LSND reloaded

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In view of the recent result from the anti-neutrino run of MiniBooNE, we suggest to repeat the original Liquid Scintillator Neutrino Detector (LSND) experiment using Super-Kamiokande, doped with Gadolinium, as detector. Due to the more than 100 times larger detector mass offered by Super-Kamiokande, the neutrino source requires a proton beam power of less than 300 kW at a proton energy around a 1 GeV. A one year run of this setup can corroborate or refute both the LSND and MiniBooNE claims at more than 5σ confidence level. If a signal is observed, the large size of Super-Kamiokande combined with its good ability to determine the position of an anti-neutrino event allows to establish the characteristic L/E-dependence of oscillation.

The LSND experiment [1–3] has reported a 3.8σ excess of \( \bar{\nu}_e \) events in a beam of \( \bar{\nu}_\mu \) and recently the MiniBooNE experiment has reported a 2.8σ excess [4] of \( \bar{\nu}_e \) events in a beam of \( \bar{\nu}_\mu \), albeit at a much higher neutrino energy and at a much longer distance. If one interprets these results with neutrino oscillation the relevant parameter is the ratio of the distance \( L \) to the neutrino energy \( E \), the so called \( L/E \). The \( L/E \) ratio is indeed very similar between LSND and MiniBooNE. The oscillation interpretation of LSND and MiniBooNE points to a mass squared difference of the order 0.1 – 10\( \text{eV}^2 \) and hence requires a sterile neutrino. While a sterile neutrino is theoretically well motivated, the actual oscillation parameters required by the LSND and MiniBooNE results are in considerable tension with the non-observation of oscillation in a number of short baseline disappearance experiments, most notably CDHS [5] and Bugey [6]. Also atmospheric and solar neutrino data show no sign of a sterile neutrino in the required parameter range. For a recent summary of the status of the oscillation interpretation of LSND, and by association also of the recent MiniBooNE result, in the context of all neutrino data, see the review [7].

MiniBooNE was designed to be the final test of the oscillation interpretation of LSND; since MiniBooNE operates at a very different energy and baseline, only the ratio \( L/E \) is similar to LSND and hence non-oscillation explanations of LSND can not be tested effectively. So far, MiniBooNE has provided us with the following results:

1. No oscillation in the neutrino mode for energies above 475 MeV [8]
2. An unexplained 3σ excess of \( \nu_e \) events in the neutrino mode below 475 MeV [9]
3. A 2.8σ excess of \( \bar{\nu}_e \) events in the anti-neutrino mode above 475 MeV, which is consistent with LSND [8].

In summary, MiniBooNE is not conclusive with respect to the LSND result and it seems unlikely that a simple increase in statistics would resolve the issue. Therefore, the question arises how to address this problem. One possibility is to repeat an LSND-like experiment with a pulsed neutrino source [10], which requires to build a new liquid scintillator detector. In reference [11] it has been proposed to study the spatial dependence of the \( \nu_e \) disappearance probability inside one detector using a radioactive source and in reference [12] the same idea was pursued using a beta-beam anti-neutrino source.

In this letter we suggest to perform a modern version of LSND, i.e. use \( \bar{\nu}_\mu \) from a stopped pion source and inverse beta decay to detect the appearance of \( \bar{\nu}_e \). The main difference with respect to the original LSND experiment is that we suggest to use Super-Kamiokande doped with Gadolinium as detector [13] [14] instead of a liquid scintillator detector. Super-Kamiokande has a fiducial mass of 22.5 kt compared to around 120 t in LSND. Gadolinium doping allows to efficiently detect the capture of the neutron which is produced in inverse beta decay. We take 67% as detection efficiency which has been obtained from direct tests inside the Super-Kamiokande detector [14] [15]. Furthermore, we use an energy resolution as given in reference [16] and an energy threshold of 20 MeV. Using a detector like Super-Kamiokande has several advantages. First, the large fiducial mass allows to use a relatively low power proton source. If we take the same proton source parameters as in reference [17] [18] it turns out that \( 4 \times 10^{21} \) neutrino per year are sufficient, which translates into a proton beam power of only 300 kW. The contamination with \( \bar{\nu}_e \) from \( \pi^- \) decays is very small and we take a value of \( 4 \times 10^{-4} \) [17] [18]. The neutrino source will be located on the axis of the cylinder which describes the fiducial volume and will be 20 m away from the first cylinder surface. The resulting signal event rates for one year of operation are shown in table I and the background event rate due to beam contamination is 765. Secondly, the large rock overbur-

| \( \Delta m^2 [\text{eV}^2] \) | 0.1 | 1 | 10 | 100 |
| --- | --- | --- | --- | --- |
| signal | 29 | 1605 | 1232 | 1314 |

**TABLE I:** Number of signal events after one year for \( \sin^2 2\theta = 10^{-3} \) including efficiency and energy resolution.
FIG. 1: The signal event rate after one year weighted with \( L^2 \) as function of the reconstructed baseline divided by reconstructed neutrino energy \( L/E \), shown as solid line. The dashed line shows the background weighted with \( L^2 \). The error bars show the statistical errors only. The oscillation signal is computed for \( \sin^2 2\theta = 10^{-3} \) and \( \Delta m^2 = 2 \text{ eV}^2 \).

LSND, reduces cosmic ray induced backgrounds to negligible levels \([17, 18]\). Also, atmospheric neutrino backgrounds are small compared to the beam induced backgrounds. Thirdly, the large dimensions of the fiducial volume, a cylinder of 14 m radius with a height of 36 m allow to observe the characteristic baseline dependence of oscillation with great accuracy. The size of the copper beam stop used in LSND was about 50 cm \([19]\) and the position resolution for electrons (or positrons) in Super-Kamiokande at energies above 10 MeV has been measured to be better than 75 cm \([20]\). Adding these two sources of baseline uncertainty in quadrature we obtain about 0.9 m. In our analysis we account for this uncertainty by using a baseline resolution width\(^1\) of 1 m. We also checked that our results hardly change for a baseline resolution of 2 m. In order to be able to perform an \( L/E \) analysis we account for an energy resolution \([16]\). Thus, with a source detector distance of 20 m and an energy range from 20 – 52 MeV the oscillation pattern can be observed for an \( L/E \) range of 0.4 – 2.8 m MeV\(^{-1}\). This is illustrated in figure \([\mathbb{1}]\), where we show the signal and background rates weighted with \( L^2 \) as a function of \( L/E \). The signal is shown in red and the background in black.

\(^1\) Obviously, in an actual experiment one would include the actual vertex resolution function and distribution of pion decays.

The reason, that we do not see a simple sine square wave is that the exposure in \( L/E \) is non-uniform, even after rescaling with \( L^2 \). The oscillation signal is computed using the usual 2 flavor expression with \( \sin^2 2\theta = 10^{-3} \) and \( \Delta m^2 = 2 \text{ eV}^2 \). Obviously, the \( L/E \) dependence is a powerful handle to reject the background and therefore our results are quite insensitive to systematic errors. The ability to study the \( L/E \) dependence in detail is crucial if a signal is observed, since it will allow to establish or refute oscillation as the underlying physical mechanism. Note, that the this kind of experiment is possible at any large Water Cerenkov detector and a very similar configuration, although for a different purpose, has been studied for the detector of the Long Baseline Neutrino Experiment (LBNE) in reference \([21]\).

For our sensitivity calculation, we take systematic errors of 5% on both the signal and the background, which are not correlated between signal and background. They are included using the pull method as described in \( e.g. \) reference \([22]\). We bin our data into 38 equally size \( L/E \) bins in the range of 0.4 – 2.8 m MeV\(^{-1}\). We perform the usual \( \chi^2 \) analysis using a Poissonian likelihood function. Ideally, one would perform a 2 dimensional binning in both \( L \) and \( E \), however the resulting increase in sensitivity would be small since the energy spread of the beam is relatively small compared to the variation in \( L \). In figure \([\mathbb{2}]\) we show sensitivity for the \( L/E \) binning analysis.
at $5\sigma$ confidence level (2 degrees of freedom) as well as the 99% confidence level allowed regions obtained from LSND and the MiniBooNE anti-neutrino run [4]. Note, that the sensitivity is limited by the magnitude of the beam background and neither increasing the neutrino luminosity or running time will yield large improvements. Therefore, our choice of $4 \times 10^{21}$ neutrinos at the source is quite optimal.

The experiment we study in this letter can test the LSND and MiniBooNE claims for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with more than $5\sigma$ significance within one year of running time. The effort appears moderate: Super-Kamiokande needs to be doped with Gadolinium and a 300 kW, low energy proton accelerator has to be installed close to Super-Kamiokande. This setup can provide a stringent test of previous results due to its high statistics, low background and the ability to study the baseline dependence in detail. The baseline dependence also may provide a clue to the underlying physics in non-oscillation scenarios, which are favored by global neutrino data [5].

The neutrino production and detection reactions are the same as in LSND and therefore this experiment will be able to return the final verdict on LSND irrespective of the underlying flavor transition mechanism.

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[1] C. Athanassopoulos et al. (LSND), Phys. Rev. Lett. 75, 2650 (1995), nucl-ex/9504002.
[2] C. Athanassopoulos et al. (LSND), Phys. Rev. C58, 2489 (1998), nucl-ex/9706006.
[3] A. Aguilar et al. (LSND), Phys. Rev. D64, 112007 (2001), hep-ex/0104049.
[4] A. A. Aguilar-Arevalo et al. (The MiniBooNE) (2010), 1007.1150.
[5] F. Dydk et al., Phys. Lett. B134, 281 (1984).
[6] Y. Declais et al., Nucl. Phys. B434, 503 (1995).
[7] M. Maltoni and T. Schwetz, Phys. Rev. D76, 093005 (2007), 0705.0107.
[8] A. A. Aguilar-Arevalo et al. (The MiniBooNE), Phys. Rev. Lett. 98, 231801 (2007), 0704.1500.
[9] A. A. Aguilar-Arevalo et al. (MiniBooNE), Phys. Rev. Lett. 102, 101802 (2009), 0812.2243.
[10] G. T. Garvey et al., Phys. Rev. D72, 092001 (2005), hep-ph/0501013.
[11] C. Grieb, J. Link and R. S. Raghavan, Phys. Rev. D75, 093006 (2007), hep-ph/0611178.
[12] S. K. Agarwalla, P. Huber and J. M. Link, JHEP 01, 071 (2010), 0907.3145.
[13] J. F. Beacom and M. R. Vagins, Phys. Rev. Lett. 93, 171101 (2004), hep-ph/0309300.
[14] H. Watanabe et al. (Super-Kamiokande) (2008), 0811.0735.
[15] S. Dazeley, A. Bernstein, N. S. Bowden, and R. Svoboda, Nucl. Instrum. Meth. A607, 616 (2009), 0808.0219.
[16] J. P. Cravens et al. (Super-Kamiokande), Phys. Rev. D78, 032002 (2008), 0803.4312.
[17] J. M. Conrad and M. H. Shaevitz, Phys. Rev. Lett. 104, 141802 (2010), 0912.4079.
[18] J. Alonso et al. (2010), 1006.0260.
[19] C. Athanassopoulos et al. (LSND), Nucl. Instrum. Meth. A388, 149 (1997), nucl-ex/9605002.
[20] M. Nakahata et al. (Super-Kamiokande), Nucl. Instrum. Meth. A421, 113 (1999), hep-ex/9807027.
[21] S. K. Agarwalla and P. Huber (2010), 1005.1254.
[22] P. Huber, M. Lindner, and W. Winter, Nucl. Phys. B645, 3 (2002), hep-ph/0204352.