Physics Program of the Short-Baseline Near Detector

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Abstract. SBND (Short-Baseline Near Detector) will be a 112 ton liquid argon TPC neutrino detector located 110 m from the target of the Fermilab Booster Neutrino Beam. SBND, together with the MicroBooNE and ICARUS-T600 detectors at 470 m and 600 m, respectively, make up the Fermilab Short-Baseline Neutrino (SBN) Program. SBN will search for new physics in the neutrino sector by testing the sterile neutrino hypothesis in the 1 eV$^2$ mass squared region with unrivaled sensitivity. SBND will measure the unoscillated beam flavor composition to enable precision searches for neutrino oscillations via both electron neutrino appearance and muon neutrino disappearance in the far detectors. With a data sample of millions of neutrino interactions (both electron and muon neutrinos), SBND will also perform detailed studies of the physics of neutrino-argon interactions, even in rare channels. In this poster the physics program of SBND will be presented.

1. The Short-Baseline Neutrino program at Fermilab
The Short-Baseline Neutrino (SBN) program at Fermilab [1] will attempt to definitively address the 1 eV sterile neutrino, whose presence is hinted at by neutrino oscillation data collected by the Liquid Scintillator Neutrino Detector (LSND) [2] and MiniBooNE [3] experiments. Three Liquid Argon Time Projection Chambers (LAr TPCs) will be exposed to the Booster Neutrino Beam (BNB) and will measure the flavour content of the beam before and after oscillations. The program’s three detectors are the Short-Baseline Near Detector (SBND), MicroBooNE and ICARUS T-600 which will be located 110 m, 450 m and 600 m from the BNB target respectively.

SBND will be a 112 ton LAr TPC whose role is primarily to measure the neutrino flux before oscillations occur. However, due to its close proximity to the BNB target, SBND will be exposed to a high neutrino flux which will provide an unprecedented amount of neutrino-argon interaction data, resulting in a rich cross section program.

2. The short-baseline sterile neutrino search
The 3 detector setup of the SBN program will allow for a sensitive search of the $\Delta m^2$ regions highlighted by the LSND and MiniBooNE experiments. The basis of the search is $\nu_e$ appearance and $\nu_\mu$ disappearance. The sensitivity of the SBN program is demonstrated assuming a 3+1 sterile neutrino model and, in such a model, the sterile oscillation probabilities are

$$P_{\nu_\mu \rightarrow \nu_e}^{3+1} \approx \sin^2 2\theta_{\mu e} \sin^2 \left( \frac{\Delta m^2 L}{4E_\nu} \right)$$

(1)
(a) $\nu_\mu \rightarrow \nu_e$ oscillation sensitivity [1].

(b) $\nu_\mu \rightarrow \nu_x$ oscillation sensitivity [1].

Figure 1: The SBN program sensitivity to neutrino oscillations in the $(\sin^2 2\theta, \Delta m^2_{41})$ planes. LAr1-ND is the former name of the SBND experiment.

$$P_{\nu_\mu \rightarrow \nu_e}^{3+1} \approx 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \left( \frac{\Delta m^2 L}{4E_\nu} \right),$$

where $\sin^2 \theta_{\mu e}$ and $\sin^2 \theta_{\mu\mu}$ are mixing amplitudes, $\Delta m^2$ is the mass squared difference between the neutrino mass eigenstates, $L$ is the propagation length of the neutrino and $E_\nu$ is the neutrino’s energy.

The sensitivity of the SBN program is calculated by mapping a $\chi^2$ surface in the $(\sin^2 2\theta, \Delta m^2_{41})$ plane. The $\chi^2$ surface is defined as

$$\chi^2 = (\vec{N}_{\text{osc}}(\sin^2 2\theta, \Delta m^2_{41}) - \vec{N}_{\text{null}})^T V^{-1} (\vec{N}_{\text{osc}}(\sin^2 2\theta, \Delta m^2_{41}) - \vec{N}_{\text{null}}),$$

where $\vec{N}_{\text{osc}}$ is a vector of oscillated event counts separated by neutrino energy and is calculated using either eqn. 1 or eqn. 2, $\vec{N}_{\text{null}}$ is a similar vector but contains event counts in the absence of oscillations and is calculated by simulating BNB-based Monte Carlo in all three detectors and $V$ is the covariance matrix which encapsulates the statistical and systematic uncertainties. From the mapped space, Confidence Limits (C.L.) can be drawn which are based on comparisons of the $\chi^2$ values relative to the overall $\chi^2$ minimum. The SBN program sensitivities to the neutrino oscillation parameters are shown in Fig. 1. For $\nu_\mu \rightarrow \nu_e$ oscillations (Fig. 1a), there is almost complete 5$\sigma$ coverage of the LSND 99% C.L. allowed region and for $\nu_\mu \rightarrow \nu_x$ oscillations (Fig. 1b) the SBN program extends an order magnitude more into the parameter space than the combined MiniBooNE and SciBooNE analysis.

3. Neutrino-argon interactions at SBND

Neutrino cross section measurement data is sparse, particularly in the 1 GeV regime and the data that does exist is dominated by large uncertainties [4]. Specifically for argon-based target measurements, ArgoNeuT is currently the only experiment to provide cross section data [5, 6]. Due to its close proximity to the BNB target, SBND will collect millions of neutrino interactions on argon leading to a rich cross section program, which includes rare interaction channels with high statistics. A short summary of available channels is shown in table 1.
Table 1: Estimated event rates using GENIE [7] in the SBND active volume (112 ton) for a $6.6 \times 10^{20}$ protons on target exposure. In calculating proton multiplicity, there is an energy threshold on proton kinetic energy of 21 MeV. The $0\pi$ topologies include any number of neutrons in the final state [1, 8].

| Process | $\nu_\mu$ Events (By Final State Topology) | No. Events | Stat. Uncert. |
|---------|-----------------------------------------|------------|---------------|
| CC Inclusive | $\nu_\mu$ | 5,200,000 | 0.04% |
| CC 0 $\pi$ | $\nu_\mu N \rightarrow \mu + Np$ | 3,600,000 | 0.05% |
| CC 1 $\pi^\pm$ | $\nu_\mu N \rightarrow \mu + n$ + $1\pi^\pm$ | 1,200,000 | 0.09% |
| CC $\geq 2\pi^\pm$ | $\nu_\mu N \rightarrow \mu + n$ + $\geq 2\pi^\pm$ | 98,000 | 0.32% |
| CC $\geq 1\pi^0$ | $\nu_\mu N \rightarrow \mu + n$ + $\geq 1\pi^0$ | 500,000 | 0.14% |
| NC Inclusive | $\nu_\mu$ | 2,000,000 | 0.07% |
| NC 0 $\pi$ | $\nu_\mu N \rightarrow n$ | 1,400,000 | 0.09% |
| NC $\geq 2\pi^\pm$ | $\nu_\mu N \rightarrow n$ + $\geq 2\pi^\pm$ | 32,000 | 0.56% |
| NC $\geq 1\pi^0$ | $\nu_\mu N \rightarrow n$ + $\geq 1\pi^0$ | 360,000 | 0.17% |
| $\nu_e$ Events | $\nu_\mu$ | 37,000 | 0.52% |
| $\nu_e$ | 14,000 | 0.83% |
| Total $\nu_\mu$ and $\nu_e$ Events | 7,300,000 | 0.04% |
| Hyperon-Producing Interactions (CC+NC) | $\Lambda^0$ production | 8,000 | 1.12% |
| $\Sigma^+$ production | 4,500 | 1.49% |
| Neutrino-Electron Scattering | $\nu + e \rightarrow \nu + e$ | 300 | 5.77% |

4. Conclusions
As a core part of the SBN program at Fermilab, SBND will provide key inputs to a high sensitivity search for sterile neutrinos in the 1 eV$^2$ mass-splitting range. SBND will also collect a large statistics dataset of neutrino interactions over its run period, providing data for a very rich cross section program.

References
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