Progress & Plans Of the International Collaboration LENS

(Low Energy Neutrino Spectroscopy)

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Abstract

Progress in basic scientific, technical and administrative aspects of LENS since the submission of the Letter of Intent to LNGS in Feb 1999 is described. The objective in the present "pilot phase" is the construction of prototype(s) at LNGS for experimental study of key questions of feasibility and detector design. On the basis of these studies, we expect to arrive in the next ~2 years at a formal Proposal leading to the constructional phase of the LENS detector

Introduction

The scientific aim of LENS is the direct observation of the energy-resolved spectrum of solar electron-neutrinos (ν_e) <2 MeV and a measurement of the specific ν_e fluxes from the p+p, ^{7}Be and CNO reactions in the sun. The ν_e detection is based on *charged-current* (inverse β-) transitions on a target of ^{176}Yb to excited levels in ^{176}Lu. The key advantages of this approach are, a highly specific ν_e tag and a low ν_e reaction threshold. The ν_e tag consists of the delayed coincidence of a 72 keV γ-ray that cascades via an isomeric state with a time-window of τ=50 ns (Fig. 1). The ν_e threshold Q =301 keV implies sensitivity to the complete spectrum of low energy solar ν_e's, identifying the individual sources including those long sought from the p-p reaction. A major technical challenge in LENS is the spectroscopic operation of the ν_e tag with a relatively low tag energy and short tag time window.

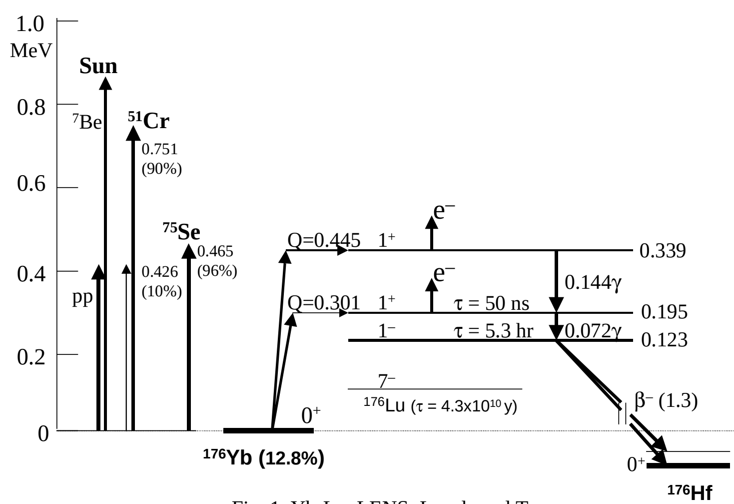

Fig. 1 Yb-Lu LENS: Levels and Tags

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Project Focus-Choice of Target

^{176}Yb is one of three proposed candidate targets with a ν_e-tag facility and a low threshold, the other two being ^{160}Gd and ^{82}Se[1]. The first step was to define the project focus: The target of choice is ^{176}Yb, based on the following reasons: 1) The natural radioactivity of inseparable Gd isotopes (e.g., α-decay of ^{152}Gd) poses serious interference in spite of the ν_e-tag facility; further, a reliable calibration of the ν_e cross-sections with a ν_e source is more problematic in Gd-Tb because the ν_e transition strength is fragmented over a large number of ν_e final states (5 states < 0.86 MeV; 13 states < 2 MeV) compared to Yb-Lu (2 states < 2 MeV); and 2) the ν_e-tag in ^{82}Se with still lower energy and time window, needs technologies far less developed than liquid scintillators (LS) applicable to Yb. A Yb-based LENS appears the most promising route to reliable low energy ν_e -fluxes.

Table1. Gamow-Teller resonance energies (<3 MeV) and strengths seen in $^{176}Yb(^{3}He,t)^{176}Lu$ and $^{160}Gd(^{3}He,t)^{160}Tb$ [$Q_\nu(Yb)$ = E(level) + 106.2 keV; Q_ν (Gd) = E(level)+105.6 keV] (from M. Fujiwara et al, ref. 2)

	Yb Level Energy (keV)	B(GT)	Gd Level Energy (keV)	B(GT)
1	194.5	0.20(4)	138.7	0.054(9)
2	338.9	0.11(2)	232.8	0.014(2)
3			478.2	0.16 (3)
4			573.0	0.021(4)
5			664.7	0.031(5)
6			1120	0.034
7			1310	0.025
8			1500	0.043
9			1610	0.034
10			1670	0.051
11			1750	0.051
12			1900	0.056
13			2040	0.0259
14	3070	0.62(8)		

Reaction Cross-sections, Solar Signal

The possible final states of the ν_e transitions and Gamow-Teller matrix elements (B(GT) needed to estimate ν_e reaction rates in Yb-LENS have been determined by charge exchange nuclear reactions (p,n) and (^{3}He,t) on ^{176}Yb with projectile energies of 120-150 MeV/nucleon at the cyclotron facilities at Indiana (IUCF) and Osaka (RCNP) Universities[2] in 1997-99. This approach is useful if these reactions are calibrated to reliably factor out the nuclear

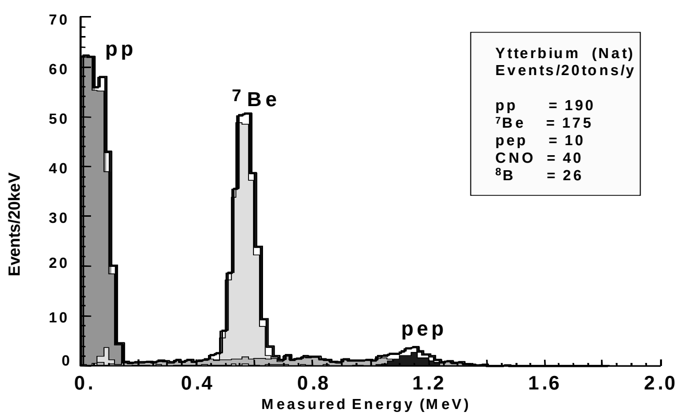

Fig. 2 Solar Neutrino Spectrum from the Standard Sun[3] observable in Yb-LENS

physics part and isolate the weak matrix elements B(GT). This was achieved by using 1) two different reactions, one of which, (p,n), employed two different bombarding energies; 2) the benchmark isobaric analog states with a precisely known Fermi matrix element B(F); and 3) the case of ^{164}Dy-^{164}Ho with a *known* weak matrix element B(GT). The close agreement of the derived nuclear physics factors in all the above variants and the agreement of the B(GT) values obtained in the two reactions provides confidence that the resulting ν_e cross sections are reliable. The possible final states and B(GT) values are given in Table I for Yb-Lu (and Gd-Tb). Only two Yb-Lu states, known previously in isotope data, are involved when $E\nu_e$ < 2 MeV. The standard solar neutrino signal spectrum obtainable with a target mass of 20 tons of natural Yb (folded tentatively with energy resolution) is shown in Fig. 2.

Response of Yb-LENS to Neutrino Conversion Scenarios

The current solar neutrino data is consistent with several non-standard neutrino models based on either matter conversion (MSW Effect) or ("just-so") vacuum oscillations with distinct sets of ν parameters These scenarios produce particularly clear and dramatic effects in the low energy solar neutrino spectral regime. Fig. 3 shows the response of Yb-LENS to these scenarios. Direct proof of conversion is visible in the large changes produced on the pp neutrino peak in three of these scenarios. In the small mixing regime (SMA) of the MSW effect, the pp flux survives (nearly) intact but the ^{7}Be line is completely converted. This charged current null signal of the Be neutrinos in LENS can be compared in direct contrast to the non-zero electron-scattering signal in Borexino produced by the converted μ/τ neutrinos via the neutral weak current. The result would constitute one of the most direct demonstrations of flavor conversion of the Be neutrino line.

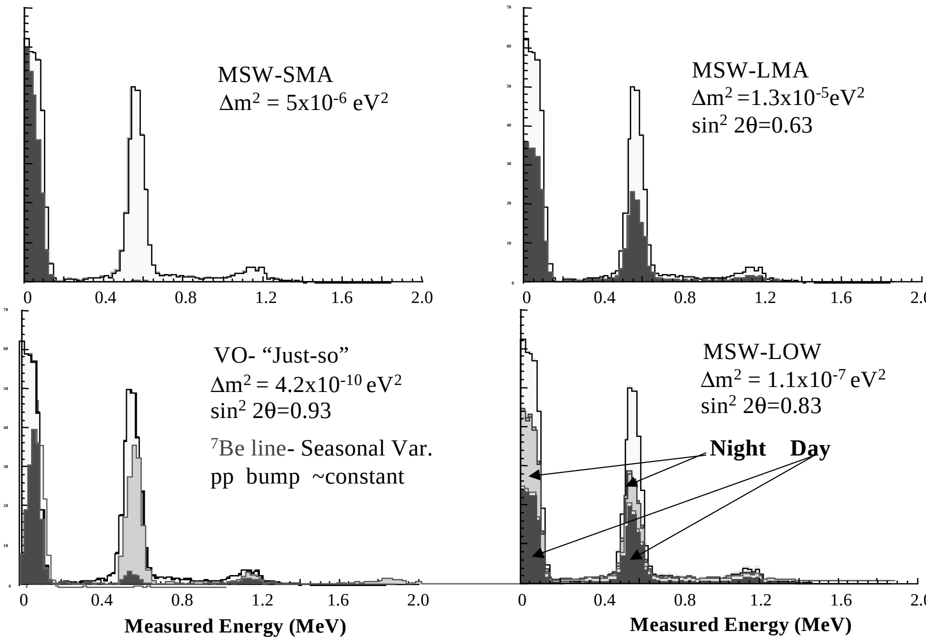

Fig. 3 Response of Yb-LENS to neutrino flavor conversion scenarios

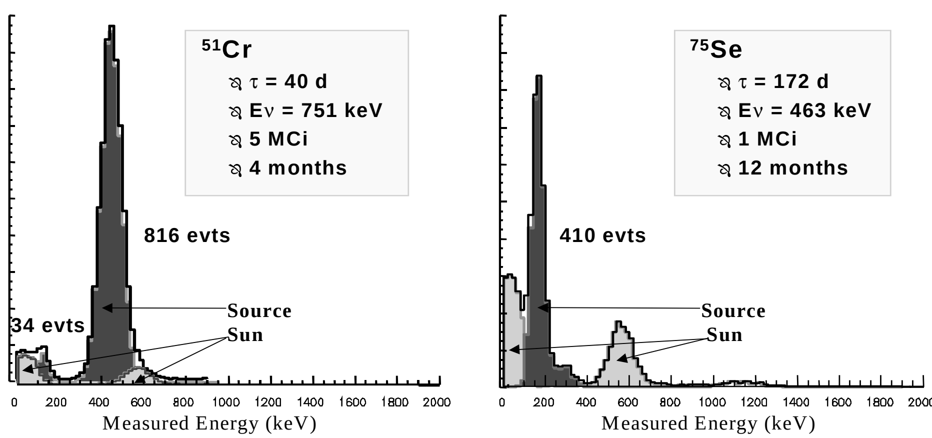

Fig. 4 Calibration of ν_e-capture cross-sections. Response of Yb LENS to MegaCurie ν_e-Sources

Neutrino Calibration

Even with a satisfactory determination of the B(GT) values as above, we plan to measure the specific ν_e cross-sections to the *two* states in Yb-Lu using *two* MCi–class radioactive sources. ^{51}Cr (~3-8 MCi; $T_{1/2}$ = 27.7d; E_ν= 0.426 (~10%), 0.751 MeV (~90%)); and ^{75}Se (~1 MCi; $T_{1/2}$ = 118.5d; E_ν = 0.465 MeV (96%)) emit ν_e lines that individually probe the two states in Yb-Lu. With this calibration strategy, the ν_e response of LENS can be characterized completely as shown in Fig. 4. The nuclear reactors and the technology for producing the sources are available only in Russia[4]. The LENS plan is to reuse the ^{50}Cr material of GALLEX to make the ^{51}Cr source and produce a new isotopically enriched target of ^{74}Se for ^{75}Se. The latter benefits from Russian experience in making kg-scale ^{82}Se material for ββ studies. The LENS application requires source radioactive purities well beyond industrial norms. The technical developments for these requirements are being coordinated at two suitable Russian reactor facilities "Ludmila" and "Demitrovgrad" by a French-German-Russian team from LENS.

Yb Liquid Scintillator (YLS) Technology

As envisaged from the beginning, the basic method for ν_e -spectroscopy in LENS is YLS technology. YLS formulations are being studied to achieve: 1) scintillation efficiency (*S*) with high Yb loading (*Yb*); 2) long light transmission lengths (λ); 3) long-term stability; 4) fast pulse timing, etc. The YLS formulation consists of 4 components: a) a chemical *compound* of Yb, generally either a nitrate or chloride; b) an *extractant* that complexes the compound; c) the aromatic *solvent* that is mixed with the complexed Yb to provide a scintillation base; and d) the fluorescent dopants (*fluors*) that waveshift the photons into the optical band (<430> nm) convenient for photo-detection. In addition to the above criteria, a major concern is the presence of two radioactive contaminants, ^{176}Lu (adjoining to Yb, thus harder to separate) and ^{235}U (0.7% in U) in the Yb part of the YLS. The rare-earth industry uses standard extractants tailored to specific compounds. These extractants are typically ×100 more efficient for actinides than rare-earths, which sets a realistic basis for ultra-low U (and Th) content in large-scale YLS materials.

The key finding in the YLS research so far, is that the industrially preferred extractants and compounds are also chemically and optically compatible with high performance scintillation liquids. Thus, the YLS formulations can be developed on a framework that *integrates spectroscopic, radiopurity as well as large-scale manufacturing* considerations. With these guidelines, a wide-ranging exploration of some 200 different combinations of YLS components (carboxyl (C=O) and phosphyl (P=O) extractants, Yb nitrates, chlorides, acetates, 1-and 2-ring aromatic solvents (PC, Anisole, PXE, IPB, DiPN, 1MN, 2MN) and fluors and shifters (PPO, BPO, POPOP, bis-MSB)) has been made on the ~100 ml scale and tested for optical and scintillation properties at Bell Labs. Other extractants have been shown to be useful in complementary Russian work[5]. The Bell Labs recipes have been reproduced on a larger scale (~1Liter) with high purity Yb compounds at Rhodia Rare Earths Inc. (France), a leading producer. YLS samples from Rhodia and Bell Labs are being tested for optical, scintillation and signal pulse timing at Saclay, with emphasis on absolute values for optical and scintillation properties. There is agreement in specific results in the work of all the laboratories involved in YLS research.

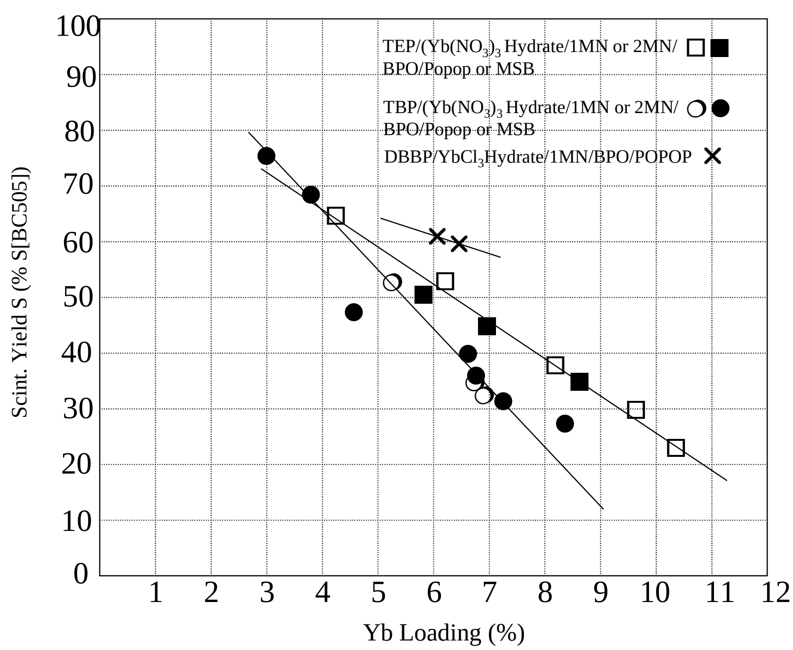

Fig. 5 Scintillation yields of YLS formulations with 1-/2-Methyl naphthalene aromatic base relative to BC505 Std (12000 ph/MeV) [Bell Laboratories, unpublished work)]

The major conclusions emerging in the YLS research can be summarized as follows:

- The highest *S –Yb* values yet are observed with 2-ethylhexanoates[1] (theoretical Yb extraction limit Yb_{th} ~25%). YLS typically with *Yb* ~12%, S~50% were made. However, serious stability problems underlies this approach and it is not possible to exploit this option without extensive basic chemical research which is continuing.
- All phosphyl extractants standard in rare-earth technology with 12 or more C-atoms per extractant molecule (Y_{th} ~14 to 20%, typically 12-17% in practice), are suitable for YLS
- The choice of Yb compound is key. Chlorides need typically heavier extractants for long term stability. So far, only DBBP (250 g/mole) and TiAPO (260 g/mole) lead to YLS stable at least for several months. The highest phosphyl *S* values are however, seen with these extractants, with most standard aromatic solvents, in particular with 1- or 2-methyl naphthalene (MN) (see Fig. 5). On the other hand, the industrial standard is the *nitrate*.
- YLS formulations based on nitrates are found to be stable for >1 yr (confirming standard industrial experience). However, nitrates do produce serious chemical quenching of the scintillation output with single-ring aromatics. The problem is alleviated by the key discovery that double ring aromatics solve the problem. The best case is 1-,2-MN with *S*-Yb values in the design range The lightest extractant in this class is TEP (183 g/mole) which, produces the highest phosphyl-nitrate *S-Yb* values (Fig. 5).
- The Yb-extracts (i.e. without the aromatic and fluor) with carefully selected components show good light transmission λ~3-4m. The λ for the overall scintillator, in the best case of 1or 2MN, has maintained this value, but only with samples of 1MN no longer available in retail. Present supplies of MN however, show a λ~1.5 m.

YLS formulations compatible with the wide-ranging requirements for LENS are thus *converging*. The most advanced YLS at present appears to be: TEP(Yb nitrate/hydrate)/1-2-MN/BPO/MSB. This case may be closest to a "default" YLS (≥300 photoelectrons/MeV) pending chemical purification and improvement of the optical transmission lengths of presently manufactured 1-/2-MN supplies by ongoing collaboration with suppliers.

Background, Contaminants

The random coincidence background of uncorrelated event-pairs are practically removed by the requirement that they occur in the same 10^{-4} to 10^{-5} fractional volume of the detector within the ν_e tag time-window, satisfying the energy profiles of the ν_e tag. Correlated events are not. Three major types of correlated background have been identified in Yb-LENS: self correlation (SC) of single pulses and coincident cascades from two specific impurities, ^{235}U and ^{176}Lu in the residual Lu in the Yb material. The SC background places an additional premium on signal quality, i.e. photoelectrons/MeV and scintillation pulse times in the YLS. The U and Lu background requires extreme chemical purification and contamination control in the YLS. The experience and technology developed for Borexino are relevant for contaminant control in the aromatic part of the YLS. In the Yb part, the problems are solvable in large measure by the rare-earth technology itself which intrinsically contains the means for ultrapurity, possibly to the required level in U (see above), but only up to a degree in the case of Lu. Special methods of Lu ultrapurification are under consideration. The salient features of the correlated background sources can be summarized as follows:

- *Self-correlation:* The low energies and short time window of the ν_e tag creates a new kind of background when both the components of the ν_e tag are detected in the same module. In this case, the time profile of photon emission from a *single* event (e.g., in the Be or pep window), can contain a (~10%) statistical fluctuation that mimics the delayed occurrence of the 72 keV gate. A key parameter controlling this background is the scintillation decay time, especially the fraction of light in the slow decay components. While this fraction is only ~1% in pure scintillators, its value in the YLS is yet unknown and sets another criterion in the YLS formulations. Simulations and experimental studies of this problem are in progress to set design goals for signal quaility (pe/MeV), pulse times and minimum delay cuts (MDC) on the time profile of events.
- *^{176}Lu:* Lu contains 2.6% long-lived ^{176}Lu which emits the $\beta\gamma$ cascade: (1100 keV-(τ =2 ns)-88 keV), a profile similar to the ν_e tag. The ^{176}Lu decay is relevant despite the short lifetime of 2 ns because its specific activity is high. Since the Lu events occur mostly >500 keV, they do not affect the pp signal (<120 keV). At 0.1 ppm Lu in Yb (considered industrially feasible), the Lu false-event rate reduces to ~4/y if the MDC = 40ns, entailing a signal loss of ~55% (worst case solution). However, this solves in large measure, also the SC problem.
- *^{235}U:* This rare U isotope (0.7%) emits a delayed $\beta\gamma$ cascade: $^{235}U \rightarrow {}^{231}Pa(\beta$ delay γ)- that closely mimics the Yb pp signal tag at 0-120 keV. The Be and pep signals are not affected. The only defence is removal of ^{235}U in the scintillator to the level 10^{-15}g/g U equivalent. This purity is said to be achievable in Yb materials because the industrial production process inherently separates U very efficiently (see above).

Purification by Isotope Dilution: The major radio-contaminants above have very low abundance [^{176}Lu (2.6%) and ^{235}U (0.7%)] in natural Lu and U. This aspect can be exploited for developing methods for extreme purification by *standard* technology, using *isotope dilution* with carriers of Lu and U highly depleted in the above radioisotopes. Carriers are available with sufficient depletion and quantity. The application of this procedure may be relatively straightforward in the case of Lu since it is also a rare-earth. Thus, this proposal needs to be developed actively because of the critical role of Lu contamination and especially, the limitations on its removal in the standard industrial process. In the U case, quantitative research is necessary to determine the possible chemical forms of the U carrier in relation to that of the U impurity in the Yb material. In both cases, development work with trial purifications on various levels are necessary before the feasibility of the approach in the large scale can be assessed

Ultratrace Assay of U and Lu: Because of the key roles of the ^{176}Lu and ^{235}U backgrounds, direct methods for *assay* of these contaminants are needed for Lu at 1ppb and ^{235}U at the 10^{-16} g/g U equivalent levels in the YLS. The Lu assay can be made by γ-ray counting in kg scale either in a protoptype YLS module or with low background underground Ge detector facilities. ^{238}U assay at 10^{-16} g/g level is now routinely made by a special neutron activation method which employs a *^{238}U tag* (a delayed coincidence of cascade radiations in the n-capture product ^{239}Np), which improves background by several orders of magnitude.[6] A parallel neutron activation technique has been proposed for specific detection of <u>^{235}U</u> with similar ultrasensitivity, based on slow neutron *fission* rather than n-capture.[7] A key prerequisite for applying these methods to YLS materials (in contrast to pure organics as achieved so far) is the need to develop low blank methods for pre-removal of macroscopic Yb from YLS samples. This becomes necessary because of the very high n-capture cross-section of the native ^{168}Yb isotope.

LENS Prototype

The issues in the design and operation of LENS outlined above need to be tested integrally in prototype before the design can be finalized. The collaboration intends to carry out the test program in research prototypes constructed at LNGS on the 100-200 liter scale even if final module sizes are larger and the final design is not modular (comparative studies of modular and unsegmented designs are being initiated).We believe that most of the outstanding questions central to LENS design can be addressed in such prototypes. The overall classes of questions can be divided broadly (and surely incompletely at the moment) as: 1) chemistry and handling of the YLS; 2) optical and scintillation issues; 3) signal processing issues; 4) correlated background of the SC and Lu types (if not also the U type); 5) shielding and external background questions with anti-coincidence layers simulating the modular assembly; 6) possible simulation and tests of the LENS ν tag by doping the scintillator with ^{175}Lu. An external neutron source can excite via (n,γ) the same levels in ^{176}Lu that are excited in the solar neutrino reactions; and so on.

We believe this program would occupy us over the next 2 years. The size of such a prototype installation is sufficiently modest (yet potentially highly informative) that it may be possible to loan the needed hardware in the larger laboratories. Resources on this scale can be accommodated in development funds already set up in several LENS laboratories. We expect to have technical details on the installation plans before the next LNGS committee meeting. We request planning of laboratory space for this program both in- and outside the underground galleries.

Central Laboratory for LENS (CELL)

As part of the prototype program, we are forming a central LENS group at LNGS. The purpose of this initiative is to foster a pioneer group to consider common questions, acquire the expertise and logistics to transfer and implement technologies developed in local laboratories and produce test programs of interest to the prototype program using the excellent facilities of LNGS such as its underground γ-ray counting set ups for quality control of radiopurity of materials, the well-instrumented chemical laboratory facility, and others. The ultimate value of CELL is the implementation of a sound infrastruture that will smooth the path to physical constructions of the prototype program. The starting phase of CELL is influenced by two points: 1) the importance of diverse chemical questions is evident from the descriptions in the document; 2) the impact of the aknowledged chemical and nuclear expertise of Russian groups can be enhanced by opportunities for research work in the excellent facilities of LNGS. Thus a small group of Russian colleagues are expected to arrive in Spring 2000 to explore these opportunities. We foresee inflow of many other groups into CELL in permanent or transient style as the pace accelerates. Last but not least we hope that CELL will act as the focus for LENS participation of <u>Italian</u> scientists and groups in and out of LNGS.

The LENS Collaboration

The sizable group of scientists that has been meeting several times in the last two years to consider the issues of LENS formally incorporated itself as an International Scientific Collaboration in the meeting at LNGS on Feb 21/22, 2000. Several institutions (some new) in practically every country of this association are forming groups explicitly comitted to LENS. Development funds for LENS acivities have been committed to in several laboratories. Major funding agencies are being briefed on the progress and prospects of LENS. The collaboration structure of LENS now is as follows:

Spokesman: **R. S. Raghavan**
Co-Spokesman: **Michel Cribier**

Members (Heads of Institutional Groups in italics):

France:

College de France, Paris: A. de Belefon, T. Beau, *H. de Kerret*, D. Kryn, M. Obolensky, D. Vignaud

Dapnia, CEA/Saclay: J. Bouchez, P. Bourgeois, C. Cavata, R. Chipaux, *M. Cribier*, G. Fioni, J. Mallet, J.-P. Meyer, C. Veyssiere, H. Zaccone

Germany:

Max Planck Inst. fur Kernphysik, Heidelberg: W. Hampel, F. Hartmann, J. Kiko, T. Kirsten, *S. Schoenert*

University of Dortmund: K. Zuber

Italy:

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Institute of Nuclear Research RAS: I. R. Barabanov, V. I. Beresnev, *L. B. Bezrukov*, V. I. Gurentsov, V. N. Kornoukhov, N. P. Nesterova, O.G. Ryazhskaya, E.A. Yanovitch, *G. T. Zatsepin*

Inst. of Physical Chemistry RAS: N. A. Danilov, V. M. Gelis , *G. V. Korpusov*, G. V. Kostikova, Yu. S. Krylov

Inst. of Chemical Technology: V. V. Yakshin

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Brookhaven Nat. Lab. R. L. Hahn

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Los Alamos Nat. Lab. *T. Bowles*, S. Brice, M. Fowler, A. Hime, G. Miller, A. Pichmaeir, J. Wilhelmy, J. Wouters

VirginiaTech: R. B. Vogelaar

[1] R. S. Raghavan, Phys. Rev. Lett. **78** , 3618 (1997); Proc. 4th Int. Conf. on Solar Neutrinos, Heidelberg (1997), W. Hampel Ed., p. 248

[2] M. Fujiwara et al, to be published; C. Goodman et al, to be published.

[3] J. N Bahcall and M. Pinnsonnault, Rev. Mod. Phys. (1998)

[4] V. N. Kornoukhov, Preprint 18-99, Inst. Th. & Expt. Phys. ITEP (1999).

[5] I. R. Barabanov et al, Preprint xxxLANL, Physics/908005 (1999).

[6]R. S. Raghavan *"Design Concepts for Borex"* AT&T Bell Labs Memo 11131-880114-02TM (1988); T. Goldbrunner, Ph. D. Thesis (TUM) (1997); R. v. Hentig, Ph. D. Thesis (TUM) (1999).

[7] R. S. Raghavan, Bell Labs Report: 11172-990818-32TM (1999).