Status and perspectives of short baseline studies

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Abstract.
The study of flavor changing neutrinos is a very active field of research. I will discuss the status of ongoing and near term experiments investigating neutrino properties at short distances from the source. In the next few years, the Double Chooz, RENO and Daya Bay reactor neutrino experiments will start looking for signatures of a non-zero value of the mixing angle $\theta_{13}$ with much improved sensitivities. The MiniBooNE experiment is investigating the LSND anomaly by looking at both the $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance channels. Recent results on cross section measurements will be discussed briefly.

1. Introduction
The relation between the flavor and mass eigenstates of the neutrinos can be described by the PMNS matrix [1, 2]. In case of 3-neutrino mixing, the parameters relevant to oscillations describing this matrix are three mixing angles, $\theta_{12}$, $\theta_{23}$ and $\theta_{13}$, and a CP-violating phase $\delta_{CP}$. The frequencies of oscillations between the different states are governed by the energy, distance and the two possible differences between the masses squared, $\Delta m_{21}^2$ and $\Delta m_{31}^2$.

Since the confirmation of neutrino oscillations a decade ago [3], great progress has been made in the measurements of these parameters. Two of the mixing angles, $\theta_{12}$ and $\theta_{23}$, and the size of the two mass splittings, $\Delta m_{21}^2$ and $\Delta m_{31}^2$, are well measured (for a recent combination of global data, see e.g. [4]). The most stringent limit on the third angle comes from the CHOOZ reactor neutrino experiment [5]: $\sin^2 2\theta_{13} < 0.16$ (90\% C.L.) at $\Delta m_{31}^2 = 2.5 \times 10^{-3}$eV. However, small contributions from various experiments add up to prefer a non-zero value of $\theta_{13} \approx 8$° at the 2$\sigma$ level [4, 6]. Several experiments currently under construction will probe well into this region. Those observing neutrinos at nuclear reactors will be covered in the next section.

However, not all measurements fit clearly into the above picture. The LSND experiment has observed an excess of $87.9 \pm 23.2$ (3.8$\sigma$) events above background in the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance search [7]. The L/E value requires a mass splitting different than the solar and atmospheric $\Delta m^2$ to explain this effect with neutrino oscillations. Three mass differences need mixing with a unobserved fourth type of neutrino with different mass, suggesting the existence of sterile neutrinos. The MiniBooNE experiment was designed to investigate this excess in detail, and will be covered in Section 3.
2. Reactor neutrino experiments

2.1. Neutrino oscillations at nuclear reactors

Nuclear reactors are a pure and isotropic source of anti-electron neutrinos produced at a rate of about $2 \cdot 10^{20}/\text{GW}_{\text{th}}/\text{s}$. The particles are produced through the decay of the fission products in the decay chain of predominantly $^{235}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$ and $^{238}\text{U}$. The $\beta$-spectra from the first three isotopes are measured to a precision of 1.8% [8, 9]. These spectra are converted into a predicted neutrino spectrum resulting in a final error of 2.5 – 4% depending on the energy. Plans are underway to decrease this error significantly by measuring the $^{238}\text{U}$ $\beta$-spectrum and performing improved conversion calculations including more branches in the decay chain.

The survival probability for anti-electron neutrinos is given by

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{1.27 L \Delta m^2_{31}}{E} \right) - \cos^2 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{1.27 L \Delta m^2_{21}}{E} \right),$$

with $L$ measured in m, $E$ in MeV and $\Delta m^2$ in eV. In case of a non-zero $\theta_{13}$, the first oscillation node is around 2 km for typical energies in nuclear reactor experiments. An observation of neutrino disappearance at this distance will constitute a clean measurement of $\sin^2 2\theta_{13}$: the last term containing the solar parameters can be neglected and the probability only depends on $\Delta m^2_{31}$, a well measured quantity. The probability is not affected by matter effects due to the short distances and is insensitive to the CP-violating phase. Several experiments have searched unsuccessfully for the disappearance of reactor neutrinos at various distances due to a non-zero $\theta_{13}$. The best limit was set by the Chooz experiment to be $\sin^2 2\theta_{13} < 0.16$ (90% C.L.) [5].

Three experiments are currently under construction with a much improved sensitivity: Double Chooz, RENO and Daya Bay. The statistical uncertainty will be lowered by building larger detectors, running for a longer time and by being located near more powerful reactors. The reduction in systematics uncertainty is mainly obtained by placing one or more identical detectors close to the reactor cores. A ratio measurement will eliminate the cross section, the neutrino flux and some detector uncertainties. There is also a gain from an improved detector design with lower thresholds, increased efficiencies and implementation of a very detailed calibration program. Further enhancements are obtained by lowering the background contamination with better veto systems, shielding, higher overburden and the use of materials with improved radio-purity.

2.2. Detection technique

The anti-electron neutrinos are measured through the inverse $\beta$-decay process $\bar{\nu}_e + p \rightarrow e^+ + n$, with a threshold energy of 1.8 MeV. Folding the neutrino flux from the reactor with the cross section results in an observable spectrum peaking just below 4 MeV.

The three experiments employ similar detector designs with three regions containing different types of liquids, separated by optically transparent acrylic vessels. The central region is filled with liquid scintillator doped with a small amount of Gadolinium, typical 0.1% in weight. The produced positron annihilates instantly and deposits a total amount of visible energy closely related to the neutrino energy: $E_{\text{vis}} \simeq E_{\nu} - 0.8$ MeV. The neutron slows down through thermalization before being captured by a nucleus. This will most often happen on Gadolinium due to its high cross section for neutron capture. The typical capture time is $30\mu$s and releases a total amount of energy around 8 MeV in the form of several gammas. The target region is surrounded by the gamma catcher: a volume with undoped scintillator to capture any gamma escaping the target. The outside region contains the photo-multiplier tubes (PMT) and is filled with non-scintillating oil. This design suppresses a large fraction of the radioactivity coming from the PMTs and surrounding material. The detectors are also surrounded by active veto detectors and passive shielding to further suppress natural radioactivity and backgrounds related to cosmic muon interactions.
The typical signature of a prompt signal plus a delayed energy deposit consistent with neutron capture on Gadolinium is used to select neutrino candidates. The background events can be categorized into two classes. The accidental backgrounds consist of a positron-like signal from natural radioactivity present in the PMTs, the detector materials and the surrounding rock, followed close in time by an independent neutron-like signal. These can be actual neutrons generated by cosmic muons interacting in the material surrounding the detector, or high energy gammas mimicking a neutron capture on Gadolinium. The correlated backgrounds are produced by one single event with multiple energy deposits. A fast neutron produced by cosmic muons slows down by recoiling on the protons in the scintillator producing electron-like signals until it gets captured by the Gadolinium. Other sources are long lived isotopes produced in high energetic showering cosmic muon interactions undergoing a $\beta$-n decay. The isotopes have typical lifetimes of $O(100\text{ms})$ and are impossible to eliminate by vetoing every cosmic muon. The largest contribution comes from $^9\text{Li}$, but other isotopes like $^6\text{He}$ and $^{11}\text{Li}$ also contribute.

### 2.3. Future experiments

The three experiments currently under construction are described below and summarized in Table 1. The expected sensitivities mentioned are always upper limits on $\sin^2 2\theta_{13}$ at 90% confidence level in case no signal is observed.

#### Double Chooz
The experiment [10] is located near the Chooz-B Power Plant in Northern France, which consists of two reactor cores operating at a total power of 8.6 GWth. The near detector will be located at a distance of about 400 m from the cores. The far detector is being constructed in the same hall as the CHOOZ experiment at a distance of 1050 m. The target regions of both detectors will be 8.3 ton.

The far detector is expected to be operational by spring 2010 for the first phase with far detector only running. After one year, the expected sensitivity to $\sin^2 2\theta_{13}$ will be 0.06. The second phase of the experiment with both detectors operational will start in 2011, with a sensitivity to $\sin^2 2\theta_{13}$ of 0.03 after three years of data taking. The expected sensitivity over time can be seen in the left plot of Figure 1. More details about and the status of the experiment are covered in [11].

#### RENO
The experiment [12] is being built near the YeongGwang power plant in the south-west of South Korea. The 6 operational cores lie on one axis and produce a total power of 17.3 GWth. The target regions of both detectors will be 20 ton. The near detector hall is located at 290 m from the closest point to the reactor cores axis and the far detector hall is at a distance of 1380 m.

| Power [GWth] | $L_{\text{Near}}$ [m] | $L_{\text{Far}}$ [m] | $M_{\text{target}}$ [ton] | $\sigma_{\text{stat}}$ [%] | $\sigma_{\text{syst}}$ [%] | $\sin^2 2\theta_{13}$ > (90% C.L.) |
|-------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Double Chooz | 8.6 400 | 1050 8.3 | 0.5 0.6 | 0.03 |
| RENO | 17.3 290 | 1380 16 | 0.3 0.5 | 0.02 |
| Daya Bay | 17.4 360 (500) | 1990 (1620) 80 | 0.2 0.4 | 0.01 |

Table 1. Total reactor power, distance $L$ to near and far detectors and far detector target mass $M_{\text{target}}$ of the Double Chooz, RENO and Daya Bay experiments. The distance for Daya Bay is to the DB plant, the ones between brackets to the LA and LA II plants. The expected statistical and systemic uncertainties and sensitivity to $\sin^2 2\theta_{13}$ at 90% confidence level are given on the right.
The expected sensitivity to $\sin^2 2\theta_{13}$ at 90% C.L. as a function of running time for Double Chooz (left) where the near detector becomes operational after 1.5 years of far detector only running; as function of $\Delta m_{31}^2$ for RENO (middle) and Daya Baye (right) after three years of data taking with all detectors and reactors fully operational.

Both detectors will be ready for data taking during the early months of 2010. The expected sensitivity to $\sin^2 2\theta_{13}$ after 3 years will be 0.02, and can be seen as function of $\Delta m_{31}^2$ in the middle plot of Figure 1.

Daya Bay. The experiment [13] will use neutrinos produced by the Daya Bay (DB) and Ling Ao (LA) Power plants located in just north-east of Hong Kong. In 2011, the LA II power plant will be operational resulting in a total power of 17.4 GWth produced by six cores. A total of 4 identical modules measuring 20 ton each will be placed at the far hall, 1990 m and 1620 m away from the DB and LA reactors, respectively. Two modules will be placed at a distance of about 360m from the DB plant, and another two at about 500m from the LA plants.

The far hall will be ready for data taking in Summer 2011. After 3 years with all detector modules operational and 6 reactor cores at full power, the sensitivity to $\sin^2 2\theta_{13}$ is expected to reach 0.01, which can be seen from the right plot in Figure 1. More details about and the status of the experiment are covered in [14].

3. The MiniBooNE experiment

3.1. Experimental setup

The MiniBooNE experiment [15] is designed to address $\nu_e$ appearance in a $\nu_\mu$ beam with the same L/E value as LSND but under different experimental conditions. A 8.9 GeV proton beam from the Booster at FNAL hits a beryllium target. The produced hadrons are focused in the forward direction by a magnetic horn. They are allowed to decay in a tunnel followed by dirt to absorb all particles but neutrinos. This results in a $\nu_\mu$ beam peaked around 700 MeV. The polarity of the horn can be reversed to select a $\bar{\nu}_\mu$ beam. An 800 ton mineral oil Čerenkov detector is placed at about 500 m downstream the neutrino beam. A short overview of the results are given in the next section. More details are covered in [16].

3.2. Results

$\nu_\mu \rightarrow \nu_e$ appearance. The full data sample of $6.5 \times 10^{20}$ protons-on-target (PoT) taken in neutrino mode is analyzed, selecting charged current quasi-elastic $\nu_e$ interactions. No excess of events was observed in the signal region above 475 MeV corresponding to the LSND results [17]. This rules out the 2-neutrino oscillation hypothesis as source of the LSND excess (assuming no CP & CPT violation). The resulting exclusion limit can be seen in the left plot of Figure 2.
Figure 2. The observed MiniBooNE exclusion limits on $\nu_\mu \rightarrow \nu_e$ (left) and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (middle) appearance and on $\nu_\mu$ disappearance (right).

However, an excess of $129 \pm 43$ events was observed above background at energies between 200 and 475 MeV [18]. The size of the signal is similar to the LSND result but the shape of the energy spectrum is not consistent with 2 neutrino oscillations. The effect is also observed looking at far off-axis neutrinos coming from the NuMI beam [19]. An improvement in the latter analysis is expected, including a larger data sample and reduced systematic uncertainties.

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance. The anti-neutrino mode is a direct test of the LSND result. Results from a limited data sample of $3.4 \cdot 10^{20}$ PoT show no significant excess over background, neither in the LSND region, nor at lower energies [20]. The obtained exclusion limits are shown in the middle plot of Figure 2. In total $5.1 \cdot 10^{20}$ PoT are recorded in anti-neutrino mode and $5 \cdot 10^{20}$ PoT more are expected. Such a threefold increase in the data sample should shine more light on these inconclusive results.

$\nu_\mu$ and $\bar{\nu}_\mu$ disappearance. Looking at this channel set limits in previously unexplored parameter space [21], which can be seen in the right plot of Figure 2 for the $\nu_\mu$ channel. The results will be updated including the data from the SciBooNE experiment, a fine-grained tracking detector located about 100m from the target and which took data from June 2007 until August 2008.

3.3. Beyond MiniBooNE
The MicroBooNE collaboration [22] proposes to build a 70 ton Liquid Argon TPC near MiniBooNE as an advanced R&D project and to investigate the observed low energy excess. If all funding is assured, the project can start to take data as early as 2011. Currently, a 170L LAr TPC, called ArgoNeut, is taking data in the NuMI beam in front of the MINOS detector [23].

OscSNS [24] is a proposal to place a MiniBooNE-like detector at 60m from the target of the Spalation Neutron Source at ORNL, a 1 GeV, pulsed (60 Hz), 1.4 MW proton beam produces $\pi^+$ which decay at rest. The experiment is expected to have a 15 times better sensitivity than the LSND experiment.

4. Cross section measurements
The intense neutrino beams also allow for much improved cross section measurements. These are in particular important for future neutrino oscillation experiments operating in the few GeV range. The currently ongoing experiments are MiniBooNE and SciBooNE [25] in the Booster neutrino beam (0.4 - 2 GeV) and MINOS [26] in the NuMI beam (1 - 20 GeV). One
of the many updated and new measurements reported on at the recent NuInt09 workshop [27] is the quasi-elastic (CCQE) cross section. All ongoing experiments prefer a value of $M_A$ around 1.35 GeV[28, 29, 30], where $M_A$ is the axial form factor in the relativistic Fermi Gas Model. These measurements on carbon and iron are higher than previous results on D$_2$, and on carbon at higher energies by NOMAD [31]. The MINERvA experiment [32] will be able to study these discrepancies in much more detail when it starts operating early 2010. This dedicated neutrino scattering experiment, located in front of the MINOS near detector, has the ability to measure cross sections on different target materials in the energy range of 1 - 20 GeV. Also the T2K [33] and NOvA [34] near detectors will provide valuable cross section measurements around 0.8 GeV and 2 GeV, respectively.

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