# The LENS experiment – peering into the heart of the Sun

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This review talk is a tribute to Prof. Raju Raghavan, who conceived an indium loaded scintillator detector to measure neutrinos from the reaction $p + p \rightarrow d + e^+ + \nu_e$ taking place in the Sun. Neutrinos from this weak process, which should constitute more than 90% of the solar neutrinos, have been only indirectly measured by the Gallium based radiochemical detectors. A prototype In-loaded liquid scintillator detector built by the Virginia Tech group is being tested at the Kimballton underground laboratory. If successful this could lead to a 125 ton Indium loaded liquid scintillator detector that could measure the energy spectrum of the *pp* neutrinos in real time. In about 5 years it could measure the "neutrino" luminosity of the sun and confront the well known photon luminosity to an accuracy of ~ 4%. Apart from addressing the energy dependence of the $\nu_e$ survival probability and comparison with the expectation based on the matter induced resonant conversion due to Mikheyev, Smirnov and Wolfenstein, such a detector could also be used to search for sterile neutrino mixing with $\Delta m^2 \sim eV^2$, which is a topic of great current interest.

## 1. Introduction

The understanding that the sun is powered by nuclear reactions taking place in its hot inner core is largely due to the seminal work of Bethe [1]. The first direct proof that nuclear reactions do take place, and are responsible for energy production in the sun, was provided by measurements on solar neutrinos. They originate in reactions mediated by the weak interaction, such as $pp \rightarrow de^+\nu_e$, and from the beta decaying nuclei produced in these reactions. Evidence for solar neutrinos came from the pioneering work [2] by Ray Davis who employed a radiochemical technique using 600 tons of the cleaning fluid $C_2Cl_4$, separating and counting the $^{37}$Ar produced when $\nu_e$ interacts with $^{37}$Cl. This method of neutrino detection was first suggested by Pontecorvo [3] in 1946. These measurements, in conjunction with calculations [4] of the solar neutrino flux by Bahcall and collaborators, led to the so called solar neutrino problem viz. the ratio of the measured to calculated flux was about 0.3-0.5. The basis for these calculations was the standard solar model (SSM) which was found to be consistent with other observables such as the characteristic low frequency oscillation spectrum of the sun (helioseismology). The neutrino oscillation solution to the solar neutrino problem was not accepted until the measurements by the Super Kamiokande(SK) collaboration on atmospheric neutrinos which measured the ratio of the upward to downward flux of muon and electron neutrinos [5]. The neutrino oscillation explanation of the solar neutrino problem was confirmed by a series of beautiful measurements at the Sudbury Neutrino Observatory using a 1 kton heavy water detector [6]. In addition to detecting electron neutrinos through the charged current weak interaction, it also measured the flux of all (active) flavours of neutrinos with $E_\nu > 5$ MeV through the neutral current weak interaction leading to deuteron breakup. These measurements indicate that the measured and calculated $^8$B neutrino fluxes agree within 20%. A related test is the comparison between the luminosities inferred from the measured flavor independent neutrino flux and from the photon spectrum. Presently the ratio of these quantities is $1.4^{+0.2}_{-0.3}$ [7] and by a subsequent analysis as $1.12 \pm 0.21$ [8] at the $1\sigma$ level. It must be emphasized that of the detectors measuring neutrinos in real time both SK and SNO have a threshold of about 5 MeV so that they only measure $^8$B neutrinos. The latter constitute $< 10^{-4}$ of the total solar neutrino flux. Borexino [9] is an ultra pure liquid scintillator (LS) detector that was built to measure the 862 keV $^7$Be neutrinos through their elastic scattering off electrons. There is no real time detector that can measure *pp* neutrinos, an area where Low Energy

Neutrino Spectroscopy (LENS) could be uniquely positioned. By measuring *pp* neutrinos, which constitute more than 90% of all solar neutrinos, the "neutrino" luminosity could be measured to much higher precision. Moreover, *pp* neutrinos are less prone to uncertainties in the relevant nuclear reaction cross sections which are needed to estimate production of the other major components viz. the $^{7}$Be and $^{8}$B neutrinos. The only detectors that were sensitive to *pp* neutrinos were the Gallium based radiochemical detectors SAGE [10] and GALLEX [11]. However, radio-chemical detectors cannot identify the direction of the measured neutrinos nor can they distinguish between the different components of the solar neutrino spectrum arising from pp reaction and $^{7}$Be and $^{8}$B beta decay. The first issue was settled by the SK measurements on $^{8}$B neutrinos. Could one have a detector with low threshold and the ability to measure the neutrino spectrum?

## 2. The LENS detector

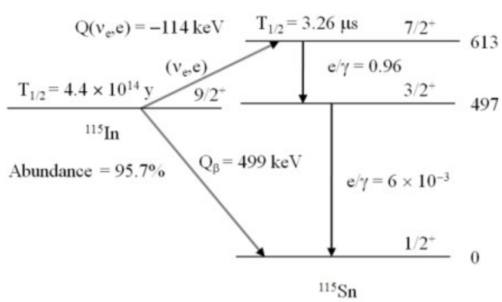


**Fig. 1** Low lying nuclear levels of $^{115}$Sn and $^{115}$In. Energies of levels are in keV.

The answer to this question was a proposal by Raghavan in 1976 [12] to use an Indium based liquid scintillator (LS) detector. The relevant energy level diagram is shown in Fig. 1. The low threshold of about 114 keV allows a measurement of the bulk of *pp* neutrinos whose spectrum extends to ~420 keV. Fig. 2 shows the calculated solar neutrino spectrum [13]. The prompt electron energy, corresponding to a ($\nu_e$,e) reaction directly populating the 7/2$^+$ state at 613 keV in $^{115}$Sn, is a measure of the neutrino energy ($E_\nu = E_e - Q$, where $Q \simeq -114$ keV, neglecting the recoil energy of $^{115}$Sn). The delayed γ-rays and conversion electrons can be used to drastically reduce the background arising from the β-decay of $^{115}$In. However, this reduction in the background using the temporal information is not enough to extract the neutrino signal from an In based detector such as a In-loaded liquid scintillator. A localization of the prompt and delayed γ/e signal in addition to a hit pattern is necessary to reduce the random coincidences so that an overall reduction in background by a factor of ~$10^{12}$ is achieved. This is necessary for a reliable extraction of the neutrino energy spectrum in the low energy region [14].

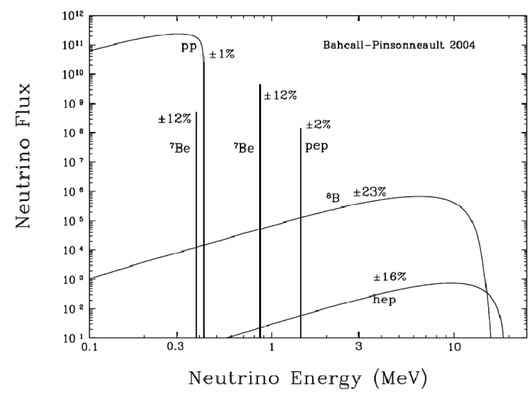


Fig. 2. Solar neutrino spectrum calculated by Bahcall *et al.* [13]

The localization of the event, with a certain position resolution, can be conceived in many ways. An ingenious method uses Teflon based reflectors to form a lattice that allows the scintillation photons produced in an interaction of a charged particle in the In-loaded liquid scintillator detector, to propagate in preferred directions dictated by total internal reflection.

The In-loaded LS (In-LS) is central to the LENS experiment. Presently, using technology based on Ref. [15], about 8% of In can be loaded in the LS. For this Indium loading the light yield is about 8000 photons/MeV and the attenuation length for the scintillation photons in the In-LS is > 8 m. The optical and chemical stability of the In-LS is measured to be > 1 year. Initial efforts at a higher loading ~15% seem promising.

The LENS collaboration has constructed a small prototype consisting of about 125 litres of In-LS and housed in the Kimballton Underground Facility in Virginia, USA, to test some of these ideas. A laboratory version is shown in Fig. 3.

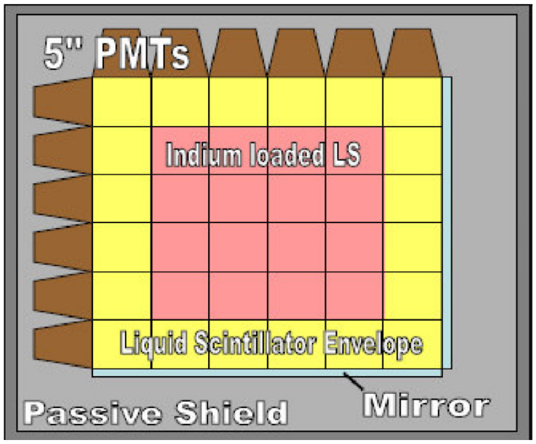


**Fig. 3**. Schematic of prototype LENS detector. The inner In-LS is surrounded by a LS-only envelope (from Ref. [14]).

Fig. 4 shows a simulation of the full scale 125 ton In-LS detector with 10 tons of Indium loading for 5 years exposure to solar neutrinos. As can be seen the signal from *pp* neutrinos can be distinguished clearly above the background from $^{115}$In beta decays. A detailed analysis shows that the *pp* neutrino flux could be measured to about 4% accuracy allowing a stringent test of the standard solar model. A novel aspect of this measurement is that it is a way of probing the *pp* fusion reaction in the sun at a Gamow energy corresponding to the core temperature. Since LENS would measure 99.5% of the neutrinos from the sun it could compare the luminosity of the sun as inferred from the neutrinos and the traditionally measured solar luminosity in the photon sector. The inputs to the neutrino flux are the nuclear reaction rates, around the relevant Gamow energy, and the physics of neutrino oscillations including matter effects. It is assumed that there is no temporal variation over time scale of the order of about 40,000 years (the time taken for a photon to propagate from the core to the surface of the sun, much longer than about 8 mins taken by a neutrino).

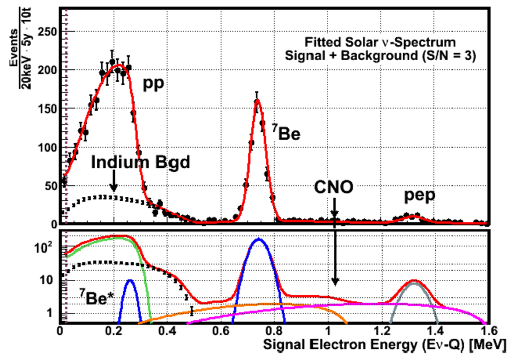


**Fig. 4.** Simulated spectrum due to solar neutrinos in LENS detector. Assumed exposure is 5 years with 10 tons of Indium loading in liquid scintillator (from Ref [14]).

The measurement of the solar neutrino spectrum would also enable a precision measurement of the $\nu_e$ survival probability as a function of neutrino energy. Our present understanding of the reduction in solar $\nu_e$ flux is that the $\nu_e$ produced in the solar interior oscillates into the 3 possible flavours ($\mu$, $\tau$ and e-type) including itself. This happens even as neutrinos propagate in vacuum. When they propagate in matter the mixing angles and masses are renormalized, the extent of which depends on the neutrino energy and matter density, or more precisely, the electron density. This was first pointed out by Mikheyev, Smirnov and Wolfenstein (MSW) [16]. At low energies the neutrinos propagate in the solar interior very much as they do in vacuum but at energies > 1 MeV they undergo resonant conversion to other flavours at a critical density which depends on its energy. The current status, showing the survival probability of the solar $\nu_e$ as a function of neutrino energy, is summarized in Fig. 5 (adapted from Ref. [9]). The data points at about 0.8 MeV and 10 MeV are from the Borexino and Super Kamiokande experiments, respectively. The point around 0.3 MeV is the $P_{ee}$ inferred for *pp* neutrinos from the Gallex and SAGE experiments after accounting for the contribution from $^7$Be and $^8$B neutrinos. A direct measurement of the *pp* neutrinos would reduce the error on this point considerably. Apart from subjecting our understanding of solar neutrinos to a more severe experimental scrutiny, a precision measurement of the solar neutrino spectrum may also throw up a surprise. This could enrich our understanding of solar physics or put to test the conventional wisdom in the neutrino oscillation sector including matter effects.

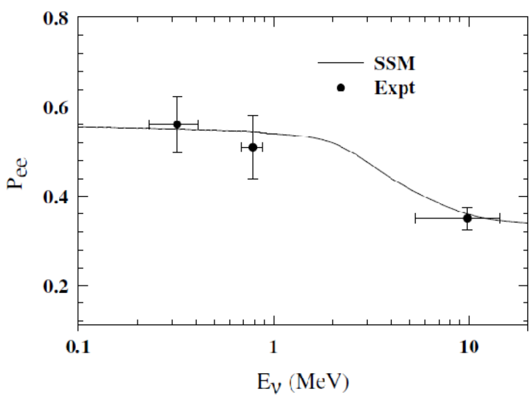


**Fig. 5.** Survival probability for solar $\nu_e$ – theory and experiment

## 3. Search for sterile neutrino mixing with $\Delta m^2 \sim eV^2$

The LSND experiment which looked for anti-$\nu_\mu$ $\rightarrow$ anti-$\nu_e$ oscillations found evidence for $eV^2$ mixing [17] in an appearance experiment and later also in the $\nu_\mu \rightarrow \nu_e$ oscillation [18] using stopped muons and in flight pion decays, respectively, at the Los Alamos Meson Physics Facility. This observation is supported by results from the MiniBooNE experiment [19] and cannot be understood within the framework of 3 neutrino flavours. Since the number of active neutrino flavours with masses < 45 GeV is constrained to three by precision $Z^0$ data from LEP, the additional neutrino(s) has to be sterile with $\Delta m^2$ of 0.1-1 $eV^2$. Here $\Delta m^2$ is the difference in the square of the sterile neutrino mass and that of any of the other mass eigenstates (in the approximation that the other 3 mass squared differences are much smaller). In such a (3+1) neutrino flavor scenario the electron neutrino survival probability is given by

$$P_{ee} \approx 1 - \sin^2 2\theta_{es} \sin^2(1.27\Delta m^2 L/E)$$

for $\Delta m^2 >> \Delta m_{21}^2$, $\Delta m_{31}^2$. Here $\Delta m^2 \approx m_s^2 - m_1^2$, $\Delta m_{21}^2 = (m_2^2 - m_1^2)$ and $\Delta m_{31}^2 = (m_3^2 - m_1^2)$ and $m_1$, $m_2$, $m_3$ and $m_s$ are the masses appearing in the (3+1) mass matrix and $\theta_{es}$ is essentially the $\nu_e$–$\nu_s$ mixing angle. For $\Delta m^2 \sim eV^2$ and neutrino energies ~ MeV the oscillation pattern should be observable over a length scale ~ 1m. The LENS detector could search for such a mixing [14] using a $^{51}Cr$ source which decays by electron capture emitting a near mono-energetic (with 90% branching) electron neutrinos ($E_\nu$=753 keV). A strong source ~10 MCi, shielded by heavy metal to attenuate the weaker 320 keV $\gamma$-rays, placed at the centre of the detector could confirm or rule out the region in the $\Delta m^2$-$\sin^2 2\theta_{es}$ plane suggested by the LSND experiment. Such a strong source has been used by the Gallex and SAGE experiments for calibrating their detectors. The authors of Ref [14] estimate a sensitivity exceeding that of MiniBooNE, which has published data consistent with the finding of LSND in the anti-$\nu_\mu \rightarrow$ anti-$\nu_e$ oscillation, in about 400 days of running time of the LENS detector.

Other possibilities for LENS are looking for possible differences in the oscillation phenomena for neutrinos and antineutrinos by using $\beta^+$/EC and $\beta^-$ decays. For the latter measurement LENS could use the inverse beta decay on protons in the LS and use the delayed neutron capture signal.

In summary, LENS will not only open up a new window for observations on the sun using the neutrinos as probes of its deep interior but could also be used to search for sterile neutrino mixing using sources of electron neutrinos and anti-neutrinos.

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