Probing Active to Sterile Neutrino Oscillations in the LENS Detector

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Sterile neutrino (ν) conversion in meter scale baselines can be sensitively probed using mono-energetic, sub-MeV, flavor pure νe’s from an artificial MCi source and the unique technology of the LENS low energy solar νe detector. Active-sterile oscillations can be directly observed in the granular LENS detector itself to critically test and extend results of short baseline accelerator and reactor experiments.

Sterile neutrinos (ν) occur naturally in models of ν mass generation and figure in a variety of contemporary problems of particle physics, astrophysics and cosmology. Evidence for sterile ν’s is thus of high interest, fueled by the LSND experiment that has claimed appearance of νe from a νe beam at a baseline of 30 m. The large Δm2 (~1 eV2) implied by LSND cannot be accommodated by the usual 3 active ν’s with small mass splittings ~10^-3 eV^2. An extended model of 3+1 (mostly sterile) mass eigenstates can explain the LSND effect as Pνe = sin^2θνe = 4U^2 eμ where U are the mixings in the 3+1 model. If so, a complementary probe is νe disappearance in reactor experiments such as Bugey3 that has set limits on Δm^2 and sin^2θνe = 4U^2 eμ (1-U^2 eμ). These limits however, exclude most of the parameter space implied by LSND. The two data do seem more compatible in a model of 3 active +2 sterile states.

The MiniBooNE-νe experiment (νe→νe) will directly test the LSND result (assuming CPT invariance). In the next step it is vital to explicitly observe active→sterile ν oscillations and measure the sterile ν mixing probabilities directly. New tools are needed for this task. In this Letter we show that this can be achieved by the unique technology of LENS (Low Energy Neutrino Spectroscopy detector) and a MCi, sub-MeV mono-energetic flavor-pure νe source. The MCi source technology is well established for the 51Cr source considered here and the LENS technology is ready for testing in a prototype (MINILENS).

The LENS νe detector is based on the charged current (CC) driven νe capture in 115In:

νe + 115In(95.6%) → e + 115Sn* → delay → 2γ + 115Sn

The νe capture leads to an isomeric state in 115Sn at 614 keV which emits a delayed (τ = 4.76 μs) cascade 2γ (= 116+498 keV) that de-excites to the ground state of 115Sn. The reaction threshold is low, Q = 114(4) keV. The νe signal energy, Eν = Ev - Q leads to the incident νe energy. The spectroscopic power of LENS is illustrated in Fig.1 by its expected result on the low energy solar νe spectrum.

The delayed 2γ signal is a powerful tag for the νe capture. The only valid events in LENS are coincidence events, the time distribution of which is shown in Fig. 1 (top panel). An exponential decay fit (with the signature lifetime of 115Sn*) to the time spectrum leads to the true signal events that occur at early delays ~10μs and the background from random coincidences at long delays. This background arises dominantly via random coincidences with β’s from the natural decay of the target 115In with the end point at 498(4) keV. It presents a severe (but soluble) problem for solar pp νe (Ee<300 keV, see Fig.1) but it is far less problematic for Ee>500 keV (e.g. for 7Be solar neutrinos in Fig. 1). The background is, in any case, measured at long delays separately and concurrently. The νe event analysis tests the validity of a candidate tag by the time and space coincidence as well as the detailed template of the 2γ tag shower. This determines the coincidence efficiency, modeled to be ~85% for signals >500 keV (51Cr provides a ~640 keV signal).

The LENS technology thus extends the power of tagged ν detection from the case of broadband νe >1.8 MeV in reactor experiments to monoenergetic sub-MeV νe that lead to explicit, meter scale oscillations detectable in modest sized granular detectors. Most issues in shape analyses of Pνe and systematic normalization errors endemic to reactor ν experiments can thus be avoided in LENS. A νe test allows direct comparison to MiniBooNE (νν) without invoking CPT invariance and with LSND and MiniBooNE (νe) to test CPT invariance.

The detection medium in LENS is a liquid scintillator chemically loaded with indium (InLS). This technology uses a robust, well tested (Bell Labs BNL, LNGS, Virginia Tech) procedure that produces high quality InLS (In loading 8-10 wt%,
scintillation output ~8000 h/MeV and signal light attenuation length L(1/e) of 8 m that is stable for >1 year.\(^6\) InLS with up to 15% In has been produced with promising properties and is currently in development. Anticipating positive results, we consider both 8% and 15% In loading.

The granular LENS detector is based on a novel "scintillation lattice chamber" design.\(^6\) In this design the detector volume is optically segmented by itself, a major first (SAGE/GALLEX are radiochemical activation experiments).

In 3+2 models, with mixing angles and oscillation frequencies in flavor states α, β, γ, τ, s\(_{12}\), mass states n=1-5 where states 4 and 5 are mostly sterile and U\(_{n\alpha}\) are the elements of the ν mixing matrix, the e-flavor survival P\(_{ee}\) is:

\[
P_{ee} = 1 - s_{e4}^2 s_{41}^2 - s_{e5}^2 s_{51}^2\]  

(2)

where cross terms such as s\(_{e4}\)s\(_{41}\)s\(_{e5}\) are neglected. In (2) the mixing terms s\(_{en}\) = sin\(^2\)△m\(_{e\nu}\)(1 - U\(_{e\nu}\)) and the frequencies s\(_{nl}\) = sin\(^2\)(△m\(_{l}\))×L(m)/E\(_{l}\)(MeV)). The values of s\(_{en}\) and △m\(^2\) are from the νe oscillation profile in detail. The result is thus far more transparent than that from usual methods with 2 to 3 static or movable detectors.

Several MCI sources of \(^{51}\)Cr have been produced and used to calibrate the Ga radiochemical solar ν\(_e\) detectors (1.7 MCI in GALLEX\(^X\) and 0.52 MCI in SAGE\(^10\)). (Recently, small inconsistencies in the SAGE ν\(_e\) calibration results has been attributed to sterile ν conversion\(^11\)). Studies show that the production of ~10 MCI \(^{51}\)Cr sources is feasible.\(^12\) The electron-capture decay (τ = 40d) of \(^{51}\)Cr emits a mono-energetic ν\(_e\) of energy 0.753 MeV (90%) which produces a ν\(_e\) signal at 0.639 MeV in LENS. We note that a MCI source experiment for precision calibration of the \(^{11}\)In ν\(_e\) capture cross-section is already part of the LENS program as LENS-CAL.\(^13\)

The source experiment requires a ~4π source-detector geometry for maximum sensitivity. The primary design criterion is then the background arising from hard γ’s of impurity activities in the source (the only γ from \(^{51}\)Cr itself is of energy 0.32 MeV, easily shielded and far below the ν\(_e\) signal energy). The source will be encased in a heavy-metal shielding container to cut down radiation outside the container below permissible safety limits. The SAGE data\(^10\) show that the dominant γ-rays outside the container are from the impurity activity \(^{40}\)Sc (3Ci/MCi \(^{51}\)Cr) of 2 hard γ’s (1.12 and 0.889 MeV). In a ~25cm radius tungsten container this releases ~10\(^7\) γ/s into the detector, <<10\(^6\)/s, the benchmark rate of \(^{11}\)In β’s that underlies all random coincidence background considerations in LENS\(^5\). Thus, a 10 MCI \(^{51}\)Cr source in a ~50 cm diameter heavy-metal sphere at the center of the LENS detector is a viable concept with state-of-the-art technology.

The ν\(_e\) spectroscopy of \(^{51}\)Cr (4x100 day exposure to a 10 MCI source) in a full scale LENS detector is shown in the bottom panel of Fig. 1 (notice the log scale). The Cr signal (~13300 events) is ~1000 times the solar "background". An internal MCi \(^{51}\)Cr source in a ~50 cm diameter heavy-metal sphere at the center of the LENS detector is a viable concept with state-of-the-art technology.
Fig. 2 Analysis of 3+1 and 3+2 models of sterile neutrinos in LENS. [In 10T = 8% In LENS-So (A); In 5\text{t}=15\% In LENS-STERILE (B); Cr=4MCi×100 d exposure to $^{51}$Cr; Fe=2y×10MCi exposure to $^{55}$Fe]

Table 1. Active-Sterile splittings and mixing parameters compatible with LSND and BUGEY (Ref. 4) with $\Delta m^2=1\, \text{eV}^2$ and $\text{E}_\nu=0.753\, \text{MeV}$. (from $^{51}$Cr), (2) full flavor recovery occurs in ~2m, directly observable in a lab-scale detector.

We consider two detector configurations, A and B (Table 2), based on the lattice array design with 7.5×7.5×7.5 cm cells. Design A is the full scale solar detector (LENS-Sol 8% In). The smaller detector B, anticipates further development of a higher density (15% In) InLS to exploit the linear dependence of the event rate with In density. It is thus specific for sterile $\nu$ search and costs ~50% less than A. With comparable (density x In mass), the event rate is comparable for a source assembly at the center of A or B in a 50 cm spherical volume.

The sensitivity of radial distributions of events in designs A and B to sterile $\nu$ oscillation parameters was analyzed by a Monte Carlo technique. The number of $v_e$ detected, $N_0$ is calculated for each cubic cell element $i$ of the detector assuming no oscillations. Then, assuming an oscillation model of (3+1) or (3+2) with parameters ($\Delta m^2$, $\sin^2 2\theta$) or ($\Delta m^2$, $\sin^2 2\theta_1$; $\Delta m^2$, $\sin^2 2\theta_2$) the number of $v_e$ detected in each cell $N_i$ is calculated. The cells are then grouped into bins $k$ according to their distance $d$, from the source. A random sample data set for one "experiment" is created under the oscillation assumption. Then the theoretical event ratio as a function of $d$, $N_i/N_0$ is fitted to the sample data set with the oscillation parameters as free parameters. The process is repeated~10$^6$ times with random data sets and each resulting set of fitted parameters ($\sin^2 2\theta$, $\Delta m^2$) is stored. The distribution of these values (see Fig. 2) is a direct measure of the statistical uncertainty of ($\sin^2 2\theta$, $\Delta m^2$) in a single measurement.

The models in Table 1 predict 2 main effects: 1) the minimum oscillation amplitude of ~5% occurs with a single frequency for 3+1 and (practically also in 3+2a); 2) two frequencies occur in 3+2b. In the analysis, we test designs A and B for 1) a single frequency and 2) double frequency as in 3+2b. Figs. 2a,b for design A (full scale solar detector) show that a 5% single frequency oscillation (3+1, 3+2a) as well as the double frequency oscillation for 3+2b can be clearly observed with 4x100 day exposure to a 10 MCi $^{51}$Cr source. The mixing parameter $\sin^2 2\theta$ can be determined with 1σ precision of 25% in both cases. In the smaller detector B the lower of the double frequency is not picked up with Cr because the radial dimension of B is insufficient to catch the $P_{ee}$ recovery. In this case, another source, $^{55}$Fe with $\text{E}_\nu=236\, \text{keV}$, can be used. A ~2-year exposure to a 10 MCi Fe source ($\tau = 3.8\, \text{y}$) (Fig. 2d), shows excellent resolution of the double frequency effect. A MCi Fe source has not been produced so far, thus, this technology awaits ab initio development.

<table>
<thead>
<tr>
<th>Model</th>
<th>$\Delta m^2$ eV$^2$</th>
<th>$U^2$</th>
<th>$4U^2(1-U^2) = \sin^2 2\theta_{ee}$</th>
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<tbody>
<tr>
<td>3+1</td>
<td>0.9214</td>
<td>0.05-0.08</td>
<td></td>
</tr>
<tr>
<td>3+2a</td>
<td>22.14</td>
<td>0.0013</td>
<td>0.005</td>
</tr>
<tr>
<td>3+2b</td>
<td>0.9215</td>
<td>0.0146</td>
<td>0.057</td>
</tr>
<tr>
<td>3+2c</td>
<td>0.4614</td>
<td>0.0081</td>
<td>0.032</td>
</tr>
<tr>
<td>3+2d</td>
<td>0.8915</td>
<td>0.0156</td>
<td>0.062</td>
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Fig. 3 shows the exclusion plots of $\Delta m^2$ vs $\sin^22\theta_{ee}$ for 90% c.l. sensitivity to oscillations in the designs A and B compared to those from BUGEY, LSND and MiniBooNE. The latter two assume an equivalent mixing ($U_{e4}=U_{\mu 4}$) thus, $\sin^22\theta_{ee}(\text{LENS, Bugey}) \approx [\sin^22\theta_{\mu e}(\text{LSND, MiniBooNE})]^{1/2}$. Fig. 4 shows that, indeed, a relatively modest 3MCi source of $^{51}$Cr is sufficient to reach the projected oscillation sensitivity of MiniBooNE.

These analyses show that the LENS approach in A or B can exclude parameter regions of active-sterile oscillations significantly beyond those suggested by BUGEY, LSND and MiniBooNE. Further, the LENS approach is complementary to the proposed NC-based $\nu_e$ disappearance test which is sensitive to $\sin^22\theta_{\mu e}$. In summary, the LENS technology offers a novel attack for discovery of active-sterile oscillations with sensitivities well beyond those in LSND, MiniBooNE and BUGEY. Design B offers the opportunity to accomplish these goals in a relatively modest detector that can map the full oscillation as a function of radius. However, R&D on the high density InLS needs to be completed and the technology of the Fe source developed ab initio. The straightforward approach would use the full scale LENS detector, design A, for which the Cr source and detector technologies are already well developed. The next step in the latter is the construction and operational tests of the prototype detector MINILENS which is now being initiated.

We thank members of the Virginia Tech neutrino group for helpful discussions.

Table 2. Design options for LENS sterile $\nu$ search

<table>
<thead>
<tr>
<th></th>
<th>Indium Density wt.%</th>
<th>Det. Dim. m</th>
<th>Indium Mass Tons</th>
<th>Total Mass Tons</th>
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<tbody>
<tr>
<td>A.(LENS-Sol)</td>
<td>8</td>
<td>5.1</td>
<td>9.9</td>
<td>125</td>
</tr>
<tr>
<td>B.(LENS-Sterile)</td>
<td>15</td>
<td>3.3</td>
<td>5.1</td>
<td>34</td>
</tr>
</tbody>
</table>

5. A. O. Bazarko [BooNe Collaboration] hep-ex/9906003
6. Detailed information on LENS technology can be found in several presentations made in the recent workshop LONU-LENS (Virginia Tech) and posted at http://www.phys.vt.edu/~dusel/low-energy-workshop/
13. See talk on LENS-CAL in ref. 6. The B(GT) matrix element needed to evaluate the cross-section has already been measured by (p,n) based on the strong interaction, as $B(GT) = 0.17 \pm 10\%$. LENS Cal will measure B(GT) directly using a $\nu_e$ source with a precision of a few %.