Probing active to sterile neutrino oscillations in the LENS detector

C. Grieb, J. M. Link, and R. S. Raghavan

Institute of Particle, Nuclear and Astronomical Sciences, Virginia Polytechnic Institute and State University,
Blacksburg, Virginia 24061, USA
(Received 24 December 2006; published 15 May 2007)

Sterile neutrino (ν_s) conversion in meter scale baselines can be sensitively probed using monoenergetic, sub-MeV, flavor-pure ν_e's from an artificial Megacurie source and the unique technology of the LENS low energy solar ν_e 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 occur naturally in models of ν mass generation and figure in a variety of contemporary problems of particle physics, astrophysics, and cosmology [1]. Evidence for sterile ν's is thus of high interest, fueled by the LSND experiment [2] that has claimed *appearance* of $\bar{\nu}_e$ from a $\bar{\nu}_\mu$ beam at a baseline of 30 m. The large Δm^2 (~ 1 eV^2) implied by LSND cannot be accommodated by the usual 3 active ν's with small mass splittings 10^{-5} to 10^{-3} eV^2. An extended model of $3 + 1$ mass eigenstates can explain the LSND effect as $P_{\mu e} = \sin^2 2\theta_{\mu e} = 4U_{e4}^2 U_{\mu 4}^2$ where $U_{\alpha 4}$ are the mixing matrix elements with the fourth (mostly sterile) mass state in the $3 + 1$ model. If so, a complementary probe is $\bar{\nu}_e$ *disappearance* in reactor experiments, such as BUGEY [3], that have set limits on Δm^2 and $\sin^2 2\theta_{ee} = 4U_{e4}^2(1 - U_{e4}^2)$. These limits, however, exclude most of the parameter space implied by LSND [4]. The two results do seem more compatible in a model of 3 active $+2$ sterile states [4].

The MiniBooNE-ν_μ experiment [5] ($\nu_\mu \to \nu_e$) will directly test the LSND result (assuming *CPT* invariance). In the next step it is vital to *explicitly* observe active to sterile ν oscillations and measure the sterile ν mixing probabilities directly. In addition, light sterile ν's, even with potentially smaller mixing angles than LSND, can fix problems with r-process nucleosynthesis in supernovae [6], so it is important to push beyond LSND regardless of what MiniBooNE finds. New tools are needed for these tasks. In this paper we show that these objectives can be achieved by the unique technology of LENS (low energy neutrino spectroscopy detector) [7] and a Megacurie (MCi), sub-MeV, monoenergetic, flavor-pure ν_e source. The MCi source technology is well established for the ^{51}Cr source considered here and the LENS technology is ready for testing in a prototype (MINILENS).

The LENS ν_e detector is based on the charged current (CC) driven ν_e capture in ^{115}In [8]:

$$\nu_e + {}^{115}\text{In}(95.6\%) \to {}^{115}\text{Sn}^* + e^-$$

$$\hookrightarrow {}^{115}\text{Sn} + 2\gamma. \tag{1}$$
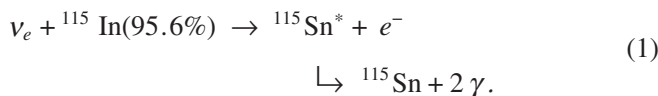
The ν_e capture leads to an isomeric state in ^{115}Sn at 614 keV which emits a delayed ($\tau = 4.76$ μs) cascade

2γ ($= 116 + 498$ keV) that deexcites to the ground state of ^{115}Sn. The reaction threshold is low, $Q = 114(4)$ keV. The ν_e signal energy, $E_e = E_\nu - Q$, leads to the incident ν_e energy. The spectroscopic power of LENS is illustrated in Fig. 1 by its expected result on the low energy solar ν_e spectrum.

The delayed 2γ signal is a powerful tag for the ν_e capture. The only valid events in LENS are *coincidence*
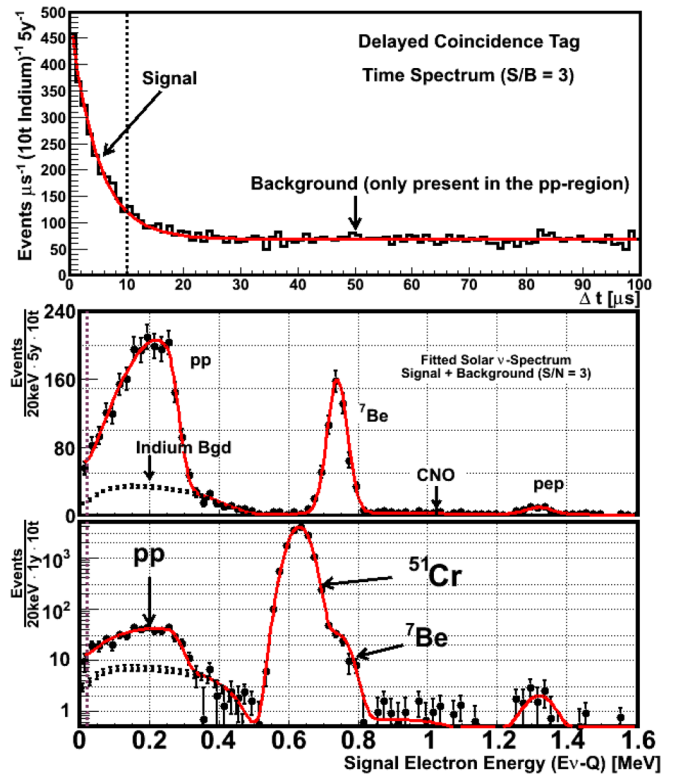

FIG. 1 (color online).   Simulated 5-year solar ν_e signal spectra in LENS. Top panel: delayed coincidence time spectrum fitted to the isomeric lifetime $\tau = 4.76$ μs. Middle panel: energy spectrum (with $\sim$2000 pp events) at delays <10 μs, and random coincidences (from the pure β decay of In target) at long delays. Bottom panel: Spectrum from 4×100 day exposure to a 10 MCi source of ^{51}Cr with the scaled solar spectrum included. The Cr signal has 1.3×10^4 events with $\sim$0.1% background (from the ^{7}Be line).

events, the time distribution of which is shown in Fig. 1 (top panel). An exponential decay fit (with the signature lifetime of $^{115}Sn^*$) to the time spectrum leads to the true signal events that occur at early delays $\sim 10~\mu$s 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 ^{115}In with the end point at 498(4) keV. It presents a severe (but soluble) problem for solar pp ν_e ($E_e < 300$ keV, see Fig. 1) but it is far less problematic for $E_e > 500$ keV (e.g. for ^{7}Be solar neutrinos in Fig. 1). The background is, in any case, *measured* at long delays separately and concurrently. The ν_e 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 (^{51}Cr provides a $\sim$640 keV signal).

The LENS technology thus extends the power of tagged ν detection from the case of a broadband $\bar{\nu}_e$ beam with $E_\nu > 1.8$ MeV in reactor experiments to monoenergetic *sub-MeV* ν_e beams that lead to explicit, meter scale oscillations directly detectable in modest sized granular detectors. Most issues in shape analyses of P_{ee} and systematic normalization errors endemic to reactor ν experiments are thus avoided in LENS. A ν_e disappearance search allows for a direct comparison to MiniBooNE (ν_μ) without invoking *CPT* invariance and to LSND and MiniBooNE ($\bar{\nu}_\mu$) as a *test* of *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 [9], BNL, LNGS, Virginia Tech) procedure that produces high quality InLS [In loading 8–10 wt.%, scintillation output $\sim$8000 hν/MeV and signal light attenuation length L(1/e) of 8 m that is stable for >1 year] [7]. 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 [7]. In this design the detector volume is optically segmented into cubic cells ($7.5 \times 7.5 \times 7.5$ cm) by a 3-dimensional cage of thin ($\sim$ 0.1 mm), double layered, transparent foils which provide an air gap between the foils (even in contact under pressure of $\sim$2 bars). The scintillation light is then channeled only along 3 coordinate axes centered on the vertex cell of the event. Coincident hits on phototubes at the end of the channels *digitally* determine the 3-D location of the event to a precision set by the cell size. Each cell is always viewed by the same combination of 6 or less phototubes. Thus LENS is, in effect, a 3-D array of 10^5 nuclear counters with benchtop sensitivity. The spherical ν_e oscillation wave can then be observed by the radial variation $P_{ee}(R)$ of ν_e from a source placed at the center of the detector. The LENS experiment thus uses 10^5 detectors to

trace the ν_e oscillation profile in detail. The result is thus far more transparent than that from usual methods with 2 to 3 static or movable detectors. As in the reactor experiment theoretical uncertainties due to the ν cross section are common to all "detectors" and thus cancel. In addition, the uncertainty from indium concentration cancels, or at least should average out because the scintillator volume is fully connected, and detection efficiency can be made flat across the detector because the monoenergetic signal allows triggering thresholds to be set to tune out any instability.

Several MCi sources of ^{51}Cr have been produced and used to calibrate the Ga radio-chemical solar ν_e detectors (1.7 MCi in GALLEX [10,11] and 0.52 MCi in SAGE [12,13]). (Recently, small inconsistencies in the SAGE ν_e calibration results have been attributed to sterile ν conversion [14]). Studies show that the production of $\sim$10 MCi ^{51}Cr sources is feasible. The electron-capture decay ($\tau = 40$ d) of ^{51}Cr emits a monoenergetic 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 ^{115}In ν_e capture cross section is already part of the LENS program as LENS-CAL [15].

The source experiment requires a $\sim 4\pi$ 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 [12] show that the dominant γ rays outside the container are from the impurity activity ^{46}Sc (3 Ci/MCi ^{51}Cr) of 2 hard γ's (1.12 and 0.889 MeV). In a $\sim$25 cm radius tungsten container this releases $\sim 10^3~\gamma$/s into the detector, $\ll 10^6$/s, the benchmark rate of ^{115}In β's that underlies all random coincidence background considerations in LENS [7]. Thus, a 10 MCi ^{51}Cr source in a $\sim$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 (4×100 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 ($\sim$ 13 300 events) is $\sim$1000 times the solar "background." An internal MCi source in a real-time rare event counting detector is, by itself, a major first (SAGE/GALLEX are radio-chemical activation experiments).

In 3 + 2 models, with flavor states e, μ, τ, s_1 and s_2 and mass eigenstates 1–5 where states 4 and 5 are mostly sterile, the e-flavor survival probability, P_{ee}, is

$$P_{ee} \simeq 1 - 4U_{e4}^2(1 - U_{e4}^2)\sin^2 x_{41} - 4U_{e5}^2(1 - U_{e5}^2)\sin^2 x_{51},$$

(2)

TABLE I.   Active-sterile splittings and mixing parameters compatible with LSND and the null short baseline data [4], as used in the analyses shown in Fig. 2.

Model	Δm_{ij}^2 (eV^2)	U^2	$\sin^2 2\theta_{ee} = 4U^2(1 - U^2)$
3 + 1	0.92_{14}	0.0185	0.073
3 + 2a	0.92_{14}	0.0146	0.057
	22.1_{15}	0.0013	0.005
3 + 2b	0.46_{14}	0.0081	0.032
	0.89_{15}	0.0156	0.062

TABLE II.   Design options for LENS-sterile ν search.

Configuration	ρ_{In} (wt. %)	d_{detector} (meters)	m_{In} (tons)	m_{total} (tons)
A—LENS-Sol	8	5.1	9.9	125
B—LENS-Sterile	15	3.3	5.1	34

where $U_{\alpha n}$ is the element of the ν mixing matrix relating flavor state α to mass state n, $x_{ij} = 1.27\Delta m_{ij}^2(\text{eV}^2)L(\text{m})/E_\nu(\text{MeV})$, and cross terms such as $U_{e4}^2 U_{e5}^2$ are neglected. The values of U_{ei} and Δm^2 (shown in Table I) are from Ref. [4]. With $\Delta m^2 = 1$ eV and $E_\nu \sim 0.753$ MeV (from ^{51}Cr), full flavor recovery occurs in ~ 2 m, directly observable in a lab-scale detector.

We consider two detector configurations, **A** and **B** (Table II), based on the lattice array design with $7.5 \times 7.5 \times 7.5$ 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 ν search and costs $\sim 50\%$ less than **A**. With a source located at the center of the detector, configuration **B** has an event rate comparable

to **A**, in spite of the fact that it is smaller, because a greater number of In targets are present close to the source where the ν flux is higher.

The sensitivity of radial distributions of events in designs **A** and **B** to sterile ν oscillation parameters was analyzed by a Monte Carlo technique. The number of ν_e detected, N_{0i}, 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 $(\Delta m_1^2, \sin^2 2\theta_1; \Delta m_2^2, \sin^2 2\theta_2)$, the number of ν_e detected in each cell, N_i, is calculated. The cells are then grouped into k bins according to their distance, d_i, 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, $N_i/N_{0i} = f(\sin^2 2\theta, \Delta m^2, d)$, is fitted to the sample data set with the
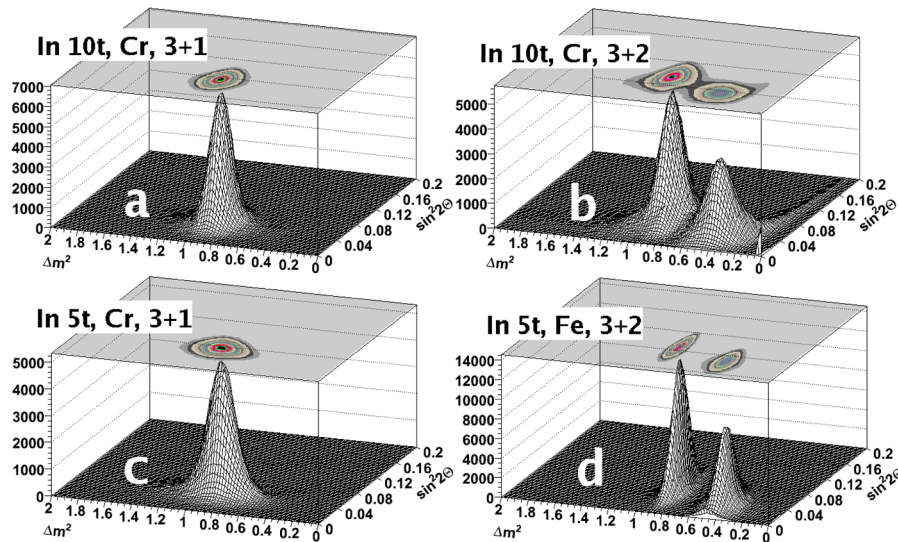
FIG. 2 (color online).   Analysis of sterile neutrino mixing for (a) LENS-Sol with $3 + 1$ mixing and a ^{51}Cr source, (b) LENS-Sol with $3 + 2$ mixing and a Cr source, (c) LENS-Sterile with $3 + 1$ mixing and a Cr source, and (d) LENS-Sterile with $3 + 2$ mixing and a ^{55}Fe source.
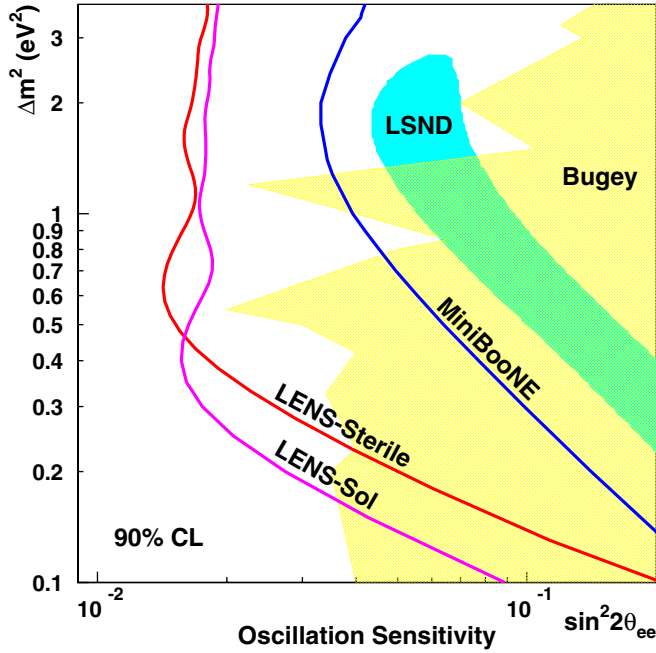
FIG. 3 (color online). Exclusion plots of sensitivity to active-sterile oscillations in LENS (with 4×100 day exposure to 10 MCi Cr source) compared to those for LSND, BUGEY, and the projected sensitivity of MiniBooNE [17]. LSND and MiniBooNE are plotted assuming the best fit U_{e4} and $U_{\mu 4}$ from Ref [4].

oscillation parameters as free parameters. The process is repeated 10^6 times with random data sets, and each resulting set of fitted parameters $(\sin^2 2\theta, \Delta m^2)_i$ 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 I 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 $3 + 2b$. Figures 2(a) and 2(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 4×100 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
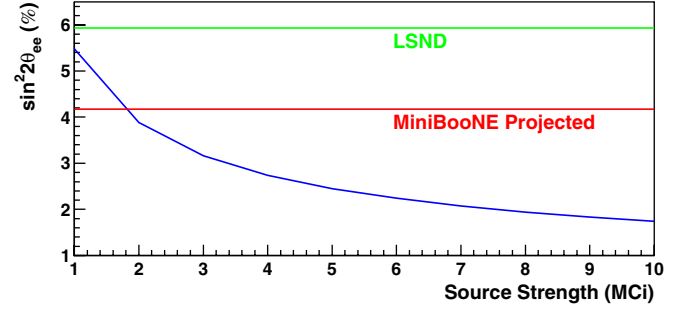

FIG. 4 (color online). Sensitivity to sterile oscillations vs ^{51}Cr source strength. The projected MiniBooNE sensitivity can be achieved with a source of less than 2 MCi.

$E_\nu = 236$ keV, can be used. A 2-year exposure to a 10 MCi Fe source $(\tau = 3.8$ y) [Fig. 2(d)] 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.

Figure 3 shows the exclusion plots of Δm^2 vs $\sin^2 2\theta_{ee}$ for 90% confidence level sensitivity to oscillations in the designs **A** and **B** compared to those from BUGEY, LSND, and MiniBooNE. Figure 4 shows that, indeed, a relatively modest 3 MCi 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 of BUGEY, LSND, and MiniBooNE. Further, the LENS approach is complementary to the proposed NC-based ν_μ disappearance test which is sensitive to $\sin^2 2\theta_{\mu\mu}$ [16].

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 this approach is the construction and operational testing of a prototype detector, MINILENS, which has not been initiated.

We thank Bruce Vogelaar, Mark Pitt, and the other members of the Virginia Tech particle and nuclear group for helpful discussions.

[1] A. Kusenko, arXiv:hep-ph/0609158.
[2] C. Athanassopoulos *et al.* (LSND), Phys. Rev. Lett. **75,** 2650 (1995).
[3] Y. Declais *et al.* (Bugey), Nucl. Phys. **B434,** 503 (1995).

[4] M. Sorel, J. M. Conrad, and M. Shaevitz, Phys. Rev. D **70**, 073004 (2004).

[5] A. O. Bazarko (BooNE), arXiv:hep-ex/9906003.

[6] G. C. McLaughlin, J. M. Fetter, A. B. Balantekin, and G. M. Fuller, Phys. Rev. C **59**, 2873 (1999).

[7] 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/.

[8] R. S. Raghavan, Phys. Rev. Lett. **37**, 259 (1976).

[9] E. C. Chandross and R. S. Raghavan, U.S. Patent No. 6809210, 2004.

[10] M. Cribier *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **378**, 233 (1996).

[11] W. Hampel *et al.* (GALLEX), Phys. Lett. B **420**, 114 (1998).

[12] D. N. Abdurashitov *et al.*, Phys. Rev. Lett. **77**, 4708 (1996).

[13] J. N. Abdurashitov *et al.* (SAGE), Phys. Rev. Lett. **83**, 4686 (1999).

[14] C. Giunti and M. Laveder, arXiv:hep-ph/0610352.

[15] See talk on LENS-CAL in Ref. [7]. The B(GT) matrix element needed to evaluate the cross section has been measured by (p, n), based on strong interactions, to be $0.17 \pm 10\%$. Lens-Cal will measure B(GT) directly using a ν_e source with a precision of a few percent.

[16] G. T. Garvey *et al.*, Phys. Rev. D **72**, 092001 (2005).

[17] A. A. Aguilar-Arevalo *et al.* (MiniBooNE), http://www-boone.fnal.gov/publicpages/runplan.ps.gz (2003).