New approach to anti-neutrino from muon decay at rest

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Neutrino physics is going through a very exciting phase. In last one and half years, crucial informations have been provided by both short and long baseline neutrino oscillation experiments. At short-baseline, recent neutrino oscillation studies seem to point towards the existence of active-sterile mixing. On the other hand at long-basline, recent T2K and MINOS data are in favor of non-zero θ_{13} opening up the possibility of observing CP-violation in the lepton sector. A stopped pion source provides neutrino beams with energy of a few tens of MeV from pion and muon decay-at-rest. A rich physics program can be accomplished with such a neutrino source. We discuss the role of such a neutrino facility to test short-baseline anomalies and to study CP violation in active neutrinos.

1 Introduction

Neutrino physics is now all set to move into the precision regime, with the emphasis now shifting to detailed knowledge of the structure of the neutrino mass matrix, accurate reconstruction of which would unravel the underlying new physics that gives rise to neutrino mass and mixing. In last couple of years, we are blessed with fantastic data which have been provided by both short and long baseline neutrino oscillation experiments.

Recent results from short-baseline (SBL) neutrino oscillation studies seem to point towards the existence of active-sterile mixing. The MiniBooNE experiment has reported an apparent excess of $\bar{\nu}_e$ events in a beam of $\bar{\nu}_\mu$ above $475\,\mathrm{MeV}$ [1] which is consistent with two-neutrino $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations at 99.4% confidence level. This result supports the claim of the LSND experiment [2;3], which has reported a $3.8\,\sigma$ excess of $\bar{\nu}_e$ events in a beam of $\bar{\nu}_\mu$. 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

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difference of the order $0.1-10\,\mathrm{eV}^2$ and hence requires a sterile neutrino. More motivation has been provoked from a recent reanalysis of the expected $\bar{\nu}_e$ flux emitted from nuclear reactors[4] that leads to an observed deficit of $\bar{\nu}_e$ at 98.6% C.L.. The overall reduction in predicted flux compared to the existing data from SBL neutrino experiments can be interpreted as oscillations at baselines of order 10–100 m[5] consistent with the LSND and MiniBooNE anti-neutrino results.

In the month of June, 2011, new exciting results have been announced by the T2K and MINOS long-baseline (LBL) accelerator neutrino oscillation experiments which are sensitive to θ_{13} driven $\nu_\mu \to \nu_e$ appearance channel. The T2K experiment in Japan has reported an indication of electron neutrino appearance from an accelerator-produced off-axis muon neutrino beam of energy about 0.6 GeV produced at J-PARC[6]. They have observed six electron-like events with an estimated background of 1.5 events in the Super-Kamiokande detector at a distance of 295 km from the J-PARC which indicates towards a non-zero value of θ_{13} at $2.5\,\sigma$ significance. Within a couple of weeks of the T2K results, the MINOS collaboration has announced the observation of 62 electron-like events with an estimated background of 49 events[7]. This favors a non-zero θ_{13} at $1.5\,\sigma$. A latest global fit of all the available neutrino oscillation data[8] indicates non-zero θ_{13} at more than $3\,\sigma$ C.L.. The results on θ_{13} from these experiments are going to play a crucial role in exploring CP violation in future large scale experimental program of long-baseline neutrino experiments[9].

The pion decay-at-rest (DAR) chain leads to a beam dominated by neutrinos between 20 and 52.8 MeV, with a well-defined flavor content of ν_e, ν_μ and $\bar{\nu}_\mu$. The source may be provided by a low energy proton accelerator with a beam impinging on a target/dump. Potentially, this can be the cyclotrons planned for the DAEδALUS CP-violation search[10–12]. In view of the recent SBL anomalies, we discuss in the first half of my talk to repeat the original LSND experiment using Super-Kamiokande, doped with Gadolinium, as detector which can be coupled with a modest-power DAR neutrino source[13] positioned within 20 m of the detector. Then in the second half of my talk, we present the possibility to replace the anti-neutrino run of a long-baseline neutrino oscillation experiment, with anti-neutrinos from muon decay at rest. The low energy of these neutrinos allows the use of inverse beta decay for detection in a Gadolinium-doped water Cerenkov detector. We show that this approach[11] yields a factor of five times larger anti-neutrino event sample. The resulting discovery reaches in θ_{13}, mass hierarchy and leptonic CP violation are compared with those from a conventional superbeam experiment with combined neutrino and anti-neutrino running.

2 The Neutrino Source and Decay-at-rest Flux

In a stopped pion source a proton beam of ~ 1 GeV energy interacts in a low-A target producing π^+ and, at a low level, π^- mesons. The pions then are brought to rest in a high-A beam stop. The π^- will be captured. The π^+ will produce the following cascade of decays

$$\begin{aligned}\pi^+ \;\; &\to \;\; \mu^+ + \nu_\mu \\ &\qquad \hookrightarrow \; e^+ + \nu_e + \bar{\nu}_\mu\end{aligned}$$

resulting in ν_μ, $\bar{\nu}_\mu$ and ν_e, but no $\bar{\nu}_e$. The resulting flux is isotropic. As a model of a DAR source, we use the DAEδALUS design[12]. The DAEδALUS accelerators are cyclotrons[14–16], an ideal low-cost source for low energy (800 MeV) protons. A detailed description of the neutrino source and DAR flux can be found in[17].

3 Final Verdict on LSND and MiniBooNE

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

Δm^2 [eV^2]	0.1	1	10	100
signal	29	1605	1232	1314

Table 1: Number of signal events after one year for $\sin^2 2\theta = 10^{-3}$ including efficiency and energy resolution.

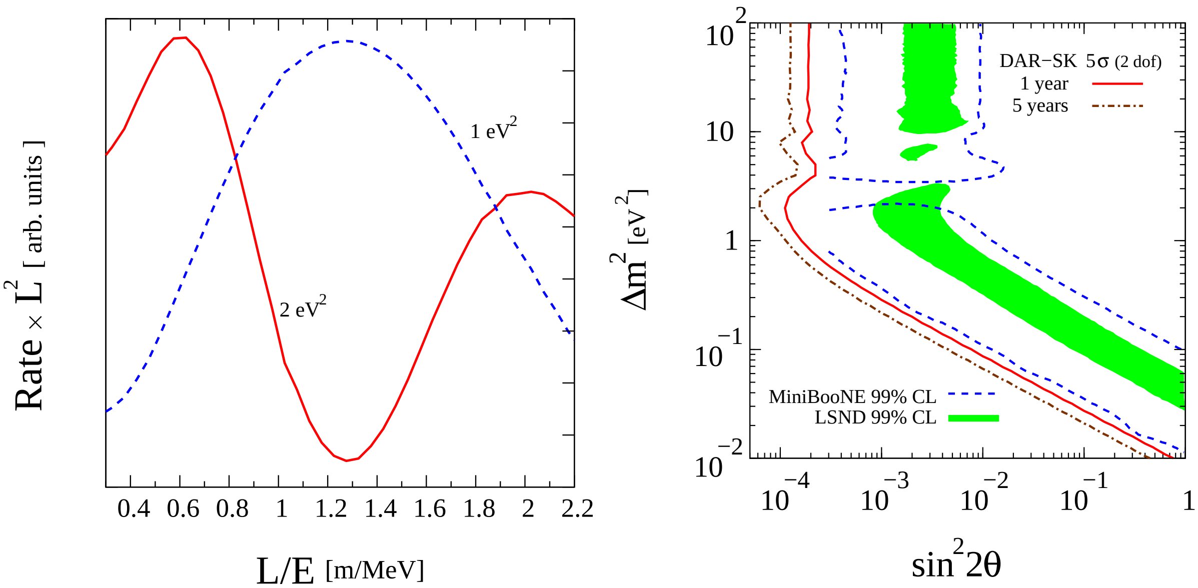

Figure 1: Left panel shows the signal event rate after one year weighted with L^2 as a function of the reconstructed L/E. The oscillation signal is computed for $\sin^2 2\theta = 10^{-3}$ and $\Delta m^2 = 2\,\mathrm{eV}^2$ (soild red line) and $1\,\mathrm{eV}^2$ (dashed blue line). Right panel depicts sensitivity limit of DAR-SK setup to sterile neutrino oscillation in the (3+1) model at $5\,\sigma$ CL (2 dof) using appearance mode. The solid red line corresponds to one year run of a 100 kW machine which can deliver 4×10^{21} $\bar{\nu}_\mu$. The dash-dotted brown line is for five years running of a 100 kW machine. The green/gray shaded region is the LSND allowed region at 99% confidence level, whereas the dashed blue line is the MiniBooNE anti-neutrino run allowed region at 99% confidence level[1].

original LSND experiment is that we suggest to use Super-Kamiokande doped with Gadolinium as detector[18] 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 with an efficiency of 67%[19;20]. Furthermore, we use an energy resolution as given in reference[21] and an energy threshold of 20 MeV. We consider a 100 kW average power proton cyclotron which provides 4×10^{21} $\bar{\nu}_\mu$ per year at the source. The contamination with $\bar{\nu}_e$ from π^- decays is very small and we take a value of 4×10^{-4}. 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 1 and the background event rate due to beam contamination is 765.

The large rock overburden of approximately 2,700 mwe at Super-Kamiokande, compared to 120 mwe in LSND, reduces cosmic ray induced backgrounds to negligible levels[10;12]. Also, atmospheric neutrino backgrounds are small compared to the beam induced backgrounds. The large dimensions of the Super-Kamiokande fiducial volume, a cylinder of 14 m radius with a height of 36 m allows 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[22] 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[23]. 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 of 1 m. Thus, with a source detector distance of 20 m and an energy range from

	$\bar{\nu}_\mu \to \bar{\nu}_e$	Background	$\nu_\mu \to \nu_e$	Background
DAR+HFN	1194	217	1532	428
HFA+HFN	231	158	766	214

Table 2: Comparison of the signal and background event rates of 6 years running of DAR+HFN and HFA+HFN. Note, that for DAR+HFN this is 6 years of simultaneous running of ν and $\bar{\nu}$, whereas for HFA+HFN this is 3 years each, run consecutively. Oscillation parameters are $\sin^2 2\theta_{13} = 0.1$ and $\delta_{\mathrm{CP}} = 0$ and normal hierarchy.

$20 - 52.8\,\mathrm{MeV}$ the oscillation pattern can be observed for an L/E range of $0.4 - 2.8\,\mathrm{m\,MeV}^{-1}$. This is illustrated in the left panel of figure 1, where we show the signal rates weighted with L^2 as a function of reconstructed L/E. The oscillation signal is computed for two different values of Δm^2 using the usual 2 flavor expression with $\sin^2 2\theta = 10^{-3}$. 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. In the right panel of figure 1 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[1].

4 An Ultimate Probe for Leptonic CP violation

Here the main idea is to combine a horn focused high energy ν_μ beam (HFN) with $\bar{\nu}_\mu$ from a DAR setup to study θ_{13}, the mass hierarchy and leptonic CP violation. We will denote this new technique as DAR+HFN. To illustrate the strength of DAR+HFN, we will study a specific setup, which closely resembles the Fermilab DUSEL concept for a long baseline experiment, currently known as LBNE. This setup has a total running time of 6 years and a 300 kt water Cerenkov detector. The entire HFN part is very similar to the setup described in detail in[24], specifically we take the source detector distance to be 1300 km and use the same detector performance. The beam delivers 6.2×10^{20} protons on target per year, which for 120 GeV protons corresponds roughly to 700 kW of beam power. For DAR setup, we consider proton cyclotrons of 1 MW beam power which can deliver 4×10^{22} of ν_e, ν_μ and $\bar{\nu}_\mu$ per flavor per year per cyclotron. We use 4 of these cyclotrons with a source detector distance of 20 km. In the context of superbeam experiments, a CP violation measurement requires data from both $\nu_\mu \to \nu_e$ *and* $\bar{\nu}_\mu \to \bar{\nu}_e$. However, the horn focused high energy $\bar{\nu}_\mu$ beam (HFA) poses a number of specific challenges: the production rate for π^-, the parent of $\bar{\nu}_\mu$, is lower than for π^+, the anti-neutrino charged current cross section is lower, the background levels are higher[b], and the systematic errors are expected to be larger. Overall, the event rate for anti-neutrinos is suppressed by a factor of 2-5, depending on the anti-neutrino energy, which is illustrated by table 2.

In figure 2, we compare the results from DAR+HFN with HFA+HFN. The reaches are given as a fraction of δ_{CP} and as a function of the true value of $\sin^2 2\theta_{13}$. In panel (a), we show the results for the discovery of the θ_{13} and find that DAR+HFN outperforms the superbeam experiment HFA+HFN for all CP phases and both hierarchies by roughly a factor two. The discovery reach for the mass hierarchy is shown in panel (b) and here, we see that for some values of the CP phase, in particular for inverted mass hierarchy, the reach is somewhat smaller for DAR+HFN. If at the end of the DAR+HFN run, the mass hierarchy has not been discovered adding a HFA run may be required. Finally, in panel (c) the discovery reach for CP violation is shown. For $\sin^2 2\theta_{13} = 0.05$, DAR+HFN has 75% CP coverage while HFA+HFN has 62%.

[b] This is due to the larger contamination from wrong sign pions.

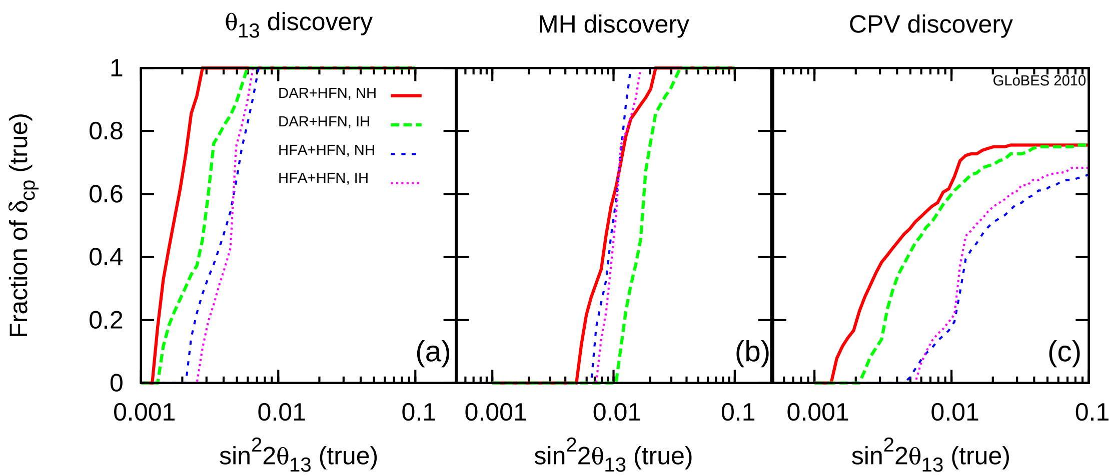

Figure 2: CP fractions for which a discovery at $3\,\sigma$ confidence level is possible as function of $\sin^2 2\theta_{13}$. From left to right for θ_{13}, mass hierarchy and CP violation. The different lines are for normal (NH) and inverted (IH) true mass hierarchies and for DAR+HFN and HFA+HFN, respectively.

5 Conclusions

In this talk, we present the physics prospects of DAR neutrino sources in testing the short-baseline anomalies and to study CP violation in active neutrinos. We have shown that Gd doped Super-Kamiokande detector combined with high intensity 100 kW cyclotron DAR neutrino source can test the LSND and MiniBooNE claims for SBL $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with more than $5\,\sigma$ significance within one year of running time. Also, we have demonstrated that a combination of low energy $\bar{\nu}_\mu$ from muon decay at rest with high energy ν_μ from a superbeam aimed at the same Gadolinium-doped water Cerenkov detector yields a moderately improved reach for θ_{13} and a significantly improved discovery reach for CP violation while only marginally affecting the mass hierarchy sensitivity. These improvements are a direct result of combining an optimized neutrino with an optimized anti-neutrino run.

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