Discovery in the New Era of Solar Neutrinos

A White Paper
Based on Proceedings of the LONU-LENS Workshop
Blacksburg Oct 14-15

http://www.phys.vt.edu/~dusel/low-energy-workshop/

Workshop Conclusion

Highest priority should be given to the precise (3-4%) measurement of the full spectrum of solar neutrinos below 2 MeV (the pp, ^{7}Be, pep and CNO neutrinos), which provides great potential for discovery including a model-independent comparison of nuclear energy generation to the photospheric luminosity, stringent tests on solar models, a solution to the uncertain CNO contribution in the sun, a test of the standard LMA model for neutrino mixing and a precise determination of θ_{12}, limits on nonstandard interactions, mass varying neutrinos and on sterile neutrino conversion. Detection technologies based on complementary charged-current and charged+neutral current modes are emerging that may be applied within 5 years to full scale detectors capable of achieving these important fundamental scientific objectives.

SCIENCE

Astrophysics

Solar Luminosity in neutrinos and photons

Over 99% of neutrinos from the sun have energies below 2 MeV, where no spectroscopic data are currently available. Measurement of the full spectrum of these neutrinos would provide a model-independent determination of the current rate of nuclear energy generation in the solar core, allowing a fundamental comparison with the current photospheric luminosity.

A precision measurement of the individual fluxes of the pp, Be, pep neutrinos and at least a reasonable definite one of CNO neutrinos is essentially a measurement of solar luminosity in neutrinos if they are massless. This neutrino luminosity can be directly compared with the photon luminosity. The comparison probes if 1) nuclear reactions are the only source of energy in the sun and 2) energy generation in the sun remains in quasi steady state in a time scale of the order of the difference between the time emission of light and and that of neutrinos of ~10^5 years for energy generated at the same time as neutrinos.

We know that neutrinos have non-zero mass and they oscillate in or on the way from the sun. Thus we must correct the measured neutrino fluxes using the best neutrino model and parameters to work back to the original fluxes in order to carry out the above neutrino-photon luminosity comparison. This process is largely independent of solar models since the parameters used to calculate the energy generated in the emission of a specific neutrino flux is unambiguously fixed by nuclear physics. The derivation of neutrino physics from measured fluxes has always been subject to the dichotomy of neutrino physics and solar models. The comparison of luminosities avoids this dichotomy and places all conclusions on an experimental basis for the first time. This comparison is therefore a powerful independent calibration of the sun's energy that tests not only the astrophysics of the sun (past, present and future) but also of the new neutrino physics.

A measure of the expected progress in luminosity comparison – via a precision measurement of the complete low energy solar neutrino spectrum – is indicated by the large uncertainties encountered in using presently measured solar neutrino data. The ratio $L(\nu)$ (inferred)/$L(h\nu)$ = 1.4 (+0.2-0.3; 1 σ) by one estimate and $1.12 \pm 0.2 (1\sigma)$ by another, instead of 1.00. The only way to improve this gap is via spectroscopic data of the individual fluxes to ~3-4% i.e., of *each* of the pp, Be, pep and a modest precision of the CNO fluxes. The importance of individual fluxes is illustrated by the fact that part of the apparent luminosity imbalance above can be traced to the complete lack of information on the CNO flux. A major experimental need for attaining precision is not only event statistics but systematics such as background. Detector technology that enables *measured* backgrounds instead estimates will be more useful.

Solar Dynamics, the CNO flux

Current dynamic solar models include motion and activity inside the sun that may transform part of the produced nuclear energy into kinetic and magnetic energy, which are not accounted for in the Standard Solar Model (SSM) (which assumes perfect and prompt transport of nuclear energy to the photosphere). Neither are they part of the luminosity balance as described above. The precise determination of current nuclear energy generation via the neutrino luminosity thus also tests the emerging dynamic solar models. Measuring the time variability of the pp neutrino flux would also put some constraint on the variability of the radiative zone in time. We already know from helioseismology that the convective zone evolves with time (rotation profile, meridianal circulation, magnetic fields), but it is more difficult to include motions (which clearly exist) of the radiative zone. The pp neutrinos are a good indicator because they are sensitive to practically 60% of the mass of the sun and their flux is not dominated by the solar temperature profile. Therefore, the pp neutrinos have a real sensitivity to density variations in latitude and are a good indicator on the dynamics of the Sun.

In contrast, even a relatively imprecise (20%) determination of the previously unmeasured CNO neutrino flux would be very interesting for understanding the metallicity of the solar core and the migration of CNO elements within the sun over time. While the CNO contribution to nuclear energy generation is small (a few percent of the total luminosity), these elements play a very important role in the solar opacity. We know that they migrate from the surface to the center of the sun over time, but the abundance of CNO isotopes in the stellar core is quite uncertain. A measurement of the CNO neutrino flux, even with modest precision, would provide crucial information on the abundance of these elements in the stellar core.

Neutrino physics

Tests of LMA and precision solar mixing angles

Current solar neutrino measurements are well described by the standard MSW-LMA model. Precision measurements of the spectrum of neutrinos below 2 MeV, coupled with the derivation of neutrino parameters that provide the best neutrino luminosity check (instead of solar models), provide a model-independent basis on which neutrino flavor physics can be formulated. In the zeroeth order we expect this procedure to test the basic LMA model of neutrino interactions. The physics tests for this are: 1) the prediction of nearly pure vacuum oscillations of the pp flux; and 2) the ratio of Be and pep fluxes to the pp flux which contains small reductions via matter effects. From 1) we have a powerful means of improving the precision of the solar mixing angle θ_{12} since a precise pp flux directly yields a precise θ_{12} if the pp flux is affected ONLY by vacuum oscillations: P_{ee} (pp) = $1 - 0.5 \sin^2 2\theta_{12}$.

The overall luminosity balance can, in principle can be affected by two neutrino physics reasons: 1) the presence of 1-3 mixing via the parameter θ_{13} (since the solar fluxes are scaled independent of energy by the factor $\cos^4\theta_{13}$) and 2) possible (in principle energy dependent) conversion to sterile neutrinos which could also result in loss of active neutrino flux. The new solar neutrino research is thus intimately connected to major efforts in measuring θ_{13} underway presently. A precise determination of this parameter in earth experiments will break some degeneracies.

Non-Standard Effects from Particle Physics

Precise ratios of pp to Be and pep fluxes are capable of revealing non-standard neutrino physics beyond (or even in place of) the LMA model. Deviations of these ratios from LMA can be produced via extensions of the Standard Model that generally predict new interactions, with couplings suppressed by the large energy scales (heavier than the weak scale) associated with new symmetries. The new couplings could appear in the interaction of neutrinos with matter in the form of neutral current four-fermion operators, both flavor preserving and flavor changing. New interactions of the order of 10-30% of the standard weak interaction are possible in the electron and tau neutrino sector. They are compatible with all the existing data from accelerator and from neutrino oscillations experiments. Such large non-standard interactions (NSI) could have observable effects on the survival probability of solar neutrinos. The NSI are constrained to mimic the standard behavior of the SuperK and SNO data in the matter-dominated region (8B neutrinos), while they must be small in the vacuum-dominated part of the spectrum (pp-neutrinos). These effects would appear in the region of the vacuum-matter transition of the MSW probability by tens of percent deviations in the ratios of pp to Be and pep neutrino fluxes well beyond that allowed by the LMA model (see above).

Mass Varying Neutrinos--Cosmology

Why are the dark matter and dark energy densities comparable today even though their ratio scales as $1/a^3$ (a is the scale factor)? The coincidence that the scale of dark energy (2×10^{-3} eV) is similar to the scale of neutrino mass splitting (0.01 eV^2) was applied recently to the puzzle of why the dark matter and dark energy densities are comparable today even though their ratio scales as $1/a^3$ (a is the scale factor). Neutrinos can thus be possibly coupled to dark energy by supposing that the dark energy density is a function of neutrino mass and imposing the condition that the total energy density of neutrinos and dark energy remain stationary under variations of the neutrino mass. Then neutrino masses vary in such a way that the neutrino energy density and the dark energy density are related over a wide range of a. A simple way to make the dark energy density neutrino mass dependent is to introduce a Yukawa coupling between a sterile neutrino s and a light scalar field φ called the *acceleron* that couples to both neutrinos and matter. In this case it may be possible to test the scenario via neutrino oscillations since the effective neutrino mass is altered by the interactions via the scalar which in turn modifies ordinary matter oscillations of neutrinos. Application of these ideas to solar neutrinos shows that the survival probability P_{ee} can produce a *higher* than vacuum value (LMA scenario) at low energies, changing to LMA values of P_{ee} high energies as measured in ^{8}B neutrinos. In between, the P_{ee} lies systematically below the LMA profile of P_{ee}. The latter effect is similar to that via NSI (see above) however, the signature effect of mass varying neutrinos is the predication of a higher than LMA pp flux.

Sterile Neutrino Spectroscopy

The technology of low energy neutrino detection has stimulated a new application to a non-solar particle physics problem of high current interest – the existence of sterile neutrinos (Grieb et al hep-ph/0611179). The LENS detector program (see below) envisions calibration of the reaction cross section using an artificial MCi source (LENS-CAL). The detection of mono-energetic, flavor pure $\nu_{e,}$ in LENS-CAL can be used *parasitically* to study sterile neutrinos as reported by LSND. By placing the source at the center of the detector, the full oscillation cycle can be observed as a disappearance and recovery of e-neutrinos as a continuous function of radius defined by the detector lattice cells in the granular design of LENS. As a disappearance experiment, the oscillation effect is first order in small mixing angles ($\sim 4U_{e4}^2$) as opposed to the appearance experiments (LSND and MiniBooNE) which are second order in small mixing angles ($4U_{e4}^2U_{\mu4}^2$), therefore the sterile oscillation effect should be significantly larger. The projected sensitivity for an exposure to four 10 MCi shots of 100 days each with Cr is shown in Figure 1. The source technology is well developed in the context of the Ga radiochemical experiments.

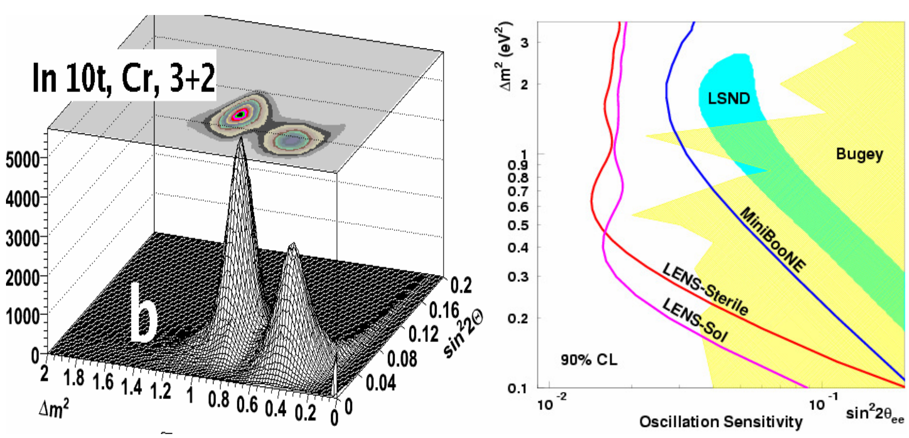

Fig. 1 Left: $\nu_e \rightarrow \nu_s$ oscillations to two sterile states in the 3+2 model observable in LENS-Sterile from 4x10 MCi ^{51}Cr exposures ; Right: Exclusion plots of sensitivity to active-sterile oscillations in LENS (with 4x100 d exposure to 10 MCi Cr source) compared to those for LSND, BUGEY and the projected sensitivity of MiniBooNE Both LSND and MiniBooNE are plotted assuming that $U_{ee}=U_{\mu\mu}$. The standard LENS design (LENS-Sol) is compared to a design optimized for the sterile measurement (denoted as LENS-Sterile) with 15% In by weight and 3.3×3.3×3.3 m^3.

TECHNOLOGY

The discovery program via low energy neutrinos described above is timely since, for the first time, major new detection technologies (based on CC and CC+NC modes) are emerging. The two techniques are complementary and use two main detection technologies, liquid scintillators (LS) and cryogenic liquids (CL) both of which emit optical scintillations in response to ionizing radiation. The experiments in current development are:

- Liquid Scintillator (LS) : LENS (CC) (Indium loaded); SNO+ (CC+NC) (pure LS)
- Cryogenic Liquids (CL): CLEAN (CC+NC) (Neon); XMass (CC+NC) (Xenon--Japan)

Thus LENS is the only CC based detector in this group and uses a tagged ν_e capture reaction on a target of Indium (95.6% ^{115}In) sensitive only to e-neutrinos. The CC+NC reaction is non-taggable ν-e scattering process with 20% sensitivity to neutrinos of all flavors. Typical signal spectra in these two categories are shown. The CC reaction in LENS has a threshold at 114 keV so that all low energy neutrinos are detectable. The energy of the neutrino can be measured so that the solar neutrino spectrum can be faithfully observed. The recoil electron spectrum in neutrino scattering is energy dispersed because of the random scattering angle involved. Solar neutrino spectra from the two approaches are shown in Fig 2 for LENS (absorption) and CLEAN (scattering). The energy threshold is set by pulse analysis limitations.
LENS, CLEAN and XMASS are capable of pp neutrino detection while SNO+ will be able to observe only the 7Be and pep neutrinos.

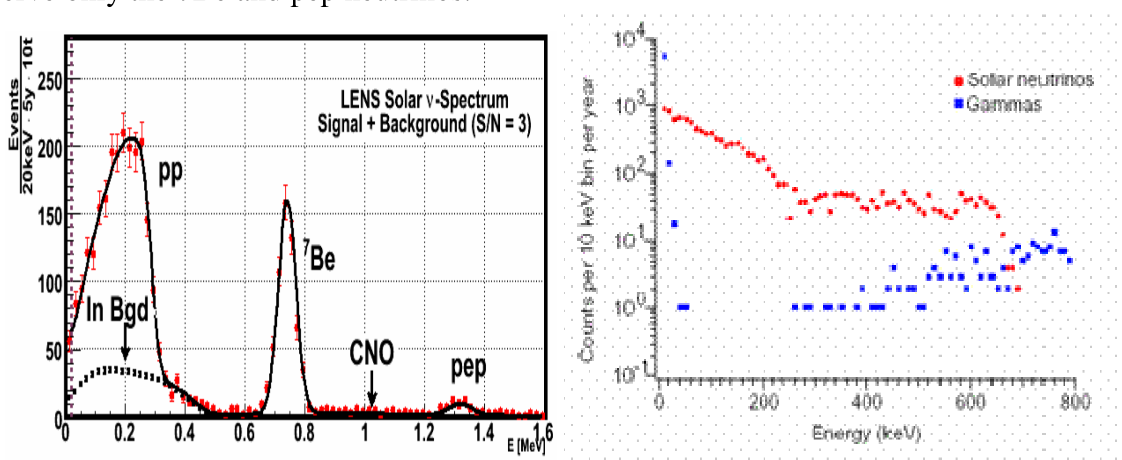

Fig 2: Low energy spectra observable in LENS (left) and CLEAN (right).

The experiments above have all developed powerful technologies and are approaching prototype testing (MINILENS, MINICLEAN in the US; SNO+ (Canada) will use the SNO detector by replacing heavy water (Cerenkov) with a suitable liquid scintillator. As such SNO+ may be the earliest in time-to-science.
All the detectors have major extra-solar objectives: LENS, for sterile neutrino spectroscopy with state of the art MCi radioactive sources, CLEAN, XMASS for WIMP dark matter detection and SNO+ for neutrinoless double beta decay using loaded Xe or Nd.
The detailed technology of LENS is described in several presentations at the recent LONU-LENS workshop and posted in:
http://www.phys.vt.edu/~dusel/low-energy-workshop/