Reactor Neutrinos after CHOOZ and KamLAND

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We review reactor neutrino physics that stayed at the cutting edge of neutrino fundamental research. We focus on middle baseline experiments that played a major role in neutrino oscillation physics from the years 1995 until now, providing, for instance, the world-best measurement of the last undetermined neutrino mixing angle θ_{13}. We intend to provide historical insight, discussing successes, but also aborted projects and open questions.

1 Introduction

There is now compelling evidence for flavor conversion of atmospheric, solar, reactor and accelerator neutrinos. Thus, neutrinos do have masses, and neutrino oscillation is the best scenario to explain all data.

Fission reactors are prodigious producers of neutrinos (about 10^{20} $\bar{\nu}_e$ s^{-1} per nuclear core). The fissioning of ^{235}U produces elements which must shed neutrons to approach the line of stability. The beta decays of this excess produce approximately six electron antineutrinos per fission. In modern reactors, the uranium fuel is enriched to a few percent in ^{235}U, but there are also significant contributions to the neutrino flux from the fissioning of ^{238}U, ^{239}Pu, and ^{241}Pu. During a typical fuel cycle, the Pu concentrations increase so the neutrino flux from ^{239}Pu, and ^{241}Pu grows with time. The $\bar{\nu}_e$ spectrum is calculated from measurements of the beta decay spectra of ^{235}U, ^{239}Pu, and ^{241}Pu [1] after fissioning by thermal neutrons. Since ^{238}U fissions with fast neutrons a summation of the $\bar{\nu}_e$ from all possible beta decay processes is performed. In 2011, a major breakthrough occured with the reevaluation of reactor neutrino spectra used until them, increasing the expected neutrino flux by several percents [2,3] (see figure 1).

Reactor neutrino experiments measure the survival probability $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ of the $\bar{\nu}_e$ emitted by nuclear power stations at a distance (L). This disappearance probability does not depend on the Dirac CP phase δ. Furthermore, thanks to the combination of the MeV range neutrino energies (E) and the short baselines (less than thousand kilometers) the modification of the oscillation probability induced by the coherent forward scattering from matter electrons (so-

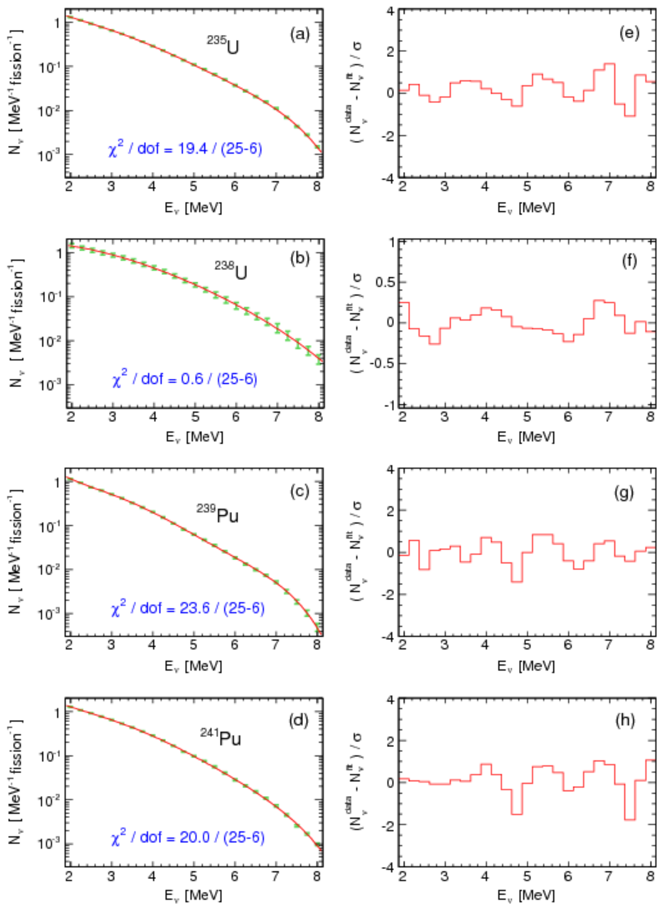

Figure 1 – Reactor antineutrino spectra as reevaluated in 2011 by the Saclay group [2,3].

called matter effect) can safely be neglected.

If neutrinos masses satisfy $m_1 < m_2 < m_3$ (so-called "Normal Hierarchy", NH), the survival probability can be written:

$$1 - P(\bar{\nu}_e \to \bar{\nu}_e) = 4\sin^2\theta_{13}\cos^2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E} + \cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2\frac{\Delta m^2_{21}L}{4E} \qquad (1)$$

$$-2\sin^2\theta_{13}\cos^2\theta_{13}\sin^2\theta_{12}\left(\cos\frac{(\Delta m^2_{31} - \Delta m^2_{21})L}{2E} - \cos\frac{\Delta m^2_{31}L}{2E}\right).$$

The first two terms of the right side of Equation (1) are, respectively, the atmospheric ($\Delta m^2_{31} = \Delta m^2_{atm}$) and solar driven ($\Delta m^2_{21} = \Delta m^2_{sol}$) oscillations, while the third term is an interference between the two contributions (see for example ref. [4] and references therein). A given experiment is only sensitive to the values of Δm^2 such that $L > L_{\rm OSC}(m) = 2.48\, E\,(MeV)/\Delta m^2(eV^2)$.

We define θ_{13} as the mixing angle that couples the heaviest neutrino field to the electron field (NH). If $\Delta m^2_{sol} << \Delta m^2_{atm}$ and/or θ_{13} is small enough, the solar driven and the atmospheric driven neutrino oscillations decouple. The mixings are then simplified, leading to two neutrino mixing approximation:

$$1 - P(\bar{\nu}_e \to \bar{\nu}_e) = \sin^2 2\theta_i \cdot \sin^2\left(1.27\frac{\Delta m^2_i[eV^2]L[m]}{E_{\bar{\nu}_e}[MeV]}\right).$$

For the reactor neutrino oscillations we can consider two extreme cases: $\Delta m^2_i = \Delta m^2_{21}$ and $\theta_i \sim \theta_{sol}$ if the baseline considered exceeds a few tens of kilometers, and $\Delta m^2_i = \Delta m^2_{31}$ and $\theta_i = \theta_{atm}$

if it is does not exceed a few kilometers. In the intermediate case, the approximation can't be used and the three neutrino oscillation formula has to be considered.

In reactor neutrino experiments electron antineutrinos are detected through the inverse beta decay process: $\bar{\nu}_e + p \to e^+ + n$. The neutrino energy is obtained from the measured positron kinetic energy with a threshold of about 1.8 MeV. Since the neutrino energy spectrum decreases with energy and the cross section increases with energy, the energy spectrum of the detected electron antineutrinos has a peak at about 3.6 MeV and decreases rapidly for larger energies, with a tail that extends up to about 10 MeV.

2 Historical context

The historical context is reviewed by Petr Vogel in these proceedings. We just give a few points here.

In the eighties and nineties, several experiments [5,6,7,8] were performed at a few ten's of meters from nuclear reactor cores at Goesgen (Switzerland), Rovno, Krasnoyarsk (Russia), and ILL Grenoble, Bugey (France). Since the knowledge of the neutrino source was not better than 10 %, they compared the neutrino rate at different distances to improve their sensitivity. A method that will become again fashionable for the measurement of the last neutrino mixing angle θ_{13}.

At that time the most stringent bounds on the oscillation parameters of this generation of experiments were obtained at Bugey. The $\bar{\nu_e}$ spectra were measured at three different source-detector distances (15, 40, and 95 m), using three identical modules filled by ^{6}Li-doped liquid scintillator. Measurements were in agreement with the no-oscillation expectation, constraining the oscillation parameters in the region $\Delta m^2_{atm} \sim 10^{-2} eV^2$ [8]. From this set of experiments the absolute normalization and the spectral shape of reactor $\bar{\nu_e}$ was thought to be known to a precision of about 2 % [9]. This agreement eventually turned out to be erronated, after the discovery of the reactor antineutrino anomaly in 2011 [10].

3 The Palo Verde and CHOOZ experiments

In the fall of the nineties, two experiments were performed to test the hypothesis that neutrino oscillations occur in the parameter region probed by the atmospheric neutrino experiments, $\Delta m^2_{atm} \sim 10^{-3}\ eV^2$ [11] (see figure 2).

The Chooz experiment [12] was located in the Ardennes region of France, 1 050 m away from the double unit Chooz nuclear reactors (PWR, 8.4 $\mathrm{GW_{th}}$). The detector was located in an underground laboratory below a 100 m rock overburden (300 m of water equivalent, mwe), providing, for the first time at reactors, a strong reduction of the cosmic ray induced backgrounds. The homogeneous detector was filled by a 5 ton Gd-doped liquid scintillator target, surrounded by a thick active (scintillating) buffer and a muon veto. The external tank was surrounded by an additional layer of low radioactive sand. This composition of shielding moderates neutrons induced by muons outside of the detector as well as the γ's produced by the rocks. Since the two Chooz reactors were commissioned after the start of the experiment, there was, at this time, a unique opportunity to perform a long in-situ background measurement.

The Palo Verde experiment [13] was located in an underground bunker under 12 meters of rock (32 mwe), 750 and 890 meters away from a 3-unit nuclear power station (11.6 $\mathrm{GW_{th}}$) in the Arizona desert. The low overburden required the use of a segmented detector to reduce the background. It was composed of 66 acrylic cells of 9 meters filled with a Gd-doped liquid scintillator, surrounded by a 1 meter thick water shielding and an efficient liquid scintillator muon veto.

Neither Chooz nor Palo Verde observed any evidence of neutrino oscillation (see figure 2). The results could be presented as the energy averaged ratio (R) between $\bar{\nu_e}$ detected and expected

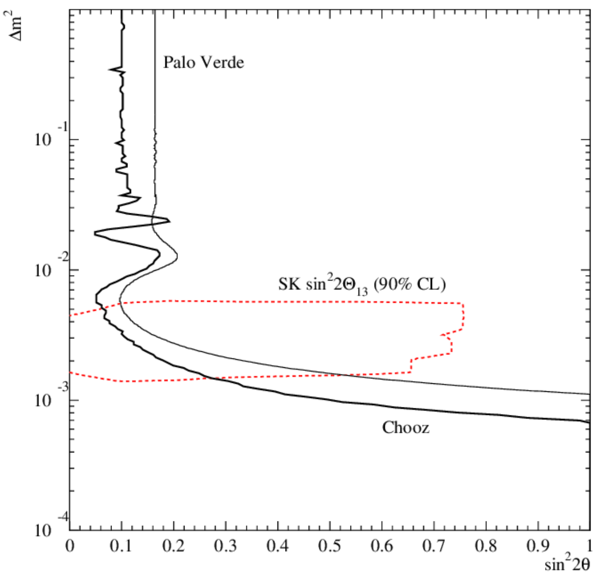

Figure 2 – Exclusion limits by the Chooz and Palo-Verde experiment [12,13].

$R_{Chooz} = 1.01 \pm 2.8\%\ (stat.) \pm 2.7\%\ (syst.)$ and $R_{PaloVerde} = 1.01 \pm 2.4\%\ (stat.) \pm 5.1\%\ (syst.)$. Both experiments excluded any $\bar{\nu_e} \to \bar{\nu_x}$ oscillation driven by $\Delta m^2_{atm} \sim 10^{-3}\ eV^2$, except for small mixing. Assuming the conservation of CPT, they excluded the $\nu_\mu \to \nu_e$ oscillation solution in the Super-Kamiokande experiment [11]. Until 2011 the Chooz experiment provided the world best direct constraint on the θ_{13} mixing angle: $\sin^2(2\theta_{13}) < 0.14$, at $\Delta m^2_{atm} = 2.5\ 10^{-3}\ eV^2$ [12].

4 The KamLAND breakthrough

A reactor neutrino experiment with a baseline distance of hundreds of kilometers is sensitive to the Large Mixing Angle (LMA) oscillation solution of the solar electron neutrino deficit. If the reactor-detector distance is slightly larger than the oscillation length, neutrino oscillations are observable as an integral reduction of the interaction rate, as well as a periodic modulation of the $\bar{\nu_e}$ spectrum, which provides a sensitivity to Δm^2_{sol}.

The KamLAND experiment [14] is located at the site of the earlier Kamiokande detector in the Kamioka mine (Japan), below 2 700 mwe of rock. The detector consists of 1 kton of ultra-pure liquid scintillator contained in a 13 m diameter transparent nylon balloon suspended in a non-scintillating oil buffer. The balloon is surrounded by about 1 900 PMTs mounted on a 18 m diameter stainless steel vessel. KamLAND is surrounded by more than 50 nuclear power units, at an averaged distance of 180 km.

The first KamLAND result, in 2001, was based on an exposure of 766 ton-year. In the absence of neutrino oscillation 365 events were expected, but only 258 $\bar{\nu_e}$ candidates were detected. Accounting for 18 expected background events, the statistical significance for reactor $\bar{\nu_e}$ disappearance is 99.998 %. Assuming CPT invariance, this result excluded all but the large mixing angle (LMA) solution to the solar neutrino deficit. It was an evidence that solar neutrino flavor transformation through the MSW matter effect [15] has a direct correspondence to antineutrino oscillations in vacuum. In addition, the energy spectrum measured by KamLAND disagreed with the expected spectral shape in the absence of neutrino oscillation at 99.6% significance and favored the distortion expected from $\bar{\nu_e}$ oscillation effect. A two-neutrino oscillation analysis led to $\Delta m^2_{sol} = 7.9^{+0.6}_{-0.5} \times 10^{-5}\ \mathrm{eV}^2$ [16].

The significance and clarity of KamLAND results were a surprise in the particle physics community. It strengthened the credibiliy of reactor neutrino physics. From that time it was clear that a new reactor neutrino experiment with a baseline corresponding to the first oscillation dip (about 60 km) could provide a high precision determination of $\sin^2\theta_{12}$. With an exposure of 60 GW_{th}kton year and a systematic error of 2 %, $\sin^2\theta_{12}$ could be determined with an uncertainty of 2 % at one standard deviation [17]. Two sites were found in France (Mont-Ventoux) and Germany (Heilbronn [4]), but the investigations did not lead to the realization of an actual project. Eventually such a measurement is being performed in China, with the JUNO experiment [18].

5 The quest for θ_{13}

Considering only the three known families, the neutrino mixing matrix is parametrized by three mixing angles. The angle θ_{12} has been measured to be large, $\sin^2(2\theta_{12}) \sim 0.8$, by the combination of the solar neutrino experiments and KamLAND. The angle θ_{23} has been measured to be close to maximum, $\sin^2(2\theta_{23}) > 0.9$, by atmospheric neutrino experiments [11] as well as by long baseline accelerator neutrino experiments. However, until 2011, we only had an upper limit on the mixing angle θ_{13}, by the Chooz experiment [12], $\sin^2(2\theta_{13}) < 0.2$. The value of θ_{13} was not only of fundamental interest to understand leptonic mixing, but also necessary to plan for the future experimental program in neutrino physics, since CP-violating observables are entangled with $\sin^2\theta_{13}$.

6 Reactor neutrinos compared to Superbeams

New accelerator neutrino beams coupled with off-axis detectors can search for a ν_e appearance signal. The observation of a ν_e excess in an almost pure ν_μ neutrino beam lead to a major evidence for a non-vanishing θ_{13}. But on the top of the statistical and systematic uncertainties, correlations and degeneracies between θ_{13}, θ_{12}, $\mathrm{sgn}(\Delta m^2_{31})$, and the CP-$\delta$ phase degrade the accessible knowledge on θ_{13} [19].

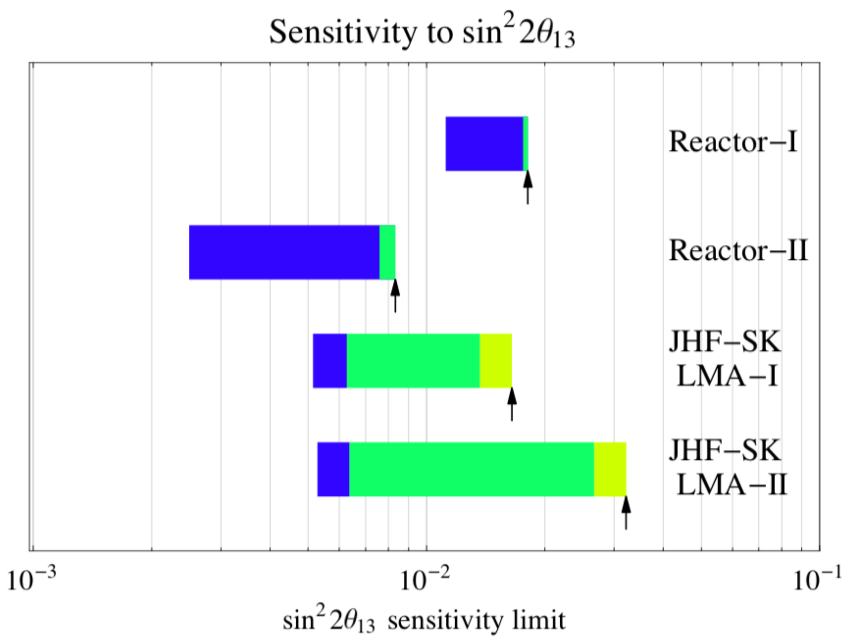

Figure 3 – First compelling study attesting the synergies between reactor and accelerator neutrino measurements of $\sin^2 2\theta_{13}$ [19].

These effects preventing beam experiments to provide a definitive precise measurement of θ_{13} were strengthened by the contribution of the group of M. Lindner that definitively clarified the complementary of the reactor and new generation neutrino accelerator programs, as illustrated in figure 3.

The importance of θ_{13}, as well as the other mixing angles, stems from it critically influencing the magnitude of any CP or mass hierarchy effects observable in forthcoming accelerator experiments.

7 The multi-detector reactor neutrino experiment concept

In order to improve the Chooz results with reactor experiments, two (or more) identical detectors close to a power station are required. The first detector has to be located at a few hundred meters from the reactor cores to monitor the $\bar{\nu_e}$ flux and spectrum before the oscillations. The second detector has to be placed between 1 and 2 km away from the core, to search for a departure from the overall $1/L^2$ behavior of the $\bar{\nu_e}$ energy spectrum, the footprint of oscillation [20].

At Chooz, the reactor induced systematic error was 1.9 %, but this class of uncertainties cancels with the new set up. After revisiting the systematics and backgrounds of the new conceptual project the Double Chooz collaboration proposed a novel 4-large-volume detector design. Two identical detectors of this new type allow relative comparison, leading to a systematic error of 0.6 %, using standard technologies [21,22].

During the years 2003-2004, a group of neutrino physicists assembled a series of workshops to explore the capabilities of a new nuclear reactor experiment. Together, they wrote a white paper called "A New Nuclear Reactor Neutrino Experiment to Measure θ_{13}" [20], addressing: The optimal baseline distances, luminosity scaling and the impact of systematics, Previous reactor Experiments, Detector Design, Calibration requirements and procedures, Detector overburden and backgrounds, Systematic error budget, Possible sites, Tunneling issues, Safety.

8 Projects that were not realized

In 2003 a short list of four sites was being thoroughly investigated in France: Penly, Paluel, Cruas and Chooz. The Chooz site was selected in summer 2003 because of the availability of the underground neutrino laboratory located at 1.05 km from the nuclear cores. In 2003-04, similar efforts were started in Angra dos Reis (Brazil), Braidwood, Diablo Canyon (US, California), Angra (Brazil), Chooz, Cruas, and Penly (France), Krasnoyarsk (Russia), Daya Bay (China), and Kashiwazaki (Japan). There were five international workshops mainly dedicated to the feasibility of new reactor neutrino experiments as well as for reviewing the potential of each site. A selection of all proposals was published in [23].

Eventually only three projects were realized, Daya Bay (China), Double Chooz (France), and RENO (Korea). These experiments can be classified into two generations. Double Chooz and RENO probing the value of $\sin^2\theta_{13}$ down to 0.02-0.03, whereas Daya Bay, approximately 10 times larger than Double Chooz, successfully endeavored to measure $\sin^2\theta_{13}$.

8.1 HLMA

The KamLAND experiment may not have been able to probe the parameter space of the solar large mixing angle (LMA) MSW solution as the origin of the solar neutrino if $\Delta m^2_{sol} > 2\times10^{-4}$ eV^2. In that case, a new medium baseline reactor experiment located at Heilbronn (Germany) was proposed to pin down the precise value of the solar mixing parameters. This reactor neutrino experiment with a baseline of $\sim$ 20 km, could be realized with detector mass of about 100 tons. With a larger mass small effects related induced by θ_{13} could be investigated. $sin^2 2\theta_{13}$ could have been probed down down to about 0.01. In 2003 new results of the KamLAND experiment were obtained after about 1 kton–year and pin down more precisely the LMA MSW solution for the solar neutrino mixing parameters. The HLMA project was not necessary anymore. Although this project was not realized, it could be considered as one of the seeds for the Double Chooz effort. The HLMA team also envisaged and quantified the possibility to measure the neutrino mass hierarchy with such a reactor neutrino experiment [4].

8.2 KR2Det

In 2001, the KR2Det russian group, led by L. Mikaelyan, was the first to propose a two-detector concept dedicated to measure the θ_{13} neutrino mixing angle. The project planned for using a reactor at Krasnoyarsk, in Russia [7]. The most attractive feature of this experiment was that the entire site is located at a depth of 600 meters of water equivalent (mwe). They proposed two detectors, each a 4.7 m diameter liquid scintillator target, enclosed in a transparent spherical balloon, viewed by 800 photomultipliers. The reactor was planned to be shut down around the year 2012, and the political situation was thus uncertain. In 2003 a visit of the facility was canceled by local securities, and development of this project ended at that time.

8.3 Kaska

Kaska was a Japanese effort aiming to start data taking end of 2008. Kaska [24] could be located close to the KAShiwazaki-KAriwa nuclear power station (BWR, 24.3 GW_{th}). The plant was composed of 7 cores divided into 2 clusters spread by 2 km. Thus, two near detectors were mandatory (each at 400 m from a cluster). The Kaska design was similar to the Double Chooz one : a 10 ton target of Gd doped liquid scintillator and a γ-catcher region enclosed in a double acrylic sphere, gamma shielding, a PMT supporting structure, and a weak scintillating region acting as a muon veto. The systematic error foreseen was between 0.5 and 1 %. The sensitivity was expected to be between $\sin^2(2\theta_{13}) < 0.017 - 0.027$ (90 % C.L., for 3 years of operation, depending on the true value of Δm^2_{atm}), in the no-oscillation case. Despite tremendeous efforts the Kaska experiment could never be funded in Japan. Therefore the Kasak group joined the Double Chooz experiment, very similar in design and aiming at the same physics goals, in term of sensitivity.

8.4 Diablo Canyon

The Diablo Canyon experiment was developed from 2003. With a large target mass, and ultra low and very well understood backgrounds, the project was proposed in order to reach a sensitivity $\sin^2(2\theta_{13}) < 0.01$ (90 % C.L.). A geological evaluation and tunnel cost estimate was performed. The excavation of a horizontal tunnel in the coastal mountains could provide overburden up to 800 mwe with tunnel distances up to 3 km. However this project lacked of political and local supports and physicists were encouraged to pursue with the Daya Bay project. This was unfortunate, since a modest excavation effort at a canyon optimally located at 1.8 km away from the reactor cores could have led to the most reasonable and optimum experiment for measuring $\sin^2(2\theta_{13})$.

8.5 Braidwood

The Braidwood experiment [25] could be located close to the Braidwood twin nuclear station (BWR, 7.2 GW_{th}), in Illinois. The area surrounding the power plant has a flat topology, thus two 120 m deep shafts as well as two large detector rooms had to be excavated. The overburden of 450 mwe would provide the same background contribution in each detector. Since all civil construction had to be realized, the detector locations could be optimized according to the true value of Δm^2_{atm}. The plan was to have $\geq$1 near detector of 25-50 tons (fiducial mass) at 270 m in the near shaft, and $\geq$2 far detectors identical to the near ones, at $\sim$1.8 km in the far shaft. The detector design of Braidwood was very different with respect to the one proposed by the Double Chooz collaboration, omitting the γ-catcher region. It could have been a real advantage now, in order to fully understand the spectral patterns. As for the case of Daya Bay the detectors were supposed to be swapped for cross calibration, by using a platform transporter as well as a high capacity crane for the operation.

8.6 Angra

The Angra experiment [26], near the 6 GW_{th} power station of Angra dos Reis in Brazil, was focusing on a high-luminosity approach to provide a full energy spectrum measurement of the spectral oscillation patterns. The far detector site could be located at 1.5 km from the primary reactor core, under 700 m of granite (1 700 mwe). The detector would be a 500 ton fiducial volume of Gd loaded liquid scintillator. The near detector could be either identical to the far detector at 300 m from the core (covered by 100 m of granite), or smaller than the far detector (non-identical) but very near to the nuclear core. If a luminosity of 6,000 GW_{th}-ton-year can be achieved, the expected sensitivity is $\sin^2(2\theta_{13}) < 0.007$. Even though supported by a fraction of the US community, the Angra project could not be eventually funded and was thus cancelled.

9 The birth of Double Chooz

The Double Chooz [21] experimental site is located close to the twin reactor cores of the Chooz nuclear power station, operated by the French company Electricité de France (EDF). The two, almost identical, detectors contain a 8 ton fiducial volume of liquid scintillator doped with 0.1 g/l of Gadolinium (Gd). The underground laboratory of the first Chooz experiment, located 1.05 km (under 300 mwe) from the cores was reused. The second detector was installed at about 400 m from the nuclear cores in a newly excavated laboratory, available from 2010. The detector design is an evolution of the Chooz detector (see figure 4).

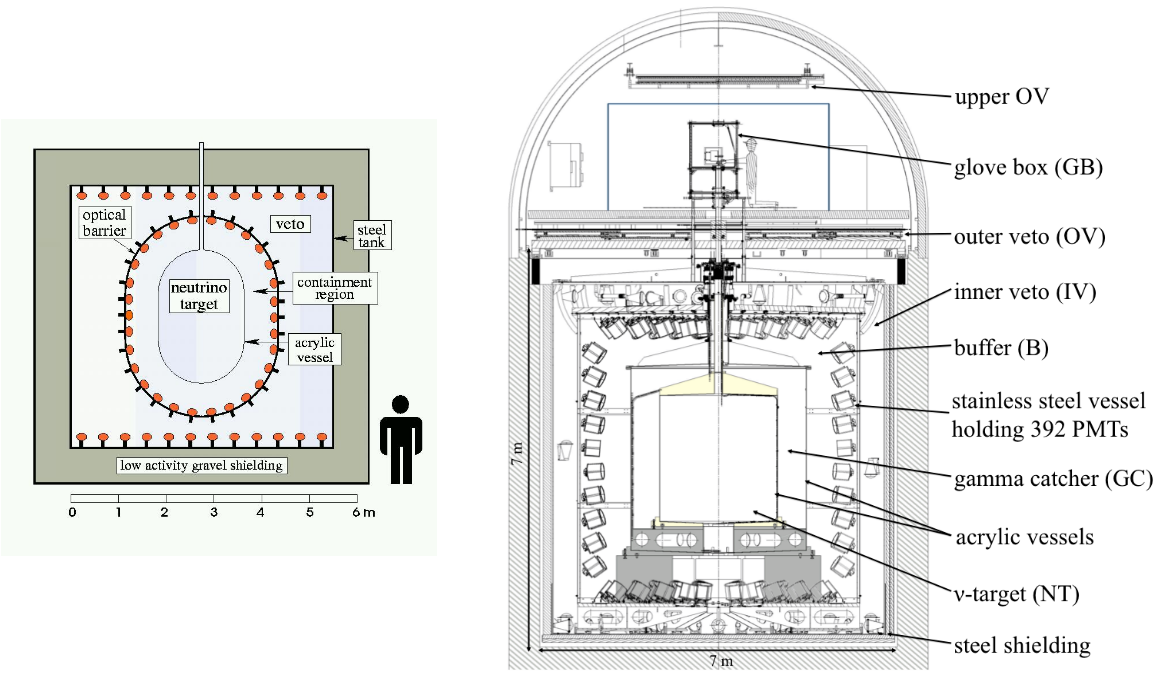

Figure 4 – (Left): Sketch of the Chooz detector. (Right): Sketch of the Double Chooz detector, a novel 4-large-volume detector design proposed by the Double Chooz collaboration and adopted by the RENO and Daya Bay experiments.

Starting from the center of the target the detector elements are as follows: the neutrino target; a thick acrylic cylinder, filled with 0.1 % Gd loaded liquid scintillator; the γ-catcher, filled with unloaded liquid scintillator (the role of this additional region is to determine the full positron energy, as well as most of the neutron energy released after neutron capture);

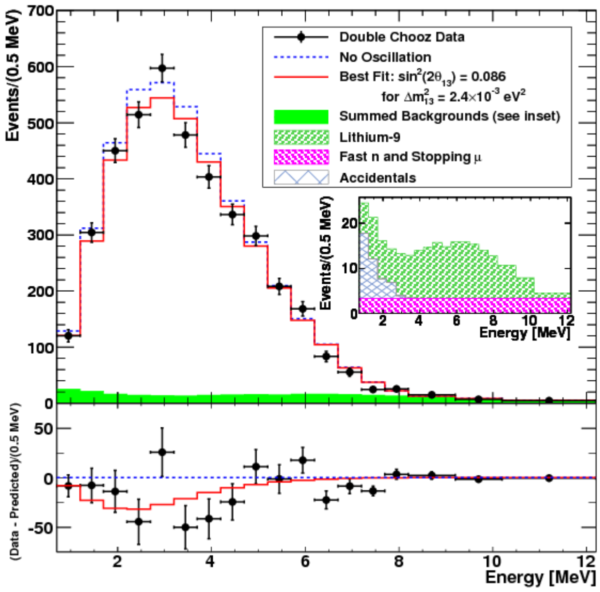

Figure 5 – First results of the Double Chooz experiment in 2011, providing the first evidence for a non-zero value of the θ_{13} mixing angle [27].

a buffer region filled with non scintillating oil, to decrease the accidental backgrounds from PMTs radioactivity ; the stainless steel structure supporting approximately 450 PMTs ; a muon veto ; an external shielding of steel protects the inner detector from the radioactivity of the rock; and finally an outer muon veto. The dominant error is the relative normalization between the two detectors. It is less than 0.6 %. Correlated events are the most severe background source. The expected sensitivity was originally estimated to be $\sin^2(2\theta_{13}) < 0.025$ (90 % C.L., for $\Delta m^2_{\rm atm} = 2.4 \times 10^{-3}$ eV^2, for 3 years of operation) in the no-oscillation case.

10 The θ_{13} discovery

The Double Chooz collaboration novel 4-large-volume detector design was later used in Daya Bay and RENO too. The experiment was approved by the French scientific councils of CEA and CNRS in 2004. The latest funding approval occurred early 2008 in Japan. Then, the near detector construction was approved in 2009. In November 2011, first results of the experiment were presented at the LowNu conference in Seoul, hinting at a non-zero value of θ_{13}. On the 29/11/2011, a preprint was submitted to present 228 days of data, excluding the no-oscillation hypothesis at 2.9 σ [27] (see figure 5). The first measurement reported was: $\sin^2(2\theta_{13}) = 0.086 \pm 0.041(stat) \pm 0.030(sys)$. Double Chooz continued to run, to reduce statistical and background systematic uncertainties. This results were confirmed and constantly improved since then. The latest Double Chooz result is $\sin^2(2\theta_{13}) = 0.105 \pm 0.014\,(stat+syst)$ [28].

The Daya Bay collaboration, started in 2004, announced on March 8, 2012, the discovery of a nonzero value for the last unknown neutrino mixing angle θ_{13}, at 5.2 σ [29], based on 55 days of data taking. The first measurement reported was $\sin^2(2\theta_{13}) = 0.092 \pm 0.016(stat) \pm 0.005(syst)$, and the most recent one is $\sin^2(2\theta_{13}) = 0.0856 \pm 0.0029\,(stat + syst)$ [30], 1958 days of operation.

The RENO experiment began in early 2004, and its proposal was approved by the Ministry of Science and Technology in Korea in May 2005. Geological survey was completed in 2007. Civil construction began in middle 2008 and was completed in early 2009. Both near and far detectors were completed in early 2011, and data taking began in early August 2011. On 3 April 2012, with some corrections on 8 April, the RENO collaboration announced a 4.9σ observation of non-vanishing $\sin^2(2\theta_{13}) = 0.113 \pm 0.013(stat) \pm 0.019(syst)$ [31]. The most recent value obtained by the RENO collaboration is $\sin^2(2\theta_{13}) = 0.0896 \pm 0.0048(stat) \pm 0.0047(syst)$ [32] using 2200 live days of data.

Although separated by more than 5 months all first results of Double Chooz, Daya Bay, and RENO eventually appeared in the same Physical Review Letter issue [27,29,31]. A history of the reactor θ_{13} experiments, as well as the contribution of the Double Chooz, can be found in reference [33].

Those results agreed well with the first 2.5 σ hint for a non-zero value of $\sin^2(2\theta_{13})$ announced by the T2K collaboration on the 15 June 2011, with the observation of six electron neutrino-like events compared to an expected background of 1.5 [34].

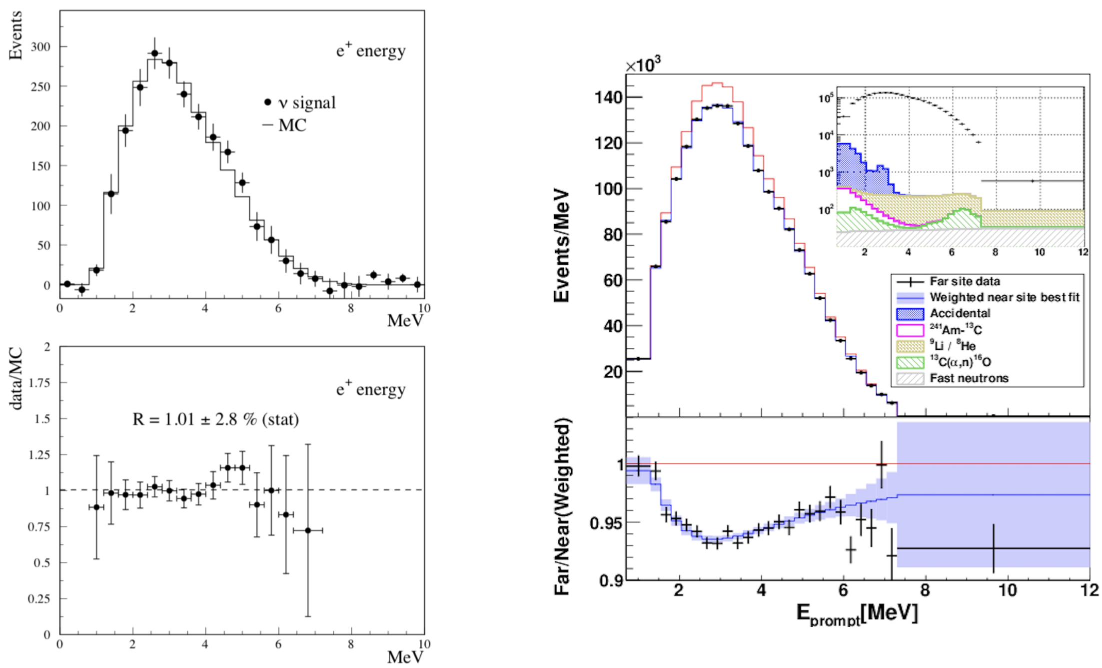

Figure 6 – (Left): The Chooz positron spectrum; the bottom panel shows the ratios of data over predictions with no oscillation. (Right): The Daya Bay background-subtracted spectrum at the far site (black points) and the expectation derived from near-site measurements excluding (red line) or including (blue line) the best-fit oscillation; the bottom panel shows the ratios of data over predictions with no oscillation [30].

Nowdays, the best knowledge of θ_{13} is inferred from high-precision reactor neutrino disappearance experiments, Daya Bay, Double Chooz, and RENO. Figure 6 gives evidence for the progress in the measurement of reactor antineutrinos, from Chooz to Daya Bay. In the early days of the preparation of those reactor neutrino projects we can remember that a sizable fraction of the particle physics community doubted that a measurement at reactors would superseed measurements planned at neutrino superbeams.

11 Open questions

A great amount of progress were realized in the field of reactor neutrino physics over the last 20 years. Nonetheless, the tremendous increase of data as well as the improvement in terms of detection and simulation led to the discovery of two important features that currently remains as open questions.

11.1 The reactor antineutrino anomaly

The reactor antineutrino anomaly was discovered in 2011 [10] as a consequence of the new calculation of Mueller et al. of the fluxes of $\bar{\nu}_e$'s produced in a reactor by the decay chains of the four fissionable nuclides ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu [2,3]. The new calculation, usually called "Huber-Mueller", predicted fluxes that are about 5% larger than the previous calculation [1]. The resulting expected detection rate turned out to be larger than that observed in several short-baseline reactor neutrino experiments with detectors placed at distances between about 10 and 100 m from the respective reactor, generating the "reactor antineutrino anomaly".

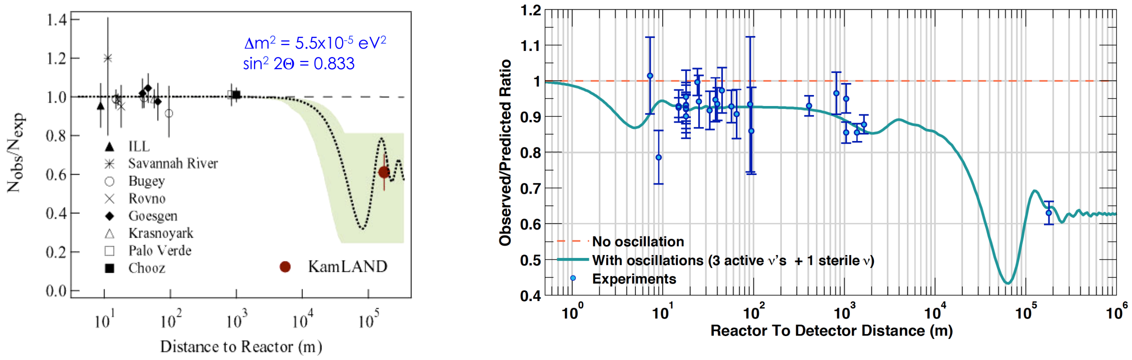

Figure 7 – (Left): Ratio of the measured to predicted antineutrino rates, before 2011 [14]. (Right): Ratio of the measured to predicted antineutrino rates, after 2011 (adapted by the author from [10]).

This change of paradigm, illustrated in figure 7, led to the realization of a sizable number of new neutrino experiments at short baseline as, given the ranges of reactor neutrino energies and source-detector distances, this deficit clould be explained by neutrino oscillations generated by a $\Delta m^2 > 0.5$ eV^2 (see ref. [35] and therein).

11.2 The 5 MeV structure

In 2014 an excess in the spectrum of detected events around 5 MeV, in comparison to the expected model, was reported by Double Chooz and then by the RENO collaborations at the Neutrino 2014 conference in Boston.

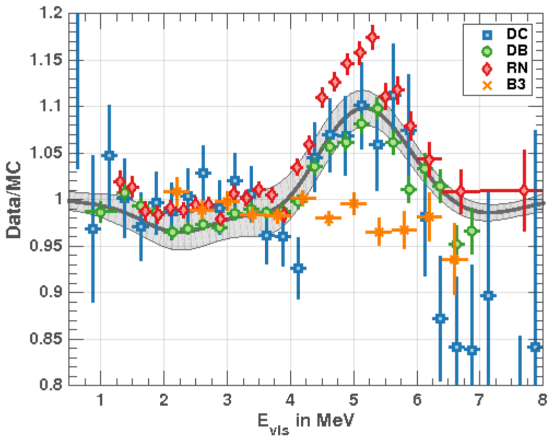

Figure 8 – Ratio of observed reactor antineutrino spectra to current best predictions [2,3]. Despite similar fuel compositions, Double Chooz (DC), Daya Bay (DB) and RENO (RN) display significant deviations around 5 MeV, while Bugey 3 (B3) does not. Figure taken from ref. [36].

It was later confirmed by the Daya Bay experiments. This structure, often called the "5 MeV bump" and displayed in figure 8 is still unexplained [37,38,39].

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