Neutrino Oscillation Experiments at Nuclear Reactors

Giorgio Gratta

Physics Department, Stanford University, Stanford, CA 94305, USA

Abstract. In this paper I give an overview of the status of neutrino oscillation experiments performed using nuclear reactors as sources of neutrinos. I review the present generation of experiments (Chooz and Palo Verde) with baselines of about 1 km as well as the next generation that will search oscillations with a baseline of about 100 km. While the present detectors provide essential input towards the understanding of the atmospheric neutrino anomaly, in the future, reactor experiments may well be our only hope to study very small mass neutrino mixing in laboratory conditions.

1. Introduction

Neutrino oscillations, if discovered, would shed light on some of the most essential issues of modern particle physics ranging from a better understanding of lepton masses to the exploration of new physics beyond the Standard Model. In addition the phenomenon of oscillations would have important consequences in astrophysics and cosmology.

Experiments performed using both particle accelerators and nuclear reactors have been carried on extensively in the past 20 years finding no firm evidence for neutrino oscillations. However, in recent years, evidence has been collected on a number of effects that could point to oscillations: the solar neutrino puzzle[1], the anomaly observed in atmospheric neutrinos[2] and the LSND effect[3].

This paper will concentrate on the first two cases that are well suited to be studied with reactor experiments. As shown in Figure 1 both effects,

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if interpreted as signals for neutrino oscillations, could suggest rather large mixing parameters and very small neutrino mass differences. We write the probability of oscillation from a flavor $\ell$ to another one $\ell'$ as

$$P_{\ell\ell'} = \sin^2 2\theta \sin^2 \frac{1.27 \Delta m^2 L}{E_\nu}$$  \hspace{1cm} (1)

where $L$ is expressed in meters, $\Delta m^2$ in eV$^2$ and $E_\nu$ in MeV. It is clear that in order to probe sufficiently small $\Delta m^2$, long baselines have to be combined with low energy neutrinos.

![Figure 1](image)

**Figure 1.** Phasespace for $\nu_e - \nu_\mu$ oscillations. The existing limits are compared with current and future experiment and the region obtained by interpreting the solar and atmospheric neutrino anomalies as due to oscillations. The MSW mechanism is used in plotting the solar neutrino regions. The sensitivity of reactor experiments is the same for $\nu_e - \nu_\tau$ oscillations.

Unfortunately we are able to collimate neutrino beams only by using
the Lorentz boost of the parent particles from which decay the neutrinos are produced. For this reason low energy neutrinos are generally produced over large solid angles while high energy ones may come in relatively narrow beams. Hence to access, for instance, the atmospheric neutrino $\Delta m^2$ region we have the choice of either using the beam from an accelerator that is rather narrow (better than $\approx 1$ mrad) but has an energy of several GeV, or detecting few-MeV neutrinos emitted uniformly over the entire solid angle by a nuclear reactor. In the first case the baseline will have to be much larger, but since the beam is pointing, both cases turn out to be quite feasible and their different features make them quite complementary. On one hand, as reactors produce exclusively electron anti-neutrinos, only $\bar{\nu}_e - \bar{\nu}_\mu$ oscillations can be observed. In addition since the neutrino energy is below the threshold for producing muons (or $78\text{eV}$), reactor experiments have to be of “disappearance” type, that is oscillation would be detected as a deficit of electron neutrinos. This feature, together with the higher energies produced in accelerator neutrino events and their time-bunched structure, makes accelerators-based experiments more immune to backgrounds and, in general, more sensitive to small mixing parameters. On the other hand the very low energy of reactor neutrinos offer the best chance to push to the limit our exploration of the small $\Delta m^2$ regime.

Two reactor-based experiments able to explore one order of magnitude below the present $\Delta m^2$ limit are starting data taking this year, while plans are made for experiments that will improve our sensitivity on this parameter by two more orders of magnitude. As shown in Figure 1 the present experiments, Chooz[4] and Palo Verde[5] will explore the parameter space relevant to the atmospheric neutrino anomaly in the $\bar{\nu}_e - \bar{\nu}_\mu$ (and $\bar{\nu}_e - \bar{\nu}_\tau$) channel, while the future ones, for instance Kamland[6], will start attacking the region of solar neutrino oscillations. It is worth noting that having a pure source of $\bar{\nu}_e$ (nuclear reactor) is a limitation in atmospheric neutrino research only.

2. Reactors as Neutrino Sources

Nuclear reactors produce isotropically $\bar{\nu}_e$ in the $\beta$ decay of the neutron-rich fission fragments. For all practical purposes the neutrino flux and spectrum depend only on the composition of the core in terms of the four isotopes $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$ and $^{241}\text{Pu}$ being fissioned in the reactor. Neutrinos are then produced by long chains of daughter isotopes and hundreds of different $\beta$-decays have to be included to account for the observed yields. The modeling of such processes is quite a formidable task but there is nowadays a very good agreement between theoretical calculations and experimental data. Two ways can be used to experimentally cross check theoretical models. In one case the electron spectra for fission-produced chains can be
experimentally measured for each of the four parent isotopes. From this data, available only for \(^{235}\text{U}, {^{239}\text{Pu}}\) and \(^{241}\text{Pu}\), anti-neutrino spectra can be derived without loss of accuracy\(^7\), obtaining a total uncertainty on the flux of about 3\%. Alternatively anti-neutrino flux and spectra have been directly measured \(^8\) in several high statistic experiments with detectors of known efficiency. These data are usually a by-product of previous reactor oscillation experiments where the anti-neutrino have been measured at different distances. Since these observations have been found to be consistent with a \(1/r^2\) law (no oscillations at short baselines) they can now be used as a determination of the absolute anti-neutrino spectra. A total error of about 1.4\% has been achieved in these measurements.

All experimental methods and calculations agree with each other within errors so that, given the history of power and fuel composition for a reactor, its anti-neutrino energy spectrum can be computed with an error of about 3\%. We note here that for this kind of experiments a “near measurement” is superfluous as, in essence, all the information needed can be readily derived from the previous generation of experiments, using their result that no oscillations take place at those shorter baselines. The real challenge consists in measuring precisely the detector efficiency.

![Graph](image)

**Figure 2.** Neutrino spectrum at the detector for no oscillations (continuous line), and oscillations at 740 m (dotted line) and 1000 m (dashed line). In the case of oscillations the parameters assumed are \(\Delta m^2 = 7.2^{-3}\text{eV}^2\) and \(\sin^2(2\theta) = 1\) \(^9\).
Since the neutrino spectrum is only measured above some energy threshold (in practice such threshold is $M_n - M_p + m_e = 1.8 \text{ MeV}$), only fast (energetic) decays contribute to the useful flux and the "neutrino luminosity" tracks very well in time the power output of the reactor. Generally few hours after a reactor turn off the neutrino flux above threshold has become negligible. Similarly, the equilibrium for neutrinos above threshold is established already several hours after the reactor was turned on.

While early oscillation experiments used military or research reactors, modern experiments have long baselines and so need the largest available fluxes (powers) that are usually available at large commercial power generating stations. Typical modern reactors have thermal power in excess of 3 GW ($> 1 \text{ GW electrical power}$) corresponding to $\approx 7.7 \times 10^{20} \nu/s$. Usually more than one such reactors are located next to each other in a power plant. The neutrino flux detected is the sum of similar contributions from each core.

Although periods of time with source off would be very useful to study the backgrounds, in the case of multiple reactors, plant optimization requires the refueling of one reactor at the time so that in practice backgrounds are often studied at partial power (instead of zero power). In practice each reactor is usually off (refueling) for about one month every year. Future experiments with baselines of the order of 100 km will detect neutrinos from a number of different plants so that one reactor refueling will change the flux by a negligible amount. Hence these experiments will presumably have to find alternative ways to measure and subtract backgrounds.

3. Searches in the Atmospheric Neutrino Region

At the time of writing two experiments are exploring the region of phase-space with $10^{-3} < \Delta m^2 < 10^{-2}$: Chooz in France (a 2-reactor site) and Palo Verde in the United States (a 3-reactor site). In order to be sensitive to long enough oscillation lengths these detectors are located about 1 km from the reactors (740 m for Palo Verde). In both cases the detection is based on the inverse-$\beta$ reaction

$$\bar{\nu}_e + p \rightarrow e^+ + n.$$  \hspace{1cm} (2)

in liquid scintillator. In general both detectors can measure the positron, and hence the anti-neutrino, energy. The anti-neutrino spectrum can be easily reconstructed from simple kinematics as

$$E_\nu = E_{e^+} + (M_n - M_p) + O(E_\nu / M_n).$$  \hspace{1cm} (3)
Given a fixed baseline, different energies will have different oscillation probabilities as shown in Figure 2 and, for a large range of $\Delta m^2$ values, the signature of oscillations is an unmistakable modulation on the energy spectrum of the type shown in the Figure. The slight difference in baselines for the two experiment could result in rather different oscillation signals, providing a nice cross-check against non-oscillation effects. Parameter sets closer to the sensitivity boundaries will ultimately give neutrino spectra similar to the case of no oscillations, so that to reach the best sensitivity both experiments will have to rely ultimately on the absolute neutrino flux measurement.

Figure 3. End view of the Palo Verde detector. Clearly visible are the outer veto counters, the water buffer volume and the central detector composed of 66 long acrylic cells.

Since at these large distances from the reactors the flux of neutrinos is rather low, special precautions have to be taken in order to suppress backgrounds from cosmic radiation and natural radioactivity. Although both detectors are located underground, background rejection is achieved
somewhat differently in the two detectors. On one hand Chooz has been built in a rather deep (300 m.w.e.) already existing underground site, while, on the other, Palo Verde was installed in a shallow laboratory (32 m.w.e.) excavated for the experiment. Hence this last experiment is segmented and uses tighter signatures to identify anti-neutrino events. In Figure 3 we show the end-view of the Palo Verde detector.

The central detector, a matrix of 66 acrylic cells each 9 m long, is surrounded by a 1 m thick water buffer that shields γ radiation and neutrons. A large veto counter encloses the entire detector, rejecting cosmic-ray muons, still rather abundant. In this detector the signal consists of a fast triple coincidence followed by the neutron capture. The triple is produced by the ionization due to the positron and, in two different cells, its two annihilation photons. Timing information at the two ends of each cell allows to reconstruct the events longitudinally and to correct for light attenuation in the cells, providing a good quality positron energy measurement.

The Chooz detector, on the other hand, being in a lower background environment, is a single spherical acrylic vessel filled with liquid scintillator. It triggers on the double coincidence between the positron and the neutron parts of the inverse β reactions. Also in this case the central detector is surrounded by a veto and some shielding layers.

In order to keep the neutron capture time short, and hence reduce the coincidence time and the background accepted in it, both experiments are using a scintillator doped with Gadolinium. A concentration of 0.1% Gd by weight reduces the capture time from 170µs to 28µs. Since a neutron capture in Gd is accompanied by a 8 MeV photon cascade, another advantage of the doped scintillator is that it allows for a very high threshold for the neutron part of the event. This threshold, well above the Th and U lines, results in further reduction of the background.

Although both detectors are built using low activity materials, this requirement is more severe for Chooz in order to have a γ-ray rate consistent with the lower cosmic-ray induced background.

Two categories of backgrounds are considered: one is given by random hits in the detector (2 for Chooz, 4 for Palo Verde) produced by independent γ-rays and/or neutrons, while the other is given by single fast neutrons produced by cosmic-ray muons mainly in a spallation process. Such neutrons can deposit some energy simulating the fast part of the event (triple or single in the two detectors) to then thermalize and capture in Gd. Unlike the case of independent hits, in this second background the event has the same time-structure as real events, so that its rejections is a priori more difficult. In addition, since spallation phenomena are poorly known, simulations are in this case not very reliable and the detectors are designed keeping in mind a rather large range of possible background rates. Both
experiments plan to use periods of low power during the refueling of some of the reactors to measure the single neutron induced background. Since the Chooz power plant is in the process of being commissioned that experiment was able to collect some precious data with all reactors off.

![Neutrino Candidates](image)

**Figure 4.** Neutrino candidates in the Chooz detector as function of time in days. The change in flux is clearly visible at the time the first reactor was turned on.

The expected rates of neutrino events for the case of no oscillations is 50 day$^{-1}$ (30 day$^{-1}$) for Palo Verde (Chooz) with a signal to noise ratio ranging from 10 to 0.1 depending on the experiment and on the model used for the spallation process.

Both groups use rather advanced trigger and data acquisition systems to select and log neutrino events.

While Palo Verde is presently being filled with scintillator, Chooz has had the chance to run for a few months already. In Figure 4 we show the rate of neutrino candidates as function of time in that detector. A clear change in flux is visible at the time when the first reactor turned on.

4. **Towards Longer Baselines**

The exploration of smaller neutrino masses calls for even longer baselines. Two projects are now at different stage of planning with a baseline of about
100 km: one would be located in Taiwan and would use as sources some large power station about equidistant from a large detector, while the other would use the infrastructure of Kamiokande in Japan and detect neutrinos from a large number of reactors 150 to 300 km away. In this paper we will only give a simple discussion of this last effort.

The detector, named Kamland, will be housed in the old Kamiokande site with 2,700 m.w.e. rock overburden. A central spherical volume will be isolated from the rest by a transparent shell and filled with 1000 tons of special liquid scintillator. Anti-neutrinos will be detected in this part. The remaining volume will be shared between a 3,500 ton mineral oil buffer and an active muon veto separated by a stainless steel spherical shell. A schematic view of the proposed detector is shown in Figure 5.

![Figure 5. Schematic view of the Kamland detector.](image)

The detector will be readout by 1,500 20-inch photomultipliers of the type already in use at SuperKamiokande to improve light collection and timing resolution respect to Kamiokande. It is expected to collect 100 photoelectrons/MeV corresponding to an energy resolution $\delta E/E = 10%/\sqrt{E}$. 

9
The use of Gd loading in Kamland is still under study since it involves the use of an unprecedented quantity of a scintillator that is known to be expensive and hard to prepare in stable form. It is conceivable that a technology for processing and purifying the scintillator on-line will be needed for the operation of such a large detector.

In Table 1 we list the power, distance and neutrino rates for the five nuclear plants giving the largest contributions.

<table>
<thead>
<tr>
<th>Reactor Site</th>
<th>Thermal Power (GW)</th>
<th>Distance (km)</th>
<th>Rate (Events/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kashiwazaki</td>
<td>24.5</td>
<td>160</td>
<td>273</td>
</tr>
<tr>
<td>Ohi</td>
<td>13.7</td>
<td>190</td>
<td>91</td>
</tr>
<tr>
<td>Takahama</td>
<td>10.2</td>
<td>210</td>
<td>60</td>
</tr>
<tr>
<td>Hamaoka</td>
<td>10.6</td>
<td>210</td>
<td>64</td>
</tr>
<tr>
<td>Tsuruga</td>
<td>4.5</td>
<td>150</td>
<td>52</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>127.0</strong></td>
<td></td>
<td><strong>700</strong></td>
</tr>
</tbody>
</table>

Table 1. Expected contribution of different reactors to the neutrino rates detected in Kamland in the case of no oscillations. Several other reactors each giving a small contribution do not have individual entries in the table but are included in the total.

Preliminary estimates place the total background to about 25 events/year. It should be remarked that, although this number appears quite low, particular care will be needed to interpret the results since in this case it will be essentially impossible to substantially reduce the signal (no single reactor contributes more than a few percent to the total neutrino rate). Another new problem arises from the fact that in case of oscillations the rate in the detector will be the superposition of a large number of baselines (one for each reactor site) each with its own specific energy spectrum (due to the particular fuel composition in the relative core). Although it is in principle easy to take into account all of this, the situation will be further confused by the statistical and systematic errors. We note here that if on one hand this will complicate the interpretation and parameter measurement in case of oscillations, on the other it should not substantially affect the $\Delta m^2$ sensitivity of the experiment that is dominated by the efficiency calibration in a regime where all sources are only a fraction of oscillation length away from the detector.

Construction for Kamland should start in early 1998 and data taking is scheduled to begin as early as mid 2000.

In addition to the neutrino oscillation physics described above the Kamland group is exploring the possibility of using their detector for a variety of
other tasks including the detection of anti-neutrinos produced by $\beta$-decay inside the Earth, the search for neutrinoless double-$\beta$ decay (loading the scintillator with Xe) and the detection of Supernovae.

So it appears like the study of reactor neutrinos is a very interesting field indeed, offering the opportunity of exciting measurements and discoveries not only in particle physics but also in astrophysics and possibly geophysics. The next 5 to 10 years should be rich of results!

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References


