LS. The modules are arrayed to satisfy the hybrid principle. Light piping in the modules in this initial design is by total internal reflection.The results of these simulations are shown in fair detail in Fig. 12. Going directly to the results (middle panel), for optimum module dimensions of 10x10x300 cm with In-LS signal efficiency of 310 pe/MeV, a detection efficiency ε~21% can be expected for *pp* ν_e signals with S/N >3 and ε ~80% for other higher energy solar ν_e..

Basically, the analysis shows that:

- the hybrid strategy is effective in solving the In-activity background completely
- the granularity required of 60x10x10 cm vertex cell is moderate and practical ;
- Avoidance of non-scintillating material in the detector can improve the precision of the analysis cuts and result in detection efficiencies somewhat better than cited above.

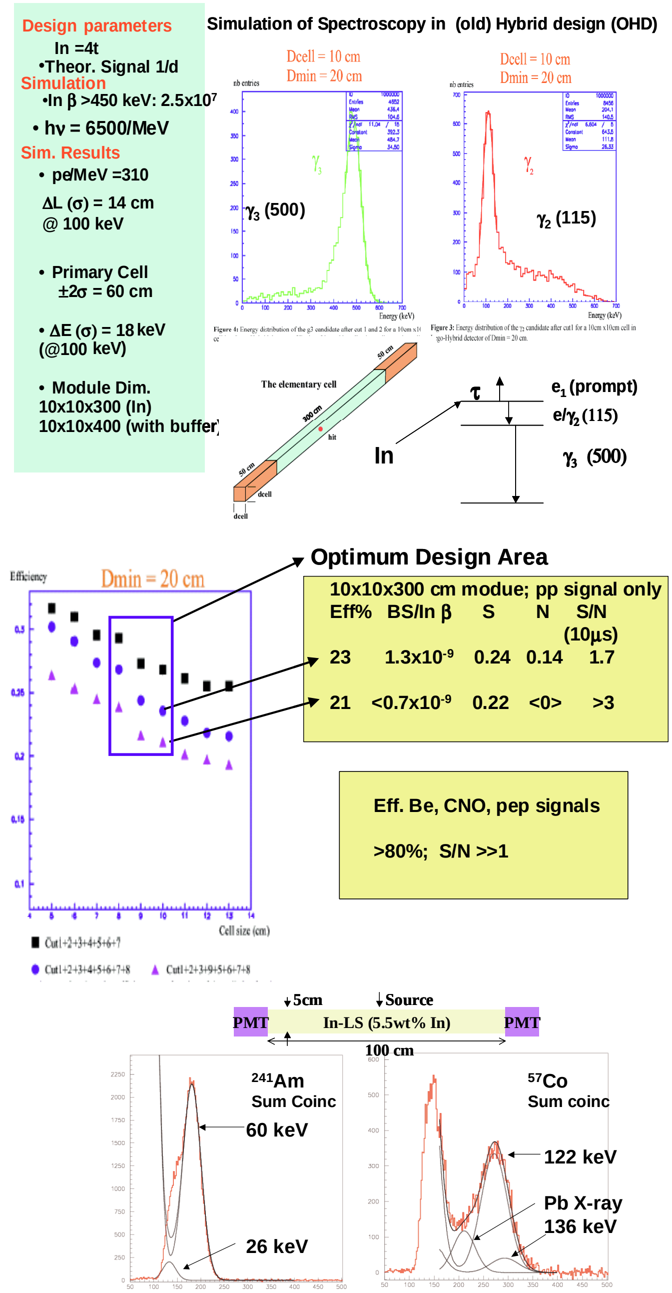

Fig. 12 Design Analysis of *old* hybrid design (Ref. 26) Top panel: spectroscopy parameters and gating spectra in 300 cm modules. Middle: Simulated detection efficiency and S/N for different In cell dimensions and spectroscopy cuts. The optimum cell sizes/cuts and results for figures of merit are shown for pp signals (top box) and for Be, pep and CNO signals (bottom box). Bottom *Experimental* In-LS quality tests: low to very low energy spectra measured in a 5.5% In loaded LS in a 5x5x100 cm square quartz module. Source in the middle of the module (least signal position). The measured In-LS signal efficiency is ~800 pe/MeV and athe signal attenuation length is ~2.5m (Data from INR-LNGS Group).

Fig. 12 lower panel shows data from long module (5x5x100cm) bench tests of the In LS (5.5% In) (early 2003) by the INR-LNGS group. The low energy (60 keV) spectra in the range of the pp signal can be seen well resolved from noise. The measured signal efficiency in this early InLS sample is ~800pe/MeV and its attenuation length is ~2.5m. The design of the In detector (see below) calls for 10x10 cm light pipes, thus, the InLS results in Fig. 12 with 5x5cm pipes are conservative.

We thus have a viable design strategy for the In experiment and the foundations of the InLS detection technology for implementing this strategy.

Non-In Decay Background

The signal in the In-detector is a *delayed coincidence* event. Random coincidences (discussed in detail above for In radioactivity) from bulk internal radio-contaminants become relevant only if their low energy activities approach that of the intense In activity. Even radiocarbon in the organic LS at the *modern carbon* activity of 0.12Hz/g C barely equals the In activity of 0.25Hz/g In. More normally, the ^{14}C activity in the LS and other material is many orders of magnitude lower. With the same reasoning, trace U and Th can be tolerated at the 10^{-12}g/g level, some 4 orders of magnitude more relaxed than the demands of Borexino.

A background that needs specific care in the design arises from sources of external γ-rays such as the phototubes (^{40}K γ-rays 1.46 MeV) as well as the radioactivity (U, Th,K) in the rock. These γ-rays, typically 1-2 MeV, can scatter on non-scintillator material inside the detector (e.g., module walls in the early architecture of Fig. 10) and produce radiation in the region of 500 keV that can simulate the γ_3 tag component. Simulations of phototube γ-rays in the hybrid model above[26] show that scattering on the 2mm module walls assumed above produce x10 the background from In decay. The detector design should therefore strive scrupulously to minimize non-scintillating materials inside the detector. An important design aspect is active scintillation buffers shielding the PMT's from the modules. Shielding of the detector as a whole from rock γ–rays is necessary with an estimated 3mwe shielding thickness. This problem has been studied in the shielded counting facility of LENS R&D (the LENS low background facility-LLBF) built underground at Gran Sasso by the MPIK-Heidelberg group The shielding comprises ~3mwe of Fe-Pb-polyethylene. An array of 9 quartz modules (5x5x100 cm) with In-free and 5% In-LS is in operation in the vault of this facility. The observed background is extremely low (quantitative analysis is in progress) consistent with shielding estimates

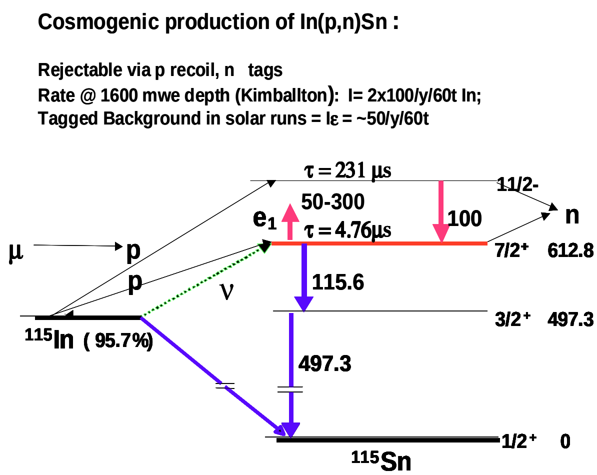

Fig. 13 Cosmogenic background of real coincidences from ^{115}In(p,n)^{115}Sn .

and demonstrates that such arrays can be built without significant extra contamination in the construction.

That leaves impurities (natural and cosmogenic) that produce isomeric nuclei with delayed cascades with a close similarity to the In tag template as the only background of *real* coincidences. An examination of possible reactions on isotopes in the region of mass 100-125 region (that could occur only as trace impurities in the 5-nines pure In) shows no such possibility except *^{115}In itself,* via ^{115}In(p,n)^{115}Sn or ^{115}In(α,4n) ^{115}Sb(EC)(45min) ^{115}Sn (the latter cannot be made by α's from internal U,Th). Fig. 13 shows the schematics of (p,n) reactions on In that excite the isomeric states at 613 keV (the ν_e tag level) and at 713 keV. Both these excitations generate the same cascade as a ν_e, thus the ν_e tag cannot separate them from solar events. The only way is to minimize their occurrence by operating at a depth at which the isomer production is sufficiently low. Fortunately, the production rates can be estimated accurately from the known (p,n) cross sections of In and ^{37}Cl and the known cosmogenic production rate of the latter at various depths at Homestake[27]. From these data the rate of the In –cosmogenic events at the Kimballton mine is expected to be ~200/year that produce solar ν_e-like background of ~50/year (with the low energy tag ε =25%) in a 60 ton In detector. Most of these 1% background events can be themselves tagged very efficiently by the neutron following the (p,n) process. Thus, while not a true background threat, the process suggests itself as a pp ν_e event *simulator*, useful in testing In detector prototypes at measurable rates at shallow depths.

Hi-Mass Indium Detector Design

The old design of Fig. 11 with individual modules is difficult to realize in practice because of the large number of modules, the limit of ~2.5m length on modules set by the optical attenuation in the InLS, and the large cost outlay necessary for the electronics due to the x5 larger detector with the In-free modules. A high In mass detector in this framework is prohibitively expensive. Key technical developments in the latter half of 2003 have changed the prospects dramatically:

- High transparency InLS technology that has improved the signal attenuation length, thus reducing the number of InLS modules;
- light pipe technology using multi-layer reflecting foils that revolutionizes module design;
- a new hybrid design that fully exploits 1) and 2) and innovates configurations that drastically cut the electronic cost outlay for the *In-free LS*.

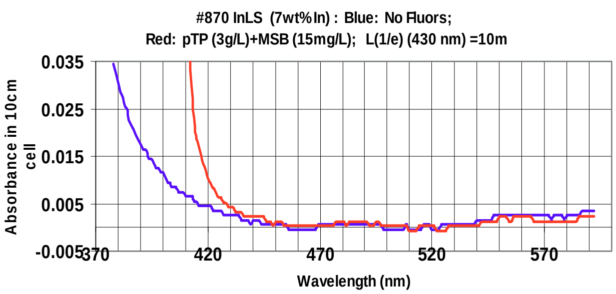

Fig. 14 Spectrophotometric scan of absorbance in InLS in a 10 cm optical cell. The red curve for InLS with flours indicates an optical attenuation length of 10m at 430 nm (ref. 28)

InLS Technology: Very recently, new chemical recipes have significantly improved the signal attenuation length L(1/e) of InLS. [28] The new results (see Fig. 13 for a typical optical scan), suggest a nominal optical value of L(1/e)~10m at 430nm. Because of the low absorbance, optical as well as counting tests in long cells are necessary to confirm the result. In any case the improvement from the previous best value of ~2.5m for the bulk light attenuation length is major progress. The typical scintillation light yield observed in the new recipe is ~42% of that in the unloaded LS (vs 65% in Fig. 12). The signal efficiency from the above light yield is ~500 pe/MeV (vs 800 pe/MeV in Fig. 12) that implies in any case, better spectral resolution than depicted in Fig. 1 (with 300 pe / MeV). The major breakthrough is that much longer InLS modular light paths than 2.5m can be used in the design, significantly reducing the electronic cost outlay for the InLS part of the detector.

In another key InLS development, the new recipe has been upgraded with a *safe* solvent--phenyl-cyclohexane (PCH)--with equal scintillation and optical performance to that above based on pseudocumene (PC). (PC, a single ring solvent with a flash point of 45C, is now considered hazardous). PCH has a flash point of ~100C and as a double ring compound, it is likely chemically less aggressive than PC—e.g. to the plastic specular reflective films that will play a central role in the design. The choice of safe solvent for the much larger mass of In-free LS is wider and less critical.

Specular Reflecting Foil Technology: Until recently, the only choice for efficient light piping in linear modules was total internal reflection (TIR) that poses severe practical problems for large array architectures. Recently, specular reflection (SR) is emerging as new alternative to TIR. Multi-layer plastic films made by a new technology from 3M are tailored to yield a reflectivity R close to 100% in the 410-440 nm optical regime, relatively independent of the angle of ray incidence. The films, only ~60μ thick, offer unprecedented advantages as specular reflecting (SR) light pipes for In detector designs. [29] The application of commercially available SR films to linear modules has been studied in simulations and experimental measurements that compare TIR and SR light piping.[30] A new experimental film (THV-130) made of fluoro-polymer is attractive for LENS-Sol as they are chemically more compatible with LS aromatics than present SR films. Optical simulations were made (at 3M) to study the variation of R (in the wavelength band 410-440 nm) with θ, the incident ray angle for the case of the THV film *immersed in a liquid* medium of index n. Fig 15 shows that in this case, R is practically *100%* over most angles except a small "leaky" window through which ~50% of the light escapes trapping in the pipe (that can be removed by a thin external absorbing layer to prevent optical interference in modular --

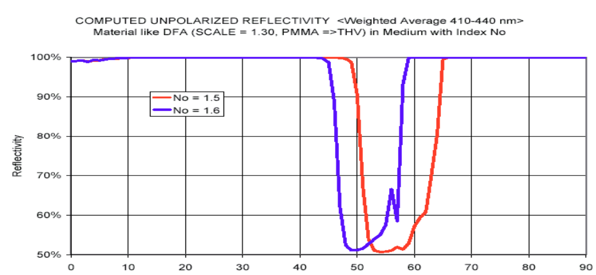

Fig. 15 Variation of reflectivity R vs. incident angle θ for THV film immersed in liquid of index 1.5 and 1.6 for the wavelength range 410-440 nm (Data courtesy of 3M)

structures). A simple estimate of the light trapping efficiency T excluding the solid angles of the leaky window in Fig. 15 is: T= 75% (n= 1.5) and T=78% (n=1.6), significantly exceeding the theoretical best value for TIR, T= 48% with n= 1. 5. Thus, the new SR films promise far better light piping than the best state–of- the-art TIR system.

.

The New Hybrid Design[31]*:* The aim of the new design (ND) is to achieve the objectives of the hybrid strategy with new features that simplify the modular structure of the "old design" (OD) of fig. 11-12 and substantially reduce the number of data channels. The OD is a straightforward application of light piping by TIR in individually constructed modules each of which is viewed by 2 PMT's. The new design adopts a different basis (that broadly upholds still, the quantitative conclusions of the analysis of the old design). Analysis of the new design itself is in progress.

- While it is necessary to view each InS module individually, the hybrid strategy requires only that the long-range 500 keV tag γ be detected in the *vicinity* of the vertex module. Thus a *group* of InLS modules can share a suitable supermodule of In-free LS. This reduces the *In-free* LS data channels, the high cost feature of the old architecture.
- The application of SR film technology allows modularity via *optical* segmentation in a large tank by thin films which vastly eases construction and bypasses the problems posed by tens of thousands of individual modules.
- The thin-film segmentation eliminates the walls of non-scintillating material of the individual modules in the old design that create high background in the interior of the detector from interactions with external γ-rays.
- Another critical advantage of thin film segmentation is the elimination of energy broadening due to random losses in non-active module material. Improved energy resolution and detection efficiency via more precise analysis cuts for pp signals appear likely.
- The application of high-transparency InLS that helps reduce the InLS data channels

Fig. 16 shows a conceptual design that applies the above principles. It consists of a large tank of In-free LS that is optically segmented by SR foils into supermodules. Each supermodule contains InLS modular segments dispersed so that each is enveloped by In-free LS. The InLS modules detect the delayed coincidence vertex while the promptly coincident γ_3 is detected in the supermodule as a whole external to the vertex module.

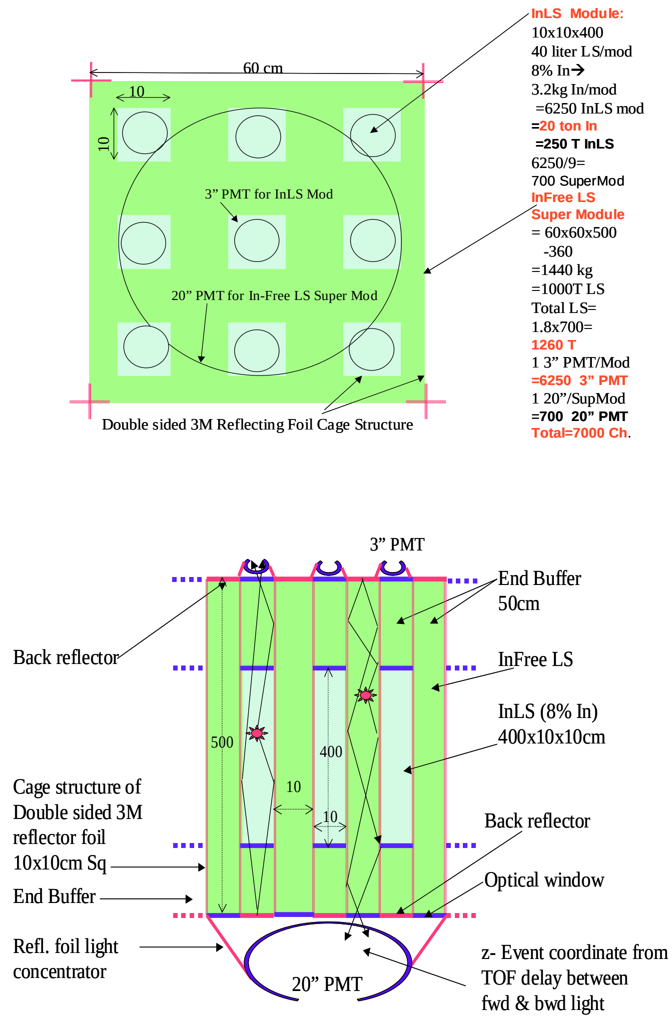

Fig. 16 Design for high mass In solar neutrino detector (Ref. 31) Top: plan view. The inventory on the right is for a 20 ton In segment. The 60 ton In full scale detector will comprise three such segments. Bottom panel: perspective showing construction details

The modules are viewed by a single PMT each, the signal trigger being a double pulse (with typical delay of 20-40ns) from direct and reflected photons reaching the PMT. This arrangement saves PMT channels and offers a convenient way to place the InLS and supermodule PMT's at opposite ends of the tank. The crucial design idea in this integral counting arrangement is the use of double-sided reflector film (with a thin absorber layer in the middle) for the segmentation so that the photons inside and outside the InLS modules are conveyed separately and without losses to the respective PMT's. The optical segmentation contains optical windows and back reflector film arrangements (as shown in the figures) that carry out the main segmentation of events to individual InLS and associated supermodules. The event vertex as well as the center of light of the photon shower of the external γ_3 are longitudinally located by the differences in times of flight as well as pulse heights of signals (gated by the timing triggers) of photons in the forward and backward directions.

The basic dimensions of the InLS module are set at 400x10x10cm, the length being compatible with the preliminary optical results of Fig.14 and the single-PMT detection method. The main tank is dimensioned to contain In-free LS for ~50cm beyond the InLS modular lengths. Active veto buffers are thus incorporated in the detector in a natural way. The buffers can be adjusted longer if necessary without further cost in data channels. The 10x10cm InLS modules (including the buffer sections) are viewed by relatively inexpensive 75 mm PMT's fitted with concentrators using reflector foils. The supermodule, typically 60x60 cm, envelopes 9 InLS modules and is viewed by one 50cm PMT fitted with reflector foil concentrator.

The overall construction of the detector thus consists of the installation of a prefabricated cage structure (containing the segmentation foils, optical windows and end reflectors) into the detector tank. Feed plumbing fills the InLS and In-free LS into the tank separately and simultaneously. The densities of the two kinds of LS fluids can be matched for minimum mechanical stresses on the cage structure. The square 2-D lattice in Fig. 16 (top) sets the In and In-free LS spacing at 10 cm. The spacing can be increased if necessary, entailing an increase only in the In-free PMT-data channels which comprise only 10% of the total data channels in the detector.

The construction parameters of the new hybrid design are listed in detail in Fig. 16 (top). A **20 T In** segment in this design consists of:

- 700x9=6300 8% InLS modules (250 T InLS)
- 700 supermodules (1000 T LS).
- 6300 7.6cm PMT's and
- 700 50cm PMT's for a total of
- 7000 data channels.
- Three such segments are necessary to build the full-scale 60 ton In detector.

What next ?

While several aspects of the R&D base need investigations and further development will continue, the project has reached the next objective phase of construction of one supermodule as in Fig. 16 as the prototype of the full scale 60t In LENS-Sol. The prototype supermodule comprises ~0.5 ton InLS and ~1.5 ton In-free LS and 10 data channels. Tests on this scale focus attention on several major aspects that are outstanding and need to be invented/developed before the first 20T phase of LENS-Sol can be undertaken:

1) Production of large-scale amounts of InLS.
2) Application of SR foils. If the new experimental THV foils do not materialize, a redesign with presently available SR foil and presently developed safe solvents must be optimized.
3) Data acquisition
4) Spectroscopy quality and control
5) Measurements and understanding of In and non-In background

The prototype phase is currently being planned for implementation at VirginiaTech in 2004.

Acknowledgements

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